NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Phase 1 Geoscientific Desktop Preliminary Assessment, Processing and Interpretation of Geophysical Data

TOWN OF CREIGHTON, SASKATCHEWAN

APM-REP-06144-0053

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PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

PROCESSING AND INTERPRETATION OF GEOPHYSICAL DATA

Town of Creighton, Saskatchewan

Prepared for

Golder Associates Ltd.
and
Nuclear Waste Management Organization (NWMO)

by

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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 (NWMO, 2010), 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 the successful completion of an initial screening conducted during Step 2 of the site selection process.

The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations. The findings of the overall preliminary assessment are reported in an integrated report (NWMO, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Creighton area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

This report presents the findings of a geophysical data interpretation assessment completed as part of the desktop geoscientific preliminary assessment of the Creighton area (Golder, 2013). The purpose of this study was to perform a detailed interpretation of all available geophysical data for the Creighton area (e.g., magnetic, electromagnetic, gravity and radiometric) to identify additional information that could be extracted from the data, in particular regarding the coincidence of geophysical features with mapped lithology and structural features in the Creighton area.

The geophysical data covering the Creighton area show variability in dataset resolution. Medium to low-resolution magnetic, gravity, radiometric and very low frequency electromagnetic (VLF-EM) data were obtained from the Geological Survey of Canada (GSC) for the entire Creighton area. Two additional high resolution magnetic/electromagnetic surveys were obtained from Hudson Bay Exploration and Development Company Limited (Hudbay) for approximately 20% of the Creighton area to the east. Seismic and gravity data from the Lithoprobe program (THOT Line 9) begins at the Town of Creighton and continues westward along Highway 106.

The coincidence between the geophysical data and the mapped lithology and structural features were interpreted using all available geophysical data sets (e.g., magnetic, electromagnetic, gravity and radiometric). In general, the coincidence between the geophysical interpretations and the published geological maps is in good agreement, but in some locations the geophysical data provided new interpretations.

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1 INTRODUCTION

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 for safely hosting a deep geological repository (Step 3). The preliminary assessment is a multidisciplinary study integrating both technical and community well-being studies, including geoscientific suitability, engineering, transportation, environment and safety, as well as social, economic and cultural considerations (NWMO, 2013).

This report presents the findings of a geophysical data interpretation assessment completed as part of the desktop geoscientific preliminary assessment of the Creighton area (Golder, 2013). The objective of the desktop geoscientific preliminary assessment is to determine whether the Creighton area contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors. The study focused on the Town of Creighton and its periphery, referred to as the "Creighton area".

1.1 Study Objective

Geophysical data forms an important component of assessing a region for its potential suitability to host a deep geological repository, and to assist in the identification of potentially suitable siting areas.

The purpose of this study was to perform a review of available geophysical data for the Creighton area, followed by a detailed interpretation of all available geophysical data (e.g., magnetic, electromagnetic, gravity and radiometric) to identify additional information that could be extracted from the data, in particular regarding the coincidence of geophysical features with mapped lithology and structural features in the Creighton area.

The role of the geophysical interpretation is to extrapolate our current understanding of the mapped lithology and extent of overburden cover to assess how the distribution of rock units may change at depth. Drillholes, wells and other underground information may be available at individual points to supplement geological data acquired on surface. However, where these individual data points are limited (or non-existent), such as for the Creighton area, the critical advantage of airborne geophysical data is that it provides a basis for interpreting the subsurface physical properties across the area. This is particularly important in areas where bedrock exposure is limited by surface water bodies and/or overburden cover, such as is the case in parts of the Creighton area. A secondary role of geophysics is that it often elucidates certain characteristics of geological formations and structures that may not be easily discerned from surface mapping and analysis. Thirdly, it can highlight tectonic and regional-scale features that may not be easily extracted from studies of a particular area on a more detailed scale.

1.2 Creighton Area

The Creighton area (660 km^2) incorporates the Town of Creighton (approximately 16 km^2) and surrounding areas, situated on the east-central edge of Saskatchewan adjacent to the Manitoba border, a few kilometres from Flin Flon, Manitoba (Figure 1). A slightly extended area (encompassing 1,210 km^2) was used for the preparation of this supporting document in order to include the entire length of some longer geological features that extend beyond the Creighton area boundaries. 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 population centre is the City of Prince Albert, about 400 km to the southwest via Highway 106 (the Hanson Lake Road) and Highway 55.

1.3 Qualifications of the Geophysical Interpretation Team

The team responsible for the geophysical review, processing and interpretation investigation component of the Phase 1 – Geoscientific Preliminary Assessment of Potential Suitability study for the Creighton area consisted of qualified experts from Paterson, Grant & Watson Limited (PGW). The personnel assigned to this study were as follows:

Dr. D. James Misener, Ph.D., P.Eng. – geophysical interpretation, report preparation

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

Stephen Reford, B.A.Sc., P.Eng. – project management, EM interpretation, report preparation

Mr. Reford is a senior consulting geophysicist and Vice-President of PGW. Mr. Reford has 31 years of experience in project management, acquisition and interpretation of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data for clients throughout Canada and around the world. Projects include management of the geophysical component of Operation Treasure Hunt for the Ontario Ministry of Northern Development and Mines as well as a similar role for the Far North Geoscience Mapping Initiative (2006-2009). Mr. Reford has served as a consultant to the International Atomic Energy Agency (IAEA) in gamma-ray spectrometry and is co-author of two books on radioelement mapping.

Edna Mueller, M.Sc. – data processing and map preparation

Ms. Mueller is a senior consulting geophysicist for PGW. She has 18 years of experience in project management, acquisition, processing and modelling of airborne magnetic, electromagnetic, radiometric, gravity and digital terrain data throughout and gamma-ray spectrometer surveys for clients throughout Canada and around the world. In recent years, she has provided management and quality control for a number of OGS magnetic, gravity and electromagnetic surveys, and has reprocessed numerous industry surveys published by OGS.

Winnie Pun, M.Sc. – data processing and map preparation

Ms. Pun will soon complete her first year as a consulting geophysicist for PGW after completing her M.Sc. in geophysics at the University of Toronto. She has prepared hundreds of geophysical maps for publication by government agencies in Nigeria and Botswana, and most recently has carried out several 2D/3D magnetic and gravity modelling studies on several iron ore projects.

Nikolay Paskalev, M.Sc. – GIS preparation

Mr. Paskalev has been the Manager, Geomatics and Cartography for Watts, Griffis and McOuat Limited (geological consultants) since 2006 and has been with the company since 2001. His work there has included a nationwide GIS of geology, ores and industrial minerals for Egypt, a GIS compilation of geological maps for a large part of Saudi Arabia and a Radarsat and DEM study for gold exploration in Sumatra. He has also worked part-time for PGW for the last 12 years, and most recently prepared a nationwide GIS for the geophysical interpretation of Nigeria. In 2011, he incorporated World GeoMaps Inc. for consulting in geomatics, cartography and GIS.

2 SUMMARY OF PHYSICAL GEOGRAPHY AND GEOLOGY

A detailed discussion of the geological setting of the Creighton area is provided in a separate report (Golder, 2013). The following sections on physical geography, bedrock geology, structural history, Quaternary geology and land use, present summaries of the information presented in Golder (2013) and J.D. Mollard and Associates (JDMA) (2013a and b) where applicable, in order to provide the necessary context for discussion of the results of this geophysical study.

2.1 Physical Geography

A detailed discussion of the physical geography of the Creighton area is provided in a separate terrain analysis report by JDMA (2013a). The Creighton area is located at the southern margin of the Precambrian Shield. Local relief is generally low with variations in elevation of less than 100 m. Ground surface elevation ranges from about 292 masl at the shore of Schist Lake in the southeast to about 369 masl 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 rugged terrain bordering them probably represent the most distinct topographic features in the area, especially in light of the relatively flat-lying terrain in between. Amisk Lake and the highly irregular terrain around its margins forms the main topographic feature in the southwestern part of the area.

The next most distinct topographic features in the Creighton area are the elevated, plateau-like surfaces, which largely represent the surface expression of plutons (Figure 4 in JDMA, 2013a). The east-west trending ridge north of Johnson Lake is probably the best example. The isolated summits on this generally flat-topped, 5 to 8 km wide feature are at elevations of 360 to 370 masl, 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 inset 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 Creighton area contains some large lakes, including Amisk Lake, which is 308 km^2 in extent, of which about 41 km^2 falls within the Creighton area. Annabel Lake (12 km^2) and Johnson Lake (7 km^2) are the only other lakes larger than 5 km^2. Schist Lake is a large lake (24 km^2), but only a small part of it is within the Creighton area. There is a high density of small lakes on the Reynard Lake pluton in an area northwest of Highway 167. Surface water covers approximately 16% of the Creighton area. The surficial hydrology exhibits drainage patterns (e.g. orientation, alignment, and shoreline morphology) that closely follow bedrock structures. Surface drainage patterns mark the location of several large shear zones, such as Annabel Lake shear zone, West Arm shear zone, Mosher Lake shear zone, and Comeback Bay shear zone (discussed further below).

2.2 Geological Setting

The Canadian Shield is the tectonically stable core of the North American continent created from a collage of ancient (Archean) cratons and accreted juvenile arc terrains that were progressively amalgamated over a period of more than 2 Ga during the Proterozoic Eon. Among the major orogenies that contributed to the assembly of the Canadian Shield is the Trans-Hudson Orogeny, which resulted from the closure of the Manikewan ocean and terminal collision of the Rae-Hearne, Superior and Sask cratons approximately 1.9-1.8 Ga. 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 (Corrigan et al., 2007).

The Creighton area is located in the Flin Flon domain, which is part of the Reindeer zone of the Trans-Hudson Orogen that comprises part of the Canadian Shield in northern Saskatchewan. The area is immediately north of the contact with the Western Canada

Sedimentary Basin, which is the Phanerozoic cover over the southern part of the province. Figure 2 depicts the regional tectonic setting.

The Reindeer zone consists of a collage of Paleoproterozoic arc and oceanic volcanic rocks, plutons, and younger molasse and turbiditic sedimentary rocks (NATMAP, 1998; SGS, 2003). Most of these rocks were formed in an oceanic to transitional subduction-related arc setting. During collision of the Sask craton with the Rae-Hearne craton these Reindeer zone rocks were thrust over the Sask craton along the Pelican thrust (Corrigan et al., 2005; Morelli, 2009). The Reindeer zone structurally overlies approximately 3.2 to 2.4 Ga old Archean metaplutonic and paragneissic rocks of the Sask craton, which are exposed in the western portion of the Flin Flon domain through the Pelican window, approximately 70 to 80 km to the west of the Town of Creighton (Lucas et al., 1999; Ashton et al., 2005).

The Flin Flon-Glennie complex occurs within the southeastern portion of the Reindeer zone in Saskatchewan (SGS, 2003; Morelli, 2009). It is an approximately 1.9 to 1.84 Ga old ductile element 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 fluvial molasse-type sedimentary rocks (Ansdell and Kyser, 1992; SGS, 2003).

2.3 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 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; Stauffer and Lewry, 1993; Fedorowich et al., 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 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

Time Period (Ga)	Geological Event
	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 Amisk Group volcanic rocks (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, shown in Figure 3.1 of Golder (2013), 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), the Kaminis (ca. 1.856 Ga) and Reynard Lake plutons (ca. 1.853 Ga) (Ansdell and Kyser, 1990). These plutons are shown on Figure 3. 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). 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 re-activated as strike-slip structures. Subsequent regional-scale brittle faulting, including brittle re-activation 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 re-activation 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 re-activation 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. Given the close proximity of the Western Canada Sedimentary Basin to the south and the apparent continuation of the sequence in the Hudson Bay area of Manitoba to the northeast 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 (145 to 66 Ma old). 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.

2.4 Structural History

Fedorowich et al. (1995) describe 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 – 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 ESE-WNW oriented transpression between ca. 1.820 and 1.790 Ga. D_4 represents the timing of activation of strike-slip shear zones, and the re-activation 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 NW-SE compression at ca. 1.691 Ga. Protracted, post-1.691 Ga brittle re-activation of faults throughout the Creighton area is collectively attributed to a D_6 deformation event.

2.5 Local Bedrock Geology

The reader is directed to Golder (2013) for a detailed description and discussion of the bedrock and structural geology of the Creighton area. The regional bedrock geology of the Creighton area is dominated by the Flin Flon greenstone belt that is intruded by several large felsic plutonic bodies (Figure 3). The geological boundaries shown on this figure are from the Geological Atlas of Saskatchewan and the NATMAP Shield Margin project (NATMAP, 1998; Saskatchewan Energy and Resources, 2010).

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, the original terminology of Flin Flon greenstone belt, or simply greenstone belt, will be retained throughout the remainder of the report when discussing the bedrock geology of the Creighton area.

The Flin Flon greenstone belt includes mafic volcanic flows, pyroclastic rocks, lesser amounts of intermediate to felsic volcanic rocks, and metasedimentary rocks that are arranged in layers of variable thickness and have been deformed by past tectonic events (Simard et al., 2010). The rocks of the Flin Flon greenstone belt are intruded by felsic to intermediate intrusive rocks of the Annabel Lake pluton, Reynard Lake pluton and Phantom-Boot Lake pluton (Figure 3). It is these three plutons that offer the most promise for a suitable siting selection, as identified in the Initial Screening study by Golder (2011). Exposed bedrock or a thin (<1 m) veneer of surficial material covers about 38% of the Creighton area.

2.5.1 Reynard Lake Pluton

The Reynard Lake pluton is located approximately 5 km southwest of Creighton, and extends approximately 25 km to the northwest. As can be seen on Figure 3, 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 the pluton's 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 in the order of approximately 1.853 Ga old, based on dating using the single-zircon Pb-evaporation technique (Ansdell and Kyser, 1992).

Surface mapping of the Reynard Lake pluton indicates that it consists of a central core of coarse-grained porphyritic microcline granite. 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 nonporphyritic biotite granodiorite. This biotite granodiorite is medium-grained with a white to pinkish colour. The margins of the pluton are generally marked by sharp contacts with metavolcanic rocks (Bunker and Bush, 1982). Two distinct foliations have been observed in the area, the first of which has a northerly trend, followed by a younger set conforming to the boundaries of the intrusive bodies.

Core samples were obtained from a deep borehole (JXWS) drilled into the Reynard lake pluton (at approximately 300 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).

2.5.2 Annabel Lake Pluton

The Annabel Lake pluton is located approximately 3 km to the northwest of the settlement of Creighton, extending 25 km further to the west. This pluton is elongated parallel to regional east- to southeast-trending shear zones along its boundaries (Figure 3). The pluton is widest (approximately 5 km) at its southeast end.

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. 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.

No specific information at depth within the Annabel Lake pluton was found through available sources. However, based on geophysical modeling, the maximum depth of the pluton is likely in the range of 5 to 5.5 km (White et al., 2005). A conceptual cross-section of the Annabel Lake pluton is provided by Simard et al. (2010) along with detailed 1:10,000 scale mapping of the area.

2.5.3 Phantom-Boot Lake Pluton

The Phantom-Boot Lake pluton is located approximately 2 km to the south of the settlement 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 in length (north-south) and 2 km in width (east-west) (Figure 3). Surface exposure of this pluton is relatively limited (Guliov, 1989).

The Phantom-Boot Lake pluton is considered a successor-arc intrusion that was emplaced later in the tectonic evolution of the area (i.e. post-Missi Group intrusion) 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 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 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 pluton is a fine- to medium-grained porphyritic pink granodiorite-tonalite with a massive to banded texture (Guliov, 1989; Simard et al., 2010). This portion of the pluton occurs along the southwest shore of Phantom Lake. The Boot Lake pluton wraps around the Phantom Lake pluton to the west, southwest, and through to the south. The Boot Lake pluton 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).

2.5.4 Flin Flon Greenstone Belt

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 tectono-stratigraphic 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), which were formerly known collectively as the Amisk Group (ca. 1.92 to 1.88 Ga), (Bailes and Syme, 1989; Syme et al., 1996; and Bailey and Gibson, 2004).

Rocks of the Flin Flon greenstone belt within the Creighton area include mostly juvenile ocean arc and ocean floor assemblages. These rocks are the oldest in the Creighton area, and they consist of basic volcanic flows, pyroclastic rocks, and lesser amounts of acidic to intermediate volcanic rocks and clastic rocks. This assemblage also includes dykes, sills, and small intrusive porphyritic bodies.

Due to the complex structure (folding and faulting) within the Flin Flon greenstone belt, thickness of individual lithologies within the assemblage can be difficult to determine; however, 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). 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). Past tectonic events deformed these units, making their stratigraphic interpretation difficult (NATMAP, 1998; Simard et al., 2010).

2.5.5 Metasedimentary Rocks of the Missi Group

The Flin Flon greenstone belt is unconformably overlain by interlayered metasedimentary conglomerates, greywackes 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; and Simard et al., 2010). Missi Group rocks are found to the north and east of the Town. These rocks are interpreted to have been deposited due to regional uplift in a collisional tectonic environment (Fedorowich et al., 1993), and are approximately 1.847 to 1.842 Ga old (Fedorowich et al., 1993). The thickness of the Missi Group rocks is estimated to be approximately 1 to 2.75 km (Byers and Dahlstrom, 1954; Byers et al., 1965).

2.5.6 Faults and Shear Zones

Structural features in the Creighton area include major ductile shear zones, such as the Annabel Lake, West Arm, and Mosher Lake shear zones and numerous brittle faults (Figure 3). This section summarizes the available information on the mapped structures observed in the region.

The Annabel Lake shear zone strikes east along Annabel Lake and Annabel Creek on the northern margin of the Annabel Lake pluton, and is marked by a zone of intense shearing and mylonitization (Byers et al., 1965; Parslow and Gaskarth, 1981). Within the Creighton area, the Annabel Lake shear zone dips sub-vertically to the north. 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 southeast through Wilson and Meridian Lakes. It is also marked by a zone of intense shearing and mylonitization, and dips sub-vertically to the southwest. The amount of movement in 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 margin of the Reynard Lake pluton and joins the West Arm shear zone at its western extent. The Mosher Lake shear zone comprises numerous branching minor faults and zones of alteration (Byers and Dahlstrom, 1954). Although the Mosher Lake shear zone has a component of sinistral displacement, the amount of displacement is unknown, (Slimmon, 1995).

Brittle deformation features are mapped to the east and north of the Annabel Lake pluton (Saskatchewan Energy and Resources, 2010). Numerous unnamed faults are located within the greenstone rocks to the east of the pluton. Most of these features are tightly spaced (in the order of 100’s of metres) and are parallel to the southern lobe of the pluton. An orthogonal set of faults with a lower frequency and larger spacing (in the order of 2 to 3 km) appears to extend some distance into the pluton. These features are noted to the south and east of Creighton Lake. A set of faults extending through the Annabel Lake shear zone are located near the northeast side of the pluton. These faults generally strike northwest to southeast, and also may extend a short distance into the pluton (Saskatchewan Energy and Resources, 2010). Along the northeast corner of the pluton, the Triangle Lake fault cuts through a portion of the pluton and is parallel to the outer edge of the pluton in this area (Byers et al., 1965).

Brittle deformation is noted along the east edge of the Reynard pluton and within the southernmost portion of the pluton (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. 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-southwest, to the south of the pluton. The spacing of these faults ranges from approximately 200 m to 2 km (Simard et al., 2010).

Brittle deformation features have been mapped around the perimeter of the Phantom-Boot Lake pluton, with the exception of the south, which is predominantly covered by wetlands (noting that much of the pluton itself is 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 and has been the target of mineral exploration activities near Bootleg Lake (boreholes drilled between 1975 to 1984 available from the SGS Atlas of Saskatchewan; Hudbay Minerals; and Simard et al., 2010).

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 (Byers, 1962; Fedorowich et al., 1993). The Ross Lake fault system is represented by near vertical north-northeast and north-northwest trending splays of lineaments with a total strike length of over 100 km (Byers, 1962; Fedorowich et al., 1993). The Ross Lake fault system is interpreted to have formed during the fifth deformational stage as it is observed to cross-cut the Embury Lake flexure and the Annabel Lake shear zone (Ansdell and Kyser, 1990; Fedorowich et al., 1993; NATMAP, 1998; Saskatchewan Energy and Resources, 2010). 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). Although not well identified (due to lack of information), it can be assumed that some of the north-northwesterly trending faults shown within the Flin Flon greenstone belt in the Creighton area may be related to the Ross Lake fault system, as subsidiary movement along several branching faults is associated with this fault system (Byers, 1962).

It is possible that the north-south trending faults in the Creighton area, including the Ross Lake fault, are related to the Tabbernor fault system (Byers, 1962). The Tabbernor fault is located approximately 80 km west of Creighton. This feature initially formed during the Trans-Hudson Orogen approximately 1.815 Ga (Davies, 1998), likely with more recent periods of reactivation (Elliot, 1996). The fault is a topographical, geophysical and geological lineament that extends a distance greater than 1,500 km. In Saskatchewan, the fault has a north-south strike and displays sinistral movement. Several researchers have discussed evidence that the Tabbernor fault zone was active as recently as the Phanerozoic (Elliot, 1996; Davies, 1998; Kreis et al., 2004), including potential Mesozoic movement (Byers, 1962). As such, evidence of neotectonics may be preserved in younger units overlying the fault zone.

Several smaller parallel faults located within the Phantom-Boot Lake pluton have also been the target of mineral exploration activities. These faults are cut by the Douglas Lake fault, which extends into the northwest lobe of the pluton with a north-south strike. Approximately 200 m (in plan view) of sinistral movement has occurred along the Douglas Lake fault (Simard et al., 2010). At least two other north-south 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-southwest direction and largely separates the Phantom Lake intrusion to the east from a portion of the Boot Lake intrusions to the west. Due to less detailed mapping in the southern portion of the pluton, less structural information is available. Byers et al. (1965) mapped one fault in the south-central portion of the pluton (southeast of Boot Lake), with a west northwest-east southeast 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.

2.5.7 Metamorphism

Two periods of metamorphic mineral growth appear to have occurred in the Creighton region (Fedorowich et al., 1993). These periods correspond to the D_2 and D_3 deformation events described in Section 2.3 and 2.4 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 consolidation resulting in contact aureoles around the plutons (Byers et al., 1965; Fedorowich et al., 1993). This first period of peak low-grade metamorphism initiated in D_2 and was likely maintained up to D_3 (Bailes and Syme, 1989). Locally, an amphibolite grade halo has been noted around the Reynard Lake pluton, suggesting the intrusions locally increased temperatures during their emplacement (Ansdell and Kyser, 1990). The contact aureoles are 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 approximately 1.826 to 1.805 Ga (Corrigan et al., 2007). This resulted in peak metamorphism to greenschist facies within the Creighton area (Ferguson et al., 1999; Parslow and Gaskarth, 1981), allowing for good preservation of primary textures and structures (Simard and MacLachlan, 2009). This regional metamorphism is superimposed 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). The contact aureoles around the plutons are locally over-printed by chlorite-actinolite as a result of this stage of regional metamorphism. 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 gneiss 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 subgreenschist (prehnite-pumpellite) in the White Lake area approximately 8 km southeast of Creighton (Bailes and Syme, 1989; Galley et al., 1991).

2.6 Quaternary Geology

Quaternary geology of the Creighton area is described in detail in a separate terrain analysis report by JDMA (2013a). Quaternary deposits cover a total of 377 km^2 or roughly 57% of the Creighton area (Figure 4). Drift cover in much of the Creighton area is generally thin (less than 2 m) and discontinuous (Henderson, 1995), although sonic and wacker drilling indicates that drift thickness is highly variable, with depths exceeding 90 m indicated in topographic lows (Saskatchewan Industry and Resources, 2010). High relief bedrock topography in parts of the Creighton area is responsible for wide variations in drift thickness over short lateral distances (Campbell, 1988). Information on drift thickness from SGS drill holes is consistent with the statements above (JDMA, 2013a).

Glacial sediments in the Creighton area record advances of the Keewatin portion of the Laurentide ice sheet during and after the last glacial maximum, known as the Late Wisconsinan glaciation (McMartin et al., 2012). The most extensively distributed till formation is a generally sandy till overlying bedrock (Henderson and Campbell, 1992), whereas a younger formation occurring as thin and discontinuous deposits of flow till overlying glaciolacustrine sediments, and in places incorporating clasts of glaciolacustrine material, record a readvance into glacial Lake Agassiz (Campbell, 1988). The younger till occurs east of Amisk Lake and north of Annabel Lake.

The main ice flow direction in the area was to the south-southwest, indicating glaciation from a dispersal centre in the District of Keewatin, but there are distinct differences in the record of ice flow indicators north and south of Annabel Lake (Henderson, 1995). South of Annabel Lake the dominant ice flow direction is south-southwest, as indicated by striated bedrock outcrops and by the orientation of roches moutonneés along the east and west shores of Amisk Lake. This dominant ice flow direction is recorded in a few places north of Annabel Lake, but in general, it has been obliterated in this area by a readvance to the southwest. A subaqueous outwash deposit 3 to 5 km wide has been mapped north of Annabel Lake, along which a large part of Highway 106 in this area has been routed. Henderson (1995) interprets this feature as an end moraine based on its positive topographic expression and that it marks the southern limit of the southwest striae.

The entire area was flooded by glacial Lake Agassiz (Campbell, 1988; Henderson, 1995), with maximum lake level estimated by Schreiner (1984) to be between 400 and 427 m. Nearshore and offshore glaciolacustrine sediments have been mapped. Nearshore sediments consist of well-sorted, generally horizontally stratified sand and gravel normally found below the 350 m elevation (Henderson and Campbell, 1992). Offshore sediments consist of massive to rhythmically bedded fine sand, silt and clay typically deposited below 340 m elevation. Offshore sediments are found extensively along the margins of Amisk Lake (Figure 4). Glaciolacustrine deposits commonly form a blanket over previously deposited sediments, with thicker deposits in depressions.

2.7 Land Use

Land use within the Creighton area includes the population centres of Creighton and Flin Flon where there are extensive mining operations. There are also road corridors along highways 106 and 167 that provide good site accessibility (JDMA, 2013a). These land use and cultural features do not negatively impact on the geophysical interpretation.

3 GEOPHYSICAL DATA SOURCES AND QUALITY

For the Creighton area, geophysical data were obtained from available public-domain sources, particularly the GSC. Two additional high quality geophysical surveys were provided by Hudbay covering a large portion of the Creighton area.

The quality of the available data was assessed to determine which datasets are suitable for inclusion in this study. The geophysical surveys covering the Creighton area show variability in dataset resolution. The quality of the data is mainly a function of the flight line or station spacing, the sensor height and equipment sensitivity. In particular, where more than one dataset overlaps, the available data were assembled using the highest quality coverage. Various geophysical data processing techniques were applied to enhance components of the data most applicable to the current study. The integrity of the higher quality data was maintained throughout.

3.1 Data Sources

Medium to low resolution geophysical data, particularly the magnetic, gravity, radiometric and VLF-EM data obtained from the GSC, cover the entire Creighton area. Two additional magnetic/electromagnetic surveys obtained from Hudbay, through a data sharing agreement, provided higher resolution coverage over approximately 20% of the Creighton area to the east (Figure 5). They provide the highest resolution magnetic data, as well as Versatile Time Domain Electromagnetic (VTEM) electromagnetic data.

The distribution of gravity measurements tend to be sparsely located throughout the greenstone and plutonic bedrock units, and also evenly spaced along Highway 106, which is concurrent with the location of the Lithoprobe seismic reflection line. Data from the Lithoprobe program (THOT Line 9) begins at the Town of Creighton and continues westward along Highway 106. This line extends across the Flin Flon and Glennie Domains and crosses the Tabbernor fault zone (Figure 2). The geophysical data sets are summarized in Table 2 and their characteristics are discussed in detail below.

3.1.1 Magnetic Data

Magnetic data were collected by various surveys using different survey parameters outlined in Table 2. Magnetic surveys help in the understanding of geological and structural variations caused by different rock types associated with their content of magnetic minerals, such as magnetite and pyrrhotite. Magnetic maps show the distribution of magnetic and non-magnetic geologic bodies within the subsurface, and are particularly useful for delineating spatial geometry of bodies of rock, and the presence of faults and folds.

The resolution of the retrieved magnetic datasets varies greatly within the Creighton area. Surveys were flown over a period of 27 years, over which time the quality and precision of the equipment as well as the quality of the processing has improved. Variability in the quality of the survey coverage also influenced the ability of the magnetic data to identify geological structures of interest relevant to this study.

Medium resolution magnetic data from the GSC (Flin Flon Sherridon A) provides complete coverage of the entire Creighton area (GSC, 2012). This survey was flown with a sensor height of 150 m and flight line spacing of 300 m, providing it with a moderate spatial resolution. The Hanson Lake survey also provides complete coverage of the Creighton area, but at a slightly reduced line spacing of 500 m. These datasets are locally superseded by higher resolution surveys provided by Hudbay.

The high resolution Hudbay surveys (Flin A and Konuto) were flown at a lower terrain clearance compared to the GSC surveys, and 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, covering approximately 20% of the Creighton area.

3.1.2 Gravity Data

Gravity data provides complete coverage of the Creighton area (GSC, 2012), consisting of an irregular distribution of 46 station measurements, comprising roughly a station every 5 to 15 km. Several of these stations are evenly spaced along Highway 106 trending towards the northwest. These gravity stations were measured concurrently with the acquisition of the Lithoprobe seismic reflection transect.

The gravity measurements were retrieved as Bouguer corrected data. The Bouguer correction is applied to compensate for the gravity effect of the material between the measurement station and the datum elevation. However, the contribution to the measurement of the gravity effects of the surrounding topographic features (i.e. terrain correction) was not applied by the GSC.

Despite the fact that data are 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 resolution of the acquired gridded data is 2 km by 2 km.

3.1.3 Radiometric Data

The GSC radiometric data and the Hanson Lake survey provide complete radiometric coverage of the Creighton area (GSC, 2012). The acquired data show the distribution of natural radioactive elements at surface: uranium (eU), thorium (eTh) and potassium (K), which can be interpreted to reflect the distribution of mineralogical and geochemical information in the area. 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.

Retrieved radiometric data consisted of measurements of four variables:

- Potassium, K (%);
- Equivalent uranium, eU (ppm);
- Equivalent thorium, eTh (ppm); and
- Total Air Absorbed Dose Rate (nGy/h).

3.1.4 Electromagnetic

Two very low frequency electromagnetic (VLF-EM) datasets (Table 2) were acquired as part of the Flin Flon Sherridon A and Hanson Lake surveys (GSC, 2012). The Flin Flon Sherridon A survey was flown concurrently with the magnetic survey at 300 m line spacing and 150 m sensor height, and it provides data for both line and orthogonal geometries. The VLF-EM data from the survey are unfortunately of poor quality. Many of the survey lines contain large base level shifts, broad spikes and/or incoherent data.

The more recent Hanson Lake survey was flown at a wider line spacing (500 m) and utilized the orthogonal configuration only. However, none of the issues encountered with the other surveys were present, and the total field and vertical quadrature channels are both coherent and reflect the geology and topography of the area. VLF-EM systems are quite sensitive to certain topographic lineaments, such as ridges, so the interpretation must incorporate screening of topographic and bedrock sources. Coupling with conductors incorporates a directional bias, where optimal coupling occurs where a conductor’s strike is directed towards the transmitter location. VLF-EM penetration is relatively shallow and is useful for locating water-filled fractures in addition to metalliferous conductors. Data were acquired using Herz Totem 2A VLF-EM system to measure the total field and vertical quadrature signal (Shives, 1995). For this survey the VLF-EM receiver was tuned into the NLK station (24.8 kHz) in Seattle, Washington. When the NLK station was not broadcasting during the survey the VLF-EM received used the NAA station (24.0 kHz) in Cutler, Maine.

Two time domain electromagnetic (TDEM) surveys carried out by Hudbay were acquired using the VTEM system, flown concurrently with magnetic data, unfortunately include poor quality data from the Konuto and Flin A survey areas. The retrieved TDEM datasets are high resolution, flown at 200 m line spacing with the terrain clearance of the receiver at 40 m above ground surface. These surveys focused on the greenstone belts to locate volcanogenic massive sulphide (VMS) deposits. VTEM and similar TDEM systems are designed to locate moderate to highly conductive ore deposits with a reduced sensitivity to conductive overburden, and can penetrate to depths of several hundred metres, depending on transmitter power and geology.

3.1.5 Seismic Reflection

Seismic reflection data acquired by the GSC Lithoprobe project was retrieved from the Trans Hudson Orogenic transect (THOT) from within the Creighton area. This THOT seismic data was originally acquired to image the deep structure of the Trans Hudson Orogeny with an objective to determine the geometry of lithotectonic rock units as well as understand the characteristics of the major faults and shear zones within and bounding the lithotectonic domains (White et al., 2005).

The Lithoprobe seismic reflection data within the Creighton area only comprises a 19 km long section of THOT Line 9 which is 1200 km long overall (Figure 2). Line 9 begins at the Town of Creighton and continues west along Highway 106, crossing the Flin Flon and Glennie Domains as well as the Tabbernor fault zone.

The seismic data from the THOT Lithoprobe line were recorded with a 240-channel telemetric recording system and four Vibroseis units with a peak of 80,000 kgf (kilogram force). Geophones were positioned every 50 m giving the array a length of 12 km. The Vibroseis source was adjusted by 100 m intervals and performed a frequency sweep from 12 to 56 Hz for 16 seconds. This frequency sweep was completed 8 times to maximize the signal to noise ratio. The combined seismic array geometry and the use of the Vibroseis source interval provide a nominal common mid-point fold of 60. Anti-alias and 60 Hz notch filters were applied to the data and were diversity-stacked to attenuate environmental noise. Seismic data quality was monitored continuously during field acquisition.

Table 2. Summary of the Characteristics for the Geophysical Data Sources in the Creighton Area

Product	Source	Type	Line Spacing/ Sensor Height	Line Direction	Coverage	Date	Additional Comments
Flin A	Hudbay	Helicopter magnetic/ VTEM	200 m/ 40 m (TDEM), 60 m (mag)	65°	East-central	2007	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage, and provides electromagnetic coverage. Focused on greenstones and covers parts of intrusive units.
Konuto	Hudbay	Helicopter magnetic/ VTEM	200 m/ 40 m (TDEM), 63 m (mag)	95°	South-central	2008	The lower height, closer line spacing and vintage of this survey greatly improves standard GSC magnetic coverage, and provides electromagnetic coverage. Focused on greenstones and covers parts of intrusive units.
Flin Flon-Sherridon A	GSC	Fixed wing magnetic/ VLF-EM	300 m/150 m	88°	Entire Creighton area	1986	Navigation and flightpath based on photomosaics (?), digitally recorded, levelled to a nationwide magnetic datum, poor quality VLF-EM.
Hanson Lake	GSC	Fixed wing magnetic/ radiometric/ VLF-EM	500 m/120 m	90°	Entire Creighton area	1993	Lowest resolution dataset. Digitally recorded, used for radiometric and VLF-EM 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.
Lithoprobe Seismic Coverage	GSC	Reflection	50 m geophone spacing		From Town of Creighton west along Highway 106	1991-1992	Line 9 as part of the Trans Hudson Orogen Transect (THOT)

Hudbay – Hudson Bay Exploration and Development Company Limited
GSC – Geological Survey of Canada

3.2 Data Limitations

The magnetic surveys that cover the Creighton area consist of a mixture of medium and high resolution coverage. The magnetic data reflect quite coherent responses that elucidate the mapped geology, particularly in areas of limited bedrock exposure, as well as the main structural regimes.

All five data types considered, magnetic, gravity, radiometric, TDEM and VLF-EM, contribute to the interpretation. The limitation in applying these data types to the Creighton area is governed mainly by the following factors:

- Coverage and quality of data – types available, density of the coverage, vintage and specifications of the instrumentation;

- Overburden – areal extent, thickness and physical properties; and

- Bedrock lithologies – physical properties and homogeneity (e.g. pluton contacts can be easily mapped but plutons themselves are sometimes quite homogeneous, making geophysical characterization of internal structure difficult).

The user of the geophysical information must bear in mind that each method relies on characterizing a certain physical property of the rocks. The degree to which these properties can be used to translate the geophysical responses to geological information depends mainly on the amount of contrast and variability in that property within a geological unit and between adjacent geological units. The usability of each dataset also depends on its quality, especially resolution.

4 GEOPHYSICAL DATA PROCESSING

All data were processed and imaged using the Oasis montaj software package (Geosoft, 2012). Three additional magnetic grids were prepared using the Encom PA software package (Pitney Bowes, 2012). The grids that resulted from the various processing steps were also loaded in ArcMAP 10 (ESRI, 2012) using a Geosoft plug-in.

4.1 Magnetic

The acquired magnetic data located within the Creighton area and surrounding buffer areas were processed using several common geophysical techniques in order to enhance the magnetic response to assist with interpretation (Milligan and Gunn, 1997). Geophysical data from the surveys were upward or downward continued (if necessary) to a common flying height of 80 m, and regridded to a common grid cell size of 40 m. All surveys in the Creighton area where projected to the UTM13N/NAD83 coordinate system.

The GSC regional compilation was downward continued 225 m and an 8th-order 800 m low pass Butterworth filter was applied to reduce noise introduced by the downward continuation and coarse data. The Butterworth filter is a type of signal processing filter designed to have as flat a frequency response as possible in the pass band. The 800 m wavelength did not reduce the geological signal due to the line spacing of 805 m and the coarse sampling of the digitized data along the flightlines. The remaining surveys were similar in flying height so that they were not downward (or upward) continued. An 8th-order low pass filter was applied to the following survey during downward continuation:

- Hanson Lake – 300 m wavelength.

The surveys were knitted together using Oasis montaj (Geosoft, 2012), where the suture path between the grids was along the edge of the grid with the original higher resolution grid cell size so that the most detailed data was retained in the final product. The resultant grid was the residual magnetic intensity grid (i.e. total magnetic field after International Geomagnetic Reference Field (IGRF) correction) and the basis for preparing the enhanced magnetic grids.

Reduction to the Pole (RTP)

The direction (inclination and declination) of the geomagnetic field varies over the Earth and influences the shape of the magnetic responses over geological sources. At the North Magnetic Pole the inducing magnetic field is vertical (i.e. inclination of 90° and declination of 0°), which results in the magnetic response being a symmetric positive magnetic peak over a source, in the absence of dip and magnetic remanence. Transforming the measured magnetic field to a pole reduced magnetic field simplifies the interpretation, particularly to determine the location and geometry of the sources (Baranov, 1957). For the Creighton area, the residual magnetic intensity grid was reduced to the pole using a magnetic inclination of 78.2° N and magnetic declination of 8.5° E (Figure 6).

The RTP filter, computed from the residual magnetic field after it is transformed to the Fourier domain, is defined as follows:

$$L(\theta) = \frac{[\sin(I) - i \cdot \cos(I) \cdot \cos(D - \theta)]^2}{[sin^2(I_a) + cos^2(I_a) \cdot cos^2(D - \theta)] \cdot [sin^2(I) + cos^2(I) \cdot cos^2(D - \theta)]}$$

$$if\ (|I_a| < |I|), I_a = I \qquad \text{(eq. 4.1)}$$

where:
L(θ) = pole-reduced magnetic field for wavenumber *θ*
I = geomagnetic inclination
I_a = inclination for amplitude correction (never less than *I*).
D = geomagnetic declination
i = imaginary number in the Fourier domain

First Vertical Derivative of the Pole Reduced Field (1VD)

The vertical derivative is commonly applied to the RTP magnetic field data in the Fourier domain to enhance shallower geologic sources in the data (Figure 7). This is particularly useful for locating contacts (e.g. the anomaly texture is revealed), and mapping structure (Telford et al., 1990). It is expressed as:

$$1VD = {}^{dRTP}/_{dZ} \qquad \text{(eq. 4.2)}$$

where Z is the vertical offset.

Second Vertical Derivative of the Pole Reduced Field (2VD)

The second vertical derivative is commonly applied to the RTP magnetic field data in the Fourier domain to further enhance shallower geologic sources in the data (Figure 8). This is particularly useful for locating contacts (e.g. the anomaly texture is revealed), and mapping structure close to surface (Telford et al., 1990). It is expressed as:

$$2VD = {}^{d^2RTP}/_{dZ^2} \qquad \text{(eq. 4.3)}$$

where Z is the vertical offset.

One limitation of this filter is that the higher order derivatives tend to also enhance the high frequency noise in the dataset. To reduce noise that resulted from aliasing during the minimum curvature gridding process, an 8^{th}-order 200 m low-pass Butterworth filter was also applied.

Tilt Angle of the Pole Reduced Field

The tilt angle (Miller and Singh, 1994) has been applied to the RTP magnetic field data to preferentially enhance the weaker magnetic signals (Figure 9). This is particularly useful for mapping texture, structure and edge contacts of weakly magnetic sources. It is expressed as:

$$TILT = \tan^{-1}\left\{\frac{\frac{dRTP}{dZ}}{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}\right\} \qquad \text{(eq. 4.4)}$$

where X and Y are the horizontal offsets in the east and north directions. The first vertical derivative is computed in the Fourier domain whereas the horizontal derivatives in X and Y are computed in the space domain.

Analytic Signal Amplitude

The amplitude of the analytic signal (AS) (Figure 10) is the square root of the sum of the squares of the derivatives in the horizontal (X and Y), and vertical (Z) directions (i.e. the Fourier domain first vertical derivative and the space domain horizontal derivatives in the X and Y directions), computed from the total magnetic field (Nabighian, 1972):

$$AS = \sqrt{\left([\frac{dT}{dX}]^2 + [\frac{dT}{dY}]^2 + [\frac{dT}{dZ}]^2\right)} \qquad \text{(eq. 4.5)}$$

The analytic signal is useful in locating the edges of magnetic source bodies, particularly where remanence complicates interpretation. It is particularly useful to interpret the contacts of intrusions.

Depth to Magnetic Sources Using Source Parameter Imaging (SPI™)

The SPI method locates the depths of edges in the gridded magnetic data (Thurston and Smith, 1997). It assumes a 2D sloping contact or 2D dipping thin sheet model. The SPI solutions extracted from the pole reduced magnetic field grid are stored in a database. The SPI values calculated are depths between the magnetic source and the instrument height. If the survey was flown at a constant terrain clearance, then the drape height could be subtracted from the SPI value to result in a depth below surface. For the surveys in the Creighton area (Flin Flon [Sherridon A], Flin A and Konuto), the radar altimeter data were included in the survey database and were consequently used to more accurately determine the distance between the magnetic sensor and the computed depth to the magnetic source. The radar altimeter channel was gridded at the original grid cell size and sampled back to the SPI database. Thus a more accurate depth to magnetic sources could be calculated. If the value of the depth to source is < 0, i.e. above ground, it is set to a value of zero. Thus, the SPI depth with respect to the ground surface is calculated as:

- SPI_depth = SPI_value – average flying height, if no radar data are available, or
- SPI_depth = SPI_value – radar value, if available.

The SPI depths were calculated for each individual dataset in the Creighton area (Figure 11). Lower resolution grids are biased with deeper basement depths due to the reduced high frequency content. Thus, where a high resolution survey overlaps with a low resolution regional survey, the SPI depths from the low resolution grid were excluded. The depth grid was calculated with a grid cell size of 200 m.

Encom Magnetic Grids

A series grids were created to highlight the edges of both shallow and deep sources and to categorize anomalous zones into different areas (Shi and Butt, 2004). These grids are:

- rtpzsedge – gradient filters applied to the pole reduced magnetic field to emphasize edges;

- rtpzsedgezone – gradient filters and amplitude equalization filters applied to the pole reduced magnetic field to emphasize edges; and
- rtpzsplateau – gradient filters and amplitude equalization filters applied to the pole reduced magnetic field to emphasize homogeneous blocks bounded by edges.

<u>Magnetic Peaks, Troughs and Edges</u>

The semi-automated extraction of magnetic anomaly peaks, troughs and edges is useful for delineating structure, foliation, texture and contacts. Anomaly peaks typically trace the center of a source or the more magnetic horizons within a larger source. Anomaly troughs often complement the peaks, indicating a less magnetic horizon. They also may map a remanent (i.e. reversely) magnetized source, or magnetite depletions (e.g. along faults) which are a less magnetic source in a more magnetic host rock. Anomaly edges mark geological contacts or the boundaries of horizons within a geological unit. Offsets and orientation changes in the peaks, troughs and edges are useful for mapping faults and shears. Detection for peaks, troughs and edges was performed based on the CET (Centre for Exploration Targeting) Grid Analysis package in Oasis montaj (Geosoft, 2012).

The phase symmetry method, a frequency-domain approach based on axes of symmetry, is used to identify arbitrarily oriented line features. The 2D image is analyzed with 1D profiles in multiple orientations and varying scales. A line feature exhibits strong symmetry responses from profiles in all orientations not parallel to the line itself. Symmetry is closely related to periodicity: the symmetry point in the spatial domain corresponds to either a minimum or maximum of its local Fourier components. Thus the detection is carried out by frequency analysis.

The frequency analysis is performed by wavelet transform, which estimates local frequency using complex valued log-Gabor filters. The filters are comprised of an even symmetric (cosine) wavelet and an odd symmetric (sine) wavelet, each modulated by a Gaussian. These filters at different scales respond to particular bands of frequencies. The local frequency information is obtained from the convolution of the wavelet filters with the 2D data. An array of filter response vectors are generated for each point in the signal for each scale. Localized frequency representation is produced from these vectors. The frequency component is represented as a complex number; its real and imaginary parts are the outputs from the even and odd symmetry filter responses, respectively. At the point of symmetry, frequency components are at their amplitude extrema. This corresponds to where the absolute values of the outputs are high from even symmetry filter and low from odd symmetry filter, for all frequencies. This 1D analysis is performed in multiple orientations to extend to 2D analysis (Holden et al., 2008).

An amplitude threshold is then applied to the output symmetry grid, to distinguish cells that contain signal of interest from the background. A lower threshold value leads to the detection of more features, but may also introduce noise in the data. The resulting grid is binary: 1 for regions of interest and dummies for background. The grid is then skeletonized to trendlines. This process also sets the minimum valid line length.

The smallest filter wavelength used in this analysis for Creighton was four cells (equivalent to 160 m), over five scales. The filter sizes were therefore 160 m, 320 m, 640 m, 1280 m and 2560 m. All orientations were considered in the search for symmetry. A threshold value of 0.1 was applied, and a minimum line length of 3 cells (120 m) was set.

Edges were enhanced by computing the balanced horizontal gradient magnitude (TDX) (Cooper and Cowan, 2006) from the RTP grid, as modified by Fairhead and Williams (2006):

$$TDX = \tan^{-1}\left\{\frac{\sqrt{\left([\frac{dRTP}{dX}]^2+[\frac{dRTP}{dY}]^2\right)}}{\frac{dRTP}{dZ}}\right\} \qquad \text{(eq. 4.6)}$$

The first vertical derivative is computed in the Fourier domain whereas the horizontal derivatives in X and Y are computed in the space domain.

The TDX of the pole-reduced magnetic field is a more accurate locator of source edges and less susceptible to noise in the data than other forms of edge detectors. Pilkington and Keating (2009) confirmed that TDX and its analog, “theta mapping”, produce identical results and are the most robust of the edge detection techniques applicable to potential field data.

The standard deviation of the TDX grid was then computed to further improve lineament detection. This step is effective for data with large and/or continuous features. The standard deviation value of a cell is a measure of its variability with respect to its neighbouring cells within a square window. A window size of 5 by 5 cells (200 m by 200 m) was set for this analysis.

The positive peak values are extracted by applying an amplitude threshold to the TDX grid to identify cells of interest. The resulting grid is binary and is skeletonized to locate the source edges. In this project, a threshold value of 0.9 was used.

The peaks, troughs and edges generated using the CET methods were not submitted directly for further lineament analysis. The Encom grids and TDX images are not presented in this report. However, all of these maps and images were used as guides during the manual interpretation process. The accuracy and reliability of these products were greatly influenced by the resolution of the original magnetic data.

4.2 Gravity

The following four gravity grids and their gravity station locations were downloaded, and gravity grids were extracted from the GSC gravity compilation (GSC, 2012) at 2,000 m grid cell size:

- Bouguer gravity field (Figure 12);

- First vertical derivative of the Bouguer gravity field (Figure 13);
- Total horizontal gradient of the Bouguer gravity field; and
- Isostatic residual gravity field.

All grids were reprojected to the Creighton area coordinate system, UTM13N/NAD83. The first vertical derivative (1VD) and total horizontal gradient (THG) were computed by the GSC using the same methodology applied to the pole reduced magnetic field, as described in Section 4.1. The total horizontal gradient of the Bouguer gravity provided similar results as the first vertical derivative, and therefore was not presented in this report. The isostatic residual compensates for mass deficiencies at depth predicted from topography, preserving the shorter wavelength components of the field due to nearer surface sources. In the Creighton area, the isostatic residual field closely resembles the Bouguer gravity field due to the relatively gentle topography, and therefore was not presented in this report. The GSC applied standard gravity reduction methods to compute the free air and Bouguer gravity fields. A Bouguer correction density of 2.67 g/cm^3 was applied, the typical value for the Canadian Shield. As the data for the Creighton area were collected as far back as 1950, for the older surveys station elevations were likely determined using barometric altimeters (much less accurate than GPS) and terrain corrections were not applied.

4.3 Radiometric

The following seven radiometric grids (radioelement concentrations and ratios) were downloaded for the Creighton area from the Hanson Lake survey flown at 500 m line spacing (GSC, 2012) at 100 m grid cell size:

- Potassium (K %);
- Thorium (eTh ppm);
- Uranium (eU ppm);
- Total air absorbed dose rate (nGy/h);
- Thorium over potassium ratio (eTh/K);
- Uranium over potassium ratio (eU/K); and
- Uranium over thorium ratio (eU/eTh).

The determination of the radioelement concentrations, dose rate and ratios followed the methods and standards published by the International Atomic Energy Agency (IAEA, 2003), many of which were developed at the GSC. All grids were reprojected to the Creighton area's coordinate system, UTM13N/NAD83. The dose rate is a calibrated version of the measured "total count", and reflects the total radioactivity from natural and man-made sources. The radiometric data are presented in Figure 14 as a ternary RGB image of the three radioelements, with the intensity of potassium (%) displayed in red, equivalent thorium (ppm) in green and equivalent uranium (ppm) in blue. Areas of highest intensity in all three radioelements show light colours and trend towards white. Areas of lowest intensity of all three radioelements are dark colours and trend towards black.

4.4 Electromagnetic

The data for the Flin A and Konuto surveys provided by Hudson Bay Exploration and Development Company Limited included VTEM electromagnetic (TDEM) data. The VTEM data consisted of 24 channels (120 to 6578 microseconds) of Z-component data, for both the measured dB/dT signal and the calculated B-field signal (i.e. the integrated dB/dT). The B-field is useful as it is more sensitive to deeper bedrock sources and less sensitive to shallow overburden sources. All of these data channels were gridded, imaged and reviewed. Although they were not perfectly levelled, they were sufficiently clean to compute their decay constants (Figure 15), which is a measure of how quickly the currents induced in the ground remain circulating in the rocks. A longer decay constant typically indicates a "good" conductor. The power line monitor was also gridded to assess the presence of cultural responses. There are numerous power lines in the survey blocks of varying strengths that produce curvilinear anomalies, which were screened out during interpretation of bedrock conductors.

The GSC surveys included VLF-EM data: Hanson Lake – line transmitter only, Flin Flon (Sherridon A) – both line and orthogonal transmitters. The VLF-EM total field and quadrature components from all surveys and all transmitters were gridded. The data from the Hanson Lake survey was by far the cleanest, and was used for picking the VLF-EM conductors. That survey used the Seattle, WA transmitter, or the Cutler, ME transmitter when the former was not operational (Shives, 1995). Due to the directional nature of the method, there is a preference of conductors oriented subparallel to the direction between the transmitter and survey rather than those that are orthogonal. This accounts for the west southwest orientation of the VLF-EM responses (Figure 16).

4.5 Seismic Reflection

The Lithoprobe seismic transect (Line 9) across the Creighton area was incorporated in a comprehensive geophysical model section across the Trans-Hudson Orogen (White et al. 2005). The authors reprocessed the previously acquired and time-migrated seismic reflection data as follows:

- Projected onto a straight line section – this more accurately represents the dips for migration processing and interpretation; and
- Applied depth migration using a velocity model developed from seismic refraction – wide-angle reflection data – this allows for direct comparison of depths in the seismic refraction model with the seismic reflection sections, and incorporation of the seismic results with depth information derived from gravity and magnetotelluric (resistivity) data.

5 GEOPHYSICAL INTERPRETATION

5.1 Methodology

The coincidence of geophysical features with mapped lithology and structural features were identified and interpreted for the Creighton area using all available geophysical datasets. In particular, the pole reduced magnetic field and its first vertical derivative were the most reliable for mapping variations in geological contacts, identifying heterogeneity, and delineation and classification of structural lineaments (faults, dykes). The results from the structural lineament interpretations are presented in the lineament report for the Creighton area (JDMA, 2013a). The first and second vertical derivatives were used to trace quasilinear magnetic anomaly peaks that are interpreted to outline the ductile structure. The features identified within the interpreted metavolcanic and mafic rocks, as well as within the intrusive, metamorphic and sedimentary rocks, are classified as lithotectonic layering.

The following enhanced grids of the magnetic field data were used to assist in the interpretation:

- Pole-reduced magnetic field – magnetic units (Figure 6)
- Pole-reduced first and second vertical derivatives – boundaries, texture, foliation (Figure 7 and Figure 8);
- Tilt angle – subtle magnetic responses (Figure 9); and
- Analytic signal – anomaly character, texture, boundaries (Figure 10).

Gravity data were of insufficient resolution to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale units were possible (Figure 12 and Figure 13). The resolution of the radiometric data is reasonable, although there is dilution of signal due to overburden and drainage (Figure 14). Conductors with bedrock sources were interpreted from both the VTEM and VLF-EM data (Figure 15 and Figure 16).

The coincidence of the lithological units with the geophysical data was mainly recognized in the magnetic images from their anomaly amplitude, texture, width, and orientation characteristics. The automated peaks, troughs and edges generated from the magnetic data assisted in more accurate location of contacts. The magnetic anomaly characteristics and geophysical contacts were compared to the current bedrock geology map in order to identify similarities and/or changes in the lithological contact locations. In some cases, difference in the boundaries determined from the magnetic data and the mapped boundaries may reflect a subsurface response which may not match the mapped surface contacts (e.g. dipping unit) and/or a contact extended through locations with limited outcrop exposure (e.g. under overburden and drainage cover). Results of the coincidence between the geophysical interpretation and the bedrock geology map are presented in Figure 17. The geophysical data were evaluated against the following published geological map:

- Saskatchewan Energy and Resources, 2010. Geological Atlas of Saskatchewan. NTS Map Sheets 73O/P, 74 A/B (Figure 2 and 3);
- Saskatchewan Geological Survey, 1954. Geology and Mineral Deposits of the Amisk-Wildnest Lakes Area, 63 L-9, 63 L-16, Saskatchewan. Report 14 (Byers and Dahlstrom, 1954); and
- Saskatchewan Geological Survey, Saskatchewan Energy and Mines, 1965. Geology and Mineral Deposits of the Flin Flon Area, Saskatchewan. Report 62 (Byers et al., 1965).

5.2 Results

The following section presents a regional-scale description and interpretation of each geophysical dataset in the Creighton area, followed by detailed interpretations of geophysical responses within the Reynard Lake, Annabel Lake and Phantom-Boot Lake plutons. Using the published regional bedrock geology maps as a starting point, the integration of all suitable geophysical information provides a preliminary interpretation of a subsurface distribution of geological units for the Creighton area presented on Figure 17.

5.2.1 Magnetic

The magnetic field data for the Creighton area is displayed in images of the reduced to pole (RTP) residual magnetic field (Figure 6), its first and second vertical derivatives (Figure 7 and Figure 8), tilt angle (Figure 9) and analytic signal (Figure 10). The magnetic field within the Creighton area has a range of 5,749 nT, from a maximum of 4,854 nT to a minimum of -895 nT. The most quiescent magnetic responses observed are generally coincident with the granodiorite-tonalite plutons, followed by the acid volcanics and metagreywacke gneisses. The plutonic units generally exhibit a moderate to low regional magnetic background where the boundaries are typically well defined adjacent to the high magnetic response associated with the metasedimentary rocks of the Missi Group and the basic to intermediate volcanic to metavolcanic units. These boundaries are well developed in the first and second vertical derivatives of the RTP magnetic field, as well as the analytic signal grid.

The highest magnetic response in the Creighton area is predominantly associated with the metasedimentary rocks of the Missi Group. These units occur predominantly along the boundaries of the Annabel Lake and Reynard Lake plutons, primarily along the northern boundary of the Annabel Lake pluton and the southern boundary of the Reynard Lake pluton. The basic to intermediate volcanics and metavolcanic units also display intermittent magnetic high responses and are distributed throughout most of the Creighton area. These units are generally reflected in the magnetic data by narrow, long curvilinear anomalies reflecting a single or multiple subparallel horizons, which wrap around the younger plutons and other intrusions. The wide variations in orientation reflect the ductile deformation history.

5.2.2 Gravity

The Creighton region has been surveyed by regional GSC ground gravity, with a total of 127 gravity stations (Figure 12 and Figure 13), of which 46 are located within the Creighton area. The bulk of the stations were measured along Highway 106, from Flin Flon west along the northern sides of Annabel and Johnson lakes. This survey line therefore crossed the northern edge of the Annabel Lake pluton and the resultant Bouguer anomaly map reveals a negative anomaly across the pluton. The gravity response increases to the south and east, corresponding to the presence of the Flin Flon greenstone belt and possibly indicating a shallower extent for the Reynard Lake pluton.

5.2.3 Radiometric

The 500 m line spacing of the radiometric survey provides signatures over the various geologic units where they are not water covered (Figure 14). The granodiorite-tonalite rock units (including Reynard Lake, Annabel Lake and Kaminis Lake plutons) display moderate-to-high radioelement responses that are generally elevated in potassium. The conglomerate and psammitic gneisses show high responses in all three radioelements. The rocks on Missi Island also display a high response in all three radioelements with elevated potassium over the leucogranodiorite-tonalite units. Rock units that are generally low in all three radioelements coincide with the basic volcanics and mafic volcanic gneisses. The acid volcanic rock units correspond to moderate radioelement responses generally elevated in thorium.

The boundaries of the radiometric data do not always match well with boundaries based on geological mapping or evident in the magnetic field data. This may be partially due to the smearing effect on the radiometric response by glacial erosion and transport of surficial material along ice flow directions.

Within the larger area covered by the Hanson Lake radiometric survey, Shives (1995) notes that three past producing gold mines (Bootleg Lake, Phantom Lake and Laurel Lake) and the West Arm Cu-Zn mine coincide with discrete Th/K ratio lows, a signature which typically reflects potassium enrichment associated with emplacement of mineralization. Additional Th/K lows are present and correlate with anomalous base metal geochemistry or stratigraphy known to host base metal occurrences in the upward ice flow directions. The Th/K values are generally low over the plutons, but this is ascribed to higher levels of potassium that reflect a lithologic signature rather than mineralization.

For the portion of the Hanson Lake survey within the Creighton area, the radioelement responses are summarized in Table 3.

Table 3: Radioelement Responses of the Creighton Area

Radioelement	Minimum*	Maximum	Mean
Potassium (%)	-0.05	2.54	0.73
Uranium (ppm)	-0.64	6.58	0.85
Thorium (ppm)	-0.52	15.91	2.38
Natural air absorbed dose rate (nGy/h)	-2.67	60.70	18.94

*Negative values are not unusual due to the statistical nature of gamma-ray spectrometer data and grid interpolation effects.

These levels are typical of intermediate to mafic volcanics, mafic intrusions and metamorphic rocks (IAEA, 2003) and well below those of felsic volcanics and felsic (alkalic) intrusions. The low uranium levels suggest low radon risk. However, radon risk is also quite dependent on soil permeability and should be verified by soil gas measurements (IAEA, 2003).

5.2.4 Electromagnetic

Both the VTEM and VLF-EM images were interpreted to map bedrock sources. This was done in conjunction with topography and the presence of Quaternary deposits as both datasets also reflect variations in electrical conductivity associated with the Quaternary units as well as various drainage responses and geomorphology, particularly ridges and steeper shorelines.

5.2.4.1 Versatile Time Domain Electromagnetic (VTEM)

The VTEM data (Figure 15) show a limited number of bedrock conductors across the Creighton area. Several linear features in the data can be traced along power lines that are reflected by the 60 Hz monitor. Additional weaker responses do not show a 60 Hz response but do follow roadways and likely are cultural in origin as well. Broader zones of weak conductivity correlate with the lakes and reflect lake bottom sediments. The strong conductive responses to the northeast occur partly over Embury Lake but also extend well onshore and reflect conductive greenstones. Some of the bedrock conductors to the northeast, southeast and southwest, reflect conductive horizons and/or faults in the greenstone units.

5.2.4.2 Very Low Frequency Electromagnetic (VLF-EM)

The orientation of the VLF-EM line transmitter relative to the Creighton area results in the best coupling with the east-southeast orientation and the worst with east-northeast (Figure 16). Much of the response follows the geomorphology of the area. The interpreted conductors are located mainly in the southwest, southeast and northeast locations and comprise predominantly northeast and east-northeast orientations. They are located mainly in the Missi Island area, the southeastern part of the Reynard Lake pluton, the quartz diorites further to the southeast and the greenstones surrounding Creighton. Most of the VLF-EM conductors are coincident with, or subparallel to, structural lineaments interpreted from the magnetic data and may reflect water-filled fractures. A few conductors that follow roads have been omitted from the interpretation as they likely reflect cultural sources.

5.2.5 Seismic Reflection

A conceptual model section summarizing the crustal architecture of the Trans-Hudson Orogen developed by White et al. (2005) is reproduced as Figure 3.2 in Golder (2013). In the Creighton area, the model section is oriented east-west, and projected approximately 25 km south of Line 9 where it runs along Highway 106. The model framework was derived from the seismic reflection data, with additional contributions from velocity (reflectivity), density and resistivity models derived respectively from seismic refraction – wide-angle reflection, gravity and magnetotelluric data. The key contributions from these models in the Creighton area are that:

- The plutonic rocks show an apparent thickness of approximately 6 km;
- The Flin Flon belt, consisting of mafic volcanics overlying arc volcanic and plutonic rocks, thicken from a few km to the west (where it is truncated by the Sturgeon-Weir fault) to 35 km to the east (where it is truncated by the Athapapuskow Lake shear zone); and
- The Flin Flon belt is underlain by two horizons of arc basement/lower crust and transitional crust, each more than 20 km thick down to the Moho.

These correlate with increasing anomalous seismic velocity to the east within the Flin Flon belt, and decreasing with depth into the underlying basement and crust.

5.3 Geophysical Interpretation of the Prospective Geology in the Creighton Area

The following section provides more detailed interpretations with a focus on identifying geophysical units, which may correspond to internal heterogeneity associated with lithology contrasts within the three major plutons (Reynard Lake, Annabel Lake, Phantom-Boot Lake) in the Creighton area. These interpretations include a description of the geophysical characteristics of each unit, as well as a refinement of geologic contacts, where possible, and the identification of internal heterogeneities within the structures where present. These interpreted units are presented alongside the current bedrock geology mapping on Figure 17, noting that the interpretations are preliminary and require future geologic validation.

5.3.1 Reynard Lake Pluton

The Reynard Lake pluton is well-defined magnetically by a flat response and exhibits a moderate to low magnetic background relative to the adjacent mafic volcanics/gneisses and the more mafic intrusions to the southeast. The outline of the Reynard Lake pluton in the magnetic data corresponds well to the bedrock geology map, with the exception of the southern geological contact. Based on results from the magnetic data, the southern boundary of the Reynard Lake pluton may display some minor inconsistencies with the bedrock geology (<1 km). This interpretation may correspond to the position of the pluton boundary at depth, and would need to be verified during subsequent stages of investigation. A number of widely spaced magnetic anomalies of low amplitude are observed trending west-northwest to northwest distributed throughout the pluton (Figure

17; units A through C). These units are suggested to reflect the presence of lithological variability towards the margins of the plutons, and may correspond to remnant basic volcanics/mafic volcanic gneiss and/or gabbro-diorite phases. They are characterized by disruptions in the long, curvilinear anomalies that reflect the foliation in the plutons and shearing along their boundaries. These areas are highly coincident with detailed field mapping described as a border zone of contaminated granodiorite units with inclusions of volcanic rock units (Byers and Dahlstrom, 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 the Reynard and Patmore lakes at its southeast end (Figure 17; unit D). This area is also highlighted by a different radiometric response than the remainder of the pluton, which is more potassium-dominant. These suggest a more quartz-rich phase of the pluton.

The gravity coverage over the pluton is too sparse to draw any conclusions. The partial VTEM and complete VLF-EM coverage shows that most of the conductive activity in the area is associated with the more mafic intrusions along the margins.

5.3.2 Annabel Lake Pluton

The magnetic response over Annabel Lake pluton is fairly similar to that of the Reynard Lake pluton. The pole reduced magnetic field data show a range of values from -110 nT to 150 nT. The Annabel Lake pluton is somewhat more magnetically active than the Reynard Lake pluton, and shows the ductile deformation patterns evident on a broader scale in the northern and eastern parts of the Creighton area. The pluton has two fairly distinct zones consisting of 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 magnetically quiet area displays a distinct change in response toward the east. This change in magnetic response is coincident with a change in bedrock composition from granodiorite dominated in the northwest towards a biotite granodiorite along the eastern portion of the pluton (Byers and Dahlstrom, 1954; Byers et al., 1965). In addition, based on structural lineation measurements within the pluton, 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). These structural lineation measurements are consistent with curvi-linear ductile features readily observed in the reduced to pole magnetic field and the processed magnetic data presented in Figure 6 to Figure 11.

The eastern portion of the Annabel Lake pluton exhibits a more active magnetic pattern. Whereas, the overall background is still subdued, zones of disrupted magnetic lineations (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 volcanic and plutonic rocks compared to what has been mapped. Similar to the Reynard

Lake pluton, the magnetic interpretation suggests the presence of small 500 m to 2 km diameter anomalies (Figure 17; units E and F), which may correspond to gabbro-diorite intrusions, characterized by disruptions in the curvilinear anomalies that reflect the foliation in the plutons and shearing along their boundaries. Agreement with available mapping with respect to these features shows some inconsistencies. For example, the available geophysical interpretation suggests that the pluton may shift further to the north and northeast towards Black Lake and Hamell Lake compared to the current bedrock geology map (NATMAP, 1998). However, the lateral extent of the remainder of the pluton is generally consistent between the available mapping and the current geophysical interpretation.

Within the pluton towards the southern edge, there is a 20 km long curvilinear magnetic anomaly. Its signature is similar to those in the northeast part of the pluton which reflect horizons of intermediate to mafic volcanics and derived gneisses along the edge or within the pluton. In this northeast area (e.g. Amer Lake to Hamell Lake), there may be more mixing of volcanic and plutonic rocks than has been mapped.

The gravity low (~20 mGal) defined along the northern edge of the Annabel Lake pluton suggests that it may have a significant depth extent. North-northeast oriented gravity traverses across the Annabel Lake and Reynard Lake plutons would provide for direct comparison between the two and provide further constraints on their dipping contacts.

The Annabel Lake pluton shows a potassium-dominant radiometric response, very similar to the northern two-thirds of the Reynard Lake pluton. The limited VTEM coverage shows this pluton to be electrically quite resistive. Towards the east end of the pluton and extending into the greenstone belt to the northeast, two sets of east-northeast oriented VLF-EM conductors strike orthogonal to the mapped faulting and local stratigraphy and magnetic foliations. They appear to be associated with a set of faults interpreted from the magnetic data. The VLF-EM responses may indicate water-filled fractures.

5.3.3 Phantom-Boot Lake Pluton

The Phantom-Boot Lake pluton is complex from both the geological and geophysical perspective. The magnetic amplitudes over this pluton and nearby intrusions are the strongest of any in the area over intrusive rocks, where the higher magnetic susceptibility indicates a more dioritic-gabbroic composition than the Reynard Lake and Annabel Lake plutons, as evident in the geological mapping. Multiple phases are evident in both the magnetic and radiometric data, where high variability in rock properties and sharp boundaries occur at scales of a kilometre or less (Figure 17). The geological mapping in this area shows a complicated distribution of intrusive phases adjacent to the volcanic rocks. They have been subdivided in the magnetic interpretation according to variations in amplitudes, widths and orientations. The granodiorite tonalite core shows northeast oriented foliations whereas to the southwest in the vicinity of Boot Lake, they run NNW as do the adjacent greenstones.

The Kaminis Lake pluton to the southeast also exhibits a more active and variable magnetic signature. 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, nor is there sufficient VTEM coverage. The VLF-EM data show one well-defined conductor lying subparallel to the north-trending foliation within the tonalite-quartz diorite on the north side of the plutonic complex.

6 SUMMARY OF RESULTS

The purpose of this study was to identify and obtain the available geophysical data for the Creighton area, followed by a detailed interpretation of all available geophysical data (e.g., magnetic, gravity, electromagnetic and radiometric) to identify additional information that could be extracted from the data. In particular, the coincidence of geophysical features with mapped lithology and structural features in the Creighton area was examined.

The geophysical data covering the Creighton area show variability in dataset resolution. Medium to low-resolution magnetic, gravity, radiometric and very low frequency electromagnetic (VLF-EM) data were obtained from the Geological Survey of Canada (GSC) for the entire Creighton area. Two additional high resolution magnetic/electromagnetic (VTEM) surveys were obtained from Hudson Bay Exploration and Development Company Limited (Hudbay) for approximately 20% of the Creighton area to the east. Seismic and gravity data from the Lithoprobe program (THOT Line 9) begins at the Town of Creighton and continues westward along Highway 106.

The coincidence between the geophysical data and the mapped lithology and structural faults were interpreted using all available geophysical datasets (e.g., magnetic, gravity, electromagnetic and radiometric). In particular, the pole reduced magnetic field (RTP) and its first vertical derivative (1VD) were the most reliable for mapping variations in geological contacts, identifying heterogeneity and ductile features. The ductile features are interpreted as being associated with the internal fabric to the rock units and may include in places sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation. In general the coincidence between the geophysical interpretations and the published geological maps is in good agreement, but in some locations the geophysical data provided new interpretations.

In places in the Creighton area, the magnetic data show a greater level of detail than the geological mapping, both in terms of the internal lithological variability or foliation and deformation. In general, the plutonic units generally exhibit a moderate to low regional magnetic background where the boundaries are typically well defined adjacent to the high magnetic response associated with the metasedimentary rocks of the Missi Group and the basic to intermediate volcanic to metavolcanic units. Zonation within the larger plutons is also evident. The greenstone units display intermittent magnetic high responses and are distributed throughout most of the Creighton area. These units are generally reflected in the magnetic data by narrow, long curvilinear anomalies reflecting a single or multiple subparallel horizons, which wrap around the younger plutons and other intrusions. The wide variations in orientation reflect the ductile deformation history. The major shears are also reflected in the magnetic data where they bound the plutons and elsewhere.

Resolution of the gravity data were insufficient to be used for interpretation of geological units and boundaries. However, some general characterizations of the regional scale geological units were possible, providing some evidence of a gravity low over the Annabel Lake pluton may indicate a significant depth extent, as well as regional highs associated with broader portions of the greenstones.

A limited number of bedrock conductors were interpreted from the VTEM data, and most of these are located in the greenstones following ductile features (which is where the surveys were concentrated). Several VLF-EM conductors were interpreted towards the south and east. The majority is located in intrusive rocks, and may reflect water-filled fractures that correlate with faults sets interpreted from the magnetic data.

Respectfully Submitted,

PATERSON, GRANT & WATSON LIMITED

D. James Misener, Ph.D., P.Eng.
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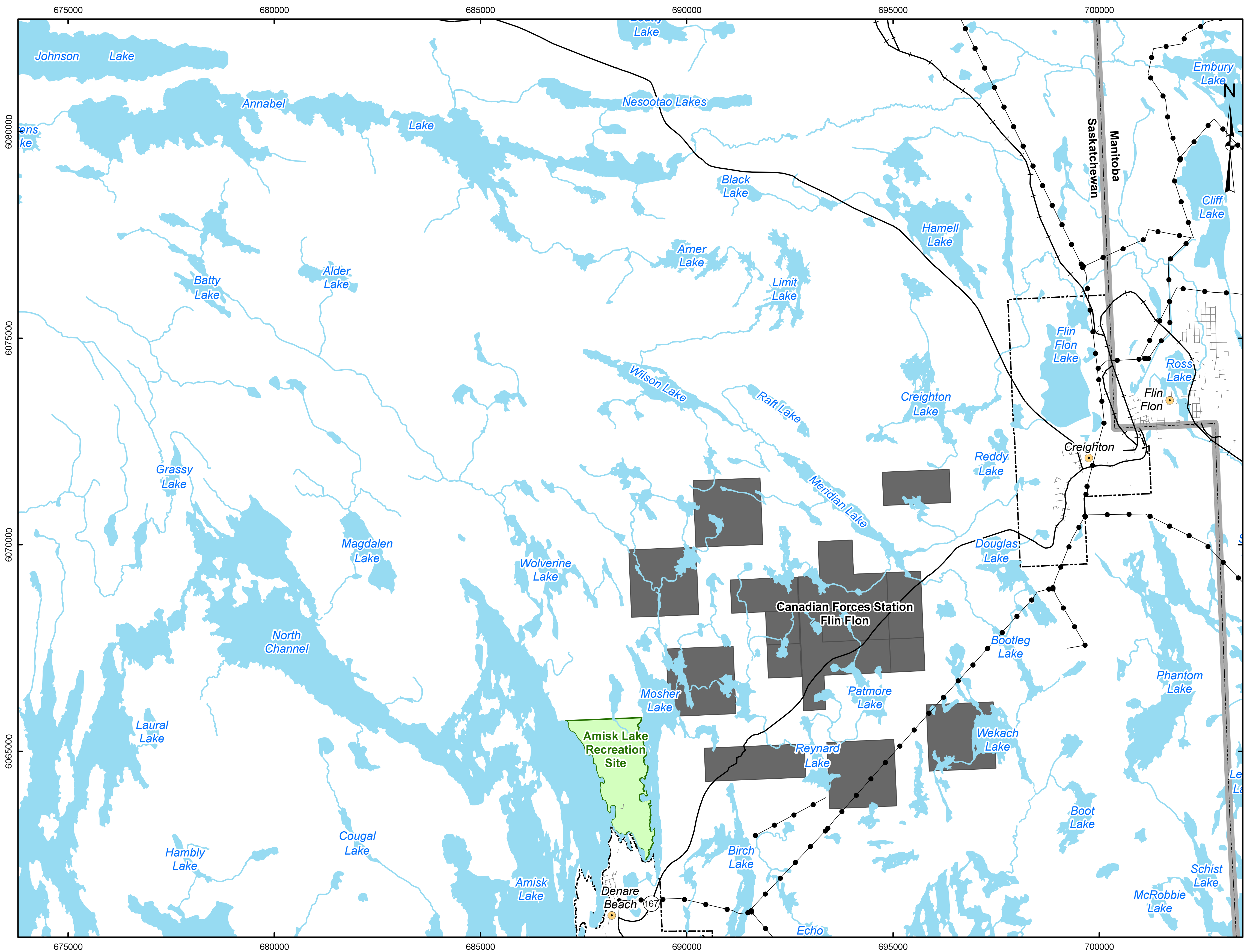
FIGURES

Figure 17. Geophysical interpretation showing distribution of bedrock units for the Creighton area

FIGURES



LEGEND

- Municipality Boundary
- Provincial Boundary
- Community
- Main Road
- Local Road
- Railway
- Transmission Line
- Watercourse
- Waterbody
- Federal Lands - Indian Reserve
- Park and Recreation Area
- Crown Reserves

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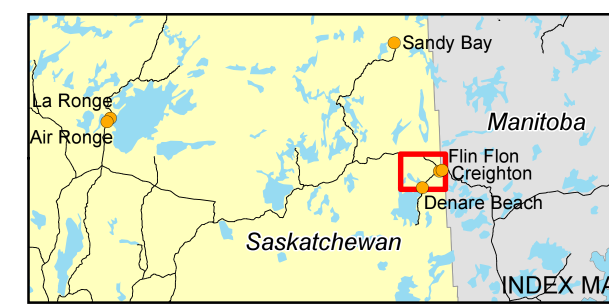

REFERENCE

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

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

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Town of Creighton and surrounding area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 1.0
DESIGN	PM	1 May 2012	FIGURE 1	
GIS	PM/JB	13 Aug 2013		
CHECK	AM	14 Aug 2013		
REVIEW	GWS	14 Aug 2013		

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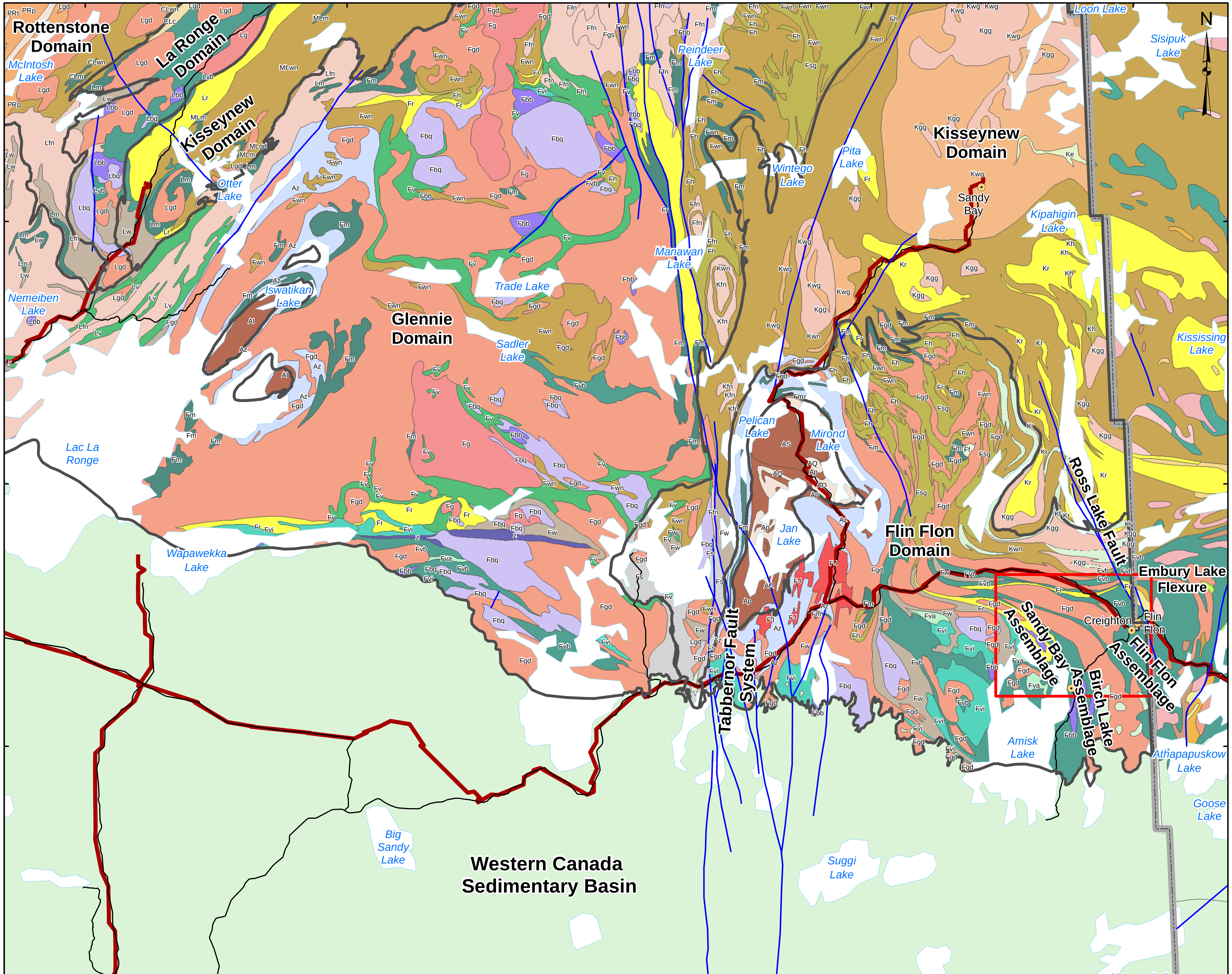


LEGEND

- Creighton Area
- 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 hornblenitic 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 13

20 10 0 20 40

SCALE 1:750,000 KILOMETRES

PROJECT

PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

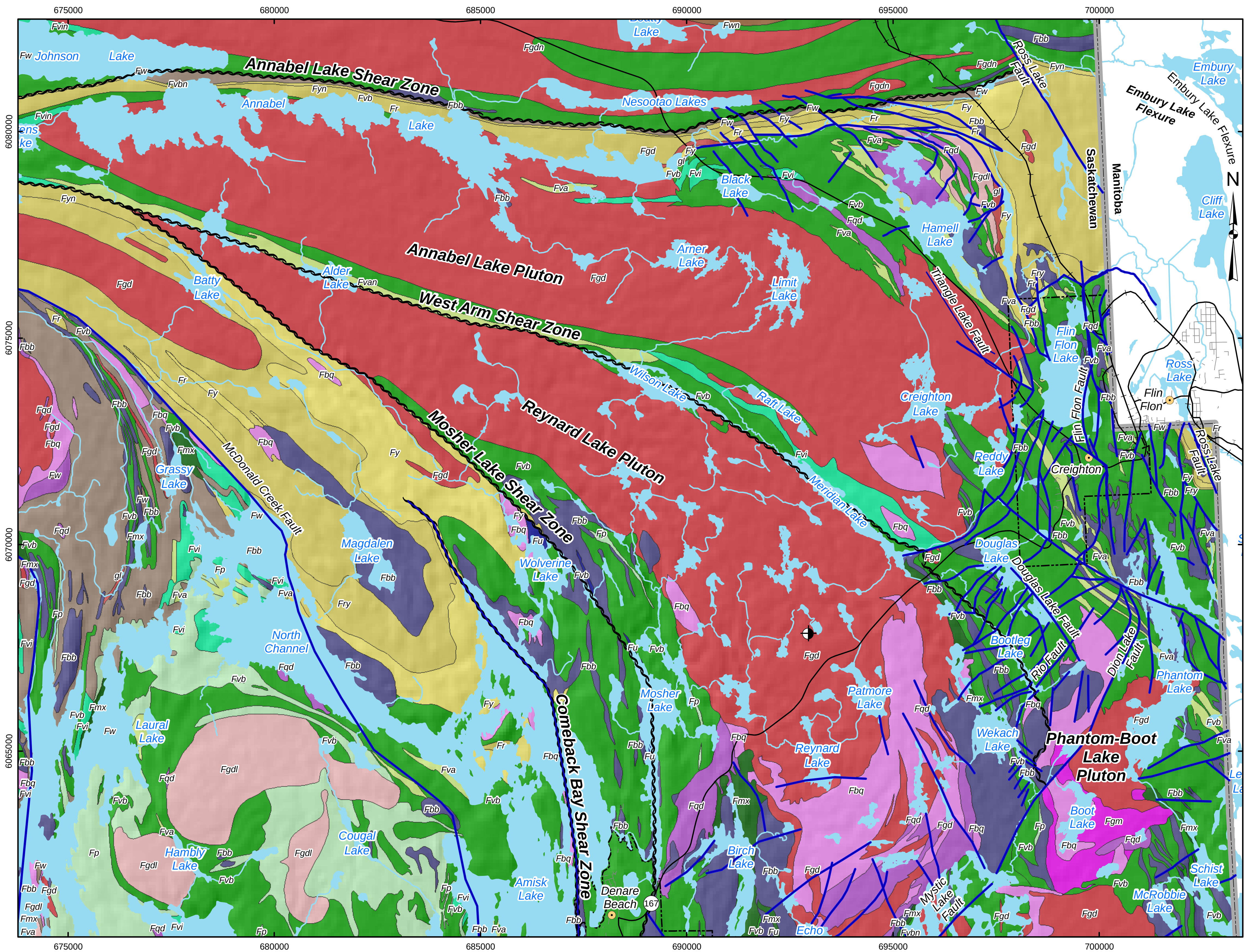
TITLE

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 2	
GIS	PMJB	28 Aug 2013		
CHECK	AM	28 Aug 2013		
REVIEW	GS	28 Aug 2013		

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



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

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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)
Geological Survey, Miscellaneous Release-Data 160.
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13

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

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

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	FIGURE 3	
GIS	PM/JB	28 Aug 2013		
CHECK	BT	28 Aug 2013		
REVIEW	GWS	28 Aug 2013		

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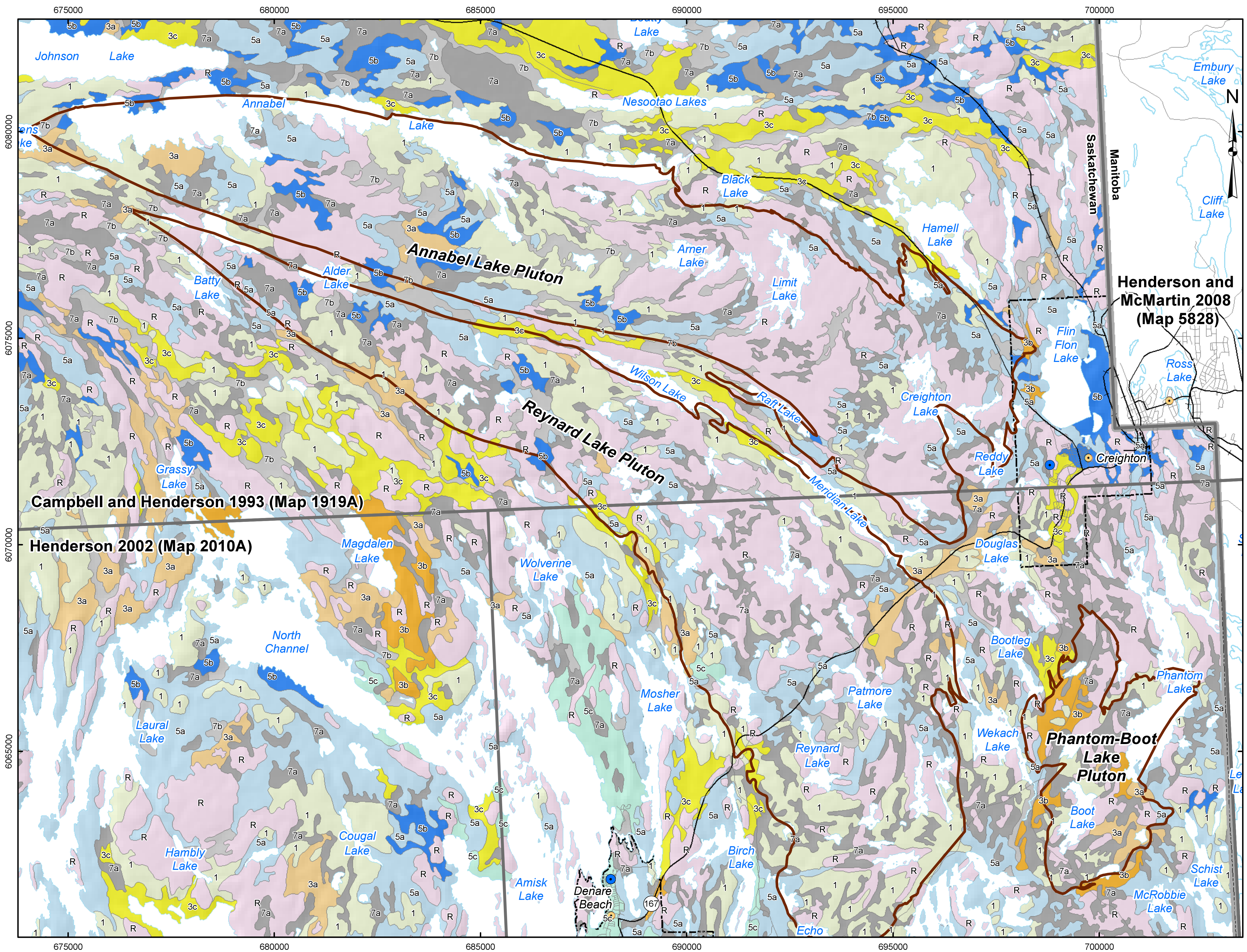

LEGEND

- Municipal Boundary
- Provincial Boundary
- Community
- Groundwater Well
- Main Road
- Local Road
- Railway
- Waterbody
- Surficial Geology Extent
- Outline of Major Pluton

Landform

- 7b - Fen peat
- 7a - Bog peat
- 6 - Alluvial
- 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
- 2 - Till blanket
- 1 - Till veneer
- R - Bedrock

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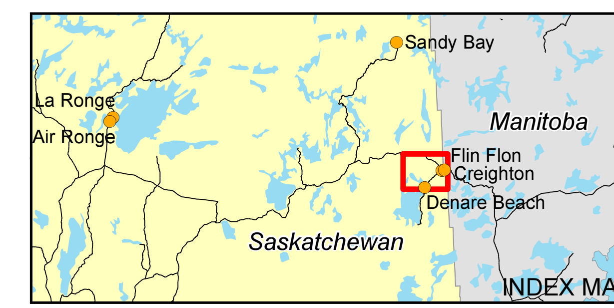

REFERENCE

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)
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 13

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

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT
GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Surficial 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	13 Aug 2013	**FIGURE 4**	
CHECK	AM	14 Aug 2013		
REVIEW	GWS	14 Aug 2013		

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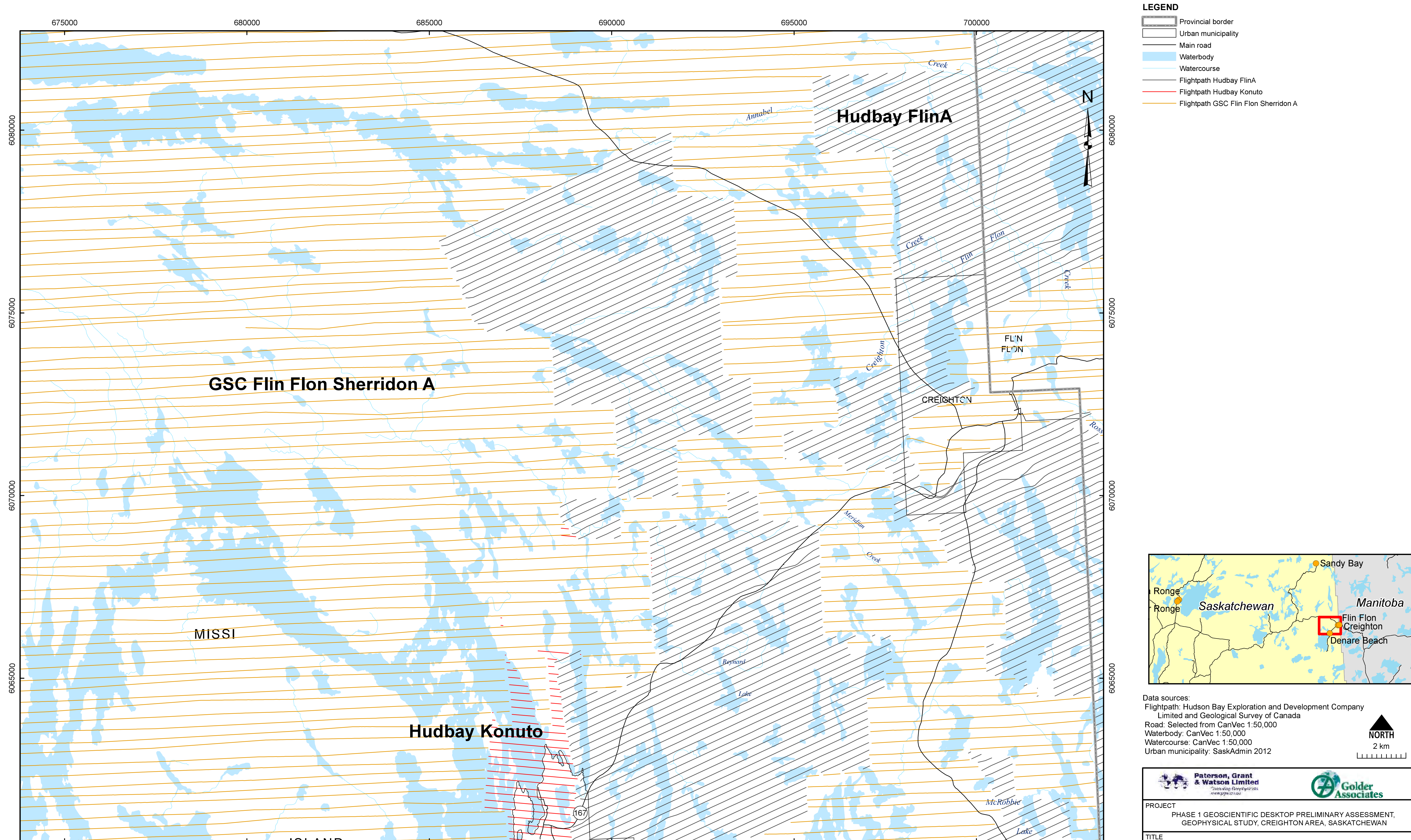

Data sources:
Flightpath: Hudson Bay Exploration and Development Company Limited and Geological Survey of Canada
Road: Selected from CanVec 1:50,000
Waterbody: CanVec 1:50,000
Watercourse: CanVec 1:50,000
Urban municipality: SaskAdmin 2012

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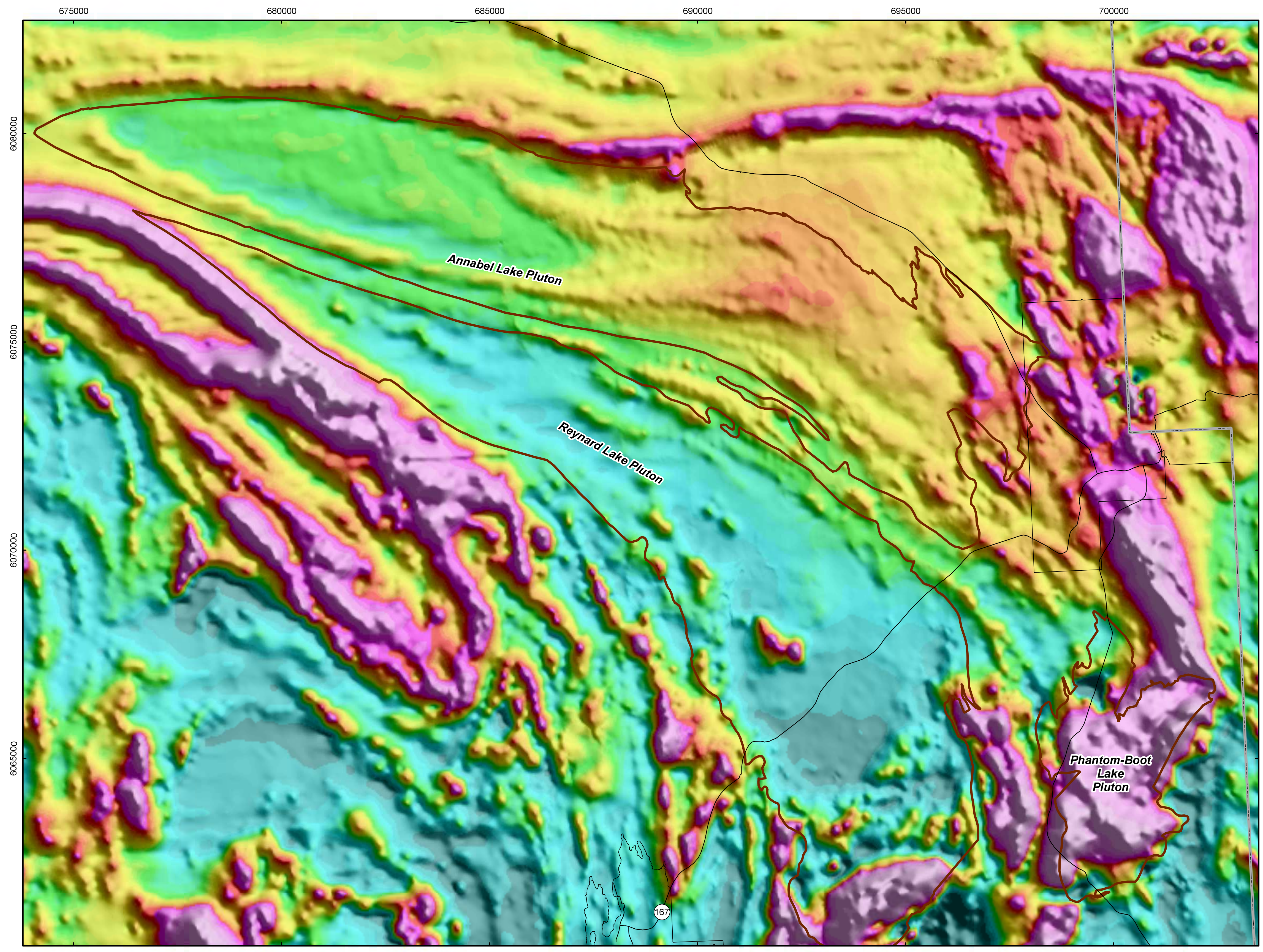
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Airborne geophysical coverage of the Creighton area

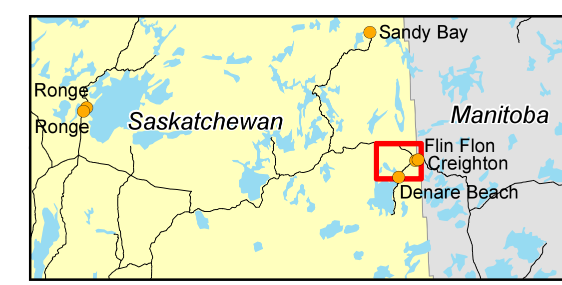
DESIGN	SWR	8 FEB 2013	FIGURE 5	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig5_PGW_Creighton_Flightpath.mxd



LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths



Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

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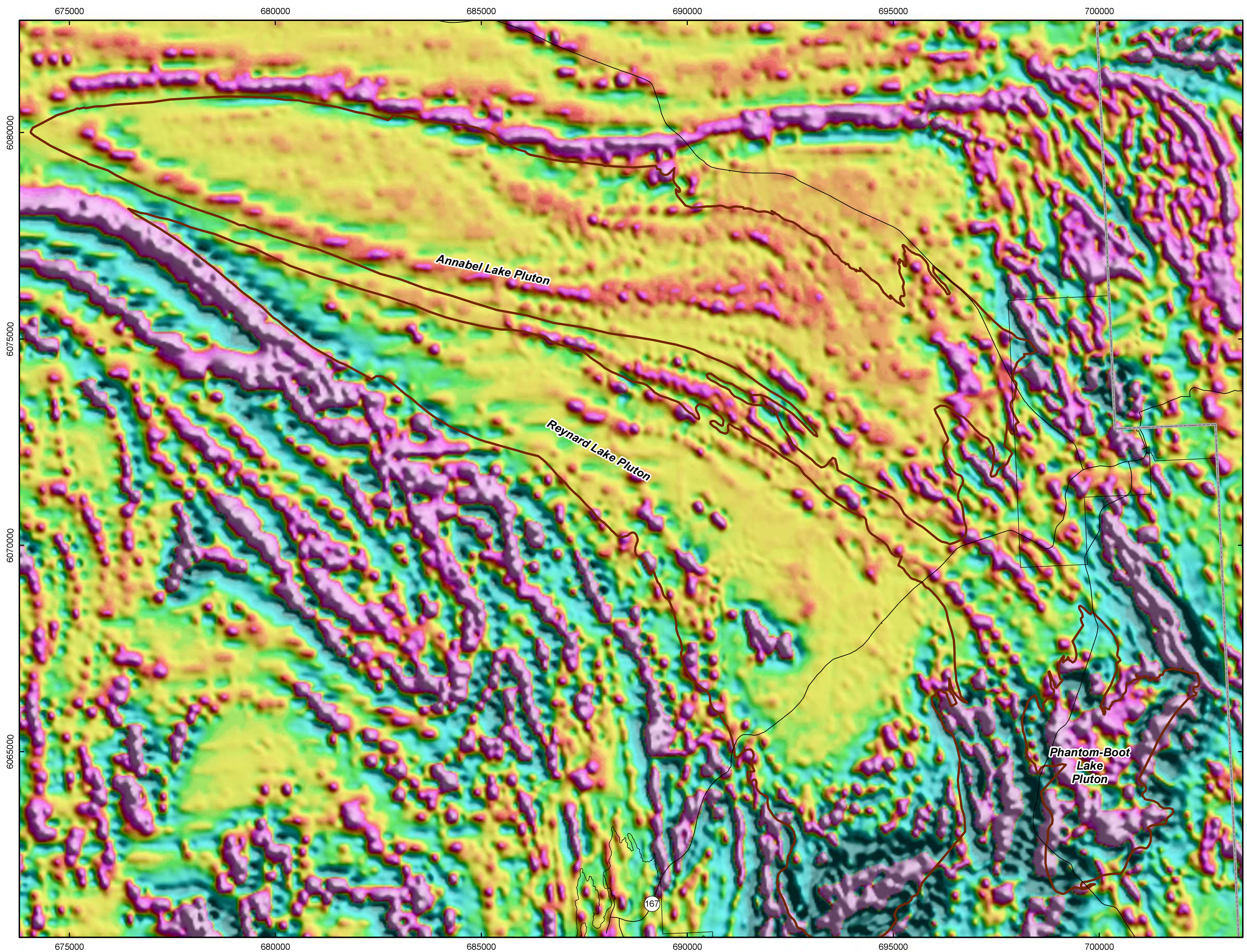
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Residual magnetic field reduced to pole

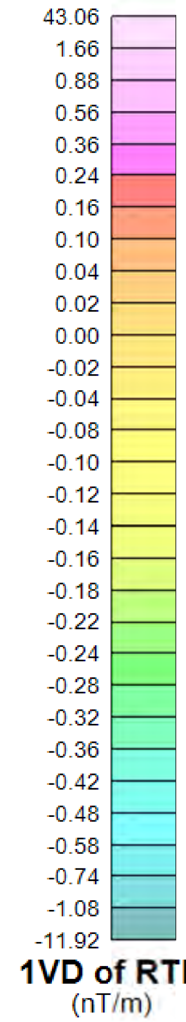
DESIGN	SWR	8 FEB 2013	FIGURE 6	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

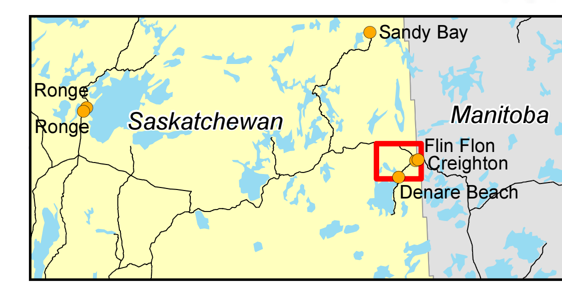
C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig6_PGW_Creighton_Mag_RTP.mxd



LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths





Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

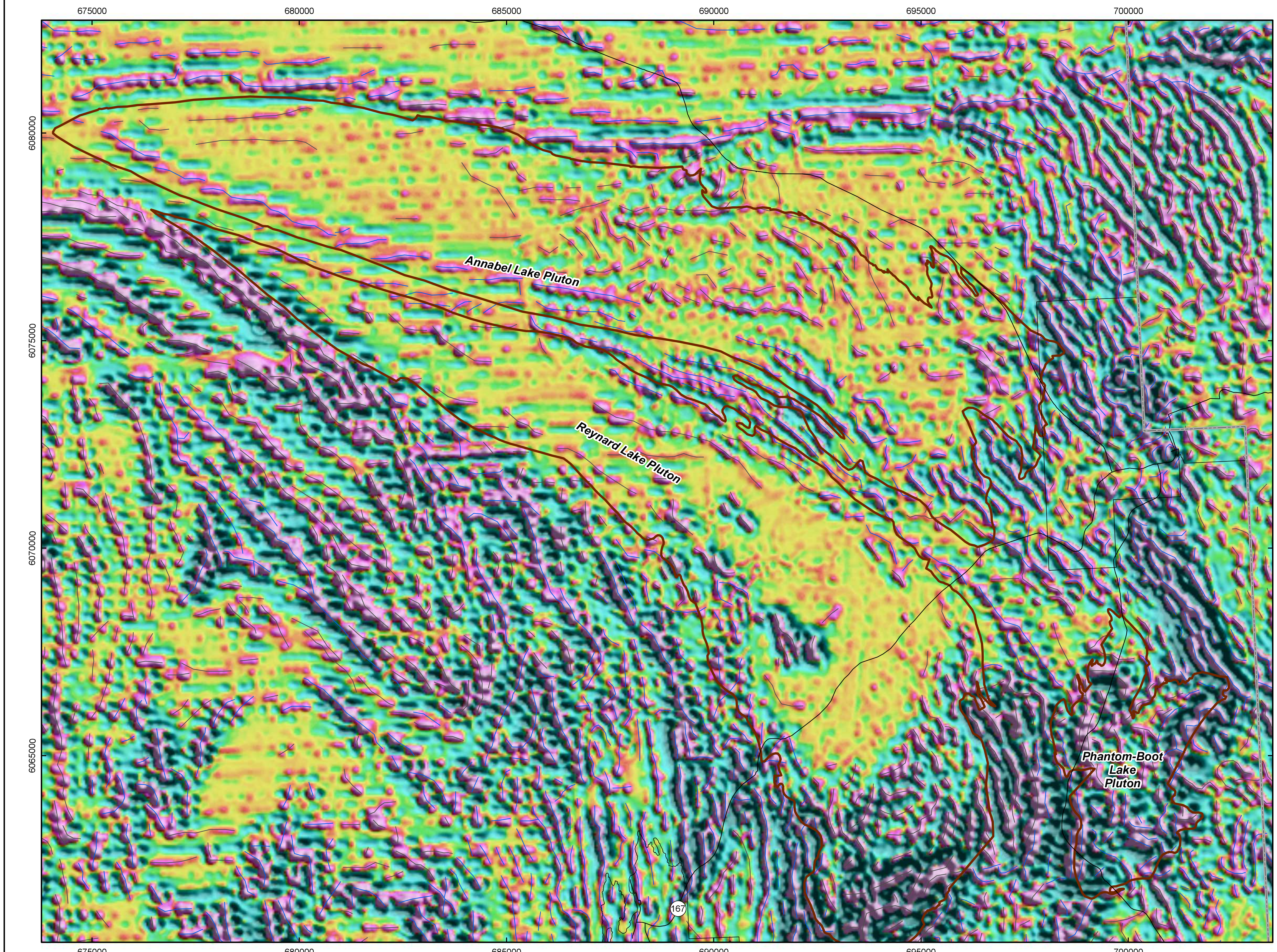
Golder Associates

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
First vertical derivative of the pole reduced magnetic field

DESIGN	SWR	8 FEB 2013	FIGURE 7	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig7_PGW_Creighton_Mag_RTP_1VD.mxd

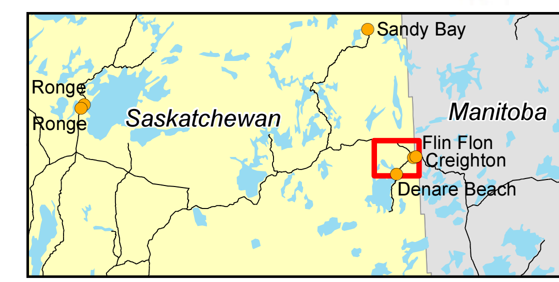


LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths
- Magnetic foliation
- Magnetic ductile lineaments

0.61867
0.00884
0.00432
0.00264
0.00176
0.00122
0.00086
0.00060
0.00042
0.00028
0.00018
0.00010
0.00002
-0.00002
-0.00008
-0.00014
-0.00020
-0.00030
-0.00040
-0.00050
-0.00064
-0.00082
-0.00104
-0.00132
-0.00170
-0.00226
-0.00310
-0.00460
-0.00834
-0.26317

2VD of RTP
(nT/m2)



Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

Paterson, Grant & Watson Limited
Golder Associates

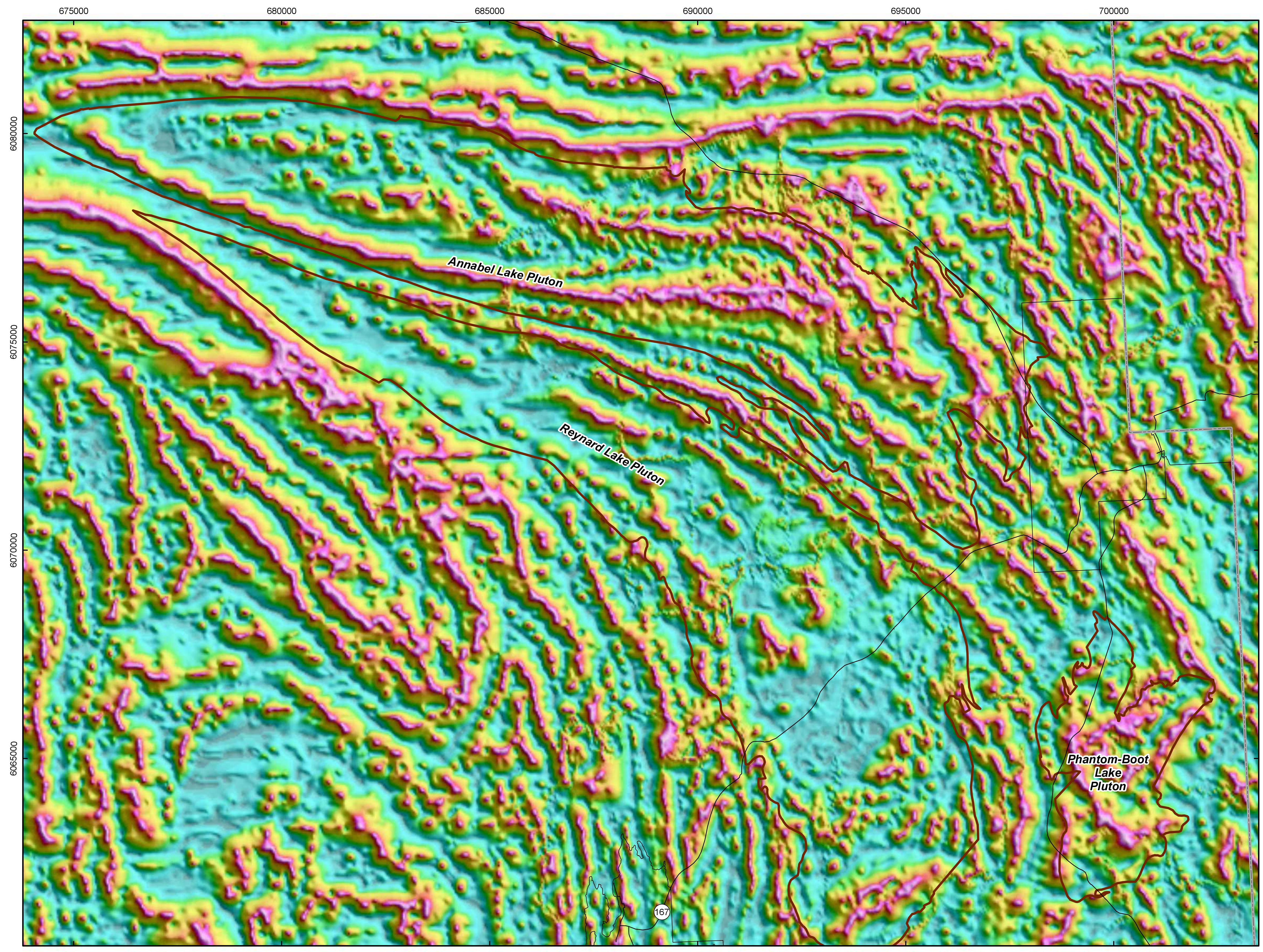
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Second vertical derivative of the pole reduced magnetic field with ductile lineaments and foliation

DESIGN	SWR	8 FEB 2013	FIGURE 8	REVISION 1.1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

6050000m.N

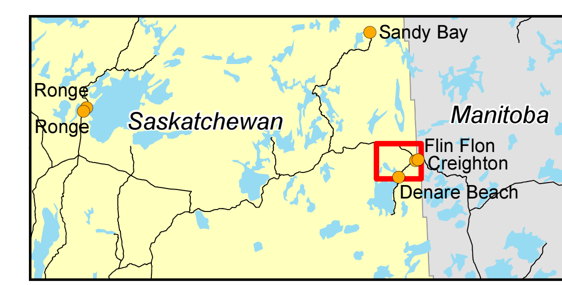
C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig8_PGW_Creighton_Mag_RTP_2VD.mxd



LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths

Tilt Angle (radians)
1.57
1.46
1.35
1.24
1.14
1.03
0.92
0.81
0.70
0.60
0.49
0.38
0.27
0.16
0.05
-0.05
-0.16
-0.27
-0.38
-0.49
-0.60
-0.70
-0.81
-0.92
-1.03
-1.14
-1.25
-1.35
-1.46
-1.57



Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

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PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

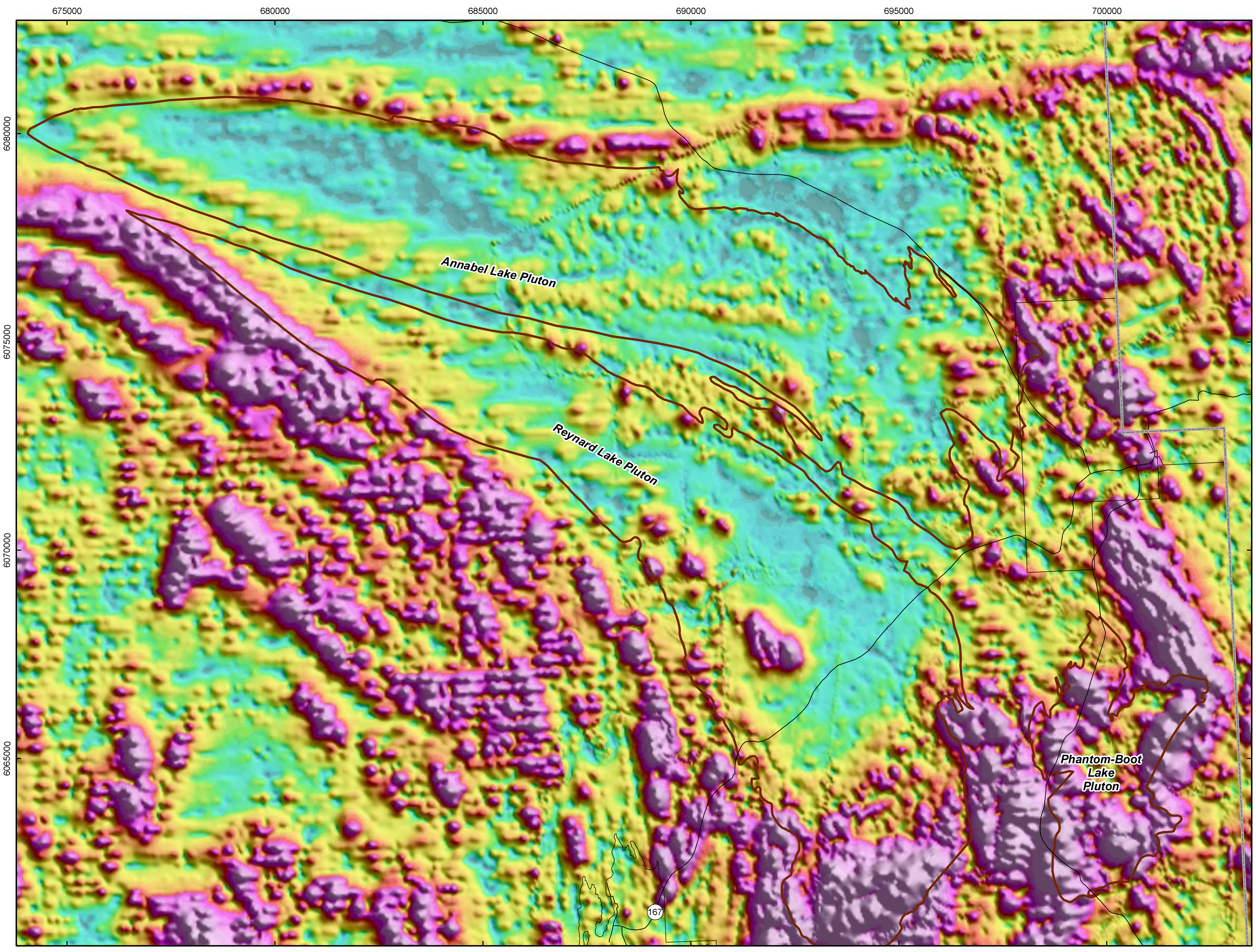
TITLE
Tilt angle of the pole reduced magnetic field

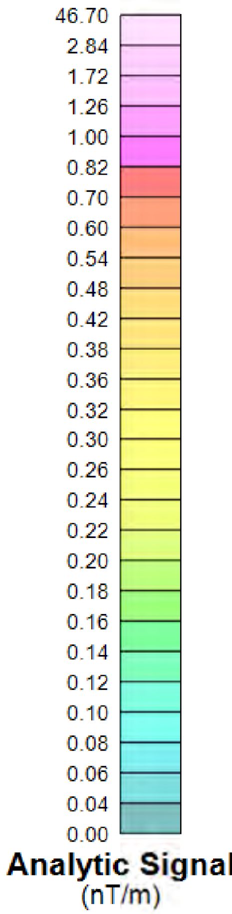
DESIGN	SWR	8 FEB 2013	FIGURE 9	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

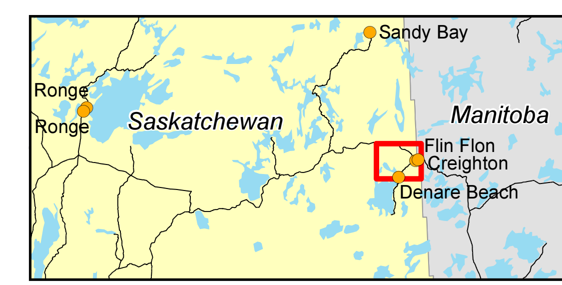
C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig9_PGW_Creighton_Mag_RTP_Tilt.mxd

LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths







Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH

2 km

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PROJECT

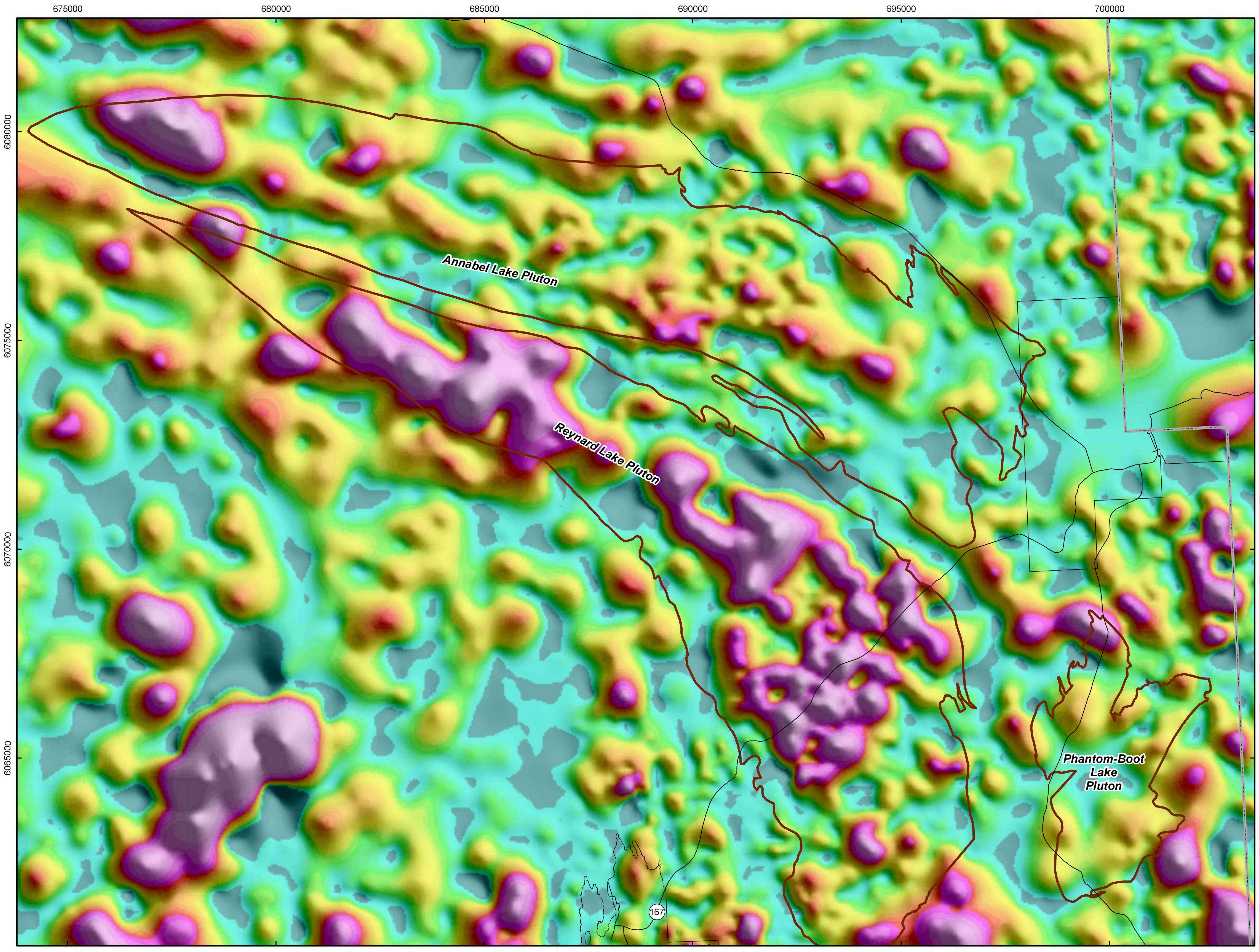
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE

Analytic signal amplitude of the total magnetic field

DESIGN	SWR	8 FEB 2013	FIGURE 10	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig10_PGW_Creighton_Mag_ASIG.mxd

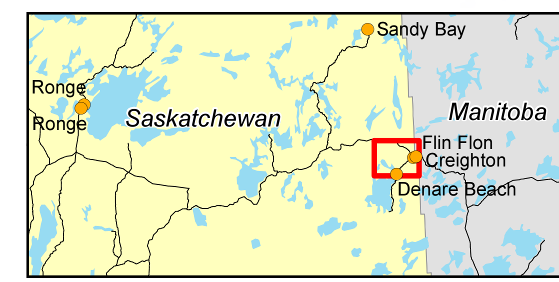


LEGEND

- Provincial border
- Urban municipality
- Main road
- Major Batholiths

Depth to Sources (m below surface)
4150
585
395
300
240
200
175
155
135
120
105
95
85
75
65
60
50
45
40
35
25
20
15
10
5
0
-133

Depth to Sources
(m below surface)



Data sources:
High-resolution magnetics: Hudson Bay Exploration and Development Company Limited
Medium-resolution magnetics: GSC surveys
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

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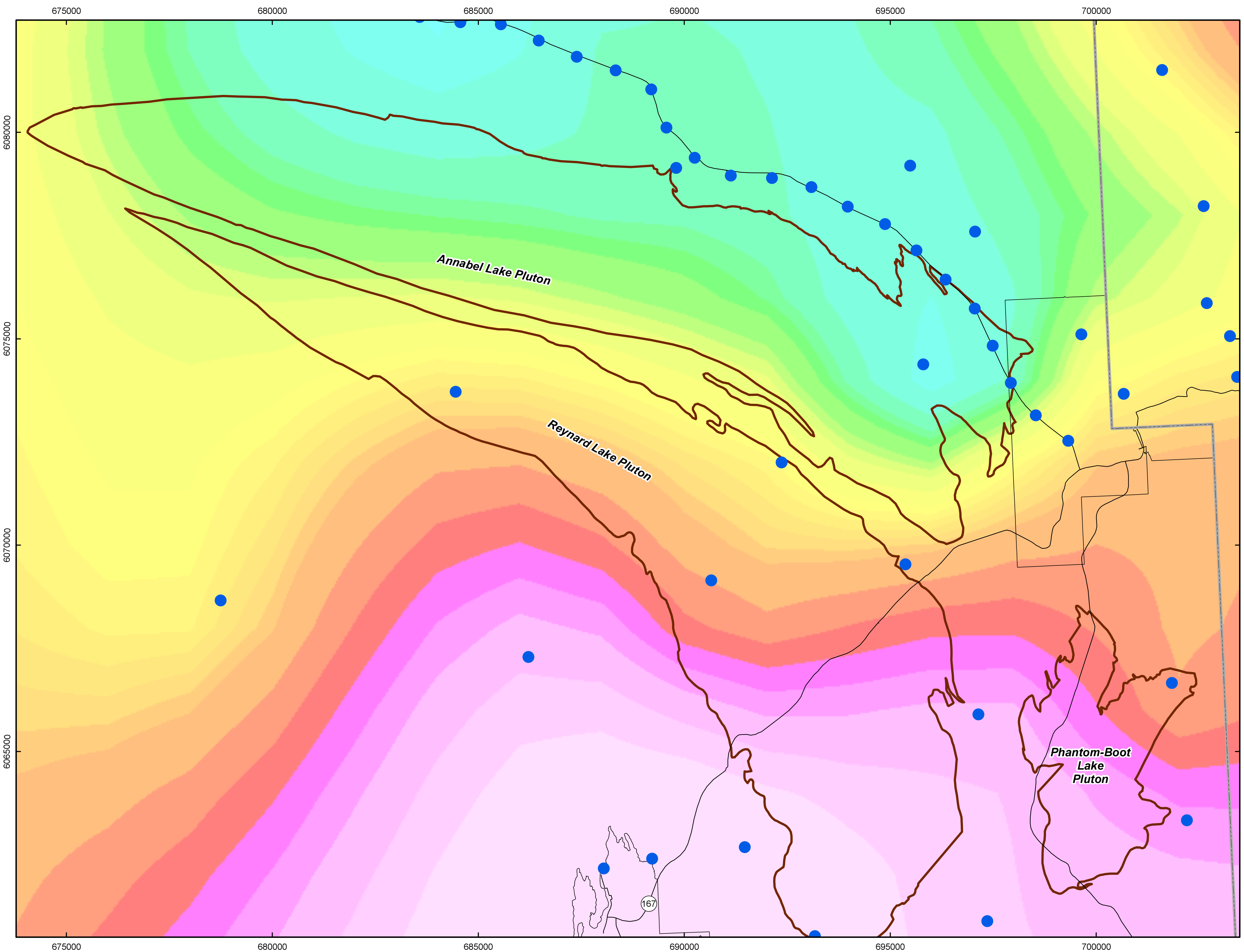
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Depth to magnetic sources from source parameter imaging

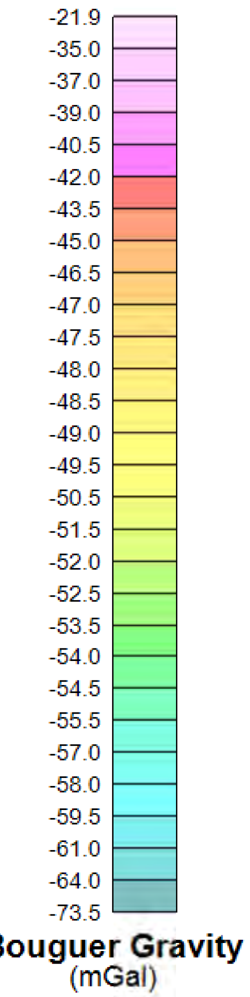
DESIGN	SWR	8 FEB 2013	FIGURE 11	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

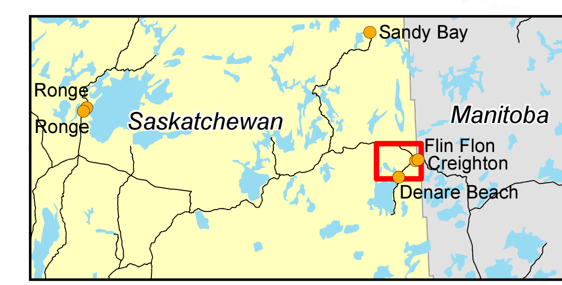
C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig11_PGW_Creighton_Mag_SPIDepth.mxd



LEGEND

- Provincial border
- Urban municipality
- Main road
- Major batholiths
- Gravity station





Data sources:
Regional Gravity: GSC nationwide compilation
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

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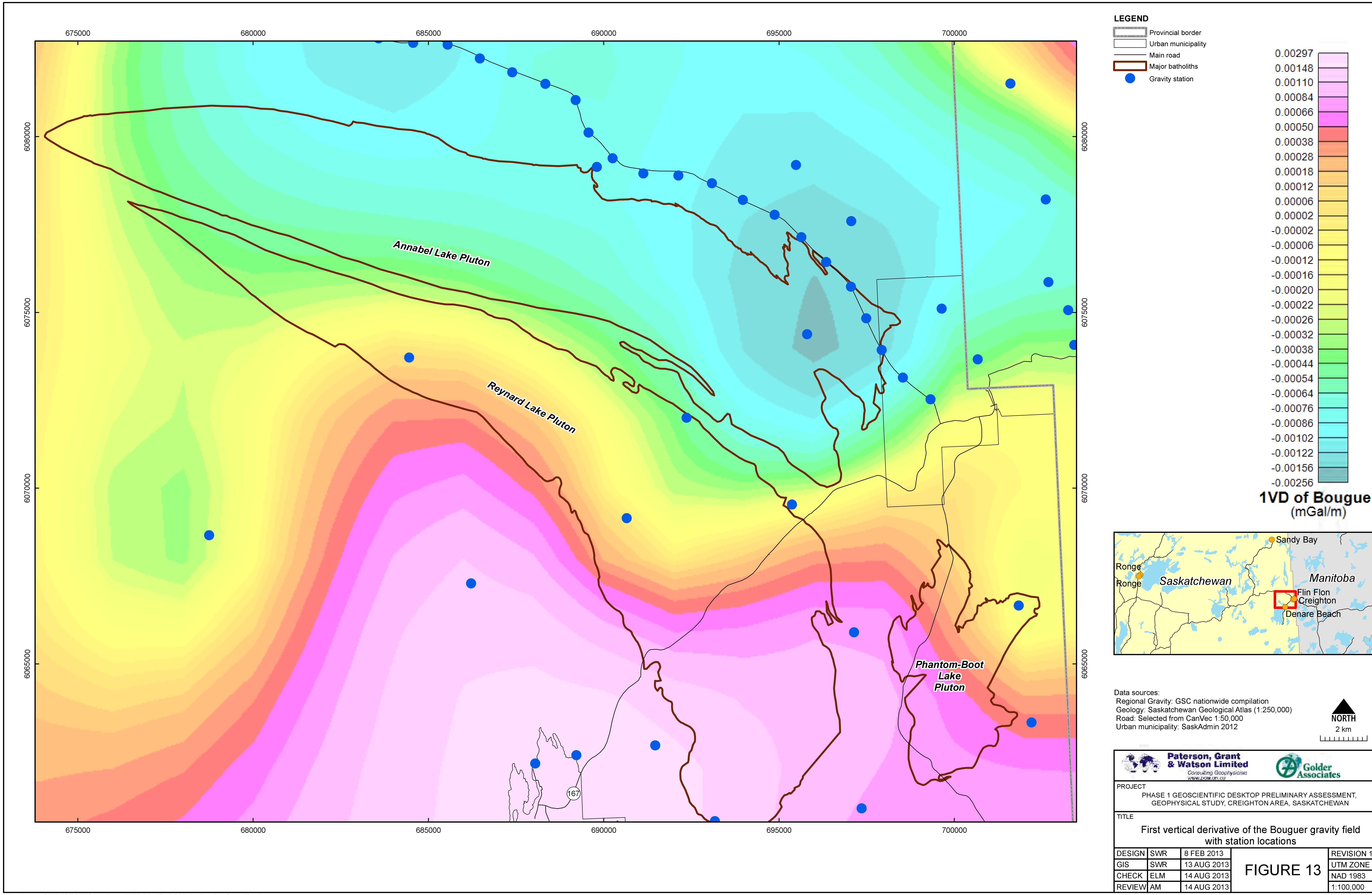
PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Bouguer gravity field with station locations

DESIGN	SWR	8 FEB 2013	FIGURE 12	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig12_PGW_Creighton_Grav_Boug.mxd



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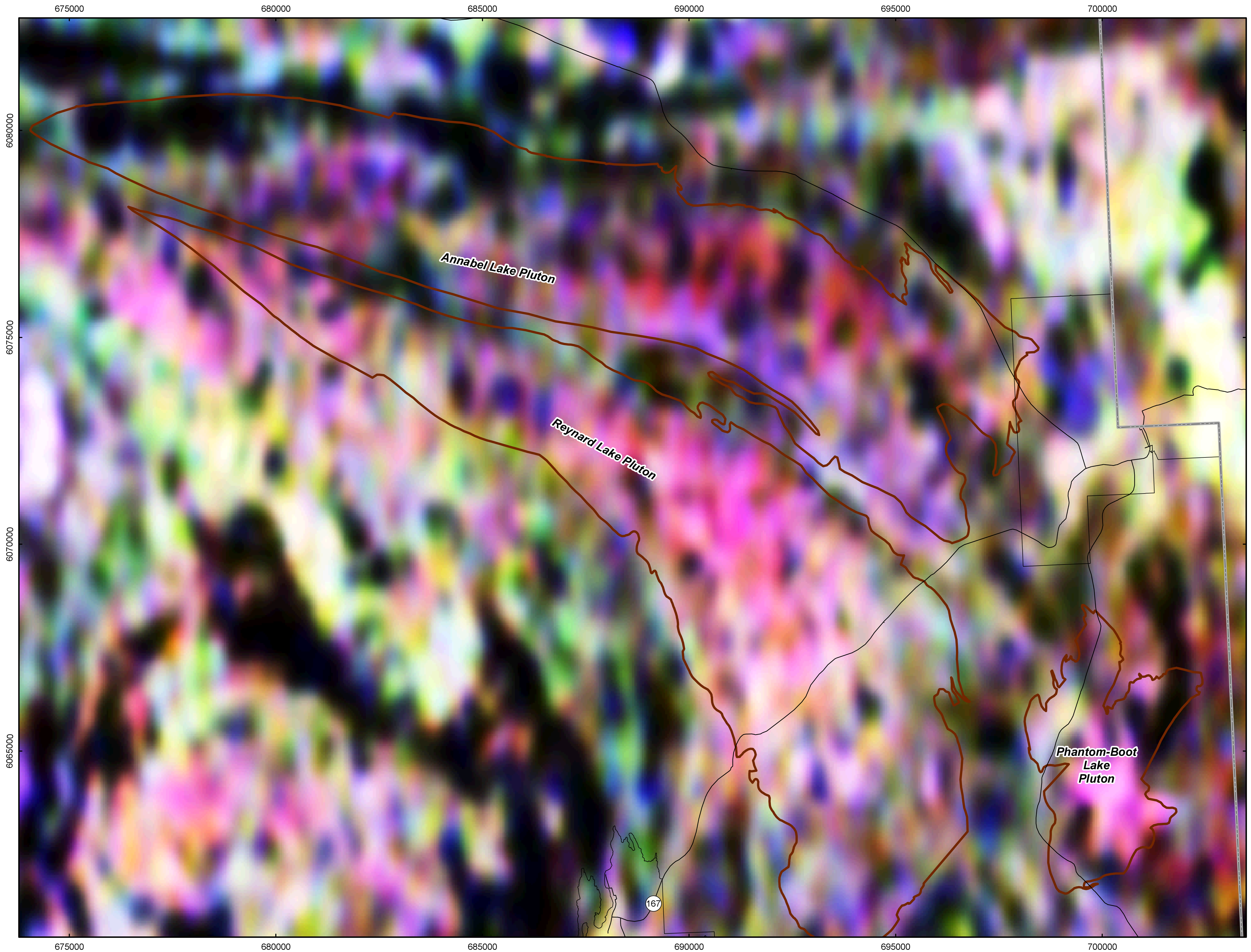
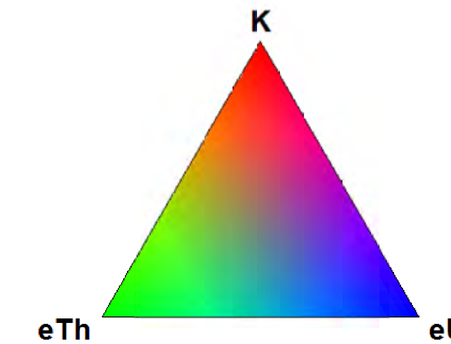
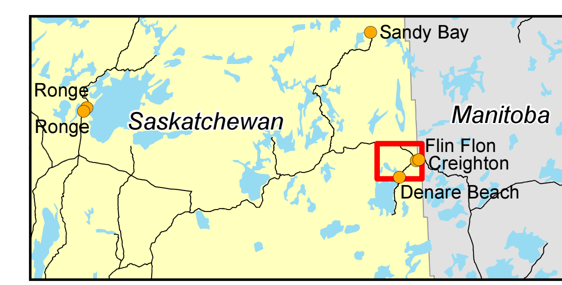


LEGEND

- Provincial border
- Urban municipality
- Main road
- Major batholiths





Data sources:
Regional Radiometrics: GSC nationwide compilation
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

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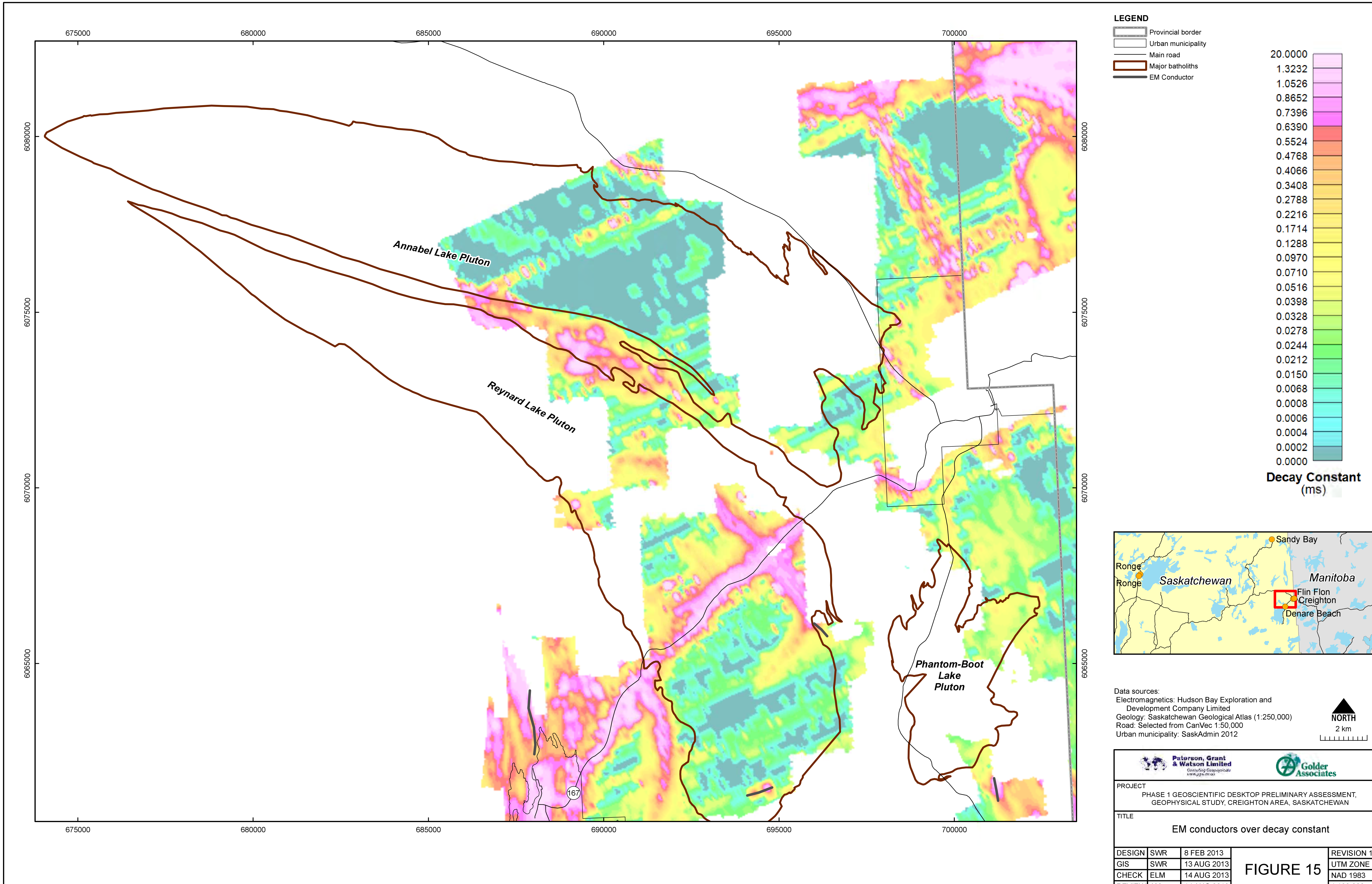
Golder Associates

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
Radiometric ternary image (RGB = K-eTh-eU)

DESIGN	SWR	8 FEB 2013	FIGURE 14	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig14_PGW_Creighton_Rad_Ternary.mxd



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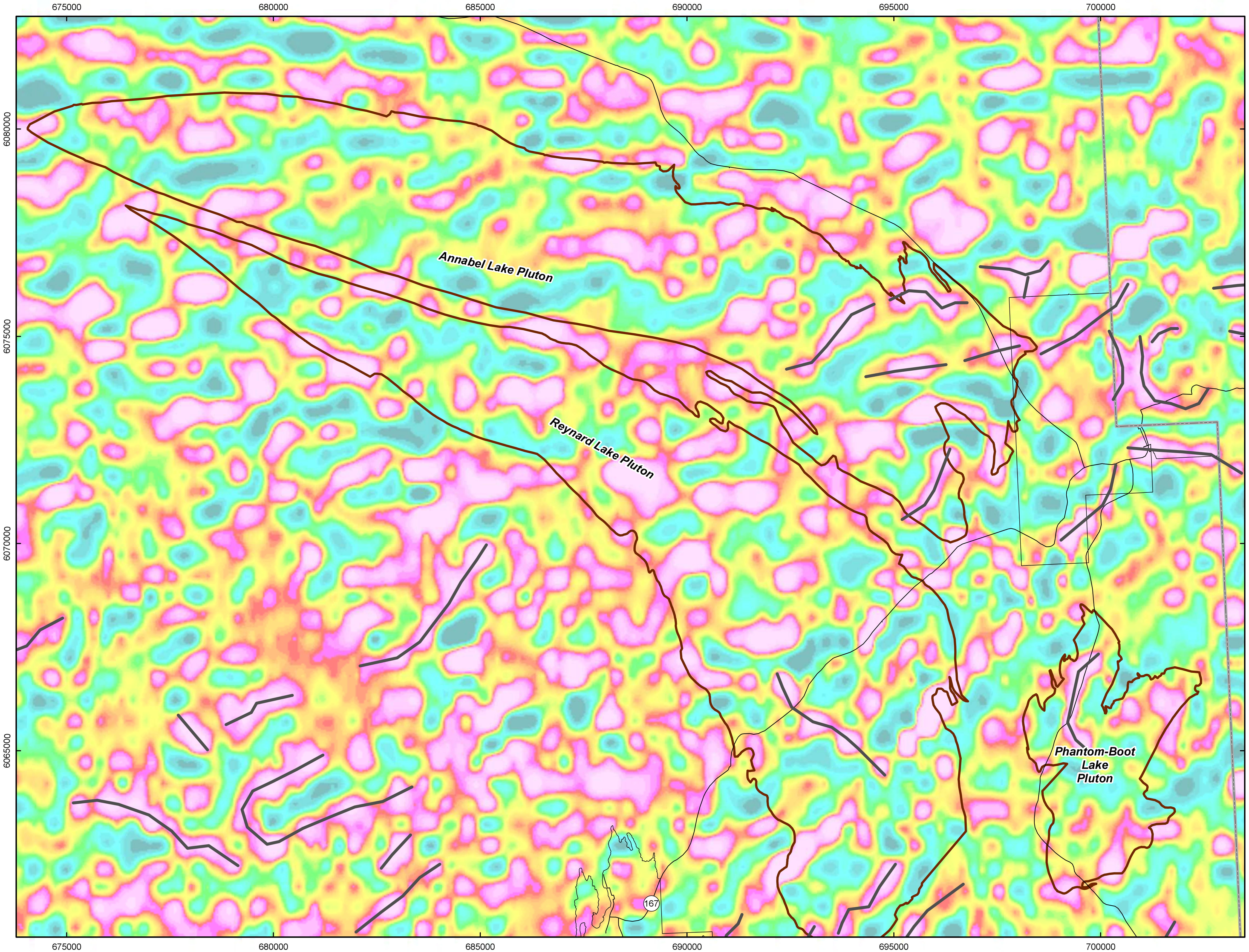
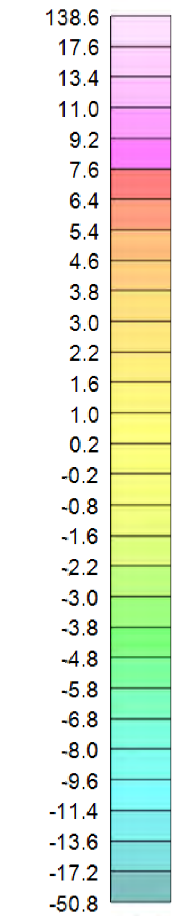
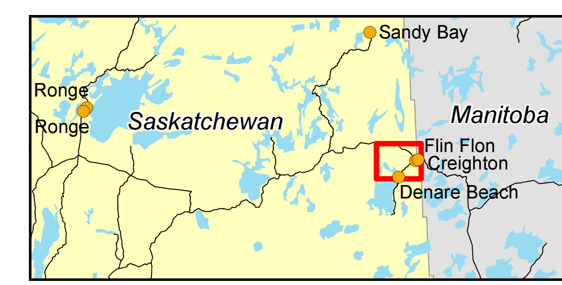


LEGEND

- Provincial border
- Urban municipality
- Main road
- Major batholiths
- VLF Conductor



VLF Total Field
(mV)



Data sources:
VLF-EM: Geological Survey of Canada
Geology: Saskatchewan Geological Atlas (1:250,000)
Road: Selected from CanVec 1:50,000
Urban municipality: SaskAdmin 2012

NORTH
2 km

Paterson, Grant & Watson Limited
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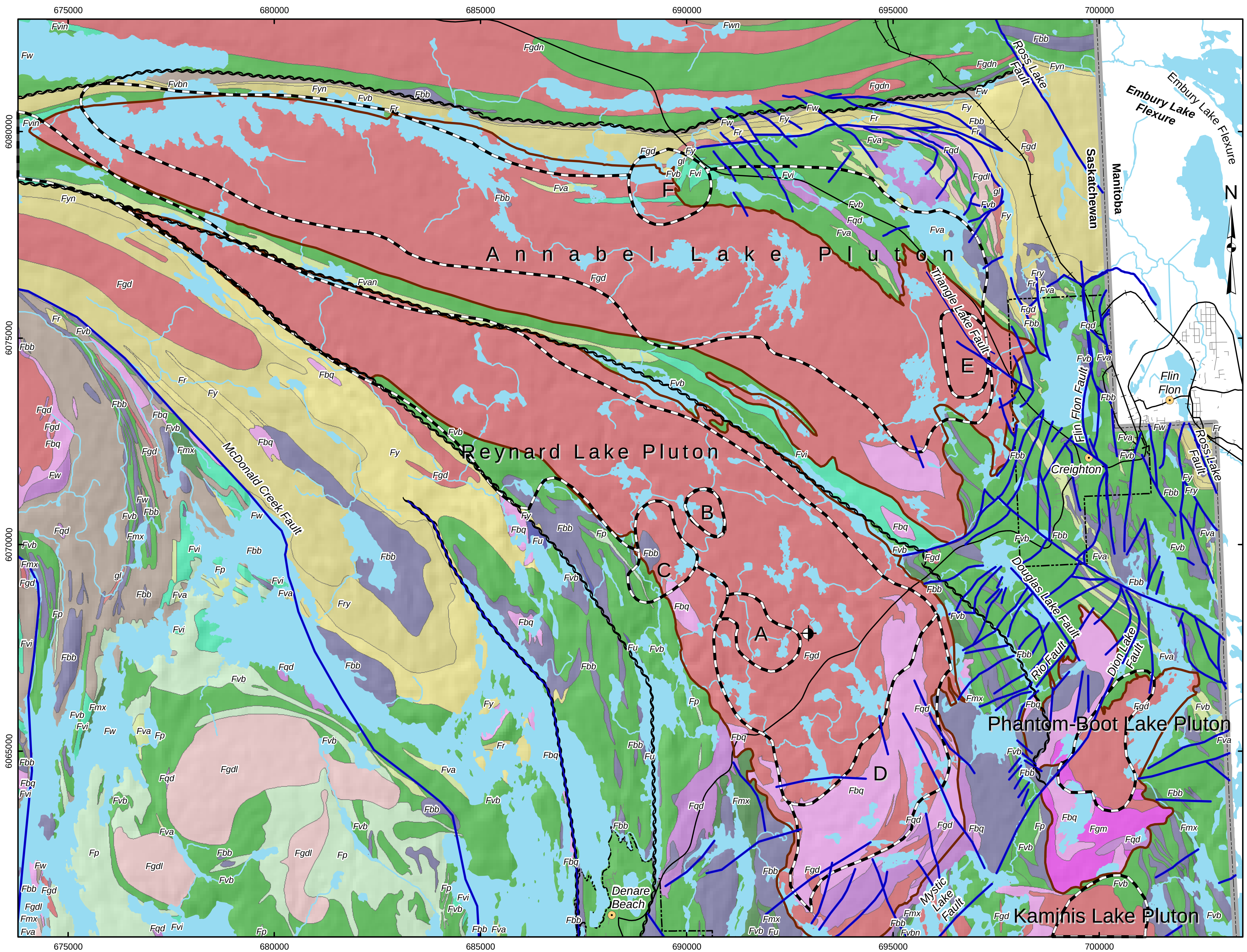
Golder Associates

PROJECT
PHASE 1 GEOSCIENTIFIC DESKTOP PRELIMINARY ASSESSMENT, GEOPHYSICAL STUDY, CREIGHTON AREA, SASKATCHEWAN

TITLE
VLF-EM conductors over VLF total field

DESIGN	SWR	8 FEB 2013	FIGURE 16	REVISION 1
GIS	SWR	13 AUG 2013		UTM ZONE 13
CHECK	ELM	14 AUG 2013		NAD 1983
REVIEW	AM	14 AUG 2013		1:100,000

C:\Users\Stephen\PGW\NWMO\PGW Reports\August 2013\Creighton\Fig16_PGW_Creighton_VLF.mxd



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

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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

- Major Batholith Outline
- Geologic Units Interpreted from Geophysics

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)
Geological Survey, Miscellaneous Release-Data 160.
Projection: Universal Transverse Mercator Datum: NAD 83 Coordinate System: UTM Zone 13

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

PROJECT
PRELIMINARY ASSESSMENT OF GEOSCIENTIFIC SUITABILITY
PHASE 1 DESKTOP STUDY

TITLE
Geophysical interpretation showing distribution of bedrock units for the Creighton area

Golder Associates
Mississauga, Ontario

PROJECT NO. 12-1152-0026			SCALE AS SHOWN	REV. 1.1
DESIGN	PM	1 MAY 2012		
GIS	SR/NP	28 AUG 2013		
CHECK	DJM	28 AUG 2013		
REVIEW	AM	28 AUG 2013		

FIGURE 17

G:\Projects\2012\12-1152-0026_NWMO_Phase1_Feasibility\GIS\MXDs\Reporting\Creighton\Draft_Integrated_Report\LocalBedrockGeology\CreightonArea.mxd