



NUCLEAR WASTE MANAGEMENT ORGANIZATION SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

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

TOWN OF CREIGHTON, SASKATCHEWAN



APM-REP-06144-0052

NOVEMBER 2013

This report has been prepared under contract to the NWMO. The report has been reviewed by the NWMO, but the views and conclusions are those of the authors and do not necessarily represent those of the NWMO.

All copyright and intellectual property rights belong to the NWMO.

For more information, please contact:

Nuclear Waste Management Organization

22 St. Clair Avenue East, Sixth Floor

Toronto, Ontario M4T 2S3 Canada

Tel 416.934.9814

Toll Free 1.866.249.6966

Email contactus@nwmo.ca

www.nwmo.ca

PHASE 1 DESKTOP GEOSCIENTIFIC PRELIMINARY ASSESSMENT

TERRAIN AND REMOTE SENSING STUDY

TOWN OF CREIGHTON, SASKATCHEWAN

November 2013

Prepared for:

G.W. Schneider, M.Sc., P.Geo.
Golder Associates Ltd.
6925 Century Avenue, Suite 100
Mississauga, Ontario
Canada L5N 7K2

Nuclear Waste Management Organization
22 St. Clair Avenue East 6th Floor
Toronto, Ontario
Canada M4T 2S3
NWMO Report Number: APM-REP-06144-0052

Prepared by:

D.P. van Zeyl, M.Sc.
L.A. Penner, M.Sc., P.Eng., P.Geo.
J.D. Mollard and Associates (2010) Limited
810 Avord Tower, 2002 Victoria Avenue
Regina, Saskatchewan
Canada S4P 0R7



EXECUTIVE SUMMARY

In December 2011, the Town of Creighton, Saskatchewan, expressed interest in learning 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 terrain and remote sensing assessment completed as part of the desktop geoscientific preliminary assessment of the Creighton area (Golder, 2013). The main information sources relied on were the Canadian Digital Elevation Data (CDED), the SPOT satellite imagery, and the maps and reports from the Saskatchewan Geological Survey (SGS). The study addresses the following seven objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate areas of exposed bedrock or relatively thin overburden cover;
- Identify features that may preserve evidence of neotectonics;
- Establish the main site accessibility constraints;
- Determine and/or confirm watershed and sub-catchment boundaries;
- Infer groundwater recharge and discharge zones and divides; and
- Infer regional and local groundwater and surface flow directions.

The report provides an overview of the bedrock and Quaternary geology within the Creighton area, including estimates of overburden thickness. Areas mapped as either rock outcrop or rock thinly covered by overburden are delineated at the scale of 1:50,000 on surficial geology maps. Rocks of the Annabel Lake and Reynard Lake plutons are better exposed at the surface than those of the Phantom-Boot Lake pluton. Drainage divides delineated in the Prairie Farm Rehabilitation Administration (PFRA) sub-basin file were reviewed and further sub-divided to assess surface

water flow patterns. Most of the area's drainage network is contained within eight major quaternary level watersheds, all of which flow into the Saskatchewan River, which flows to Lake Winnipeg. A small portion of the Creighton area (north-central) drains towards the Churchill River, which flows to Hudson Bay. Groundwater flow within drift deposits and in shallow bedrock aquifers in the Creighton area likely mimics the pattern of surface flow, with groundwater divides coinciding with drainage divides and discharge occurring into creeks, rivers, lakes and wetlands.

Conclusive identification of features indicative of paleoseismic events and reactivation of ancient bedrock structures due to cycles of glacial loading and unloading cannot be identified using currently available sources of information. Field investigations would be required to identify such features.

Access is good onto the eastern margins of the Annabel Lake and Reynard Lake plutons, where these intrusive bodies are widest and where the most extensive bedrock exposure is located. Road construction of 6 to 12 km would be required to access these areas. An aggregate resource, which could be used for road materials, exists within a 10 to 15 km radius of these areas.

TABLE OF CONTENTS

LIST OF FIGURES (IN ORDER FOLLOWING TEXT)	V
LIST OF TABLES	V
1 INTRODUCTION	1
1.1 OBJECTIVES.....	1
1.2 CREIGHTON AREA.....	2
1.3 DATA AND METHODS.....	2
1.3.1 SGS AND GSC MAPS AND REPORTS	2
1.3.2 SGS DRILL HOLE DATA	4
1.3.3 WATER WELL INFORMATION DATABASE.....	5
1.3.4 CDED.....	5
1.3.5 SPOT.....	7
2 SUMMARY OF GEOLOGY	11
2.1 GEOLOGICAL SETTING.....	11
2.2 GEOLOGICAL HISTORY	12
2.3 STRUCTURAL HISTORY	15
2.4 LOCAL BEDROCK GEOLOGY	16
2.4.1 REYNARD LAKE PLUTON.....	17
2.4.2 ANNABEL LAKE PLUTON.....	17
2.4.3 PHANTOM-BOOT LAKE PLUTON.....	18
2.4.4 FLIN FLON GREENSTONE BELT	19
2.4.5 METASEDIMENTARY ROCKS OF THE MISSI GROUP.....	19
2.4.6 FAULTS AND SHEAR ZONES	20
2.4.7 METAMORPHISM.....	22
2.5 QUATERNARY GEOLOGY	23
3 TOPOGRAPHY	25
3.1 ELEVATION	25
3.2 RELIEF.....	26
3.3 SLOPE.....	27
4 DRAINAGE	29
4.1 WATERBODIES AND WETLANDS	29
4.2 CATCHMENTS AND SUBCATCHMENTS.....	31
4.3 SURFACE FLOW	32
5 TERRAIN CHARACTERISTICS	35
5.1 DRILL HOLE AND WATER WELL DATA.....	35
5.1.1 SGS DRILL HOLE DATA	35
5.1.2 WATER WELL INFORMATION DATABASE.....	36
5.2 TERRAIN UNITS FROM SURFICIAL MAPPING	37
5.2.1 MORAINAL.....	38
5.2.2 GLACIOFLUVIAL	38
5.2.3 GLACIOLACUSTRINE	39
5.2.4 ORGANIC	40
5.2.5 BEDROCK.....	40

6	GROUNDWATER	43
7	NEOTECTONIC FEATURES	44
8	ACCESSIBILITY CONSTRAINTS	47
9	SUMMARY.....	49
	REFERENCES	51
	REPORT SIGNATURE PAGE.....	57
	FIGURES	59

LIST OF FIGURES (IN ORDER FOLLOWING TEXT)

- Figure 1 Town of Creighton and surrounding area
- Figure 2 Bedrock geology of the Creighton area
- Figure 3 Surficial geology of the Creighton area
- Figure 4 Elevation and major topographic features
- Figure 5 Departure in elevation within 20 km radius
- Figure 6 Departure in elevation within 2 km radius
- Figure 7 Range in elevation within 250 m radius
- Figure 8 Density of steep ($\geq 6^\circ$) slopes within 2 km radius
- Figure 9 Water bodies and wetlands within the Creighton area
- Figure 10 Watersheds within the Creighton area
- Figure 11 SPOT imagery of Annabel Lake and Reynard Lake plutons

LIST OF TABLES

Table 1 Characteristics of SPOT 4 and 5 multispectral bands.....	8
Table 2 List of SPOT 4 and 5 multispectral images acquired in this study.	8
Table 3 Summary of the geological and structural history of the Creighton area.	13
Table 4 Approximate maximum depths of lakes with depth surveys in the Creighton area.	30
Table 5 Water well records available for the Creighton area.	37
Table 6 Thickness and areal extent of surficial deposits over the three main plutons.	38

1 INTRODUCTION

In December 2011, the Town of Creighton, Saskatchewan expressed interest in learning 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 terrain and remote sensing study 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 and its periphery, referred to as the Creighton area, contains general areas that have the potential to meet NWMO's geoscientific site evaluation factors (NWMO, 2010).

1.1 OBJECTIVES

This report presents an analysis of the terrain in the Creighton area using existing remote sensing and geoscientific information sources. Information will enhance and expand upon that presented in the initial screening report for the Town of Creighton (Golder, 2011). The main information sources relied on in this study are the Canadian Digital Elevation Data (CDED), the multispectral SPOT satellite imagery, and the maps and reports describing the surficial geology produced by the Saskatchewan Geological Survey (SGS) and the Geological Survey of Canada (GSC).

This study makes use of remote sensing and geoscientific information sources to address the following seven objectives:

- Evaluate the nature, areal extent and depth of overburden materials;
- Delineate areas of exposed bedrock or relatively thin overburden cover;
- Identify features that may preserve evidence of neotectonics;
- Establish the main site accessibility constraints;
- Determine and/or confirm watershed and sub-catchment boundaries;
- Infer groundwater recharge and discharge zones and divides; and
- Infer regional and local groundwater and surface flow directions.

These objectives were addressed for the area described in Section 1.2 using the data and methods described in Section 1.3. Terrain features associated with two potentially suitable host rock formations, the Annabel Lake and Reynard Lake plutons (Golder, 2011), as well as the Phantom-Boot Lake pluton are discussed in greater detail as appropriate.

1.2 CREIGHTON AREA

The Creighton area is a rectangular area approximately 30 km by 22 km in size (Figure 1), encompassing an area of about 660 km². The approximate western, northern, eastern and southern limits of the area are (UTM Zone 13, NAD83): 673780, 6082720, 703480, and 6060500 m.

1.3 DATA AND METHODS

This section summarizes the remote sensing and geoscientific data sources available for the Creighton area, including an evaluation of the quality of the data.

1.3.1 SGS AND GSC MAPS AND REPORTS

The bedrock geology of the Creighton area has been mapped extensively. Geological mapping coverage is good and generally up to date throughout most of the Creighton area (Figure 2). Most of this information is focused on the greenstone belts for their mining potential. However, the plutons of interest to this assessment have also been mapped to some degree. One of the most detailed publicly available maps produced for the area is a 1:10,000 scale map produced jointly by the Manitoba Geological Survey (Geoscientific Map MAP2010-1) and the Saskatchewan Ministry of Industry and Resources (Geoscience Map 2010-02) (Simard et al., 2010). The coverage of this map focuses on the areas with mining potential, but includes portions of the Annabel Lake pluton and the Phantom-Boot Lake pluton. Greater coverage of the Reynard Lake and Annabel Lake plutons was provided by the NATMAP Shield Margin Project, which included 1:100,000 scale synthesis mapping of the entire Creighton area (Lucas et al., 1999; NATMAP, 1998). Additionally, part of the Phantom-Boot Lake pluton was mapped by MacLachlan (2006) at a scale of 1:3,000 and includes the bedrock geology of the Douglas Lake area.

The surficial geology of the Creighton area was mapped regionally in the late 1970s and in detail in the late 1980s and 1990s. The notes below describe the maps and reports associated with the main surficial geology mapping projects conducted in the Creighton area.

Overburden deposits within the Creighton area were mapped as part of a regional surficial mapping program covering the Precambrian Shield of Saskatchewan undertaken between 1974 and 1984 by the Saskatchewan Research Council under contract to the SGS (Schreiner, 1984b). Field investigations were preceded by interpretation of aerial photographs at a scale of about 1:60,000 and photo-mosaics at a scale of about 1:50,000. Much of the field campaign consisted of shoreline mapping around lakes sufficiently large to accommodate float-equipped aircraft, with additional field investigations conducted along roads where exposures and borrow pits provided valuable sections. Along roads, a power auger was used to drill holes to a depth of 9.6 m, with lithologic strip logs recorded on map margins.

Schreiner et al. (1975) summarized the field investigations forming the basis of the 1:250,000-scale surficial geology map sheet covering the Creighton area (Schreiner, 1984a), involving ninety-two sites investigated of which seventeen were auger holes. Several auger holes were completed along Highway 106, with lithologic strip logs presented on the map margin.

In support of gold exploration, Campbell (1987b, 1988) conducted the most detailed surficial geology mapping available in the Creighton area. This mapping was based on interpretation of 1:20,000-scale air photographs, with ground checking carried out at 218 sites. The mapping extends about 15 km east of the east margin of Amisk Lake, covering the Phantom-Boot Lake pluton and the southern portion of the Reynard Lake pluton (Figure 3). Hand augered holes or small pits were dug to an average depth of 0.8 m at most sites. Subsurface information was obtained from eleven sonic drill holes along Highway 167 and the West Arm Mine Road to depths of 2 to 11.6 m, with holes either terminating in bedrock or large boulders.

The surficial geology mapping in the late 1980s (Campbell, 1987b, 1988) and in the 1990s (Henderson and Campbell, 1992; Henderson, 1995), which was conducted in support of gold and base metal exploration, resulted in two 1:50,000 scale surficial geology maps covering the Saskatchewan portion of the Creighton area (Figure 3). These maps are GSC Map 1919A (Campbell and Henderson, 1997) and GSC Map 2010A (Henderson, 2002). Two additional maps cover the Manitoba portion of the Creighton area (McMartin, 1997; Henderson and McMartin, 2008). JDMA integrated the available digitized surficial geology map data into a single polygon shapefile. The map covering a narrow band along the southeast border of the Creighton area (McMartin, 1997) is not available in digital vector format.

Henderson and Campbell (1992) and Henderson (1995) provide reports on the surficial geology and the work programs forming the basis of the 1:50,000-scale maps covering the Saskatchewan portion of the Creighton area. This work was based on interpretation of air photographs at a scale

of about 1:50,000. Ground truthing was undertaken in problematic areas where access could be obtained along Highway 167 and 106, and along shorelines accessed by boat on the larger lakes. Observations were made in hand-dug pits about one metre deep and in natural and man-made exposures.

A recent cross-border surficial geology map compilation was produced by McMartin et al. (2012), which resulted in the production of a generalized surficial geology map at a scale of 1:500,000. Although this publication provides no map information on the surficial geology of the Creighton area not already contained in the existing maps (Campbell and Henderson, 1997; Henderson, 2002), it provides a useful written summary of the surficial geology in this part of Manitoba and Saskatchewan.

1.3.2 SGS DRILL HOLE DATA

The SGS drill hole database contains data on overburden thickness. However, there are some issues with the use of these data for characterizing drift thickness. The assessment files on which the data are based have not been reviewed to check on data accuracy. Many of the assessment files are not available digitally, and it is difficult to look up the assessment files associated with particular drill holes using the available SGS online system. It was not stated in the information accompanying this database how the coordinates of the drill holes were established or their level of accuracy, but it is suspected that some of the coordinates are only accurate to within several tens of metres or perhaps several hundreds of metres. It is unknown whether the depth to bedrock value has been biased by overburden stripping carried out at the drill sites. In some cases, it is suspected that drilling was carried out on lake ice platforms and it is unknown whether the height of the water column has been excluded from the reported depth to bedrock value. As a result, the analysis of drill hole data presented in Section 5.1.1 is preliminary.

There are 59 drill holes located within the Creighton area stored in the SGS core libraries with enough information to allow the determination of overburden thickness. These holes were drilled between 1954 and 1992, with dips ranging from 40 to 90° and an average dip of 57°. The vertical depth to bedrock was calculated based on the dip angle and the uncorrected length of drill hole to bedrock. Section 5.1.1 summarizes data on drift thickness extracted from the 59 drill holes described above.

1.3.3 WATER WELL INFORMATION DATABASE

The Water Security Agency of Saskatchewan maintains a database of drilling records submitted by water well drillers. The database does not contain all the wells completed in the province, only those that were submitted by drillers. Sixteen water well records were found within the Creighton area, drilled between 1966 and 1993. Fifteen of these wells are located in the urban municipality of Denare Beach, five of which were accurately located using a GPS (± 5 m), whereas the other ten were located within a quarter section (± 570 m). The well in the urban municipality of Creighton was located within a section ($\pm 1,140$ m). Review of the well logs indicated that all sixteen of the wells were completed in overburden. Thus, the well depth provides a minimum value for the depth of overburden at the well site. Section 5.1.2 provides data on drift thickness obtained from water well records.

1.3.4 CDED

This subsection describes the digital elevation model used to evaluate the terrain in this study, starting with an overview of the source data and the processing completed by JDMA and then it provides a description of the quality of the data. Section 4.2 describes the drainage basin analysis conducted in this study.

Canadian Digital Elevation Data (CDED), 1:50,000 scale, 0.75 arc second (20 m) elevation models (GeoBase, 2011a) served as important data sources for analyzing and interpreting the terrain in the Creighton area. The digital elevation models (DEM) used for this study were constructed by the Mapping Information Branch of Natural Resources Canada (NRCan) using 1:50,000 scale source data from the National Topographic Data Base (NTDB). The source data were produced by the Surveys and Mapping Branch of Energy, Mines and Resources Canada based on black and white air photographs acquired in the late 1960s and 1980s at scales of 1:60,000 to 1:70,000. Four main NTDB data types were used: contours, spot heights, streams, and lakes. CDED datasets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) with an ellipsoid based on the Geodetic Reference System (GRS 80). Files are referenced vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level.

CDED generally provides a representation of the land surface that is reasonable for the scale of the data and the underlying photogrammetric method used to generate the elevation data. However, relatively poor quality representation can be found in flat areas, where the elevation model is, in some instances, based on elevation values obtained from a single elevation contour,

resulting in large areas around the contour where elevation values must be interpolated. These areas display a distinct stair-step or terraced pattern in the DEM. In the Creighton area, the low-relief terrain results in a low quality DEM in general, and there is a distinct change in quality going from NTS map sheet 63L to 63K, with 63K displaying consistently very poor quality throughout. The poor quality is related to a larger contour interval in the 63K topographic map sheets (50 feet) as compared with that used in NTS map 63L (25 feet). The 63K maps contain large areas where only one contour is present.

JDMA transformed the files obtained from GeoBase from geographic coordinates to Universal Transverse Mercator (UTM) projection using bilinear resampling, which assigns a value to each output cell based on a weighted average of the four nearest cells in the input raster. Compared with cubic convolution, bilinear resampling can sometimes produce a noticeably smoother surface, whereas cubic convolution can produce a sharper image. However, the differences between the two methods are generally trivial. After projecting the files, they were then assembled into a mosaic.

Surface analyses were performed on the digital elevation model to characterize slope and relief. Slope was calculated using the standard grid-based method employed in ArcGIS, which involves fitting a plane to the elevation values of a three by three neighbourhood centred on the processing cell. Slope is defined as the maximum slope of that plane, which can also be thought of as the dip of the plane, and aspect is equivalent to the dip direction. Relief was calculated in two ways. The first was by subtracting the average elevation within 2 and 20 km radii from the elevation value in the processing cell. This relief calculation represents a high pass filter. The second was defined as the range in elevation within a 250 m circular window.

Slope density was calculated because at other sites on the Precambrian Shield, areas of high density generally correlated with areas of thin drift. The reason for this correlation is that much of the relief on the Shield is related to bedrock topography and areas of low relief (lacking steep slopes) are often associated with drift filling the lows in the bedrock topography. However, for reasons outlined in Section 3.3, this correlation was not found in the Creighton area, and the slope density map has been included only for completeness. The density of steep slopes was calculated as the number of points with slope at least 6° within a 2 km radius.

1.3.5 SPOT

SPOT multispectral orthoimagery at a resolution of 20 m formed an important information source for identifying exposed bedrock within the Creighton area (GeoBase, 2011b). SPOT multispectral data consist of several bands, each recording reflected radiation within a particular spectral range, and each having a radiometry of 8-bits (or a value ranging from 0 to 255). SPOT 4 and 5 images were acquired using the HRV-IR and HRG sensors, respectively (Table 1). Each image covers a ground area of 60 km by 60 km. For quality control, NRCan provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15°. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using UTM projection referenced to North American Datum 1983 (NAD83).

Four SPOT images (scenes) provided complete coverage for the Creighton area (Table 2). The scenes are from both SPOT 4 and 5 satellites acquired between 2005 and 2006, with all scenes acquired in September.

To assist with the interpretation of the location and extent of bedrock outcrops in the Creighton area, JDMA performed two types of multivariate analyses on the SPOT multispectral data: principal component analysis and unsupervised classification. Prior to performing these analyses, water bodies were removed from the SPOT images to maximize contrast in the dry areas. This was accomplished by removing values from the shortwave-infrared band (band 4) that were below a threshold. The shortwave band displays a bimodal histogram with one high-valued mode representing dry land surfaces that reflect shortwave radiation and a lower-valued mode for areas that largely absorb shortwave radiation. The latter mode generally represents water bodies, but can also represent dark forest areas or shadows in front of north-facing cliffs where sunlight is absorbed.

Principal component analysis based on all four SPOT bands was found to generate composite images that provided good definition of the various land cover types thereby enabling optimal interpretation of the presence of bedrock exposures. For that purpose, principal component analysis (PCA) produced composite images that were generally superior to those produced by combining any of the raw SPOT bands. For each image, four components were generated and then the first three components were used to generate the composite image, which is referred to here as the PCA composite image. Campbell (1987a) provides more information on the use of principal component analysis in remote sensing.

Table 1 Characteristics of SPOT 4 and 5 multispectral bands.

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

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

Scene ID	Satellite	Date of image
S4_10146_5435_20050920	SPOT 4	September 20, 2005
S5_10243_5435_20060902	SPOT 5	September 2, 2006
S5_10229_5503_20060902	SPOT 5	September 2, 2006
S4_10135_5503_20060919	SPOT 4	September 19, 2006

An unsupervised classification was performed, which generates distinct unimodal groups from the four SPOT bands using an iterative self-organizing (ISO) cluster procedure employed within ArcGIS. The first step that JDMA took in the unsupervised classification was to classify the four SPOT bands into fifteen classes and to interpret the fifteen classes in light of the features (e.g., bedrock outcrops) interpreted in the PCA composite image. If a set of the fifteen classes delineated the interpreted bedrock exposures exclusively, then this completed the classification and these classes were used to generate a map depicting bedrock exposures. However, in many cases the classes mapping bedrock exposures also mapped wetlands or other land classes. The next step was to mask the four SPOT bands to exclude areas that were both distinctly unrelated to bedrock exposures and effectively delineated by a set of classes, such as areas with a high vegetation index. The cluster analysis was then performed a second time on the masked data and this generally produced a set of classes that delineated the interpreted bedrock exposures to a reasonable degree.

After some effort in attempting to produce good results from the unsupervised classification, it was found that there remain challenges in using unsupervised classification to map the exposed bedrock accurately and reliably. For instance, certain parts of wetlands can exhibit similar spectral characteristics as exposed bedrock. Alluvial sediments exposed in creek valleys also display similar spectral properties. Additional issues contribute to the unreliability of this technique. As a result, our interpretation of bedrock exposure from the SPOT imagery has relied on the PCA composite images and panchromatic images rather than on unsupervised classification.

Note that Google Earth imagery has also been cross checked against the SPOT imagery in many instances where satellite imagery have been used to identify exposed bedrock or other features such as roads or wetlands. The true-colour composite images currently displayed in Google Earth contain a higher spatial resolution than the SPOT imagery used in this study.

2 SUMMARY OF GEOLOGY

A detailed discussion of the geological setting of the Creighton area is provided in a separate report (Golder, 2013). The following sections (Sections 2.1 through 2.4) on bedrock geology and structural history present summaries of the information presented in Golder (2013) to provide the necessary context for discussion of the results of this study.

2.1 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).

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 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).

2.2 GEOLOGICAL HISTORY

The chronology of tectonic events that occurred during the Trans-Hudson Orogeny provides a framework for understanding the geological history of the Creighton area. The important phases of the Trans-Hudson Orogeny that produced the present geological conditions observed in the rocks of the region are summarized in Table 3 below. The summary is based primarily on the picture of geodynamic evolution detailed in Fedorowich et al. (1995). However, it 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 et al., 2005; Corrigan et al., 2005, 2007, 2009; Hajnal et al., 2005; Whitmeyer and Karlstrom, 2007). 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 Ma (Fedorowich et al., 1995), followed by a much more protracted history of localized brittle deformation that may have continued into the Mesozoic Era.

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, 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 2. 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.

Table 3 Summary of the geological and structural history of the Creighton area.

Time period (Ga)	Geological event
ca. 2.075	Passive margin phase associated with initiation of deposition of the Wollaston Supergroup on the eastern margin of the Hearne craton. Manikewan ocean opens at the east of Hearne craton.
1.906 to 1.886	A series of volcanic assemblages, including the La Ronge-Lynn Lake arc and a series of arc oceanic assemblages (including Amisk Group/Flin Flon greenstone belt), coexisted in the Manikewan ocean.
1.886 to 1.86	Closure of Manikewan ocean produced accretion of various tectonic assemblages resulting in the formation of the Flin Flon-Glennie complex. Activation of earliest regional shear zones. [D ₁]
1.86 to 1.834	Ongoing subduction and accretion during collision induces crustal thickening, thrust faulting and shear zone activation, and on-going folding. [D ₂] Deposition of the Missi Group between ca. 1.847 and 1.842 Ga. Emplacement of successor arc intrusions between ca. 1.86 and 1.834 Ga (including the Annabel and Reynard Lake plutons).
1.83 to 1.79	Terminal collision of Trans-Hudson Orogen and final closure of the Manikewan ocean under conditions of peak metamorphism. Transpressional reactivation of regional shear zones, including Needle Falls shear zone and Tabbemor 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., Tabbemor fault system. [D ₆]

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 2). 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 Ma old) of the Western Canada Sedimentary Basin unconformably overlie Precambrian basement rocks over the entire southern half of Saskatchewan. The present 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 Ma 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). 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.

2.3 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. D₄ represents the timing of activation of strike-slip shear zones, and the re-activation of some pre-existing faults under retrograde metamorphic conditions. D₄ also produced the Embury Lake flexure, the dominant map-scale fold structure in the Creighton area. D₄ is constrained to have occurred between ca. 1.790 and 1.760 Ga. D₅ 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 D₆ deformation event.

2.4 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 2). 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 2). These plutons offer the most promise for a suitable siting selection, as identified in the initial screening study by Golder (2011). Areas mapped as either rock outcrop or rock thinly covered (< 0.5 m) by surficial materials or as a discontinuous till veneer (< 1.0 m) interspersed with rock outcrop account for about 38% of the portion of the Creighton area not covered by water. In comparison, the Annabel Lake and Reynard Lake plutons exhibit higher percentages of this terrain characteristic (47% and 51%, respectively) than the Phantom-Boot Lake pluton (23%).

2.4.1 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 2, the pluton is tear-drop shaped, with its lobe situated at the southeast end of the pluton. The lobe is approximately 6 km wide at its widest point. The Reynard Lake pluton is inferred to have intruded the older Flin Flon greenstone belt during the Trans-Hudson Orogeny. The pluton is estimated to be approximately 1.853 Ga old, based on dating using the single-zircon Pb-evaporation technique (Ansdell and Kyser, 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 non-prophyritic 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).

2.4.2 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 2). 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 modelling, 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.

2.4.3 PHANTOM-BOOT LAKE PLUTON

The Phantom-Boot Lake pluton is located about 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 2). 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 old and a granite phase of the Phantom Lake pluton at approximately 1.840 Ga old, respectively. They also obtained an age of approximately 1.834 Ga old for the associated granite dykes of the Phantom Lake pluton. Heaman et al. (1992) in turn obtained an age of approximately 1.838 Ga old 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).

2.4.4 FLIN FLON GREENSTONE BELT

The majority of the Town of Creighton itself is underlain by metavolcanic rocks of the Flin Flon greenstone belt (Figure 2). 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).

2.4.5 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 west of the Town (Figure 2). 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).

2.4.6 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 2). 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 shear zone is unknown, although Ashton et al. (2005) have noted evidence of sinistral movement.

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 near 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 100s 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 trend. 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.

2.4.7 METAMORPHISM

Two periods of metamorphic mineral growth appear to have occurred in the Creighton region (Fedorowich et al., 1993). These periods correspond to the D₂ and D₃ deformation events described in Section 2.1 and 2.2 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 D₂ and was likely maintained up to D₃ (Bailes and Syme, 1989). Locally, an amphibolite grade halo has been noted around the Reynard Lake pluton, suggesting the intrusions locally increased in temperature during 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 D₃ 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 Kiskeynew 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 D₅ 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).

2.5 QUATERNARY GEOLOGY

Although drift cover in much of the Creighton area is generally thin and discontinuous (Henderson, 1995), drilling data indicate that drift thickness is highly variable, with depths up to 30 to 70 m observed (Campbell, 1988; Saskatchewan Energy and Resources, 2010; Section 5.1). High relief bedrock topography is responsible for wide variations in drift thickness over short lateral distances (Campbell, 1988).

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 (Figure 3), along which part of Highway 106 has been routed. Figure 3 shows only the southeast margin of this feature. 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 elevation estimated by Schreiner (1984b) 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 3). Glaciolacustrine deposits commonly form a blanket over previously deposited sediments, with thicker deposits in depressions. The distribution and thickness of the various terrain units found in the Creighton area are detailed in Section 5.

3 TOPOGRAPHY

The Creighton area is located in the Kazan Upland Physiographic Region of the western Precambrian Shield (Bostock, 1970). Kazan Upland topography is typical of the Canadian Shield, with large areas of bedrock that form broad, smooth uplands and lowlands. First-order relief is smooth and gently rolling, whereas second-order relief is more complex, consisting of bedrock-controlled ridges and valleys. Much of this relief was produced during glaciation due to preferential erosion of structural and lithological weaknesses. Ice movement and meltwater erosion smoothed and polished resistant bedrock hills and scoured out weakness zones in the bedrock. Valleys and depressions between rock ridges and knolls typically contain lakes, bogs and relatively thick overburden deposits.

Topography is an important aspect of the terrain, as it plays an important role in controlling surface and shallow groundwater flow directions and can reveal much about the potential extent of overburden deposits in the Creighton area. The following descriptions of the topography in the Creighton area rely heavily on the representation of the landscape by the CDED digital elevation model.

3.1 ELEVATION

The Creighton area is located at the southern margin of the Precambrian Shield. Within the Creighton area (Figure 4), there is less than 100 m of relief, with elevation ranging from about 292 m at the shore of Schist Lake in the southeast to about 369 m in the north, immediately south of Ahrens Lake. The major gradients are from north to south into Amisk Lake and 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 form the main topographic feature in the central-west part of the area.

The next most distinct topographic features in the Creighton area are the elevated, plateau-like surfaces in the area, which largely represent the surface expression of plutons. The east-west trending ridge north of Johnson Lake is probably the best example (Figure 4). Only the southeast margin of this feature is shown in Figure 4. The isolated summits on this generally flat-topped, 5 to 8 km wide feature are at elevations of 360 to 370 m, which are generally 30 m above the lakes on either side of the ridge. A smaller example of a flat-topped feature raised 10 to 20 m above the

surrounding terrain is the elongate intrusion mapped as granodiorite-tonalite immediately south of Martin Lake, which is located immediately west of the Creighton area, southwest of Ahrens Lake. The elevated aspect of these plateau-like intrusive bodies is due to 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.

3.2 RELIEF

Relief is a metric that can be defined in different ways, and the calculated value of relief depends on the horizontal scale of the neighbourhood considered in the calculation. As indicated in Section 3.1, the total relief in the Creighton area is about 77 m, which places an upper limit on the amount of relief within local zones. Relief was calculated in two ways. The first was by subtracting the average elevation within a radius from the elevation value in the processing cell, providing an indication of the degree to which a point is expressed negatively or positively within an area. The second was defined as the range in elevation within a circular window, providing an indication of the maximum relief within the window.

A map of departures from the average elevation within a 20 km radius (Figure 5) provides additional definition of the plateau-like areas of high ground within the Creighton area. The inset map provided on Figure 5 shows in red the areas that are at least 10 m higher than average at this scale of calculation. Several features worth describing stand out in this image. A greater proportion of the Annabel Lake pluton is represented as high ground, as compared with the Reynard Lake pluton, the southern part of which contains some areas of below average elevation. In addition, the areas of high ground (> 10 m) mapped on the Reynard Lake pluton are represented as discontinuous patches. In contrast, the Annabel Lake pluton is mapped as high ground continuously except along the north margin in association with the Annabel Lake shear zone, and along a trough associated with Arner Lake. This trough is expressed as a linear depression 10 to 20 m deep, 1 to 2 km wide, and 20 km long extending along the long axis of the Annabel Lake pluton. It displays a topographic expression that is similar to that displayed along the shear zones forming the margins of the pluton. Finally, the Phantom-Boot Lake pluton appears on the Figure 5 inset as a local topographic depression except for the area bordering onto its northern margin.

A map of departures from the average elevation within a 2 km radius (Figure 6) highlights the knobs, ridges and trenches in the more rugged parts of the Creighton area. Knobs and ridges are shown in red whereas trenches are shown in blue. The most pronounced local highs and lows

extend about 30 m at most above or below the surrounding terrain. The surface of the Reynard Lake pluton is somewhat more knobby than that of the Annabel Lake pluton (Figure 6 inset), with the irregular shaped knobs on the former pluton typically about 500 m to 2 km in extent.

A map showing the range in elevation within a 250 m radius (Figure 7) provides an indication of the location and extent of high and low relief areas. Within the Creighton area, the maximum relief within a 250 m to 1 km radius is about 50 m. A larger search radius would produce larger relief values, with about 77 m representing the upper limit within the Creighton area.

The areas of greatest relief are located around the margins of the large lakes and the relief might be associated with strength contrasts in the bedrock and related differential erosion. For example, within about 1 to 2 km of the west, north and east shores of Amisk Lake, there are extensive areas with 25 to 45 m of relief. Virtually all of this relief is believed to be bedrock controlled and associated with rock ridges. In addition, Henderson and Campbell (1992) suggest that some of the linear lows between bedrock ridges around Amisk Lake are associated with subglacial meltwater channels. Some of the linear depressions between bedrock ridges along the northwest shores of Amisk Lake are 200 to 500 m wide and 15 to 30 m deep. It is likely that meltwater erosion has exploited a lithological fabric in the bedrock in the area mapped as the Welsh Lake assemblage (Figure 2) consisting of narrow zones of gabbro-diorite and metavolcanic rocks forming the highs and metagreywacke forming the lows. Perhaps competency contrasts in the bedrock are partly responsible for the high relief around the shores of Amisk Lake.

Figure 7 illustrates the extent of the low-relief areas on the surfaces of the Annabel Lake and Reynard Lake plutons, and the relatively high relief around their margins. A comparison of Figure 7 with Figure 2 illustrates that many of the other areas mapped as plutons are expressed as low-relief areas with high-relief margins. It seems plausible that the reason for the low-relief expression of the plutons in the area is related to relatively uniform lithologies, as compared with the great contrasts in strength that can be found within the older assemblages.

3.3 SLOPE

At many sites on the Precambrian Shield, areas of high slope density are generally correlated with areas of thin drift. The reason for this correlation is that much of the relief on the Shield is related to bedrock topography and areas of low relief (lacking steep slopes) are often associated with drift filling the lows in the bedrock topography. As a result, a map showing the density of steep ($\geq 6^\circ$) slopes within a 2 km radius was prepared to determine whether the areas of high slope density correlate with areas of thin drift (Figure 8).

In the Creighton area, much of the exposed bedrock shown in the SPOT imagery and delineated in the surficial maps (Figure 3) is located on the surfaces of the Annabel Lake and Reynard Lake plutons, which are expressed as low-relief surfaces with a low density of steep slopes. Many of the areas of high slope density display significantly less exposed bedrock than the areas of low slope density. As a result, it appears that the areas of thin drift are not associated with high relief and steep slopes. This is favourable from the point of view of construction capability.

4 DRAINAGE

The distribution of surface water and surface water drainage are important factors to consider in the preliminary assessment, as surface flow is a useful surrogate for groundwater flow at shallow depth. Section 4.1 provides some information on the size, distribution and depth of lakes in the Creighton area. Section 4.2 describes the existing watershed map file and the drainage analysis conducted by JDMA, and then Section 4.3 describes surface drainage in the area with a focus on the Annabel Lake, Reynard Lake and Phantom-Boot Lake plutons.

4.1 WATERBODIES AND WETLANDS

The Creighton area contains some large lakes (Figure 9), including Amisk Lake, which is 308 km² in extent, and three other lakes with areas greater than 10 km²: Annabel Lake (12 km²), Embury Lake (13 km²), and Schist Lake (24 km²). Only small parts of Schist Lake and Embury Lake extend into the Creighton area.

A number of lakes in the Creighton area represent internal drainage systems, with no outlets. These areas were not removed from the watersheds delineated in Section 4.2. Examples include Birch Lake and six small lakes (less than 0.4 km²) on the southern margin of Reynard Lake pluton (Figure 9). Water stored within these lakes could recharge the underlying surficial deposits. Groundwater beneath the lakes could eventually discharge into creeks and waterbodies within the same basin or perhaps into an adjacent basin.

After reviewing the wetlands shown in the SPOT imagery, it was found that the mapping of wetlands in the topographic maps was inadequate, with only 5% of the Creighton area covered by wetlands. As a preliminary attempt to improve the mapping, the organic deposits mapped in the surficial geology maps (units 7a and 7b in Figure 3) were merged with those shown on topographic maps (Figure 9). Note that the surficial geology in the Manitoba portion of the Creighton area south of latitude 54°45' has not been digitized (see Figure 3). Therefore, the representation of wetlands in this area is based only on topographic map data, and this results in a false impression of relatively few wetlands in this area. The merged file indicates that 18% of the Creighton area is covered by wetlands.

The organic deposits mapped in the surficial geology maps represent peat and muck about 1 to 5 m thick located within poorly drained ground forming swamps, marshes, bogs and fens,

typically associated with topographically enclosed basins or with extensive areas underlain by fine-grained, poorly drained glaciolacustrine deposits.

The most extensive wetlands in the Creighton area and nearby are located in the southeast part of the area (Figure 9), particularly east of Mystic Lake. Smaller wetlands are distributed throughout the Creighton area. The abundance of wetlands in the area is partly a function of the low relief.

Information on lake depths in the Creighton area was obtained from depth surveys conducted by the Saskatchewan Fisheries Branch in the 1960s, 1970s and 1980s (Table 4). Additional information on the maximum depth of lakes was found in Van Loon and Beamish (1977) and Franzin and McFarlane (1976). Although it was not possible to obtain depth data on all of the lakes in the Creighton area, the variety in lake sizes and shapes included in Table 4 and shown in Figure 9 is thought to capture much of the variability that exists within the area in terms of maximum lake depth. Many of the surveyed lakes appear to be less than or equal to 10 m deep in their deepest parts, including Phantom Lake. The deepest lakes in the area reach approximate maximum depths of 30 to 45 m.

Table 4 Approximate maximum depths of lakes with depth surveys in the Creighton area.

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

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

²Approximate maximum depth after Franzin and McFarlane (1976)

4.2 CATCHMENTS AND SUBCATCHMENTS

A watershed, also known as a catchment, basin or drainage area, includes all of the land that is drained by a watercourse and its tributaries. JDMA conducted a drainage basin analysis to confirm and, where possible, partition the most detailed available mapping of watersheds in the Creighton area. The delineation of drainage divides is useful to infer regional and local, surface water and shallow groundwater flow directions.

The best available drainage area delineation for the Creighton area is the sub-basin file produced by the Prairie Farm Rehabilitation Association (PFRA), which has been renamed recently as Agriculture and Agri-Food Canada (AAFC). According to the metadata for this file, the sub-basin delineation of the PFRA Watershed Project consists of 47 sub-basins delineated at a scale of roughly 1:250,000 covering the Canadian Prairies. The spatial extent of the sub-basin file covers all of Alberta, Saskatchewan and Manitoba, and portions of adjacent jurisdictions (British Columbia, the Northwest Territories, Nunavut, Ontario, and the United States) into which Prairie watersheds extend. The sub-basin file is the authoritative source for gross and effective drainage areas in the Prairie Provinces. The PFRA sub-basins extending into the Creighton area average around 2,000 km² in size and match the Environment Canada sub-sub-division of drainage areas except in some locations where PFRA refined and subdivided the sub-basins.

The locations of hydrometric gauging stations and boundaries of the PFRA sub-basins were delineated manually from paper topographic maps of the National Topographic Survey (NTS), usually at a scale of 1:50,000. The drainage boundaries were then digitized by personnel at the Saskatchewan Water Corporation, with digitizing information such as mapsheet number, name, edition, projection and datum, and root mean squared error recorded. The horizontal positional accuracy of the sub-basin boundaries is variable depending on the distinctiveness of the drainage boundary and the accuracy of the topographic data, and thus cannot be quantified without onsite investigation and verification. In addition, the hand-mapping process influences the positional accuracy, with a 1 mm thick hand-drawn boundary on the map producing a 250 m error at 1:250,000. Additional errors would be introduced during digitization.

JDMA modelled the movement of water over the landscape using the watershed analysis function in the program TNTmips and the CDED elevation model. The CDED digital elevation model was created by NRCan using the same NTS topographic data that is shown in the 1:50,000 scale NTS topographic maps. As a result, the DEM used here is comparable with the data used by the PFRA to construct the sub-basin boundaries.

The procedure that JDMA followed in the drainage analysis was to confirm the sub-basin boundaries and then to subdivide the sub-basins where possible. It is important to note that the sub-basins do not represent the smallest catchments that can be delineated in most areas, as local ridges and highland complexes are present within many of the sub-basins that serve to further divide surface flow directions within the basin.

The result of the drainage analysis is a single set of lines and polygons, which represents a merged watershed file (Figure 10). It is important to note that many of the watersheds delineated in the merged file could be further subdivided, but that JDMA had to limit the minimum size of basin to maintain a consistent scale of delineation across the Creighton area. Where drainage divides created by JDMA matched reasonably with the sub-basin boundaries, the procedure was to accept the existing sub-basin boundary (labelled 'confirmed' in Figure 10). Newly delineated drainage divides were then used to subdivide the sub-basins. A field entitled 'Type' was created in the merged file denoting whether each portion of the catchment boundary was delineated by JDMA and PFRA (0) or only JDMA (1). JDMA made an effort to ensure that the newly delineated drainage divides honoured the existing watercourse map file where possible.

4.3 SURFACE FLOW

Most of the Creighton area is contained within the Sturgeon-Weir River sub-sub basin (Figure 10), which is located within the Nelson River watershed that drains into Hudson Bay. The Sturgeon-Weir River drains through Amisk Lake and eventually empties into the Saskatchewan River at Cumberland House about 50 km south-southwest of the outlet on Amisk Lake. The Saskatchewan River empties into Lake Winnipeg, which is drained by the Nelson River. In contrast, the north-central fringe of the Creighton area drains into the Churchill River, which flows towards Hudson Bay. This northern part of the area is located within the Central Churchill – Highrock Lake sub-sub basin.

Drainage within the Sturgeon-Weir portion of the Creighton area is directed either towards Athapuskow Lake, located about 10 km south of the southeast corner of the Creighton area, or towards Amisk Lake located in the southwest portion of the area. The watersheds that feed into Amisk Lake have been coloured in shades of blue on Figure 10 for convenience, whereas those draining into Athapuskow Lake are shown in shades of brown.

The portion of the Creighton area that drains towards Athapuskow Lake can be sub-divided into three main watersheds (Figure 10). Flow on the surface of the northern part of Annabel Lake pluton is directed into Annabel Lake, where it flows eastward into Annabel Creek and then into

Embury Lake, Big Island Lake and the Inlet Arm of Schist Lake with the latter two features located east of the Creighton area. Drainage of the eastern margin of Annabel Lake pluton, around Creighton Lake, is directed through Creighton Creek and Flin Flon Creek into Ross Lake, which is drained by Ross Creek into the Northwest Arm of Schist Lake (east of the Creighton area). The eastern portion of the Phantom-Boot Lake pluton drains into Phantom Lake, which drains into the West Arm of Schist Lake, labelled as Schist Lake in Figure 9.

The part of the Creighton area that drains towards Amisk Lake can be divided into at least five watersheds (Figure 10). The areas around Johnson Lake drain into Neagle Lake, which is drained into the West Channel through Neagle Creek. Most of this watershed is located outside the Creighton area to the west. The area around Welsh Lake drains into the North Channel. The western portion of the Reynard Lake pluton drains mainly into Wolverine Lake and into Comeback Bay, although a smaller part of this watershed drains into Magdalen Lake and into the North Channel. The south-central part of the Reynard Lake pluton drains into Mosher Lake before feeding into Comeback Bay. The northern and eastern margins of the Reynard Lake pluton and the southern part of Annabel Lake pluton drain through Meridian Creek through Wekach Lake, Mystic Lake, and Table Lake before emptying into Amisk Lake. The western portion of the Phantom-Boot Lake pluton is also located within the basin described above.

A product of the elevated plateau-like aspect of many of the plutons in the Creighton area and vicinity is the presence of creeks tracing along the pluton margins and drainage divides winding along the low relief surfaces of the plutons. Annabel Lake and Reynard Lake plutons are good examples of this phenomenon. The abundance of exposed bedrock on the elevated pluton surfaces might suggest that these features should be well drained. However, there is an abundance of narrow wetlands filling structurally controlled lows on the pluton surfaces, which trap runoff for varying lengths of time before releasing it through evapotranspiration or into streams or lakes. The abundance of wetlands is partly a function of the low relief terrain, but also a function of the irregularities in the bedrock surface.

5 TERRAIN CHARACTERISTICS

Although drift cover in much of the Creighton area is generally thin and discontinuous (Henderson, 1995), drilling data indicate that drift thickness is highly variable, with depths of 30 to 70 m observed (Campbell, 1988; Section 5.1). An assessment of the distribution and thickness of overburden deposits is helpful for interpreting the lineament investigation. Areas covered by thick overburden deposits are areas where the least amount of information is available on the presence and extent of geological structures. Another important reason for investigating the distribution of surficial deposits is to delineate areas of exposed bedrock. Areas of exposed bedrock or thin drift are more readily amenable to site characterization utilizing surface investigative techniques for structural mapping and rock mass characterization. In areas devoid of exposed bedrock or thin drift, site characterization would have to rely solely on subsurface methods of investigation.

This section provides information on the nature, areal extent and thickness of overburden deposits within and immediately surrounding the Creighton area (Figure 3). The information was derived largely from map unit descriptions of Campbell and Henderson (1997) and Henderson (2002), from water well and drill hole data, and from the mapping of rock outcrops using multispectral and panchromatic SPOT imagery.

5.1 DRILL HOLE AND WATER WELL DATA

The drill hole and water well data presented below provide values of total overburden thickness at a few points within the Creighton area. In contrast to these data, the surficial mapping information presented in Section 5.2 provides an indication of the distribution of areas of exposed bedrock or thin drift throughout the area, but deposit thickness values reported for many of the surficial deposits do not represent the total overburden thickness. They merely represent the thickness of the uppermost surface deposit.

5.1.1 SGS DRILL HOLE DATA

Section 1.3.2 described the SGS drill hole data that were reviewed for information on overburden thickness within the Creighton area. Figure 3 shows the locations of the drill holes. Depth to bedrock was as great as about 70 m, but, as stated in Section 1.3.2, it is unknown whether some of the drill holes were completed over lake ice platforms and whether the height of the water column

has been excluded from the depth to bedrock value. All six drill holes with depth to bedrock greater than 10 m are located within or near lakes. Due to the unknown accuracy of the drill hole coordinates, it is difficult to know how many of these six drilling sites are truly located over water and whether the height of the water column could be included within some of the largest reported depth to bedrock values. However, it would not be surprising if the drift was generally thicker within the major lake basins due to increased glaciolacustrine sedimentation into these topographic lows associated with glacial Lake Agassiz.

5.1.2 WATER WELL INFORMATION DATABASE

The Water Well Information Database contains records for 16 water wells located within the Creighton area (Table 5). Fifteen of these wells are located in the urban municipality of Denare Beach, and one well is located within the urban municipality of Creighton. As stated in Section 1.3.3, all of the 16 water wells are completed in overburden deposits (Table 5). Thus, the well depths represent minimum values for overburden thickness.

The developed portion of the urban municipality of Denare Beach, where 15 of the wells are located, is included within the main nearshore glaciolacustrine deposit mapped in the Creighton area (Figure 3). The wells are about 6 to 60 m deep with an average depth of 30 m. Sand is the most common material encountered in these wells. Some of the wells were reported to encounter only sand. Variable amounts of gravel, silt and clay were noted in some wells. As nearshore sediments in this area are reported to represent a drape or blanket 1 to 5 m thick of sand (Henderson, 2002), it is likely that the gravel, silt and clay layers encountered at depth in some of the wells could represent other Quaternary sediments, possibly including glacial and interglacial deposits. For example, the three wells drilled in 1993 in Denare Beach terminated within a grey, unoxidized clay formation, which might represent till. Each of these wells intersected about 30 m of fine to gravelly sand above the clay formation, and the 30 m thick sand unit was capped by a layer of grey silt or clay 1.5 to 2.0 m thick. The deepest well reported in the Creighton area (Table 5) indicated 62 m of sand, with the well terminating in boulders. This could illustrate that the nearshore glaciolacustrine deposits can be much thicker than the 1 to 5 m thickness suggested by the surficial geology map in the area (Henderson, 2002).

Table 5 Water well records available for the Creighton area.

ID	Date	UM ¹	Depth ² (m)	Well use	Aquifer
103299	1993.03.28	DB	37	Municipal (Withdrawal)	Glacial
103300	1993.03.22	DB	34	Municipal (Withdrawal)	Glacial
103298	1993.03.22	DB	34	Municipal (Observation)	Glacial
071065	1977.05.01	DB	30	Municipal (Withdrawal)	Glacial
071064	1977.05.01	DB	30	Municipal (Withdrawal)	Glacial
071082	1977.05.01	DB	24	Municipal (Observation)	Glacial
052871	1977.06.20	DB	30	Municipal (Withdrawal)	Glacial
052872	1977.06.15	DB	30	Municipal (Withdrawal)	Glacial
026311	1966.11.09	DB	24	Domestic (Withdrawal)	Glacial
026312	1966.11.08	DB	24	Domestic (Withdrawal)	Glacial
071079	1977.05.01	DB	24	Municipal (Water Test Hole)	Glacial
071080	1977.05.01	DB	20	Municipal (Water Test Hole)	Glacial
071081	1977.05.01	DB	36	Municipal (Water Test Hole)	Glacial
071083	1977.05.01	DB	62	Municipal (Observation)	Glacial
052553	1977.08.19	DB	6	Domestic (Withdrawal)	Glacial
051853 ¹	1977.07.21	CR	15	Domestic (Withdrawal)	Glacial

¹Urban Municipality (DB = Denare Beach; CR = Creighton)

²Total well depth

5.2 TERRAIN UNITS FROM SURFICIAL MAPPING

As described in Section 1.3.1, the surficial geology of the Creighton area has been mapped in detail. The surficial mapping programs outlined the morainal, glaciofluvial, glaciolacustrine and organic deposits and delineated areas of exposed bedrock or rock thinly covered by surficial materials. A summary of the areal extent of the surface deposits covering the Annabel Lake, Reynard Lake and Phantom-Boot Lake plutons has been compiled in Table 6. It is important to note that the surface deposit thickness reported in Table 6 does not necessarily refer to the total overburden thickness. For example, in the case of organic, glaciofluvial and glaciolacustrine deposits, the surface deposit is expected to be underlain by other Quaternary deposits. Only in the cases of the till veneer and till blanket map units are the deposit thickness values expected to be indicative of total overburden depth. Note that the term ‘veneer’ refers to a deposit that is generally less than one metre thick. The following sections describe the composition and areal extent of the surficial deposits in the Creighton area.

Table 6 Thickness and areal extent of surficial deposits over the three main plutons.

Map unit	Thickness	Areal extent of pluton (%)		
		Annabel Lake pluton	Reynard Lake pluton	Phantom-Boot Lake pluton
Till veneer	< 1 m	15	20	0
Till blanket	> 1 m	0	0	11
Sand and gravel	1-5 m	2	3	5
Glaciofluvial ice-contact	1-5 m?	0	0	10
Glaciofluvial subaqueous outwash	> 20 m	0	2	0
Glaciolacustrine offshore veneer	< 1 m	13	13	4
Glaciolacustrine offshore blanket	< 10 m?	3	1	0
Glaciolacustrine nearshore	1-5 m	0	0	0
Organic	1-5 m	19	20	27
Bedrock	< 0.5 m	32	31	23
Water	N/A	15	10	20

5.2.1 MORAINAL

Glacial deposits mapped within the Creighton area have been divided into till blankets and till veneers (Campbell and Henderson, 1997; Henderson, 2002). These glacial deposits consist of sandy to silty diamicton deposited at the margin of or beneath glaciers. Till blankets have only been mapped south of the Creighton area (Figure 3), with all other till mapped as a veneer. Till veneers represent discontinuous deposits generally less than one metre thick interspersed with bedrock outcrops. However, thicker deposits can fill bedrock depressions within this map unit. Approximately 15% of the surface of the Annabel Lake pluton is mapped as till veneer (Table 6), with the largest areas of till veneer located in the extensively drift-covered central part of the pluton, west of Arner Lake (Figure 3). About 20% of the surface of the Reynard Lake pluton is mapped as till veneer, with a particular abundance mapped around its low-lying southern margin. Till veneers have been mapped in small areas on the Phantom-Boot Lake pluton, and these shallow deposits cover about 11% of the surface of the pluton.

5.2.2 GLACIOFLUVIAL

Three types of glaciofluvial deposits have been mapped in the Creighton area: Subaqueous outwash deposits, ice-contact deposits, and sand and gravel deposits of undetermined origin (Campbell and Henderson, 1997).

Subaqueous outwash deposits consist of thick sequences of stratified sand and gravel that can be greater than 20 m thick. These deposits can be found within valleys or meltwater channels, where they were deposited subaqueously within glacial Lake Agassiz by subglacial meltwater streams (Henderson, 2002). They can also occur as ice-contact deltas and recessional, end or interlobate moraines. For example, an extensive subaqueous outwash deposit is mapped north of Annabel Lake (Figure 3), which Henderson (1995) interprets as an end moraine. This feature is located largely north of the Creighton area. Schreiner (1984a) reported two auger holes in this deposit. One recorded nine metres of sand over bedrock (EC-102), and the other recorded five metres of sand overlying two metres of till over bedrock (EC-104).

Ice-contact stratified drift generally appears in the form of sinuous to straight ridges or irregular hummocks, which represent features deposited by subglacial, englacial or supraglacial streams or ponds (Henderson, 2002). This map unit includes eskers, kames, crevasse fillings and lee-side deposits. None of these deposits are mapped on the surfaces of the Annabel Lake or Reynard Lake plutons. However, about 10% of the surface of the Phantom-Boot Lake pluton has been mapped as ice-contact stratified drift.

The sand and gravel deposits of undetermined origin make up only about 5% or less of the surfaces of Annabel Lake, Reynard Lake and Phantom-Boot Lake plutons (Table 6). Some of these deposits are distributed within creek valleys near the margins of the larger plutons.

5.2.3 GLACIOLACUSTRINE

Glaciolacustrine deposits mapped in the Creighton area have been divided into three types: nearshore sediments, offshore blankets, and offshore veneers (Figure 3). Nearshore sediments represent a drape or blanket 1 to 5 m thick of sand grading basinward into finer grained material (Henderson, 2002). The main nearshore deposit mapped in the area is located between Mosher Lake and Comeback Bay (Figure 3). Water wells in the Village of Denare Beach drilled through this nearshore deposit indicate sand deposits reaching thicknesses of 30 to 60 m.

Glaciolacustrine offshore blankets form flat poorly drained landforms commonly mantled by peat (Henderson, 2002), with the deposits consisting of silt or clay and minor sand. The thickness of these deposits is unknown, but they could reach 10 m in places. These offshore blanket deposits occur extensively along the east-west trending ridge located north of Annabel Lake (Figure 3). Glaciolacustrine offshore veneers are mapped throughout the Creighton area (Figure 3). They consist of thin or discontinuous deposits of silt and clay that are generally less than one metre thick, although greater thicknesses can be found in depressions.

The glaciolacustrine offshore blankets make up less than 5% of the surfaces of the Annabel Lake and Reynard Lake plutons (Table 6), being mapped only in the western portions of the plutons. In contrast, glaciolacustrine offshore veneers are relatively abundant and more evenly distributed on the surfaces of these two plutons. Isolated glaciolacustrine offshore veneers have been mapped over the Phantom-Boot Lake pluton. It is important to note that many of the organic deposits mapped over the plutons are expected to be underlain by glaciolacustrine offshore blankets or veneers, which could suggest that an additional 10 to 20% of the surface of the plutons is covered by offshore glaciolacustrine sediments.

5.2.4 ORGANIC

Holocene organic deposits have been mapped throughout the Creighton area, with some extensive deposits north of Annabel Lake, near Johnson Lake, and south of the Creighton area near Spectral Lake (Figure 3). The later organic deposit coincides closely with the mapped extent of the Kaminis Lake pluton (Figure 2). Organic deposits are typically 1 to 5 m thick, and they represent swamps, marshes, bogs and fens. The areas mapped as fen swamp or marsh include wet sedge peat or organic muck, and minor moss peat located within flat, waterlogged, grassy surfaces with few trees and can include areas with visible surface water (Henderson, 2002). The areas mapped as bog peat consist of decomposed sphagnum moss and woody peat occupying raised irregular surfaces with an open to closed tree canopy.

Organic deposits cover approximately 20% of the surfaces of the Annabel Lake and Reynard Lake plutons (Table 6). Most of them are discontinuous features forming rims around small lakes or filling local structurally controlled bedrock depressions (Figure 3). Organic deposits cover almost a third of the Phantom-Boot Lake pluton.

5.2.5 BEDROCK

Areas mapped as rock outcrop or rock covered by less than 0.5 m of overburden are generally located within topographically prominent parts of the Creighton area (Figure 3). Bedrock is mapped over about a third of the Annabel Lake and Reynard Lake plutons, which are two of the most topographically prominent features in the area (Section 3.2). The Oddan Lake pluton, located west of the Creighton area, provides another example of a topographically prominent feature with extensive areas of exposed bedrock. In contrast to the above examples, a smaller percentage of the Phantom-Boot Lake pluton displays exposed bedrock, and very little bedrock has been mapped around the Kaminis Lake pluton.

As stated above, about a third of the Annabel Lake and Reynard Lake plutons have been mapped as bedrock (Figure 3). The areas of exposed bedrock on these plutons are displayed reasonably well in the SPOT imagery shown in Figure 11. The coloured SPOT images in the main part of Figure 11 represent the PCA composite images described in Section 1.3.5. The greyscale images shown in the insets are panchromatic SPOT images. Outcrops appear in pink in the composite images, whereas they appear in white in the panchromatic images. The PCA composite images display wetlands in colours ranging from yellowish green to reddish orange or brownish red. Note that the imagery displays many wetlands that were too small to be represented explicitly as organic deposits in the surficial geology mapping.

The insets shown in Figure 11 were selected to illustrate in detail the nature of the exposed bedrock and organic deposits within internal portions of the Annabel Lake and Reynard Lake plutons where extensive bedrock exposure is displayed in the SPOT imagery.

The central-left part of the inset area on the Annabel Lake pluton shown in Figure 11 contains a radial pattern of structurally controlled bedrock lows filled with organic deposits. Outside of the linear swamp-filled lows in this area, there appears to be abundant bedrock exposure. It is expected that the rock masses near the structures associated with these lows would show signs of greater tectonic damage than the zones outside of the lows. The rock outcrops in this area are separated from one another by the swamp-filled lows. The largest areas of exposed bedrock on the Annabel Lake pluton are located closest to the northern margin of the pluton.

The central-left portion of the inset area on the Reynard Lake pluton contains an area of abundant bedrock exposure roughly 1.5 km in diameter, which appears to be associated with a slight topographic high. This subtle topographic high displays no linear, swamp-filled depressions like those displayed on the inset for the Annabel Lake pluton. The main area of outcrop is characterized by a single contiguous area of exposed bedrock, not intersected by any distinct linear depressions. This subtle topographic high is located approximately equal distances from the north and south margins of the pluton.

6 GROUNDWATER

In general, shallow groundwater flow within bedrock and surficial aquifers should mimic the pattern of surface flow suggested by Figure 10 and as can be inferred in detail from the elevation and relief maps (Figure 4, Figure 5, and Figure 6). Groundwater divides should generally coincide with surface drainage divides. Section 4.3 provides a description of surface flow over the Annabel Lake, Reynard Lake and Phantom-Boot Lake plutons.

As areas mapped as bedrock (Figure 3) are typically located in topographically prominent positions such as plutons, the absence of permeable drift deposits in these areas is expected to result in abundant surface runoff rather than recharge. However, these areas also contain numerous bedrock structures and, therefore, they could contain recharge zones for bedrock aquifers. For example, the abundant linear, swamp-filled lows and the small lakes displayed on the pluton surfaces (e.g., Figure 11) could represent bedrock recharge zones. Bedrock aquifers within the area are expected to be shallow, with a large proportion of the groundwater probably confined to fractures and faults in the upper 45 to 60 m.

The glaciofluvial deposits (Figure 3), representing the key permeable deposits in the area, are typically located in topographically low positions, although some notable deposits are located in elevated positions. The subaqueous outwash deposits located in the topographic lows around the pluton margins are expected to be recharge zones. Surface flow from the areas of exposed bedrock above should supply abundant runoff to recharge these deposits, which will eventually discharge into nearby creeks and lakes.

No information has been obtained on the permeability of the major shear zones in the area (Figure 2). However, it seems plausible that the lakes overlying these features (e.g., Annabel Lake, Wilson Lake, and Meridian Lake) could be important recharge zones for shallow bedrock aquifers related to possible elevated secondary permeabilities associated with these structures.

The extensive subaqueous outwash deposits mapped along the east-west trending ridge north of Annabel Lake (Figure 3) represent permeable deposits located in an elevated position. These deposits likely represent significant recharge zones. Groundwater within this deposit is expected to discharge into the nearby lakes and streams.

No information has been generated on groundwater at repository depth or on groundwater resources beyond that presented in the initial screening study (Golder, 2011).

7 NEOTECTONIC FEATURES

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

The movement and interaction of tectonic plates creates horizontal stresses that result in the compression of crustal rocks. The mean of the current major principal stress orientation in central North America, based on the World Stress Map (Heidbach et al., 2009), is NE ($063^\circ \pm 28^\circ$). This orientation coincides roughly with both the absolute and relative plate motions of North America (Heidbach et al., 2009; Baird and McKinnon, 2007), and is controlled by the present tectonic configuration of the North Atlantic spreading ridge (Sbar and Sykes, 1973), which has likely persisted since the most recent Paleocene-Eocene plate reorganization (Rona and Richardson, 1978; Gordon and Jurdy, 1986).

Repeated cycles of glaciation and deglaciation throughout the Quaternary have induced stresses by sequentially loading and unloading the Earth's crust. The loads associated with glaciation are sufficient to depress the crust by hundreds of metres. Crustal rebound takes place once the weight of the ice is removed and rebound continues to occur today in this area, albeit slowly. The greatest rates of rebound typically occur near the ice-centres.

The stresses associated with cycles of ice loading and unloading interacting with the tectonic stress field may result in displacements along ancient discontinuities in the bedrock.

In addition to bedrock deformations associated with glacial loading and unloading, the ice also exerts stresses on the crust during its motion across the landscape. For instance, the glacier can thrust itself against topographic barriers resulting in damage to the rock and potential movement along existing discontinuities.

The study of neotectonic features in the area may reveal the timing and magnitude of glacially-induced seismic activity and deformations. However, conclusive identification of features indicative of reactivation of ancient bedrock structures due to cycles of glacial loading and unloading cannot be identified using the information sources available in the current study. Field investigation would be required to identify such features.

No major fault scarps associated with paleoseismic events have been identified in the area. Evidence of postglacial reactivation of bedrock structures could be searched for in future studies incorporating field investigations. One possible type of evidence to search for would be deformation within glaciolacustrine deposits draped over major bedrock structures. The deposits to target for this type of evidence would be the glaciolacustrine offshore veneer deposits that are notably draped over obvious bedrock structures.

8 ACCESSIBILITY CONSTRAINTS

Access to the eastern margins of the Annabel Lake and Reynard Lake plutons, where the plutons are widest and where the best bedrock exposure is located, is generally considered good. Although the terrain is generally of low relief, some of the irregularities in the bedrock surface would require blasting or fills during road construction. Mollard (1962) was responsible for selecting the route for Highway 167, which extends from Creighton to Denare Beach, traversing across the Reynard Lake pluton. Minimizing bedrock excavation and minimizing distance over the deeper wetlands were major factors considered in route selection in this area.

In the case of the Reynard Lake pluton, Highway 167 provides access across the southeast part of the pluton, but the best bedrock exposure is located about 12 km north of the highway along the axis of the pluton (Figure 11). The surface of the Reynard Lake pluton contains a relative abundance of positively expressed bedrock irregularities that might require blasting during construction. Road routing and construction activities would also need to consider the many small lakes dotting the surface. Detailed Google Earth imagery suggests the presence of an access road that winds its way along the cutline that extends through the inset area on the Reynard Lake pluton shown in Figure 11.

The eastern part of the Annabel Lake pluton, between Limit Lake and Creighton Lake, where the best bedrock exposure and widest part of the pluton are found, is located 6 to 10 km from Highway 106 (Figure 11). Fills would be required to cross the many linear swamp-filled lows during road construction. Aggregate resources should be available nearby within the large subaqueous outwash deposit mapped north of Annabel Lake (Figure 3). Gravel pits within this deposit are shown in Google Earth imagery immediately south of Tyrrell Lake.

Access onto the Phantom-Boot Lake pluton is provided by the West Mine Road extending north south along the western margin of the pluton. The detailed Google Earth imagery indicates the presence of roads or trails extending from the West Mine Road into the pluton.

No obvious forest harvesting activity and associated roads appear to be present on the Annabel Lake and Reynard Lake plutons.

Additional information on the availability of access roads for field reconnaissance can be obtained by reviewing FlySask imagery, and from descriptions of access routes in the available assessment reports from mining claims extending into the plutons from the margins.

9 SUMMARY

This report has compiled information on the terrain in and around the Creighton area from a variety of data sources, including topographic map data, digital elevation models and surficial geology all at the scale of 1:50,000. Section 1.3 provided a description of the main information sources used, including statements on the quality of the data.

The nature, areal extent and depth of overburden deposits within the Creighton area were outlined in Sections 2 and 5. Areas of rock outcrop or rock thinly covered by surficial materials, referred to as 'bedrock' on surficial geology maps, were delineated as part of the detailed mapping projects conducted in the area. Much of the area mapped as bedrock is associated with topographically prominent landforms such as some of the plutons. For example, about a third of the surfaces of the Annabel Lake and Reynard Lake plutons have been mapped as bedrock. The Phantom-Boot Lake pluton displays a lower percentage (about 20%) of areas mapped as bedrock than the two plutons described above. A map showing the actual areas of rock outcrop on the eastern margins of the Annabel Lake and Reynard Lake plutons was presented in Section 5.2.5 based on multispectral and panchromatic SPOT imagery.

Our approach to subdividing the PFRA sub-basins was described in Section 4.2, and the updated set of watersheds was presented in Section 4.3. There is a tendency for the granitic intrusions in the area to be expressed positively in the landscape, exhibiting low-relief plateaux-like surfaces (Section 3.2). The major topographic features in the area are the large lakes (Amisk Lake and Schist Lake) and the high relief terrain around their margins (Section 3.1). Surface flow within the Creighton area is directed towards either Amisk Lake or Athapapuskow Lake, with the local topographic prominence of the Annabel Lake, Phantom-Boot Lake, and Kaminis Lake plutons responsible for dividing the flow. Surface flow and shallow groundwater flow from the Reynard Lake pluton is directed into Amisk Lake. Flow from the Annabel Lake pluton is divided, with over half of the area draining into Athapapuskow Lake and the remainder into Amisk Lake.

Access is good onto the eastern margins of the Annabel Lake and Reynard Lake plutons, where these intrusive bodies are widest and the most extensive bedrock exposure is located (Section 8). Road construction of 6 to 12 km would be required to access these areas. An aggregate resource, which could potentially be used for road materials, exists within a 10 to 15 km radius of these areas. Larger wetlands on the Phantom-Boot Lake pluton would render access somewhat less favourable than on the two larger plutons.

REFERENCES

- Ansdell, K.M., 1993. U-Pb zircon constraints on the timing and provenance of fluvial sedimentary rocks in the Flin Flon Domain, Trans-Hudson Orogen, Manitoba and Saskatchewan. In: Radiogenic Age and Isotopic Studies, Report 7, Geological Survey of Canada, Paper 93-2, pp. 49-57.
- Ansdell, K.M., L.M. Heaman, N. Machado, R.A. Stern, D. Corrigan, P. Bickford, I.R. Annesley, C.O. Böhm, H.V. Zwanzig, A.H. Bailes, R. Syme, T. Corkery, K.E. Ashton, R.O. Maxeiner, G.M. Yeo, G.D. Delaney, 2005. Correlation chart of the evolution of the Trans-Hudson Orogen – Manitoba-Saskatchewan segment. *Canadian Journal of Earth Sciences*, 42, 761-762.
- Ansdell, K.M. and T.K. Kyser, 1990. Age of granitoids from the western Flin Flon Domain: An application of the single-zircon Pb-evaporation technique. Saskatchewan Geological Survey, Misc. Rep. 90-4, pp. 136-142.
- Ansdell, K.M. and T.K. Kyser, 1992. Geochemistry of granitoids in the western Flin Flon Domain. Saskatchewan Geological Survey, Misc. Rep. 92-4, pp. 149-157.
- Ashton, K.E., J.F. Lewry, L.M. Heaman, R.P. Hartlaub, M.R. Stauffer and H.T. Tran, 2005. The Pelican Thrust Zone: basal detachment between the Archean Sask craton and Paleoproterozoic Flin Flon – Glennie Complex, western Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 42, 685-706.
- Bailes, A.H. and E.C. Syme, 1989. Geology of the Flin Flon-White Lake area. Manitoba Energy and Mines, Geological Services Branch. Geo. Rep. 87-1.
- Bailey, K.A. and H.L. Gibson, 2004. A field description of the Myo Rhyolite, Flin Flon and Creighton, Saskatchewan. Saskatchewan Geological Survey, Misc. Rep. 2004-4.2, Paper A-1.
- Baird, A. and S.D. McKinnon, 2007. Linking stress field deflection to basement structures in southern Ontario: results from numerical modelling. *Tectonophysics*, 432, 89-100.
- Bostock, H.S., 1970. Physiographic subdivisions of Canada. In: R.J.W. Douglas (ed.), Geology and Economic Minerals of Canada. Geological Survey of Canada.
- Brown, A., R.A. Everitt, C.D. Martin and C.C. Davison, 1995. Past and Future Fracturing in AECL Research Areas in the Superior Province of the Canadian Precambrian Shield, with Emphasis on The Lac Du Bonnet Batholith. Whiteshell Laboratories, Pinawa, Manitoba.
- Bunker, C.M. and C.A. Bush, 1982. Radioelements and radiogenic heat in the Reynard Lake pluton, Saskatchewan near Flin Flon, Manitoba, Canada. U.S. Geological Survey, Open-File Report 82-147, 23p.
- Byers, A.R., 1962. Major faults in the western part of Canadian Shield with special reference to Canada. In: Stevenson, J.S. (ed.), The Tectonics of the Canadian Shield. Royal Society of Canada, Special Publication 4, pp. 40-59.
- Byers, A.R. and C.D.A. Dahlstrom, 1954. Geology and mineral deposits of the Amisk-Wildnest Lakes Area, 63 L-9, 63 L-16 Saskatchewan. Saskatchewan Geological Survey, Geological Report 14.
- Byers, A.R., S.J.T. Kirkland and W.J. Pearson, 1965. Geology and mineral deposits of the Flin Flon Area, Saskatchewan. Saskatchewan Geological Survey, Geological Report 62.
- Campbell, J.B., 1987a. Introduction to Remote Sensing. The Guilford Press.

- Campbell, J.E., 1987b. Quaternary geology of the East Amisk Lake area, applied to prospecting for gold. Saskatchewan Geological Survey, Misc. Rep. 87-4, pp. 148-150, includes two maps, scale 1:20,000.
- Campbell, J.E., 1988. Quaternary geology and till geochemistry of the east Amisk Lake area: progress report. Saskatchewan Geological Survey, Misc. Rep. 88-4, pp. 172-174.
- Campbell, J.E. and P.J. Henderson, 1997. Surficial geology of the Amisk Lake area (NTS 63L/9 and parts of 63K/12). Geological Survey of Canada, Map 1919A, scale 1:50,000.
- Corrigan, D., A.G., Galley and S. Pehrsson, 2007. Tectonic Evolution and Metallogeny of the Southwestern Trans-Hudson Orogen. In: Goodfellow, W.D. (ed.), Mineral Deposits of Canada: a Synthesis of Major Deposit Types, District Metallongeney, the Evolution of the Geological Provinces and Exploration Methods. Geological Association of Canada, Mineral Deposits Division, Special Publication 5, pp. 881-902.
- Corrigan, D., Z. Hajnal, B. Nemeth and S.B. Lucas, 2005. Tectonic framework of a Paleoproterozoic arc-continent to continent-continent collision zone, Trans-Hudson Orogen, from geological and seismic reflection studies. *Canadian Journal of Earth Sciences*, 42(4): 421-434.
- Corrigan, D., S. Pehrsson, N. Wodicka and E. de Kemp, 2009. The Palaeoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes. Geological Society, London, Special Publications, 327, 457-479, doi: 10.1144/SP327.19.
- Cumming, G.L. and B.P. Scott, 1976. Rb/Sr Dating of rocks from the Wollaston Lake Belt, Saskatchewan. *Canadian Journal of Earth Sciences*, 13(2), 355-364.
- Davies, J.R., 1998. The origin, structural style, and reactivation history of the Tabbernor Fault Zone, Saskatchewan, Canada. M.Sc. Thesis. McGill University.
- Davis, C.E. and H.Y. Tammemagi, 1982. A case history of a deep borehole in the Reynard Lake pluton, Saskatchewan-Manitoba Border. Atomic Energy of Canada Limited. File No. 06819-09050.1-230.
- Elliot, C.G., 1996. Phanerozoic deformation in the "stable" craton, Manitoba, Canada. *Geology*, 24(10), 909-912.
- Fedorowich, J.S., R. Kerrich and M.R. Stauffer 1993. Timing of shear zones and regional metamorphism in the Central Flin Flon Domain. Saskatchewan Geological Survey, Misc. Rep. 93-4, pp. 142-152.
- Fedorowich, J.S., R. Kerrich and M.R. Stauffer, 1995. Geodynamic evolution and thermal history of the central Flin Flon domain Trans-Hudson orogen: Constraints from structural development, $^{40}\text{Ar}/^{39}\text{Ar}$, and stable isotope geothermometry. *Tectonics*, 14, 472-503.
- Ferguson, I.J., A.G. Jones, Y. Sheng, X. Wu and I. Shiozaki, 1999. Geoelectric response and crustal electrical-conductivity structure of the Flin Flon Belt, Trans-Hudson Orogen, Canada. *Canadian Journal of Earth Sciences*, 36(11), 1917-1938.
- Franzin, W.G. and G.A. McFarlane, 1976. Bathymetry and morphometry of Schist Lake, Manitoba (54°40'N, 101°45'W). Fisheries and Marine Service Technical Report No. 674.
- Galley, A.G., A.H. Bailes, E.C. Syme, W. Bleeker, J.J. Macek and T.M. Gordon, 1991. Geology and mineral deposits of the Flin Flon and Thompson belts, Manitoba. Geological Survey of Canada, Open File 2165.
- GeoBase, 2011a. Canadian Digital Elevation Data: <http://www.geobase.ca/>.
- GeoBase, 2011b. GeoBase Orthoimage 2005-2010: <http://www.geobase.ca/>.

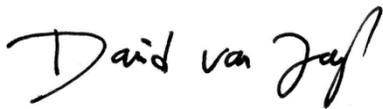
- Golder (Golder Associates Ltd.), 2011. Initial Screening for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel. Town of Creighton, Saskatchewan. Nuclear Waste Management Organization, June 2011.
- Golder (Golder Associates Ltd.), 2013. Phase 1 Desktop Geoscientific Preliminary Assessment of Potential Suitability for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel, Town of Creighton, Saskatchewan. Report for the Nuclear Waste Management Organization (NWMO). NWMO report number: APM-REP-06144-0051.
- Gordon, R.G. and D.M. Jurdy, 1986. Cenozoic global plate motions. *J. Geophys. Res.*, 91, 12,389-12,406.
- Gordon, T.M., P.A. Hunt, A.H. Bailes and E.C. Syme, 1990. U-Pb ages from the Flin Flon and Kisseynew belts, Manitoba: Chronology of Crust formation at an early Proterozoic accretionary margin. In: J.F. Lewry and M.R. Stauffer (eds.), *The Early Proterozoic Trans-Hudson Orogen of North America*. Geological Association of Canada, Special Paper 37, pp. 177-200.
- Gulioy, P., 1989. Building stone investigations in the Creighton – Denare Beach area. Saskatchewan Geological Survey, Misc. Rep. 89-4, pp. 153-156.
- Hajnal, Z., J. Lewry, D.J. White, K. Ashton, R. Clowes, M. Stauffer, I. Gyorfi and E. Takacs, 2005. The Sask craton and Hearne Province margin: seismic reflection studies in the western Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 42, 403-419.
- Hajnal, Z., S. Lucas, D. White, J. Lewry, S. Bezdan, M.R. Stauffer and M.D. Thomas, 1996. Seismic reflection images of high-angle faults and linked detachments in the Trans-Hudson Orogen. *Tectonics*, 15, 427-439.
- Heaman, L.M., S.L. Kamo, K.E. Ashton, B.A. Reilly, W.L. Slimmon and D.J. Thomas, 1992. U-Pb geochronological investigations in the Trans-Hudson Orogen, Saskatchewan. Saskatchewan Geological Survey, Misc. Rep. 92-4, pp. 120-123.
- Heidbach, O., M. Tingay, A. Barth, J. Reinecker, D. Kurfeß, B. Müller, 2009. The World Stress Map based on the database release 2008, equatorial scale 1:46,000,000, Commission for the Geological Map of the World, Paris, doi:10.1594/GFZ.WSM.Map2009.
- Henderson, P.J., 1995. Surficial geology and drift composition of the Annabel Lake-Amisk Lake area, Saskatchewan (NTS 63L/9, L/16, and part of 63K/12 and K/13). Geological Survey of Canada, Open File 3026.
- Henderson, P.J., 2002. Surficial geology, Annabel Lake – Flin Flon, Saskatchewan. Geological Survey of Canada, Map 2010A, scale 1:50,000.
- Henderson, P.J. and J.E. Campbell, 1992. Quaternary studies in the Annabel Lake – Amisk Lake area (NTS areas 63L-9 and -16, and part of 63K-12 and -13). Saskatchewan Geological Survey, Misc. Rep. 92-4, pp. 172-176.
- Henderson, P.J. and I. McMartin, 2008. Surficial geology, Flin Flon, Manitoba-Saskatchewan. Geological Survey of Canada, Open File 5828, scale 1:50,000.
- Kreis, L.K., F.M. Haidl, A.R. Nimegeers, K.E. Ashton, R.O. Maxeiner and J. Coolican, 2004. Lower Paleozoic Map Series – Saskatchewan. Saskatchewan Geological Survey, Misc. Rep. 2004-8.
- Lucas, S.B., E.C. Syme and K.E. Ashton, 1999. New perspectives on the Flin Flon Belt, Trans-Hudson Orogen, Manitoba and Saskatchewan: an introduction to the special issue on the NATMAP Shield Margin Project, Part 1. *Canadian Journal of Earth Sciences*, 36, 135-140.
- Lucas, S.B., D. White, Z. Hajnal, J. Lewry, A. Green, R. Clowes, H. Zwanzig, K. Ashton, D. Schledewitz, M. Stauffer, A. Norman, P.F. Williams and G. Spence, 1994. Three-dimensional collisional structure of the Trans-Hudson Orogen, Canada. *Tectonophysics*, 232, 161-178.

- MacLachlan, K., 2006. Bedrock geology Douglas Lake area, Flin Flon Domain, (Part of NTS 63K/12) at 1:3,000 scale. Saskatchewan Geological Survey, Misc. Rep. 2006-4.2.
- McMartin, I., 1997. Surficial geology, Athappauskow Lake area, Manitoba (NTS 63K/11 and K/12). Geological Survey of Canada, Open File 3526, scale 1:100,000.
- McMartin, I., J.E. Campbell, L.A. Dredge and L. Robertson, 2012. Surficial geology map compilation of the TGI-3 Flin Flon Project area, Manitoba and Saskatchewan. Geological Survey of Canada, Open File 7089.
- Mollard, J.D., 1962. Airphoto route location study, Creighton to Denare Beach. Report prepared for Department of Highways and Transportation, 22 August 1962.
- Morelli, R.M., 2009. Sub-Phanerozoic geological mapping of the Precambrian Flin Flon-Glennie Complex: 2009 update. Saskatchewan Geological Survey, Misc. Rep. 2009-4.2, Paper A-11, 18p.
- Mossop, G.D. and I. Shetsen, 1994. Geological atlas of the Western Canada Sedimentary Basin. Canadian Society of Petroleum Geologists and Alberta Research Council.
- NATMAP, 1998. Geology, NATMAP Shield Margin Project Area (Flin Flon Belt), Manitoba-Saskatchewan. Geological Survey of Canada Map 1968A, Manitoba Energy and Mines Map A-98-2, Sheets 1 to 7, Saskatchewan Energy and Mines Map 258A-1, scale 1:100,000.
- NWMO (Nuclear Waste Management Organization), 2010. Moving forward together: process for selecting a site for Canada's deep geological repository for used nuclear fuel. Nuclear Waste Management Organization, May 2010. (Available at www.nwmo.ca).
- NWMO (Nuclear Waste Management Organization), 2013. Preliminary Assessment for Siting a Deep Geological Repository for Canada's Used Nuclear Fuel - Town of Creighton, Saskatchewan – Findings from Phase One Studies. NWMO Report Number: APM-REP-06144-0049.
- Parslow, G.R. and W.J. Gaskarth, 1981. Flin Flon Base Metals Project: Annabel Lake Area. Saskatchewan Geological Survey, Misc. Rep. 81-4, pp. 101-104.
- Peltier, W.R., 2002. On eustatic sea level history: Last Glacial Maximum to Holocene. *Quaternary Science Reviews*, 21(1-3), 377-396.
- Rona, P.A. and E.S. Richardson, 1978. Early Cenozoic Global Plate Reorganization. *Earth Planet. Sci. Letters*, 40, 1-11.
- SGS (Saskatchewan Geological Survey), 2003. Geology, and Mineral and Petroleum Resources of Saskatchewan. Saskatchewan Industry and Resources, Misc. Rep. 2003-7.
- Saskatchewan Energy and Resources, 2010. Geological Atlas of Saskatchewan. URL: http://www.infomaps.gov.sk.ca/wesite/SIR_Geological_Atlas/viewer.htm.
- Sbar, M.L. and L.R. Sykes, 1973. Contemporary compressive stress and seismicity in eastern North America: An example of intra-plate tectonics. *Geol. Soc. America Bull.*, 84, 1861-1882.
- Schreiner, B.T., 1984a. Quaternary geology of the Amisk area (63-L, K) Saskatchewan. Saskatchewan Geological Survey, Open File Report 84-2, scale 1:250,000.
- Schreiner, B.T., 1984b. Quaternary geology of the Precambrian Shield, Saskatchewan. Saskatchewan Geological Survey, Open File Report 221.
- Schreiner, B.T., D.W. Alley and E.A. Christiansen, 1975. Quaternary geology: 63L, 63M, 64D and 74A areas. Saskatchewan Geological Survey, Misc. Rep. 75-4, pp. 73-75.

- Shackleton, N.J., A. Berger and W.R. Peltier, 1990. An alternative astronomical calibration of the lower Pleistocene timescale based on ODP Site 677. *Transactions of the Royal Society of Edinburgh: Earth Sciences*, 81(4), 251-261.
- Simard, R.L. and K. MacLachlan, 2009. Highlights of the new 1:10 000-scale geology map of the Flin Flon area, Manitoba and Saskatchewan (parts of NTS 63K/12 and /13). Saskatchewan Geological Survey, Misc. Rep. 2009-4.2, Paper A-10.
- Simard, R.L., K. MacLachlan, H.L. Gibson, Y.M. DeWolfe, C. Devine, P.D. Kremer, B. Lafrance, D.E. Ames, E.C. Syme, A.H. Bailes, K. Bailey, D. Price, S. Pehrsson, E. Cole, D. Lewis and A.G. Galley, 2010. Geology of the Flin Flon area, Manitoba and Saskatchewan (part of NTS 63K12, 13). Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Geoscientific Map MAP2010-1 and Saskatchewan Ministry of Energy and Resources, Geoscience Map 2010-2, scale 1:10,000.
- Slimmon, W.L., 1995. Shield margin remapping project: Amisk Lake (East) and Hanson Lake-Sturgeonweir River areas. In: Richardson, D.G. (ed.), *Investigations Completed by the Saskatchewan Geological Survey and the Geological Survey of Canada Under the Geoscience Program of the Canada-Saskatchewan Partnership Agreement on Mineral Development (1990-1995)*. Saskatchewan Energy and Mines, Open File Report 95-3, pp. 27-32.
- Stauffer, M.R. and J.F. Lewry, 1993. Regional Setting and Kinematic Features of the Needle Falls Shear Zone, Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 30, 1338-1354.
- Syme, E.C., A.H. Bailes and S.B. Lucas, 1996. Tectonic Assembly of the Paleoproterozoic Flin Flon Belt and Setting of VMS Deposits – Field Trip Guidebook B1. Geological Association of Canada/Mineralogical Association of Canada Annual Meeting, Winnipeg, Manitoba, May 27-29, 1996.
- Van Loon, J.C. and R.J. Beamish, 1977. Heavy-metal contamination by atmospheric fallout of several Flin Flon area lakes and the relation to fish populations. *Journal of the Fisheries Research Board of Canada*, 34, 899-906.
- White, D.J., M.D. Thomas, A.G. Jones, J. Hope, B. Németh and Z. Hajnal, 2005. Geophysical transect across a Paleoproterozoic continent–continent collision zone; The Trans-Hudson Orogen. *Canadian Journal of Earth Sciences*, 42, 385-402.
- Whitmeyer, S.J. and K.E. Karlstrom, 2007. Tectonic model for the Proterozoic growth of North America. *Geosphere*, 3(4), 220-259.

REPORT SIGNATURE PAGE

J.D. Mollard and Associates (2010) Limited



David van Zeyl, M.Sc.



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

FIGURES

Figure 1 Town of Creighton and surrounding area

Figure 2 Bedrock geology of the Creighton area

Figure 3 Surficial geology of the Creighton area

Figure 4 Elevation and major topographic features

Figure 5 Departure in elevation within 20 km radius

Figure 6 Departure in elevation within 2 km radius

Figure 7 Range in elevation within 250 m radius

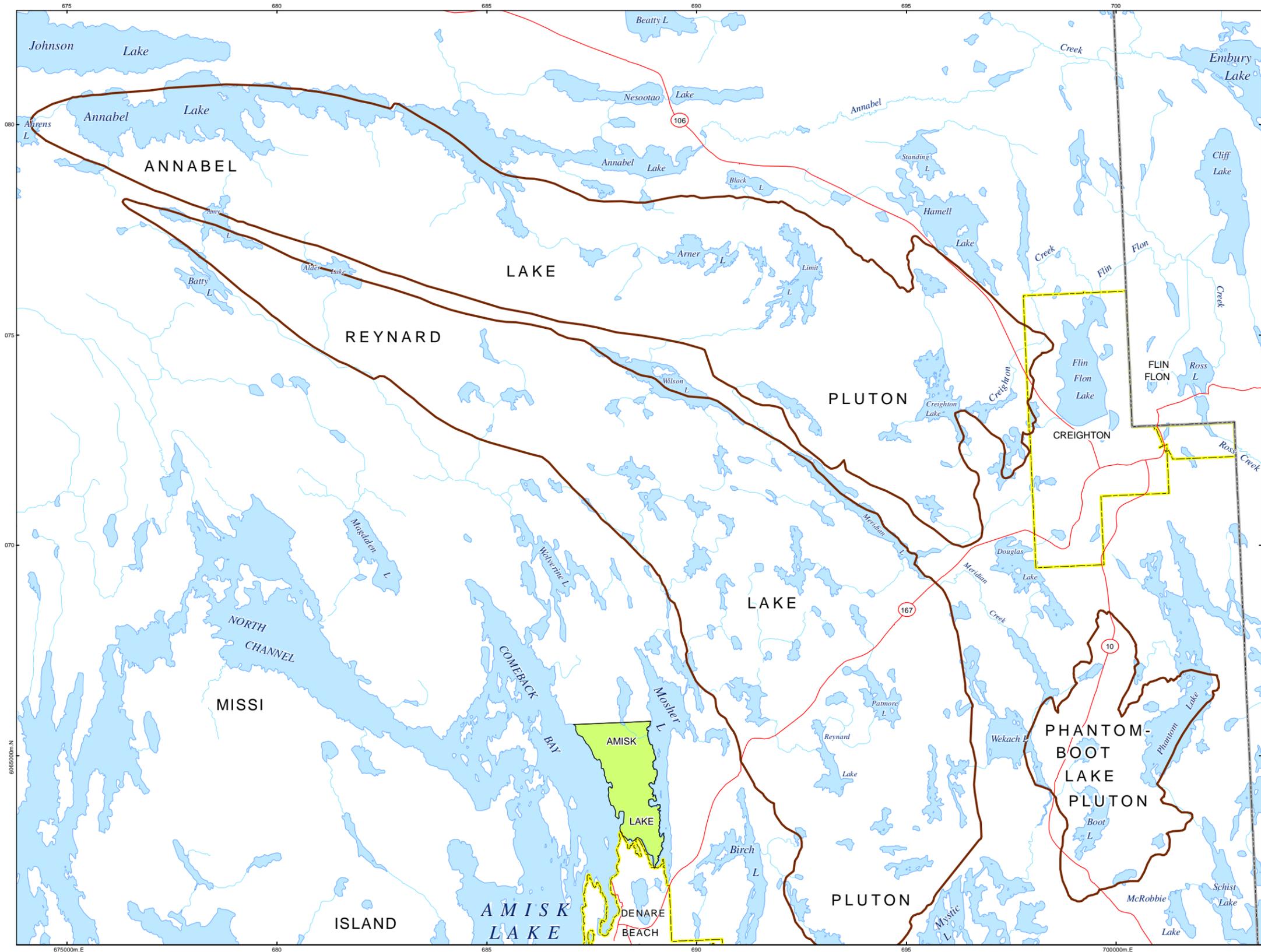
Figure 8 Density of steep ($\geq 6^\circ$) slopes within 2 km radius

Figure 9 Water bodies and wetlands within the Creighton area

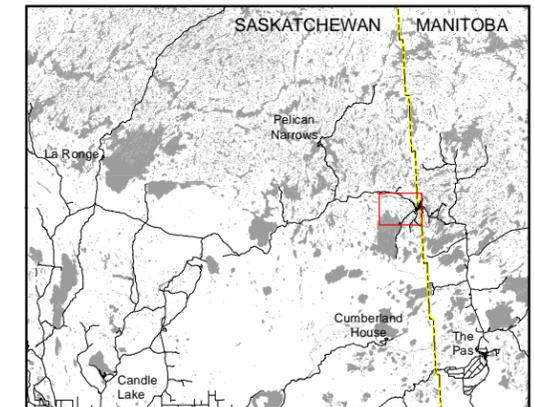
Figure 10 Watersheds within the Creighton area

Figure 11 SPOT imagery of Annabel Lake and Reynard Lake plutons

FIGURES



- LEGEND**
- Indian Reserve
 - Pluton
 - Main road
 - Provincial border
 - Urban municipality
 - Waterbody
 - Watercourse
 - Recreation site



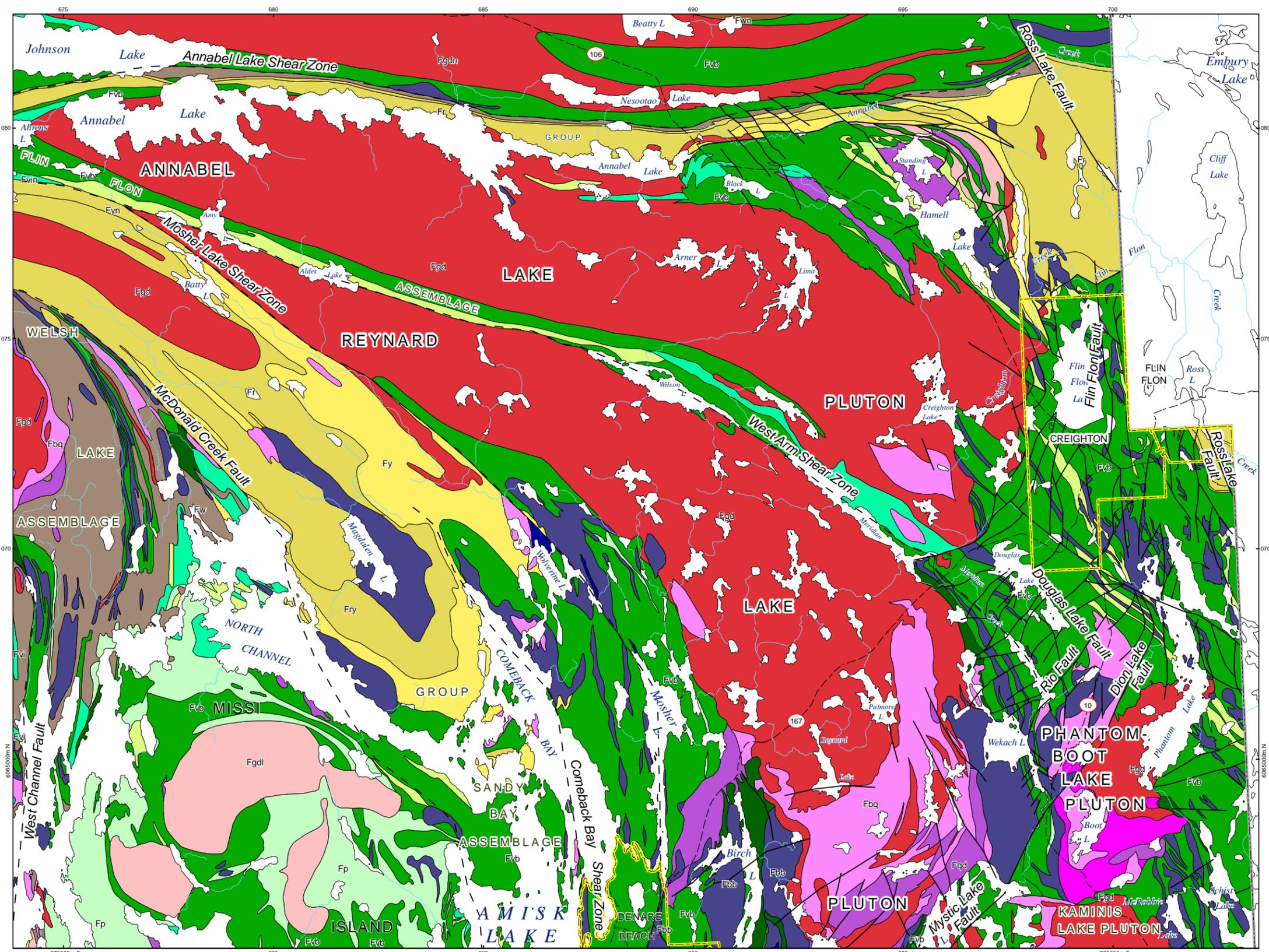
Data sources:
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012



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

TITLE
 Town of Creighton and surrounding area

DESIGN	DVZ	06 JUL 2012	FIGURE 1	REVISION 3
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

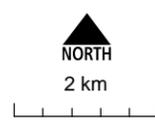
- Urban municipality
- Provincial border
- Shear
- Fault
- Main road
- Waterbody
- Watercourse

Flin Flon domain

- gl - Alaskite-aplogranite
- Fr - Sst, crossbedded sst (Missi Grp)
- Fry - Pebbly sst, pebble cgl, sst. (Missi Grp)
- Fy - Polymictic cgl, sst (Missi Grp)
- Fyn - Cgl gneiss, local psammitic gneiss (Missi Grp)
- Fw - Metagreywacke
- Fwn - Metagreywacke gneiss
- Fgm - Granite-monzogranite-quartz monzonite
- FgdI - 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 - Mafic protomylonite to mylonite
- Fp - Rhyolite, dacite, porphyry
- Fva - Acid volcanics
- Fvan - Felsic gneiss derived from felsic volcanics
- Fvi - Intermediate volcanics
- Fvin - Gneiss derived from intermediate to mafic volcanics
- Fvb - Basic volcanics
- Fvbn - Mafic gneiss derived from basic volcanics

Flin Flon Assemblage

Data sources:
 Geology: Saskatchewan Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012

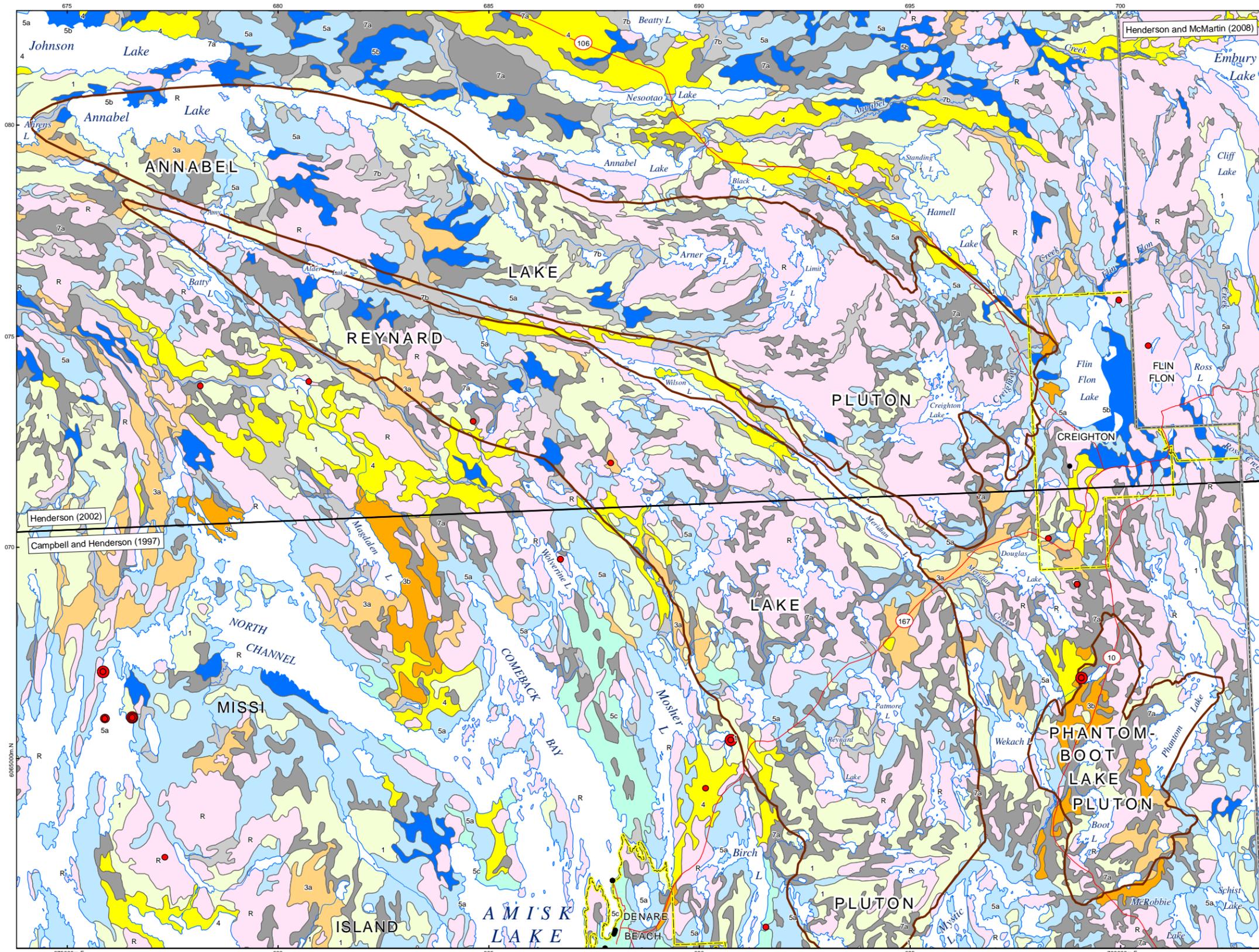


J D MOLLARD
AND ASSOCIATES (2010) LIMITED

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

TITLE
 Bedrock geology of the Creighton area

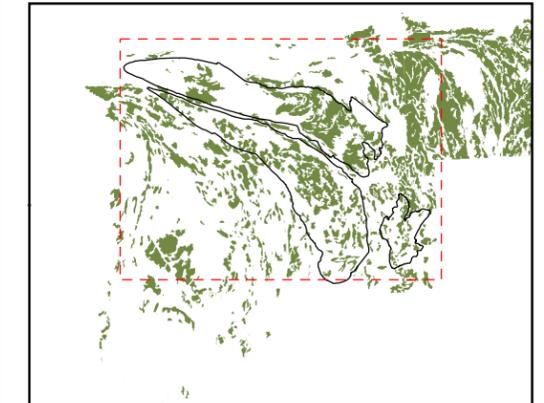
DESIGN	DVZ	06 JUL 2012	FIGURE 2	REVISION 3
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

- Pluton
 - Main road
 - Provincial border
 - Surficial geology map
 - Waterbody
 - Urban municipality
 - Watercourse
- Quaternary geology**
- 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
- Drill hole**
- Depth to bedrock (m)**
- 0.0 - 10.0
 - 10.1 - 20.0
 - 20.1 - 71.3

Areas delineated as bedrock in surficial geology maps



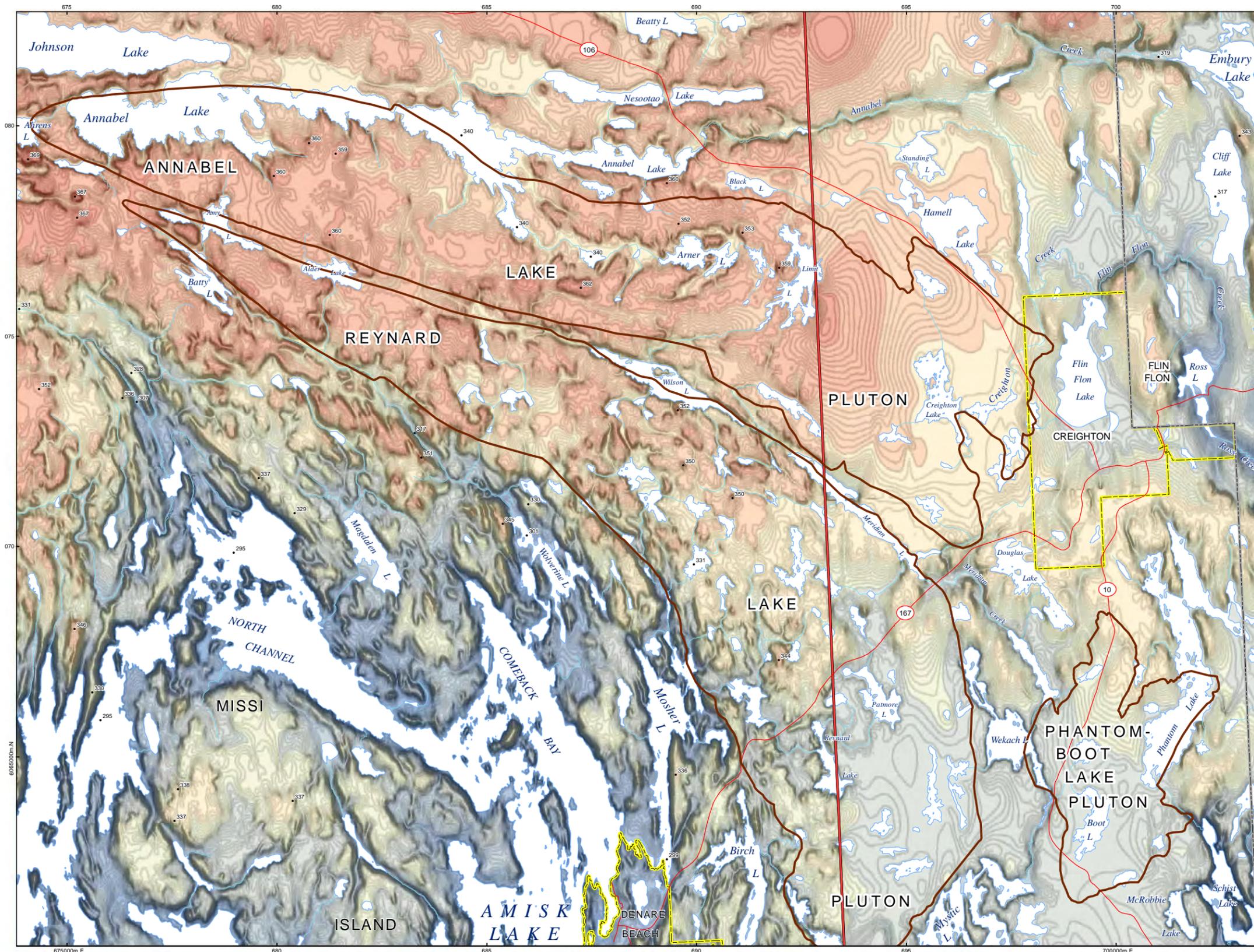
Data sources:
 Pluton: After Sask Geological Atlas (1:250,000)
 Geology: 1:50,000 scale geology as referenced
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012



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

TITLE
 Surficial geology of the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 3	REVISION 2
GIS	DVZ	08 FEB 2013		UTM ZONE 13
CHECK	LAPVAM	08 FEB 2013		NAD 1983
REVIEW	GS	08 FEB 2013		1:150,000



LEGEND

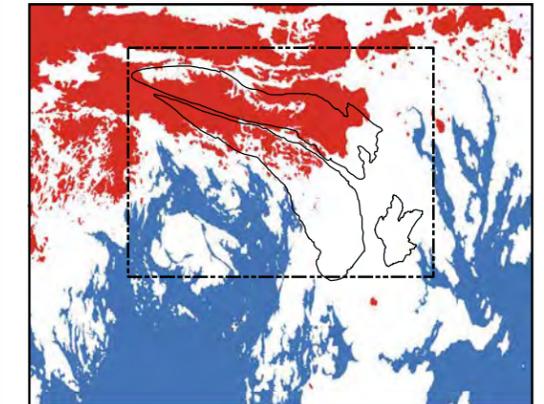
- Pluton
- Spot height (m)
- Main road
- Provincial border
- Urban municipality
- CDED quality division line
- Waterbody
- Watercourse

- Slope (°)**
- 0 - 0.1
 - 0.2 - 1.2
 - 1.3 - 2.3
 - 2.4 - 3.4
 - 3.5 - 4.5
 - 4.6 - 5.6
 - 5.7 - 6.7
 - 6.8 - 22.5

Elevation (m)

- 292 - 297.4
- 297.5 - 306.1
- 306.2 - 314.9
- 315 - 323.6
- 323.7 - 332.4
- 332.5 - 341.1
- 341.2 - 349.9
- 350 - 358.6
- 358.7 - 367.4
- 367.5 - 369

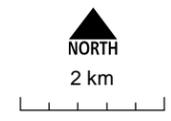
Reclassified map of elevation



Elevation (m)

- 290 - 310
- 311 - 342
- 343 - 377

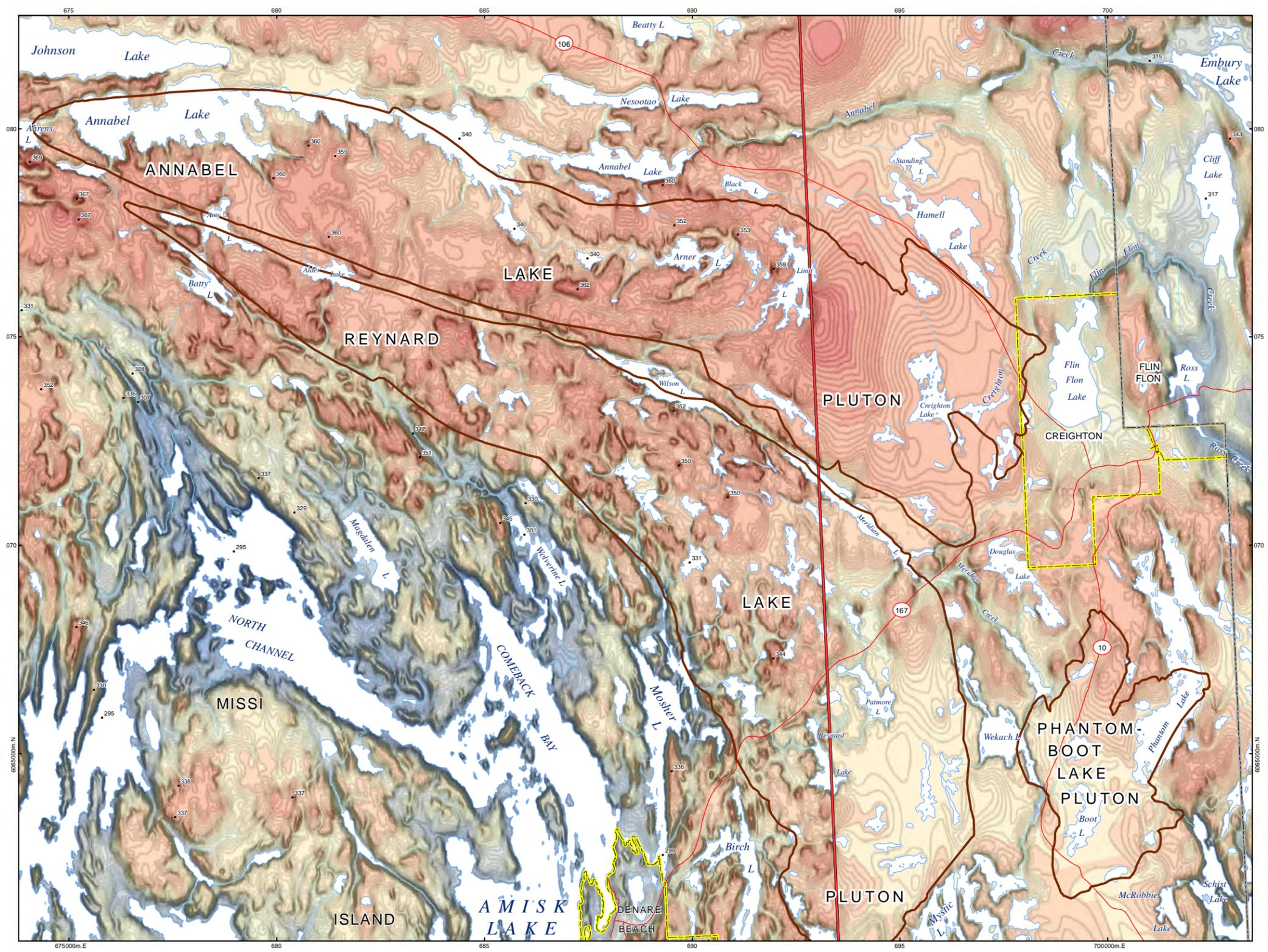
Data sources:
 DEM: CDED 1:50,000
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012



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

TITLE
 Elevation and major topographic features

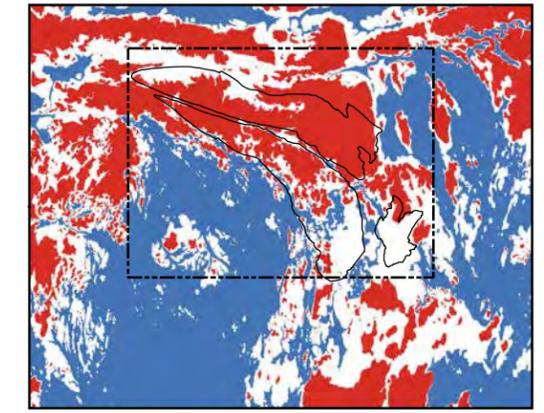
DESIGN	DVZ	06 JUL 2012	FIGURE 4	REVISION 3
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

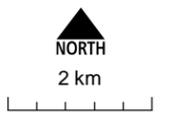
- Pluton
 - Spot height (m)
 - Main road
 - Provincial border
 - Urban municipality
 - CDED quality division line
 - Waterbody
 - Watercourse
-
- Relief (m)**
- 35 - -29.2
 - 29.1 - -22.3
 - 22.2 - -15.4
 - 15.3 - -8.5
 - 8.4 - -1.6
 - 1.5 - 5.3
 - 5.4 - 12.1
 - 12.2 - 19
 - 19.1 - 25.9
 - 26 - 32.2
-
- Slope (°)**
- 0 - 0.1
 - 0.2 - 1.2
 - 1.3 - 2.3
 - 2.4 - 3.4
 - 3.5 - 4.5
 - 4.6 - 5.6
 - 5.7 - 6.7
 - 6.8 - 22.5

Reclassified map of high and low ground



- Relief (m)**
- 35 - 0
 - 0.01 - 10
 - 11 - 41

Data sources:
 DEM: CDED 1:50,000
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012

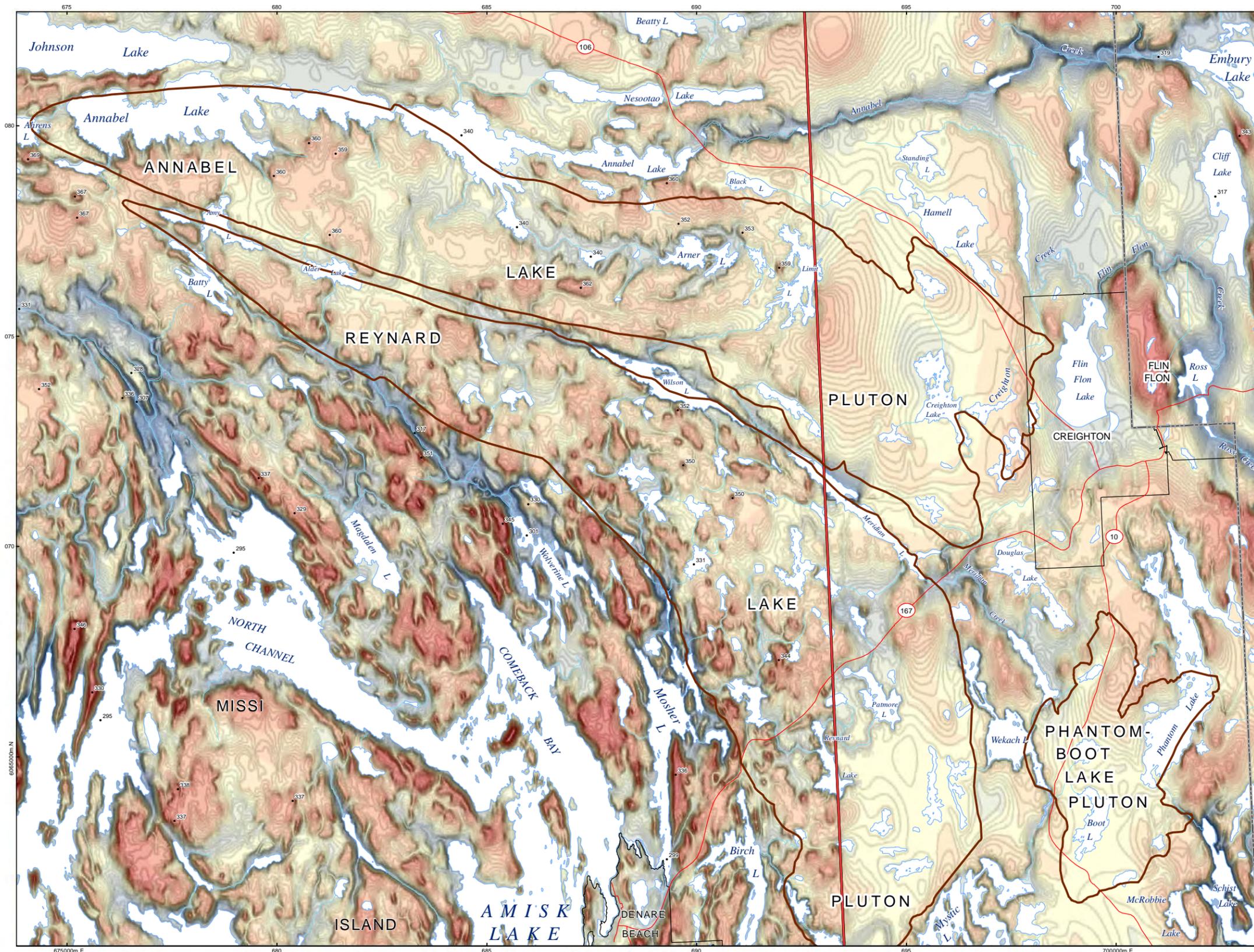


J.D. MOLLARD & ASSOCIATES (2010) LIMITED

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

TITLE
 Departure in elevation within 20 km radius

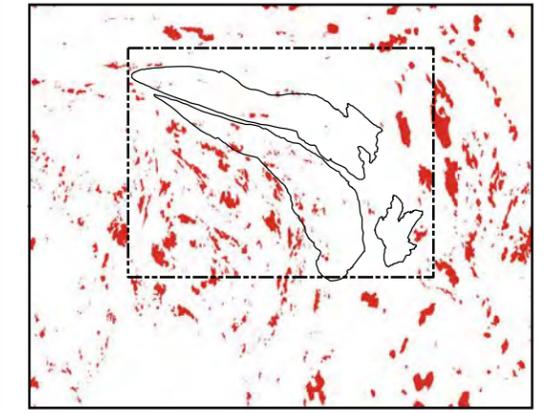
DESIGN	DVZ	06 JUL 2012	FIGURE 5	REVISION 3
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

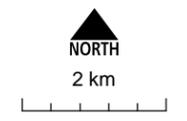
- Pluton
 - Spot height (m)
 - Main road
 - Provincial border
 - Urban municipality
 - CDED quality division line
 - Waterbody
 - Watercourse
-
- Slope (°)**
- 0 - 0.1
 - 0.2 - 1.2
 - 1.3 - 2.3
 - 2.4 - 3.4
 - 3.5 - 4.5
 - 4.6 - 5.6
 - 5.7 - 6.7
 - 6.8 - 22.5
-
- Relief (m)**
- 26.8 - -19
 - 18.9 - -15.6
 - 15.5 - -12.2
 - 12.1 - -8.8
 - 8.7 - -5.4
 - 5.3 - -2
 - 1.9 - 1.4
 - 1.5 - 4.8
 - 4.9 - 8.2
 - 8.3 - 11.6
 - 11.7 - 15.1
 - 15.2 - 18.5
 - 18.6 - 31.8

Reclassified map of high areas



- Relief (m)**
- 32.8 - 10
 - 10.1 - 36.2

Data sources:
 DEM: CDED 1:50,000
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012

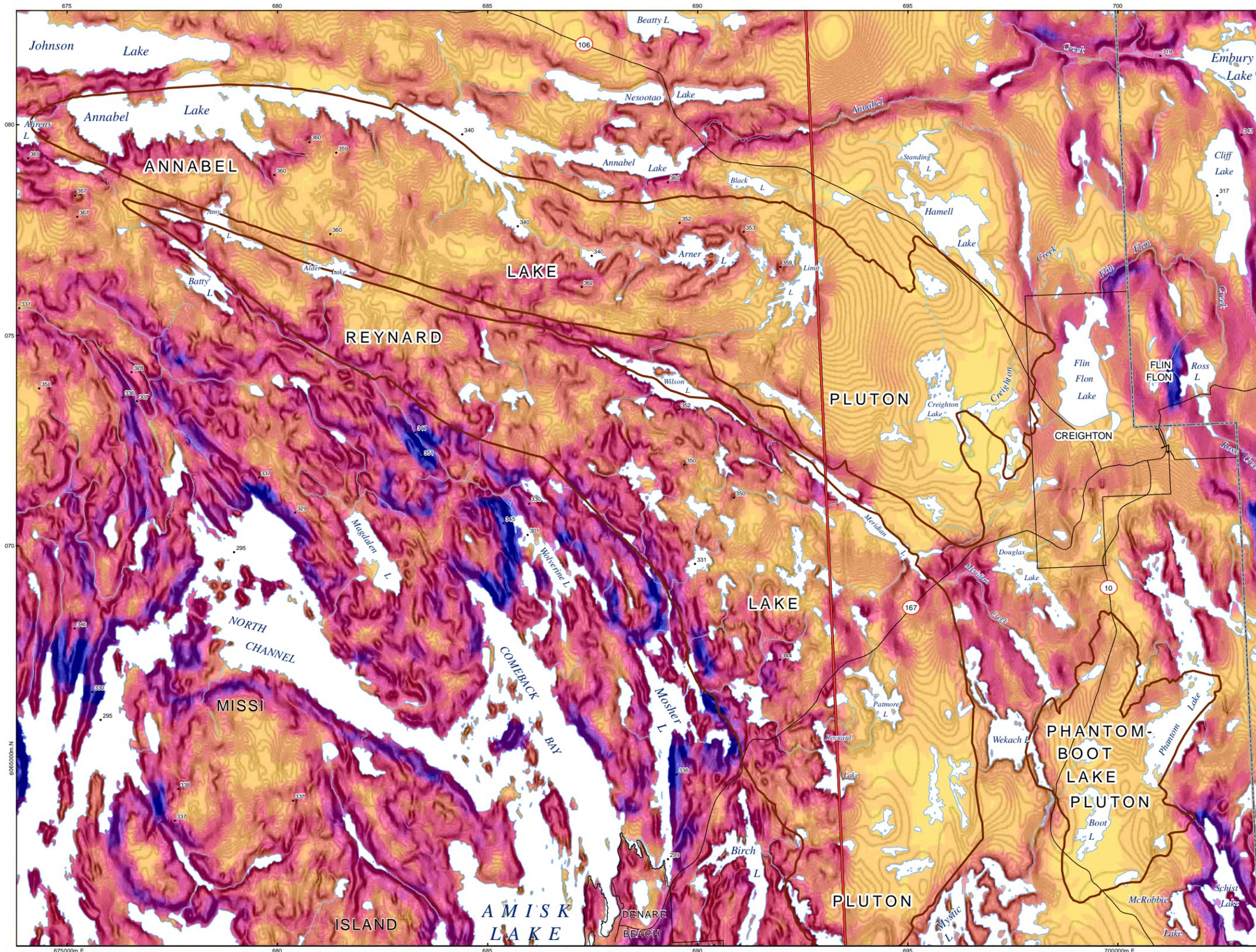


J D MOLLARD
AND ASSOCIATES (2010) CHARTERED

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

TITLE
 Departure in elevation within 2 km radius

DESIGN	DVZ	06 JUL 2012	FIGURE 6	REVISION 2
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

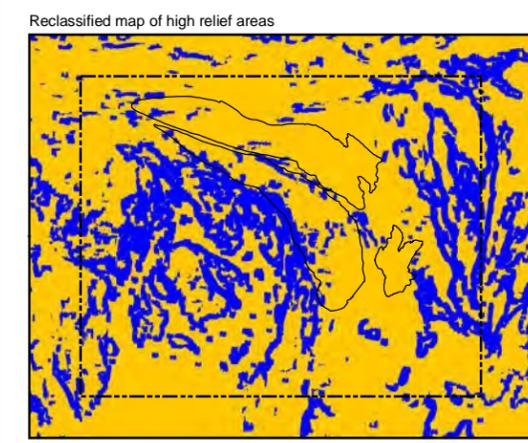
- Pluton
- Spot height (m)
- Main road
- Provincial border
- Urban municipality
- CDED quality division line
- Waterbody
- Watercourse

Slope (°)

- 0 - 0.1
- 0.2 - 1.2
- 1.3 - 2.3
- 2.4 - 3.4
- 3.5 - 4.5
- 4.6 - 5.6
- 5.7 - 6.7
- 6.8 - 22.5

Relief (m)

- 0 - 1.6
- 1.7 - 5.8
- 5.9 - 10
- 10.1 - 14.2
- 14.3 - 18.4
- 18.5 - 22.6
- 22.7 - 26.8
- 26.9 - 31
- 31.1 - 35.2
- 35.3 - 51



Relief (m)

- 0 - 15
- 16 - 51

Data sources:
 DEM: CDED 1:50,000
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012

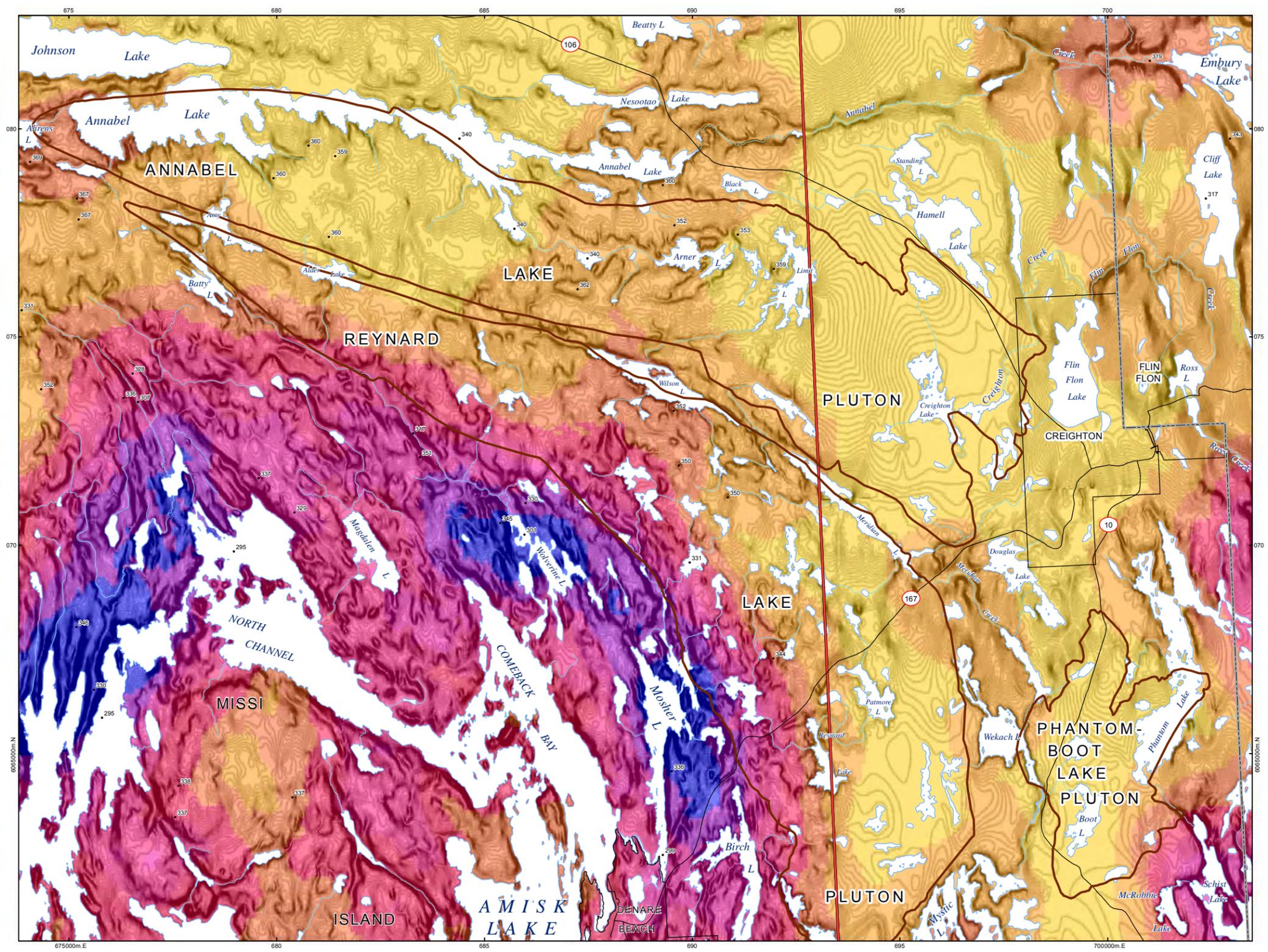
NORTH
 2 km

J. D. MOLLARD
AND ASSOCIATES (2001) LIMITED

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

TITLE
 Range in elevation within 250 m radius

DESIGN	DVZ	06 JUL 2012	FIGURE 7	REVISION 2
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

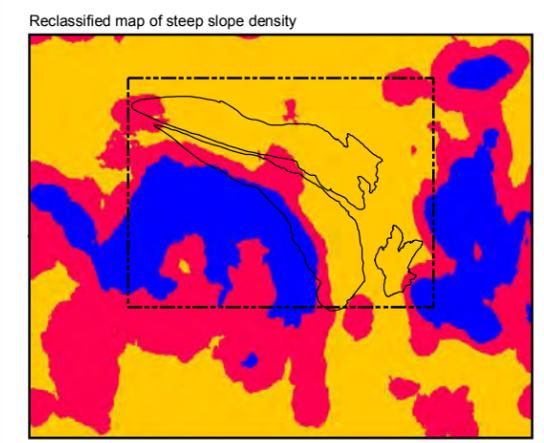
- Pluton
- Spot height (m)
- Main road
- Provincial border
- Urban municipality
- CDED quality division line
- Waterbody
- Watercourse

Slope (°)

- 0 - 0.1
- 0.2 - 1.2
- 1.3 - 2.3
- 2.4 - 3.4
- 3.5 - 4.5
- 4.6 - 5.6
- 5.7 - 6.7
- 6.8 - 22.5

Slope density Points/km²

- 0 - 50.1
- 50.2 - 121
- 121.1 - 192
- 192.1 - 262.9
- 263 - 333.9
- 334 - 404.9
- 405 - 475.8
- 475.9 - 596.2



Density

- 0 - 100
- 110 - 250
- 260 - 600

Data sources:
 DEM: CDED 1:50,000
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012

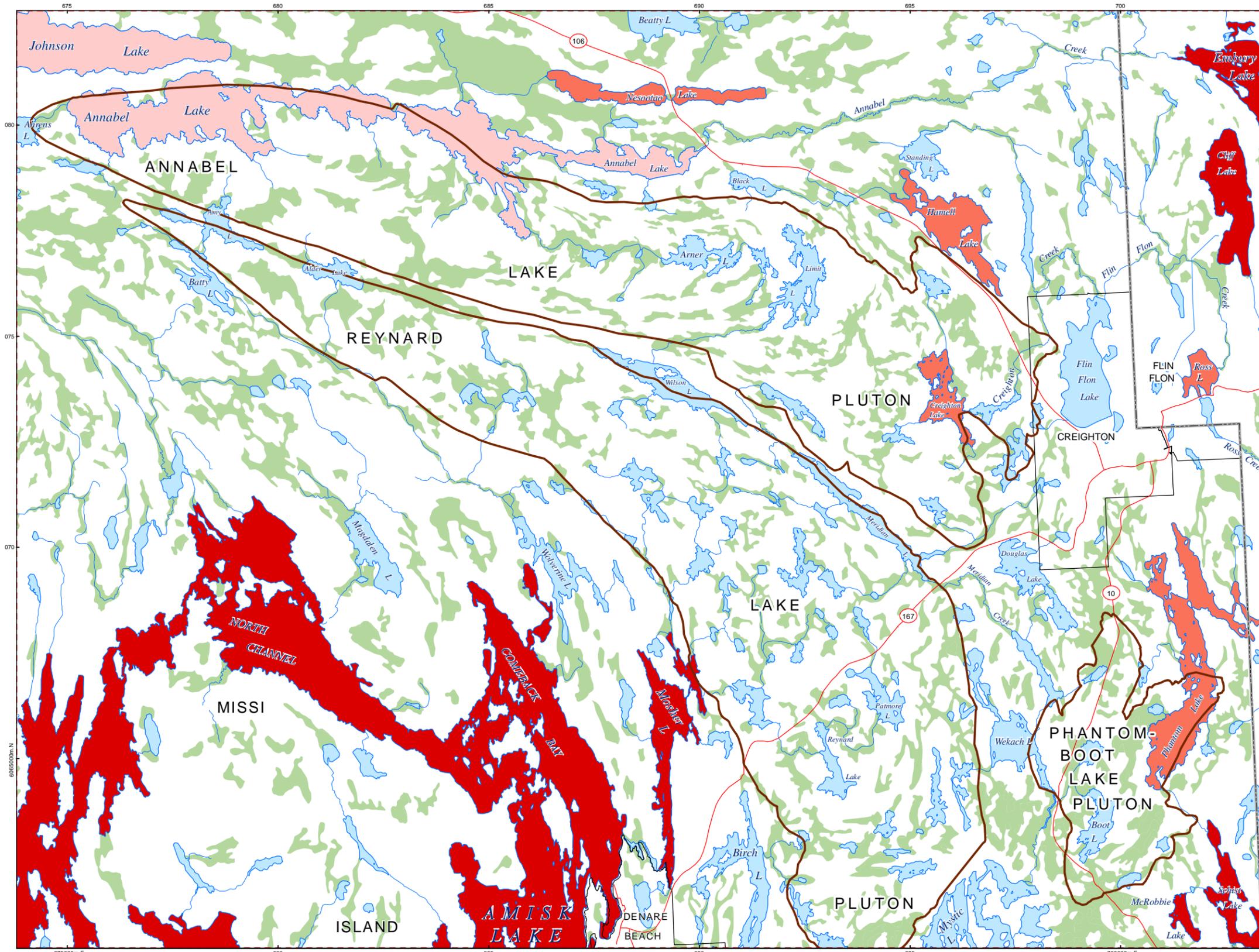


J D MOLLARD
 AND ASSOCIATES (2010) LIMITED

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

TITLE
 Density of steep ($\geq 6^\circ$) slopes within 2 km radius

DESIGN	DVZ	06 JUL 2012	FIGURE 8	REVISION 2
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

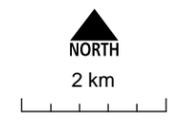
- Creighton area
- Pluton
- Main road
- Provincial border
- Urban municipality
- Waterbody
- Watercourse
- Wetland

Waterbody (with depth data)

Maximum depth (m)

- 3.7 - 5.0
- 5.1 - 10.0
- 10.1 - 45.0

Data sources:
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Wetland: Updated JDMA (see Section 4.1)
 Urban municipality: SaskAdmin 2012

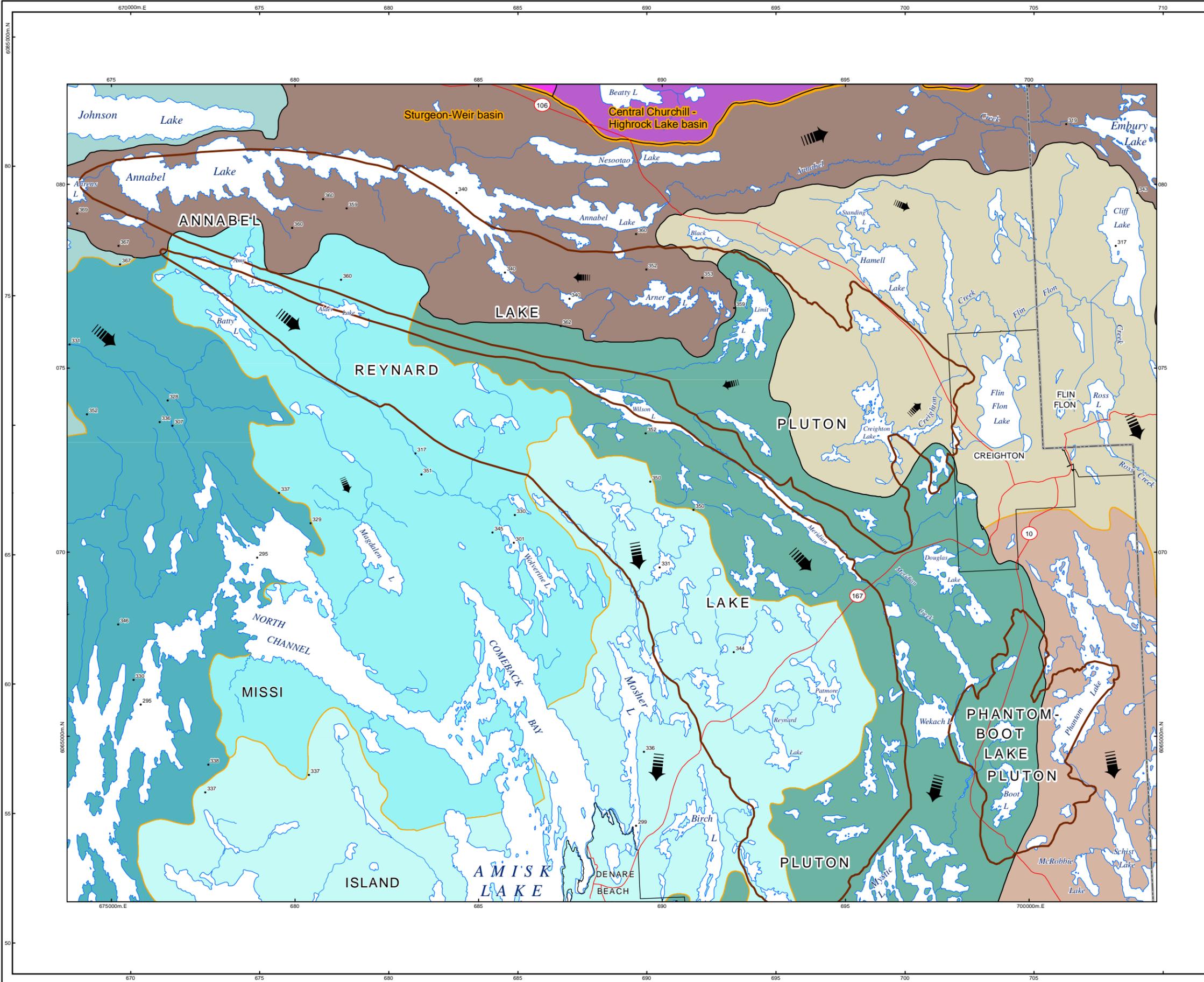


J D MOLLARD
AND ASSOCIATES LTD. LIMITED

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

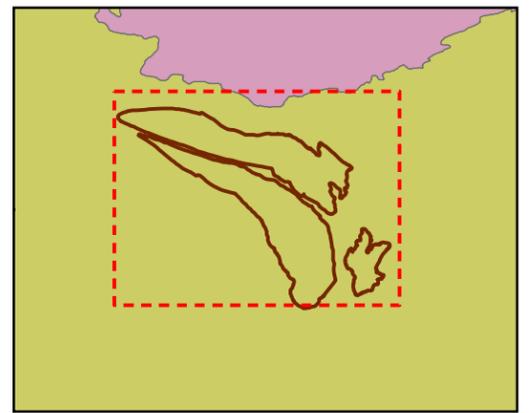
TITLE
 Waterbodies and wetlands within the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 9	REVISION 2
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



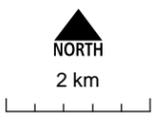
LEGEND

- Pluton
 - Spot height (m)
 - Main road
 - Provincial border
 - Urban municipality
 - Waterbody
 - Watercourse
 - Environment Canada sub-sub basin
- Drainage divide**
- Confirmed
 - JDMA
 - PFRA
- Flow direction**
- Minor
 - Major



- Environment Canada sub-sub basin**
- Sturgeon-Weir
 - Central Churchill-Highrock Lake

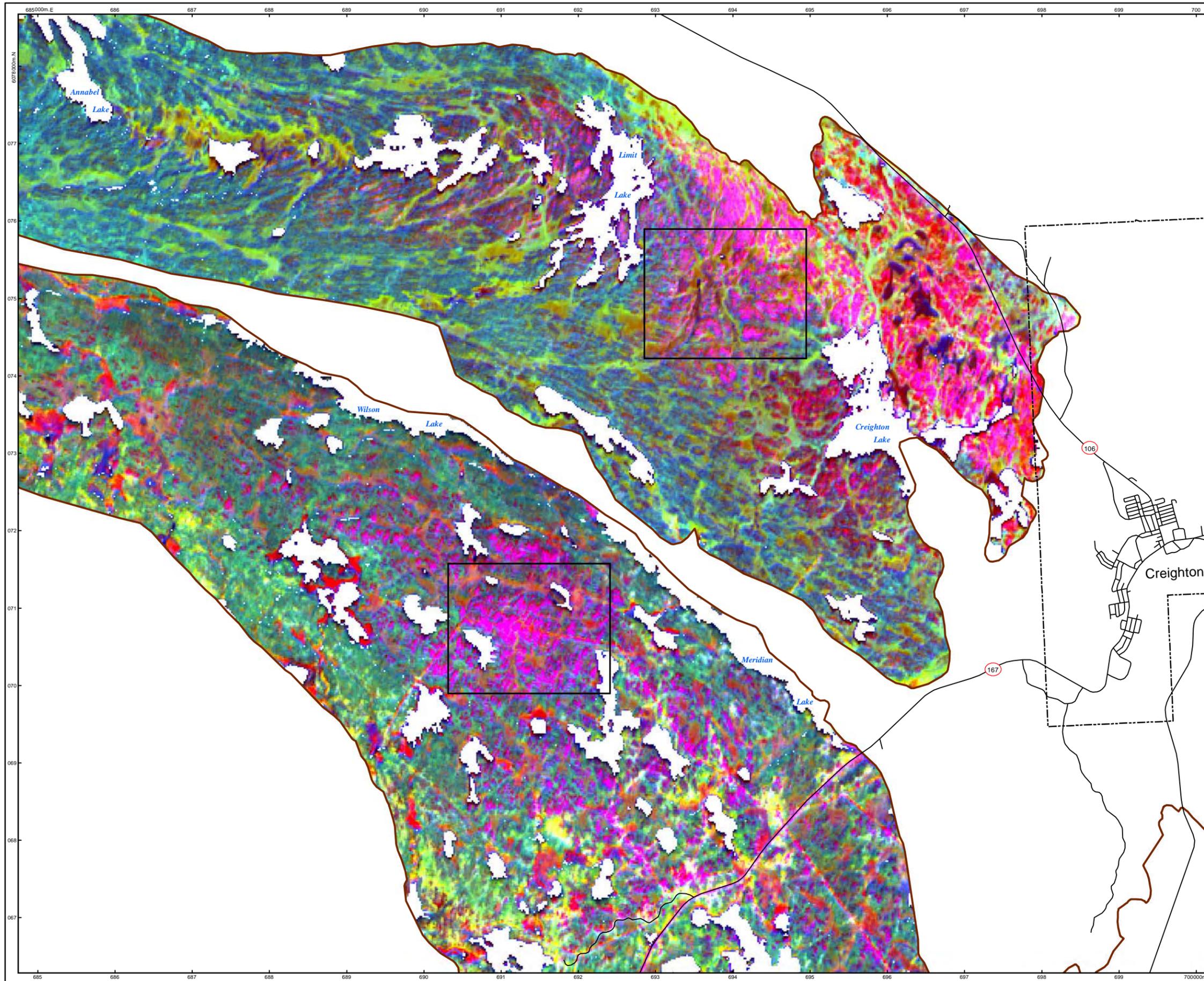
Data sources:
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: Selected from CanVec 1:50,000
 Waterbody: CanVec 1:50,000
 Watercourse: CanVec 1:50,000
 Urban municipality: SaskAdmin 2012



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

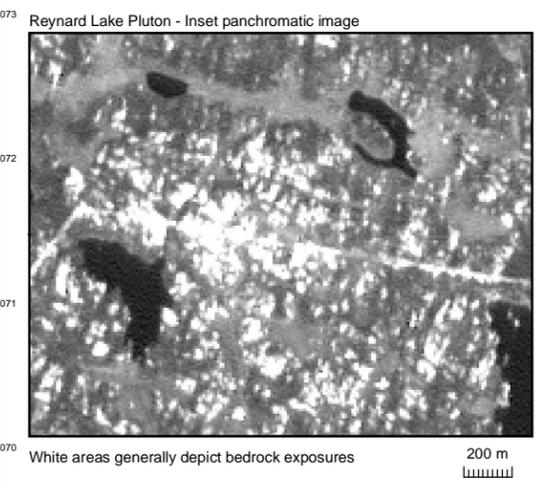
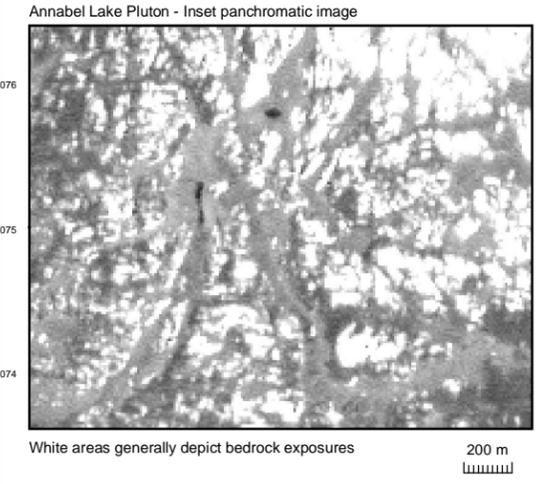
TITLE
 Watersheds within the Creighton area

DESIGN	DVZ	06 JUL 2012	FIGURE 10	REVISION 2
GIS	DVZ	01 AUG 2013		UTM ZONE 13
CHECK	LAPVAM	01 AUG 2013		NAD 1983
REVIEW	GS	01 AUG 2013		1:100,000



LEGEND

- Urban municipality
- Road (SURN11)
- Pluton



Data sources:
 SPOT: GeoBase (02 Sep 2006 image)
 Pluton: After Sask Geological Atlas (1:250,000)
 Road: SURN 2011
 Urban municipality: SaskAdmin 2012



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

TITLE
 SPOT imagery of Annabel Lake and Reynard Lake plutons

DESIGN	DVZ	06 JUL 2012	FIGURE 11	REVISION 1
GIS	DVZ	14 NOV 2012		UTM ZONE 13
CHECK	LAPIAM	14 NOV 2012		NAD 1983
REVIEW	GS	14 NOV 2012		1:50,000