NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

# Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Interpretation

**TOWNSHIP OF EAR FALLS, ONTARIO**

**APM-REP-06144-0022**

**NOVEMBER 2013**

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**Phase 1 Desktop Geoscientific Preliminary Assessment**

# Lineament Interpretation

# Township of Ear Falls, Ontario

**Report Prepared for**

## Nuclear Waste Management Organization

**Report Prepared by**

SRK Consulting (Canada) Inc.

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NWMO Report Number: APM-REP-06144-0022

**November, 2013**

# Lineament Interpretation Township of Ear Falls, Ontario

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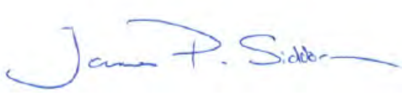

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# Executive Summary

In February, 2012 the Township of Ear Falls, Ontario expressed interest in learning more about the Nuclear Waste Management Organization nine-step site selection process, and requested that a preliminary assessment be conducted to assess the potential suitability of the Ear Falls 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 Township of Ear Falls and its periphery, referred to as the “Ear Falls area”, contain general areas that have the potential to meet NWMO’s geoscientific site evaluation factors.

This report presents the findings of a lineament investigation assessment completed as part of the desktop geoscientific preliminary assessment of the Ear Falls area (Golder, 2013). The lineament assessment focused on identifying surficial and geophysical lineaments and their attributes using publicly-available digital data sets, including geophysical (aeromagnetic) and surficial (satellite imagery, digital elevation) data sets for the Ear Falls area. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO’s geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Golder, 2013). The lineament investigation interprets the location and orientation of potential bedrock structural features (e.g., individual fractures or fracture zones) within the context of the local and regional geological setting. The approach undertaken in this desktop lineament investigation is based on the following:

- Lineaments were interpreted from multiple, publicly-available data sets;
- Lineament interpretations were made by documented specialist observers and using a standardized workflow;
- Lineament interpretations were analyzed based on an evaluation of the quality and limitations of the available data sets;
- Interpreted lineaments were separated into three categories (ductile, brittle, dyke) based on their character;
- Lineament interpretations were analyzed using reproducibility tests, particularly the coincidence of lineaments extracted by different observers, coincidence of lineaments extracted from different data sets, relative ages and/or documentation in literature; and
- Final classification of the lineament interpretation was done based on length and reproducibility.

The distribution of lineaments in the Ear Falls area reflects the bedrock structure, resolution of the data sets used, and surficial cover. Surface lineament density, as demonstrated in this assessment, is closely associated with the distribution and thickness of overburden cover that locally masks the surficial expression of bedrock structures. Surficial lineament density was observed to be highest over the Bluffy Lake batholith and Winnipeg River plutons in the northeastern and southwestern parts of the Ear Falls area where the thickness and extent of surficial cover is relatively low. The lowest density of surficial lineaments was observed in the areas south of Pakwash Lake and over the Bruce Lake pluton where extensive overburden cover and wetlands mask much of the bedrock

structure. Aeromagnetic lineaments primarily reflect the varying resolution of the geophysical coverage.

It is difficult at the desktop stage to provide any further constraint of the timing of lineament development beyond noting that the identified lineaments in the Ear Falls area are interpreted to represent successive stages of brittle-ductile and brittle deformation. At the desktop stage of preliminary assessment, it is still uncertain whether or not each interpreted lineament is in fact an actual geological feature with a significant expression at depth.

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# IMPORTANT NOTICE

Golder Associates Ltd. (Golder), on behalf of the Nuclear Waste Management Organization (NWMO), commissioned SRK Consulting (Canada) Inc. (SRK) to compile a structural lineament interpretation of remote sensing data for the Ear Falls area in Ontario. The opinions expressed in this report have been based on the information acquired from public domain sources or supplied to SRK by Golder and NWMO. These opinions are provided in response to a specific request from NWMO, and are subject to the contractual terms between SRK and Golder. SRK has exercised all due care in reviewing the supplied information. Whilst SRK has compared key supplied data with expected values, the accuracy of the results and conclusions from the review are entirely reliant on the accuracy and completeness of the supplied data. SRK does not accept responsibility for any errors or omissions in the supplied information and does not accept any consequential liability arising from commercial decisions or actions resulting from them. Opinions presented in this report apply to the site conditions and features as they existed at the time of SRK's investigations, and those reasonably foreseeable. These opinions do not necessarily apply to conditions and features that may arise after the date of this report.

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# 1 Introduction

In February, 2012 the Township of Ear Falls, Ontario expressed interest in learning more about the Nuclear Waste Management Organization nine-step site selection process (NWMO, 2010), and requested that a preliminary assessment be conducted to assess the potential suitability of the Ear Falls area for safely hosting a deep geological repository. 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 lineament investigation assessment completed by SRK Consulting (Canada) Inc. (SRK) as part of the desktop geoscientific preliminary assessment of the Ear Falls area (Golder, 2013). The lineament assessment focussed on identifying surficial and geophysical lineaments and their attributes using publicly-available digital data sets, including surficial (satellite imagery, digital elevation) and geophysical (magnetic) data sets for the Ear Falls area. The assessment of interpreted lineaments in the context of identifying general areas that have the potential to meet NWMO's geoscientific site evaluation factors is provided in the desktop preliminary geoscientific assessment report (Golder, 2013).

## 1.1 Scope of Work and Work Program

The scope of work included the completion of a desktop structural lineament interpretation of remote sensing and geophysical data for a region denoted as the "Ear Falls area" in Ontario (Figure 1).

The Ear Falls area to be used for the interpretation is approximately 3,688 square kilometres ($km^2$) and was provided by NWMO as a shape file for a rectangular area with the following approximate corner point coordinates (UTM NAD83, Zone 15N; Figure 1).

- 442508 mE; 5590141 mN;
- 522756 mE; 5636096 mN.

The lineament investigation interpreted the location and orientation of possible individual fractures or fracture zones and aided in evaluating their relative timing relationships within the context of the local and regional geological setting. For the purpose of this report, a lineament was defined as, 'an extensive linear or arcuate geologic or topographic feature. The approach undertaken in this desktop lineament investigation was based on the following:

- Lineaments were mapped from multiple, publicly-available data sets that included aeromagnetic geophysical survey data, satellite imagery (LandSAT; SPOT) and digital elevation models (Canadian Digital Elevation Data; CDED);
- Lineament interpretations from each source data type were made by two specialist observers for each data set. Ductile lineaments were interpreted from the aeromagnetic geophysical survey data set by a single documented specialist observer;
- Lineaments were analyzed based on an evaluation of the quality and limitations of the available data sets, reproducibility tests, particularly the coincidence of lineaments extracted by the two different observers, coincidence of lineaments extracted from different data sets, and (or) documentation in literature; and
- Classification was applied to indicate the significance of lineaments based on length and reproducibility.

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

At this desktop stage of lineament investigation, the remotely sensed character of interpreted features allows only for their preliminary categorization, based on expert judgement, into three general lineament classes, including ductile, brittle (including brittle-ductile), and dyke lineaments. Each of these three lineament categories is described in more detail below in the context of its usage in the desktop geoscientific preliminary assessment.

**Ductile lineaments**: Features which were interpreted as being associated with the internal fabric of the rock units (including sedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation) were classified as ductile lineaments. This category also includes recognizable penetrative shear zone fabric.

**Brittle lineaments**: Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets), including those that offset the continuity of the ductile fabric described above, were classified as brittle lineaments. This category also includes brittle-ductile shear zones, and brittle partings interpreted to represent discontinuous re-activation parallel to the ductile fabric. At the desktop stage of the investigation, this category also includes features of unknown affinity. This category does not include interpreted dykes, which are classified separately (described below).

**Dyke lineaments**: For this preliminary desktop interpretation, any features which were interpreted, on the basis of their distinct character, e.g., scale and composition of fracture in-fill, orientation, geophysical signature and topographic expression to be dykes were classified as dyke lineaments. Dyke interpretation is largely made using the aeromagnetic data set, and is often combined with pre-existing knowledge of the bedrock geology of the Ear Falls area. No dyke lineaments were interpreted in the Ear Falls area.

The desktop interpretation of remotely-sensed data sets necessarily includes a component of uncertainty as a result of data quality, the scale of Ear Falls area, expert judgement, the quality of the pre-existing knowledge of the bedrock geology of the Ear Falls area, and the absence of site reconnaissance to “ground truth” tentative hypotheses. Therefore the ductile and brittle categorization of each identified feature, as described herein, is preliminary, and would need to be confirmed during future stages of the site evaluation process.

## 1.2 Qualifications of SRK and the SRK Team

The SRK Group comprises of more than 1,200 professionals, offering expertise in a wide range of resource engineering disciplines. The independence of the SRK Group is ensured by the fact that it holds no equity in any project it investigates and that its ownership rests solely with its staff. These facts permit SRK to provide its clients with conflict-free and objective recommendations on crucial issues. SRK has a proven track record in undertaking independent assessments of mineral resources and mineral reserves, project evaluations and audits, technical reports and independent feasibility evaluations to bankable standards on behalf of exploration and mining companies, and financial institutions worldwide. Through its work with a large number of major international mining companies, SRK Group has established a reputation for providing valuable consultancy services to the global mining industry.

This lineament investigation and the compilation of this report were completed by Mr. Jean-François Ravenelle, M.Sc., P.Geo. (Senior Consultant – Structural Geology, APGO #2159). Mr. Ravenelle is an expert in geological interpretation of remote sensing data, including geophysical and satellite data, primarily applied to mineral exploration. Mr. Charles Mitz, M.Eng., P.Geo. (Senior Hydrogeologist, APGO #0277) from Golder was the second interpreter and primary author of the geoscience review section. Dr. James P. Siddorn, P.Geo. (Practice Leader – Structural Geology, APGO #1314), supervised and reviewed drafts of the lineament analysis and this report prior to their delivery to NWMO as per SRK's internal quality management procedures.

## 1.3 Report Organization

The report is organized into sections that describe the geological setting of the Ear Falls area, the methodology used in identifying lineaments, the findings of the lineament interpretation, and a discussion of the results in the context of the local and regional geological framework.

Section 1 of this report includes an introduction and background for the completed structural lineament investigation.

Section 2 provides an overview of the geological setting of the Ear Falls area and documents its structural history on the basis of available literature. A brief outline of the physical geography, Quaternary geology, and land use in the Ear Falls area are also included in this section.

Section 3 documents the methodology applied for the lineament investigation for the Ear Falls area. The source data used for the lineament interpretation are outlined and the interpretation workflow for the subsequent stages of the investigation is described.

Section 4 documents the findings of the lineament investigation in the Ear Falls area. This includes a description of interpreted lineaments by data set, and major geological unit. Also, lineament density and reproducibility are described.

Section 5 includes a discussion of how the lineament investigation for the Ear Falls area may be used as a guide to identify general areas that have the potential to meet NWMO's geoscientific site evaluation factors.

Section 6 is a brief summary of the main findings of this investigation.

## 1.4 Acknowledgements

SRK would like to acknowledge the support and collaboration provided for this assignment by Golder, including Mr. Charles Mitz and Mr. George Schneider. The collaboration of Mr. Mitz as the second interpreter and primary author of the geoscience review section was greatly appreciated. Also, SRK would like to thank NWMO personnel, including Dr. Sarah Hirschorn, Dr. Alec Blyth, Mr. Aaron DesRoches, and Ms. Maria Sanchez-Rico Castejon, and also Mr. Thomas Campagne from MIRA Geoscience Ltd. for a fruitful collaboration on this project.

# 2 Summary of Physical Geography and Geology

A detailed discussion of the geological setting of the Ear Falls area, including bedrock geology and structural history, is provided in a separate report (Golder, 2013), and a summary is presented below.

The Township of Ear Falls is situated mainly within the English River Subprovince (Figure 2). The English River Subprovince is an east-west trending, 30 to 100 km wide by 650 km long belt of metasedimentary and metamorphosed intrusive rocks extending from Manitoba to the Moose River Basin in the James Bay Lowlands. The English River Subprovince is bordered to the north by the Uchi Subprovince and, in the Ear Falls area, by the Winnipeg River Subprovince to the south.

The Uchi Subprovince is a relatively narrow, east-west trending region dominated by belts of metasedimentary and metavolcanic rocks that interweave intrusive complexes up to 3 billion years old (Stott and Corfu, 1991).

The Winnipeg River Subprovince is a terrane more than 500 km long and composed of Mesoarchean metaplutonic rocks variably intruded by Neoarchean plutons (Beakhouse, 1991).

The northern part of the Ear Falls area is within the Uchi Subprovince, while the southern limit falls within the Winnipeg River Subprovince. Provincial-scale mapping by Percival and Easton (2007) and Stott et al. (2010) place the boundary between the English River Subprovince and the Winnipeg River Subprovince to be south of the Township of Ear Falls, although the contact between the two subprovinces is not sharply defined by any specific mappable geological feature.

## 2.1 Physical Geography

The physical geography of the Ear Falls area is described in detail in JDMA (2013). A summary of the main features is provided here for reference.

The Township of Ear Falls is situated in the District of Kenora in northwestern Ontario, at the northwestern end of Lac Seul, as shown on Figure 1. The Township of Ear Falls is located approximately 98 km northwest of Vermilion Bay, and approximately 65 km southeast of Red Lake and covers approximately 350 $km^2$ (Ear Falls Official Plan, 2004).

The Township of Ear Falls is located in the Canadian Shield physiographic region, a low-relief, dome-like, gently undulating land surface with an elevation range within the physiographic region of about 150 metres above sea level (masl) in the north, increasing to about 450 masl towards the south.

The Township of Ear Falls lies within the Severn Uplands, a broadly rolling surface of Precambrian bedrock that occupies most of northwestern Ontario and which is either exposed at surface or shallowly covered with Quaternary glacial deposits.

The land surface elevation within the Ear Falls area ranges from a low of about 316 m at the shores of Oak Lake in the southwest to a high of 452 m on a hill about 8 km south of Celt Lake. The northern part of the Township of Ear Falls is an area of low relief dominated by Bruce and Pakwash lakes and their associated watercourses. In the central portion of the Township, there is an area of high relief that trends roughly east-northeast to west-southwest. Further to the south, the topography is still moderately high, although the terrain has been eroded in places by tributaries of the Chukuni River. Surface topography is also high at the southernmost end of the Township of Ear Falls, in the immediate vicinity of the settlement area of Ear Falls. The southwest boundary of the Township is dominated by the low topography of the Chukuni and English rivers, which partially form the Township's boundary. At the periphery of the Township of Ear Falls, higher elevations are identified mostly to the east.

The north-south trending Lac Seul moraine is a dominant topographic feature in the Ear Falls area and represents the western extent of glacial ice during a re-advance of the Hudson Bay ice lobe, approximately 9,900 years ago (Teller, 1985). The moraine passes immediately to the east of the settlement area of Ear Falls in a north-south orientation and extends north and south of the Township.

The Township of Ear Falls is located within the English River watershed, which is in turn part of the Winnipeg River sub-basin, which drains into the Nelson River basin, and eventually, Hudson Bay (Lake of the Woods Control Board, 2010). Surface water generally flows through the Township of Ear Falls from the north and east, to the southwest. At the northeast corner of the Township, the Trout Lake River flows into Bruce Lake from the northeast and then into Pakwash Lake to the west. The outflow of Pakwash Lake is the Chukuni River, which flows to the south along the southwestern township boundary, where it joins the English River. The English River is the outflow from Lac Seul and it exits the lake at the southeast corner of the Township of Ear Falls. Water levels in Lac Seul are controlled by a hydroelectric dam operated by Ontario Power Generation. The English River flows to the west, to where it joins the Chukuni River and then flows south into Camping Lake, and further to the southwest, where it is joined by the Wabigoon River, eventually joining the Winnipeg River.

## 2.2 Bedrock Geology

### 2.2.1 Gneissic metasedimentary rocks of the English River Subprovince

The Ear Falls area is dominated by gneissic metasedimentary rocks of the English River Subprovince (Figure 3) formed as a result of high-grade metamorphism of sedimentary rocks deposited between approximately 2.704 and 2.696 billion years ago (Sanborn-Barrie et al., 2004) in a foreland sedimentary setting (van de Kamp and Beakhouse, 1979; Breaks, 1991; Breaks and Bond, 1993). The generation of migmatites is attributed to low to medium pressure, high-temperature metamorphism that occurred at approximately 2.691 billion years ago (Corfu et al., 1995). The sedimentary protoliths have been interpreted as being mainly greywacke and mudstone/shale derived from reworked volcanic source rocks within the Uchi Subprovince (Breaks and Bond, 1993). In a small sector of the Township of Ear Falls, between the Bruce Lake and Pakwash Lake plutons, metasedimentary rocks also comprise chert-magnetite ironstone (Sanborn-Barrie et al., 2004). Along the western shore of Bruce Lake, the metasedimentary rocks include an 80 m thick banded iron formation (Griffith deposit). Metavolcanic rocks are not common, accounting for only about 2 % of the English River Subprovince.

Nitescu et al. (2006) infer that the metasedimentary rocks throughout the English River Subprovince are on the order of less than 1 km thick where they are underlain by intrusions, and up to 4 km thick in narrow regions along the boundaries of the belt and between intrusive bodies. These depth estimates are based on the integration of surface geologic mapping with gravity and magnetic data, and Lithoprobe seismic data.

### 2.2.2 Plutonic Rocks

Five large plutonic bodies occur within the Ear Falls area: the Wenasaga Lake batholith, the Bruce Lake pluton, the Bluffy Lake batholith, the Wapesi Lake batholith, and the Pakwash Lake pluton

(Figure 3). Other smaller granitic and tonalitic intrusions are mapped in the southern portion of the Ear Falls area.

The Wenasaga Lake batholith is estimated to be of a similar age to the surrounding metasedimentary rocks, between approximately 2.700 and 2.691 billion years old (Breaks, 1991; Nitescu et al., 2006). It consists of a peraluminous granite mass approximately 7 km wide by 26 km long that likely formed by the partial melting of the sedimentary host rock in conjunction with local injections of fresh magma (Breaks, 1991). The Wenasaga Lake batholith is well exposed in a blast cut along the former Griffith iron mine rail line near Detector Lake (Breaks et al., 2003). At this location, biotite-muscovite pegmatitic leucogranite grades into a biotite-rich granite containing inclusions of metasedimentary gneiss incorporated from the surrounding country rock. The Wenasaga Lake batholith has been examined for potential linkage with a metasedimentary-hosted, rare-element pegmatite mineralization (the Sandy Creek beryl deposit) located adjacent to the southwestern flank of the batholith (Breaks et al., 2003). The gravity field over the Wenasaga Lake batholith exhibits a slight negative response contrasting with the surrounding country rock suggesting that the batholith extends to substantial depth.

The Bruce Lake pluton, which covers approximately 200 km$^2$, intrudes clastic metasedimentary rocks near the contact between the Uchi and English River subprovinces. The presence of at least one schistosity pre-dating the Bruce Lake pluton in the metasedimentary rocks around the intrusion (Shklanka, 1970), and the timing of the regional deformation described by Breaks (1991) and Stott and Corfu (1991), suggests emplacement between approximately 2.690 and 2.670 billion years ago. The Bruce Lake pluton is composed of various phases including biotite-hornblende-bearing diorite, quartz diorite, monzodiorite, and gabbro. Enclaves of metasedimentary and metavolcanic rocks, including mafic metavolcanic rocks and hornblendite, commonly occur within the pluton (Breaks and Bond, 1993; Sanborn-Barrie et al., 2004). Enclaves of intermediate metavolcanic rocks, trondhjemite, or quartz-diorite also occur but are not common. The gravity field shows no discernible response to the Bruce Lake pluton and cannot be differentiated from the regional trend. Therefore, the thickness of the Bruce Lake pluton is unknown.

The approximately 2.698 billion years old Bluffy Lake batholith (Corfu et al., 1995) is located approximately 12 km east of the Township of Ear Falls and has a surface extension of approximately 705 km$^2$. The Bluffy Lake batholith is an intrusive complex composed of several units, with composition ranging from trondhjemite to quartz-diorite, and textures ranging from massive to foliated and locally exhibits a gneissic texture. Contacts with the metasedimentary rocks are typically sharp (Breaks, 1991). Breaks and Bond (1993) noted that heterogeneous, multicyclic intrusions and intrusive complexes are mainly found in the Winnipeg River Subprovince and that the Bluffy Lake batholith is an example of these in the English River Subprovince. The Bluffy Lake batholith shows a slight negative gravity response relative to the surrounding rocks within the Ear Falls area. Based on available gravity data, Gupta and Wadge (1986) suggest a sheet thickness of 1.5 to 3 km for the Bluffy Lake batholith.

The Wapesi Lake batholith covers an area of approximately 635 km$^2$, though only a portion of the batholith (approximately 50 km$^2$) occurs within the extreme southeast of the Ear Falls area. Breaks and Bond (1993) describe the batholith as a southwesterly-tapering, massive, coarse-grained to pegmatitic muscovite-biotite and biotite-muscovite quartz-monzonite diatexite, and suggest that the batholith is the result of anatectic melting of the metasedimentary country rock. The age of the Wapesi Lake batholith is reported by Breaks (1991) as between approximately 2.692 and 2.668 billion years old. No information regarding the thickness of the Wapesi Lake batholith has been found in the available literature.

Several small elongated granitic bodies are mapped along the Sydney Lake fault zone and a number of elliptical 4 to 6 km long granitic bodies are mapped within the gneissic rocks south of Ear Falls and between Ear Falls and Manitou Falls (Figure 3). For example, the Pakwash Lake pluton is relatively small (10 $km^2$) and is located in the northwestern section of the Township of Ear Falls (mostly beneath Pakwash Lake). The Pakwash Lake pluton is similar in mineralogy to the Bruce Lake pluton, with composition ranging from quartz-diorite to diorite. Compared to the Bruce Lake pluton, the Pakwash Lake pluton has less quartz and more mafic minerals. Shklanka (1970) suggests a common parentage and contemporaneous age for the Bruce Lake and Pakwash Lake plutons based on their mineralogical similarities. The smaller bodies are concordant to the ductile fabric of the gneissic belt and may have been generated during the migmatization of the surrounding sedimentary rocks. An unnamed granitic pluton is present in the extreme southeast portion of the Ear Falls area within rocks belonging to the Winnipeg River Subprovince. No information on the thickness of these smaller intrusive bodies was found in the literature. Other relatively large intrusive bodies occur in the northwestern and southwestern parts of the Ear Falls area, and are documented as tonalite to diorite and tonalite to granodiorite, respectively (Sanborn-Barrie et al., 2004).

### 2.2.3 Mafic Dykes

A series of Proterozoic mafic dykes crosscuts all earlier rock types in the areas bordering the Ear Falls area. Such dykes have not been identified nor mapped within the Ear Falls area. However, mafic dykes referred to as the “Ear Falls dykes” were documented at the former Griffith mine. While there is evidence of Mesozoic-age emplacement of kimberlitic pipes and dykes elsewhere in northern Ontario, no post-Precambrian rocks are known to be present within the Ear Falls area (Stott and Josey, 2009).

### 2.2.4 Faults and Shear Zones

Two km-scale east-trending shear zones have been mapped within the Ear Falls area: the Sydney Lake fault zone and the Long Legged Lake fault zone (Figure 3). The Sydney Lake fault is 0.5 to 2 km wide (Bethune et al., 2006) and separates the metavolcanic and felsic plutonic rocks of the Uchi Subprovince to the north from the migmatized metasedimentary rocks of the English River Subprovince to the south. Displacement along the Sydney Lake fault is interpreted to have evolved from reverse (south over north) motion to dextral motion. The displacement magnitude of the dextral component is estimated to vary from 6 km (Stott and Corfu, 1991) to 30 km (Stone, 1981) along strike, whereas the displacement magnitude of the reverse component is estimated to be between 2 and 3 km (Stott and Corfu, 1991; Corfu et al., 1995). The Long Legged Lake fault runs along the northeast margin of the Bruce Lake pluton (Figure 3) and is interpreted to be related to the Sydney Lake fault. Cataclastic textures are superimposed on mylonitic textures indicating that brittle deformation followed ductile deformation (Stone, 1981).

### 2.2.5 Metamorphism

Studies on metamorphism in Precambrian rocks across the Canadian Shield have been summarized in a few publications since the 1970s, including Fraser and Heywood, (1978); Kraus and Menard (1997); Menard and Gordon (1997); Berman et al. (2000); Easton (2000a and 2000b) and Berman et al. (2005). The thermochronologic record for major parts of the Canadian Shield are given in a number of studies such as those by Berman et al. (2005), Bleeker and Hall (2007), Corrigan et al. (2007), and Pease et al. (2008).

The Superior Province largely preserves low to medium pressure – high temperature Neoarchean metamorphism from approximately 2.710 to 2.640 billion years ago, but there is a widespread tectonothermal overprint of Archean crust by Paleoproterozoic deformation and typically amphibolite facies metamorphism across the Churchill Province through northernmost Ontario under the northern Hudson Bay lowland, western Manitoba, northern Saskatchewan and Nunavut (e.g., Skulski et al., 2002; Berman et al., 2005).

In the Archean Superior Province, the relative timing and grade of regional metamorphism corresponds to the lithologic composition of the subprovinces (Easton, 2000a; Percival et al., 2006). Granite-greenstone subprovinces contain the oldest, Neoarchean metamorphism of lower greenschist to amphibolite facies in volcano-sedimentary assemblages and synvolcanic to syntectonic plutons. Both metasedimentary and associated migmatite-dominated subprovinces, such as the English River and Quetico subprovinces, and dominantly plutonic and orthogneissic subprovinces, such as the Winnipeg River Subprovince, display younger, syntectonic middle amphibolite to granulite facies metamorphism (Breaks and Bond, 1993; Corfu et al., 1995).

Sub-greenschist facies metamorphism in the Superior Province is restricted to limited areas, notably within the central Abitibi greenstone belt (e.g., Jolly, 1978; Powell et al., 1993) and locally within the Uchi Subprovince (Thurston and Paktunc, 1985). Most late orogenic shear zones in the Superior Province experienced lower to middle greenschist retrograde metamorphism. Post-metamorphic events along faults in the Abitibi greenstone belt show a drawn-out record through $^{40}Ar/^{39}Ar$ dating to approximately 2.500 billion years ago (Powell et al., 1995). The distribution of contrasting grades of metamorphism is a consequence of relative uplift, block rotation and erosion from Neoarchean orogenesis and subsequent local Proterozoic orogenic events and broader epeirogeny during Proterozoic and Phanerozoic eons. In northwestern Ontario, the concurrent post-Archean effects are limited to poorly documented reactivation along faulted Archean terrane boundaries (e.g., Kamineni et al., 1990 and references therein).

Overall, most of the Canadian Shield, outside of unmetamorphosed late tectonic plutons, contains a complex episodic history of tectonometamorphism largely of Neoarchean age with broad tectonothermal overprints of Paleoproterozoic age around the Superior Province and culminating at the end of the Grenville Orogeny approximately 950 million years ago.

Major regional deformation and metamorphism within the English River Subprovince culminated approximately 2.691 billion years ago with two later episodes of metamorphism and pegmatite emplacement approximately 2.680 and 2.669 billion years ago (Corfu et al., 1995; Sanborn-Barrie et al., 2004). Corfu et al. (1995) consider the timing (short lived and apparently cyclical) of metamorphism in the English River Subprovince to be consistent with thermal perturbations related to injection of granitic magmas generated through partial crustal melting.

Metamorphic grades are lower within the Uchi Subprovince in the north part of the Ear Falls area where lower amphibolite facies dominate along the contact with the adjacent English River strata grading to greenschist facies over most of the remainder of the Uchi Subprovince (Breaks et al., 1978).

Upper-greenschist facies metamorphic grade in the English River Subprovince is rather restricted to near its contact with the greenstone belts at the north of the subprovince. Metamorphic grade rapidly increases southward reaching upper-amphibolite facies (Breaks et al., 1978; Breaks and Bond, 1978, 1993), although variable uplift of the English River Subprovince and the extensive fault systems frequently obscure this trend (Stone, 1981; Breaks and Bond, 1993). Two main occurrences of hornblende-granulite facies metamorphism occur near the Ear Falls area: one proximal to left side of the Miniss River fault, approximately 80 km east of the Ear Falls area, and the other about 30 km west of the settlement area of Ear Falls. Thermobarometry indicates pressure-temperature conditions of 4-6 Kbar and approximately 700-725 $^{o}$C for the granulite facies indicating granulite metamorphism of low to medium pressure and high temperature (Chipera and Perkins, 1988; Breaks and Bond, 1993). Potential exists for the granulite isograds to extend eastward into the Ear Falls area, given the relative proximity of granulite facies metamorphism to the area. This could result in a possible lateral gradation of granulite-amphibolite facies within the Ear Falls area. Confirmation of the existence of lateral gradation in metamorphic grade across the Ear Falls area would need to be investigated in future stages of the evaluation process.

## 2.3 Geological and Structural History

Direct information on the geological and structural history of the Ear Falls area is limited. The geological and structural history summarized below integrates the results from studies undertaken elsewhere throughout and proximal to the region of the Ear Falls area. It is understood that there are potential problems in regional correlation of specific structural events within a $D_x$ numbering system and in the application of such a system to the local geological history. Nonetheless, the summary below represents an initial preliminary interpretation for the Ear Falls area, which may be modified after site-specific information has been collected.

Rocks of the English River Subprovince have been subjected to multiple Archean deformation events (Westerman, 1977; Breaks et al., 1978; Breaks, 1991) as summarized in Table 1. These deformation events have been traditionally interpreted as involving three folding events and one faulting event (Breaks, 1991) but this interpretation has recently been revised by Hrabi and Cruden (2006). Hrabi and Cruden (2006) interpreted the deformation events as components of a single, protracted, and complex orogeny. The work of Hrabi and Cruden (2006), which considers $D_1$ to $D_5$ events to be components of a single protracted and complex orogeny, offers a descriptive summary of the deformation events in the English Subprovince and is regarded as the most applicable interpretation of the structural geology of the Ear Falls area. Along with a protracted younger history of brittle deformation, herein termed $D_6$, these six deformation events form the basis of the following description of the structural history.

The first deformation event ($D_1$) is interpreted to have generated a weak foliation ($S_1$) oriented parallel to bedding in low-grade metamorphic rocks located in the north and south margins of the English River Subprovince (Hrabi and Cruden, 2006). At higher metamorphic grades, $S_1$ is enhanced by migmatitic leucosomes (Hrabi and Cruden, 2006). $D_1$ is interpreted to have overlapped with the initial migmatization stages of sedimentary rocks and is bracketed between the time of deposition of sedimentary rocks, before approximately 2.704 billion years ago, and the age of a suite of tonalite intrusions dated at approximately 2.698 billion years old and deformed by $D_2$ (Hrabi and Cruden, 2006). Folds related to this fabric are not commonly found and have only been documented by Breaks (1991) and Hynes (1997, 1998).

The second deformation event ($D_2$) was the most pronounced, and generated an east-trending moderate to intense foliation ($S_2$) and a stretching lineation ($L_2$) of varying orientation (Hrabi and Cruden, 2006). $F_2$ folds are isoclinal and fold the $S_1$ foliation and migmatitic leucosomes (Hrabi and Cruden, 2006). Migmatization of sedimentary rocks continued during $D_2$ and the resulting migmatitic layering is interpreted to represent a composite $S_0$-$S_1$-$S_2$ foliation (Hrabi and Cruden, 2006). The maximum approximate age of the $D_2$ deformation is constrained by the approximately 2.698 billion year old suite of tonalite intrusions which are overprinted by the $S_2$ foliation (Hrabi and Cruden, 2006).

Hrabi and Cruden (2006) attribute $D_3$ deformation to a period of extension. Extensional faults are indirectly evident from Lithoprobe seismic reflection profiles and are attributed to $D_3$. This extensional phase is consistent with the presence of approximately < 2.701 billion year old conglomeratic basins distributed along the south margin of the English River Subprovince and the three-dimensional geometry of the Uchi and English River subprovinces inferred from Lithoprobe profiles (Calvert et al., 2004) with upwarp of the Moho beneath the English River Subprovince. Based on the timing of the $D_2$ event, $D_3$ is therefore constrained to have occurred between approximately 2.691 and 2.68 billion years old.

The fourth deformation event ($D_4$) is attributed to curved east- to northeast-trending sinistral shear zones (Hrabi and Cruden, 2006). Upright moderately east- to southeast-plunging $F_4$ folds associated with a steeply-dipping penetrative $S_4$ foliation are also attributed to $D_4$ (Hrabi and Cruden, 2006). In terms of geometry and kinematics, $D_4$ shear zones are similar to the well-documented Miniss River fault located about 80 km east of the Ear Falls area (Hrabi and Cruden, 2006). The Miniss River fault is 1 to 2 km wide (Breaks, 1991), with a long history of ductile and brittle deformation (Bethune et al., 1999). The approximate age of a portion of the mylonitic ductile strain along the Miniss River fault is constrained by the age of a granitic dyke dated at approximately 2.681 billion years old, which is deformed and offset by a sinistral shear band within the fault (Bethune et al., 2006). Dextral reactivation of the southwestern portion of the Miniss River fault is interpreted to have occurred approximately 2.670 billion years ago (Bethune et al., 2006). The age of titanite porphyroblasts generated during retrograde metamorphism was linked to the reactivation of the fault (Corfu et al., 1995), and may be attributed to $D_5$ (see below). Therefore an age range of between approximately 2.68 and 2.669 billion years ago is considered a suitable approximation for the timing of $D_4$.

Geometric and kinematic relationships strongly suggest a protracted history of late fault movement that is collectively ascribed to a $D_6$ phase of deformation. For example the latest displacement of the Sydney Lake fault crosscuts the Miniss River fault (Bethune et al., 2006). This interpretation is consistent with Ar-Ar geochronology indicating that motion along the Sydney Lake fault continued until approximately 2.640 billion years ago (Hanes and Archibald, 1998). However these regional fault systems are known to have a protracted displacement history and early thrust faulting along the Sydney Lake fault zone is likely to have pre-dated the most significant component of displacement on the Miniss fault (Stone, 1981). Hrabi and Cruden (2006) hence assign faults associated with the Sydney Lake fault to a fifth deformation event ($D_5$). Bethune et al. (2006) propose that dextral reactivation of the Miniss River fault about 2.670 billion years ago was effectively driven by the stress regime of the younger Sydney Lake fault. Hrabi and Cruden (2006) consider $D_1$ to $D_5$ events to be components of a single protracted and complex orogeny. In addition, Hanes and Archibald (1998) suggest that approximately 2.400 billion years ago regional differential uplift was associated with movement along major fault zones throughout the Superior Province. Therefore the $D_5$ episode is considered to have been a protracted event of shear zone activation and re-activation that occurred until approximately 2.400 billion years ago.

Further episodes of brittle deformation are inferred to have caused the formation of brittle fractures and faults, and to have reactivated pre-existing faults and fractures in the region. Numerous generations of fracture formation or reactivation have been identified post-dating approximately 2.5 billion years in northwestern Ontario (Brown et al., 1995; Kamineni et al., 1990).

**Table 1: Summary of the Geological and Structural History of the Ear Falls Area**

| Time Period (billion years ago) | Geological Event |
|---|---|
| **ca. 3.4 to 2.8** | Progressive growth of the North Caribou and Winnipeg River terranes through the additions of magmatic and crustal material in continental arcs and through accretion |

| Time Period (billion years ago) | Geological Event |
|---|---|
| | of allochthonous crustal fragments (Tomlinson et al., 2004). |
| **ca. 2.740 to 2.735** | Emplacement of early plutons in the Uchi Subprovince. |
| **ca. > 2.704 to 2.69** | Timing of collision between the North Caribou terrane and the Winnipeg terrane (Corfu et al., 1995; Hrabi and Cruden, 2006; Sanborn-Barrie and Skulski, 2006). [$D_1$]<br>• Emplacement of late granitic to granodioritic plutons within the Winnipeg River Subprovince between approximately 2.71 and 2.69 billion years ago (Breaks and Bond, 1993).<br>• Accumulation and syn-depositional deformation of sediments in the English River Subprovince between approximately 2.704 and 2.699 billion years ago (e.g., (Sanborn-Barrie et al., 2004). |
| **ca. 2.698** | Timing of intrusion of calc-alkaline plutons into sedimentary rocks of the English River Subprovince (Hrabi and Cruden, 2006). Their emplacement provides constraint on the maximum age of $D_2$ deformation. [2.698 > $D_2$ > 2.691 billion years ago] |
| **ca. 2.691 to 2.68** | Major regional deformation, amphibolite to granulite facies metamorphism, anatexis and emplacement of peraluminous granitic intrusions (Sanborn-Barrie et al., 2004). [$D_3$] |
| **ca. 2.68 to > 2.67** | Dextral semi-brittle movement in the Sydney Lake fault zone (Sanborn-Barrie et al., 2004; Hrabi and Cruden, 2006). [$D_4$]<br>• Granulite facies metamorphic event approximately 2.680 billion years ago within the Winnipeg River Subprovince (Corfu et al., 1995).<br>• Continued metamorphism and pegmatite emplacement within the English River Subprovince (Sanborn-Barrie et al., 2004). |
| **ca. 2.67 to 2.64** | Late fault (re)activation (Hrabi and Cruden, 2006). [$D_5$] |
| **ca. < 2.64 to > 1.9** | Post-2.6 billion years old regional faulting and brittle fracturing (Kamineni et al., 1990). [$D_6$] |
| **ca. 1.9 to 1.7** | Emplacement of the Ear Falls dykes (Symons et al., 1983). [$D_6$ con't] |
| **Post-1.7** | A complex interval of erosion, brittle fracture, repeated cycles of burial and exhumation, and glaciations, particularly from the latest Miocene to the present. [$D_6$ con't] |

## 2.4 Quaternary Geology

Quaternary geology in the Ear Falls area is described in detail in JDMA (2013). A summary of the main features is provided here for reference.

The contact between bedrock and the overlying unconsolidated Quaternary sediments in the Ear Falls area represents an unconformity exceeding one billion years. Figure 4 illustrates the extent and type of Quaternary terrain features in the Ear Falls area. The Quaternary geology of the area is dominated at surface by deposits of glaciolacustrine silts and clays that accumulated with the progressive retreat of the ice sheet during the end of the Wisconsinan glaciation. This period of glaciation began approximately 115,000 years ago and peaked about 21,000 years before present, at which time the glacial ice front extended south of Ontario into what is now Ohio and Indiana

(Barnett, 1992). At surface there are also minor amounts of glaciofluvial (sand and gravel) deposits as well as post-glacial deposits of peat, muck, organic-rich silts, and clays found in bogs and swamps throughout the area. Recently deposited alluvial silts and clayey silts are also present along parts of the English River and some small streams.

Ice from the Wisconsinan glaciation laid down the oldest known Quaternary deposit in the Ear Falls area: a stratum of sandy, stoney till mapped by Ford (1981), who described the unweathered till as massive to fissile with poor to moderate matrix cohesion. Unweathered till is usually olive-grey, whereas the weathered till is brown to greyish brown. The extent of till over the Ear Falls area is unknown due to the extensive overlying mantle of glaciolacustrine clays and silts at the surface. The till is not exposed at the surface within the township limits except for a small area near the northeast corner of Bruce Lake. While earlier glacial and interstadial deposits are encountered in a few northern Ontario locations (e.g., the interstadial or interglacial Missinaibi Beds of the Moose River drainage or the interstadial Owl Creek Beds of the Timmins area), none are known to be present in the Ear Falls area, and it is likely that any earlier deposits in the Ear Falls area have been largely or entirely removed by glacial erosion that stripped away the pre-existing overburden and eroded the crystalline bedrock. Glaciofluvial deposits are exposed in several areas within the Township of Ear Falls and include a number of small eskers, portions of the Lac Seul moraine, and numerous sand bodies scattered about the area. The sands are typically fine- to medium-grained and are moderately well-sorted and quartz-rich (Ford, 1981). The northward retreat of the ice sheet in the Ear Falls area started approximately 12,000 years ago and the Ear Falls area first became ice-free approximately 10,500 years ago (Dyke et al., 2003). Ice front fluctuations during the deglaciation resulted in the deposition of the Lac Seul moraine, which forms a prominent northwest-trending linear feature that can be traced for more than 200 km across northwestern Ontario.

During the waning of the Wisconsinan glaciation, drainage was blocked from flowing northward by the residual ice mass still remaining over the Hudson Bay Basin. This created a large ice-dam lake, known as Lake Agassiz that covered much of northwestern Ontario and the majority of the Ear Falls area. Lake Agassiz was the largest of several glacial lakes that bordered the southern margin of the retreating ice sheet during the late Wisconsinan glaciations and covering a maximum area of approximately 1 million $km^2$ (Bajc et al., 2000). Clays and silts were laid down as Lake Agassiz gradually inundated the area approximately 9,900 years ago and these fine-textured glaciolacustrine deposits cover much of the Ear Falls area to thicknesses exceeding 4 m, as indicated in water well records. Wave action in Lake Agassiz also produced a series of well-developed terraces on the Lac Seul moraine and sandy aprons bordering the moraine (Shklanka, 1970).

Information on the thickness of Quaternary deposits in the Ear Falls area was inferred from terrain evaluation and measured thicknesses are limited to a small number of water well records for rural residential properties, a small number of water well records along the highways, and from diamond boreholes in the former Griffith mine and in the periphery of the Township to the north. Recorded depths to bedrock in the Township of Ear Falls range from 0 to 45 m and are typically less than 10 m. The thickest overburden is inferred along the axis of the Lac Seul moraine, a north-south trending glaciofluvial ice deposit and topographic high that runs along the easternmost portion of the Township of Ear Falls (Figure 4).

## 2.5 Land Use

Land use in the Ear Falls area is described in detail in Golder (2013). A small portion of the Township of Ear Falls is covered by domestic and industrial infrastructure, with developments limited mainly to roadways and the settlement area itself (Figure 1). These features do not negatively impact the interpretation of bedrock lineaments. The areas at the periphery of the Township of Ear

Falls are also largely undeveloped, with limited natural or physical constraints such as major infrastructure or permanent water bodies.

# 3 Methodology

## 3.1 Source Data Descriptions

The lineament interpretation of the Ear Falls area was based on available remote sensing data sets, including airborne geophysical (aeromagnetic) data, topography (CDED elevation models), and satellite imagery data (SPOT and LandSAT). The available geophysical data were assessed for quality, and the data were processed and reviewed before being used in the lineament interpretation (Mira, 2013). The geophysical data set for the Ear Falls area included low resolution coverage across the entire Ear Falls area as well as smaller regions of increased resolution within the area (Figure 5). In all cases, with the exception of a small area in the northern portion of the Ear Falls area overlying the greenstone belt, the best resolution data available was used for the lineament interpretation. The geophysical data were used to evaluate deeper bedrock structures and proved useful in identifying bedrock structures beneath areas of surficial cover. Topography (CDED) and satellite imagery (SPOT) data sets were used to identify surficial lineaments expressed in the topography, drainage, and vegetation. The resolution of the CDED and SPOT data sets was consistent across the Ear Falls area and provided sufficient detail to allow for the identification of surficial lineaments as short as 80 m in length. Comparing surficial lineaments to aeromagnetic lineaments allowed for the comparison of subsurface and surficial expressions of the bedrock structure. Table 2 provides a summary of the source data sets used for the lineament interpretation, including their resolution, coverage and acquisition dates.

**Table 2: Summary of Source Data Information for the Lineament Interpretation, Ear Falls Area**

| Data Set | Product | Source | Resolution | Coverage | Acquired | Additional Comments |
|---|---|---|---|---|---|---|
| Aero-magnetic | Ontario #06 | GSC | 805 m line spacing; Sensor height 152 m | Ear Falls area north of 5,594,200mN | 1960 | Flight line azimuth: 0° |
| | Ontario #07 | GSC | 805 m line spacing; Sensor height 305 m | Ear Falls area south of 5,594,200mN | 1965 | Flight line azimuth: 0° |
| | Uchi-Bruce Lakes area (GDS1026) | Ontario Geological Survey | 200 m line spacing; Sensor height 60 m | Covers 9.8% (360 km$^2$) of the Ear Falls area | 1991 | Flight line azimuth: Block A1: 0° Block A2: 45° |
| | Pakwash Lake area (GDS1218-REV) | Ontario Geological Survey | 250 m line spacing; Sensor height 120 m | Covers 3.3% (122 km$^2$) of the Ear Falls area | 1992 | Flight line azimuth: North Block: 178° South Block: 83° |
| | Trout Lake River area (GDS1222-REV) | Ontario Geological Survey | 200 m line spacing; Sensor height 73 m | Covers <1% (25 km$^2$) of the Ear Falls area of the Ear Falls area | 1997 | Flight line azimuth: Block A: 334° Block B: 0° Block C: 15° |
| | Goldpines South Property | Laurentian Goldfields Ltd. | 100 m line spacing; Sensor height 30 m | Covers 18.5% (683 km$^2$) of the Ear Falls area | 2010 | Flight line azimuth: 0° |
| DEM | Canadian Digital Elevation Data (CDED); 1:50,000 scale | Geobase | 8-23 m (0.75 arc seconds) depending on latitude | Entire Ear Falls area | 1995 (published in 2003) | |

| Data Set | Product | Source | Resolution | Coverage | Acquired | Additional Comments |
|---|---|---|---|---|---|---|
| Satellite Imagery | SPOT 4/5; Orthoimage, multispectral/ panchromatic | Geobase | 20 m (multispectral) 10 m (panchromatic) | Entire Ear Falls area | 2005-2010 | |
| | LandSAT 7 Orthorectified imagery | Geobase | 30 m (multispectral) | Entire Ear Falls area | 2004 | |

The lineament interpretation was built in two-dimensions in ArcGIS™ in UTM NAD83, zone 15 North. Each data set used in the interpretation required manipulation in ErMapper™, including creating ErMapper ECW (Enhanced Compression Wavelet) raster images (mostly colour mosaics) as end products for each data set prior to import into ArcGIS.

### 3.1.1 Geophysical Data

The geophysical data set incorporates aeromagnetic, gravity and radiometric data available across the entire Ear Falls area, however only aeromagnetic data was used for this lineament interpretation. MIRA Geoscience identified and evaluated available geophysical data sets for the Ear Falls area (Mira, 2013). This evaluation highlighted the presence of the highresolution Uchi-Bruce Lakes area (GDS1026; OGS, 2003), Pakwash Lake area (GDS1218; OGS, 2002a), and the Trout Lake River area (GDS1222; OGS, 2002b). Such data sets locally overlap each other and overall only cover 12.4% of the Ear Falls area (459 km$^2$). Another aeromagnetic data set, the GSC Regional Magnetic Compilation data (GSC, 2012), covers the entire Ear Falls area but has a low resolution (805-metre line spacing; gridded using 200-metre grid cells). In the Ear Falls area, this data set comprises two separate surveys (Ontario #6 and Ontario #7) acquired by the GSC. Source data information for these data sets is included in Table 2 and their footprints are indicated on Figure 5. The quality of geophysical data varied significantly across the Ear Falls area, as a function of the flight line spacing, the flying height and the age of the survey. The integrity of the higher quality data was maintained throughout, with the exception of a small area overlying the greenstone belt. The poorest resolution data was only used where higher resolution data was unavailable. It was determined that the quality of the data was sufficient to perform the lineament interpretation at the scale of the Ear Falls area.

The magnetic data located within the Ear Falls area were processed using several common geophysical techniques in order to enhance the magnetic response to assist with the interpretation of geophysical lineaments. The enhanced magnetic grids used in the lineament interpretation include the first and second vertical derivatives, and the tilt angle grids. These enhanced grids were processed and imaged using WinDisp in the GOCAD Mira Mining Suite software package. Acquisition parameters, processing methods and enhanced grids associated with the geophysical data sets used in the lineament interpretation are discussed in detail in Mira (2013). The combination of all of the enhanced magnetic grids provide much improved resolution of subtle magnetic fabrics and boundaries in areas that appear featureless in the total magnetic field.

During the course of the assessment, raster images of a high resolution aeromagnetic survey covering the Laurentian Goldfields' Goldpines South Property became available (Laurentian Goldfields Ltd., 2010). These images cover 18.5% of the Ear Falls area (682 of 3,688 km$^2$). Raster images of the first vertical derivative of this data set were utilized for the lineament interpretation without further processing. Other available raster images of high resolution aeromagnetic surveys include coverage over the Dixie Lake Property (Fronteer Development Group Inc., 2004; Grandcru Resources Corp., 2005). The Fronteer Development Group Inc. survey was not utilized in this assessment because its georeferencing information is ambiguous. The GrandCru Resources Corp. survey was also not utilized because it largely overlaps with the Laurentian Goldfields' survey which is considered to be of better resolution. Figure 5 shows the first vertical derivative of the combined aeromagnetic data for the Ear Falls area.

### 3.1.2 Surficial Data

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

Canadian Digital Elevation Data, 1:50,000 scale, 0.75 arc second (20 m resolution) elevation models (GeoBase, 2012) served as important data sources for analyzing and interpreting lineaments in the Ear Falls area. The digital elevation model (DEM) used for this assessment, shown as a slope raster on Figure 6, was constructed by the Ontario Ministry of Natural Resources (MNR). The data represented 1:20,000 scale source data acquired through the Ontario Base Mapping (OBM) program, which was a major photometric program conducted across Ontario between 1978 and 1995. Four main OBM data sets were used: OBM contours, OBM spot heights, WRIP stream network, and lake elevations derived using the OBM spot heights and OBM water features. CDED data sets are provided in geographic coordinates, referenced horizontally using North American Datum 1983 (NAD83) and vertically based on the Canadian Geodetic Vertical Datum 1928 (CGVD28). Ground elevations are recorded in metres relative to mean sea level.

The CDED topography data covering the entire Ear Falls area is available in 18 USGS DEM format individual tiles, each tile covering approximately 500 km$^2$. The tiles that cover the area are listed in Table 3.

**Table 3: Summary of 1:50,000 scale CDED tiles used for the Lineament interpretation**

| NTS Tiles | East/West Coverage | Ground Resolution (arcsec.) |
|---|---|---|
| 052k/ 05-07 | Both | 0.75 |
| 052k/ 10-15 | Both | 0.75 |

These files have an accuracy of less than 5 m and a resolution of 0.75 arc seconds, which is equivalent to approximately 16 to 23 m in the Ear Falls area. The 18 individual tiles were merged, levelled, and saved as a compressed raster image (Figure 6).

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

SPOT multispectral (20 m resolution) and panchromatic (10 m resolution) orthoimagery (the latter is shown on Figure 7), were used for identifying surficial lineaments and exposed bedrock within the Ear Falls area (GeoBase, 2012). 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). Seven SPOT images (scenes) provided complete coverage for the Ear Falls area (Table 4). The scenes are from the SPOT 4 and 5 satellites, with six images captured in 2006 and one in 2008. SPOT 4 and 5 images were acquired using the High Resolution Geometric (HRG) sensor. Each image covers an area of approximately 3,600 km$^2$.

**Table 4: Summary of SPOT imagery scenes used for the Lineament interpretation**

| Scene ID | Image Center (Lat/Long) | Satellite | Date of Image |
|---|---|---|---|
| S4_09211_5050_20060911 | 50°50', -92°11' | SPOT 4 | 11-Sep-2006 |
| S4_09224_5022_20060911 | 50°22', -92°24' | SPOT 4 | 11-Sep-2006 |
| S5_09218_5050_20081003 | 50°50', -92°18' | SPOT 5 | 3-Oct-2008 |
| S5_09250_5050_20060830 | 50°50', -92°50' | SPOT 5 | 30-Aug-2006 |
| S5_09303_5022_20060507 | 50°22', -93°03' | SPOT 5 | 7-May-2006 |

| | | | |
|---|---|---|---|
| S5_09334_5050_20060904 | 50°50', -93°34' | SPOT 5 | 4-Sep-2006 |
| S5_09347_5022_20060904 | 50°22', -93°47' | SPOT 5 | 4-Sep-2006 |

The seven multispectral tiles were merged, levelled, and a false natural colour image was created in ErMapper and saved as a compressed raster image. The seven panchromatic tiles were also merged and levelled, and a black and white image was created in ErMapper and saved as a compressed raster image.

For quality control, Natural Resources Canada (NRCan) provides images that have a maximum of 5% snow and ice cover, 5% cloud cover and a maximum viewing angle of 15°. NRCan orthorectified the SPOT images using three data sources: 1:50,000 scale Canadian Digital Elevation Data (CDED), National Road Network (NRN), and Landsat 7 orthoimagery. The orthoimages are provided in GeoTIFF format, projected using Universal Transverse Mercator (UTM) projection referenced to the North American Datum 1983 (NAD83). The LandSAT 7 Orthorectified Image for the Ear Falls area is available as five individual tiles containing ten Geotiff images each representing various bands including: one panchromatic band, six multispectral bands, two thermal infrared bands, and a combined image of bands 7, 4, and 3. Each tile covers approximately 33,400 km$^2$. The tiles that cover the Ear Falls area are listed in Table 5.

**Table 5: Summary of LandSAT 7 imagery scenes used for the Lineament interpretation**

| Scene ID | Date of Image |
|---|---|
| 029024_0100_020706_l7 | 6-Jul-2002 |
| 029025_0100_010516_l7 | 16-May-2001 |
| 028025_0100_000826_l7 | 26-Aug-2000 |
| 028024_0100_000826_l7 | 26-Aug-2000 |
| 027025_0100_000718_l7 | 18-Jul-2000 |

The tiles were merged and levelled, and a false natural colour image and an image with bands 7, 4, and 1 were created in ErMapper and saved as compressed raster images.

It was determined that the resolution of the SPOT data set, when overlain with the LandSAT data set using 70% transparency was sufficient to undertake the lineament interpretation. The scenes were processed to create a single mosaic (Figure 7). The colour composite of the Landsat imagery shown as part of Figure 7 was created by assigning a primary colour (red, green and blue) to three of the spectral bands (7, 4 and 1). Different materials reflect and absorb solar radiation differently at different wavelengths and therefore have varying intensities within each of the Landsat bands. When combined into a single image, the colour assignment results in a pixel colour that tends to approach a “natural” representation. Image processing and different colour assignments can be used to enhance the presence of different material categories, such as vegetation type, water, soil or man-made features.

An automated contrast matching technique was applied to the images which minimized sharp variances in pixel intensity, giving the single image a cohesive appearance. The images were extended beyond the defined boundaries of the Ear Falls area to allow for the mapping of continuous lineaments extending beyond the Ear Falls area.

The SPOT 4/5 satellite, LandSAT 7 satellite, and CDED topography data cover the entire Ear Falls area with good resolution (e.g., SPOT, 10-metre resolution). However, the bedrock structural information available from these three data sets is limited by lakes and Quaternary cover (Figure 4). Although this locally limits the use of satellite imagery and topography data to identify lineaments in the bedrock in this area, it offers better resolution in areas only covered by the low resolution SMGA magnetic data. The area of Quaternary cover where the satellite (SPOT 4/5 and LandSAT 7) and topography (CDED) data were of limited use due to lakes is approximately 400 $km^2$ (10.8 percent of the 3,688 $km^2$ Ear Falls area; Figure 4).

## 3.2 Lineament Interpretation Workflow

Lineaments were interpreted using a workflow designed to address issues of subjectivity and reproducibility that are inherent to any lineament interpretation. The workflow followed a set of detailed guidelines using the publicly available surficial (DEM, SPOT) and geophysical (aeromagnetic) data sets described above. The interpretation guidelines for brittle (including brittle-ductile) lineaments involved three stages:

- Stage 1: Independent lineament interpretation by two individual interpreters for each data set and assignment of certainty level (1, 2 or 3);
- Stage 2: Integration of lineament interpretations for each individual data set (Figures 8, 9 and 10) and first determination of reproducibility (RA_1); and
- Stage 3: Integration of lineament interpretations for all three data sets (Figures 12 and 13) and determination of coincidence (RA_2).

Ductile geophysical lineament interpretations (Figure 11) were made using the aeromagnetic geophysical survey data by a single documented specialist observer.

Each identified lineament feature was classified in an attribute table in ArcGIS. The description of the attribute fields used is included in Table 6. Fields 1 to 9 are populated during Stage 1. Fields 10 and 11 are populated during Stage 2. Fields 12 to 19 are populated during Stage 3, the final stage.

**Table 6: Summary of Attribute Table Fields Populated for the Lineament Interpretation**

| ID | Attribute | Brief Description |
|---|---|---|
| 1 | Rev_ID | Reviewer initials |
| 2 | Feat_ID | Feature identifier |
| 3 | Data_typ | Data set used (MAG, CDED, SPOT) |
| 4 | Feat_typ | **Type of feature used to identify each lineament**<br><br>**Satellite Imagery:**<br>A. Lineaments drawn along straight or curved lake shorelines;<br>B. Lineaments drawn along straight or curved changes in intensity or texture (i.e., vegetation);<br>C. Lineaments drawn down centre of thin rivers or streams;<br>D. Lineaments drawn along a linear chain of lakes; or<br>E. Other (if other, define in comments).<br>**Digital Elevation Model:**<br>A. Lineaments drawn along straight or curved topographic valleys;<br>B. Lineaments drawn along straight or curved slope walls; or<br>C. Other (if other, define in comments).<br>**Airborne Geophysics (magnetic data):**<br>A. Lineaments drawn along straight or curved magnetic high;<br>B. Lineaments drawn along straight or curved magnetic low;<br>C. Lineaments drawn along straight or curved steep gradient; or<br>D. Other (if other, define in comments). |
| 5 | Name | Name of feature (if known) |
| 6 | Certain | Value describing the interpreters confidence in the feature being related to bedrock structure (1-low, 2-medium or 3-high) |
| 7 | Length* | Length of feature is the sum of individual lengths of mapped polylines (not end to end) and is expressed in kilometers |
| 8 | Width** | **Width of feature; This assessment is categorized into 5 bin classes:**<br>A. < 100 m<br>B. 100 – 250 m |

| ID | Attribute | Brief Description |
|---|---|---|
| | | C. 250 – 500 m<br>D. 500 – 1,000 m<br>E. > 1,000 m |
| 9 | Azimuth | lineament orientation expressed as degree rotation between 0 and 180 degrees |
| 10 | Buffer_RA_1 | Buffer zone width for first reproducibility assessment |
| 11 | RA_1 | Feature value (1 or 2) based on first reproducibility assessment |
| 12 | Buffer_RA_2 | Buffer zone width for second reproducibility assessment |
| 13 | RA_2 | Feature value (1, 2 or 3) based on second reproducibility assessment (i.e., coincidence) |
| 14 | Geoph | Feature identified in geophysical data set (Yes or No) |
| 15 | DEM | Feature identified in topography data set (Yes or No) |
| 16 | SAT | Feature identified in satellite data set (Yes or No) |
| 17 | F_Width | Final interpretation of the width of feature |
| 18 | Rel_age | Relative age of feature, in accord with regional structural history |
| 19 | Comment | Comment field for additional relevant information on a feature |

*The length of each interpreted feature is calculated based on the sum of all segment lengths that make up that lineament.
**The width of each interpreted feature is determined by expert judgment and utilization of a GIS-based measurement tool. Width determination takes into account the nature of the feature as assigned in the Feature type (Feat_typ) attribute.

A detailed description of the three workflow stages is provided below; this includes the methodology for populating the associated attribute field for each interpreted brittle (including brittle-ductile) lineament.

### 3.2.1 Stage 1: Lineament Interpretation and Certainty Level

To accommodate the generation of the best possible, unbiased lineament interpretation, two individual interpreters followed an identical process for structural lineament analysis during Stage 1. The first step of the lineament interpretation was to have each individual interpreter independently produce GIS lineament maps, and detailed attribute tables, for each of the three data sets. The following components were addressed in the order specified:

- Magnetic Data:

  Throughout the interpretation of magnetic data sets, priority was given to the highest resolution data set available. Other available magnetic data were only used where the Ear Falls area was not covered by the highest resolution data set. The interpretation of magnetic data included two steps:

  Interpretation of ductile lineaments:

    Drawing of stratigraphic and structural form lines using first vertical derivative magnetic data. The form lines trace the geometry of magnetic high lineaments and are tentatively termed ductile lineaments as they represent the geometry of stratigraphy within metavolcanic and metasedimentary rocks or the internal fabric (foliation) within granitoid batholiths and gneissic rocks. This process highlighted discontinuities between form lines, particularly in stratigraphic form lines (e.g., intersecting form lines) that represent structural lineaments (e.g., faults, folds, unconformities, or intrusive contacts).

    For this assessment, form lines were drawn using first vertical derivative data.

  Interpretation of brittle (including brittle-ductile) lineaments:

    This part of the interpretation involved the drawing of lineaments, representing all interpreted faults or fractures regardless of interpreted age, style (e.g., brittle, brittle-ductile) or kinematics. Evidence for interpreted faults was derived from several sources in the magnetic data, including discontinuities between form lines (as outlined above), offset of magnetic units, or the presence of linear magnetic lows. Lineaments were drawn using the first vertical derivative image of combined high and low resolution aeromagnetic data sets listed in Table 2, with the tilt angle image for validation and enhancement.

- Topography Data:

  The lineament interpretation of topography data involved the drawing of lineaments along topographic valleys, slope walls or escarpments, drainage patterns and abrupt changes in topography that were visible in a colour mosaic constructed from the CDED topography data.

- Satellite Imagery:

  The lineament interpretation of satellite imagery involved the drawing of lineaments along linear features including changes in bedrock colour and texture (changing lithology), vegetation cover, and drainage patterns, such as rivers and streams and linear chains of lakes that were visible in LandSAT and SPOT satellite image data.

All lineaments were drawn up to a maximum of 40 km outside the Ear Falls area boundary, to express their full extent, or in the case of longer lineaments, to better estimate their maximum length within a buffer around the Ear Falls area. Lineaments displayed on maps included in this report are truncated at the boundary of the margins of the Ear Falls area; however, the full length of the lineaments was included in the attribute table (Table 6).

The higher resolution of the topography and satellite imagery data sets helped identify a greater density of smaller scale lineaments that were not evident in the lower resolution Magnetic Supergrid data sets and the SMGA aeromagnetic data set.

The Stage 1 lineament analysis resulted in the generation of one interpretation for each data set (magnetic, satellite imagery (SPOT and LandSAT), and topography (CDED)) for each interpreter, resulting in a total of six individual GIS layer-based interpretations. During Stage 1, identified lineaments were attributed with fields 1 to 9 as listed in Table 6. For attribute field six, each interpreter assigned a certainty/uncertainty descriptor (attribute field 'Certain' = 1-low, 2-medium or 3-high) to each lineament feature in their interpretation based on their judgment concerning the clarity of the lineament within the data set. Where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of 3. Where a lineament represented a bedrock feature that was inferred from linear features, such as orientation of lakes or streams or linear trends in texture, it was assigned a certainty value of either 1 or 2. For geophysical lineaments, a certainty value of 3 was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either 1 or 2 was assigned when the signal was discontinuous or more diffuse in nature. The certainty classification for all three data sets ultimately came down to expert judgment and experience of the interpreter.

In the determination of attribute field nine, SRK used ET$^{TM}$ EasyCalculate 10, an add-on extension to ArcGIS. This add-on provides a function (polyline_GetAzimuth.cal) that calculates the azimuth of each polyline at a user-specified point and populates an assigned attribute field. SRK used the mid-point of each interpreted lineament to calculate the azimuth.

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

### 3.2.2 Stage 2: Reproducibility Assessment 1 (RA_1)

During Stage 2, individual lineament interpretations produced by each interpreter were compared for each data set. This included a reproducibility assessment based on the coincidence, or lack thereof, of interpreted lineaments within a data set-specific buffer zone. For example, if a lineament was identified by both interpreters within an overlapping buffer zone, then it was deemed coincident. The two individual lineament interpretations for each data set were then integrated to provide a single interpretation for the aeromagnetic (Figure 8), DEM (Figure 9) and SPOT (Figure 10) data that included the results of the first stage reproducibility assessment (RA_1). A discussion of the parameters used during this stage follows.

#### Buffer Size Selection

Buffer sizes for lineaments in each data set were initially based on the resolution of each data set. It was determined using trial-and-error over a selected portion of the lineament interpretation that buffer sizes of five times the grid cell resolution of each data set (2.5 times for SMGA GDS 1036) provided a balanced result for assessing reproducibility.

A buffer of 500 m (either side of the lineament) was generated for the SMGA data set. This value is equivalent to 2.5 times the data set grid cell resolution (200 m). A buffer of 200 m (either side of the lineament) was generated for the higher resolution Laurentian Goldfields and Red Lake Magnetic Supergrid magnetic data sets. This value is equivalent to five times the data set grid cell resolution (40 m) of the Magnetic Supergrid data set. A buffer of 150 m (either side of the lineament) was generated for the satellite data. This value is equivalent to five times the resolution of the LandSAT data (30 m), which is the coarser of the two available satellite data sets. A buffer of 125 m (either side of the lineament) was generated for the topographic data. This value is approximately equivalent to five times the resolution of the CDED topography data (23 m).

The buffers were used as an initial guide to determine coincidence between lineaments, with the expert judgement of the interpreter ultimately determining which lineaments were coincident. The buffer size widths were included in the attribute fields of each interpretation file (Table 6).

#### Reproducibility Assessment

The generation of an integrated lineament interpretation for each data set, including the reproducibility assessment, followed a three-step process, during which the lead lineament analyst (i.e. the first “interpreter”) was given precedent at all decision points:

- Lineament buffers generated for the second Stage 1 interpretation (i.e. those from the second “interpreter”) were overlain on top of the buffers generated for the lead Stage 1 interpretation for each data set. The lead interpretation Stage 1 lineaments were then overlain on top of these buffers, and all lineaments that occurred within overlapping buffers were carried forward and copied into a new file for Stage 2. These lineaments were attributed with a reproducibility value (RA_1; Table 6) of two in the Stage 2 attribute table.
- The remaining lineaments in the lead Stage 1 interpretation were then manually analyzed by both interpreters on the basis of the available imagery for each data set. In some instances, this included adapting the shape and extent of individual lineaments to increase the accuracy of spatial location or length of the lineament, and carrying the adapted lineament forward into the Stage 2 interpretation file. These lineaments were attributed a RA_1 value of one in the Stage 2 attribute table.

- Finally, the lineament interpretation of the second Stage 1 interpretation was overlain on top of the Stage 2 integrated file, and all remaining lineaments in the second interpreter's Stage 1 interpretation were then manually analyzed on the basis of the available imagery for each data set. In some instances, this included adapting the shape and extent of individual lineaments to increase the accuracy of spatial location or length of the lineament, and carrying the adapted lineament forward into the Stage 2 interpretation file. These lineaments were attributed a RA_1 value of one in the Stage 2 attribute table.

As specified above, the decision on whether or not to adapt the shape and extent of an individual lineament and (or) whether the lineament was carried forward to the next stage followed analysis of the specified lineament with the available imagery and was based on expert judgement. The following guidelines were applied:

- If a lineament was drawn continuously by one interpreter but as individual, spaced or disconnected segments by the other interpreter, a single continuous lineament was carried forward to the Stage 2 interpretation with a RA_1 value of two, if expert judgement deemed the continuous lineament to be more correct.
- If more than two thirds of a lineament were identified by one interpreter compared to the other interpreter, the lineament was carried forward to the Stage 2 interpretation with a RA_1 value of two. If less than two thirds of a lineament were identified by one interpreter compared to the other interpreter, the longer lineament was segmented, and each portion was attributed with RA_1 values accordingly.

### 3.2.3 Stage 3: Coincidence Assessment 2 (RA_2)

During Stage 3, the integrated lineament interpretations for each data set were amalgamated into one final interpretation following a similar methodology as described above in Stage 2. A discussion of the parameters used during this stage follows below.

Since the satellite imagery data set has the highest resolution and completely covers the Ear Falls area, it was used as the foundation data set for the integration. It was determined using trial-and-error over a selected portion of the lineament interpretation that a buffer size of 225 m (either side) provided a balanced result for assessing reproducibility. This buffer was generated around interpreted satellite imagery lineaments, and was used for comparison with lineaments derived from the topographic data set. This buffer size was included as an attribute field for interpreted lineaments (Buffer RA_2). As part of this comparison, coincident lines were identified and attributed. Next, non-coincident lineaments were evaluated and if required, were adapted and carried forward to the final Stage 3 data set.

The combined lineaments derived from topographic and satellite data were evaluated against lineaments derived from the magnetic data set in a similar fashion but using a buffer of 200 m and 500 m for regions covered by high and low resolution aeromagnetic data, respectively. During this process, each lineament was attributed with a text field highlighting in which data sets it was identified. The following rules were applied for determining reproducibility between the data set-specific lineaments:

- If any coincidence of lineaments occurred between two lineament data sets, the longest lineament was carried forward to the Stage 3 interpretation and attributed as derived from two (or more) data sets, regardless of the length of overlap between the lineaments. This meant that if any part of a lineament derived from one data set was identified in another data set, it was considered that this lineament was reproduced.

- If lineaments from two (or more) data sets were aligned and were separated by less than 3 km, the two (or more) lineaments were combined and carried forward to the Stage 3 interpretation and attributed as derived from two (or more) data sets. This was done on the basis that the surficial and (or) magnetic expression of a given fault may change along its strike. Following this assessment, lineament segments were merged, resulting in lineament length corresponding to the sum of all parts.
- In a scenario where a lineament from any data set would fall within the buffers of different segments and did not deviate significantly from the orientation of lineaments identified in other data sets, it was considered that this lineament was reproduced.
- Short (less than 1 km) lineaments that are at high angles to lineaments in other data sets, largely overlapped with buffer zones, and had no further continuity (i.e., singular elements), were not carried forward to the final interpretation. This was done on the basis that these short segments represent a subsidiary fault that is related to a broader fault zone already included as a fault lineament in the final interpretation.

The final reproducibility value (RA_2; Table 6) was then calculated as the sum of the number of data sets in which each lineament was identified.

The resulting lineament framework, representing the integration of all data sets, was then evaluated and modified (within the limits of relevant buffers) in order to develop a final lineament interpretation that is consistent with the known structural history of the Ear Falls area. This included inferring tentative age relationships of the interpreted lineaments on the basis of possible crosscutting relationships between different generations of fault lineaments and populating attribute fields for each lineament for the relative age (Rel_Age; Table 6).

This incorporated a working knowledge of the structural history of the Ear Falls area, combined with an understanding of the fault characteristics in each fault lineament population and resulted in the classification of brittle-ductile and brittle lineaments. The preliminary interpretation of the structural history of the area, including the potential problems in regional correlation of specific structural events within a Dx numbering system and in the application of such a system to the local geological history, is described in Section 2.3. The preliminary interpretation of the structural history of the Ear Falls area is summarized below.

- $D_1$ Deformation:
  - Associated with weak foliation oriented parallel to bedding;
  - Interpreted to have overlapped with the initial migmatization stages of sedimentary rocks between approximately 2.704 billion years ago and 2.698 billion years ago (Hrabi and Cruden, 2006);
  - $F_1$ folds are not common; and
  - Not recognized in lineament analysis.
- $D_2$ Deformation:
  - Main deformation in the area and linked to migmatization;
  - Generated east–trending moderate to intense foliation, stretching lineation, and isoclinal folds;
  - Minimum age is constrained by 2.698 billion years old suite of tonalite intrusions that are affected by the $S_2$ fabric (Hrabi and Cruden, 2006); and

  - Not recognized in lineament analysis.
- $D_3$ Deformation:
  - Attributed to period of extension (Hrabi and Cruden, 2006); and
  - Not recognized in lineament analysis.
- $D_4$ Deformation:
  - Attributed to curved east- to northeast-trending sinistral brittle-ductile shear zones (Hrabi and Cruden, 2006) linked to the Miniss River fault;
  - Minimum age of sinistral ductile strain is constrained by deformed granitic dyke dated at approximately 2.681 billion years old (Bethune et al., 2006).
  - Brittle-ductile dextral reactivation is interpreted to have occurred approximately 2.670 billion years ago (Bethune et al., 2006) and may be attributed to $D_5$;
  - $F_4$ folds are upright moderately east- to southeast-plunging folds associated with a steeply-dipping penetrative foliation (Hrabi and Cruden, 2006); and
  - $D_4$ faults represent the oldest structures interpreted in the lineament analysis.
- $D_5$ Deformation:
  - Attributed to km-scale east-trending brittle-ductile shear zones including the Sydney Lake fault and the Long Legged Lake fault.
  - Displacement is interpreted to have evolved from reverse (south over north) motion to dextral motion.
  - Cataclastic textures are superimposed on mylonitic textures indicating that brittle deformation followed ductile deformation (Stone, 1981).
  - Stress regime of the Sydney Lake and Long Legged faults may have caused dextral reactivation of the Miniss River fault at approximately 2.670 billion years ago (Bethune et al., 2006).
- $D_6$ and subsequent deformation events:
  - Interpreted to represent late brittle faults that postdate the main movement along the Sydney Lake fault;
  - Not clearly documented in the literature; and
  - Considered to primarily consist of brittle faults and fractures.

This interpretation is preliminary and would need to be verified by field investigations.

Finally, following the amendment of selected lineaments, the azimuth and length attribute fields were recalculated. The attribute field for the final interpretation of the width of each lineament (F_Width; Table 6) was populated according to available information on the width of known faults in the Ear Falls area. All figures and additional analyses described further below in this report were carried out using the final interpretation. The final lineament interpretation shows a network of lineaments throughout the Ear Falls area (Figures 12 and 13).

# 4 Findings

## 4.1 Description of Lineaments by Data Set

### 4.1.1 Geophysics Data

Interpreted brittle and brittle-ductile lineaments from the aeromagnetic geophysical data sets are shown on Figure 8. The geophysical data set was also used to interpret ductile lineaments for the Ear Falls area (Figure 11), however these lineaments are not included in the statistical analysis undertaken below. A comparison of the brittle (Figure 8) and ductile (Figure 11) features identified from the aeromagnetic data set shows that both interpretations highlight an overall east-trending structural grain in the bedrock. The following paragraphs provide an overview of the geophysical interpretation of brittle (including brittle-ductile) structures.

A total of 404 lineaments comprise the data set (RA_1) of merged lineaments identified by the two interpreters from the aeromagnetic data (Figure 8). All of the 404 lineaments are interpreted as fractures and no dykes were interpreted. The length of the aeromagnetic lineaments ranges from 660 m up to 59.4 km, with a geometric mean length of 5.5 km and a median length of 5.2 km. Azimuth data for the aeromagnetic lineaments, weighted by length, exhibit dominant east and east-northeast orientations. Other prominent orientations include minor northwest- and northeast-trends (Figure 8 inset).

Of the lineaments interpreted from aeromagnetic data, 196 (48.5%) lineaments were assigned the highest level of certainty (certainty = 3), while 206 (51.0%) and 2 (0.5%) of the interpreted lineaments were given certainty values of two and one, respectively. The reproducibility assessment identified coincidence for 80 lineaments (19.8%; RA_1 = 2) and a lack of coincidence for 324 of the interpreted lineaments (80.2%; RA_1 = 1).

Based on the magnetic geophysical data, none of the interpreted lineaments in the Ear Falls area are interpreted as dykes.

### 4.1.2 Surficial data sets (CDED topography and satellite imagery)

Interpreted lineaments from the CDED topography and satellite imagery data sets are shown on Figure 9 and Figure 10, respectively. The following paragraphs provide an overview of these surface-based interpretations.

A total of 556 lineaments comprise the data set (RA_1) of merged lineaments identified by the two interpreters from the CDED topography data (Figure 9). These lineaments range in length from 20 m to 39.9 km, with a geometric mean length of 3.6 km and a median length of 3.6 km. CDED topographic lineament orientations display strong east and east-northeast orientations. Other prominent orientations include north and north-northwest trends (Figure 9 inset). A total of 157 of the CDED topography lineaments (28.2%) were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 377 (67.8%) and 22 (4.0%) of the CDED topography lineaments, respectively. The reproducibility assessment shows coincidence for 183 of the CDED topography lineaments (32.9%, RA_1 = 2) and a lack of coincidence for 373 of the CDED topography lineaments (67.1%, RA_1 = 1).

The satellite imagery (SPOT and LandSAT) lineament data set (RA_1) compiled from the merger of lineaments identified by the two interpreters yielded a total of 702 lineaments (Figure 10). These lineaments range in length from 26 m to 37.4 km, with a geometric mean length of 2.5 km and a median length of 2.4 km. Satellite imagery lineament orientations display a strong east-northeast trend and prominent east and northeast trends (Figure 10 inset). A total of 177 of the satellite imagery lineaments (25.2%) were assigned a certainty value of 3. Certainty values of 2 and 1 were assigned to 445 (63.4%) and 80 (11.4%) of the satellite imagery lineaments, respectively. The reproducibility assessment shows coincidence for 240 of the satellite imagery lineaments (34.2%, RA_1 = 2) and a lack of coincidence for 462 of the satellite imagery lineaments (65.8%, RA_1 = 1).

Lineament orientation trends appear broadly similar across the different data sets with the dominant orientations following an east-west alignment generally paralleling the Sydney Lake fault zone and the general ductile fabric of the Ear Falls area. Northeastern and northwestern alignments appear more prominent in the CDED data set than the Satellite imagery however this is partially the result of the greater resolution in the satellite imagery which allows for the identification of shorter features than would be discernible in the topography.

## 4.2 Description and Classification of Integrated Lineament Coincidence (RA_2)

The integrated lineament data set produced by merging all lineaments interpreted from the geophysical, CDED topography, and satellite imagery data is presented on Figure 12 and Figure 13. Figure 12 displays the lineament classification based on Reproducibility Analysis 2 (RA_2). Figure 13 displays the lineament classification based on length of interpreted lineaments. The merged lineaments were classified by length using four length bins: >10 km, 5-10 km, 1-5 km and <1 km. These length bins were defined based on an analysis of the lineament length frequency distributions for the Ear Falls area.

The merged lineament data set contains a total of 1,175 lineaments that range in length from 80 m to 68.8 km. The geometric mean length of these lineaments is 4.0 km and the median length is 3.9 km. Lineaments in the >10 km and 5-10 km length bins represent 18% and 22% of the merged lineaments, respectively, while lineaments in the 1-5 km and <1 kilometre length bins represent 52% and 8% of the merged lineaments, respectively. Orientation data for the merged lineament data set exhibit the same dominant trends as described in the previous section, namely dominant east-northeast and east-trending lineaments with minor northwest, north, and northeast trends. It should be noted that the rose diagrams on Figures 12 and 13 are weighted by lineament length, and thus, these orientations are influenced by longer lineaments.

Results from the Reproducibility Assessment 2 (RA_2) for the merged lineament data set show 113 lineaments (10%) were identified and coincident in all three data sets (RA_2 = 3). A total of 261 lineaments (22%) were coincident with lineaments from one other data set (RA_2 = 2), while 801 lineaments (68%) lacked a coincident lineament from the other data sets (RA_2 = 1). A total of 172 lineaments (42.6%) observed in aeromagnetic data were coincident with a mapped surficial lineament. A total of 315 surficial lineaments (33.4%) were coincident in both CDED topography and satellite imagery data.

## 4.3 Description of Lineaments by Geological Units in the Ear Falls Area

The following subsections describe the characteristics of the interpreted lineaments for each of the main lithological units/areas, as well as an interpretation of the relative age of the lineaments identified in the Ear Falls area.

### English River Gneissic Metasedimentary Rocks

A total of approximately 800 lineaments were mapped within the English River gneissic belt in the Ear Falls area (Figures 12 and 13). Many of the longer lineaments extend beyond the metasedimentary rocks into the plutonic rocks. Overall, lineament density is relatively low compared to intrusions such as the Wenasaga Lake batholith, Long Legged Lake dome and Bluffy Lake batholith.

Figures 9 and 10 show the surficial lineament distribution over the gneissic metasedimentary rocks. These lineaments range in length from approximately 1 to >35 km. The surficial lineament density is variable across the gneissic metasedimentary rocks, likely reflecting differing thicknesses of overburden cover across the gneissic belt. Higher surficial lineament densities generally coincide with areas of good outcrop exposure, where interpreted surficial lineament spacings are typically in the range of 0.5 to >3 km.

Figure 8 shows the geophysical lineament distribution of the gneissic metasedimentary rocks. The geophysical lineaments range in length from <1 to 68.8 km, with a geometric mean length of 5.5 km and a median length of 5.7 km. The generally low density of geophysical lineaments across the gneissic belt likely reflects the low resolution aeromagnetic data set available for most of the gneissic metasedimentary rocks, and the low regional magnetic susceptibility of metasedimentary migmatites (Breaks, 1991). The geophysical lineament density is markedly higher in the area south of Pakwash Lake where higher resolution (Laurentian Goldfields Ltd.) aeromagnetic coverage is available. This high resolution aeromagnetic coverage shows linear magnetic features that appear to reflect gneissic banding along with cross-cutting features having a strong northwesterly orientation and a subsidiary orientation to the northeast. Geophysical lineament spacing in the high resolution coverage area is generally on the order of 1 to 3 km.

Orientation data for the gneissic metasedimentary rocks (Figure 14) exhibit dominant east-northeast and east trends with minor northwest, north, and northeast trends.

### Wenasaga Lake Batholith

A total of 55 lineaments were mapped over the Wenasaga Lake batholith (Figures 12 and 13). Many of the long interpreted lineaments extend beyond the batholith into the gneissic metasedimentary rocks of the English River Subprovince.

Interpreted surficial lineaments (Figures 9 and 10) range in length from approximately 1.5 to 23 km, with dominant orientations of northeast and northwest. The surficial lineament density is moderate to high across the batholiths even though overburden cover is extensive over most of the batholiths. Surficial lineaments are spaced approximately 1 to 3 km apart.

Figure 8 shows the geophysical lineament distribution over the Wenasaga Lake batholith. These lineaments range in length from 8 to 32 km. The geophysical lineament density is generally low, with geophysical lineaments identified primarily along only the northern and southern margins of the batholith, where they follow a northeasterly trend paralleling the Sydney Lake fault zone and the general ductile fabric of the area.

## Bruce Lake Pluton

A total of 48 interpreted lineaments were mapped over the Bruce Lake pluton (Figure 14). Many of the long interpreted lineaments extend beyond the pluton into the metavolcanic rocks of the Birch-Uchi greenstone belt.

Figures 9 and 10 show the surficial lineament distribution over the Bruce Lake pluton. These lineaments range in length from approximately 2 to 30 km. The surficial lineament density is low over the Bruce Lake pluton, likely due to the extensive overburden cover.

Figure 8 shows the geophysical lineament distribution over the Bruce Lake pluton. These lineaments range in length from 4 to >50 km. The geophysical lineament density is low in the western half of the pluton, and low to moderate in the eastern half. The aeromagnetic data resolution is higher in the western half of the pluton, where fewer geophysical lineaments were interpreted, suggesting that the low lineament density is not a result of poor survey resolution. The dominant orientation of the lineaments in the Bruce Lake pluton is north-east trending, with variably-oriented features also interpreted.

## Bluffy Lake Batholith

A total of 168 lineaments were mapped over the 324 $km^2$ of the Bluffy Lake batholith within the Ear Falls area (Figure 14). Many of the long interpreted lineaments extend beyond the batholith into the gneissic metasedimentary rocks of the English River Subprovince.

Figures 9 and 10 show the surficial lineament distribution over the Bluffy Lake batholith. These lineaments range in length from <1 to 36.9 km and appear to include at least three orientations northeast, north-northeast, and north-northwest within the Bluffy Lake batholith. Spacing of the interpreted surficial lineaments is variable, ranging from approximately 0.5 to 2 km. The surficial lineament density is moderate across the batholiths, likely due to the extensive bedrock exposure of the batholith in the Ear Falls area.

Figure 8 shows the geophysical lineament distribution over the Bluffy Lake batholith. These lineaments range in length from approximately 6 to more than 20 km. The geophysical lineament density is moderate over the batholith, and shows a higher density than is observed in the gneissic metasedimentary rocks of the English River Subprovince. The dominant orientation of the geophysical lineaments is east-trending, and geophysical lineament spacings are approximately 1 to 7 km. This relatively wide spacing may reflect the low resolution of the aeromagnetic coverage over the Bluffy Lake batholith in the Ear Falls area (Figure 8).

## Wapesi Lake Batholith

A total of 23 lineaments were mapped within the small portion of the Wapesi Lake batholith included within the Ear Falls area (Figure 14). Many of the long interpreted lineaments extend beyond the batholith into the gneissic metasedimentary rocks of the English River Subprovince.

Figures 9 and 10 show the surficial lineament distribution over the Wapesi Lake batholith. These lineaments range in length from approximately 0.77 to more than 45 km, and are spaced up to 5 km apart. The surficial lineament density is generally low across the portion of the Wapesi Lake batholith in the Ear Falls area.

Figure 8 shows the geophysical lineament distribution. These lineaments range in length from 6 to 35 km with most of their length attributed to the extension of the lineaments beyond the batholith boundaries. The geophysical lineament density is very low over the portion of the Wapesi Lake batholith in the Ear Falls area, with only three geophysical lineaments identified. This may reflect the low resolution aeromagnetic coverage over this portion of the batholith.

## Minor Intrusions

In addition to the intrusive bodies described above, the Ear Falls area contains a number of smaller intrusions, including: the Pakwash Lake pluton, the eastern extension of the Long Legged Lake dome, the McKenzie Bay stock, and a number of small unnamed bodies intruded into the gneissic metasedimentary rocks of the English River Subprovince. In the southwestern portion of the Ear Falls area there are also granitic intrusions of the Winnipeg River Subprovince.

A total of 10 lineaments were identified on the Pakwash Lake pluton, which covers an area of 32 $km^2$ (Figure 14). The interpreted lineaments range in length from 1.5 to approximately 20 km, with dominant trends to the northeast and northwest. Lineament density over this small pluton is relatively low, likely due to the extensive overburden and lake cover.

The eastern extension of the Long Legged Lake dome and its bordering tonalite units covers approximately 220 $km^2$ in the northwestern corner of the Ear Falls area, where 112 lineaments were mapped. The lineaments range in length from <1 to more than 30 km. Dominant orientations are east-northeast with subsidiary orientations to the northwest and north-northeast (Figure 14)

Intrusions of the Winnipeg River Subprovince occur in the southwestern corner of the Ear Falls area and collectively cover approximately 101 $km^2$ of the Ear Falls area. A total of 109 lineaments were mapped over these intrusions. Many of the long interpreted lineaments extend beyond the intrusions into the gneissic metasedimentary rocks of the English River Subprovince. Figures 9 and 10 show the surficial lineament distribution over the intrusions. These lineaments range in length from <1 to nearly 60 km. Dominant trends are to the northeast, east and northwest, with a small number of north-trending structures. Surficial lineament density is moderately high over these intrusions, even though there is significant overburden cover. Surface lineament spacing is variable ranging from about 0.5 to approximately 2 km. Figure 8 shows the geophysical lineament distribution over the intrusions. These lineaments range in length from 8 to 58 km with a low overall density, likely reflecting the low resolution of the available aeromagnetic data. Geophysical lineaments exhibit the same general orientations as the surface lineaments.

Numerous (n = 50) east-trending lineaments were observed within the Birch-Uchi greenstone belt. Many of these are concordant or subconcordant to stratigraphy but some may reflect the presence of shearing within the greenstone belt as the stratigraphy generally parallels the regional east-trend followed by the Sydney Lake and Long Legged Lake shear zones. Cross-cutting lineaments are prevalent in the surface lineaments and occur in two general trends, north-northeast (paralleling some of the minor mapped faults in this area) and northwest.

# 5 Discussion

The following sections are provided to discuss the results of the lineament interpretation in terms of lineament density, reproducibility, and lineament length as well as their relative age relationships.

## 5.1 Lineament Density

The density of all interpreted lineaments in the Ear Falls area was determined by examining the statistical density of individual lineaments using ArcGIS Spatial Analyst. A grid cell size of 50 m and a search radius of 1.5 km (equivalent to half the size of the longest boundary of the minimum area size of a repository-scale area) were used for this analysis. The spatial analysis used a circular search radius examining the lengths of polylines intersected within the circular search radius around each grid cell, following this equation:

$$\text{Density} = (L1 + L2) / (\text{area of circle}),$$

where L1 represents the length of Line 1 within the circle and L2 represents the length of Line 2 in the circle, assuming that only two lineament polylines intersect the circle search radius.

The distribution of lineament density varies significantly in the Ear Falls area. Such variations are interpreted to result from the discontinuous distribution of exposed bedrock and cover sequences. The greatest density of lineaments in the Ear Falls area occurs within and proximal to areas containing exposed bedrock (mainly large plutons and/or batholiths such as the Bluffy Lake batholith, the Long Legged Lake dome, and the plutons within the Winnipeg River Subprovince of the Ear Falls area (Winnipeg River plutons). The lowest lineament density in the Ear Falls area occurs in areas of extensive overburden cover such as the Bruce Lake pluton.

An understanding of the distribution and thickness of overburden cover within the Ear Falls area is essential for interpreting the results of the lineament interpretation, particularly for interpreting information on the length and density of surficial lineaments. Thick drift deposits are able to mask the surface expression of lineaments. In areas of thick and extensive overburden, major structures could exist completely undetectable in the SPOT and CDED data, particularly if these areas also contain large lakes. The interpretation of geophysical lineaments, on the other hand, is less affected by surficial cover. The variability of the density of geophysical lineaments in the Ear Falls area may be influenced by the resolution of the available aeromagnetic data (Figure 8), more than the presence or absence of overburden cover. High-resolution aeromagnetic data are available only for the northeast portion of the Ear Falls area (i.e. the Pakwash Lake area and lands along the Sydney Lake fault zone and along the northern edge of the Ear Falls area north of the Bruce Lake pluton).

Among potentially suitable rock units in the Ear Falls area, the lowest lineament density is observed in Bruce Lake pluton. However, this low lineament density is likely an artifact related to the Quaternary cover that overlies most of the pluton, and the low resolution of the magnetic data in this area. Several areas of low lineament density also occur within the gneissic metasedimentary rocks in the west and east-central portions of the Ear Falls area although these too may reflect the presence of overburden cover. The Bluffy Lake batholith, which is not significantly overlain by Quaternary cover, contains a moderate to high density of lineaments. The balance of the metasedimentary rocks, and intrusions such as the Wenasaga Lake and Wapesi Lake batholiths, McKenzie Bay stock and the Winnipeg River plutons have lineament densities intermediate between those described above.

## 5.2 Lineament Reproducibility and Coincidence

Reproducibility values assigned to the lineaments provide a measure of the significance of the bedrock structures expressed in the different data sets. The approach used to assign reproducibility values involved checking whether lineament interpretations from different interpreters (RA_1), and from different data sets (RA_2), were coincident within a specified buffer zone radius. Reproducibility values are discussed in detail in Sections 4.1 and 4.2.

The findings from the reproducibility assessment RA_1 indicate that approximately 26% of surficial lineaments were identified by both interpreters (see Figures 9 and 10). Importantly, longer lineaments with higher certainty values were identified more often by both interpreters. The reproducibility assessment of the geophysical lineaments shows that approximately 20% of the lineaments were identified by both interpreters (Figure 8). As with the surficial lineaments, longer geophysical lineaments with higher certainty values were also recognized more often by both interpreters (RA_1=2).

There are some differences in the individual Stage 1 lineament interpretations. These differences can be explained by two main factors: 1) the person carrying out the interpretation, and 2) the lineament information that can be derived from specific data sets. The lineament interpretations carried out by two different interpreters is subjective and, in part, may be affected by the interpreter's experience. The lineament information that can be derived from each data set may have a strong impact on the quality and resolution of an interpretation. As discussed earlier in this report, topographic and satellite data only provide information about the potential surficial expressions of lineaments. However, these data sets may include lineaments that are related to erosional features, such as glacial features, that do not have a structural origin. It can be challenging to distinguish such features from structural features, and careful evaluation, combined with a working knowledge of the glacial history of the area is required. For the final lineament interpretation in the Ear Falls area, lineaments that were interpreted during Stage 1 and Stage 2 that strike roughly north (i.e., parallel to the ice flow direction), with short lengths, were considered as suspect and likely to represent glacial features that were incorrectly interpreted as structural features. Therefore, these lineaments were not included in the final Stage 3 interpretation.

Coincidence between features identified in the various data sets was evaluated for the second Reproducibility Assessment (RA_2). Of the 943 lineaments observed on surficial data sets, 315 lineaments (33%) were coincident in both CDED topography and satellite imagery data, which corresponds to 26.8% of total lineaments that were coincident between CDED and satellite (315 out of 1,175). This is in part explained by the fact that lineaments interpreted from the satellite imagery and the digital elevation data represent surficial expressions of the same bedrock feature. For example, a lineament drawn along a stream channel shown on the satellite imagery is expected to be coincident with a lineament that captures the trend of the associated topographic valley expressed in the digital elevation data. Of the 404 lineaments observed in aeromagnetic data, 172 lineaments (42.6%) were reproduced in at least one surficial data set, which corresponds to 14.6% of total lineaments being observed in the geophysical data and in at least one of the surficial data sets (172 out of 1,175).

The resolution of each available data set has a strong impact on the reproducibility and number of interpreted lineaments. The grid cell resolution of available magnetic data varies between 40 and 200 m over the area. The SPOT 4/5 satellite, LandSAT 7 satellite, and CDED topography data cover the entire Ear Falls area with a 30 m (and less) grid cell resolution. The better resolution of the surficial data sets (topography and satellite data) may explain why a larger number of lineaments are identified from these data compared to the geophysical data sets. The density of lineaments identified from these surficial data sets is the greatest in areas where bedrock is exposed, namely the west, southwest and east parts of the Ear Falls area. The presence of glaciolacustrine deposits in the central, northwest, and southeast portion of the area (Figure 4) limits the practical interpretation of lineaments from surficial data in those areas. High resolution aeromagnetic data is available in the northwestern part of the Ear Falls area (Laurentian Goldfields Ltd., Goldpines South Property) and in the northern part of the area (Red Lake Magnetic Supergrid). Such high resolution data sets provide adequate information to complete a suitable structural lineament interpretation. Elsewhere, only SMGA low resolution aeromagnetic data is available, which diminishes the quantity and the accuracy of identified lineaments. Regardless of the degree of coincidence, the observed overlap in dominant lineament orientation between all data sets (see insets on Figures 8, 9, and 10) suggests that all data sets are identifying the same regional sets of structures.

For these reasons, it is necessary to objectively analyze the results of the RA_2 assessment with the understanding that RA_2 = 1 does not necessarily imply a low degree of confidence that the specified lineament represents a true geological feature (i.e., a fracture), specifically in areas where high resolution magnetic data are not available. The true nature of the interpreted features will need to be investigated further during subsequent stages of the site evaluation process.

## 5.3 Lineament Length

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

As discussed in Section 5.2, longer interpreted lineaments generally have higher certainty and reproducibility values. Although the existence of interpreted lineaments would need to be confirmed through field observations, certainty and reproducibility values provide a preliminary indication that the longer features are related to bedrock structures.

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

## 5.4 Fault and Lineament Relationships

As discussed above in Section 4, approximately 1,175 lineaments were interpreted in the Ear Falls area. The known mapped regional faults in the area include the east- to northeast-trending Sydney Lake and Long Legged Lake fault zones (Figure 3). These fault zones were only partially reproduced during the lineament interpretation. The fault zones are reproduced as several lineaments and lineament segments rather than single continuous lineaments, however most of the observed lineaments correlating with the mapped fault zones have reproducibility assessment (RA_2) values of 3, indicating that the fault zones were observed in all three data sets, even though the traces of the observed lineaments may diverge from the mapped faults. Most mapped (but unnamed) northwest and north-northeast trending faults were not reproduced during the lineament analysis.

The principal horizontal neotectonic stress orientation in central North America is generally oriented approximately east-northeasterly (63º ± 28º; Zoback, 1992), although anomalous stress orientations have also been reported in the mid-continent that include a 90º change in azimuth of the maximum compressive stress axis (Brown et al., 1995) and a north-south maximum horizontal compressive stress (Haimson, 1990). Local variations, and other potential complicating factors involved in characterizing crustal stresses, including, the effect of shear stress by mantle flow at the base of the lithosphere (Bokelmann, 2002; Bokelmann and Silver, 2000), the degree of coupling between the North American plate and the underlying mantle (Forte et al., 2010), the effects of crustal depression and Holocene rebound, and the influence of the thick lithospheric mantle root under the Canadian Shield, make it premature to correlate the regional neotectonic stress orientation with the orientation of mapped lineaments at the desktop stage.

However, it is possible to broadly speculate on the potential behavior of the identified lineaments if they were to be reactivated by the regional east-northeastern neotectonic stress regime. These features were formed by Precambrian paleostress regimes and constitute zones of weakness that are more amenable to reactivation under certain stress conditions than the surrounding rock mass. On this basis, should the identified lineaments be reactivated under the current stress regime, the predominant east-trending lineaments would likely reactivate as strike slip faults. The subordinate north-trending lineaments would likely also re-activate as strike-slip faults, while the northeast-trending set would likely re-activate in tension. Finally, the more northwesterly oriented lineaments would likely re-activate as reverse-sense faults.

## 5.5 Relative Age Relationships

The structural history of the Ear Falls area, outlined in Section 2.3, provides a framework that aids in constraining the relative age relationships of the interpreted bedrock lineaments. In brief summary, six regionally distinguishable Archean deformation episodes ($D_1$ to $D_6$) are inferred to have overprinted the bedrock geological units of the Ear Falls area. However, only three episodes ($D_4$ to $D_6$) are interpreted to have generated recognizable lineaments in the available data sets.

$D_4$ deformation is associated with curved east- to northeast-trending sinistral shear zones (Hrabi and Cruden, 2006) and its minimum age is approximately 2.681 billion years old (Bethune et al., 2006). $D_4$ faults represent the oldest structures recognized in the lineament analysis. Dextral reactivation is interpreted to have occurred approximately 2.670 billion years ago (Bethune et al., 2006) and may be attributed to $D_5$ (see below). $D_5$ deformation is associated with km-scale east-trending shear zones including the previously mapped Sydney Lake fault and the Long Legged Lake fault. Displacement is interpreted to have evolved from reverse (south over north) motion to dextral motion. Cataclastic textures superimposed on mylonitic textures indicate that brittle deformation followed ductile deformation (Stone, 1981). $D_6$ deformation is not well documented in the literature but is interpreted to represent late brittle faults/fractures that postdate the main movement along the Sydney Lake fault. Such features represent the youngest structures in the lineament analysis but no information on their absolute age is available.

The identified lineaments in the Ear Falls area are interpreted to represent successive stages of brittle-ductile and brittle deformation. $D_4$ and $D_5$ features are interpreted as Archean brittle-ductile faults characterized as zones of strongly-developed foliation, potentially with overprinting cataclastic textures caused by superimposed brittle deformation. $D_6$ features are interpreted as younger brittle fractures or faults characterized as zones of gouge and (or) cataclasite. At the desktop stage of preliminary assessment, it is still uncertain whether or not each interpreted lineament is in fact an actual brittle-ductile or brittle geological feature with a significant expression at depth.

# 6 Summary

This report documents the source data, workflow and results from a lineament interpretation of publicly available digital data sets, including geophysical (aeromagnetic) and surficial (satellite imagery, topography) data sets for the Ear Falls area (approximately 3,688 $km^2$), in northwestern Ontario.

The lineament analysis provides an interpretation of the location and orientation of possible individual fractures on the basis of remotely sensed data, and helps to evaluate their relative timing relationships within the context of the regional geological setting. The three step interpretation process used involved a workflow that was designed to address the issues of subjectivity and reproducibility.

The distribution of lineaments in the Ear Falls area reflects the bedrock structure, resolution of the data sets used, and surficial cover. Surface lineament density, as demonstrated in this assessment, varies significantly in the Ear Falls area, and is closely associated with the distribution and thickness of overburden cover that masks the surficial expression of bedrock structures. The greatest density of lineaments occurs within and in proximity of areas containing exposed bedrock such as the Bluffy Lake batholith and the Winnipeg River plutons. In the Ear Falls area, the lowest lineament density is observed in the Bruce Lake pluton and portions of the English River gneissic metasedimentary belt. However, this low lineament density is likely influenced by the extensive Quaternary cover that overlies most of the pluton. Lineament density is also influenced by the resolution of the available aeromagnetic data sets.

In terms of reproducibility, longer interpreted lineaments generally have higher certainty and reproducibility values. Comparison between the various data sets (RA_2) indicates that 172 (42.6%) of the 404 lineaments observed from aeromagnetic data were reproduced on at least one surficial data set and have an RA_2 value greater than 1. Of the 943 lineaments observed on surficial data sets, 315 lineaments (33%) were coincident in both CDED topography and satellite imagery data. The lower reproducibility of surficial lineaments relative to geophysical lineaments may be due to the higher resolution of surficial data sets that allow the interpretation of lineaments that are not readily recognizable in the lower resolution magnetic data sets.

The orientations observed for the combined set of lineaments from all sources include strong trends to the east-northeast and east-southeast with subsidiary orientations to the northwest and northeast. It may be possible, with further detailed investigation, to assign the formation of the identified lineaments to distinct deformation events. However, it is difficult at the desktop stage to provide any further constraint on the timing of lineament development beyond noting that the identified lineaments in the Ear Falls area are interpreted to represent successive stages of brittle-ductile and brittle deformation. $D_4$ and $D_5$ features are interpreted as Archean brittle-ductile faults characterized as zones of strongly-developed foliation, potentially with overprinting cataclastic textures caused by superimposed brittle deformation. $D_6$ features are interpreted as younger brittle fractures or faults characterized as zones of gouge and (or) cataclasite. At the desktop stage of preliminary assessment, it is still uncertain whether or not each interpreted lineament is in fact an actual brittle-ductile or brittle geological feature with a significant expression at depth.

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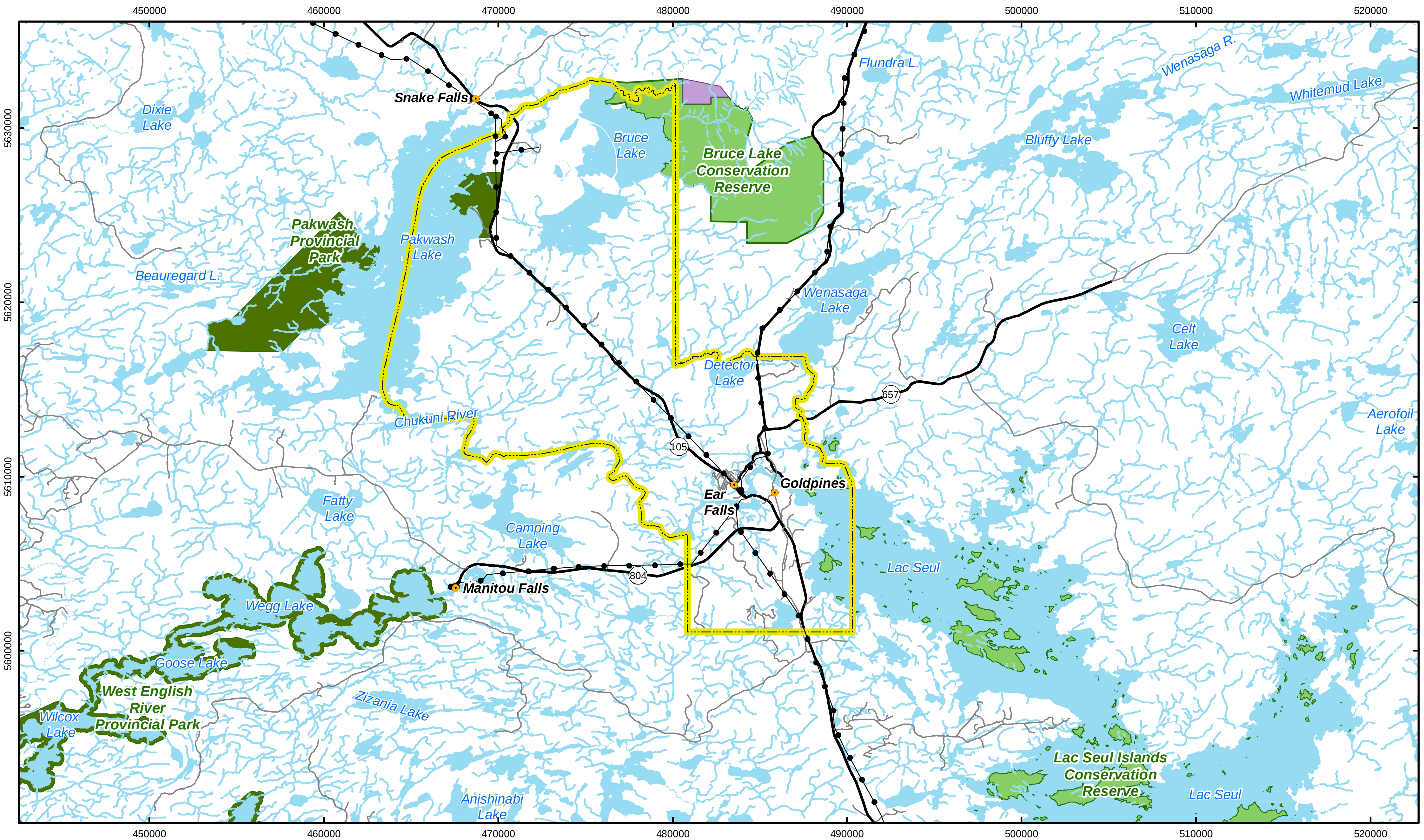
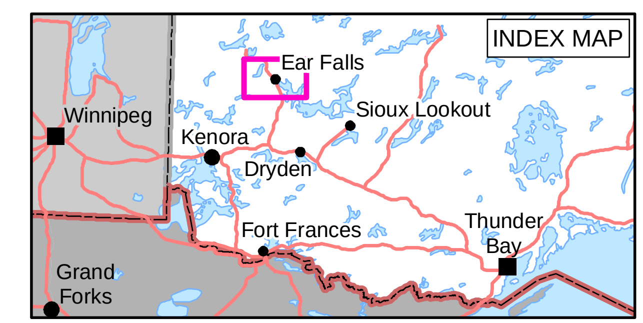
# FIGURES

N

## LEGEND

- Community
- Transmission Line
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Watercourse, Intermittent
- Water Area, Permanent
- Federal Land - Indian Reserve
- Forest Reserve
- Provincial Park
- Conservation Reserve

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0 5 10 15 20
Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Township of Ear Falls and Surrounding Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 1 | REVISION 13 |
| GIS | PM/JB | 30 Jul 2013 | | UTM ZONE 15 |
| CHECK | JFR | 30 Jul 2013 | | NAD 1983 |
| REVIEW | JFR | 30 Jul 2013 | | 1:275,000 |

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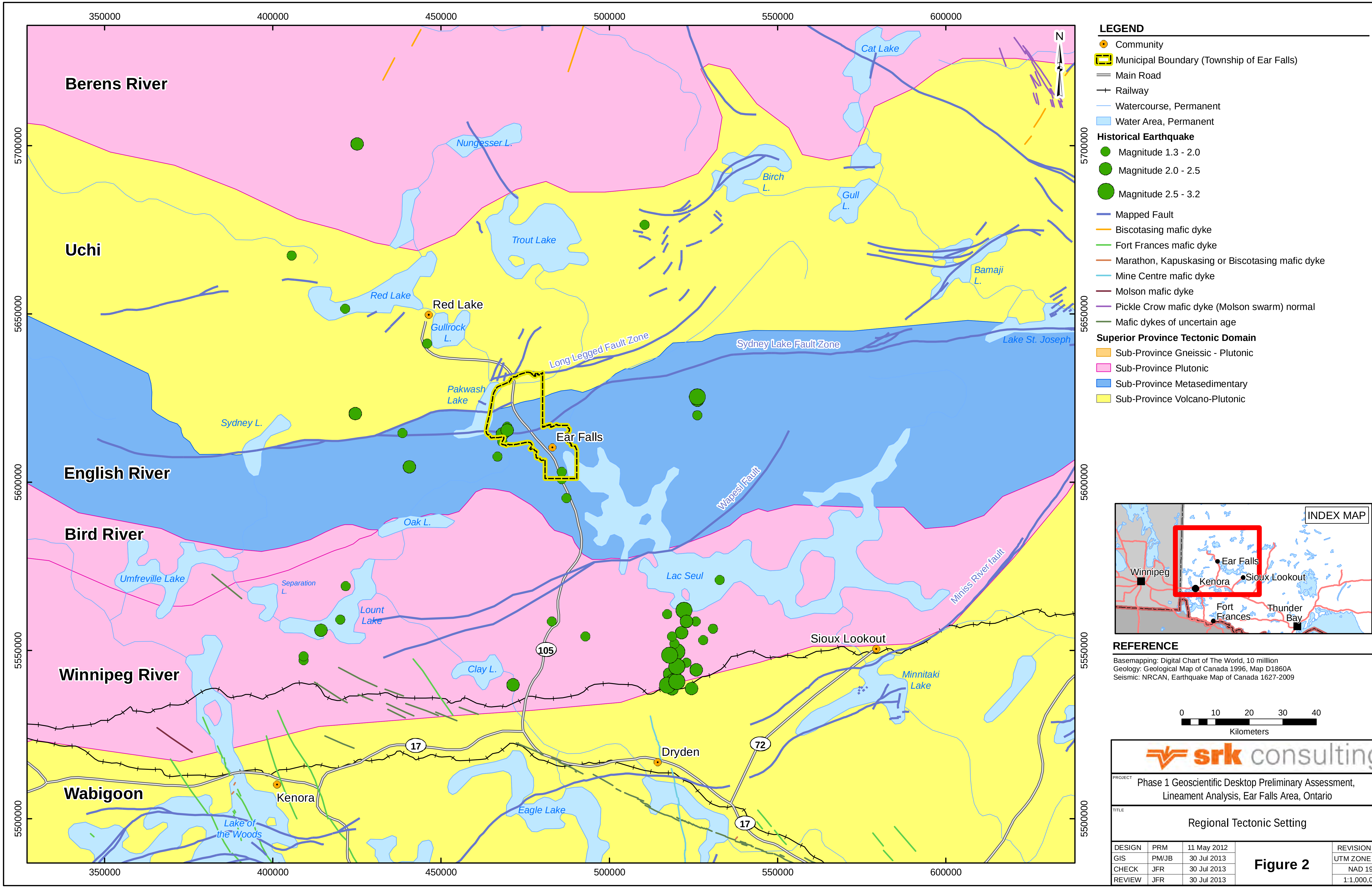


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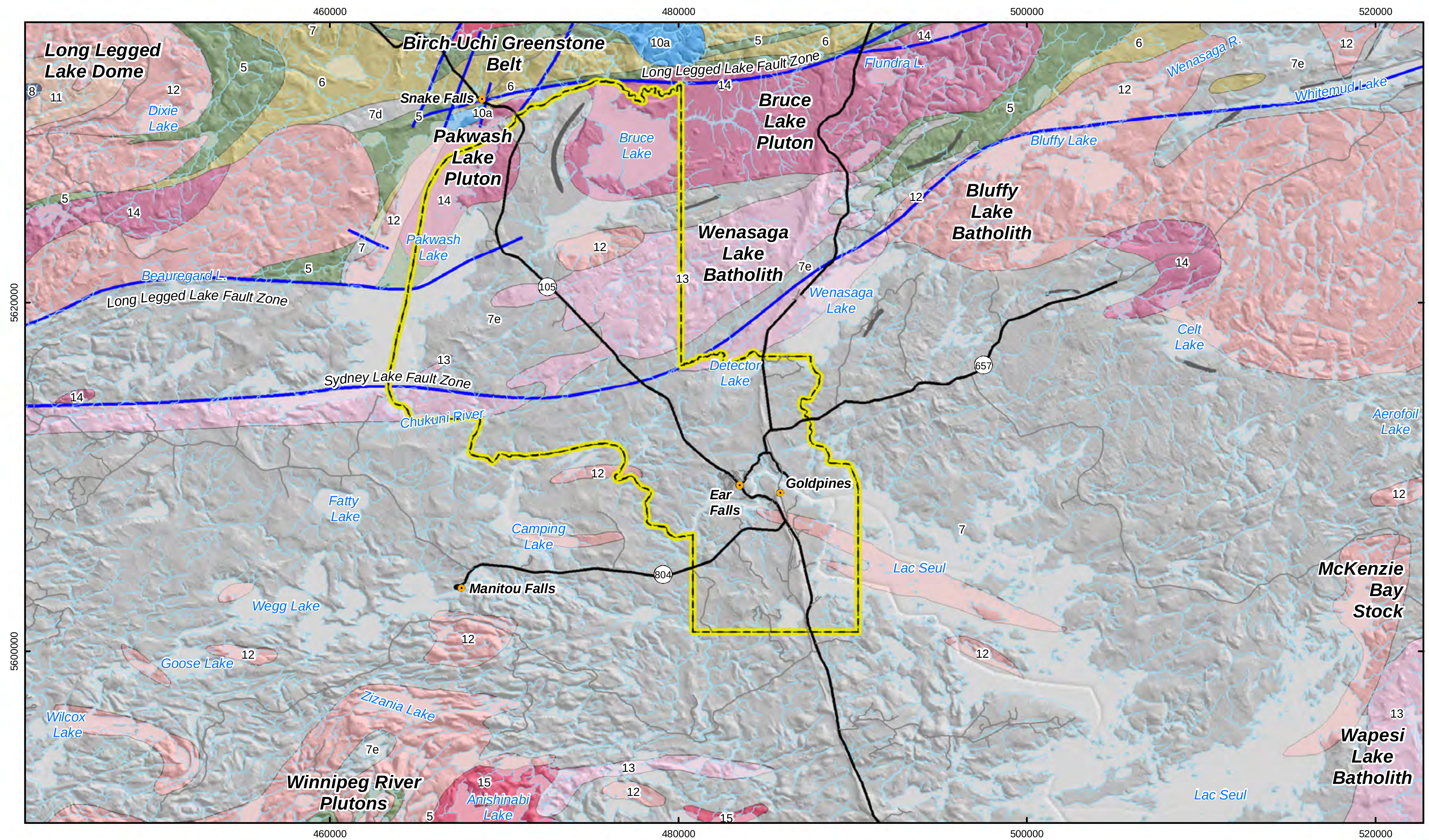


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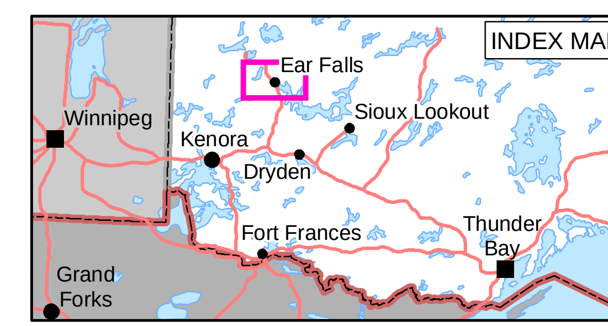
## LEGEND

- Community
- Municipal Boundary (Township of Ear Falls)
- Municipal Boundary
- Main Road
- Local Road
- Watercourse, Permanent
- Watercourse, Intermittent
- Water Area, Permanent
- Mapped Faults

**Bedrock Geology**

- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
  - 10a Gabbro
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7d Conglomerate and arenite
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 5 Mafic to intermediate metavolcanic rocks
- Iron Formation

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Geology - MRD126-Bedrock Geology of Ontario, 2011
Hillshade DEM - CDED
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0 5 10 15 20
Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Local Bedrock Geology of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 3 | REVISION 13 |
| GIS | PM/JB/JA | 30 Jul 2013 | | UTM ZONE 15 |
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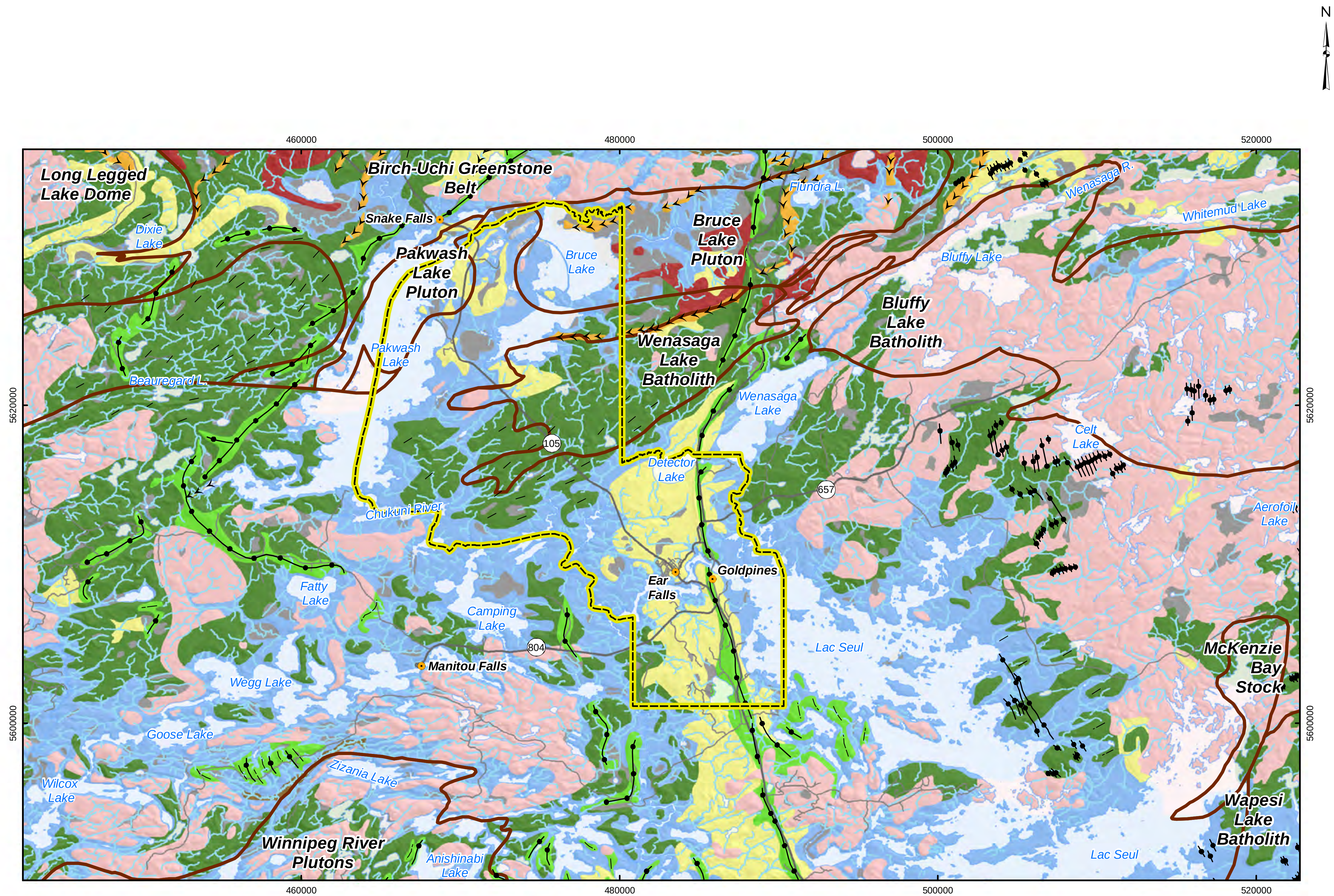



## LEGEND

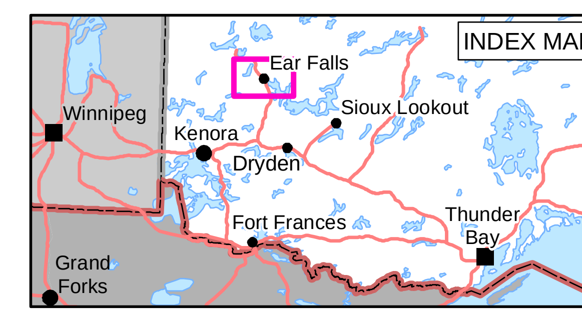
- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Watercourse, Intermittent
- Water Area, Permanent
- Outline of Major Batholith/Pluton

**Surficial Landforms**

- Esker
- Major End Moraine
- Drumlin
- Other Linear Ice-Flow Features

**Surficial Geology**

- Ground moraine
- End moraine
- Esker
- Outwash
- Ice-contact delta
- Glaciolacustrine
- Alluvial plain
- Organics
- Bedrock

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Geology - Overburden: OGS MRD-160 (1:100,000)
Hillshade DEM - CDED
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Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Terrain Features of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 4 | REVISION 13 |
| GIS | PM/JB | 30 Jul 2013 | | UTM ZONE 15 |
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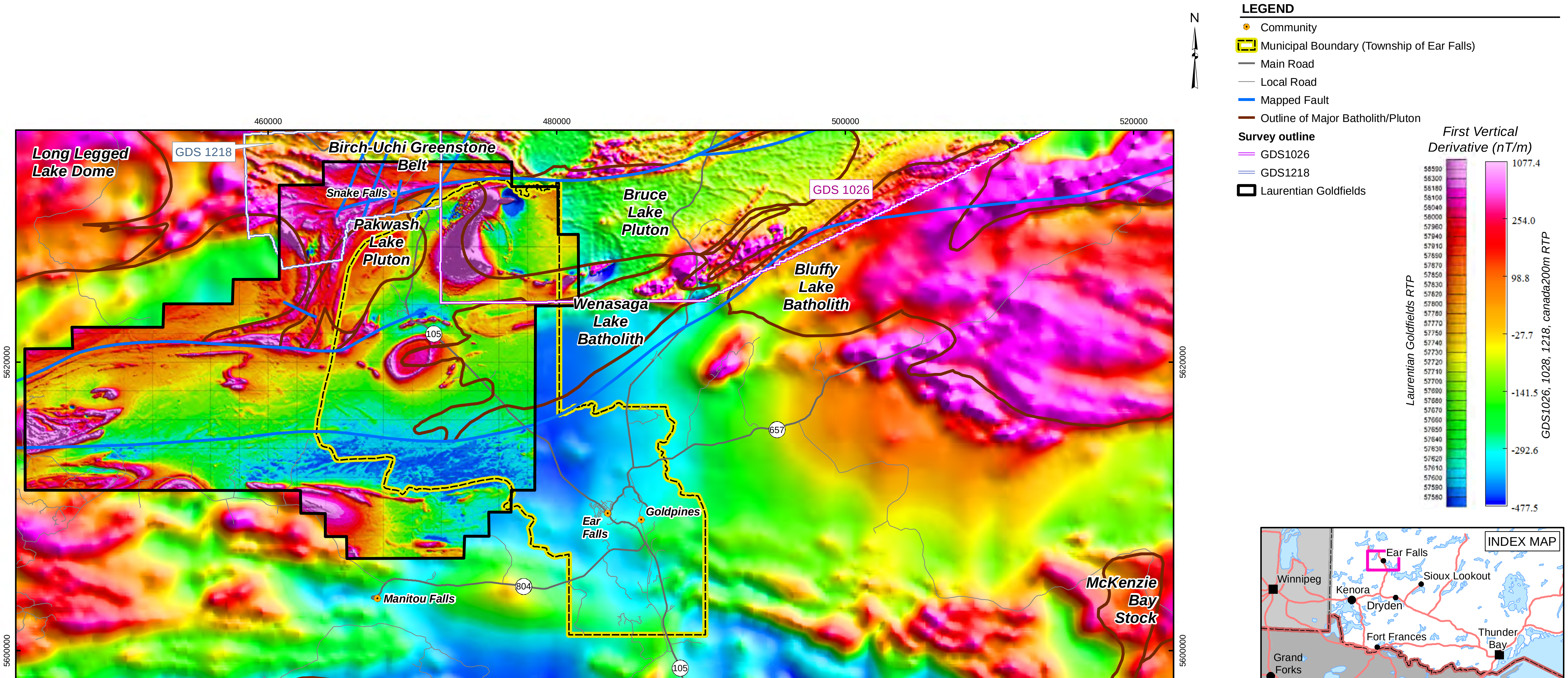


## REFERENCE

Base Data - MNR LIO, obtained 2009-2012
Ontario Ministry of Natural Resources, © Queens Printer 2012
Geophysical Data:
- GSC Canada 200m Compilation, Aug 2010
- OGS Uchi-Bruce Lakes Area, GDS1026
- OGS Red Lake Area Survey, GDS1028
- OGS Pakwash Lake Area Survey, GDS1218
- Laurentian Goldfields Ltd., Goldpines South Property , total magnetic field not GSC-Levelled
- OGS Bedrock Geology of Ontario, MRD 126-REV1 (1:250,000)

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Kilometers

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PROJECT Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE First vertical derivative of the pole reduced magnetic field data of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | **Figure 5** | REVISION 13 |
| GIS | PM/JB | 30 Jun 2013 | | UTM ZONE 15 |
| CHECK | JFR | 30 Jun 2013 | | NAD 1983 |
| REVIEW | JFR | 30 Jun 2013 | | 1:275,000 |

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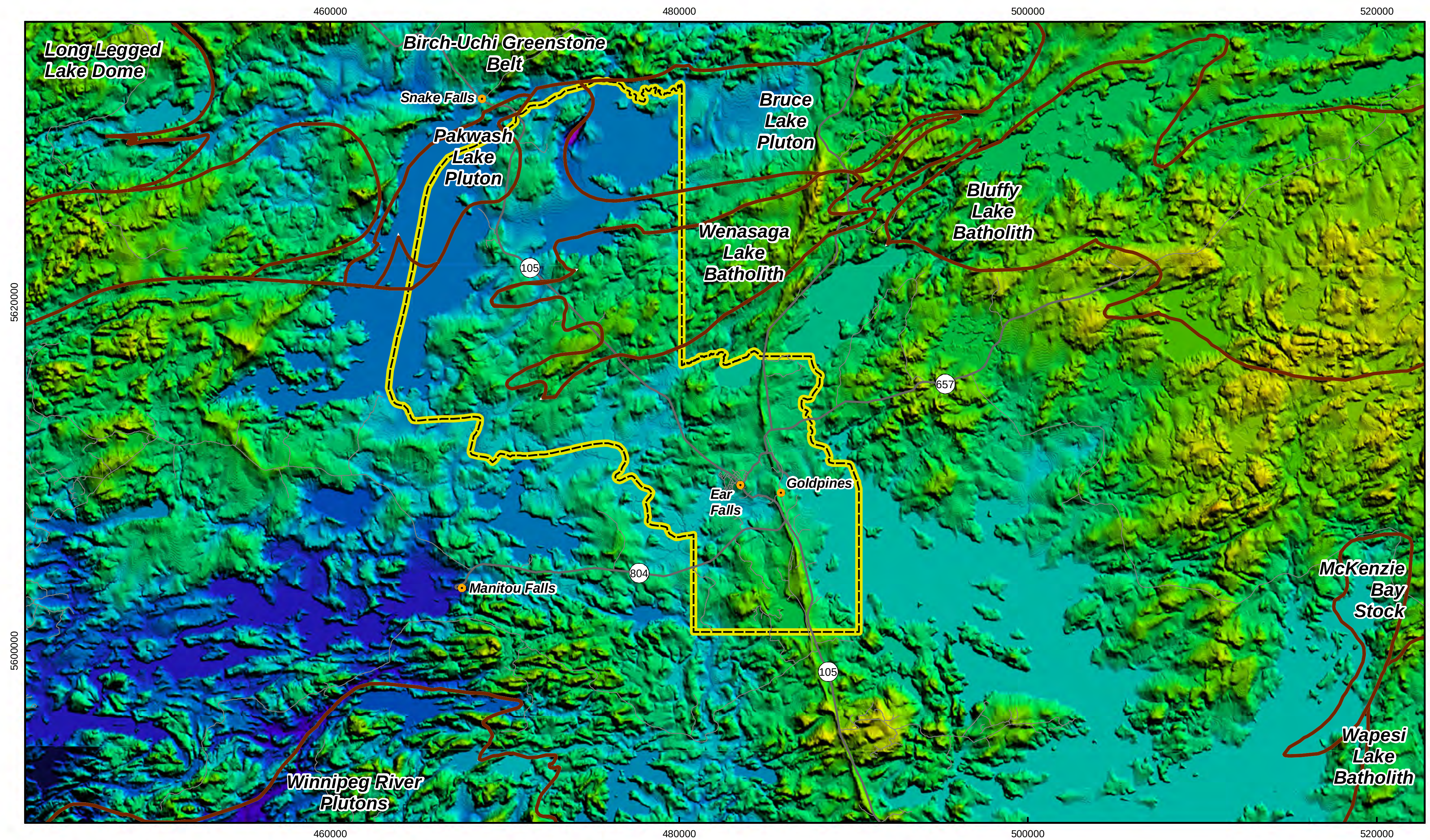
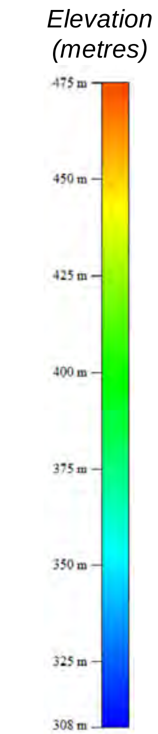
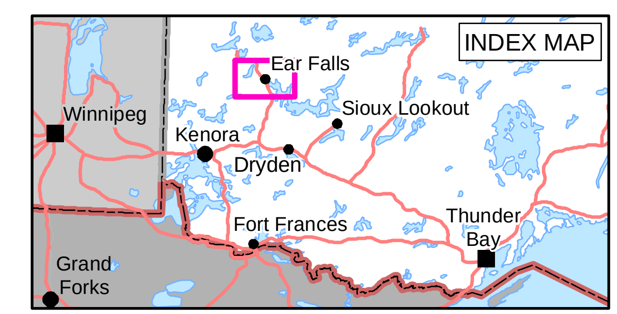
**LEGEND**

- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Outline of Major Batholith/Pluton

N

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Base Data - MNR LIO, obtained 2009-2012
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NRC CDED Topography Data
OGS Bedrock Geology of Ontario, MRD 126-REV1 (1:250,000)

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Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Digital Elevation Model of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 6 | REVISION 13 |
| GIS | PM/JB/JA | 30 Jul 2013 | | UTM ZONE 15 |
| CHECK | JFR | 30 Jul 2013 | | NAD 1983 |
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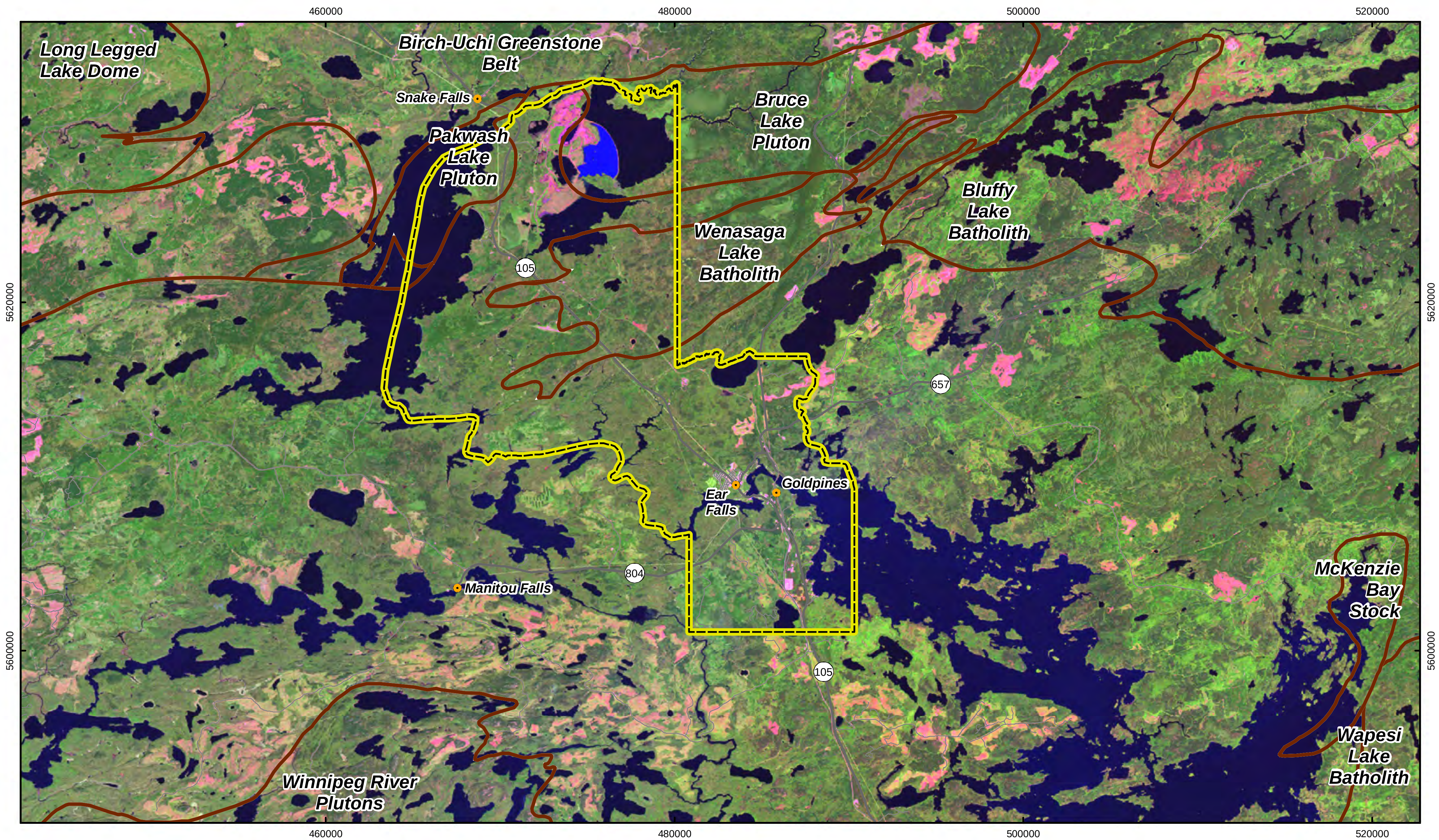


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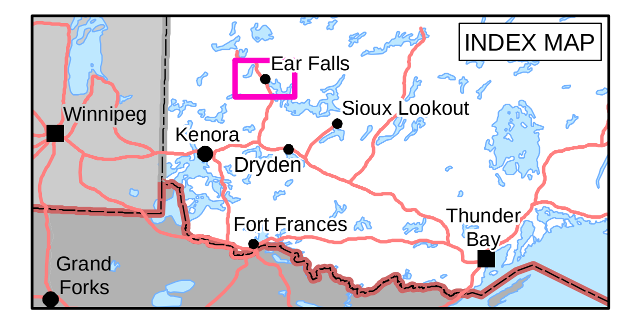
**LEGEND**

- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Outline of Major Batholith/Pluton

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LandSAT 7-4-1 20m composite
SPOT 10m pan-sharpened

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Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Satellite Remote Sensing Data of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 7 | REVISION 13 |
| GIS | PM/JB/JA | 30 Jul 2013 | | UTM ZONE 15 |
| CHECK | JFR | 30 Jul 2013 | | NAD 1983 |
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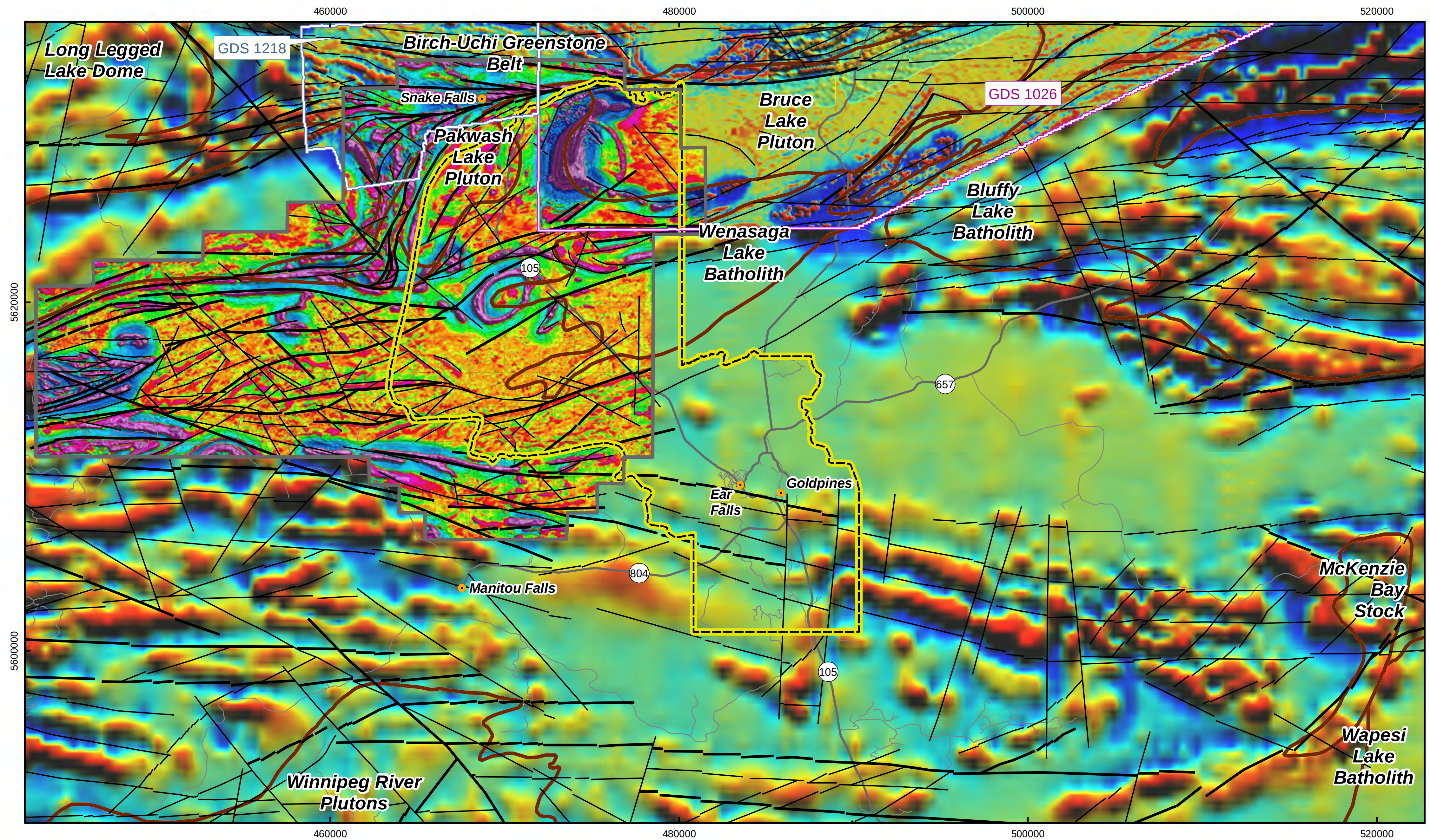


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**LEGEND**

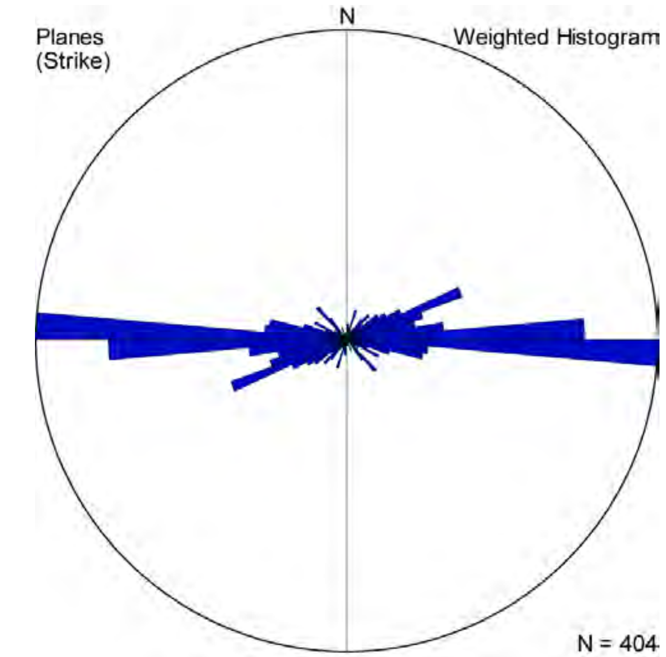
- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Outline of Major Batholith/Pluton

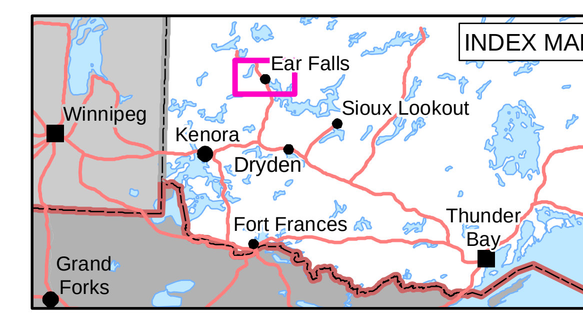
**Survey outline**

- GDS1026
- GDS1218
- Laurentian Goldfields

**Reproducibility (RA-1)**

- 1
- 2

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Geophysical Data:
- GSC Canada 200m Compilation, Aug 2010
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- OGS Red Lake Area Survey, GDS1028
- OGS Pakwash Lake Area Survey, GDS1218
- Laurentian Goldfields Ltd., Goldpines South Property , total magnetic field not GSC-Levelled
- OGS Bedrock Geology of Ontario, MRD 126-REV1 (1:250,000)

0 5 10 15 20
Kilometers

srk consulting

PROJECT Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE Aeromagnetic Reproducibility Assessment (RA_1) of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 8 | REVISION 13 |
| GIS | PM/JB/JA | 13 Aug 2013 | | UTM ZONE 15 |
| CHECK | JFR | 13 Aug 2013 | | NAD 1983 |
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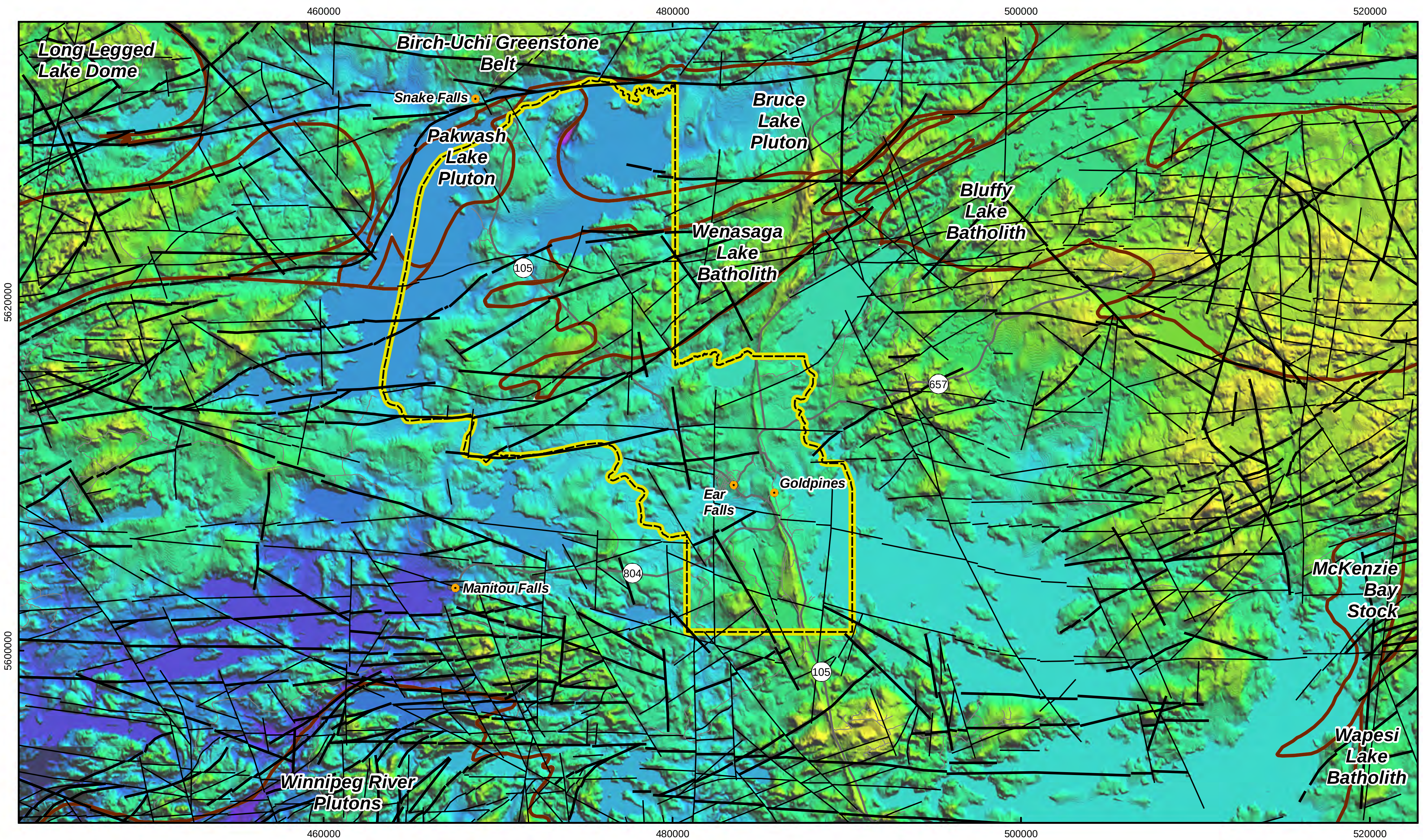



N

**LEGEND**

Community

Municipal Boundary (Township of Ear Falls)

Main Road

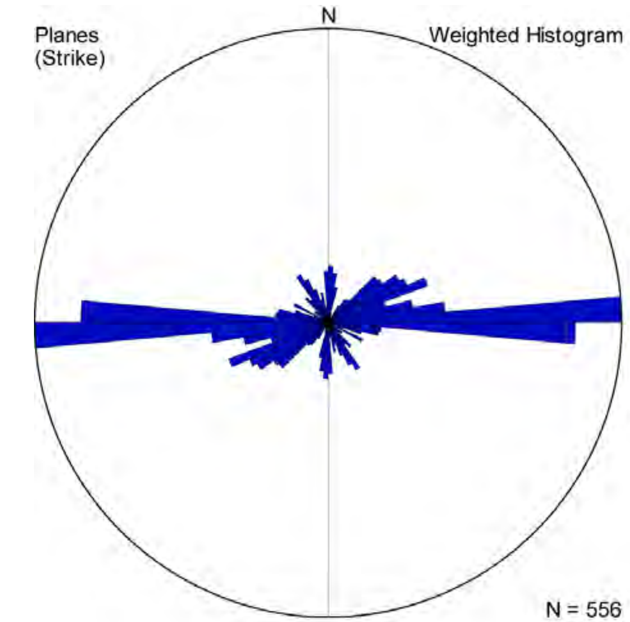
Local Road

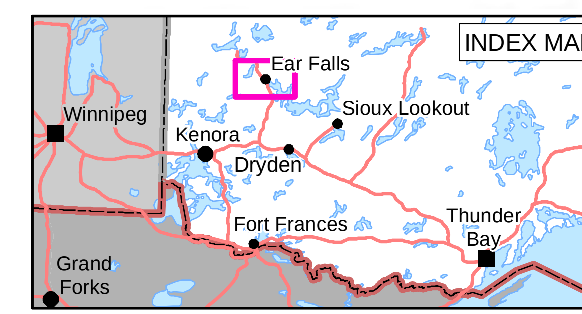
Outline of Major Batholith/Pluton

**Reproducibility (RA-1)**

1

2

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NRC CDED Topography Data

OGS Bedrock Geology of Ontario, MRD 126-REV1 (1:250,000)

0 5 10 15 20

Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Digital Elevation Model Reproducibility Assessment (RA_1) of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 9 | REVISION 13 |
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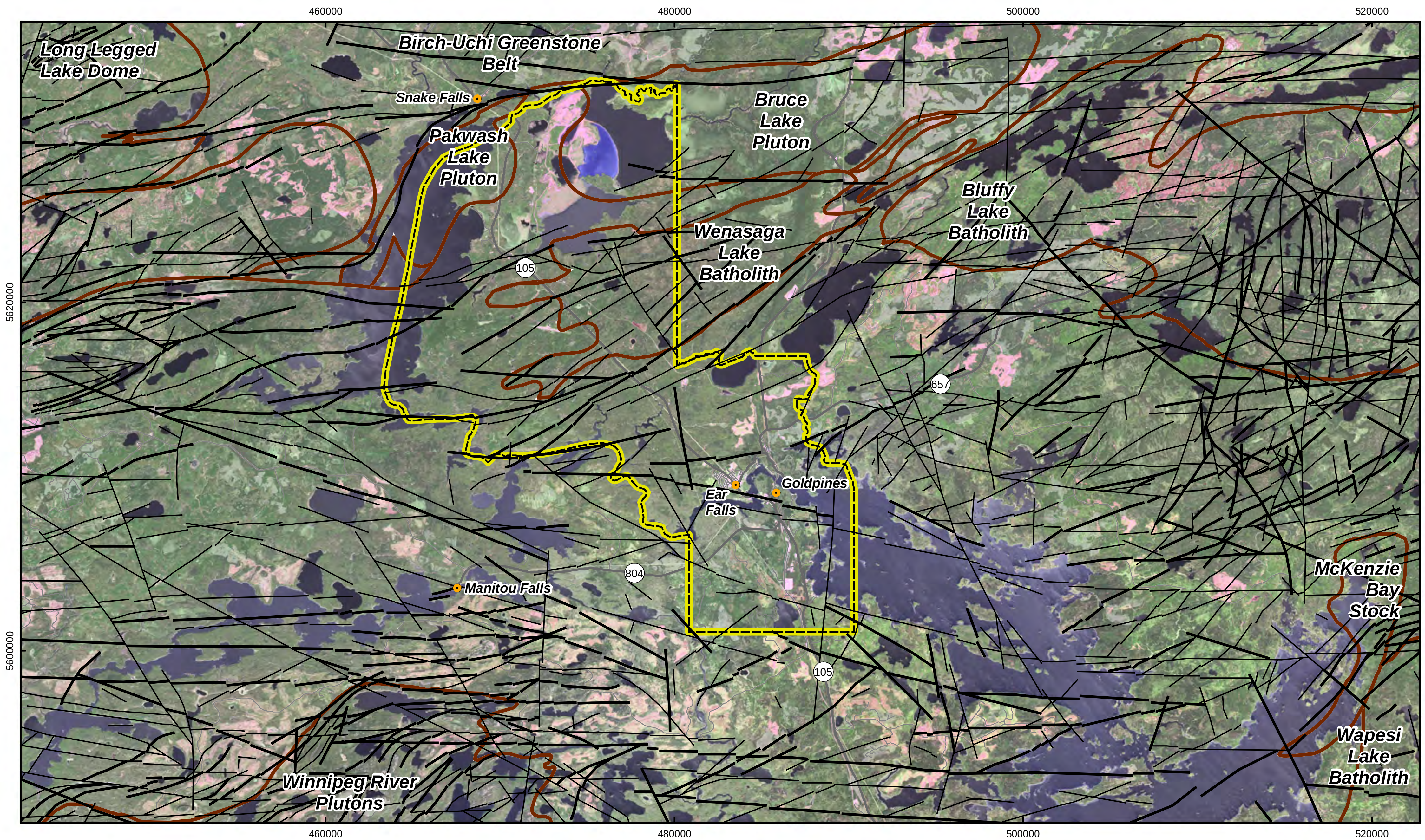


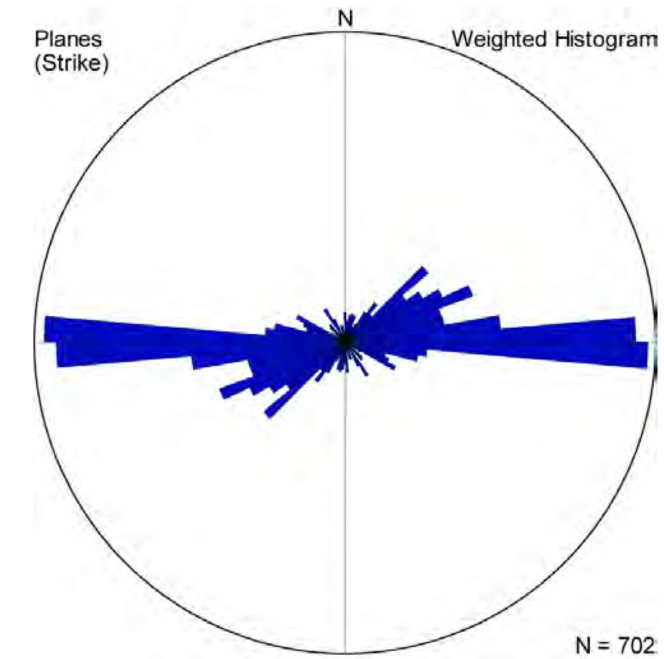

N

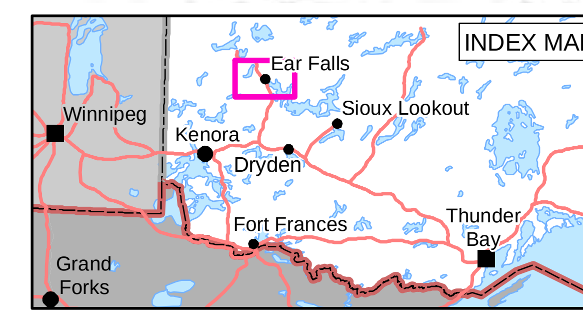
**LEGEND**

- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Outline of Major Batholith/Pluton

**Reproducibility (RA-1)**

- 1
- 2

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LandSAT 7-4-1 20m composite
SPOT 10m pan-sharpened

0 5 10 15 20
Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Satellite remote sensing Reproducibility Assessment (RA_1) of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 10 | REVISION 13 |
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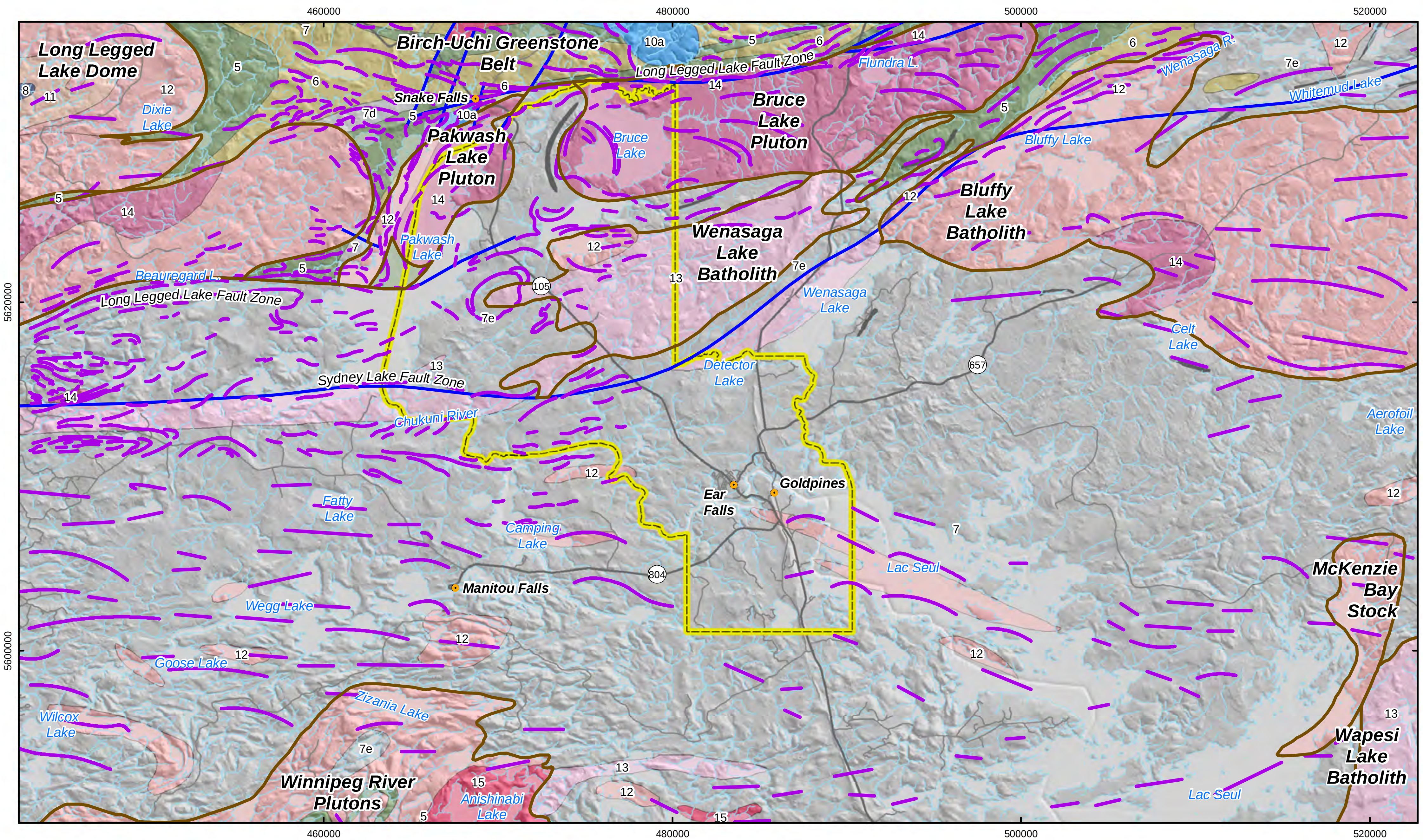


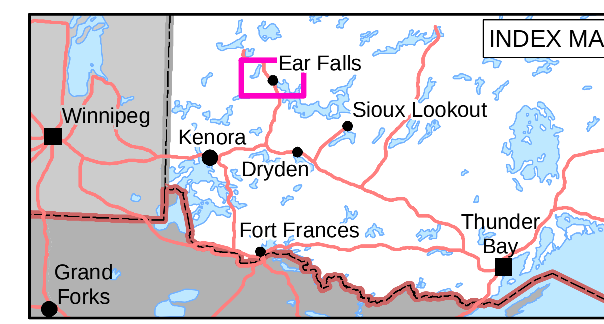

N

## LEGEND

- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Watercourse, Intermittent
- Water Area, Permanent
- Outline of Major Batholith/Pluton
- Mapped Faults
- Ductile Lineament

**Bedrock Geology**

- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
- 10a Gabbro
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
- 7d Conglomerate and arenite
- 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 5 Mafic to intermediate metavolcanic rocks
- Iron Formation




## REFERENCE

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Geology - MRD126-Bedrock Geology of Ontario, 2011
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0 5 10 15 20
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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Ductile Features of the Ear Falls Area

| DESIGN | PRM | 11 May 2012 | Figure 11 | REVISION 13 |
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| GIS | PM/JB/JA | 30 Jul 2013 | | UTM ZONE 15 |
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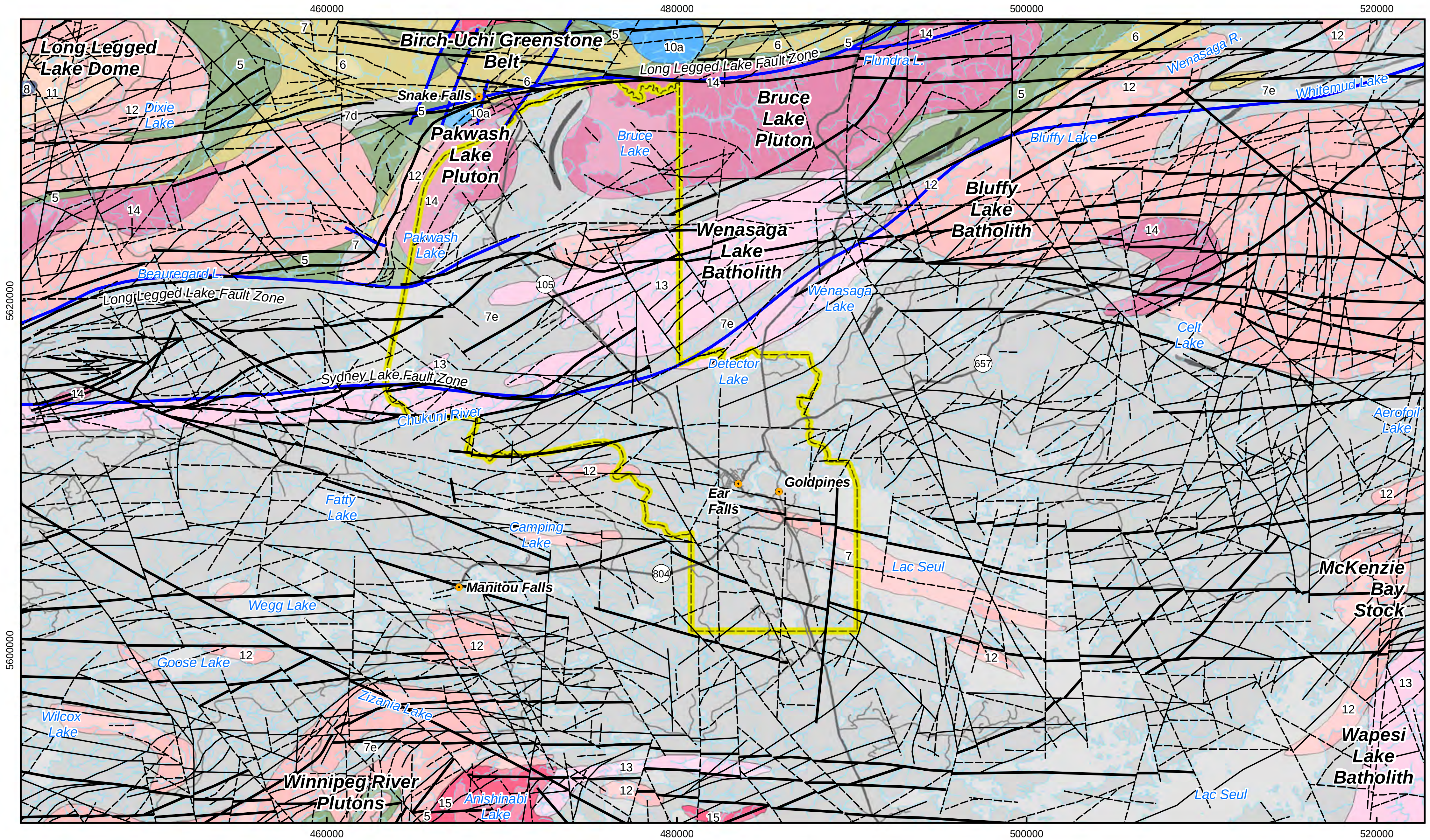



N

## LEGEND

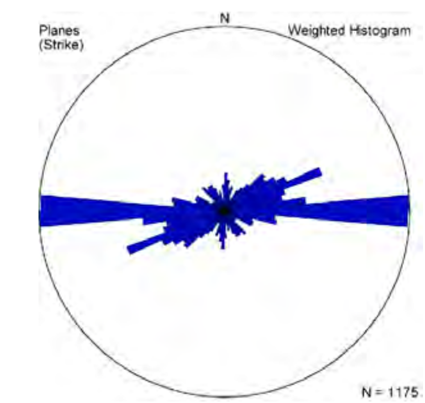
- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Water Area, Permanent

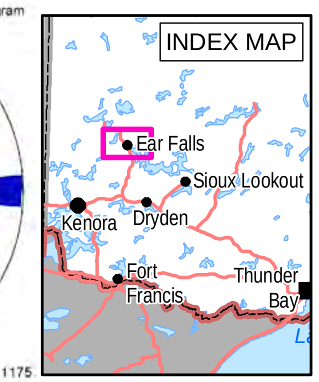
**Reproducibility (RA-2)**

- 1
- 2
- 3
- Mapped Faults

**Bedrock Geology**

- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
  - 10a Gabbro
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7d Conglomerate and arenite
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 5 Mafic to intermediate metavolcanic rocks
- Iron Formation




## REFERENCE

Base Data - MNR LIO, obtained 2009-2012
Geology - MRD126-Bedrock Geology of Ontario, 2011
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0 5 10 15 20
Kilometers

srk consulting

PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment,
Lineament Analysis, Ear Falls Area, Ontario

TITLE
Lineament Classification by Reproducibility
Assessment (RA_2) of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 12 | REVISION 13 |
| GIS | PM/JB/JA | 13 Aug 2013 | | UTM ZONE 15 |
| CHECK | JFR | 13 Aug 2013 | | NAD 1983 |
| REVIEW | JFR | 13 Aug 2013 | | 1:275,000 |

Name: SRK_NWMO_EarFalls_Fig12_RA2_rev13.mxd


N

## LEGEND

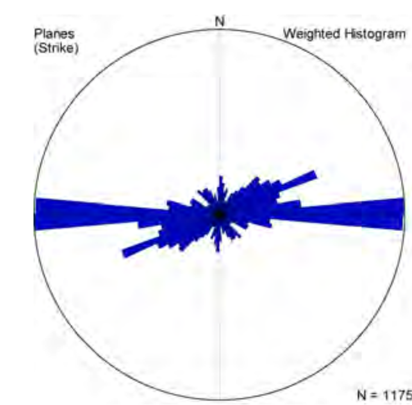
- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Water Area, Permanent

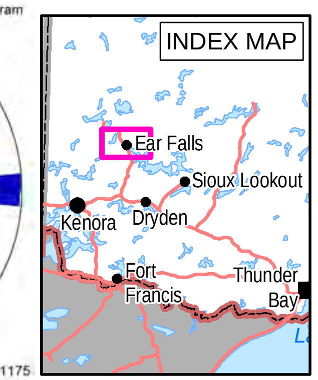
**Length**

- < 1 km
- 1 - 5
- 5 - 10
- > 10 km
- Mapped Faults

**Bedrock Geology**

- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks
- 10a Gabbro
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
- 7d Conglomerate and arenite
- 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 5 Mafic to intermediate metavolcanic rocks
- Iron Formation

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0 5 10 15 20
Kilometers

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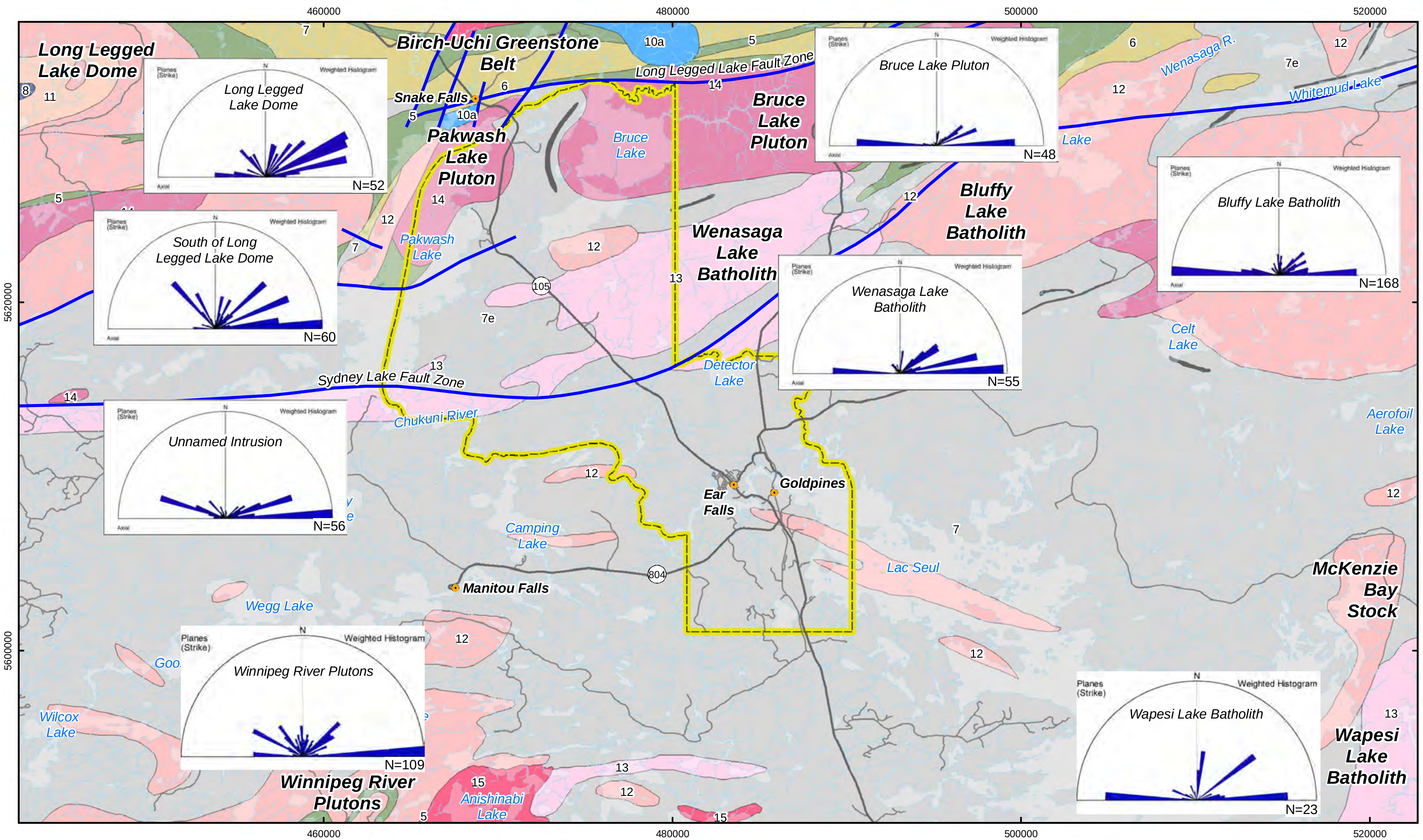
PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Lineament Classification by Length of the Ear Falls Area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 13 | REVISION 13 |
| GIS | PM/JB/JA | 13 Aug 2013 | | UTM ZONE 15 |
| CHECK | JFR | 13 Aug 2013 | | NAD 1983 |
| REVIEW | JFR | 13 Aug 2013 | | 1:275,000 |

Name: SRK_NWMO_EarFalls_Fig13_Length_rev13.mxd



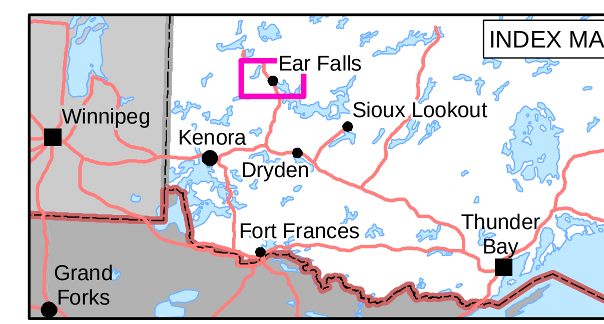

N

**LEGEND**

- Community
- Municipal Boundary (Township of Ear Falls)
- Main Road
- Local Road
- Watercourse, Permanent
- Watercourse, Intermittent
- Water Area, Permanent
- Mapped Faults

**Bedrock Geology**

- 15 Massive granodiorite to granite
- 14-Diorite-monzodiorite-granodiorite suite
- 13 Muscovite-bearing granitic rock
- 12 Foliated tonalite suite
- 11 Gneissic tonalite suite
- 10 Mafic and ultramafic rocks, gabbro
- 8 Migmatized supracrustal rocks
- 7 Metasedimentary rocks
  - 7d Conglomerate and arenite
  - 7e Paragneiss and migmatites
- 6 Felsic to intermediate metavolcanic rocks
- 5 Mafic to intermediate metavolcanic rocks
- Iron Formation

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Kilometers

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PROJECT
Phase 1 Geoscientific Desktop Preliminary Assessment, Lineament Analysis, Ear Falls Area, Ontario

TITLE
Lineament Orientations of batholiths, plutons and metasedimentary rocks in the Ear Falls area

| | | | | |
|---|---|---|---|---|
| DESIGN | PRM | 11 May 2012 | Figure 14 | REVISION 13 |
| GIS | PM/JB/JA | 13 Aug 2013 | | UTM ZONE 15 |
| CHECK | JFR | 13 Aug 2013 | | NAD 1983 |
| REVIEW | JFR | 13 Aug 2013 | | 1:275,000 |

Name: SRK_NWMO_EarFalls_Fig14_Orientation_rev13.mxd