THE UTILITY OFHIGH-RESOLUTION GEOPHYSICAL DATA FOR ASSESSING GEOSCIENTIFIC SUITABILITY OF CRYSTALLINE ROCK

A.DesRoches[1]J. Siddorn[2],A. Palmer[3], M. Bates[3],M. Ben Belfadhel[1], S. Hirschorn[1]
[1]Nuclear Waste Management Organization, Toronto, Ontario, Canada
[2]SRK Consulting, Toronto, Ontario, Canada
[3]Sander Geophysics Ltd, Ottawa, Ontario, Canada
adesroches@nwmo.ca, jsiddorn@srk.com, apalmer@sgl.com,
mbates@sgl.com,bbelfadhel@nwmo.ca, shirschorn@nwmo.ca

Abstract

The Nuclear Waste Management Organization (NWMO) is currently conducting initial field studies in a number of communities participating in a site selection process to find an informed and willing community to host Canada's deep geological repository for used nuclear fuel.Initial field studies involve activities such as high resolution airborne geophysical surveys and direct geological mapping observations. These field activities are designed to further advance the geological understanding of the areas being studied, building on previously conducted desktop studies. Consistent with NWMO's approach, all field activities are planned and conducted with the involvement and collaboration of the communities and Aboriginal peoples.

This paper provides a description of how high resolution airborne magnetic and gravity geophysical surveys are used to extract and interpret the geological and structural characteristics of crystalline rocks over large areas.A description of the site evaluation process and the geological mapping to ground-truth remotely-sensed geological interpretations areprovided in twocompanion papers.

Interpretationof high-resolution airborne magnetic and gravimetric data relies on relative contrasts to identify the spatial patternsover large areas. The collected data can be integrated in conjunction with other remote sensing data (e.g. aerial imagery, digital elevation model)to identify potential structural lineaments such as fractures, faults and dykes.Lineament interpretations require professional expertise, and follow established structural rules. In order to ensure consistency between assessments, a systematic three-step workflow for lineament interpretationswas developed, which included: (1) lineament interpretations being completed by two interpreters working independently; (2) interpreted lineaments were integrated to determine reproducibility between the two interpreters; and (3) integration of lineament interpretations for the surficial data sets followed by integration of the combined surficial data set with the magnetic data set. Over the course of these three steps, a comprehensive list of attributes for each lineament was compiled (e.g. certainty, reproducibility, coincidence, length, and orientation).

Keywords:crystalline rock, geophysics, structural lineament, deep geological repository, used nuclear fuel

1. Introduction

The Nuclear Waste Management Organization (NWMO) is currently conducting initial field studies in a number of communities participating in a site selection process to find an informed and willing community to host Canada's deep geological repository for used nuclear fuel.Initial field studies involve activities such as high resolution airborne geophysical surveys and direct geological mapping observations. These field activities are designed to further advance the geological understanding of the areas being studied, building on previously conducted desktop studies. Consistent with NWMO's approach, all field activities are planned and conducted with the involvement and collaboration of the communities and Aboriginal peoples.

This paper provides a description of how high resolution airborne magnetic and gravity geophysical surveys are used to extract and interpret the geological and structural characteristics of crystalline rocks over large areas.A description of the site evaluation process and geological mapping to ground-truth remotely-sensed geological interpretations areprovided in twocompanion papers [1], [2].

2. Data sources

High-resolution airborne magnetic and gravity surveys over a number of communities in northern Ontario were completed by Sander Geophysics Limited (SGL) as a part of the NWMO's initial field studies (e.g. [3], [4], [5]). Geophysical data were acquired by flying along traverse lines spaced at 100 m, and orthogonal control lines spaced at 500 m. Surveys were flown at an altitude of 80 m above ground level, with an average ground speed of 100 knots (approximately 185 km/h or 50 m/s). Magnetic data were recorded using a single magnetometer sensor mounted in a fibreglass stinger extending from the tail of each of the aircraft. Gravity data were recorded using SGL's AIRGravgravimeter, which includes three orthogonal accelerometers mounted on a gyro-stabilized inertial platform inside the cabin of the aircraft.

Figure 1 Aircraft used to acquire geophysical data.

The acquired magnetic and gravity data were processed and enhanced in order to emphasize geological features. The magnetic and gravity data were gridded using a cell size of 25 m over the survey areas. Data processing and enhancements were applied to the total field magnetic intensity and gravity data by Sander Geophysics Limited (SGL)to generate the following products:

- Magnetic anomaly
- Magnetic anomaly reduced to the pole
- Free air gravity
- Bouguer gravity
- First vertical derivatives of magnetic and gravity data
- Second vertical derivative of magnetic data
- Tilt angle of magnetic data
- Analytic signal of magnetic data
- Total horizontal derivative of magnetic and gravity data
- Low and high pass filtered magnetic and gravity data

Digital elevation data were collected using a radar altimeter and a laser altimeter both mounted to the base of the aircraft. Elevation data were sampled at a rate of 10 Hz, which is consistent with a sample roughly every 6m. Laser elevation data were sampled at a rate of 3.3 Hz, which is consistent with a sample roughly every 15 m. An iterative process was applied to the laser data to remove the effect of trees, and a bare earth digital elevation model (DEM) was derived by subtracting the altimeter data from the differentially corrected global positioning system (DGPS) altitude with respect to the Canadian Geodetic Vertical Datum 2013 (CGVD2013). The digital elevation data were gridded to form a DEM grid using a cell size of 25 m over the survey areas.

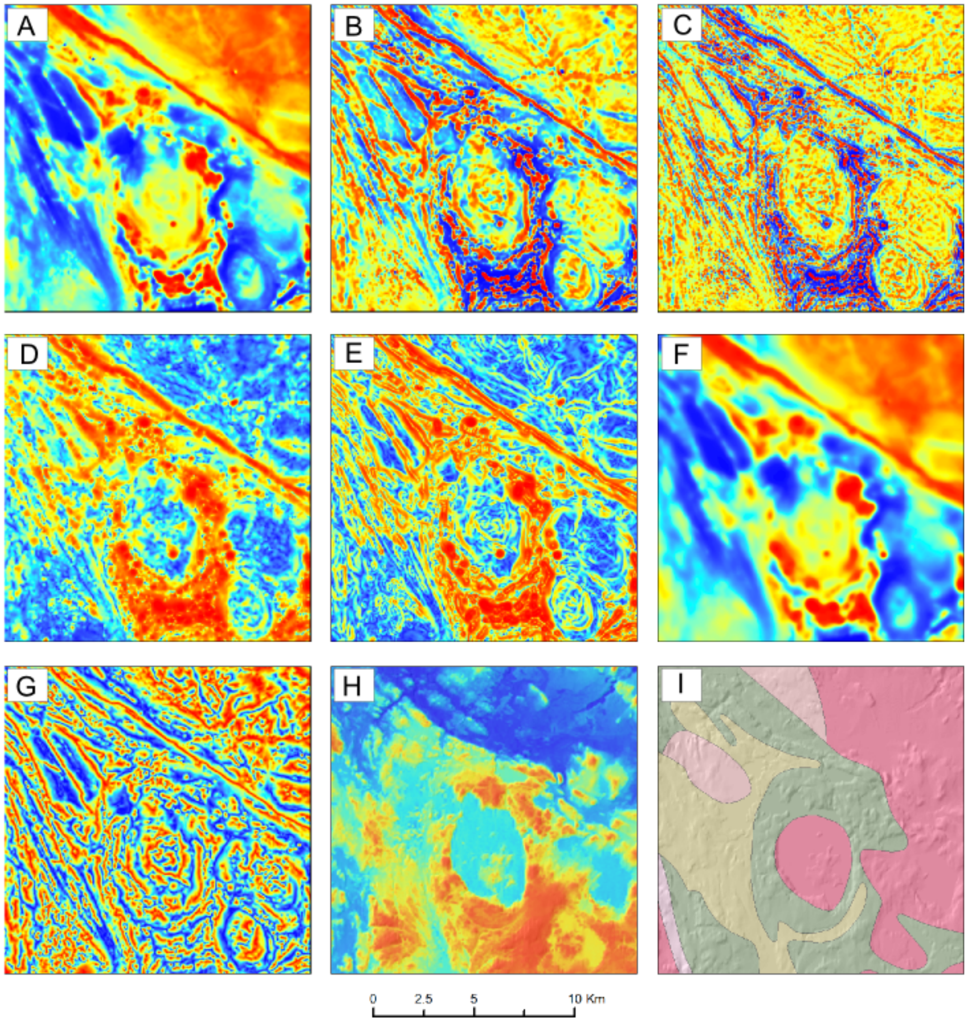

Figure 2Examples of high resolution aeromagnetic data and enhanced grids (scale 1:300,000). (A) reduced to pole magnetic intensity; (B) first vertical derivative of reduced to pole magnetic intensity; (C) second vertical derivative of reduced to pole magnetic intensity; (D) analytic signal of magnetic intensity; (E) horizontal derivative magnitude of reduced to pole magnetic intensity; (F) low-pass filter of reduced to pole magnetic intensity; (G) tilt angle of reduced to pole magnetic intensity; (H) bare earth digital elevation model; and (I) mapped regional bedrock geology [6].

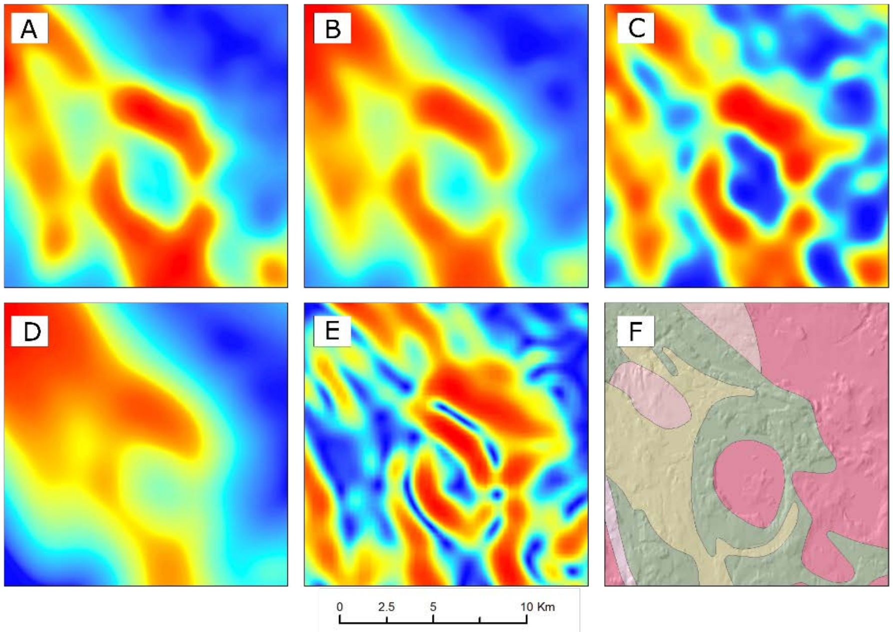

Figure 3Examples of high resolution gravity data and enhanced grids (scale 1:300,000). (A) Free air gravity; (B) Bouguer gravity reduced to 2.67 g/cc; (C) first vertical derivative of Bouguer gravity; (D) Low-pass filter of Bouguer gravity; (E) horizontal derivative magnitude of Bouguer gravity; and (F) mapped regional bedrock geology [6]

3. Interpretation approach

3.1 Geophysical data analysis

Interpretation of high resolution magnetic and gravity data sets was completed by Sander Geophysics Ltd (SGL). The objective of the interpretation was to evaluate variation in the geophysical character that may indicate changing composition of the bedrock or other potential heterogeneities.This interpretation was performed both qualitatively and quantitatively.

The qualitative assessment involved analyzing the magnetic and gravity data, and determining the coincidence of magnetic responses with mapped bedrock lithology and structures.In general, anomaly characteristics and interpreted contacts were compared to bedrock geology maps in an area in order to identify similarities and/or changes in the lithological contact locations. The magnetic data and their vertical derivative products (Figure 2) were used for interpreting geological contacts, identifying lithological heterogeneity, and assessing the nature of structural features through the surveyed area. The gravity data (Figure 3) were valuable for interpreting geological contacts between rock units with differences in density. In some cases, the geophysical data provided a refined interpretation of the bedrock geological contacts, especially in areas of limited bedrock exposure (e.g. under overburden or water cover).

In order to develop a rough approximation of the thickness of geological units in an area, quantitative assessments of the data in the form of preliminary forward modelling were conducted (Figure 4). The purpose of the preliminary modelling is to calculate the relatively deep and shallow parts of the bedrock units, and obtain a rough approximation of the depth to the bottom of these bedrock units.The preliminary modelling used the gravity, magnetic and digital elevation data sets, accompanied with constraints from the qualitative interpretation of the geophysical data and the mapped bedrock geology to provide a preliminary image of the subsurface.

In order to assess the sensitivity of the assigned density and magnetic susceptibilities on the modelledgeometry and thickness of the bedrock units, a series of alternative models were also considered for some of the profile lines. It is important to acknowledge the limitations and preliminary nature of these models at this early stage of the assessment due to limited availability of bedrock densities and magnetic susceptibilities that are key for constraining the model. It is anticipated that the preliminary models would be revised and refined asmore field data arecollected in the future.

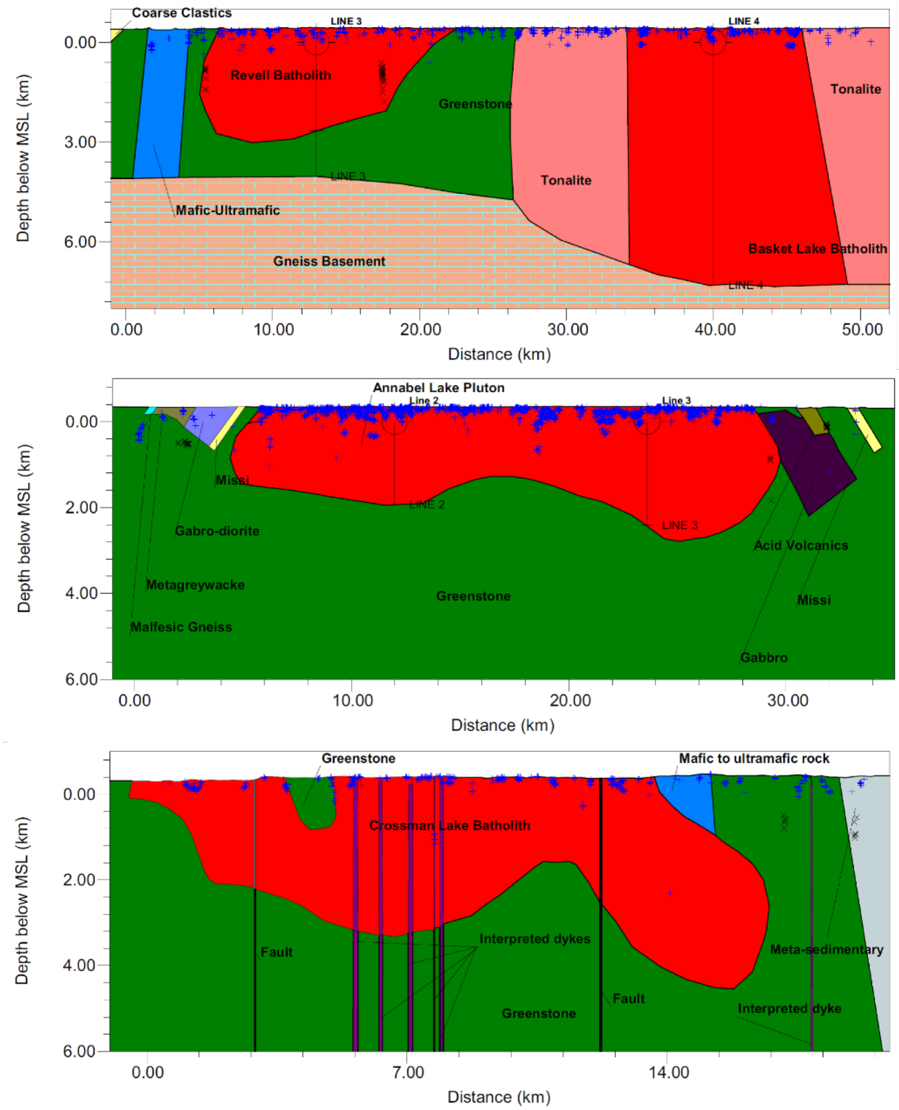

Figure 4 Examples of preliminary modelsto show interpreted geometry of batholiths at depth.

3.2 Structural lineament assessment

Performing a structural lineament interpretation is an important component of the assessment of a crystalline bedrock setting. Lineaments are linear features that can be observed on remote sensing and geophysical data, and which may represent geological structures such as faults and fractureswith the potential to represent potential groundwater pathways.

The purpose of the lineament interpretations was to provide an updated interpretation of the structural characteristics of the potentially suitable bedrock units located within the survey areas, using the newly acquired high-resolution data.The interpretation of geological structures was performed by SRK Consulting (Canada) Inc.(Eg. [7], [8], [9])based on high-resolution remote sensing data sets, including a high-resolution magnetic survey, topographic data collected during the airborne survey, andhigh resolution digital aerial imagery [10].

Lineaments were interpreted using a workflow designed to address issues of subjectivity and reproducibility that are important in any lineament interpretation. The workflow follows a set of detailed guidelines using the high resolution airborne geophysical (magnetic), and high resolution surficial (DEM, digital aerial imagery) data sets. The interpretation guidelines involved three steps (Figure 5):

- **Step 1**: Independent lineament interpretation by two individual interpreters for each data set and assignment of certainty level (1, 2, or 3 representing low, medium and high certainty).
- **Step 2**: Integration of lineament interpretations for each individual data set and first determination of reproducibility (in Figure 5 see (a) magnetic, (b) digital imagery, and (c) digital elevation data).
- **Step 3**: Integration of lineament interpretations for the surficial data sets (in Figure 5 see (d) integration of DEM and digital aerial imagery) followed by integration of the combined surficial data set with the magnetic data set (in 5 see (e) integration of surficial with magnetic), with determination of coincidence in each integration step.

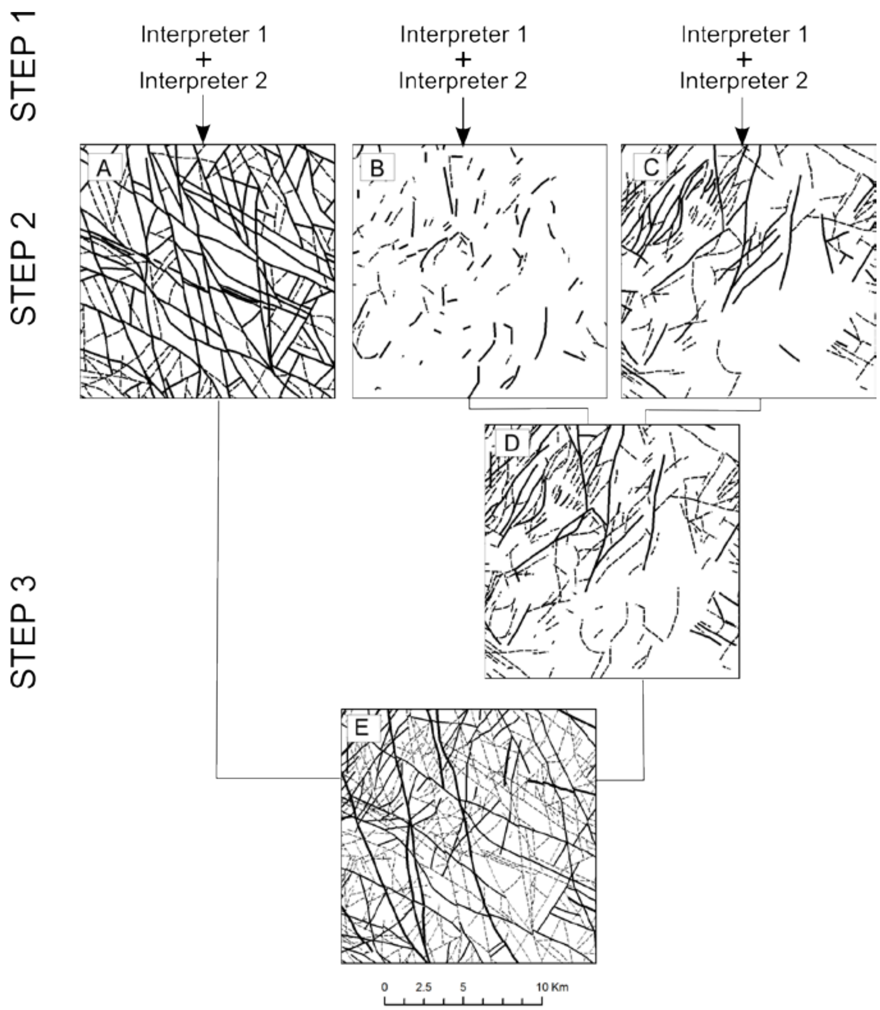

Figure 5Example of the integrated structural lineament interpretation workflow. The thickness of the line defines whether the lineament was interpreted by an individual interpreter (thin dashed lines), or both interpreters (thick black lines). The lineament data sets presented are: (A) Magnetic lineaments; (B) aerial imagery lineaments; (C) digital elevation data lineaments; (D) surficial lineaments integrated from digital imagery and digital elevation data; (E) final lineaments integrated from surficial and magnetic lineaments.

Following the workflow described above, the interpreted features were classified into threelineament types based on an understanding of the structural history and bedrock geology of an area. These categories includeductile, brittle and dyke lineaments, described as follows:

- **Ductile lineaments**:Features which were interpreted as being associated with the internal fabric of the rock units (including metasedimentary or volcanic layering, tectonic foliation or gneissosity, and magmatic foliation).

- **Brittle lineaments:**Features interpreted as fractures (joints or joint sets, faults or fault zones, and veins or vein sets) were classified as brittle lineaments. Brittle lineaments are commonly characterized by continuous magnetic lows, offsets of magnetic highs or ductile lineaments, and breaks in topography and vegetation.

- **Dyke lineaments**: Features interpreted, on the basis of their distinct character, e.g., scale and composition of fracture in-fill, orientation, geophysical signature and topographic expression, were classified as dykes. Dykes were largely interpretedfrom the magnetic data set, and are commonly characterized by continuous linear magnetic highs. The interpretation of dykes is often combined with pre-existing knowledge of the bedrock geology of the study area.

Lineaments from each of the data sets areassigned attributes by each interpreter to characterize what type of feature the lineament was drawn along,the interpreters certainty that the lineament represents a bedrock structure, and the general width of the topographic feature.

Table 1 Lineament attributes assigned to each lineament during the interpretation

ID	Attribute	Brief Description
1	Rev_ID	Reviewer initials
2	Feat_ID	Feature identifier
3	Data_typ	Data set used (MAG, DEM, FRI)
4	Feat_typ	Type of feature used to identify each lineament Aerial Imagery: A. Lineaments drawn along straight or curved lake shorelines B. Lineaments drawn along straight or curved changes in intensity or texture (i.e., vegetation) C. Lineaments drawn down centre of thin rivers or streams D. Lineaments drawn along a linear chain of lakes E. Other (if other, define in comments) Digital Elevation Model: A. Lineaments drawn along straight or curved topographic valleys B. Lineaments drawn along straight or curved slope walls C. Other (if other, define in comments) Airborne Geophysics (magnetic and electromagnetic data): A. Lineaments drawn along straight or curved magnetic high B. Lineaments drawn along straight or curved magnetic low C. Lineaments drawn along straight or curved steep gradient 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 isthe sum of individual lengths of mapped polylines and is expressed in kilometres
8	Width**	Width of feature; this assessment is categorized into 5 bin classes: A. < 100 m B. 100 – 250 m C. 250 – 500 m D. 500 – 1,000 m E. > 1,000 m
9	Azimuth	Lineament orientation expressed as degree rotation between 0 and 180 degrees
10	Buffer_RA_1	Buffer zone width for reproducibility assessment (in metres)
11	RA_1	Feature value (1 or 2) based on first reproducibility assessment
12	Buffer_RA_2	Buffer zone width for coincidence assessment (in metres)
13	RA_2	Feature value (1, 2 or 3) based on coincidence assessment
14	MAG	Feature identified in geophysical data set (Yes or No)
15	DEM	Feature identified in DEM data set (Yes or No)
16	SAT	Feature identified in aerial imagery data set (Yes or No)
17	F_Width	Final interpretation of the width of feature
18	Rel_age	Interpretation of relative age of feature, in accord with regional structural history
19	Comment	Comment field for additional relevant information on a feature
20	Object	Geological element identified, e.g., dyke, fault, joint, contact

* 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.

Over the course of these three stages, a comprehensive list of attributes for each lineament was compiled.Key lineament attributes and characteristics used in the assessment include certainty, length, density and orientation:

- **Lineament Certainty**: Certainty (low, medium or high) was defined based on the clarity of the lineament interpreted in the data, which provides confidence in the feature being related to bedrock structure. For example, where a surface lineament could be clearly seen on exposed bedrock, it was assigned a certainty value of high. 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 low or medium. For magnetic lineaments, a certainty value of high was assigned when a clear magnetic susceptibility contrast could be discerned and a certainty value of either low or medium was assigned when the signal was discontinuous or more diffuse. The certainty classification for all three data sets involved expert judgment and experience of the interpreter. For the purpose of this assessment, emphasis was put on lineaments interpreted with high and medium certainty.

- **Lineament Length**:Interpreted lineaments were classified according to their length, which is calculated based on the sum of all segment lengths that make up a lineament. Longer interpreted lineaments may extend to greater depths than shorter interpreted lineaments. In general, longer interpreted lineaments also tend to have higher certainty values.

- **Lineament orientation**: The orientation of interpreted lineaments was expressed in degrees ranging between 0 and 180. Lineament with similar orientations are grouped into lineament sets. The number of identified lineament sets, and their variation in orientation, provides a measure of the complexity of the potential individual fractures or fracture zones.

- **Lineament Density**: The density of interpreted brittle lineaments was determined by examining the statistical density of individual lineaments using a moving window with a search radius of 1.25 kilometres. The spatial analysis used a circular search radius examining the lengths of lineaments intersected within the circular search radius. Analysis of lineament density provides insight on the distribution of bedrock structures.

As an example, Figure 6 shows the final integrated lineament dataset classified to highlight the four different key attributes previously discussed. This is an important visualization tool to show the spatial variations in lineaments based on their assigned attributes.

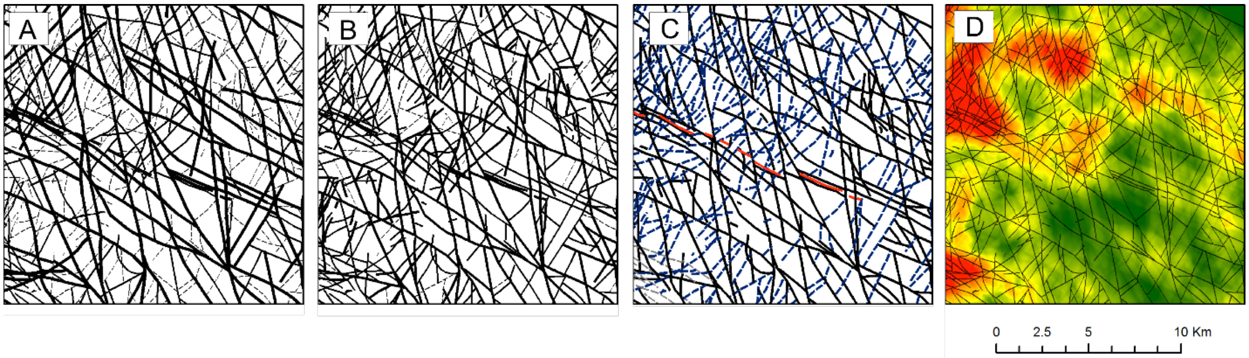

Figure 4 Classification of lineaments based on attribute characteristics. The following images are classified by (A) length bins [blue < 2.5km; red <5km and >2.5km; black >5km]; (B) interpreters confidenceof a bedrock structure [blue=low; red=moderate; black=high]; (C) lineament sets based on orientation clusters; and (D) calculated lineament density.

4. Summary

The Nuclear Waste Management Organization (NWMO) is currently conducting initial field studies in a number of communities participating in a site selection process to find an informed and willing community to host Canada's deep geological repository for used nuclear fuel.These field activities are designed to further advance the geological understanding of the areas being studied, building on previously conducted desktop studies.

This paper described the systematic workflow tointerpret the geological and structural characteristics of crystalline rocksusing high-resolution airborne geophysical surveys for a number of communities in northern Ontario.The workflow was developed to ensure consistency between the various assessments, as well as between the various specialists involved in the interpretations.

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