Mapping McFaulds Lake 'Ring of Fire' crystalline basement architecture in Ontario, Canada from airborne gravity gradiometry (AGG) data using steerable filter and normalized-cut image segmentation

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Summary

Two of the most important tasks of interpreting gravity or magnetic data over sedimentary basins are, (1) to extract lineaments which often reflect concealed structural elements such as faults, fractures and lithological contacts, and (2) to partition the crystalline basement into segmented blocks or domains that may reflect possible litho-tectonic terrane boundaries. These two tasks play a major role in oil and gas exploration because they provide pathway for their migration, accumulation and they may also enhance reservoir permeability effectiveness. Occasionally, these two tasks are accomplished by generating a suite of filtered map enhancements that are visually inspected by experienced interpreter to pick lineaments. In some cases an attempt is made to partition the crystalline basement into segmented blocks based on their gravity, magnetic or seismic signatures complemented by other geological information such as well logs. However, the process of picking lineaments and partitioning the basement into different blocks using conventional approach is tedious and time consuming, and to some extent subjective. Therefore, in this study we developed a new approach to automate and accelerate the process. This new approach is much faster, cost effective and is less subjective than the conventional approach. Furthermore, it is more suitable to process a large volume of data such as those acquired by marine and airborne geophysical surveys.

Two powerful image processing techniques are used in this new approach; steerable filter and normalized-cut segmentation filter. Steerable filter is a rotated filter that is able to pick geological features at any orientation or angle defined by the geophysical interpreter. Thus, steerable filter is able to efficiently extract linear, curvilinear and circular geological edges and ridges, a feature that is difficult to accomplish by using the conventional approach. The normalized-cut segmentation filter which is based on graph theory is used to partition or classify the crystalline basement into different segmented blocks. However, in this study the segmentation filter is used as a test to evaluate its effectiveness in delineating various density blocks using the Bouguer gravity anomaly (gD) for this purpose. The segmentation filter is using the gravity intensity, color and distance between pixels to partition the basement. We applied these two techniques to the Bouguer gravity anomaly (gD) derived from a publicly available Falcon airborne gravity gradiometry (AGG) survey that was flown over part of the McFaulds Lake 'Ring of Fire' area, Ontario, Canada. The results reveal mapping various lineaments related to edges and ridges over the study area and considerable number of them are coinciding with already mapped structural elements. In addition, we were also able to partition the crystalline basement into segmented basement blocks. The preliminary results are interesting and it may be used as an initial approach to mark litho-tectonic terranes of the study area.

Introduction

The study area is located in Ontario, Canada and it covers part of the McFaulds Lake 'Ring of Fire' which is considered to be one of the most prospective areas for mineral and possibly for oil and gas exploration (Figure 1). The gravity gradiometry survey was flown in 2011 by Fugro Airborne Surveys (currently CGG) with 250m line spacing in the NW-SE direction and orthogonal tie lines with 2500m line spacing and flown at a nominal terrain clearance of 100m. The 'Ring of Fire' area straddles the boundary between Archean basement rocks of the Superior Province and uncomfortably overlies Paleozoic sedimentary rocks of the Hudson Platform. The area is underlain by the arcuate Neoarchean McFaulds Lake greenstone belt and sub vertically dipping mafic to ultramafic intrusions, at least some of which are layered and crosscut the western portion of the belt (Cranston, 2010). Figure 2 shows the Bouguer gravity anomaly (gD) that was used as an input image in this study, overlain by generalized major tectonic and geological elements. The crystalline basement is in general very shallow and it is covered with thick Quaternary rocks. Regional mapping suggests that the Quaternary rocks cover highly deformed Precambrian ultramafic igneous complex rocks toward the western end of the study area and younger Paleozoic sedimentary rocks on its eastern part (Figure 2). Volcanogenic massif sulfide as well as chromite deposits are mined within the Precambrian ultramafic complex (Dyer and Burke, 2012). Several large Archean layered intrusions, mostly along or close to a major northwest-trending, sheared terrain boundary were also known to occur in the study area. The detailed geology of the area around the Ring of Fire intrusion is inferred from airborne geophysical data supplemented by sparse gravity and diamond drill data. Magnetic patterns suggest a basement complex comprising volcanic and sedimentary belts between large expanses of granite and gneisses (Cranston, 2010). The crystalline basement rocks of the 'Ring of Fire' have been extensively deformed over the past geological eras. Some of these deformations have influenced the overlain intra-sedimentary rocks and hence led to the formation of fractures, faults and folds that often displayed as linear, curvilinear and circular features on the Bouguer gravity anomaly (gD) due to their high density contrast.

Figure 1: Map showing the location of the study area

The first goal of this study is therefore to extract lineaments from the Bouguer gravity anomaly (gD) image using an effective technique based on steerable filters (Mathews and Unser, 2004; Hassan and Peirce, 2007). Conventionally, we use edge enhancing filters such as the total horizontal gradient of the Bouguer gravity data to map lineaments. These filters are usually computed from a moving square window along the X-axis or the Y-axis of the gridded data. Thus, they are able to efficiently enhance linear geological features in the N-S or in the E-W directions. However, these filters often fail to enhance oriented geological structures at certain angles. To overcome this problem, one could analyze the Bouguer gravity image with a range of rotated filters that covers the whole band of angles present in the image. Using steerable filters, the computations can be restricted to compute the whole range of orientations present in the image in a single run. Therefore, the process is much faster, cost-effective and less subjective than the conventional technique. In addition to linear features, steerable filters are able to detect curvilinear or circular features represented as edges or ridges in an image.

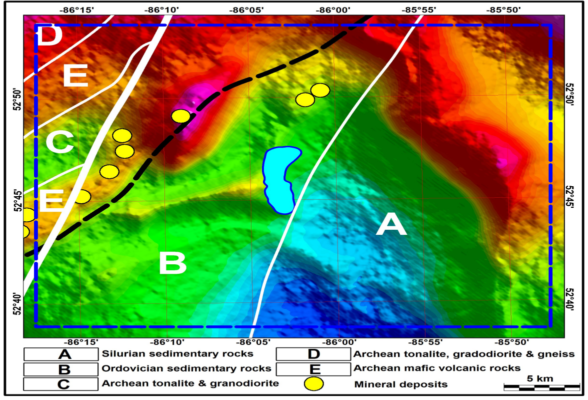


Figure 2: Bouguer gravity anomaly (gD) overlain by generalized major geological and structural elements

The second goal of this study was to partition the crystalline basement into segmented blocks or compartments based on the Bouguer gravity anomaly (gD) signatures where each block has its unique gravity or density characteristics. For this purpose, we applied a powerful segmentation technique called 'normalized-cut segmentation' (Shi and Malik, 1997) to the Bouguer gravity anomaly (gD) image displayed in Figure 2.

Methodology

The following is a brief description of the two techniques used in this study:

Steerable filter:

Steerable filter is a rotated filter that formed by a linear combination of a set of oriented basis filters $h^{\theta a}(x, y)$. These basis filters are designed to detect curvilinear or circular features represented as edges or ridges in an image (Figure 3). Freeman and Adelson (1991) proposed an efficient scheme for computing arbitrary rotations of 2D steerable filters. In this scheme an impulse function $h^{\theta a}(x,y)$ rotated by an arbitrary angle θa was formulated as a linear combination of oriented basis functions $h^{\theta i}(x, y)$ as illustrated in Figure 3 and described in the following formula:

$$I(x,y) * h^{\theta a}(x,y) = \sum_{i=1}^{m} K_i(\theta a) I(x,y) * h^{\theta a}(x,y)$$

where $I(x,y)$ is the input Bouguer gravity anomaly (gD) image and $K_i(\theta a)$ are the coefficients of the bases.

The steerable edge and ridge detectors are based on Gaussian derivatives. The complexity of the filter depends on the highest order derivate used, which for the edge detectors are the 5th order derivate of the Gaussian. The 5th order steerable edge detectors rotations are computed using 12 pre-calculated base templates. The base templates are convolutions of the original image with 1st, 3rd, and 5th derivatives of the Gaussian. Higher order detectors result in fewer false detections as well as more precise detection of the feature. This is due to the higher signal-to-noise ratio and orientation selectivity of the higher order detectors (Jacob and Unser, 2004).

We applied the steerable filter, edge and ridge detectors, on the Bouguer gravity anomaly (gD) grid and was displayed in Figure 2. The results after skeletonization by using Canny filter (Canny, 1986) are shown in Figures 6 and 7. Skeletonization is a process of converting the image into a binary form where we assign a value of one to the signal of interest (here the location of the lineaments) and a value of zero to the background based on a selected threshold value.

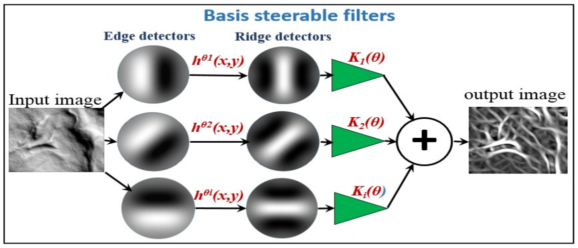


Figure 3: Diagram illustrating the basic concept of steerable filter

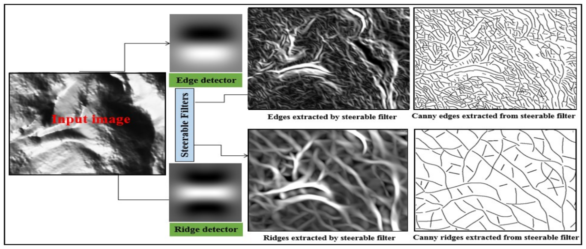


Figure 4: Diagram showing the flow work of running steerable filter to Bouguer gravity anomaly (gD) image

***Normalized-cut Segmentation**:*

The partition of the crystalline basement was carried out by using normalized-cut segmentation technique developed by Shi and Malik in 1997. This technique is based on graph theory (Figures 5) where we assume that the Bouguer gravity data contains vertices (pixels) and these vertices are connected by lines (Edges) to form a graph **G = (V, E)** with vertices **V** and edges **E**. A subset of weak edges can be cut to partition **G** into subgroups. For simplicity, we have divided the gravity image into two regions, **A** and **B** and two subgroups $\mathbf{G_A = (A, E_A)}$ and $\mathbf{G_B = (A, E_B)}$. Normalized-cut segmentation cut the lines connected the two subgroups if they are similar. By doing so we end up with different segments and each segment is connected to all the segments that touch each other. Similar segments are joined with an edge of less weight. Dissimilar blocks are joined with edges of high weight. The grouping is based upon the dissimilarity between the two blocks. This dissimilarity is quantified by a graph cut:

$$Ncut(A,B) = \frac{cut(A,B)}{assoc(A,V)} + \frac{cut(A,B)}{assoc(B,V)}$$

where ***Ncut(A,B)*** is the normalized-cut measure of dissociation between the blocks **A** and **B**.

In the same essence, we can define a measure for total normalized association between **A** and **B**:

$$Nassoc(A,B) = \frac{assoc(A,A)}{assoc(A,V)} + \frac{assoc(B,B)}{assoc(B,V)}$$

Minimizing ***Ncut(A,B)*** is equivalent to maximizing ***Nassoc(A,B)***. The degree of dissimilarity between **A** and **B** can be computed as total weight of the edges that have been cut. In graph theory this can be expressed as:

$$Cut(A,B) = \sum_{i \in A, j \in B} w(i,j)$$

were ***w(i,j)*** is the weight given to an edge and also known as the cost Matrix.

The goal, is then to minimize not simply the ***Cut (A, B)***, but also to minimize the ***Ncut (A, B).***

In order to oprimize the partition, Shi and Malik converted the process into a generalized eigenvector problem by putting the system into matrix representation. Let ***D(i,j)*** be ***NxN*** matrix to represent the sum of the costs:

$$D(i,j) = \sum w(i,j)$$

Ncut can be written as:

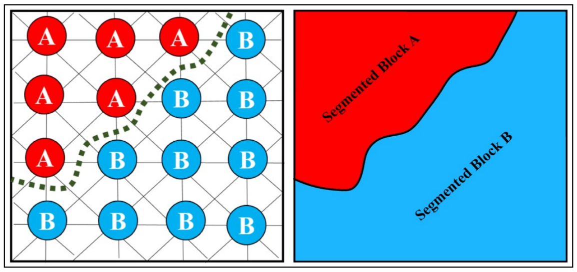
$$Ncut(A,B) = \frac{y^T(D-w)y}{y^T D_y}$$

were ***y*** is the segmentation matrix.

Afterward we can solve the following equation for Eigenvectors with the smallest eigenvalues:

$$(D-w)y = \lambda Dy$$

The eigenvector with the second smallest eigenvalue (**λ**) is then used to optimize the partition of the graph.



Figur 5: Graph plot illustrating normalized-cut segmentation

The results of normalized-cut segmentation are displayed as color-coded image in the background of Figure 6 and 7. These segmented basement blocks may highlight different tectonic terranes in the study area.

Results

The results of this study are displayed in Figures 6 and 7 for edge and ridge lineaments, respectively. These edge and ridge lineaments were extracted by using steerable filter with 5th and 4th order, respectively followed by Canny edge filter. Figures 6 and 7 also show that these edge and ridge lineaments are computed at two different Gaussian smoothing (σ = standard deviation) as indicated in Figures 6 and 7, respectively. The extracted lineaments from Figures 6 and 7 were plotted over the segmented basement blocks partitioned by normalized-cut segmentation. Figure 8 displays the extracted edge and ridge lineaments computed with Gaussian smoothing of 3 and 4, respectively. Figures 6, 7 and 8 reveal that most of the detected lineaments are continuous and highly coherent and conformal with the prominent geological structure of the study area (Figure 2).

Conclusions

Two powerful image processing techniques were used in this study to interpret gD Bouguer gravity data over part of the McFaulds Lake 'Ring of Fire'; steerable filter and normalized-cut segmentation. Steerable filter served to delineate linear, curvilinear and circular lineaments efficiently, a feature that cannot be achieved using traditional lineament detection techniques such as the total horizontal gradient. In this way, it was possible to extract various categories of lineaments that were difficult to map using conventional lineament picking techniques. The detected lineaments are continuous and coherent. Normalized-cut segmentation is used to partition the crystalline basement into different block segments based their gravity signatures. These segmented basement blocks may be attributed to different tectonic units or terrane boundaries in the study area.

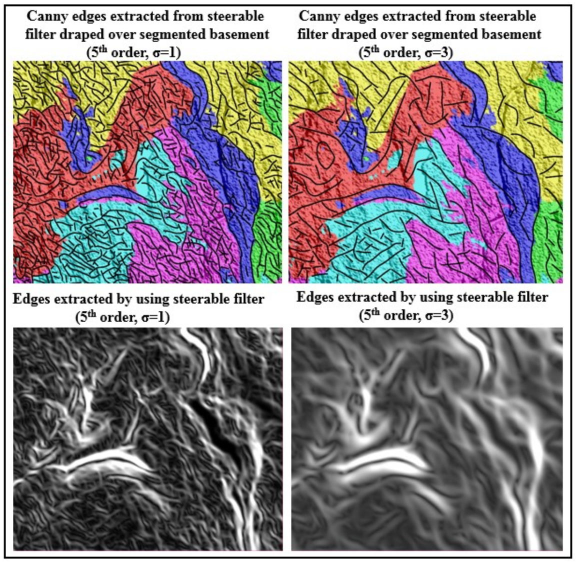


Figure 6: Extracted edge lineaments by using steerable filter of 5th order and with three different Gaussian smoothing filters

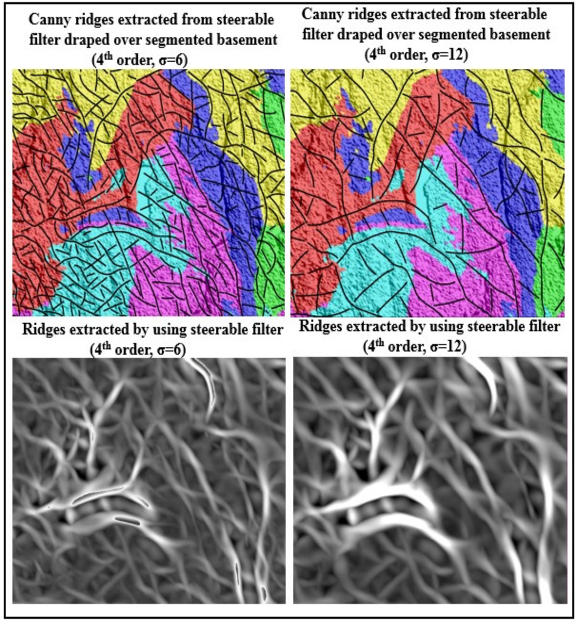


Figure 7: Edge and ridge lineaments extracted from Bouguer gravity (gD) grid

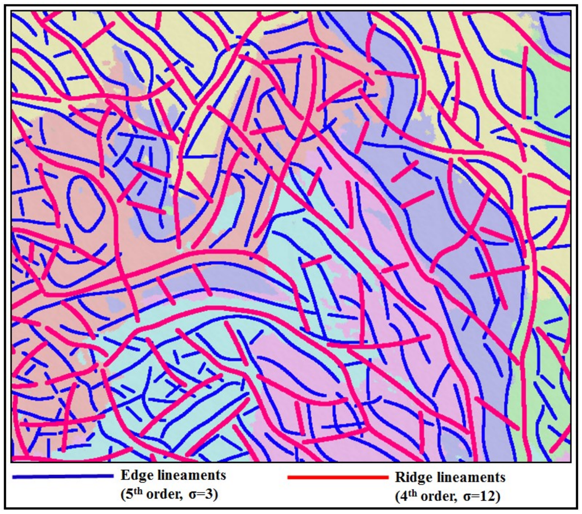


Figure 8: Extracted edge and ridge lineaments by using steerable filter of 5th and 4th order, respectively. The segmented basement blocks are displayed in the background.

Acknowledgments

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