Delineation of curvilinear structures on magnetic images using eigenvalues of Hessian based vesselness filter

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Summary

One of the main objectives of using magnetic data in geological interpretation is to delineate concealed geological structures that are often displayed as linear or curvilinear anomalies on magnetic images. These curvilinear anomalies are attributable to faults and fractures that are most often formed as a result of juxtaposition of rocks with contrasting magnetic susceptibility values. Therefore, accurate delineation of curvilinear geological structures is vital for oil and gas exploration as well as for obtaining a reliable interpretation of magnetic data. In this study a new 2D/3D Hessian based filtering technique called 'vesselness' is used to delineate curvilinear geological structures on magnetic images. This relatively new filtering technique was developed in 1998 by Frangi to delineate tube-shaped blood vessels on medical images and since then it has been used extensively in several disciplines. Even though blood vessels and geological structures are different in principle they are similar in concept. Unlike traditional intensity-based filters such as the horizontal gradient, vesselness is a structure-based filter and it relies on the shape of the structure. Traditional filters whose responses are independent of the shape of the structures rely on the intensity contrast of the structure and they often fail to delineate structures with low intensity contrasts (for example, weak or narrow structures). Vesselness filter uses the eigenvalues (λ_1, λ_2 and λ_3) computed by spectral decomposition of a 2D/3D Hessian matrix of an image.

The main goal of this work is to test the effectiveness of vesselness filter to delineate faults and fractures related curviliear geological structures displayed on magnetic images. To achieve this goal, vesselness filter was applied to a reduced to pole total magnetic intensity image acquired during an airborne survey over the McFaulds Lake area in Ontario, Canada. The results obtained appear to be very promising and the vesselness filter was able to delineate all sorts of curvilinear geological structures including weak and narrow structures that are often missed detection by traditional filters such as the horizontal gradient. In addition to delineating curvilinear geological structures, it appears that vesselness filter is able to remove noise while preserving geological structures on the image.

Introduction

Magnetic data are very useful for mineral as well as petroleum exploration because they are effective in mapping concealed geological structures such as faults, fractures and lithological contacts. There are plenty of filtering techniques available to delineate linear or curvilinear geological structures from magnetic images. However, most of the existing filtering techniques are intensity-based and they usually fail to delineate weak or narrow geological structures on images with low intensity contrasts. To alleviate this problem a new kind of filter called 'Vesselness' is used in this study to delineate geological structures on magnetic images. This filter was introduced by Frangi in 1998 (Frangi *et al*., 1998) to delineate blood vessels. Unlike traditional filters, vesselness is a structure-based filter that is able to capture shapes (line, tube and sphere) of geological structures using the three principal eigenvalues (λ_1, λ_2 and λ_3) obtained by spectral decomposition of a 2D/3D Hessian matrix of an image.

To test the effectiveness of vesselness filter in delineating curvilinear geological structures on magnetic images, we applied vesselness filter to a reduced to pole total magnetic intensity image (Fig. 1) acquired during an airborne gravity gradiometry survey over the McFaulds Lake area (aka, Ring of Fire) in Ontario, Canada. The airborne survey was flown by Fugro Airborne Surveys (currently CGG) in 2011 using the Falcon system with 250m line spacing in the NW-SE direction and orthogonal tie lines with 2500m line spacing flown at a nominal terrain clearance of 100m. The survey was carried out on behalf of the Ontario Geological Survey and the Geological Survey of Canada (OGS and GSC, 2011). The study area (Fig. 2) is considered to be one of the most prospective areas for mineral and possibly for oil and gas exploration. Geologically speaking, the area (Fig. 2) 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 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). The 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. Magnetic patterns suggest a basement complex comprising volcanic and sedimentary belts between large expanses of granite and gneisses (Cranston, 2010).

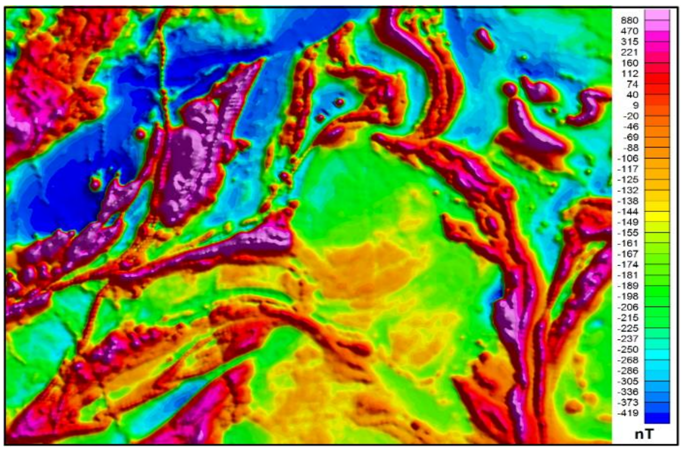

Figure 1. Reduced to pole magnetic image (RTP)

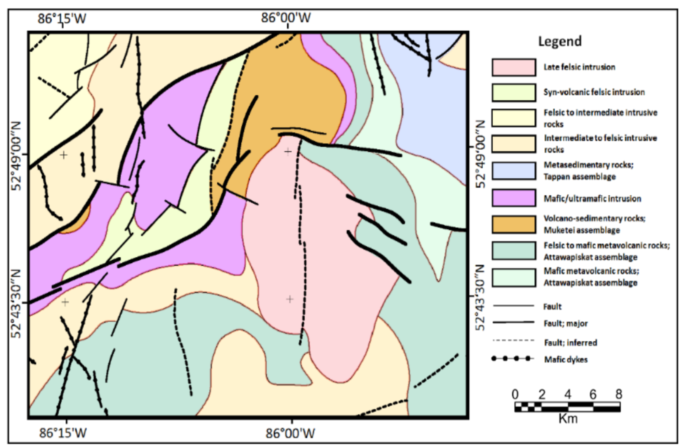

Figure 2. Geology of the study area

Theory

Vesselness filter was developed by Frangi *et al.* (1998) for the detection of vascular structures that relies on the analysis of the second derivatives of the image and in particular the three eigenvalues (λ_1, λ_2 and λ_3) of the Hessian matrix. The Hessian matrix is a powerful tool for linear and curvilinear structure detection. For a 3D image *I*(x, y, z), as an example, the Hessian matrix *H*(x, y, z) is defined as the matrix of the second order derivatives of the image:

$$H(x,y,z) = \begin{bmatrix} \frac{\partial^2 I}{\partial x^2} & \frac{\partial^2 I}{\partial x \partial y} & \frac{\partial^2 I}{\partial x \partial z} \\ \frac{\partial^2 I}{\partial y \partial x} & \frac{\partial^2 I}{\partial y^2} & \frac{\partial^2 I}{\partial y \partial z} \\ \frac{\partial^2 I}{\partial z \partial x} & \frac{\partial^2 I}{\partial z \partial y} & \frac{\partial^2 I}{\partial z^2} \end{bmatrix} \quad (1)$$

Diagonalization of *H* matrix provides three eigenvalues (λ_1, λ_2 and λ_3) and their corresponding eigenvectors (e_1, e_2, e_3) and they are closely related to the following decomposition:

$$H = [Q].[\Lambda].[Q]^T \quad (2)$$

Where Q is a square matrix whose i-th column is the eigenvector e_i and Λ is a diagonal matrix having three eigenvalues at its diagonal as illustrated below:

$$H = [e_1 \ e_2 \ e_3] \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} [e_1 \ e_2 \ e_3]' \quad (3)$$

After solving equation (3) for λ_1, λ_2 and λ_3, we computed vesselness using the following equation (Frangi *et al*., 1998):

$$V = \left(1 - exp\left(-\frac{\lambda_2^2}{2\alpha^2\lambda_1^2}\right)\right) exp\left(-\frac{\lambda_3^2}{2\beta^2\lambda_1\lambda_2}\right)\left([1 - exp\left(-\frac{\lambda_1^2+\lambda_2^2+\lambda_3^2}{2\gamma^2}\right)\right) \quad (4)$$

The parameters α, β and γ are user-defined and control the sensitivity of vesselness measures. Frangi *et al.* (1998) recommended to use a value of 0.5 for α and β whereas γ can be tuned by the user for optimum results.

The Vesselness filter V (Equation 4) incorporates three shape-dependent components (R_A, R_B and S) described below:

$$R_A = \frac{|\lambda_2|}{|\lambda_3|} \quad (5)$$

R_A distinguishes between plate-like and line-like structures. If R_A approaches zero it implies a plate-like structure. If R_A approaches one it implies a line-like structure.

$$R_B = \frac{|\lambda_1|}{\sqrt{|\lambda_2.\lambda_3|}} \quad (6)$$

R_B detects spherical or blob-like structures. If R_B approaches one it implies a spherical structure.

$$S = \sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2} \quad (7)$$

S differentiates between a structure and a noise. The smaller *S* is, the more likely is noise. *S* has the highest value when close to the centreline of the structure.

Equation (4) can be modified and rewritten as follow after incorporating the above three parameters:

$$V = \left(1 - exp\left(-\frac{R_A^2}{2\alpha^2}\right)\right) exp\left(-\frac{R_B^2}{2\beta^2}\right)\left([1 - exp\left(-\frac{S^2}{2\gamma^2}\right)\right) \quad (8)$$

Examples

Reduced to pole total magnetic image shown in Figure 1 was used as input to compute the vesselness filter using Equation 4. Prior to compute vesselness, the magnetic image was standardized (i.e., with a mean of zero and a standard deviation of one) in order to stabilize the DC shift component. The preliminary results of one of the tests is shown in Figure 3 and it appears to be very intriguing because it shows that vesselness filter is able to effectively delineate in detail the curvilinear geological structures on the magnetic image of the study area. Comparing the results with the traditional horizontal gradient filter (Fig. 4), that we often use for this purpose, it appears that the results from vesselness filter is far more superior. In addition, vesselness filter appears to have a better resolving power than the horizontal gradient filter because the curvilinear structures delineated by vesselness filter (Figure 3) are well separated from each other in comparison to their counterparts on the horizontal gradient image (Fig. 4).

Figure 3. Delineated structures by vesselness filter

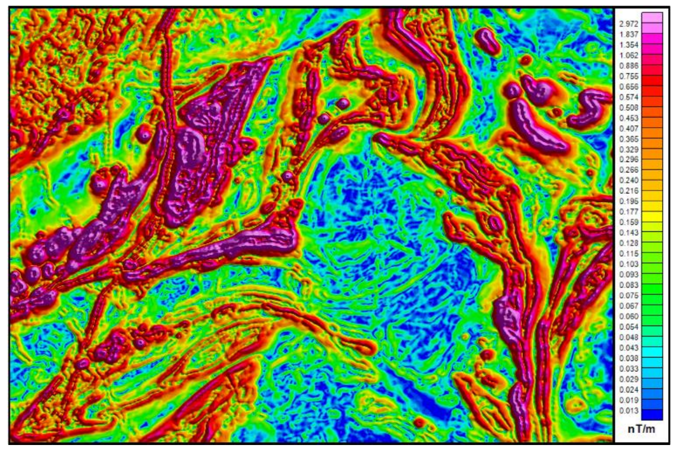

Figure 4. Delineated structures by horizontal gradient

Conclusions

In this study a new filtering technique was introduced called ‘vesselness’ to delineate curvilinear geological structures on magnetic images. The results obtained from applying vesselness filter to a magnetic image from McFauld Lake area in Ontario are intriguing. We were able to delineate subtle, weak and narrow curvilinear geological structures that may be attributable to faults and fractures in the study area. Weak or narrow geological structures are often difficult to detect by using traditional filtering techniques such as the horizontal gradient. The results also suggest that the vesselness filter has a better resolving power than traditional filters because most of the curvilinear structures delineated by the vesselness filter are well separated from each other in comparison to their counterparts on the horizontal gradient. Besides, it appears that vesselness filter is able to remove noise while preserving curvilinear structures.

References

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