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Automatic identification of basement geomorphic features in the Peace River Arch using curvature attributes of magnetic data

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Summary

The boundary between crystalline basement rocks and overlying sedimentary rocks in a sedimentary basin represents one of the best targets for magnetic surveys because of its high magnetic susceptibility contrast. The high magnetic susceptibility contrast at the basement/sedimentary boundary is often produced as a result of high concentration of magnetic minerals in the basement rocks relative to the overlying sedimentary rocks. For that reason, most of the magnetic signals observed on magnetic images are most likely related to basement geomorphic features such as ridges (horsts) and valleys (grabens). Mapping shapes and orientations of basement geomorphic features using magnetic data is vital for oil and gas exploration because the basement is often control the overlying sedimentary rocks and their related geological structures, including the formation of their oil and gas plays. Thus, this abstract describes a new approach to automatically identify shapes of basement geomorphic features beneath the Peace River Arch structure of Western Canada Sedimentary Basin using curvature attributes of magnetic data. Two shape indicator curvature attributes were used for this purpose; the Geological Curvature (GC) attribute and the Shape Index (SI) curvature attribute. The Geologic Curvature (GC) attribute is based on using combined information obtained from the Gaussian (G) and the Mean (M) curvatures whereas the Shape Index (SI) curvature attribute is based on information obtained from the two principal curvatures (κ_1 and κ_2).These two shape indicator curvature attributes were applied to a public domain airborne magnetic data acquired over the Peace River Arch area and it was download from Canada Natural Resources Geoscience Data Repository website. The results obtained from the two shape indicator curvature attributes are strikingly similar and very interesting. They reveal that the basement geomorphic features of the Peace River Arch structure is dominated by a series of ridges (horsts) and valleys (grabens) that run mainly in the NE-SW direction and to some degree in the NE-SW direction. Besides ridges and valleys other basement geomorphic features such as basins, domes and saddles were also identified but to a lesser extent. The results may also provide new insights into the tectonic evolution of the Peace River Arch structure in the study area. They can also be used to constrain the basement geometry during forward modeling and inversion of gravity and magnetic data.

Introduction

Curvature is the amount by which a surface deviates from being a flat. Surface curvature can be estimated quantitatively by the Gaussian (G) and the Mean (M) curvatures, which are calculated from the two principal curvatures (κ_1 and κ_2). The principal curvatures (κ_1 and κ_2) represent the two eigenvalues of a 2-D Hessian matrix. The Gaussian curvature (G) is the multiplication product of the two principal curvatures whereas the Mean curvature (M) is the average of the two principal curvatures. Joint information from the Gaussian (G) and the Mean (M) curvatures allows identifying different shapes. For example, if G>0 and M=0, the surface is a ridge (horst) and if G<0 and M=0, the surface is a valley (graben) as illustrated in Figure 1. The sign or the direction of the Normal curvature (N) also plays a significant role in determining the shape of the feature. A negative curvature suggests a basin or a valley whereas a positive curvature suggests a dome or a ridge (Fig. 2). It is also of interest to note that curvatures are inversely proportional to the radius of a circle tangent to the curved surface (Fig. 2). Large circle has relatively smaller curvature values than smaller circle.

Based on the combined information obtained from the four main curvatures (κ_1, κ_2, G and M) several shape indicator curvature attributes were developed during the last two decades. Among these, the GM curvature attribute of Besl and Jain (1986) and Shape Index (SI) curvature attribute of Koenderink and Doorn (1992) are the most powerful shape indicators because they are able to identify shapes of a range of geomorphic features. Accordingly, these two shape indicator curvature attributes were used in this study. The GM shape indicator curvature attribute is also referred to as the Geologic curvature (GC) because it is widely used to identify shapes of geological features (Roberts, 2001; Bergbauer and Pollard, 2003; Mynatt *et al*., 2007; Burtscher *et al*., 2012). The Shape Index (SI) curvature attribute of Koenderink and Doorn (1992) has values ranging between -1.0 and 1.0 (Fig. 1). If the value of the shape index (SI) is close to -1.0 the shape is a basin and if the shape index is close to +1.0 the shape is a dome (Fig. 1).

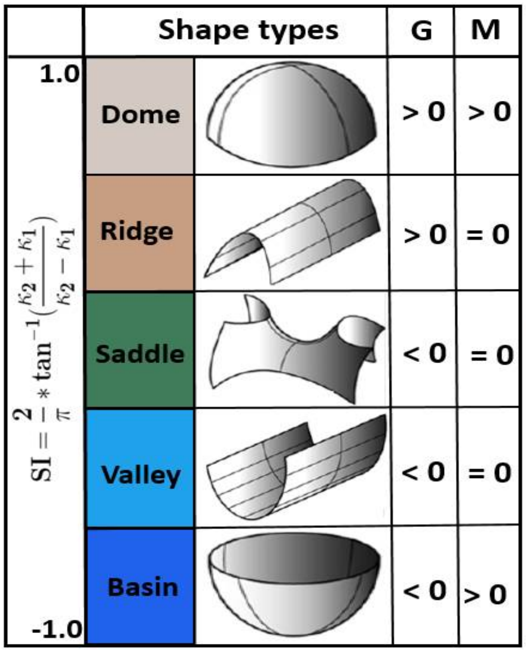

Figure 1. Shapes identified in this study

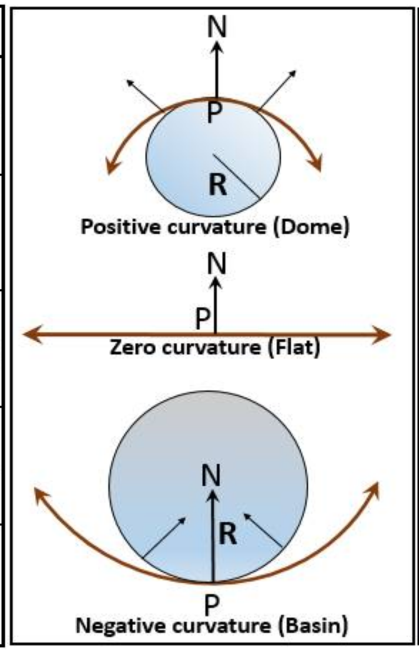

Figure 2. Examples of curvatures

Figure 3. Index of the study area

Both shape indicator curvature attributes, the Geologic and the Shape Index (SI), were applied to a public domain magnetic grid covering the Peace River Arch structure of the Western Canada Sedimentary Basin (Fig. 3). This magnetic grid (Fig. 4) was downloaded from Canada Natural Resources Geoscience Data Repository website. The downloaded magnetic grid (Fig. 4) which was used as input in this study appears to be of good quality as illustrated in Figure 5. Figure 5 shows the output of a cascaded high-boost and plan curvature filters applied to the input magnetic grid. The bright lines of Figure 5 highlight faults and fractures in the basement of the study area. From geological point of view, the Peace River Arch (Figure 4) which spreads beyond the study area is a large E-NE trending anticlinal structure in the Western Canada Sedimentary Basin. It extends from northeast British Columbia into northwest Alberta for approximately 750 km (O'Connell, 1994). The overlying Middle Devonian to Upper Cretaceous sedimentary rocks have been a focus of extensive oil and gas exploration since 1949. Although most of the research in the Peace River Arch area has focused on exploration of the overlying sedimentary strata, some of the mechanisms created the oil and gas traps have been found to be fault controlled. The Precambrian core of the Peace River Arch area consists mainly of granites that have been subjected to several tectonic episodes over the past 400 million years. Each tectonic episode created its own set of faults and fractures that eventually acted as structural traps for oil and gas accumulation. The main structural elements of the study area along with mapped faults and fractures are plotted in Figure 4 over the input magnetic grid.

Theory

The principal curvatures (κ_1 and κ_2) of the input magnetic image *I*(x, y) can be captured by a 2-D Hessian matrix (*H*):

$$H(x,y) = \begin{bmatrix} \frac{\partial^2 I}{\partial x^2} & \frac{\partial^2 I}{\partial x \partial y} \\ \frac{\partial^2 I}{\partial y \partial x} & \frac{\partial^2 I}{\partial y^2} \end{bmatrix} = \begin{bmatrix} I_{xx} & I_{xy} \\ I_{yx} & I_{yy} \end{bmatrix} \qquad (1)$$

The principal curvatures (κ_1 and κ_2) of *I*(x, y) are the eigenvalues of the Hessian matrix *H*(x, y) and can be computed by solving for κ as follows:

$$|H - \kappa I_n| = 0 \qquad (2)$$

where I_n is the identity matrix. The principal curvatures (κ_1 and κ_2) as well as the Gaussian (G) and the Mean (M) curvatures can also be calculated from the partial derivatives of the input magnetic image *I*(x, y) as described below:

$$G = \frac{I_{xx} I_{yy} - I_{xy}^2}{(1 + I_x^2 + I_y^2)^2} \qquad (3)$$

$$H = \frac{(1 + I_x^2) I_{yy} + (1 + I_y^2) I_{xx} - 2 I_x I_y I_{xy}}{2\sqrt[3]{(1 + I_x^2 + I_y^2)^2}} \qquad (4)$$

where,

$$I_x = \frac{\partial I}{\partial x}, \; I_y = \frac{\partial I}{\partial y}, \; I_{xx} = \frac{\partial^2 I}{\partial x^2}, \; I_{xy} = \frac{\partial^2 I}{\partial x \partial y}, \; I_{yy} = \frac{\partial^2 I}{\partial y^2}$$

$$\kappa_1 = M + \sqrt{M^2 - G} \qquad (5)$$

$$\kappa_2 = M - \sqrt{M^2 - G} \qquad (6)$$

The shape index (SI) curvature (Koenderink and Doorn, 1992) is computed as follow:

$$SI = \frac{2}{\pi} * tan^{-1}\left(\frac{\kappa_2 + \kappa_1}{\kappa_2 - \kappa_1}\right) \quad \kappa_1 \geq \kappa_2 \qquad (7)$$

Using the combined information obtained from these curvatures we were able to identify different geological shape features at the basement of the Peace River Arch structure.

Examples

Prior to computing the two shape indicator curvature attributes, the input magnetic grid (Fig. 4) was reduced to the pole in order to position magnetic anomalies over their causative sources. Next, a 5km low-pass filter was applied to the reduced to the pole grid in order to remove any contribution from magnetic sources within the sedimentary section of the basin that may interfere with the results. Afterward, we computed the Geologic Curvature (GC) and shape Index (SI) curvature attributes of the input magnetic grid. The results, after standardization (i.e., with a mean of zero and a standard deviation of one) are shown in Figures 6 and 7, respectively. Standardization was performed to be able to compare the two sets of results. As shown in Figures 6 and 7, both results are strikingly similar and consistent. They reveal a series of ridges (horsts) and valleys (grabens) that dominate the Peace River Arch basement. These geomorphic features are mainly oriented in the NW-SE direction and to some degree in the NE-SW direction. In addition to ridges and valleys the results show a small number of basins, domes and saddles structures that are randomly scattered over the study area. These results are significant because they may add new insights into the tectonic evolution of the Peace River Arch structure of the study area. The results can also be used to constrain gravity and magnetic forward modeling and inversion of the basement.

Conclusions

Two shape indicator curvature attributes; Geologic Curvature (GC) and Shape Index (SI) were computed for the reduced to pole total magnetic intensity grid acquired over the Peace River Arch structure in order to identify shapes of the basement geomorphic features. The results of both attributes reveal that the basement is dominated by a series of ridges (horsts) and valleys (grabens) oriented in the NW-SE direction and to a lesser extent in the NE-SW direction. Besides ridges and valleys a small number of basins, domes and saddles were also identified over the area. These results may provide new insights into the tectonic and structural evolution of the study area. The results can also be used as a guide to model the geometry of the basement.

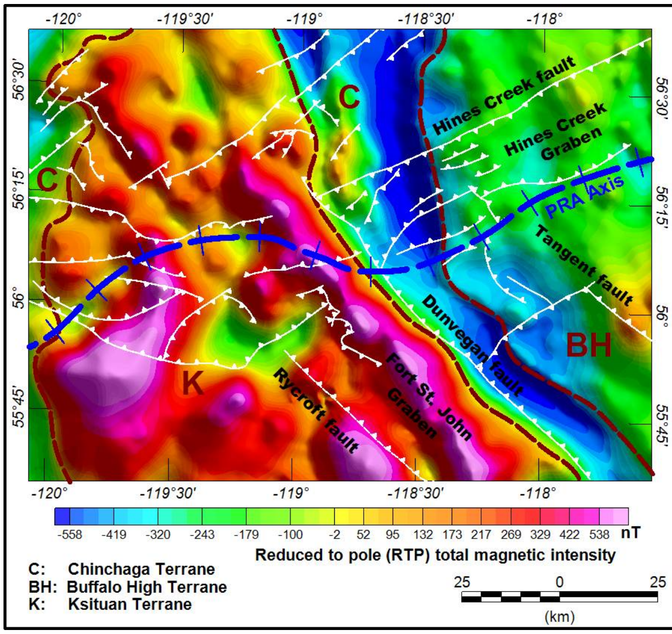

Figure 4. Input magnetic grid overlaid by mapped faults

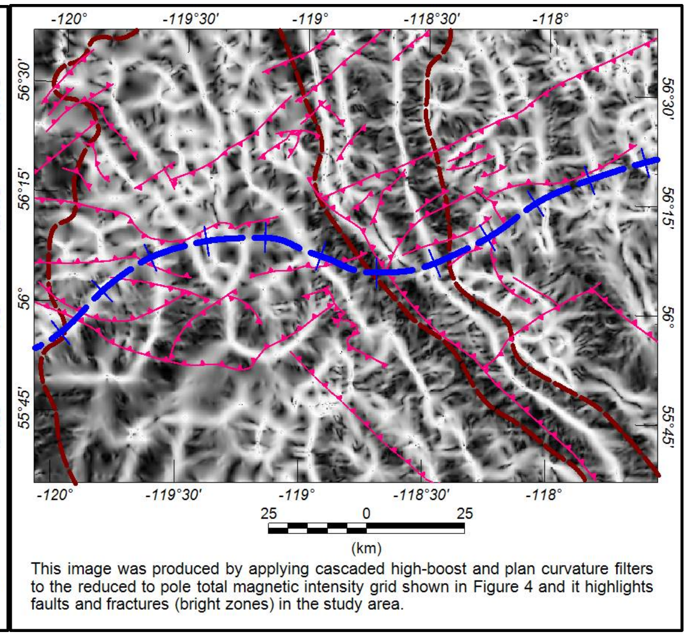

Figure 5. Edge enhancement filter of the magnetic grid

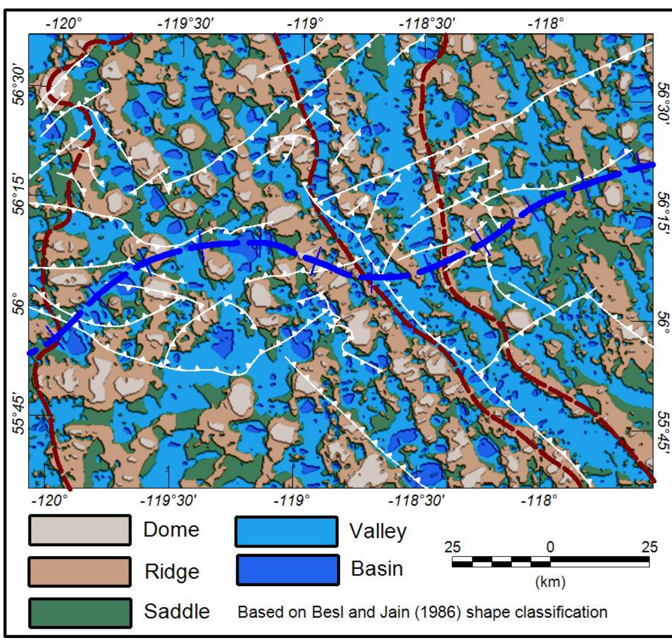

Figure 6. Results obtained from applying Geologic curvature (CG) to input magnetic grid

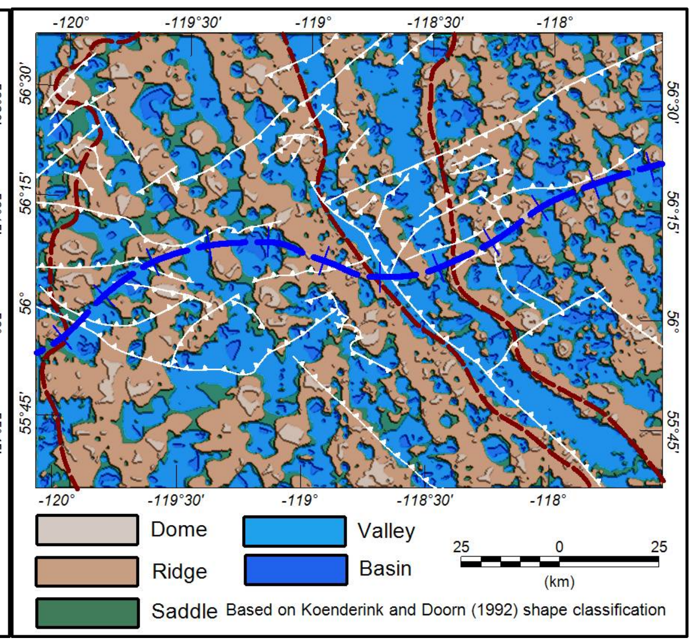

Figure 7. Results obtained from applying Shape Index (SI) curvature to input magnetic grid

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