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Mapping Basement Structures in the Peace River Arch of Alberta Using Monogenic Signal Decomposition of Magnetic Data

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Figure 1. Location of the study area.

Summary

The magnetic method is well-known as one of the most powerful tools used to map concealed geological structures especially those associated with magnetic crystalline basements. Crystalline basements play an important role for oil and gas exploration in sedimentary basins because they influence the geology of the overlying sedimentary rocks and subsequently the formation of their oil and gas plays. Magnetic data from sedimentary structures are in general characterized by their low susceptibility contrast and poor signal-to-noise ratio and it is often challenging to extract subtle geological features from these data. Therefore, image enhancement techniques are very vital for extracting optimum geological and structural information from magnetic data. In this abstract, a new magnetic image enhancement approach is proposed. This approach is based on a recently developed digital processing technique known as monogenic signal decomposition. This new technique is able to decompose 2D magnetic signals into three primary attributes (amplitude, phase and orientation) and two secondary attributes (directional Hilbert and Riesz transforms). Although many magnetic attributes have been utilized to map subtle geologic features, these five particular attributes appear to add more valuable information to magnetic data interpretation. The aim of this study is therefore to explore the monogenic signal decomposition approach as an alternative technique to extract geological and structural information from magnetic data.

This abstract describes the rotation-invariant monogenic signal decomposition and demonstrates its use in enhancing magnetic data. The monogenic signal decomposition technique was first tested on the total magnetic intensity (TMI) grid of a synthetic magnetic data and after obtaining satisfactory results the technique was applied to field magnetic data. The synthetic magnetic data was derived from Bishop 3D magnetic model whereas the actual field data was derived from an aeromagnetic survey flown over the Peace River Arch structure of Western Canada Sedimentary Basin (WCSB). The results obtained from the synthetic and field data indicate that the proposed approach has excellent performance in extracting structural features especially geological boundaries, faults and fractures from the data. Furthermore, it appears that this new approach is superior in enhancing structural features in aeromagnetic data than conventional enhancing techniques such as the horizontal and total gradient methods.

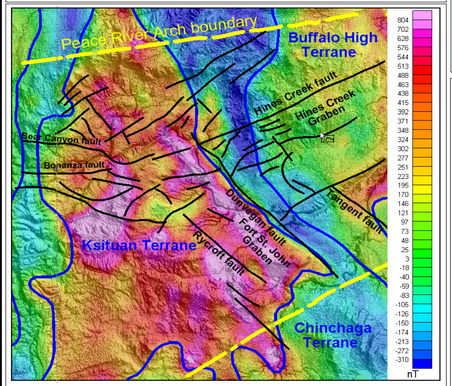

Figure 2. Major structural elements of the Peace River Arch overlain on top of total magnetic intensity grid. Black solid lines represent previously mapped thrust faults.

Introduction

The present work introduces a new approach to enhancing magnetic data in order to map subtle geological features related to basement structures. This new approach is based on monogenic signal decomposition and it is useful in computing instantaneous attributes of magnetic signal, particularly amplitude, phase and orientation. The monogenic signal is a 2D generalization of the analytic signal using the Riesz transform instead of a Hilbert transform. In so doing, the essential property of the analytic signal, the split of identity, is preserved. Split of identity means the separation of the signal into structural (phase) and energy (amplitude) information. The work presented here is primarily concerned with the phase of the signal because it relates to the structure of the data. In magnetic data, for example, the phase provides information about geological contacts, faults, fractures and other structural features. The amplitude provides information on magnetic susceptibility variations within the basement and other rocks of igneous origin. The monogenic signal decomposition was first introduced in 2001 by Felsberg and Sommer to decompose a 2D signal into three complementary components; amplitude, phase and orientation. In this abstract we show only the results of three attributes; the directional Hilbert, the instantaneous phase and the instantaneous orientation.

In order to test the strength of the monogenic signal decomposition in mapping structural features of magnetic data, it was first applied to synthetic magnetic data from Bishop 3D model (Reid, et al., 2005). After obtaining satisfactory results, the technique was applied to real magnetic data from the Peace River Arch area of Western Canada Sedimentary Basin (Fig. 1). The Peace River Arch is a large ENE-WSW 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 which created the oil and gas traps have been found to be fault controlled. The Precambrian basement underneath the Peace River Arch structure 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 fractures and faults that eventually acted as structural traps for oil and gas accumulation. The main structural elements of the study area are displayed in Figure 2. Figure 2 also shows the total magnetic intensity (TMI) grid draped on NE-shaded relief topography of the area.

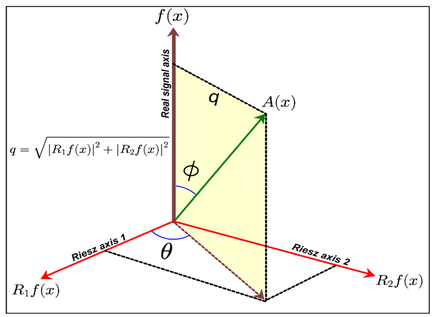

Figure 3. Monogenic signal decomposition attributes.

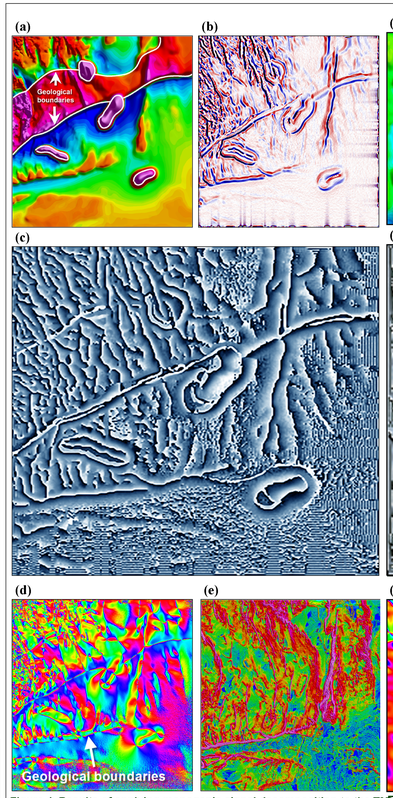

Figure 4. Results of applying monogenic signal decomposition to the TMI synthetic data of Bishop 3D model
(a) input TMI , (b) directional Hilbert transform, (c) instantaneous phase, instantaneous orientation and (e) horizontal gradient of input TMI.

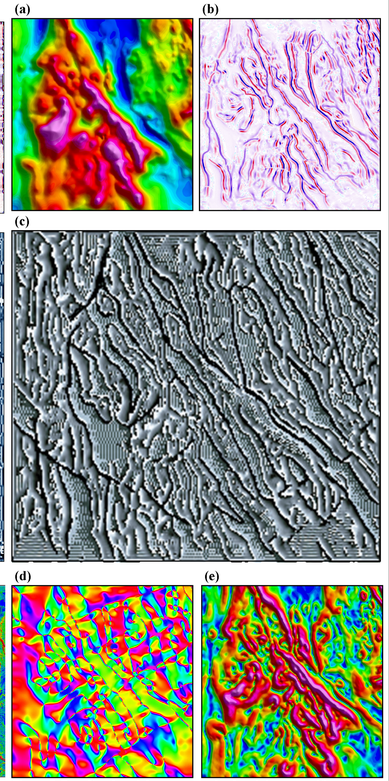

Figure 5. Results of applying monogenic signal decomposition to the TMI synthetic data of Bishop 3D model

Conclusions

In this abstract, a new approach based on monogenic signal decomposition is proposed for processing of magnetic data. This new approach decomposes 2D magnetic signal into amplitude, phase, orientation, directional Hilbert and Riesz transform attributes that enhance geological structures of the data. The proposed approach was applied to synthetic data as well as real data from the Peace River Arch area in Alberta. The results obtained from both data sets are very interesting and demonstrate the monogenic signal decomposition's ability to extract geological and structural features from magnetic data, including lithological contacts, fractures and faults. The results of this study also suggest that the monogenic signal decomposition is superior to traditional processing techniques such as horizontal gradient in detecting structural trends in magnetic data. Although the technique described here is proved to be useful for magnetic data, it has potential applications for other data including gravity and 3D seismic

Methodology

The monogenic signal decomposition technique converts a simple magnetic signal f(x) into a complex signal with three parts: one real and two imaginary. In the mathematical sense, complex signal is referred to as a signal that has both real (in-phase) and imaginary (quadrature) parts (Fig. 3). Thus, it allows us to compute three complementary magnetic attributes; amplitude A(x), phase (ϕ) and orientation (θ) as illustrated in Figure 3. The local amplitude contains energetic information or the strength of the signal. The phase describes structure information such as geological edges, faults, peaks and troughs encountered in magnetic images. Orientation describes the geometric information of the data. The angle between orientation vectors directly relates to the rotational misalignment of corresponding structures in the image plane. The colors displayed in the orientation attribute correspond to the vector orientation and the intensity to its magnitude.

Therefore, for magnetic signal f(x) the complex analytic signal is composed of the original signal f(x) as the real part and its Hilbert transform as the imaginary part as indicated below:

$$f_A(x) = f(x) + iH\left[f(x)\right]$$

Where H[f(x)] is the Hilbert transform of f(x).

The complex Riesz transform can be expressed as:

$$Rf(x) = (R_1 + jR_2)f(x)$$

The monogenic signal $f_M(x)$ is defined as the combination of the original signal f(x) and it's Riesz transform pairs:

$$f_M(x) = (f(x), R_1 f(x), R_2 f(x))$$

Where f(x) represents the real part of the monogenic signal and $R_1f(x)$ and $R_2f(x)$ represent the imagery parts (Fig. 3). Based on the real and the two imagery parts of the monogenic signal, the magnetic signal can be decomposed into instantaneous amplitude A(x), instantaneous phase (Φ) and instantaneous orientation (θ) attributes as shown below:

$$A(x) = \sqrt{|f(x)|^2 + |R_1 f(x)|^2 + |R_2 f(x)|^2}$$

$$\phi(x) = tan^{-1}\left(\frac{\sqrt{|R_1 f(x)|^2 + |R_2 f(x)|^2}}{f(x)}\right)$$

$$\theta(x) = tan^{-1}\left(\frac{|R_2 f(x)|^2}{|R_1 f(x)|^2}\right)$$

Where f(x) represents the real part of the monogenic signal and $R_1f(x)$ and $R_2f(x)$ represent the imaginary parts.

In addition to above attributes, the directional Hilbert (H_θ) and Riesz transform (q) attributes were also computed using the following equations:

$$H_\theta f(x) = cos\theta(R_1 f(x)) + sin\theta(R_2 f(x))$$

$$q = \sqrt{|R_1 f(x)|^2 + |R_2 f(x)|^2}$$

However, only the results of directional Hilbert, phase and orientation attributes are presented in this abstract.

Examples

In order to assess the ability of monogenetic signal decomposition technique to extract structural features from magnetic data, it was first tested on synthetic data. After obtaining sound results it was then applied to real data as described below:

***Synthetic Data*:** The synthetic magnetic grid (Fig. 4a) used as an input for the test was derived from the Bishop 3D synthetic magnetic model. The Bishop 3D model is composed of a synthetic magnetic basement at depths ranging from 100m to 10,000m below the sea-level and overlain by non-magnetic sedimentary rocks. Thus most of the magnetic signal is coming from the magnetic basement. The total magnetic intensity response grid (Fig. 4a) that was generated from the Bishop model by 3D forward and inversion magnetic modeling was used as an input to test the monogenic signal decomposition technique. The monogenic signal decomposition attributes, the directional Hilbert, phase and orientation, are displayed in Figure 4. The results reveal that the geological boundaries marked as solid white lines on Figure 4a are well defined on the three computed monogenic signal decomposition attributes; directional Hilbert (Fig. 4b), phase (Fig. 4c) and orientation (Fig. 4d). In addition to geological boundaries these attributes appear to delineate subtle geologic features that might be related to variation in basement surface topography.

***Real Data*:** The real data used as input in this study were derived from the regional total aeromagnetic intensity grid over the Peace River Arch. This grid was assembled from various aeromagnetic surveys that were acquired over the period from 1990 to 1992, mainly by the Geological Survey of Canada (GSC). Due to the regional nature of the data, most of the magnetic anomalies displayed on the magnetic image are most likely related to the Precambrian basement rocks. Using the same parameters applied to the synthetic data, the monogenic signal decomposition attributes were calculated for the Peace River Arch aeromagnetic grid (Fig. 5a). The results (Fig. 5) are very intriguing and they clearly reveal the ability of monogenic signal decomposition to image major geological terranes, faults and fractures of the area. It appears that most of the linear features shown on the monogenic signal decomposition attributes (Fig. 5) correlate well with known faults in the area, for example the Dunvegan Fault (Fig. 2).

The results obtained from monogenic signal decomposition of the real and the synthetic data (Figs. 4 and 5, respectively) were visually compared with the results obtained from using one of the commonly used traditional enhancement techniques such as the horizontal gradient method (Figs. 4c and 5c). This comparison reveals that the monogenic signal decomposition technique is much superior to the traditional techniques in extracting geological trends. Furthermore, the geological trends extracted from the monogenic decomposition techniques are continuous, more coherent and more focused.

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