

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

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## Abstract

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 in oil and gas exploration in sedimentary basins because they influence the geology of the overlying sedimentary rocks and subsequently on the formation of their oil and gas plays. Magnetic data are in general characterized by their low contrast and poor signal-to-noise ratio and therefore it is always challenging to extract subtle geological features from these data. Therefore, image enhancement is vital for extracting optimum geological and structural information from magnetic data. In this study, 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 transform). Although many magnetic attributes have been utilized to map subtle geologic features, these five 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 article 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 real magnetic data. The synthetic magnetic data was derived from Bishop 3D magnetic model, whereas the real 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 real data indicate that the proposed approach has excellent performance in extracting structural features, especially geological boundaries, faults and fractures from the data.

## Introduction

This work introduces a new approach to enhance 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 wherein the Riesz transform is used instead of the Hilbert transform. Therefore, the essential property of the analytic signal, the split of identity, is preserved during this process. Split of identity means the separation of the signal into structural (phase) and energy (amplitude) information. This article is more 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 the geological contacts, faults, fractures and other structural features of the data. The amplitude provides information about lithological variations in magnetic basements. 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 addition to these three primary attributes, the directional Hilbert and the Riesz transform attributes that were generated during the process were also presented in this article.

In order to test the strength of the monogenic signal decomposition in mapping structural features in 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 ([Figure 1](#)). The Peace River Arch is a large east-northeast 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 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 1](#) which also shows the total magnetic intensity (TMI) grid draped on northeast-shaded relief topography of the area.

## Theory

The monogenic signal decomposition technique converts a simple magnetic signal  $f(x)$  into a complex one containing three parts: one real and two imaginary. In mathematical sense, complex signal is referred to as a signal that has a real (in-phase) and imaginary (quadrature) parts ([Figure 2](#)). Thus, it allows us to compute three complementary magnetic attributes; amplitude  $A(x)$ , phase ( $\phi$ ) and orientation ( $\theta$ ) as illustrated in [Figure 2](#). 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.

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

$$f_A(x) = f(x) + iH[f(x)]$$

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 its pairs Riesz transform:

$$f_M(x) = (f(x), R_1f(x), R_2f(x))$$

where  $f(x)$  represents the real part of the monogenic signal and  $R_1f(x)$  and  $R_2f(x)$  represent the imaginary parts ([Figure 1](#)). Based on the real and the two imaginary parts of the monogenic signal, the magnetic signal can be decomposed into instantaneous amplitude ( $A(x)$ ), instantaneous phase ( $\Phi$ ) and instantaneous orientation ( $\theta$ ) attributes as shown below:

$$A(x) = \sqrt{|f(x)|^2 + |R_1f(x)|^2 + |R_2f(x)|^2}$$

$$\phi(x) = \tan^{-1} \left( \frac{\sqrt{|R_1f(x)|^2 + |R_2f(x)|^2}}{f(x)} \right)$$

$$\theta(x) = \tan^{-1} \left( \frac{|R_2f(x)|^2}{|R_1f(x)|^2} \right)$$

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 ( $H\theta$ ) and Riesz transform ( $q$ ) attributes were also computed using the following formulas:

$$f_{\theta}(x) = f(x) + jH_{\theta}f(x)$$

$$q = \sqrt{|R_1f(x)|^2 + |R_2f(x)|^2}$$

## Examples

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

### Synthetic Data

The synthetic magnetic grid ([Figure 3a](#)) 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 100 m to 10,000 m below 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 ([Figure 3a](#)) 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: amplitude, phase and orientation along with the directional Hilbert and Riesz transform attributes are displayed in [Figure 3](#). The results reveal that the main features displayed by these attributes, especially the phase and orientation attributes ([Figure 3d](#) and [Figure 3f](#)), correlate well with the geological boundaries plotted as white lines on the TMI image ([Figure 3a](#)). The colors displayed in the orientation attribute correspond to the vector orientation and the intensity to its magnitude. In addition to geological boundaries, these attributes delineate subtle features associated with variation in basement relief 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 ([Figure 4a](#)). The results ([Figure 4](#)) are very intriguing and they clearly reveal the ability of monogenic signal decomposition to image major geological terrains, faults and fractures of the area. It appears also that most of the linear features shown on the monogenic signal decomposition attributes ([Figure 4](#)) correlate well with known faults in the area, for example the Dunvegan Fault ([Figure 1](#)).

## Conclusions

In this abstract, a new approach based on monogenic signal decomposition is proposed for processing 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 are very interesting and demonstrate the monogenic signal decomposition's ability to extract geological and structural features, including lithologic contacts, fractures and faults from magnetic data. The results of this study also suggest that the monogenic signal decomposition is superior to classical processing techniques, such as FFT, in detecting structural features 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.

## References Cited

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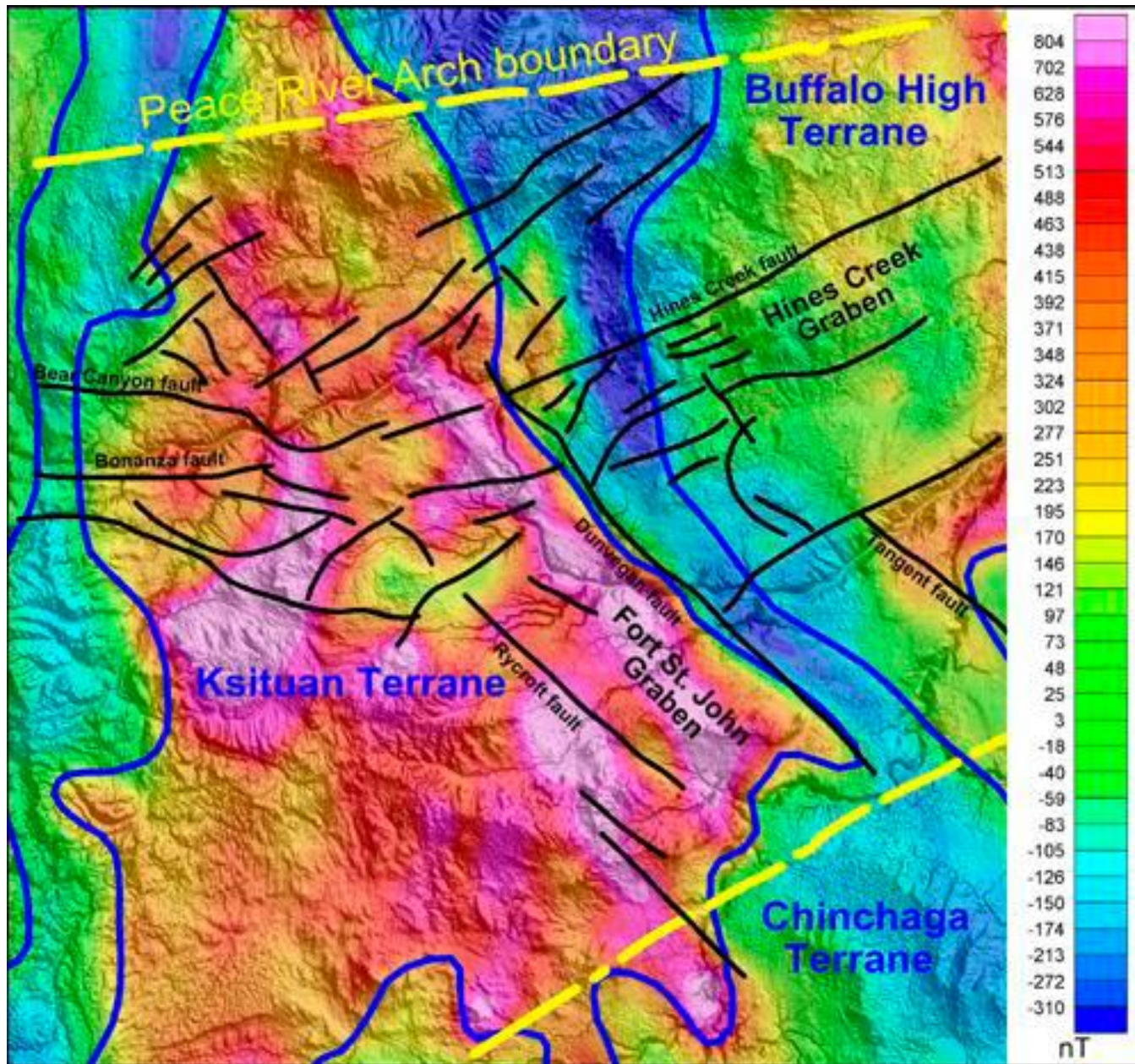


Figure 1. Major structural elements of Peace River Arch overlain on the total magnetic intensity grid. Black lines represent previously mapped thrust faults.

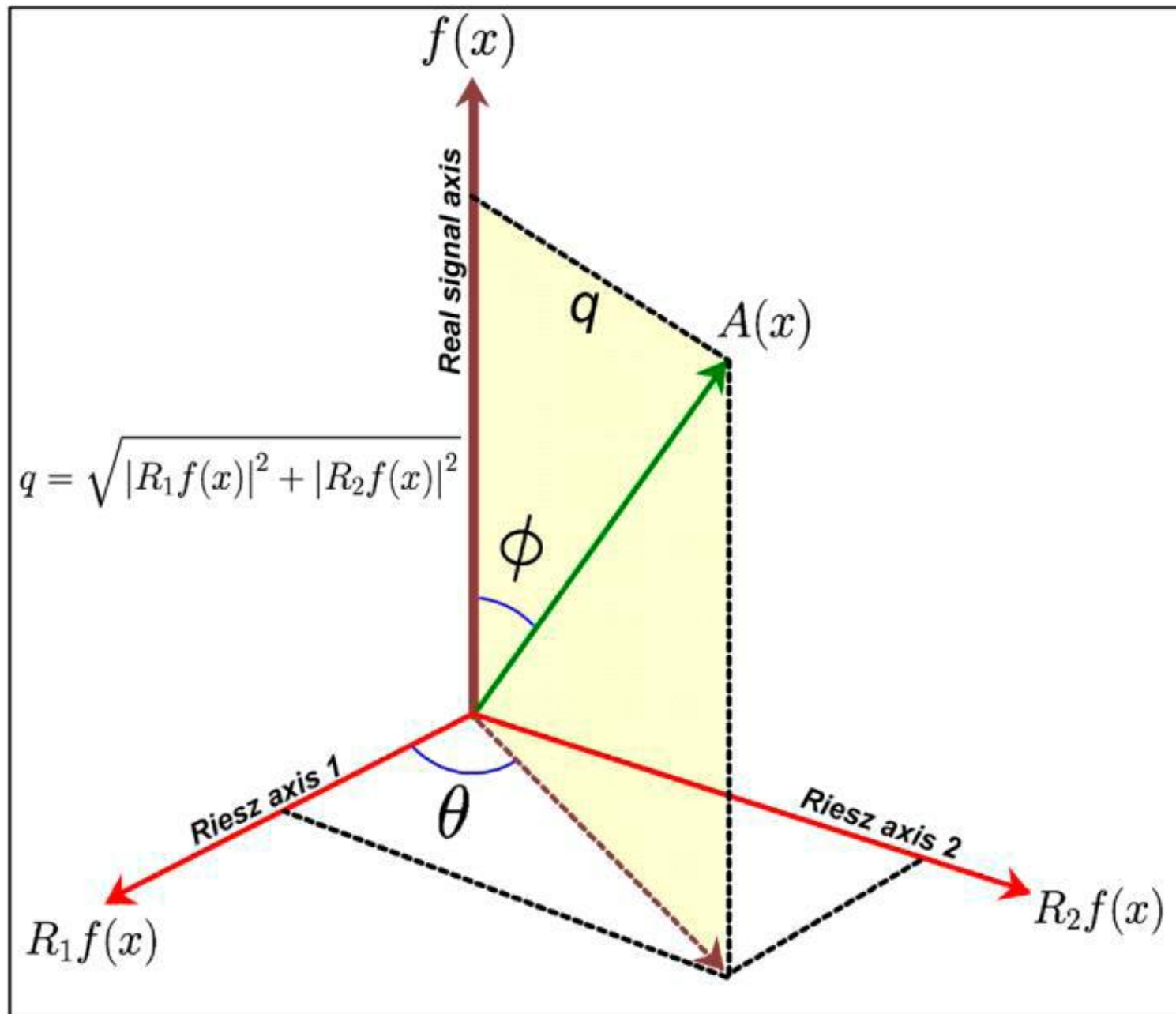


Figure 2. Monogenic signal decomposition attributes.

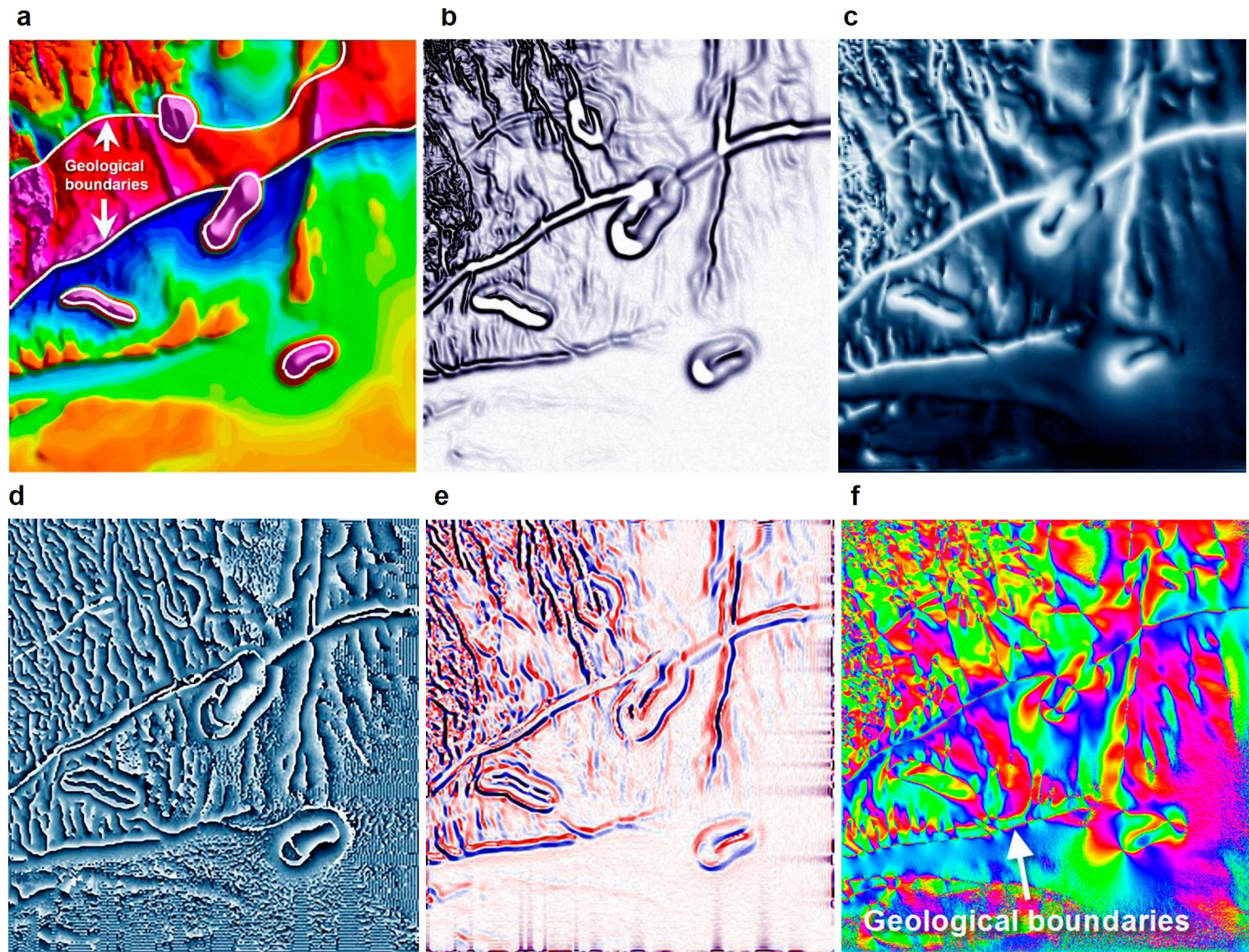


Figure 3. Results of applying monogenic signal decomposition to the TMI synthetic data of Bishop 3D model. (a) Input TMI showing geological boundaries in white, (b) Riesz transform, (c) amplitude, (d) phase, (e) directional Hilbert transform, and (f) orientation.



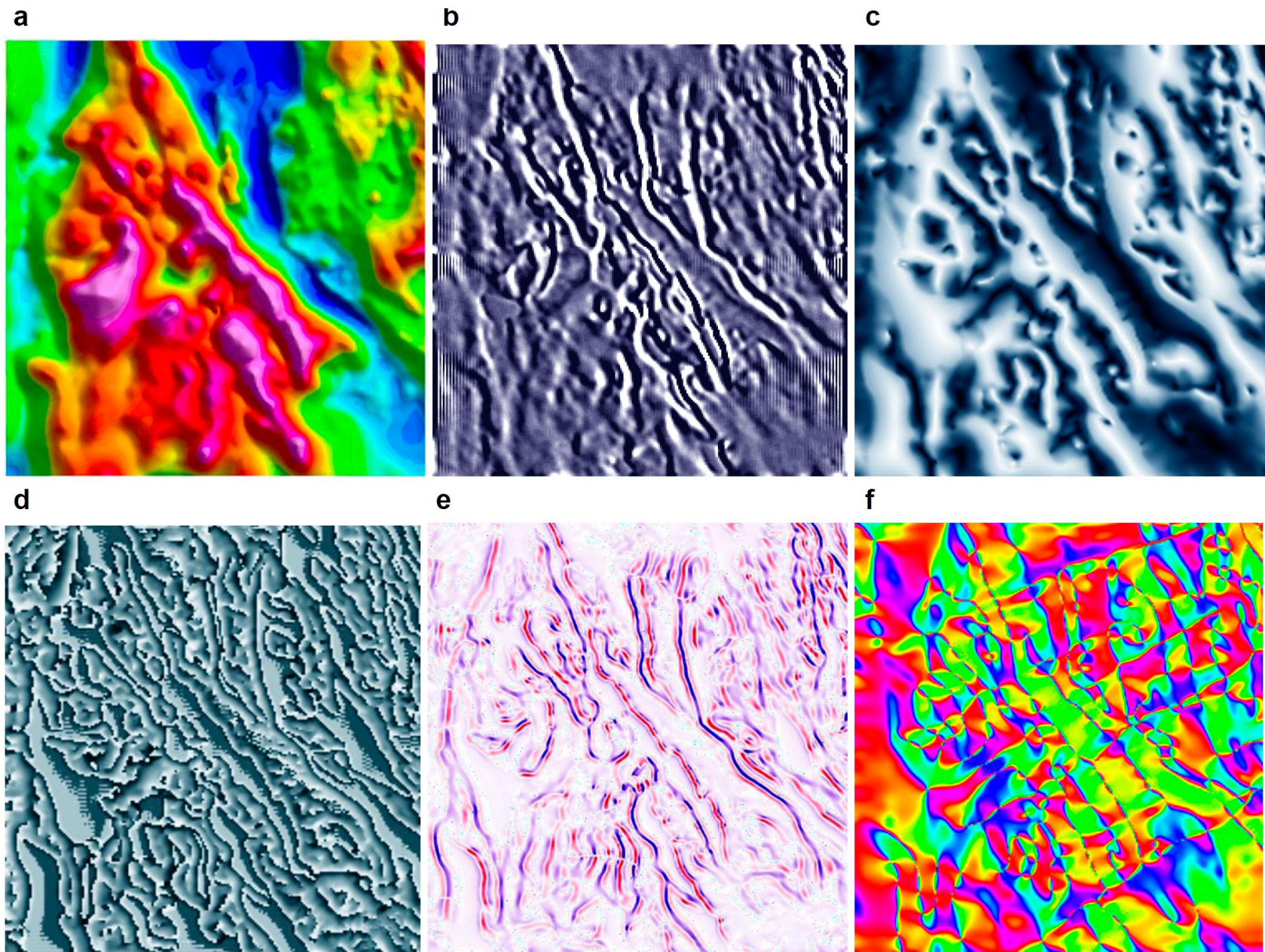


Figure 4. Results of applying monogenic signal decomposition to the TMI data of Peace River Arch. (a) Input TMI, (b) Riesz transform, (c) amplitude, (d) phase, (e) directional Hilbert transform, and (f) orientation.