EAGE extended abstract:

Lineament detection over shale gas play of Horn River Basin using monogenic phase congruency of magnetic data

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Introduction

The significant of interpreting lineaments for oil and gas exploration in general and for shale gas in particular is overwhelming because they often reflect subsurface geological features such as faults, and fractures. Hence, they provide pathway for oil and gas migration and accumulation essential in defining potential shale gas plays. It is well documented in literature that there is a positive correlation between fault and fracture related lineaments with total content of gas in shale (for example, Ding et al. 2011). In addition, lineaments provide information on the present day maximum horizontal stress that controls the direction of hydraulic fracture propagation which is necessary for effective hydraulic fracture treatment design (Gale et al. 2007).

While most of the existing geophysical methods can identify lineaments, magnetic is perhaps one of the most favourable because it has the ability to collect data over large area in a short period of time and at low cost. Furthermore, the airborne magnetic method can be operated remotely, a feature that is not possible for some geophysical methods such as seismic. Several approaches exist to delineate lineaments from magnetic data and among these approaches the gradient based filters such as Sobel, Prewitt and the total horizontal gradient are the most popular ones. However, the gradient based approaches suffer from a number of disadvantages because they use the magnitude part of magnetic images to extract geological features. The magnitude carries little structural information and thus the detected lineaments are in general weak and often do not mapped appropriately. Besides, gradient based filters are sensitive to variations in image direction, rotation, magnitude and scale and consequently lead to inaccurate locations of lineaments. For these reasons, we are exploring a new lineament detection approach that we believe is more efficient and accurate than gradient based filters because it is using the local phase of the image instead of it local magnitude. Unlike magnitude based gradient filters, phase based filters carry most of the structural information in the image and the detected features are invariant to image direction, rotation, magnitude and scale. Therefore, the detected lineaments are expected to be sharper, more coherent and positioned at the right locations. Our new approach is derived from two powerful phase based filters; the ‘monogenic signal’ and ‘phase congruency’. For simplicity we call it the ‘monogenic phase congruency’ throughout this study. Phase congruency attempts to find locations in a signal where all the FFT harmonics in the frequency domain are in-phase. These locations correspond to zones of dislocations or in general term lineaments in a magnetic signal. Unlike gradient based filters which excel in identifying edge features lineaments, phase congruency is able to identify all kind of lineaments that include edges and lines. Edges, in geological term, correspond to fault, fracture and lithological contact. Lines, on the other hand, correspond to ridges, igneous dikes, and buried channels. Normally, phase congruency is computed from FFT, wavelet or log-Gabor algorithms but in this work the phase congruency was computed from the local phase information of the monogenic signal. By doing so more lineaments can be detected at more locations than if phase congruency computed from log-Gabor. This uses local phase information derived from the monogenic signal, which is the natural 3-D extension of the analytic signal where Hilbert transform is replaced by Riesz transform. We applied the monogenic phase congruency filter to high resolution aeromagnetic (HRAM) data flown over the Horn River Basin (Fig. 1) which represents one of the largest shale gas plays in Canada. The area selected to test monogenic phase congruency is located in the Horn River of NE British Columbia, Canada. The magnetic dataset (Fig. 2) used is owned by CGG Multi-Physics and was flown with a flight line spacing of 400m oriented NE/SW and a tie line spacing of 1200m oriented EW. The Horn River Basin is located at the eastern edge of the Foothills thrust belt and it is separated from the Liard Basin by a prominent Bovie Fault Zone (Fig. 2). The basin is intersected by three main Precambrian litho-tectonic magnetic basement terranes; Nahanni at the center, Fort Simpson Magmatic Arc to the east, and Fort Nelson Magmatic Arc to the west. The Fort Simpson and Fort Nelson Magmatic Arc Terranes have distinctive NS trending magnetic high and are characterized by the presence of ferrimagnetic minerals, most likely magnetite, which has a sufficiently high susceptibility to produce high amplitude anomalies characteristic of this terrane. The Nahanni terrane which is associated with a magnetic low is interpreted as thinned Fort Simpson basement. The Precambrian basement is covered by sedimentary rocks of the Horn River Basin. The Horn River Basin contains a sequence of stratigraphic horizons and plays that are considered potential for shale gas exploration. The preliminary results are very interesting and we were able to detect various lineaments in a more coherent fashion than is typical when gradient based filters are used. In addition, we were able to rank the lineaments according to the magnitude of phase congruency as weak (magnitude ~ 0) or strong (magnitude ~ 1.0).

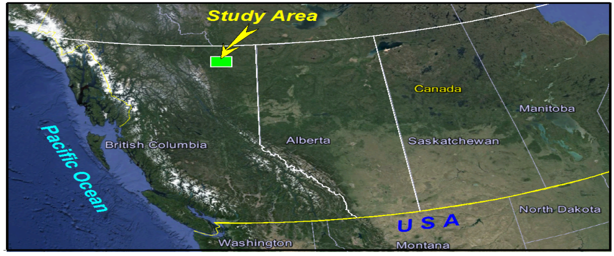


Figure 1. Index map of Horn River Basin.

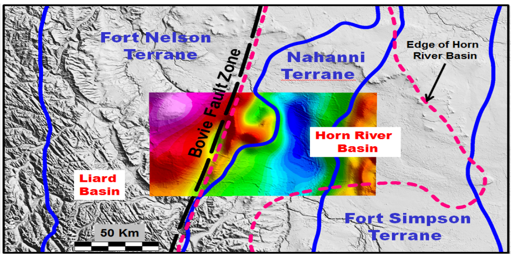


Figure 2. Generalized geology of Horn River Basin showing RTP grid draped on SRTM.

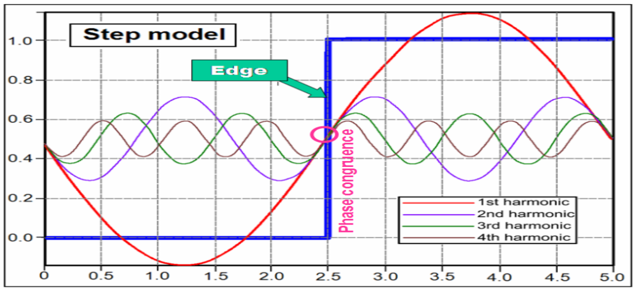
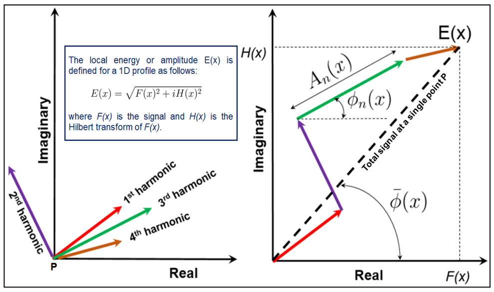


Figure 3. Step function and its FFT harmonics showing phase congruency location.


The local energy or amplitude E(x) is defined for a 1D profile as follows:

$$E(x) = \sqrt{F(x)^2 + iH(x)^2}$$

where F(x) is the signal and H(x) is the Hilbert transform of F(x).

Figure 4. The total signal computed at the location P.

Method

Normally, lineaments are shown as dislocations or discontinuous zones on magnetic images. If these zones are presented as step (edge) function as shown in Figure 1, a condition arises where the Fourier frequency decomposition components (harmonics) of the magnetic image are maximally in-phase. This in-phase condition happens at the break of the step function and is referred to as phase congruency. We exploit this condition to efficiently map lineaments in magnetic data. Being phase based filter, phase congruency is able to effectively map edge lineaments (faults and fractures) as well as line lineaments (i.e. ridges, igneous dikes and buried channels). The computation of phase congruency of an in-phase point **P** is illustrated in Figure 2 for 1-D data. The Fourier harmonics at a location **P** in the signal will each have an amplitude $A_n(x)$ and a phase angle $\phi_n(x)$. Fig. 1 show the magnetic of the total signal vector at point **P** computed from the four Fourier harmonics complex vectors from the origin to the end point local energy $E(x)$.

Phase congruency is a dimensionless quantity that was first introduced by Morrone and Owens (1987) for 1-D data. However, Kovesi (2003) made improvement to the algorithm and extended it to 2-D data. Since then, the algorithm is used in several fields of disciplines including geophysics. For example, Russell *et al.* (2010) used phase congruency to pick faults and fractures from 3-D seismic data. Phase congruency in general is computed from FFT, wavelet or log-Gabor filters but in this study it is computed from the monogenic signal. Therefore, it is referred to as ‘monogenic phase congruency’ throughout this paper. Monogenic signal is the natural 3-D extension of the analytic signal where Hilbert transform is replaced by Reisz transform (Felsberg and Sommer, 2001; Hassan and Yalamanchili, 2013).

The phase congruency (PC) algorithm that was developed by Kovesi (2003) and used in this paper is described below:

$$PC(x,y) = \frac{\sum_s \sum_o W(x,y) \lfloor A_{so}(x,y)\Delta\Phi_{so}(x,y) - T \rfloor)}{\sum_s \sum_o A_{so}(x,y) + \varepsilon} \qquad (1)$$

Where *s* and *o* denotes computation over scales and orientations, respectively; The symbols $\lfloor\ \rfloor$ denote that the enclosed quantity is equal to itself if it is positive, and equal to zero otherwise; *W*(x,y) is the sigmoid function used to weight a phase congruency; *T* is a quantity introduced to compensate image noise; ε is a small positive constant used to prevent division of zero; and $\Delta\Phi_{so}$(x,y) is a sensitive phase deviation function defined as:

$$\triangle\Phi_{so}(x,y) = cos(\phi_{so}(x,y) - \bar{\phi}(x,y)) - |\, sin(\phi_{so}(x,y) - \bar{\phi}(x,y))| \qquad (2)$$

The monogenic signal $f_M(x,y)$ is therefore defined as the three-dimensional vector formed by the real signal *f(x,y)* with its real (h_1) and the imaginary (h_2) Riesz transforms as follow:

$$f_M(x,y) = f(x,y) + i[h_1(x,y) * f(x,y)] + j[(h_2(x,y) * f(x,y)] \qquad (3)$$

The monogenic amplitude (A_{so}) and phase (Φ_{so}) can be computed as follow:

$$A_{so}(x,y) = \sqrt{I_{so}^2 + (h_1 * I_{so})^2 + (h_2 * f)^2} \qquad (4)$$

$$\phi_{so}(x,y) = tan^{-1}\left(\frac{I_{so}}{\sqrt{(h_1 * I_{so})^2 + (h_2 * I_{so})^2}}\right) \qquad (5)$$

Thus the monogenic phase congruency can be obtained by substituting equations (4) and (5) in equation (1) above.

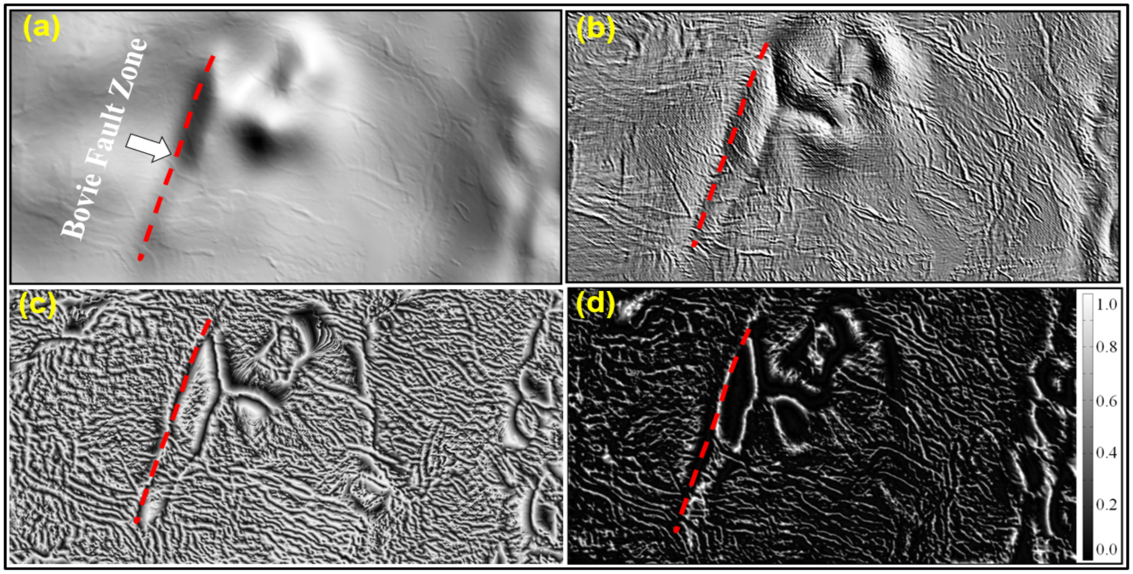


Figure 5. Input data and its corresponding monogenic phase congruency results, (a) RTP total magnetic intensity image used as input, (b) Horizontal gradient of RTP image, (c) Phase of RTP image computed using the monogenic signal, and (d) computed monogenic phase congruency of the RTP total magnetic field image shown in Figure 5a.

Results

The reduced to the pole (RTP) total magnetic intensity image (Fig. 5a) was used as an input to calculate the monogenic phase congruency. Figure 5b shows the total horizontal gradient image of the input image (Fig. 5a) that we normally use for lineament detection. Prior to computing the monogenic phase congruency the phase (Fig. 5c) and the amplitude of the monogenic signal were computed. The lineaments displayed on the monogenic phase (Figures 5c) appear to be focused and more coherent in contrast to the one computed using traditional way of enhancing lineaments (Fig. 5b). The Bovie Fault zone, for example, is well defined in Figures 5c in comparison to Figure 5b. The monogenic phase congruency image computed from equation (1) is displayed in Figure 5d. In addition to lineaments, Figure 5d shows lineament magnitudes ranging from zero to one; zero (dark areas) indicates that no lineaments exist and one (bright areas) indicates strong lineaments. For example, the Bovie Fault Zone is associated with monogenic phase congruency of one (i.e., strong lineament).

Conclusion

In this paper, a new approach based on the monogenic signal and phase congruency filter called ‘monogenic phase congruency’ is introduced to analyze lineaments over shale gas play of the Horn River Basin of NE British Columbia, Canada. This new approach appears to be more superior than traditional lineament mapping techniques such as the total horizontal gradient that we typically use to analyze lineaments as it gives better results (i.e., sharper, more coherent and continuous). Furthermore, with the monogenic phase congruency it is possible to rank lineaments into weak or strong based on their magnitude. Weak lineaments are associated with low magnitude monogenic phase congruency whereas strong lineaments, such as the Bovie Fault Zone in the Horn River Basin example, are associated with high magnitude monogenic phase congruency.

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