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IDENTIFYING GEOLOGICAL STRUCTURES USING MULTI-SCALE EDGE DETECTION: EXAMPLES FROM THE HOPEDALE AREA, LABRADOR (NTS Map Sheets 13M/01, 02, 07, 08, 09, 10, 15, 16 and 13N)

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ABSTRACT

In mineral exploration, potential field methods, which are geophysical techniques that use variations in the Earth's gravity and magnetic fields, play a critical role in mapping near-surface and deep geological structures. In addition to conventional applications, the data-processing technique of multi-scale edge analysis is a powerful tool for identifying structural and lithological boundaries at various depths by analyzing sharp changes in magnetic and gravity data. This study explores the application of multi-scale edge-detection techniques, particularly the worming method, to enhance the structural interpretation of potential field data. It focuses on horizontal and vertical derivative-based methods, such as the tilt angle and horizontal gradient magnitude, which are interpreted to highlight sharp lateral changes in rock properties. Additionally, pseudo-gravity transformation was employed to enhance the expression of deeper structures while reducing the dominance of shallow sources. This study integrates upward continuation techniques to examine the geological boundaries at different depths.

The methodology was applied to aeromagnetic data from the Hopedale block, Labrador, revealing multi-scale edge structures that provide insights into fault zones, contacts and the geometry of subsurface sources. The results demonstrate that the worming approach effectively delineates both shallow and deep-seated geological features, aiding mineral exploration and structural interpretation. This report summarizes the theoretical underpinnings and historical development of these geophysical techniques, setting the stage for a detailed presentation of the methodology and findings in the Hopedale area.

INTRODUCTION

Potential field methods are geophysical techniques used to study variations in the Earth's gravitational and magnetic fields to infer subsurface structures (Milsom and Eriksen, 2013). These methods rely on naturally occurring fields (*i.e.*, gravity and magnetism) to detect changes in rock density, magnetic susceptibility, composition and structure, without direct physical contact or sampling. Potential field methods are widely used in mineral exploration and geological mapping, where magnetic surveys help identify ore bodies with high magnetic susceptibility (*e.g.*, iron ore, if present, as magnetite) or gravity surveys help detect dense ore bodies (*e.g.*, massive Pb–Zn mineralization). Potential field data have traditionally been interpreted using a standard set of data processing techniques. Raw data are processed to remove noise and instrumental errors by applying several standard corrections (*e.g.*, diurnal correction to remove variations in the Earth's magnetic field due to solar activity, levelling, tie line correction, *etc.*). Further enhancements and filtering of the data are applied to highlight specific features. Examples include reduction-to-the-pole, which converts magnetic anomalies to appear as if measured at the Earth's north magnetic pole, reducing distortion due to the Earth's magnetic inclination. Once the data are ready, various edge-detection techniques, which are the purpose of the current study, can be used to delineate geological structures. Knowledge of these boundaries is crucial for investigating structural settings, environmental and engineering applications, and for utilizing the information as constraints in 2D and 3D modelling.

Boundary analysis methods include traditional methods such as first and second directional derivatives, analytical signal (*e.g.*, simple analytic signal, enhanced analytic signal and theta map), and tilt angle methods (*e.g.*, tilt angle, horizontal derivative of tilt angle, hyperbolic tilt angle, directional and second tilt angle), Enhanced Horizontal derivative, normalized statistics and Euler deconvolution. Detecting the horizontal boundaries of gravity and magnetic anomaly sources is frequently required in potential field interpretation. However, accurately locating these boundaries is challenging because of the inherent loss of resolution in the anomalous shape compared to the source shape, especially for deeper sources. Boundary analysis of gridded gravity or magnetic anomalies is typically done using wavelet analysis (Hornby *et al.*, 1999), a mathematical function used to decompose a signal into different frequency components, allowing analysis at multiple scales (Kumar and Foufoula-Georgiou, 1997). This can help identify both shallow and deep sources of magnetization. Wavelet analysis is closely related to methods used in potential field analysis, such as the analytic signal (total gradient), tilt derivative functions, Euler deconvolution and curvature functions, which have all been used to map the edges of source bodies (Blakely and Simpson, 1986; Grauch and Cordell, 1987). Other methods include directional derivatives and analyzing horizontal and vertical derivatives (Nabighian *et al.*, 2005), which help identify sharp lateral changes in rock properties (Blakely and Simpson, 1986). The gradients, enhanced by multi-scale edge detection in gravity and magnetic data, provide information from different depths by integrating gravity, pseudo-gravity and aeromagnetic data (Archibald *et al.*, 1999). This study discusses the horizontal derivative of the tilt angle method and produces worms for identifying and mapping geological boundaries using magnetic and pseudo-gravity data. It can help structural geologists with geological mapping by highlighting both deep and shallow anomalies and identifying the dip direction of the contacts.

Historical advances in data processing include the method proposed by Blakely and Simpson (1986), which provides an effective approach for automatically identifying and analyzing the peaks (maxima) of the horizontal gradient magnitude. Thurston and Brown (1994) designed a convolution operator to regulate the frequency content of horizontal derivatives, thereby refining the resulting edges. Cooper and Cowan (2003) introduced the integration of visualization techniques with fractional horizontal gradients to more accurately emphasize subtle features of interest. Pilkington and Keating (2004) compared five edge-detection methods, including tilt angles, and found that no single technique was ideal for reliable contact mapping. High-resolution methods tend to amplify noise, demonstrating the usual trade-off between resolution and stability. They recommended using all five methods together, as overlapping results increase confidence in contact locations and reduce the impact of factors such as source magnetization, dip, interference and depth.

METHODS AND TECHNIQUES

The tilt angle-based methodology encompasses several key techniques aimed at optimizing the detection of geological boundaries. The following sections describe the horizontal derivative of TA, and the process for generating worms (geological boundaries). Each step is selected for its ability to enhance different aspects of the potential field data. Figure 1 depicts the flowchart of the edge-detection process.

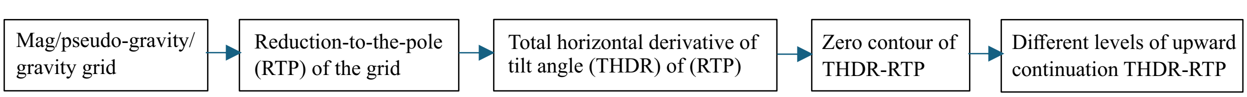

Figure 1. *Flowchart of the THDR edge-detection process.*

TILT ANGLE BASED METHODS

Tilt Angle (TA)

Measures of the local phase, such as the tilt angle (TA), can aid interpretation. The TA is defined as the arctangent of the ratio of the first vertical derivative to the total horizontal gradient (Miller and Singh, 1994). The TA can be used to estimate the horizontal location and lateral extent of the magnetic sources (Miller and Singh, 1994) after applying the reduction-to-the-pole (RTP) transformation. This method is useful for identifying high-angle contacts, faults, and shear zones. The following equations control the vertical and horizontal gradients along a horizontal line perpendicular to the vertical contact where two bodies with varying magnetic susceptibilities come into contact:

The Tilt Angle (T) is defined as

$$T=\tan^{-1}\left[(\delta f/\delta z)/(\delta f/\delta h)\right]$$

$$\delta f/\delta h = \sqrt[2]{((\delta f/\delta x))^2 + (\delta f/\delta y)^2)}$$

where f is the magnetic or gravity field.

For every anomaly, the TA ranges from +90° over the top of a vertical mass to -90° at infinity from the body. Directly above the point where a magnetic source and the surrounding rock make contact is the 0° angle line. This represents the angle between the vertical and horizontal vectors (Zengerer, 2018), which enables precise source location estimation. It is positive over the source, passes through zero over or near the edge (where the vertical derivative is zero and the horizontal derivative is maximum), and is negative outside the source region.

Miller and Singh (1994) discussed that the TA, as a dimensionless ratio, is effective in detecting sources at both shallow and deep sources equally well, without being influenced by the depth of the source. Because the TA is based on the ratio of derivatives, it enhances large- and small-amplitude anomalies. The TA is effective in balancing the amplitudes of the different anomalies. However, it is not primarily an edge-detection filter (Cooper and Cowan, 2008).

Horizontal Derivative of the Tilt Angle

Verduzco *et al.* (2004) suggested using the total horizontal derivative (THDR) of the tilt angle as an edge detector. Although the basic TA helps balance the amplitudes, it can sometimes blur the exact location of the edges. In contrast, THDR is the derivative of the TA. It is specifically designed to detect edges more precisely. It also clearly highlights boundaries (Verduzco *et al.*, 2004).

The formula for the THDR is given as the square root of the sum of the squares of the horizontal derivatives of the TA.

$$THDR = \sqrt{((\delta T/\delta x)^2 + (\delta T/\delta y)^2)}$$

Pilkington and Keating (2004) showed that the THDR is closely related to local frequency. According to Thurston and Smith (1997), the local or instantaneous frequency is a derivative-based attribute. It reflects how quickly the direction of the signal changes at each point. This helps to highlight edges or boundaries in geophysical data, such as geological contacts or faults.

The THDR of the TA method enhances magnetic data interpretation by precisely identifying the edges of the geological structures. It reliably maps vertical contacts and improves the clarity of underground sources. Additionally, zero contours of the tilt angle, derived from multiple upward continuation levels, offer valuable insights into the spatial distribution of the geological boundaries.

WORMING

APPLICATION OF WORMING TO MAGNETIC AND GRAVITY

Worming is a geophysical technique used specifically in multi-scale edge detection of potential field data to identify the edges of magnetic or gravity sources as they extend deeper into the subsurface. This method identifies local maxima in the total horizontal gradient of the potential field data, where these maxima are typically associated with the boundaries of the source bodies. The total horizontal gradient method (magnitude of the horizontal gradient of the field, $\sqrt{((\partial f/\partial x)^2 + (\partial f/\partial y)^2)}$) enhances the edges, but the result is often dominated by the response from shallower, larger amplitude anomaly bodies. However, in the current study, local maxima in the horizontal gradient of the tilt angle (THDR) were used. By using the TA, which balances amplitudes, THDR can highlight both shallow and deeper edges more effectively. However, careful application is required to avoid misinterpretation (Grauch and Cordell, 1987). The migration of these maxima is tracked across a series of upward-continuation heights. This process helps distinguish between shallow and deep structures, as larger, deep-seated features retain strong signals over greater distances, whereas smaller, localized sources become less prominent (Holden *et al.*, 2000; Lahti and Karinen, 2010). Smaller scale edges are typically associated with shallow sources, whereas larger scale edges are associated with deeper structures. This approach is particularly effective for large-scale structural analyses. Cordell and Grauch (1982, 1985) developed a three-step method for identifying the edges of magnetic bodies: A) Pseudo-gravity Transformation: Magnetic data are converted into a pseudo-gravity field using the method introduced by Baranov (1957); B) Gradient Calculation: The horizontal gradient of the pseudo-gravity anomaly is computed, as peak gradients generally align with the edges of shallow magnetic sources; and, C) Edge Detection through Contour Mapping: The maxima of these gradients are mapped to identify linear features, representing the boundaries of magnetic bodies. For gravity data, only the gradient calculation and contour analysis steps are required (Cordell, 1979). This method effectively highlights geological boundaries by transforming magnetic data into gradients that delineate source edges. Contour maps provide a visual representation of these features, offering insights into the gradient strength, source geometry, dip direction, and depth. Magnetic edge-detection methods have evolved since the original work of Cordell and Grauch (1982, 1985). Although the pseudo-gravity transformation is not essential for generating "worms" (*i.e.*, edge detection *via* maxima of horizontal gradients) in modern workflows, it remains useful in specific contexts, particularly for enhancing deeper or regional structures. In the present study, edge detection was performed using both the original magnetic data and its pseudo-gravity transformation.

The magnetic data were first reduced to the pole (RTP), then transformed to pseudo-gravity to enhance the visibility of deeper features and enhance the accuracy of edge detection. This step helps compensate for the limitations of the total horizontal derivative of the tilt angle. THDR may perform better with shallow sources and underrepresent deeper anomalies. By using both, the magnetic and pseudo-gravity data, the analysis provides a more comprehensive delineation of geological structures at varying depths.

Field Example

In 2018, a large aeromagnetic survey was conducted in the Hopedale area, Labrador, funded by the GEM GeoNorth program (Coyle, 2019). The survey was flown with a line spacing of 200 m, and tie line at a spacing of 1200 m at N135°E and N45°E, respectively. The altitude and terrain clearance was 100 m. The flight specifications are listed in Table 1. Tie line processing was rigorously applied to the Hopedale survey dataset, yielding a highly consistent and well-levelled dataset. This dataset is available for viewing on the NL Geoscience Atlas.

Table 1. The Hopedale area aeromagnetic survey characteristics

Area	Traverse Line Azimuth	Line-km	Spacing	Tie Line Azimuth	Line-km	Spacing	Terrain Clearance
Hopedale	N135°E	105 361	200 m	N45° E	17 710	1200 m	100 m

The processing steps were applied to the aeromagnetic data of this survey.

Before the transformation to pseudo-gravity, the residual magnetic intensity data need to be reduced-to-the-pole (Figure 2).

Pseudo-gravity (Magnetic Potential)

The pseudo-gravity transformation converts magnetic data into a gravity-like response, utilizing principles established within potential field theory, notably Poisson's equation (Baranov, 1957). This mathematical correlation indicates that, under conditions of uniform magnetization and a constant density-to-magnetization ratio, the RTP magnetic field approximates the vertical gradient of the gravitational field. The implementation of the pseudo-gravity transformation begins with the reduction of magnetic data to the pole (RTP) and is subsequently followed by a vertical integration operation. This process converts the magnetic field into a gravity-like field by treating the magnetic sources as gravity sources. This is predicated on the differential decay rates of magnetic and gravity fields, while the former diminishes with distance according to a $1/r^2$ relationship, emphasizing near-surface anomalies. The latter decays at a more gradual rate of $1/r$, which accentuates deeper structural features. Hence, the transformation augments the decay characteristics of the magnetic field, aligning it more closely with that of the gravitational field, thereby improving the visualization of deeper geological formations.

Essentially, the transformation incorporates an inverse vertical derivative operation, which significantly enhances the long-wavelength components within the magnetic signal. Long-wave-

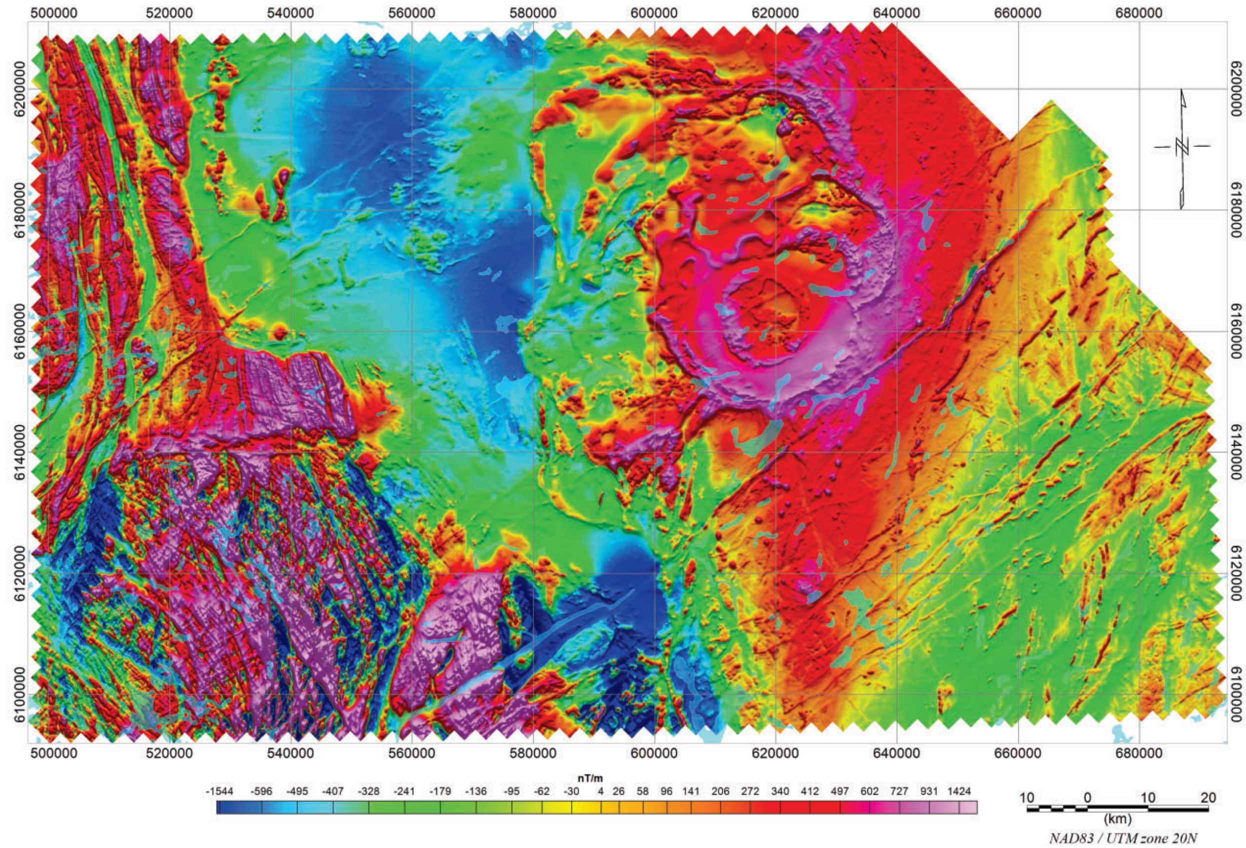

Figure 2. *RTP magnetic data of the Hopedale block, Labrador.*

length anomalies typically correspond to extensive, deeply seated geological structures in contrast to short-wavelength anomalies that align with smaller, more superficial sources. By emphasizing these longer wavelengths, the pseudo-gravity transformation effectively highlights significant geological features such as tectonic boundaries and extensive crustal intrusions, while concurrently diminishing the influence of shallow, high-frequency anomalies.

Similar to gravity anomalies, pseudo-gravity anomalies exhibit the steepest gradients that are roughly aligned with the edges of geological formations. Consequently, Cordell and Grauch (1982, 1985) utilized the crests of the horizontal gradient magnitude of the pseudo-gravity field as an approximate method to identify the edges of magnetic bodies. This approach can also be effectively applied to RTP magnetic fields. This can help to highlight deeper or smoother source edges. Figure 3 shows the pseudo-gravity transformation of RTP magnetic data of the Hopedale block, representative of regional geological features helps highlight deep, large-scale anomalies. Compared with the RTP magnetic data, the pseudo-gravity transformation more clearly emphasizes longer-wavelength responses associated with deeper or more extensive sources.

Upward Continuation Processing

The next step applies to different levels of upward-continuation processing. Upward continuation is a low-pass filtering method emphasizing broader regional features whilst diminishing

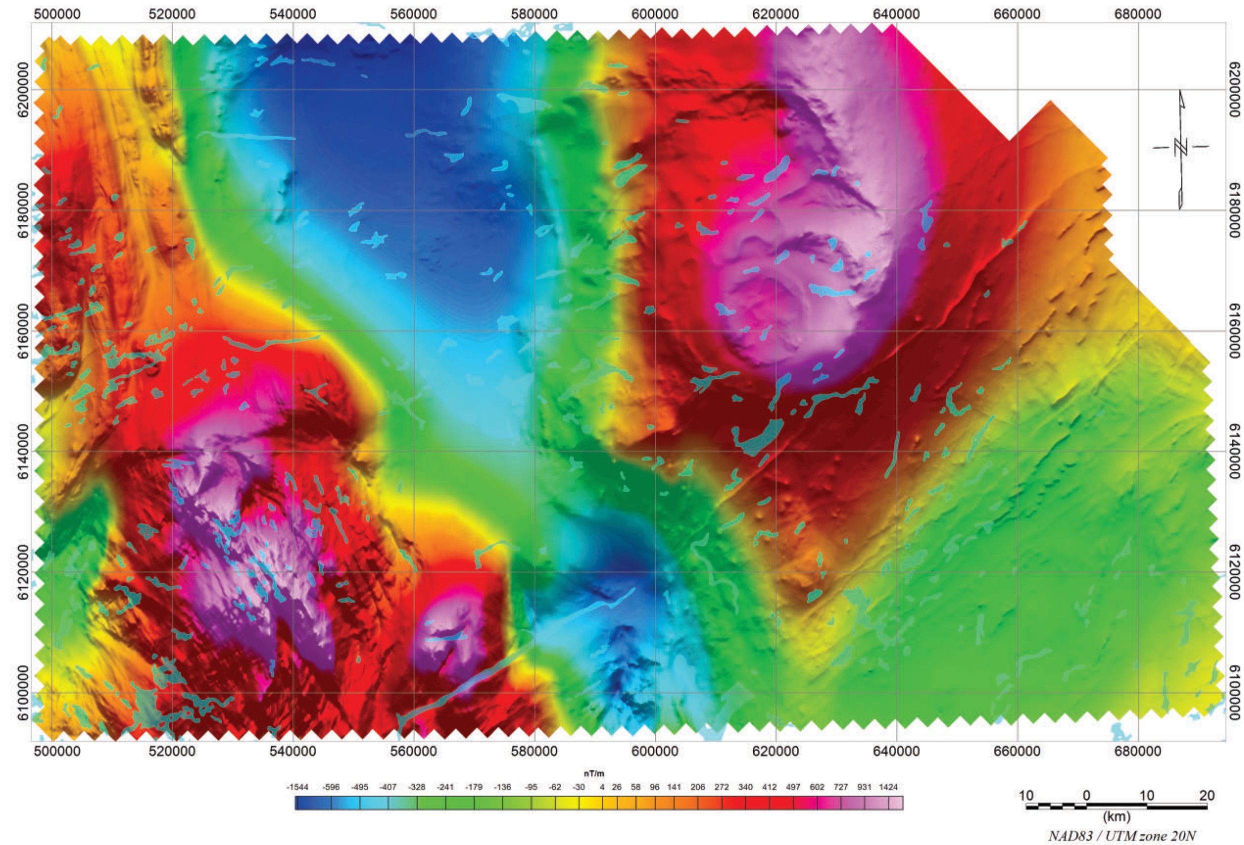

Figure 3. *Pseudo-gravity transformation of magnetic data of the Hopedale block after RTP.*

finer high-frequency details. The upward continuation simulates the magnetic responses as if the same survey were conducted at higher altitudes. As the distance between the detector and source increases, the data resolution and amplitude decrease, preserving only longer wavelength and deeper features. Figure 4 shows different upward continuation levels of the A) magnetic and B) pseudo-gravity data of the Hopedale survey.

Calculating the Total Horizontal Derivative of the Tilt Angle

Various methods have been developed to illustrate the relationship between the geometry of an anomaly and its derivative edges, which indicate contrasts in rock properties. Among these various methods, calculating the full 3D local wavenumber is complex (Huang and Versnel, 2000), whereas focusing on 2D sources yields superior results (Phillips, 2000; Pilkington and Keating, 2004). A simpler alternative for calculating the 3D local wavenumber is to use the horizontal gradient magnitude of the tilt angle which provides a useful approximation (Miller and Singh, 1994; Pilkington and Keating, 2004). The THDR of the TA of the magnetic data and its pseudo-gravity transformation were computed at various levels of upward continuation for the Hopedale area. Figure 5 shows the THDR of pseudo-gravity before upward continuation.

Comparing to THDR, the TDX method (the magnitude of the horizontal gradient of the field, $\sqrt{((\partial f/\partial x)^2 + (\partial f/\partial y)^2)}$), enhances edges, but the result is often dominated by the response from

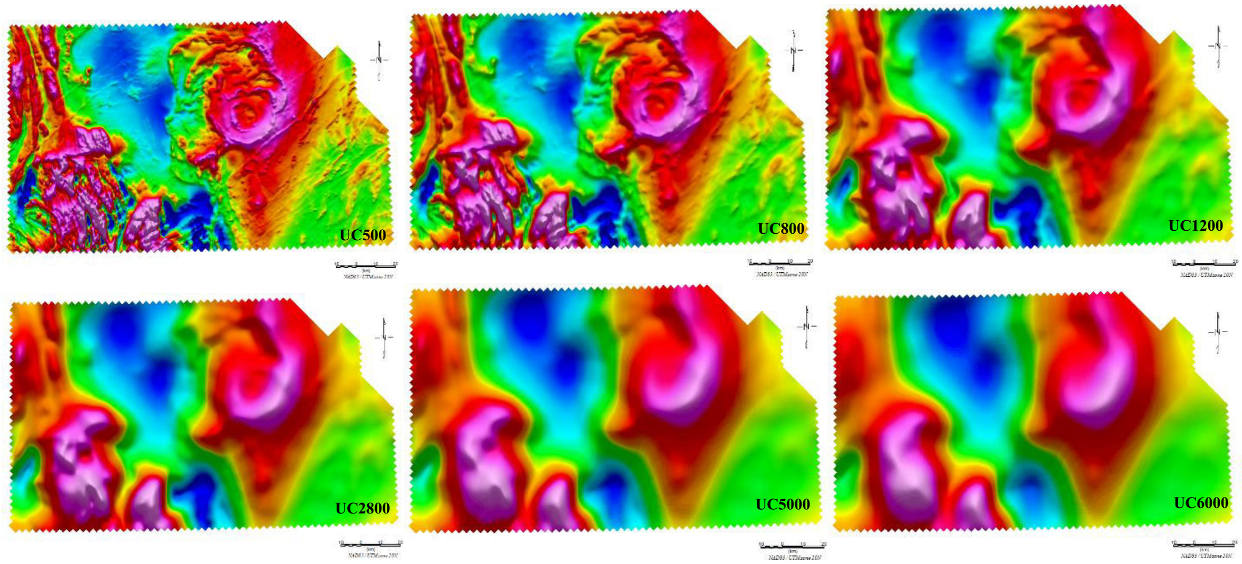

Figure 4. *Different levels of the upward continuation for the magnetic and its pseudo-gravity transformation, Hopedale survey, Labrador.*

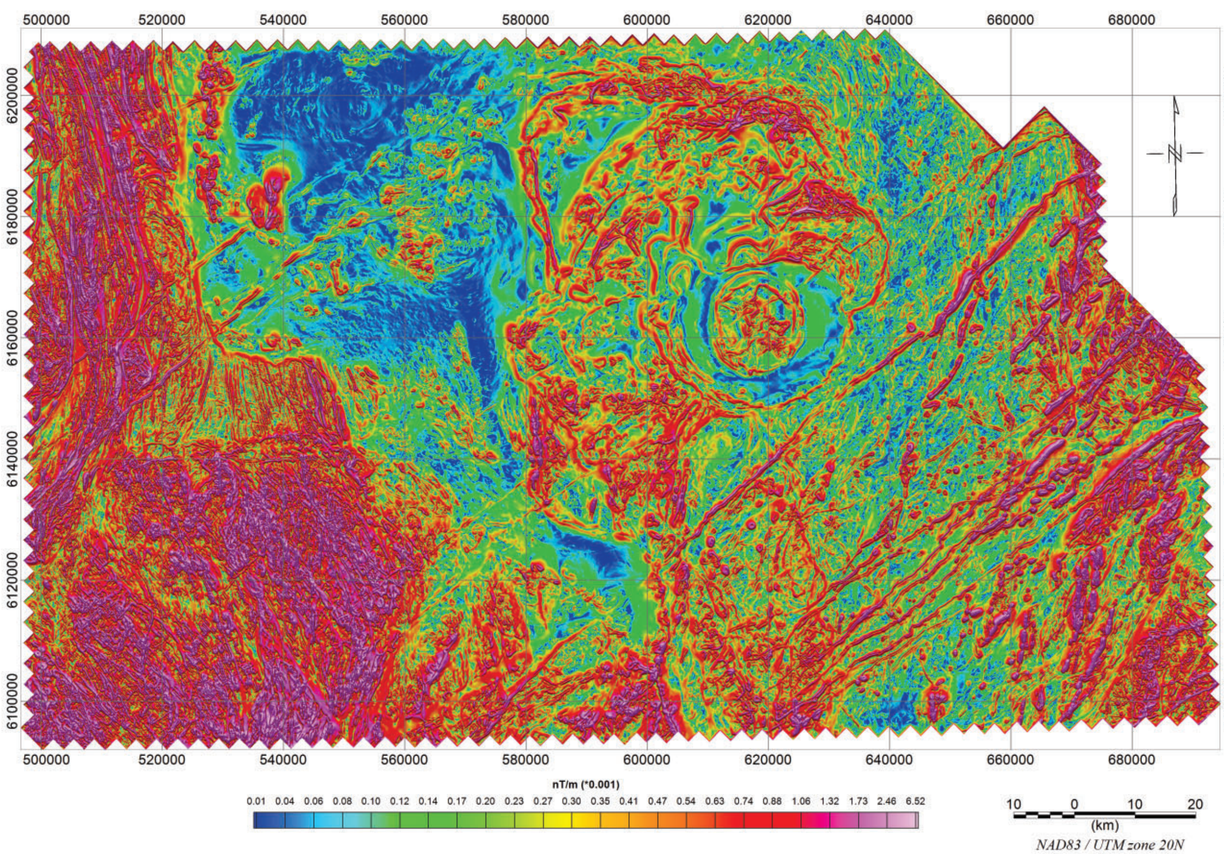

Figure 5. *Total horizontal derivative of the tilt angle of pseudo-gravity transformation (before upward continuation), Hopedale survey, Labrador.*

shallower, larger amplitude anomaly bodies, while THDR, by using the TA, which balances amplitudes, aims to improve upon this problem. In Figure 6, A) the total horizontal derivatives of the tilt angle of RTP magnetic data and B) the total horizontal derivatives of the tilt angle of pseudo-gravity are compared. This illustrates that THDR successfully delineates the edges of the largest amplitude anomaly.

Zero Contours of the Tilt Angle and Maxima of the THDR

These maxima can be identified and mapped as discrete points, thereby providing an objective estimate of their locations for interpretation. A contour map of the TA before any upward continuation was analyzed to identify the linear maxima. In Figure 7, the colours represent gradient strength, and the points align with the inferred edges of the shallow magnetic bodies. This process can create continuous strings that can be mapped at various levels of upward continuation and visualized in 3D, with the upward continuation height serving as the z-dimension. In 3D analysis, these strings offer insights into the gradient strength, source-body edges, dip directions (determined by the dip of multi-scale edge sheets), and depth (Figures 8 and 9).

Interpretation of Worms

Figure 10 illustrates fractured and transfer fault zones interpreted by worming techniques; the red dots represent deep worms, whereas purple dots represent shallow worms.

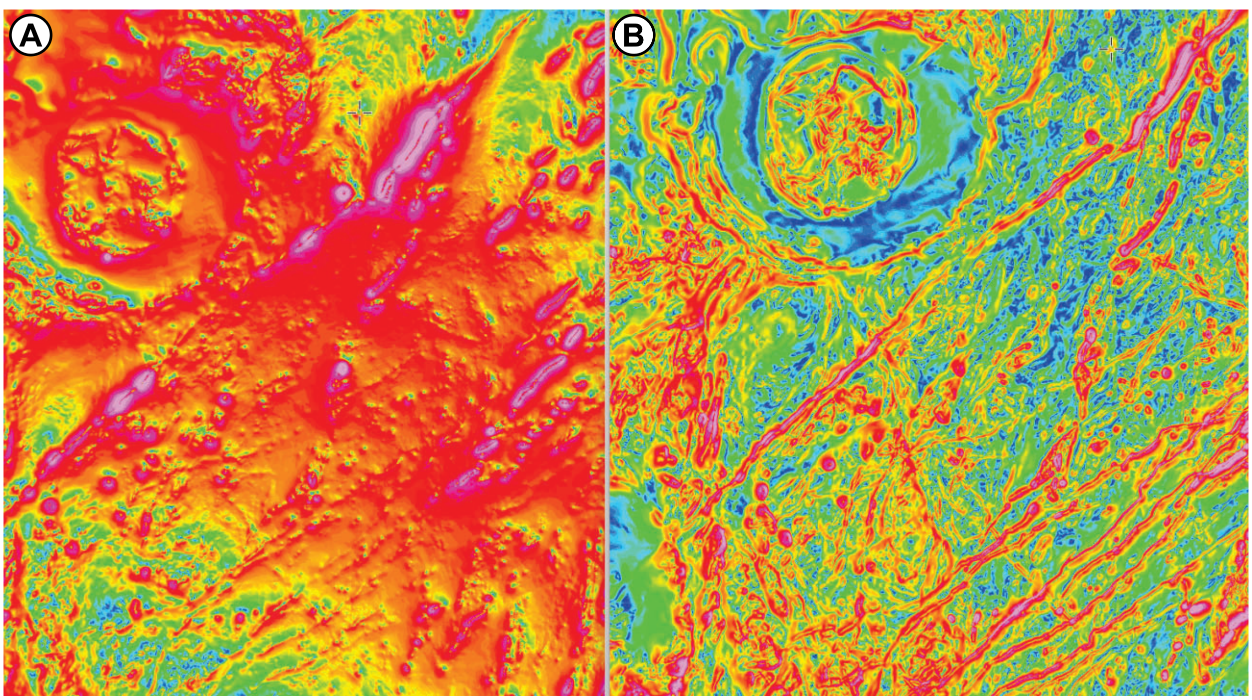

Figure 6. *A) Total horizontal derivative of the tilt angle of RTP magnetic; B) Total horizontal derivative of the tilt angle of pseudo-gravity.*

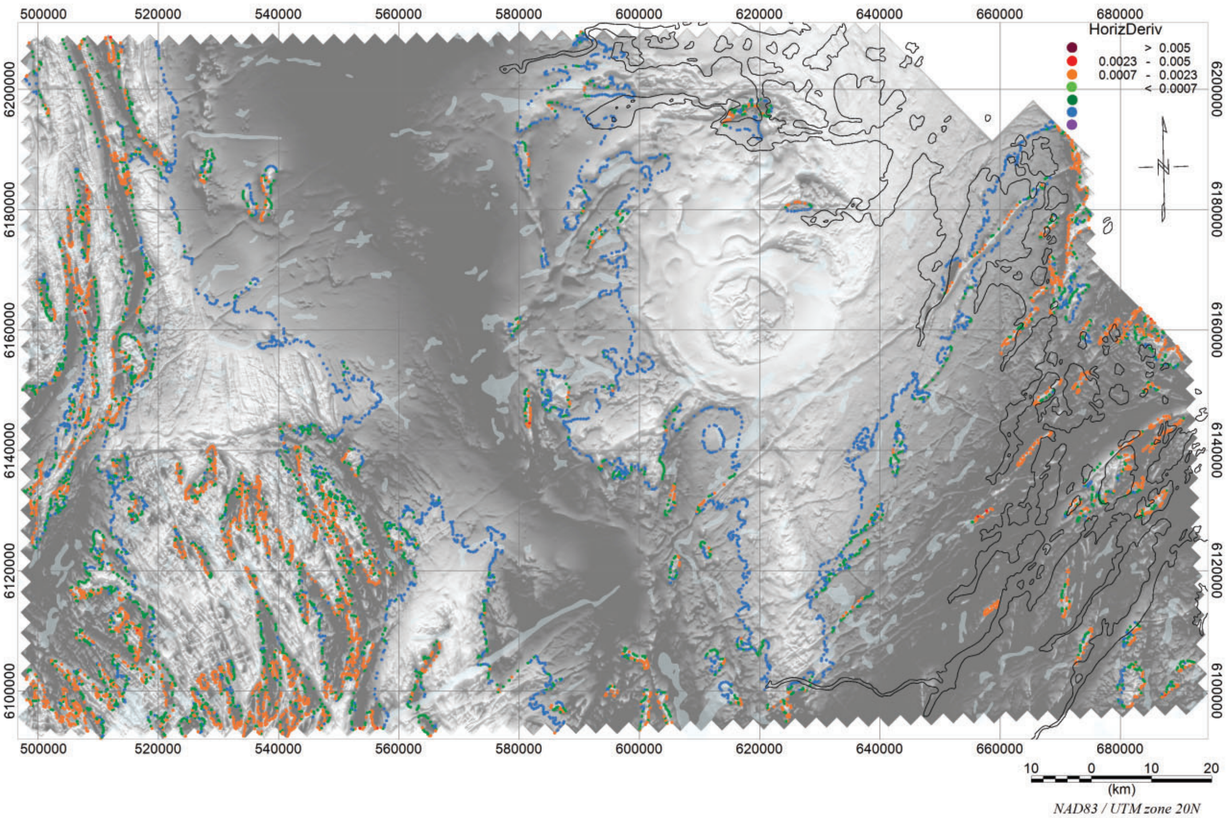

Figure 7. *Points representing the positions of the THDR maxima of the total horizontal derivative (before any upward continuation), coloured by the strength of the gradient, overlying a grey-scale image of the tilt derivative of pseudo-gravity of the Hopedale block dataset.*

CONCLUSIONS

This study demonstrates the effectiveness of multi-scale edge-detection techniques in enhancing geological interpretation using potential field data. By integrating horizontal and vertical derivative-based methods, such as the tilt angle and its horizontal gradient magnitude, this study successfully highlighted structural boundaries at various depths. The application of pseudo-gravity transformation further improved the delineation of deep-seated geological features by reducing the dominance of shallow sources.

The upward continuation technique plays a crucial role in refining geological boundary detection by filtering high-frequency noise and emphasizing broader structural trends. The analysis of aeromagnetic data from the Hopedale area, Labrador, reveals well-defined multi-scale edge structures, aiding in the identification of fault zones, lithological contacts and subsurface geometries. The results indicate that the worming method provides a systematic tool for mapping geological boundaries at different depths.

Overall, these findings highlight the importance of multi-scale edge detection and filtering techniques in geophysical studies. The methodologies presented in this study contribute to improved geological mapping and mineral exploration and offer valuable insights into subsurface

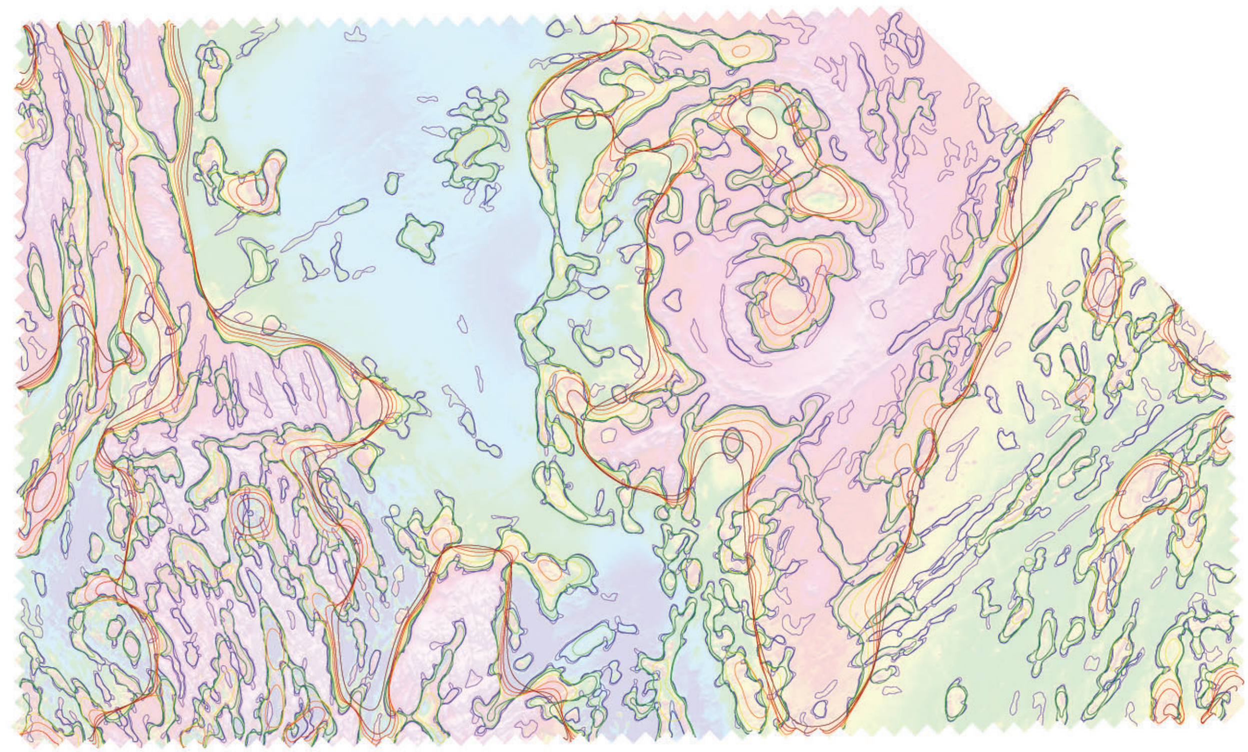

Figure 8. *Location of magnetic boundaries for both shallow and deep structures. Worms generated from magnetic data; different colour multi-scale edges were produced from different upward continuation levels. Red contours show deep worms, and blue ones show shallow worms.*

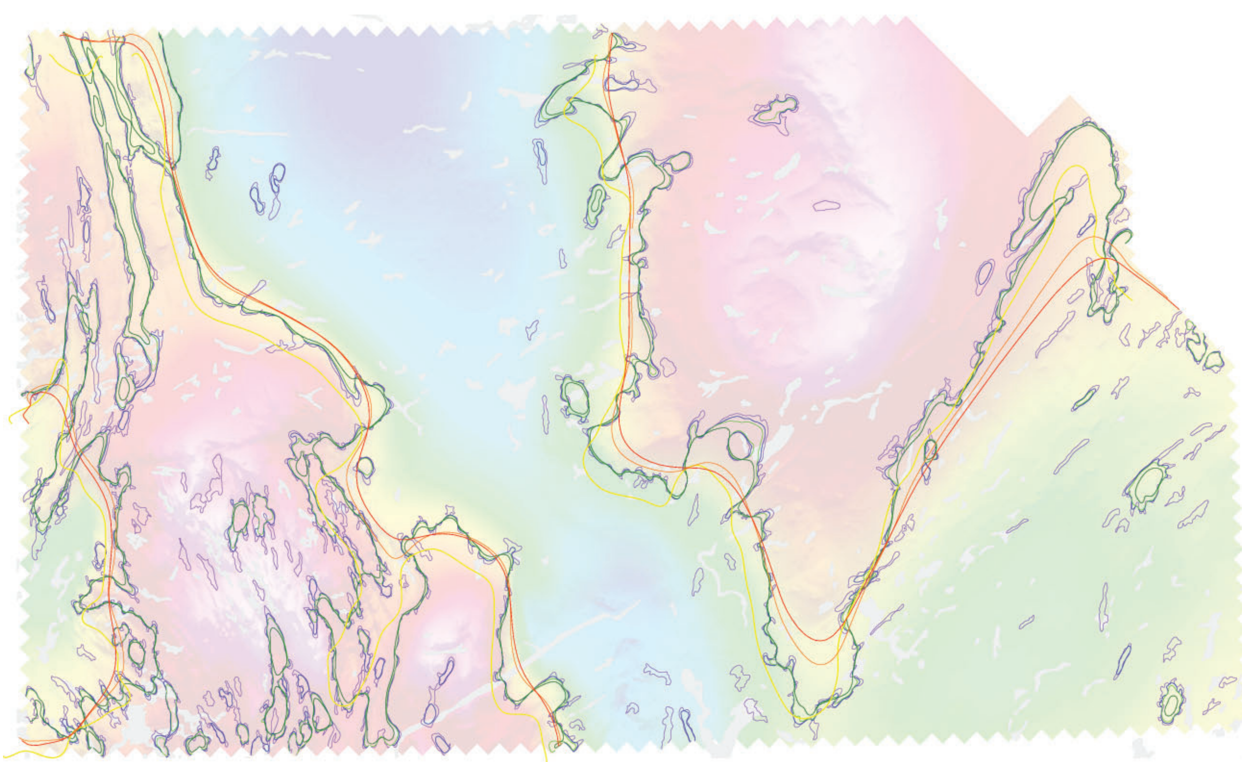

Figure 9. *Contour zero of tilt derivative of the pseudo-gravity transformation, representative of maxima of its horizontal gradient, for different upward continuation levels. Red contours show deep worms, and blue ones show shallow worms (solid line worms).*

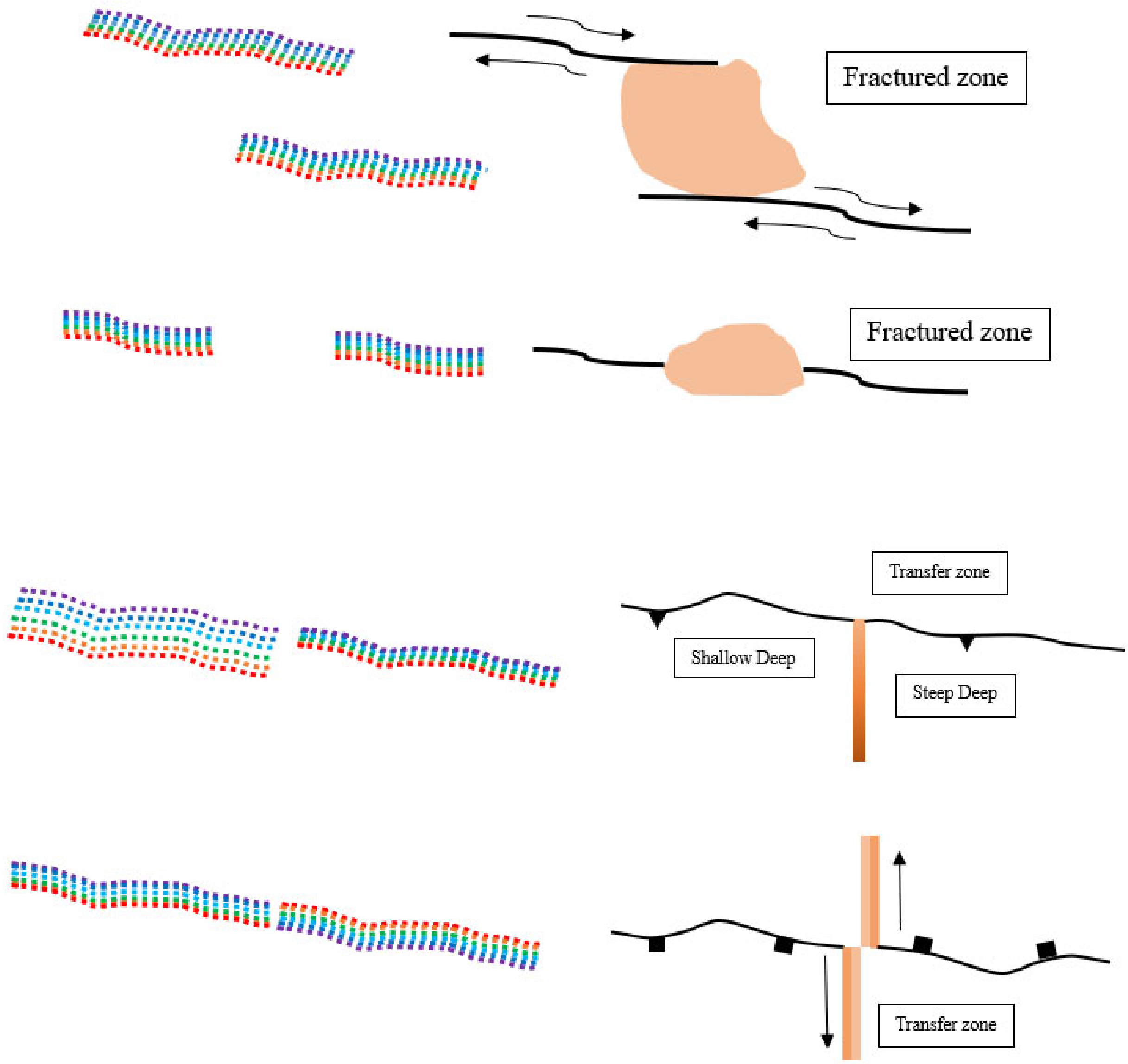

Figure 10. *Interpretation of worms (fractured and transfer fault zones), red dots represent deep worms and purple ones show shallow worms.*

structures. Future research can expand upon these methods using the Enhanced Horizontal Derivative (EHD) method, a new high-resolution technique to define horizontal source locations, as well as integrating 3D inversion modelling and machine-learning techniques to further refine geological interpretations.

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