

Advancements in Magnetic Field Data Processing: Addressing False Edges and Edge Halos

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Abstract

Interpreting magnetic anomalies in complex geological settings is often hindered by false edges and halo artifacts introduced by traditional edge-detection techniques. To overcome these challenges, this study introduces and refines advanced edge-detection filters, including the Modified Total Horizontal Derivative (MTDX) and Modified Theta Angle (MTHETA) filters. Additionally, the study develops Normalized MTDX (NMTDX) as the normalized counterpart of MTDX and Normalized Second-Order Enhanced Analytical Signal (NNSAS) as the normalized version of NSAS, ensuring improved edge delineation and reduced halo artifacts. These improvements effectively suppress spurious anomalies, enhance boundary delineation, and minimize halo effects. The proposed methods are systematically evaluated using both synthetic models and real magnetic data from the Siriz iron ore deposit in Iran. The results demonstrate that the refined filters successfully isolate closely spaced magnetic sources, improve edge resolution, and reduce interpretation ambiguities. Furthermore, drilling results validate the accuracy of the detected anomalies, confirming the reliability of the proposed techniques. The integration of these enhanced filtering approaches with geological and drilling data provides a more robust framework for magnetic anomaly interpretation and subsurface exploration.

Introduction

The geographical distribution of subsurface magnetic sources, which can have different geometries and physical characteristics depending on their depths and locations, can be crucially understood from magnetic anomaly data. Variable magnetic source depths, remanent magnetization strengths, and regional magnetic impacts, among other things, might make it difficult to identify boundaries, making the interpretation of these data intrinsically complicated (Ferreira et al, 2013; Hosseini et al. 2024a). As precisely defining geological structures is crucial for maximizing exploratory drilling, cutting expenses, and improving geophysical interpretations, there is an urgent need for trustworthy edge detection techniques (Blakely 1996; Blakely and Simpson 1986; Varfinezhad et al. 2023; Hosseini et al. 2024b; Hosseini et al. 2024c; Ghanbarifar et al. 2024a; Ghanbarifar et al. 2024b; Talebi et al. 2023).

Magnetic data play a crucial role in geophysical studies, particularly in mapping subsurface structures for resource exploration and environmental applications. By detecting variations in the Earth's magnetic field, these data reveal insights into mineral deposits, geothermal reservoirs, and fault zones. However, interpreting magnetic anomalies presents significant challenges due to overlapping signatures and noise, necessitating the application of advanced filtering and inversion techniques (Hosseini et al. 2021; Hosseini et al. 2025). To address the issue of non-uniqueness in magnetic anomaly interpretation, this study employs multiple filtering techniques, including newly developed normalized filters, to refine and validate the results. A comprehensive and reliable interpretation is achieved through the integration of geological information and the incorporation of drilling results, which provide direct subsurface confirmation. The analysis of outcomes from multiple techniques allows for precise determination of the magnetic source location. By combining these methodologies, the reliability of the findings is enhanced, and ambiguity in identifying the true position of the subsurface body is minimized.

Edge detection filters are widely employed for enhancing potential field data to identify anomaly boundaries and geometries. These filters, often based on horizontal and vertical derivatives, highlight the centers or edges of anomalies through distinct minimum, maximum, or zero-gradient values. Among them, horizontal derivatives like the Total Horizontal Derivative (THD) and variations thereof, such as the Theta angle and TDX filters, are frequently used for boundary delineation (Ma and Du 2013). Yet, derivative-based filters are prone to limitations, including the formation of halo artifacts around edges and the appearance of extraneous edges that may hinder accurate interpretation.

Building on these advancements, researchers have introduced more sophisticated methods to enhance edge detection. For example, the analytic signal filter, introduced by Nabighian (1972, 1984), combines horizontal and vertical derivatives and is independent of magnetic inclination, representing a key advancement in edge enhancement. Similarly, some local phase filters, such as the Total Horizontal Derivative (THD), Theta, and TDX filters, have been developed to improve boundary clarity and reduce false edge artifacts. These filters optimize the application of horizontal and vertical derivatives and analyze phase-related properties in potential field data, enhancing the delineation of subsurface structures. In this study, we employed several well-established filters: the THD filter, which emphasizes lateral variations in potential field data; the Theta filter, which enhances structural boundaries through phase-based analysis; and the TDX filter, which provides sharp gradient detection through vertical derivative normalization for improved sensitivity. Additionally, modified versions of the Theta and TDX filters, namely MTHETA and MTDX, were introduced to further refine edge detection by reducing false artifacts and optimizing derivative applications. Recent studies have also highlighted the effectiveness of normalized approaches to the Total Horizontal Derivative and higher-order derivative filters, underlining the evolving role of filter modification in addressing edge detection challenges (Yao et al. 2016). These approaches represent significant advancements in potential field data processing, as demonstrated in this work (Cooper and Cowan 2006; Ai et al. 2024a, b; Ai et al. 2023, Alvandi and Ardestani 2023; Alvandi et al. 2023; Alvandi et al. 2024; Hosseini et al. 2024a; Ghiasi et al. 2023). This study develops and refines novel edge detection techniques and incorporates normalization to minimize halo and false edge effects while enhancing edge resolution for magnetic anomaly interpretation. By applying these refined filters to both synthetic models and real-world magnetic data from Iran, the effectiveness of these improvements is demonstrated in enhancing boundary detection and resolution for complex geological structures.

Edge detection is a fundamental technique used in geophysical data analysis to highlight significant transitions in potential field data, aiding in the delineation of geological boundaries and subsurface structures. While commonly associated with image processing, its application in geophysics is distinct, as it enhances geophysical interpretation rather than merely enhancing images. Compared to inverse modeling, which relies on mathematical and statistical methods to extract subsurface properties like magnetic susceptibility and density contrast (Hosseini et al. 2025; Sadraeifar et al. 2024; Sadraeifar and Abedi 2024a, b; Ghari et al. 2024; Ghari et al. 2023; Ghanbarifar et al. 2024c), edge detection provides a computationally efficient alternative for structural interpretation. Inverse modeling, particularly in 3D applications, demands significant computational resources and extensive data processing to minimize

cost functions and incorporate geophysical constraints (Li and Oldenburg 2003; Varfinezhad et al. 2019). Despite its computational intensity, inversion remains a powerful tool for estimating depth, geometry, and physical characteristics of geological structures (Abedi et al. 2014). However, edge detection techniques, by comparison, offer a less time-consuming approach to deriving rapid interpretations from potential field data (Hosseini et al. 2024a; Hosseini et al. 2024b; Ghiasi et al. 2023; Ai et al. 2024a).

Recent advancements in geophysical data processing techniques, such as Joint Euler deconvolution, have enhanced depth estimation accuracy for potential field magnetic and gravity data. The effectiveness of these approaches in complex geological settings has been demonstrated, aligning with the present study's focus on accuracy improvement in determining the surface manifestations of magnetic anomalies (Ghanbarifar et al. 2024a, b).

Improved interpretational techniques, including enhanced edge detection filters, have proven valuable for distinguishing geological features in magnetic data. Ghiasi et al. (2023) applied such techniques to the Charmaleh iron deposit, revealing insights into subsurface structures that standard filters could not discern. This research builds on these findings by further refining filters to accurately delineate anomaly edges without producing unnecessary halos or false boundaries (Ghiasi et al. 2023).

Investigations into the geomagnetic characteristics of complex geological regions, such as the Sabzevar ophiolite belt, underscore the need for advanced magnetic processing techniques, which help to distinguish subtle geophysical signatures in structurally diverse environments. Hosseini et al. (2024b) highlighted that unique geomagnetic signatures in areas with complex tectonic features, like those in northeastern Iran, can be effectively interpreted with refined edge detection methods, aiding in accurate boundary delineation of magnetic anomalies.

Geophysical data analysis frequently encounters challenges related to noise and resolution, making precise edge detection of buried sources difficult. Certain techniques have demonstrated effectiveness in improving boundary clarity by refining horizontal gradient calculations and minimizing noise interference. Recent studies indicate that these approaches enhance the reliability of edge detection in complex geological environments, offering a more refined framework for accurately identifying boundaries in magnetic and gravity field data (Ai et al. 2024a, b).

In this research, the TDX and Theta filters are refined and enhanced through effective normalization, resulting in the MTDX and MTHETA formulas. Subsequently alongside MTDX, the NSAS formula (Yao et al. 2016) is normalized between 0 and 1 to achieve accurate results.

Edge detection methods

The most commonly used filter for estimating the boundaries of potential field anomalies is the Total Horizontal Derivative (THD) filter (Blakely 1996; Cordell 1979; Cordell and Grauch 1985):

$$THD = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2} \quad (1)$$

In the equation above, “f” represents the gravity or magnetic field. The maximum value of the horizontal gradient indicates the boundaries of the body, which are influenced by the dip angle of the magnetic body. Since the edges exhibit the highest degree of horizontal variation, they consequently define the maximum values of the edges. However, this filter faces certain challenges, which are addressed by utilizing normalized versions of this filter, such as the theta map and TDX. It's important to note that in magnetic data, the presence of remanent magnetization can cause shifts in anomaly positions, making horizontal gradient methods unreliable. To address this, reducing the magnetic anomaly to the pole (RTP) and applying pseudo-gravity transformations can improve anomaly alignment with the sources. However, if significant remanent magnetization is present, caution must be taken, as the horizontal gradient may not accurately reflect the subsurface structure. The Normalized Source Strength (NSS) method can also effectively suppress the influence of remanent magnetization by normalizing the total-field anomaly using its gradient components. This transformation enhances source localization by reducing dependence on the magnetization direction, making the results comparable to gravity anomalies. The approach is particularly useful in areas with strong remanent magnetization, as it highlights structural features rather than dipolar magnetic effects. (Long et al. 2024, 2025).

The Analytical Signal (AS) is commonly defined as the square root of the sum of the squared first-order spatial derivatives of the magnetic field. Mathematically, it is expressed as:

$$AS(x, y) = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 + \left(\frac{\partial f}{\partial y}\right)^2 + \left(\frac{\partial f}{\partial z}\right)^2} \quad (2)$$

where:

- f is the magnetic field,
- $\left(\frac{\partial f}{\partial x}\right)$, $\left(\frac{\partial f}{\partial y}\right)$ and $\left(\frac{\partial f}{\partial z}\right)$ are the first-order spatial derivatives of “f” in x, y, and z directions respectively.

It's worth noting that this formulation is based on the Euclidean norm (also known as the Frobenius norm in matrix form)."

In the Theta map filter, the total horizontal derivative is normalized by the first-order amplitude of the analytical signal, and its value is calculated from equations (1) and (2) (Wijns et al. 2005):

$$Theta = \cos^{-1}(THD/AS)$$

In this context, the numerator of the fraction represents the total horizontal gradient, while the denominator reflects the amplitude of the analytical signal (total gradient). This filter aids in estimating the boundaries of the source bodies that produce potential field anomalies. The cosine of the theta angle can also be utilized to determine the dip of the body, as the graph's shape becomes asymmetrical, with its deviation increasing in the direction of the body's slope. A limitation of using this filter for magnetic data is that the data must first be reduced to the pole or equator to eliminate their dipolar characteristics (Cowan and Cooper 2005). In this case, the minimum values indicate the boundaries of the source body responsible for the magnetic anomaly.

The TDX filter was introduced by Cooper and Cowan (2006). In this filter, the absolute value of the first-order vertical derivative (FVD) is used to normalize the Total Horizontal Derivative (THD), with the relationship expressed as follows:

$$TDX = \tan^{-1} (THD / |\frac{\partial f}{\partial z}|)$$

4

The TDX filter exhibits the sharpest gradient at the edges of structures or bodies (Cooper 2015). In this context, normalization (filtering) is conducted using the vertical derivative of potential data, which increases the filter's sensitivity to noise. Typically, the Total Horizontal Derivative (THD), theta, and TDX filters are commonly used local phase filters that identify the edges of potential field anomalies based on both horizontal and vertical derivatives (Blakely 1996; Cordell and Grauch 1985; Roest et al. 1992; Hsu et al. 1996; Fedi and Florio 2001).

Naghbian (1972, 1984) and Roest et al. (1992) utilized the maximum amplitude of the analytical signal (AS) to identify the edges of anomaly sources. One of the main advantages of the analytical signal is that its magnitude is independent of the characteristics of the mass magnetization vector, including inclination angle, declination angle, residual magnetism, and mass slope (Salem and Ravat 2003). However, a challenge associated with the analytical signal technique is the potential interference from nearby anomaly sources (Hsu et al. 1996). In earlier studies, researchers such as Ma (2012) and Cooper (2014, 2015) have used enhancements of the analytical signal to estimate depths from magnetic data.

Yao et al. (2016) engaged the first to third orders of the enhanced analytical signal to locate the edge, in conjunction with the application of diverse vertical derivative orders of potential field data for normalization, referred to as normalized enhanced analytical signals. In this study, the second order, which yields the most favorable results, is taken into account. The second-order formula for the enhanced analytical signal amplitude (SAS) and its normalized counterpart (NSAS) is as follows:

$$SAS = \sqrt{\left(\frac{\partial f_z}{\partial x}\right)^2 + \left(\frac{\partial f_z}{\partial y}\right)^2 + \left(\frac{\partial f_z}{\partial z}\right)^2}$$

5

$$NSAS = \tan^{-1} \left(\frac{SAS}{|\partial^2 f / \partial z^2| + p \cdot \max(SAS)} \right)$$

6

In this formula, f_z represents the first-order vertical derivative of the potential field. Also, $\frac{\partial f_z}{\partial x}$, $\frac{\partial f_z}{\partial y}$, and $\frac{\partial f_z}{\partial z}$ denote the first order derivatives of f_z . Additionally, $\frac{\partial^2 f}{\partial z^2}$ corresponds to the second-order vertical derivative of the potential field, while p represents a non-negative continuous value within the range of 0 to 0.5, as defined by the interpreter. Yao et al. (2016) introduced the p -value to avert the creation of unrealistic edges when anomalies encompass both positive and negative instances. If the anomalies are uniformly positive or negative, the p -value can be set to zero. Otherwise, the p -value remains as a constant and positive value. A substantial p -value reduces the effectiveness of the balancing capacity, whereas a small p -value enhances the identification of edges for anomalies with minimal amplitudes. It's worth noting that $p \cdot \max(SAS)$ represents the multiplication of the chosen p by the maximum value of the SAS. The selection of an optimal p -value is based on the geological characteristics of the study area and the assessment of multiple filtered results, allowing the interpreter to achieve well-normalized and precise maps. However, when multiple bodies exhibit similar magnetization but are at different depths, this procedure primarily strengthens the uppermost body. Nonetheless, deeper effects can still be detected unless their influence is explicitly suppressed. This is particularly relevant since real magnetization data is often uncertain, making the choice of the p -value and the overall interpretation of the results more challenging. To mitigate these uncertainties and achieve a more comprehensive interpretation, it is essential to apply multiple filters and consider various influencing factors. This highlights the necessity of applying multiple filters and considering various factors to ensure a robust final interpretation. Importantly, this approach provides geoscientists with the flexibility to select the most suitable results from a broad range of edge-detection outputs by testing multiple p -values along with applying and comparing various different filters, ultimately enhancing the reliability of the interpretation. The boundaries are determined by the highest NSAS value (Yao et al., 2016). Utilizing Laplace's equation (Blakely 1996), Yao et al. (2016) computed the second-order vertical derivative required for the NSAS filter.

$$(7) \frac{\partial^2 f}{\partial z^2} = - \left(\frac{\partial^2 f}{\partial x^2} + \frac{\partial^2 f}{\partial y^2} \right)$$

Modified Theta Angle Filters (MTHETA) and Normalized Total Horizontal Derivative (TDX)

A similar problem exists in the Theta angle filters and the Normalized Total Horizontal Derivative (TDX), which is the generation of additional and false edges around the source body of magnetic anomalies (Fig.s 2c and 2e). To eliminate these false edges from these filters, we will modify the two filters using

the method proposed by Yao et al. (2016). For the Normalized Total Horizontal Derivative (TDX) filter and the Theta angle filter, we will have the following:

$$MTDX = \tan^{-1} \left(\frac{THD}{|\partial f / \partial z| + p \cdot \max(THD)} \right)$$

8

$$MTheta = \cos^{-1} \left(\frac{THD}{AS + p \cdot \max(THD)} \right)$$

9

Here, the parameter p has a characteristic similar to p in Eq. (6). In this context, we use the maximum value of the Total Horizontal Derivative to modify both filters. The minimum values of MTHETA and the maximum values of MTDX indicate the edges of the source body of magnetic anomalies.

Data normalization

One challenge associated with edge-detection filters is the formation of halos around the edges, causing them to appear broader. To tackle this problem, the data is first normalized to a range between zero and one, and then the resulting data is raised to a specified power n . The following formula is used for normalizing the data between zero and one:

$$Z = \frac{x - \min(x)}{\max(x) - \min(x)}$$

10

Equation (10) represents a method of normalizing data to a range between 0 and 1, ensuring that the entire dataset is on a consistent scale. Briefly described, Z stands for the normalized value of a data point x . x is the original value that needs to be normalized. Known as Min-Max normalization technique, this method is widely utilized in data preprocessing for multiple engineering problems, machine learning and statistical analysis to ensure that variables with different scales (e.g., noise or background minimal value data) do not disproportionately influence the general analysis. Indeed, it guarantees that the minimum value in the dataset is normalized to 0, the maximum value is normalized to 1, and all other values fall between 0 and 1. As a result, data containing undesired amplitudes such as noise or excessive halos would diminish during the data processing procedure, resulting in more precise final outcomes (Lattimore and Szepesvári 2020).

Since the thresholds of the new set of numbers remain constant through exponentiation of Eq. (10), there will be no issues with calculation of exponents greater than one. therefore, using this approach the NSAS and MTDX filters are normalized in the following:

$$NNSAS = \left[\frac{NSAS - \text{Min}(NSAS)}{\text{Max}(NSAS) - \text{Min}(NSAS)} \right]^n$$

11

$$NMTDX = \left[\frac{MTDX - \text{Min}(MTDX)}{\text{Max}(MTDX) - \text{Min}(MTDX)} \right]^n$$

12

the *NMTDX* filter, the minimum value resulting from applying the *MTDX* filter is represented as *Min* (*MTDX*), and the maximum value is represented as *Max*(*MTDX*).

In both filters, *n* represents a non-negative continuous value that consists of numbers equal to or greater than one, as defined by the interpreter. When using exponents greater than one, lower values tend to approach zero more closely than higher values, resulting in a clear contrast between high and low numbers, which effectively delineates the peak values in the data. Although using $n \geq 1$ may lead to some information loss by weakening small-amplitude effects while amplifying larger ones exponentially, this approach is intentional. It helps remove unwanted anomalies, leading to a more precise identification of the main anomalies. The choice of *n* is made based on multiple filters and geological information from the study area, ensuring optimal interpretation. In this study, drilling results further validate that normalized filters successfully eliminate certain artifacts. These findings will be discussed in more detail in the manuscript. It is important to note that normalizing the NSAS filter data produces the NNSAS filter, while normalizing the MTDX method data results in the *NMTDX* filter. For both filters, edges are identified by the maximum values. The performance of these filters will subsequently be evaluated on both synthetic and real datasets.

Utilizing synthetic data

An effective way to assess the accuracy of various data processing techniques is by applying them to established synthetic models. In this section, we will analyze the outcomes of implementing the proposed methods on a 3D synthetic model to evaluate their efficiency and illustrate their effectiveness and resolution in identifying the edges of multiple closely located geological features.

Additionally, to investigate the effect of ambient noise on the results of the different edge estimation filters discussed in this study, a 2% Gaussian noise has been added to the model's magnetic data. To evaluate the methods in a more realistic context, a dataset requiring the use of an RTP transformation has been chosen instead of using synthetic anomalies located at the magnetic pole. To examine the ability of the developed filters to improve edge quality, reduce interference between anomalies and the edges of closely situated magnetic bodies, and assess the balance between surface and subsurface masses, a model consisting of four geological masses at different depths and separations has been created. The detailed specifications of this model can be found in Table 1.

Table 1
Synthetic model characteristics

Magnetic Susceptibility (SI)	Top surface depth (m)	Depth expansion (m)	Width (m)	length (m)	Magnetic source
0.08	15	40	40	150	1
0.08	20	40	44 (top) 52 (bottom)	90	2
0.08	35	40	35 (top) 29 (bottom)	90	3
0.08	40	40	40	150	4

The synthetic model covers a rectangular area measuring 280 by 400 square meters, with magnetic inclination and declination angles of (I, D) = (+ 50°, + 3°). The data sampling grid for this model is set at 2 by 2 square meters. The distances between the four adjacent geological masses are as follows: 30 meters between the first and second masses, 78 meters between the first and third masses, 70 meters between the second and fourth masses, and 37.5 meters between the third and fourth masses. Thus, the distances among the first to fourth masses are 30, 78, 70, and 37.5 meters, respectively.

Considering the prevalence of faults in different areas of the Earth and their important role in geophysical interpretations, this significant geological phenomenon has been included in the design of the synthetic model. Specifically, a normal deep slip fault mechanism is assumed to be present between the P2 and P3 masses illustrated in Fig. 1.

Figure 1a shows a three-dimensional schematic of the constructed synthetic model, highlighting the configuration of the geological masses and the corresponding magnetic response. Figure 1b provides a two-dimensional top-down view, displaying the horizontal distances between the masses in the synthetic model. The geological masses are labeled as P1 to P4 in the figures.

To enhance the comparison and interpretation of the maps, as well as to allow for a more thorough analysis of the filters' effectiveness, the boundaries or edges of the model masses are outlined with black rectangles in all the images.

Figure 2 Filtered results of the model data. (a) TMA map of the model data, (b) NSAS of the model data in (a), (c) THETA of the model data in (a), (d) MTHETA of the model data in (a) with $p = 0.007$, (e) TDX of the model data in (a), and (f) MTDX of the model data in (a) with $p = 0.015$

Figure 2a displays the magnetic response derived from the synthetic model, whereas Figs. 2b–f sequentially show the edge-detection results obtained by applying the NSAS, THETA, MTHETA, TDX, and MTDX filters to the cleaned magnetic data presented in Fig. 2a.

In the case of the Theta filter, the minimum values correspond to the edges. As illustrated in Fig. 2c, the accuracy of boundary estimation using this method is fairly good. The filter's relationship includes the total horizontal derivative in the numerator and the analytical signal in the denominator, which leads to somewhat normalized outputs from the Theta angle filter. Figure 2c indicates that this method detects the boundaries of bodies (particularly those located at greater depths) in a scattered and halo-like fashion, causing the boundaries to appear quite broad. A significant drawback of this filter's results is the occurrence of false edges surrounding the framework of the model.

Figure 2e displays the map generated using the TDX filter, where the edges are marked by the maximum values of the anomalies. Like the Theta filter, this method normalizes the total horizontal derivative by the vertical derivative, which leads to relatively accurate edge identification. However, this filter also outlines the boundaries of deeper bodies in a scattered and halo-like manner. As a result, additional edges are produced around the framework of the image created by applying this filter.

As noted earlier, the Theta angle filters and the normalized total horizontal derivative create extra and false edges around the body generating the anomaly, which compromises the reliability of these filters. To mitigate this issue, we employed a modified version of these filters.

Figure 2d illustrates the response from the MTHETA filter, where the minimum values represent the edges. This filter is a modified version of the Theta filter, designed to eliminate the false edges found in the Theta angle filter's response by adjusting the parameter p (in this case, $p = 0.007$ was selected). As shown in Fig. 2d, this filter effectively removes false edges; however, it suffers from poor resolution and the low quality of edges for deeper masses.

Figure 2f presents the response of the MTDX filter, where edges are indicated by the maximum values of the anomalies. This filter is a modified version of the TDX filter, and it aims to eliminate the false edges found in the TDX filter's response by selecting an appropriate value for the parameter p (in this case, $p = 0.09$). As depicted in Fig. 2f, this filter has successfully removed extraneous edges; however, similar to the Theta angle filter, it experiences poor resolution and low quality of edges for deeper masses.

Overall, it is evident that the MTHETA and MTDX methods have effectively eliminated the false edges associated with the Theta and TDX methods, enhancing the accuracy and ease of interpreting magnetic maps. Furthermore, as shown in Fig. 2b, the NSAS filter performs well in distinguishing adjacent masses at both shallow and deep depths and closely aligns the filter response size with the actual size of the masses.

As previously noted, one of the challenges with edge-detection filters is the halo effect they create around the edges, which makes them appear broader. To minimize this halo, we propose normalizing the output of the NSAS and MTDX filters to a range between zero and one. The maximum values from these two filters indicate the edges.

Figure 3 displays the responses of the NNSAS and NMTDX filters applied to the data shown in Fig. 2a. Figure 3a represents the response of the NMTDX filter. As illustrated, the NMTDX filter has significantly mitigated the halo effect around the edges. For this filter, the data obtained from the MTDX filter were first normalized to a range between zero and one, and then these values were raised to the fourth power. This approach has also successfully achieved good separation between closely spaced masses.

Figure 3b displays the response of the NNSAS filter. As depicted, the NNSAS filter has also significantly diminished the halo effect around the edges. For this filter, the data derived from the NSAS filter were normalized to a range between zero and one and then raised to the third power.

As illustrated in Figs. 3a and b, the modified filters not only achieve excellent separation of adjacent bodies but also greatly reduce the halo surrounding the edges of the responses from the NSAS and MTDX filters. This improvement has notably enhanced the accuracy of edge detection.

Figure 4 Application of various edge detection methods to the synthetic model data from Fig. 1, contaminated with 2% Gaussian noise: (a) TMA map, (b) NSAS map, (c) Theta map, (d) MTHETA map with $p = 0.007$, (e) TDX map, and (f) MTDX map with $p = 0.015$

To evaluate the influence of noise on the performance of the introduced filters, we compare their results on the synthetic data presented in Fig. 2a, which has been contaminated with 2% white Gaussian noise (Fig. 4). Figure 4a displays the noisy magnetic anomaly, while Figs. 4b–f show the application of the NSAS, THETA, MTHETA, TDX, and MTDX filters to the data in Fig. 4a, respectively.

The NSAS method (Fig. 4b), which utilizes second-order derivatives, is more susceptible to noise compared to the other methods. This sensitivity makes it difficult to detect the edges of deeper bodies and obscures the edges of medium-depth bodies with noise. The other filters are also affected by noise due to their reliance on derivatives. As seen in Figs. 4b and 4e, the use of lower-order derivatives leads to a reduced impact from noise, while Figs. 4d and 4f demonstrate that the lower order of derivatives enables the MTHETA and MTDX filters to successfully identify the edges.

Overall, the NSAS filter's reliance on second-order derivatives of the analytical signal can pose challenges when the data is accompanied by high levels of noise. Consequently, this filter has difficulty accurately defining the edges of the bodies that cause anomalies. As illustrated in Fig. 4, the MTDX and MTHETA methods are less influenced by noise compared to the NSAS method; however, they still exhibit a considerable halo around the edges identified by these filters.

Figure 5 Application of filtering techniques to the noisy synthetic model from Fig. 4a: (a) NMTDX with $n = 8$ and (b) NNSAS with $n = 4$

Figure 5 depicts the response of the NNSAS and NMTDX methods applied to the noisy synthetic data of Fig. 4a, with the addition of 2% white Gaussian noise.

As illustrated in Fig. 5a, the NMTDX filter shows very low sensitivity to noise. Even with the added noise in the data, this filter has successfully delineated the edges of the bodies responsible for the magnetic anomalies.

In Fig. 5b, the NNSAS method is more affected by noise compared to the NMTDX method because it relies on second-order derivatives. This filter uses the second derivative of the analytical signal amplitude, leading to poor performance when applied to high-noise data.

Furthermore, to examine the effect of the power on relationships 10 and 11, the value of this parameter can be increased, and its effect is observed as follows:

Figure 6a) NNSAS of the model data in Fig. 4a with $n = 1$, b) NNSAS of the model data in Fig. 4a with $n = 5$. c) NMTDX of the model data in Fig. 4a with $n = 1$, d) NMTDX of the model data in Fig. 4a with $n = 4$

As observed in the Fig. 6, increasing the power results in a reduction of false anomaly margins and a clearer delineation of the edges in the two mentioned filters. This enhancement improves the interpretation of the data. It is also important to highlight that the optimal power value is determined empirically by the interpreter.

Finally, it is essential to note that the filters used for edge detection are only capable of identifying lateral and horizontal changes in anomalies and cannot detect deep bodies at their actual size. While the applied amplification enhances the interpretation of high-amplitude anomalies and improves edge delineation, it is important to note that this approach may miss deeper or less magnetic bodies that could still be relevant to the research. The filters are effective in identifying near-surface anomalies but may not accurately represent deep bodies or weakly magnetized materials.

Application to the real data

As a case study, the application of the above-mentioned filters on the magnetic data collected on the Siriz iron ore mine are investigated.

Geological setting. The iron ore mine of Sadat Siriz in Iran is located in the province of Kerman, Zarrand county, 40 km away from the city of Siriz. The mine area is situated in the zone no 40 and has the general coordinates (m E 388991 - m N 3435117) and (m E 385026 - m N 3431095). This area is covered by the 1:250000 geological map of Ravar and the 1:10000 geological map of Siriz .

The Siriz region is geologically situated within the microcontinent of Central Iran and in terms of structural divisions, lies in the southwest of the sub-zone of the Bafq-Pasht Badam block, which is one of the most significant structural blocks in the Central Iran zone. Among the essential features related to this block are the metamorphic outcrops attributed to the Precambrian, primarily consisting of volcanic

and volcanoclastic rocks, along with limestone and dolomitic marbles. The magmatic rocks in this block are not confined to the Precambrian; rather, the late Precambrian to early Cambrian sequences, especially in northern Kerman, are associated with alkaline lavas of a continental origin.

The dominant lithology of the area consists mainly of an intrusive with a monzonitic composition, the Kuhbanan carbonate series, and the Shemshak shale and sandstone formation. The iron mineralization in the form of magnetite is primarily controlled by metasomatic alteration zones with a greenish color, and minerals such as phlogopite, tremolite, and actinolite are abundantly present.

According to field evidence and geological maps, iron mineralization in the Siriz area occurs as irregular masses and lenses within skarn zones adjacent to the Siriz granitoid intrusion, which has a composition ranging from quartz syenite to quartz monzonite. The host rock for iron mineralization is mostly green skarn-type metasomatite, which has been altered due to the intrusion of the Siriz granitoid. The juxtaposition of the metasomatic zone and the intrusive body, as well as the formation of high-temperature minerals such as garnet and diopside within the skarn zone, indicate the role of the intrusive body as a heat source for skarn formation in the area. The intrusion of the quartz syenitic to quartz monzonitic body in Siriz caused the injection of iron-bearing hydrothermal solutions into the adjacent rocks, and through reaction with them and the formation of various calcium and magnesium silicate minerals, it led to iron mineralization.

Among the main fault structures surrounding this area are the Anar fault system, the Kuh Niw fault, the Davaran fault, the Siriz fault, and the Jorjafak fault.

The map shown in Fig. 7 provides a better understanding of the geological information of the structure under investigation.

As depicted below, Fig. 8 represents the total magnetic anomaly for the entire area, calculated using the analytical signal method and overlaid on a satellite map. The research region's location within Iran is illustrated, accompanied by a depiction of significant geological fault lines in the vicinity of the study area. This representation offers a general overview of the region's topography and the overall shape of the magnetic anomaly in the area of study.

Utilizing filters on the real data

In this section, we will examine and evaluate the filters to assess their efficiency and effectiveness by analyzing the outcomes of applying them to actual magnetic data. The magnetic data utilized in this study was collected from Kerman province, Iran. The survey grid has a spacing of 10 meters by 10 meters, encompassing a study area of 1.5 kilometers by 1.2 kilometers.

Figure 9a displays the total magnetic anomaly (TMA) for the study area. The data has undergone daily corrections and adjustments based on the International Geomagnetic Reference Field (IGRF), with the values being exclusively derived from the magnetic characteristics of the region's rocks.

Figures 9b-f present the responses from the NSAS, Theta, MTHETA, TDX, and MTDX methods applied to the actual magnetic data. Notably, the MTHETA and MTDX methods have successfully removed the false edges that appear in the responses of the Theta and TDX methods. Additionally, as illustrated in Fig. 9b, the NSAS method effectively distinguishes between closely spaced and small geological bodies.

Figure 10 shows the responses of the NNSAS and NMTDX methods applied to the real magnetic data depicted in Fig. 9a. It is clear that the excess values have been entirely removed. The remaining edges are solely due to the bodies that produce the magnetic anomalies, and the halo surrounding these edges has also lessened. Based on these results, we can conclude that the NMTDX and NNSAS methods have high resolution and are capable of identifying more edge information compared to other filters.

Overall, the results depicted in Figs. 3, 5, and 10 demonstrate that the NNSAS method is more effective at distinguishing between closely spaced edges than the NMTDX method. However, the NNSAS method is also more vulnerable to noise interference. Therefore, these two methods can be utilized as complementary techniques.

Figure 11 presents the MTDX and NMTDX results over the Siriz mine data, highlighting two of the developed filters in this study. As shown, drilling operations have been conducted within the area, with boreholes exhibiting recorded magnetite mineralization distinguished by color from those without captured magnetite. Notably, the circled area on the right side of both maps corresponds to a zone overlying altered syenite rocks. The observed discrepancy between the anomaly (some metasomatized rocks) and the background host (syenite) can be interpreted as the cause of the apparent anomaly in this zone. As inferred from the figures, drilling operations revealed no significant mineralization or high iron grade within the circled area. This finding aligns with the results obtained from the applied filters. Specifically, while the MTDX filter indicates this area as a potential anomaly, the NMTDX filter suggests that it is less likely to be of particular significance for magnetite mineralization. This highlights the importance of incorporating multiple maps and considering various factors for a comprehensive interpretation. It is also worth noting that the average iron grade of the host rocks across the entire study area was 4%. For boreholes where magnetite anomalies were captured, the average iron grade was 32% within the primary anomaly or mining zone. In contrast, within the circled area on the right side of the maps, the average iron grade was 6%, which is relatively lower.

To gain deeper insights into the subsurface properties of the anomalies delineated in Fig. 11, geological cross-sections along profiles A–B and C–D are illustrated in Fig. 12. These sections offer a comprehensive representation of the lithological variations and structural influences governing the detected magnetic anomalies, as inferred from the applied methodologies.

As illustrated in Fig. 12a, the host rock within the study area is syenite, with substantial magnetite mineralization occurring within this syenitic matrix. Additionally, the presence of metasomatized units indicates a degree of chemical alteration induced by subsurface fluid activity. Furthermore, minor hematite occurrences have been identified near the surface.

As depicted in Fig. 12b, Section C-D, another prominent anomaly within the study area, predominantly consists of syenite host rocks. The identified magnetite mineralization in this section is also distinctly captured within the borehole data. It is worth noting that these geological sections were meticulously used to design the extractive drilling operations for mining purposes, which have been progressing successfully. These geological sections further highlight the necessity of integrating geophysical filtering techniques with direct geological and drilling data to ensure a more accurate and reliable interpretation of magnetic anomalies. In conclusion, based on the precise drilling results, it can be asserted that the edge-detection techniques developed in this study effectively identified the surface locations of the causative sources.

Conclusions

Bipolarity and intricate spatial distributions are common features of magnetic anomaly data, which can make it difficult to accurately interpret geological limits. By minimizing false edges and halo artifacts, this study shows that enhanced edge-detection filters—more especially, the modified Theta (MTHETA) and modified TDX (MTDX) filters—offer notable advantages over traditional methods, particularly in complex geological settings. High-resolution delineation of magnetic boundaries is provided by the NSAS and MTDX filters in particular, which allow for more accurate interpretation of closely spaced structures while also successfully controlling the effects of noise. Drilling results cross-validated the developed filters, further confirming their reliability in practical applications.

Our results indicate that by minimizing artifacts and offering distinct boundary resolutions, the NMTDX and NNSAS filters perform exceptionally well in identifying precise boundaries. Because it selectively amplifies actual boundary signals while suppressing noise and unwanted halos, the normalizing technique employed in this study appears to be a valuable boost in filter response. This is particularly useful in regions where it can be difficult to discern between nearby magnetic sources due to complex underlying geometries.

All things considered, the altered filters described in this work have potential for a variety of geophysical uses, especially in mineral and hydrocarbon exploration, where accurate boundary recognition can lower exploratory drilling expenses and improve the precision of resource assessments. These techniques could be improved for even better edge clarity and noise resistance in future studies, providing a strong foundation for deciphering magnetic anomaly data in ever-more complicated subsurface environments.

Declarations

Competing interests

The authors report there are no competing interests to declare.

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Author Contribution

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were conducted by M.A., B.O., and S.H.H. The first draft of the manuscript was written by M.A., B.O., and S.H.H., and all authors provided feedback on the processing the data and providing the initial version of the manuscript for submission. All authors read and approved the final manuscript.

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Data Availability

Data sets generated during the current study are available from the corresponding author on reasonable request.

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Figures

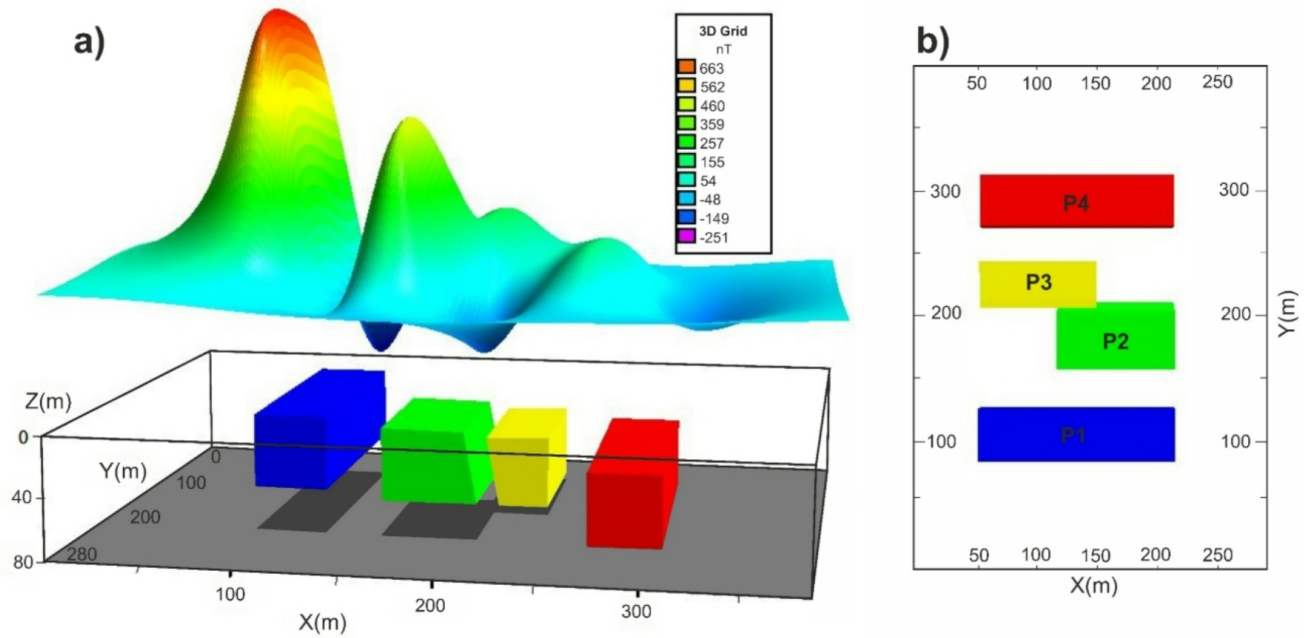


Figure 1

a) The designed 3D synthetic model scenario, b) Vertical plan view. The model consists of cubes with different dimensions, located at depths of 20 m (P1), 25 m (P2), 35 m (P3), and 40 m (P4), and separated by various distances

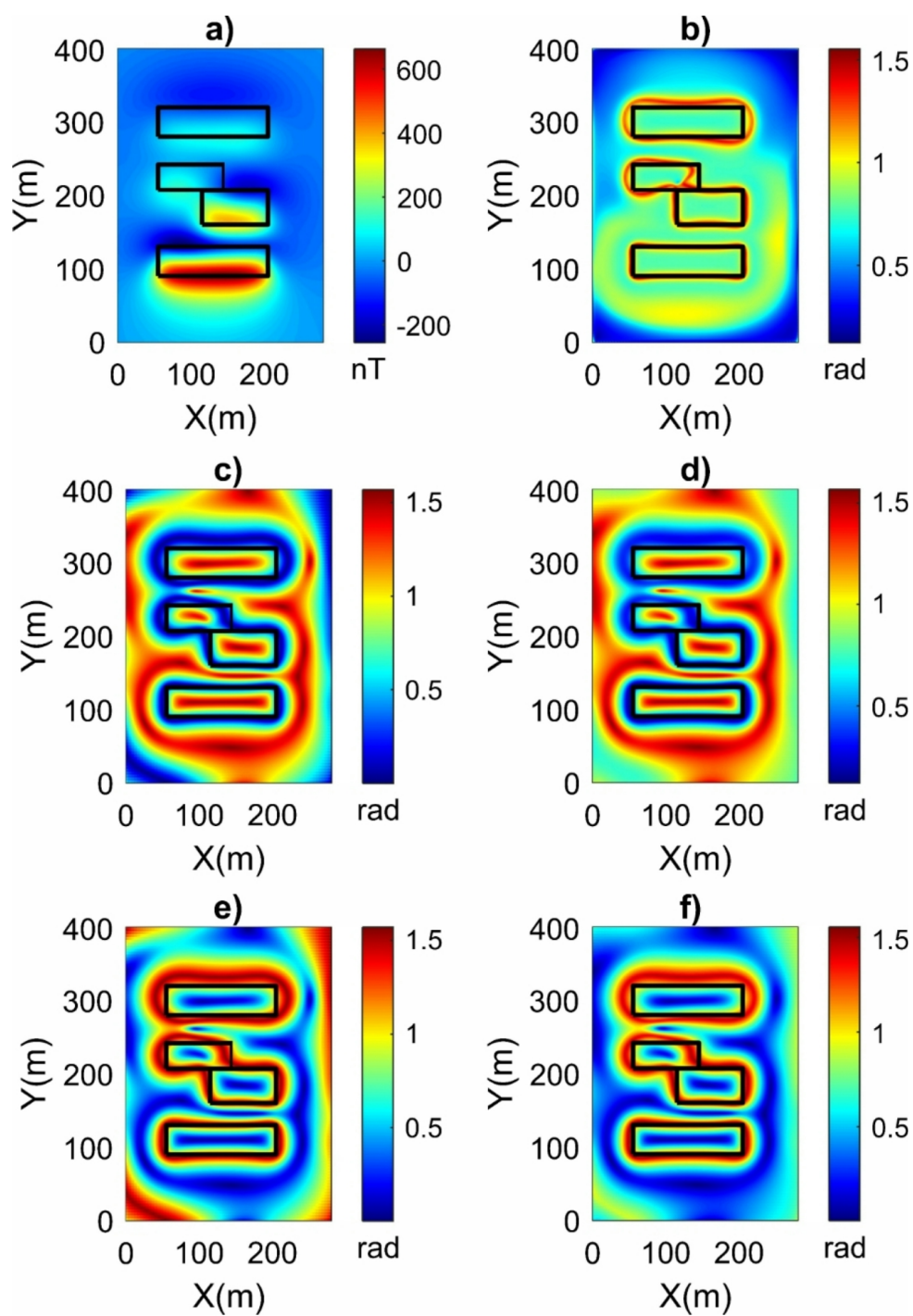


Figure 2

Filtered results of the model data. (a) TMA map of the model data, (b) NSAS of the model data in (a), (c) THETA of the model data in (a), (d) MTHETA of the model data in (a) with $p = 0.007$, (e) TDX of the model data in (a), and (f) MTDX of the model data in (a) with $p = 0.015$

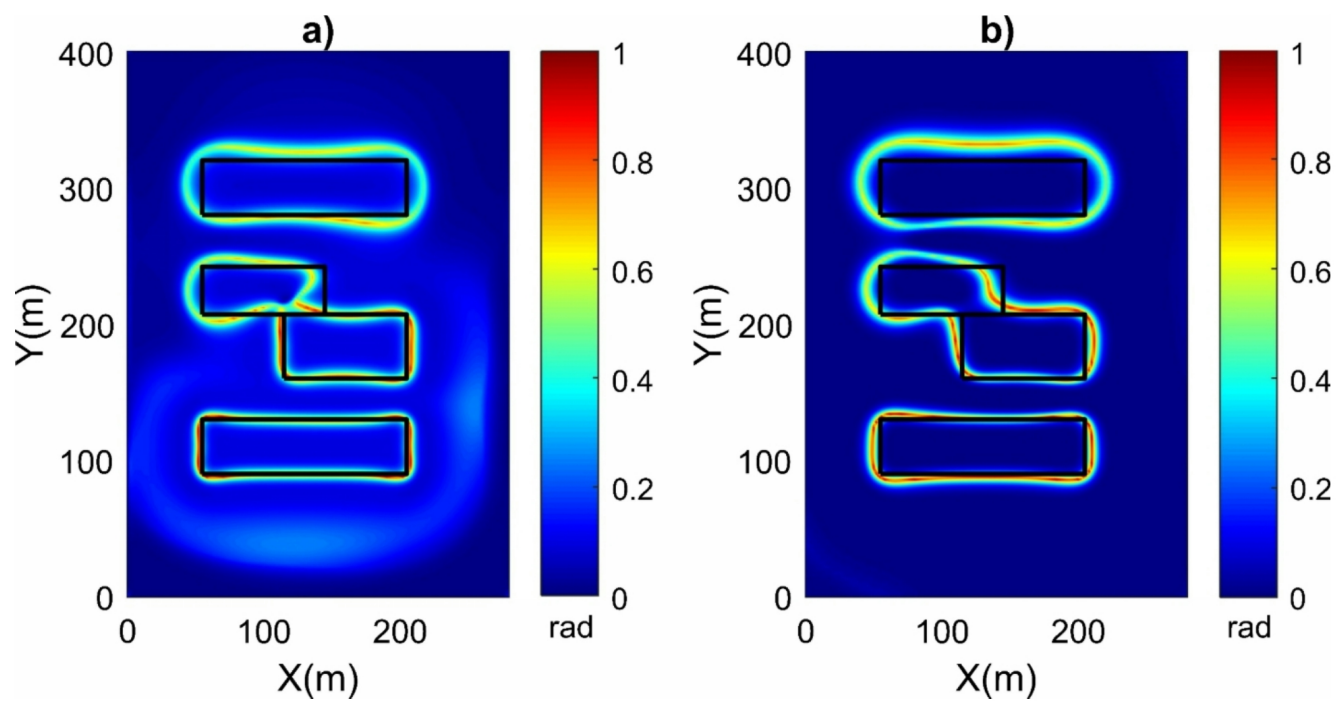


Figure 3

Comparison of filtering techniques applied to the model data: (a) NMTDX filter with $n=6$ and (b) NNSAS filter with $n=3$

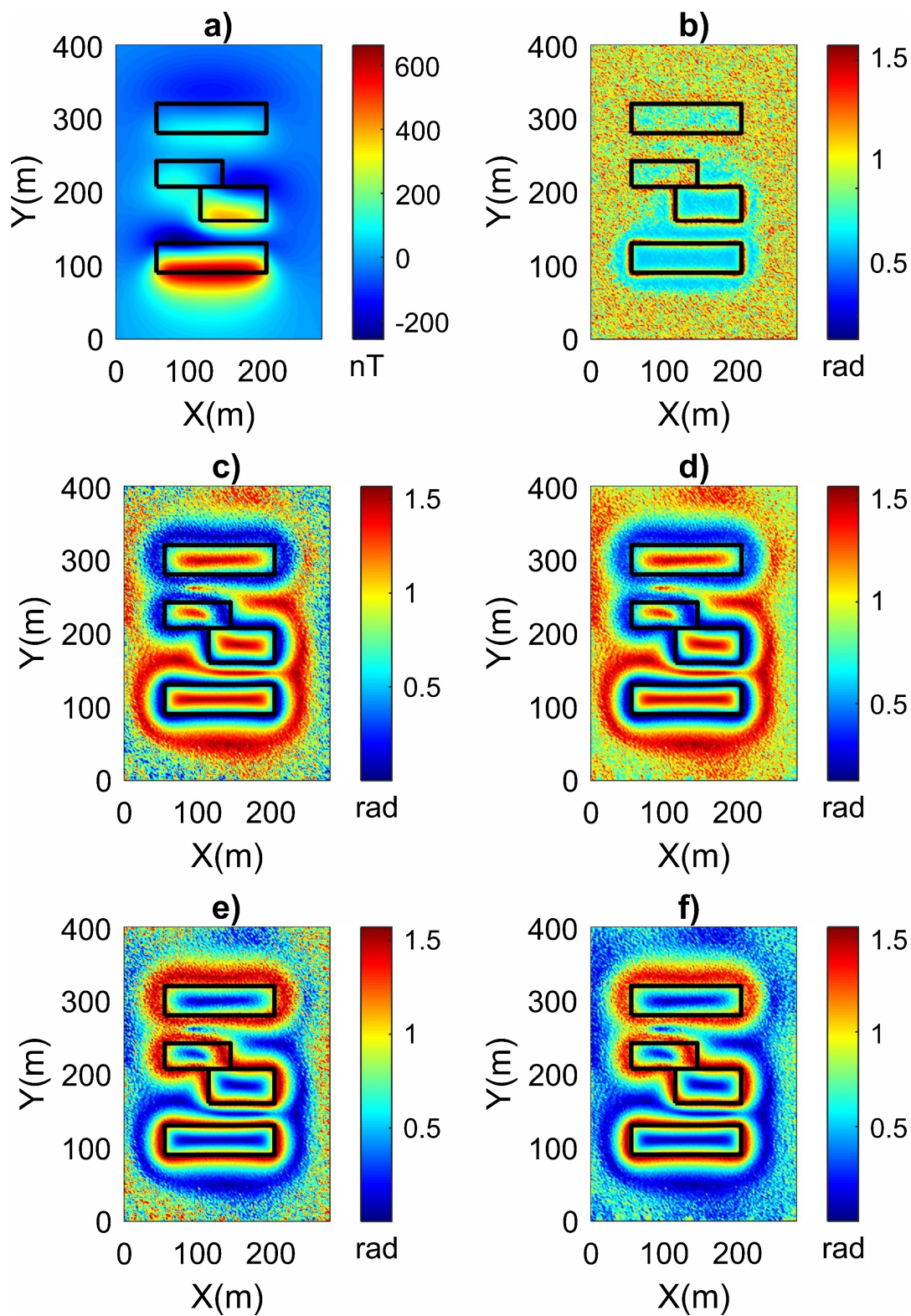


Figure 4

Application of various edge detection methods to the synthetic model data from Fig. 1, contaminated with 2% Gaussian noise: (a) TMA map, (b) NSAS map, (c) Theta map, (d) MTHETA map with $p=0.007$, (e) TDX map, and (f) MTDX map with $p=0.015$

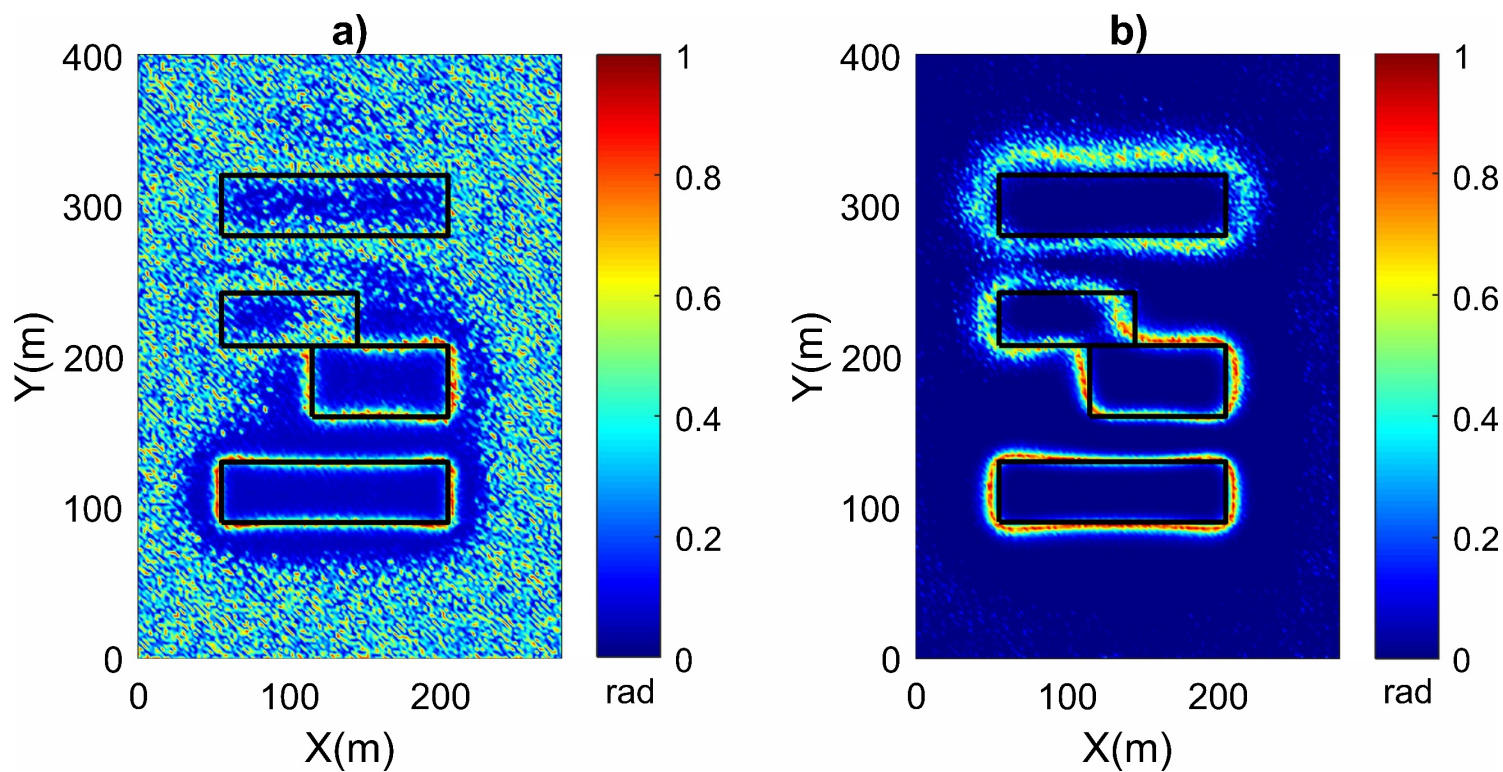


Figure 5

Application of filtering techniques to the noisy synthetic model from Fig. 4a: (a) NMTDX with $n=8$ and (b) NNSAS with $n=4$

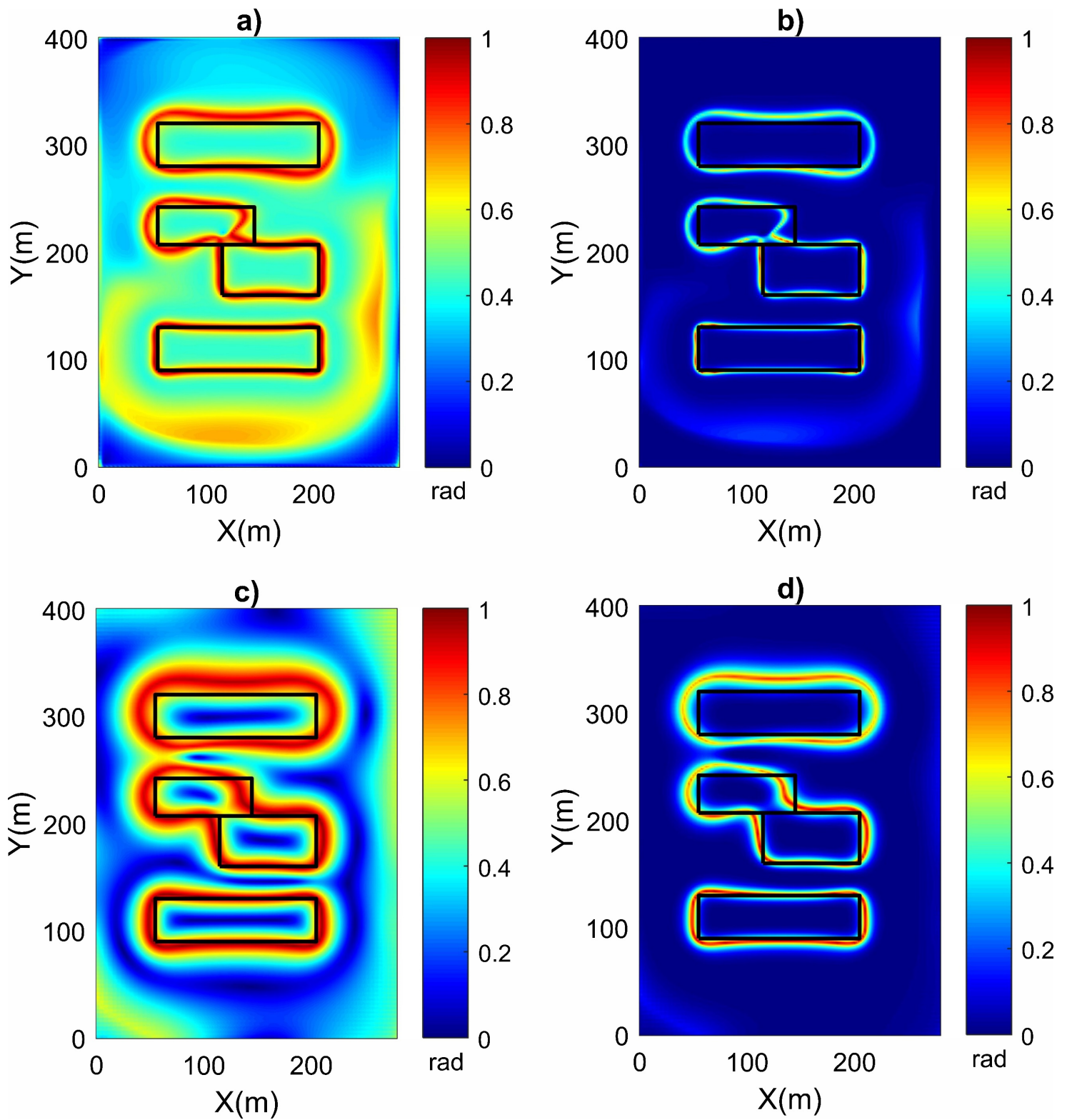


Figure 6

a) NNSAS of the model data in Fig. 4a with $n = 1$, b) NNSAS of the model data in Fig. 4a with $n = 5$.

c) NMTDX of the model data in Fig. 4a with $n=1$, d) NMTDX of the model data in Fig. 4a with $n=4$

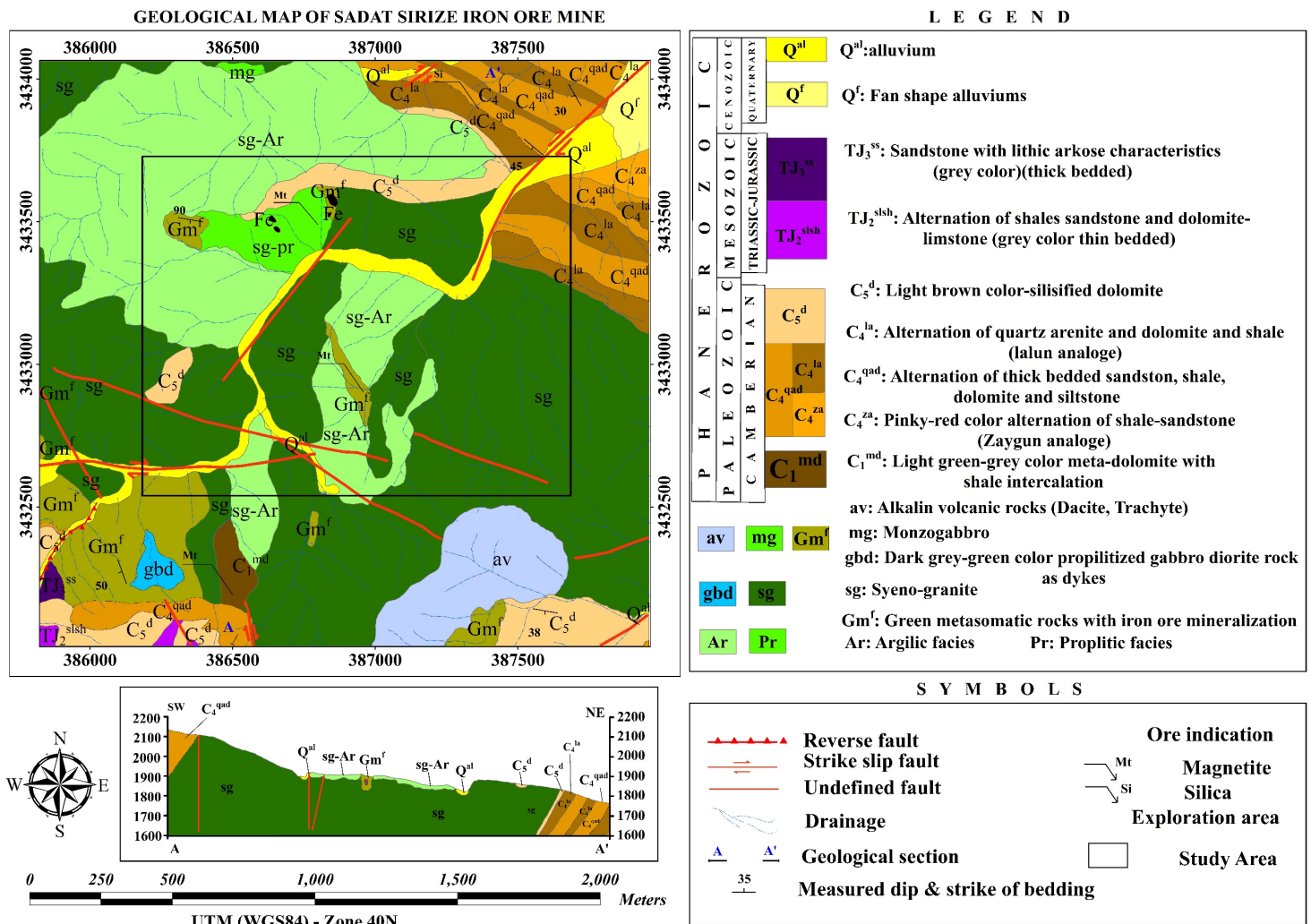


Figure 7

Geological map of the Sadat Siriz iron ore mine

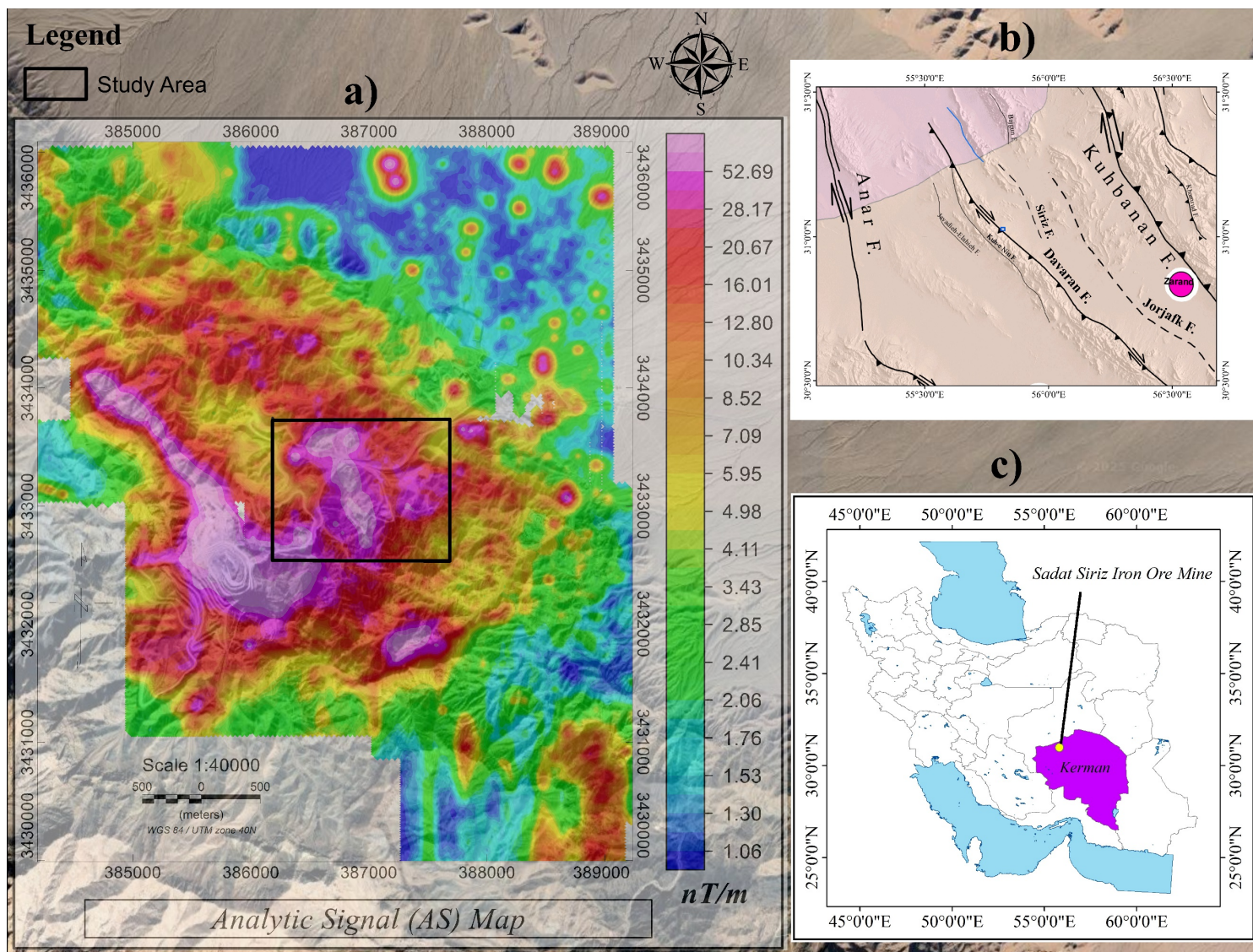


Figure 8

(a) Analytical signal map superimposed on the satellite imagery of the study area, (b) depiction of the major fault system in the vicinity of the study area, and (c) geographic location of the study area within Kerman Province, Iran

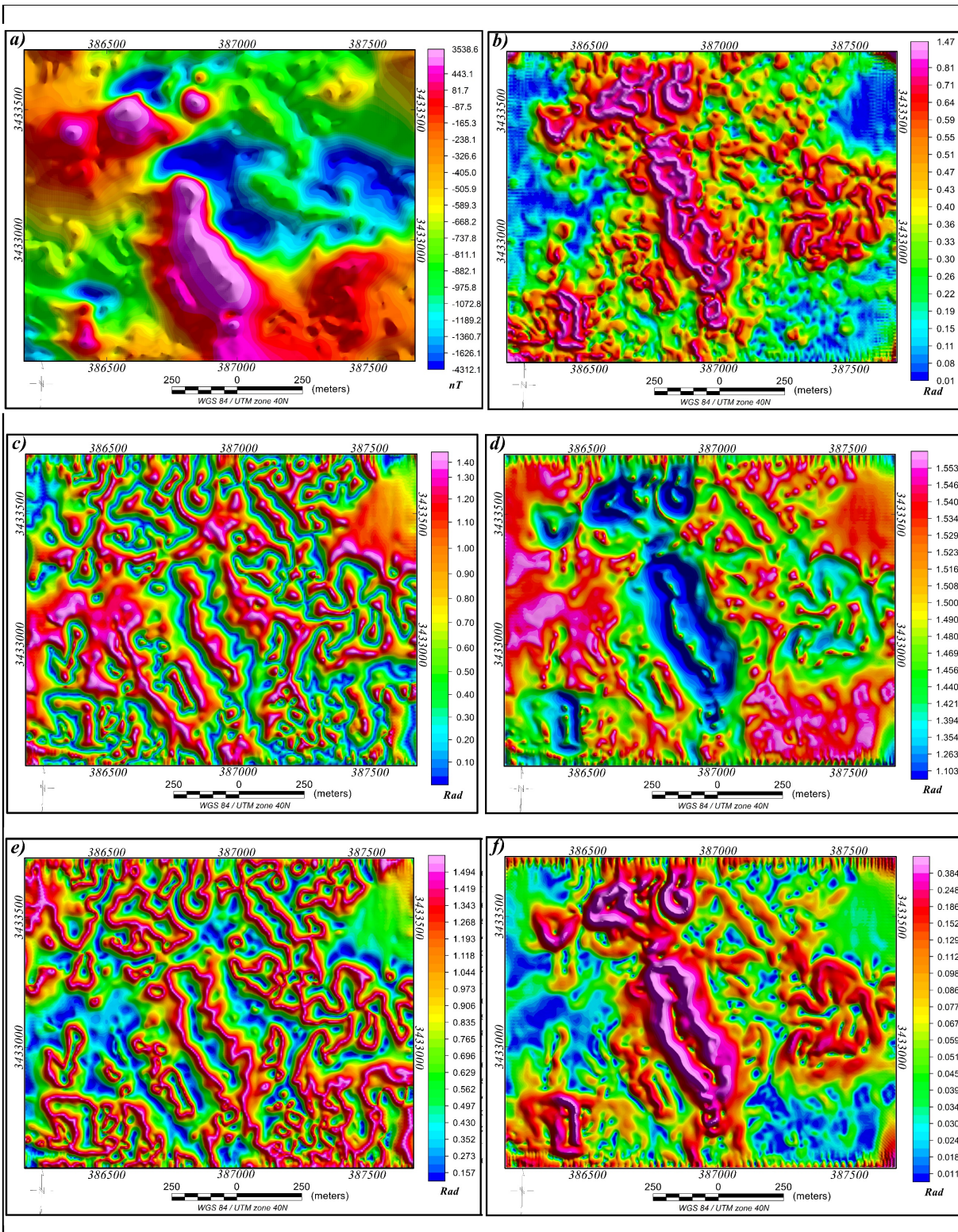


Figure 9

Comparative analysis of various edge detection methods applied to the Siriz Mine dataset, Kerman, Iran: (a) TMA map, (b) NSAS map (n=0.3), (c) Theta map, (d) MTHETA map (n=0.45), (e) TDX map (n=0.01), and (f) MTDX map (n=0.48)

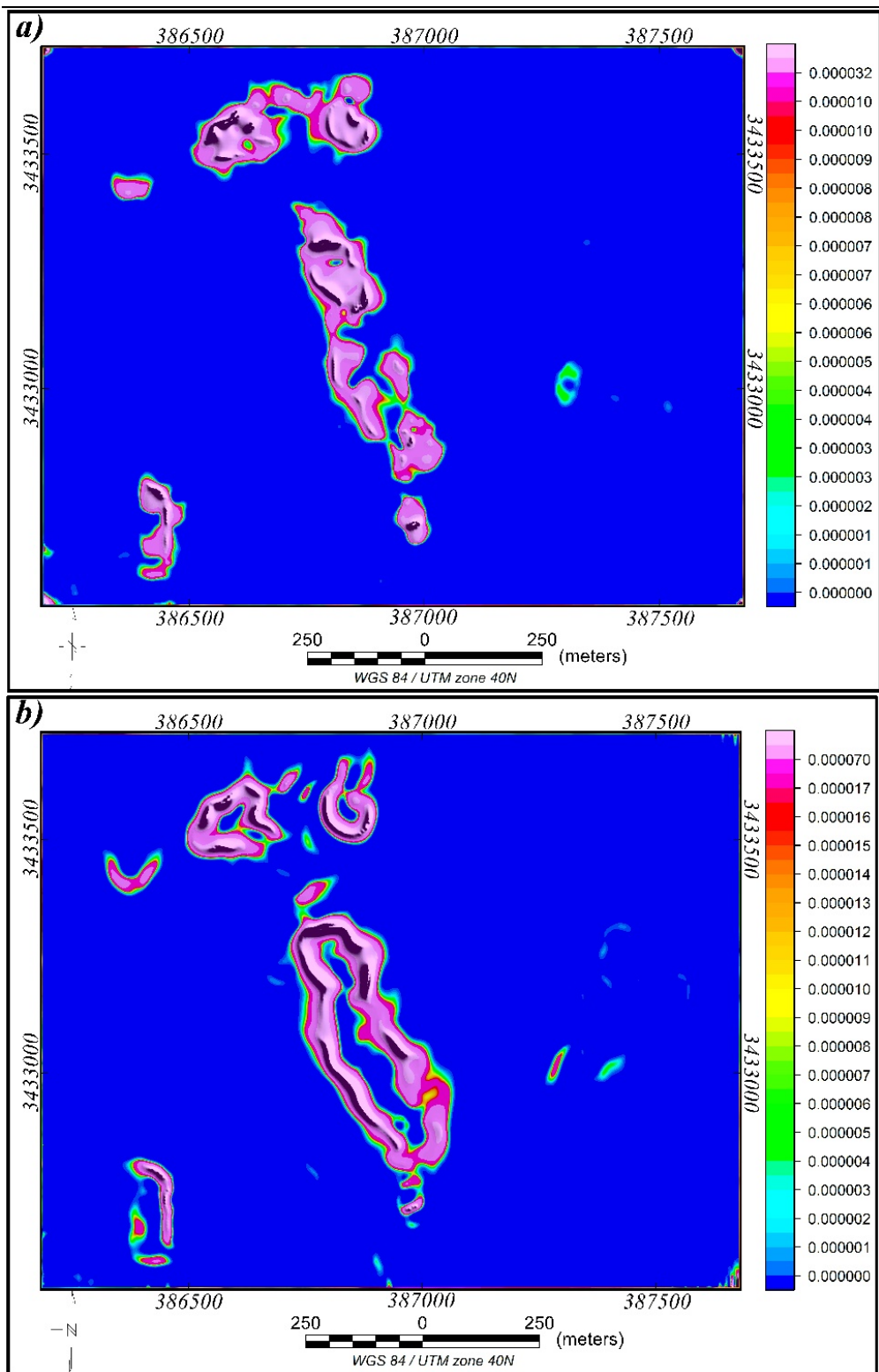


Figure 10

(a) NNSAS map of the Siriz Mine dataset (n=7), and (b) NMTDX map of the Siriz Mine dataset (n=10)

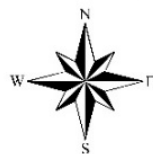
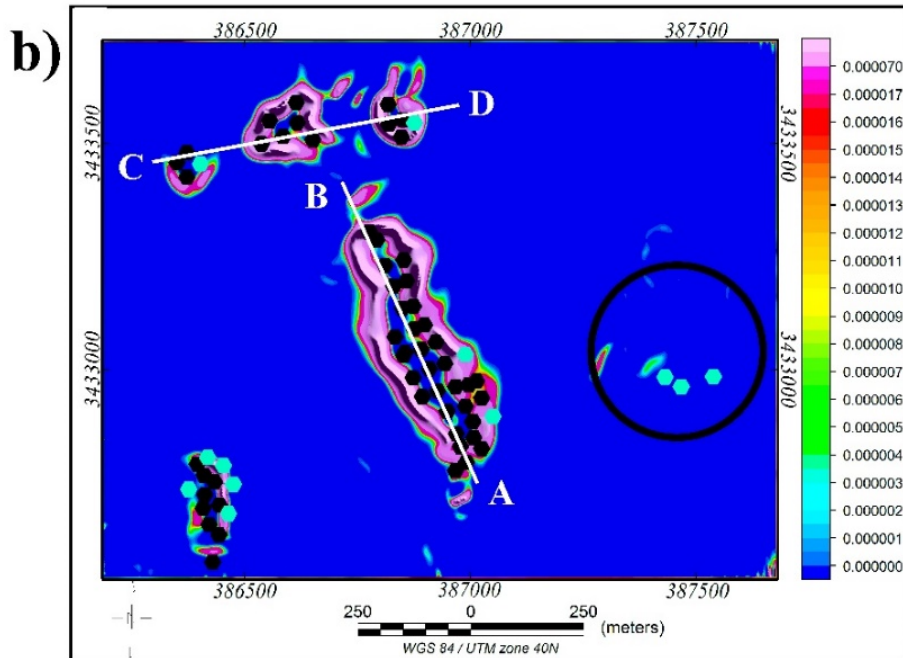
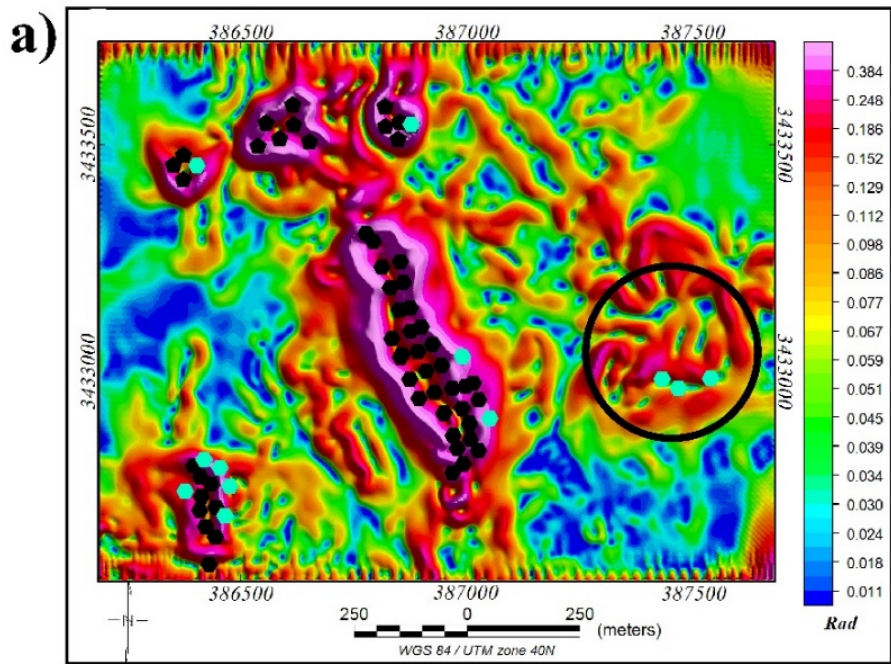


Figure 11

Drilling operation locations superimposed on (a) the MTDX map and (b) the NMTDX map for n=10. Boreholes with and without captured magnetite are distinguished. Sections A–B and C–D delineate the geological cross-sections

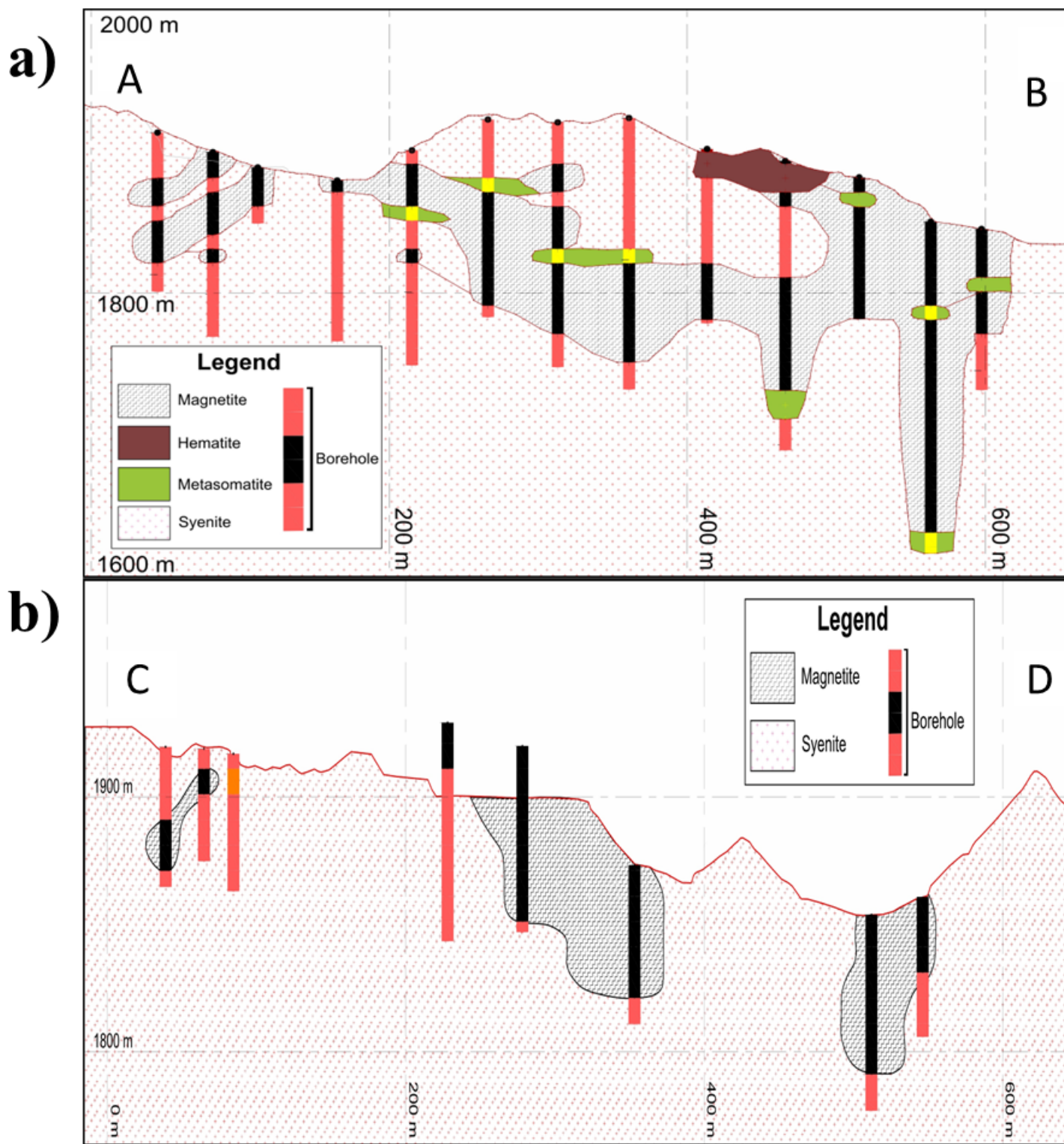


Figure 12

Geological cross-sections derived from borehole drilling across the primary anomalies identified in Fig. 11: (a) Section A–B and (b) Section C–D. Black regions within the boreholes indicate magnetite mineralization. Note that the boreholes extending above ground level in (b) are currently undergoing drilling