Journal of the Earth and Space Physics, Vol. 40, No. 3, 2014, P. 13-21

Comparison of derivative-based methods by normalized standard deviation approach for edge detection of gravity anomalies

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(Received: 23 Dec 2009, Accepted: 31 Jan 2012)

Abstract

This paper describes the application of the so-called normalized standard deviation (NSTD) method to detect edges of gravity anomalies. Using derivative-based methods enhances the anomaly edges, leading to significant improvement of the interpretation of the geological features. There are many methods for enhancing the edges, most of which are high-pass filters based on the horizontal or vertical derivatives of gravity data. The normalized standard deviation, a new edge detection filter, is based on the moveable windows through gradient data, i.e. gravity gradient. The NSTD method (as an equation of the ratio of the related normalized standard deviations of the gravity data gradients) along with comparable techniques, including analytic signal, total horizontal derivative (THD), tilt angle, total horizontal derivative of tilt angle (THDT) and theta map, are examined for noise-free and noise-added synthetic data. The aim is to demonstrate the suitability of the NSTD in edge enhancement. Having obtained satisfactory results, the methods are applied successfully to the real gravity data of Dehloran Bitumen and the Karst zones in SabzKoh. The main aim of the edge detection methods in our study is to determine the appropriate locations of exploratory drillings in gravity prospect. It is demonstrated that suitable locations are determined based on these methods.

Keywords: Edge detection, NSTD method, Dehloran Bitumen, Karst zones in SabzKoh

1 Introduction

The interference among diverse geological features with different shapes, densities and depths yields gravity anomalies. Of particular interest to a geologist are gravity anomalies in the produced maps which may be due to the existence of buried faults, mineral occurrences, contacts and other tectonic and geological features (Oruc, 2011).

Maps of the magnetic and gravity field of the Earth are used worldwide as part of exploration programs for mineral resources. A range of high-pass filters such as downward continuation or vertical derivatives of potential field data can be applied to bring out fine detail from such anomalies in mineral exploration (Cooper and Cowan, 2006).

A variety of methods based on the use of directional derivatives of the gravity anomalies have been developed for edge detection of causative sources. These techniques include analytic signal, total horizontal derivative, tilt angle, total horizontal derivative of tilt angle and theta map.

After a brief introduction of various edge detection methods, the normalized standard deviation (NSTD) approach proposed by Cooper and Cowan (2008) is applied to the gravity anomalies in order to enhance the edges of the causative sources. To evaluate the capability of this method with prevalent edge detection methods, comparable methods are implemented to noise-free and noise-added synthetic data. Following obtaining satisfactory results, all these methods are applied to the real gravity data of Dehloran Bitumen and the Karst zones in SabzKoh, Iran.

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2 Synthetic model

A collection of rectangular prisms provides a straightforward way to simulate different varieties of causative sources in gravity prospect (Figure 1). If small enough, each prism can be assumed to have a constant density. Then, by the principle of superposition, the gravitational anomaly over the simulated sources at each point could be approximately calculated by summing the effects of all the prisms.

The vertical field of the gravitational attraction from a single rectangular prism is obtained by integration over the limits of the prism. For instance, a rectangular prism with constant density ρ and with dimensions described by the limits $x_1 \le x \le x_2$, $y_1 \le y \le y_2$ and $z_1 \le z \le z_2$ has a vertical gravitational attraction at origin given by

$$\gamma \rho \int_{z_1}^{z_2} \int_{y_1}^{y_2} \int_{x_1}^{x_2} \frac{z'}{\left[x'^2 + y'^2 + z'^2 \right]^{\frac{3}{2}}} dx' dy' dz' \qquad (1)$$

Moving the observation point to the origin simplifies the integral, a common trick that is used frequently to solve the equation (Blakely, 1995). Plouff (1975) provided a derivation of the preceding integral with the following results:

$$G = \gamma \rho \sum_{i=1}^{2} \sum_{j=1}^{2} \sum_{k=1}^{2} \mu_{ijk} \begin{bmatrix} z_k \arctan \dfrac{x_i y_j}{z_k R_{ijk}} - \\ x_i . \log(R_{ijk} + y_j) - \\ y_j . \log(R_{ijk} + x_i) \end{bmatrix} \qquad (2)$$

where $R_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2} \qquad \mu_{ijk} = (-1)^{i+j+k}$

and γ is a universal gravity constant.

A collection of four synthetic prisms are used to simulate causative sources in gravity prospect. The properties and observed anomalies of the synthetic data are shown in Table (1) and Figure 2. Sources 1, 2 and 3 are noise-free, while the fourth model is corrupted by random Gaussian noise, so that gravity data amplitude has a standard deviation of 10 %. The fourth model also locates in the deepest situation, about 50 meters as regional effect. In the following sections, the aim is to identify whether or not the edge detection methods can enhance boundaries of gravity anomalies, which leads to find appropriate locations for exploratory drillings.

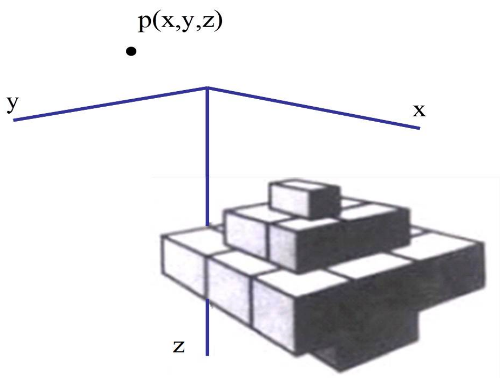

Figure 1. Approximation of the 3D mass by a collection of rectangular prisms to simulate different bodies (Blakely, 1995).

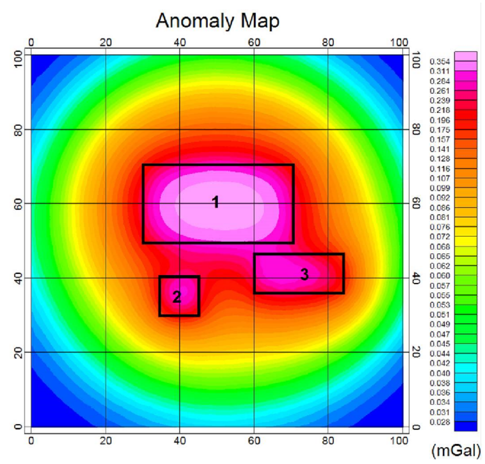

Figure 2. Gravity anomaly of synthetic models assuming properties shown in Table 1.

Table 1. Properties of synthetic models.

Model No.	Dimensions (meter)	Depth (meter)	Density Contrast (gr/cm^3)
1	$40\times20\times20$	5	1.2
2	$10\times10\times10$	2	1.5
3	$25\times10\times10$	3	1.3
4	$40\times40\times20$	50	1

3 Methodology

Many edge detection techniques are available to enhance subtle detail in potential filed data (gravity and magnetic) such as downward continuation, horizontal and vertical derivatives and other forms of high-pass filters. One of these techniques is the analytic signal method. The basic concepts of the analytic signal method for magnetic data in 2D were extensively discussed by Nabighian (1972, 1974 and 1984) and Green and Stanley (1975). Their counterparts, in the case of gravity data, have been introduced by Klingele et al. (1991). Marson and Klingele (1993) defined the analytic signal of the vertical gravity gradient produced by a 3D source as follows (Saibi et al., 2006),

$$\left|A_g(x,y)\right| = \sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2 + (\frac{\partial g}{\partial z})^2} \qquad (3)$$

Where $\left|A_g(x,y)\right|$ is the amplitude of the analytic signal at (x, y), g is the observed gravity field at (x, y), and ($\partial g/\partial x$, $\partial g/\partial y$, $\partial g/\partial z$) are the two horizontal and vertical derivatives of the gravity field, respectively. Figure 3a shows the analytic signal result of the synthetic models shown in Figure 2. Acceptable results are obtained based on the analytic signal method. Indeed, boundaries of synthetic multi-source gravity anomalies have been enhanced compared to the real edges.

A commonly used edge detection filter is the total horizontal derivative (THD):

$$THD = \sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2} \qquad (4)$$

Figure 3b shows the THD result for synthetic models. The edges of the synthetic models have been enhanced appropriately according to the actual boundaries of the causative sources. The main point of this method after examining various synthetic models is that the result is dominated by the response from the shallower (and hence large-amplitude anomaly) bodies (Cooper and Cowan, 2008).

Miller and Singh (1994) introduced the tilt angle and the amplitude of the normalized vertical derivative as follows:

$$T = \tan^{-1}\left(\frac{\frac{\partial g}{\partial z}}{\sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2}}\right) \qquad (5)$$

As the tilt angle is based on the ratio of derivatives, it enhances large and small amplitude anomalies. Figure 3c shows the tilt angle results from synthetic models. Although it is not an edge detection filter, the tilt angle is effective in balancing the amplitudes of the different anomalies (Cooper and Cowan, 2008). The tilt angle is a technique to determine the depth at the top of the causative sources and the zero contours of the tilt angle correspond to the boundaries of geological discontinuities (Oruc, 2011).

Verduzco et al. (2004) have suggested to use the total horizontal derivative of the tilt angle as an edge detector (THDT):

$$THDT = \sqrt{(\frac{\partial T}{\partial x})^2 + (\frac{\partial T}{\partial y})^2} \qquad (6)$$

Figure 3d shows the THDT results from synthetic models. The THDT successfully delineates the edges of the larger amplitude anomaly, although the results for deeper and noisy bodies are less effective. As the THDT uses derivatives of a derivative-based filter, i.e. the tilt angle, it can also increase the noise of the data (Cooper and Cowan, 2008). As a result, while having low level noise, the THDT solely can be a useful method to enhance boundaries of large amplitude anomalies.

The theta map uses the analytic signal amplitude to normalize the total horizontal derivative (Wijns and Kowalczyk, 2005). It is given by:

$$\theta = \cos^{-1}\left(\frac{\sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2}}{\sqrt{(\frac{\partial g}{\partial x})^2 + (\frac{\partial g}{\partial y})^2 + (\frac{\partial g}{\partial z})^2}}\right) \qquad (7)$$

Figure 3e shows the theta results from synthetic models that appropriately delineate the actual boundaries of the causative sources. The amplitude of the response from the three local models is similar.

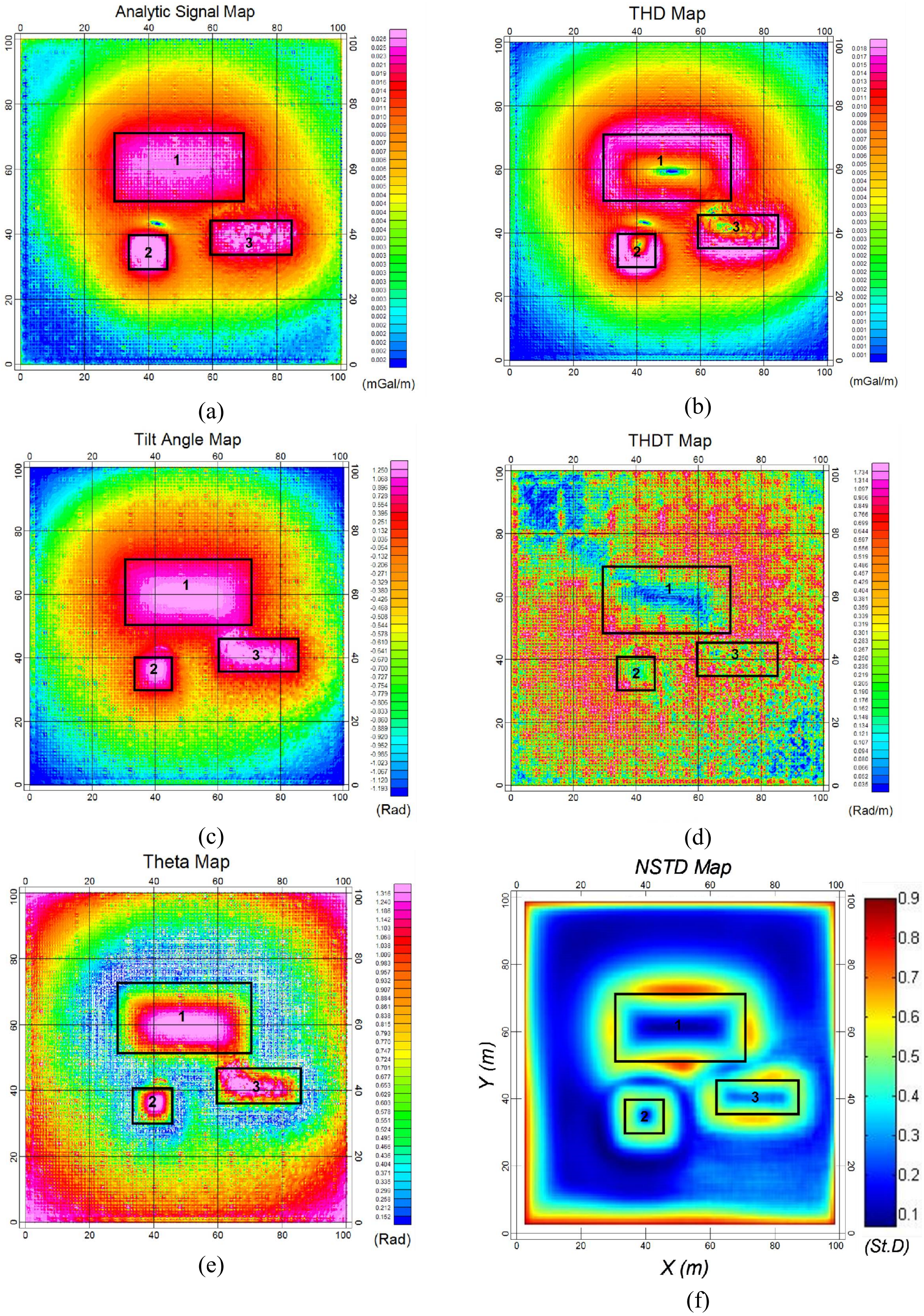

Figure 3. Results of applying edge detection methods to gravity anomalies of synthetic models, (a) Analytic Signal, (b) THD, (c) Tilt Angle, (d) THDT, (e) Theta map, (f) NSTD.

A windowed computation of the standard deviation of a gravity map is a simple measure of the local variability. The NSTD in Eq. 8 will be low when there is no anomalies, while it is expected to have relatively large NSTD when anomaly exists, e.g. over edges of the gravity anomalies (Cooper and Cowan, 2008). If it is used as an edge detector, the response over large amplitude gradients will dominate the results, similar to other mentioned filters. This filter is based on the ratio of the related NSTD of the gravity gradients to simultaneously enhance the edges of large and small (outputs of the Eq. 8) causative sources (Cooper and Cowan, 2008):

$$NSTD = \frac{\sigma\left(\frac{\partial g}{\partial z}\right)}{\sigma\left(\frac{\partial g}{\partial x}\right) + \sigma\left(\frac{\partial g}{\partial y}\right) + \sigma\left(\frac{\partial g}{\partial z}\right)} \qquad (8)$$

The standard deviations (σ) in Eq. 8 are computed using a moving squared-window of data points, which scan all locations of the observed data (Cooper and Cowan, 2008).

Figure 3f shows the NSTD results from synthetic models. This image processing method clearly gives better resolution of the edges for deeper models than the THDT or theta map.

4 Application to real gravity data

Two case studies are presented here to consider the capability of the methods:

4-1 Dehloran Bitumen

The area under study is located in western Iran over the Zagros tectonic zone (Figure 4) where we are looking for Bitumen. Layers of medium bedded limestone with intermediate marl-limestone are the dominant formations in the area and the hydrocarbon zone is one of the most important characteristics of the area.

A Scintrex CG3 gravimeter with a sensitivity of 5 micro-Gals was used for reading the data. The station separation of about 20 meters was chosen. The gravity measurement was done by the gravity branch of the Institute of Geophysics, University of Tehran in July 2006.

After gravity corrections, the Bouguer gravity anomalies were calculated. As we were looking for the local gravity anomalies, residual gravity anomalies were computed by removing a trend degree 2 from the Bouguer anomalies (Figure 5).

Aforementioned methods are applied to real data and the obtained results are indicated in Figure 6. Only the THDT map does not show satisfactory results because it is sensitive to noise level of the observed gravity data (note that real data are usually corrupted by noise). An interpreter should use all the results simultaneously to have an appropriate edge detection interpretation. In the region of interest, the point (x=60 m, y=50 m) is the best location for drilling. It should be noted that the results of the NSTD are similar to other methods in Figure 6.

Figure 4. Geographic location of Dehloran and SabzKoh field in the map of Iran.

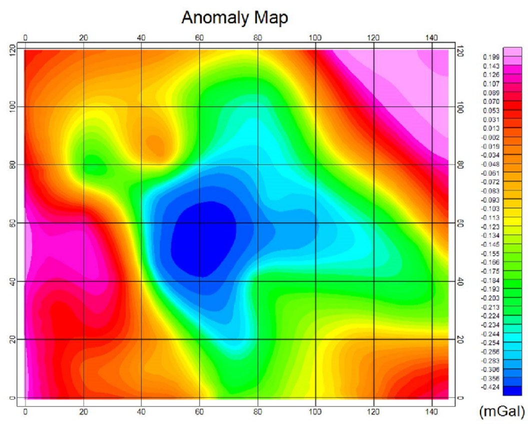

Figure 5. Residual gravity anomaly of Dehloran bitumen.

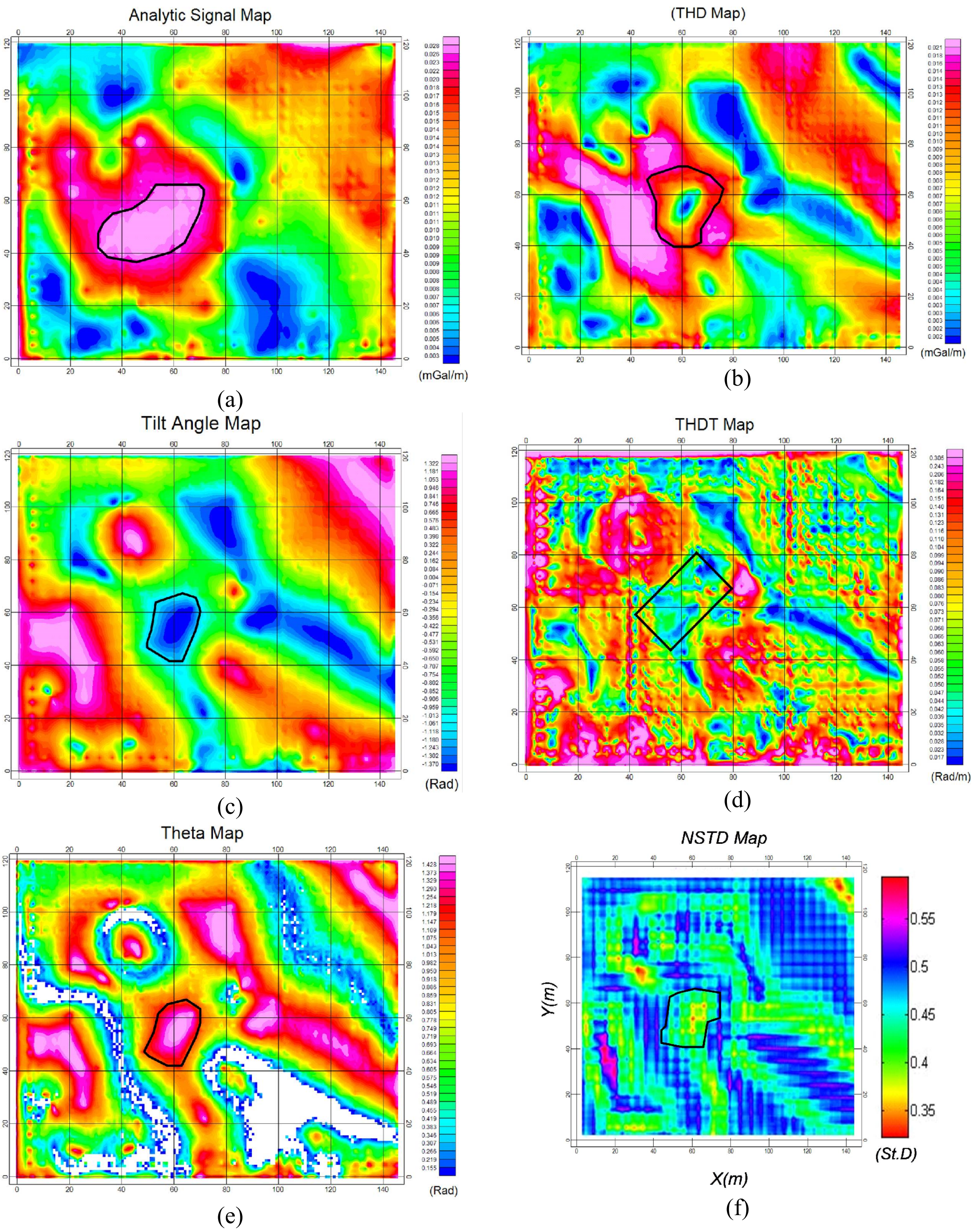

Figure 6. Results of applying edge detection methods to gravity anomalies of Dehloran Bitumen, (a) Analytic Signal, (b) THD, (c) Tilt Angle, (d) THDT, (e) Theta map, (f) NSTD.

4-2 Karst Zone in SabzKoh

The edge enhancement filters are applied to gravity data provided by the gravity branch of the Institute of Geophysics to highlight gravity signatures of Karst zones in the Zagros Mountains in an area considered for excavating a water tunnel in SabzKoh area (Figure 4). The Karstic limestone aged Cretaceous (Sarvak and Kajdomi formations) are the dominant geological signatures in the studied area.

A Scintrex CG3 gravimeter with a sensitivity of 5 micro-Gals was used to obtain the data. Station altitude was measured with a total station, model Laika Tc 407, with accuracy of 1-3 mm in horizontal and vertical coordinates (x, y, h). The gravity and altitude measurement was done by the gravity branch of the Institute of Geophysics, University of Tehran.

The gravity station grid consists of 197 measurement points on a grid with 50 to 100 m separation. Through standard methods, the data were corrected for the effects caused by variations in latitude, elevation and topography. After correction, the Bouguer gravity anomalies were computed. Using the polynomial fitting method, the residual anomalies were computed and shown in Figure 7. The map shows some negatives anomalies (four anomalies) of the Karst zones. Figure 8 shows the better maps of the residual anomalies of 2 and 3.

All edge detection methods applied to SabzKoh karst zone data and the results are shown in Figure 9. All of them approximately have similar results and show three separated anomalies for zones 2 and 3. Center of these separated anomalies can be appropriate candidates for exploratory drillings.

To sum up, all the edge detection methods have similar results rather than the THDT map for which the results can be affected by the noise level of the observed gravity data. Therefore, boundary enhancement of gravity anomalies provides suitable information to locate high potential zones for exploratory drillings.

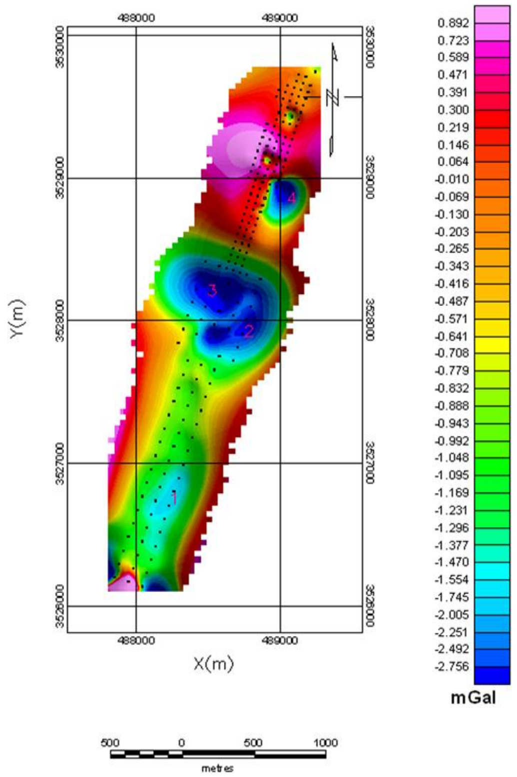

Figure 7. Residual gravity anomaly of the Karst Zones in SabzKoh.

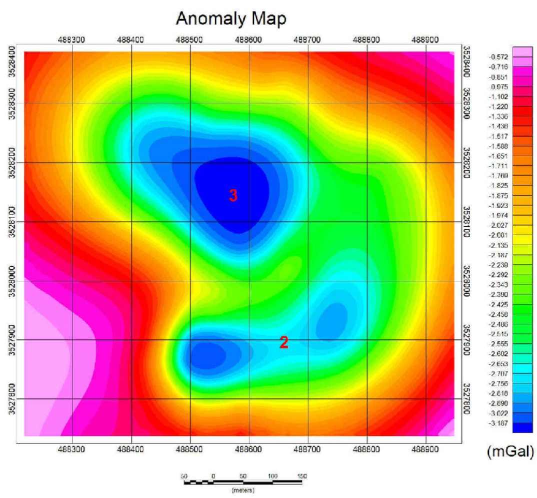

Figure 8. Residual gravity anomaly for zones 2 and 3 Shown in Figure 7.

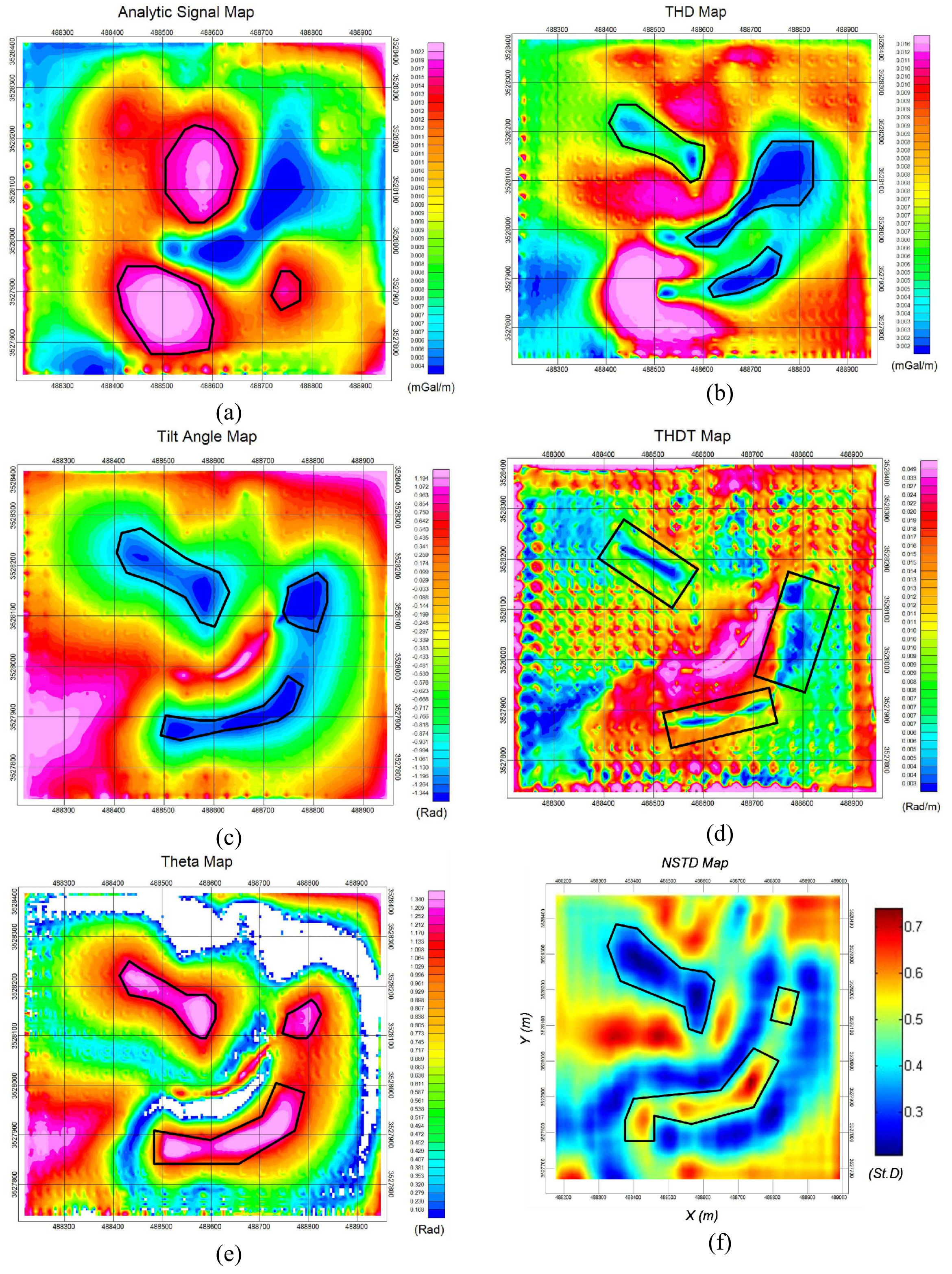

Figure 9. Results of applying edge detection methods to gravity anomalies of karst zones in SabzKoh, (a) Analytic Signal, (b) THD, (c) Tilt Angle, (d) THDT, (e) Theta, (f) NSTD.

5 Conclusion

In this study, various edge detection methods including analytic signal, THD, tilt angle, THDT, theta map and NSTD were applied to evaluate the capability of these approaches to enhance the edges of the gravity anomalies. All of these techniques were implemented on the synthetic data, and their output maps were compared. Except the THDT map which is sensitive to the noise level of the observed gravity data, other methods have similar results. The main reason for this study was to evaluate a new edge detection method, called NSTD which is based on the windowed standard deviation of the derivatives of the potential filed data. Its outcome showed acceptable results, so that it enhanced the edges of the synthetic anomalies. All edge detection techniques were successfully applied to the gravity anomalies of Dehloran Bitumen and the Karst Zone in SabzKoh. As a consequence, the NSTD can be a new edge detection tool for gravity anomalies, and can be applied for other potential field data such as magnetic anomalies.

Acknowledgment

The authors are thankful to the Faculty of Mining Engineering and the Institute of Geophysics, University of Tehran for all their supports.

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