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An improved method for geological boundary detection of potential field anomalies

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Abstract

Potential field methods such as gravity and magnetic methods are among the most applied geophysical methods in mineral exploration. A high-resolution technique is developed to image geologic boundaries such as contacts and faults. Potential field derivatives are the basis of many interpretation techniques. In boundary detection, the analytic signal quantity is defined by combining the values of horizontal and vertical derivatives. The outlines of the geologic boundaries can be determined by tracing the maximum amplitudes of analytic signal. However, due to superposition effects, in some cases that a variety of sources are adjacent, the detected boundaries are blurred. To overcome this problem, this study used enhanced analytic signal composed of the nth- order vertical derivative of analytic signal. The locations of its maximum amplitudes are independent of magnetization direction and geomagnetic parameters. This technique is particularly suitable when interference effects are considerable and when remanent magnetization is not negligible. In this paper this technique has been applied to gravity data of southwest England. Using this method, five granites outcrops and their separating faults are enhanced accurately.

Keywords: *Potential field data, horizontal derivative, vertical derivative, enhanced analytic signal, magnetization direction.*

1. Introduction

A variety of automatic or semiautomatic methods based on horizontal and/or vertical derivatives of potential field anomalies have been developed as efficient tools for the determination of geometric parameters such as location of boundaries and depth to top of the causative body [1, 2, 3, 4]. The validation of these methods depends on the fact that quantitative and semi-quantitative solutions are found with no or few assumptions [5].The analytic signal is formed through a combination of the horizontal and vertical gradients (derivatives) of potential field anomaly. The analytic signal has a form over causative bodies that depend on the location of the bodies [5]. The main advantage of using the maximum amplitudes of analytic signal to edge detection of structural features or geological structures is that the result is independent of the direction of magnetization and earth magnetic field [1, 2, 5].

Euler deconvolution method is an automatic depth estimation method that uses gradients of potential field anomalies and can be used as an edge detection method too [6]. The problem of using this method is the structural index selection that depends on the causative body geometry. Another edge detection method is total gradient of pseudo-gravity anomaly that its maximum lies over boundaries [4, 7]. Disadvantage of this technique is that the magnetization direction should be known or assumed, and the results will be affected by this assumption.

Since potential field data, especially magnetic data, correspond to the superposition effects from all adjacent causative bodies, the simple analytic signal is not sufficient for boundary detection and usually produces mislocations and detachment between boundaries of adjacent bodies [7]. To reduce interference effects, one may apply downward continuation filter on data. Although this technique may increase resolution, it is not very stable with respect to taking high-order derivatives [2].

Based on Nabighian' suggestion for the 2-D case [2], an enhanced analytic signal technique for the interpretation of 3-D potential field anomaly in the frequency domain has been produced [6], which reduces superposition effect, however because of the frequency domain calculation the results may be noisy [5]. In this paper we applied this technique in the spatial domain in gravity data from southwest England.

2. Enhanced analytic signal

The analytic signal for potential field anomalies was initially defined as a "complex field deriving from a complex potential" [8,10]. Nabighian [1,2] applies the analytic signal concept to potential field data in two-dimensions. For a potential field $\varphi(x)$ measured along the x-axis at a constant observation height z and generated by 2D source aligned parallel to the y-axis, the horizontal derivative φ_x and the vertical derivative φ_z are the Hilbert transform pair. We could thus write the analytic signal of potential field data in two dimensions as:

$$A(x) = \varphi_x + i\varphi_z \tag{1}$$

where the 2D analytic signal amplitude (ASA) of potential field data is [11]

$$|A(x)| = \sqrt{\varphi_x{}^2 + \varphi_y{}^2} \tag{2}$$

Roest et al. have written the analytic signal in three dimensions as a vector encompassing the horizontal derivatives and their Hilbert transform, and the 3-D analytic signal (A(x,y)) and its amplitude (ASA) of potential field data $\varphi(x, y)$ are defined as [11]:

$$A(x, y) = \varphi_x \hat{x} + \varphi_y \hat{y} + i\varphi_z \hat{z} \tag{3}$$

$$|A(x, y)| = \sqrt{(\varphi_x)^2 + (\varphi_y)^2 + (\varphi_z)^2} \tag{4}$$

where, $\hat{x}$, $\hat{y}$, $\hat{z}$ are unit vectors in the x, y and z directions.

This function can be computed easily in the frequency domain, its real part being the horizontal derivative of the field and its imaginary part being the vertical derivative. Analytic signal processing and interpretation requires few initial assumptions regarding the source body geometry and magnetization direction, therefore this quantity has an important role in potential field data processing[1,2].

In the 2-D case, Nabighian suggested the use of the following bell-shaped function to enhance the analytic signal [2]:

$$\left(\frac{\partial^n \varphi_h}{\partial h^n}\right) + \left(\frac{\partial^n \varphi_z}{\partial h^n}\right) = \frac{\left(1^2 \times 2^2 \times 3^2 \times \ldots \times n^2\right)\alpha^2}{\left(d^2 + h^2\right)^{n+1}} \tag{5}$$

Where, φ_h and φ_z are horizontal and vertical potential field anomaly respectively; h is the distance along the x-axis, which is perpendicular to the strike of the 2-D structure; n is positive integer (vertical derivative order); d is the depth to the top surface of the source, while the lower surface is at infinity; α is the ambient parameter and is equal to $\alpha = 2kF\sin\theta$ when the step model of magnetic anomaly applied, k is the susceptibility contrast of the step model;

F is the earth magnetic field; θ is the dip angle of the step model, $c = 1 - \cos^2 i \sin^2 B$ for total magnetic field anomaly; I is geomagnetic inclination; and B is the angle between magnetic north and h-axis (Figure 1).

By extending Equation (5) from 2-D case into the 3-D case, the nth-order enhanced analytic signal is defined as:

$$AS_n(x, y) = \frac{\partial}{\partial x}\left(\frac{\partial^n \varphi}{\partial z^n}\right)\hat{x} + \frac{\partial}{\partial y}\left(\frac{\partial^n \varphi}{\partial z^n}\right)\hat{y} + i\frac{\partial}{\partial z}\left(\frac{\partial^n \varphi}{\partial z^n}\right)\hat{z} \tag{6}$$

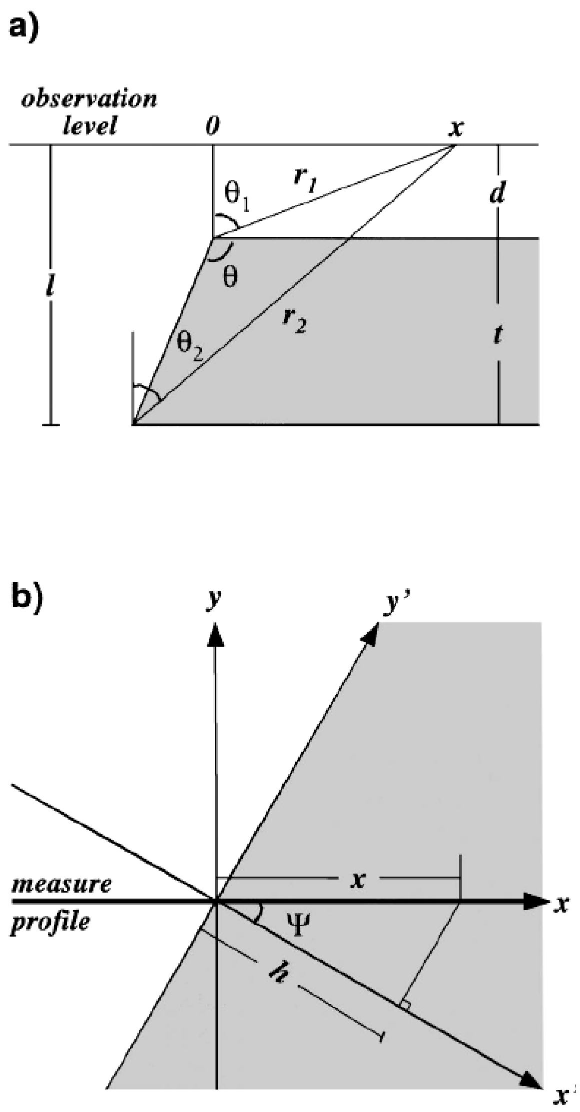

Figure 1. (a) Cross-sectional view of a step model. (b) Plane view of the step model whose strike is along the y-direction, but the survey is supposed to be conducted along the x-direction.

If the above equation is written in the following form:

$$AS_n(x,y) = \frac{\partial^n}{\partial z^n}\left(\frac{\partial \varphi}{\partial x}\right)\hat{x} + \frac{\partial^n}{\partial z^n}\left(\frac{\partial \varphi}{\partial y}\right)\hat{y} + i\frac{\partial^n}{\partial z^n}\left(\frac{\partial \varphi}{\partial z}\right)\hat{z} \quad (7)$$

Then the amplitude of nth-order enhanced analytic signal in Equation 6 can be written as:

$$|AS_n(x,y)| = \sqrt{(\nabla^n \varphi_x)^2 + (\nabla^n \varphi_y)^2 + (\nabla^n \varphi_z)^2} \quad (8)$$

where, $\nabla^n = \dfrac{\partial^n}{\partial z^n}$ evitavired lacitrev senifed operator $\varphi_x = \dfrac{\partial \varphi}{\partial x}, \varphi_y = \dfrac{\partial \varphi}{\partial y}, \varphi_z = \dfrac{\partial \varphi}{\partial z}$ are two horizontal and one vertical derivative of 3-D potential field anomaly $\varphi(x,y)$ respectively.

It is clear that for n=0, Equation 8 corresponds to amplitude of 3-D simple analytic signal in Equation 4. For n=1, 2 Equation 8 corresponds to the amplitude of 1-oeder and 2-order vertical derivative of simple analytic signal (enhanced analytic signal) in Equations 9 and 10 respectively.

$$|A_1(x,y)| = \sqrt{(\nabla \ \varphi_x)^2 + (\nabla \ \varphi_y)^2 + (\nabla \varphi_z)^2} \quad (9)$$

$$|A_2(x,y)| = \sqrt{(\nabla^2 \varphi_x)^2 + (\nabla^2 \varphi_y)^2 + (\nabla^2 \varphi_z)^2} \quad (10)$$

Because of interference effects (superposition effects from different adjacent bodies), the use of the simple analytic signal in the 3-D case seems insufficient to detect geological boundaries [6]. Since the existing interference effect is usually inevitable, and analytic signal is one of the best quantities in potential field interpretation, improving resolution becomes a requirement. Since the vertical derivative narrows the anomaly width and locates boundaries more accurately, then superposition effect in using simple analytic signal problem can be solved by computing vertical derivative of it (enhanced analytic signal) [7], but we must consider noise induction problem in higher order of vertical derivative since vertical derivative acts as a high-pass filter and the filtered image may be noisy. To reduce the noise problem in filtered image vertical derivative, we computed vertical derivative of analytic signal in the spatial domain. Based on previous experience in the application of vertical derivative as an edge detection method, in this regard second-order vertical derivative of analytic signal produces acceptable results. Therefore Equation 10 is used as a new filter to demonstrate the improvement of the detection of geological boundaries due to different geological structures. To compare the enhanced analytic signal and simple analytic signal in boundary detection, in Figure 2 three prismatic models in different depth and inclination have been presented and in Figure 3 and Figure 4 simple and 2- order enhanced analytic signal images are shown respectively. In each case the maximum value of analytic signal indicates the models boundaries. In Figure 3 due to adjacent different models the detected boundaries are ambiguous and it is complicated to delineate boundaries of three models. However, in Figure 4 the enhanced analytic signal presents improvement resolution.

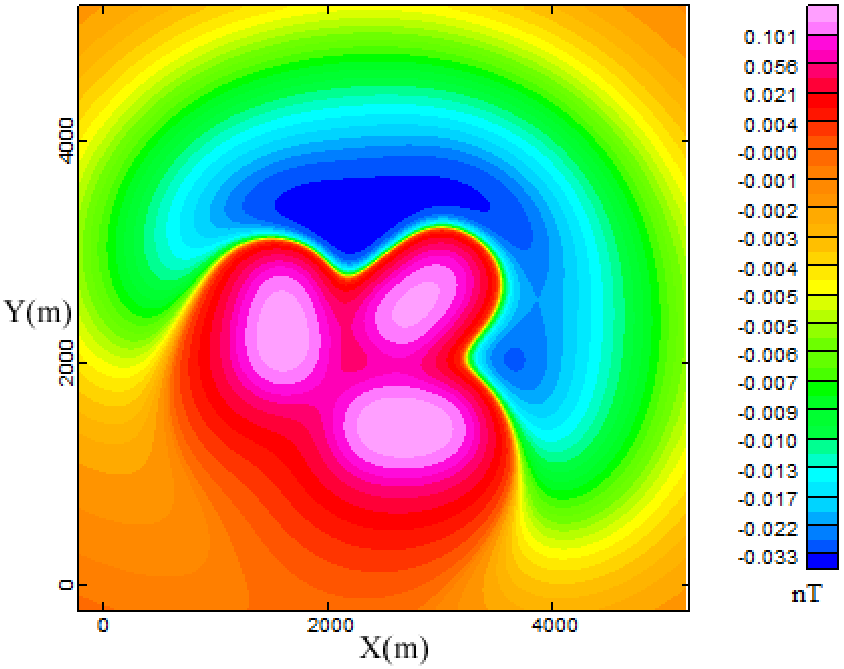

Figure 2. Magnetic response from three prismatic models with vertical sides in different depth and inclination.

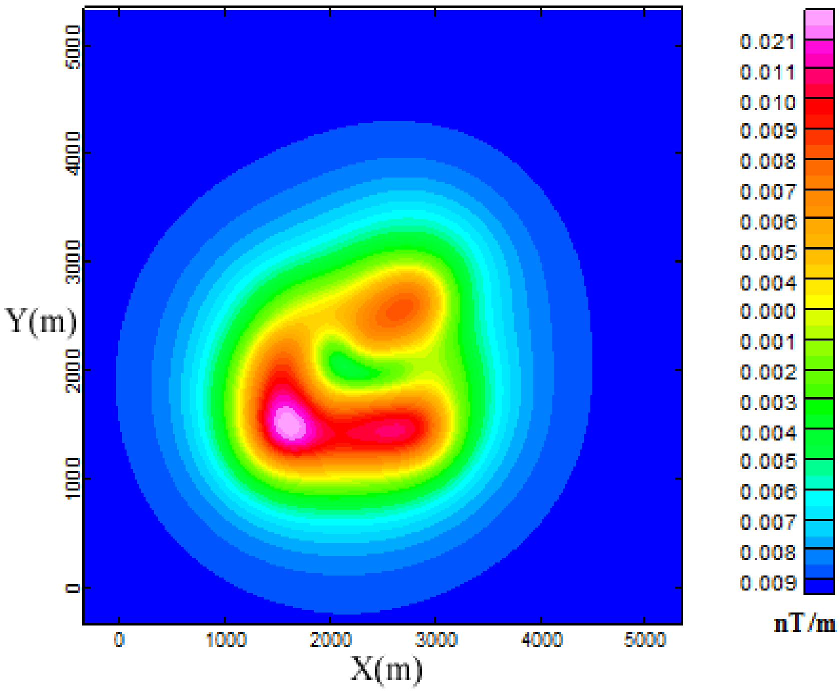

Figure 3. Boundaries detection of three models in Figure 2 using simple analytic signal.

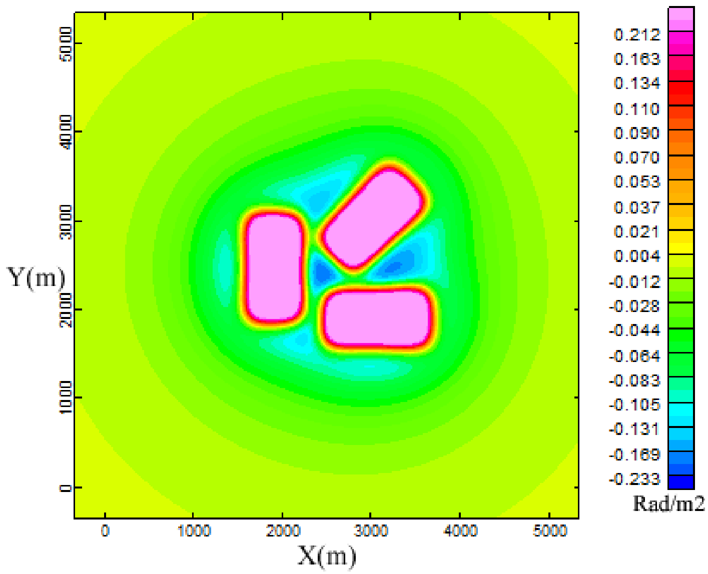

Figure 4. Boundaries detection of three models in Figure 2 using second- order vertical derivative of analytic signal.

3. Application to real gravity data

The Cornubian Batholith of southwest England underlies the counties of Cornwall and Devon, running down the axis of the peninsula for in excess of 200 km. It is exposed onshore in five major plutons (east to west: Dartmoor, Bodmin Moor, St Austell, Carnmenellis and Land's End) [12]. It outcrops further west at the Scilly Isles (28 km west of Land's End) and beyond (gravity surveys in 1963-65 by the Bedford Institute of Oceanography indicated a 100 mile seaward extension of the batholith). The Haig Fras granite bosses, 95 km WNW of the Scilly Isles, out in the Western Approaches are also of Variscan age [13] though appear to represent a separate plutonic body. The batholith intrudes a succession of deformed, low-grade, regionally metamorphosed sediments and igneous rocks of Devonian and Lower Carboniferous age (Figure 5). The rocks of the batholith are granitic [12] in nature and their origin is related to the later stages of the Variscan Orogeny (late Carboniferous) that had previously deformed [13] and metamorphosed the sedimentary pile. The batholith is also highly mineralized and this mineralization has been exploited by deep mining continuously for the last 400 years within local records, and for some 2000 years prior to that by shallow surface mining and working placer deposits. This area has been used as a model for vein mineralization and contributed significantly to the understanding of ore forming processes. South-west England has undergone major thrusting and faulting during the Variscan orogeny and consequently there are a large number of structural lineaments present in both study areas. The identification of basement lineaments, that represent deep faults that may have acted as a conduit for mineralizing fluids, is important in the definition of prospective areas (Figure 5).

The first substantial geophysical work to be undertaken across Cornwall was a pendulum gravity survey [6]. This survey established the pattern of bouguer anomalies (with pronounced negative anomalies over the granite outcrops) across the peninsula, but made no interpretation of the results. This work was followed up by a major survey (acquiring gravity and magnetic data) in the late 1950's covering Cornwall, Devon and Somerset. The results of this survey were published in 1958 and this seminal work has formed the basis of the gravity interpretation of the batholith to the present day [12]. Regional gravity data collected as part of a national survey by the BGS have a distribution of about one station per km^2.

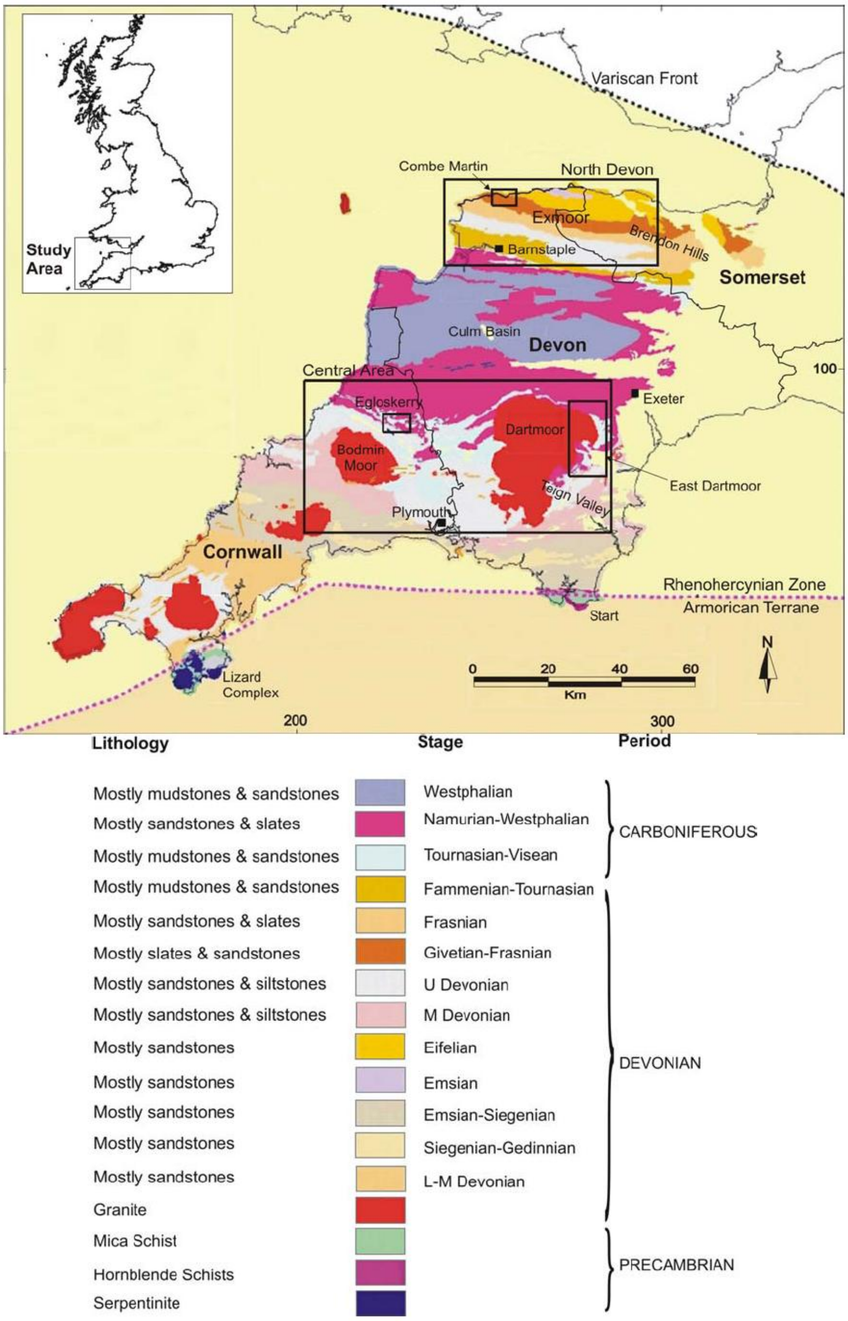

Figure 5. A simplified geological map of Cornubian massif in Southwest England [12].

Regional reconnaissance magnetic surveys carried out by (British Geological Surveys(BGS)) in the 1950s identified a prominent high frequency aeromagnetic anomaly in the central area of Devon and east Cornwall which approximately follows the mapped outcrop of Lower Carboniferous strata along the northern margins of the Dartmoor and Bodmin Moor granites. The form of the magnetic anomaly indicates that its source has a strong Natural Remnant Magnetisation (NRM) vector. The most important ferromagnetic mineral in the area was shown to be pyrrhotite that has a Curie temperature in the range 270–330° C. The pyrrhotite appears to have been formed at about the time of granite intrusion, either by metasomatism or by recrystallisation of syngenetic pyrite [13, 14, 15].

The present investigation concerns the gravity dataset in order to enhance body’s locations and their separating faults from gravity data.

In order to enhance the boundaries of granite batholith and separating faults analytic signal was applied.

Figure 6a shows gravity map of the southwest England which its intense low gravity with NE-SW trend corresponds to granite batholith. The Cornubian batholith has previously been modeled using gravity data [8]. It has been shown that the batholith widens from about 10 km near the surface to between 30 and 50 km at the base, which is at a depth of between 10 and 12 km [11, 12, 13, 16]. Figure 6b is the Theta map of the data in Figure 6a. In this figure the minima of the Theta filter lie over bodied location but there are no detachment between them. In order to enhance the boundaries of granite batholith and separate faults, the analytic signal of the gravity data was computed (see Figure 6c). Due to interference effects of granite batholiths, the detected boundaries are blurred in which there is no detachment between granites bodies. As mentioned before to overcome this problem, enhanced analytic signal (vertical derivative of analytic signal) is computed. In Figure 6d the first- order vertical derivative of the analytic signal presented. Finally, Figure 6e is the second – order vertical derivative of the analytic signal map. In this map, the maximum values lie over granite batholiths. The separating faults and margin of the granite bodies are enhanced with respect to surrounding rocks. The results of Figure 6e have a suitable correlation with geological evidences.

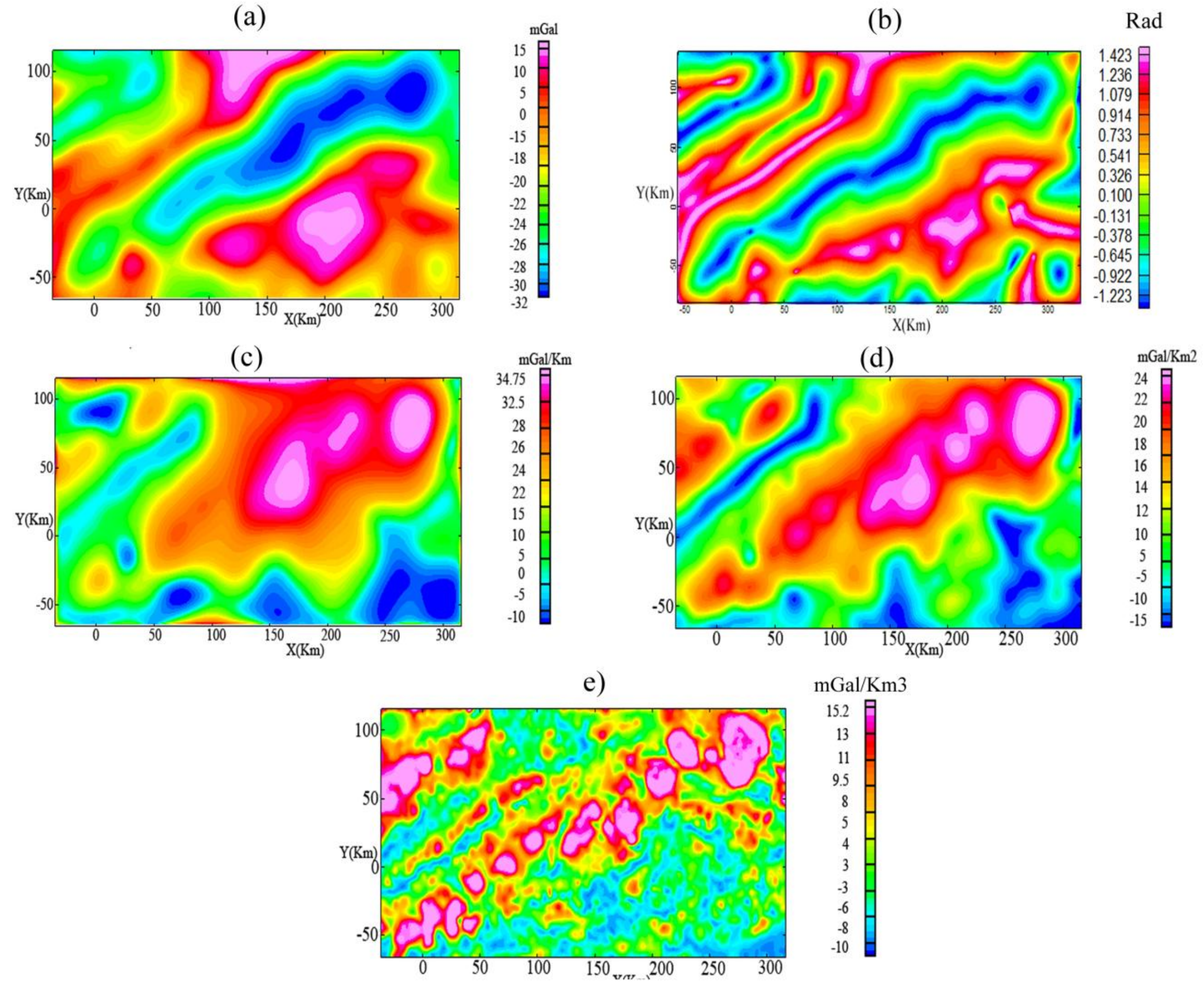

Figure 6. Application of the proposed filters on gravity data of southwest England: (a) Bouguer gravity map of the study area; (b) Theta map of the data in Figure 6a.; (c) Analytic Signal map of the gravity in Figure 6a.; (d) First – order vertical derivative of the analytic signal; (e) Second – order vertical derivative of the analytic signal.

4- Conclusions

Potential field gradients including vertical and horizontal gradients (derivatives) are most applicable quantities in interpretation of potential field anomalies. Applications of these quantities are included from depth estimation (Euler method) to boundary detection. In boundary detection a variety of filters are used that based on potential field gradients. One of these filters is analytic signal (total gradient) which is the combination of vertical and horizontal gradients. Maximum value of analytic signal lies over source boundaries and creates a contrast between source and surrounded area. This filter has two advantages: (1) its amplitude is independent of direction of magnetization; (2) this specification is suitable when the given body has undefined remnant magnetization. However, due to superposition of different adjacent bodies analytic signal method cannot enhance body boundaries. To overcome this problem, vertical derivative of analytic signal is computed. In this regard, 2-order vertical derivative produces the best results. In this paper we applied this method on gravity data of southwest England. In this area five outcrops of granite intrusion that have been separated with variety of faults exist. In simple analytic signal image boundary of granite bodies and faults are not determined which by using enhanced analytic signal geological and structural features (granite bodies and faults) were determined more accurately.

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