Geophysica (2011), 47(1–2), 43–55

A Gravity Model Study for Differentiating Vertical and Dipping Geological Contacts with Application to a Bouguer Gravity Anomaly Over the Foumban Shear Zone, Cameroon

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(Received: September 2009; Accepted: June 2010)

Abstract

The determination of the type of the contacts from gravity data is an important step in the determination of a model of geological structures. In this paper we present the multi-scale horizontal derivative of the vertical derivative (MSHDVD) method which allows us to efficiently differentiate vertical from dipping geological contacts and to determine the direction of dip. The method determines the locations of the maxima of the horizontal gradient of the vertical derivative of upward continued gravity field at different height levels. The technique to compute the vertical derivative at different levels is also suggested. The MSHDVD method is tested on synthetic data and on the Bouguer gravity anomaly over the Foumban Shear Zone (FSZ) in Cameroon, within an area around Foumbot, where the granite-gneiss basement is widely covered by volcanic rocks of the Cameroon Volcanic Line. The MSHDVD method shows the presence of a deep fault, oriented N68°E and dipping towards southeast.

Key words: gravity, vertical derivative, horizontal derivative, Foumban Shear Zone

1. Introduction

To determine the source parameters in gravity interpretation, the vertical derivatives and/or horizontal derivatives of the gravity field have been used commonly (*Cordell,* 1979*; Cordell and Grauch,* 1985*; Blakely and Simpson,* 1986*; Marson and Klingel,* 1993). For example, *Khattach et al*. (2004) associated the horizontal gradient magnitude of the Bouguer gravity anomaly to the upward continuation of the field to characterize faults of the Triffa basin in North Morocco. However, it must be noted that the maxima of the horizontal gradient magnitude can be offset from a position directly above the geologic contacts, especially when contacts are not steep or when several contacts are close together (*Grauch and Cordell*, 1987). *Fedi and Florio* (2001) proposed that, when the gravity fields of several sources interfere, it is more accurate to use the vertical derivative of the field rather than the field itself to determine the location of contacts of the sources. This is in part due to the vertical derivative being able to isolate the gravity effects of individual sources better than the Bouguer anomaly. Hence, the signatures of small scale features that are not easily identified in Bouguer anomaly maps can be identified and mapped using the vertical derivative response. The vertical derivative can amplify short wavelength noise coming from poor data processing and/or from local subsurface density variations not corrected for. This problem is controlled in this study by using a multi-scale vertical derivative on the gravity field. From the corresponding horizontal derivative magnitude, it is then possible to outline and differentiate vertical and dipping geological contacts as well as the direction of the dip. In this paper we apply the MSHDVD method to synthetic gravity data and the Bouguer gravity anomaly over the Foumban Shear Zone, in the West region of Cameroon, to illustrate how the method works.

2. The MSHDVD method

The upward continuation of the gravity field at increasing heights highlights the gravity effect of deeper sources. In the case of a geologic contact, the highest upward continuation corresponds to the gravity response of the deepest part of the contact. If the contact is vertical, then the maxima of the total horizontal gradient of the upward continued fields are located at the same position. On the other hand, if the maxima systematically shift in horizontal direction, then the dip direction of the contact can be identified.

The MSHDVD method involves the following steps:

a) Calculating the first-order vertical derivative for upward continued gravity field at different heights, called here the MSVD (multi-scale vertical derivative);

b) Determining the maxima of the horizontal gradient of the MSVD;

c) Superposing the maps obtained for different continuation heights.

2.1 Calculation of the vertical derivative

The first-order vertical derivative of the gravity field at each height is calculated in the space domain using the method of finite differences proposed by *Florio et al.* (2006). This method is more stable than the continuation in frequency domain (*Gunn*, 1975) which in some cases enhances data errors, depending on the signal/noise ratio. It also has the advantage of allowing the calculation of vertical derivative at several heights, using a stable operator like upward continuation (*Jacobsen*, 1987).

Using forward differences, the vertical derivative of the gravity field g at the height h, is defined as

$$g_{vd} = \left(\frac{\partial g}{\partial z}\right)_h = \frac{g^{up}_{h+\Delta h} - g^{up}_h}{\Delta h} \qquad 1$$

where g_h^{up} is the field upward continued at the height h, $g_{h+\Delta h}^{up}$ is the field upward continued at a slightly higher level $h+\Delta h$, and Δh is a small height difference lying between 1/10 and 1/100 of the data sampling interval. Conventionally, the vertical derivative should be assigned to an altitude of $h + \Delta h/2$, but since Δh is so small, we can set the vertical derivative to level h (*Florio et al.*, 2006).

2.2 Determination of the maxima of the total horizontal gradient

The total horizontal gradient (derivative) of the vertical derivative is also calculated in space domain and its value is defined as

$$g_{hdvd} = \sqrt{\left(\frac{\partial g_{vd}}{\partial x}\right)^2 + \left(\frac{\partial g_{vd}}{\partial y}\right)^2} \tag{2}$$

The maxima of the total horizontal gradient of the vertical derivative are found using the method of *Blakely and Simpson* (1986). The procedure, which is illustrated in figure1 finds the location of the maxima of the horizontal derivative defined on a regular grid by comparing the value at a centre point of a 3 x 3 grid window to the surrounding eight points along four main directions: horizontal, vertical, and both diagonals. As a first criterion, the centre point is compared to the surrounding points in the four directions and whenever it is found bigger than the other two surrounding points, its index value, N, is increased. For each direction that fulfills the first criterion, a second order polynomial is fitted and the peak position of the parabola is computed. The position of the largest peak value that is located inside the area of the central grid cell (square box in Fig. 1) is then used as the maximum position of the horizontal derivative. The index N gives an indication of the linearity of a maximum: if $N = 1$, the anomaly is linear along one of the four directions; and if $N = 4$, the maximum is a local peak. *Blakely and Simpson* (1986) found that, in general, indices 2 and 3 produced most useful maps.

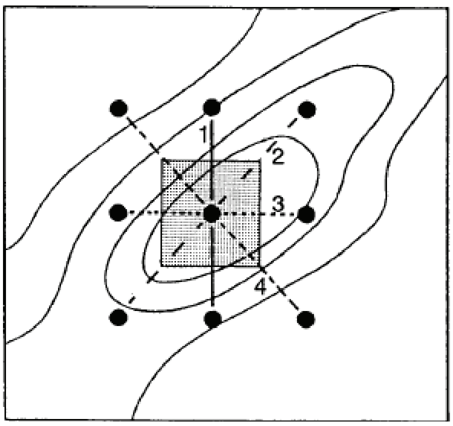

Fig. 1. Determination of the field maxima from gridded values using a 3 x 3 point windows (after *Blakely and Simpson*, 1986). Curves represent contours of the horizontal gradient of the gravity. A parabola is fitted through the four triplets along the four main directions. The number of parabolas that reach a maximum inside the area of center grid cell gives index N.

3. *Synthetic example*

To test the MSHDVD method, we created gravity maps using two prismatic bodies, with a sampling interval of 1 km along x and y directions. The four tests are illustrated in figure 2. Four models of the subsurface are considered: model M1 in which the contact between the two bodies is vertical, model M2 with a contact dipping at 62°, oriented towards the East, model M3 where the contact is dipping 32° towards the East, and model M4 which is like the mirror image of M3, with dip angle 148°. Table 1 gives the parameters of the bodies for each model. For each body, the density contrast is the difference between its density and the density of the background. Figure 2 (a'), (b'), (c') and (d') shows models and the east-west directed gravity profiles AA' above them.

Table 1. The parameters of the four prism models (see Fig. 2 a', b', c', d').

Models	**Bodies**	**Length along y (km)**	**Width of the top surface along x (km)**	**Thick-ness along z (km)**	**Depth to top (km)**	**Density contrast (g/cm^3)**	**Dip**
M1	1	20	18	20	2	-0.25	90°
	2	20	12.8	20	2	0.25	
M2	1	20	19.8	19	2	-0.25	62°
	2	20	33.9	19	2	0.25	
M3	1	20	19.8	20	2	-0.25	32°
	2	20	33.9	20	2	0.25	
M4	1	20	39.5	20	2	-0.25	148°
	2	20	15.7	20	2	0.25	

Before processing, a Gaussian noise with a mean equal to 0 and variance equal to 10% of the anomaly range was added to the synthetic field data (Fig. 3). For each model, the vertical derivative of the gravity field was computed in the space domain using the finite difference algorithm at heights 3 km, 4 km, 5 km and 6 km. To compute the vertical derivative at height 3 km for example, we calculated the upward continuations at 3 km and 3.1 km (i.e. 3 km + 100 m), and used the formula (1) between the calculated upward continuations with Δh = 100 m. Fig. 4 illustrates how the derivative changes with increasing height in each model and allows the tracking of the location of the maxima as well as the direction of dip.

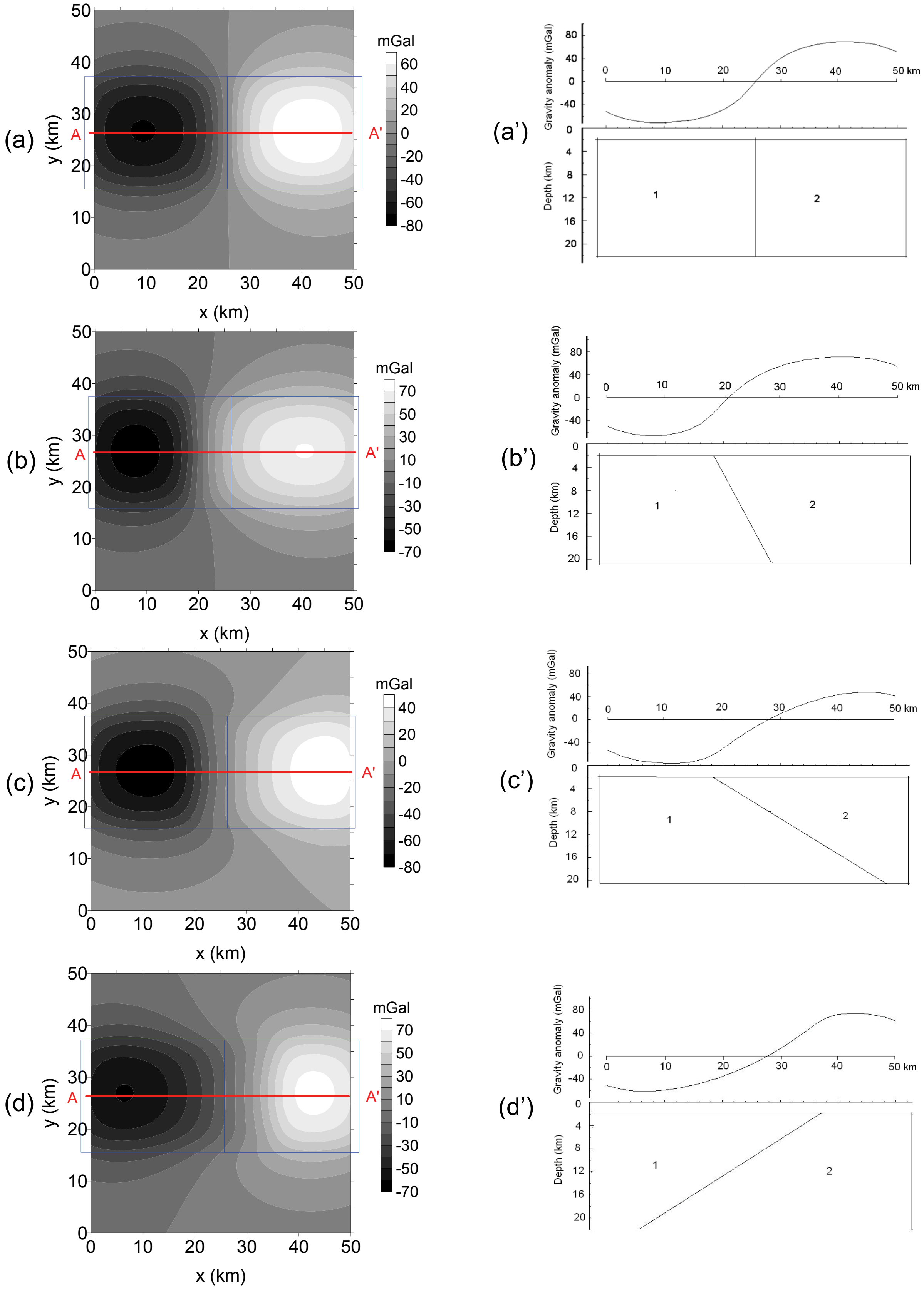

Fig. 2. Synthetic gravity anomaly maps showing in solid blue line the top of the source boundaries and in solid red line a profile AA’. The grid interval is 1 km and the contour interval is 20 mGal: (a), (b), (c) and (d) are gravity maps generated by models M1, M2, M3 and M4, respectively. (a’), (b’), (c’) and (d’) are synthetic gravity anomaly along E-W profiles AA’ above the models M1, M2, M3 and M4, respectively.

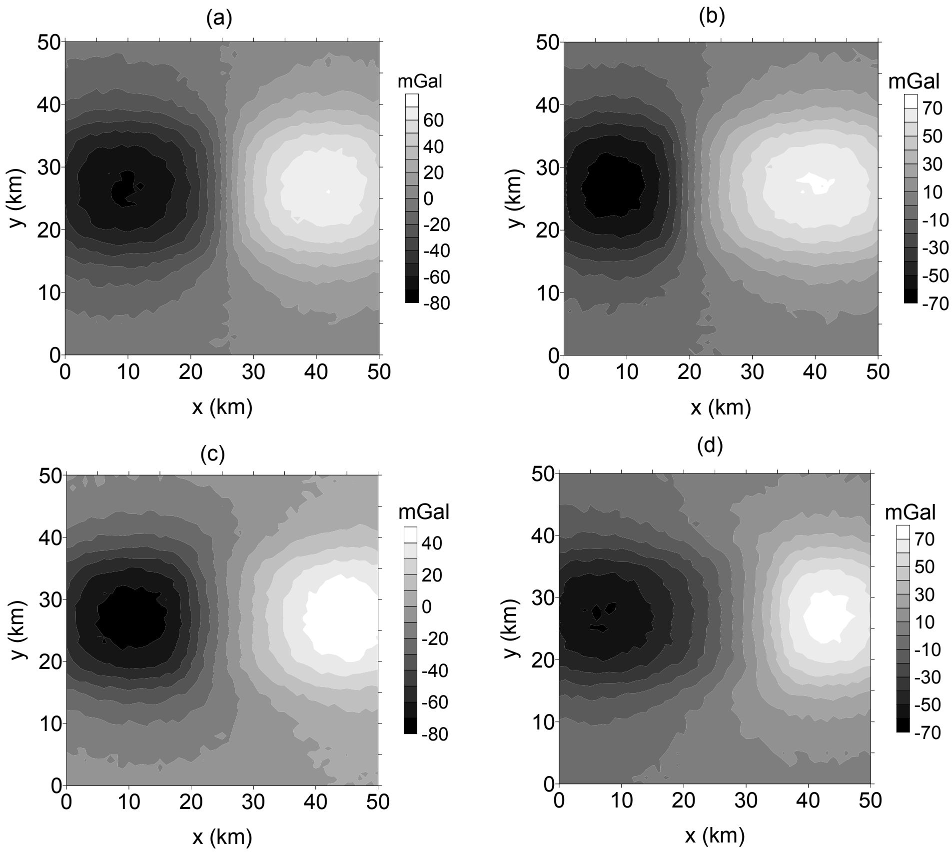

Fig. 3. Gravity maps of the models presented in Fig. 2, corrupted with Gaussian noise with variance equal to 10% of the gravity anomaly range.

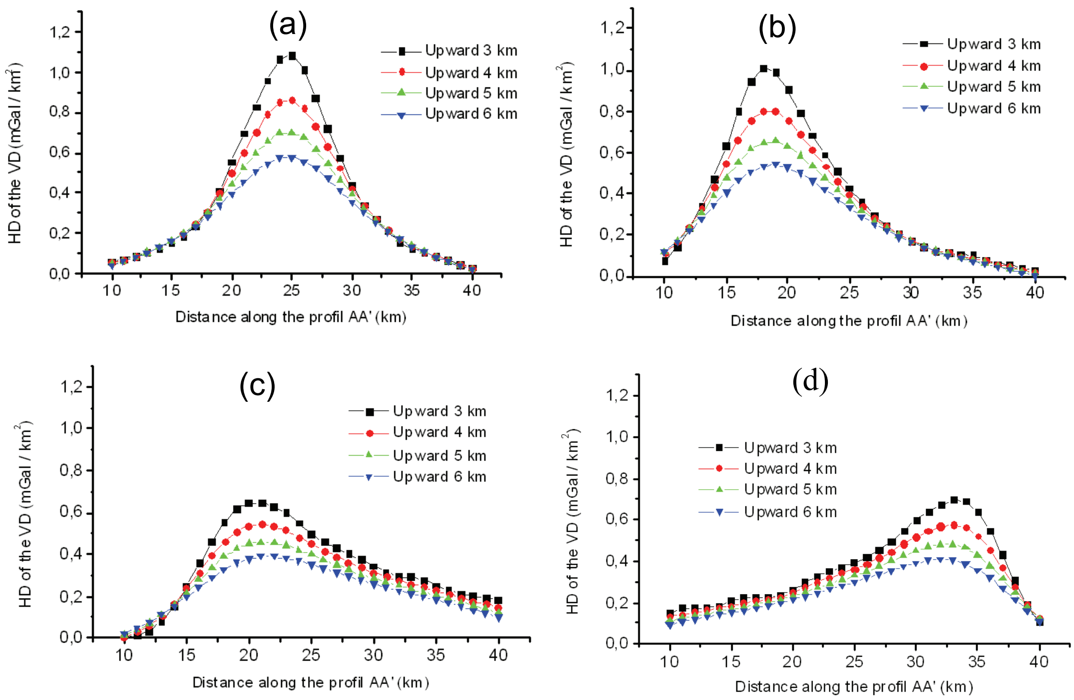

Fig. 4. Variation of the horizontal gradient of the MSVD along the profile AA' for (a) model M1, (b) model M2, (c) model M3 and (d) model M4. See how the maximum decreases when the height of the upward continuation increases. For a vertical contact, the maxima are situated on the same vertical line, whereas for dipping contacts, the maxima gradually move in the direction of dip.

Figure 5 shows a series of maps that illustrate the boundaries of the sources outlined by the positions of the maxima of the total horizontal gradient of the vertical derivative upward continued field (Figs. 5 a-d) and the upward continued field itself (Figs. 5 a'-d'). The location of maxima is determined by the method of *Blakely and Simpson* (1986) using indices 2 and 3. For the N-S contact we can see that for different continuation heights, the maxima are superposed on the same straight line in model M1, whereas in models M2 and M3, the position of the maxima moves towards east and in model M4 it moves towards west as the height of upward continuation increases. The directions of displacement of the maxima are shown by arrows, and they correlate well with the dip orientation of the contacts.

By comparing the results of the MSHDVD method with those obtained by the upward continued gravity field in Figs. 5 a'-d', we notice that the MSHDVD method defines the superposition of the maxima of the horizontal gradient magnitude at different levels better than the upward continued gravity anomaly, which tends to displace the maxima systematically outside the body's boundaries. In addition, the MSVD method produces a reliable method for outlining all the boundaries of source model. The mislocation of some maxima along the HDVD map's boundary is caused by artifacts due to the boundary effects in the computation of the vertical derivative.

4. Field example

We applied the MSHDVD method to the Bouguer gravity anomaly over an area located within the Foumban Shear Zone (FSZ) in Cameroon (see Fig. 6). The FSZ is part of the ENE-WSW trending called Central African Shear Zone (CASZ), a dextral shear zone that extends some 2000 km from west Cameroon to Sudan (*Ngako et al.*, 1992; *Cornacchia and Dars*, 1983). This fault zone is considered to be the continuation of the pernambucco lineament in Brazil prior to continental separation (*De Almeida and Black*, 1967) and represents a zone of weakness within the African lithosphere, reactivated since Cretaceous to recent times and may have facilitated magma ascent to the surface (*Browne and Fairhead*, 1983). The geological setting of the studied area (Fig. 7a) is characterized by Precambrian basement rocks, mainly gneisses which are sometimes intruded by granites. The basement is widely superimposed by volcanic formations of the Cameroon Volcanic Line (CVL), including Basalts, trachytes, trachy-andesites and rhyolites (*Le Maréchal*, 1976).

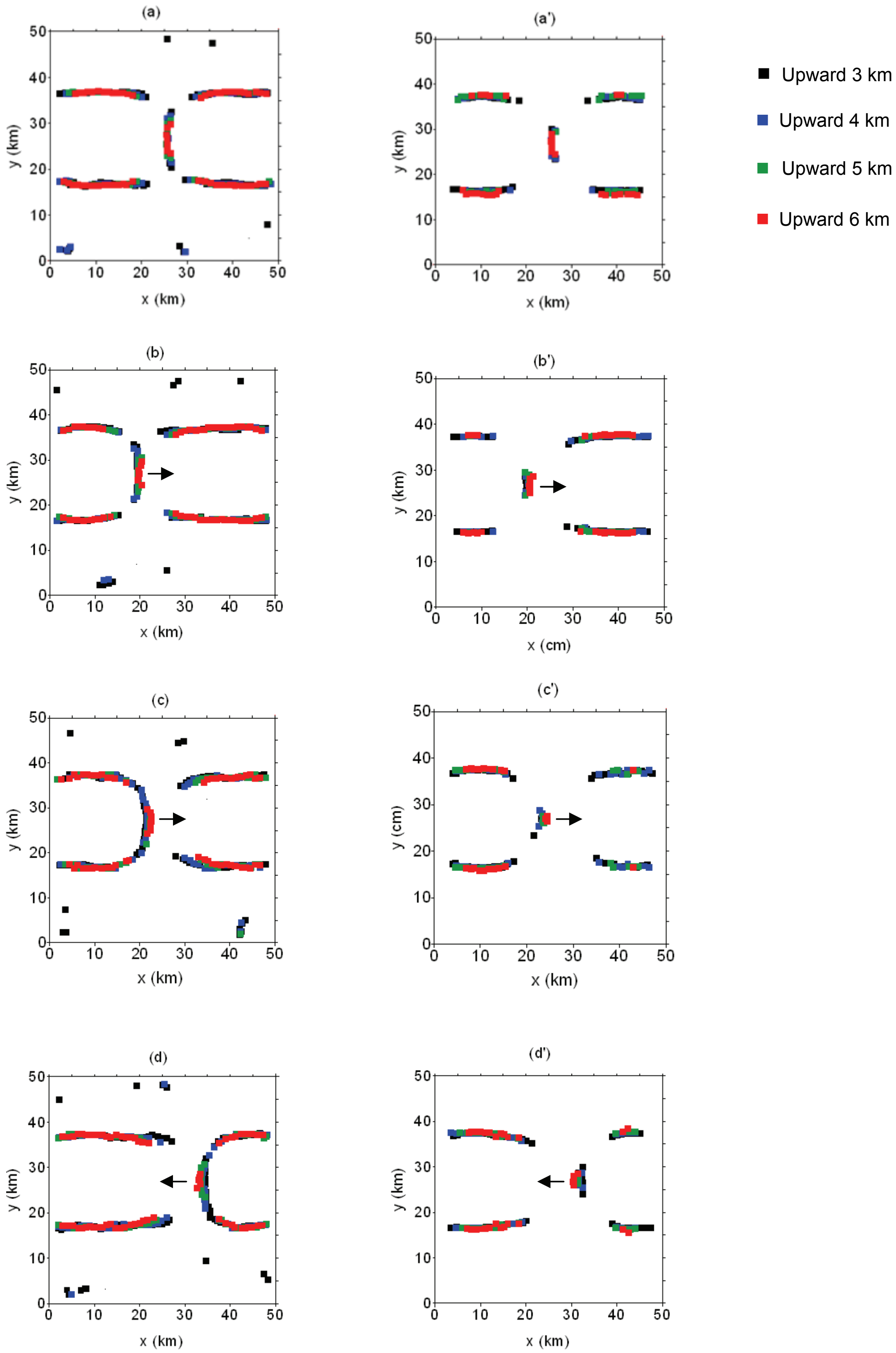

Fig. 5. Location maps of the maxima of the HDVD determined by the method of *Blakely and Simpson* (1986) (a, b, c, d) compared to the maxima of upward continued gravity field (a', b', c', d') corresponding to the four models M1-M4. The solid arrows on the maxima corresponding to the MSHDVD method indicate the direction of displacement of maxima and hence the dip angle.

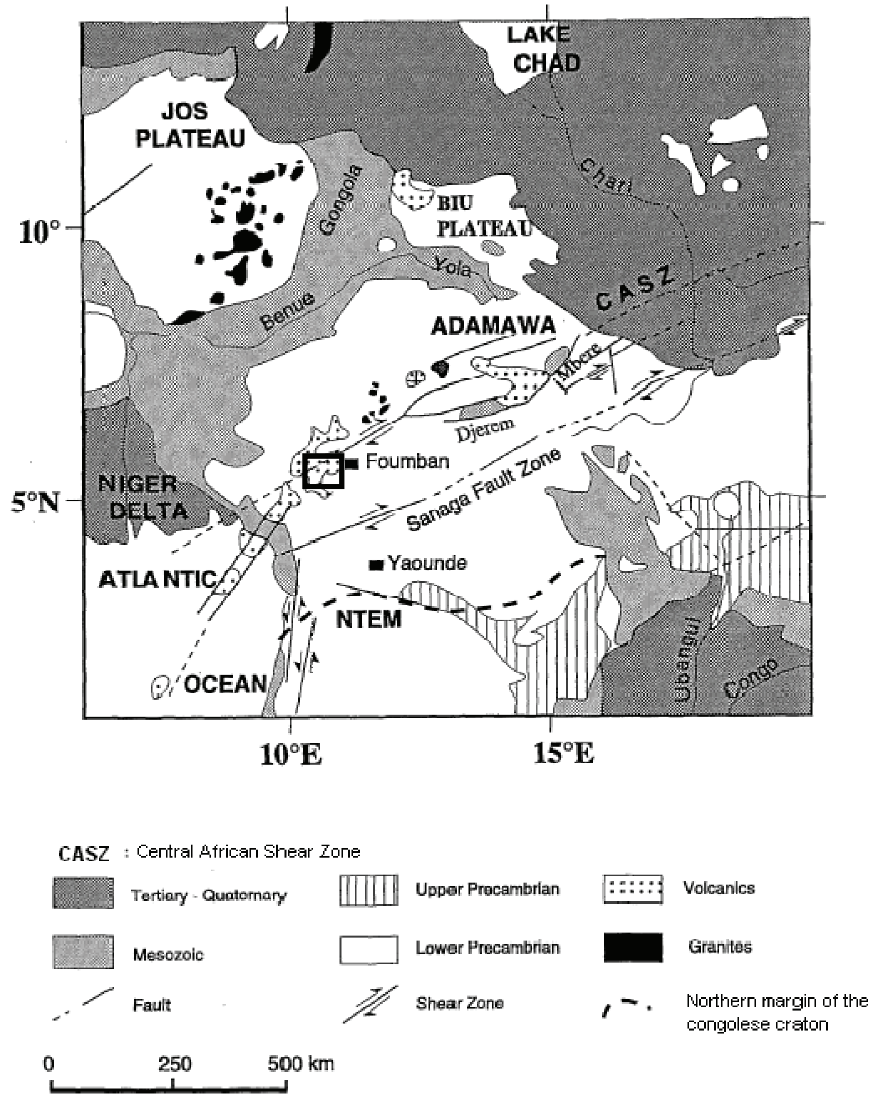

Fig. 6. Simplified geological map of the Adamawa uplift (after *Poudjom et al.*, 1995) and the location of the study area (black box) of the field example.

The gravity data used in the study area were acquired during several surveys carried out in Cameroon by (1) ORSTOM (Office de Recherche Scientifique des Territoires d'Outre Mer, France) in 1960, (2) IRGM (Institut de Recherche Géologique et Minière, Cameroon) in collaboration with University of Leeds (UK) between 1982 and 1985. A density reduction of 2.67 g/cm^3 was used for the Bouguer correction and all the data were tied to the IGSN71 reference system. Data were then interpolated on a 5 by 5 km rectangular grid using the minimum curvature method; computation was carried out using the GETECH's GETgrid software. The Bouguer anomaly map (Fig. 7b) shows NNE-SSW oriented contour lines and strong horizontal gradient perpendicular to this main direction of the FSZ. The MSHDVD method is used to outline the fault covered by volcanic series. The horizontal gradient of the vertical derivative (HDVD) field map at surface level (Fig. 8a) shows an anomaly sub-parallel to the FZS. The peak magnitude of the HDVD is between 0.20 and 0.25 mGal/km^2. The maxima computed at different heights (Fig. 8b) show the presence of a deep geological contact (fault) oriented N68°E and dipping towards southeast.

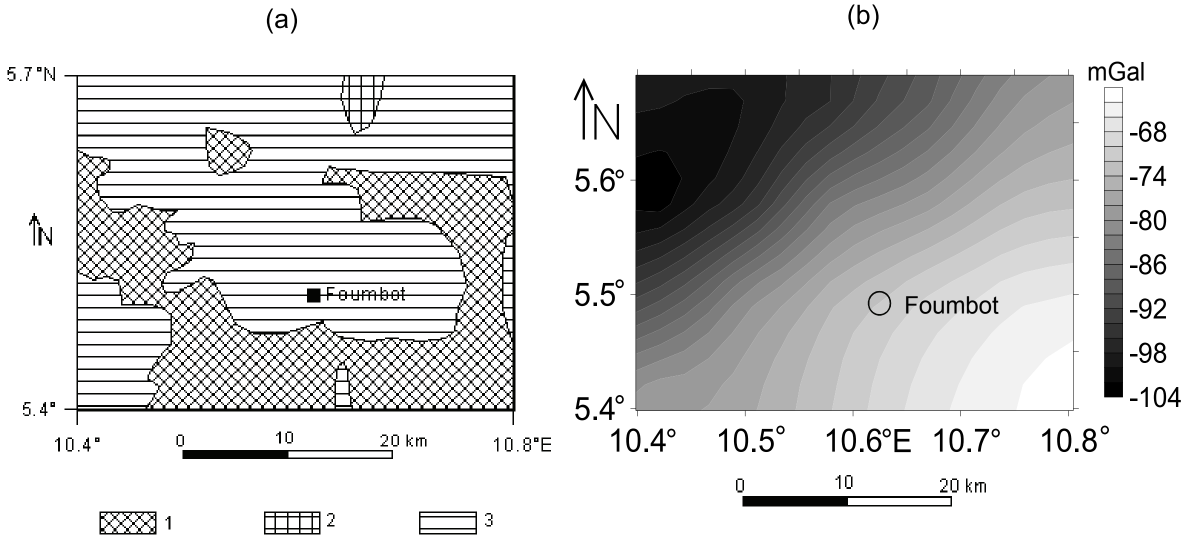

Fig. 7. (a) Simplified geological map of the study area: 1: Undifferenciated gneisses (mainly Pan-African); 2: Pan-African syntectonic granites; 3: Tertiary volcanism. (b) Shaded relief map of the Bouguer anomalies of the study area.

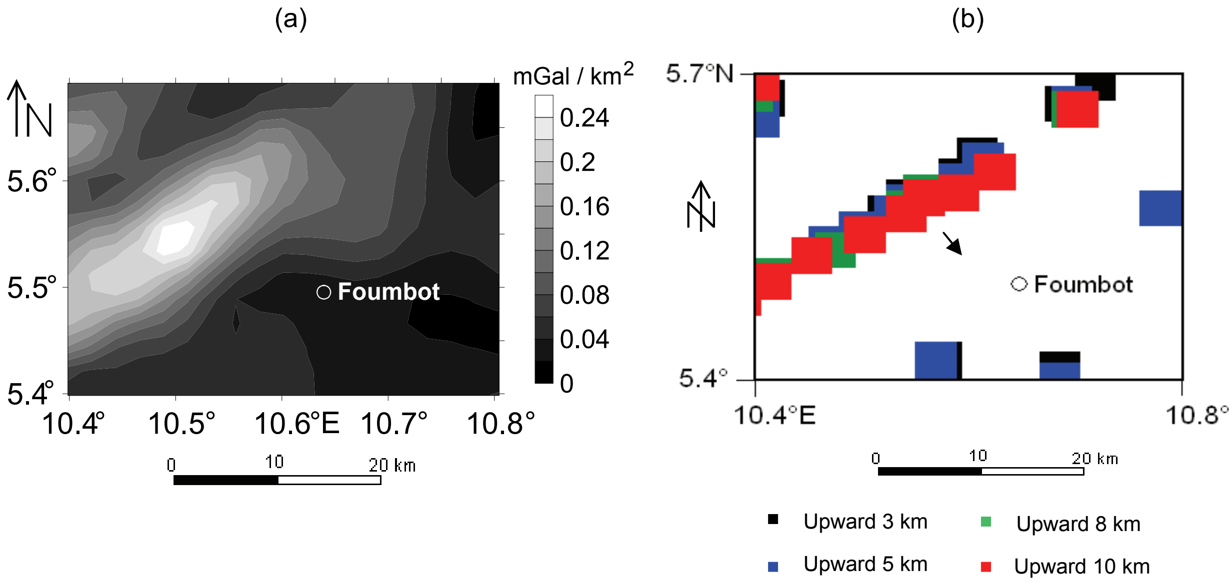

Fig. 8. (a) HDVD gravity map of the study area for height h = 0. (b) Location of the total horizontal gradient maxima based on the method of *Blakely and Simpson* (1986), with significance levels N = 2 and 3.

5. *Discussion*

Since the horizontal gradient of the gravity depends on the lateral variation of the density, larger density differences between the sources outline the contact at different heights better. In practice, the maximum level of the upward continuation needs to be known beforehand. Knowledge on the depth of the geological structures of the study area obtained by other geophysical methods is usually useful in this estimation. If this knowledge is not available, the optimum upward continuation height may be determined by the empirical method of *Zeng et al.* (2007). The method consists of calculating correlation factor r between upward continuated fields at two successive heights. The correlation factor between two gravity fields g_1 and g_2 is calculated by the formula proposed by *Abdelrahman et al.* (1989):

$$r_{g_1,g_2} = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} g_1(x_i,y_j)\, g_2(x_i,y_j)}{\sqrt{\sum_{i=1}^{M}\sum_{j=1}^{N} g_1^2(x_i,y_j) \sum_{i=1}^{M}\sum_{j=1}^{N} g_2^2(x_i,y_j)}} \tag{3}$$

where M and N are the number of sampling data along x-direction and y-direction respectively. The correlation factor is plotted as a function of increasing continuation height. The height increases from zero to a level where the change in correlation values has clearly passed the point giving rise to a maximum deflection (see Fig. 9a). The height that gives the maximum deflection is the optimum height (see Fig. 9b).

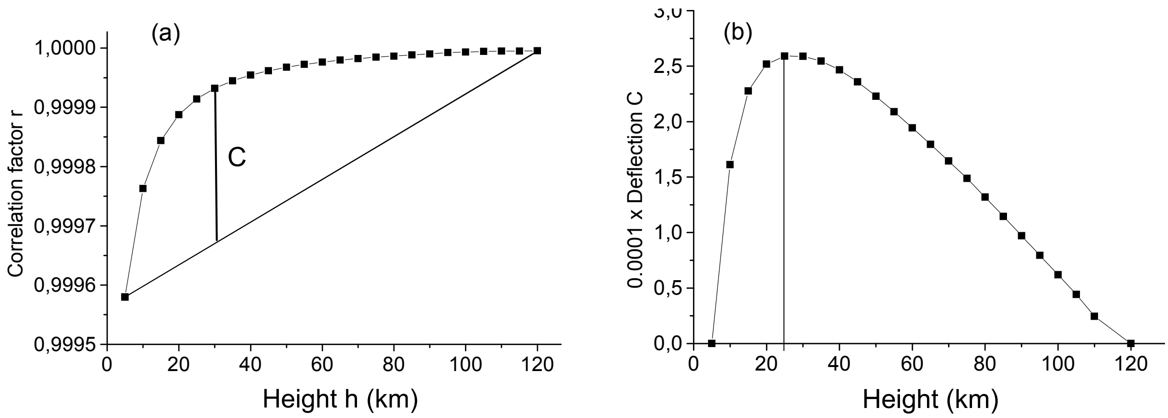

Fig. 9. Determination of the optimum upward-continuation height for the Adamawa region by the method of *Zeng et al*. (2007). Cross-correlation between two successive upward continuated gravity field as a function of the continuation height (a) and the deflection C of the cross-correlation curve (b). The optimum height corresponds to the maximum deflection C.

The optimum height thus found can then be used as the maximum upward continuation level in the MSHDVD method. In the case of the Adamawa uplift which includes the FZS, the upward continuation was made at a height up to 120 km. The optimum height level found with the method of *Zeng et al*. (2007) was 25 km as illustrated in figure 9.

6. Conclusion

The MSHDVD method based on the multi-scale evaluation of maximum of the horizontal gradient of the first-order vertical derivative of the gravity field allows discriminating between vertical and dipping contacts. The application of the method to synthetic and real data show that the MSHDVD method gives good results compared to those derived directly from upward continuated gravity field. This practical tool can be very useful in the preliminary steps of the 2-D and 3-D modelling. The application of the MSHDVD method on the gravity anomaly map over the Foumban Shear Zone shows that, around Foumbot, volcanic formations hide a fault oriented N68°E and dipping towards southeast.

Acknowledgements

The authors are very grateful to GETECH Group plc (Leeds, UK) and its General Manager for providing the gravity data used in this study. We would also like to thank Professor J. D. Fairhead and one anonymous reviewer for their kind help in making the manuscript clearer and more correct.

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