Analytic Signal and Reduction-to-the-Pole in the Interpretation of Total Magnetic Field Data at Low Magnetic Latitudes

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ABSTRACT

The problem of interpreting total magnetic field data collected at low magnetic latitudes is addressed through the use of 3-D analytic signal amplitude (Nabighian, 1972, Roest, 1992) applied to the total magnetic field and the vertical integral of the magnetic field. This technique is contrasted with conventional reduction to the pole as implemented by Grant and Dodds in 1972.

The amplitude of the analytic signal of the total magnetic field produces maxima over magnetic contacts regardless of the direction of magnetization. When applied to the vertical integral of the magnetic field, results are more similar to pseudo-gravity (Baronov, 1957), in that the strength of magnetization of underlying rocks is related to the amplitude of the analytic signal. The direction of magnetization, which may vary depending on the level of induced magnetization, permanent (remanent) magnetization and magnetic anisotropy, is removed by the process of calculating the analytic signal. Where rocks are magnetized predominantly by induction of the earth's field, the amplitude of the analytic signal is still dependent on the geologic strike, but this dependency is very much easier to deal with in the interpretation of analytic signal amplitude as compared to the original or pole reduced magnetic field.

Results are shown for the application of this method to synthetic data and total magnetic field data collected over the Crixás greenstone belt in Goiás, central Brazil.

INTRODUCTION

When dealing with two-dimensional magnetic field data, an important goal of data processing is to simplify the complex information provided in the original data. One such simplification is to derive a map on which the amplitude of the displayed function is directly and simply related to a physical property of the underlying rocks. For example, the gravity field over a body of a certain density contrast exhibits this simplicity. Magnetic data, however, is distorted by the inclination of the magnetizing vector. Figure 1. illustrates this distortion by comparing the magnetic and gravity responses over a simple vertically dipping prism. The body is magnetized by induction only for an inclination of -10° and declination of 20° West.

Baranov (1957) showed how a measured 2-D magnetic field could be converted to 'pseudo-gravity' by an operation that involves reduction to the pole (RTP) and vertical integration. Baranov's intention was to produce a magnetic map that coud be interpreted more simply and directly, which is also the goal of this paper. Although Baranov's procedure is referred to as pseudo-gravity, the process does not imply that the distribution of magnetism in the earth is necessarily related to the density distribution. It was only intended to simplify the interpretation of magnetic field data by thinking of magnetization in the same way as density.

The difficulty of pseudo-gravity processing at low magnetic latitudes lies in the reduction to the pole operation, which assumes that all magnetic sources have the same direction of magnetization. In fact this can be a problem at any latitude where remenently magnetized bodies exist. Furthermore, at very low latitudes, typically between ±10° inclination, the amplitude correction for north-south trending features unreasonably amplifies noise and severely distorts magnetic anomalies from sources magnetized in directions different from the inducing field.

REDUCTION TO THE POLE

A number of authors have addressed the problem of reduction to the pole. The methods either modify the amplitude correction in the magnetic North-South direction using frequency domain techniques (Hansen and Pawlowski, 1989, Mendonça and Silva, 1993), or calculate an equivalent source in the space domain (Silva, 1986). In all cases, induced magnetization of magnetic sources is assumed. We have found that the simplest and most effective technique that addresses the amplitude problem is that developed by Grant and Dodds in the development of the MAGMAP FFT processing system in 1972.

The reduction to the pole operator can be expressed as

$$L(\theta)=\frac{1}{\left[\sin(I)+i\cos(I)\cos(D-\theta)\right]^2} \qquad (1)$$

where θ is the wavenumber direction, I is the magnetic inclination and D is the magnetic declination. From (1), it can be seen that as I approaches 0 (the magnetic equator), and $(D - \theta)$ approaches $\pi/2$, the operator approaches infinity (Mendonça and Silva, 1993).

Grant and Dodds (1972) addressed this problem by introducing a second inclination (I') that is used to control the amplitude of the filter near the equator:

$$L(\theta)=\frac{1}{\left[\sin(I')+i\cos(I)\cos(D-\theta)\right]^2} \qquad (2)$$

In practice, I' is set to an inclination greater than the true inclination of the magnetic field. By using the true inclination in the $i\cos(I)$ term, the anomaly *shapes* will be properly reduced to the pole (induced magnetization only), but by setting ($I' > I$), unreasonably large amplitude corrections are avoided. Controlling the RTP operator then becomes a matter of choosing the smallest I' that still gives acceptable results. This will depend on the quality of the data and the amount of non-induced magnetization present in the area under study.

Although the amplitude correction of the RTP operator can be easily controlled, results will still be invalid for remanently magnetized bodies and where or anisotropy is present. Furthermore, such bodies are difficult to interpret even when not distorted by reduction to the pole. It would seem to be preferable to produce a result that simply provides a measure of the amount of magnetization, regardless of direction.

ANALYTIC SIGNAL

Nabighian (1972, 1984) developed the notion of analytic signal, or energy envelope, of magnetic anomalies. An important characteristic of the analytic signal is that it is independent of the direction of magnetization of the source. The amplitude of the analytic signal is simply related to amplitude of magnetization. Roest, et al (1992), show that the amplitude of the analytic signal can be easily derived from the three orthogonal gradients of the total magnetic field using the expression

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

where M is the observed magnetic field.

Nabighian (1972) showed that the analytic signal peaks over the edges of magnetic bodies. For qualitative interpretation, it may be preferable to have a function that produces highs over magnetic bodies. This can be partially achieved by first vertically integrating the total magnetic field. In the frequency domain this can be accomplished by the following simple operator:

$$L(\mu, \nu) = \frac{1}{\sqrt{\mu^2 + \nu^2}} \qquad (4)$$

where μ and ν are the wavenumbers in the x and y directions respectively (after Bhattacharyya, 1966, Grant, 1972). This operator is most sensitive to small wavenumbers, so it is important to resolve the discrete FFT to as small an increment of μ and ν as possible by increasing the size of the grid. We have simply set the operator to 0 when $\mu=\nu=0$, which is not significant since the zero wavenumber represents a base level that is of no interest. Calculation of the amplitude of the analytic signal then requires calculation the X and Y derivatives of the vertical integral, and the use of the original total field (IGRF removed) in expression (3).

SYNTHETIC EXAMPLE

To illustrate this process, we have applied the method to the prism model presented in figure 1. The top of the magnetized prism is located at a depth of 50 metres, has a square horizontal top 200 by 200 metres, and a thickness of 5000 metres. This body is magnetized by induction only in a field with inclination of -10° and declination of 20° West. Figure 2a. shows the analytic signal derived directly from the synthetic total field and it's calculated orthogonal gradients. As we would expect, the analytic signal shows highs over the edges of the prism, with an amplitudethat is related to the degree of magnetization at that edge. The North and South edges of the prism intersect the inducing field at a more accute angle than the East and West edges and be thought of as having a greater magnetization, which results in a greater amplitude in the analytic signal.

Figure 2b. shows the analytic signal calculated from the vertical integral. It is very close to the optimum function represented by the gravity field over the prism (figure 1b.). Note that the function still shows local maxima over the North and South edges due to relatively greater magnetization.

CRIXÁS GREENSTONE BELT

Figure 3a. shows a contour map of the total magnetic field over the Crixás greenstone belt in the state of Goiás, central Brazil. The data is from the Brazil - Canada project conducted in the late 1970's. The survey was flown at a nominal terrain clearance of 150 metres on North-South flight lines roughly 1 km apart. The magnetic field was measured every 50 metres to an accuracy of 1 nT. The data quality is generally quite good, but some North-South flight line leveling error is apparent on the West side of the area. This survey is located in a geomagnetic field that has an inclination of -10° and a declination of 20° West.

The Goiás greenstone belt is a fairly typical collection of highly deformed, low-grade metamorphic, volcano-sedimentary Archean rocks roughly 2.8 Ga in age (Jost and De Oliveira, 1991). The magnetic rocks consist of komatiites, banded iron formations, metabasalts, and presumably low-grade magnetic metasediments. These rocks are framed on the East and West by high-grade metamorphic gneisses in which magnetite has been oxidized into other forms and therefore have little magnetization.

The primary use of the magnetic data is to help to outline the extent of the greenstone belt, and perhaps to help distinguish between various rock members in the belt. The original magnetic field (figure 3a.) shows an increase in magnetic activity down the centre of the map, but the magnetic field is predictably complex. The presence of banded iron formation is likely to introduce significant anisotropic effects in the field as well as permanent magnetic effects. Figure 3b. shows the result of reducing this data to the pole using an amplitude inclination of -20° and phase inclination of -10°. The North-North-West trending features are a side-effect of the RTP operation, and where RTP is not producing such noise, the anomalies are still complex.

Figure 4. shows the amplitude of the analytic signal calculated from the original total field (4a.) and the vertical integral of the total field (4b.) By interpreting these result as magnetization maps, the outline of the magnetic components of the greenstone formation is more clear.

CONCLUSIONS

The interpretation of total magnetic field data at low magnetic latitudes can be improved by a process of vertically integrating the magnetic field and calculating an analytic signal of the result. This process yields an 'apparent magnetization' map on which the degree of magnetization of the underlying rocks is related to the amplitude of the result.

When working with such a map, the interpreter should keep in mind those factors that affect magnetization. These include the magnetic susceptibility; the amount of permanent magnetization, which is also related somewhat to magnetite content; and the direction of the inducing field which will give East-West striking features a stronger magnetization. The last factor noted might be improved by careful reduction to the pole, but the problems of remanent and anisotropic effects in the data make this improvement difficult to achieve.

ACKNOWLEDGMENTS

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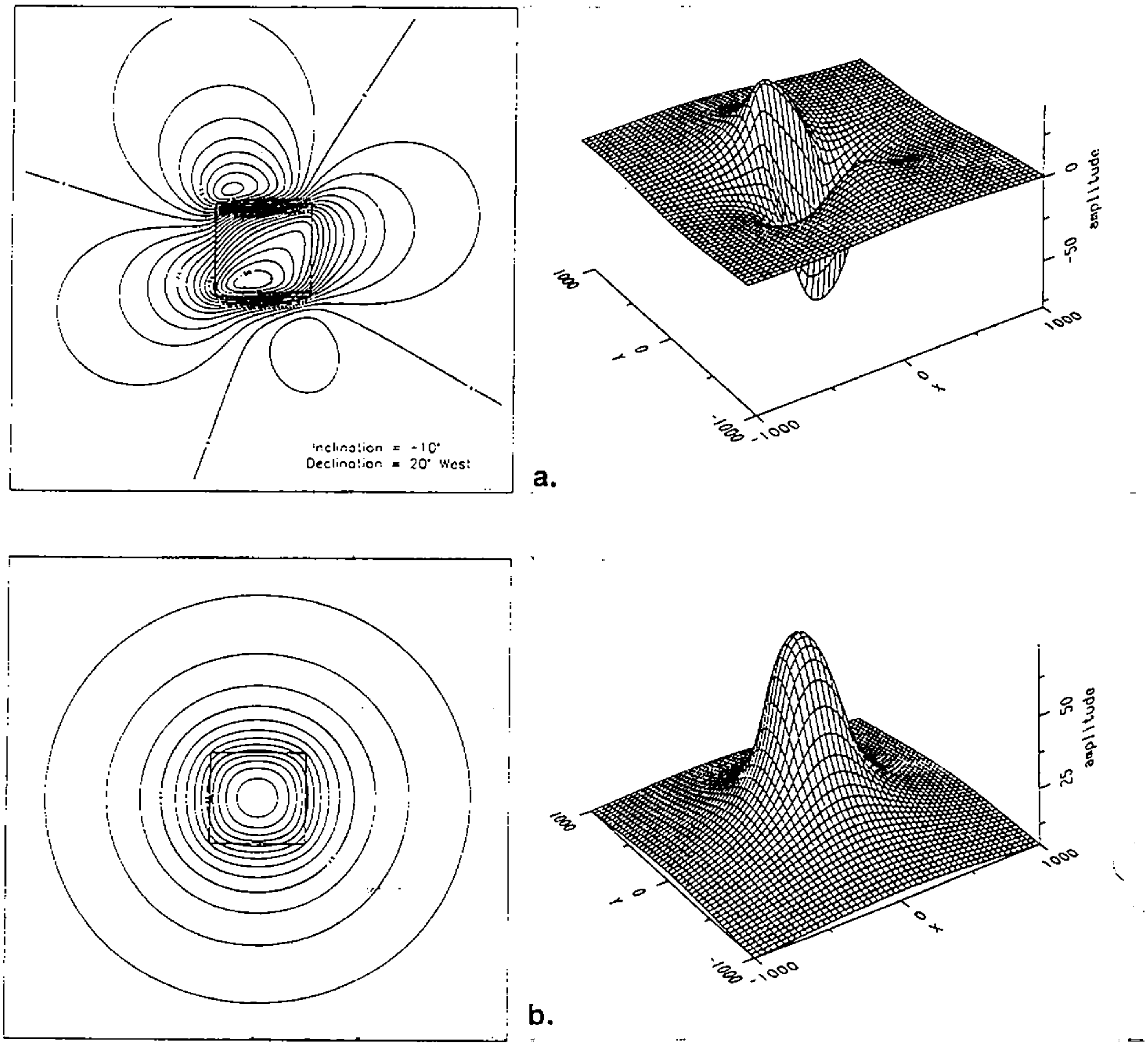


Figure 1. The magnetic and gravity anomalies over a vertically dipping prism, 200 x 200 metres square, 5000 metres thick, 50 metres below plane of observation: a) Total magnetic field anomaly for a 10° inclination and declination of 20° West; b) gravity anomaly.

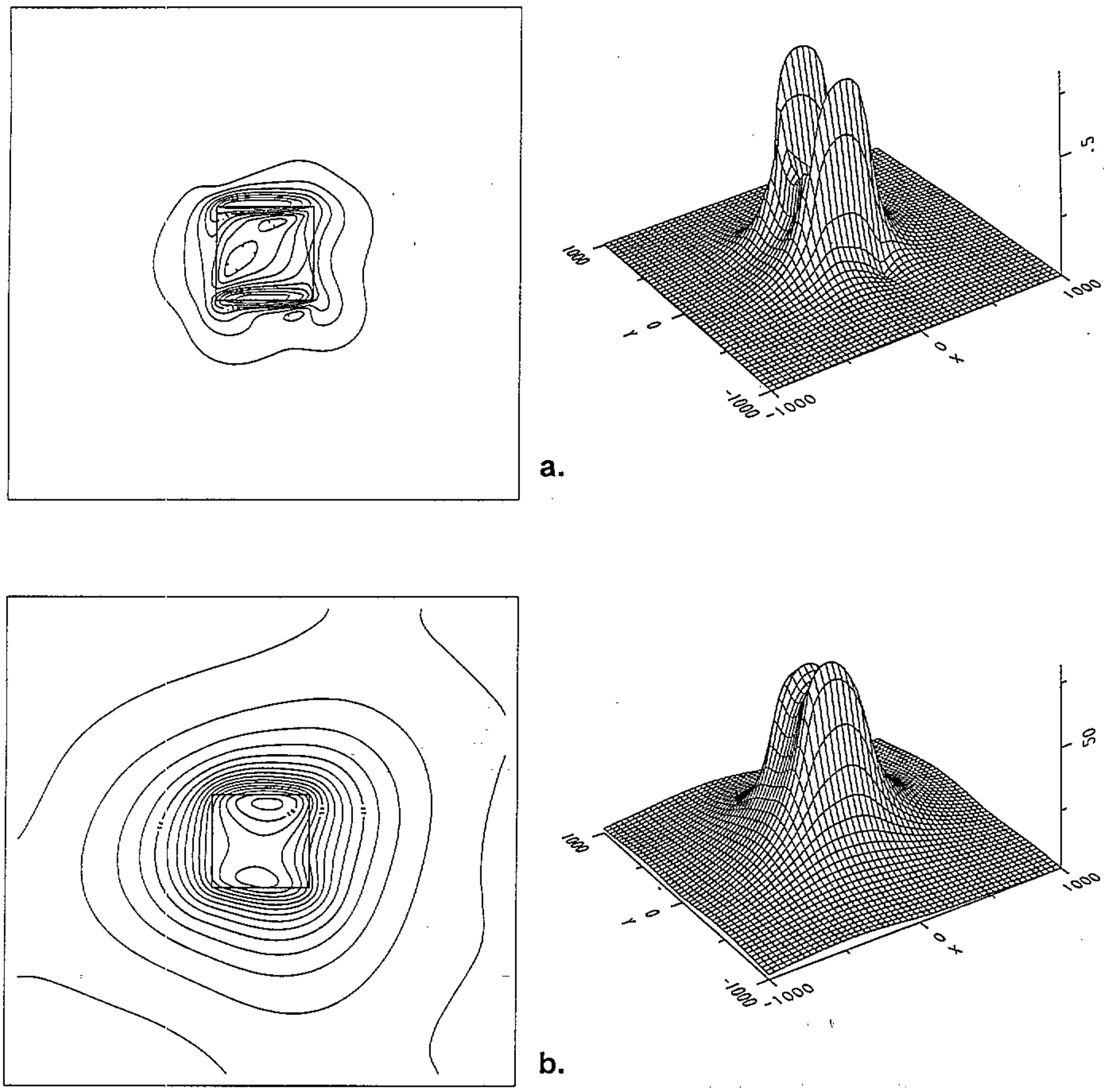
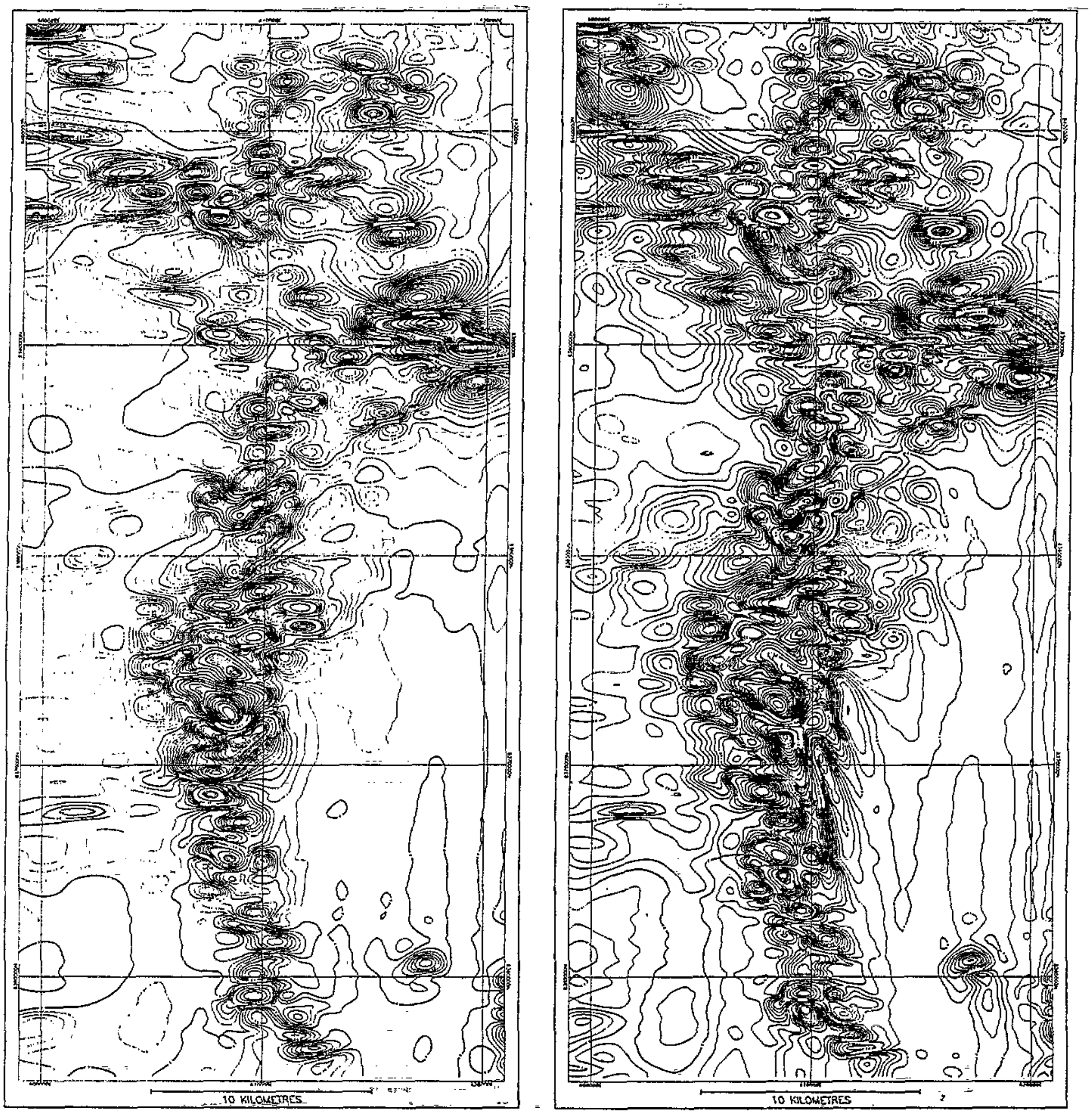
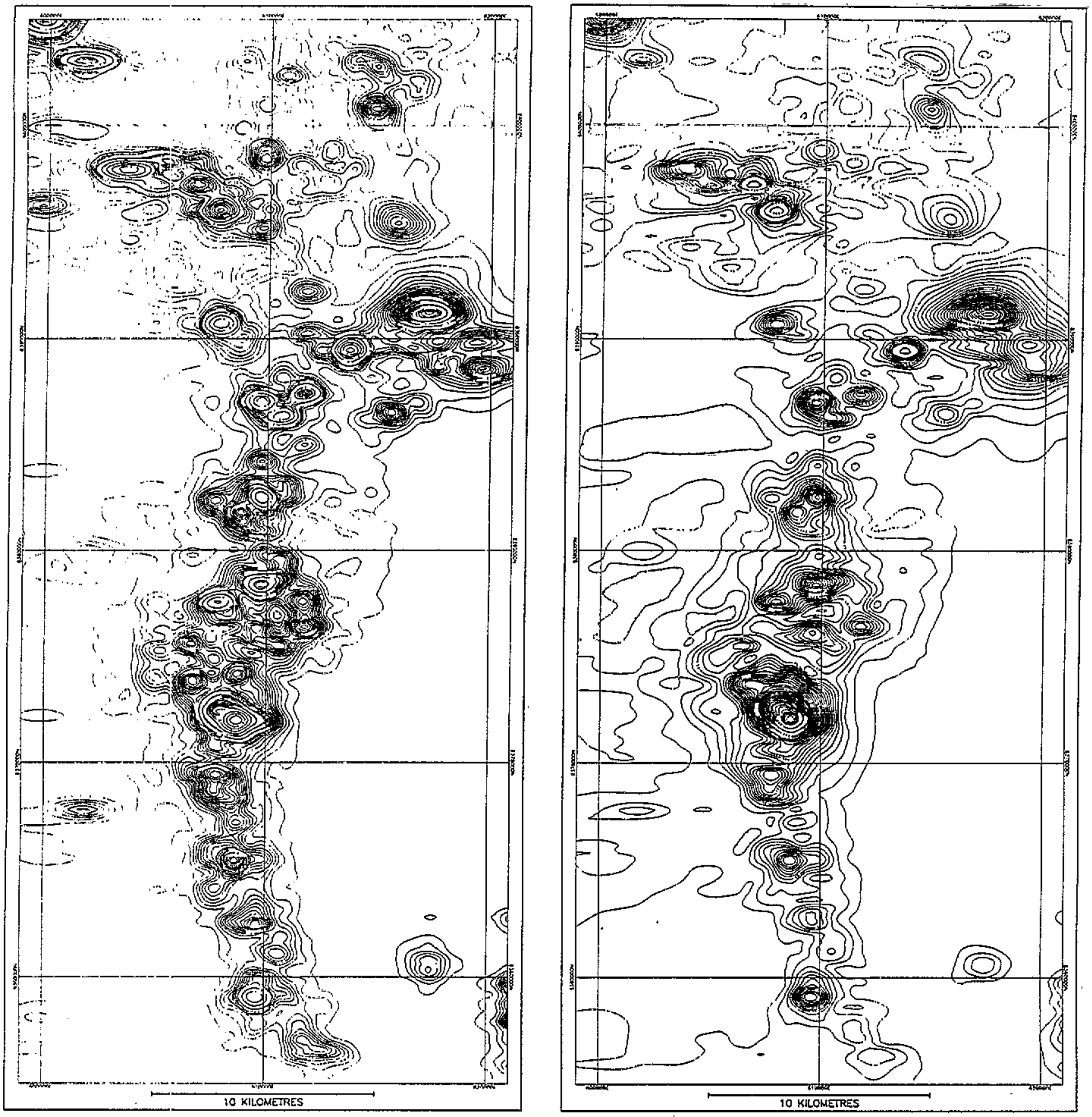


Figure 2. a) The amplitude of the analytic signal calculated from the total magnetic field shown in Figure 1. b) The amplitude of the analytic signal calculated from the vertical integral of the total magnetic field shown in figure 1.



a. b.

Figure 3. a) The observed total magnetic field over the Crixás greenstone belt. b) The same data reduced to the pole using the method of Grant and Dodds (1972) with an amplitude inclination of -45°.



a. b.

Figure 4. a) The amplitude of the analytic signal calculated from the total magnetic field shown in figure 3a. b) The amplitude of the analytic signal of the vertical integral calculated from the total magnetic field shown in figure 3a.