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The Milos Island Bouguer anolmaly revisited by means of a complex attribute analysis and inferred source parameter estimates

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***Abstract**: A complex attribute analysis is used to extract parameters of the buried structures that give rise to the anomalous gravity field in the island of Milos (Greece, the Central Aegean Sea). The attributes themselves assist in the interpretation because they can delineate the edges of the concealed targets. However, source parameters like the local depth, strike and dip are obtained from the complex attributes on the basis of an analytical expression for the effect of a simple subsurface model. The simplest one, i.e. the sloping contact model, is used in this study.*

A complex attribute analysis is also applied to the pseudomagnetic transformation of the data. The result cannot be considered satisfactory though it cannot be considered false either. This is attributed to the extra noise induced to the pseudomagnetic data by the transform process.

The estimated local parameters are in agreement with the results obtained by previous interpretations. They can be used either independently or in combination with other methods for interpreting the anomalous field.

***Key Words**: Milos, Complex Attributes, Potential Fields*

INTRODUCTION

A potential field observed at the surface is the superposition of the fields due to all sources in the neighbourhood. Thus, no information can practically be extracted unambiguously from the data in the absence of a model. The simplest model is that of a contact or interface between domains of different susceptibility or density. It is possible to show that this disambiguates the problem although some of the parameters (e.g. the dip angle) may depend considerably on the data and may therefore be not accurately determined in the presence of noise.

The ultimate goal of a potential field survey is to estimate the parameters of the causative source, i.e. its burial depth, depth extent, lateral extent and magnitude of the contrast of physical properties. In general, inversion offers the means to extract from the signal those quantities which describe the causative source. Thus, if the source is mapped, and the interference from other sources is suppressed, then we obtain the desired result.

A number of techniques can be applied in an automatic mode to yield the spatial distribution of parameters describing the source. For example, Werner deconvolution (Hartman *et al.,* 1971), 3-D Euler deconvolution (Reid *et al*., 1990), multiple source Werner deconvolution (Hansen and Simmonds, 1993) and the 3-D analytic signal technique (Roest *et al*., 1992) are advanced and popular automatic interpretation schemes.

The use of the analytic signal amplitude (Nabighian, 1972; 1974) offers some attractive features for any sort of potential fields prospecting. Its advantageous geophysical property is that it peaks exactly over the edge of the buried dipping contact causing the magnetic anomaly (Nabighian, 1972). Its amplitude is also independent of inclination, declination, remanent magnetisation and dip if the sources are 2-D (Blakeley, 1995; Thurston and Smith, 1997). The only disadvantage is that the analytic signal anomalies are relatively much broader than the lateral extent of the buried target. Recent results from the use of the analytic signal, particularly for magnetic gradiometer data (e.g., Tabbagh *et al*., 1997), have shown the potential of the technique.

The present paper deals with the exploitation of the complex attributes of the Bouguer gravity signal in order to extract properties of the sources of the anomalous fields. The analytic signal certainly comprises the best known among them. The “local phase” and the “instantaneous wavenumber” comprise the other two quantities that also lead to source parameters mapping. This work follows the basis and terminology of the work of Thurston and Smith (1997). They formed an automatic interpretation scheme for magnetic data based on the complex attributes which they named "Source Parameter Imaging (SPI^{TM})" method.

The aim is to delineate the edges of the buried bodies, to estimate their extent, to assess strike angles and produce burial depth estimates simultaneously. The complex attributes analysis offers the means to carry this out. It is exactly its applicability and effectiveness in exploring the subsurface using gravity data that is investigated in this work.

The gravity field is a potential field and the analysis used in this work depends on this fact. In particular, the analysis depends on both the fact that the gravity field is a potential field and the fact that due to the two-dimensionality of the contact model already introduced, the field is two-dimensional. This implies that the vertical and horizontal derivatives of the field form a Hilbert transform pair. Derivatives in general play a role in potential fields interpretation because they isolate contacts over which the field can be expected to change rapidly and therefore to have large values for its derivatives. More specifically, in this case the analysis yielding the contact parameters involves both the vertical and the horizontal derivatives. For more details, see Thurston and Smith (1997).

The particular combinations of derivatives introduced by Thurston and Smith are the *local phase* and the *local wavenumber*. The local phase is the arctangent of the ratio of the vertical to horizontal derivative of the field. Local frequency and local wavenumber are essentially synonymous; the former is generally used in the discussion of time series whereas the latter is a more appropriate term for spatially distributed data. In either case, these are (up to a scale factor which actually only determines the units) the gradient of the local phase.

An attempt is here made to interpret the gravity field of the Island of Milos by using a complex attribute analysis. This relatively recent method was not available when the data were interpreted (Tsokas, 1985, 1996). Furthermore, the application of the complex attribute analysis is attempted for first time for gravity data. Thus, the paper also aims to study the effectiveness and reliability of the method in interpreting anomalous gravity fields.

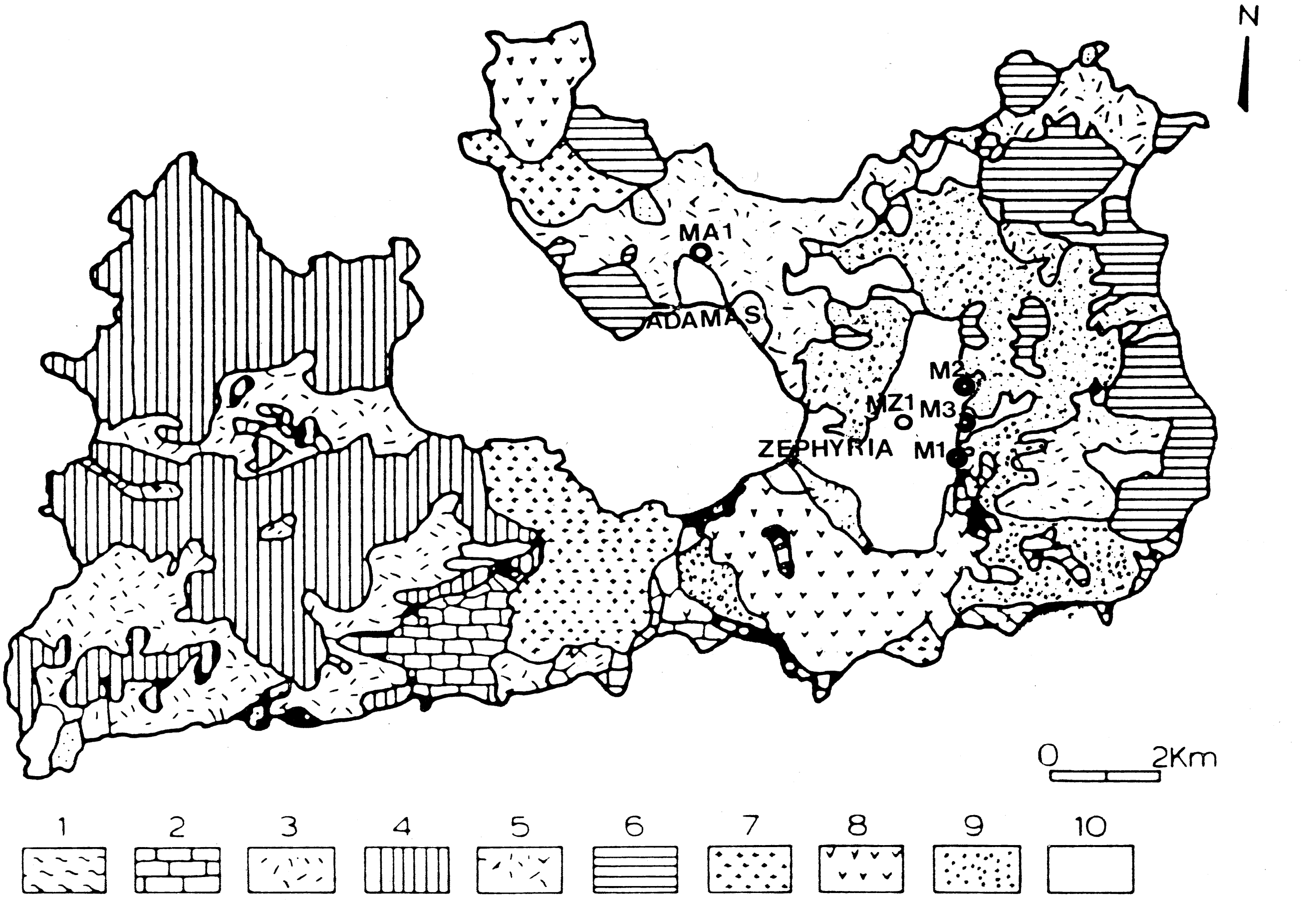

FIG. 1. Simplified geological map of the island (Fytikas, 1977;1989). (1) Metamorphic basement (Middle-Upper Pleiocene), (2) Transgressive marine sediments (Upper Miocene - Lower Pliocene), (3) Basal pyroclastic series (Middle-Upper Pliocene) , (4) Complex domes and lava flows , (5) Pyroclastic series (lower Pleistocene). (6) ,(7) Lava domes. (8) Rhyolitic complexes (Upper Pleistocene), (9) Products of phreatic activity , (10) Alluvium. The locations of the deep boreholes are marked.

The aim is to study the major tectonic features which have shaped the relief of the concealed metamorphic ba*sement in the Island of Milos. This information is essential for the geothermal mechanism revealing the main fault systems responsible for the hot fluid circulation.

In the following section of Thurston and Smith's results are re-derived and detailed definitions of the terms just discussed are given.

THE COMPLEX ATTRIBUTES

The analytic signal of any function, *f(x)*, measured along a profile on the earth's surface, is defined as

$$a(x) = f(x) - iF_I(x) \tag{1}$$

where $F_I(x)$ is the Hilbert transform of f(x). In potential fields, equation (1) reduces to

$$a(x,z) = \frac{\partial \varphi}{\partial x} + i\frac{\partial \varphi}{\partial z} \tag{2}$$

where $\varphi(x,z)$ is the potential and the case is two dimensional (Blakeley, 1995). Nabighian (1972; 1974) showed that for the simple contact model and the magnetic total field, *T*, the analytic signal becomes

$$a(x,z) = \frac{\partial T(x,z)}{\partial x} - i\frac{\partial T(x,z)}{\partial z} \tag{3}$$

Note that this convention is slightly different from that of Blakeley's (1995).

Equation (3) is the one used by Thurston and Smith (1997) and Smith *et al.* (1998). It follows that the analytic signal amplitude is

$$|A| = \sqrt{\left(\frac{\partial T}{\partial z}\right)^2 + \left(\frac{\partial T}{\partial x}\right)^2} \tag{4}$$

and the local phase, i.e. the phase of the analytic signal for any particular location is

$$\vartheta = \tan^{-1}\left[\frac{\partial T}{\partial x} / \frac{\partial T}{\partial z}\right] \tag{5}$$

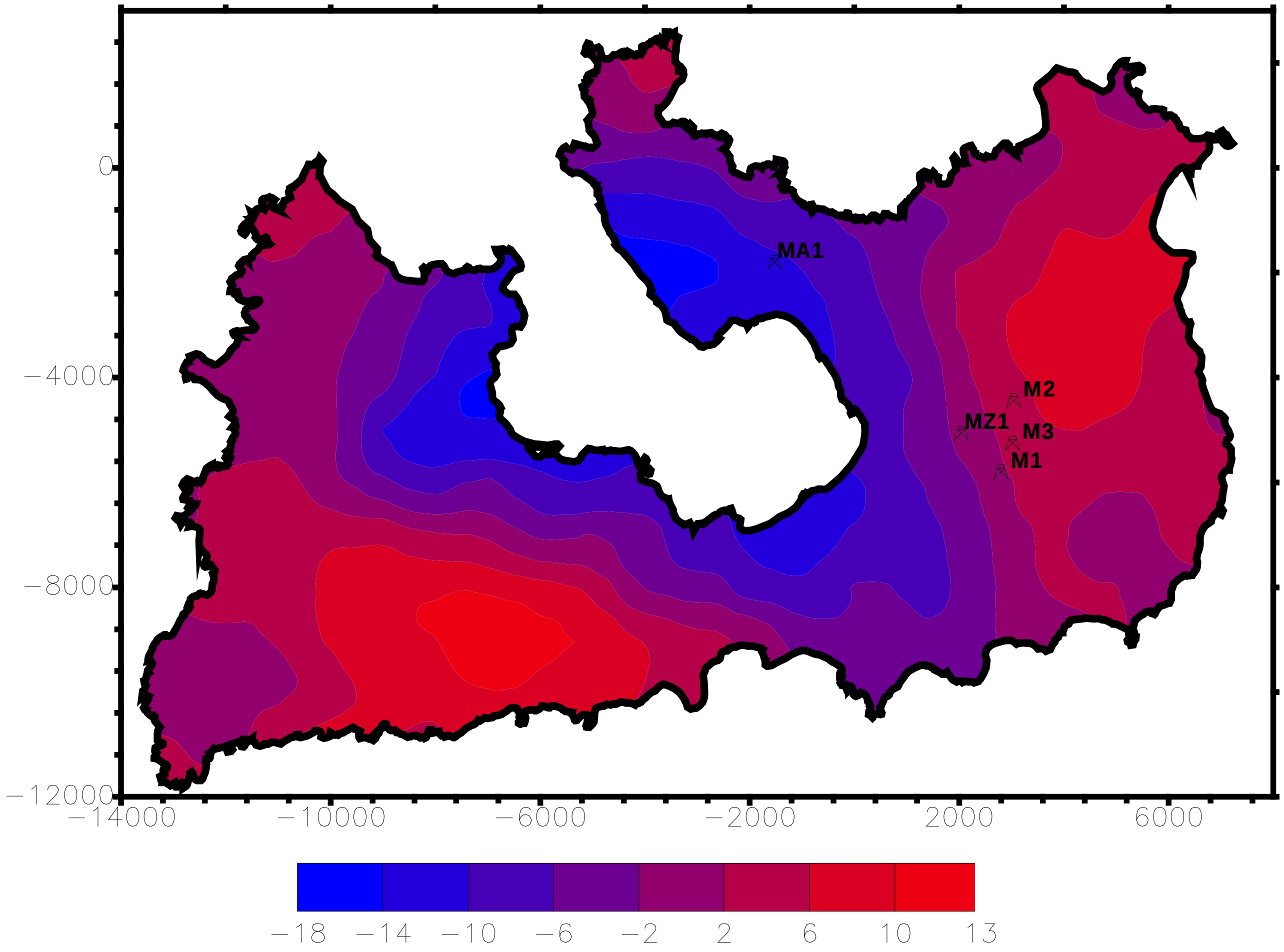

FIG. 2. A first order residual of the Bouguer gravity field in the island of Milos. The locations and the names of the boreholes are marked

The local frequency is defined as the rate of change of the local phase, i.e.

$$f = \frac{1}{2\pi}\frac{\partial}{\partial x}\tan^{-1}\left[\frac{\partial T}{\partial x} / \frac{\partial T}{\partial z}\right] \tag{6}$$

Customarily, the local wavenumber is used instead of the local frequency, that is

$$k = 2\pi f \tag{7}$$

Differentiation at the right hand side of (6) is easily performed, and substitution into equation (7) yields

$$k = \frac{1}{|A|^2}\left(\frac{\partial^2 T}{\partial x \partial z}\frac{\partial T}{\partial z} - \frac{\partial^2 T}{\partial x^2}\frac{\partial T}{\partial z}\right) \tag{8}$$

What is needed next is an analytic expression for the total field anomaly of the contact combining the parameters of a causative subsurface magnetisation distribution. The formulas derived in this paragraph will subsequently yield analytic expressions for the complex attributes.

Nabighian (1972) derived expressions for the vertical and horizontal gradients of the anomaly produced by a sloping contact of infinite depth extent. There is no need to repeat these expressions here, but if we substitute them into the local wavenumber formula, (8) yields

$$k = \frac{h}{h^2 + x^2} \tag{9}$$

where h is the depth to the contact (Thurston and Smith, 1997; Smith *et al.*, 1998), if we define the coordinate system such that x=0 directly over the edge of the buried contact. The maximum of the local wavenumber occurs at the same point. Furthermore, this expression is independent of magnetisation, dip and susceptibility contrast. It also offers a means for burial depth estimation since

$$h = \frac{1}{k} \tag{10}$$

at x=0.

Thurston and Smith (1997) devised also a technique to estimate the local dip and local susceptibility contrast by means of equation (5). That is

$$d = \theta + 2I - 90^{\circ} \tag{11}$$

again at x=0 but assuming that no remanent magnetisation exists in this case. In this formula, the dip d is measured from the positive x axis, θ, is the local phase and

$$\tan I = \tan i / \cos\alpha ,$$

where i the inclination of the ambient field and α is the angle between the positive x axis and magnetic north.

The local susceptibility is obtained by substituting the expressions for the derivatives of the total field to equation (5). Then, using the estimates yielded by equations (9) and (11) instead of depth and dip, we get

$$\mu = \frac{|A|}{2kFc\sin d} \tag{12}$$

where F is the magnitude of the Earth's magnetic field and

$$c = 1 - \cos^2 i \sin^2 \alpha .$$

In the above expression, i is the inclination and a the bearing of the measuring profile.

IMPLEMENTATION

The United States Geological Survey suite of programs for potential field analysis (Phillips, 1997) was exclusively used to implement the various parts of the complex attribute computation. The spatial derivatives and Fourier Transforms, where necessary, were computed using Hildenbrand's (1983) software.

The sloping contact model used in the derivation of the analytic expressions of the local source attitude (equations 10, 11 and 12) was considered to extend infinitely in depth. Thus, the first vertical integral of the anomaly was computed and used throughout this work instead of the anomaly itself (Phillips, 1997).

The analysis of the previous paragraph concerns the magnetic signal and the effect of the sloping contact model. It can be applied directly to pseudomagnetic data since they comprise signals of the same pattern as magnetic ones. In attempting to apply the former analysis to gravity data, one has either to base a similar reasoning to the analytical expression of the sloping density contact, or to consider the gravity field as a form of the reduced to the pole magnetic. The second approach has been used in this study.

In general, the depth from the magnetic field tends to be a lower bound; the depth from the pseudogravity is an upper bound. One might consider using the complex attributes on both the gravity and the pseudomagnetic signal in the same way. It is evident that fairly crisp density contrasts are needed to get meaningful results. The Bouguer anomaly of Milos Island justifies this consideration because the density contrast between the metamorphic basement and the overlain volcanic products is about 0.5 gr/cm^3.

GEOLOGICAL AND TECTONIC SETTING

The Island of Milos has an area of 150 km^2, an irregular topographic relief and it is located at the central

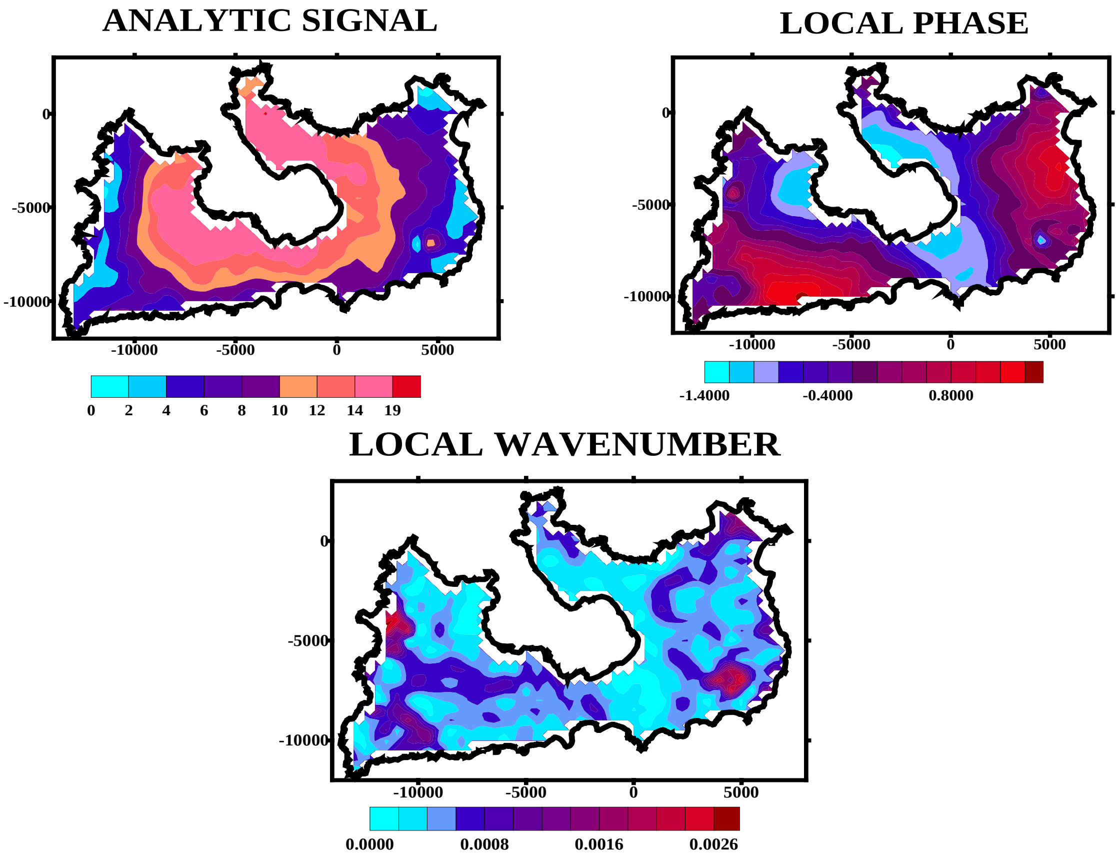

FIG. 3. Complex attributes of the 1st order residual Bouguer anomaly in the island of Milos.

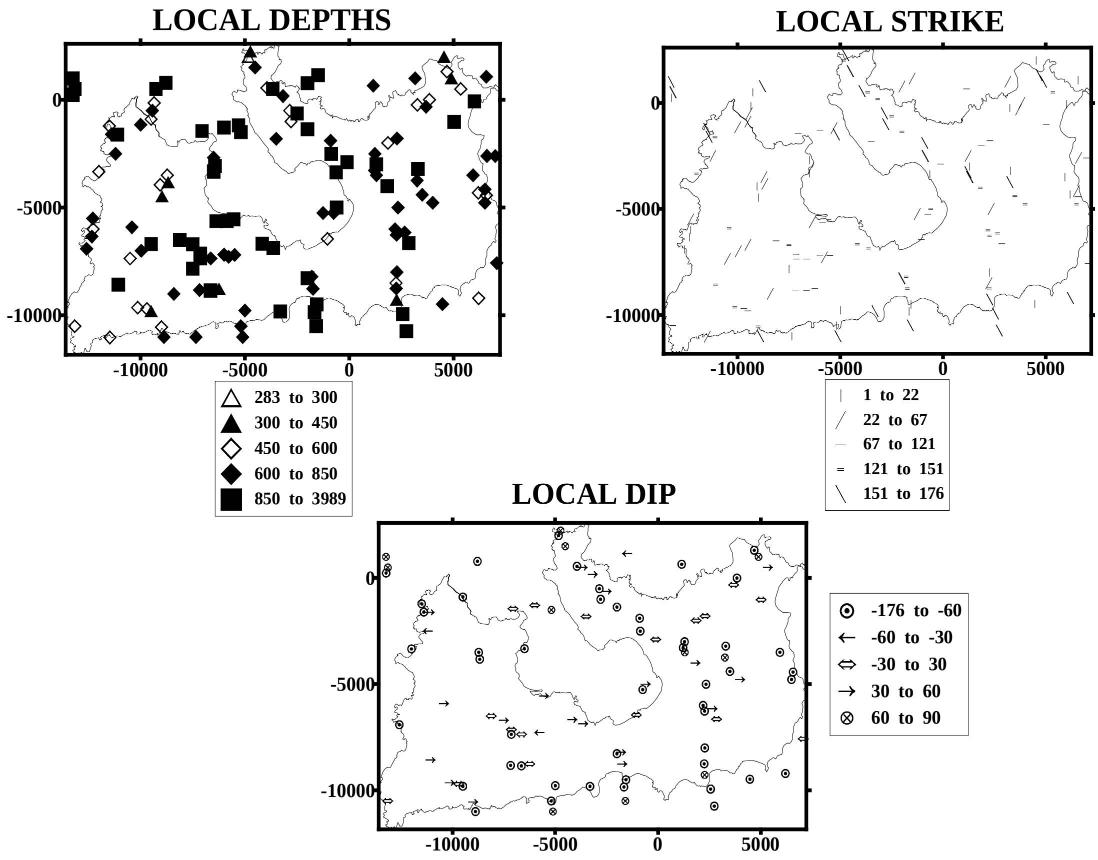

FIG. 4. The inferred source parameters estimates using the complex attributes of Figure 4.

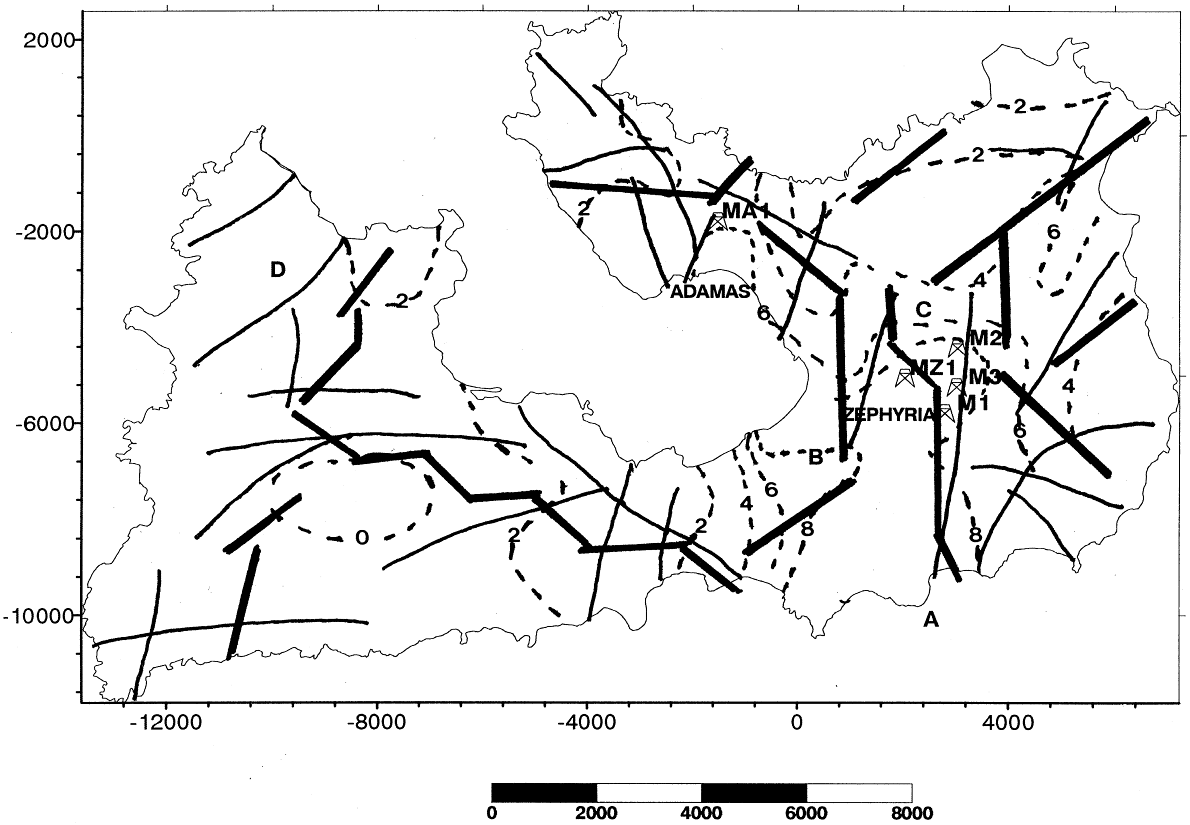

FIG. 5. Map showing the thermal gradient contours (dashed lines) along with the main visible faults (thin solid lines). The thick solid lines represent the faults obtained by the interpretation of the terraced gravity data (Tsokas,1996).

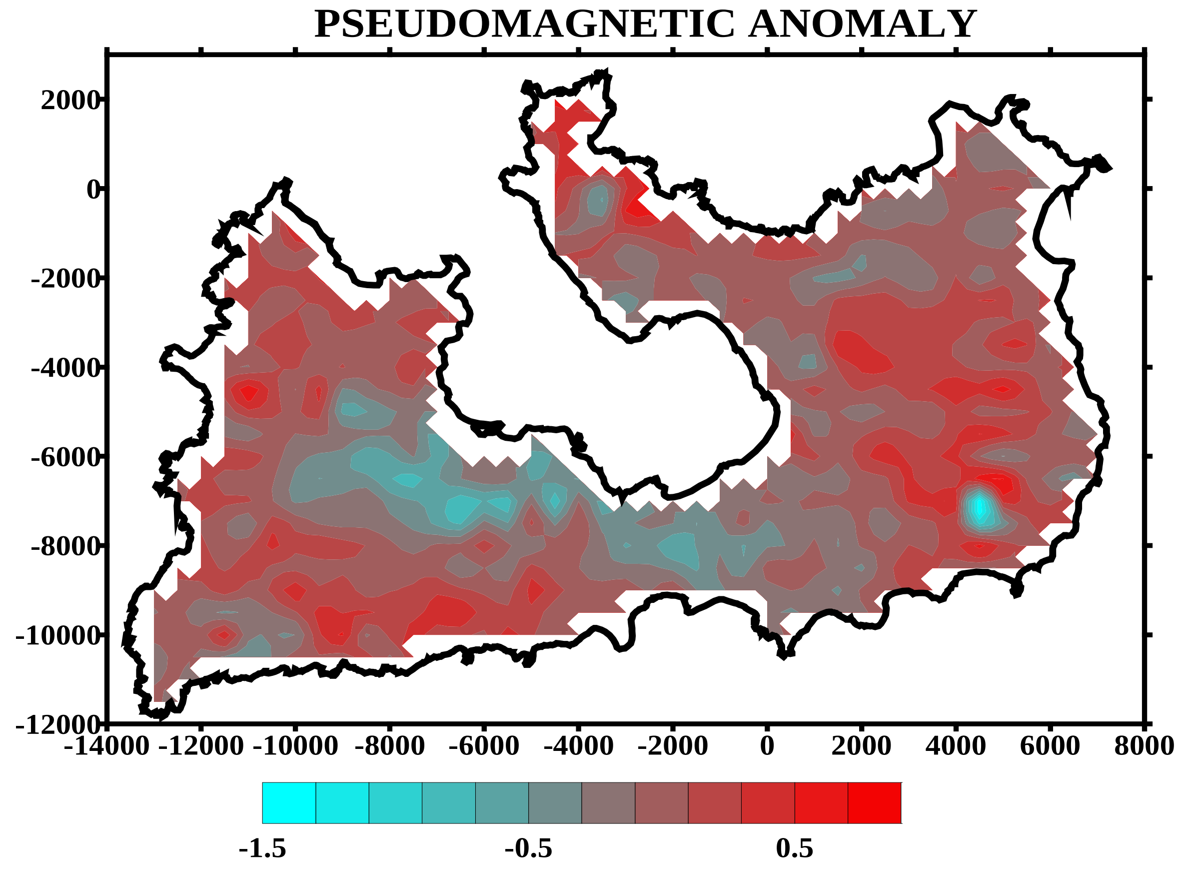

FIG. 6. Pseudomagnetic transformation of the Bouguer gravity anomaly of Milos island.

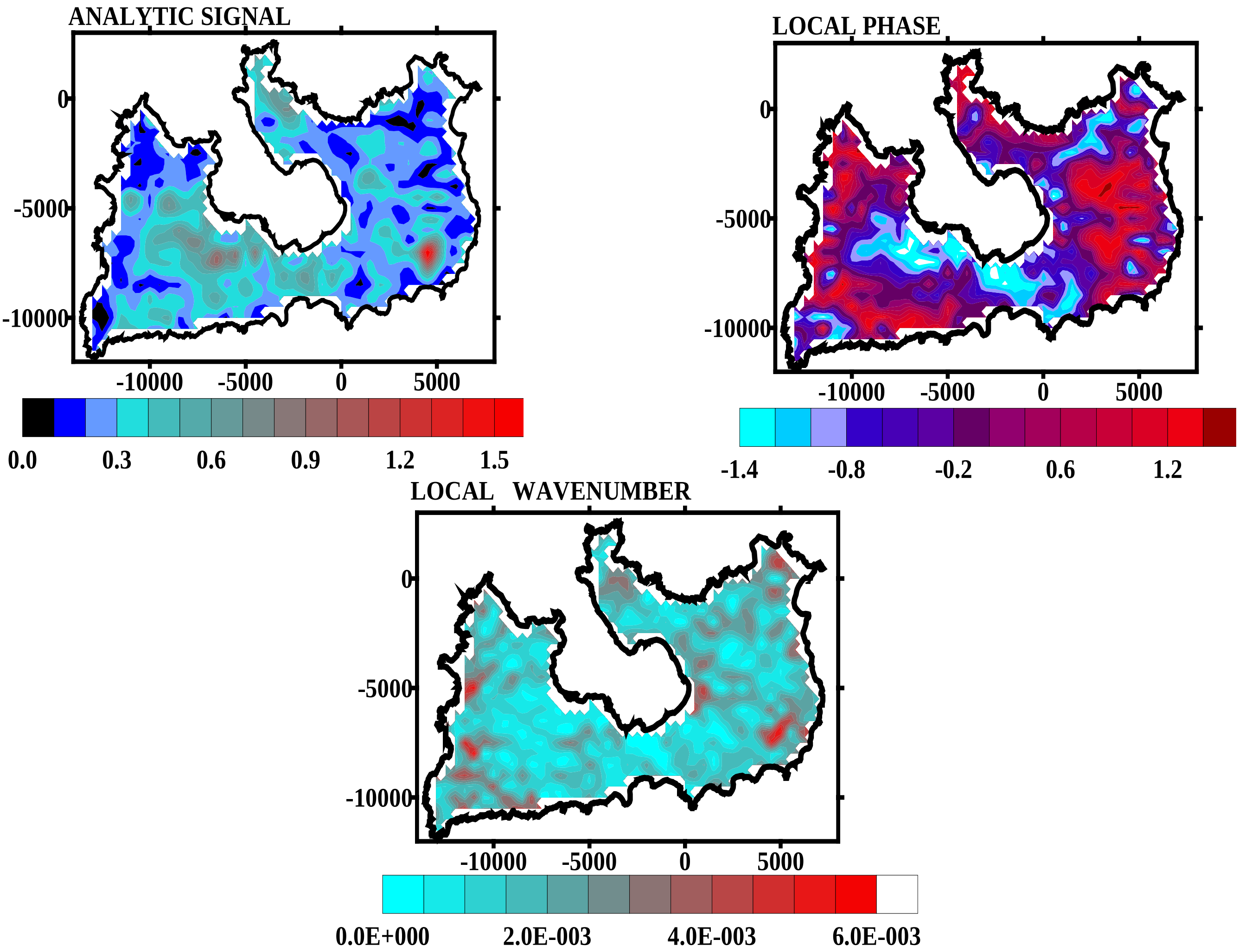

FIG. 7. Complex attributes of the pseudomagnetic anomaly. The analytic signal units are arbitrary as are the units of the pseudomagnetic anomaly itself. Local phase is in rads and local wavenumber in meters divided by 2π.

part of the South Aegean Volcanic Arc. The position of the island is shown in the inlet map of Figure 1. The volcanism is caused by the subduction of the African plate under the Eurasiatic one.

Figure 1 shows a comprehensive geological map of the island (Fytikas, 1977, 1989). The oldest formation that crops out is the metamorphic basement. This is mainly made of greenschist facies, and it has very limited outcrops. It is overlain by a transgressive sedimentary series of Neogene age which is not present everywhere, consisting of an alternation of limestones, marls and conglomerates with maximum visible thickness of 150 m in the western part of the island.

Extensive orogenic volcanic activity occured during the Middle to Upper Pliocene (Fytikas *et al*., 1976) and continued up to 0.08 mA before present time. The oldest members of the volcanic series are products of submarine pyroclastic activity. Following these are andesitic-dacitic domes and lava flows. Acid domes, and lava flows as well as products of the phreatic activity overlie these. Near the top of the series, a chaotic formation occurs which covers almost half of the island and is considered to be a product of phreatic activity.

Limited, non-volcanic deposits are the youngest members in the lithologic sequence of Milos. These crop out mainly on the plain of the western part of the island (Fig. 1).

The island has a high enthalpy geothermal field which is considered to be one of the biggest in Europe.

Five deep exploratory boreholes have been drilled in the island at the locations shown in Figure 2. Four of them were conducted in the plain of the western part. A production zone was encountered at about 1000 m depth within the metamorphic basement.

Another reservoir, at a depth of about 700 m, was found in the Neogene limestone and the overlying lava-breccias. The fifth borehole (denoted as MA1 in Figure 2) penetrated it.

The ascent of magmas is connected to a strong extensional tectonic regime. Intense faulting in the directions of WNW-ESE, E-W, N-S, N20°E- S20°W and N60°E-S60°W is observed.

DATA USED

A total number of 466 gravity stations were measured and used in the compilation of the Bouguer anomaly map of the island. A first order residual of the Bouguer anomaly map is shown in Figure 2. The location of the measuring stations is shown in the same map as well. Small dark diamonds depict these gravity stations. The density of the surface formations was set to 2.0 gr/cm^3 resulting from 8 Nettleton profiles measured at various locations on the island (Thanassoulas, 1983, Tsokas, 1985).

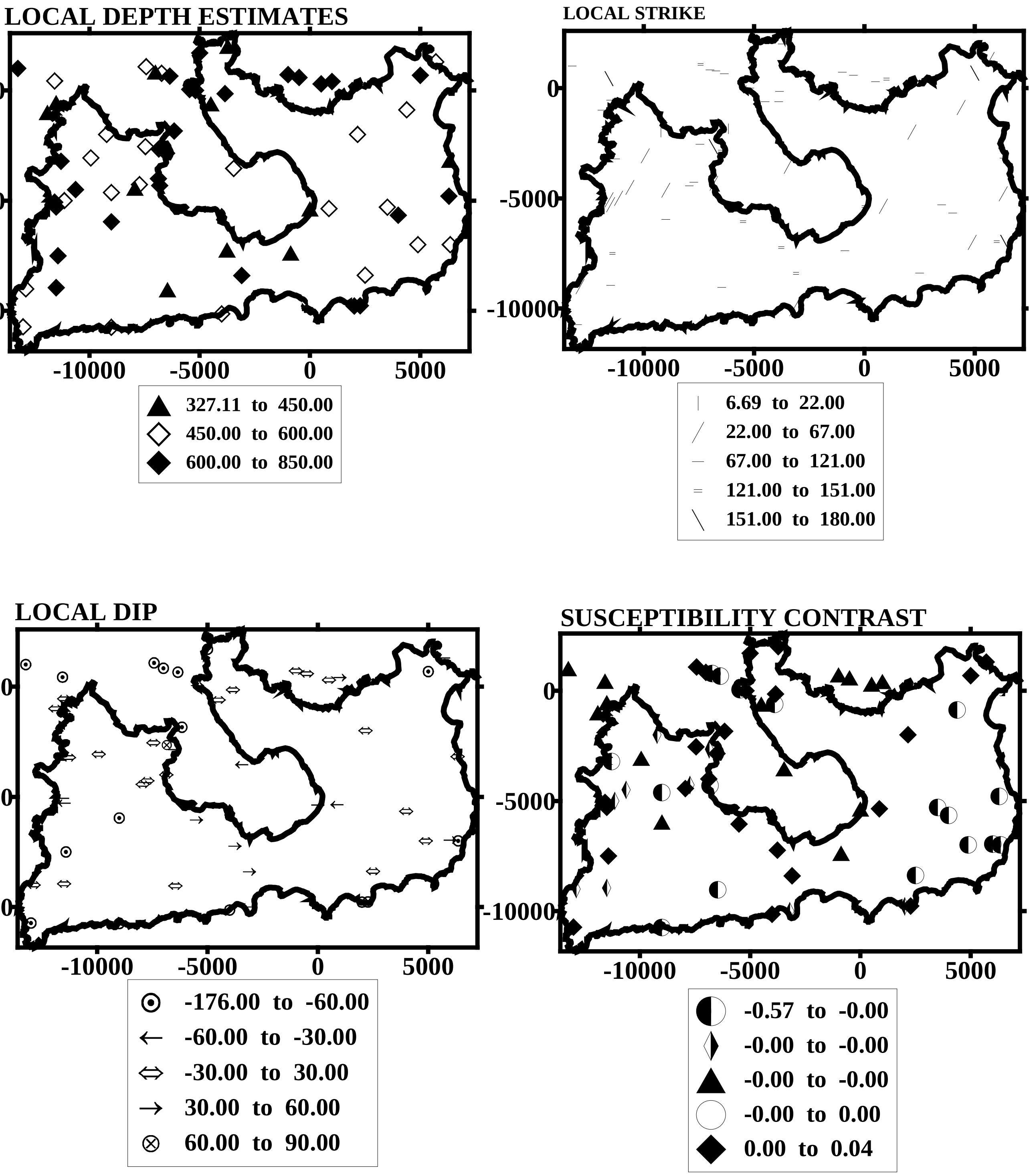

FIG. 8. Source parameter estimates inferred from the pseudomagnetic transformation of the gravity data.

Tsokas (1985) computed the derivatives of the field and interpreted the residual field using mainly the Tsuboi-Tomoda-Aki method (Tsuboi, 1983) as it was implemented by Thanassoulas and Tsokas (1985). The morphology of the top of the formation, which has a density of 2.5 gr/cm^3 was thus evaluated. That formation was considered to coincide with the metamorphic basement as it checked at various outcrops and from the depths encountered in the boreholes.

Tsokas (1996) reinterpreted the anomalous field using most modern techniques and derived more accurate estimates.

RESULTS AND DISCUSSION

Figure 3 shows the complex attributes distribution over the area of Milos Island. The location of the major tectonic features is delineated in the plot of the local wavenumber distribution. The other two attributes can also be used in the same context.

The inferred source parameters, following the baselines described in the relevant paragraph, are plotted in Figure 4. Before attempting to comment on them, one should bear in mind that major faults in the island have almost vertical downthrow and surface expression.

The distribution the estimates are certainly arranged along these main features, a fact that can be verified by simple inspection of the tectonic map of the island shown in Figure 5. It should be noted that the fault of greatest geothermal interest is the one that crosses the eastern part of the island along the NS direction. In fact, geothermic surface manifestations are observed all along its trace and hot water springs occur beneath the sea surface on its southern end. Taking into acciount this major tectonic feature, the strike and dip angles are chosen rather correctly. However, the estimates indicate a mean downthrow of about 600 to 850 m. These depth estimates are overestimated as compared with those derived by Tsokas (1996) and the depths inferred from the lithological logs of the deep exploratory boreholes. In fact, the greatest downthrow along this major feature is of the order of 350 m. The overestimation is expected as explained in previous paragraph. Another cause for this large discrepancy may be the fact that the fault should have affected the deep formations, i.e. those underlying the metamorphic basement. Nevertheless, these depth estimates might be considered as upper bounds.

The same comments could be made on all other major tectonic features of the island.

The pseudomagnetic anomaly computed by means of Hildenbrand's (1983) software is shown in Figure 6. In fact, only remanent magnetisation was considered for this transformation and the susceptibility contrast was set to 0.0004 (emu). The computed complex attributes distributions are shown in Figure 7. It can easily be seen that the local phase shows more or less the same features as the local phase computed from the gravity data. The analytic signal and the local wavenumber show a far more complex picture than the attributes computed from gravity.

The inferred source parameters (Fig. 8) do not show any obvious alignment this time, they comprise rather scattered points. The depth estimates are lower than before while no reasonable conclusion can be made from the strike and dip angles. This situation could be attributed to the extra noise induced by the transformation process. The same conclusion holds for the local susceptibility estimates.

CONCLUSIONS

Complex attributes analysis can certainly aid the interpretation scheme in gravity prospecting. The attributes and the source parameters inferred from them can be used either as a stand alone scheme or in tandem with other techniques to interpret the anomalous field.

In the particular case of the Bouguer field in the island of Milos, the complex attributes analysis added to the overall effort to obtain information for the subsurface. Further, they strengthen previous conclusions and revealed extra info for the relief of the ceiling of the metamorphic basement.

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