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AN INTERPRETATION OF ABNORMALLY SHAPED MAGNETIC ANOMALIES IN SOUTH-EASTERN ITALY

Abstract. A study of two magnetic anomalies in eastern Italy is presented. It consisted of three phases: the total magnetization direction of the sources was first estimated; then the depth of the sources was calculated by means of a spectral analysis; finally a 3D interpretation was carried out, after selection of the best geological model. A direction of the source total magnetization very different from that of the present inducing field was detected. The sources were estimated to be at an intermediate to deep crustal depth. A geological model involving deep intrusions along crustal fractures was favoured. The most probable cause of these abnormal magnetic anomaly shapes is here identified with a clockwise rotation of crustal blocks.

INTRODUCTION

In this paper two abnormally shape aeromagnetic anomalies located in south-eastern Italy are considered (Fig. 1). The first is the so-called "Foggia anomaly" located in northern Apulia, and the second (called here the "Melfi anomaly") is located in the Mt. Vulture volcano area. Both the anomalies are on the outer front of the Apennines overthrusts. These anomalies are said to have an abnormal shape since their peak-to-trough axis is not aligned with the local magnetic meridian (Fedi and Rapolla, 1988). They are of particular interest due to their geologic significance and to the questions arising from their abnormal shape. Their wavelength is of some tens of km.

The interpretation of these anomalies is here developed in three phases. The first involves an estimate of the total magnetization direction by a distortion analysis of the magnetic anomalies (Florio, 1992; Fedi et al., 1994). Although the total magnetization direction estimate represents useful information in itself, allowing a correct interpretation of the magnetic anomalies, in the case of abnormally shaped magnetic anomalies it is a matter of primary importance. In fact the detection of a direction that does not correspond to that of the present inducing field may point to the presence of a strong remanent magnetization component in the sources (Fedi et al., 1991a; Florio et al., 1993). In this case the magnetic anomally abnormal shapes may indicate a rotation of the source bodies.

The second phase involves a preliminary estimate of the depth to the magnetic source tops using the Spector and Grant (1970) spectral method.

Finally, after a discussion about the most probable geological model, an attempt is presented to compute a geometric model for these anomalies, using the results of the former interpretation phases. Even if there are no independent constraints available for this quantitative interpretation and so its significance may be questionable, the computation of a geometric model is useful as a basis for further studies and to check the reliability of the geological model considered.

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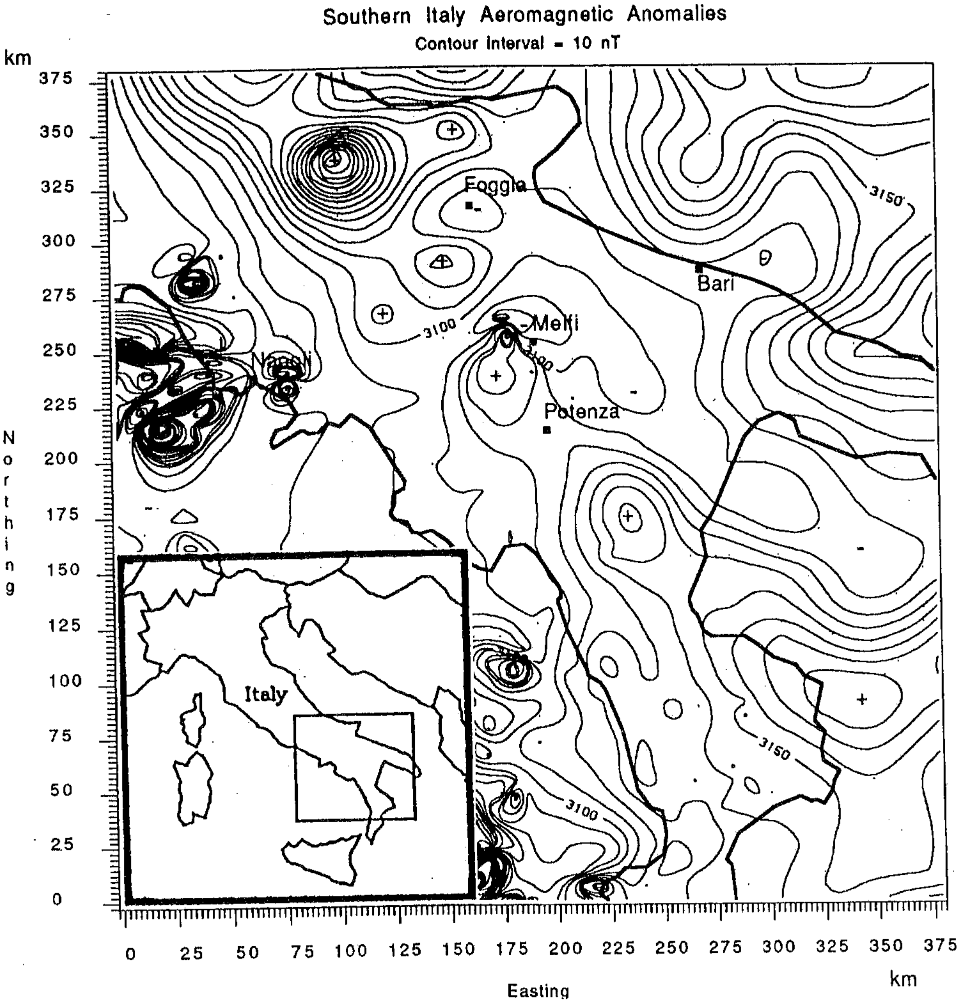

Fig. 1 — Southern Italy aeromagnetic anomalies.

To model these anomalies, a 3D method described by Fedi et al. (1991b) was used.

The data used are from the AGIP Aeromagnetic Map of Italy (1981) and they were digitized using a 6 km×6 km grid.

THE ESTIMATE OF TOTAL MAGNETIZATION DIRECTION

As already mentioned, in the study of abnormally shaped magnetic anomalies the estimate of the total magnetization direction is of particular interest. In fact, knowledge of this parameter is not only essential to perform a correct geometric interpretation of the magnetic anomalies, but it is also very important in itself, allowing deductions on the nature of the source magnetization. For example, detecting the presence of a strong remanent magnetization in deep seated anomaly sources is very interesting, because it is still debated if such a magnetization could have a high intensity at crustal depths (e.g. Shive, 1989a; Worm, 1989; Shive, 1989b). In fact, some authors are skeptical about the possibility of the remanent magnetization representing a large percentage of the total magnetization. Acquisition of the magnetization in the earth's alternating field (Schlinger, 1985; Shive, 1989a) and its slow viscous decay along the direction of the present

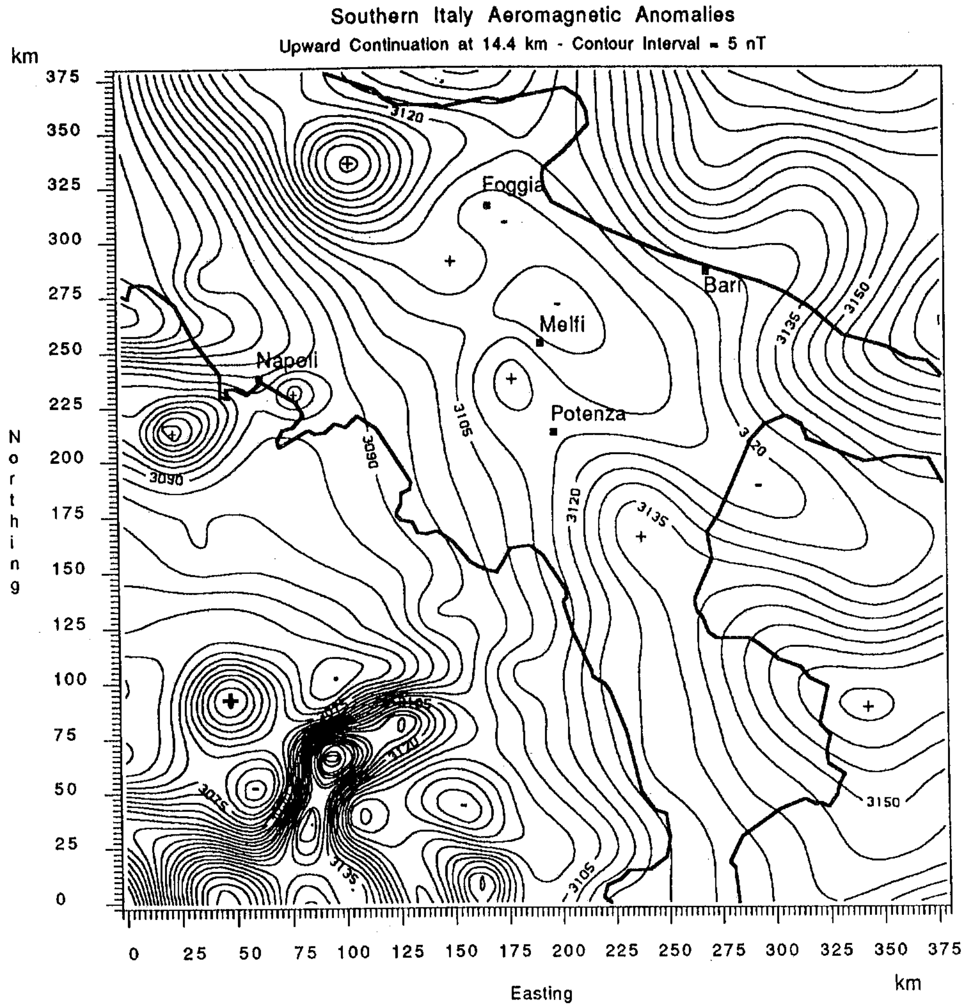

Fig. 2 — Southern Italy magnetic anomalies upward continued to 14.4 km.

field (Pullaiah, 1975) would result in weak remanent magnetization. On the other hand, several authors have measured deep crustal samples with high Koenigsberger ratios, and other have interpreted magnetic anomalies with models involving remanent magnetization.

The method used is based on the distortion of the anomaly when transformed by the reduction to the pole operator for a number of total magnetization directions. The best estimate of the total magnetization direction has proved to be that corresponding to the transformed anomaly with highest value of the associated minimum (Florio, 1992; Fedi et al., 1994). Limitations to the applicability of this method are that the results are reliable only if the anomalies are sufficiently well isolated, and if there is no strong influence from long period trends.

This study was done on the Melfi anomaly since it is more isolated than the Foggia anomaly. However the results are also considered valid for the Foggia anomaly because of the overall similarity between the two anomalies (azimuth of the peak-to-trough axis, anomaly amplitude, wavelength, position with respect to the Apennines).

To study the Melfi anomaly by means of the distorsion method, it is necessary to reduce interference from nearby anomalies. So, the first operation was a smoothing of the high-frequency magnetic anomaly related to the Mt. Vulture volcano. To this end the data were upward continued to 14.4 km (Fig. 2), which is the lowest altitude for which the high frequency disturbing anomaly

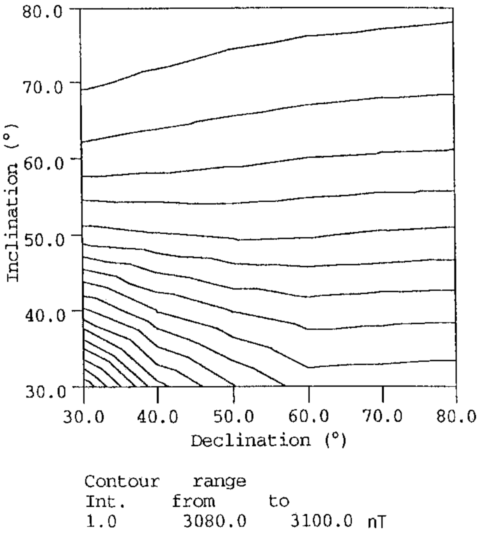

Fig. 3 — Map of the results of the distorsion analysis for the Melfi maagnetic anomaly upward continued to 14.4 km. Note that this function has no maximum so that no estimate of the total magnetization direction can be made.

is totally removed. At this altitude any intereference with the Foggia anomaly is also absent. The anomalies of interest are now smooth, but retain their abnormal shape. This is preserved even when continuing the anomalous field to higher altitudes, which, following Fedi and Rapolla (1990), demonstrates that the abnormal anomaly shape is not due to a shape anisotropy of the sources.

The results of the distorsion method application are illustrated in a contour map of the anomaly minimum as a function of the total magnetization declination and inclination used to perform the reductions to the pole. The coordinates of the maximum area on these contour maps represent the estimate of the total magnetization direction. In Fig. 3 the map shows no maximum, so it is impossible to estimate the magnetization direction. However, following Florio (1992) and Fedi et al. (1994), to overcome this problem, which is probably due to the presence of a long-period trend, the anomalies were high-pass filtered with cut-off $\lambda = 200$ km (Fig. 4). This cutoff wavelength was chosen after several trials as the best for separating the anomalies of interest from the low-frequency field. By applying the distortion method to this filtered anomaly field the results illustrated in Fig. 5 were obtained.

In this case the declination ranges from 50° to 60°, while the inclination ranges from 60° to 70°. A rough estimate of the error in these values is given by the sampling step of the data mapped in Fig. 5, that is 10°. The direction found is very different from the direction of the inducing field which, in this area, has a declination of about 0° and an inclination of about 56°. In particular, while the inclination found can be considered to be in the normal range, the declination is very different from that of the present inducing field.

SPECTRAL ANALYSIS TO ESTIMATE THE DEPTH OF THE MAGNETIC SOURCES

A spectral analysis using the Spector and Grant (1970) method was carried out to obtain information on the depth at which the magnetic sources are located. To this end the two-dimensional power spectrum and its azimuthal means were computed to obtain a radial spectrum. This analysis was carried out on the area of the anomalies (Fig. 6), and also on an area wider than that of interest (Fig. 1) to allow detection of the longer wavelengths and hence of the very deep sources. The radial spectra and the asymptotic segments on which the depth estimates were computed are shown in Fig. 7. The overall shape of the two spectra is rather similar:

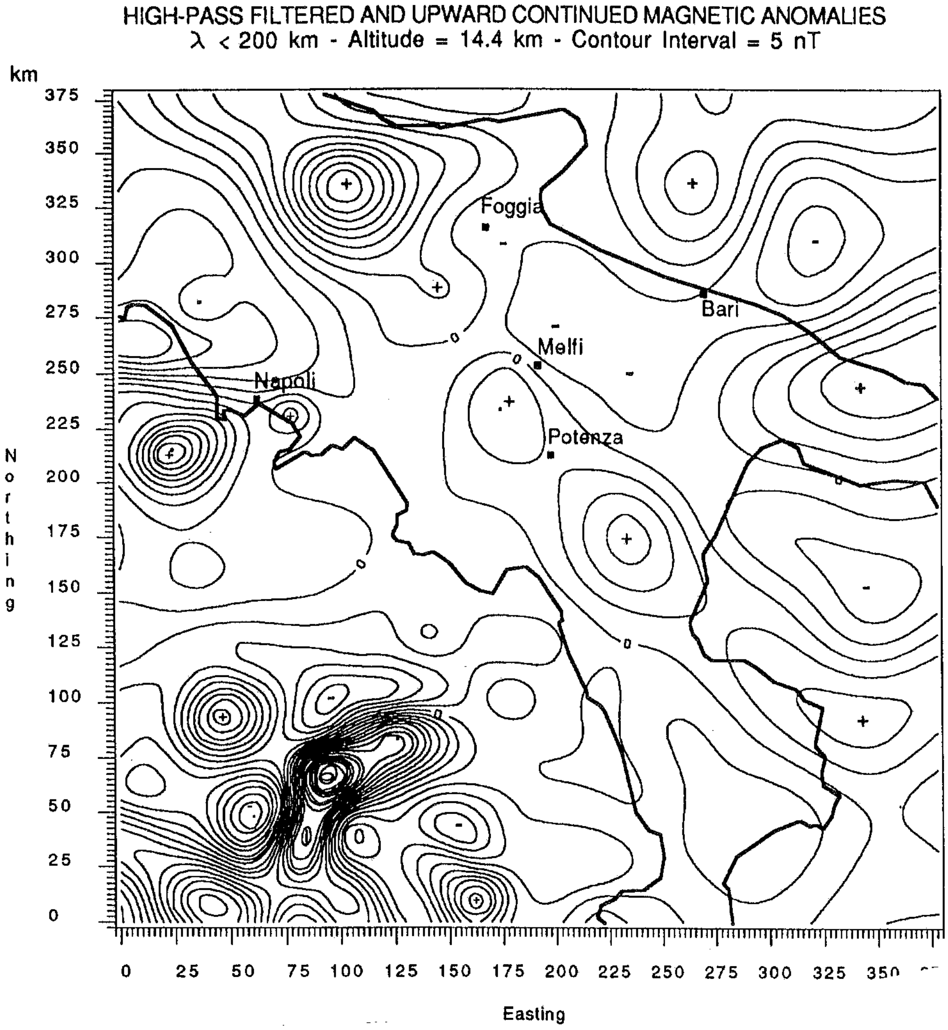

Fig. 4 — Southern Italy magnetic anomalies upward continued to 14.4 km and high-pass filtered with cut-off λ = 200 km.

both show, at lower frequencies, a linear decay without a peak at smaller wavenumbers. This would indicate that the sources responsible for this part of the spectrum are not limited in thickness. At higher frequencies both of the spectra present a peak with associated linear decay. The depths computed range from 20.4 to 24.0 km for the deeper sources, and from 10.0 to 11.6 km for the intermediate sources.

Therefore the spectral analysis led to the conclusion that the sources of these magnetic anomalies should be located in intermediate to deep crust.

3D MODELLING

In this section a quantitative interpretation of the geometry of the sources will be described, taking into account the results found in the previous sections.

- *A geologic model for the south east Italian magnetic anomalies*

Many authors have proposed explanations for the presence of the south east Italian magnetic anomalies. Here a brief overview of these geological models is presented.

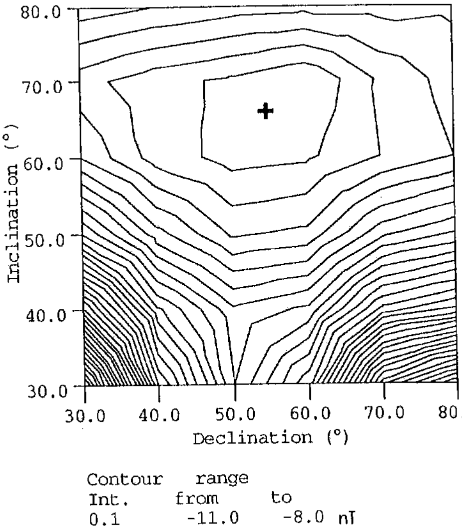

Fig. 5 — Map of the results of the distorsion analysis for the Melfi magnetic anomaly upward continued to 14.4 km and high-pass filtered with cut-off $\lambda = 200$ km. The coordinates of the maximum give the estimate of the total magnetization declination and inclination of the sources.

Magnetic studies (Corrado et al., 1977) attribute the long wavelength magnetic anomalies surveyed in south eastern Italy to a crust with particularly basic composition. A gravity study of this region agrees with this hypothesis, indicating a denser crust than normal (Corrado and Rapolla, 1981). By a qualitative analysis of the aeromagnetic field in this region, Arisi Rota and Fichera (1985) showed the presence of a crystalline basement "more basic than normal". This is explained either by an intense basic magmatism at depth or by geochemical modifications in the rocks induced by geodynamical processes. Following Rapolla (1986) these characteristics of the crust in south eastern Italy may be due to the presence of some oceanic remnant trapped during the continental collision that led to the building of the Apennines.

Morphologic highs in the magnetic basement are invoked by Cassano et al. (1986) to explain most of the magnetic anomalies characterized by intermediate to low frequency in south eastern Italy. Under this hypothesis the magnetic basement is divided into adjacent blocks with quite different susceptibilities. Other anomalies would be caused by the presence of volcanites interbedded within the sedimentary sequence. These bodies, detected by drilling deep wells down to 3-5 km from the surface (AGIP, 1977), should have very low thicknesses and limited horizontal extension. Nevertheless, being very shallow and small it is unlikely that these magnetic bodies could really represent the geologic sources of the anomalies discussed in this paper.

Following Locardi and Nicolich (1991) the magnetic anomalies of south eastern Italy would be due to the accumulation and cooling in that region of a subcrustal melt from two asthenospheric diapirs in the Tyrrhenian area. In fact they interpret a seismic low-velocity layer as a magmatic subcrustal layer. The Apennine tectonics would be governed by the movements of this layer whose fronts would correspond to the foredeep, that is the area of the anomalies. An interpretation of seismic data suggested to these authors that such intrusions should be huge.

However, to define a geological model suitable to the south east Italian magnetic anomalies, a careful study of the area in which they are located and of the relative position to the main structural features is needed. For example, the correspondence of the Melfi magnetic anomaly to the Mt. Vulture volcano is notable. The geochemical and petrographical characteristics of the products erupted from this volcano led De Fino et al. (1986) to hypothesize that the magma originated in the mantle. This implies that there must be a feeding fracture system through the crust down to the mantle.

Incoronato et al. (1985) and Ortolani and Pagliuca (1987) singled out some strike-slip crustal

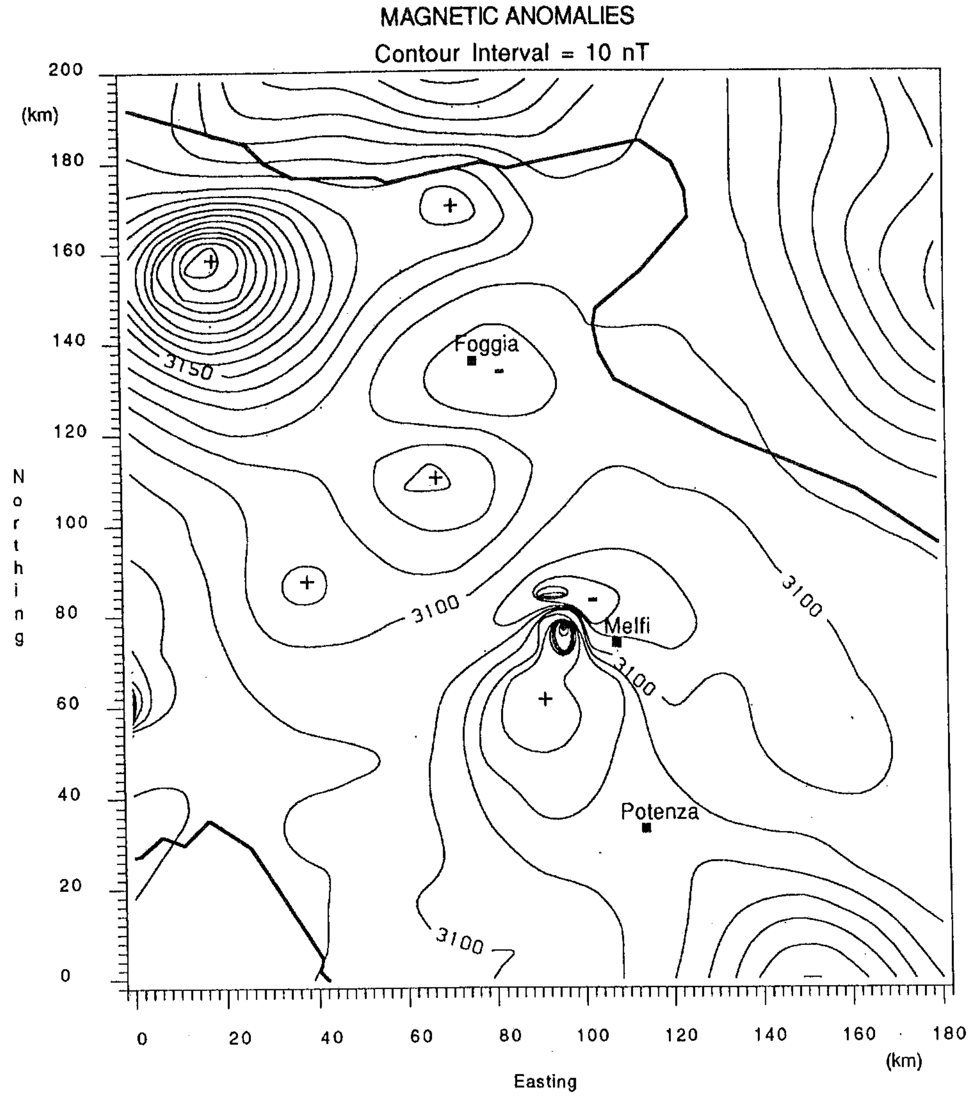

Fig. 6 — Foggia and Melfi magnetic anomalies area for which the radial spectrum of Fig. 7b was computed.

faults in the southern Apennine scrossing the chain in a SW-NE direction. According to these authors, one of the faults should be exactly in area of Mt. Vulture. Evidence for important crustal fractures in this area and in the southern Apennines is also pointed out by other authors, although their interpretation is often different.

The existence of such crustal faults at the front of the Apennine nappes could explain the presence of the magnetic anomalies. Magmatic intrusions from the mantle could have gone up along these fractures and cooled down in the intermediate to deep crust becoming sources of magnetic anomalies. This appears as the most probable hypothesis because: a) it is consistent with the source depths found by spectral analyses, b) it is compatible with former magnetic and gravimetric interpretations (Corrado et al., 1977; Corrado and Rapolla, 1981; Arisi Rota and Fichera, 1985) indicating a crust more basic and dense than normal and c) it is coherent with the presence of volcanic evidence at the surface as well as at depth.

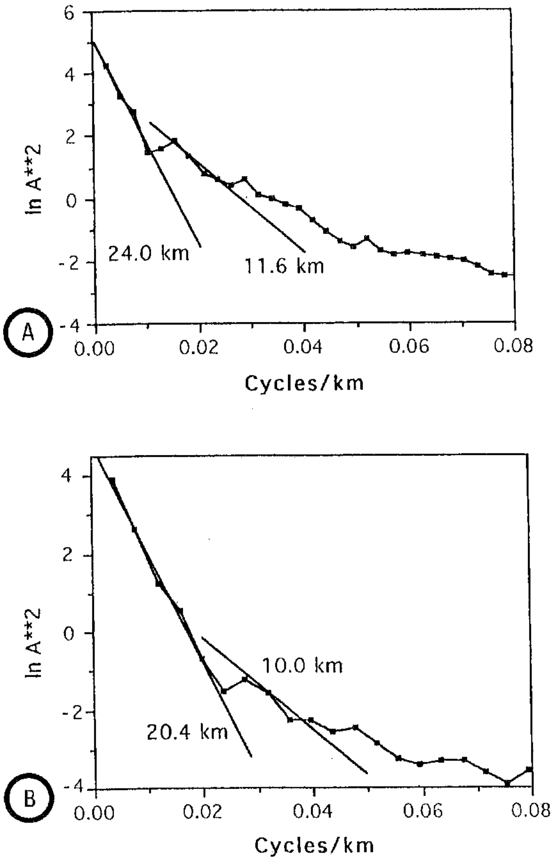

Fig. 7 — a) Southern Italy magnetic anomaly (Fig. 1) radial spectrum; b) Foggia and Melfi magnetic anomalies (Fig. 6) radial spectrum.
The segments on which the estimate of the sources depth were made are indicated.

-3D geometric interpretation

Due to the lack of other geophysical data to constrain this interpretation, the main purpose of the modelling is to help verify the reliability of the geologic model proposed above.

The method used (Fedi et al., 1991b) provides a 3D two-layer model of the sources. By a deconvolution process, a map of the magnetic anomalies reduced to the pole is transformed into the equivalent susceptibility map, assigning the maximum and minimum depth of the surface separating the two layers. A map of this surface can be easily computed from the equivalent susceptibilities. No assumption about the susceptibility contrast is needed.

The first operation was a low-pass filtering of the area with cut-off $\lambda = 35$ km (Fig. 8) to remove the Mt. Vulture volcano high-frequency magnetic anomaly. The total magnetization direction found in Section 2 was used for the reduction to the pole, while the source depths found in Section 3 were used in the computation of the equivalent susceptibility map as depth range for the surface separating the two layers of the model.

In Fig. 9 a map of the surface morphology separating the two layers of the model is shown. Two large highs in this map correspond to the Foggia and Melfi anomalies. The depths and the shape of these highs could well represent the crustal intrusions we referred to before.

To verify the solution obtained and to find the susceptibility contrast needed to correctly model the magnetic anomalies, the surface separating the two layers of the model was approximated by 456 cubic (6×6×6 km) prisms and its magnetic effect then calculated. The

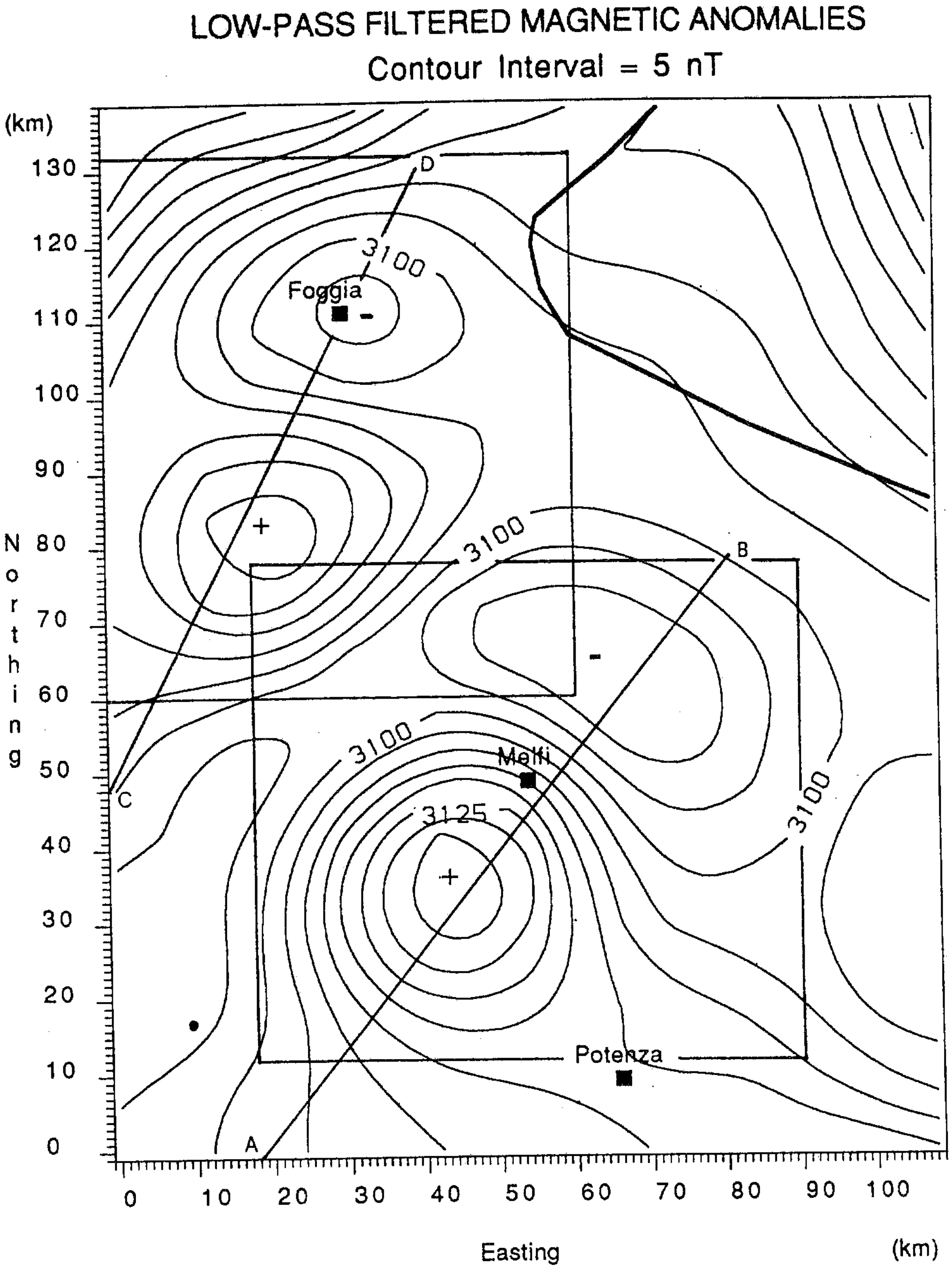

Fig. 8 — Foggia and Melfi magnetic anomalies low-pass filtered with cut-off λ=35 km. In the boxes are shown the areas on which the standard deviation was computed. The two profiles shown in Figs. 12 and 13 are also indicated.

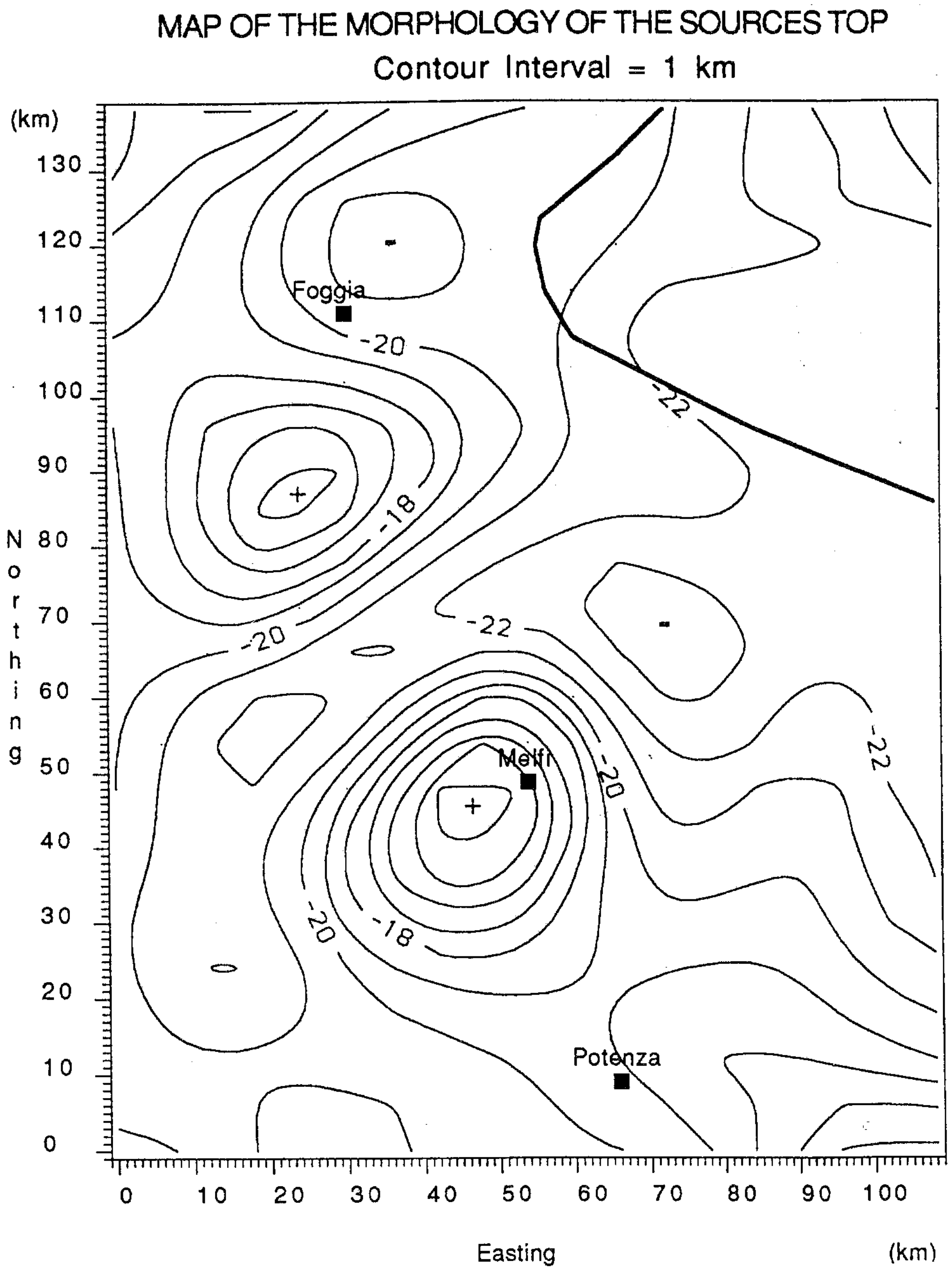

Fig. 9 — Map of the morphology of the synthetic source tops.

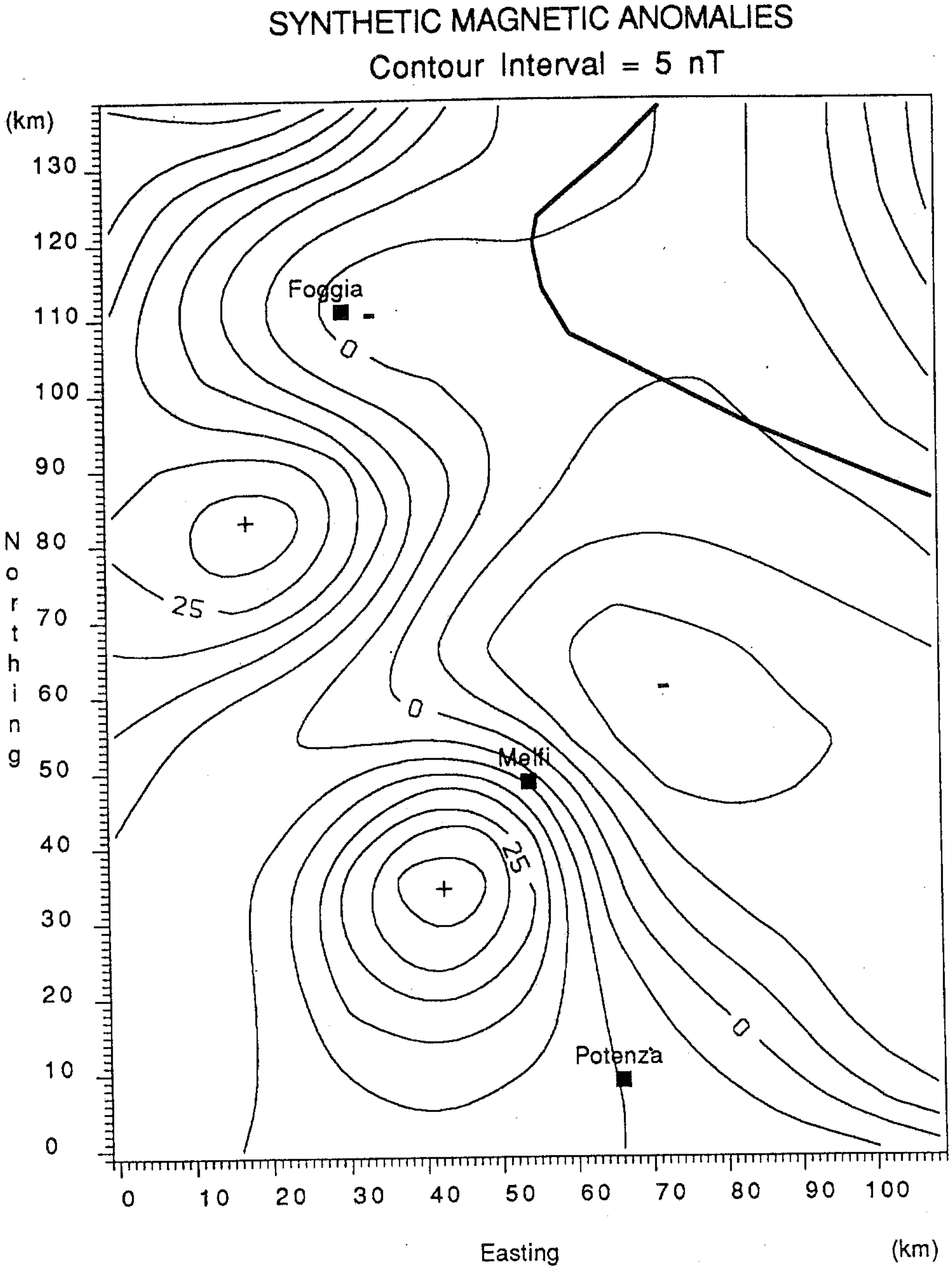

Fig. 10 — Magnetic anomalies generated by the sources illustrated in Fig. 9. Susceptibility contrast is 2.15×10^{-2} SI (1.7×10^{-3} e.m.u.).

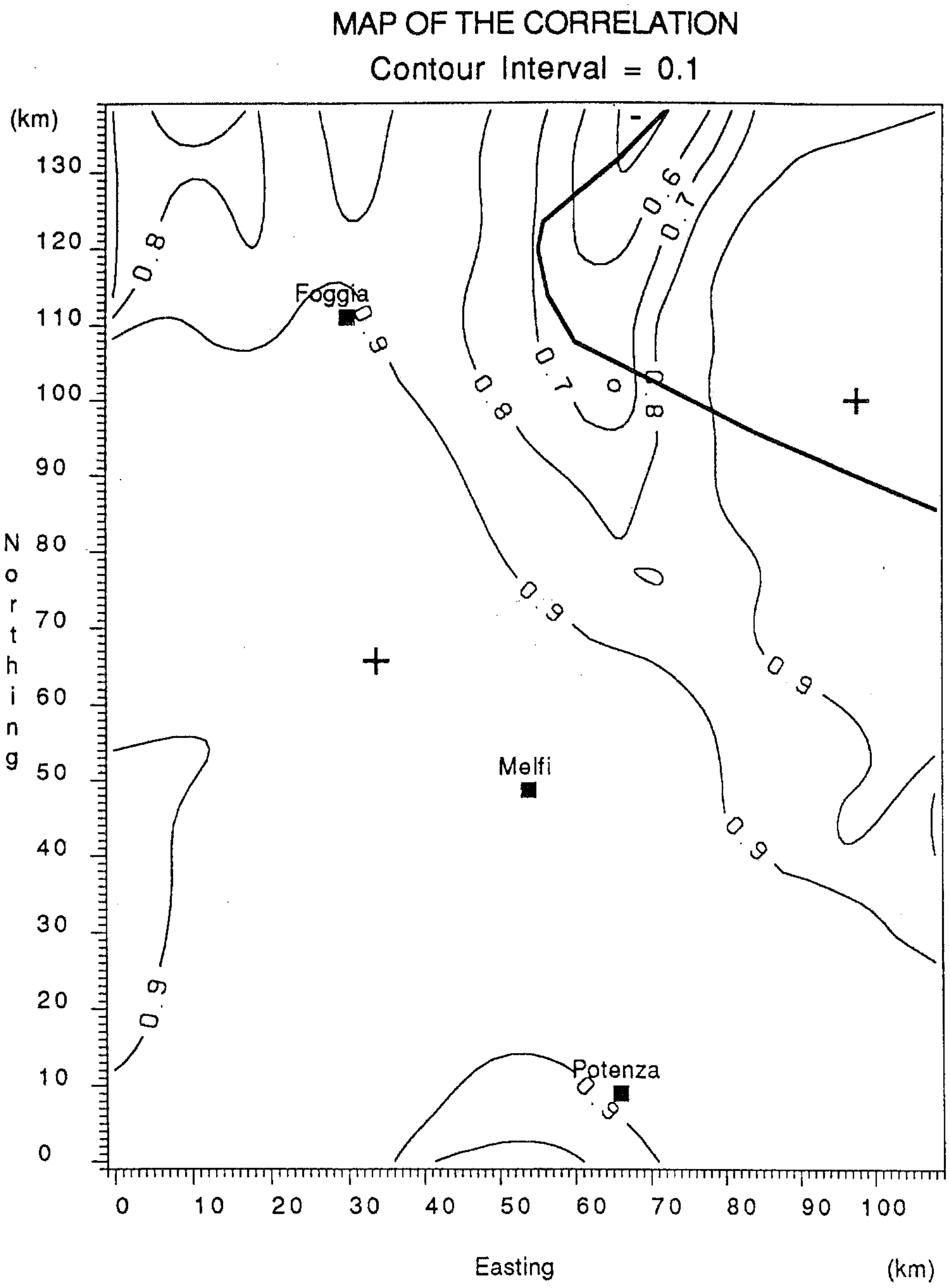

Fig. 11 — Map of the correlation between the anomalies of Fig. 1 and Fig. 10, for the same window as in Fig. 10.

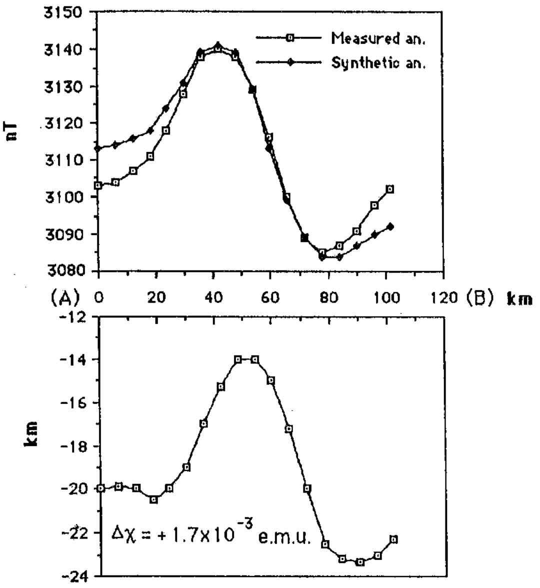

Fig. 12 — Comparison between the actual, and model generated magnetic anomalies along the profile AB shown in Fig. 8 across the Foggia anomaly.

results are shown in Fig. 10; a susceptibility contrast of 2.15×10^{-2} SI (1.7×10^{-3} emu) was used. This susceptibility contrast can be justified by the presence of basic plutonic rocks in an intermediate to deep continental crust.

To evaluate the quality of the fit, a correlation map between the real anomalies (Fig. 8) and the synthetic anomalies (Fig. 10) was done using a linear regression of the two sets of data in a 48 km square moving window. The mean value of the correlation (Fig. 11) was 0.897, with maxima in the areas of the Foggia and Melfi anomalies. This high correlation value indicates that the model reproduces well the actual anomalies. An estimate of the standard deviation between the actual anomaly data and the synthetic data was computed for the areas shown in the box in Fig. 8. For both the anomalies the standard deviation was less than 9% of the anomaly amplitude. In Figs. 12 and 13 two profiles across the Melfi and Foggia anomalies are shown. In these profiles, a constant value has been added to the synthetic anomalies to make them comparable with the measured ones.

DISCUSSION AND CONCLUSIONS

In this paper, two magnetic anomalies of abnormal shape situated in south eastern Italy were interpreted. By different analyses, the total magnetization direction of the sources and the depth at which they are located were determined.

As the first important result, this study showed very different source total magnetization direction from that of the present inducing field. Such evidence could imply that:

a) the magnetic sources are affected by strong anisotropy of the magnetic susceptibility (AMS), deflecting significantly the direction of the inducing field;

b) the sources of the magnetic anomalies have a total magnetization with a high remanent magnetization component. This could imply that the sources have undergone rotation since they acquired their magnetization in a field with direction similar to the present, or that the remanent magnetization was acquired at a time when the inducing field had a direction very different from the present.

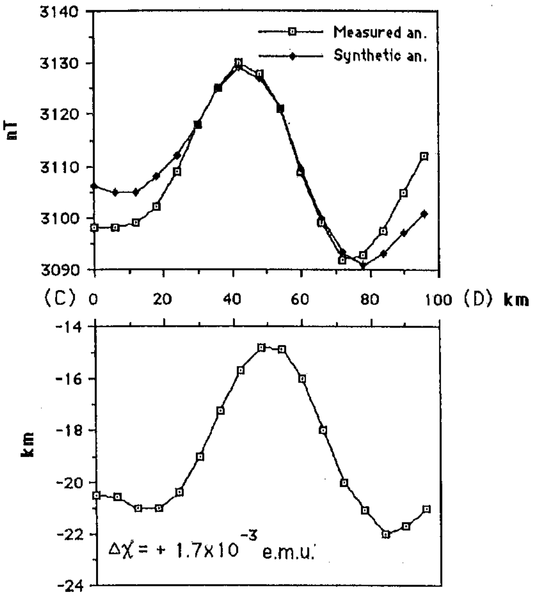

Fig. 13 — Comparison between the actual, and model generated magnetic anomalies along the profile CD shown in Fig. 8 across the Melfi anomaly.

Florio et al. (1993), on the basis of AMS measurements on deep crustal samples, and after modelling magnetic anomalies with AMS, excluded that it could be the cause of the abnormal shape of the Melfi and Foggia magnetic anomalies, and indicated, on the contrary, the presence of remanent magnetization as the most probable explanation of their abnormal shape.

Moreover, the polar wandering from Cambrian to Cretaceous times shows only small changes of declination in the inducing field for the Italian region (e.g. Sharma, 1978), while for later ages the geomagnetic field is closely approximated by a dipole almost coincident with the Earth's rotation axis (Irving, 1964). So, even considering a very wide range for the magnetization age (from Cambrian to Present), it can be stated that the remanent magnetization has not been acquired in a field with direction very different from the present one.

Thus, the most probable conclusion is that the sources have rotated clockwise by about 40° since the acquisition of remanent magnetization. Such a clockwise rotation is seen only in local paleomagnetic studies of the southern Apennines (Incoronato, 1992; Tozzi et al., 1988) and at present there is no geodynamic model of the southern Apennines in which such a rotation has been considered. Unfortunately, the time at which it occurred cannot be easily determined.

Since the anomaly sources are located in the intermediate to deep crust, recognition of the presence of remanent magnetization represents an important contribution to the discussion on the possibility that remanent magnetization could have a strong intensity at depth (e.g. Shive, 1989a; Worm, 1989; Shive, 1989b).

Finally, the direction of total magnetization and the depth of the sources found were then utilized in a subsequent 3D modelling. From an examination of the geological models proposed in recent years for these anomalies, a model of deep seated intrusions from the mantle appeared favourite, considering also the surface geological features. This 3D modelling, although not constrained by other geophysical data, allowed us to verify that the geological model proposed could generate the studied magnetic anomalies.

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