Marine Geophysical Researches (2003) 24:207–221
DOI 10.1007/s11001-004-4220-1

Analysis of the magnetic anomaly field of the volcanic district of the Bay of Naples, Italy

M. Secomandi[1], V. Paoletti[1,*], G. Aiello[2], M. Fedi[1], E. Marsella[2], S. Ruggieri[2], B. D'Argenio[1,2] & A. Rapolla[1]
[1]*Dipartimento di Scienze della Terra, Università di Napoli Federico II, Largo S. Marcellino, Naples, Italy*
[2]*Istituto per l'Ambiente Marino Costiero, Geomare Sud Napoli (CNR), Calata Porta di Massa, Naples, Italy; *Corresponding author (Tel: +39 081 2538334; Fax: +39 081 5525611; E-mail: paoletti@unina.it)*

Received 14 September 2004; accepted 10 March 2004

Key words: Bay of Naples, gravity field, magnetic field, Phlegrean offshore, Vesuvius offshore.

Abstract

We here present and discuss the results of the analysis and qualitative interpretation of two magnetic surveys performed in the Bay of Naples in 1998 and 2000. A map of the Bay of Naples based on the data acquired during these surveys has already been published by the Italian CNR-IAMC Research Institute. We re-processed the same data to produce maps of the pole reduced, analytic signal and horizontal derivative data and correlated them with the bathymetry and the gravimetric data of the area. The analysis shows strong anomalies in the NW and NE volcanic areas of the Bay of Naples, while the central area seems magnetically quiet. In the Phlegrean area the maps clearly show the southern rim of the Phlegrean caldera and demonstrate that while the Magnaghi Canyon is correlated to gravimetric highs and magnetic structures, and can therefore be interpreted as an active lineament, most of Dohrn Canyon is not characterized by volcanic activity and does not correlate to any gravimetric or magnetic structures. An important round-shaped magnetic anomaly is for the first time identified in the central slope of the gulf between the two canyons, probably correlated to a large buried volcanic edifice. In the Vesuvian area some intense circular anomalies, aligned in the NNW–SSE direction, are localized in the Torre del Greco and Torre Annunziata offshore, related to the submerged part of Vesuvius and possibly connected to buried vents.

Introduction

Although several geophysical studies of the Campanian Plain, southern Italy, have been performed, it was only after the Phlegrean Fields bradyseismic crisis of the 1980s that an overall image of the main structures of the Bay of Naples was obtained both from magnetic and seismic studies, as the result of the need for new scientific knowledge (e.g., Finetti and Morelli, 1974; Fusi et al., 1991; Florio et al., 1999; Bruno et al., 2003). These studies focused mainly on the north-western side of the bay, the Phlegrean Fields, where both NE–SW and NW–SE normal faults were recognized, and allowed the border of the Phlegrean caldera and other volcanic structures (Barberi et al., 1978, 1991; Armenti et al., 1983; Orsi et al., 2003, 2004) to be located in the offshore area.

However, a complete detailed magnetic study of the entire Bay of Naples has never been performed. Therefore, in order to have a more complete knowledge of the structural setting and of the pattern of magnetic sources of this volcanic area, an oceanographic cruise was organised by the Consiglio Nazionale delle Ricerche, Istituto per l'Ambiente Marino Costiero (CNR IAMC, former Geomare Sud), in collaboration with Parthenope University and the Earth Science Department of the University of Naples Federico II. Siniscalchi et al. (2002) have recently published a magnetic map of the Bay of Naples based on these data. We re-processed the same data to produce a pole reduced map, and maps of the analytic signal and of the horizontal derivative of the field, in order to more clearly see relation between the spatial location of the magnetic anomalies and their sources.

Several active volcanic areas have been successfully studied and interpreted by means of their magnetic field; it has been demonstrated that magnetic signatures provide important insights into the subsurface structure of many volcanic areas, which are normally characterized by the overall effects of regional and local anomalies and where recent loose volcanic sediments often cover important volcanic structures. Meaningful studies of the structure of volcanoes by magnetic methods have been carried out, e.g., the Island of Hawaii (Hildenbrand et al., 1993), Piton de la Fournaise (Lénat and Aubert, 1982), Mt. St. Helens (Finn and Williams, 1987), Unzendake Volcano (Nakatsuka, 1994), the Canary Islands (Arana et al., 2000), the West Antarctic Rift System (Ferraccioli et al., 2002) and the Haifa Bay (Rybakov et al., 2000).

The aim of this paper is to perform an analysis and a mainly qualitative interpretation of the magnetic signatures of the active volcanic area of the Bay of Naples in order to locate the lateral boundaries of submerged calderas and other buried volcanic structures on the sea floor of the region and give a basis for the delineation of a geo-volcanological and structural framework of this complex volcanic area.

Geological and volcanological framework

The Bay of Naples is located in a structural depression called the Campanian Plain (Figure 1a). The plain was formed during the Plio-Pleistocene, as a result of the foundering of a carbonate platform related to the complex geodynamic events connected with the opening of the Tyrrhenian Sea and to the anti-clockwise rotation of the Italian Peninsula (Scandone et al., 1991). As a consequence, the Tyrrhenian margin was affected by tensile tectonics, characterized by N–S and NNW–SSE normal faults, and then by NW–SE and NE–SW normal faults and W–E strike-slip faults (e.g., Doglioni, 1991). Along the Campanian border, NE–SW trending normal faults produced two Quaternary basins: the Bay of Naples and the Bay of Salerno (Figure 1a).

Intense volcanism has characterised this area since the late Miocene. The volcanic activity on the western border of Italian peninsula seems to be in close spatial relation with the NE–SW faults (e.g., Florio et al., 1999). The products of the Campanian volcanism belong to two cycles: an older one (Miocene–Pleistocene), with calc–alkaline, andesitic and basalitic lavas, only found in Parete and Villa Literno wells (see Figure 1a) (Di Girolamo et al., 1976) and an alkaline-potassic one, related to the previous mentioned Plio-Pleistocene extensional tectonics, which characterised the so-called Roman Co-magmatic Province and includes the Vesuvian and the Phlegrean volcanic districts (Figure 1a).

The volcanic activity of the Phlegrean area, whose oldest outcropping strata are pyroclastic deposits and lava domes 50 Ky years old (Cassignol and Gillot, 1982), was connected to important ground vertical movements, both internal and external to the Neapolitan Yellow Tuff caldera (Figure 1b). This structure was formed about 12 Ka as a consequence of the second most important eruption in the history of this volcanic area (Di Girolamo et al., 1984). After this eruption the Phlegrean Fields were the subject of general subsidence, interrupted by an uplift localized inside the caldera in the city of Pozzuoli. This was interpreted as a "resurgence" of the caldera which occurred after the arrival of new magma in a shallow feed chamber about 4500 years ago (Orsi et al., 1996). The last eruption occurred in 1538. In very recent times two major uplift events localized in the center of the caldera generated a net vertical displacement of 3.5 m.

Somma–Vesuvius, whose most ancient outcropping products are 25 Ka (Alessio et al., 1974), is a strato-volcano characterized by products of both explosive and effusive eruptions. The complex, formed by an older volcanic center (Mt. Somma) and a more recent one (Mt. Vesuvius), is located in an area where a sedimentary, carbonate basement extends to depths of a few thousand meters below sea level, as shown by gravity methods (Carrara et al., 1974) and seismic reflection data (Bruno et al., 1998). After the last eruption in 1944, which left the conduit closed, a quiescent period started. The presence of ejecta consisting of metamorphosed carbonate rocks (Barberi and Leoni, 1980) and the study of fluid inclusions of ejected nodules (Belkin and De Vivo, 1993) are petrological indications of the possible presence of a shallow minor magma chamber. However, gravity studies (Cella et al., 2003) instead detected a deeper intra-crustal low density source with an average density contrast compatible with a partially molten trachybasaltic body. This was interpreted as the main magmatic reservoir of the volcanic activity of the whole Neapolitan region. The presence of such a deep magmatic source was also proposed by Rolandi et al. (2004) on the basis of a geo-volcanological study.

In the Bay of Naples a morphologic structure formed by a continental shelf, a continental slope and a basin can be singled out (Milia, 1999; Aiello et al., 2001) (Figure 1). The continental shelf has a width of about 20 km in the central area, decreasing towards SE, to 2.5 km near the island of Capri. In the northern area of the bay, the Phlegrean Fields offshore, the shelf is irregular, because of the presence of several banks whose morphologic characteristics suggests that they are volcanic edifices (Orsi et al., 1996). In particular, the sea floor is characterized by the presence of monogenic volcanoes, small calderas, tuff cones and lava extrusion (Milia, 1999). Most of them correspond to mound-shaped highs in the bathymetry.

A structural high formed by a horst of the carbonate basement (Banco di Fuori) is extended in a NE–SW direction in the central area of the bay, between Capri and Ischia Islands, with a minimum depth of 130 m (Fusi et al. 1991; Aiello et al. 2001). The maximum depth of the bay is 1330 m, near the island of Capri. The bay is dominated by two submarine canyons: the Magnaghi and the Dohrn Canyons, both having a preferential NE–SW trend. The Magnaghi Canyon, about 15 km long and having a trilobate head, mainly drained the volcanoclastic input supplied by Ischia and Procida Islands during their eruptive activity. In contrast, Dohrn Canyon is about 25 km long and formed by two branches which merge into a main branch NW of Capri Island, draining the siliciclastic supply from the Sarno–Sebeto River plain (Dohrn south-eastern branch) and as well as volcanic material from the Phlegrean Fields through the "Ammontatura" Channel (Dohrn north-western branch) (see Figure 1b).

Seismic reflection data from the Bay of Naples (Finetti and Morelli, 1974), recently reprocessed by Bruno et al. (2003) show faults cutting Pleistocene sediments with a prevailing NE–SW strike, except in the Neapolitan Yellow Tuff caldera, where NW–SE faults also occurs. In particular, a NE–SW normal fault, that seems to continue onshore (Bruno et al., 1998), was recognized in the Vesuvian area. This fault is the well-known Vesuvian Fault (Finetti and Morelli, 1974; Bruno et al., 1998) (see Figure 1b) and could be considered one of the preferential pathways for Vesuvian magma. Many NE-SW faults and fractures are located between Ischia and Procida Islands, some of them correlating with some well-known volcanic banks (Bruno et al., 2003). High resolution seismic reflection studies in the Vesuvius offshore detected a complex fault system associated with recent magmatic intrusions and lava domes (Milia et al., 1998). More recently, a detailed seismo-stratigraphic analysis in the same area showed interlayered volcanic and marine units in the Upper Quaternary succession, allowing the identification and mapping of two thick deposits located on the continental shelf and interpreted as the product of debris avalanche (Milia et al., 2003).

A structural pattern composed of several NE–SW trending normal faults, imaged by seismic profiles and named the "Magnaghi–Sebeto" line (Bruno et al., 2003) divides the Bay of Naples into two areas: a western area, characterized by several volcanic banks and reliefs and an eastern one, characterized by a NE-dipping monoclinal structure made of sedimentary rocks (see Figure 1b).

With regard to the potential field data in the whole Campanian Plain, the Bouguer anomaly field (Cassano and La Torre, 1987) and the regional aeromagnetic field (AGIP, 1981) allow NE–SW and NW–SE structural lineaments to be identified in the Gulf of Naples. A boundary analysis of the Bouguer anomaly field of the Campanian Plain (Florio et al., 1999) highlighted, in the Vesuvian area, a NE–SW oriented fault, running both onshore and offshore, and complex structures west of the offshore part of this fault. In the Bay of Pozzuoli (Figure 1), a boundary analysis of gravity data and of a detailed pole-reduced aeromagnetic data set on land and coastal areas (Florio et al., 1999), allowed the location of a curved structure to be interpreted as the border of the Neapolitan Yellow Tuff caldera (see Figure 1b). Furthermore, the analysis of magnetic data located a lineament running NE–SW from the western coastline of Naples and separating the

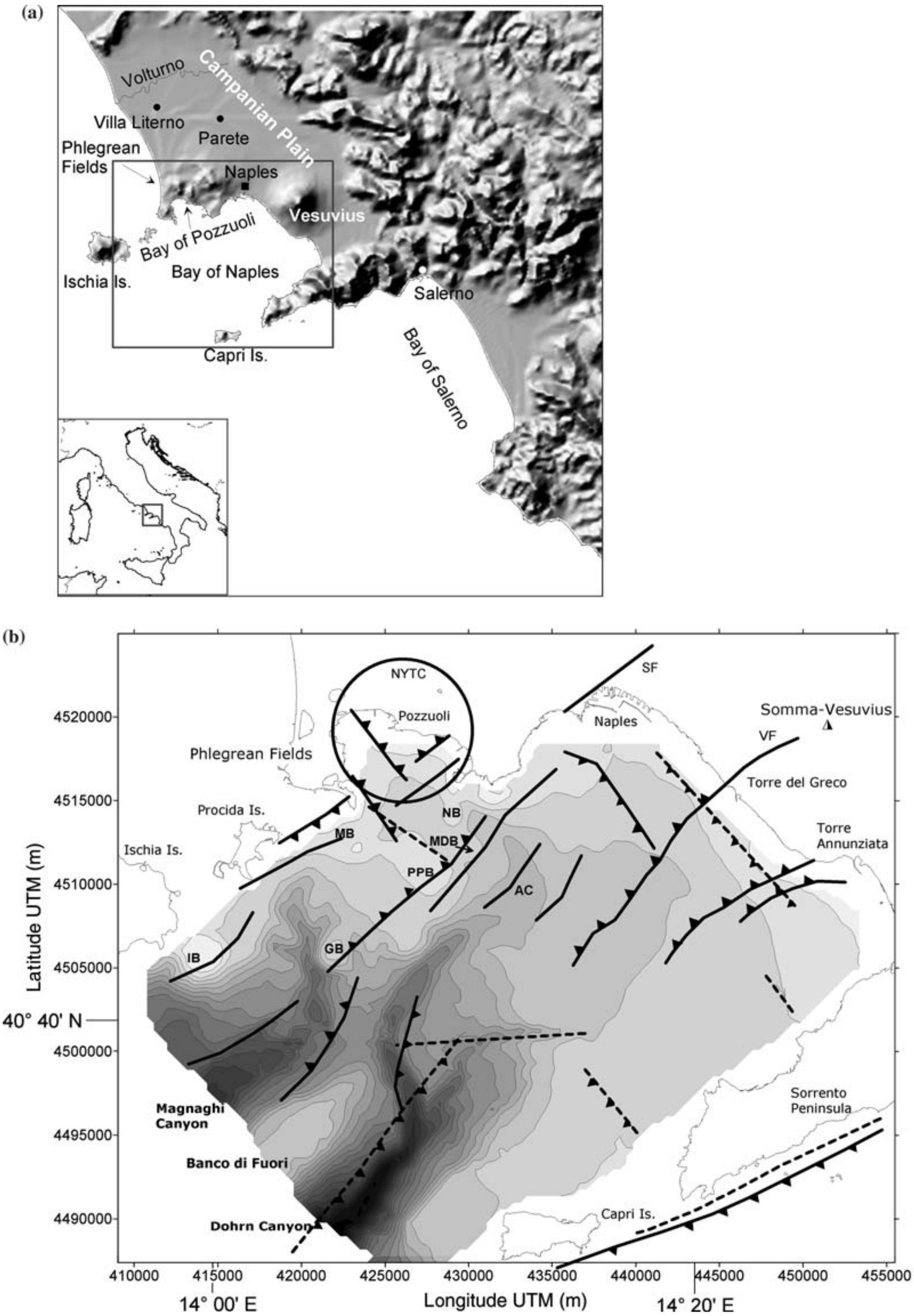

Figure 1. (a) Location of the study area. (b) Bay of Naples bathymetric and tectonic scheme. The bathymetry is obtained by single beam data acquired during the surveys, integrated with the data of the nautical map of the gulf. The faults are singled out by seismic studies: dashed lines indicate the faults located by Milia and Torrente (1999), while solid lines the faults located by Bruno et al. (2003); barbs are on the downthrown side, arrows indicate the direction of the strike-slip movement. IB: Ischia Bank; MB: Miseno Bank; NB: Nisida Bank; PPB: Pentapalummo Bank; GB: Gaia Bank; MDB: Monte Dolce Bank; AC: Ammontatura Channel; NYTC: Neapolitan Yellow Tuff caldera; SF: Sebeto Fault; VF: Vesuvius Fault.

magnetized Phlegrean region from the eastern non-magnetic area (Florio et al., 1999).

Paoletti et al. (2004) integrated the existing aeromagnetic data of the Pozzuoli area with a new detailed data set measured in the northern sector of the Phlegrean Fields, leading to a new aeromagnetic map of the whole Phlegrean Volcanic Area. The analysis of this new data set clearly showed the borders of the Neapolitan Yellow Tuff caldera and confirmed the existence of two main structures which may represent volcanic seismogenetic trends within the caldera (Florio et al., 1999). In the northern part of the investigated area Paoletti et al. (2004) found a number of volcanic structures that align along an E–W trend, fairly coincident with the well known Tyrrhenian 41 °N parallel magnetic lineament.

Data acquisition

The magnetic data analysed in this work were acquired during oceanographic survey GMS 2000–05 performed in October and November 2000, on board the R/V Urania. During this cruise about 950 km of magnetic and seismic profiles were acquired in the Bay of Naples (Figure 2). The survey consisted of 32 survey lines, trending NW–SE and spaced 400 m apart, and 20 tie lines, trending NE–SW and spaced 800 m apart. Sampling time was 3 s (Marsella et al., 2001). Acquisition was made by the EG & G Geometrics proton magnetometer G-811, with an instrumental resolution of 0.5 nT. The measured data were integrated with the magnetic data acquired in 1998 during oceanographic cruise GMS98–01, organized by CNR-IAMC Institute, to fill the data gap in the SW area of the bay. Siniscalchi et al. (2002) describe other data acquisition details.

Data processing and analysis

Generally the use of base station data to monitor the diurnal variation and the consequent diurnal variation correction are not sufficient to cancel the effects of the time-varying magnetic field, especially when the base station is far from the survey area or when the investigated area is particularly wide. Because of this, magnetic surveys are normally performed along intersecting orthogonal lines, in order to obtain a set of intersecting points with a repeat value of the magnetic field. The values at the intersection points between the survey lines and the tie lines will generally not be equal, mainly because of the time-varying magnetic field, but also because of position errors (especially in areas of high horizontal gradients) and of random noise. These differences at intersection points between the two data set are called mis-ties (e.g., Mauring et al. 2002).

The process of minimizing the mis-ties is called levelling. Traditionally, the first step is a "zero order network adjustment", consisting in a sum or subtraction of a constant value to the survey and tie lines, in order to minimize the mis-tie values. Then, the tie lines are levelled by subtracting from each line a function approximating the mis-tie values. Finally, the survey lines are levelled with respect to the corrected tie lines (e.g., Mauring et al., 2002).

Aeromagnetic surveys are generally programmed only with few tie lines and, after the levelling corrections, only the survey lines are used to obtain the magnetic map. In marine surveys, however, a great number of both survey lines and tie lines may be available as the magnetic survey is often performed together with other kind of surveys (e.g., seismic) that need many lines in both directions. This is the case of the surveys in the Bay of Naples, where a predominance of survey lines exists in some areas, while in other areas the tie lines are predominant and it may be difficult to choose a single data set to obtain a map without losing useful data. Therefore, in order to improve the significance of our magnetic data, we used both data sets by performing first a reciprocal levelling and then gridding the data in order to considering all the lines of both data sets.

The obtained data were then processed to compute: (a) a pole-reduced data set; (b) an analytic signal data set; (c) a horizontal derivative data set. For an extensive discussion about these analysis methods (see Rapolla et al., 2002).

Reduction to the pole is a frequently utilised and well-known linear transformation of the original field performed in the frequency domain, which simplifies the shape of magnetic anomalies measured at intermediate latitudes, making them

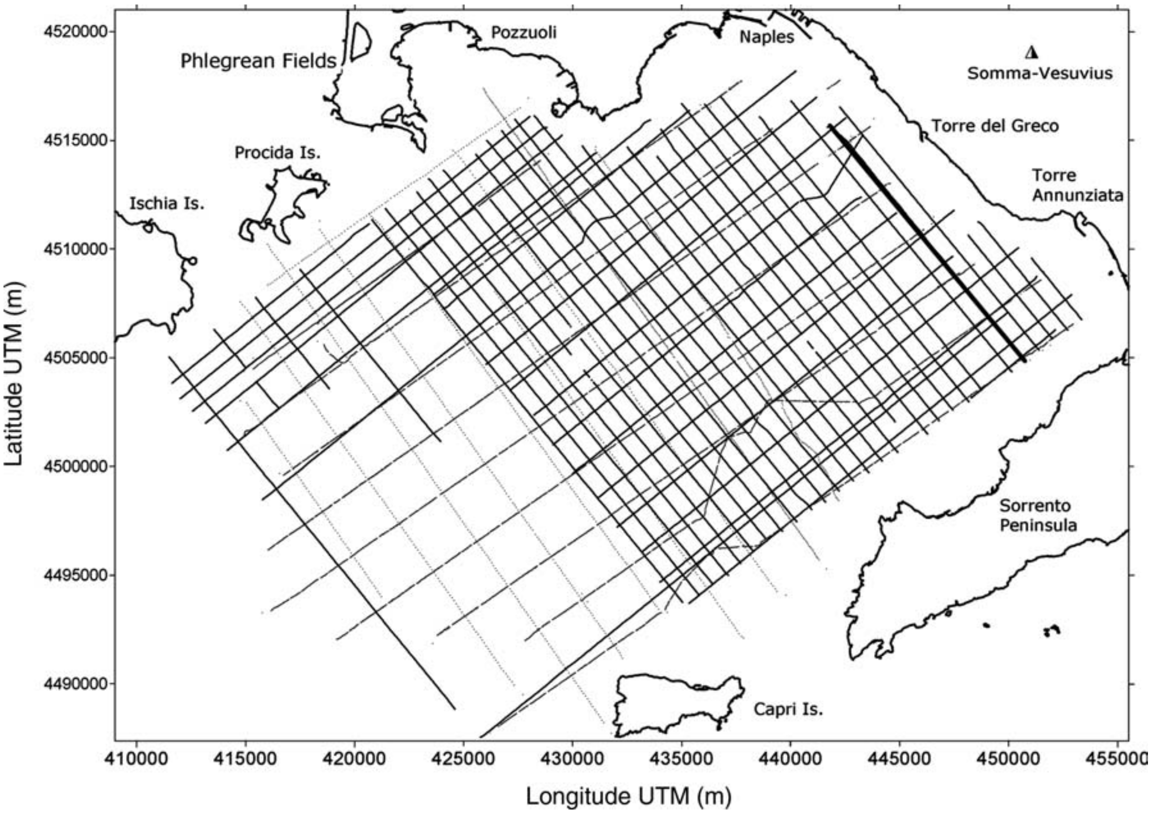

Figure 2. Navigation lines. Black lines were surveyed during the 2000 cruise, while grey lines were collected during the 1998 cruise. The bold line shows the profile analysed in Figure 9.

similar to the anomalies that would be measured above the same sources having vertical magnetization at the magnetic pole. As inclination and declination of the induced and total magnetization vectors, we used the direction of the present field in the study area for both vectors (declination = 0°; inclination = 56°). The obtained map (Figure 3) shows strong magnetic anomalies in the northwestern and northeastern sectors of the bay, corresponding to the volcanic areas of the Phlegrean Fields and of Vesuvius, while the central area seems to be magnetically quiet and characterized by low gradients. In the Phlegrean area there are small anomalies superimposed on a regional anomaly. The southern area of the Bay of Pozzuoli is characterized by a curved anomaly between Miseno Cape and Nisida Island probably corresponding to the southern border of the Neapolitan Yellow Tuff caldera (Orsi et al., 2004) (A, Figure 3). South of this structure, there is a WNW–ESE alignment of high frequency anomalies.

However, we note that some magnetic anomalies continue to show a significant dipolar shape even after pole reduction. This is the case, for example, of an anomaly SE of Ischia Island (I, Figure 3). This may happen because some of the body-sources have a significant remanent magnetization vector with a direction different from that of the present inducing field.

For this reason we also computed the analytic signal (Nabighian, 1984) of the data. The analytic signal is a complex function constituted by the sum of horizontal and vertical gradients of the potential field whose amplitude is a bell-shaped function having its maxima localized on the magnetic structure lateral boundaries. When the resolution of the field is not very high, the analytic signal displays a single high localized above the magnetic sources, allowing the ready identification of the position of sources, similarly to the pole-reduced anomalies. The main advantage of the analytic signal with respect to the pole reduction is that analytic signal is practically

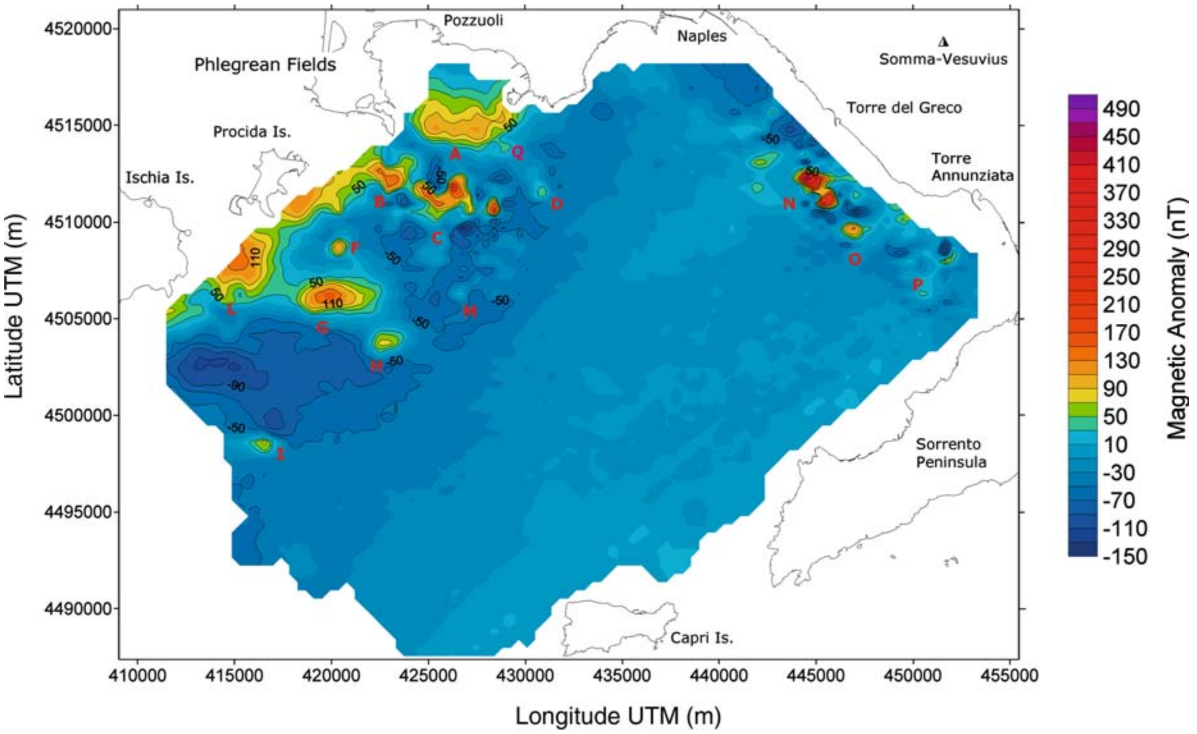

Figure 3. Map of the pole-reduced magnetic anomalies of the Bay of Naples.

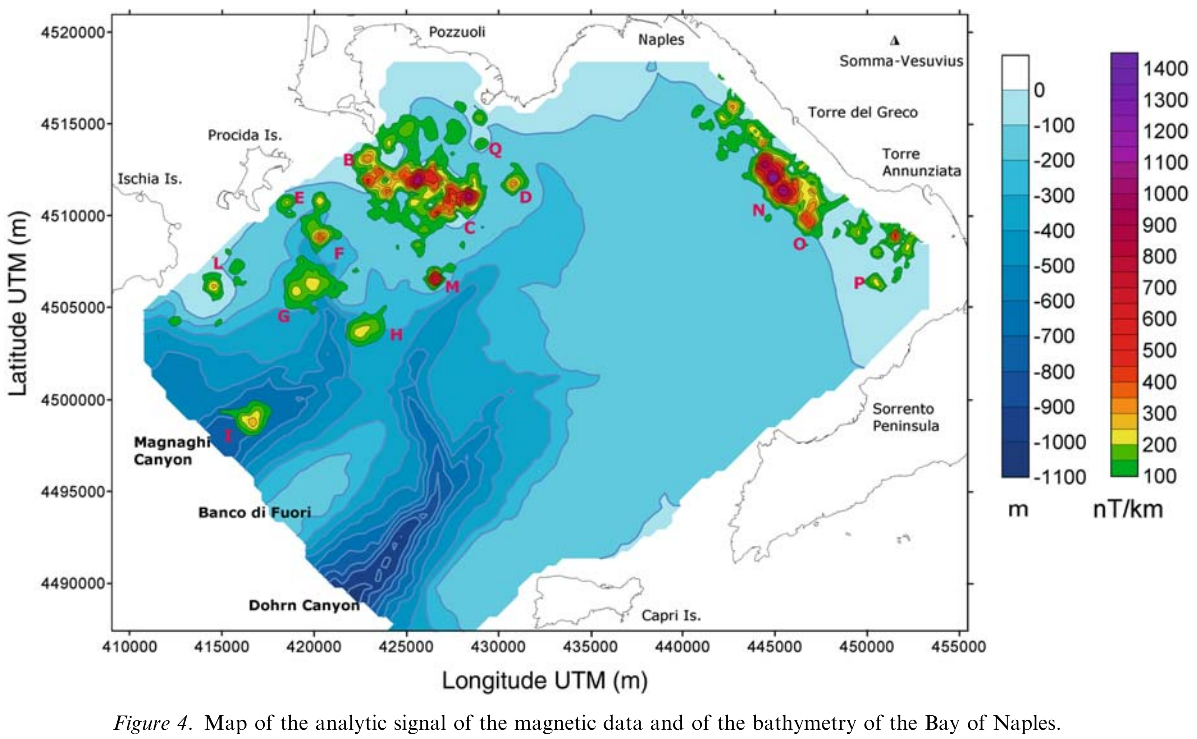

Figure 4. Map of the analytic signal of the magnetic data and of the bathymetry of the Bay of Naples.

insensitive to the direction of the total magnetization vector.

The computation of the horizontal derivative (Grauch and Cordell, 1987) of a data set allows for the location of the lateral boundaries of the sources of magnetic (and gravity) anomalies to be estimated, without subjective assumptions. The only assumption in its use is that the magnetization contrast between body-source and surrounding rocks is abrupt and nearly vertical, otherwise the boundaries are shifted towards the dip direction. However these effects are small and become irrelevant in regional surveys. The lateral boundaries of the magnetic sources correspond to the maximum amplitudes of the horizontal derivative.

In Figures 4 and 5 we show, respectively, the maps of the analytic signal and the horizontal derivative of the magnetic data overlain on the bathymetry of the bay. These maps show sub-circular structures, that seem to follow preferential directions and are often correlated with the bathymetry. The horizontal derivative map shows ring-shaped structures representing the boundaries of the sources, while the analytic signal map presents single highs localized above the magnetic sources (B, D, F, G, H, I and N, Figures 4 and 5). In most cases the horizontal derivative map seems to identify the borders of the magnetic sources more precisely than the analytic signal map. The border of the Phlegrean Fields caldera is, in fact, well evidenced in the horizontal derivative map but not clearly defined in the analytic signal map (A, Figures 4 and 5). With regard to the magnetic structures associated to the Ischia Bank and the Nisida Bank, these are not clearly shown in the horizontal derivative map, while the analytic signal map shows them clearly as circular structures (L and Q in Figures 4 and 5). In the Vesuvian area some circular structures, aligned NNW–SSE, are localized in the Torre del Greco offshore (N, Figures 4 and 5), while other small and localized anomalies, less intense than the previous ones, are in the Torre Annunziata offshore (O, Figures 4 and 5).

Discussion

The magnetic maps analysed in this study (Figures 3–5) show that the Bay of Naples is divided into two domains: a domain including the NW and NE parts of the bay, offshore the Phlegrean Fields and the Vesuvian volcanic areas, which is characterized by strong anomalies often correlated with the bathymetry, and a sedimentary one in the SE area, magnetically quiet and characterized by low gradients. The presence of two different sectors, characterised by geological and geophysical differences, was also proposed by Fusi et al. (1991) and Bruno et al. (2003).

In order to understand the origin of the anomalies measured in the area we studied the correlation between the magnetic structures located by the horizontal derivative map and the bathymetry of the bay (see Figures 5). The correlation shows that all the volcanic banks of the Phlegrean sector of the bay are associated with magnetic signatures except the Gaia Bank, a monogenic volcano about 2.25 km wide and 150 m high (Milia, 1999). The lack of magnetic signature associated with this bank could be due to a low contrast in magnetization between this body and the surrounding areas. No bathymetric high is observed corresponding with the Neapolitan Yellow Tuff caldera (A anomaly) or with the anomalies offshore the Vesuvian area (N, O and P).

In the Phlegrean area anomalies B, C, D, L and Q correspond to volcanic structures already known in the literature (Miseno Bank, Pentapalummo Bank, Monte Dolce Bank, Ischia Bank and Nisida Bank, respectively) (e.g., Orsi et al., 1996) (see Figure 1b). Miseno Bank, interpreted by some authors (e.g., Milia, 1999) as a small caldera, is clearly identified by a sub-circular magnetic structure (B). Pentapalummo Bank corresponds to a complex series of magnetic signatures (C), which form a WNW–ESE alignment together with the anomaly associated to Miseno Bank. The magnetic structures associated with Monte Dolce Bank (D) and Ischia Bank (L) appear slightly shifted toward the east with respect to the bathymetric reliefs and the Ischia Bank (L) signature appears of low intensity compared to the dimension of the bank. Nisida Bank corresponds to a tuff cone (Fusi et al., 1991) and is associated with a rather low magnetic signature (Q).

We note then that a series of magnetic structures follows Magnaghi Canyon (E, F, G, H and I). More specifically, anomalies F and G are between the branches of Magnaghi trilobate head, H anomaly corresponds to a depression, and I anomaly seems to correspond to a small

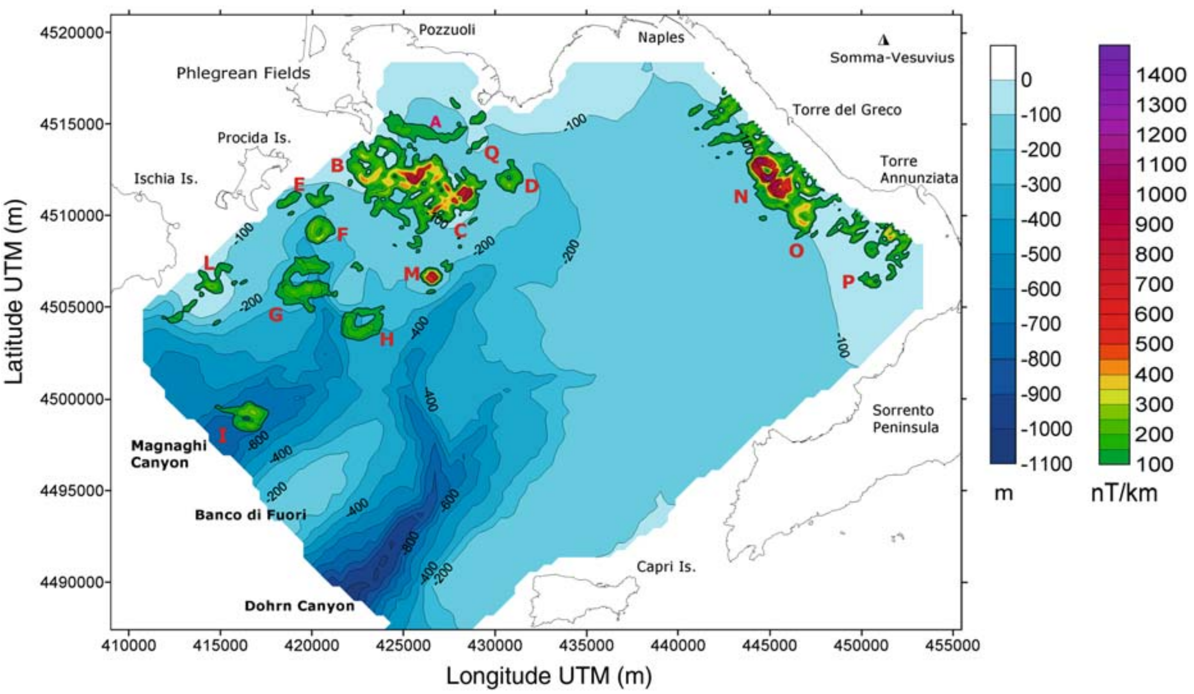

Figure 5. Map of the horizontal derivative of the magnetic data and of the bathymetry of the Bay of Naples.

relief, located in the canyon axis. Even though the H anomaly seems to correspond to a bathymetric depression, it could be possibly interpreted as a large buried volcanic edifice, as suggested also by the interpretation of high resolution seismic reflection profiles recorded on the same lines (Marsella et al., 2002). To confirm this hypothesis we performed an inversion of the G and H anomalies. A 3-D representation of the bathymetry of the area with overlapped magnetic anomalies considered for the inversion is shown in Figure 6, while in Figure 7 the 3-D model obtained from the inversion is plotted. We used a nonparametric discretization of the inverse problem and assumed a source volume of specified depth and horizontal extent, in which the solution is piecewise constant within a 3-D grid of prisms. The discretization used for the inversion is composed of $37 \times 32 \times 30$ prisms in the x, y and z directions, respectively, while the dimension of the prisms is 200 m in the x and y direction and 80 m in the z direction. The solution shows the presence of two body sources, a bigger and deeper one relative to the G anomaly and a shallower and smaller one corresponding to the H anomaly. The widths of these sources are

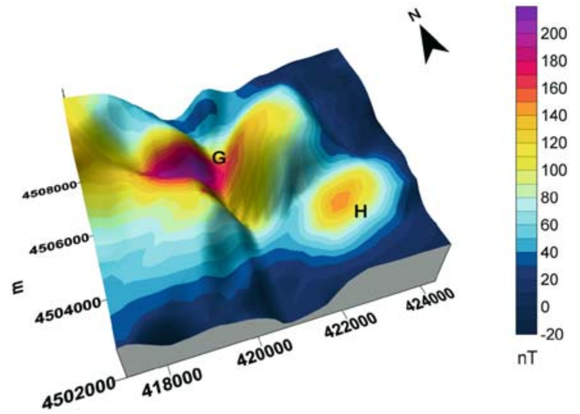

Figure 6. Magnetic anomalies in the Phlegrean offshore considered for the inversion overlapped to a 3-D representation of the bathymetry of the area.

comparable with the lateral dimensions shown by the horizontal derivative map for the G and H anomalies (Figure 5); their magnetization of about 0.8 A/m is fairly consistent with the magnetization of the tuffs of the area (Cassano and La Torre, 1987). We therefore interpreted these body sources as being related to buried vents

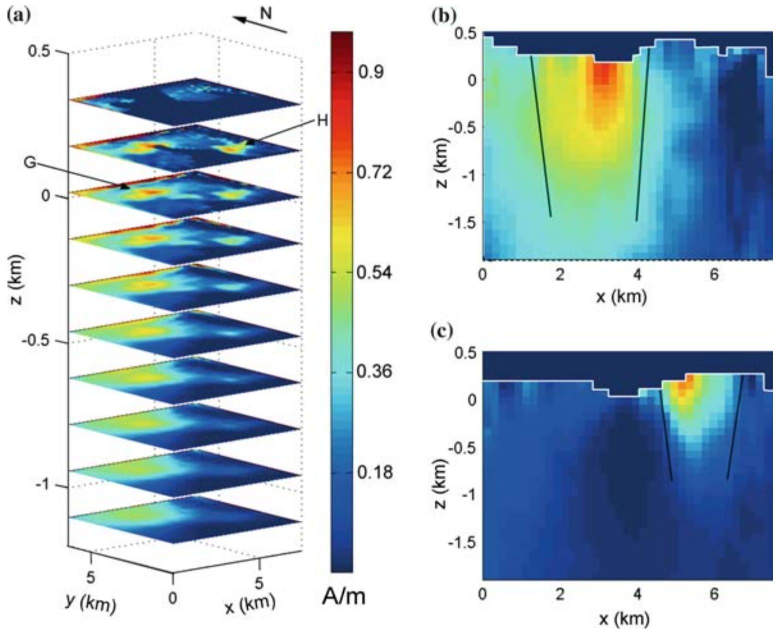

Figure 7. (a) 3-D magnetization model obtained from the inversion of the G and H anomalies represented in slices. (b) E–W section along the source body corresponding to the G anomaly, the inferred limits of the source are marked in black. (c) E–W section along the source body related to the H anomaly, the inferred limits of the source are marked in black.

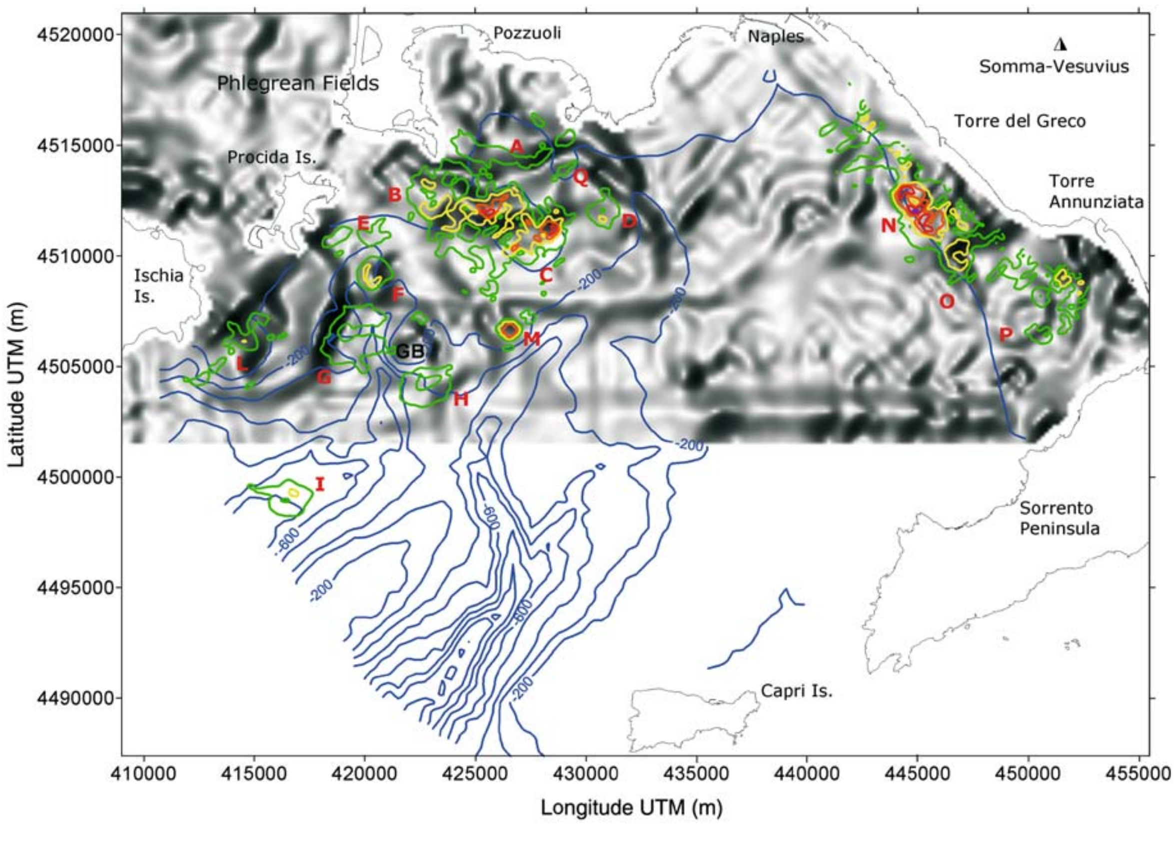

Figure 8. Shaded relief map of the horizontal derivative of the filtered gravity data set of the bay, overlain by the horizontal derivative of the magnetic data and the bathymetry.

which were possibly activated along the Magnaghi Canyon.

No significant magnetic anomalies were found along the Dohrn Canyon, whose NW branch seems to delimitate the SE extent of the magnetized Phlegrean area. The small circular magnetic anomaly M is located at the shelf break of the bay which runs along the 140 m isobath, offshore the Phlegrean Fields volcanic complex; this anomaly is produced by three small monogenic volcanic edifices, clearly shown by high resolution multibeam bathymetry recently produced by the CNR-IAMC Institute (Aiello et al., 2001) and genetically correlated to the Late Quaternary volcanism in the bay. Conversely, anomaly D, located in a bathymetric range of 150–180 m west of the ''Ammontatura'' slope channel, is probably correlated to a large area composed of irregularly mound-shaped structures, shown in high resolution multibeam bathymetry and reflection seismic studies (Aiello et al., 2001). These structures, cropping out at the sea bottom or partially buried by sediments, have been sampled by piston coring and consist of shales and volcanogenic sands interlayered with thick pumice levels (Aiello et al. 2001).

In the Vesuvian area the interpretation of the total magnetic anomaly field shows that three intense dipolar magnetic anomalies (N, O and P in Figure 5) are aligned along a NW–SE direction, parallel to the Bay of Naples shoreline. Single beam bathymetry of the area (see Figure 1) shows the occurrence of a shallow and extended continental shelf, with low gradients; the transition from the shelf to the upper slope, occurring about along the 140 m isobath, is gradual. These magnetic structures correspond only partially to bathymetric highs and are located at some convexity of the isobaths at depths ranging from 70 m down to 110 m.

In order to correlate the described magnetic structures with the gravimetric structures of the Bay of Naples, we compared the map of the horizontal derivative of the pole-reduced magnetic data with the map of the horizontal derivative of a gravity data set of the area (Figure 8). This data set was obtained by digitising the gravimetric map by Berrino et al. (1998) and filtering the data through a method based on discrete wavelet transform (Fedi and Quarta, 1998), in order to remove the regional trend. The map of the horizontal derivative of the filtered gravity data demonstrates the presence of NE–SW and E–W lineaments in the Bay of Naples. Some of them are also located by seismic studies (Milia and Torrente, 1999; Bruno et al., 2003). In the Bay of Pozzuoli the figure shows the pattern of the southern rim of the Neapolitan Yellow Tuff caldera, whose inner border corresponds to the magnetic structure marked with A. We also notice the presence of NNE–SSW lineaments, while in the Magnaghi Canyon area we see that the NW shelf of the canyon is characterized by a gravimetric NE–SW lineament. Furthermore, a correspondence between gravimetric highs and the magnetic structures associated with the Ischia Bank (L) and with the F and M anomalies can be pointed out. No gravimetric highs are instead associated with the magnetic structures D, E, G, H and Q; this could be due to a low contrast in density between those structures and the surroundings. On the contrary the Gaia Bank (GB in Figure 8), while not magnetically detectable, is characterized by a clear gravimetric signature. Finally, two NW–SE gravimetric lineaments are shown in front of Naples and along the Ammontatura Channel.

In the Vesuvius offshore the map shows some gravimetric highs (Figure 8), which seem to be correlated to the NW–SE trend of magnetic structures marked with N, O and P. These structures should be connected to the submerged part of the Vesuvius structure and are genetically related to the eruptive activity of the volcano during recent and historical times (Arnò et al., 1987). Indeed, this lineament was already identified as a fault by seismic data (Milia and Torrente 1999). Seismic interpretation of high resolution profiles and multichannel seismic profiles (Marsella et al., 2002; Aiello et al., 2002) (Figure 9) acquired along the same navigation lines (see Figure 2) indicated mound-shaped, acoustically transparent bodies in this area. These are interpreted as buried vents possibly of historical age, as suggested by the warping of the Upper Pleistocene-Holocene (Aiello et al., 2002) thin sedimentary cover. Figure 9 shows that the strong magnetic anomalies marked with N correspond to two dome-shaped bodies with width of about 700 m each, while the anomaly O is placed over a dome about 1 km wide. This evidence allows us to tentatively interpret this lineament

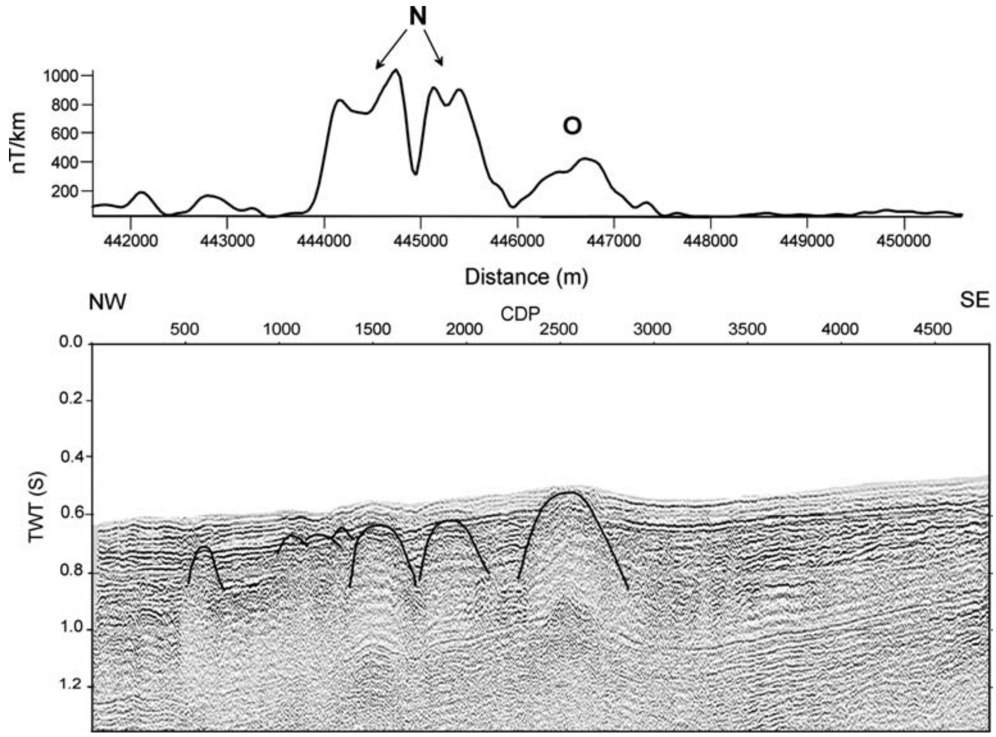

Figure 9. Comparison between a multichannel seismic profile (from Marsella et al., 2002) and the horizontal derivative of magnetic data over the N and O magnetic anomalies. The location of the analysed profile is shown in Figure 2.

as an active normal fault genetically related to the activity of Vesuvius.

The comparison of the magnetic profiles in the Vesuvius offshore and the seismic profiles analysed by Milia et al. (1998, 2003) showed the correspondence between magnetic anomalies and reflection-free structures interpreted as being due to near-surface intrusions (Milia et al., 1998) and to the terminal scarp of thick debris avalanches deposits (Milia et al., 2003).

Conclusions

Figure 10 shows the main gravimetric and magnetic structures of the area highlighted by our analysis, together with the lineaments located by seismic studies. This map demonstrates the presence in the bay of: (i) anti-Apenninic lineaments (NE–SW), not characterized by magnetic signatures, except in the Phlegrean area, where these lineaments are correlated to volcanic activity; (ii) apenninic lineaments (NW–SE), correlated to magnetic anomalies only in the Vesuvius offshore; and (iii) E–W lineaments, which are not characterized by magnetic signatures. The map also shows the lateral boundaries of the main volcanic structures and calderas of the area, whose different magnetic and gravimetric signatures are likely due to the different characteristics of the pyroclastic deposits forming those bodies. The detected structures can be interpreted as diffused local vents possibly activated along structural discontinuities. In particular, the presence of the observed magnetic structures along the Magnaghi Canyon and the seismic evidence (Bruno et al., 2003) of a main alignment of NE–SW striking faults and fractures connecting the Magnaghi Canyon with the Sebeto Fault (a NE–SW structural lineament running through the city of Naples, see Figure 1b) suggests that the Magnaghi Canyon is an active lineament where preferential magma upwelling may occur. This hypothesis is also confirmed by the seismic evidence of volcanic activity along this system (Bruno et al., 2003). The analysis of the NW–SE magnetic structures in the Vesuvian offshore and the comparison of our results with the

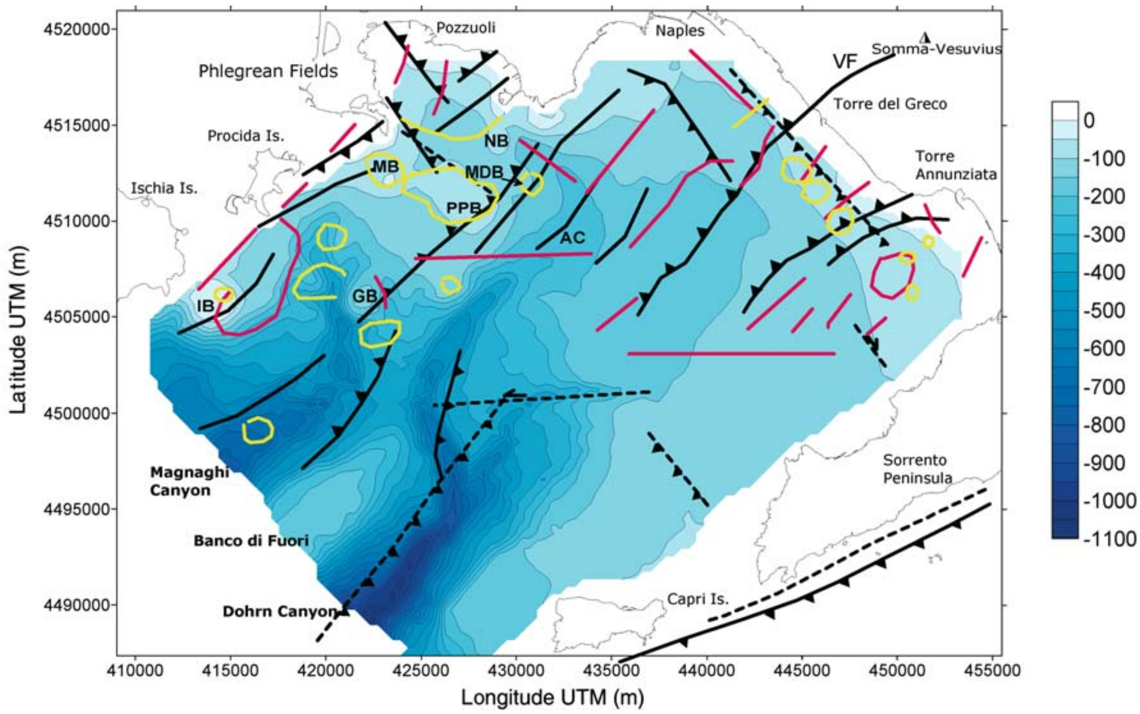

Figure 10. Map of the main magnetic (in yellow) and gravimetric (in red) structures of the bay and seismic lineaments (Milia and Torrente, 1999; Bruno et al., 2003) (in black) and bathymetry of the area.

gravimetric and seismic NW–SE lineament in the same area (Aiello et al., 2002) lets us see this structure as an active discontinuity genetically related to the activity of Vesuvius and characterized by magmatism.

The high complexity of the structural framework of the bay is due to the superimposition of caldera collapses in a region affected by extensional tectonics. As previously noted (see ‘‘Geological and volcanological from work’’ section), this tectonism occurred along NW–SE normal faults and secondarily along NE–SW faults interrupting often the continuity of the NW–SE basins. W–E strike-slip faults are also present.

The magnetic investigation of the bay, together with the analysis of gravimetric and seismic data, allowed all these different structures to be located showing some similarities between the studied area and the Ethiopian Rift. Similar to the Neapolitan district, the Ethiopian region is characterized by Quaternary normal faults and extensional fractures trending mainly NW–SE and secondarily NNE–SSW and by calderas and vents aligned along E–W trending faults (Acocella et al., 2003) which are an expression of silicic magmatism.

Our analysis of the Bay of Naples confirms the tectonic control of the Campanian volcanism. The alignment of the detected magnetic structures, interpreted as volcanic bodies, along NE–SW and NW–SE directions supports the hypothesis that the magma rises along normal faults cutting the carbonate platform of the Campanian Plain, causing diffused volcanic activity in the whole Neapolitan area, both onshore and offshore.

These results lead to the delineation of a general geo-volcanological and structural framework of the Bay of Naples and point out the presence of many interesting anomalies both in the Phlegrean and Vesuvian offshore. A more detailed study of some of these areas is object of current study.

Acknowledgements

The authors are grateful to P. Clift, J. Dyment and I. Giori. Their valuable and constructive suggestions were a great help in improving our paper.

References

Acocella, V., Korme, T., Salvini, F. and Funiciello, R., 2003, Elliptic calderas in the Ethiopian Rift: control of pre-existing structures, *J. Volc. Geother. Res.* **119**, 189–203.

AGIP, 1981, Carta Areomagnetica d'Italia (scala 1:500 000), Att. Min., Direz. Espl. Idrocarburi, S. Donato Milanese.

Aiello, G., Budillon, F., Cristofalo, G., de Alteriis, G., De Lauro, M., Ferraro, L., Marsella, E., Pelosi, N., Sacchi, M. and Tonielli, R., 2001, Marine geology and morphobathymetry in the Bay of Naples (South-eastern Tyrrhenian sea, Italy), in Faranda, F.M., Guglielmo, L. and Spezie, G. (eds.), *Mediterranean ecosystems: structures and processes,* pp. 1–8, Springer Verlag, Italy,

Aiello, G., Angelino, A., Bruno, P., Di Fiore, V., Fedi, M., Florio, G., Marsella, E., Paoletti, V., Pelosi, N., Rapolla, A., Ruggieri, S. and Siniscalchi A., 2002, Newly detected magnetic anomalies offshore the Somma-Vesuvius volcanic complex (Italy) and related seismic structures. Atti 21° Convegno Nazionale Gruppo Nazionale Geofisica della Terra Solida (GNGTS) – 2° Convegno Nazionale EAGE-SEG, Rome, November 19–21 2002, CNR, Italy.

Alessio M., Bella, F., Improta, S., Belluomini, G., Cortesi, C. and Turi, B., 1974, University of Rome Carbon – 14 Dates XII, *Radiocarbon* **16**, 358–367.

Arana, V., Camacho, A.G., Garcia, A., Montesinos, F.G., Blanco, I., Vieira, R. and Felpato, A., 2000, Internal structure of Tenerife (Canary Islands) based on gravity, aeromagnetic and volcanological data, *J. Volc. Geother. Res.* **103**, 43–64.

Armenti, P., Barberi, F., Bizouard, A., Clocchiatti, R., Innocenti, F., Metrich, N., Rosi, M. and Sbrana, A., 1983, The Phlegrean Fields: magma evolution within a shallow chamber, *J. Volc. Geother. Res.* **17**, 289–311.

Arno', V., Principe, C., Rosi, M., Santacroce, R. and Sheridan, M.F., 1987, Eruptive history, In: Santacroce, R. (ed.), *Somma-Vesuvius, Quaderni de la Ricerca Scientifica*, **114**, pp. 53–103, Progetto Finalizzato Geodinamica, CNR, Rome, Italy.

Barberi, F., Innocenti, F., Lirer, L., Munno, R., Pescatore, T. and Santacroce, R., 1978, The Campanian Ignimbrite: a major prehistoric eruption in the Neapolitain area (Italy), *Bull. Volc.* **41**, 10–33.

Barberi, F. and Leoni, L., 1980, Matamorphic carbonate ejecta from Vesuvius plinian eruptions: evidence of the occurrence of shallow magma chambers, *Bull. Volc.* **1**, 107–120.

Barberi, F., Cassano, E., La Torre, P. and Sbrana, A., 1991, Structural evolution of Campi Flegrei in light of volcanological and geophysical data. *J. Volc. Geother. Res.* **48**, 33–50.

Belkin, H.E. and De Vivo B.D., 1993, Fluids inclusions studies of ejected nodules from plinian eruptions of Mt. Somma-Vesuvius, *J. Volc. Geother. Res.* **58** (1/4), 89–100.

Berrino, G., Corrado, G. and Ricciardi, U., 1998, Sea gravity data in the Gulf of Naples: a contribution to delineating the structural pattern of the Vesuvian area, *J. Volc. Geother. Res.* **82**, 139–150.

Bruno, P.P., Cippitelli, G. and Rapolla, A., 1998, Seismic study of the mesozoic carbonate basement around Mt. Somma-Vesuvius volcanic complex (Italy). *J. Volc. Geother. Res.* **84**, 311–322.

Bruno, P.P., Rapolla, A. and Di, Fiore V., 2003, Structural settings of the Bay of Naples (Italy) by seismic reflection data: implications for Campanian volcanism, *Tectonophysics* **372**, 193–213.

Carrara, E., Iacobucci, F., Pinna, E. and Rapolla, A., 1974, Interpretation of gravity and magnetic anomalies near Naples, Italy, using computer techniques, *Bull. Volc.* **2**, 1–10.

Cassano, E. and La Torre, P., 1987, Geophysics. In: Santacroce, R. (ed.), *Somma-Vesuvius, Quaderni de la Ricerca Scientifica* **114**, pp. 175–196, Progetto Finalizzato Geodinamica, CNR, Rome, Italy.

Cassignol, C. and Gillot, P.Y., 1982, Range and effectiveness of unspiked potassium-argon dating: experimental ground work and application, In: Odin, G. S. (ed.), *Numerical dating in stratigraphy*, pp. 160, J. Wiley and Sons, New York.

Cella, F., Fedi, M., Florio, G., Grimaldi, M., Paoletti, V. and Rapolla, A., 2003, Deep and shallow structure of Somma-Vesuvius volcano from potential field data interpretation, Proceedings of the Workshop Vesuvius: Inside the Volcano, Ercolano, Italy, May 8–10, 2003, p. 11.

Di Girolamo, P., Nardi, G., Rolandi, G. and Stanzione, D., 1976, Occurrence of calc-alkaline two piroxene andesites from deep bore-holes in Phlaegrean Fields; Petrographic and petrochemical data, *Rend. Acc. Sc. Fis. Mat. Soc. Naz. Sc. Lett.* **43**, Arti in Napoli, Italy.

Di Girolamo, P., Ghiara, M.R., Lirer, L., Munno, R., Rolandi, G. and Stanzione, D., 1984, Vulcanologia e petrologia dei Campi Flegrei, *Boll. Soc. Geol. It.* **103**, 349–413.

Doglioni, C., 1991, A proposal for the kinematic modelling of W-dipping subsections-possible applications to the Tyrrhenian-Appennines system, *Terra Nova* **3**, 423–434.

Fedi, M. and Quarta, T., 1998, Wavelet analysis for the regional-residual and local separation of potential field anomalies, *Geophys. Prospect.* **46**, 507–525.

Ferraccioli, F., Bozzo, E. and Damaske, D., 2002, Aeromagnetic signatures over western Marie Byrd Land provide insight into magmatic arc basement, mafic magmatism and structure of the Eastern Ross Sea Rift flank, *Tectonophysics* **347**, 139–165.

Finetti, I. and Morelli, C., 1974, Esplorazione sismica a riflessione nei golfi di Napoli e Pozzuoli, *Boll. Geof. Teor. Appl.* **16**, 175–222.

Finn, C. and Williams, D.L., 1987, An aeromagnetic study of Mount St. Helens, *J. Geophys. Res.* **92**, 10194–10206.

Florio, G., Fedi, M., Cella, F. and Rapolla, A., 1999, The Campanian Plain and Phlegrean Fields: structural setting from potential field data, *J. Volc. Geother. Res.* **91**, 361–379.

Fusi, N., Mirabile, L., Camerlenghi, A. and Ranieri, G., 1991, Marine geophysical survey of the Gulf of Naples (Italy): relationship between subarine volcanic activity and sedimentation, *Mem. Soc. Geol. It.* **47**, 95–114.

Grauch, V.J.S. and Cordell, L., 1987, Limitations of determining density or magnetic boundaries from the horizontal gradient of gravity or pseudo-gravity data, *Geophysics* **52**, 118–121.

Hildenbrand, T.G., Rosenbaum, J.G. and Kauahikaua, J.P., 1993, Aeromagnetic study of the island of Hawaii, *J. Geophys. Res.* **98**, 4099–4119.

Lénat, J.F. and Aubert, M., 1982, Structure of Piton de la Fournaise volcano (La Reunion Island, Indian Ocean) from magnetic investigations. An illustration of the analysis of magnetic data in a volcanic area, *J. Volc. Geother. Res.* **12**, 361–392.

Marsella, E., Aiello, G., Pelosi, N., Angelino, A., Budillon, F., Giordano, F., Rapolla, A., Di Fiore, V., Siniscalchi, A., d'Isanto, C. and Ruggeri, S., 2001, Cruise report GMS00_5: oceanographic cruise N/O Urania – 26 Oct./15 Nov. 2000.

Marsella, E., Aiello, G., Angelino, A., Bruno, P.P., Di Fiore, V., Giordano, F., Pelosi, N., Siniscalchi, A., d'Isanto, C. and Ruggieri, S., 2002, Shallow geological structures and magnetic anomalies in the Gulf of Naples: an integrated analysis of seismic and magnetometric profiles, *Boll. Geof. Teor. Appl.* **42** (1–2), 292–297.

Mauring, E., Beard, L.P., Kihle, O. and Smethurst, A., 2002, A comparison of aeromagnetic levelling techniques with an introduction to median levelling, *Geophys. Prospect.* **50**, 43–45.

Milia, A., 1999, The geomorphology of Naples Bay continental shelf (Italy), *Geogr. Fis. Dinam. Quat.* **22**, 73–78.

Milia, A., Mirabile, L., Torrente, M.M. and Dvorak, J.J., 1998, Volcanism offshore of Vesuvius Volcano in Naples Bay, *Bull. Volc.* **59**, 403–413.

Milia, A. and Torrente, M.M., 1999, Tectonics and stratigraphic architecture of a pery-Tyrrenian half-graben (Bay of Naples, Italy), *Tectonophysics* **315**, 301–318.

Milia, A., Torrente, M.M. and Zuppetta, A., 2003, Offshore debris avalanches at Somma-Vesuvius volcano (Italy): implications for hazards evaluation, *J. Geol. Soc.* **160**, 1–10.

Nabighian, M., 1984, Toward a three-dimensional automatic interpretation of potential field data via generalized Hilbert transforms: Fundamental relations, *Geophysics* **49**, 780–786.

Nakatsuka, T., 1994, Aeromagnetic anomalies over the area of Unzendake volcano, *J. Geomag. Geoelectr.* **46**, 529–540.

Orsi, G., De Vita, S. and di Vito, M., 1996, The restless resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration, *J. Volc. Geother. Res.* **74**, 179–214.

Orsi, G., De Vita, S., Di Vito, M., Nave, R. and Heiken, G., 2003, Facing volcanoes and related hazards in the Neapolitain area, In: Heiken, G., Fakundiny, R, Sutter, J. (eds.), *Earth Sciences in Cities* **56**, pp. 121–170, American Geophysical Union, Washington.

Orsi, G., De Vita, S., Di Vito, M. and Isaia, R., 2004, The Campi Flegrei Nested Caldera (Italy): a Restless, Resurgent Structure in a Densely Populated area, In: Balmuth, M. (ed.), *The Cultural Response to the Volcanic Landscape,* Archeological Institute of America, in press.

Paoletti, V., Fedi, M., Florio, G., Supper, R. and Rapolla, A., 2004, The new integrated aeromagnetic map of the Phlegrean Fields Volcano and surrounding areas, *Ann. Geofis.*, in press.

Rapolla, A., Cella, F., Fedi, M. and Florio, G., 2002, Improved techniques in data analysis and interpretation of potential fields: examples of application in volcanic and seismically active areas, *Ann. Geofis.* **45**, 733–751.

Rolandi, G., Bellucci F., Heizler M.T., Belkin H.E. and De Vivo B., 2004, Tectonic controls on the genesis of ignimbrites from Campanian Volcanic Zone, southern Italy, *Mineral. Petrol.*, in press.

Rybakov, M., Goldshmidt, V., Fleischer, L. and Ben-Gai, Y., 2000, 3-D gravity and magnetic interpretation for the Haifa Bay area Israel, *J. Appl. Geoph.* **44**, 353–367.

Scandone, R., Bellucci, F., Lirer, L. and Rolandi, G., 1991, The structure of the Campanian Plain and the activity of the Neapolitan volcanoes (Italy), *J. Volc. Geother. Res.* **48**, 1–31.

Siniscalchi, A., Angelino, A., Ruggieri, S., Aiello, G., Marsella, E. and Sacchi, M., 2002, High resolution magnetic anomaly map of the Bay of Naples (Southern Tyrrhenian Sea, Italy), *Boll. Geof. Teor. Appl.* **42**, 99–104.