The integration of magnetic data in the Neapolitan volcanic district

V. Paoletti  
M. Secomandi  
M. Fedi  
G. Florio  
A. Rapolla  
Dipartimento di Scienze della Terra, Università di Napoli Federico II, Largo S. Marcellino 10, 80138 Naples, Italy

ABSTRACT

In this paper we present an example of the integration of airborne and marine magnetic data sets measured recently in the Neapolitan area, southern Italy. The integration involved detailed data measured recently in the Phlegrean Fields, in the Somma-Vesuvius area and in the Bay of Naples, that produced a high-resolution magnetic map of the whole active volcanic district. The data sets partially overlapped and characterized varying flight height and line spacing. Integration was therefore performed through several procedures including continuation between general surfaces. The integration produced a new, detailed, draped magnetic data set of the Neapolitan region characterized by a terrain clearance of 200 m, giving a meaningful overall view of the volcanic area. The study of the main magnetic features of the area was carried out by computing the horizontal gradient of the pole-reduced draped data. The analysis of the obtained map showed the presence of lineaments of preferential magma upwelling and buried volcanic structures and allowed the delineation of a geovolcanological and structural framework of the whole Neapolitan volcanic district.

Keywords: aeromagnetic survey, marine magnetic survey, data sets integration, magnetic data analysis.

INTRODUCTION

Magnetic anomaly maps provide insights for a better understanding of the geologic, tectonic, and geothermal characteristics of an area. This is particularly true for volcanic zones, where recent volcanic activity and volcaniclastic deposits often cover important volcanic structures. In those cases magnetic data can locate buried structures such as lineaments, faults, and volcanic and intrusive structures. As noted by Finn (1999), composite data sets allow a more complete view of patterns and trends that individual data sets may not provide. The author gives an overview of the procedures for merging magnetic surveys into a regional digital compilation and shows, through the illustration of the case of Washington State, the usefulness of these procedures for providing synoptic views of regional features. Chiappini et al. (1999, 2002) merged magnetic data acquired in the Antarctic region over the areas of the Ross Sea and the Transantarctic Mountains in the framework of the Antarctic Digital Magnetic Anomaly Project. They produced an integrated grid that resulted in a fundamental tool for regional interpretation of the tectonic and geologic characteristics of this area of Antarctica. Damske (1999) gives another example of the compilation of an integrated aeromagnetic map from data sets flown over areas with very different topographies in the Antarctic region (Central Queen Maud Land). Golyshky et al. (2002) merged airborne and marine magnetic observations in East Antarctica and adjacent seas of the Indian Ocean and compiled an integrated magnetic anomaly map that provided new insight on the tectonic features of the East Antarctic.

In this paper we present and analyze a new, detailed magnetic map of the whole Neapolitan active volcanic district, southern Italy (Fig. 1). This was obtained by merging recently acquired airborne, land, and marine magnetic measurements.

In this study we aim to gain insights into the characteristics of the Neapolitan volcanic area from an overall view of its magnetic field. The analysis of the newly merged magnetic data set should enable the characterization of the main buried volcanic structures such as vents and calderas, providing a better understanding of the connection between tectonics and volcanism in the Neapolitan volcanic district.

THE NEapolitan VOLCANIC DISTRICT: GEOLOGICAL FRAMEWORK AND GEOphysical STUDIES

The Neapolitan volcanic district is located on the Tyrrhenian margin of the Campanian Plain (Fig. 1A). This plain was formed during the Plio-Pleistocene as the result of the complex geodynamic events connected with the opening of the Tyrrhenian Sea and the anticlockwise rotation of the Italian Peninsula (Scandone et al., 1991). A tensile stress regime thus affected the Tyrrhenian margin, causing N-S and NNW-SSE normal faults, and then NW-SE and NE-SW normal faults and W-E strike-slip faults (e.g., Doglioni, 1991). Along the Campanian border, the Quaternary basin of the Bay of Naples was produced by NE-SW–trending normal faults. Intense volcanism has characterized this area since the late Miocene. This volcanic activity seems to be in close spatial relation with the NE-SW faults (e.g., Bruno et al., 2003). The present Campanian volcanism started 1–2 Ma (Capaldi et al., 1985). Currently the active areas are the island of Ischia (last eruption in 1302), the Phlegrean Fields (last eruption in 1538), and the Somma-Vesuvius (last eruption in 1944). The products of the Campanian volcanism belong to two cycles: an older cycle (Miocene–Pleistocene), evidences of which were only found in the Parette 2 Well (see Fig. 2), and a second cycle related to the previously mentioned Plio-Pleistocene extensional tectonics.

For permission to copy, contact editing@geosociety.org  
© 2005 Geological Society of America  
85

Geosphere; October 2005; v. 1; no. 2; p. 85–96; doi: 10.1130/GES00003.1; 7 figures.
The so-called Roman Comagmatic Province, which includes the Vesuvian and the Phlegranean volcanic districts, belongs to this second cycle (Fig. 1B).

The main characteristics of the Bouguer anomaly map of the Campanian Plain (Florio et al., 1999) are intense maxima corresponding to carbonatic reliefs bordering the plain and a wide minimum area broken up by Vesuvius and Parete highs. The horizontal gradient of these data shows some maxima aligned in three E-W lineaments, two of which border the Acerra depression to the north and the south, and the third is South of Vesuvius. The Acerra depression is closed by two other NE-SW alignments of maxima that seem to cut the Vesuvius and Phlegranean Fields volcanic area (Fig. 2).

The Vesuvian Area

Somma-Vesuvius is a stratovolcano characterized by products of both explosive and effusive eruptions. The complex is formed by an older volcanic center (Mount Somma), which underwent a calderic collapse, and a more recent one, Mount Vesuvius. It is located in an area where a carbonate basement extends to depths of a few thousand meters below sea level (mbsl) (Carrara et al., 1973; Bruno et al., 1998). The Trecase 1 well, drilled inside the Vesuvius volcanic area, detected the sedimentary basement at ~1700 mbsl (Bernasconi et al., 1981). Rock magnetism measurements from Somma-Vesuvius and the Trecase 1 well (Cassano and La Torre, 1987) showed magnetization values ranging from 6.8 A/m (lavas from Vesuvius) to 0.5 A/m (tuffs), and an intense remanent magnetization, with a Koepersberger ratio of ~8.6.

The presence of a shallow magma chamber (between 4 and 10 km bsl) was assumed from a study of fluid inclusions of ejected nodules (Belkin and De Vivo, 1993). However, seismic studies (Zollo et al., 1996; De Natale et al., 1998) seem to exclude the presence of a magmatic melt above 4–5 km bsl in the Vesuvius area. Gravity studies (Cella et al., 2003) detected a deeper intracrustal low density source that was interpreted as being 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. (2003) on the basis of geochemical, stratigraphic, and structural studies.

A study of the distribution of the magnetizations in the Vesuvian area by detailed airborne data is described in Paoletti et al. (2004). A boundary analysis of the data clearly showed the southern rim of the caldera of Mount Somma. In the area surrounding the Somma-Vesuvius edifice, the authors detected the magnetic anomaly pattern of the lateral boundaries of some buried small volcanic structures and showed some magnetic trends possibly consistent with trends detected by other geophysical studies (Fedi et al., 2005b; Bruno et al., 1998).

The Bay of Naples

In the Bay of Naples, a morphologic structure formed by a continental shelf, a continental slope, and a basin can be identified (Milia, 1999; Aiello et al., 2001). In the northern area of the bay, the Phlegranean Fields offshore, the shelf is irregular and characterized by the presence of monogenic volcanoes, small calderas, tuff cones, and lava extrusion (Milia, 1999). The bay is dominated by two submarine canyons: the Magnaghi and the Dohrn Canyons (Fig. 1B). The Magnaghi Canyon is ~15 km long, has a trilobate head, and has...
INTEGRATION OF MAGNETIC DATA

Figure 2. Geological sketch map of the Campanian Plain (Bonardi et al., 1988). Solid black lines indicate the main faults singled out by seismic studies (Bruno et al., 1998, 2003; Milia and Torrente, 1999), barbs are on the downthrown side. Dashed lines show fault location extrapolated from seismic data. Blue lines show the main gravimetric and magnetic lineaments identified by Florio et al., 1999. Yellow lines indicate the faults in Ischia Island (quoted in Nunziata and Rapolla, 1987). MSF—Magnaghi-Sebeto fault; VF—Vesuvius fault; 41 PL—41st-N-parallel magnetic lineament; P2—Parete 2 well; TC1—Trecase 1 well.
first a N-S, then a NE-SW trend. The Dohrn Canyon, with a preferential NE-SW trend, is ~25 km long and formed by two branches, which merge into a main branch northwest of Capri Island. 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 the Capri and Ischia Islands, with a minimum depth of 130 m (Milia, 1999; Aiello et al., 2001). Seismic reflection data from the Bay of Naples (Finetti and Morelli, 1974), recently reprocessed by Bruno et al. (2003), show a structural pattern of normal faults cutting Pleistocene sediments with a prevailing NE-SW strike. This trend is named the Magnaghi-Sebeto line (see MSF in Fig. 2) (Bruno et al., 2003) and divides the Bay of Naples into two areas: a western area, characterized by several volcanic banks, and an eastern one, characterized by a NE-dipping monoclinal structure made of sedimentary rocks. In the Vesuvian area, we recognized a NE-SW normal fault that seems to continue onshore (Bruno et al., 1998; Judenherc and Zollo, 2004). This is known as the Vesuvian fault (VF in Fig. 2) and was also located by a boundary analysis of the Bouguer anomaly field (Florio et al., 1999), which highlighted a NE-SW-oriented fault running both onshore and offshore.

Secomandi et al. (2005) performed a study of the magnetic gravity data of the Bay of Naples and characterized some of the most meaningful marine anomalies of the area. The study demonstrated that while the Magnaghi Canyon is correlated to gravimetric highs and magnetic structures, and can therefore be interpreted as a lineament of magma uprisings, most of Dohrn Canyon is not characterized by volcanic activity and does not correlate to any gravimetric or magnetic structures. Finally, the analysis showed the presence in the Vesuvian area of some intense circular anomalies, aligned in the NW-SE direction possibly connected to buried vents. Those structures were also identified by seismic data (Aiello et al., 2002).

The Phlegrean Fields

The volcanic district of the Phlegrean Fields (see Figs. 1B and 2) is located west of the town of Naples and is characterized by a number of small volcanoes. The oldest outcropping strata of the area are pyroclastics and lava domes from 50 ka (Cassignol and Giliot, 1982), while the main products are pyroclastics with a variable composition from trachybasalts to phonolitic alkali-trachytes (e.g., Rosi and Sbrana, 1987). Some lava flows and domes are present, mainly connected to the early stages of activity. The apex of the activity was reached ~37 ka (dated by Deino et al., 1994), with the eruption of the Campanian Ignimbrite. The eruption of the Neapolitan Yellow Tuff, which occurred ~12 ka, is the second in order of importance because of its lower volume. In the last 12,000 yr the Phlegrean Fields have been subsiding, except for local uplifts localized inside the caldera.

The Phlegrean Fields are also an area of particular geothermal interest. Boreholes drilled in 1987 by the Agenzia Generale Italiana Petroli (AGIP) and Ente Nazionale Elettrica show high temperature gradients in all of the Phlegrean area. The 200 °C isotherm is at a depth of 500 m in the Baia area, then deepens, reaching 1000 m southeast of the Astroni Volcano. This strong thermal anomaly probably caused thermal mineral alteration in the rocks (Rapolla et al., 1989).

The analysis of well logs (Cassano and La Torre, 1987) shows a stratigraphic difference between the internal and external part of the Phlegrean Fields. In the central area, the successors are poorer in lavas, and the thermal alteration of rocks is deeper than in the external areas. This analysis and another stratigraphic, volcanological, and geophysical study pointed out the existence of collapsed structures, interpreted as calderas, which formed as a consequence of the two Phlegrean major eruptions. The origins and limits of these structures are an object of debate. According to some authors (Rosi and Sbrana, 1987; Fish-er et al., 1993), a caldera was produced by the Campanian Ignimbrite eruption, while according to other authors (Scandone et al., 1991; De Vivo et al., 2001), the Ignimbrite erupted in other areas and the caldera collapse was due to the Neapolitan Yellow Tuff eruption. Recently, Orsi et al. (1996, 1999) proposed a new scheme including a complex structure formed by two nested calderas. Judenherc and Zollo (2004), however, suggested a single caldera rim common to both eruptions.

The gravity map of the Phlegrean area has its main features in a circular gravity low in the Pozzuoli Bay and a gravity high in the northern Phlegrean Fields, near Parete (Cas-sano and La Torre, 1987). In regard to the area of the Pozzuoli Bay, a boundary analysis of both gravity and aeromagnetic data on land and coastal areas (Florio et al., 1999) showed a curved structure, which was interpreted as the border of the Phlegrean Field Caldera (see Fig. 2). These borders are less clear in the magnetic map than in the gravity map. In particular, the limits of the caldera correspond to a ring of magnetic minima, very likely due to the presence of hydrothermally altered and demagnetized rocks at the caldera flanks. The southern rim of the caldera was clearly identified by Paoletti et al. (2004) on the basis of a boundary analysis on an integrated high-resolution aeromagnetic data set.

The gravity high near Parete located in the northern sector of the Phlegrean Fields by Cassano and La Torre (1987) was interpreted as due to a volcanic structure (Barbieri et al., 1976) or as a buried carbonate horizon with magnetic intrusions along its bordering faults. This latter hypothesis was supported by the local magnetic signature appearing on a land based magnetic profile (Carrara et al., 1973). The study carried out by Paoletti et al. (2004) identified a number of volcanic structures that seem to be aligned along an E-W trend, showing the presence of diffused volcanic activity all over the Campanian Plain.

Bruno et al. (2000) performed a seismic study of the northern sector of the Phlegrean Fields and showed that the so-called 41st-parallel magnetic lineament is characterized by ESE-WNW and E-W strike-slip faults whose activity developed during the Pliocene–early Pleistocene. The authors interpreted the 41st-parallel line as a deep-seated transfer fault system formed as a consequence of the different rates of opening of the Tyrrenian Sea in the frame of the NW-SE extension of the Appennines belt.

Ischia Island

Ischia Island is the oldest volcanic complex in the Neapolitan area. It is entirely composed of volcanic rocks with a chemical composition of lavas ranging from trachybasalts to alkali-trachytes and phonolite (Capaldi et al., 1985). Its geological structure was first described by Rittmann (1948), who interpreted Mount Epomeo (the highest Ischia mountain) as a volcanic-tectonic horst uplifted because of magma intrusion in a shallow magmatic chamber. Orsi et al. (1991) showed the existence of a shallow magmatic chamber and presented a dynamic model of the Mount Epomeo uplift, which should be the highest part of a block bounded by subvertical faults inclined toward inner.

From the last eruption in 1301, the only volcanic activity in the island is fumarolic and hydrothermal. High temperatures of 106 °C have been measured at a depth of 15 m (Barberi et al., 1979).

A gravity and magnetic study of Ischia Island (Nunziata and Rapolla, 1987) defines shallow structures of pyroclastic nature with local domes and lava flows of high density and susceptibility. The Ischia basement was
interpreted as a horst elongated in the E-W direction.

SURVEY LAYOUTS AND DATA PREPROCESSING

Logistical Characteristics of the Surveys

The integrated map of the Neapolitan region was obtained by merging five different magnetic data sets. Four of them are from aeromagnetic surveys and one is from a marine survey (Fig. 3). They have the following characteristics:

Data set A. The helicopter-borne survey in the Vesuvian area (A in Fig. 3) was carried out in 1999 (Supper et al., 2001; Paoletti et al., 2005). The flight lines, with a N-S azimuth, were spaced ~600 m apart. The cross-track tie lines were spaced ~2 km apart. The sample spacing along each flight line was ~4 m.

The survey was flown at a constant terrain clearance of ~200 m. The instrumentation used for the survey was supplied by the Geological Survey of Austria and consisted of a ground and a flight section. The ground section contained two magnetometers used to monitor the external field activity during the flights and a global positioning system (GPS)–reference station used for the differential correction of satellite data. The flight section consisted of: (1) a cesium magnetometer having a precision of 0.01 nT, which was contained in a “bird” flown 30 m below the helicopter, (2) a GPS sensor for the horizontal positioning of the helicopter, having a precision of ±1 m after the differential correction, (3) a laser-altimeter for the vertical positioning of the helicopter, and (4) a computer for data acquisition.

Data set B. The magnetic data in the Bay
of Naples (B in Fig. 3) were acquired during a Consiglio Nazionale delle Ricerche (CNR)–Istituto per l’Ambiente Marino Costiero (IAMC) oceanographic survey performed in 2000 onboard the R/V Urania (Marsella et al., 2002; Secomandi et al., 2005). The survey consisted of 32 survey lines, which were 400 m apart and trended northwest-southeast, and 20 tie lines, which trended northeast-southwest and were 800 m apart. The sampling time was 3 seconds.

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 to fill the data gap in the southwest area of the bay. Siniscalchi et al. (2002) describe other data acquisition details.

Data set C. The aeromagnetic data set in the Pozzuoli Bay (C in Fig. 3) was measured by AGIP in 1985 along N-S flight lines ~250 m apart and at an altitude of 700 m above sea level (masl). More details about this survey are quoted in Ente Nazionale Idrocarburi (ENI) (1985).

Data set D. This helicopter-borne survey in the northern Phlegraean area (D in Fig. 3) was carried out in 1999 and 2001 at ~70 m above ground level (Paoletti et al., 2004). The flight lines (having a W-E azimuth) were spaced 400 m apart, while the tie-lines (having a N-S azimuth) were ~2.5 km apart. The instrumentation used for this survey was also supplied by the Geological Survey of Austria and consisted of the same sections used for the acquisition of data set A.

Data set E. This aeromagnetic data set in the area north of Vesuvius (E in Fig. 3) was measured by AGIP in 1981. The survey was performed at a constant altitude of 1460 masl with N-S survey lines 2 km apart. More details about this survey are quoted in AGIP (1981).

Data set F. The data set of Ischia Island (F in Fig. 3) was acquired during a land survey by the Department of Geophysics and Volcanology of the University of Naples Federico II. The total magnetic field intensity was measured in 725 randomly located stations. For more details about the survey see Nunziata and Rapolla (1987).

Data Preprocessing

The preprocessing relative to the aeromagnetic data included the following steps: (1) removal of spikes and gaps in the data; (2) flight path check and repositioning, which consisted in the removal of wrong coordinates and double records, differential correction of the GPS data, and check of the flight altitude; (3) Earth’s magnetic field diurnal variation corrections, which were performed using the local base station and, in some cases, the data from the magnetic observatory of L’Aquila, Italy; (4) removal of the International Geomagnetic Reference Field (IGRF), performed using the Italian Geomagnetic Reference Field updated for 2000 (De Santis et al., 2003); (5) statistical leveling, consisting in a minimization of the differences between the field values measured at the crossing points between flight lines and tie lines; and (6) decorrelation, a directional filtering to allow the removal of the directional anomalies still present along the flight lines. The Ischia Island land magnetic data were preprocessed following the steps 1, 3, and 4.

For the marine survey, the preprocessing phase included the same first four steps of the aeromagnetic data treatment, while the leveling procedure was performed in a different way. Aeromagnetic surveys are generally programmed with only a few tie lines and, after the leveling 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 kinds of surveys (e.g., seismic) that need many lines in both directions. This is the case of the marine survey 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 type of lines by first performing a reciprocal leveling and then by charting the data in order to consider all of the lines measured.

INTEGRATION OF THE DIFFERENT DATA SETS

The integrated map was obtained by merging the high-resolution data sets relative to the new surveys (in the Somma-Vesuvius area, in the Bay of Naples, and in the northern Phlegraean Fields) with previous data sets (in Ischia Island, in the Pozzuoli Bay, and north of the Vesuvian area). The data sets were partially overlapping and characterized by different details and altitudes. Furthermore, while data sets B, C, D, and E were measured at constant altitudes, data set A was characterized by a draped acquisition and data set F was relative to a land survey and therefore was characterized by different altitudes. The data sets integration was performed through several procedures including continuation between general surfaces. More specifically, the integration of the different data sets was made through the following steps:

- Downward and upward continuations of data sets B, C, D, and E from flat surfaces, corresponding to the flight altitudes or to the sea surface, to an arbitrary surface parallel to the topography and/or to the bathymetry of the area. For data set F, an upward continuation between arbitrary surfaces was performed. This led to draped data sets all placed at a distance of 200 m from the ground. The continuation between general surfaces was performed by an algorithm based on the Continuous Wavelet Transform (CWT) (Ridsmill-Smith, 2000).
- Determination of the mismatch between data values of the data sets across the boundary of the different surveyed areas; this mismatch can be due to imprecision of the field around the boundaries, to inaccuracy in the compilation of data for contouring, and to removal of inaccurate IGRF around the edges of an area (Bhattacharyya et al., 1979).
- Removal of the mismatch between the two data sets; this mismatch is a function of the spatial coordinates and may be represented by a quadratic surface matching the fields on both sides of the boundary (Bhattacharyya et al., 1979). In the specific case presented here, we used a polynomial surface of zero order.
- Merging of the separate grids into one grid performed using Kriging and an interval consistent with all the different data sets (200 m).

THE NEW INTEGRATED DRAPEd MAGNETIC MAP OF THE NEAPOLITAN VOLCANIC REGION

The integration of the different data sets and their continuation between arbitrary surfaces led to a new high-resolution draped magnetic map of the whole volcanic Neapolitan region. The obtained magnetic map was then pole reduced (I = 60°, D = 0°) and overlaid to the topography and bathymetry of the area (Fig. 4A). Please note that the map is draped, i.e., relative to different heights above and below sea level, with a constant clearance of 200 m. This should minimize the effect of magnetized terrain on the data (Bhattacharyya and Chan, 1977). The NE section of the map lacks detail because it has been obtained from a regional data set (data set E in Fig. 3). In Figure 4B the data are overlaid by the outcropping volcanic rocks of the area in order to better evalu-
Figure 4. Map of the reduced-to-the-pole (rtp) integrated magnetic data set of the whole volcanic Neapolitan region. A: The draped data (clearance 200 m) are overlain on the topography and bathymetry of the area. See text for definitions. B: The rtp map overlaid by a sketch map of the outcropping volcanic rocks (Bonardi et al., 1988) and by the main mapped faults (Bruno et al., 1998, 2003; Milia and Torrente, 1999; Nunziata and Rapolla, 1987) of the area. 41 PL—41st-N-magnetic parallel lineament; MSF—Magnaghi-Sebeto fault; VF—Vesuvius fault.

The analysis of Figure 4A allows us to note that all of the main anomalies of the area, except the anomalies marked with F in Figure 4A, seem connected to a positive contrast of magnetization. The most remarkable feature of the map is the anomaly related to the Somma-Vesuvius complex (anomaly D in Fig. 4A). This anomaly, whose amplitude is ~3100 nT, aligns in the direction of the inducing field and is characterized by a roughly elliptical shape elongated toward the southeast. A three-dimensional magnetic model of the Somma-Vesuvius edifice (Paoletti, 2002; Fedi et al., 2002) reveals the presence of a heterogeneous magnetized edifice, whose highest magnetizations (of 6–7 A/m) are in the emergent part the volcano, below the Mount Vesuvius cone. This evidence seems to indicate the presence of igneous rocks plugging the volcanic conduit. Magnetized rocks appear to extend down to a depth of ~2 km bsl, while magnetization values below this level are negligible.

The area surrounding the edifice is characterized by several high-frequency anomalies (E, F, and G in Fig. 4A). A study of the magnetic field in the Vesuvian area (Paoletti et al., 2004) showed that anomalies E and F, whose amplitude is ~400 nT, may be due to the superimposition of antropic and geological sources. More specifically, they seem partly connected to the presence of railway lines and partly related to buried geological sources, which were already identified by gravity methods (Florio et al., 1999; Fedi et al., 2005b). The correlation between the anomalies and the outcropping volcanics of the area (Fig. 4B) shows that these anomalies are in correspondence with pyroclastic fall units and/or alluvial units, and this let us hypothesize that their sources are buried. We also noticed that anomalies F and G do not have any topographic evidence and coincide fairly well with mapped faults. As regards the reversed anomalies of F, a possible pre-ignimbritic origin of their sources was hypothesized by Paoletti et al. (2005). The authors interpreted those anomalies as very likely connected to reversely magnetized rocks originated from the activity of small local vents during one of the polarity excursions recorded in the Brunhes epoch. The analysis of the power spectra of the F anomalies resulted in a depth-to-the-top-of-the-sources measurement of ~210–230 mbsl (Paoletti, 2002).

With regard to the anomalies in the Vesuvius offshore (G in Fig. 4A), they have an amplitude of ~830 nT, and Secomandi et al. (2005) showed that they correspond to buried dome-shaped bodies singled out by seismic studies (Aiello et al., 2002). These are interpreted as buried vents, possibly of historical age, as suggested by the warping of the thin late Pleistocene–Holocene sedimentary cover (Aiello et al., 2002). The analysis of Figure...
Figure 5. Three-dimensional inversion of the two main anomalies measured in the northern Phlegrean Fields, marked with A and B in Figure 4A. A: Close-up of the reduced-to-the-pole anomalies in the Parete area. B: Magnetization model obtained from inversion. See text for details.

4B shows that these sources align along a fault mapped by Milia and Torrente (1999).

The magnetic field in the Bay of Naples is characterized by the presence of anomalies both in the NW and NE sectors of the bay, while the central area seems magnetically quiet. The anomalies in the NW area of the bay correspond to several volcanic edifices. More specifically, the H anomalies have an amplitude of ~600 nT and are related to volcanic banks, which have an age of 37–14 ka (Orsi et al., 1996). The analysis of Figure 4B shows that no mapped fault cut these banks.

The I, L, R, and Q anomalies correspond to volcanic edifices, and except for L, which is buried, are located along the Magnaghi-Sebeto fault.

Anomalies I, L (with an amplitude of ~150), O, and P (with an amplitude of ~250) align in the Magnaghi Canyon. In particular, L and P are located on the canyon axis, while I and O are on the canyon border.

A three-dimensional inversion of anomalies I and P (Secomandi et al., 2005) shows the presence of two body sources whose depth to the bottom ranges from 0.5 to 1.5 km bsf and whose magnetization of 0.8 A/m is consistent with the magnetization of the tuffs of the area (Cassano and La Torre, 1987). Those sources were interpreted by the authors as being related to buried vents, which were possibly activated along the Magnaghi Canyon.

The area of Dohrn Canyon is not characterized by any magnetic anomaly. The lack of anomaly in the southeastern sector of the bay is due to the presence of sedimentary units (Secomandi et al., 2005).

The data in the Phlegrean sector of the map are characterized by the presence of large anomalies both in the southern and northern Phlegrean Fields. The southern sector is characterized by a curved belt of anomalies (C in Fig. 4A), connected to the Phlegrean Field Caldera, that follow the Astroni and Torregaveta relief inland and do not correspond to any bathymetric high in the Pozzuoli Bay. The Astroni and Torregaveta anomalies have amplitudes ~250 nT and ~300 nT, respectively, and are placed above pyroclastic flows (Fig. 4B). The lack of anomalies in the area of Baia could be due to thermal alteration related to high temperatures measured in this sector of the bay (Rapolla et al., 1989).

The offshore anomalies partially correspond to known faults and have an amplitude of ~200 nT.

The field measured in the Ischia area is...
INTEGRATION OF MAGNETIC DATA

Figure 6. A: Map of horizontal derivative of the reduced-to-the-pole draped data set of the Neapolitan region. See text for definitions. B: Same map as in A overlain with the main lineaments from seismic studies (in red) (Bruno et al., 1998, 2003; Milia and Torrente, 1999), the outline of Phlegrean caldera from gravimetric horizontal-gradient-maxima (in white) (Florio et al., 1999), and the Ischia faults (Nunziata and Rapolla, 1987). The axes of the two canyons of the Bay of Naples are in yellow. 41 PL—41st-N-magnetic parallel lineament; MSF—Magnaghi-Sebeto fault; VF—Vesuvius fault.

characterized by the presence of four main anomalies (N in Fig. 4A). They have amplitudes of ~300 nT and are located above alkali-trachytic domes and lava flows with a magnetization of ~2.3 A/m (Nunziata and Rapolla, 1987). While the anomaly in the southeastern area is crossed by a NE-SW fault, the one in the southwestern edge of the island is bounded by a NW-SE fault (Fig. 4B).

In the northern sector of the Phlegrean Fields, we noticed two anomalies in the areas of Patria Lake and Parete (A and B in Figure 4A, with amplitudes ~300 nT and 250 nT, respectively) and two small anomalies in the Volturno River Plain (S and T in Figure 4A, with amplitudes of ~50–100 nT). They are all buried and placed in correspondence with pyroclastic-fall and alluvial units (see Fig. 4B).

In order to study the geometric and magnetization characteristics of the two main volcanic sources of the northern Phlegrean sector, we carried out a three-dimensional inversion of the magnetic anomalies measured in the Patria Lake and Parete areas, which are characterized by a remarkable thickness of volcanic rocks. About 1.5 km of basaltic and andesitic lavas, starting from a depth of ~300 m, were found in the Parete 2 well (P2 in Fig. 2) (Baldi et al., 1976; Barbieri et al., 1976). More specifically, the lavas with a prevailing basaltic composition start from a depth of ~1200 m. Figure 5A shows a close-up of the magnetic anomalies considered for the inversion. 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 three-dimensional grid of prisms (see, e.g., Fedi et al., 2005a). The discretization used for the inversion is composed of 13 3 13 prisms in the x, y, and z directions, respectively, while the dimension of the prisms is 1400 m in the x and y direction and 250 m in the z direction.

The solution (Fig. 5B) shows the presence of two body sources, a bigger one relative to the anomaly measured near the Patria Lake (A in Fig. 4A) and a smaller one corresponding to the anomaly measured above Parete (B in Fig. 4A). The depth-to-top of these sources (~500 m) is compatible with the characteristics of the basaltic and andesitic lavas found in the Parete 2 well, as well as their magnetization of ~3.5 A/m (Carmichael, 1989). The inversion results obtained below ~2500 m cannot be trusted because of the loss of resolution with depth. The widths of these bodies are finally comparable with the lateral dimensions shown by the horizontal gradient map anomalies (see following section).

ANALYSIS OF THE MERGED DATA SET

The study and identification of the lateral boundaries of the magnetic sources of the region were carried out by computing the maximum horizontal gradient of the reduced-to-the-pole (rtp) draped data (Fig. 6A). Cordell and Grauch (1985) showed that the maxima of the horizontal derivative of gravity or rtp magnetic anomalies are located above changes of density or magnetization. Since the horizontal-gradient method assumes that the boundaries are single, near-vertical, and sharp, the location of the gradient maximum can be offset from the boundary when the contact is not vertical or when several boundaries are close together (Grauch and Cordell, 1987). The amount of this offset depends on the depth of the top edge of the boundary below the observation and on the dip of the boundary.

In Figure 6B, the structures mapped by seismic studies (Bruno et al., 1998, 2003; Milia and Torrente, 1999) and the Phlegrean caldera located by a boundary analysis on gravimetric data (Florio et al., 1999) are overlaid on the horizontal gradient maxima (hgm) map in order to study the correlation between magnetic structures and known faults and calderas. In the Vesuvian region the map of the hor-
horizontal gradient maxima shows that the Somma-Vesuvius is placed at the intersection of different systems of faults and shows the pattern of the Mount Somma caldera (D in Fig. 6A), whose southern sector lacks surface evidence. This structure corresponds fairly well to the southern caldera rim of Mount Somma inferred by Rosi et al. (1987). In the area surrounding the edifice, the map points out the lateral boundaries of several small sources whose pattern is quite complex. The comparison between these structures and the mapped faults (Fig. 6B) shows that some of them (E, F, and G in Fig. 6A), not characterized by any topographic or bathymetric high, align along faults located by seismic studies. These faults can therefore be interpreted as lineaments along which the magmatic activity developed.

In the Bay of Naples, the map shows the boundaries of the main volcanic structures and calderas of the bay. These structures are only placed in the northwestern part of the bay and in most cases correspond to bathymetric highs. Their comparison with the mapped faults shows that some of the magnetic sources coincide with the lineaments located by seismic studies. More specifically, while the magnetic structures I, L, Q, and R are crossed by the Magnaghi-Sebeto fault, the structures H, O, M, and P are bounded by these faults. This evidence suggests that, similarly to the fault in the Vesuvius offshore, the Magnaghi-Sebeto fault is a preferential way of magma upwelling. The lack of magnetic structures between the R structure and the Sebeto fault seems due to the low amount of magnetic data in this area of the bay.

The presence of the magnetic structures O and P in the trilobate head of the Magnaghi Canyon lets us hypothesize the presence of a lineament of magma upwelling not only in the southwestern portion of the canyon, but also in its northeastern part.

In the southeastern area of the bay, the mapped faults do not coincide with any magnetic boundaries. The Dohrn Canyon is, indeed, not characterized by magnetic activity, and the faults in this area cut sedimentary rocks, as also observed by Bruno et al. (2003).

In regards to the Pozzuoli Bay, the faults located by seismic studies partly follow the magnetic structure, marked with C, that highlights the southern rim of the Phlegraean Caldera. This magnetic structure doesn't have bathymetric evidences and coincides well with the structure located by gravity data (Florio et al., 1999) (see Fig. 6B). It is worthwhile to note that while the southern rim of the Phlegraean caldera is clearly shown by the hgm map, its northern borders are not clearly identified from the analysis of magnetic data and are not characterized by distinctive topographic evidence. This lack of magnetic signature is likely due to the presence of hydrothermally altered rocks at the caldera flanks (Florio et al., 1999).

In Ischia Island, the main signatures on the hgm map (N in Fig. 6A) are an elongated structure in the northwestern edge of the island, located on a lava flow, and three quasi-circular bodies, which correspond to small craters (Nunziata and Rapolla, 1987).

In the northern Phlegrean Fields area, the map highlights a subcircular structure, with a diameter of ~10 km, in the Patria Lake area (A in Fig. 6A) and a number of complex structures in the Parete area (B in Fig. 6A). These structures are related to buried sources, like those shown by the inversion of the magnetic field (see previous section), and seem aligned along an E-W trend that may be viewed as an eastward prolongation of the so-called Tyrrhenian 41st-N-parallel magnetic lineament (Lavecchia, 1988). Finally, the presence of buried sources in the Volturino River Plain (S and T and other small structures in Fig. 6A) suggests...
a diffused volcanic activity all over the Campanian Plain.

**DISCUSSION AND CONCLUSIONS**

The integration of different remote-sensing magnetic data sets measured in the active volcanic Neapolitan region led to a new high-resolution, draped magnetic data set of the region, allowing an overall view of this volcanic area (Figs. 4 and 6).

The study of the rtp and hgm magnetic maps provided insights into the characterization of the main, buried, and outcropping volcanic structures of the area.

With regard to the Phlegrean Caldera, our analysis led to the identification of its southern rim, while the northern boundary was not clearly located. For a more comprehensive investigation of the Phlegrean caldera area, we compared the magnetic structures with the location of volcanic vents of different ages (Orsi et al., 1996) (Fig. 7A). This comparison shows that the vents older than 12 ka, i.e., pre-Phlegraean Yellow Tuff, do not seem characterized by any magnetic signature except for the vents in the Torregaveta and Pozzuoli offshore areas. This can be due to the difference in their products that are mainly pyroclastics, except for the Torregaveta lava flows. The correspondence between these lava flows and the magnetic anomalies suggests that similar products can be found in the Pozzuoli offshore area. As regards the vents younger than 12 ka, they have a clear magnetic signature except in the northwestern sector of the area. This lack of correlation between the vents and the magnetic anomalies could be explained by hydrothermal alteration connected to the high temperatures of the area.

Figure 7A shows a good correspondence between the hgm and the circular pattern of the vents active between 12 ka and 5.5 ka in the Pozzuoli Bay, allowing us to make a hypothesis about the northwestern outline of the caldera rim (see Fig. 7B), which slightly differs from the one proposed by Florio et al. (1999). This result seems to suggest that the caldera is connected to the Yellow Tuff eruptions. No significant magnetic signature was found associated with the northern boundary of the more external of the two calderas, whose presence was hypothesized by Orsi et al. (1996) on the basis of the positions of the vents older than 12 ka.

The correlation between magnetic data, outcropping volcanics, and mapped faults provided insights on the characteristics of the Neapolitan volcanic district, allowing us to make some hypotheses about the evolution of the area.

The presence of several magnetic structures, interpreted as lava and/or pyroclastic domes and local vents, aligned along known faults suggests that these faults are preferential ways of magma upwelling and predate the volcanism of the region. This evidence confirms that the Neapolitan volcanism in the Bay of Naples is controlled by both a pre-Pleistocene NE-SW and a more recent NW-SE regional-stress regime, as also observed by Judenherc and Zollo (2004).

The lack of correspondence between magnetic boundaries and faults in the southeastern sector of the Bay of Naples suggests that the lineaments bounding the magnetized areas (Fig. 7B) also limit the volcanic Neapolitan district from an area characterized by sedimentary units and by lack of volcanic activity.

The analysis of Figure 7B, which summarizes the results of our study, allows the location of the lateral boundaries of buried and diffused volcanic structures, suggesting the presence of volcanic fields not only in the Phlegrean area, but also in the Vesuvian area.

**ACKNOWLEDGMENTS**

The authors thank Carol A. Finn for her constructive help in improving the manuscript. The authors acknowledge the support of the Istituto Nazionale di Geofisica e Vulcanologia—Osservatorio Vesuviano grants to A. Rapolla and to R. Pece (Programma Quadro 2000–2002). The authors also acknowledge I. Giori (Agenzia Generale Italia Petrol—Ente Nazionale Idrocarubi), for the availability of the Phlegraean aeromagnetic data set from 1985, and E. Guzzella (Istituto per l’Ambiente Marino Costiero—Geomare Sud) for the availability of the marine data set in the Bay of Naples. The authors are also grateful to Bill McGann for language revision.

**REFERENCES CITED**


Capaldi, G., Civetta, L., and Gillot, P., 1985, Geochronology of Plio-Pleistocene rocks from southern Italy: Rendiconti Societa Mineralogica Petrologica, v. XL, n. 1, p. 25–44.


**INTEGRATION OF MAGNETIC DATA**
PAOLETTI et al.


MANUSCRIPT RECEIVED BY THE SOCIETY 21 DECEMBER 2004
REVISED MANUSCRIPT RECEIVED 13 JULY 2005
MANUSCRIPT ACCEPTED 29 JULY 2005

Printed in the USA