

Magnetic signature of submarine volcanoes in the Phlegrean Fields-Ischia Ridge (North-Western side of the Bay of Naples, Southern Italy)

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Abstract

This paper presents a study of the Phlegrean Fields-Ischia submarine ridge by the analysis and interpretation of high-resolution aeromagnetic data recently acquired in the Western Procida offshore. The investigated area is located along the ridge connecting Ischia to the Phlegrean Fields and is characterized by the existence of several monogenetic volcanoes aligned on a NE-SW system of faults. The high-resolution magnetic data yielded new information on the area, highlighting particularly the signature of a volcanic body located between Pt. Serra and the Ruommoli shoal. This structure has not been clearly described before and we named it as the *Pt. Serra submarine volcano*. The computation of the analytic signal and horizontal gradient of the data distinctly located this structure and defined the position of its rims. A 2D modeling and 3D inversion of data provided information on the volcano's thickness, width and magnetization, disclosing a meaningful igneous body extending down to several hundred meters b.s.l.

Key words Aeromagnetic survey – Submarine volcanoes – Phlegrean Fields-Ischia Ridge – Procida offshore

1. Introduction

The Phlegrean Fields, along with the islands of Ischia and Procida, are active volcanoes developed on a ENE-WSW structural trend bordering the North-Western side of the Bay of

Naples, Southern Italy (fig. 1). The volcanic activity in this area, which started in Upper Pleistocene, is controlled by regional strain fields (Di Girolamo *et al.*, 1984; Vezzoli, 1988). Ischia and Procida are the emerged part of a main volcanic ridge separating a continental shelf to the North-West from a deeper sea floor topography to the South-East, in correspondence with the Bay of Naples (De Alteris and Toscano, 2003). The Ischia and Procida offshore areas are characterized by several monogenetic edifices aligned along a NE-SW system of faults that connects the South-Eastern sector of Ischia to the Phlegrean Fields (Di Girolamo and Stanzione, 1973). The existence of this group of faults was confirmed by gravity data (Imbò *et al.*, 1964). The monogenetic edifices of the area have been mainly formed through subaqueous explosive eruptions (hyaloclastites) of

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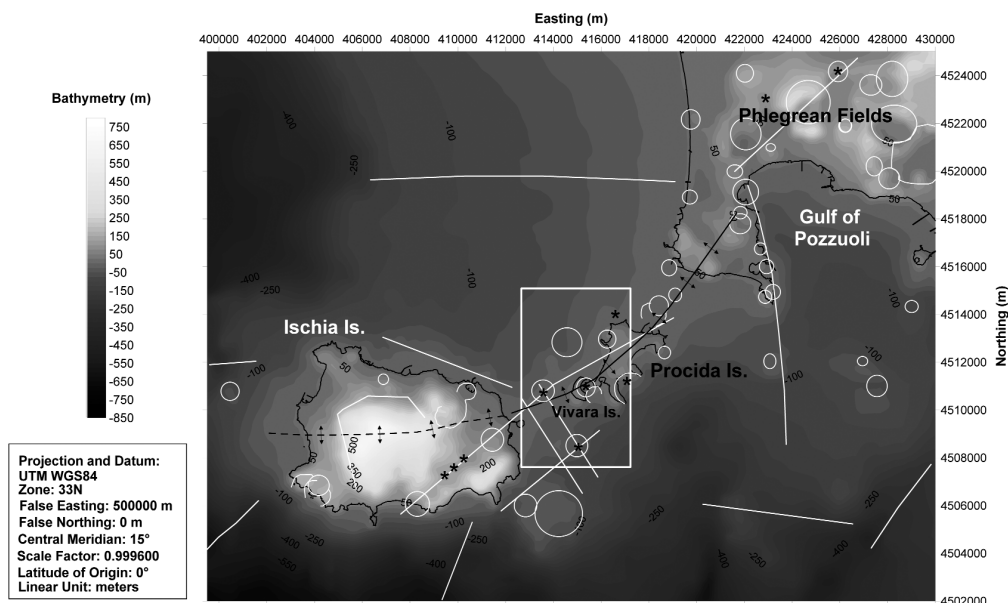


Fig. 1. Topographic and bathymetric map of the Phlegrean Fields-Ischia ridge. The main structural features are redrawn from Di Girolamo and Rolandi (1975): white lines are faults, black lines are ridges, circles are crater rims, asterisks are latitebasaltic and latite volcanoes. The square shows the area considered in this study.

a potassic magma with latitebasaltic-latic composition (Di Girolamo and Rolandi, 1975); a few lava domes can also be found (Di Girolamo *et al.*, 1984). Petrochemical correlations with the volcanics from the nearby islands of Procida, Vivara and Ischia show a close similarity for all the magmatic products of this region (Di Girolamo and Rolandi, 1975).

In this study we aim to gain insight into the features of the Phlegrean Fields-Ischia submarine ridge from the analysis and interpretation of high-resolution aeromagnetic data recently acquired in the Western Procida offshore (fig. 2). It is well-known that magnetic anomaly maps can provide useful information about the geo-volcanologic and structural characteristics of submarine volcanic areas.

Despite the geo-structural complexity characterizing the onshore and offshore areas of the Phlegrean Fields and Ischia, little information on this region derived from high-resolution magnetic data are presently available. The first detailed magnetic map of the Gulf of Naples, shown in Siniscalchi *et al.* (2002), was based on

data collected during a high-resolution oceanographic cruise. Later Secomandi *et al.* (2003) performed a boundary analysis on these data showing the pattern of the magnetic sources and structures of the gulf. Aiello *et al.* (2005) combined the interpretation of the magnetic and seismic data measured during the above cited cruise and described the buried volcanic structures of the Gulf of Naples.

High resolution aeromagnetic surveys performed recently in the Phlegrean Fields (Paoletti *et al.*, 2004) and Vesuvian regions (Paoletti *et al.*, 2005a) allowed the characterization of some of the main geo-structural features of these areas. The integration of different high-resolution magnetic data sets measured in the Neapolitan district yielded an overall view of the magnetic structures of the whole volcanic region (Paoletti *et al.*, 2005b).

As regards the Ischia Island surroundings, Bruno *et al.* (2002) and de Alteris *et al.* (2002) analysed 600 km of new seaborne seismic and magnetic profiles in the Western offshore of the island. The study allowed the authors to high-

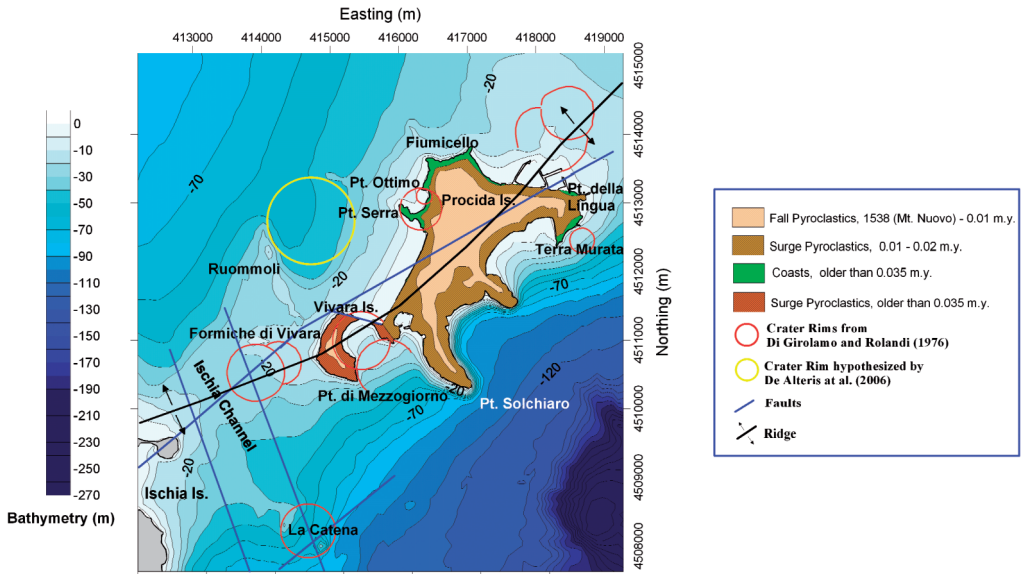


Fig. 2. Geologic map of the Procida Island and bathymetric map of its Western offshore. The geological units are from Di Girolamo *et al.* (1984). The main lineaments are redrawn from Di Girolamo and Rolandi (1975). The crater rims are from Di Girolamo and Rolandi (1975) and De Alteris *et al.* (2006). Bathymetry digitized from De Alteris *et al.* (2006).

light previously unreported E-W and NE-SW volcanic ridges that follow the regional structural patterns.

However these studies did not directly involve the Island of Ischia and the Phlegrean Fields-Ischia Ridge. Therefore, given the lack of detailed magnetic data on this region, a new high-resolution airborne survey was carried out in 2005. The survey covered the island of Ischia and the nearby submarine areas (fig. 3a). This paper focuses on the data measured in the western offshore of Procida Island (fig. 3b) and we aim at the characterization of the main submarine volcanic structures of this zone.

2. Survey Layout and Data Processing

2.1. Logistical characteristics of the survey

The helicopter-borne survey covered the entire area of the island of Ischia, extending also to the near Western Procida offshore (fig. 3). The investigation was set up in the form of a

conventional airborne survey with a line spacing of 300 m (N-S azimuth) and tie-lines (E-W azimuth) 4 km apart. The sample spacing along each flight line was about 5 m. The survey was flown at a constant clearance of about 300 m. To avoid some numerical problems during the successive gridding phases that could be related to the different sample rate in the N-S and E-W directions, we re-sampled the data along each line with a spacing of 50 m.

The instrumentation used for the survey was supplied by the Geological Survey of Austria and included ground and flight units. The ground unit consists of a magnetometer used to monitor the external field activity during the flights and a GPS base receiver used for the differential correction of satellite data. The flight unit includes: 1) a cesium magnetometer measuring the total magnetic field intensity with a sensitivity of 0.01 nT. The magnetometer sensor was mounted in a «bird» towed 30 m beneath the helicopter; 2) a GPS receiver for the horizontal positioning of the helicopter, having an accuracy of about ± 1 m after post-

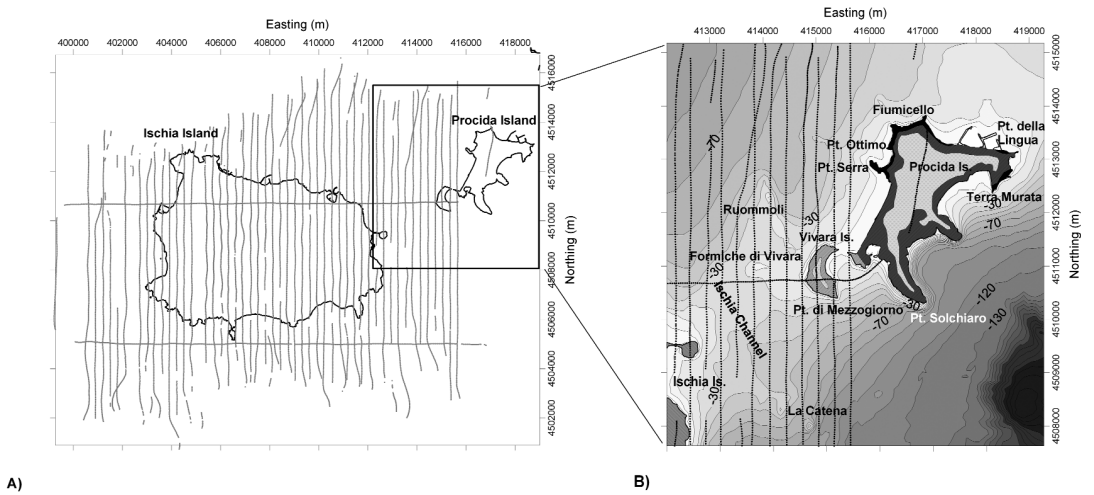


Fig. 3a,b. A) Network of aeromagnetic profiles collected over Ischia Island in October 2005 (from Paoletti *et al.* 2009); B) Close-up of the lines flown in the Western Procida Island offshore.

processing of GPS data, 3) a laser-altimeter for the vertical positioning of the helicopter, 4) computer for data acquisition and 5) a video-camera.

2.2. Data processing

The processing of the aeromagnetic data set acquired over the island of Ischia, from which we took the data set analyzed in this paper, included the following steps: 1) removal of spikes and gaps in the aeromagnetic data; 2) flight path check and repositioning, differential correction of the GPS data and check of the flight altitude; 3) Earth's magnetic field diurnal variation correction, performed using the base station data; 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 and cross-over analysis, consisting in a minimization of differences between magnetic field values measured at crossing points of flight lines and tie-lines.

3. Aeromagnetic Data of the Western Procida Offshore

As we can see in fig 3b, the surveyed area covered the known shoals of Ruommoli, Formiche di Vivara and La Catena. Di Girolamo and Rolandi (1975) thoroughly studied the structures of Formiche di Vivara and La Catena and identified them as remnants of submarine latitebasaltic-latic pyroclastic volcanoes formed through subaqueous explosive eruptions. The cited authors, and later Ferranti *et al.* (1994), found that the hyaloclastites volcano of Formiche di Vivara is the relict of a *tuff ring* with a terminal lava dome of the same latitebasaltic-latic composition. This lava bank is 400 m long and 200 m wide and has a thickness of at least 7 m. For their tectonic position and petrochemical characteristics, the Formiche di Vivara and La Catena edifices are considered as a junction between the islands of Ischia and Procida-Vivara (Di Girolamo and Rolandi, 1975). An exploration of the sea floor in the Ischia Channel allowed De Alteris *et al.* (1997) to interpret the shoal of Ruommoli as the relict of a mostly subaerial morphogenesis

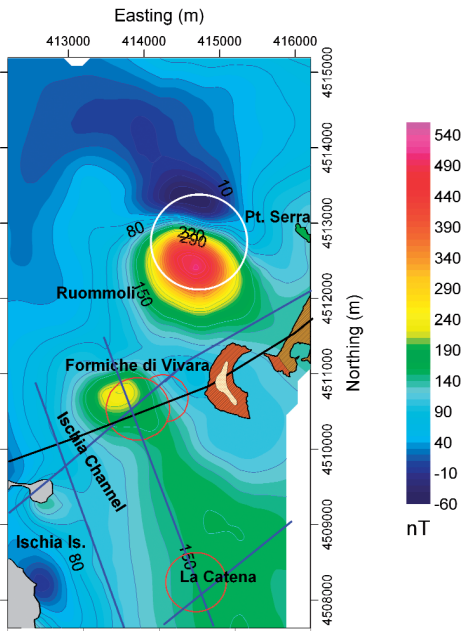


Fig. 4. High resolution aeromagnetic field of the Western Procida offshore. The rim of the tuff structure hypothesized by De Alteris *et al.* (2006) is drawn as a white circle, red circles show the rims of the Formiche di Vivara and La Catena volcanoes. The black line is the NE-SW ridge connecting Ischia and Phlegrean Fields. Faults are outlined by blue lines. For the geological units of the Procida Island refer to the legend of fig. 2.

on a monogenic edifice composed of hyaloclastic tuff. The original shape of this edifice is no longer traceable.

Figure 4 shows the aeromagnetic map of the Western Procida offshore obtained by gridding the data at a 150 m cell size with a kriging algorithm. The main feature of the map is a prominent anomaly between Pt. Serra and the shoal of Ruommoli. This anomaly has an amplitude of about 480 nT and seems to be related to a positive contrast of magnetization. An anomaly with smaller amplitude and dimension occurs in correspondence with the area of the Formiche di Vivara submarine volcano. The values of the anomalies appear to be influenced by a long wavelength trend not detectable at our scale of study.

It should be noted that while the Formiche di Vivara submarine volcano was extensively studied (see the above cited authors), very little is known about the submarine source connected to the prominent anomaly measured between Pt. Serra and Ruommoli. A recent detailed survey of the bathymetry of the Phlegrean Fields-Ischia offshore (De Alteris *et al.*, 2006) showed that the pattern of the sea floor between Pt. Serra and Ruommoli outlines two small ridges. These ridges seem to roughly indicate the rim of a volcanic edifice (a *tuff ring*, see fig. 2), very likely older than the Vivara volcano. As we can see in fig. 4 the correspondence between the bathymetric rim and the magnetic anomaly is fairly distinct. Moreover, the amplitude of the anomaly let us suppose the existence of deposits with magnetization values higher than those normally characterizing tuffs. The geometry and magnetization of this structure is analyzed in the next section.

As regards the monogenic edifice La Catena, a hyaloclastic volcano of latitic composition (Di Girolamo and Rolandi, 1975), it is not associated with any meaningful isolated magnetic anomaly (fig. 4). This evidence suggests an absence of significant magnetization contrast between this volcano and its surroundings. However it should be noted that the area around La Catena is characterized by a NW-SE trending anomaly which could be related to smaller volcanogenic sources distributed along the faults characterizing the area between La Catena and the Ischia Island.

3.1. Data Analysis and Interpretation

In order to understand the nature of the magnetic source located between Pt. Serra and Ruommoli we performed a qualitative and quantitative analysis of the aeromagnetic data. The horizontal position of the causative source was determined by compiling a 3D analytic signal map (fig. 5a). This map clearly shows two separate bell shapes, a smaller one over the structure of Formiche di Vivara and a bigger one over the source located between Pt. Serra and Ruommoli. We named this structure as the *Pt. Serra submarine volcano*.

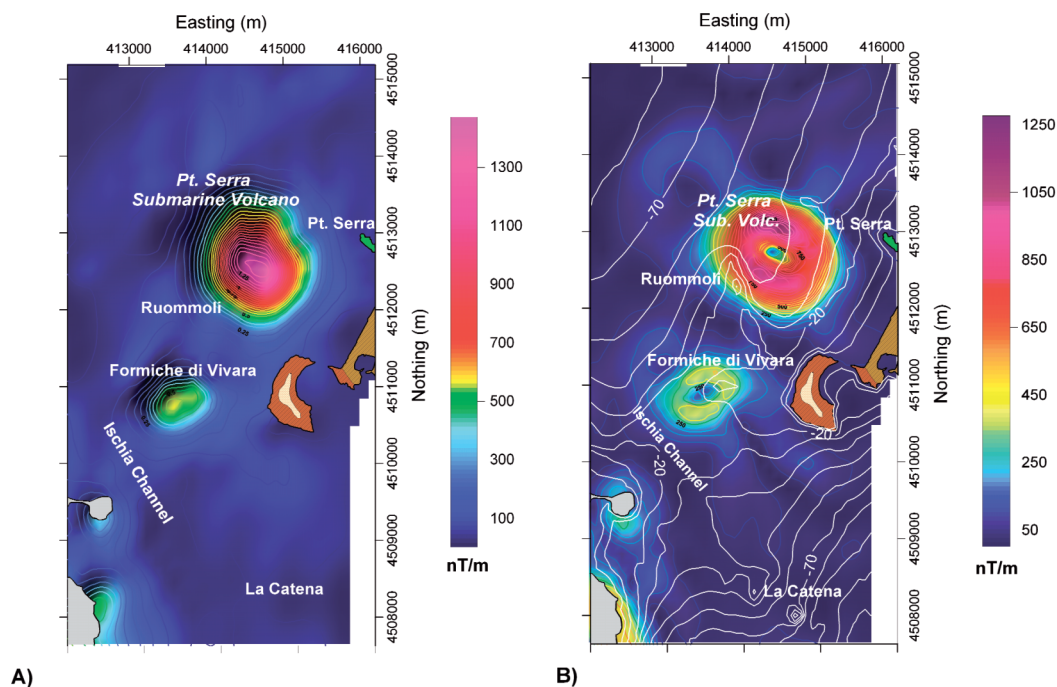


Fig. 5a,b. A) 3D analytic signal map of the magnetic data set measured in the Western Procida offshore; B) 3D horizontal gradient map of the pole-reduced data set measured in the Western Procida offshore. White contours show the bathymetry of the area from De Alteris *et al.* (2006).

The lateral boundaries of both the above cited anomaly sources were clearly defined by analyzing the maximum horizontal gradient of the reduced to the pole data (fig. 5b). As we can see, the limits of the *Pt. Serra submarine volcano* indicated by the maxima of the horizontal gradient function correspond fairly well with the bathymetric pattern. Note that, as the horizontal gradient method assumes that the boundaries can be approximated as single, near-vertical, sharp boundaries, when the boundaries are not represented by a vertical contact or when several boundaries are close together, the location of the gradient maximum can be offset from the actual boundary.

In order to have an estimation of the geometric and magnetization characteristics of the Formiche di Vivara and *Pt. Serra submarine volcano*, we carried out a three-dimensional inversion of the magnetic field and computed Singular Value Decomposition (SVD) solu-

tions. 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.*, 2005; 2007). In the adopted inversion approach the a priori information is incorporated in the regularization matrix in the form of high-order derivatives in the x , y and z directions. Provided that enough SVD components are available for the solution - *i.e.*, the problem is not strongly underdetermined and the data noise level is not too high - and a suitable regularization matrix is used, depth resolution can be obtained without resorting to any subjective choice of depth weighting.

The discretization used for the inversion is composed of $13 \times 13 \times 13$ prisms in the x , y , and z directions respectively, *i.e.*, the solution consists of $N = 2197$ prisms. The dimension of the prisms is 403 m in the x and y direction and 110 m in

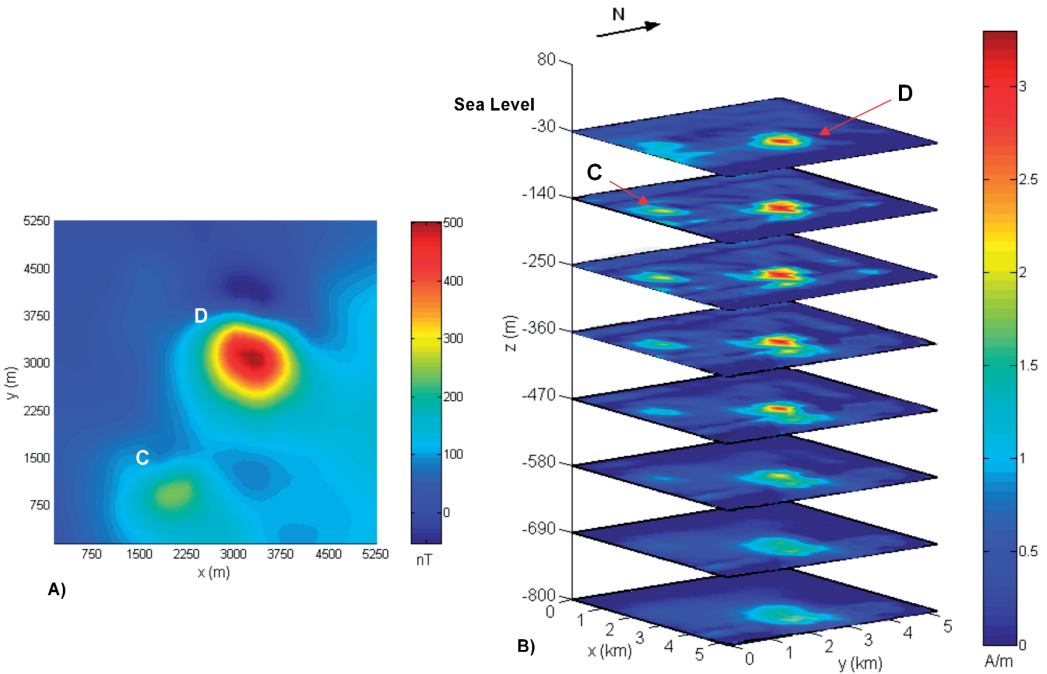


Fig. 6a,b. SVD (Singular Value Decomposition) inversion of the magnetic data. A) Data set used for the inversion; B) Three-dimensional magnetization model.

the z direction. Moreover, we used $P = 1225$ data points arranged in a 35×35 grid, covering an area of 5.25×5.25 km². The data points are located 300 m above the sea level. Figure 6a shows the data we inverted, while in fig. 6b we see the reconstruction obtained with 450 SVD components.

The solution shows the presence of two dyke-like bodies, a larger one relative to the anomaly measured over the *Pt. Serra submarine volcano* (D in fig. 6b) and a smaller one corresponding to the Formiche di Vivara anomaly (C in fig. 6b). Both sources start from the sea floor, about 30 meters below sea level. But while the depth-to-the-bottom of the most magnetized part of the Formiche di Vivara source is less than 500 m b.s.l., the bottom of the *Pt. Serra submarine volcano* is much deeper. The inversion results obtained beneath about 1000 m b.s.l. cannot be trusted because of the loss of resolution with depth of the inversion.

An important feature shown by the inversion results is the maximum magnetization of the sources that is about 2 A/m for the Formiche di Vivara body and 3.3 A/m for the *Pt. Serra submarine volcano*. This suggests the presence of compact igneous material. The different value of magnetization of the two bodies could be explained by a different degree of alteration of the igneous material and/or a different thickness of the clastic deposits in the uppermost part of the bodies.

The above results were confirmed by 2D modeling of the data along a profile (see fig. 7a). The modeling was carried out by using GMSYS (Grav/Mag Modeling Software, www.nga.com), assuming a model compatible with that obtained from the inversion. As we can see in fig. 7b, a good fit between measured and computed data was achieved supposing the presence of two dike-like igneous bodies with magnetization values of 2.4 to 3.6 A/m for Formiche di Vivara and the *Pt.*

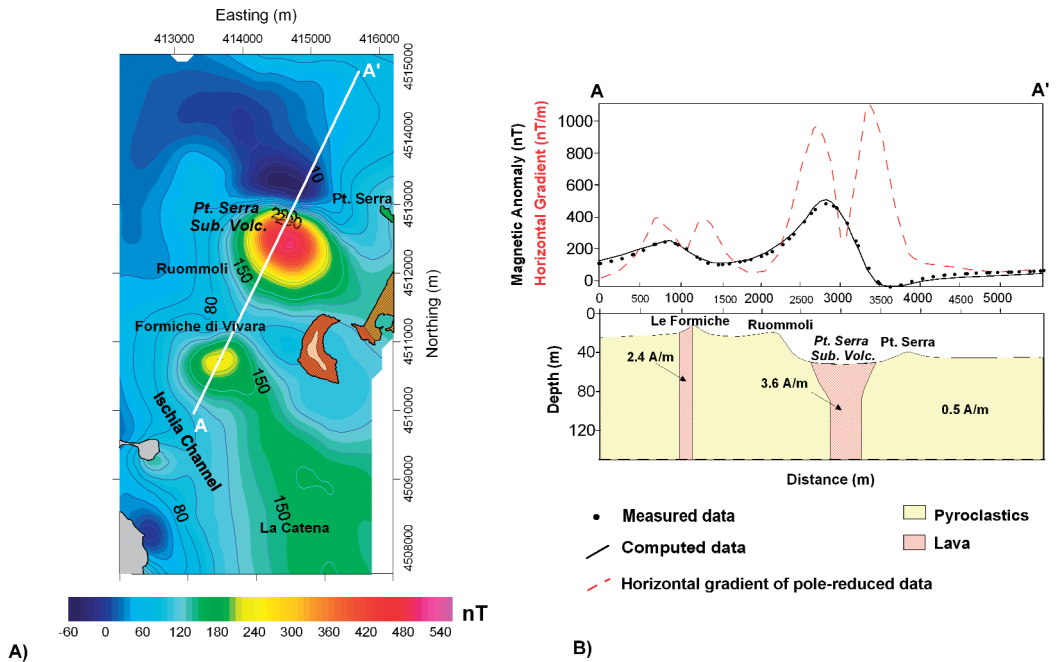


Fig. 7a,b. Magnetic modeling along profile AA' of the anomalies measured over Formiche di Vivara and Pt. Serra submarine volcano. A) Location of the profile; B) 2D modeling. Here we show the shallowest 150 meters of the interpretative model.

Serra submarine volcano, respectively. The widths of these structures are about 200 m for the Formiche di Vivara source and 600-800 m for the *Pt. Serra submarine volcano*. The results of the modeling also show that the bathymetric rims of the *Pt. Serra submarine volcano* are characterized by low magnetization values. This may indicate the presence of pyroclastic material, such as tuff, in the outer rims of the volcano.

4. Conclusions

We performed a study of the Western Procida offshore analyzing and interpreting a detailed aeromagnetic data set recently measured in Ischia region (figs. 3a-3b). The area investigated is the submarine zone between the islands of Ischia and Procida, along the Phlegrean Fields-Ischia ridge (fig. 1). Here geological and

volcanological studies (Di Girolamo and Rolandi, 1975; Ferranti *et al.*, 1994; De Alteris *et al.*, 1997; 2006) showed different monogenic submarine volcanoes aligned along a NE-SW system of faults.

The new high resolution aeromagnetic data (fig. 4) yielded new evidence on the area, highlighting the signature of a volcanic body placed between Pt. Serra and the shoal of Ruommoli that had not been clearly described and characterized before and that we named *Pt. Serra submarine volcano*. The position of this volcano was highlighted by the analytic signal map (fig. 5a), while the horizontal gradient map located the rims of the structure and showed that these rims roughly follow the bathymetric pattern (fig. 5b).

The thickness and magnetization values of this volcano were obtained by a three-dimensional inversion of the magnetic data. The solu-

tion showed a dyke-like igneous body extending to a depth of several hundred meters b.s.l., with a maximum magnetization of about 3.3 A/m (fig. 6). A 2D modeling of the data (fig. 7) confirmed the outcome of the inversion.

The surveyed area also covered the Formiche di Vivara and La Catena volcanoes (figs. 3b-4). The analysis and interpretation of the data collected over the Formiche di Vivara volcano showed a dyke-like igneous body smaller than the *Pt. Serra submarine volcano* (figs. 6-7). The non-existence of prominent isolated magnetic anomalies over the monogenic hyaloclastite volcano of La Catena allowed us to argue the absence of significant magnetization contrast between this volcano and its surroundings.

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