Reconstructing the Vulcano Island evolution from 3D modeling of magnetic signatures

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Abstract

High-resolution ground and marine magnetic data are exploited for a detailed definition of a 3D model of the Vulcano Island volcanic complex. The resulting 3D magnetic imaging, obtained by 3-D inverse modeling technique, has delivered useful constraints both to reconstruct the Vulcano Island evolution and to be used as input data for volcanic hazard assessment models. Our results constrained the depth and geometry of the main geo-structural features revealing more subsurface volcanic structures than exposed ones and allowing to elucidate the relationships between them. The recognition of two different magnetization sectors, approximatively coincident with the structural depressions of Piano caldera, in the southern half of the island, and La Fossa caldera at the north, suggests a complex structural and volcanic evolution. Magnetic highs identified across the southern half of the island reflect the main crystallized feeding systems, intrusions and buried vents, whose NNW-SSE preferential alignment highlights the role of the NNW-SSE Tindari-Letojanni regional system from the initial activity of the submarine edifice, to the more recent activity of the Vulcano complex. The low magnetization area, in the middle part of the island may results from hydrothermally altered rocks. Their presence not only in the central part of the volcano edifice but also in other peripheral areas, is a sign of a more diffuse historical hydrothermal activity than in present days. Moreover, the high magnetization heterogeneity within the upper flanks of La Fossa cone edifice is an imprint of a composite distribution of unaltered and altered rocks with different mechanical properties, which poses in this area an high risk level for failure processes especially during volcanic or hydrothermal crisis.

Keywords: Vulcano Island, magnetic survey, 3D inverse model, volcanic complex.

Introduction

The definition of the internal structure of an active volcano is of primary importance to fully understand the eruptive processes, to reveal its volcanic history, and to identify the main volcanic

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and tectonic subsurface structures. Since regional and local structures, that are not often exposed, may play an important role on volcanic evolution, they should be clearly detected and their link with the eruptive processes should be elucidated.

Vulcano Island is an active volcanic complex which is potentially affected by significant geohazards associated with the activity of the magmatic and hydrothermal systems. Indeed, even if, in recent times no magmatic eruptions have taken place at the island, sudden and intense changes in a set of geophysical and geochemical monitored parameters have been periodically observed. These episodes have been characterized by simultaneous increase in the fumaroles temperatures and in the gas emission rate, and by changes in the chemical composition toward more magmatic signatures, which are generally accompanied by low magnitude seismic-volcanic sequences located below La Fossa cone (Chiodini et al., 1992; Aubert et al., 2008; Alparone et al., 2010). These manifestations reflect the strong activity of the hydrothermal system in La Fossa area and, even if no evidence of magmatic rising has been recently observed (Granieri et al., 2006), it cannot be excluded that a possible unrest can lead to violent phreatomagmatic eruptions, as happened in the past (Frazzetta and La Volpe, 1991). Moreover, flank instability and failure with the subsequent formation of tsunamis, can occur during period of unrest, as happened in 1988 (Tinti et al., 1998, De Astis et al., 2003), since they can be triggered by dynamic phenomena, associated with the eruptive activity, such as intrusions and earthquake swarms, and by the hydrothermal processes also in the absence of the injection/intrusion of new magmatic fluids.

Although Vulcano had been extensively studied from volcanological, geochemical and geophysical point of view (Chiarabba et al., 2004; Revil et al., 2008) and different models, from 2D to 2.75D (Blanco-Montenegro et al., 2007), of its structural system have been produced, these models represent a first-order approximation of the internal structure of the volcanic complex. This is due to the several assumptions made throughout the modeling process, such as the infinite length of the structures in strike direction in the 2D modeling techniques, the constant geometry and finite length of buried bodies along the strike in 2.5D modeling, or the possible structural inconsistencies in the geometrical arrangement of units from one cross-section to the other related to the need that the section to be modeled is perpendicular to the structures direction. On the contrary, 3D modeling techniques consider any shape of structures in any direction of space improving considerably geologic interpretation. Up to date, no 3D modeling of Vulcano complex has been performed and not all the relationships between subsurface structures and the surficial deposits have been clearly elucidated, indeed some of them are still inferred or speculated (De Astis et al., 2013) exclusively on the basis of the available geological and geophysical data. Recently, magnetic field imaging has strongly contributed to a better understanding of the internal structure and evolution of different

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volcanic systems such as maar volcanoes (Blaikie et al., 2014), volcanic seamount (Napoli et al., 2007), large calderas (Finn and Morgan, 2002) and composite volcano (Nicolosi et al., 2014). In this paper, ground and marine magnetic data gathered in 1989, 1994 (Del Negro et al., 1997) and 2001 over the entire island have been processed and a detailed magnetic anomaly map has been obtained. In order to recover 3D subsurface magnetization distribution responsible for the detected magnetic anomalies, we invert the magnetic data using a quadratic programming (QP) algorithm with bound constraints on remanent magnetization values. We obtain a 3D model, which, besides to being in agreement with geological and geophysical information already gathered over the island (Chiarabba et al., 2004; Blanco-Montenegro et al., 2007; De Astis et al., 2013), provides a better definition of the size and geometry of the buried volcanic bodies. Moreover, the modeling results elucidate the relationships between the main tectonic and volcanic features of the shallow part of the volcanic complex, up to 1 km below sea level (b.s.l.), which are not fully exposed since hidden by the growth of the overlying volcanic successions.

Geological setting and previous geophysical studies

Vulcano Island belongs to a NW-SE elongated submarine volcanic ridge that lies inside a graben-like structure (Iacobucci, 1977, Barberi et al., 1994) and rises more than 1 km from the continental slope (Romagnoli et al., 2013). The ridge develops along two main systems of NW–SE trending right-lateral strike-slip faults, parallel to the NW-SE Tindari-Letojanni system, which represents the northward propagation of the regional discontinuity of the Malta escarpment (Ventura et al. 1999) and extends up to NE Sicily (De Astis et al., 2003; De Ritis et al., 2005) intersecting the NE–SW and E–W features of the southeastern Tyrrhenian margin (Gabbianelli et al. 1991). Although Vulcano structural pattern is generally dominated by a NNW–SSE trend, representing a surficial expression of the Tindari–Letojanni system, minor N-S to NE-SW trending normal faults and cracks are also reported by Ventura et al. (1999) and associated to the main NW–SE shear zone. In particular, they described as tensional features and horsetails, strongly controlled the younger stages of the island development (De Astis et al., 2003, Iacobucci, 1977, Barberi et al., 1994). The subaerial morphology of the island is characterized by two main overlapping structural depressions more than 2.5 km wide, named the Piano caldera and La Fossa caldera, located on the southeastern and northwestern parts of the island, respectively (Fig.1). They are bounded by the NNW–SSE, N–S and NE–SW-trending lineaments (Mazzuoli et al., 1995; Ventura et al., 1999) and consequently interpreted as pull-apart-type basins with a negligible volcano tectonic or volcano-related component (De Astis et al., 2013). The pyroclastic edifice of Vulcanello and its lava platform form

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a roughly circular peninsula on the northern tip of the island, while La Fossa cone, a 390 m high composite edifice, is located within the central sector of La Fossa caldera (Chiarabba et al., 2004; Revil et al., 2008).

The dated volcanism, occurred from about 130 ka to present times, has been characterized by a wide spectrum of eruptive-explosive activities, including explosive phreatic and phreatomagmatic eruptions producing wet and dry pyroclastic surges, pumice fall deposits, and highly viscous lava flows (Frazzetta and la Volpe 1991; De Astis et al., 2013). Since the last eruption of La Fossa cone, occurred from 1888 to 1890, the volcano activity has been characterized by recurrent thermal and seismic crises due to magma-water interaction (Federico et al., 2010; Alparone et al., 2010). An active hydrothermal system has been detected beneath La Fossa caldera, between 500 and 1,000 m b.s.l. by gravity, seismological and geochemical studies (Berrino 2000; Chiodini et al., 1992; Alparone et al., 2010). Intense fumarolic emissions are concentrated within La Fossa crater where a few high temperature (400-500 °C) zones are active (De Astis et al., 2003), and on the southern and northern flanks of the edifice, especially in the Grotta Palizzi area, and in the area of the Porto di Levante harbor (Fig. 1), where also SP and CO_2 anomalies were identified and temperatures generally do not exceed 98°C (Barde-Cabusson et al., 2009). Strong increases in fumaroles temperature and in superficial manifestations, with a remarkable enlargement of the exhalative area and a progressive increase in the gas emission rate, are generally observed when input of fluids of magmatic origin occurs even without evidence of magmatic rising, as happened in 2004-2006. In these cases the anomalous degassing episodes could derive from changes in rock permeability (Todesco, 1997; Harris et al., 2012) or reflect a pulsating degassing process from a deep pressurized stationary magma body (Granieri et al., 2006).

Since the first aeromagnetic and gravimetric surveys, dating back to the 70s, which characterized the large-scale structures of Aeolian Islands including Vulcano (Iacobucci, 1977, Barberi et al., 1994), several geophysical studies were executed at local scale to detect and define the shallow structures of volcano complex. Valuable information on the subsurface structure of the La Fossa caldera were obtained, by the intra-caldera sequences revealed by two deep geothermal drillings (Fig.1) in 1983–1987 (Giocanda and Sbrana, 1991), located at the foot of the south-western and northern flanks of the Fossa crater. The former encountered a shallow monzodioritic intrusion at about 1350 m b.s.l., and reached a vertical depth of 2,050 m where a temperature of 419 C° was founded. The second well, found a temperature of 243°C at 1,338 m and between 350 and 400°C at 1,578 m (Faraone et al. 1986). The entire pile revealed the occurrence of a differential collapse, supporting a primary tectonic origin under control of the Tindari–Letojanni system for this caldera (Gioncada & Sbrana, 1991).

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Few gravity surveys were carried out on the Vulcano Island (Budetta et al., 1983; Sugihara et al., 2002) and the data coverage is quite uneven, therefore, their interpretation is consequently limited in areas scarcely covered. Anyway, two gravity highs were detected beneath the La Fossa crater and inside the Piano caldera. The former was related to the self-sealed volcanics under which geothermal fluids circulate, and the latter was ascribed to a rising discontinuity between superficial loose pyroclastics and more compact underlying materials. A shallow seismic tomography (0-2 km b.s.l.) obtained from the analysis of local earthquakes (Chiarabba et al., 2004) reconstructed the geometry and distribution of main intrusions (intrusive bodies and lava pile), responsible for the high-velocity anomalies, and recognized some intra-caldera depressions filled by pyroclastics, tuffs and hyaloclastites, related to the low-velocity anomalies. Different high-resolution aeromagnetic surveys were carried out in the last years (De Ritis et al., 2005; Blanco-Montenegro et al., 2007) which revealed magnetic anomalies ascribable to the main crystallized feeding systems, intrusions, and buried vents. In particular, Blanco–Montenegro et al. (2007) highlighted a large volume of hydrothermally altered materials in La Fossa caldera area suggesting a larger hydrothermal system than the active one. The results from aeromagnetic studies, in agreement with the tomography support that the volcano complex has grown under the control of the Tindari-Letojanni fault system and the associated N-S extensional faults (De Ritis et al., 2005), these last structures, in particular, strongly controlled the uprising of magma and the location of eruptive vents at depth lesser than 0.5 km b.s.l. This is also confirmed by the few available bathymetric and seismic data (Gabbianelli et al., 1991; Favalli et al., 2005; Romagnoli et al., 2013), which revealed on the western flank of the volcano complex some submarine volcanic features aligned along NNW–SSE regional trends, related to the early stage of its development. While, volcanic features ascribable to a more recent activity appear radially elongated along the submarine southern and eastern flanks.

Magnetic data

The survey strategy is aimed to capture the Vulcano Island magnetic signatures and to correlate them with the main volcanic and tectonic features in order to image the subsurface structures of the volcanic complex in a 3D framework. More than 18,000 magnetic data were retrieved from three high resolution ground magnetic surveys carried out at Vulcano Island in 1989, 1994 and 2001. Shipborne data were also gathered offshore in 1994, along a profile parallel to the coast line, to constrain the magnetic field just a few tens meters from the coast. Practically, the surveys cover the emerged tip of the volcanic edifice, for about 42 km^2, corresponding to the entire island. Data were acquired along lines describing an irregular grid (Fig. 1A) by an ELSEC 770, a Geometrics G-856 and an Overhauser effect magnetometer. During each survey a base station was used to correct for

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the magnetic external variations (Del Negro et al., 1997). The magnetic surveys were carried out during days characterized by geomagnetic K index values < 2, ensuring a suitable data accuracy in the removal of time variations of external origin. Moreover, International Geomagnetic Reference Field (IGRF) models available at the time of the three different surveys (IGRF-4, IGRF-5 and IGRF-8) have been subtracted to make the data comparable. Finally, the data from these three surveys were merged to provide a data set for the entire area. Therefore, in order to obtain the magnetic anomaly map, data were reduced to a regular grid with a constant spacing of 0.5 km using a minimum curvature algorithm, ending up with a final dataset of 4521 observational points. A regional field was then estimated that linearly fitted the magnetic data by the least-squares criterion, and was subsequently subtracted from them. The total-intensity residual anomaly map is shown in Fig. 1B. To suppress spurious anomalies related to shallow magnetic sources, data were upward continued (Fig. 2A) to a constant altitude of 550 m, namely 50 m from the highest elevation of the island (Mt. Aria). The data highlight intense maximum in the La Fossa cone south-eastern flank. Other magnetic highs, NNW-SSE elongated, dominate the Piano caldera rims. In particular, along the western rim of Piano caldera a maximum with a sub-elliptical shape extends for about 3 km parallel to the caldera rim overlapping, from south to north, the Timpe del Corvo, the Scoglio Conigliara and the Mt. Saraceno basaltic cone. Also the eastern rim of the caldera is characterized by the presence of a high magnetization area, elongated in the NNW-SSE direction for about 1 km, but in this case no surface evidence of eruptive centers is observed. Another maximum with a regular circular shape appears well isolated in the central area of the caldera. On the contrary, a wide area of low magnetization spreads in the middle part of the island, within La Fossa caldera in the sea sector between Vulcanello and La Fossa cone and in the area of Grotta Palizzi. The main magnetic anomalies detected are in agreement with those obtained by the previous aeromagnetic surveys (De Ritis et al., 2005; Blanco-Montenegro et al., 2007), even if the very close sampling step of 3 m adopted during our ground magnetic surveys allowed to highlight shorter wavelengths related to very shallow magnetic features. In particular, in the resulting magnetic anomaly map the shape of the magnetic anomalies appear more articulated and their locations are better defined than previous studies.

Imaging of Vulcano Island

A 3-D subsurface magnetization model was obtained by a Quadratic Programming algorithm (Napoli et al., 2007). In order to allow the maximum flexibility for the model to represent geologically realistic structures, the island was represented as a crustal block of 8.5×6.7 km^2 in area

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and 1.5 km in thickness. Indeed, the crustal block extends offshore to take into account the side effect of the source bodies surrounding the observational area. The ground surface was generated from a digital elevation model of Vulcano Island from the 30 m Shuttle Radar Topography Mission (SRTM) data and the GEBCO bathymetry database (http://www.gebco.net). The crustal block was discretized into a set of rectangular prisms. Horizontal and vertical dimensions of rectangular prisms were taken as variables (Fig. 3) to account for the higher resolution required in diverse areas. In particular, in order to better approximate the topographic relief, we considered a set of prisms above the sea level, each 0.125×0.125×0.125 km^3 in size. Below sea level, prisms have 0.25×0.25 km^2 horizontal area and a thickness of 0.25 km. Finally, the bottom depth of the model was assumed to be 1.0 km b.s.l., thus formalizing an inversion problem with 8921 unknowns on the magnetization values. The depth resolution is closely related to the extension of the survey (Fedi and Rapolla, 1999). The anomaly field was inverted assuming that the average direction of the total magnetization is close to Earth's present-day field direction (inclination of 54°N, declination of 0.9°W). The remanent magnetization is generally much greater than induced magnetization and rocks of Vulcano Island were emplaced about 135 ka (De Astis et al., 2003) after the last field reversal (786 ka, Lowrie and Kent 2004). Parameters used for the data inversion are summarized in Table 1.

Volcanic rocks are usually highly magnetic due to their relatively high magnetite content. The intensity of magnetization of these rocks is largely dependent upon several factors such as the magma composition, cooling rate, grain size, volatile content and alteration history. Therefore, the intensity of magnetization is extremely variable and there can be considerable overlap between different lithologies (Kearey and Brooks, 1991). Anyway, high values (up to 10 Am^{-1}) of intensity of magnetization are generally generated by high concentrations of magnetite and small grains that usually are associated to magma intrusions and compact lava flows, on the contrary low values (few Am^{-1}) are related to low concentrations of magnetite and to the presence of larger grains such as it has been observed in volcaniclastic deposits (Hildebrand, Rosenbaum & Kauahikaua, 1993; Napoli et al., 2007).

In Vulcano Island the great variety of erupted volcanic products (lava flows, dikes, pyroclastic deposit, etc..) produces a significant heterogeneity in rock magnetic properties. In particular, laboratory tests executed on rock specimens (Zanella and Lanza, 1994) of Vulcano Island revealed that the highest magnetization values correspond to the lavas of Vulcanello, followed by the lava flow of Punta Roja, and the less magnetic lava flows are those of the Lentia edifice and the Fossa cone, whereas lavas of the Primordial Vulcano show intermediate magnetization values. Ash deposits of the Fossa caldera show the lowest total magnetization values in the island (Blanco-

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Montenegro et al., 2007). In agreement with these results in the inversion procedure, we imposed constraints on the intensity of natural remanent magnetization (JNRM) range from 0 to 10 Am^{-1}. The accuracy on the obtained magnetization values was estimated from the square-root of the diagonal elements of the inverse Q matrix (Gill et al., 1981). The accuracy is related to the prisms' depth, location, and, in particular, it reaches a maximum value of about 0.9 Am^{-1} for deeper prisms, whereas it is below 0.6 Am^{-1} for shallower ones.

The computed field well matches with the observed one with residuals having a standard deviation of 8 nT (Figs. 2B, C). The volcano magnetization model resulting from the constrained inversion of data set is shown in Fig. 4.

Horizontal layers from 250 m above sea level to 750 m below sea level (Fig.4), and N-S and E-W sections (Fig. 5) provide a detailed imaging of the shallow part of the volcanic complex. The southern part of the island is characterized by a NNW-SSE alignment of different magnetization highs, with an intensity greater than 8 Am^{-1}, located along the Piano caldera rims. The magnetic structures observed along the western rim can be related to the presence of magnetic bodies associated to feeding conduits of eruptions and magmatic intrusions that supplied the construction of Mt. Saraceno basaltic cone (8 ka, De Astis et al., 2003), and to non-outcropping mafic massive rocks along the Timpa del Corvo eruptive fissure, extending further south, parallel to the caldera rim.

Both the intensity and areal extent increase with depth reaching the maximum value of 9 Am^{-1} and over 3 km in length respectively, at the sea level where the magmatic feeding systems seem to be connected each other forming a single volume (Fig. 6) along the NNW–SSE trend that is one of the main regional fault systems (the Tindari-Letojanni system) characterizing Vulcano Island (De Astis et al., 2013). It is reasonable to suppose that this assumed preferential pathway for magma ascent, strongly controlled by the regional stress field, and by the minor associated N–S to NE-SW trending extensional structures has also produced the basaltic lava flows outcropping near Scoglio Conigliara in the central part of this Piano caldera rim. Indeed, the proximity between this important magnetic structure and these lava flows strongly suggests a clear correlation between them. Moreover, till now, no surface evidence of the eruptive vents from which these lava flows were outpoured has been detected, and due to the limited exposures, a certain identification of the source area was not possible (De Astis et al., 2013).

Below the sea level (Fig.4) the magnetic high related to the Timpa del Corvo fissure becomes smaller and disappears at 0.75 km b.s.l. On the contrary, beneath Mt Saraceno cone, at the junction between the Piano caldera and La Fossa caldera structures, the magnetized volume is still present with a magnetization of about 5 Am^{-1}, showing the presence of magnetized rocks reasonably related

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277 to a previous activity in this area. This region was already identified by Blanco-Montenegro et al.
278 (2007) from aeromagnetic data and was supposed to be the remnants of an early submarine volcano.
279 Other two different magnetization highs were observed along the eastern rim of the caldera. The
280 former is centered beneath Mt. Luccia at the northeast edge of the caldera rim, while the latter
281 marks the eastern rim of the caldera where no volcanic center outcrops. Both of them are
282 characterized by a magnetization intensity of about 8 Am^{-1}, that is a high value generally associated
283 to massive intrusions and/or feeding systems of volcanic centers, and show a NNW-SSE
284 preferential alignment. These evidences suggest that also in this area of the island the Tindari-
285 Letojanni regional fault system and the associated N–S to NE-SW striking normal faults could have
286 produced favorable conditions for magma ascent. This area is characterized by the presence of the
287 Piano di Luccia formation, welded strombolian to hawaiian fallout products filling the Piano
288 caldera, whose source area has been speculated (De Astis et al., 2013) but has not yet been clearly
289 identified. Considering the proximity between the Piano Luccia formation and the detected
290 magnetic highs, it is reasonable to assume that they are related to each other and suppose that the
291 outcropping products are the results of the activity originated from these volcanic features. In the
292 middle of Piano caldera the 3D model reveals at very shallow depths a wide area of low
293 magnetization intensity of about 2 Am^{-1} ascribed to pyroclastic products. Magnetization highs
294 appear with increasing depth. Indeed, two magnetized volumes with an intensity of about 8 Am^{-1}
295 are detected at the north of Mt. Aria and may be related to the presence of magnetic bodies
296 interpreted as the feeding conduits of basaltic eruptions and magma intrusions that supplied the
297 construction of the Monte Rosso volcanic center.
298 Within La Fossa caldera a very low magnetization area is observed in correspondence of the
299 northern and western flanks of La Fossa cone. This magnetic signature could be related to the low
300 magnetization of pyroclastic deposits forming this part of the volcanic edifice (Blanco et al., 2007),
301 that, however, do not cover all the inferred low magnetized volume. Two other possible hypotheses
302 can be proposed to properly account for the origin of this low magnetization volume. As a first
303 hypothesis, the low magnetization could be ascribed to thermal demagnetization processes
304 generated by heat transfer from the subcrustal magma chamber. Regarding this hypothesis, at
305 Vulcano the Curie temperature of most lithotypes, ranges between 550 and 580°C (Zanella and
306 Lanza 1994), that is reached at 1.5-3 km depth (De Ritis et al., 2013) and pyroclastic products lose
307 50% of their initial magnetization already at 200°C (Zanella and Lanza 1994). These high
308 temperatures are encountered by drillings only at depths greater than 1 km (Faraone et al., 1986),
309 that is below the bottom of our model. This excludes the hypothesis of thermal demagnetization
310 processes generated by volcano-scale heating in the investigated volume. As a second hypothesis,

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311 the presence of intense fumarolic emissions whose temperature, during episodes of unrest, can
312 increase up to 700°C in very limited spaces (fumarolic conduits and vents), (De Astis et al., 2003;
313 Granieri et al., 2006) and the evidence of limited thermoelastic deformation enhanced in this zone
314 (Bonaccorso et al., 2010), favor a more straightforward explanation in terms of hydrothermal
315 alteration which can decrease, and even nullify the magnetic signature of the volcanic host rocks
316 (Reid et al., 2001; Tivey and Dyment, 2010).
317 Although, the whole La Fossa cone is covered by pyroclastic deposits, the 3 D model reveals in the
318 eastern flank of the volcanic edifice a magnetized body with intensity of about 8Am^{-1} elongated in
319 the North-South direction for about 1 km. It corresponds to the high-velocity body found by
320 Chiarabba et al. (2004), and can be related to the lava flows that were emitted during the early
321 volcanic activities of La Fossa cone (Keller, 1980) and that outcrop at its northeastern base (De
322 Astis et al., 2013). With increasing depth, magnetization and areal extension diminish, but at about
323 0.5 km b.s.l. the magnetized volume is still present. For this magnetic body we obtained a
324 horseshoe-shaped volume of about $5.3x10^7$ m^3 (Fig. 6), and considering the high magnetization
325 values we can interpret it as the magmatic feeding system of this eruptive center suggesting a more
326 significant effusive activity than that speculated on the basis of lava flows outcropping.
327 Another low magnetization area, with intensity less than 1 Am^{-1}, is observed in the western sector
328 of La Fossa caldera, where it overlays a part of the active hydrothermal system, in the sea sector
329 between Vulcanello and La Fossa cone and in the area of Grotta Palizzi, and a part of the well-
330 known depression between the Lentia domes and La Fossa cone (Fig. 4). This area, which is filled
331 by tuffs, pyroclastics and hyaloclastites (Giocanda and Sbrana, 1991), is characterized by low
332 magnetization values, 0-2 Am^{-1}, (Giocanda and Sbrana, 1991; Blanco-Montenegro et al., 2007) and
333 is coincident with the low Vp zone detected by the seismic tomography of the island (Chiarabba et
334 al. 2004).
335 Northwest, in correspondence with the Lentia complex, the model reveals an area of magnetization
336 intensity of about 4 Am^{-1} with a N-S orientation. This value is comparable to that associated to the
337 subaerial lava flows and domes of the Lentia complex (Blanco-Montenegro et a., 2007). At
338 Vulcanello, small magnetized volumes with intensity of 8 Am^{-1} are detected and are well correlated
339 with the high seismic velocity (Vp) zone (Chiarabba et al., 2004) and associated to leucite-bearing
340 lava platform forming Vulcanello (Fig.4). The magnetization intensities observed both at Lentia and
341 at Vulcanello diminish with increasing depth and the relative sources seem to be confined to the
342 shallow part of the volcano supporting the idea that they are related to the most recent phases of the
343 volcano activity. From 250 to 750 m b.s.l. the magnetization intensity drastically diminishes over
344 the whole island and its distribution appears more homogeneous. Magnetized highs are founded in

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345 the northwest and northeastern areas of the island, but not completely described since they continue
346 offshore where no measurements were gathered. Anyway, they seem to be in good agreement with
347 the offshore anomalies detected and interpreted by De Ritis et al., (2005), as the crystallized Lentia
348 plumbing system and Vulcanello lavas. Below 0.5 km b.s.l., only the NNW-SSE oriented magnetic
349 volume persists inside the Piano caldera, where it has been speculated the presence of the main
350 feeding system which gave rise to the Primordial Vulcano (Keller, 1980; De Astis et al., 1997;
351 2013). Other two magnetic structures are still present in correspondence of La Fossa cone and Mt
352 Saraceno representing the deeper and consequently the older volcanic structures here recognizable
353 on the basis of the data resolution.
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356 **Discussions and conclusion**
357 Following the 3D magnetization model the volcanic complex of Vulcano Island can be divided in
358 two different sectors approximatively coincident with the structural depressions of Piano caldera, in
359 the southern half of the island, and La Fossa caldera at the north. The former, is characterized by
360 clusters of high-magnetization (about 9 Am^{-1}) regions, the most intense over the island, detected
361 along the rims and within the Piano caldera, which correspond to the main eruptive centers of this
362 sector of the island, such as Timpe del Corvo, Scoglio Conigliara, Mt. Rosso and Punta Luccia, and
363 represent the magnetic signatures of their feeding systems, massive intrusions, and buried vents.
364 Their extension reveals more subsurface magmatic volumes and/or shallow and local volcanic
365 structures than exposed ones. The 3D model provides a detailed definition of the size and geometry
366 of these subsurface structures (Fig. 5) allowing to elucidate the relationships between them and to
367 link them to surface deposits such as lava flows of Scoglio Conigliara and Piano Luccia formation,
368 whose source areas were not previously detected. These volcanic features appear structurally
369 controlled by the NNW-SSE regional structural lineament at any depth, supporting the key role
370 played by the Tindari-Letojanni system in controlling the location and shape of the volcanic edifices
371 from the initial activity of the submarine edifice, to the more recent activity of Mt Saraceno. On the
372 other hand, in the more recent La Fossa caldera sector the NNW-SSE preferential alignment is not
373 so evident. In particular, in this area only a few magnetized highs were detected: (i) a N-S magnetic
374 body along the eastern flank of La Fossa cone (ii) the Lentia complex N-S magnetized volume
375 along the western rim of the caldera, and (iii) the intensely magnetized volumes of Vulcanello. The
376 Lentia complex and Vulcanello lavas are detected only in the shallow part of the model, up to 250
377 m b.s.l., and none of them shows the NNW-SSE alignment. This largely follows the suggestions of
378 Mazzuoli et al. (1995) and Ventura et al. (1999) that the most recent phases of the volcano activity

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were controlled by north–south to NE–SW tectonic lineaments and the Tindari-Letojanni system no longer dominated.

In La Fossa caldera sector, large zones of reduced magnetization are mainly concentrated in the shallowest layers. They are the evidence for alteration related to hydrothermal processes and extend over a region wider than that affected by the current active hydrothermal system. This suggests that in the past the hydrothermal system had a greater extension and had primarily developed in this area of the island. On the basis of available data, it is not possible to assert if there was a really large active area at some time, or alternatively different areas were active at different times. Both conditions may have occurred or more probably they may have coexisted.

Finally, our results reveals low magnetized volumes forming the northern and southern flanks of La Fossa cone edifice, that could be reasonably ascribed to pyroclastic and hydrothermally altered rocks. These flanks are bounded eastwards by a significant volume of lava pile which may be less permeable and consequently less amenable to hydrothermal alteration than the other parts of La Fossa cone acting as an impermeable limit to the fluids circulation. This could explain the fumarolic emission patterns, which are not spread homogenously in the La Fossa area but are locally concentrated in the northern and southern flanks formed by more permeable pyroclastic deposits. Their relatively steep slopes, the active fluids circulation, proved by the presence of fumaroles and hydrothermal alteration, could promote large collapses in these areas, which can more easily undergo flank failure. Therefore, in case of volcanic or hydrothermal crisis a high level of hazard is posed to these flanks of the volcano, especially in the transition zones between the hydrothermally altered rocks and lava pile.

By providing a detailed description of the main geo-structural features and of distributions of unaltered and altered rocks, our findings from the 3D magnetic imaging provide new constraints to be used in aiding the Vulcano Island hazard assessments.

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References

Alparone, S., Cannata, A., Gambino, S., Gresta, S., Milluzzo, V., Montalto, P., 2010. Time-space variation of the volcanoseismic events at La Fossa (Vulcano, Aeolian Islands, Italy): new insights into seismic sources in a hydrothermal system. Bull. Volcanol. 72, 803-816.

Aubert, M., Diliberto, S., Finizola, A., Chébli, Y., 2008. Double origin of hydrothermal convective flux variations in the Fossa of Vulcano (Italy). Bull. Volcanol. 70:743–751, DOI 10.1007/s00445-007-0165-y.

Barberi, F., Gandino, A., Gioncada, A., La Torre, P., Sbrana, A., Zenucchini, C., 1994. The deep structure of the Eolian arc (Filicudi–Panarea–Vulcano sector) in light of gravity, magnetic and volcanological data. J Volcanol. Geotherm. Res. 61:189–206.Barde-Cabusson, S., Finizola, A., Revil, A., Ricci, T., Piscitelli, S., Rizzo, E., Angeletti B., Balasco, M., Bennati, L., Byrdina S., Carzaniga, N., Crespy, A., Di Gangi, F., Morin, J., Perrone, A., Rossi, M., Roulleau, E., Suski, B., Villeneuve, N.,.2009. New geological insights and structural control on fluid circulation in La Fossa cone (Vulcano, Aeolian Islands, Italy). J. Volcanol. Geotherm. Res. 185, 231–245.

Berrino, G., 2000. Combined gravimetry in the observation of volcanic processes in Italy. J Geodyn. 30:371–388.

Blaikie, T. N., Ailleres, L., Betts, P.G., Cas, R. A. F., 2014. Interpreting subsurface volcanic structures using geologically constrained 3-D gravity inversions: Examples of maar-diatremes, Newer Volcanics Province, southeastern Australia. J. Geophys. Res. Solid Earth, 119, 3857–3878, doi:10.1002/2013JB010751.

Blanco-Montenegro, I., de Ritis, R., Chiappini, M., 2007. Imaging and modelling the subsurface structure of volcanic calderas with high-resolution aeromagnetic data at Vulcano (Aeolian Islands, Italy). Bull. Volc., 69, 643–659, doi:10.1007/s00445-006-0100-7.

Bonaccorso, A., Bonforte, A., Gambino, S., 2010. Thermal expansion-contraction and slope instability of a fumarole field inferred from geodetic measurements at Vulcano. Bull. Volcanol. DOI 10.1007/s00445-010-0366-7.

Budetta, G., Nunziata, C., Rapolla, A., 1983. A gravity study of the island of Vulcano, Tyrrhenian Sea, Italy. Bull. Volcanol. 46:183–192.Chiarabba, C., Pino, N.A., Ventura, G., Vilardo, G., 2004. Structural features of the shallow plumbing system of Vulcano Island Italy. Bul.l Volcanol. 66,477–484.

Chiodini, G., Cioni, R., Falsaperla, S., Guidi, M., Marini, L., Montalto, A., 1992. Geochemical and seismological investigations at Vulcano (Aeolian islands) during 1978–1989. J. Geophys. Res. 97:11025–11032.

Corresponding author, e-mail address: rosalba.napoli@ingv.it (R. Napoli)

447 De Astis, G., Ventura, G., Vilardo, G., 2003. Geodynamic significance of the Aeolian volcanism
448 (southern Tyrrhenian Sea, Italy) in light of structural, seismological and geochemical data.
449 Tectonics, 22, 4 DOI 10.1029/2003TC001506.
450 De Astis, G., Lucchi, F., Dellino, P., La Volpe, L., Tranne, C. A., Frezzotti, M. L., Peccerillo, A.,
451 2013. Geology, volcanic history and petrology of Vulcano (central Aeolian archipelago).
452 Geological Society, London, Memoirs 2013, 37; p281-349. doi: 10.1144/M37.11.
453 De Ritis, R., Blanco-Montenegro, I., Ventura, G., Chiappini, M., 2005. Aeromagnetic data provide
454 new insights on the tectonics and volcanism of Vulcano island and offshore areas (southern
455 Tyrrhenian Sea, Italy). Geophys. Res. Lett., 32 (L15305). DOI 10.1029/2005GL023465.
456 Del Negro, C., Branciforte, M., Ferrucci, F., Napoli, R., Sicali, A., Tabacco, S., 1997. High
457 resolution magnetic survey of the Island of Vulcano. CCE funded TekVolc project, contract n.
458 EV5V-CT92-0191, report.
459 Faraone, D., Silvano, A., Verdiani, G., 1986. The monzogabbroic intrusion in the island of Vulcano,
460 Aeolian archipelago, Italy. Bull. Volcanol. 48:299–307.
461 Favalli, M., Karatson, R., Mazzuoli, R., Pareschi, M.T., Ventura, G., 2005. Volcanic
462 geomorphology and tectonics of the Aeolian archipelago (southern Italy) based on integrated
463 DEM data. Bull. Volcanol. 68:157–170.Federico, C., Capasso, G., Paonita, A., Favara, R., 2010.
464 Effects of steam-heating processes on a stratified volcanic aquifer: Stable isotopes and dissolved
465 gases in thermal waters of Vulcano Island (Aeolian archipelago). J. Volcanol. Geotherm. Res.
466 192, 178–190 doi:10.1016/j.jvolgeores.2010.02.020.
467 Fedi, M., Rapolla, A., 1999. 3-D inversion of gravity and magnetic data with depth resolution.
468 Geophysics, 64, 452–460.
469 Finn, C. A., Morgan, L.A., 2002. High-resolution aeromagnetic mapping of volcanic terrain,
470 Yellowstone National Park, J. Volcanol. Geotherm. Res., 115(1–2), 207–231.
471 Frazzetta, G., La Volpe, L., 1991. Volcanic history and maximum expected eruption at ‘‘La Fossa
472 di Vulcano’’ (Aeolian Islands, Italy), Acta Volcanol., 1, 107– 113.
473 Gabbianelli, G., Romagnoli, C., Rossi, P. L., Calanchi, N., Lucchini, F., 1991. Submarine
474 morphology and tectonics of Vulcano (Aeolian Islands, Southeastern Tyrrhenian Sea). Acta
475 Vulcanologica, 1, 135–142.
476 Gill, P.E., Murray, W.,Wright, M.H., 1991. Practical optimization. Academic Press, London.
477 Gioncada, A. Sbrana, A., 1991. “La Fossa caldera”, Vulcano: inferences from deep drillings. Acta
478 Vulcanol., 1, 115–125.
479 Granieri, D., Carapezza, M.L. Chiodini, G., 2006. Correlated increase in CO2 fumarolic content and
480 diffuse emission from La Fossa crater (Vulcano, Italy): Evidence of volcanic unrest or increasing

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gas release from a stationary deep magma body? Geophys. Res. Lett., 33, L13316, doi: 10.1029/2006GL026460.

Harris, A., Alparone, S., Bonforte, A., Dehn, J., Gambino, S., Lodato, L., Spampinato, L., 2012. Vent temperature trends at the Vulcano Fossa fumarole field: the role of permeability. Bull. Volcanol. 74:1293 1311 DOI 10.1007/s00445-012-0593-1.

Hildenbrand, T.G., Rosenbaum, J.G., Kauahikaua, J.P., 1993. Aeromagnetic study of the Island of Hawaii, J. Geophys. Res., 98, 4099-4119.

Iacobucci, F., Incoronato, A., Rapolla, A., Scarascia, S., 1977. Basement structural trends in the volcanic islands of Vulcano, Lipari, and Salina (Aeolian Islands, Southern Tyrrhenian Sea) computed by aeromagnetic and gravimetric data. Boll. Geofis. Teor. Appl. 20:73–74, 49–61.

Kearey, P., Brooks, M., 1991. An introduction to geophysical exploration. Oxford, Blackwell Scientific Publications, Second edition, pp. 1-254.

Keller, J., 1980.The island of Vulcano. Rend. Soc. Ital. Mineral. Petrol., 36,369–414. Lowrie, W., Kent, D.V., 2004. Geomagnetic polarity timescales and reversal frequency regimes. In: Channell J.E.T., Kent D.V., Lowrie W., Meert J., editors. Timescales of the Palaeomagnetic Field. America Geophysical Union. p. 117-129.

Mazzuoli, R., Tortorici, L., Ventura, G., 1995. Oblique rifting in Salina, Lipari and Vulcano Islands (Aeolian Islands, Southern Tyrrhenian Sea, Italy). Terra Nova, 7, 444–452.

Napoli, R., Currenti, G., Del Negro, C., 2007. Internal structure of Ustica volcanic complex (Italy) based on a 3D inversion of magnetic data. Bull. Volcanol. DOI 10.1007/s00445-007-0115-8.

Nicolosi, I, D'Ajello Caracciolo, F., Branca, S., Ventura, G., Chiappini, M., 2014. Volcanic conduit migration over a basement landslide at Mount Etna (Italy). Scientific Reports, 4 : 5293. DOI: 10.1038/srep05293.

Reid, M.E., Sisson, T.W., Brien, D.L., 2001. Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington. Geology, 29, 9: 779–782.

Revil, A., Finizola, A., Piscitelli, S., Rizzo, E., Ricci,T., Crespy, A., Angeletti,B., Balasco, M., Barde Cabusson, S., Bennati, L., Bole`ve, A., Byrdina, S., Carzaniga, N., Di Gangi, F., Morin, J., Perrone, A., Rossi, M., Roulleau, E., Suski, B., 2008. Inner structure of La Fossa di Vulcano (Vulcano Island, southern Tyrrhenian Sea, Italy) revealed by high-resolution electric resistivity tomography coupled with selfpotential, temperature, and CO2 diffuse degassing measurements. J. Geophys. Res., 113, B07207–1, 21 doi: 10.1029/2007JB005394.

Romagnoli C., Casalbore, D., Bosman, A., Braga, R., Chiocci, F.L., 2013. Submarine structure of Vulcano volcano (Aeolian Islands) revealed by high-resolution bathymetry and seismo-acoustic data. Marine Geology, 338, 30–45, DOI: 10.1016/j.margeo.2012.12.002.

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Sugihara, M., Okuma, S., Nakano, S., Furukawa, R., Komazawa, M., Supper, R., 2002. Relationship between geothermal activity and gravity anomalies on Vulcano Island, Italy. Proceedings 24th NZ Geothermal Workshop 2002.

Tinti, S., Bortolucci, E., Armigliato, A., 1998. Numerical simulation of the landslide-induced tsunami of 1988 on Vulcano Island, Italy. Bull Volcanol 61 :121–137.

Tivey, M.A., Dyment, J., 2010. The magnetic signature of hydrothermal systems in slow spreading environments, in Rona, P.A., Devey, C.W, Dyment, J., and Murton, B.J., eds., Diversity of hydrothermal systems on slow spreading ridge: American Geophysical Union, Geophysical Monograph Series, 188, 43–66.

Todesco, M., 1997. Origin of fumarolic fluids at Vulcano (Italy). Insights from isotope data and numerical modeling of hydrothermal circulation. J. Volcanol. Geotherm. Res. 79, 63–85 doi:10.1016/S0377-0273(97)00019-X.

Ventura, G., Vilardo, G., Milano, G., Pino, N. A., 1999. Relationships among crustal structure, volcanism and strike-slip tectonics in the Lipari-Vulcano volcanic complex (Aeolian Islands, Southern Tyrrhenian Sea, Italy). Physics of the Earth and Planetary Interiors, 116, 31–52.

Zanella, E., Lanza, R., 1994. Remanent and induced magnetization in the volcanites of Lipari and Vulcano (Aeolian Islands). Ann. Geophys. 37:1149–1156.

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Figure

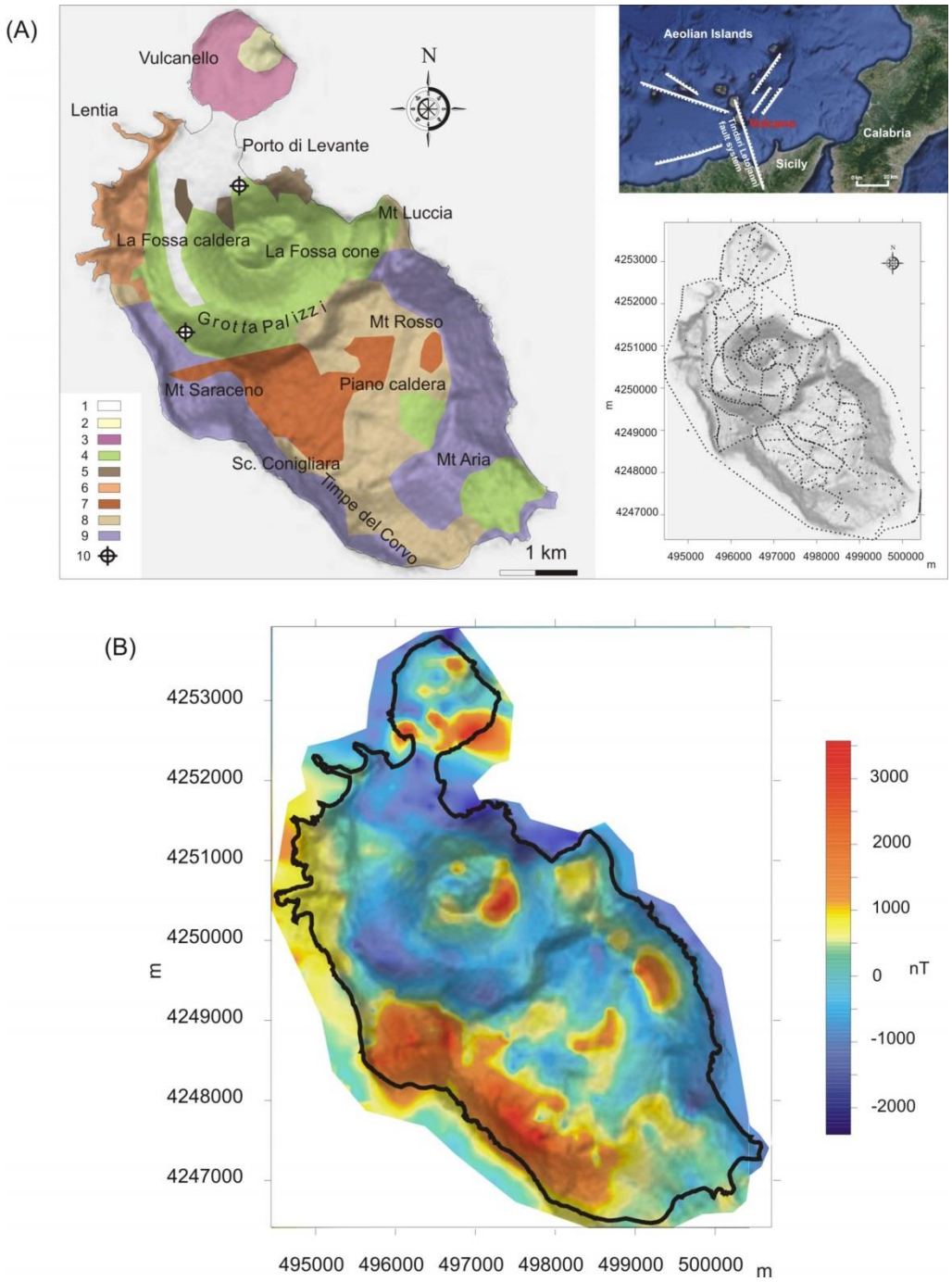

Figure 1 - (A) Simplified geological map of Vulcano Island. Legend: 1) alluvium and beach deposits; 2) Vulcanello pyroclastics: 3) Vulcanello lava flows; 4) Fossa cone pyroclastics; 5) Fossa cone lava flows; 6) Lentia domes and lava flows; 7) hyaloclastites and pillow lava; 8) lava flows and minor pyroclastics; 9) South Vulcano lavas and scorias; 10) drilling location. In the inset the black dashed lines represent measurement tracks. (B) Total-field magnetic anomaly map of Vulcano Island.

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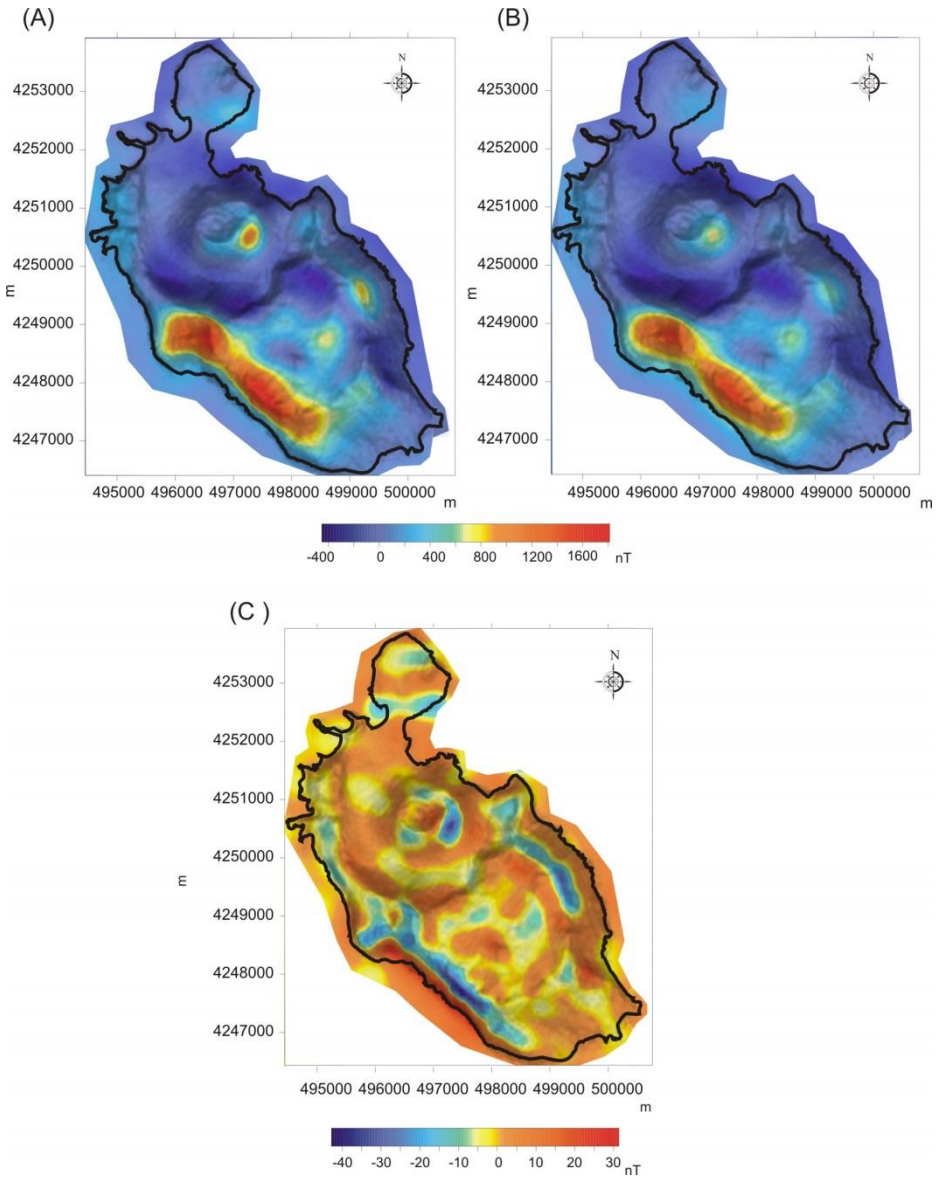

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564 Figure 2 - (A) Map of the local residual anomalies produced by subtracting the 3D regional trend
565 on the upward continued field. (B) Computed magnetic anomaly map. (C) Residual, total-field
566 magnetic anomaly map produced by subtracting the computed field from the observed field.
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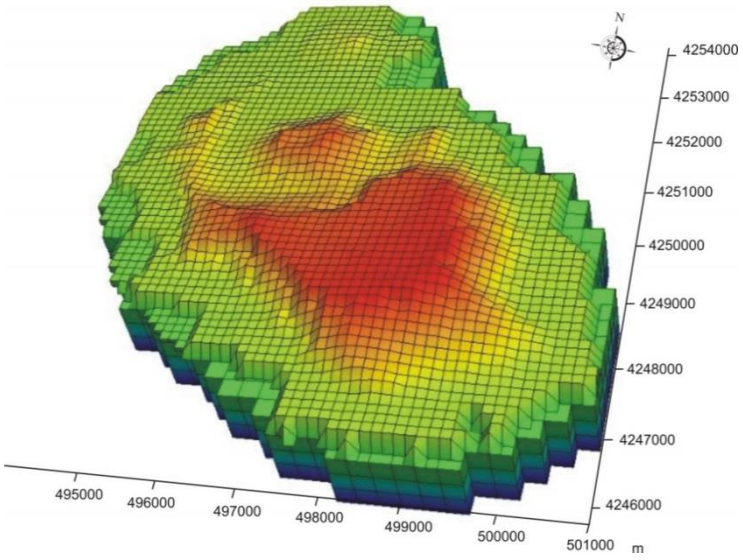

Figure 3 - Schematic configuration of the synthetic model used for the inversion process.

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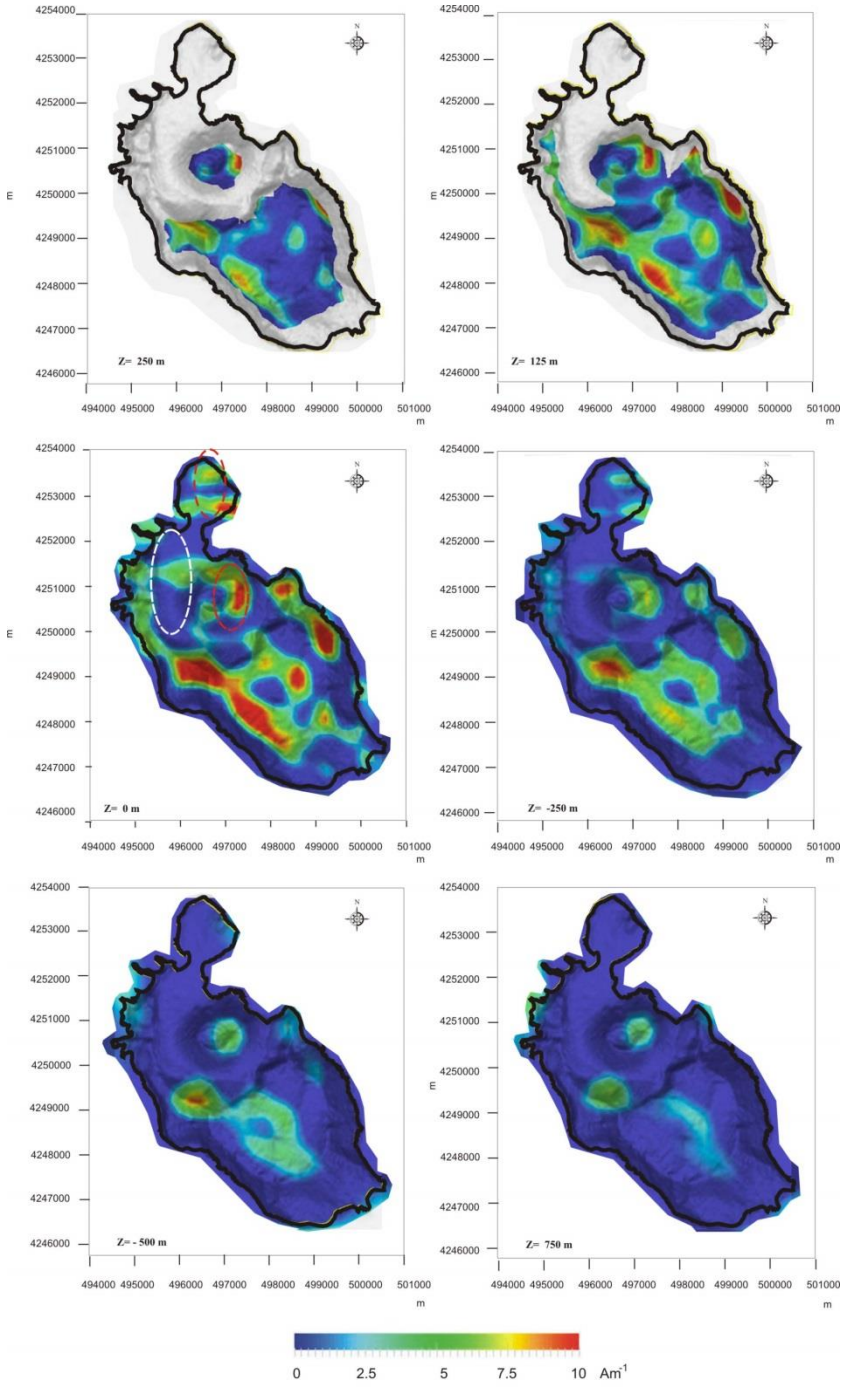

Figure 4 - The 3D magnetization model of the Vulcano complex. Horizontal layers of the model from 250 above sea level to 750 m below sea level. The dashed areas, in the layer at 0 km of depth, represent the low (white ellipse) and high (red ellipses) Vp seismic anomalies detected by Chiarabba et al., (2004).

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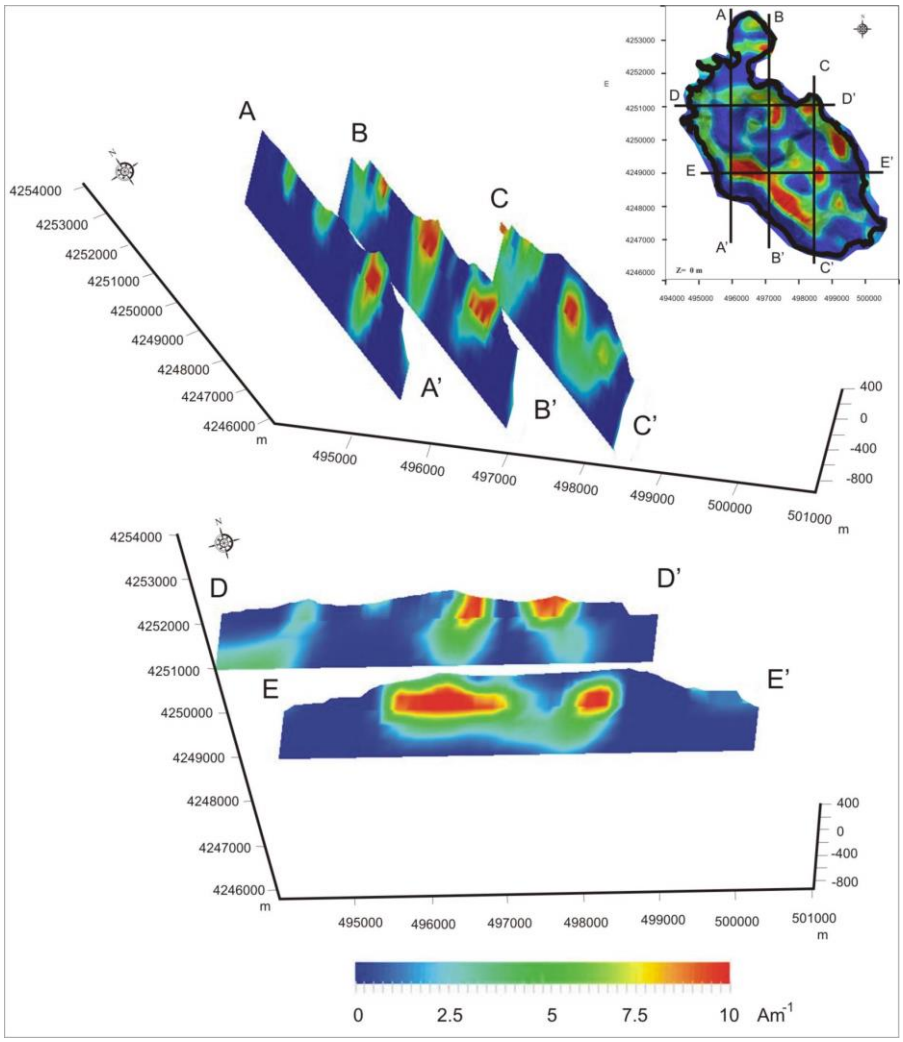

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584 Figure 5 – North South and West-East vertical sections of the 3D magnetization model of the
585 Vulcano complex. The inset shows the location of each profile superimposed to the horizontal layer
586 at 0 km depth.

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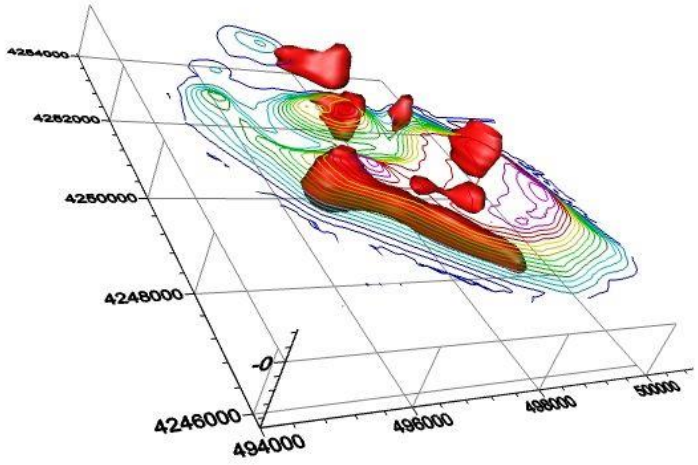

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591 Fig.6 – Three-dimensional volumes of the high-magnetization (more than 6 Am^{-1}) regions of the

592 Vulcano complex.

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