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3-D density structure and geological evolution of Stromboli volcano (Aeolian Islands, Italy) inferred from land-based and sea-surface gravity data

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ABSTRACT

We present the first density model of Stromboli volcano (Aeolian Islands, Italy) obtained by simultaneously inverting land-based (543) and sea-surface (327) relative gravity data. Modern positioning technology, a 1 × 1 m digital elevation model, and a 15 × 15 m bathymetric model made it possible to obtain a detailed 3-D density model through an iteratively reweighted smoothness-constrained least-squares inversion that explained the land-based gravity data to 0.09 mGal and the sea-surface data to 5 mGal. Our inverse formulation avoids introducing any assumptions about density magnitudes. At 125 m depth from the land surface, the inferred mean density of the island is 2380 kg m^{-3}, with corresponding 2.5 and 97.5 percentiles of 2200 and 2530 kg m^{-3}. This density range covers the rock densities of new and previously published samples of Paleostromboli I, Vancori, Neostromboli and San Bartolo lava flows. High-density anomalies in the central and southern part of the island can be related to two main degassing faults crossing the island (N41 and N64) that are interpreted as preferential regions of dyke intrusions. In addition, two low-density anomalies are found in the northeastern part and in the summit area of the island. These anomalies seem to be geographically related with past paroxysmal explosive phreato-magmatic events that have played important roles in the evolution of Stromboli Island by forming the Scari caldera and the Neostromboli crater, respectively.

1. Introduction

The island of Stromboli (surface area 12.6 km^2) in the Aeolian archipelago (Southern Italy, north of Sicily) is part of a volcanic arc that developed along a NE–SW regional extensional fault system. It rises 2400–2700 m above the sea floor and peaks at 924 m above sea level. Stromboli is characterized by a complex geological structure caused by the interplay of six distinct eruptive epochs and important vertical caldera-type and lateral collapses. These collapses have largely conditioned the deposition of younger products by providing topographic lows, but also barriers to lava flows. They have also played key roles in ending eruptive epochs (Hornig-Kjarsgaard et al., 1993; Pasquarè et al., 1993; Tibaldi, 2010; Francalanci et al., 2013). In contrast to the many detailed geological studies, very few attempts have been made to image the internal 3-D structure of Stromboli using geophysical methods.

Bossolasco (1943) performed a land-based magnetic survey on Stromboli, while Okuma et al. (2009) presented the first 3-D model by inverting airborne magnetic data. They found an important magnetization low below the summit craters that they explained by demagnetization caused by the heat of conduits and hydrothermal activity, as well as accumulation of less magnetic pyroclastic rocks. The magnetic highs are located in areas exposed by basaltic-andesite to andesite lavas. Bonasia and Yokoyama (1972) and Bonasia et al. (1973) presented gravity data from Stromboli. They found a Bouguer anomaly low in the central part of the island using 37 relative gravity measurements with a vertical positioning accuracy of ±3 m. Their interpretation of a corresponding density-low in the summit area is questionable as no terrain or bathymetric corrections were carried out (see discussion in Okuma et al., 2009). Indeed, topographic and bathymetric effects on volcanic islands are extremely important and will, if left unaccounted, mask any information about density variations. It is thus very likely that the negative Bouguer anomaly inferred by Bonasia et al. (1973) in the central part

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of the island is mainly caused by unaccounted topography. Furthermore, their positive Bouguer anomalies to the northeast and southwest are likely due to unaccounted effects of shallow platforms located below the sea level (Gabbianelli et al., 1993). This implies that no reliable information exists to date about the density structure of Stromboli.

Three-dimensional inversions of gravity data from volcanic islands are rather common. For instance, inversions have been performed using gravity data acquired over the Canary Islands (e.g., Montesinos et al., 2006, 2011), the Azores (e.g., Represas et al., 2012), and at La Soufrière volcano (Coutant et al., 2012). These studies typically relied on 93 to 365 land-based gravity data (and sometimes sea-surface data; e.g., Montesinos et al., 2006). They definitively helped to improve the understanding of structural settings and their control on volcanic activity.

Gravity inversions are typically performed using finely discretized models and least-square methods that seek smooth property variations (e.g., Coutant et al., 2012) or methods that seek the appropriate location, shape and volume of anomalies with predefined density contrasts (Camacho et al., 2000; Montesinos et al., 2005). The first category refers to linear inverse problems that are easily solved, but the resulting models have smoothly varying property variations that make the identification of geological contacts difficult. The second category leads to more time-consuming nonlinear inverse problems, but allows resolving the volume of anomalous bodies provided that the appropriate density contrasts are known. Previous gravity studies on volcanic islands (see citations above) suggest that the quality of the density models are not only dependent on the coverage and quality of the gravity data, but that they are also strongly affected by (1) the resolution and precision of the topographic and bathymetric models and (2) how this information is included in the inversion.

We present results from the first detailed land-based gravity survey on Stromboli. A total of 543 gravity stations were complemented with a subset of 327 sea-surface gravity data. The data were inverted in 3-D to better understand the geological structure at depth and its control on the hydrothermal system. The inversion incorporated a high-resolution and precise digital elevation model (DEM) including the bathymetry. The resulting density model was interpreted in the light of previous geophysical studies and present-day geological understanding of this volcanic edifice.

2. Geological setting

The edification of the emerged part of Stromboli can be subdivided in the following six main epochs (Francalanci et al., 2013), shown in Fig. 1:

(1) Epoch 1: (Paleostromboli I period: from 85 to 75 ka). This period is mainly associated with massive to blocky lava flows and pyroclastic products. Paleostromboli I ended with the formation of the Paleostromboli I caldera (see "PST I" in Fig. 1).

(2) Epoch 2: (Paleostromboli II period: from 67 to 56 ka). This second epoch is characterized by massive to blocky lava flows interbedded with scoriaceous deposits and ended with the Paleostromboli II caldera that can be evidenced in Vallone di Rina.

(3) Epoch 3: (Paleostromboli III period and Scari Units: from 56 to 34 ka). The Paleostromboli III period is particularly developed in the Vallone di Rina. Sub-period 3a displays mainly pyroclastic products with lava flows alternating with scoriaceous beds in the upper part of the geological succession and ends with a caldera formation. Sub-period 3b is mainly associated with lava flows. This period ended with the hydromagmatic Scari Unit deposits, located in the northeastern part of the island. Nappi et al. (1999) suggested its eruptive center from sector of provenance of ballistic ejecta (see Fig. 1). No caldera boundary has been evidenced in this area, probably due to its refilling by younger products. Epoch 3 ended with the formation of the Paleostromboli III caldera ("PST III" in Fig. 1).

(4) Epoch 4: (Vancori Period: from 26 to 13 ka). The Vancori period is characterized by successions of lava flows and is subdivided into three sub-periods 4a, 4b, 4c, separated by a caldera formation, a quiescence period and a sector collapse.

(5) Epoch 5: (Neostromboli Period: from 13 to 4 ka). The Neostromboli period is essentially characterized by lava flows and scoriaceous deposits and it is subdivided into three sub-periods 5a, 5b, 5c, separated by sector collapse, and two strong hydromagmatic eruptions. These eruptions associated with pyroclastic and pumice deposits (Punta Labronzo deposits) were responsible for the formation of the Neostromboli crater (Fig. 1).

(6) Epoch 6: (Pizzo and Present-day activity: since 2 ka). This last period is subdivided into 3 sub-periods. Sub-period 6a is associated with the pyroclastic successions related to the Pizzo activity, lava flows, such as, San Bartolo (Fig. 1) and it ends with the Rina Grande sector collapse (Fig. 1). Sub-period 6b is associated with scoriaceous and pumiceous products of the Present-day activity, massive lava flows, and the Sciara del Fuoco sector collapse (Fig. 1). Sub-period 6c began after this last major collapse (1631–1730 AD) and is characterized by scoriaceous (pumiceous) and lava flow deposits related to Present-day activity in the Sciara del Fuoco area, and to reworked scoriaceous product in the Rina Grande area. The most recent effusive eruption of Stromboli took place in 2007 from February 27 to April 2. This eruptive event was characterized by persistent lava flows along Sciara del Fuoco and by a paroxysmal explosion on March 15.

During these six main epochs of activity, lava flows can be considered as the main eruptive dynamics of the emerged part of the Stromboli edifice.

3. Method

3.1. Forward modeling

The least-square smoothness-constrained gravity inverse problem is linear and easy to solve, but inversion results can be severely affected by inaccurate forward modeling. Our 3-D forward model was thus designed to accommodate precise positioning, a high-quality DEM with a resolution of 1 × 1 m (Marsella and Scifoni, private communication) covering the aerial part of the island and a bathymetric model with a resolution of 15 × 15 m (Casalbore et al., 2011).

The modeling domain was discretized by rectangular parallelepipeds. The vertical component of the gravity response of each parallelepiped was calculated using the analytical solution of Banerjee and Das Gupta (1977). To accurately account for the bathymetry and its effect on the gravity data, the discretized modeling domain had a lateral extent exceeding 20 km. In addition, external forward model cells were extended 10^6 m to the sides to avoid boundary effects. A 10 × 10 m resolution model was derived from the mean values of 10 × 10 m blocks of the DEM and by interpolation of the bathymetric model. The gravity forward model used this 10 × 10 m resolution model to calculate the integrated response of larger inversion cells when these cells intersected the land surface or the sea floor. The forward model discretization was further refined to 1 × 1 m for inversion cells centered within 100 m of a given measurement location.

3.2. Inverse modeling

The smoothness-constrained least-squares inverse problem consists of solving the following system of equations in a least-squares sense (e.g., Coutant et al., 2012):

$$\begin{bmatrix} \mathbf{C}_d^{-0.5}\mathbf{F} \\ \lambda \mathbf{W}_m \end{bmatrix} [\mathbf{m}] = \begin{bmatrix} \mathbf{C}_d^{-0.5}\mathbf{d}' \\ \mathbf{0} \end{bmatrix}, \tag{1}$$