Influence of crust type on the long-term deformation of a volcano: example from Mt. Etna (Italy)

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Introduction

The volcanic areas experience the greatest deformation in term of velocity and spatiotemporal variability. Cyclic episodes of short-term inflation and deflation, registered during eruptions, are related to magma chambers or dykes migration. Long-term deformations are ascribable to intrusion of large subvolcanic bodies into the crust or even to sub-crustal processes like the rise of a mantle plume. Unfortunately, is not always possible to discriminate among all these processes because they superimpose in space and in time.

In this research, bringing the example of Mt. Etna volcano (Italy), we highlight the existence of a source of deformation not directly related to a volcanic process, but that is rather related to the nature of the crust hosting the volcanism.

The occurrence of “anorogenic” volcanism such Mt. Etna in the collisional context of the Central-Mediterranean area can sometimes appear anomalous (Lustrino et al. 2011), and is a part of why the tectonic origin of volcanism of Mt. Etna is still debated. Also debated is the nature of the crust on which Mt. Etna emplaced about 500 ka. Several authors suggest that this crustal block is not continental but it is rather a remnant of an old, weathered oceanic crust (Sapienza and Scribano 2000; Ciliberto et al. 2009; Manuella et al. 2013; Barreca 2014).

In this work we are able to accurately describe and model the altimetric distribution of a stratigraphic marker within the Etnean substratum and, taking into account the geological features of the area, we identify the different individual Quaternary deformation processes that have interacted.

Late quaternary deformation at Mt. Etna

A basin filled with more than 1000 m of pelagic sediments (dated at 1.2-0.6 Ma; Di Stefano and Branca 2002) lie south of Mt. Etna. The marine deposits are widespread below the entire volcanic edifice although they crop out only locally where they have not been covered by younger deposits and lava flows. They comprise 600 m of marly clays with rare, thin, sand levels evolving upwards in tens of meter of thicker yellow sands with intercalations of polygenic conglomerate. The transition between marly clays and sand is easy to detect in boreholes or geophysical surveys and represents a very useful stratigraphic marker. We detected this marker in 3056 borehole logs; the overall altitude range of the data is between -98 m below and 452 m above sea level.

Knowing the deposition depth and the age of the deposit we can estimate the vertical deformation rate for the marker. Moreover, considering the main tectonic features of the study area (Catalano et al. 2011), we are able to detect sources of deformation with different magnitude (from 0.2 mm/y to 1.3 mm/y) and acting at different scale (local and regional). In detail we recognize:

1. homogeneous, regional uplift (from 0.3 mm/y to 0.5 mm/y) interpreted either as an isostatic response to the passive subduction of the detached Ionian slab (Wortel and Spackman 2000) or as an asthenospheric flow at the lateral edge accompanying the rollback of the slab (Shellart 2010; Faccenna et al. 2011);
2. localized uplift coherent with the activity of two local thrust ramps;
3. differential uplift component linearly increasing northwards and not ascribable to the known features of the area.

Other morphological markers (Late-Pleistocene marine terraces and a submerged marine platform of 20 ka) are consistent with the last, so far unknown, source of deformation. Our study suggests that it acted in the same area, constantly over time, and with rates ranging from 0.16 mm/y to 0.75 mm/y (De Guidi et al., 2014). Considering its bell-like pattern and its almost axial position with the volcano, we propose a volcano-related origin for this uplift component.

Certainly very short-term deformations affect the volcanic edifice, (e.g. inflation and deflation), but, it is reasonable to suppose that over long periods these localized, cyclic deformations become negligible and, we require a greater, stable source of deformation to explain the pattern of surface doming.

Modelling

To model the doming we performed an analytical inversion of the whole buried sedimentary substrate of Mt. Etna. To minimize effects of erosion before the substrate was covered by lava flows we selected only the ridges of the paleovalleys, therefore avoiding the areas with greatest loss of material.

The estimated vertical component of the domical deformation was used as an input to constrain an isotropic half-space elastic inversion model, as is routinely done with GPS and InSAR ground-deformation data. Values of 30 GPa and 0.25 were assumed for the shear modulus and Poisson's ratio in the half-space, respectively. The value of the shear modulus chosen corresponds to a typical value of crustal rigidity commonly used in modeling which is found to be an average rigidity value for Mt. Etna (Chiarabba et al. 2000). The inversions were performed by using the genetic algorithm approach. Because of the data's distribution and the 1D nature of deformation data, to model the observed vertical ground deformation pattern we adopted the point source model (Mogi 1958), representing the simplest source used in volcano deformation modeling. In order to test biases due to our chosen starting parameters, we performed several inversions with different sets of model parameters. In all inversions, the algorithm converged rapidly to a similar solution. The best result indicates a pressure source located at a depth of 16.4 km b.s.l. beneath the upper western flank of the volcano with a volume change of $3.8 \cdot 10^6$ m^3/yr . This source is able to explain a large amount of the observed uplift and rates, reproducing well the wavelength of the deformation pattern (Fig. 1).

Although a viscoelastic rheology could be more appropriate to describe the medium at the mantle-crust transition, we retain a simple elastic rheology because i) the deformation's vertical component alone is insufficient to constrain the depth of the pressurized magma body using a viscoelastic rheology, because the main effect of viscous deformation is to reduce the contribution of the horizontal component of deformation with respect the vertical component as function of the viscosity, and ii) there is little known about the viscoelastic medium beneath Etna at depths greater than 10 km.

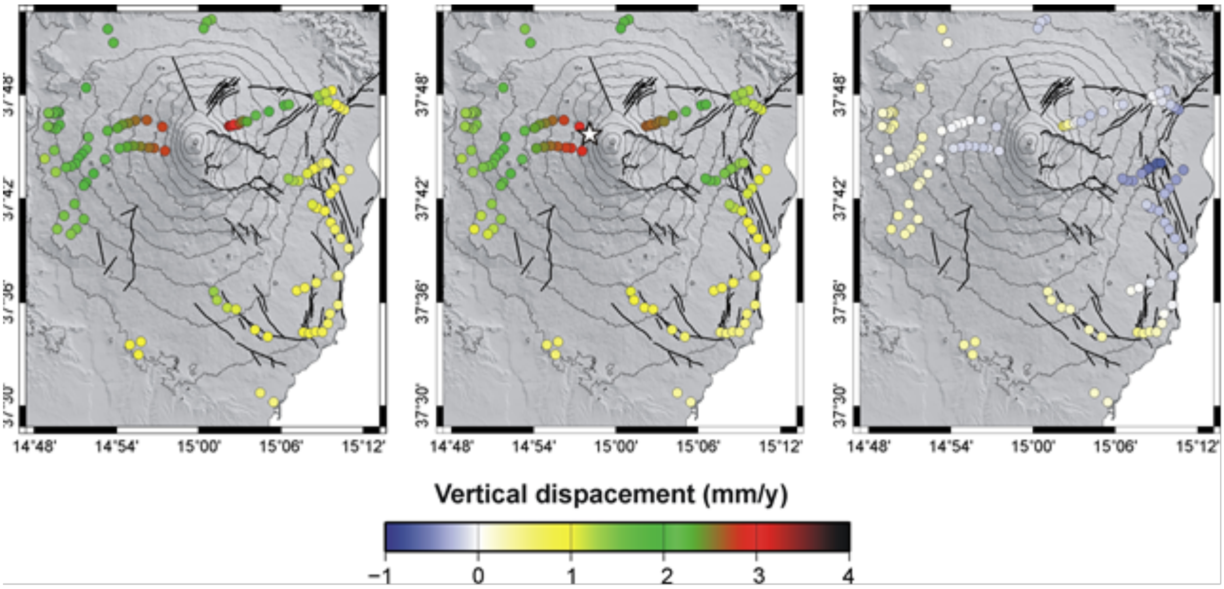

Fig. 1.: Observed deformation pattern of the buried sedimentary substrate (left), calculated deformation (centre) and residual differences between observed and calculated (right); the white star represent the projection of the source of deformation; black lines represent the faults.

Conclusions

Several authors suggest that the Hyblean crust (i.e. the crust under Mt. Etna) is a remnant of an old, weathered oceanic crust. It is also confirmed the existence of a Triassic hydrothermal fossil system which reactivation, connected with magmatic episodes, caused the diapiric emplacement of serpentinized clays at shallow level in the crust (Scribano et al. 2006; Manuella et al. 2012; Barreca 2014).

The process and the mechanism leading to the formation of serpentinites intrusions are consolidated in the literature (Fryer and Fryer 1987; Fryer 2002). The increase of volume that drives the diapiric uprise has been estimated to be ∼40% (Iyer et al. 2010) and the uplift rate ranging from mm to cm per year (Skelton and Jakobsson 2007). Giant diapirs up to 2 km in height have been recognized worldwide showing conical shapes at surface (Fryer et al. 1990; Fryer 2002; Schuiling 2011). Within this frame, the doming of Mt. Etna could result from a volcano-driven diapiric emplacement of a notable amount of hydrothermal material from the lower crust to the shallow levels. In various areas of this crustal block (onshore and offshore) there are geological and geophysical evidences of such intrusions (Catalano et al. 2000; Manuella et al. 2012). Minor evidences of this phenomenon are represented by superficial hydrothermal activity widespread all around the volcanic edifice. Moreover the contemporaneous beginning of the doming and of the volcanic activity at Mt. Etna (∼ 600 ky) strongly support this hypothesis.

Even agreeing with the mantle-plume origin of Mt. Etna as suggested by some authors (Tanguy et al. 1997; Clocchiatti et al. 1998; Montelli et al. 2003) a rising thermal anomaly would melt the lithospheric mantle rather than provoke its volumetric expansion causing, in the long term, the thinning of the overlying crust and not the crustal arching (Burov and Guillou-Frottier 2005; Sleep et al. 2006; Leng and Zhong 2010), therefore a mantle-related process is definitely excluded.

Volcanic doming with similar uplift patterns and magnitude is encountered in other volcanic districts (Acocella and Mulugeta 2001; Zhong and Watt 2002; Pim et al. 2008; Marturano et al. 2011), but the causative mechanism has sometimes been neglected. Therefore considering the nature of the crust is of fundamental importance approaching the long.-term deformation of a volcano.

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