Large scale ground deformation of Etna observed by GPS between 1994 and 2001

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[1] We have processed thirty Global Positioning System (GPS) campaigns carried out at Etna from 1994 to early 2001 between the last two main flank eruptions of the Mt. Etna (Sicily, Italy). This rest period allowed us to investigate the deep magma plumbing system of the Mt. Etna. The temporal dynamics of twenty-three points observed three times or more were analyzed. All the time series show a first-order linear trend during the five years period. It suggests that the volcano was continuously deformed by the action of a deep source while a discrete activity of the volcano was observed at the summit. We have interpreted the residual deformation field as the result of an major eastward motion of the eastern flank of the volcano.
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1. Introduction

[2] Etna is the most active volcano in Europe. Several active tectonic structures are located in its eastern part. Some of these structures, such as the Timpe fault system (extensive fault system trending NNW-SSE belonging to the Maltese escarpment) and the NNE-SSW faults (belonging to the Messina-Comiso line) were inherited from its geodynamic setting [*Monaco et al.*, 1997; *Laigle et al.*, 2000; *Nicolich et al.*, 2000; *Jacques et al.*, 2001]. Others, such as the Valle del Bove [*Calvari et al.*, 1998], the Pernicana fault system [*Azzaro et al.*, 1998, 2001a, 2001b], and the rift zones [*Tibaldi and Groppelli*, 2002] (Figure 1), are linked to Mt. Etna's activity.

[3] The Etna volcano GPS network, conceived in the late eighties, improved and maintained by Istituto Nazionale di Geofisica e Vulcanologia (INGV) research team, is composed of two main parts. Firstly, a local reference frame, relatively far from Mt. Etna's influence and assumed stable. Secondly, a monitoring network on the volcano dedicated to the study of the volcano dynamics [*Puglisi et al.*, 2004]. Thus, this network is able to detect both volcanic and tectonic deformations of the area.

[4] The last three flank eruptions of Mt. Etna occurred in 1991–1993, in July 2001 and November 2002 [*Branca and Del Carlo*, 2004]. The time interval of our study was chosen to investigate the deep magma plumbing system of Etna [*Patane et al.*, 2003] while the GPS network remained stable [*Puglisi et al.*, 2004].

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2. Data and Data Processing

[5] Between 1994 and early 2001, thirty GPS campaigns were carried out by the INGV research group at twenty-three different benchmarks (Figure 1). All INGV receivers were Trimble 4000 SST/SSI. The various campaigns used in this study were designed for various aims (i.e., monitoring surveys, specific experiment in support to kinematic surveys or photogrammetry). Therefore, they were not homogenous in terms of duration of observations, sampling rates, number of measured benchmarks, number of instruments involved. Typically measurement sessions last two to four hours at 10, 20, or 30 seconds sampling rate. Station 98, located on the roof of the INGV building in Catania, records continuously during the campaigns.

[6] To tie the local network to the European Reference Frame (EUREF), we have processed the available data from permanent sites located in southern Europe with our local data set using GAMIT software [*King and Bock*, 1999]. All the ambiguities have been fixed for baselines shorter than 500 km only. Adjusting the computed baselines for each campaign using the GLOBK software [*Herring*, 2005], we established a set of coordinates for each campaign for the points measured on Etna as well as for the International GPS Service (IGS) stations.

3. Stability of the Local Reference Frame

[7] Our first objective was to establish the stability of the site 98 (Catania) and the four other sites (10, 18, 20, and 32) located around Etna and belonging to the local reference frame. The velocities were estimated and compared to the International Terrestrial Reference Frame (ITRF2000) solutions [*Altamimi et al.*, 2002]. Figure 2 shows the velocity vectors obtained for the IGS sites plus five sites of the local reference frame. Moreover, the comparison between our solutions and ITRF2000 solutions at permanent sites allows us to be confident in our results (Figure 2).

[8] The site Catania (98) show a clear difference with respect to Noto which is considered as representative of the stable Nubia plate [*Hollenstein et al.*, 2003]. Indeed, Catania is moving on average at a velocity of 7 mm/yr in the N120E direction with respect to Noto. Like the regular IGS stations (not shown) the time series of Catania site show also a first-order linear trend while the east component of Catania shows a higher noise with respect to the north component. In the Catania area, the bending of the anticline structure identified by [*Borgia et al.*, 2000] might produce

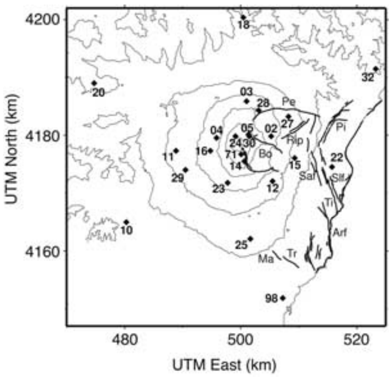

Figure 1. Location of the GPS benchmarks and tectonic settings [from *Monaco et al.*, 1997]. MA: Mascalucia, TI: Timpe, BO: Valle del Bove, PE: Pernicana-Provenzana, Slf: San Leonardello,Rip: Ripa della Naca, Pi: Piedimonte, Ma: Mascalucia-Tremesieri, Tr: Tremestieri, Arf: Aci Reale, Ti: Timpe, Saf: San Alfio.

the measured velocity vector. However, the magnitude obtained here is one order of magnitude lesser than reported by *Borgia et al.* [2000] while the direction is slightly different (ESE here and SE by *Borgia et al.* [2000]). This discrepancy might be due to the different location of the benchmarks and/or to the different GPS data set considered in the two papers, the data set used here being much more complete both in time and space.

[9] The general behavior of the reference frame shows a general radial extension around the volcano of 10 mm/yr at a distance of 25 km from the summit. This observation confirms the previously published work of *Puglisi et al.* [2004] and suggests that a deep source could be invoked to model the Mt. Etna's deformations during this period.

4. Displacements of Points on Etna and Point Source Model

[10] To discuss the stability of the other points in the local reference frame and the evolution of the points located on Etna, we removed from each time series of coordinates the velocity of Noto in order to plot local time-series (Figure 3).

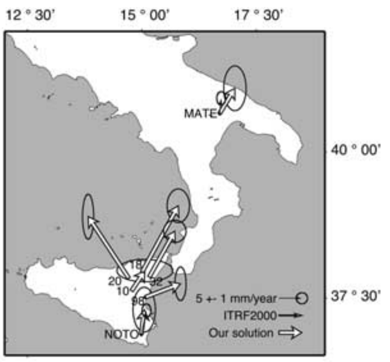

Figure 2. Velocities of the five benchmarks of the local reference frame of Mt. Etna with respect to stable Eurasia plate in ITRF2000 [*Altamimi et al.*, 2002]. The consistency of our solution with the ITRF2000 is checked at NOTO and MATE permanent sites.

As with the others benchmarks, it is interesting to note that the evolution of the coordinates of everyone of the measured benchmark on the volcano are linear to first-order during the period 1994–1999. This observation confirms the previous results presented by *Puglisi et al.* [2003] and [*Lundgren et al.*, 2004] using radar data sets.

[11] This allows us to compute the mean velocities of each benchmark from the plotted time-series using the formal errors on the slope of each regression line (Figure 4). Errors were computed by using a least-square approach on the noise of every time-series (Figure 4). The computed errors are one order larger than the formal ones provided by GLOBK and are no doubt more realistic with commonly observed day to day repeatabilities.

[12] The velocities are radially distributed and seem to be organized as the result of a ponctual source in a overpressure state located beneath Mt. Etna. As the state of this deep source was already discussed by *Patane et al.* [2003], we have chosen to model the velocity field associated to the over-pressure of a Mogi point source [*Mogi*, 1958].

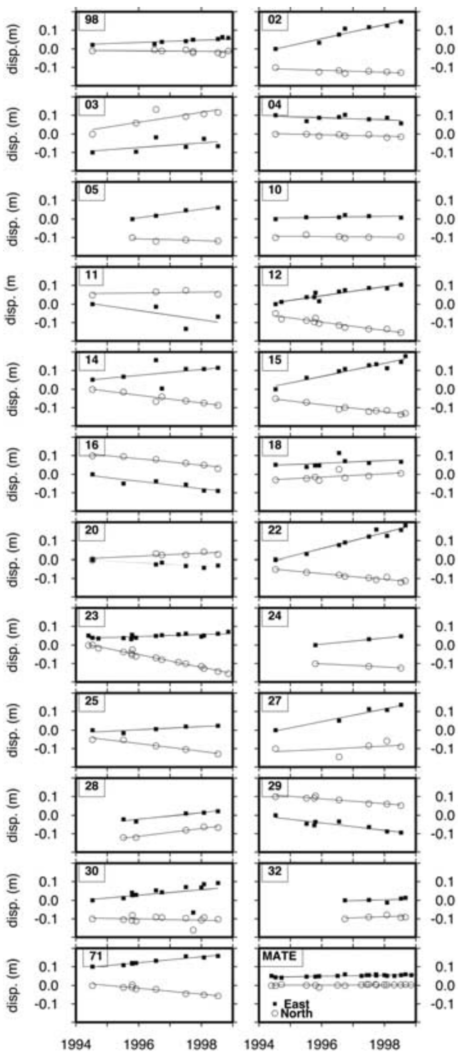

Figure 3. Time-series of displacement for 22 sites with respect to NOTO permanent site. All benchmarks exhibit an first-order linear evolution between 1994 and 1999.

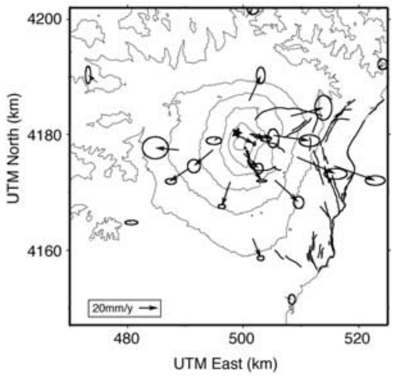

Figure 4. Velocities computed from time-series presented in Figure 3 (reference NOTO). The location of the source is symbolized by a black star.

[13] The best-fit solution of the Mogi point is located near the summit of the volcano (East 499.0 km, North 4180.5 km UTM33).

[14] The best fitting solution is a Mogi point source located 9.5 ± 1 km beneath the summit assuming a vertical maximal velocity of 80 ± 5 mm/yr (Figure 5; see Table S1[1]). The depth of this source is in agreement with the results of several studies carried out by modeling ground deformation data (both GPS and INSAR; see Table S2) [*Bonaccorso*, 1996; *Lanari et al.*, 1998; *Puglisi et al.*, 2001; *Bonforte and Puglisi*, 2003; *Lundgren et al.*, 2003, 2004]. The volume rate of this source was estimated to 60.10^6 m^3/yr. The vertical accuracy of the GPS velocities were not accurate enough to test the impact of the topography of the volcano on our modelling. However, the numerical simulations of the impact of the topography on the deformation field allow us to estimate that the computed vertical maximal inflation were overestimated of 30 percent near the summit (24 mm/yr).

[15] The point source model explain the observations except in the eastern part of the volcano (Sites 15 and 22) and along the Pernicana fault system (Site 27, Figure 5). The fact that the model does not fit exactly in the eastern part of the network along the Ionian coast (Figure 6) is in agreement with the eastward movement of the eastern part of the volcano toward the sea [*Rasà et al.*, 1996; *Froger et al.*, 2001; *Puglisi et al.*, 2003]. The magnitude of the site 15 's velocity (11 mm/yr to the East) supports the hypothesis of the existence of a large slough located along the Ionian coast limited by the Pernicana fault to the north, Ionian coast to the East and Timpe fault system to the West. The volume of this slough was estimated from 5 to 50 km^3 by *Houlié* [2005] while the mechanism driving the dynamic of these units is not clearly identified yet.

5. Discussion

[16] While our vertical processing is not accurate enough to compute vertical velocities to be discussed here, there is no doubt that vertical displacements downward have been occurred during the studied period between the eastern fault system in extension (Pernicana fault and the Timpe fault

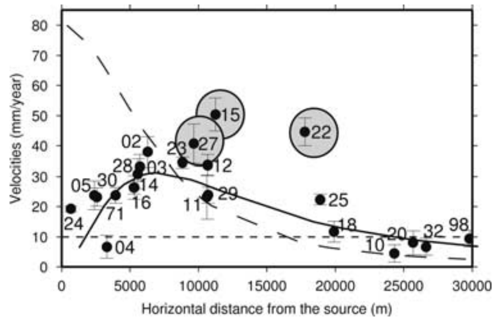

Figure 5. Data (black filled circles) and best model (black lines) plotted versus the horizontal distance from the source [*Mogi*, 1958]. The computed horizontal displacements are symbolized by a continuous black line while the vertical one by a dashed one. Three sites dynamics do not fit with the modeled displacements (15, 22 and 27). Those are highlighted by grey filled black circles.

system) as described by *Monaco et al.* [1997] using long-term tectonic evidences and *Puglisi et al.* [2003] using Permanent Scatterer Synthetic Aperture Radar (PSSAR).

[17] In our study, it has been shown that the volcano expanded nearly linearly during 5 years. This pattern might be justified by an inflating point source located about 6.5 ± 1 km b.s.l. The modeled source is close to the source of deflation detected after the 1991–1993 crisis by *Massonnet et al.* [1995]. As a result, the source involved in the two crises seems to be the same. This source is similar to the one presented by *Métrich et al.* [2004] and explains the lava composition during the 2001 to 2003 eruptions. However, the existence of a large magma chamber is still discussed. A very complex area, located around our source center should be the place of repeated injected dikes. We think the amount of available data is not sufficient to discriminate the two models.

[18] The residual velocity field is coherent with already published works about the large flank instability of the eastern part of Mt. Etna [*Borgia et al.*, 2000; *Froger et al.*, 2001; *Bonforte and Puglisi*, 2003; *Lundgren et al.*, 2003]. Therefore, we trust that a Mogi point source is able to describe the long-term behaviour of this volcano rather than in a general radially distributed collapse of Mt. Etna which

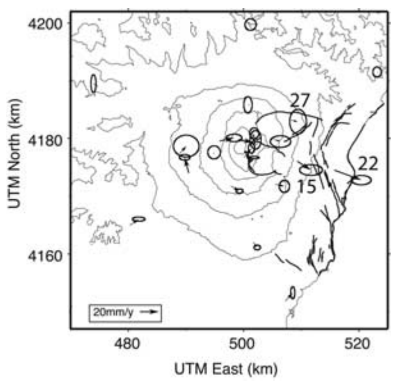

Figure 6. Residuals velocities after removing the point source model. To the east, benchmarks 15 and 22 present the largest residuals.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL024414.

could reflect some short term event[*Lundgren and Rosen*, 2003].

[19] As the velocities across the Timpe fault system are up to twenty times faster [*Houlié*, 2005] than those expected by its tectonic setting [*Monaco et al.*, 1997], the velocities along this fault system are maybe irregular during time, possibly linked to the volcano activity, and introduce the possibility of a recent cyclic activity of the volcano [*Métrich et al.*, 2004]. The non-occurrence of some large seismic events ($M > 6$) in the Etna area [*Jacques et al.*, 2001; *Chiarabba et al.*, 2005] and our work brings support to this thesis.

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