Modeling ground deformations of Panarea volcano hydrothermal/geothermal system (Aeolian Islands, Italy) from GPS data.

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Abstract

Panarea volcano (Aeolian Islands, Italy) was considered extinct until November 3, 2002 when a submarine gas eruption began in the area of the islets of Lisca Bianca, Bottaro, Lisca Nera, Dattilo and Panarelli, about 2.5 km east of Panarea Island. The gas eruption decreased to a state of low degassing by July 2003.

Before 2002 the activity of Panarea volcano was characterized by mild degassing of hydrothermal fluid. The compositions of the 2002 gases and their isotopic signatures suggested that the emissions originated from a hydrothermal/geothermal reservoir fed by magmatic fluids.

We investigate crustal deformation of Panarea volcano using the GPS velocity field obtained by the combination of continuous and episodic site observations of the Panarea GPS network in the time span 1995-2007.

We present a combined model of Okada sources which explains the GPS results acquired in the area after December 2002. The kinematics of Panarea volcano show two distinct active crustal domains characterized by different styles of horizontal deformation, supported also by volcanological and structural evidences. A subsidence in the order of several mm/yr is affecting the entire Panarea volcano and a shortening of 10^{-6} yr^{-1} has been estimated in the Islets area.

Our model reveals that the degassing intensity and distribution are strongly influenced by geophysical-geochemical changes within the hydrothermal/geothermal system. These variations may be triggered by changes in the regional stress field as suggested by the geophysical and volcanological events that occurred on 2002 in the Southern Tyrrhenian area.

Key words: GPS monitoring, model, gas eruption, active volcanism, Aeolian arc.

1. Introduction

Crustal deformation measurements are among the most sensitive and reliable indicators to evaluate the volcanic hazard related to volcanic unrests (Dvorak and Dzurisen, 1997) caused by magma emplacement and/or fluid migration (Gottsmann et al., 2007). A clear link for the hydrothermal fluid contribution to geophysical signals has been found in several volcanoes (Todesco et al., 2004; Tikku et al., 2006) .

On November 3 2002, a gas eruption began about 2.5 km offshore, east of Panarea Island (Aeolian Islands, Italy). Submarine craters opened at the top of a 2.3 km^2 shallow rise of the seafloor, between -2 m and -30 m below sea level in the area surrounded by the islets of Panarelli, Lisca Bianca, Bottaro, Lisca Nera and Dattilo (hereinafter as the “Islets area”) (Figure 1) (Anzidei et al., 2003a, 2003b; Esposito et al., 2006). The degassing of Panarea on November 3rd followed a sequence of geophysical and volcanological events which occurred in the southern Tyrrhenian zone (Anzidei et al. 2003b; Esposito et al., 2006): the offshore earthquake (Ml=5.6) between Palermo and Ustica Island on September 6th, the onset of the paroxysmal eruption at Mt Etna on October 27th and the eruption at Stromboli that started on December 28th (Figure 1 a).

Until November 2002, the presence of a hydrothermal/geothermal system at Panarea was interpreted in terms of post-volcanic phenomena caused by fluid circulation due to cooling of a magmatic source (Romano 1973; Bellia et al.,1986; 1987; Gabbianelli et al., 1990; Italiano and Nuccio, 1991; Calanchi et al., 1995, Anzidei, 2000). A deep and a shallow zone were recognized (Italiano and Nuccio 1991; Calanchi et al. 1995). However, gas eruptions of similar intensity to the 2002 eruption had not been previously observed during the last century (Mercalli, 1883). Gas compositions and isotopic signatures suggested that the 2002 emissions originated from a hydrothermal/geothermal reservoir fed by sea water and magmatic fluids

(Caliro et al., 2004; Chiodini et al., 2006; Capaccioni et al, 2005, 2007). Geomorphological evidence of past phreatic explosions, like that of November 2002, have been found in the relics of several craters on the seafloor, revealed by multibeam bathymetry (Anzidei et al., 2005), as well as by geological investigations (Esposito et al., 2006). Intense hydrothermal activity is also evident in the Islets area.

Prior to the 2002 event one GPS station was present on Panarea Island as part of Tyrgeonet Mediterranean GPS network (Anzidei et al., 1995) After November 2002, a dedicated GPS network was planned and set up to monitor the short-term surface and subsurface dynamics at Panarea volcano. In this paper we show and discuss results from GPS data from 1995 to 2007 which include the discontinuous data from the single station for the pre-eruption period and seven non-continuous and two continuously monitoring stations for the post-eruption period. We estimate the active strain and discuss the relationship between the deformation processes related to the hydrothermal/geothermal system and the regional and local tectonic setting. We use an elastic Okada model to fit the GPS velocity field to explain the present evolution of the hydrothermal/geothermal system in the post eruption stage.

2. Structural and Volcanic setting

Panarea Island is located on the eastern sector of the Aeolian volcanic arc, located along the margin of the Southern Tyrrhenian Sea, facing the Calabrian-Peloritan mountain chain to the south-east and the abyssal Marsili basin to the north-west (Barberi et al., 1973, Beccaluva et al., 1985). The Aeolian volcanoes comprise of seven major islands (Alicudi, Filicudi, Salina, Lipari, Vulcano, Panarea and Stromboli), and several seamounts (Figure 1 a) emplaced on a 15 - 20 Km thick continental crust. Their products have been dated between 1.3 Myr and the present (De Astis et al., 2003 and reference therein). Volcanism started during the Pliocene, in connection with the subduction of the Ionian lithosphere beneath the Calabrian Arc. Structural, seismological, geodetic and geochemical data suggest that since the Pleistocene, the south-eastern propagation of the Tyrrhenian rifting and the western margin roll-back have been controlled by the NNW-SSE fault system (Tindari-Letojanni fault system) and different styles of rifting processes have been recognized (Gvirtzman and Nur, 1999; 2001; Faccenna et al., 2001; De Astis et al., 2003). Recent regional geodetic data show maximum strain contraction axes with a N-S trend off of Sicily and in the western portion of the Aeolian Islands and a minor NW-SE extension in the eastern Aeolian Islands (Hollenstein et al., 2003; Pondrelli et al., 2004; D'Agostino and Selvaggi, 2005, Esposito, 2007). The transition from compressional to extensional regime happens through an area with transtensional deformation clustering along the NNW-trending Tindari-Letojanni fault system which runs across the central Aeolian Islands (Pondrelli et al. 2004; D'Agostino and Selvaggi, 2005, Serpelloni et al., 2005; Esposito, 2007). Panarea Island is located on the eastern active sector of the Aeolian volcanic arc which also includes Stromboli Island and the Lamentini, Alcione and Palinuro seamounts. A prevailing NNE- to NE trending fault system affects the Panarea and Stromboli Islands (Gabbianelli et al., 1993; De Astis et al., 2003; Tibaldi et al., 2003).

Panarea volcano is the emergent portion of a submarine stratovolcano ~ 1600 m high and ~18 km across (Gabbianelli et al., 1993; Gamberi et al., 1997; Favalli et al., 2005) characterized by a large and ellipsoidal shaped platform, at ~100 m. The emergent portion of this platform forms Panarea Island (421 m a.s.l.) and the small archipelago with the islets of Basiluzzo, Dattilo, Panarelli, Lisca Bianca, Bottaro, Lisca Nera and Le Formiche. Panarea and the Islets are made of high-K calcalkaline, andesite to dacite and rhyolite rocks, lava domes, plugs, coulees and lava flows, interbedded with subordinated pyroclastic deposits also of external provenance. Age ranges from 149±5 to 54±8 ka (Calanchi et al., 1999; Lucchi et al., 2007).

Recently, the youngest age of the Panarea dome complex was determined at 20 ± 2 ka (Dolfi et al., 2007). The outcropping lava units on the Islets area are characterized by a variable degree of hydrothermal alteration that have heavily modified their mechanical parameters (Cas et al., 2007).

Gravimetric measurements revealed the existence of a positive local gravimetric anomaly between the islet of Basiluzzo and the island of Panarea (Gabbianelli et al., 1990). Cocchi et al. (2008) estimated a negative magnetic anomaly between Panarea and the Islets area. In the Islets area a positive residual magnetic anomaly is present. A NE-trending gravity minimum, centered on the west of Panarea was also measured (Cocchi et al., 2008).

Before November 2002, Panarea volcano had been undergoing active subsidence at 1.87 mm yr^{-1} for the last 2000 years (Tallarico et al. 2003) and continuous exhalative activity from several fumaroles located both inland and offshore (La Calcara, Punta Levante and Lisca Bianca – Bottaro, in Figure 1).

Panarea volcano shows faults and fractures with a prevailing NE-NNE-trend and minor NW-trend (Gabbianelli et al., 1990, 1993; De Astis et al., 2003). During the 2002 gas eruption (Anzidei et al., 2005; Esposito et al., 2006, 2008) two fracture systems opened on the seafloor in the degassing area: NNE-SSW and NW-SE trending (Anzidei et al., 2005; Esposito et al., 2006; 2007).

3. GPS networks and data analysis

The Panarea GPS network includes seven non-continuous stations and two continuous stations (Figure 2). Two of the non-continuous stations are located on Panarea Island (PANA-PA3D; PCOR) and the others on the Islets area (BA3D, LIBI, BOTT, LINE, and PNRL) (Figure 2 and Table 1) (Anzidei et al. 2003b; Esposito et al., 2008). BA3D, BOTT, LINE, PNRL, PA3D stations were established after the 2002 gas eruption while PANA station is part of the Tyrrhenian Geodetic Network (Anzidei et al., 1995) and LIBI and PCOR of the IGMI network (Surace, 1993). Only PANA station, which is located ~3 km west of the degassing zone, was repeatedly occupied during five distinct campaigns before 2002 (Figures 2 and 3). So far most of the GPS data were collected within the 2002-2006 time span (Table 1), after the gas eruption. After the 2004 campaign, PANA was replaced by PA3D, located on the same building at a distance of ~3 m.

The two continuous stations were installed at Panarea Island (CPAN) and at Lisca Bianca Islet (LI3D) (Figure 2) on May 2004 and they are included in the RING network (Selvaggi et al., 2006).

The non-continuous stations of Panarea network was repeatedly measured every six months in the 2002-2006 time span using observation windows of 48-120 hour periods in each campaign (Table 1).

We analyzed the GPS data set (1995-2007) of the Panarea network together with some southern Italian and European EUREF permanent sites using the Bernese GPS software v.5.0 (Dach et al., 2007).

Daily loosely constrained solutions were generated for each campaign and later combined with ~ 10 years of loosely constrained solutions of a regional network of continuous stations in Italy, and surrounding regions, provided routinely by the INGV (Serpelloni et al., 2007). To assure a reliable combination, nine continuous anchor IGS sites (Figure 2a) were always included in all daily solutions. To express the time series in a stable reference frame, the Panarea solutions were combined with other available clusters whose networks cover a large part of the European region (Serpelloni et al., 2007). This strategy allowed us to obtain a daily Helmert transformation on the ITRF2005 reference system (Altamimi et al., 2007), based on

20 common sites. The combined daily solutions were then transformed into the ITRF2005 reference system by estimating four parameters: three translations and a scale factor .

Fitting the ITRF2005 time series we estimated site velocities together with periodic signals, eventual steps, always using the complete covariance matrix. To properly calibrate the formal errors, the standard errors were re-scaled, according to the procedure proposed by Williams (2003).

The velocity field with respect to the fixed Eurasian plate (Table 2) suggests a complex kinematic framework, where regional tectonics and local volcanic and tectonic deformations coexist. Comparing the residual velocity field relative to the Panarea network barycenter (Panarea reference frame) with the one computed with respect to the Calabrian rigid block (Gvirtzman and Nur, 1999, 2001; Doglioni et al.1991, D'Agostino and Selvaggi, 2004), defined by the GPS sites PORO, CELL, VLSG and MSRU, did not reveal any significant difference (0.39 ± 0.25 mm/yr) in the deformation field of Panarea. We therefore, concluded that adopting the Panarea reference frame would allow to describe the local magmatic and tectonic deformation from the regional deformation.

Velocity and strain rate fields

The GPS time series shown in Figure 3 are relative to the fixed Eurasian plate. A general subsiding trend affects all the stations of the Panarea network with values ranging from -3 to -9 mm/yr, with the exception of PCOR station. The latter is placed on the west sector of Panarea Island and does not show any vertical motion.

PANA is the only GPS station observed before 2002 (Figure 3a), hence we used its data to test the possibility of a change in the subsidence rate caused by the gas eruption. After November 2002, PANA was occupied during three different campaigns in December 2002, May 2003 and May 2004. Our analysis does not reveal any significant change in the rate of the Up component of PANA, before and after the 2002 gas eruption (-6.7 ± 1.3 mm/yr before November 2002; -7.4 ± 0.9 mm/yr after November 2002). A relevant feature recorded in the PANA time series, a 4.2 ± 0.1 cm uplift, occurred between June 2000 and November 2002, probably during the 2002 gas eruption.

Another puzzling discontinuity occurred at LI3D continuous station, located on Lisca Bianca Islet (Figure 3b). Between June 18th and 19th 2005 an instantaneous step in the horizontal components, of 12.1 ± 0.7 mm in the SE direction, was recorded. The inspection of this site did not reveal any manipulation or failure of the receiver-antenna equipment and the GPS data were continuously recorded during the event. Neither did the sky plot (i.e. the intrinsic noise of each single GPS satellite range observation) reveal any anomaly during the entire month of June 2005. For these reasons we argue that the signal recorded by LI3D is related to volcano dynamics. In the same time the other continuous station, CPAN, not recorded a the horizontal displacement indicate by an offset in time serie (Figure 3b)

The velocity field of the Panarea volcano with respect to the Panarea reference frame is shown in Figure 2. PANA is the only site that was measured before the 2002 gas eruption and where the pre- and post- event velocity can be estimated. Before the gas eruption its velocity was low (1.8 ± 1.3 mm/yr) and WNW trending. Just after the gas eruption, it changed abruptly in direction and magnitude, pointing towards SSE.

The horizontal velocity field, within the 2002 – 2007 time span, subdivides the Panarea area into two different parts, which are separated by a major NE-trending fault system revealed by bathymetric surveys (Gabbianelli et al., 1990; Gamberi et al., 1997; Anzidei et al., 2005). We labeled "Area A" the one corresponding to the NW portion of Panarea Island and "Area B" the one corresponding to the Islets area and the SE portion of Panarea Island (Figure 2). The velocities of Area B are roughly convergent towards the 2002-2003 degassing area.

The horizontal strain rate estimated by STRAINGPS software (Pietrantonio and Riguzzi, 2004) of Area B, is shown in Figure 2b. The current deformation of the Islets area shows contraction at 3.7 ± 0.5 μstrain/yr with a WNW trend.

4. **Modeling of GPS data**

Esposito et al. (2006) interpreted the 2002 gas eruption in terms of an accumulation at depth of pressurized gas from a steady or quasi-steady release of gas from a deep magmatic source, probably a cooling magma body, and from the periodic release of the overpressure when the tensile strength of the overlying rocks is overcome either by the increased internal pressure or by external changes in the tectonic stress.

Starting with this qualitative model of Panarea volcano we analytically modeled the GPS results collected between 2002, after the November crisis, and 2007.

We defined the computational domain of Panarea volcano (Figure 4) as composed of a largely submarine volcano extended below sea level for 1100 m and of emerged islands above sea level characterized by the presence of a hydrothermal-geothermal system where volcanic gas sampled in 2002-2003 had an estimated temperature of up to 300°C and a bulk fluid pressure of about 100 bar (Chiodini et al., 2006). We also considered the presence of a) a regional NE-SW fault system as suggested by structural data (Gamberi et al., 1997; De Astis et al., 2003; Esposito et al., 2006; Esposito, 2007; Acocella et al., 2008) and constrained by GPS results; b) two main vertical fracture systems with NNE and NW trends located west of Bottaro Islet that have been the main pathways for upwelling of hydrothermal fluids(Esposito et al., 2006).

We exploited the capability of the Okada solutions (Okada, 1985) to model the GPS data. Although such models account for only an elastic behavior, neglecting heterogeneities and structural discontinuities, they are widely used in the modeling of volcanic areas (Dvorak and Dzurisin, 1997; Miura et al., 2000; Lowry et al., 2001; Jousset et al., 2003; Lagios et al., 2005; Sepe et al., 2006) where cracks or discontinuities slightly alter the elastic constants but not the fundamental elastic behavior of a volcano (Jaeger and Cook, 1977; Dvorak and Dzurisn, 1997).

To reproduce the realistic hydrothermal-geothermal system (Figure 4), we carefully set up a system of four tensile/shear sources, partially constrained (see Table 3) by the geochemical, volcanological and structural remarks illustrated above.

The depth of the pressure source is assessed to be between 800 m and 900 m accounting for the geochemical data (Chiodini et al., 2006). The NE major regional fault system, dipping 70° with an azimuth of 45° from the north (Gamberi et al. 1997; De Astis et al., 2003; Esposito, 2007; Acocella et al., 2008), is considered to have an infinite length to avoid the unrealistic border effects; finally, the two vertical fracture systems, NNE (27°) and NW (135°) located at Islets area, are modeled with two segments of length 1100 m and 800 m, respectively (Esposito et al., 2006).

For the retrieval of the source parameters left free (Table 3), we used a non-linear inversion algorithm based on the Levenberg-Marquardt least-square approach (Levenberg, 1944; Marquardt, 1963) and its implementation in the MINPACK library (Moré et al, 1980). This algorithm is an efficient combination of the gradient descent and the Gauss-Newton algorithms (Press et al., 1992) and the best-fit configuration of the parameter vector **m** is found by minimization of a cost function of the type:

$$\chi^2(\mathbf{m}) = \sum_{i}^{N} \left[\frac{d_{i,obs} - d_{i,mod}(\mathbf{m})}{\sigma_i} \right]^2$$

where, for the i^{th} point, d_{obs} are the observed data, $d_{mod}(\mathbf{m})$ are the predicted data based on the model **m** and σ_i are the standard deviations coming from the GPS data processing.

Our results (Table3) show that the source that best fits the GPS velocities during post eruption stage is a composite by inflation/deflation of a hydrothermal /geothermal system combined with movement along the regional NE-SW fault and displacements of the fracture systems at the 2002 degassing area.

The model results show (italic in Table 3) the horizontal source located at a depth of 900 m and characterized by a vertical movement of -0.7 cm/yrs. The NE regional fault, 800 m wide, shows a rake of -120°, 0.2 cm/yrs of slip and an opening of 0.3 cm/yrs. The NW fracture system is 800 m wide with a negligible displacement while the NNE fracture system, 900 m wide, shows a closing of -0.7 cm/yrs. Results show good reliability: the RMS of the residual of the best-fit solution is 0.2 cm/yrs and the normalized χ^2 is 1.1. Figure 2 shows the velocity field obtained by GPS data and the results of the inversion .

In addition, we tried to test the reliability of a Mogi (1958) point-pressure source, setting this source beneath the Islets area. Unfortunately, this simple model could not explain the displacements of the Panarea GPS network, because of the wide discrepancy between the observed and the modeled data (χ^2 = 3.12), and was therefore, excluded.

5. Discussion

Gas eruptions are typical of active volcanoes as a consequence of the combination of several processes that may involve only the variations of pressure and temperature conditions in hydrothermal/geothermal systems and/or the response to shallow magmatic intrusions

(Battaglia et al., 2006; Gottsmann et al., 2007). The 2002 gas eruption at Panarea volcano reflects a deep magmatic intrusion which modified the equilibrium of the hydrothermal/geothermal system reservoir (Chiodini et al., 2006; Capaccioni et al., 2007).

We propose a sketch to explain the evolution of the 2002 gas eruption using GPS velocities compared to the volcanological and structural framework. The sketch defines three stages *pre*-, *syn*- and *post*-gas eruption (Figure 5). The hydrothermal/geothermal system is represented by two layers: a) a fluid reservoir b) a shallow reservoir characterized by a mixture of volcanic fluids and marine water. We consider that Area A, including the NW portion of Panarea Island, is mostly made of coherent rocks, whereas Area B, representing the SE portion of Panarea Island and the Islets, is characterized by highly fractured and permeable rocks.

Pre-eruption stage – Stage 1

In the *pre*-eruption stage the PANA GPS site recorded a subsidence of 6.7 ± 1.3 mm/yr (Figure 3) with a WNW motion of about 2 mm/yr (Figure 2). During this period degassing was mild and mostly located in Area B (Islets area) and, subordinately, in Panarea Island (La Calcara, Figures 1 and 4) and Basiluzzo (Punta Levante, Figures 1 and 4). In stage 1, conditions for degassing depend on the rock properties. Hydrothermal fluids upwell mostly through the highly fractured rock mainly present in Area B, without overpressure since fractures are semi-opened. The gas pressure inside the reservoir (Figures 4 and 5) is P_1 and the tensile strengths of rocks are τ_A and τ_B in correspondence of Area A and Area B, respectively. We assumed $\tau_B < \tau_A$ since Area B is characterized by more intense fracturing. P_1 does not reach the tensile strengths of the rocks.

Syn-eruption stage - Stage2

The addition of magmatic gases in 2002 (Caliro et al., 2004; Capaccioni et al., 2007) within the hydrothermal/geothermal system induced an increase of pressure and temperature and produced the gas eruption in the Islets area (Area B), with the opening of hundreds of gas vents aligned NNE and NW trending (Anzidei et al., 2005; Esposito et al., 2006) and vertical crustal deformation of 4.2±0.1 cm recorded at PANA site, located at ~3 km to the west, in Area A. Furthermore, about 20 low magnitude (Md ≥ 1.0) and high-frequency seismic events occurred on November 3, 2002 between 3:37 GMT and 5:00 GMT i.e. only a few hours before the local inhabitants of Panarea witnessed boiling sea in the surroundings of Lisca Bianca and Bottaro (Saccorotti et al., 2003; Linde et al., 1994). Stage 2 is characterized by an increase in pressure inside the horizontally extended reservoir, where $P_2 >> P_1$, favors conditions for the initiation of hydrofractures and rupture. This condition is expressed by the relation $p_l + p_e \geq \sigma_3 + \tau$ (Gudmundsson et al., 2001) where p_l is the lithostatic pressure, p_e is the exceeding pressure obtained by the difference between pressure P_2 , in the reservoir at the time of the rupture and the lithostatic pressure, σ_3 is the minimum compressive (considered positive) principal stress, acting perpendicular to the fractures and τ is the tensile strength of the rocks (τ_A and τ_B at Area A and Area B, respectively). Normally, rupture and initiation of hydrofractures occur when p_e reaches the tensile strength of the local rocks (Gudmundsson et al., 2001).

Post-eruption stage - Stage 3

GPS data collected after the gas eruptive event in the 2002 - 2007 time span, (Figure 3) show a general subsidence with a mean rate from -3 to -9 mm/yr. This subsidence is likely to be associated with degassing of the hydrothermal/geothermal system, though a rate of subsidence spread over the region of the Aeolian Islands is present (Bonaccorso, 2002; Mattia et al., 2008). The planar velocities of Area B are roughly convergent towards the 2002 degassing area (Figure 2). The pre-eruption conditions, in terms of flux intensity and geochemical characters, were restored in a relatively short time as suggested by Capaccioni et al. (2007). Gas pressure decreased ($P_3 << P_2$) and the degassing became located only along the principal locations of vents opened during the gas eruption within Area *B*.

Post-eruptive conditions may also involve the discharge of hydrothermal fluids through opened fractures at Area B causing a progressive closure of some fractures by self-sealing processes induced by the progressive drop of pressure and temperature (Gudmundsson 1999, 2001; Olsen et al., 1998; Cas et al., 2009) and changing the intrinsic value τ of the tensile strength of the rocks.

Continuous GPS data collected at the Islets area have also shown a clear and very rapid deformation with horizontal, but not vertical, displacements at the Lisca Bianca site (Figure 3).

According to the results of the Okada model (Table 3) the decrease in fluid pressure ΔP that occurred passing from Stage 2 to Stage 3, can be determined by using the relation (Gudmundsson, 1999)

$$\Delta P = \frac{\Delta W \cdot E}{2L\left(1 - \nu^2\right)}$$

where ΔW is the modeled displacement, E is Young's modulus of the rocks in Area B, L is the length of the modeled faults and ν is Poisson's ratio of the rocks.

Assuming that the static Young's modulus of the basaltic-dacite outcropping in Area B is E=15 GPa , ν =0.25 (Gudmundsson, 1999; Schultz, 1995), and ΔW and L are given by the Okada modeling (Table 3), we obtain a decreased fluid pressure of 0.05 MPa for the NNE system and negligible variations for the NW source.

This rough estimate of the pressure suggests that the present-day degassing of the Panarea hydrothermal/geothermal system is mainly controlled by the NW faults system present in Area B. At any rate, the effects of pressure and temperature changes within the hydrothermal/geothermal fluids, are distributed throughout Panarea volcano, as shown by the subsidence trend and by the horizontally extended reservoir model (Table 2 and Figures 2 and 5).

The scenario proposed by the modeling of post-eruption stage deformations is consistent with GPS pattern velocities and with tectonic and volcanic data. Velocity patterns can generally be interpreted in terms of simple source geometries that represent sills, dikes or plugs. The migration of hot fluid inside the hydrothermal/ geothermal system plays a role to magnitude and geometry of ground surface displacements in volcanic systems (e.g. Todesco et al., 2003, 2004; Battaglia et al., 2006; Hurwits et al., 2007).

Our model results point out the role of NE- and NW- trending fractures as the main pathways for the gas exhalation in the Islets area and identify the crucial role of the regional discontinuity NE-SW located between Panarea island and Islets area (Gamberi et al., 1997; De Astis et al., 2003; Esposito et al., 2006; Esposito, 2007; Acocella et al., 2008). The November 2002 gas eruption can be interpreted as the evolution of a hydrothermal system fed by a deep source of magmatic fluids capable to build up pressure and temperature at some shallow level where the migration of fluids causes periodically the tensional strength of the confining rocks to be overcome allowing the sudden release of the pressurised gas

The relationship between earthquake and volcano eruption was revealed by certain statistical analysis of events of global scale (Newhall and Dzurisin, 1988; Linde and Sacks, 1998). In events with Ml ≥ 8 the seismic wave produced by the earthquake may disturbs: a) the magma reservoir, leading to eruption b) the status of the regional stress by changing it.

The November 3, 2002 gas eruption followed the earthquake (Ml 5.6) of September 6th between Palermo and Ustica Island, correlating with several aftershocks, the strongest of which of Ml 4.3 (Azzaro et al., 2004, Rovelli et al., 2004) and with the onset of the strong eruption at Mt Etna on October 27th. It preceded the paroxysmal eruption at Stromboli that began December 28th and finished with an explosion on April 5, 2003. The Palermo earthquake changed the regional strain and triggered the reservoirs of three volcanoes (Walter et al., 2009). The eastern portion of the Aeolian Islands is characterized by an extensional regional strain consistent with a greater vulnerability to the dynamic triggering (Hill, 2008). A similar sequence of events occurred in the Southern Tyrrhenian area in 1865 (Esposito et al., 2006; Billi and Funiciello, 2008) as reported by Mercalli (1883).

6. Conclusion

The implementation and monitoring of the Panarea local GPS network have allowed to define a detailed pattern of deformation, unknown before the 2002 gas eruption. Results from the local GPS network are mainly sensitive to the local deformation field rather than the extensional regional deformation field recognized in the eastern sector of the Aeolian Islands.

Two different kinematic domains have been recognized in the Panarea area, separated by the regional NE-SW fault: Area A, which includes NW portion of Panarea Island, and Area B which includes the Islets area and SE portion of Panarea Island. In the Islets area, a shortening WNW-trend in the order of 10^{-6} yr^{-1}, has been estimated within the 2002-2007 time span. GPS results (2002-2007) have been modeled by an elastic, homogenous, isotropic half-space system strongly influenced and related to hydrothermal/geothermal fluid migration. The best-fitting model for GPS data collected at post eruption stage, was found through a combination of Okada sources. One wide and horizontally extended reservoir simulates the source of pressure within the hydrothermal/geothermal system, at a depth of ~ 900 m. The upwelling of gas along the NNE- and NW trending fractures at Islets area on 2002-2003 was favored by tectonic setting and the mechanical property of rocks. The present day WNW shortening is consistent with closing along NNE fractures, as suggested by the Okada model. The overpressure data suggests that, presently, the degassing of the Panarea hydrothermal/geothermal system is mainly controlled by NW fracture systems.

We also believe that the continuous and general subsidence trend observed, during the 1995 – 2007 time span, is mainly due to a decrease of the thermo-baric conditions within the hydrothermal/geothermal system although also a subsidence in the region of the Aeolian Islands is recognized (Bonaccorso, 2002; Mattia et al., 2008).

The November 3, 2002 degassing was triggered by changes in the extensional regional strain oriented NW-SE in the eastern Aeolian arc. Modeling of GPS data also provides new indications on the regional NE-SW fault system, that has an oblique kinematics, suggesting an additional component of dextral shear and a predominantly NW-SE normal extension observed by structural data. The extension value estimated by the model (0.3 cm/yrs) is consistent with the value <100 nanostrain/yr (D'Agostino and Selvaggi, 2004, Esposito, 2007) recognized in the eastern Aeolian arc.

The continuous GPS data recording on the Islets area has allowed to monitor the evolution of the degassing phases, evidencing that horizontal quasi-instantaneous displacement occurred on June 2005 at Lisca Bianca Islet. Such displacement is characterized by aseismic spreading and/or cracks closure while vertical displacement has not been recorded. This sudden offset is recorded only at LI3D continuous station. We suppose that it may be connected to a very local fracture system rather than a signal of broader tectonic origin, probably due to migration of ppressurised fluids that exert an additional pore-pressure over country rocks..

The GPS Panarea network is a powerful tool to understand the ground deformations at a local scale, in the short and long-term, due to fluid migration in the hydrothermal/geothermal systems.

Therefore, the Panarea volcano deserves the same monitoring and hazard assessment effort of any active volcano located nearby human settlements. In particular, the most critical scenario, of the potential hazard, is related to phreatic eruptions that may occur offshore as well as on the inhabited island of Panarea.

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Captions of Figures

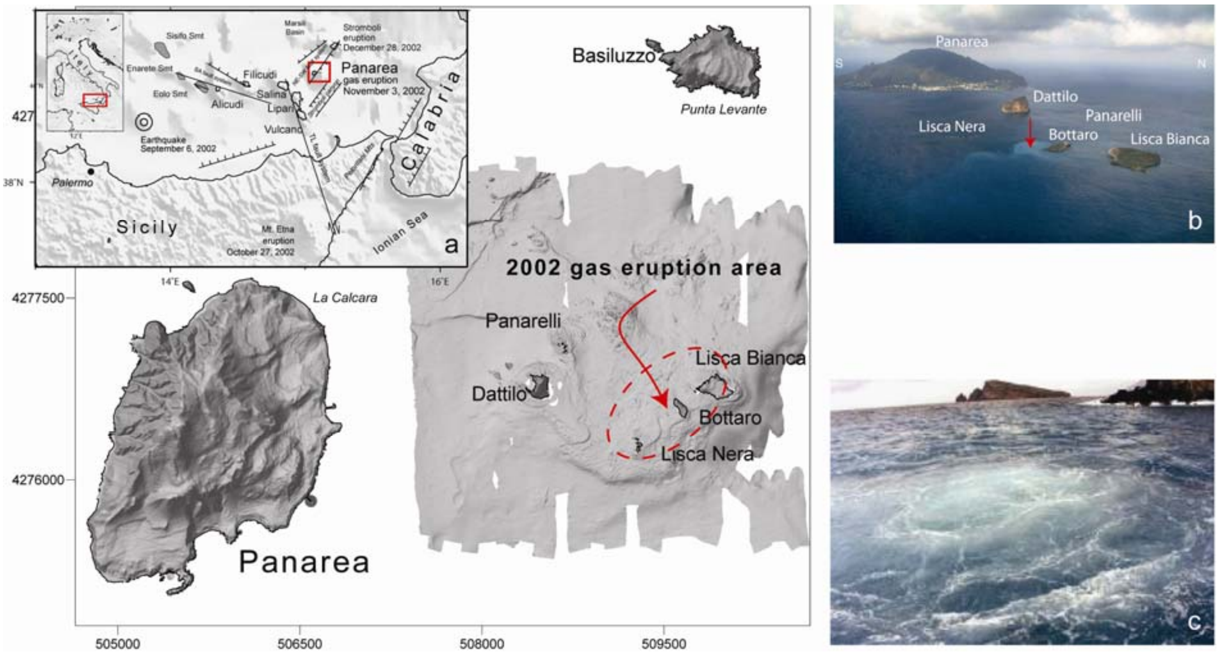
Figure 1 – Location of the 2002 gas eruption (DTM from Anzidei et al, 2006) a) Structural sketch map of the Southern Tyrrhenian Sea and Aeolian Islands (After De Astis et al., 2003) (TL Tindari-Letojanni fault system, SA Sisifo-Alicudi fault system). Also shown are the chronology and location of eruptions and earthquakes during late 2002; b) Aerial view of Panarea Island and the archipelago. The arrow indicates the location of major emission point to the SW of Bottaro; c) The gas rose to the sea surface forming bubbles some meters in diameter.

Figure 2 – Panarea GPS network. GPS velocities with 1 σ uncertainties relative to Panarea reference frame. Fit of four Okada sources (green arrows) and comparison between estimated GPS velocities. a) Anchor IGS sites;. b) Principal axes of the horizontal strain rate tensor and associated 1 σerror calculated from relative velocity fields

Figure 3 – Coordinate time series of Panarea GPS network relative to Eurasia reference frame. The vertical line represents the estimated step. Formal error 1σ. Inside each box rate is shown. **a)** Coordinate time series of PANA station pre and post 2002 gas eruption in time span 1995-2004. PANA time series show a clear offset between 2000 and 2002. **b)** Coordinate time series of the two continuous and the seven non-continuous stations in time span 2002.8 – 2007.5. The station of LI3D recorded a horizontal displacement in the middle of 2005 (from June 18th to June 19th)

Figure 4 –Conceptual model of Panarea volcano a) projection and section in WNW direction

Figure 5 – Schematic evolution of the Panarea hydrothermal- geothermal system during the 1995 – 2007 time span



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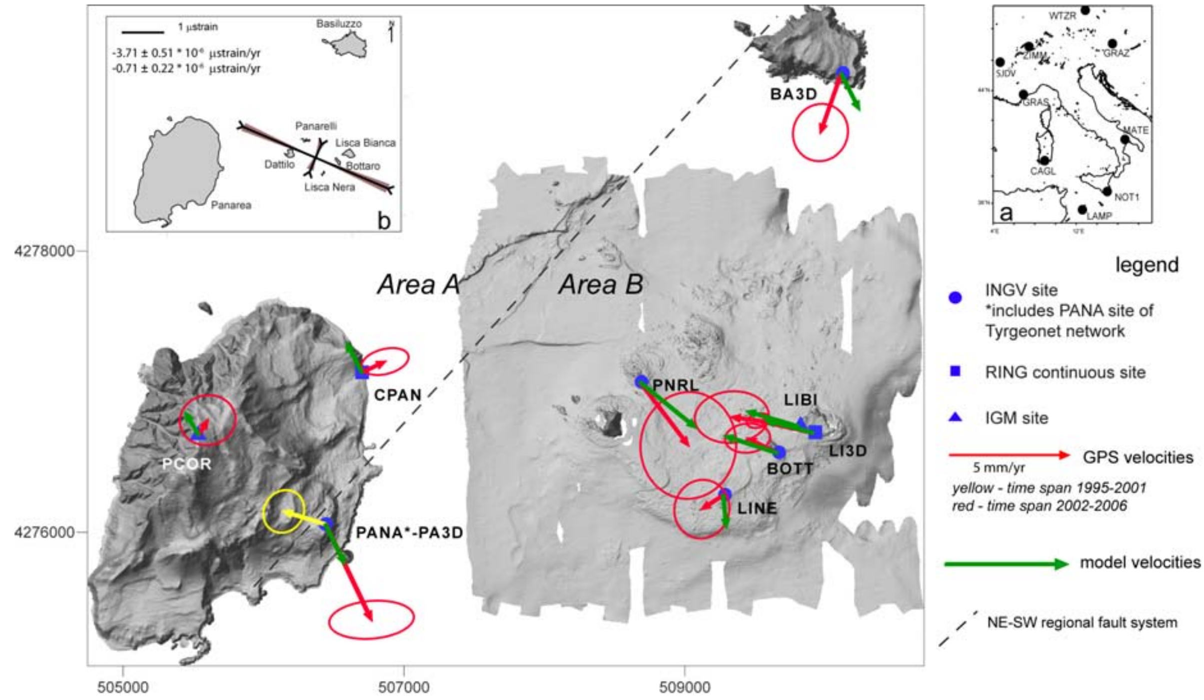

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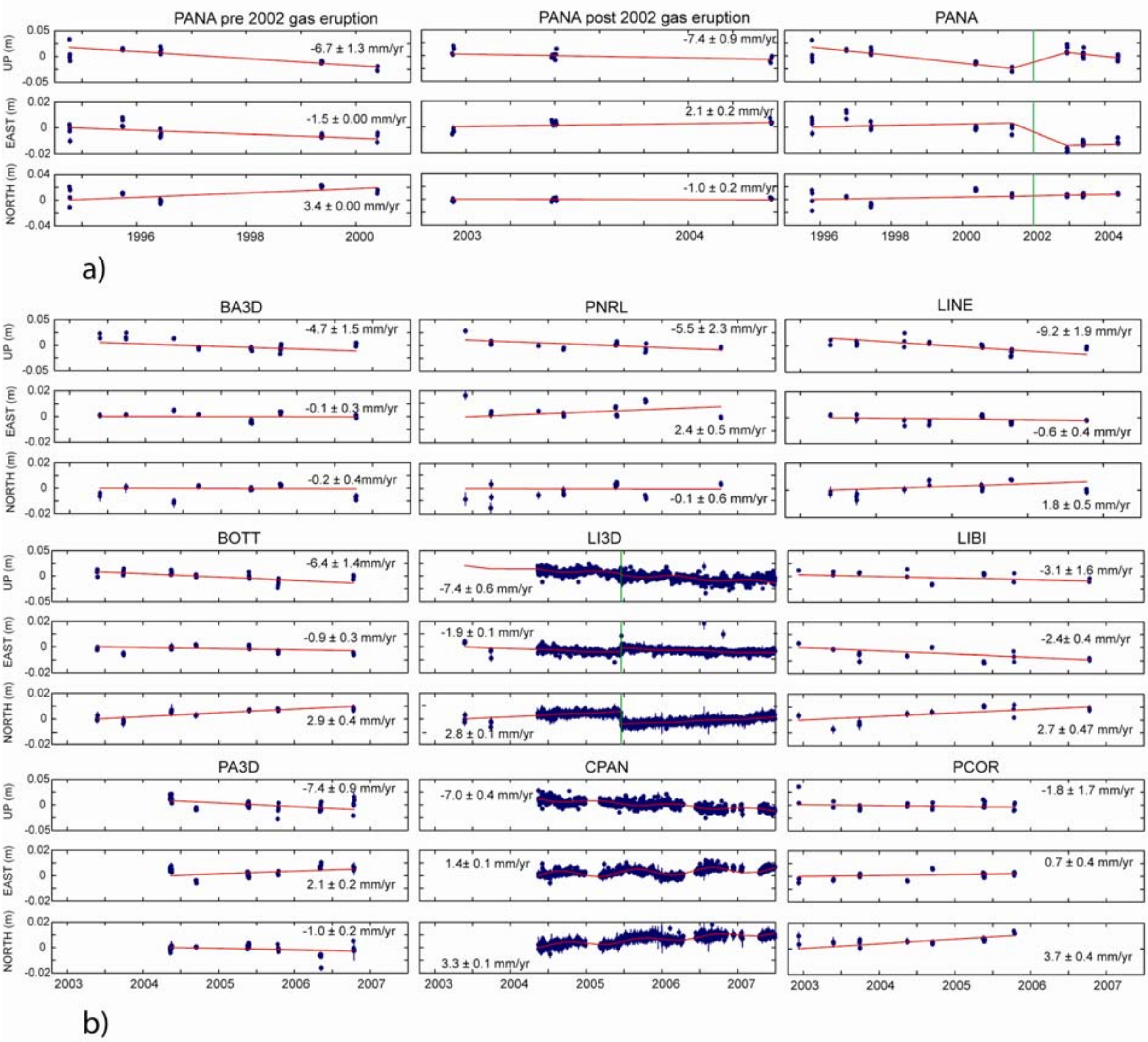

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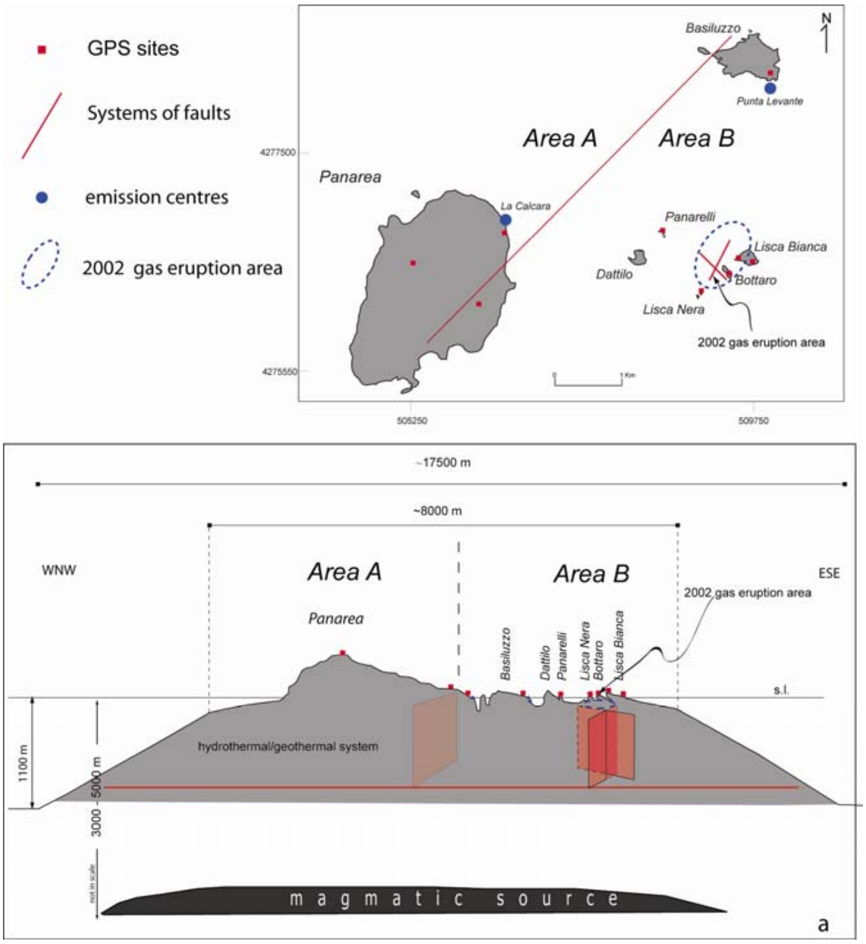

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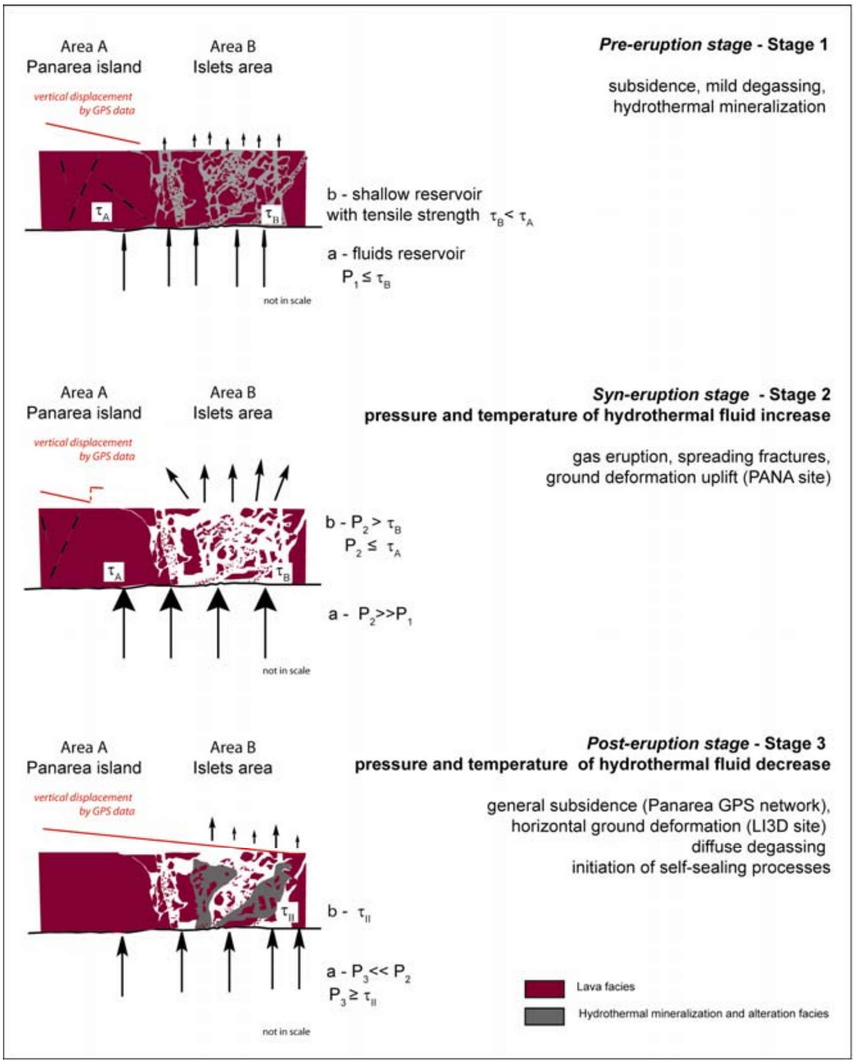

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Tables

Table 1 – Non-continuous stations of Panarea network: observation history, networks

		95	96	97	98	99	00	01	02	03	03	04	04	05	05	06	
1	BA3D									●	●	●	●	●	●	●	**Panarea**
2	BOTT									●	●	●	●	●	●	●	**Panarea**
3	LI3D*									●	●						**Panarea**
4	LIBI			●					●	●	●	●	●	●	●	●	**IGM**
5	LINE									●	●	●	●	●	●	●	**Panarea**
6	PA3D										●	●	●	●	●	●	**Panarea**
7	PANA	●	●	●			●	●	●	●	●	●					**Tyrgeonet**
8	PCOR								●	●	●	●	●	●	●	●	**IGM**
9	PNRL									●	●	●	●	●	●	●	**Panarea**

*permanent site from May 2004
● campaign measurements

Table 2 - GPS site positions, Velocities, 1 - σ uncertainties

			relative to Eurasia					
SITE ID	lon °	lat °	East mm/yr	σE mm/yr	North mm/yr	σN mm/yr	Up mm/yr	σUp mm/yr
BA3D	15.116	38.661	-0.1	1.1	-0.2	1.2	-4.7	2.9
BOTT	15.111	38.637	-0.9	0.9	2.9	0.6	-6.4	1.1
CPAN	15.077	38.642	1.3	1.0	3.3	0.6	-7.0	0.9
LI3D	15.114	38.638	-1.9	0.5	2.8	0.3	-7.4	0.4
LIBI	15.113	38.639	-2.4	1.5	2.7	1.1	-3.1	2.4
LINE	15.107	38.634	-0.6	1.1	1.8	1.2	-9.2	2.8
PANA-PA3D	15.074	38.632	2.1	1.7	-1.0	0.8	-7.3	2.7
PCOR	15.064	38.638	0.7	1.1	3.7	1.0	-1.8	3.0
PNRL	15.100	38.641	2.4	2.0	-0.1	2.2	-5.5	5.3

			relative to rigid motion of Panarea volcano					
SITE ID	lon °	lat °	East mm/yr	σE mm/yr	North mm/yr	σN mm/yr	Up mm/yr	σUp mm/yr
BA3D	15.116	38.661	-0.9	1.1	-2.4	1.2	-4.7	2.9
BOTT	15.111	38.637	-1.2	0.9	0.6	0.6	-6.4	1.1
CPAN	15.077	38.642	0.9	1.0	0.4	0.6	-7.0	0.9
LI3D	15.114	38.638	-2.3	0.5	0.5	0.3	-7.4	0.4
LIBI	15.113	38.639	-2.7	1.5	0.4	1.1	-3.1	2.4
LINE	15.107	38.634	-0.9	1.1	-0.6	1.2	-9.2	2.8
PANA-PA3D	15.074	38.632	1.9	1.7	-3.9	0.8	-7.3	2.7
PCOR	15.064	38.638	0.4	1.1	0.6	1.0	-1.8	3.0
PNRL	15.100	38.641	2.0	2.0	-2.6	2.2	-5.5	5.3

	Horizontal source	**NE-SW fault system**	**NNE fracture system**	**NW fracture system**
Length (m)	infinite	infinite	**1100**	**800**
Width (m)	infinite	*800*	*900*	*800*
Depth (m)	*900*	**0**	**0**	**0**
Azimuth angle (°)	n.a.	**45**	**27**	**135**
Dip angle (°)	**0**	**70**	**90**	**90**
Rake angle (°)	**0**	*-120*	**0**	**0**
Slip (cm·yr^{-1})	**0**	*0.2*	**0**	**0**
Opening (cm·yr^{-1})	*-0.7*	*0.3*	*-0.7*	*0*

Table 3 – Best-fit configuration of the four elastic sources. In italic are the parameters retrieved by non-linear inversion; in bold those constrained by geochemical, volcanological and structural data. The location of the sources is indicated in Figure 4.