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Tilt measurements at Vulcano Island

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Abstract
A network of tiltmeters has been operational on Vulcano Island for numerous years. At present, the network comprises five functioning borehole stations, four of which are installed at 8-10 m and allow recording very stable, high precision signals with very low noise. We report observations over the last 12 years that illustrate impulsive variations linked to seismicity and long-term (several years) trends in the signals. We suggest a relationship between tilt changes correlated to the strongest regional seismic events and site acceleration; long-term tilt variations analyzed in combination with other ground deformation data seem to represent evidence of a contraction of the La Fossa cone. We also analyzed how the tilt device has the capability to detect possible magma migrations; we considered previous studies that have imaged spatially well-defined levels of magma accumulation beneath La Fossa, and Vulcanello; we concluded that the Vulcano tilt network should be capable of detecting the upward migration of small magma volumes. Finally, we show that no evidence of changes are visible on tilt signals during anomalous degassing episodes (linked to a building up input of magmatic fluids) at the La Fossa thereby evidencing that no magma migration occurred during such events.

Key words *tilt monitoring – tilt variations – earthquakes – deflation – magma migration*

1. Introduction

The island of Vulcano is a composite volcanic edifice located in the south-central sector of the Aeolian Archipelago (Tyrrhenian Sea, Italy). The island, together with Lipari and Salina islands (fig. 1), represents the emerged part of the Tindari-Letojanni system (TL), a NW-SE elongated volcanic ridge affected by a right-lateral strike slip, moving in response to a N100E regional extension field (Mazzuoli *et al*., 1995). N-S and NE-SW striking normal faults are also visible on Vulcano; they are tension fractures associated with the main NW-SE shear zone and the primary volcanic structures (dikes, vents and eruptive fissures) are aligned in this direction (Mazzuoli *et al*., 1995; Ventura *et al*., 1999). Eruptive activity of Vulcano (Keller, 1980; De Astis *et al*., 1997) has been characterized by a S-SE to N-NW migration of the eruptive centres: the primordial Vulcano (120-100 ka), the Lentia complex (28-13 ka), La Fossa cone (6 ka to 1888-1890 A.D.) and Vulcanello (183 B.C. to 1550 A.D.). Recent eruptions on the island have taken place at Vulcanello and La Fossa cone (391 m a.s.l.), with volcanic products consisting mainly of pyroclastic material with lesser volumes of lava flows. At present, volcanic activity is restricted to fumarolic degassing, mainly at La Fossa with maximum temperatures generally ranging between 200° and 300°C. La Fossa is also characterized by the occurrence of periodical anomalous degassing episodes with increasing temperature and output of the fumarole more than by chemical changes (*e.g.*, Granieri *et al*., 2006).

Ground deformation at Vulcano is monitored geodetically by GPS, EDM and levelling campaigns and by continuous tilt and GPS (fig. 1). EDM and levelling measurements began at the end of 1970s and since 1997 the EDM lines

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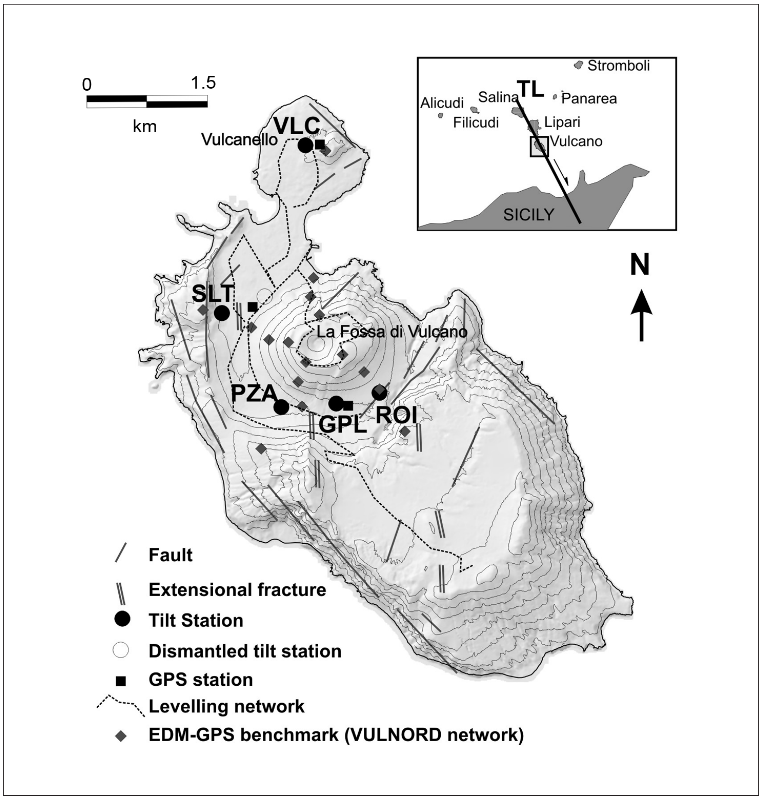


Fig. 1. Ground deformation networks and structural scheme at Vulcano Island.

have been measured using GPS. In the late 1980s, continuous ground deformation monitoring using a few tilt stations was initiated. From 1994, the tilt network was improved and expanded to yield a good areal coverage of Vulcano and higher quality data acquisition. Since 2004, the network has operated with five functioning stations that allow a high signal to noise ratio to be achieved.

2. Tilt network

At present, the Vulcano Island permanent tilt network (fig. 1) comprises five borehole stations equipped with bi-axial instruments, four of which installed at 8-10 m depth beneath the ground.

The instruments are AGI 722 models, with a precision of 0.1 μrad, and an AGI 510 model, with a precision of 0.01 (GPL station), that uses a high precision electrolytic bubble sensor to measure angular movement. All the bi-axial sensors are installed inside a sand covered hole oriented towards the crater and a positive signal indicates crater uplift (radial component). The second axis is oriented 90° counter-clockwise (tangential component).

Air and ground temperatures are also recorded at different depths in the hole. The control datalogger (model Campbell CR10) is programmed for 48 data/day sampling (1 sample every 30 min) and includes the acquisition of the two tilt components, air and ground temperatures, and instrumental control parameters, such as power supply and dc/dc converter voltage. All data are sent to the island of Lipari via Radio-Frequency and then to INGV-Catania. The GPL, VLC and VCS stations were installed in the 1980s in shallow boreholes at about 2-3 m depth. These tiltmeters have shown several kinds of noise that prompted undertaking an experiment (Bonaccorso *et al.*, 1999).

The experiment was conducted in 1994 at the Grotta dei Palizzi (GPL) station, where three instruments were installed in the same hole at depths of 7.6, 5 and 3 m.

This experiment verified that in the first few meters the temperature noise on the sensor is significant and is superimposed on the thermoelastic tilt signal. The shallowest instrument showed that some instability can affect the upper superficial layer without being detected in the deeper parts.

As a consequence of these findings, the tilt network was expanded in 1997 by the addition of other stations (PZA, SLT and ROI) that have all been positioned at 10 m deep, while the VCS station has been dismantled.

As expected, installing tiltmeters in deep boreholes produced an improvement in the signal-to-noise ratio relative to a near-surface installation, because the amplitude of noise attenuates strongly with depth.

Unfortunately, ROI and SLT stations have only been active for 1-2 years and logistic difficulties delayed their reconditioning, which took place in 2004.

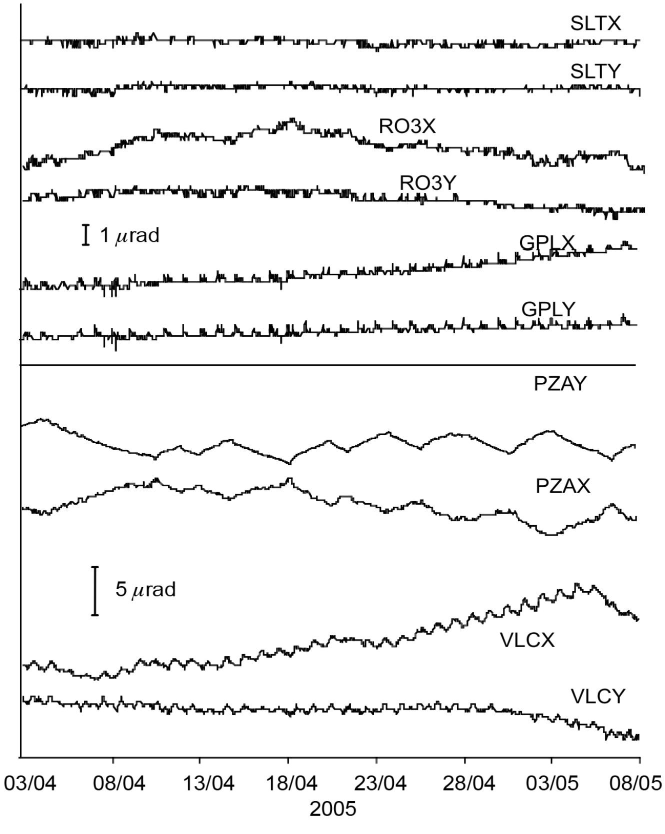


Fig. 2. Example of tilt signals recorded on the 5 permanent stations that evidence the low noise characterizing almost all the stations.

3. Data

Tilt measurements play a fundamental role in real time monitoring because they enable detection of ground deformation with a high level of precision.

At Mt. Etna (Italy) for example, the INGV-CT tilt network has detected slow inflation/deflation phases, as well as rapid and sharp variations over hours to days, such as those recorded during intrusions and eruptive fissure propagation (*e.g.*, Bonaccorso *et al.*, 2004; Aloisi *et al.*, 2006).

At Vulcano Island the tilt network is able to record very stable, high precision signals with very low noise (fig. 2) that allow the detection of low levels of ground deformation (0.2-0.5 μrad at GPL, SLT and ROI stations and 0.4-0.8 μrad for VLC and PZA).

Data reported in this paper cover the period 1994-2005. During these last 12 years the tilt network has recorded: impulsive variations linked to the strongest seismic events located in a radius of about 30 km from Vulcano and long-term signals outside the seasonal noise; no rapid variations (over hours to days) correleted to magma migration have ever been evidenced; in particular we focused our observation on tilt signals recorded during the last anomalous degassing episode occurring at the end of the 2005.

3.1. *Co-seismic effects*

Continuous tilt measurements are prone to record noise in response to ground shaking (*e.g.*, Wyatt, 1988; Gambino, 2002; Aloisi *et al.*, 2003).

We considered the seismic events located by the INGV-CT seismic network in the Aeolian Archipelago from 1994. The seismic network (fig. 3) comprises 12 stations on the archipelago (four of which are on Vulcano Island) and *ca.* 10 stations located in Sicily and Calabria. The dataset used contains 400 earthquakes with magnitude $M_d \geq 2.0$. Hypocentral parameters were computed using Hypo71 (1994-1999) and Hypoellipse (2000-2005) routines and a 1D velocity model derived from Jeffreys and Bullen (1967).

The mean accuracy of the locations is about 1.2 km for the epicentral coordinates, and 1.5

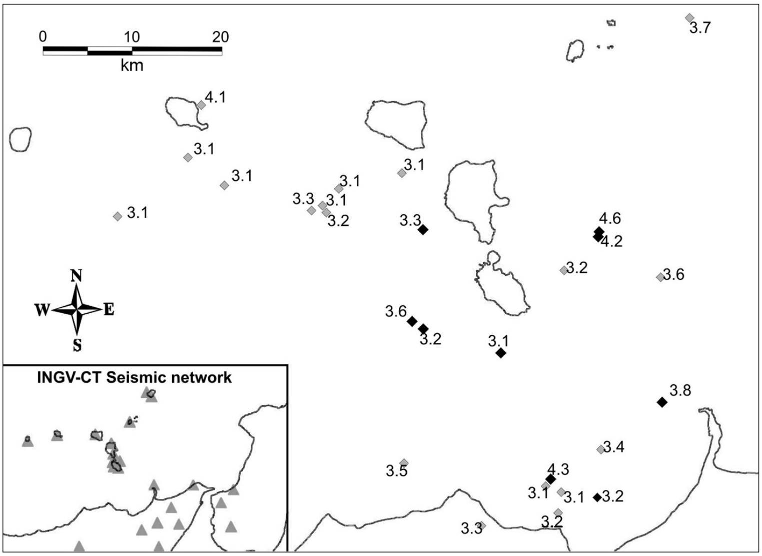


Fig. 3. Epicentral locations of the $M \geq 3.1$ (a total of 27 events) recorded between 1994 and 2005. Black diamonds indicate seismic events that caused tilt offsets. The inset reports the seismic network.

Table I. Tilt offset recorded at GPL and PZA station between 1994 and 2005. n.a. = not active; n.f. = not functioning.

No.	Data	Time	Lat	Long	M_d	H km	RMS	M_o dyne-cm	GPL-3 mod	GPL-3 ang	GPL-5 mod	GPL-5 ang	GPL-8 mod	GPL-8 ang	PZA rad	PZA ang
1	27/11/94	07:26	38.36	14.86	3.6	6.0	0.25	7.94E+21	0.7	162	0.0	-	1.4	82	n.a.	n.a.
2	27/08/95	19:42	38.28	15.18	3.8	11.6	0.34	1.26E+22	2.7	156	3.2	162	8.5	121	n.a.	n.a.
3	18/01/96	16:06	38.33	14.97	3.1	7.2	0.17	2.51E+21	0.6	162	0.0	-	0.5	135	n.a.	n.a.
4	19/03/97	08:12	38.35	14.87	3.2	5.7	0.19	3.16E+21	0.6	342	0.0	-	1.1	139	n.a.	n.a.
5	01/11/97	23:38	38.46	14.88	3.0	7.5	0.20	2.00E+21	0.0	-	0.0	-	0.0	-	0.5	318
6	14/02/99	11:45	38.19	15.03	4.3	14.5	0.26	3.98E+22	2.1	121	3.2	312	6.5	122	4.4	68
7	05/04/02	04:52	38.45	15.10	4.6	11.1	0.19	7.94E+22	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	48.0	72
8	13/06/03	23:19	38.18	15.09	3.2	6.7	0.29	3.16E+21	n.f.	n.f.	n.f.	n.f.	n.f.	n.f.	−2.6	176

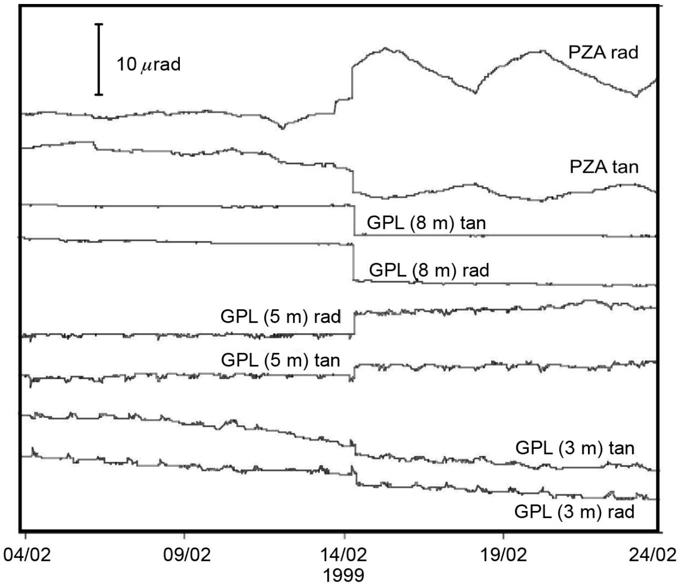


Fig. 4. Impulsive tilt variation observed at two stations correlated with the local M_d=4.3 seismic event recorded on 14/02/1999 at 11:45 GMT and located *ca.* 20 km south of Vulcano.

km for the focal depth. Figure 3 reports the epicentral locations of the 27 $M_d \geq 3.1$ (a total of 27 events); the depth of this seismicity is generally between 5 and 15 km.

The Vulcano Island tilt network has recorded 8 episodes of tilt variations which have been linked to regional earthquakes with $M_L \geq 3.0$. The tilt signal amplitude has generally not been higher than a few microradians (table I and fig. 4) showing no homogeneous values at different sensors.

3.2. *Rainfall effects*

Rainfall at Vulcano is not abundant (about 500 mm annually) and is distributed over 50-100 days/year. Rainfall effect on Vulcano tilt signals is absent or very small (fig. 5 in Bonaccorso *et al.*, 1999). Variations smaller than 1.0 μrad characterize the GPL signals; no significant variations are visible at the other stations.

3.3. *Tilt long-term variations*

Long-term trends can be recognized on two continuously recording deep stations: GPL and PZA. In particular, for GPL station Bonaccorso *et al.* (1999) had already highlighted good coherence between the long-term signals of the three instruments installed, even though the shallowest instrument seems to be affected by instabilities of the upper superficial ground layer. We do not consider the VLC shallow signals that show a continuous trend of 15-20 μrad/year linked to a local instability or to instrumental drift (fig. 5a-c).

Identification of long-term trends in tilt is not straightforward. There is a strong seasonal signal, so tiltmeters may have some difficulties in detecting variations comprised between several months to 1-2 years; moreover, signals are affected by short-term variations linked in particular to seismic and rainfall; GPL and PZA in fig. 5a-c comprise signals longer than 7 years, filtered for diurnal component, re-sampled one datum per day and cleaned from all short-term variations.

GPL station shows a significant decrease in radial tilt between 1994 and 2001; the two sensors detected a common long term trend of about 3-4 μrad/year (fig. 5a-c), while the tangentials are almost stable, evidencing a contemporaneous and coherent change in 1998. The slight differences between the signals of different instruments may be due to a possible slow drift characterizing one of the sensors.

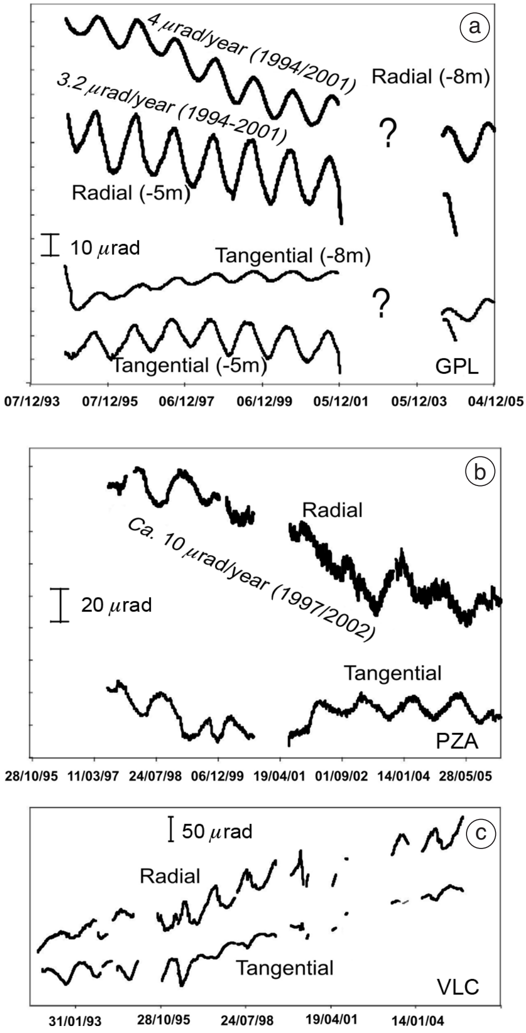


Fig. 5a-c. Long-term signals recorded at a) GPL; b) PZA; and c) VLC stations.

Unfortunately, acquisition of GPL was interrupted for about two years and recent signals, despite showing a similar behavior, may be shifted owing to possible offsets during the interruption.

PZA seems to show similar trends to GPL with a pronounced decrease in tilt (about 10 μrad/year between 1997 and 2002); the tangential signal is approximately constant.

3.4. *Tilt recorded during the crisis episodes at La Fossa: the 2005 case*

La Fossa is characterized by the occurrence of periodical «crises» with a growing input of magmatic fluid as testified by strong increases in the magmatic component that in the fumarole composition is mainly hydrothermal (*e.g.*, Chiodini *et al.*, 1995; Todesco, 1997; Paonita *et al.*, 2002). During the last 30 years, inputs of magmatic fluid were detected in 1979-1981, 1985, 1988, 1996, 2004 and 2005 (Granieri *et al.*, 2006).

We consider tilt data recorded during the 2005 episode to be the best monitored (fig. 6). The 2005 crises happened in a period comprised between *ca.* 20 October and 10 December (S. Di Liberto, pers. comm.) and were preceded by a seismic sequence of 5 faulting events ($M_{\max}=2.5$) occurring between 12 and 22 of September and located between la Fossa and Vulcanello (fig. 7). Faulting earthquake swarms occur sporadically inside Vulcano Island. These shocks are characterized by low magnitude ($M_{\max}=2.5\text{-}2.6$), depths between 1 and 5 km and may accompany the anomalous degassing episodes (*e.g.*, 1985 and 1988: Montalto, 1996). However some anomalous degassing episodes (*e.g.*, 1996 and 2004) have not been affected by shear fracturing seismicity. Tilt data recorded during the period September-December 2005 do not show significant variations (fig. 6).

4. Tilt network potential at Vulcano Island

We previously showed how the Vulcano Island tilt network is able to record very stable, high precision signals; moreover tilt data of the last 4 months of 2005 seem to evidence no changes that may lead to suppose magma migration; thus an evaluation of the volumes of a magma migration that the tilt network may detect is an important parameter for the discussion.

We have tried to obtain magma volume change by taking into consideration a recent work on CO_2 fluid inclusions in quartz xenoliths (Zanon *et al.*, 2003) that suggests that two, spatially well-defined, levels of magma accumulation exist beneath Vulcano, one in the upper crust (3-5 km depth), and the other in the

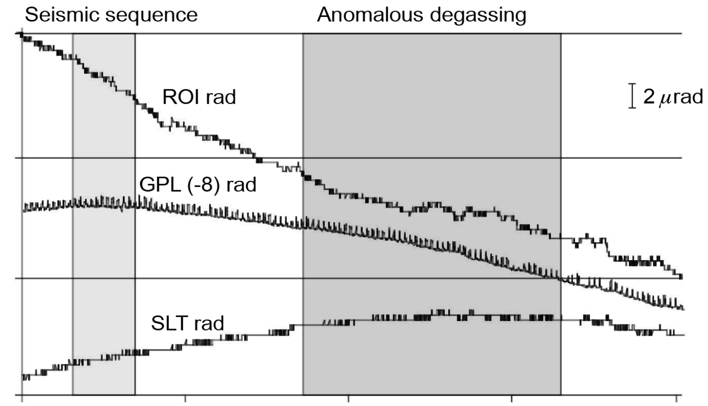
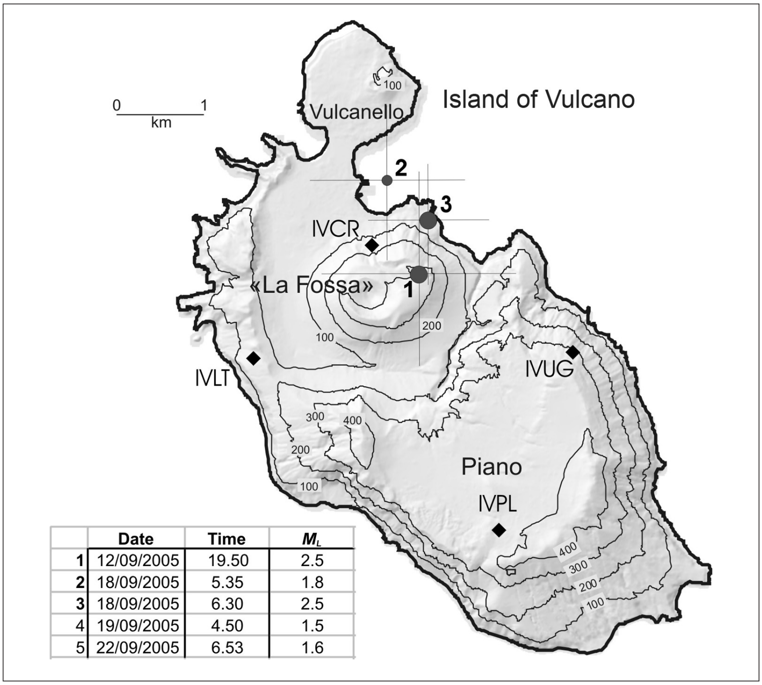


Fig. 6. Radial components of ROI, GPL and SLT tilt data recorded during the period September-December 2005.



	Date	Time	M_L
1	12/09/2005	19.50	2.5
2	18/09/2005	5.35	1.8
3	18/09/2005	6.30	2.5
4	19/09/2005	4.50	1.5
5	22/09/2005	6.53	1.6

Fig. 7. Epicentral map of the more energetic earthquakes recorded on September 2005 located by using the HYPOELLIPSE program (Lahr, 1989) and a velocity model derived by Falsaperla *et al.* (1985).

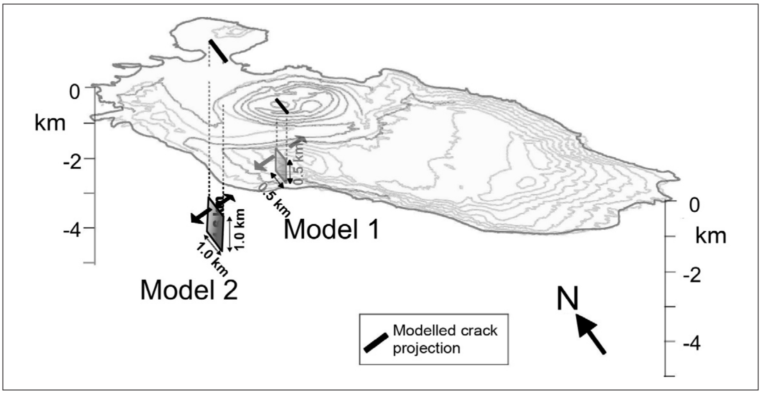


Fig. 8. Sketch map of the sources locations (Models 1 and 2) used for the inversions.

lowermost crust (18-21 km depth), close to the upper mantle boundary. Combining these results with those of De Astis *et al.* (1997) and Clocchiati *et al.* (1994) led Zanon *et al.* (2003) to suggest that two independent shallow reservoirs feed the volcanic system:

i) A plexus of small dikes and magma pockets beneath La Fossa at 1.6 km depth, which form a storage area in which magma mixing and interaction with seawater might occur.

ii) A reservoir at about 3-5 km beneath Vulcanello.

We hypothesize a possible intrusion from these two sources (fig. 8) considering two separate Models (1 and 2) each composed of a tabular tensile dislocation (Okada, 1985), N-S ori-

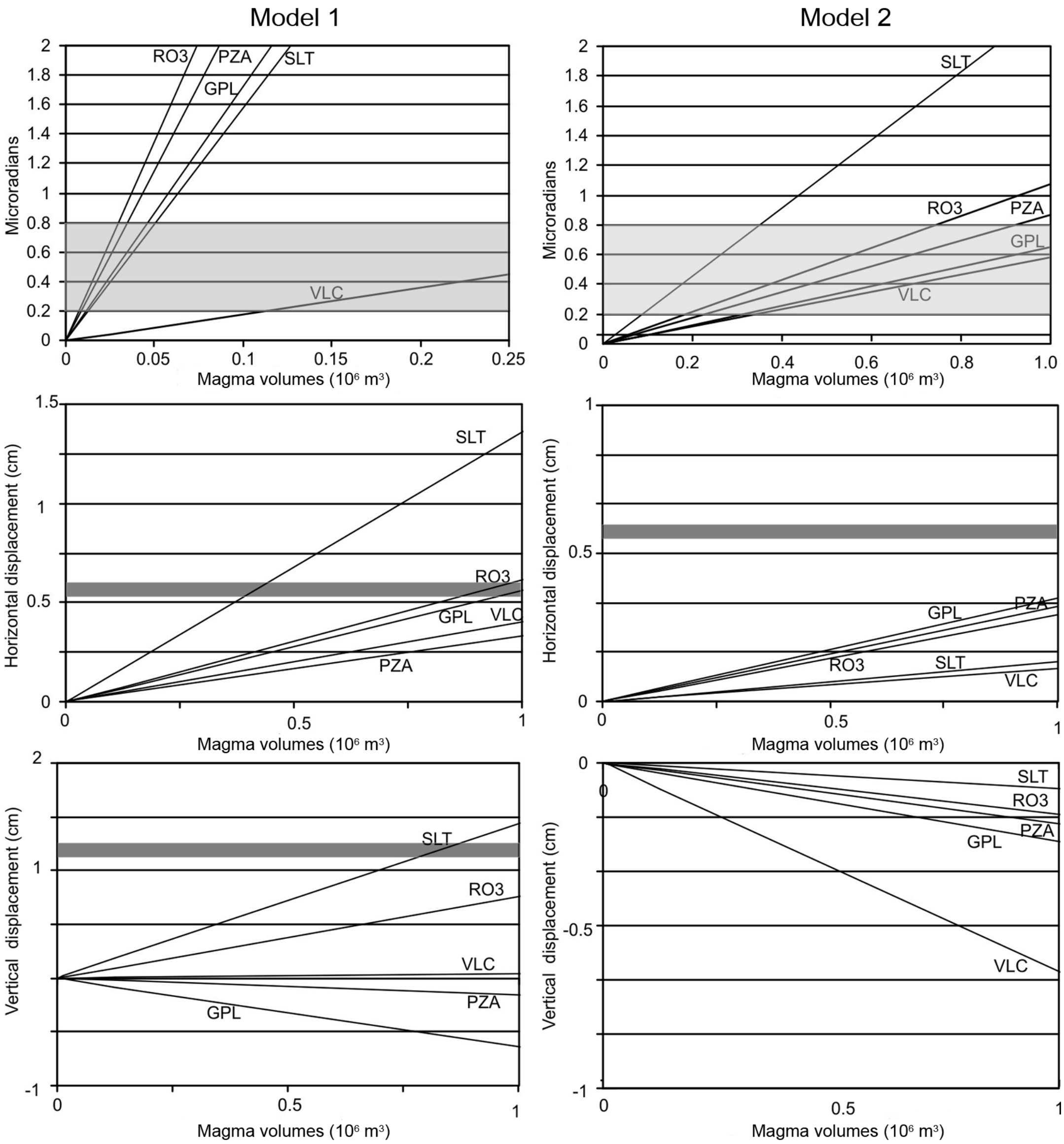


Fig. 9. Results of modeling analyses showing tilt, horizontal and vertical displacements changes related to magma volumes involved in Models 1 and 2. Grey area highlights the detectable threshold of tiltmeters and GPS.

ented, subvertical, located in correspondence of La Fossa Crater (top of structure at 1.5 km depth) and under Vulcanello (3.5 km depth).

The two assumed models are indicative; they only serve to help us define an uprising magma volume detectable by tilt. For Model 1, we considered a length and width of 0.5 km; 1.0 km for Model 2. Then we take into consideration a short-term (hours to days) variable tensile opening involving magma volumes up to 1.0×10^6 m^3 for the two models.

Figure 9 shows tilt, horizontal and vertical variations *versus* magma volumes involved in Model 1 and 2, evidencing how detectable tilt module variations are sensitive to very low volumes (respectively *ca.* 0.1×10^6 m^3 and *ca.* $1.0\times\times10^6$ m^3) of magma intruded; the horizontal and vertical changes obtained for the two models are small to be detectable with other continuous ground deformation devices.

5. Discussion

Starting from 1994, the Vulcano Island tilt network has evidenced 8 episodes of co-seismic tilt. It is well known that discrepancies between coseismic tilt and predicted surface displacement for local and far earthquakes often exist and, in particular, bore-hole sensors often show greater sensitivity to these effects. This is also observed on Vulcano, where tilt has a large amplitude compared with theory calculated using dislocation fault models. For example, if we consider a tabular dislocation model located at the event no. 6 (table I) hypothesing a SW-NE oriented source (consistent with the regional trend), 3 km width, 4 km length and 5 cm of left strike-slip (Okada, 1985) we predict tilt of *ca.* 0.01-0.05 μrad for tiltmeters on Vulcano Island. The observed tilt (table I) occurs simultaneously at the stations showing irregular ranging between 1 and 10 μrad (fig. 4). Bonaccorso *et al.*, (1999) concluded that different kind of instrument may give different responses and that the larger offsets recorded by the GPL deepest sensor (AGI 510) may be due to instrumental problems (the motor control unit used for the automatic levelling of the sensor). Wyatt (1988) suggested that short base-length, near-surface measurements are strongly affected by site acceleration that, over a certain level may produce exaggerated coseismic tilt.

We estimated site acceleration using the empirical relationship of Espinosa (1979), for events within 100 km

$$\log A_H = M_L - 27.7 + 11.9\cdot\log\Delta - 1.56\cdot(\log\Delta)^2 \tag{5.1}$$

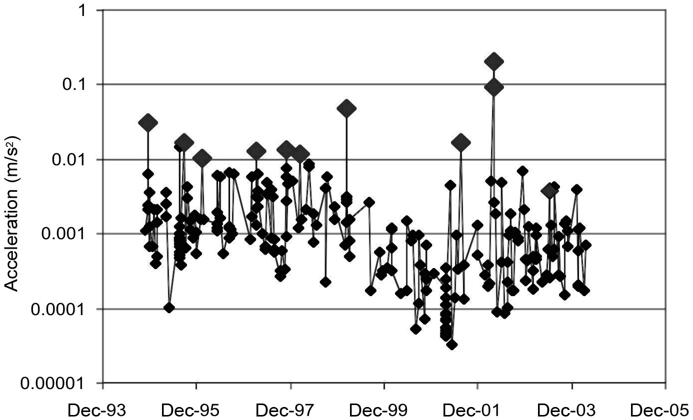


Fig. 10. Calculated acceleration for all local events in a radius of about 30 km from Vulcano. Large diamonds mark events that caused coseismic offsets.

where A_H is the acceleration, M_L the magnitude and Δ the epicentral distance.

Figure 10 shows the calculated acceleration for all the local events recorded between 1994 and 2005; we observed that coseismic offsets at Vulcano Island occurred only when site acceleration exceeded 0.01 m/s^2 (with the only exception of event no. 8 in table I). Amplitude and direction of tilt changes may depend on the general site conditions (hole stratigraphy, existence of minor cracks/fractures, sand compactness).

Long-term trends recorded at two continuously recording deep stations (GPL and PZA) have been observed in combination with EDM data recorded on the geodimeter trilateration network (VULNORD) that has been measured since 1987 (fig. 1; fig. 5a). This network covers the active volcanic structure of La Fossa cone and was periodically reoccupied using EDM, at four monthly intervals, until 1997. From 1998, the network has been reoccupied yearly using static GPS.

Since 1990, EDM data has shown a general extension between the lines connecting the benchmarks positioned on the edifice and the most external ones. In particular, a major positive variation (up to 8 cm) is recorded at all the lines

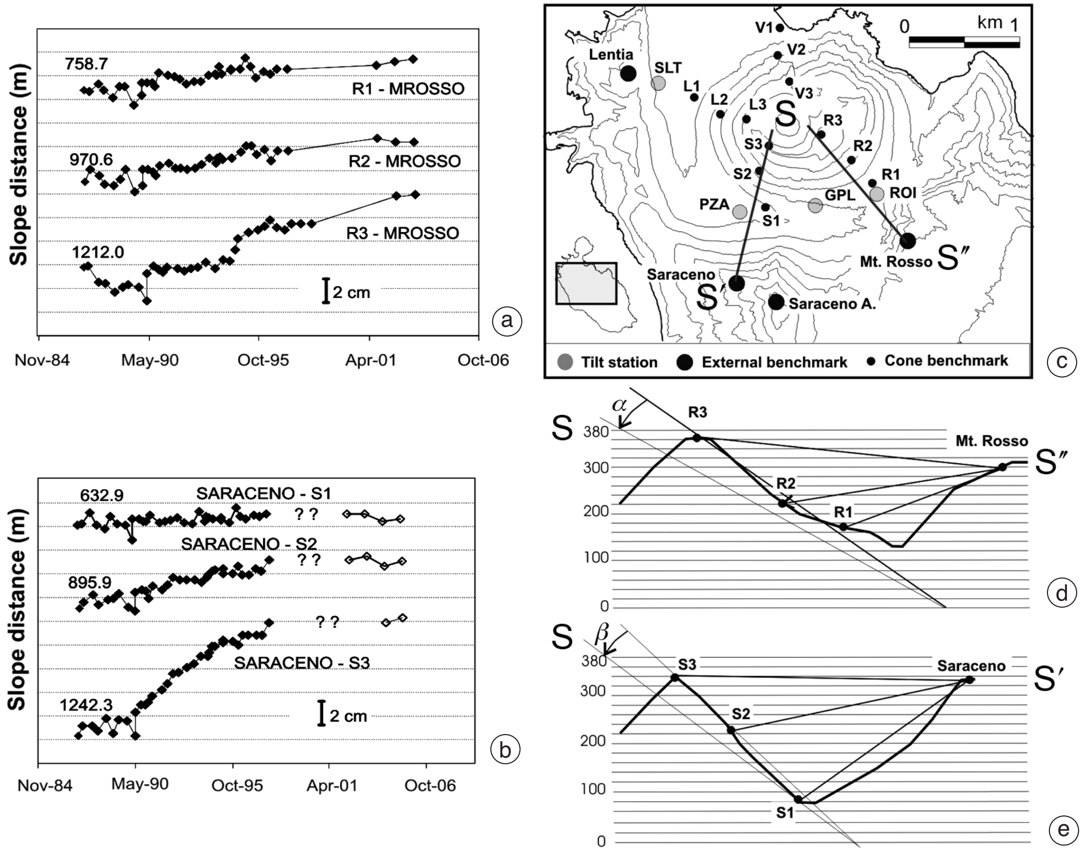


Fig. 11a-e. Distance variations (a, b) measured on selected lines of the south sector of La Fossa area (c). Cross-section along S-S′ and S-S″ (d, e) utilized for estimating distance changes related to α=−3.5 μrad/year and β= =−10.0 μrad/year tilt (see text and table II). Since 1998, Saraceno benchmark has been replaced with Saraceno Alto and S3 has been rebuilt so that there is no continuity with previous measurements.

joining the external benchmarks to those on the crater summit area (fig. 11b,c). This behaviour seems consistent with the hypothesis of contraction of the crater area (Bonaccorso *et al.*, 2000). Moreover, precise levelling along the northern slope of the crater line, between 1990 and 1996 also showed incremental subsidence (from Porto Levante to the northern rim) up to 4.0 cm (Obrizzo *et al.*, 1993, 1994; Obrizzo, 1998, 2000).

EDM lines and levelling data have been modeled by Gambino and Guglielmino (2006) that obtained a volume decrease source positioned under the crater at the sea level depth, suggesting a fluid loss from a sea level geothermal reservoir as a plausible candidate for the 1990-96 deflation of the La Fossa area.

Since 1997, discrete slope distances present several interruptions caused by the GPS measurements technique used during 1998-2001 and by some benchmarks missing and substituted; moreover no precise levelling survey along the northern slope of the crater line has been possible to perform after 1996. We analyzed slope distances measured on the network lines closer to GPL and PZA stations and in particular the lines linking M. Rosso with R1, R2, R3 and Saraceno with S1, S2, S3 (fig. 11a). The measurement error, *i.e.* standard error of a single measurement, is 5 mm + 1 ppm of the measured length, which in these lines corresponds to about 0.6 mm.

Assuming that external benchmarks are stable and that line extension is simply the result of a tilting of the cone area linked to a general deflation of the cone (fig. 11a-e), we calculated (fig. 11d,e) the distance changes related to a negative radial tilt of 10 μrad/year (PZA) for S-S′ section in the 1990-2002 period and 3.5 μrad/year for S-S″ section (near to GPL) in the 1990-1997 period; even if we consider the several assumptions made, the coherence between calculated values and distance changes recorded with EDM-GPS results (table II) still seems surprising.

Moreover we also inverted EDM and tilt data in order to image the observed deformation pattern under the boundary conditions of a homogeneous, isotropic and elastic half-space using the point source (Mogi, 1958).

The Mogi source is the conventional and simpler model usually applied to the location of the volcanic source and represents the decrease/increase of pressure or volume of a spherical chamber depth.

Table II. Recorded and aspected distance changes.

Line	Period	Aspected from tilt mm/year	Detected with EDM-GPS mm/year
SAR-S1	1990-2002	1.5	2.6
SAR-S2	1990-2002	5.1	6.0
SAR-S3	1990-2002	11.0	10.6
ROS-R1	1990-1997	1.3	1.1
ROS-R2	1990-1997	2.5	2.3
ROS-R3	1990-1997	5.0	4.5

We considered the time spanning period (1994-1996) where EDM and tilt data are both measured. In order to invert the datasets we applied the Genetic Algorithm (GA) implemented by Nunnari *et al.* (2005). The inversion results show a good fitness with an EDM mean error of ±3mm and tilt components mean error < 1 μrad.

Modeling results (fig. 12a,b) are in agreement with a volume decrease (-3.6×10^4 m^3) of a spherical source positioned beneath the summit Crater and about at the sea level depth.

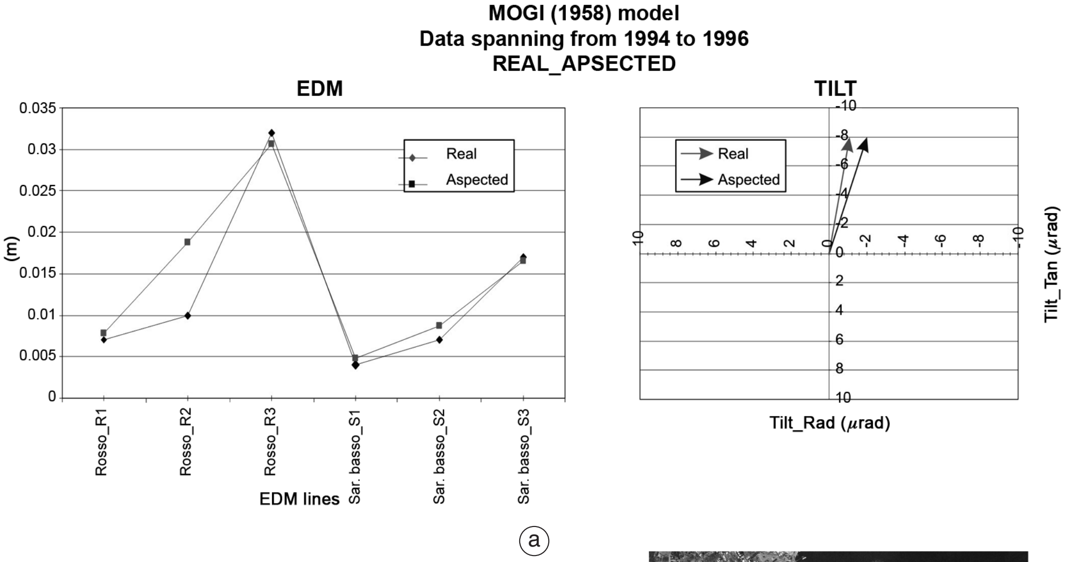
Finally, we considered tilt data recorded during the 2005 La Fossa periodical «crises».

This episode, like the previous (1979-1981, 1985, 1988, 1996, 2004) was characterized by an increase in the fumarole temperature and output and by chemical changes showing a growing input of magmatic fluid (Granieri *et al.*, 2006).

Some authors (*e.g.*, Nuccio and Paonita, 2001) attributed the chemical changes recorded at the fumarole to upraise of magma; others (*e.g.*, Granieri *et al.*, 2006) suggest a pulsating degassing process from a deep pressurized stationary magma body. We have not evidenced tilt variations for the 2005 crises occurring between 20 October and 10 December as also during the seismic sequence of faulting events between 12 and 22 of September 2005 (fig. 6).

6. Conclusions

12 years of continuous recording have shown that the Vulcano Island tilt network records im-



Parameters	Calculated value	Min	Max
ΔV (mc)	$-3.6*10^4$	$-1.00*10^6$	$-1.00*10^2$
Xs-(m)	496983	494000	499000
Ys-(m)	4250791	4246000	4254000
Depth (m)	-256	-1000	-100

Reference level = 281 m

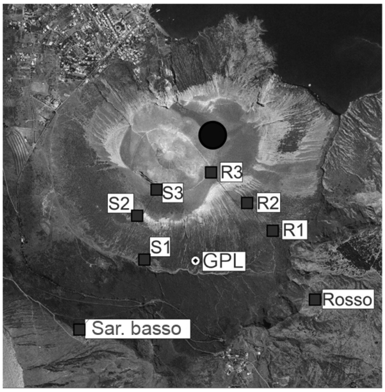


Fig. 12a,b. Mogi point source simultaneous joint inversion result. a) The figure shows the expected and calculated values of EDM and Tilt data. b) In box are reported the data inversion results and the location of the source.

pulsive variations linked to seismicity and long-term (several years) trends.

We observed that coseismic tilt changes are correlated to the strongest seismic events located in a radius of about 30 km from Vulcano and generally occur when earthquake ground acceleration is more than 0.01 m/s^2.

Tilt long-term data, recorded up to 2001-2002, show negative trends toward the crater area on the stations of the southern sector of the La Fossa area in agreement with EDM and levelling measurements. The coherence between tilt and EDM data and modelling results suggest that tilt long-term trends, have been dominated by the cone deflation effects linked to a volume decrease of a shallow geothermal reservoir.

Tilt is an important monitoring tool used to detect the change in volume (or pressure) of a magma source or magma movement (Dzurisin, 1992; Bonaccorso *et al.*, 2004). No rapid variation (over hours to days) correlated to magma migration has ever been evidenced and this is particularly manifest on focusing our observation on tilt signals recorded during the last anomalous degassing episode at the end of the 2005 for which we have the most precise set of data.

We have also tested the Vulcano Island network capability to detect changes related to magma migration, by imaging the deformation pattern linked to an intrusion from two spatially well-defined levels of magma suggested by Zanon *et al*. (2003).

The tilt network detects variations related to very small magma volumes (about 0.1-1.0×10^6 m^3) that are undetectable with other ground deformation techniques operating on the volcano.

Considering that our tests have evidenced the high sensitivity of the Vulcano tilt network in detecting magma migration we may conclude, in accordance with Granieri *et al*. (2006), that anomalous episodes at La Fossa are not linked to magma movements.

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