Ground deformations related to the effusive eruptions of Stromboli: the 2002-2003 case

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Abstract

Stromboli volcano erupted suddenly on 28 December 2002 after a long period of typically persistent and moderate explosive activity. Lava flows outpoured from the northern wall of the NE crater and descended into the Sciara del Fuoco (SdF). On December 30th, 2002, two landslides occurred on the northern part of the SdF, producing a tsunami that caused significant damage. This event led to the upgrading of the ground deformation monitoring system. The new requisite was the real-time detection of the deformation related both to the magma movements within the eruptive feeding system and to potential slope failures of the SdF. To this end, a remotely controlled monitoring system, based both on high-frequency (1 Hz) instantaneous GPS and terrestrial geodetic techniques (manual EDM measurements, transformed in automated terrestrial geodetic measurements) was planned and set up in a few months.

During the recorded eruptive phases, the new monitoring system aided the Department of Civil Protection in making decisions related to hazards from landslides and volcanic activity and, more generally, on the evolution of volcanic phenomena throughout the eruption. The measurements carried out on the benchmarks located on the high flank allowed us to make some hypotheses on the dynamics of the craters. In particular, the behaviour of the EDM baselines, showing alternating periods of increase and periods of stop in length variation, could be linked to movements of the magmatic column within the craters. Moreover, the monitoring system gave us the opportunity to observe the effects of an effusive vent opening on February 16th.

The new geodetic network provided, for the first time, useful information on ground deformations due to shallow and very shallow volcanic sources at Stromboli.

1.0 Introduction

The volcanic phenomena occurring on Stromboli in December 2002, prompted the scientific community and the national Department of Civil Protection (DPC) to implement new systems aimed at detecting and monitoring any movements within the Sciara del Fuoco (SdF). These systems were primarily to provide information on the instability of the SdF and, furthermore, to monitor the dynamic of the area around the summit craters, for evaluating potential evolutions of the eruption, as is usually done on other active volcanoes. Due to these requirements, a monitoring system based on terrestrial geodetic techniques and a remotely controlled GPS station, with high-frequency (1 Hz) instantaneous positioning capabilities, were planned and set up around the summit craters in about two months.

The following chapter presents and discusses the data that this new geodetic monitoring system provided in the first months of the eruption, i.e. before its complete destruction caused by the 5 April paroxysm. In particular, the chapter is principally devoted to the dynamic of the area around the summit craters, more or less directly linked to the magma movements within the shallow plumbing system of Stromboli.

2.0 Monitoring system description

Since 1993, Stromboli ground deformations have been monitored by GPS and clinometric techniques. Before the 2002-2003 eruption, the monitoring system on the island focused on measuring the effects of the plumbing system dynamic at medium-shallow depths (1-2 km b.s.l.) without the real-time detection requirement. To this end, four permanent GPS and three tiltmeters stations were set up between 1993 and 1997 at a lower altitude (50-150 m) around the island’s perimeter [green points in Fig. 1].

After the December 30th 2002 landslide, it became evident that the most urgent requirement of the monitoring system was to detect real-time deformations related to potential slope failures of the SdF. A new monitoring system, based on the integration of different measurement techniques (EDM, clinometric and GPS), was planned and set up during the first two months of 2003 (Puglisi et al, 2005). Twenty-two EDM control points were installed within the Sciara and three pillars were set up for the measurement instruments [Fig. 1]. Moreover, a permanent GPS network, specifically designed for the real-time monitoring of movement at the core of the potential failure zone and close to the summit craters, was built within the SdF [Fig. 1]. Finally, a robotized Total Station was installed to automate the terrestrial geodetic measurement along the northern sector of the SdF (Puglisi et al, 2005).

The EDM was the first technique adopted to evaluate hazard evolution in the SdF during the initial days of the volcanic crisis. It was composed of four sub-networks. The first one (named “Fossa”, in the following) was installed on the summit area of the volcano named Fossa area, the part of Crater Terrace included between the PSF and the Craters. This sub-network [Fig. 1] consisted of five reflectors (named FOS1 to FOS5) that were installed along a profile crossing several fractures and fumaroles on the ground. These control points were surveyed from the iron pillar set up at PSF [STR in Fig. 1]. The second sub-network (named “Reference”, in the following), composed of 4 reflectors (BAST, SLF, FORT and VANC), was installed on the upper part of the volcano outside and around the SdF area, on sites located outside or along the rim of the Upper Vancori Sector Collapse (Tibaldi, 2001), thus considered stable with respect to the recent movements of the SdF (i.e. younger than 13 ky). This second one allowed us to check the actual stability of these areas and verify the repeatability of the distance measurements carried out from the STR pillar, in order to detect systematic errors due, for example, to atmospheric effects. A third monitoring sub-network (named “Bastimento”, in the following) was installed below the Bastimento. This sub-network consisted of six control points (from PST1 to PST6), placed in the area of the niche of the December 30th landslide [Fig. 1]. In particular, the first two (PST1 and

PST2) were installed above the NE-trending eruptive fissure, which originated the first lava flows on 28-30 December, while the other four were distributed downslope from the fissure, on the lava flows produced in December. These benchmarks were measured from the STR pillar and two of them (PST4 and PST6) were equipped with two reflectors, in order to be measured also from another pillar, located on the lower flank of the volcano, at Punta Labronzo (PLB). This pillar was set up with the aim of enabling monitoring on the lower part of the SdF area, not visible from the STR pillar (the network of the benchmarks installed in the medium-lower part of the SdF, measured from the PLB pillar, and the relevant data are discussed in Chapter 3.1).. Throughout the EDM monitoring activities, angular measurements were sometimes carried out from the pillars by using a theodolite, in order to evaluate the three-dimensional movements of the benchmarks.

After the events of December 30th, the INGV section of Catania, in conjunction with the National Department of Civil Protection, decided to set up a new GPS network (named *SciaraDat*), aimed at the real-time monitoring of displacements in the highest part of the SdF, under the realistic hypothesis that any future flank collapse would be preceded by initial deformations in these areas (Mattia et al., 2004; Puglisi et al., 2005). *SciaraDat* consisted of 4 stations (SCRA, SDIC, SSBA, SVIN; Fig. 1). The stations were placed on the upper SdF slope and around the summit craters by using helicopters in order to work safely (Puglisi et al., 2005). The traditional approach based on the post-processing of 24 hours/day of GPS measurements, sampled every 30 seconds, wasn’t able to give fast enough responses for early warning to the population of large regions of Southern Italy, potentially affected by a large scale tsunami (Tinti et al, 1999). To provide data at suitable frequency, we adopted the CRNet software (Leica and Geodetics Inc., 2002) which applies the LAMBDA (Least squares AMBiguity DecorrelAtion technique; Teunissen, 1993) method for the fast resolution of the phase ambiguities. The software is able to resolve the problem using the so-called “Epoch-by-Epoch” (Bock et al., 2000) algorithm. Each time a single epoch of GPS data is collected, this algorithm produces a 3D position of the remote stations, with respect to a “master” whose coordinates are assumed fixed (SVIN in our case). The levels of accuracy in positioning are in the order of 1-2 cm in planimetry and 2-6 cm in altimetry, as demonstrated with internal tests performed on a selected baseline on Mt. Etna during August 2002 (Mattia and Rossi, 2004). We adopted 1Hz as the sample frequency for SciaraDat. Usually, three kinds of result were produced for each remote station: the 1Hz position, the median of 10-minute of data positions and the median of 1 day of data positions.

One of the aims of this network was to trigger an alarm when significant deformation phenomena are observed on the GPS data. To achieve this, some useful statistics were introduced. CRNet multi-epoch statistics are based on two robust estimators, the median and the interquartile range (IQR), which are less sensitive to data outliers than the traditional mean and standard deviation. When a data sample is drawn from a normal distribution, its mean very nearly equals its median and its standard deviation equals about three quarters of the IQR. For intervals longer than a single epoch, the position coordinates are determined as the median value of all single-epoch positions within the interval, excluding position coordinate outliers which are defined on an appropriate multiple of the IQR. Although the 1Hz data are very precise, multipath effects and local transient radio signals can degrade the level of precision. For this reason, the alarm was set up using the median of a 10-minute data set, with the threshold alarm at 0.1 m on planimetry and 0.2 m in altimetry.

3.0 Data discussion

Data collected from this complex monitoring system allowed us to effectively monitor the deformations related both to the downslide movements of the SdF and to the evolution of the volcanic activity. In Chapter 3.1, we briefly discuss some significant aspects of the dynamics of the shallow plumbing system of the volcano, throughout the period of the lava effusion, while in Chapter 3.2, the geodetic data relevant to the stability of the SdF are discussed together with those provided by GBInSAR (Bonforte et al. this volume). For simplicity, we can group the discussion by areas since there were specific events to be investigated in each of these.

3.1 Area below Bastimento

The geodetic monitoring system enabled us to observe the effects of the migration of effusive activity from about 500 m of elevation to a new vent at 580-590 m of elevation, below Bastimento, occurring between 15 and 17 February (Marsella et al., this volume). This phenomenon produced a deformation field, whose evolution was monitored both by GPS and EDM systems. From 15 February, several distances measured both from the STR and PLB pillars showed significant variations with respect to the previous days, on benchmarks located below the Bastimento area [Fig. 2]. PST2 anticipated the deformation, showing a lengthening on 11 February. The climax of this phenomenon was on 16 February, just after the opening of the vent at 580-590 m of elevation that fed the lava flows until the end of the eruption, in July. After the vent opening, the SSBA GPS station, just installed, measured a significant NW displacement [Fig. 3]. The integration between the 3D movement detected by the GPS station and the displacements relevant to dense distribution of the reflectors installed below the Bastimento, measured from PLB pillar (Fig. 4), enabled us to characterize the spatial and temporal evolution of this phenomenon. Only benchmark PST4 recorded a very high ground deformation (about 80 cm between 15 and 16 February), while the other benchmarks close to PST4 (within a radius in the order of one hundred of meters) recorded smaller movements by two orders of magnitude [Fig. 4]. The abrupt spatial decay of the deformation and the stability of the reference points on the summit area, as well as the absence of movements at the GPS permanent network at the foot of the volcano, confirmed that this phenomenon was local and did not affect either the entire volcano or the whole unstable flank. This sustained the hypothesis of a very shallow migration of magma, towards the new active vent that opened on February 16th, at 580-590 m elevation. All these data were provided in real-time to the scientists involved in monitoring activities. This capability, the appropriate dense network configurations and the integration between information provided by different techniques, enabled giving accurate and timely information to the Department of Civil Protection, avoiding raising a false alarm of the potential major failure of the

SdF flank. A few days after the beginning of the deformation episode, a new vent opened and the lava flow emitted by this vent destroyed the SSBA station on 20 February 2003. The activity of the vent at 580-590 m destroyed many reflectors installed below the Bastimento and on the SdF slope also. However, there was no flank failure. A simple elastic source model for this episode was not feasible because of its very limited spatial extent and lack of data in the far field where the elastic conditions are satisfied.

On the basis of the results of the above analysis, we think that a similar ground deformation pattern evolution, even if with smaller magnitude, also occurred during the opening of the 670 m vents [Fig. 4], in the January – February period (Calvari et al., 2005). From 20 January to 7 February, only 3 benchmarks were measured in the Bastimento area [Fig. 2], two of these (PST1 and PST2) located uphill from the eruptive fissure formed during the first days of the eruption, thus in a relatively stable area [Fig. 4]. The third benchmark (PST3) recorded an abrupt and permanent deformation between 21 and 24 January [Fig. 2], of about 4 cm, which was confirmed by the subsequent measurements until 28 January. We think that this deformation was related to the opening of the 670 m vent on 23 January (Calvari et al., 2005). The next measurement, on 7 February, recorded another deformation, of about 1.5 cm, which probably was due to the repeated opening of the 670 m vent on 28, 29, 30, 31 January and 1, 2 and 3 February (Calvari et al., 2005). However, only the measurements on the PST3 benchmark were suitable for this period in this area, preventing any further analysis on the spatial evolution of the deformation pattern as above performed for the 15-17 February event.

3.2 Fossa and summit area

Two questions arose during the first days of the eruption, both concerning the stability of critical parts of the volcano: the summit craters and the Sciara del Fuoco. It is obvious, indeed, that if either the summit craters or the Sciara del Fuoco should collapse, the risk would dramatically increase not only for the Stromboli island but also for the Aeolian Archipelago and south Italy as a whole.

The EDM measurement carried out on the two sub-networks “Fossa” and “Bastimento”, together with the data provided by the SciaraDat network, allowed us to investigate the dynamics of these areas and provide information about the evolution of the volcanic risk during the first week of the eruption.

Since the first measurements collected from the STR pillar, the reference sub-network installed around the summit area of the Stromboli confirmed that the Pizzo area, as well as the upper part of the rim of the Sciara del Fuoco (from Bastimento to SLF station), was stable. In fact, the EDM measurement did not record any significant deformation of the reference sub-network [Fig. 5]. This was the first significant result of the monitoring geodetic activities, which excluded the possibility of a sector collapse involving the Pizzo area that might produce a large phreatomagmatic explosion and a giant tsunami. The hypothesis of the sector collapse was based on previous studies of the evolution of SdF (Tibaldi, 2001), which showed that this phenomenon occurred a few times, through the evolution of the volcano, alternating with growth phases (the Vancori Collapse, ~13 ka according Tibaldi, 2001). According to Tibaldi (2001) “the younger sliding planes tended to become more superficial and to decrease the areal extent”, involving the low-middle sector of the SdF. Our observations concur with this scheme of the evolution of the SdF and suggest that its current dynamic was not evolving toward catastrophic events, which might involve a sector collapse.

The increase in the distances between the STR pillar and the benchmarks of la Fossa area [Fig. 5] allowed making some hypotheses on the dynamic of the craters. The deformation pattern was characterized by a period of a quasi-linear distance increase at the beginning, followed by a pause, and then a second phase of deformation starting after 7 February. This peculiar behaviour could be linked either to the sliding towards the sea of the summit craters and Sciara del Fuoco, altogether, or to the movements of the magmatic column within the craters. In order to discriminate between these two possible origins of the observed movements, we may consider the measurement performed at the two GPS stations, SDIC and SCRA [Fig. 3]. The absence of significant movements at these stations, during their working period, suggests excluding the sliding phenomena of the summit craters, at least with velocities and pattern comparable to those measured by the EDM "Fossa" sub-network ranging from 1 to 5 cm/month. Thus, the movement measured by the EDM network should be related to a local phenomenon, probably due to the movement of the magmatic column within the conduits.

It is noteworthy that the principal increases of the distance between the crater flanks and the STR pillar occurred during two main periods: from the beginning (18 January) until 30 January, and from 7 to 16 February, approximately. These periods correspond to the rising of the vents from 500 m up to about 580-590 m or 670 m of elevation (Calvari et al., 2005; Marsella et al., this volume). Thus, it is reasonable to assume that the increase in the distance was related to vent migration, which in turn was related to the variation of magmatic column within the shallow plumbing system. In this view, the vents "represented the passive fingering of magma from the central conduit and NE fissure" (Calvari et al., 2005).

Above, we showed how the ground deformations pattern related to the second of these periods was characterized by a high areal gradient measured by both EDM and GPS networks, suggesting that its origin was very local and shallow. Unfortunately, during the first of these periods the geodetic monitoring system installed below Bastimento area was incomplete, because only the PST1, PST2 and PST3 EDM benchmarks were installed. However, it is noteworthy that the PST3 distance jumped on 24 January, with respect to the measurement carried out on 21 January [Fig. 2].

The data discussed until now highlight that the movements measured during the first months of the eruption at the benchmarks located both at "La Fossa" and "below Bastimento" areas are temporally associated to the development of the "temporary" vents on the SdF, observed from about 500 m up to about 600 m (Calvari et al, 2005; Marsella et al., this volume). Considering that both these vents and the benchmarks are located within the α slide (Tommasi et al, this volume), it seems reasonable to assume that the movement of the α slide is at the origin of both the EDM movements and the vent formation. The mechanism we assume is that irregular movements of portions of the α slide induced the infiltration of magma within the body of the slide, from the central conduit [Fig. 6b]; these infiltrations were forming the new “temporary” vents which remained active for a few hours or days, i.e. until the magma could flow through the body of the slide, before its cooling. Consequently, this passive fingering produced a lowering of the magma column top. So, we were able to deduce that the increase in the distances should be related to the lowering of the top of the magma column within the conduits [Fig. 6b] for feeding the vent in the SdF (580-590 m or 670 m in our case) and to the consequent lowering of the SE rim of the craters area [Fig. 6b].

Conversely, the periods of stopping in length variation could be linked to a stasis of the magmatic column within the craters, during the magma emission from the 500 m elevation vent [Fig. 6a].

Although this hypothesis needs more investigation to understand the role of the fractures existing between STR and the craters in the Fossa area and to explain the absence of significant movements at the SCRA station, it is noteworthy that similar phenomena, even with larger morphological evidences, occurred during the first days of the 2007 eruption. The Fossa area, indeed, completely collapsed within the craters, while the seaward flank of the craters remained relatively stable and the collapse evolved along a ring-shaped fracture system very similar to that observed during 2002-03 eruption.

4.0 Conclusions

The geodetic monitoring of the Stromboli volcano enabled us to collect important data on the dynamic of the eruption. In particular, we were able to investigate the opening of eruptive vents on 16 February, and elaborate a model of magmatic column movements within the shallow plumbing system of the craters during the first month of the eruption.

We explained the EDM baselines lengthening on the Fossa area as the result of the movements of the magmatic column within the craters, when new vents in the SdF were forming. Thus, the pauses we measured in the increase in the distances between the STR pillar and the benchmarks of la Fossa area, were related to a stasis of the magmatic column within the craters.

Moreover, the local effects of an effusive vent opening on February 16th were observed. During this phenomenon, the very high ground deformation recorded only locally and the abrupt spatial decay of the deformation around the benchmark where the maximum of deformation was measured, as well as the stability of the points on the summit area and at the foot of the volcano, meant excluding the possibility an imminent flank failure and contributed to the decision to avoid declaring a state of emergency. A deep deformation source, which could trigger a new landslide, indeed, should produce a wider ground deformation field than the one actually measured. Furthermore, the opening of the vents from about 500 m up to about 600 m of elevation during the January – February period, possibly produced a similar ground deformation pattern, even with smaller magnitude, which was not investigated due to the suitability of only one benchmark in this area during this period.

All this information certainly represents a valuable dataset for future research to understand how the plumbing system of this volcano works, especially during eruptive events. The twofold aspect (eruption and landslide) of the Stromboli volcanic crisis emphasized the role of geodetic monitoring activities on active volcanoes. The strategy adopted at Stromboli was to implement many different types of real-time or near real-time survey techniques, taking cost-effective and logistic constraints into account.

Our experience underlines that the current development of surveying techniques allow performing a detailed real-time monitoring of ground deformations, in a very wide spectrum of operational conditions. The achievable accuracies in 3D positioning are suitable for scientific and early warning purposes. These positive results then suggest that Stromboli monitoring system will be a useful tool to identify movements for forecasting large future landslides that could occur on the SdF.

Figure captions

Figure 1. Ground deformation monitoring system after the 2002-2003 eruption onset. The map also shows the main volcanic features formed during the first two days of the 2002 eruption: the fracture opened on the northern flank of the NE crater (white line), the outpoured lava flows (black area) and the slid area (gray area). In the inset, the geographical setting of Stromboli volcano.

Figure 2. EDM data collected from STR pillar, related to the sub-network, installed below the Bastimento. The data are shown in the top and bottom panels at different scale.

Figure 3. Ten-minute average values of 1 Hz displacement time series of the three GPS stations station from the start of operations on 11 February until the destruction of SSBA station caused by the lava on 20 February.

Figure 4. 3D vector deduced by EDM and theodolite measurements at PST4, from February 13th to February 19th. To show the abrupt decay of the deformation, we reported a table with the modules and the vertical variations of many points located near PST4.

Figure 5. EDM data collected from STR pillar, related to the “Reference” and “Fossa” sub-networks.

Figure 6. Scheme of the interpretation of the phenomena originating the variations in the EDM measurements collected by the “Fossa” sub-network. A) During the first phase (corresponding to the period of no-lengthening of distances) the landslide in the SdF is stable, the passive fingering is not fed, thus the level in the conduit of the craters remains stable; B) During the second phase (corresponding to the lengthening of distances) the movement of the landslide induces the feeding of the passive fingering, producing a lowering of the magma level within the conduits.

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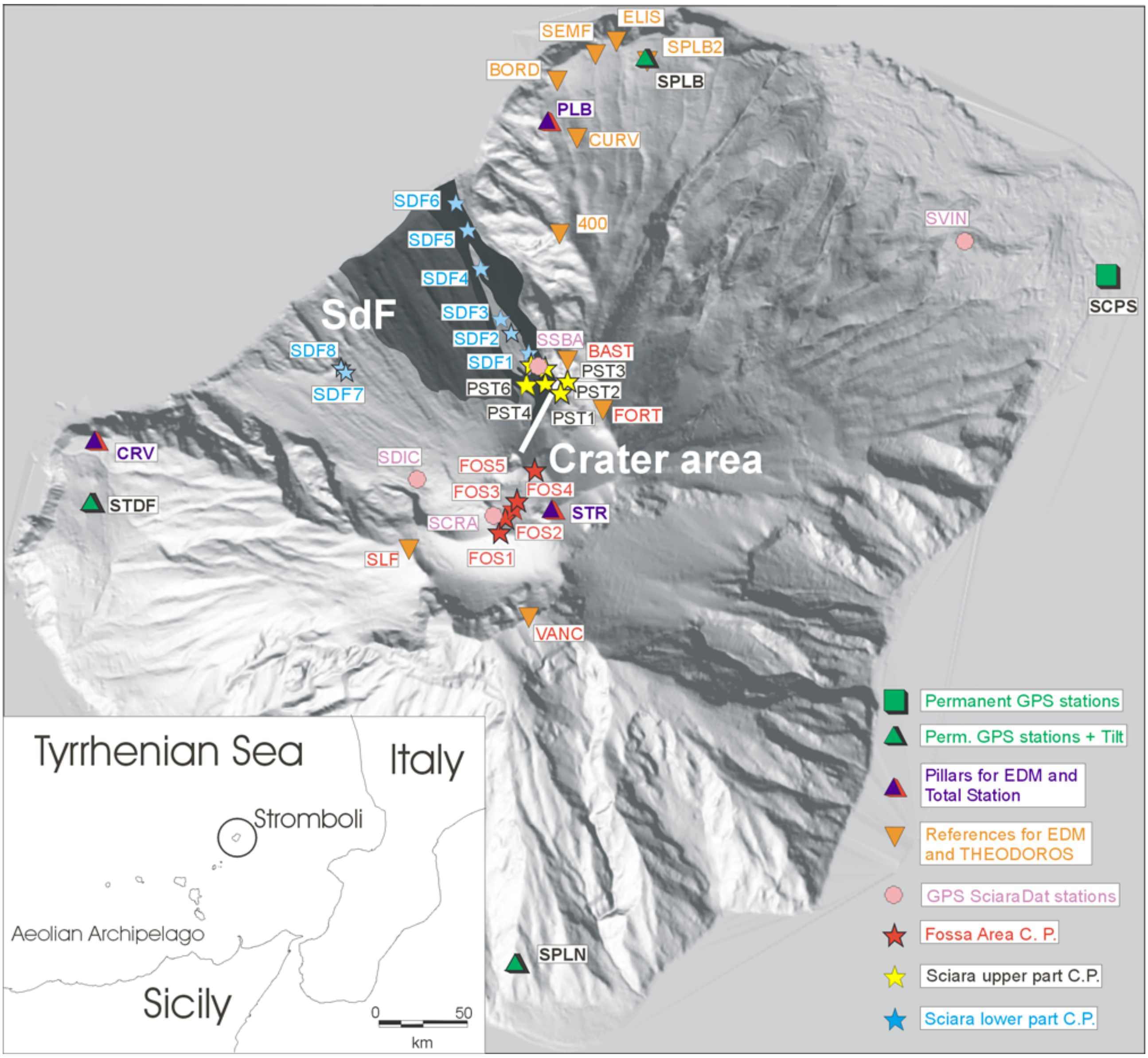
ELIS
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SDIC
FOS5
Crater area
FOS3
FOS4
STDF
STR
SCRA
FOS2
SLF
FOS1
VANC
Tyrrhenian Sea
Italy
Stromboli
Aeolian Archipelago
Sicily
0
50
km
SPLN
Permanent GPS stations
Perm. GPS stations + Tilt
Pillars for EDM and Total Station
References for EDM and THEODOROS
GPS SciaraDat stations
Fossa Area C. P.
Sciara upper part C.P.
Sciara lower part C.P.

Figure 1

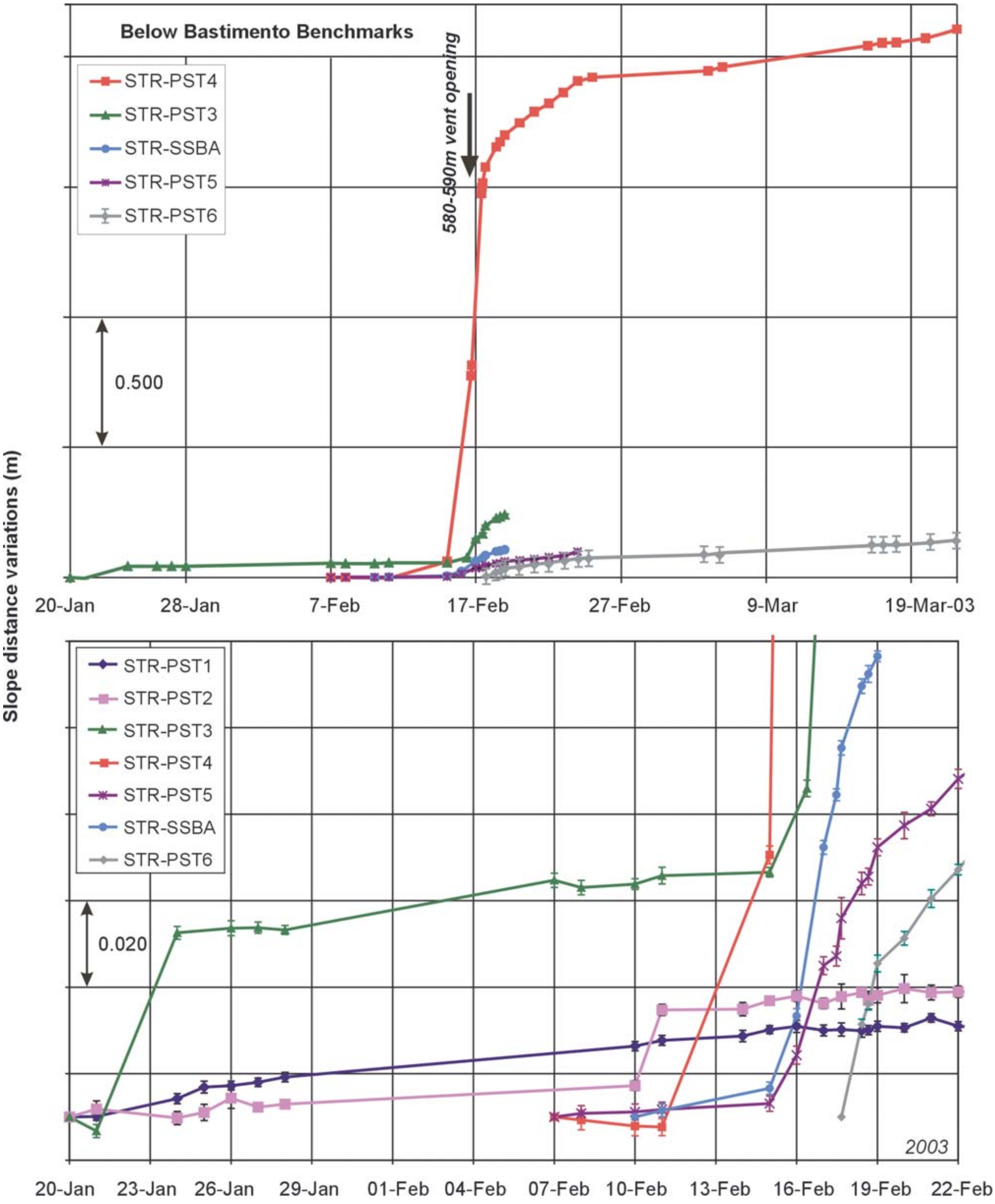

Below Bastimento Benchmarks
STR-PST4
STR-PST3
STR-SSBA
STR-PST5
STR-PST6
580-590m vent opening
0.500
Slope distance variations (m)
20-Jan
28-Jan
7-Feb
17-Feb
27-Feb
9-Mar
19-Mar-03
STR-PST1
STR-PST2
STR-PST3
STR-PST4
STR-PST5
STR-SSBA
STR-PST6
0.020
2003
20-Jan
23-Jan
26-Jan
29-Jan
01-Feb
04-Feb
07-Feb
10-Feb
13-Feb
16-Feb
19-Feb
22-Feb

Figure 2

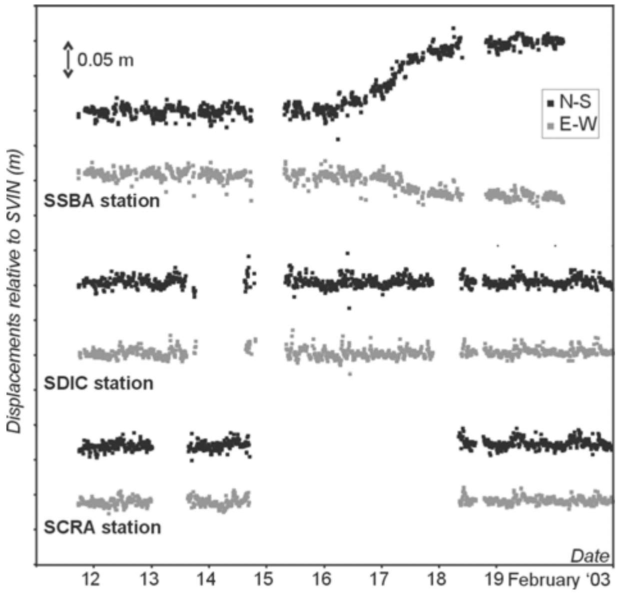
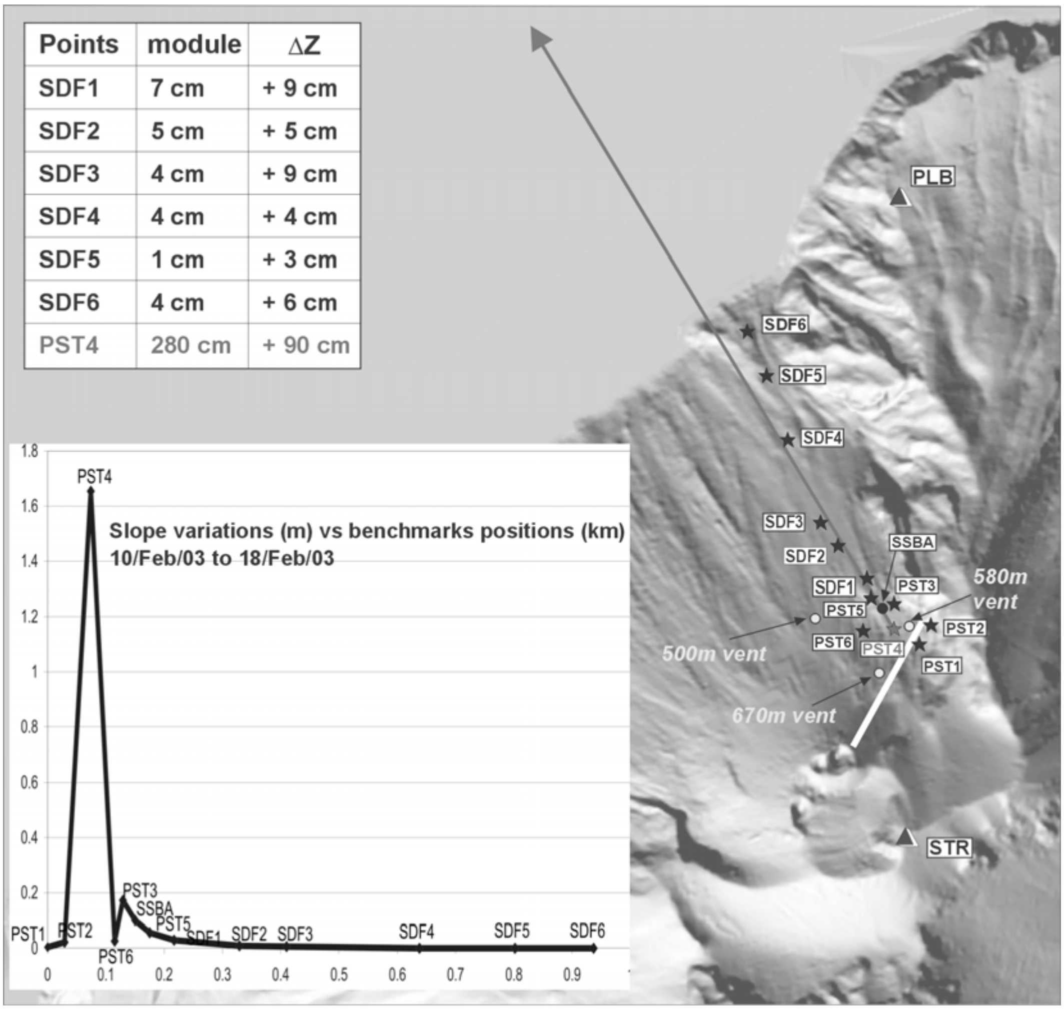

0.05 m
■ N-S
■ E-W
SSBA station
SDIC station
SCRA station
Displacements relative to SVIN (m)
Date
12
13
14
15
16
17
18
19 February '03

Figure 3



Points	module	ΔZ
SDF1	7 cm	+ 9 cm
SDF2	5 cm	+ 5 cm
SDF3	4 cm	+ 9 cm
SDF4	4 cm	+ 4 cm
SDF5	1 cm	+ 3 cm
SDF6	4 cm	+ 6 cm
PST4	280 cm	+ 90 cm

Slope variations (m) vs benchmarks positions (km)
10/Feb/03 to 18/Feb/03

Figure 4

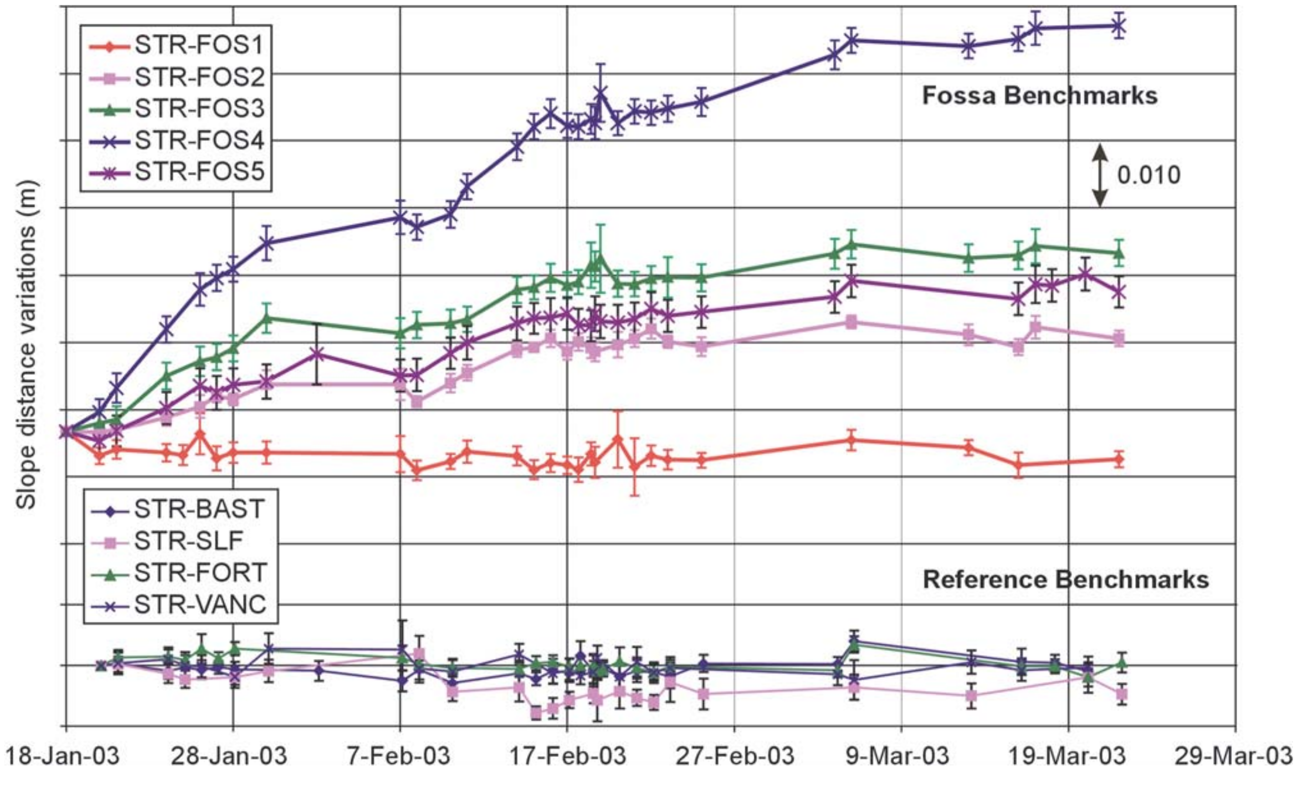

STR-FOS1
STR-FOS2
STR-FOS3
STR-FOS4
STR-FOS5
Fossa Benchmarks
0.010
Slope distance variations (m)
STR-BAST
STR-SLF
STR-FORT
STR-VANC
Reference Benchmarks
18-Jan-03
28-Jan-03
7-Feb-03
17-Feb-03
27-Feb-03
9-Mar-03
19-Mar-03
29-Mar-03

Figure 5

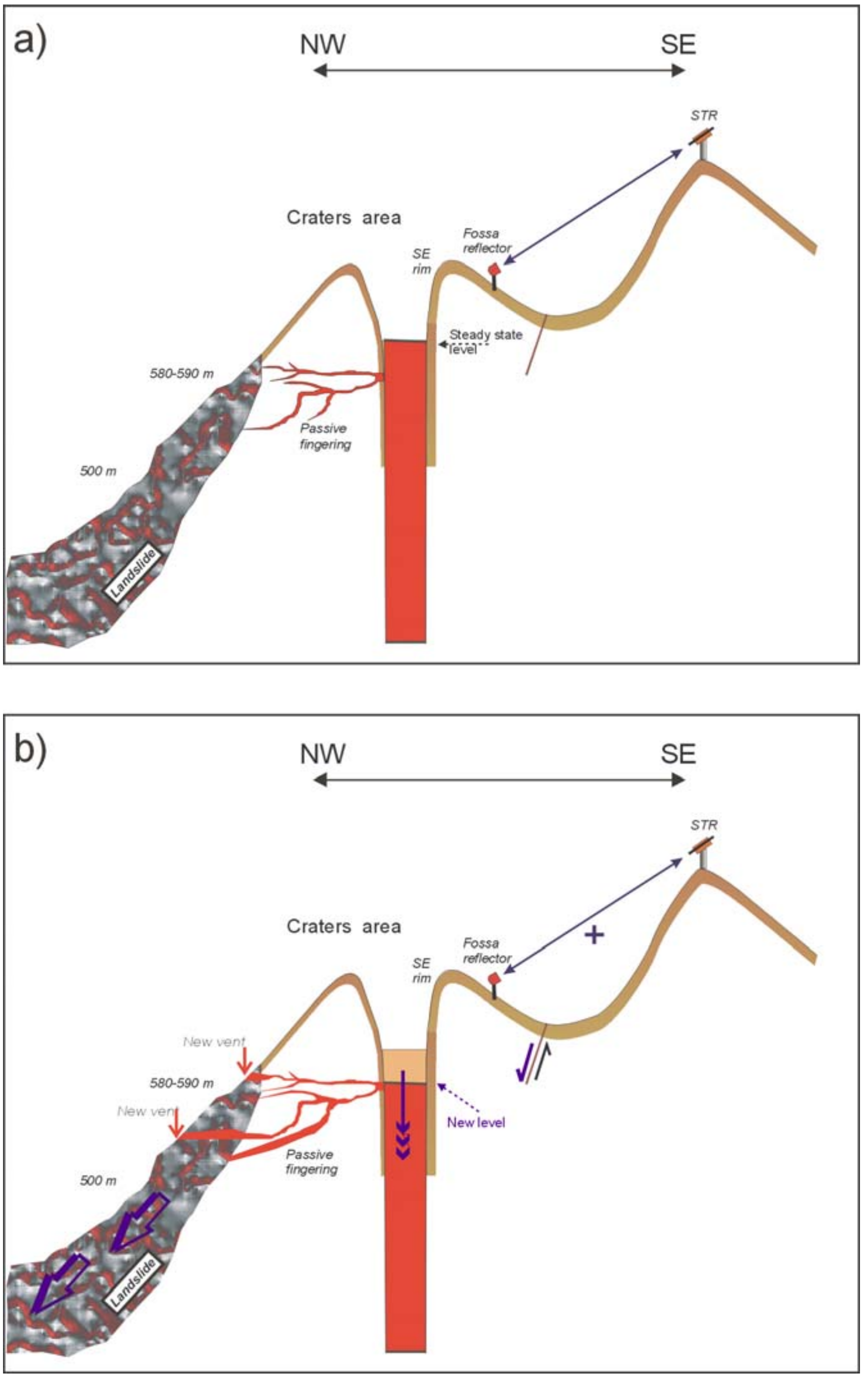

a)
NW
SE
STR
Craters area
SE rim
Fossa reflector
Steady state level
580-590 m
Passive fingering
500 m
Landslide
b)
NW
SE
STR
Craters area
SE rim
Fossa reflector
+
New vent
580-590 m
New vent
New level
Passive fingering
500 m
Landslide

Figure 6