The shallow plumbing system of Stromboli Island as imaged from 1 Hz instantaneous GPS positions

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[1] The Stromboli volcano (Aeolian Islands, Italy) erupted suddenly on 28 December 2002 after a 17-year period of typically persistent but moderate eruptive activity, followed two days later by a tsunamigenic landslide on its NW flank (Sciara del Fuoco) felt in the coastal areas of southern Italy. Three continuous GPS stations were quickly deployed near the volcano's rim sampling at 1 Hz, with instantaneous positions computed relative to a fourth station on its flank. We report on two deformation episodes. A vent migration on 16–17 February 2003 caused significant displacements at only one site and contributed to the decision not to issue a warning of an impending tsunamigenic landslide. The second episode on 5 April 2003, a paroxystic explosion from the summit crater, allowed us to model, for the first time with geodetic data, the shallow magma chambers that give rise to Strombolian explosive activity. *INDEX TERMS:* 3210 Mathematical Geophysics: Modeling; 8145 Tectonophysics: Physics of magma and magma bodies; 8414 Volcanology: Eruption mechanisms; 8419 Volcanology: Eruption monitoring (7280). **Citation:** Mattia, M., M. Rossi, F. Guglielmino, M. Aloisi, and Y. Bock (2004), The shallow plumbing system of Stromboli Island as imaged from 1 Hz instantaneous GPS positions, *Geophys. Res. Lett.*, *31*, L24610, doi:10.1029/2004GL021281.

1. Introduction

[2] Stromboli volcano is characterized by persistent and moderate explosive ("Strombolian") activity (5–6 events per hour), which once or twice a year reaches paroxystic levels posing risks for the two villages of Stromboli and Ginostra on the volcano's flanks, and for the many tourists that reach the summit area every year. The Stromboli volcano has been affected by several collapses; the youngest one produced the horseshoe-shaped amphitheatre of the NW flank of this volcano, called the Sciara del Fuoco. Related to these collapses is the hazard of tsunami waves generated by landslides along the very steep slopes of the Sciara del Fuoco. Ground deformation studies such as the one by *Bonaccorso* [1998] confirm the role of NE-SW oriented dykes, as shown by many geological and structural investigations on the island [e.g., *Pasquarè et al.*, 1993; *Tibaldi*, 2001]. Recent seismological studies have revealed magma storage at shallow levels under Stromboli's summit [*Chouet et al.*, 2003; *La Rocca et al.*, 2004] and, despite meaningful differences, there is a general agreement that these are the source of the Strombolian activity. *Falsaperla and Spampinato* [2003] hypothesize that a shallow magma chamber is also the origin of paroxystic explosions of the Stromboli volcano. This study uses high-frequency (1 Hz) instantaneous GPS positions [*Bock et al.*, 2000] from the 4-station "Sciaradat" network (Figure 1) collected on Stromboli Island from February to April 2003, as part of a tsunamigenic early warning system for the coastal areas of Calabria and Sicily. We report here on the observation of a vent opening near one of Sciaradat stations on 16–17 February 2003. The absence of deformation at the other Sciaradat stations and at other geodetic instruments allowed INGV (Istituto Nazionale di Geofisica e Vulcanologia) to rapidly exclude the possibility of incipient flank failure. Next, we present the recording of the three stages of a 90 s paroxystic explosion on 5 April 2003, which allows us to observe and model, for the first time with geodetic data, the shallow magma chambers that give rise to Strombolian activity.

2. The 2002–2003 Eruption and the Sciaradat Network

[3] Although intense explosive activity was observed on Stromboli in May 2002, the 2002–2003 eruption sequence started without warning on 28 December from a NE trending eruptive fissure. In a few hours the lava flow reached the sea after a fast run along the Sciara del Fuoco. New fractures were observed on 30 December that contoured the upper part of the flank and at 13:14 and 13:22 (local time) two landslides of the northern part of the Sciara del Fuoco triggered a tsunami wave [*Bonaccorso et al.*, 2003]. After the events of 30 December, the Italian National Department for Civil Defense moved quickly to supplement the monitoring networks on Stromboli Island, as a way of mitigating the hazards of a large flank failure that could induce a catastrophic tsunami wave with serious impact on the population of cities along the shorelines of southern Italy [*Tinti et al.*, 2003]. Four CGPS stations were operating at sea level on the flanks of the volcano since 1997 (Figure 1), but revealed no significant displacements before or during the eruption of 28 December 2002 [*Bonaccorso et al.*, 2003], so the decision was made to target the shallow magma chambers detected previously by seismic data [e.g., *Chouet et al.*, 2003; *La Rocca et al.*, 2004]. Based on the seismic data, a shallow source of limited extension (few hundreds of meters wide and above sea level) would result in ground deformation observable with geodetic techniques only in a limited area on the steep

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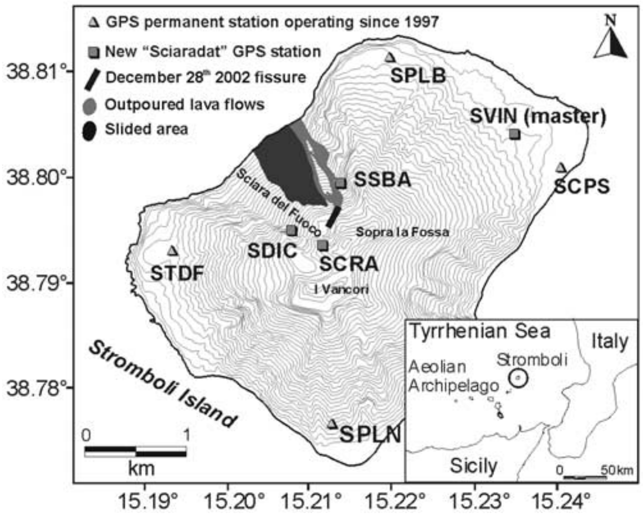

Figure 1. Continuous GPS monitoring stations on Stromboli Island.

slope of the Sciara del Fuoco. It is too hazardous to install monitoring instruments on the volcano's summit during Strombolian activity. However, it is possible to work in this area during an eruption because the explosive activity is very low or absent. It was decided, therefore, to quickly deploy three CGPS stations in the summit area of the volcano with the aim of monitoring three strategic points: 1) the cone of the crater (station SCRA - Cratere); 2) the area where the lava flow was accumulating (SSBA – Sotto Bastimento); and 3) a fracture field on the southern side of the Sciara del Fuoco (station SDIC - Dicco), potentially susceptible to mass movements of the flank. The three stations on the volcano's rim were linked via wireless radio communications to the master GPS station (SVIN) at the Advanced Operative Center (COA) of S. Vincenzo on the volcano's base. It was decided that the method of instantaneous GPS positioning [*Bock et al.*, 2000], previously applied to seismic monitoring [*Bock et al.*, 2004], was best suited to this environment. Instantaneous positioning provides independent relative position estimates, at each observation epoch, by resolving integer-cycle phase ambiguities anew for each epoch. On Stromboli, distances between the base station and the summit stations are less than 2.5 km so that differential ionospheric effects are small and can be neglected. At these distances, single-epoch position precision (1 σ) is about 5 mm in the horizontal and 25 mm in the vertical [*Bock et al.*, 2000].

3. Vent Opening and Hazards Assessment

[4] The Sciaradat network was declared operational on 12 February 2003. Within four days, station SSBA began to show a significant displacement signal (Figure 2), with an absence of deformation at the other two summit sites. The instantaneous analysis of the continuous GPS data stream and nearby observations from an EDM network helped us to quickly quantify and understand that the signal was related to the opening of a new eruptive vent localized in the vicinity of station SSBA and a single nearby monument in the EDM network. The absence of deformation at the other two crater rim GPS stations allowed us to exclude the possibility of an incipient flank failure, and contributed to the decision to avoid declaring a state of emergency. 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. However, there was no flank failure. A realistic source model for this episode was not feasible because of its very limited spatial extent and paucity of data. Furthermore, the shallow level of the deformation field excluded the possibility of a simple elastic model.

4. Model of a Paroxystic Explosion

[5] The two remaining Sciaradat summit stations (SDIC and SCRA) did not exhibit any further meaningful displacements until 5 April 2003, when a paroxystic explosion from the summit crater ejected blocks of basaltic rocks in the direction of Ginostra village, destroying houses and walls and causing significant damage to the island's monitoring networks. The radio modems and solar panels at the summit stations were also damaged, but not before data from the approximately 90-second explosive episode were transmitted and analyzed. We have identified three phases to this event. In the first phase, from 7:12:33 to 7:13:05, station SDIC was displaced to the SW and a positive height variation was recorded. In the second phase, from 7:13:05 to 7:13:17, the vector of SDIC was displaced to NW direction, with a marked decrease in elevation. The third phase, from 7:13:17 to 7:13:55, represents the arrival of a sustained magmatic column in the upper part of the conduit with both stations affected by the explosion. We inverted the displacement data for the three stages of the explosion, assuming a homogeneous, isotropic and elastic halfspace [*Okada*, 1985]. Starting from the data of the stations SDIC, SCRA and SCPS (the only station of the 4 located at the base of the volcano with an acceptable acquisition rate) and using a Genetic Algorithm (GA) [e.g., *Nunnari et al.*, 2004], we estimated 10 tabular dislocation parameters for each stage: coordinates of the top, dimensions (length and width), orientation (azimuth and dip) and displacements (strike slip, dip slip, opening). The limited number of available data forced us to fix some parameters (Table 1) based on the known kinematics and geology of the investigated area. GA is generally better suited than typical gradient-based techniques to finding global minimums for non-linear optimization problems with many variables. Starting with an initial range of models, the GA progressively modifies the solution by incorporating the evolutionary behavior of "biological" systems [e.g., *Tiampo et al.*, 2004]. The goodness of each

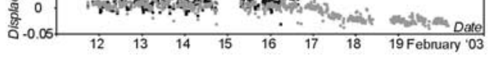

Figure 2. Ten-minute average values of 1 Hz displacement time series of the SSBA station from the start of operations on 11 February until a lava flow destroyed it on 20 February. Data gaps are due to radio communication outages.

Table 1. Estimated Models Parameters[a]

First Phase	Second Phase	Final Phase
Long = 518202.7 ± 8.2 m	Long = 518202.0 m[b]	Long = 518300.0 m[b]
Lat = 4293901.9 ± 16.4 m	Lat = 4293901.0 m[b]	Lat = 4293850.0 m[b]
Azimuth = N35.8°E ± 3.2°	Azimuth = N35.0°E[b]	Azimuth = N29.7°E ± 1.4°
Z = 188 ± 11 m	Z = 283 ± 6 m	Z = 36 ± 7 m
Length = 430 ± 50 m	Length = 712 ± 36 m	Length = 563 ± 9 m
Width = 173 ± 30 m	Width = 333 ± 8 m	Width = 368 ± 19 m
Dip = 55.0° ± 0.5°	Dip = 55.0°[b]	Dip = 73.0° ± 3°
Strike slip = 0.0 ± 0.01 m[c]	Strike slip = 0.0 m[b]	Strike slip = 0.50 ± 0.01 m
Dip slip = 0.0 ± 0.01 m[c]	Dip slip = 1.08 ± 0.02 m	Dip slip = −0.22 ± 0.03 m
Opening = 1.47 ± 0.17 m	Opening = 0.25 ± 0.04 m	Opening = 0.64 ± 0.06 m

[a]The reference surface (z = 0) has been assumed at 740 m, which is the mean altitude of the two highest modeled stations. The uncertainties of each of the estimated source parameters are the standard deviations calculated from the solutions that minimize the fitness function at the 95% confidence level (see text). The projection is UTM-WGS84.

[b]fixed.

[c]Assumed ≥ 0.

solution is measured by the fitness function, using the fitness value

$$J = \frac{\sum_{i=1}^{N} (P_i - O_i)^2}{\sum_{i=1}^{N} \left(\left|P_i - \overline{P}\right| + \left|O_i - \bar{O}\right| \right)^2}$$

where N represents the number of measured points, O_i and P_i the observed and predicted values, respectively, and $\overline{O}$ and $\overline{P}$ their mean values. The search process was stopped when, minimizing the fitness function, the 95% confidence level was achieved. The results of the GA search are shown in Table 1 and Figure 3. The source of the first stage is in the same area defined by seismic data, and the sudden inflation may be due to the pressure of a "slug" of gas through to the surface. The second stage indicates only a small opening component and a normal dip-slip of more than 1 meter. The source is wider with respect the first stage, but the dip angle is the same. In this stage the deflation of

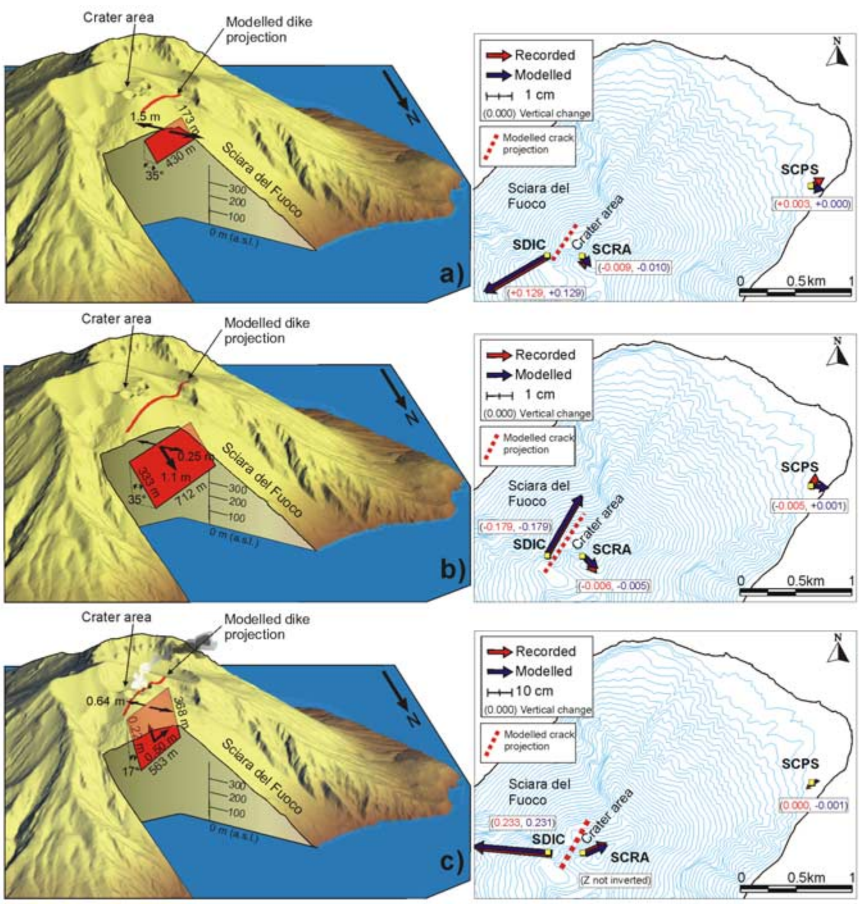

Figure 3. Three-dimensional model sketches and observed-model displacement vectors of the Sciaradat network and CGPS station SCPS on the volcano's base during the 5 April explosion, for the a) first phase of the explosion; b) second phase; c) final phase.

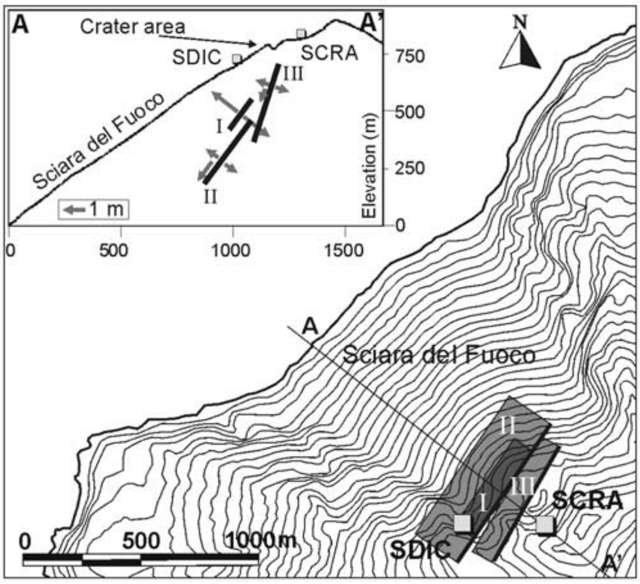

Figure 4. Projection of the estimated three models in plane and cross-sectional views.

the source due to the sudden rise of magma along the paths of the summit conduits is the dominant ground deformation pattern. At the second stage, the shallow source lost pressure and, with a mechanism similar to when a champagne bottle is opened, the magmatic fluids were "squeezed" and rose along the conduit. In the third stage, a source dipping 73° (whose projection coincides with the crater area) shows opening, inverse dip and left strike slip components. This stage is related to the arrival of a sustained magma column in the crater area. In this last inversion the height component of the SCRA station was disregarded because its value was unrealistic. We are now able to fix three aspects of the recent events on Stromboli, taking into account the limits of the data and of modeling process. In agreement with recent papers using seismic data [e.g., *Falsaperla and Spampinato*, 2003], the source of the paroxystic explosion is the same as for the typical low-energy continuous (Strombolian) explosive activity. Second, the source can be localized to a shallow magma storage zone located in the body of the volcano (Figure 4), above sea level, and located in the same area discussed by *Chouet et al.* [2003]. The action of a deeper source is ruled out by the data of the four other CGPS stations located at sea level (Figure 1); these stations showed no significant displacements on April 5, and during the entire period of the 2002-2003 eruption. The rising process occurred along a double inclination dike, similar to a "knee" (from 55° to 73° by moving from the storage zone to the summit area) (Figure 4). This change of slope could indicate the possible source of the typical explosive activity of Stromboli. In fact, *Chouet et al.* [2003] demonstrated that the inclination of the conduit is a crucial element in the degassing process. Finally, we succeeded in recording precise 1 Hz displacements for the 90 s period of the explosion, with a latency of less than 1 s. The time span necessary for a tsunami wave to reach the coasts of Sicily and Calabria has been estimated by *Tinti et al.* [2003] to be at least 800 seconds. Although not sufficient warning for mitigating hazards on the island from a paroxystic explosion, this amount of lead time is of use as part of a tsunami warning system for the coasts of Sicily and Calabria in the event of an imminent tsunamigenic landslide, which could result in a serious loss of life.

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