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Modelling of the April 5, 2003, Stromboli (Italy) paroxysmal eruption from the inversion of broadband seismic data

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Abstract

On April 5, 2003, one of the largest eruptions in the last decades was observed at Stromboli volcano, Italy. The eruption occurred in a period of increased volcanic activity, following a first explosion in December 2002, which interrupted the typical moderate "Strombolian" behaviour. We present an exhaustive analysis of the available broadband seismic data and relate them to the observed eruption phases. Prominent features of the seismic signals include an ultra long period signal starting a few tens of seconds prior to the explosive eruption as well as a strong energetic signal a few seconds after the onset of the eruption. Both signals are not exactly synchronized with the other geophysical observations. We present a detailed study of those signals using spectral and particle motion techniques. We estimate eruption parameters and seismic source characteristics by different inversion approaches. Results clearly indicate that the paroxysmal eruption was triggered by a shallow slow thrust-faulting dislocation event with a moment magnitude of $M_w = 3.0$ and possibly associated with a crack that formed previously by dike extrusion. At least one blow-out phase during the paroxysmal explosion could be identified from seismic signals with an equivalent moment magnitude of $M_w = 3.7$ and is represented by a vertical linear vector dipole and two weaker horizontal linear dipoles in opposite direction, plus a vertical force.

Keywords: volcano seismology; paroxysm; Stromboli; source inversion; eruption dynamic

1. Introduction

Stromboli volcano is one of the most active and deeply studied volcanoes on earth. The volcano is located in the Northeastern edge of the Aeolian archipelago in the southern part of the Tyrrhenian Sea, about 55 km offshore from the Italian coasts of Calabria and Sicily. The summit of Stromboli Island reaches an altitude of 924 m a.s.l., even if the volcano edifice rises up to a height of nearly 3000 m with respect to the seafloor. The three main craters are located SW of the summit, at about 700 m a.s.l. North-west of the craters, a steep slope, named Sciara del Fuoco (SDF), drops steeply down to approximately 1700 m below sea level (Romagnoli et al., 1993). The SDF is known to be continuously sliding. It has been at the origin of several subareal and submarine landslides in historic and pre-historic times. The last slide occurred on December 30,

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2002. The volcanic activity at Stromboli is better known from the frequent occurrence of moderate explosions, a behaviour known as "Strombolian", which has a typical rate of 3 to 10 events per hour (Chouet et al., 1974). This behaviour is occasionally interrupted by the occurrence of major eruptions, often accompanied by lava flows reaching the sea along the SDF. Since the last eruption in 1985, Stromboli showed its typical moderate and persistent eruptive activity, which was interrupted on December 28, 2002, by a large explosion. This unexpected eruption was followed by lava flows, starting from different fissures located approximately 300 m below the crater terrace. After 3 months, the lava supply decreased more and more, but the typical Strombolian activity did not restart. On April 5, 2003, finally a paroxysmal explosion occurred, the largest one since September 11, 1930, and the only one recorded simultaneously by such a multitude of different scientific instruments.

The present paper focuses on the event, which started on April 5, 2003, 07:12 UTC, and which occurred at the end of the 4-month eruption period. After a short overview of the crisis chronology and results available from other authors, we present the available seismic data, discuss their main characteristics and derive a model able to explain the eruption dynamics and the seismic source.

2. Overview on chronology and geophysical data

The eruption of December 28, 2002, was characterized by the opening of a main NE–SW trending fissure and by the subsequent lava flows toward the SDF slope (Calvari et al., 2005). Two days later, on December 30th, the collapses of portions of the NW flank produced two landslides in the area of the SDF. The slides generated a local tsunami on Stromboli Island with a maximal run-up height of about 11 m, causing several damages at the island villages (Tinti et al., 2006). At this time, a new effusive fissure (fissure 1) was observed at about 550 m a.s.l. During the following 2 months, the lava flows descending the SDF were mostly fed by this fissure. The estimated volume of extruded magma was about 6×10^6 m^3 (Calvari et al., 2005). Occasionally decreased flow rate at this fissure was accompanied by an increased effusive flow rate from a second fissure (fissure 2) that had formed 170 m above, at 670 m a.s.l., and was first observed on December 30th. The lava flow from fissure 1 was finally interrupted on February 15, 2003. Since that time, the effusive activity was taken over by the upper fissure 2 (Calvari et al., 2005). About 2 months later, on April 5, 2003, a paroxysmal eruption from the summit crater area occurred, starting at craters 1 and 3 (Calvari et al., 2006). During the whole volcanic crisis, from December 2002 and at least until April 1, 2003, the summit conduit, including its three vents at this time, was blocked, as indicated by the cessation of Strombolian activity and the lack of high-temperature vents in the crater area from measurements with a thermal camera (Calvari et al., 2005).

Different studies reported a wide set of geophysical data (Mattia et al., 2004; Calvari et al., 2006; Rosi et al., 2006; D'Auria et al., 2006), recorded during the eruptive process of April 5, 2003. The monitoring program included deformation, seismic, gas and infrared measurements, as well as visual observations. GPS data from four stations were analyzed by Mattia et al. (2004). Most of the GPS stations were damaged by the April 2003 explosion, and could still be used to identify three different eruptive phases. The observed deformations and uplift prior to the explosive eruption have been interpreted as caused by the slow ascent of a magmatic column in a feeder dike toward the crater area. The general behaviour can be summarized by the ascending or filling of a dike with a dip angle of 55–73° and a strike angle of 209–215° (sub-parallel to the SDF slope). The authors found also indications that the extension, orientation and opening of the dike slightly changed over a time period of about 45 s prior to the explosion.

A different set of information was used by Rosi et al. (2006), which describes the visual observations of the climactic explosions and their relation with infrared data from a sensor pointed toward the craters. The interpretation of these data led to the description of four phases of the explosive eruption, which correlate only partly with those defined by Mattia et al. (2004).

The first eruption phase in both studies is identified with the eruption onset. It started at 7:12:33 UTC (time R1), with the emission of red ash from two of the summit vents and later extended to the third one (Rosi et al., 2006). At exactly the same time, GPS data from station SDIC, located SW of the crater region, measured a movement upward and away from the vents (Mattia et al., 2004). Eruption phase 2 of Rosi et al. (2006) starts about 33 s later at 7:13:07 (R2), when the onset of the infrared thermal signal is observed, also associated with ash emission. The beginning of this phase is also marked by a change in the deformation direction, which has been modelled by a loss of pressure in the feeder conduit (Mattia et al., 2004). However, the GPS-based onset of eruption phase 2 starts about 2 s earlier (7:13:05). Visual observations during phase 2 indicate the emission of dark ash plumes with jets extending toward NNE. An