The Stromboli Volcano

An Integrated Study of the 2002–2003 Eruption

Sonia Calvari, Salvatore Inguaggiato,
Giuseppe Puglisi, Maurizio Ripepe, Mauro Rosi
Editors

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Cover Photo: Landslides after the tsunami of 30 December 2002 (courtesy of Istituto Nazionale di Geofisica e Vulcanologia, sezione di Catania (INGV-CT)).

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PREFACE

Stromboli is recognized among volcanologists to have been characterized by a persistent, mild explosive (strombolian) activity for at least 1500 years, with gas, ash, and bombs ejected up to heights of 50-300 m in explosive events, typically at a rate of ~10 times an hour. Because of its persistent activity and the easy access to its summit craters, Stromboli has always been considered a volcano laboratory by volcanologists who have used it to investigate eruptive and degassing processes, organize experiments and test new techniques of volcano monitoring.

In addition to eruptive processes, Stromboli is also an important site for the study of volcano flank instability problems, as its NW flank (Sciara del Fuoco) has produced at least four major catastrophic collapses during the past 10,000 years. Flank instability on volcanic islands is one of the main sources of tsunami waves and thus represents a volcanic hazard with a major impact on society.

Between December 2002 and July 2003, an effusive eruption occurred at this volcano and involved a number of processes (such as lava flow output, explosive activity, flank instability, submarine and subaerial landslides, tsunami, paroxysmal explosive events). It activated the entire spectrum of hazards related to a volcano, making the monitoring of this volcano a real challenge. To face this eruptive crisis, and estimate the potential hazard, a number of novel multidisciplinary techniques have been applied to this volcano.

Volcanic risk climaxed on December 30th, when landslides triggered tsunami waves that hit the settled areas of Stromboli and of other Aeolian Islands, reaching the Sicilian and Calabrian coasts. Had the tsunami occurred during the tourist season, the number of victims and economic loss could have been enormous. The volcanic crisis was a challenge for the national Civil Protection and for the volcanological community that was called on to give scientific support to manage the crisis.

The scientific community was required to rapidly (within weeks) upgrade the already existing monitoring system on Stromboli. Thus, a large number of instruments, some of which were used for the first time in a volcanic context, were deployed, providing an unprecedented documentation on eruptive phenomena at Stromboli. In the meantime, a new observatory was set up on the island, collecting in one place all data coming from different institutions and monitoring networks. The observatory also acted as the headquarters, facilitating the interaction between the scientific community and the Civil Protection. Indeed, a valuable result of this experience was the daily, multidisciplinary scientific approach to the evaluation of the hazard, with continuous exchanges concerning the results from the multi-disciplinary networks among the scientists involved.

We believe that the multi-disciplinary monitoring systems applied to this volcano and the resulting interpretative theoretical models obtained by the analysis of data collected during this eruptive crisis, discussed during a number of meetings, can be used as examples for monitoring other active volcanoes.

The volume derives from presentations and discussions at several informal meetings devoted to comparing results and understanding the volcanic processes occurring during the 2002–03 volcanic crisis. To further enhance the project, several other researchers, who had long-time experience with the monitoring of Stromboli, were asked to join the project, and many agreed.

As editors, we are very grateful to all authors, who worked hard to meet the deadline and did everything they could to make this project a success. We appreciate the help, patience, and expertise of AGU staff, who worked diligently to publish the book. We are grateful to the reviewers who devoted so much of their time and effort helping to improve the volume, and especially to Stephen Conway for having improved the English in all the papers from INGV Catania. We would like to thank the technical staff of the geochemical laboratories of INGV Palermo. These colleagues made a great effort to acquire a solid and unique geochemical data set, which allowed improving our knowledge of the Stromboli plumbing system.

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The Stromboli Volcano: An Integrated Study of the 2002–2003 Eruption—Introduction

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On 28 December 2002, after 17 years of steady strombolian activity, following a gradual increase in the frequency of explosions and in the magma level within the summit craters, a 300-m-long eruptive fissure opened on the upper NE flank of Stromboli volcano. As a result, low energy explosive activity from a lateral vent fed hot avalanches that flowed down the Sciara del Fuoco (SDF) to the sea. The avalanche activity was followed, minutes later, by an intense emission of lava spilled from the NE crater that fed a very fast lava flow. Eruptive activity stopped a few hours later and resumed early morning on 29 December with a new small lava flow from the lowermost tip of the fissure.

On 30 December, fractures formed along the SDF, causing the failure of two large portions of this already unstable flank of the volcano. The landslides triggered two tsunami waves extending over 100 m inland, that caused extensive damage to buildings and boats along the east coast of the island, and minor injuries to a few people. Large waves also struck the town of Milazzo on the northern coast of Sicily, 60 km south of Stromboli. Starting from 30 December, the national Department of Civil Protection, operating under the direct authority of the Prime Minister, took responsibility for the management of the emergency. The first action consisted in providing lodging and full assistance to residents who spontaneously decided to leave the island. The temporarily evacuated residents returned to the island at the beginning of February. A significant effort of the scientific community has since been devoted to monitoring the movement of the SDF and the summit craters, with different kinds of novel techniques employed at this volcano for the first time.

The major landslide of 30 December was accompanied by intrusion of lava into the fracture, and a new effusive vent formed within the largest landslide scar. Explosive activity ceased at the summit craters of Stromboli following the start of the flank eruption. Persistent effusive activity became concentrated within the 30 December landslide scar on the SDF, resulting in a perched, compound lava flow field.

While lava was still erupting on the upper SDF, an extremely powerful explosive event began on 5 April 2003 at the summit craters, which had been inactive since the onset of the flank eruption. This event was the strongest recorded at Stromboli during the last century, and its timing has been reconstructed on the basis of photos and thermal images taken during a helicopter survey over the volcano before, during and after the paroxysm. The paroxysm lasted about 9 min, with bombs up to 4 m wide falling on the village of Ginostra, on the west flank of the island, and destroying two houses. This event signaled the start of the declining phase of the effusive eruption. Around 20 June, a resumption of strombolian explosions at the summit craters and a corresponding declining phase in the lava output, were observed. After 10 July, lava flows had become confined to the upper, proximal lava field, and there was a total cessation of effusive activity between 21 and 22 July.

This book examines the December 2002—July 2003 eruptive crisis at Stromboli which involved a variety of processes. We present the experience gained from a multi-disciplinary, integrated approach to the monitoring of the eruptive activity, including an overview and synthesis of the over 60 papers published in selective international journals, as well as new results.

The book is organized in six sections. The first section is an overview of the volcanic system of Stromboli gained over the last two decades. The second, third, fourth, fifth sections describe special phases of the eruption: the eruption onset, the landslide on the SDF and its related tsunami and slope instability, the effusive phase, the 5 April paroxysmal event, respectively. The last section describes the Civil Protection management of the crisis and its synergy with the scientific community. Each chapter contains multi-disciplinary, integrated contributions from the scientists who have contributed to the monitoring of the eruption. Most of the papers are reviews of previously published data, and present integrated models and interpretations of the phenomena that took place during the crisis. However, the book is also a record of all the relevant original information that has been collected but had not yet been published in scientific papers.

Major advances in the fields of structural geology, dynamics of strombolian activity, degassing processes, and petrology of the active plumbing system of the volcano have been made in the last two decades. Flank instability processes and caldera collapses were recognized to play a fundamental role in controlling the Holocene and late Pleistocene evolution of the volcano. The paper by *Tibaldi et al.* offers a review of work published on these topics, discussing this process in the light of the mechanical properties of materials of the volcanic cone and flank stability models. One of the outstanding discoveries made on the plumbing system of the volcano was the identification of a gas-rich, crystal-poor magma erupted during highly energetic explosive events (paroxysms). *Bertagnini et al.* discuss the origin of the most energetic phases in relationship to the rapid rise of gas-rich magma pockets through the resident crystal-rich volatile poor magma. The dynamics of the persistent strombolian activity has been extensively investigated over the past two decades with the aid of geophysical tools. The papers by *Ripepe et al.* and *Chouet et al.* provide complementary aspects regarding the mechanism of generation, ascent and explosion of gas slugs in the upper conduit.

An accurate description of the geochemical system is outlined by *Grassa et al.* based on a review of the main scientific results obtained during the past decade. *Allard et al.* complete the picture showing the primary control of the magmatic gas phase on the eruptive regime of the volcano.

The second section presents several integrated and multi-parametric data illustrating the conditions of the volcano before and during the initial stages of the flank eruption. On the basis of thermal mapping, gas measurements and geophysical monitoring, *Burton et al.* present an integrated analysis of the events that preceded the onset of the flank eruption, suggesting a gradual increase in the magma level within the upper conduit. *Pioli et al.* describe small-scale instability processes occurring during the opening of the eruptive fissure on the uppermost SDF through eyewitness reports, geophysical monitoring, field and laboratory studies of the erupted products, and daily temperature measurements using a handheld thermal camera. A geochemical surveillance program started at Stromboli in 1999 focused on identifying signals that might predict impending energetic explosive events. *Federico et al.* present the main geochemical signals occurring before the 2002 eruption, with the significant anomalies recorded prior to the eruption both in the coastal aquifer and in the summit area, indicative of a new gas-rich magma batch.

The instability of the SDF was one of the distinctive features of the 2002-03 eruption. The contributions of the third section focus on investigating the origin, effects and evolution of the December 2002 landslides, as well as their relationships with the eruption and with the current dynamics of this flank of the volcano. *Tinti et al.* propose a critical reconstruction of the two tsunamis based on field observations, eyewitness statements and results from numerical simulations. Aerophotogrammetric and bathymetric surveys carried out before and after the eruption were fundamental for assessing the flank dynamics of the SDF as well as the geometry and evolutions of the lava flow field. By integrating these data together with field observations and with the geotechnical behavior of the volcanics, *Tommasi et al.* set out a reconstruction of the sequence of landslides that occurred soon after the eruption onset. *Baldi et al.* monitored the continuous morphological changes on the subaerial and submarine flank of the SDF during the whole eruption, estimating the volume involved. *Marani et al.* estimated the volume of sediments deposited on the offshore from the SDF landslide from multi-beam bathymetry, side-scan sonar data and seabed visual observations. Heritage of the 2002-03 eruption was the integrated multi-parametric system for monitoring ground deformations on the SDF, which comprises a ground-based linear synthetic aperture radar (GB-InSAR), and an automated topographic monitoring system (named THEODOROS). *Bonforte et al.* described the design and set up of this system, initially based on periodic geodetic surveys and an innovative real-time GPS network, both destroyed during the eruption, and of its evolution during and after the 2003.

The fourth section deals with the emplacement of the lava flow field on the SDF. It describes the monitoring techniques used to analyze and quantify flow field growth in terms of structure, effusion rate, volume erupted, composition, deformation caused by the emplaced mass, gas released through the magma column and the ground surrounding the craters, and associated seismic activity. *Spampinato et al.* show the lava flow field growth monitored with a thermal camera from land and helicopter, describing its structure and relationship with the measured parameters. Periodic lava sampling carried out during the entire duration of the effusive eruption, and a fairly homogeneous composition of the lava, allowed *Landi et al.* to rule out important changes in the dynamics of the plumbing system shortly before the eruption. *Marsella et al.* studied the filling of the subaerial and submarine landslide scars by lava flows and debris, using a quantitative analysis of the photogrammetric surveys carried out during the effusive eruption. Integrated with field observations, this showed that at the end of the eruption the scar left by the December 2002 landslide was only partially filled.

Aloisi et al. describe the newly installed ground deformation systems necessary to monitor the effusive phases. This supported the Civil Protection in making decisions related to hazards from landslide movements and volcanic activity, and allowed the authors to make some hypotheses on the dynamics of the craters. The transition from effusive to explosive activity was investigated by *Marchetti et al.* through the analysis of VLP seismic activity, delay times between infrasonic and thermal onsets of explosions, and SO_2 flux recorded during a one-year period. The synergy of these multiple geophysical observations pointed to a migration of the magma column.

Continuous monitoring of CO_2 flux from soil performed by *Madonia et al.* and integrated by daily field observations, showed that CO_2 flux and soil temperature are closely related to volcanic events. The seismological data set used by *Martini et al.* covers most of the effusive phase and the subsequent recovery of the explosive activity, and shows that the shallow magmatic system has not undergone significant changes during this period. Fluid flow mapping and profiles carried out by *Finizola and Sortino* with self-potential, temperature, and soil gas measurements since 1994 in the summit area, show the importance of old structural boundaries in the opening of part of the 2002-03 fracture field.

The fifth section describes many aspects of the 5 April paroxysm, and opens with a paper from *Harris et al.* presenting a new and updated revision of the timing and dynamics of this episode on the basis of thermal and visual images recorded during the explosion from helicopter, and from a fixed thermal sensor 450 m away. *Pistolesi et al.* present detailed mapping through field and laboratory description of the explosive deposits that allowed to calculate the volume, assess the eruptive mechanism, and calculate the peak discharge rate (eruptive intensity) of the event. Mineralogical, geochemical and isotopic compositions of the juvenile and fresh subvolcanic ejecta have been carried out by *Francalanci et al.*, indicating moderate pressure conditions for the mechanisms triggering this episode.