

The Stromboli Volcano

*An Integrated Study
of the 2002–2003 Eruption*



Sonia Calvari, Salvatore Inguaggiato,
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Editors

Contents

PREFACE

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

Section I: The Volcanic System of Stromboli

Geological–Structural Framework of Stromboli Volcano, Past Collapses, and the Possible Influence on the Events of the 2002–2003 Crisis

1. INTRODUCTION
2. GEOLOGICAL AND STRUCTURAL EVOLUTION OF
THE ISLAND
3. LATERAL INSTABILITY
4. SUBMERGED STRUCTURES
5. DISCUSSION AND CONCLUSIONS

Volcanology and Magma Geochemistry of the Present-Day Activity: Constraints on the Feeding System

1. INTRODUCTION

2. VOLCANOLOGICAL CHARACTERISTICS OF THE PRESENT-DAY ACTIVITY

3. MINERALOGICAL, CHEMICAL, AND ISOTOPIC CHARACTERISTICS OF PRODUCTS FROM THE PRESENT-DAY ACTIVITY

4. CONTRIBUTIONS FROM MICROANALYTICAL SR ISOTOPE DATA

5. CONTRIBUTIONS FROM MELT INCLUSIONS

6. CONSTRAINTS ON THE FEEDING SYSTEM AND DYNAMICS OF THE PRESENT-DAY ACTIVITY

Dynamics of Strombolian Activity

1. CURRENT EXPLOSIVE ACTIVITY AT STROMBOLI

2. SHALLOW CONDUIT PROCESSES

3. DYNAMICS OF THE GAS SLUG

4. POSITION OF THE MAGMA LEVEL

5. GAS FLUX CONTROL

6. DEGASSING MAGMA COLUMN

7. CONCLUSIONS

Fluid Geochemistry of Stromboli

1. INTRODUCTION

2. VOLATILE BUDGET AT STROMBOLI ISLAND

3. GEOCHEMICAL INVESTIGATIONS ON THERMAL WATERS

4. CONCLUDING REMARKS

Crater Gas Emissions and the Magma Feeding System of Stromboli Volcano

1. INTRODUCTION
2. METHODOLOGIES FOR CRATER GAS STUDIES
3. QUIESCENT MAGMA DEGASSING
4. EXPLOSIVE MAGMA DEGASSING
5. IMPLICATIONS FOR THE MAGMA FEEDING SYSTEM
6. CONCLUSIONS

Upper Conduit Structure and Explosion Dynamics at Stromboli

1. INTRODUCTION
2. CONDUIT STRUCTURE IMAGED FROM WAVEFORM INVERSION
3. DISCUSSION AND CONCLUSIONS

Section II: Eruption Onset

Volcanic and Seismic Activity at Stromboli Preceding the 2002–2003 Flank Eruption

1. INTRODUCTION
2. METHODS
3. VOLCANIC ACTIVITY AT STROMBOLI PRIOR TO THE 2002–2003 ERUPTION
4. SEISMIC INVESTIGATIONS ON STROMBOLI DURING 2002
5. DISCUSSION
6. CONCLUSIONS

The Eruptive Activity of 28 and 29 December 2002

1. INTRODUCTION
2. METHODS
3. RESULTS
4. DATA INTERPRETATION
5. CONCLUSIONS

Geochemical Prediction of the 2002-2003 Stromboli Eruption From Variations in CO₂ and Rn Emissions and in Helium and Carbon Isotopes

1. INTRODUCTION
2. DATA GATHERING: METHODOLOGY
3. THE PIZZO SOPRA LA FOSSA AREA
4. THE BASAL THERMAL AQUIFER
5. GEOCHEMICAL CHANGES BEFORE THE ERUPTION ONSET
6. CONCLUSIONS

Section III: Landslides, Tsunami, and the Sciara del Fuoco Instability

Slope Failures Induced by the December 2002 Eruption at Stromboli Volcano

1. INTRODUCTION
2. GEOLOGIC FRAMEWORK

- 3. INVESTIGATIONS
- 4. THE 28-30 DECEMBER INSTABILITY SEQUENCE
- 5. RECONSTRUCTION OF THE GEOMETRY OF THE SLIDES
- 6. HYPOTHESES ON THE INSTABILITY MECHANISMS
- 7. Conclusive Remarks

The Double Landslide-Induced Tsunami

- 1. INTRODUCTION
- 2. INSTRUMENTAL DATA
- 3. EYEWITNESS ACCOUNTS
- 4. TSUNAMI FIELD SURVEYS
- 5. NUMERICAL SIMULATIONS
- 6. CONCLUSIONS

Deep-Sea Deposits of the Stromboli 30 December 2002 Landslide

- 1. INTRODUCTION
- 2. STROMBOLI ISLAND
- 3. THE SUBAERIAL SDF AND THE 30 DECEMBER 2002 PARTIAL COLLAPSE EVENT
- 4. DATA AND METHODS
- 5. OUTLINE MORPHOLOGY
- 6. BATHYMETRIC DIFFERENCE ANALYSIS OF THE SDF FLANK
- 7. THE LANDSLIDE DEPOSITS
- 8. DISCUSSION
- 9. CONCLUSIONS

Integrated Subaerial-Submarine Morphological Evolution of the Sciara del Fuoco After the 2002 Landslide

1. INTRODUCTION
2. FIELD SURVEYS AND DATA PROCESSING
3. DATA ANALYSIS AND DISCUSSION
4. CONCLUSIONS

Movements of the Sciara del Fuoco

1. INTRODUCTION
2. MONITORING NETWORKS
3. COMPARISON AMONG EDM, THEODOROS, AND
GB-INSAR DATA
4. WARNING SYSTEM
5. DISCUSSION AND CONCLUSIVE REMARKS

Section IV: The Lava Flow Emission on the Sciara Del Fuoco

Evolution of the Lava Flow Field by Daily Thermal and Visible Airborne Surveys

1. INTRODUCTION
2. METHODOLOGY
3. CHRONOLOGY OF THE ERUPTION
4. LAVA FLOW FIELD EMPLACEMENT MECHANISMS
5. MAIN PARAMETERS CONTROLLING LAVA FLOW
EMPLACEMENT
6. DISCUSSION

7. CONCLUSIONS

Textural and Compositional Characteristics of Lavas Emitted During the December 2002 to July 2003 Stromboli Eruption (Italy): Inferences on Magma Dynamics

1. INTRODUCTION

2. THE 2002-2003 ERUPTIVE ACTIVITY

3. SAMPLING

4. PETROGRAPHY AND CHEMISTRY OF THE PRODUCTS

5. DISCUSSION

6. THE TRIGGER OF THE EFFUSIVE ACTIVITY

2002-2003 Lava Flow Eruption of Stromboli: A Contribution to Understanding Lava Discharge Mechanisms Using Periodic Digital Photogrammetry Surveys

1. INTRODUCTION

2. REMOTE-SENSING TECHNIQUES FOR LAVA FLOW MONITORING

3. 2002-2003 STROMBOLI ERUPTION MONITORING

4. METHOD ADOPTED FOR DEFINING THE LAVA FLOW FIELD AND VOLUME COMPUTATION

5. ERUPTION NARRATIVE AND EVOLUTION OF THE LAVA FLOW FIELDS

6. RESULTS FROM THE PHOTOGRAMMETRIC SURVEYS

7. LAVA DISCHARGE BEHAVIOR DURING THE ERUPTION

8. CONCLUDING REMARKS

Ground Deformations Related to the Effusive Eruptions of Stromboli: The 2002–2003 Case

1. INTRODUCTION

2. MONITORING SYSTEM DESCRIPTION

3. DATA DISCUSSION

4. CONCLUSIONS

Gas Flux Rate and Migration of the Magma Column

1. INTRODUCTION

2. DATA ACQUISITION

3. VERY LONG PERIOD EVENTS AND GAS FLUX DURING THE ERUPTION

4. MAGMA SUPPLY RATE, LAVA EFFUSION, AND SO₂ FLUX

5. INFRASONIC-THERMAL DELAY TIMES AND POSITION OF THE MAGMA COLUMN

6. MIGRATION OF THE VLP SEISMIC SOURCE

7. CONCLUSION

Variations of Soil Temperature, CO₂ Flux, and Meteorological Parameters

1. INTRODUCTION
2. STRUCTURE OF THE MONITORING NETWORK
3. SYNTHESIS OF THE ERUPTION PHASES
4. DATA PRESENTATION AND DISCUSSION
5. CONCLUDING REMARKS

Seismological Insights on the Shallow Magma System

1. INTRODUCTION
2. VOLCANIC TREMOR
3. LP EVENTS AND EXPLOSION QUAKES
4. VLP EVENTS
5. DISCUSSION

Fluid Circulation and Permeability Changes in the Summit Area of Stromboli Volcano

1. INTRODUCTION
2. FLUID FLOW MEASUREMENT TECHNIQUES
3. DATA ACQUISITION
4. RESULTS
5. INTERPRETATION AND DISCUSSION
6. CONCLUSION

Section V: The 5th April Paroxysmal Explosive Event

The 5 April 2003 Explosion of Stromboli: Timing of Eruption Dynamics Using

Thermal Data

1. INTRODUCTION
2. THE 5 APRIL PAROXYSM
3. EFFECTS ON THE INSTRUMENT ARRAYS AND THERMAL IMAGE ACQUISITION
4. EVENT CHRONOLOGY
5. TIMING ERRORS AND UNCERTAINTIES
6. CONCLUSIONS

The Paroxysmal Event and Its Deposits

1. INTRODUCTION
2. METHODS
3. DEPOSIT FEATURES
4. PHYSICAL FEATURES OF THE ERUPTED MATERIAL
5. ERUPTIVE DYNAMICS
6. COMPARISON WITH OTHER PAROXYSMAL EVENTS
7. CONCLUSIONS

Mineralogical, Geochemical, and Isotopic Characteristics of the Ejecta From the 5 April 2003 Paroxysm at Stromboli, Italy: Inferences on the Preeruptive Magma Dynamics

1. INTRODUCTION
2. JUVENILE EJECTA
3. SUBVOLCANIC LITHIC EJECTA

4. CONCLUSIONS

The 5 April 2003 Paroxysm at Stromboli: A Review of Geochemical Observations

1. INTRODUCTION

2. ERUPTIVE ACTIVITY DURING 2002-2003

3. METHODS

4. GEOCHEMICAL CHANGES HERALDING THE 5 APRIL PAROXYSM

5. CONCLUDING REMARKS

Ground Deformation From Ground-Based SAR Interferometry

1. INTRODUCTION

2. THE INSTRUMENT

3. THE 5 APRIL 2003 PAROXYSM AS MEASURED BY THE LISA SYSTEM

4. EVALUATION OF THE EXPLOSION ONSET TIME

5. ANALYSIS OF THE EXPLOSION-INDUCED GROUND DEFORMATION

6. CONCLUSION

Section VI: Risk Management

Stromboli (2002-2003) Crisis Management and Risk Mitigation Actions

1. INTRODUCTION

2. THE ISLAND OF STROMBOLI BEFORE THE CRISIS

- [3. VOLCANIC ERUPTIONS AND DAMAGE OF THE 20TH CENTURY](#)
- [4. EFFECTS OF THE 30 DECEMBER TSUNAMI AND 5 APRIL EXPLOSION](#)
- [5. THE ITALIAN CIVIL PROTECTION SYSTEM](#)
- [6. FIRST RESPONSE TO THE TSUNAMI](#)
- [7. EMERGENCY MANAGEMENT](#)
- [8. INTEGRATION OF CIVIL PROTECTION AND THE SCIENTIFIC COMMUNITY](#)
- [9. OTHER MEASURES FOR THE VOLCANIC RISK MITIGATION](#)
- [10. INFORMATION AND EMERGENCY EXERCISE](#)
- [11. DISCUSSION](#)
- [12. CONCLUSIVE REMARKS](#)

[Scientific Community and Civil Protection Synergy During the Stromboli 2002–2003 Eruption](#)

- [1. INTRODUCTION](#)
- [2. ONSET OF THE ERUPTIVE ACTIVITY AND THE ASSOCIATED EMERGENCY](#)
- [3. MAIN IMMEDIATE INTERVENTIONS](#)
- [4. MAIN SCIENTIFIC ACTIONS PLANNED AND UNDERTAKEN IN THE COURSE OF 2003](#)
- [5. CONCLUDING REMARKS](#)

[Index](#)

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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 SO₂ 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 CO₂ flux from soil performed by *Madonia et al.* and integrated by daily field observations, showed that CO₂ 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 *Franca Lanci et al.*, indicating moderate pressure conditions for the mechanisms triggering this episode.