European Seismological Commission

Università degli Studi di Catania

Istituto Nazionale di Geofisica e Vulcanologia

Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Abstracts

Annual Workshop 2003, September 23 to 28, Pantelleria, Sicily

Theme:

"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"

Pantelleria

WG Chairman
Jürgen Neuberg
Dept. of Earth Sciences,
Univ. of Leeds, UK

WG Secretary
Roberto Carniel
Dip. Georisorse e Territorio,
Univ. of Udine, Italy

Organizing Committee
Maria Serafina Barbano
Dep. Geol. Sc., Univ. of Catania, Italy
barbano@unict.it

Susanna Falsaperla
INGV, Sez. Catania, Italy,
falsaperla@ct.ingv.it

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Programme

Tuesday 23 September

Morning and Afternoon:
Arrival of the participants at Cossyra and Mursìa Hotel

19:00 - Ice-Breaker

Wednesday 24 September

09:00 Introduction to the workshop:
Maria Serafina Barbano, Susanna Falsaperla (organisers) & Jürgen Neuberg (WG chairman)

09:15 - 13:00 Scientific Session:
Seismic, tectonic, and deformation features of volcanoes (first part)
Chairperson: Jürgen Neuberg

09:15 J. Jones, R. Carniel, and S. Malone:
Seismic characteristics of lava lake convection at Erta Ale, Ethiopia.

09:45 H. Soosalu:
Low-frequency earthquakes at the Katla volcano, Iceland - evidence of path effects.

10:15 M. Hellweg, and D. Seidl:
A warning bell? Tornillo events at Galeras Volcano, Colombia.

10:45 - 11:00 Coffee-Break

11:00 R. Camiel, and M. Di Cecca:
Remote user-friendly data browsing and first analysis of volcanic geophysical data within the MULTIMO project.

11:30 R. Carniel, and R. Ortiz:
Spectral and dynamical evolution of volcanic tremor prior to the 5 April 2003 explosion at Stromboli Volcano.

12:00 V. Acocella, B. Behncke, S. D'Amico, V. Maiolino, M. Neri, A. Ursino, and R. Velardita:
The 2001 and 2002-2003 eruptions of Mount Etna (Italy): evidence of different triggering mechanisms.

12:30 S. Falsaperla, S. Spampinato, and H. Langer:
Analysis of volcanic tremor associated with the volcano unrest at Mt. Etna, Italy, in 2002-2003.

13:00 - Lunch

16:30 - 19:30 Scientific Session:
Seismic, tectonic, and deformation features of volcanoes (second part)
Chairperson: Roberto Carniel

16:30 H. Langer, S. Falsaperla, and S. Spampinato:
Monitoring volcanic tremor - chances and pitfalls.

17:00 A. Garcia-Aristizabal, H. Yepes, M. Ruiz, L. Troncoso, F. Gil-Cruz, M. Segovia, A. Alvarado, I. Molina, D. Basualto:
Seismic unrest at Cotopaxi volcano (Ecuador): an overview of the crescent activity.

17:30 - 18:00 Coffee-Break

18:00 V. Tenorio:
Seismic precursors of volcanic eruptions at Nicaraguan volcanoes San Cristóbal, Telica and Cerro Negro.

18:30 D. C. Roman:
Horizontal rotation of the stress field in response to magmatic activity - Examples from Crater Peak (Mt. Spurr), Alaska, and beyond.

19:00 S. Borgström, C. Del Gaudio, P. De Martino, G. P. Ricciardi, C. Ricco, V. Achilli, and G. Salemi:
Geodetical monitoring of Campi Flegrei area (Naples, Italy).

Evening: White wine tasting session
Chairman: Jürgen Neuberg

Thursday 25 September

09:00 - 10:30 Scientific Session:
Volcanic and geophysical studies of the island of Pantelleria
Chairperson: Maria Serafina Barbano

09:00 G. Orsi:
Geology and volcanism of Pantelleria (invited paper).

9:30 M.S. Barbano and M. Cosentino:
Historical earthquakes and eruptions in the Sicilian Straits.

10:00 B. Behncke, G. Berrino, and R. Velardita:
Ground deformation and gravity changes on the island of Pantelleria in the geodynamic framework of the Sicily channel (invited paper).

Thursday 25 September

10:30 A. Bonaccorso, O. Campisi, O. Consoli, G. Falzone, S. Gambino, M. Mattia, B. Puglisi, G. Puglisi, and M. Rossi:
Ground deformation monitoring of Pantelleria island (invited paper).

11:00 - 11:30 Coffee-Break

11:30 - 13:00 Scientific Session:
Seismic, tectonic, and deformation features of volcanoes (third part)
Chairperson: Peggy Hellweg

11:30 E. Rivalta, T. Dahm:
A new method for the analysis of dyke stability, preliminary tests on real data.

12:00 E. Rivalta, T. Dahm:
Dyke interaction with the earth surface and layering interfaces: theoretical models and experiments evidence accelerated motion.

12:30 Y. Formenti, and T. Druitt:
The role of magmatic gas during Vulcanian explosions and pyroclastic flows emplacement, at Montserrat.

13:00

15:00 - 16:30 Scientific Session.
Seismic, tectonic, and deformation features of volcanoes (fourth part)

15:00 J. Neuberg and S. Sturton:
Dispersion analysis of low-frequency earthquakes on Montserrat - and what it reveals.

15:30 A. Graps and R. Carniel:
Wavelets for Seismology

16:00 S. Vinciguerra, C. Trovato, P.G. Meredith, P. Benson, J. Imme', and G. De Natale:
Laboratory measurements of seismic velocities on rocks from Etna region (Italy).

16:30 P. Lesage, M.M. Mora, G.E. Alvarado, C. Leandro, and J.P. Métaxian:
Shallow velocity structure and seismic site effects at Arenal volcano, Costa Rica.

17:00 - Brief visit of the island of Pantelleria

20:00 - Social dinner

Friday 26 September

Field trip on geology and volcanism of Pantelleria.
Evening: Red wine tasting session
Chairman: Roberto Carniel

09:00 - 13:00 Scientific Session:
Volcano unrest at Montserrat
Chairperson: Susanna Falsaperla

09:00 D. Green, V. Cayol, and J. Neuberg:
Pressurisation of Soufriere Hill's volcanic edifice.

09:30 D. Green and J. Neuberg:
Waveform analysis of low-frequency earthquakes, with examples from prior to the July 12th dome collapse, Montserrat.

10:00 J. Neuberg, D. Green, E. Doyle, A. Jolly, and G. Norton: ***Temporal and lateral variation of earthquake characteristics during various dome growth episodes.***

10:30 J. Neuberg, S. Sturton, and H. Tuffen:
Ideas on the excitation mechanism of low-frequency earthquakes.

11:00 - 11:30 Coffee-Break

Chairperson: Olivier Jaquet

11:30 Y. Formenti:
Particle motion analysis of some low-frequency seismic episodes at Monserrat.

12:00 T. Powell:
Automated event classification and parameter retrieval on Montserrat.

12:30 H. Langer, S. Falsaperla, T. Powell, and G. Thompson: ***Classification of seismic transients recorded on Soufrière Hills volcano, Montserrat, using Artificial Neural Networks.***

13:00 O. Jaquet, R. Carniel, R. Namar, and M. Di Cecca: ***Development of a forecasting approach using stochastic methods applied to the Soufrière Hills volcano.***

13:30 - Lunch

16:30 - ***General discussion and conclusion of the workshop***

17:30 - 18:00 Coffee-Break

Sunday 28 September

Departure of Participants

Monday 29 September

One-day post-workshop field trip on Mount Etna with departure and arrival point in Catania.

Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Wednesday 24 September

Annual Workshop 2003, September
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Theme:
"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"

SEISMIC CHARACTERISTICS OF LAVA LAKE CONVECTION AT ERTA ALE, ETHIOPIA

J. Jones [1], R. Carniel [2], and S. Malone [1]

[1] *Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA*

[2] *Dipartimento di Georisorse e Territorio, Università di Udine, Via Cotonificio, 114; 33100 Udine, Italy*

Analysis of thermal, seismic, and video data, collected between 17 and 19 February, 2002, reveals that Erta Ale lava lake cycles between low (~0.03 m s^{-1}) and high (~0.1 m s^{-1}) convective regimes, with 60 to 220 minute periods. We attempt to characterize the seismic signature of each convective regime using spectral content, polarization analysis, and amplitude-based location of the continuous tremor. We identify the distinguishing spectral characteristics of each convective regime from continuous spectrograms. This information, combined with the covariance analysis method of Jurkevics (1988), is used to analyze the wavefield composition. For both convective regimes, we find that the wavefield from 0.85-3 Hz is dominated by rectilinear polarization, with azimuths and angles of incidence most consistent with P waves. At higher frequencies, for both convective regimes, the wavefield becomes more complex, and planar polarization dominates, suggesting that the higher frequency energy is mostly comprised of scattered S and Rayleigh waves. Because the majority of energy is concentrated at the lower frequencies, where body waves dominate, we assume an isotropic source, and locate windows of tremor from each convective regime with a method based on Gottschämer and Surono (2000). Our modified method uses least-squares inversion, based on tremor amplitudes recorded at three separate 3-component stations, to determine tremor epicenters and source power. By dividing each time window into shorter segments, and locating each segment of data, we find that the tremor source regions obtained for the low and high convective phases differ significantly. We also find a weak relationship between average frequency and tremor location. The similar wavefield composition of both convective phases suggests that they may share a common source process. However, their locations argue strongly that the source process is not only non-stationary, but is distributed over a small, unique volume for each of the two convective phases.

LOW-FREQUENCY EARTHQUAKES AT THE KATLA VOLCANO, ICELAND - EVIDENCE OF PATH EFFECTS

H. Soosalu

Nordic Volcanological Institute, Reykjavík, Iceland,(heidi@hi.is)

The Katla volcano is located under the Mýrdalsjökull glacier in south Iceland. Katla is one of the most active and most hazardous Icelandic volcanoes with its violent, phreatic eruptions and glacial floods. It has in average two eruptions per century, and is now long overdue after its latest eruption in 1918. A minor, subglacial eruption possibly occurred in 1955. Katla volcano has a 10-km diameter caldera; its highest rims reach 1380 m a.s.l. A shallow magma chamber, with a bottom at the depth of 3 km, was revealed by a 2-D seismic shooting through the caldera (Guðmundsson et al. 1994). The thickness of the magma reservoir was estimated to be 1 km and the volume of it 10-12 km^3.

There are two distinct seismic areas under the Mýrdalsjökull glacier. The most active area is located at the Goðabunga rise in the western part of the glacier, and the other one in the Katla caldera in the middle part. Seismic records of Katla earthquakes show typically volcanic characteristics. They can start with rather high frequencies, and the onset is anything between clearly impulsive and emergent. The continuation of the signal consists of lower frequencies only. S-arrivals seem not to exist in many cases, especially not in the signals from Goðabunga.

Katla seismicity has a seasonal pattern, particularly in the Goðabunga area – earthquakes concentrate in the latter part of the year. The seismicity is interpreted to be related to the deloading of the thin crust above the magma chamber due to the summer melting of the ice cap, and to high groundwater pressure in the caldera roof at the same time (Einarsson and Brandsdóttir 2000).

Since 1999 Katla has shown signs of unrest. In July 1999 a small glacial flood lasting less than 24 hours was observed. It was possibly caused by an intrusion of magma or even a small subglacial eruption. So far this has not been followed by further eruptive activity. Seismicity in 1999, on the other hand, was not exceptional. In 2002 seismic activity in the Goðabunga area started to rise dramatically and earthquakes have occurred continuously ever since.

A network of four broadband Güralp 6TD seismometers was run in the spring-summer 2003 in the Mýrdalsjökull area, with one station (GODA) directly at the locus of the Goðabunga activity. The observations of this net were combined with the data of the permanent Icelandic digital seismograph network, run by the Icelandic Meteorological Office. A data set of well-located earthquakes shows that the activity at Goðabunga is concentrated in a small area with dimensions of about 2-3 km, and that the events are shallow, within uppermost 2 km. A possible interpretation is that they are indications of an intruding dome.

The records of the station GODA reveal constant seismicity on hourly basis; many of the earthquakes are too small to be detected elsewhere. Multiple events are common: a very small event precedes a bigger one occurring almost immediately after. Most of the events have a high-frequency appearance of ordinary earthquakes at GODA, P is implosive and the polarity is easily seen. S is often also clear, though due to the vicinity of the focus can be hard to read. If these events are seen at other stations they show a low-frequency appearance of volcanic earthquakes, often with no reliable S-arrival and a long coda with surface waves. The attenuation of higher frequencies is observed to be higher at stations close to the caldera than at a more distant station on the south side of the volcano. Large events, about the size of local magnitude 2, typically start with high frequencies at GODA but have a low-frequency coda.

The observations of the local network point to that the events originally are ordinary earthquakes caused by brittle failure, but path effects caused by magma start to affect the appearance of the signals very close to their focuses. Larger earthquakes apparently can trigger the magma effect thus that it is also seen at the closest station GODA as a low-frequency coda.

A WARNING BELL? TORNILLO EVENTS AT GALERAS VOLCANO, COLOMBIA

M. Hellweg[1] and D. Seidl[2]

[1] *Berkeley Seismological Laboratory, UCB, Berkeley, CA,USA*
[2] *SZGRF-Bundesanstalt für Geowissenschaften und Rohstoffe, Erlangen, Germany*

In 1993, five of the six ash eruptions at Galeras Volcano, Colombia were preceded by distinctive seismic events, called tornillos. These unusual tremor wavelets have quasi-sinusoidal waveforms with screw-like envelope profiles and can last up to several minutes. Since December 1990, more than 60 of these events have been recorded at Galeras Volcano. As a class, they appear to be more complex than those previously recorded with the broadband instruments or with the shortperiod network of the Observatorio Vulcanológico y Sismológico in Pasto. They are multichromatic with a varying number of spectral peaks between 1 and up to 50 Hz. The peaks for frequencies which extend into the coda are extremely narrow, while those present only during the initial excitation are relatively broad. We parameterize the tornillo signals in the time and frequency domains, examining differences in the two classes of spectral peaks, and derive distribution and correlation functions for signal parameters such as frequency, Q, energy, and polarization. We investigate variations in these parameters with regard to ash eruptions during the past 3 years. In addition, we use the parameters along with the signal signature to derive qualitative conclusions about possible underlying processes and excitation mechanisms and to provide constraints for modelling variations of the source process, as, for example, a cavity resonator. For example, the distribution of frequencies for the suite of tornillos appears to be discrete below 6 Hz and a continuum above, as would be expected for a cavity.

REMOTE USER-FRIENDLY DATA BROWSING AND FIRST ANALYSIS OF VOLCANIC GEOPHYSICAL DATA WITHIN THE MULTIMO PROJECT

R. Carniel and M. Di Cecca

Dipartimento di Georisorse e Territorio, Università di Udine, Italy

In the framework of the EU-funded project "Multi-disciplinary monitoring, modelling and forecasting of volcanic hazard" (MULTIMO), multiparametric data have been recorded at the MULTIMO station in Montserrat. Moreover, several other long time series, recorded at Montserrat and at other volcanoes, have been acquired in order to test stochastic and deterministic methodologies under development.

A need for a consistent way of browsing such a etherogeneous dataset in a user-friendly way therefore arised. Additionally, a framework for applying the calculation of the developed dynamical parameters on the data series was also needed in order to easily keep these parameters under control, e.g. for monitoring, research or forecasting purposes.

The solution which we present in this work is completely based on Open Source software, including Linux operating system, MySql database managemenet system, Apache web server, Zope application server, Scilab math engine.

From the user point of view the main advantage is the possibility of browsing through datasets recorded on different volcanoes, with different instruments, with different sampling frequencies, stored in different formats, all via a consistent, user-friendly interface that transparently runs queries to the database, gets the data from the main storage units, generates the graphs and produces dynamically generated web pages to interact with the user.

SPECTRAL AND DYNAMICAL EVOLUTION OF VOLCANIC TREMOR PRIOR TO THE 5 APRIL 2003 EXPLOSION AT STROMBOLI VOLCANO

R. Carniel [1] and R. Ortiz [2]

[1] *Dipartimento di Georisorse e Territorio, Università di Udine, Udine - Italy*
[2] *Dpto. Volcanología. Museo Nacional de Ciencias Naturales, CSIC, Madrid, Spain*

Stromboli is well known for its continuous strombolian activity. However, from time to time (the latest in 1985/1986) the volcano enters an effusive phase. The volcano is currently (July 2003) in one of these phases, which started on 28 December 2002. However, this effusive phase showed different paroxysmal events which led to considerable hazard for Stromboli inhabitants and tourists.
On 30 December 2002 a major sector collapse interested the Sciara del Fuoco slope, leading to the formation of a tsunami. On 5 April 2003 a powerful explosion, which can be compared in size with the latest one of 1930, covered with bombs a good part of the normally tourist-accessible summit area. The explosion was not preceded by any classical precursor, although the island was effectively monitored by a dense deployment of instruments installed by Civil Defense after the 30 December 2002 tsunami. In this paper we investigate the spectral and dynamical evolution of the volcanic tremor recorded prior to the 5 April 2003 event, in order to estimate the timescale of the dynamical phase that lead to the paroxysmal event. This could give information on the existence of possible useful precursors.

THE 2001 AND 2002-2003 ERUPTIONS OF MOUNT ETNA (ITALY): EVIDENCE OF DIFFERENT TRIGGERING MECHANISMS

V. Acocella [1], B. Behncke [2], S. D'Amico [3], V. Maiolino [3], M. Neri [3], A. Ursino [3], R. Velardita [3]

[1] Dip. Scienze Geologiche Roma TRE, Largo S.L. Murialdo 1, 00146 Roma, Italy
[2] Dipartimento di Scienze Geologiche, Università di Catania; Corso Italia, 55; 95129 Catania, Italy
[3] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania; Piazza Roma, 2; 95123 Catania, Italy

Mount Etna (Italy) produced two important flank eruptions in 2001 and 2002-2003, which were peculiar for their high degrees of explosivity and for the simultaneous emission of two compositionally distinct magmas. From a strictly volcanological point of view, the 2001 and 2002-2003 eruptions showed many similarities. Both affected two sides of the volcano (the southern and northeastern flanks), and both were actually "two-eruptions-in-one", with a part of the activity being fed by the lateral draining of the central conduit system (central-lateral activity), while much of the activity was fed from a source independent of the central conduit system (eccentric activity). However, when placed in a wider geodynamic context, the two eruptions are fundamentally different. While the 2001 eruption was heralded by an intense seismic swarm and vigorous ground deformation, very few such premonitory signs preceded the 2002-2003 eruption, which, however, was accompanied by a major slip of Etna's unstable eastern to southeastern flank, and by widespread seismicity and ground rupturing in the moving sector. This suggests that the dynamics of magma ascent and eruption were anything but identical in the two eruptions.

The deformation of the volcanic edifice during the 2001 eruption clearly indicates forceful dike intrusion, probably under N-S regional compression (tectonic triggering). During the first stage of this eruption, earthquakes began to cluster along the active faults traversing and delimiting the unstable sector on the eastern flank, marking the onset of accelerated spreading of that flank. For the 2002, nearly all of the seismicity was concentrated along these faults, mostly on the eastern and southeastern flanks, but in September more vigorous flank slip began along the Pernicana Fault System on the northeastern flank of the volcano. Magma migration into the Northeast Rift began as a response to this event, and a second, much more significant slip event five weeks later, permitted the uprise of magma not only on the Northeast Rift, but also on the southern flank. The seismic and deformation data preclude any forceful intrusion of magma in the case of the 2002-2003 eruption, which was mainly triggered by the large-scale slip of the unstable eastern flank of the volcano (slip triggering).

ANALYSIS OF VOLCANIC TREMOR ASSOCIATED WITH THE VOLCANO UNREST AT MT. ETNA, ITALY, IN 2002-2003

S. Falsaperla, S. Spampinato, and H. Langer

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania,
P.zza Roma 2, 95123 Catania, Italy

Mt. Etna is a basaltic strato-volcano characterized by persistent volcanic activity. Apart from tectonic earthquakes, long-period events, and explosion quakes, a typical seismic signature of Mt. Etna is the continuous volcanic tremor, which precedes, accompanies, and follows episodes of volcano unrest. Accordingly, tremor has been used to shed light on the volcanic feeder, since changes in this signal are commonly interpreted as due to movements of magma and/or volcanic fluids within the conduits.

In this paper, we analyze the seismic signal recorded at Mt. Etna with particular reference to the volcano unrest in 2002-2003. The flank eruption 2002-2003 offers indeed the opportunity to discuss some methods of seismic data analysis, which can provide useful insights into the volcanic system.

MONITORING VOLCANIC TREMOR – CHANCES AND PITFALLS

H. Langer, S. Falsaperla, and S. Spampinato

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, P.zza Roma 2, 95123 Catania, Italy

Among the seismic signals recorded on active volcanoes, volcanic tremor has proven to be one of the most significant measures for surveillance and the study of the long-term behavior of a volcano. The problem of the huge data masses accumulated during the continuous acquisition of the tremor signal can be successfully resolved by data condensation and parameter extraction, in particular by carrying out multivariate statistics and unsupervised classification. We analyze seismic data recorded at Mt Etna and Stromboli, Italy, as case studies, discussing the relations between the extracted data parameters and observed volcanic activity. The extracted data parameter may be biased, however, by the presence of numerous transient signals not being related to tremor generating mechanisms. As transients mixed among more stationary signals can significantly alter the amplitude statistics of the overall signals, we may use this effect to reduce biases in the estimation of signal parameters related to volcanic tremor.

SEISMIC UNREST AT COTOPAXI VOLCANO (ECUADOR): AN OVERVIEW OF THE CRESCENT ACTIVITY

A. Garcia-Aristizabal[1], H. Yepes[1], M Ruiz[1], L. Troncoso[1], F. Gil-Cruz [2], M. Segovia[1], A. Alvarado[1], I. Molina[1], D. Basualto[1]

[1] Instituto Geofísico – Escuela Politécnica Nacional – Quito, Ecuador. Email: agarcia@igepn.edu.ec
[2] Ingeominas – Observatorio Vulcanológico de Manizales – Manizales, Colombia

In the last five years four Ecuadorian volcanoes have shown eruptive activity, each of them with a characteristic seismicity and particular eruptive style (Cerro Azul-Galápagos, Guagua Pichincha, Tungurahua and Reventador).

Since November 2001 a new volcano has shown signals of unrest: Cotopaxi. It is a large volcano (5897 m high) located at the center of the Ecuadorian Andes, about 80 Km at SSE of Quito, the political and administrative capital of Ecuador. The Instituto Geofisico – EPN has maintained a permanent instrumental vigilance of Cotopaxi since 1976. Considering the large population that potentially could be directly affected by an eruption, it is considered to be the most dangerous volcano in the country.

The seismic activity at Cotopaxi volcano is dominated by Long Period-LP (88%) and Volcano-Tectonic-VT (12%) events, with a monthly average of about 113 events during the last two decades. On November 22, 2001, a seismic swarm of tectonic earthquakes took place at about 20 Km western of the volcano, close to the small village Pastocalle. Two days latter, on November 24 and 25 a swarm of VT earthquakes was registered an located behind the volcano at about 5 to 25 Km depth (125 events/day). Significant seismicity of shallower LP and VT was also recorded with a daily average of 33 events. Similar swarms occurred on December 10, 2001 and January 05, 2002. The period between November 2001 and January 2002 could be considered the start of an important activity cycle for Cotopaxi volcano, Evidence of this activity is still observed at the present, July 2003 (see fig. 1).

The most remarkable factors observed during almost the last two years of activity are:

1. Appearance of New “big” long period events. These events can be recorded at stations as far as 200 km away from the volcano, and it is possible to observe longer period oscillations (>5 sec) at the beginning of the event.
2. Appearance of New Long Period, monochromatic, tornillo-type (screw) events. The frequency range of these events is between 2.5 and 3.3 Hz. The coda decay (growth rate) has been observed decreasing harmonically or with amplitude oscillations with an harmonic decay trend.
3. The presence of at least 156 tremor episodes, which fluctuate from high frequency tremor (> 5 Hz) to low frequency harmonic tremors. The harmonic tremor is in the 0.91 to 3.3 Hz frequency range, showing more than 3 harmonics that last from 150 up to 500 seconds.

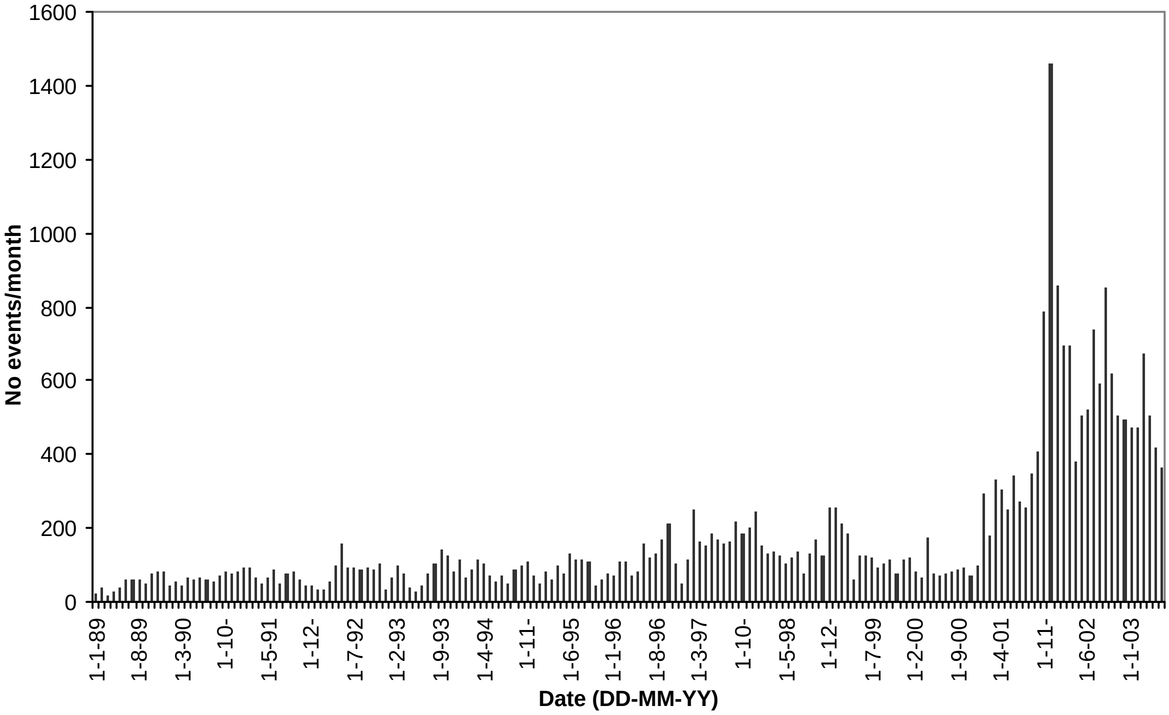


Figure 1. Histogram with the weekly seismicity recorded at Cotopaxi volcano (Jan. 1989-Jul 2003).

In summary, a clear increase in the activity level at Cotopaxi volcano is observed along with the apparition of new type of signals (considering the record since the last 25 years), with a wide frequency range (from many seconds up to 15 Hz). This brings up the significant hazard that Cotopaxi volcano represents for more than 80,000 people and to the Ecuadorian economy. Thus, it deserves immediate attention from the Geophysical Institute and even from the scientific community in general not only on a monitoring level, but in developing applied research on volcano seismology oriented to the understanding of the volcano behavior and therefore as a tool for risk mitigation.

HORIZONTAL ROTATION OF THE STRESS FIELD IN RESPONSE TO MAGMATIC ACTIVITY – EXAMPLES FROM CRATER PEAK (MT. SPURR), ALASKA, AND BEYOND

D. C. Roman

Department of Geological Sciences, University of Oregon, USA
(droman@newberry.uoregon.edu)

A complete understanding of the initiation, evolution, and termination of volcanic eruptions requires corresponding knowledge of conduit structure and development, as well as reliable monitoring tools and techniques to detect changes in the conduit system during periods of activity. Analysis of the stress field orientation around an active volcano is an ideal way to investigate conduit structure, as different configurations (e.g., cylinders vs. dikes) should produce unique stresses when pressurized that may be observable through careful analysis of seismicity. Additionally, case studies of stress field orientation prior to, during, and after magmatic activity can be used to develop an understanding of the relationship between changes in the stress field and processes in the conduit.

Horizontal rotation of the local axis of maximum compressive stress (perpendicular to the regional axis) has been observed during periods of magmatic activity at Crater Peak (Mt. Spurr), Alaska, and at several other volcanoes where sufficient data are available. This horizontal rotation may reflect pressurization of a dike-like conduit system by an influx of magma. If this relationship can be established through further data analysis and modeling, monitoring of the local stress field orientation at restless volcanoes is a potentially useful tool for predicting changes in the behavior of a volcano. However, this type of monitoring would require that the network of seismic instruments be large enough to allow the calculation of well-constrained fault-plane solutions for earthquakes of small magnitudes over a range of depths.

The 1992 eruption sequence at Crater Peak, Alaska was well-monitored seismically, producing a high-quality data set suitable for fine-scale temporal analysis of stress field orientation. Changes in the local stress field orientation during the period 1991-1997 were analyzed by calculating and inverting subsets of over 150 fault-plane solutions. Local stress tensors for four time periods (Figure 1), corresponding approximately to changes in activity at the volcano, were calculated based on the misfit of individual fault-plane solutions to a regional stress tensor. Results indicate that for nine months prior to the eruption, local maximum compressive stress was oriented perpendicular to regional maximum compressive stress. A similar horizontal rotation was observed beginning in November of 1992, coincident with an episode of elevated earthquake and tremor activity indicating intrusion of magma into the conduit. During periods of quiescence the local stress field was similar to the regional stress field.

Similar horizontal rotations have been observed at other volcanoes prior to and during eruptive activity, including Mt. Ruapehu, New Zealand (Miller and Savage 2001), Usu Volcano, Japan (Fukuyama et al. 2001), and Unzen Volcano, Japan (Umakoshi et al. 2001). Horizontal rotation of the local stress field may be a common occurrence at restless or erupting volcanoes. However, because only a small fraction of active volcanoes worldwide are monitored by extensive seismic networks, this is presently a difficult hypothesis to test.

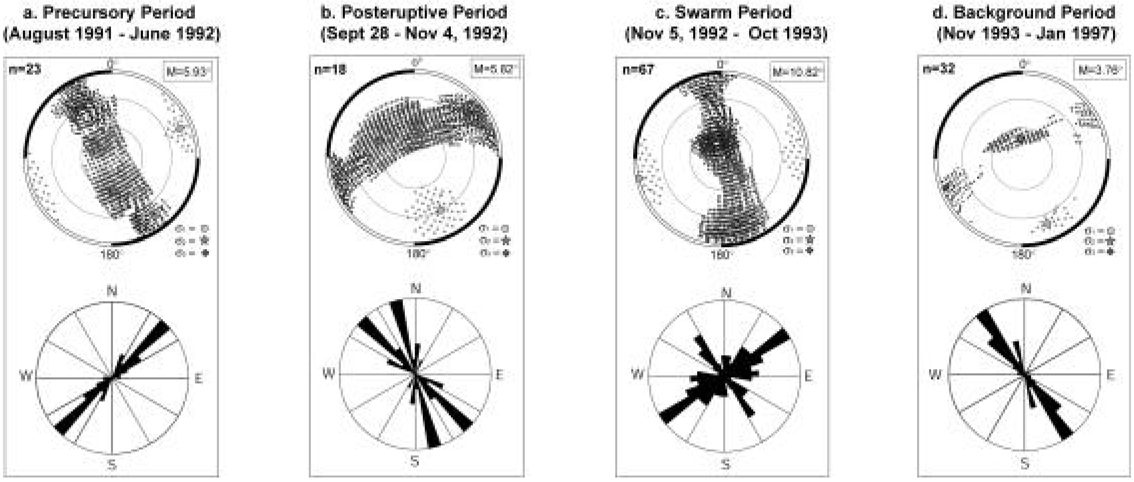


Figure 1. Orientation of the local stress field during four periods of activity at Crater Peak (Mt. Spurr), Alaska. The results of stress tensor inversions, as well as Rose diagrams of pressure axis azimuths, are shown for each period. Regional maximum compressive stress is subhorizontal and from the NNW-SSE during the entire study period. Stress tensor solutions show best-fit (large symbols) and all 95% confidence solutions, as well as the number of fault-plane solutions and average misfit to each solution.

GEODETICAL MONITORING OF CAMPI FLEGREI AREA (NAPLES, ITALY)

S. Borgström [1], C. Del Gaudio [1], P. De Martino [1], G. P. Ricciardi [1], C. Ricco [1],
V. Achilli [2], G. Salemi [2]

[1] *Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Vesuviano, Naples (Italy)*
e-mail: {sven, delgaudio, demartino, ricciardi, ricco}@ov.ingv.it
[2] *DAUR Facoltà di Ingegneria dell'Università di Padova, Padua (Italy)*
e-mail: {vladimiro.achilli, giuseppe.salemi}@unipd.it

The Campi Flegrei (CF) caldera, on the west of the city of Naples, is the result of two main collapse events: the first one, occurred 37 ky ago and related to the Campanian Ignimbrite eruption, caused the structural setting of the outer part of the caldera, while the inner part grew up 12 ky ago, after the Neapolitan Yellow Tuff eruption. The CF magmatic system is still active, as testified in recent time by the bradyseismic crises of the years 1969-72 (maximum ground uplift of about 170 cm) and 1982-84 (maximum uplift of about 180 cm). From January, 1985 the area is undergoing a slow but continuous subsidence phase, with only short uplift events recorded in 1989, 1994 and, more recently, in the period from March up to August, 2000.
The space-temporal monitoring of ground deformations in CF area is systematically carried out by the INGV-Osservatorio Vesuviano by *continuous* and *periodical* networks. The spirit levelling network has more than 320 benchmarks on about 120 linear km; the whole network is yearly measured whereas the coast line, crossing the maximum deformation area, is measured twice a year. The GPS network has 35 3D vertices, eight of which equipped with continuously recording instruments. The layout of the geodetic surveillance system is completed by a continuous tiltmetric network, with four surface and one borehole sensor, besides a tide gauge and a gravimetric network.
Such a monitoring system allows a geodetic control with centimetric and/or sub-centimetric accuracies, but gives an information related only to the networks geometry: as a consequence, such a system is not able to highlight eventual migrations of the deformation field outside the nets. Moreover, excluding the continuous networks which, for obvious economical reasons, are quite limited in terms of recording points, the measurement of the periodical networks is typically carried out once a year, as mentioned before. From here the need to thicken the geodetic data sampling, in both space and time, in order to guarantee a suitable level of surveillance in a densely populated area.
Remote sensing techniques and specially spaceborne Differential SAR Interferometry (DIFSAR) is well suited in this case, allowing at present near monthly geodetic monitoring, depending on the orbit parameters. In contrast, DIFSAR is limited with respect to GPS because it provides only one component of deformation, that is the 3D vector displacement projected into the radar line-of-sight (LOS). Such a limitation can be greatly relieved by using DIFSAR data from both satellite tracks (ascending and descending), such that the two images look from nearly opposite directions and any changes in shape of the deformation reflect differences in the vertical versus horizontal deformation. From here the importance of an integration between the information obtained from both classical geodesy and SAR Interferometry: such an attempt will be hereby presented and discussed. In particular, we concentrate on the uplift event of 2000, that interrupted the caldera's recent trend of subsidence. In this case several SAR dataset, acquired by the ERS-2 satellite of the European Space Agency (ESA), were available as well as continuous GPS and levelling measurements:

the availability of such amount of geodetic data has therefore allowed an accurate comparison between different dataset.
Ground deformations measurement in CF area is a crucial point for two main reasons. First of all, because during the uplift events ground deformations precede the beginning of seismic activity, as also confirmed during the 2000 event: in this case, seismic activity begins on July, 2nd, whereas ground deformations are already observed starting from March. Secondly, such measurements are essential for a precise definition of the dynamics acting in the area, contributing to the deformation source modelling. As a matter of fact, the deformation field now acting in the area is further on complicated by the presence of an horizontal component of ground motion, highlighted from GPS data and confirmed by differences in the deformation pattern from ascending and descending interferograms. The availability, in the next future, of a good interferometric dataset from different tracks will therefore represent an effective tool for increasing the knowledge of the area.
The comparative analysis between classical geodetic and DIFSAR data has shown a clear agreement between the different techniques in both space and time. The main limitations toward achieving a better comparison between interferometric and geodetic data from the monitoring networks are due to both the poorer *temporal* sampling of the periodical networks (i.e. levelling and GPS) and the poor *spatial* coverage of the continuous GPS sites versus the space-temporal coverage of SAR data, only available in the radar LOS. The availability, for the future, of deformation maps not only from descending interferograms as in the case of this work but also from ascending ones, should reduce such a discrepancy.
The encouraging results coming from the joined approach of the 2000 event monitoring open a new way towards a new monitoring system and the optimization of the surveillance apparatus, therefore representing a relevant result in civil protection scenarios. Such an approach may be successfully used in the next future also for other active volcanic areas, as it was preliminarily done for ground deformations monitoring in Mt. Vesuvius area.

Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Thursday 25 September

Annual Workshop 2003, September
23 to 28, Pantelleria, Sicily

Theme:
"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"

GEOLOGY AND VOLCANISM OF PANTELLERIA

G. Orsi

Osservatorio Vesuviano – INGV. Via Diocleziano 328, 80124 Napoli, Italy. orsi@ov.ingv.it

The island of Pantelleria (Fig. 1), the type locality for pantellerite, represents the emergent portion of a volcanic edifice that rises about 1,000 m above sea floor. It is composed dominantly of volcanic rocks which include lavas and pyroclastic deposits, varying in compositions from pantellerite, through pantelleritic trachyte and comenditic trachyte, to mildly alkali basalt, in order of decreasing abundance. Felsic rocks range in age from 324 to 4 ka. Exposed mafic rocks dated at 118±9, 83±5, and about 29 ka, are restricted to the north-western portion of the island, where drilling for geothermal research has revealed a basaltic sequence several hundreds of meters thick.

The island is located in the NW-SE trending Sicily Channel Rift Zone (SCRZ), which results from transtensional tectonics along the northern margin of the African plate, related to the opening of the Tyrrhenian Sea. Rifting began in Late Miocene and was intense in Pliocene to Late Quaternary. Intense volcanism in the SCRZ has generated two emergent volcanoes which form the islands of Pantelleria, along the axial ridge, and Linosa, at the periphery of the rift zone. Some of the many submerged volcanoes have been active in the last few centuries.

The structural and volcanological features of Pantelleria, as well as the mineralogical and geochemical characteristics of the volcanic rocks, have been the topics of a large number of scientific investigations since the 19th century.

The structural setting of the island is defined by both tectonic and volcano-tectonic lineaments. The tectonic lineaments include faults and fractures related to regional deformation events, which have the same orientation as the rift-bounding faults. NW-SE trending fractures and strike-slip faults are the dominant lineaments, although NE-SW and N-S trending features are common. All these regional features occur outside the area of caldera collapse. A NE-SW tensile fault system divides the island into two sectors and most likely represents a crustal discontinuity along the axial ridge of the rift (Fig. 1). The north-western sector includes most of the exposed basaltic rocks, whereas the south-eastern sector includes silicic peralkaline rocks. The former has been affected only by NW-SE crustal fractures through which mafic magmas have reached the surface. In the south-eastern sector, eruption of differentiated magmas and occurrence of calderas suggest that crustal magma chambers were established, probably at the intersection of the main tectonic lineaments. The volcano-tectonic features of the island include caldera collapses and resurgence inside the youngest caldera. At least two caldera collapses have affected the island in recent times. The oldest caldera (La Vecchia caldera), is dated at 114 ka, while the youngest (Monastero caldera), is related to the eruption of the Green Tuff (50 ka). Inside the Monastero caldera resurgence has taken place with uplifting and tilting of the Montagna Grande block, through a simple-shearing mechanism.

The volcanic history of the island is characterised by large explosive eruptions alternating with periods dominated by less energetic eruptions. The history prior to 50 ka cannot be reconstructed in detail because only remnants of the erupted products are exposed. This is due either to repeated collapse of the central part of the island and erosion along the coastal cliffs, or to blanketing of the whole island by the Green Tuff. The history since this last large eruption has been subdivided into six silicic cycles sometimes intercalated with basaltic eruptions. The Green Tuff, representative of the first silicic cycle, is the product of a complex eruption and includes ignimbrites, and fall and surge beds. The chemical composition of the

Green Tuff varies from the base upwards from pantellerite to comenditic trachyte. All the other silicic cycles, dated at around 35-29, 22, 20-15, 14-12 and 10-4 ka, respectively, are characterized by eruptive products ranging in composition from pantellerite to pantelleritic trachyte, or to comenditic trachyte. For many cycles it has been demonstrated that the most differentiated magmas were erupted earlier. This has been interpreted as the consequence of eruptions tapping a zoned magma chamber at progressively deeper levels during each eruptive cycle.

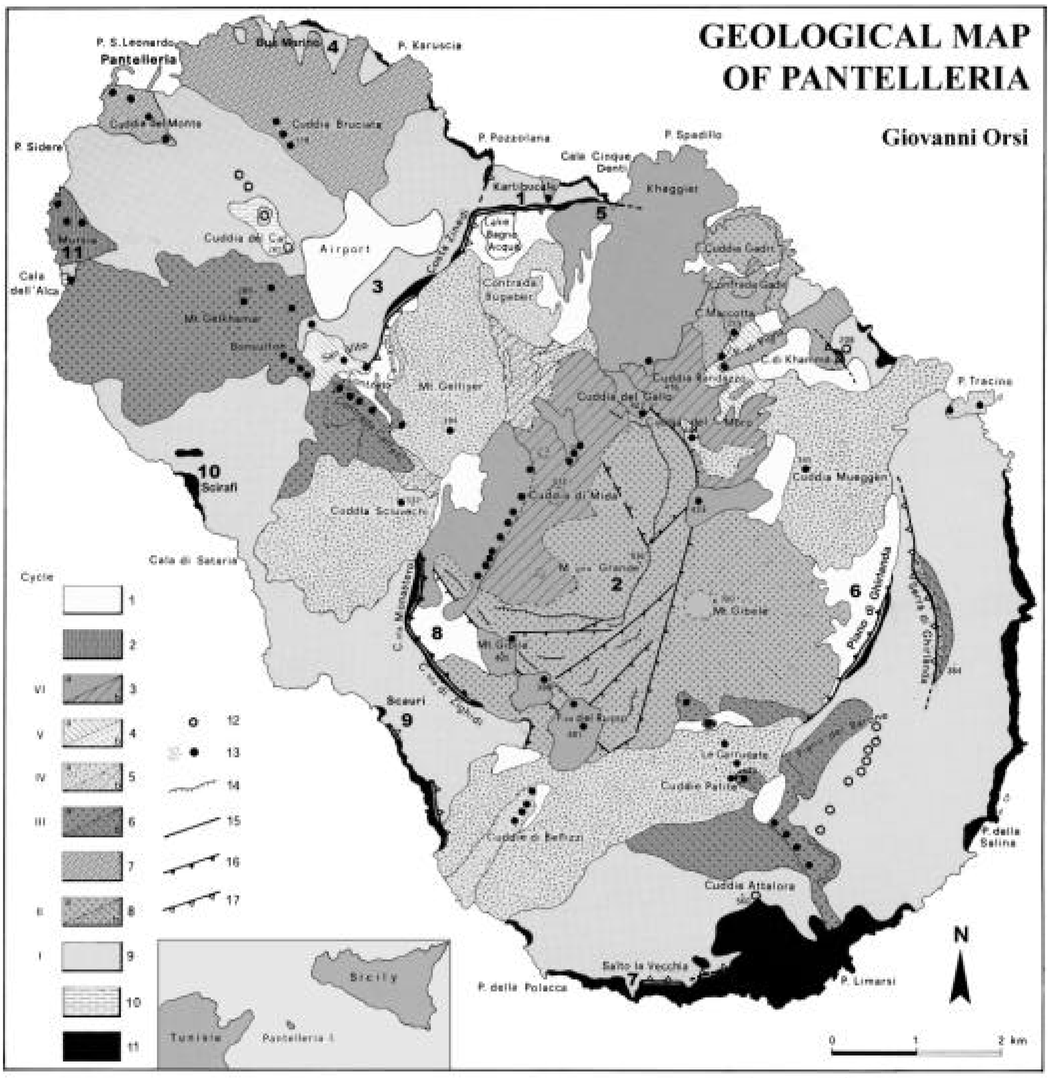


Figure 1 – Geological sketch map of the island of Pantelleria. 1, Alluvium; 2, Mursia basalts: lava flows and cinder cones younger than 10 ka; 3, volcanics of the VI silicic cycle (4-10 ka), a) lava flows and domes, b) pumice-fall deposits; 4, volcanics of the V silicic cycle (12-14 ka), a) lava flows and domes, b) pumice-fall deposits; 5, volcanics of the IV silicic cycle (15-20 ka), a) lava flows and domes, b) pumice-fall deposits; 6, volcanics of the III silicic cycle (22 ka), a) lava flows and domes, b) pumice-fall deposits; 7, Punta San Leonardo basalts (29 ka): lava flows and cinder cones; 8, volcanics of the II silicic cycle (35-29 ka), a) lava flows and domes, b) pumice-fall deposits; 9, volcanics of the I silicic cycle (50 ka): Green Tuff; 10, basalts older than 50 ka: lava flows and cinder cones; 11, silicic rocks older than 50 ka; 12, eruption vents older than 50 ka; 13, eruption vents younger than 50 ka; 14, top of escarpment of volcano-tectonic origin; 15, volcano-tectonic faults; 16, Monastero caldera (50 ka) rim; 17, La Vecchia caldera (114 ka) rim.

Numbers 1 through 11 indicate stops location of the field trip.

HISTORICAL EARTHQUAKES AND ERUPTIONS IN THE SICILIAN STRAITS

M. S. Barbano and M. Cosentino

Department of Geological Science - University of Catania,
Corso Italia 55, 95129 - Catania - Italy

The volcanic island of Pantelleria lies in the Straits of Sicily, on the Pantelleria Rift which forms the deepest part of the Straits and whose floor consists of continental crust (having a thickness of only 20-21 km). In the Straits there are also other volcanic sites as the Linosa Island, the Banco Graham, the Banco Nerita, and the Banco Terribile. These volcanic sites are aligned N-S, from the Linosa Island to the Sicilian coast near Sciacca, in the separation belt between the Malta trough and the Pantelleria trough. The first information about eruptions in the area regards the Banco Graham and date 1632. In the same site the 1701, 1831 and 1863 eruptions occurred. In the sea offshore of Agrigento the 1845 and 1846 eruptions were also observed. The last known eruption was in 1891 and took place 4 km away of Pantelleria (volcano Foestner).

There are very few information about the seismicity in the area, probably because most of the earthquakes are located in the sea. Seismic activity occurs typically in swarms, lasting several months, with shocks accompanied by underground roars, as observed in the 1578, 1724, 1727, 1740, 1831 and 1891 sequences. These events did not cause heavy damage in the hit localities along the Sicilian coast. All these shocks could be likely linked to volcanic activity although there are evidences only for the 1831 and 1891 sequences.

GROUND DEFORMATION AND GRAVITY CHANGES ON THE ISLAND OF PANTELLERIA IN THE GEODYNAMIC FRAMEWORK OF THE SICILY CHANNEL

B. Behncke [1], G. Berrino [2], R. Velardita [3]

[1] *Dipartimento di Scienze Geologiche, Sezione di Geologia e Geofisica, Università di Catania. Corso Italia, 55. 95129 Catania, Italy. e-mail behncke@unict.it*
[2] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano. Via Diocleziano, 328. 80124 Napoli, Italy. e-mail: berrino@ov.ingv.it*
[3] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania. P.zza Roma, 2. 95123 Catania, Italy. e-mail: velardita-r@ct.ingv.it*

Since the 1980's the island of Pantelleria has been periodically surveyed by means of geodetic and geophysical methods to monitor the regional and local volcanic dynamics. Horizontal and vertical ground movements and deformation are monitored through EDM, levelling and GPS. Additionally, high precision gravity measurements aimed to detect underground mass movements were started in 1990.

The results obtained by the analysis of the gravity data, collected during several field surveys carried out from 1990 to 1996, have shown that the gravity field changes generally appear composed by the superposition of short and long wavelengths, due to the combined effect of shallow and deep level sources. They also seem to reflect, to some degree, the structural setting of the island as sketched by the Bouguer anomaly field which indicates that the island is constituted by a basement dislocated in two main blocks. These latter are also bordered by two SE-NW and ENE-WSW trending lineaments, probably regional faults related to the global geodynamics of the Sicily Channel Rift Zone. A strong direct correlation between the gravity variation fields with the large-scale basement feature is apparent, mainly with the ENE-WSW lineation, visible along the Kaggiar-Cuddia Caffefi trend and corresponding to the limits between the two blocks.

Moreover, there is an inverse correlation between the gravity and altimetric variations. The joint analysis of gravity and elevation changes implies that Pantelleria appears to be divided in two blocks also from the kinematic behaviour.

In addition, comparison of the geological-structural setting of Pantelleria with that of the Sicily Channel, as outlined by geophysical and geological data, suggests that the observed phenomena may be also ascribed to the influence of the geodynamics of the Sicily Channel.

The present study is aimed at a comprehensive analysis of the time-space features of the horizontal ground deformation and gravity changes.

On the base of the previous conclusions we re-analysed all the EDM data collected on the island from 1979 to 1997, after which they were properly reorganized for comparison with gravity and altimetric data. This allows a joint interpretation taking also into account the structural setting and the geodynamics of the Sicily Channel to evaluate its influence on the local volcanic dynamics of the island.

GROUND DEFORMATION MONITORING OF PANTELLERIA ISLAND

A. Bonaccorso, O. Campisi, O. Consoli, G. Falzone, S. Gambino, M. Mattia, B. Puglisi, G. Puglisi, M. Rossi

Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania,

P.zza Roma 2, 95123 Catania, Italy

Pantelleria is a volcanic island situated at the centre of the Sicily Channel continental rift. It represents the emerged part of a huge volcanic structure situated along a tectonic trend extending in a NW-SE direction for nearly 135 km. Since 1979 a network of geodetic benchmarks has been installed on the island of Pantelleria for the study of ground deformation. After a first period of regular, annual measurement of the network (1979-1982), no surveys were made until the network was reoccupied in 1995 and since then the technique of execution of the measurements has been replaced from EDM to GPS. The ground deformation monitoring device has been completed during 2000 with the installation of three permanent GPS and tilt station. In this work we show the results of these monitoring activities and a possible model for their interpretation.

A NEW METHOD FOR THE ANALYSIS OF DIKE STABILITY, PRELIMINARY TESTS ON REAL DATA

E. Rivalta, T. Dahm
Departement of Geophysics, University of Hamburg
rivalta@dkrz.de

Volcanic edifices are often characterized by intense fracturing. The generation of these cracks is caused by several factors related to volcanic activity, like degassing, chemical action of hydrothermal fluids and stress corrosion, whereas fracturing is also a consequence of the intense stress produced by repetitive magma injections. Intrusion processes are accompanied by seismic swarms, documenting the genesis of shear processes that develop diffusely around the intrusion. The rock resistance sinks with increasing fracture density, and it is important to quantify the effects of this weakening on the dike itself.

At this purpouse a boundary element approach is used to model dike intrusions in cracked media. The dike is modeled as a pressurized opening crack, and many fractures are randomly distributed around it and are free to open or shear under the stress field produced by the dike. In other words, normal and tangential stress on the dike and fractures surfaces represent the boundary conditions of the problem and normal and tangential displacement represent the unknowns. We quantify how the intrusion width and the stress intensity factor increase with increasing crack density. This is leading to a complex cause-effect interaction: (1) a dike intrudes in a medium, (2) fracturing is produced and fracture density increases while decreasing the elastic strength of the rocks, (3) the width of the dike and the intensity of the stress field increase, (4) new fracturing is generated, returning to point (2) and starting a cyclical process. A self-accelerating mechanism may thus be possible and lead to eruptions if the stress intensity factor reaches the critical value represented by the fracture toughness. Analytic relations deduced from effective media theories have been found to good approximate the results, particularly for minor values of the crack density.

To test the model we chose one of the most energetic swarms ever recorded, the 2000 Izu Islands earthquake swarm. More than 4000 earthquakes with magnitude $M \geq 3$ (catalog of the ERC, NIED, Japan) accompanied the dike injection, which started at Miyakeshima Island and developed towards the Kouzushima and Niijima islands. The dike experienced a first rapid propagation and subsequently a continuous opening until it reached about 20 m expansion progressively increasing the distance between the Kouzushima and Niijima islands.

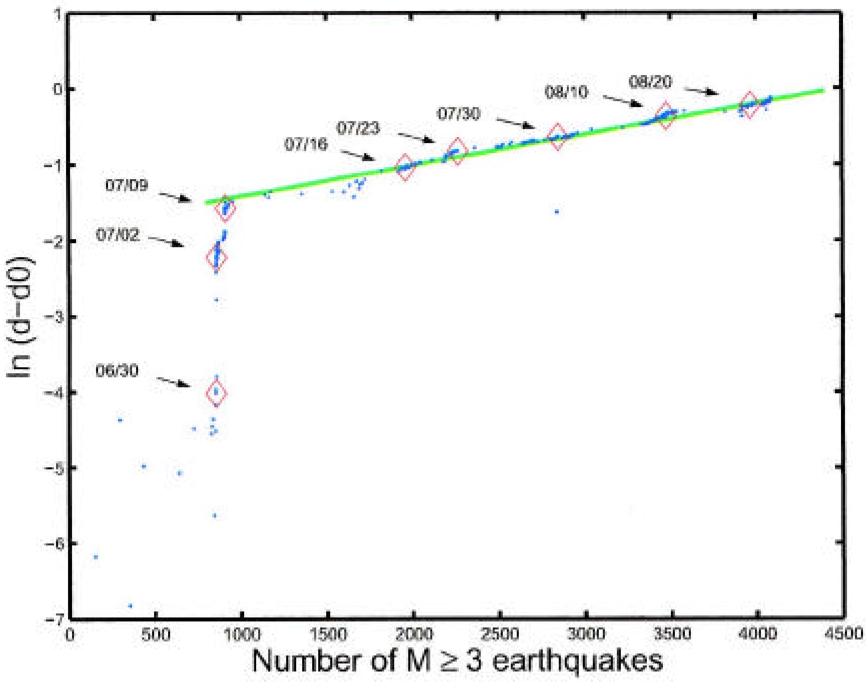
Our model predicts for a stable dike a linear relationship between deformation data and cumulative seismicity:

$$\ln d = \underbrace{\ln d_0 + \frac{S}{A}N_0}_{a} + \underbrace{\frac{S}{A}}_{b} N$$

where d is the relative coordinate change between two arbitrary points outside the dike and N is the total number of aerthquakes.

We plotted the logarithm of the change in K-N distance against the cumulative number of earthquakes with $M \geq 3$ every 6 hours interval. The resulting curve shows, after a preliminary complex trend, the predicted linear relation. The model presupposes a fixed length for the dike, so it is not suitable for the first time interval, when it is rapidly increasing in dimension. The advantage is that it is possible to assess in real time the state of propagation of the dike: when the linear trend starts, the dike has become stable and the seismicity is caused by its expansion.

The method has to be tested on other volcanic areas.



DIKE INTERACTION WITH THE EARTH SURFACE AND LAYERING INTERFACES: THEORETICAL MODELS AND EXPERIMENTS EVIDENCE ACCELERATED MOTION

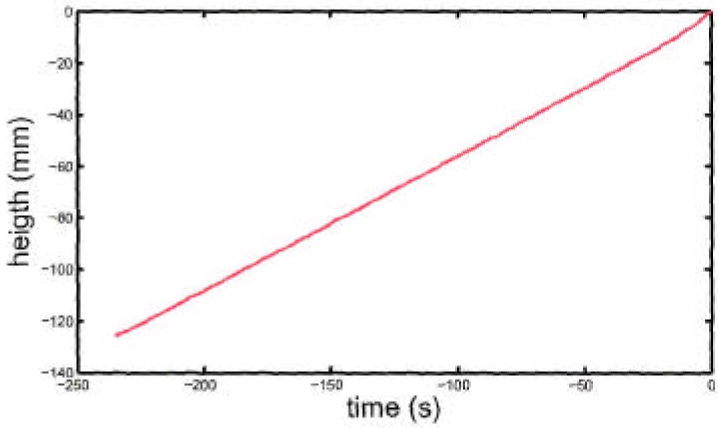
E. Rivalta, T. Dahm
Departement of Geophysics, University of Hamburg
rivalta@dkrz.de

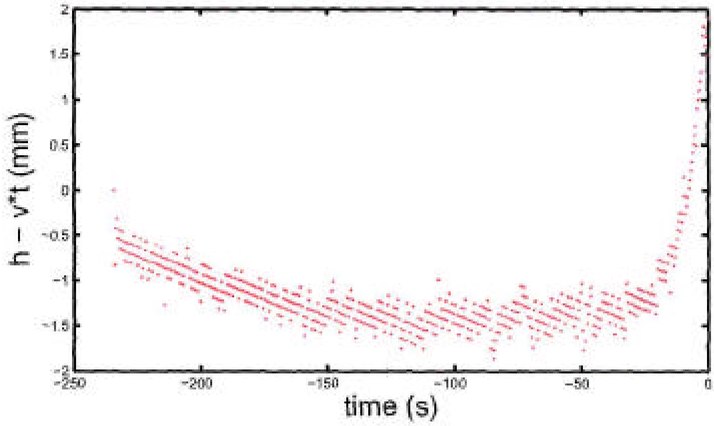
The influence of the earth surface on dike propagation has been object of several investigations, but the dynamic of this process is still poorly understood. Moreover, strong heterogeneities are very common in volcanic areas, and are recognized to have a great influence on the stress field generated by magma intrusions. Layering, represented by strong discontinuities in the elastic parameters, is able to significantly concentrate and enhance stress. For instance, at Moho depth where elastic and viscoelastic parameters change, or beneath volcanic edifices, that are made up by a stiff basaltic basement covered by softer materials produced by repetitive activity.

Numerical and (semi)analytical studies have shown how a free surface and layering influence the shape of the intrusion and the surrounding stress field.

However, it is important to quantify how layering influences the propagation of dikes, in order to understand the physics controlling the dynamic of the interaction between dikes and the elastic parameters of the medium. The stress intensity factor is a measure of the tendency of the dike to break new rock and to propagate, and is therefore an useful parameter to analyse the migration process. It has been calculated with both semianalytic and numerical procedures and has been plotted as a function of the depth in relation to different rigidity contrasts. The stress intensity factor is found to increase when the dike is embedded in the stiffer medium and propagates towards a softer one, and to decrease in the opposite situation. This may produce stops, pauses or accelerations in the migration process that may be mirrored in the seismicity recorded during injection events.

Additionally to analytical and numerical studies, analogue experiments have been conducted to verify the theoretical findings. The ascent of air-filled fractures in solid gelatine has been recorded and processed in order to obtain the path of motions and derive the fracture velocity. The detrended plot clearly shows an accelerated motion when the fracture is approaching the free surface.





Combining stress intensity factor studies and the theory of fluid-filled fracture propagation in elastic materials helped us to develop a theoretical model for the process. An expression for the velocity of a dike in function of the distance from the free surface has been obtained and compared with the experimental results, finding a good agreement.

THE ROLE OF MAGMATIC GAS DURING VULCANIAN EXPLOSIONS AND PYROCLASTIC FLOWS EMPLACEMENT, AT MONTSERRAT

Y. Formenti and J. Druitt

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

Magmatic gas play an important role in many volcanic processes such as the fragmentation of the magma or the pyroclastic flows. In this study, we have constrained the amount of magmatic gas involved in the 1997 explosive eruptions of the Soufriere Hills Volcano of Montserrat. As a first work, we have studied the videos of three Vulcanian explosions, amongst the 88 that occured in 1997 at Montserrat, in order to estimate their physical parameters. This study has shown that over the first ten seconds of each explosion, the magma involved in the fragmentation of the magma was less and less degased, exsolved water contents increasing from 0.13 to 1.22 wt%, and more and more pressurised, gas pore pressures increasing from 1.1 to 10.8 MPa. The other part of this study has focused on the estimation of the role of the remaining magmatic gas on the mobility and the fluidisation of poyroclastic flows. Vesicularity measurements and SEM observations have shown that pumice can retain magmatic gas after the fragmentation of the magma. These gas can then be released by attrition of pumice during pytroclastic flows emplacement. We have developped a model that shows that this process can contribute to the fluidisation of the fountain-collapse pyroclastic flows and therefore enhanced their mobility.

DISPERSION ANALYSIS OF LOW-FREQUENCY EARTHQUAKES ON MONTSERRAT - AND WHAT IT REVEALS

J. Neuberg and S. Sturton

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

The first part of this contribution summarises models of low-frequency seismic wave propagation in and around a volcanic conduit/dyke. FD models of encreasing complexity match data characteristics as observed on Montserrat and other volcanoes. The second part focusses on the dispersion relations of low-frequency events and thelinks those provide to estimate both, the magma properties in the conduit and the shape/dimensions of the relevant plumbing system.

WAVELETS FOR SEISMOLOGY

A. Graps [1], R. Carniel [2]

[1] *Istituto di Fisica delle Spazio Interplanetario, Roma, Italy*
[2] *Dipartimento di Georisorse e Territorio, Università di Udine, Italy*

Wavelet analysis is one of the more recent tools to decode data streams and it may be one of the most flexible. Wavelets can be conceptualized as a kind of microscope to see signals or functions through a scale-varying window.
The seismological use of wavelets that we present in this survey talk: 1) examining frequencies, 2) data compression, 3) denoising, 4) object detection, can be found in many engineering and scientific fields. The wavelet transform won't replace the Fourier transform, but it can complement the Fourier transform by acting as a prototyping tool to help one quickly identify localized features (singularities and irregular structures) in a signal. Moreover, if you suspect that your time series is nonperiodic, or that chaotic processes underlay features in your data, or that a pattern at different scales better describes your data, then perhaps the wavelet transform is for you. As an example of the use of wavelets in seismology, we will show a wavelet transform of seismic signals recorded at Stromboli volcano in March/April 2003, during the effusive phase.

LABORATORY MEASUREMENTS OF SEISMIC VELOCITIES ON ROCKS FROM ETNA REGION (ITALY).

S. Vinciguerra [1,2], C. Trovato [1], P.G. Meredith [3], P. Benson [3], J. Immè [2], G. De Natale [1]

[1] Osservatorio Vesuviano- Istituto Nazionale di Geofisica e Vulcanologia, Napoli, Italy
[2] Dipartimento di Fisica e Astronomia, Universita' di Catania, Catania, Italy
[3] Department of Earth Sciences, University College London, London, U.K.

The improvement of techniques of monitoring has resulted in interpretative models of the physical and chemical changes associated with the renewal of activity of volcanic systems.
However, understanding the relationship between the build-up of tectonic stress, precursory deformation and the precursory patterns requires a priori precise knowledge of rock physical and mechanical properties. Whereas the acquisition of data in the recent years is enormously improved, laboratory measurements of the volcano edifice rock physical and mechanical properties are almost absent.
Ultrasonic laboratory measurements of seismic velocities waves (Vp and Vs) and permeability have been measured using the steady state flow method in a servo-controlled permeameter (Fig.1), at effective pressure 5-90MPa for basalts of the Etna region, basalts from Iceland and Tuffs of the Campi Flegrei. Piezoelectric contact transducers (resonance frequency at 1MHz) were used to generate and record seismic velocity waves.
Seismic wave velocities varying from1.5Km/s and 3.0Km/s have been found for buffs, while from 3 and 6 Km/s for basalts
Some of the samples have been thermally treated up to 900°C. Acoustic emissions have marked the thresholds of thermal damage increment. A strong dependence between thermal cracking and seismic wave velocities has been found for Campi Flegrei Tuffs. Conversely basalts mechanical behaviour in terms of seismic wave velocities and permeability seems to be strongly controlled by the degree of fracturing characteristic of the microstructure, which is quite insensitive to temperature treatments

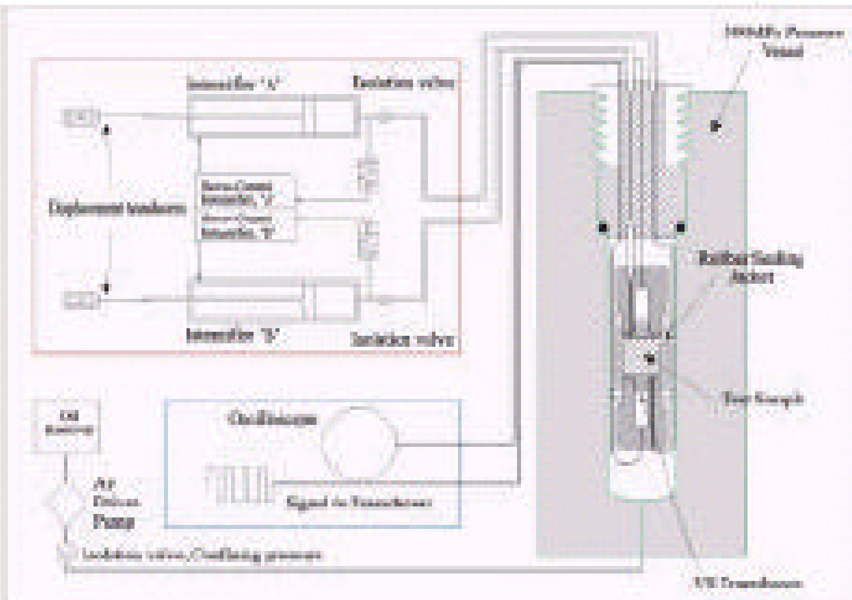


Fig. 1 – Schematic sketch of the apparatus for measuring seismic velocity waves and permeability, under variable effective pressure.

SHALLOW VELOCITY STRUCTURE AND SEISMIC SITE EFFECTS AT ARENAL VOLCANO, COSTA RICA

P. Lesage[1,2], M. M. Mora[1,3], G. E. Alvarado[3,4], C. Leandro[4], J. P.Métaxian[1,5]

[1] *Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, France. lesage@univ-savoie.fr*
[2] *Coordination de la Recherche Volcanologique (CNRS)*
[3] *Escuela Centroamericana de Geología, Universidad de Costa Rica, San José, Costa Rica. mmmora@geologia.ucr.ac.cr*
[4]*Instituto Costarricense de Electricidad, San José, Costa Rica*
[5] *Institut de Recherche pour le Développement, France*

The shallow structure of Arenal volcano has been investigated using a combination of several approaches. Two seismic refraction profiles, carried out on the West and East flanks of the volcano, provided 2-D velocity models down to 150 m depth. They reveal complex structures with strong lateral variations of the thickness and velocity of the layers at short distances (less than 100 m). We also applied the spatial correlation method (Aki, 1957) to estimate vertical velocity models down to 400 m depth below two semicircular arrays located about 4 km northeast and west of the craters. In the case of the West survey, two solutions were obtained when inverting the correlation coefficients. The differences between the two solutions are related to the existence of a marked increase of the correlation coefficients at about 6 Hz for the three components of the motion. The correlation coefficients calculated with one solution fit this peak while those of the other solution do not adjust it. We selected the latter model by checking the consistency of the corresponding theoretical S-waves transfer functions with the H/V spectral ratios calculated from the data. The latter ratios indicate a site effect near that frequency. We interpret those observations as the result of the resonance of the shallow structure, which increases the correlation between the sensors. Thus the H/V spectral ratios can help detecting strong lateral heterogeneities underneath an array and can be used to test the plane layers hypothesis of the spatial correlation method. Similar site effects are observed at many places along the linear and semicircular arrays, producing strong variations of the waveforms and spectral peaks of the volcanic tremor.

Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Saturday 27 September

Annual Workshop 2003, September 23 to 28, Pantelleria, Sicily

Theme:
"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"

PRESSURISATION OF SOUFRIERE HILL'S VOLCANIC EDIFICE

D. Green[1], V. Cayol[2], and J. Neuberg[1]

[1] *Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England*
[2] *Lab. Magmas et Volcans, UMR 6524, Universite Blaise Pascal 5, rue Kessler 63038, Clermont-Ferrand cedex, France*

The deformation of the volcanic edifice of Montserrat has been studied intensely since the beginning of the current eruptive phase in 1995. Electronic Distance Meters, Global Positioning Systems and Tiltmeters have all been used to provide quantitative estimates of deformation parameters. All studies so far have noted that deformation on Montserrat can be partitioned into near-field and far-field regions. The near-field (<1500m from the dome) is characterised by continuous shortening of survey lines, whereas in the far-field some rebound is observed within the data. This has been interpreted as an indication of an elastic far-field response and a non-elastic permanently deformed dome region. Previous studies have differed on where the source of the pressurisation is located, with most research advocating a shallow source. Supporting this theory are cyclical changes in tilt which have been observed close to the dome, indicating shallow periodic pressurisations.
This presentation will focus on the use of a 3D boundary-element model to constrain the source location and geometry. This form of study is hoped to provide estimates of the pressures that result from changes within the volcanic conduit. It is shown that data from the period of dome growth in 1996-1997 is consistent with a shallow source, however results must be analysed with caution due to the fact large azimuthal gaps are present within the data.

WAVEFORM ANALYSIS OF LOW-FREQUENCY EARTHQUAKES, WITH EXAMPLES FROM PRIOR TO THE JULY 12TH DOME COLLAPSE, MONTSERRAT

D. Green and J. Neuberg

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

Most classification schemes of low-frequency earthquakes on volcanos worldwide concentrate on the frequency content of such signals. However, significant amounts of information may be found within the waveforms of such signals. It is shown that swarms of low-frequency events on Montserrat contain groups of extremely similar waveform patterns. These groups, or families, are localised in time and can be used to categorise low-frequency events. In all the low-frequency earthquake swarms studied more than one family is observed, suggesting there is more than one location for event triggering. It is shown that the groups are long lived, with the same waveforms present in successive swarms suggesting a stable path for the seismic waves is maintained. Analysis of data from 1997 will be presented to provide an introduction to the techniques used and the insights gained from studying the waveforms. Further results from prior to the July 12th, 2003 dome collapse at the Soufriere Hills, Montserrat, will be presented which indicate how continuous data provides information relating to the source of seismic signals at this volcano.

TEMPORAL AND LATERAL VARIATION OF EARTHQUAKE CHARACTERISTICS DURING VARIOUS DOME GROWTH EPISODES

J. Neuberg, D. Green, E. Doyle, A. Jolly, and G. Norton

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

Seismicity and magma movement leading to dome growth and collapse are associated. In this contribution we study lateral and temporal variations in seismic parameters such as polarisation and spectral content to check for systematic changes during different episodes of dome growth. Results include a distance-dependent classification pattern of hybrids and long-period events, and an indication that cyclic polarisation changes represent magma ascent and slumping, respectively.

IDEAS ON THE EXCITATION MECHANISM OF LOW-FREQUENCY EARTHQUAKES

J. Neuberg, S. Sturton, and H. Tuffen

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

Observations of low-frequency earthquake swarms on Montserrat point to a non-destructive, repeatable source mechanism in a confined area inside or near the volcanic plumbing system. While the seismic wave propagation pattern of the subsequent resonance in and around the conduit is well studied, the actual trigger mechanism has been unknown. In this contribution we suggest a trigger mechanism based on new observational evidence of tuffisites in relation to seismic observations from Montserrat. As a seismic trigger we suggest a stick-slip motion of magma in glass transition that leads to the opening of shear cracks in highly brittle material. These cracks of the dimension of a few meters are rapidly filled with fine grain material (volcanic ash) suspended in gas escaping through the cracks. This provides a fast healing mechanism in the order of tens of seconds. Due to a strong viscosity gradient in the magma highly brittle phases near the conduit walls co-exist with fluid phases in the conduit centre such that brittle failure provides the seismic trigger mechanism while the fluid part can still act as a seismic resonator.

PARTICLE MOTION ANALYSIS OF SOME LOW-FREQUENCY SEISMIC EPISODES AT MONTSERRAT

Y. Formenti

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

Low-frequency seismic events are comon features accompanying volcanic eruptions. These events generally occur in swarms merging into tremors and precede dome collapse events and rock falls activities. Their occurrence is believed to indicate a pressurization of the volcanic system. The purpose of this study was to constrain the triggering mechanism of the low-frequency seismic events by analyzing the particle motions at the onset of each event, which corresponds tothe arrival of the direct P-wave. This direct P-wave is believed to be related to the triggering mechnism of these events. We have studied the paticle motions of some events on the five broad band stations on Montserrat. These events occured in 1997 on the 1st of April, 19th of May and 22nd-23rd of June. Our analysis shows that the particle motions of most events are compatible with a shear fractures at the margin of the magmatic conduit, due to upward and downward movements of the magma.

AUTOMATED EVENT CLASSIFICATION AND PARAMETER RETRIEVAL ON MONTSERRAT

T. Powell

Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England

The intermittency and event energy are important parameters for the analysis of the low-frequency earthquakes on Montserrat. For large datasets, we can find these events and classify them using our Automated Event Classification Analysis Program (AECAP), which has a classification accuracy of around 85%.

The low-frequency energy retrieved from the events is compared to the cyclic tilt from June 1997. Previous comparisons of the tilt to RSAM suggest that the low-frequency events are linked to the pressurisation of the volcanic edifice. However, when we compare the seismic energy to the derivative of the tilt (pressurisation), it is apparent that the low-frequency events are depressurising the volcanic edifice.

Assuming that the trigger mechanism is a stick-slip source, we look at the relationship between pressure and fault movement, to see if this matches the seismic parameters obtained from AECAP.

CLASSIFICATION OF SEISMIC TRANSIENTS RECORDED ON SOUFRIERE HILLS VOLCANO, MONTSERRAT, USING ARTIFICIAL NEURAL NETWORKS

H. Langer[1], S. Falsaperla[1], T. Powell[2], and G. Thompson[3]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania, P.zza Roma 2, 95123 Catania, Italy*
[2] *Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England*
[3] *Montserrat Volcano Observatory, Montserrat, British West Indies*

The Soufriere Hills on the island of Montserrat form an andesitic volcano complex. The volcano resumed its activity in 1995, reaching a climax in 1997 when dome collapses, pyroclastic flows, and lahars destroyed the airport of Montserrat and the town of Plymouth. A more recent volcano unrest occurred in mid July 2003, with a major dome collapse and powerful explosive activity, after a period of lava-dome growth lasted several months. On this type of volcano the seismic energy radiation forms various types of transient signals, each of them being important for the assessment of the state of the volcano system and possible implications for warning. Seismic transients, which are continuously monitored by the Montserrat Volcano Observatory (MVO), can be separated into different classes with respect to their origin. The huge quantity of seismic data daily recorded makes the application of automatic processing highly recommendable. We focus therefore our attention on the identification and classification of these transients using Artificial Neural Networks (ANN). Despite the rather tricky nature of the classification problem, this application of ANN shows promising results. Additionally, it discloses the possibility to revise a-posteriori classifications of human operators.

We tested the automatic classification using a data set of ca. 6000 events, which covers the years 1996-2000. We could identify a significant number of events which were a-priori misclassified during the visual routine classification. We propose the application of this method to provide update and fast information on the distribution in time of the different classes of seismic transients, which may lead to infer possible developments in eruptive scenarios. The ultimate aim of this study is to classify approximately 184,000 seismic events recorded on the MVO's analog seismic network between July 1995 and March 2001 and associated with the eruption of the Soufriere Hills Volcano. This task would become unaffordable if it had to be carried out manually, and is an ideal application for a neural network.

DEVELOPMENT OF A FORECASTING APPROACH USING STOCHASTIC METHODS APPLIED TO THE SOUFRIÈRE HILLS VOLCANO

O. Jaquet[1], R. Carniel[2], R. Namar[1] and M. Di Cecca[2]

[1] *Colenco Power Engineering, Baden, Switzerland*
[2] *Dipartimento di Georisorse e territorio, Udine University, Italy*

Within the framework of the EU-project MULTIMO (Multi-disciplinary monitoring, modelling and forecasting of volcanic hazard), a stochastic methodology aiming at forecasting volcanic activity in the near future is currently under development. This approach is based on geostatistical concepts and allows the characterisation of the behaviour for time series recorded at active volcanoes.

The following steps are considered for analysis and simulation of discrete and continuous variables taken from multi-parametric data sets: (a) analysis and parameterisation of time behaviour by variogram calculation, (b) stochastic simulation for Monte Carlo forecasting and (c) kriging analysis for estimation of time components related to precursors of volcanic activity.

Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Field Trip
Geology and Vulcanism of Pantelleria

Friday 26 September

Annual Workshop 2003, September
23 to 28, Pantelleria, Sicily

Theme:
"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"

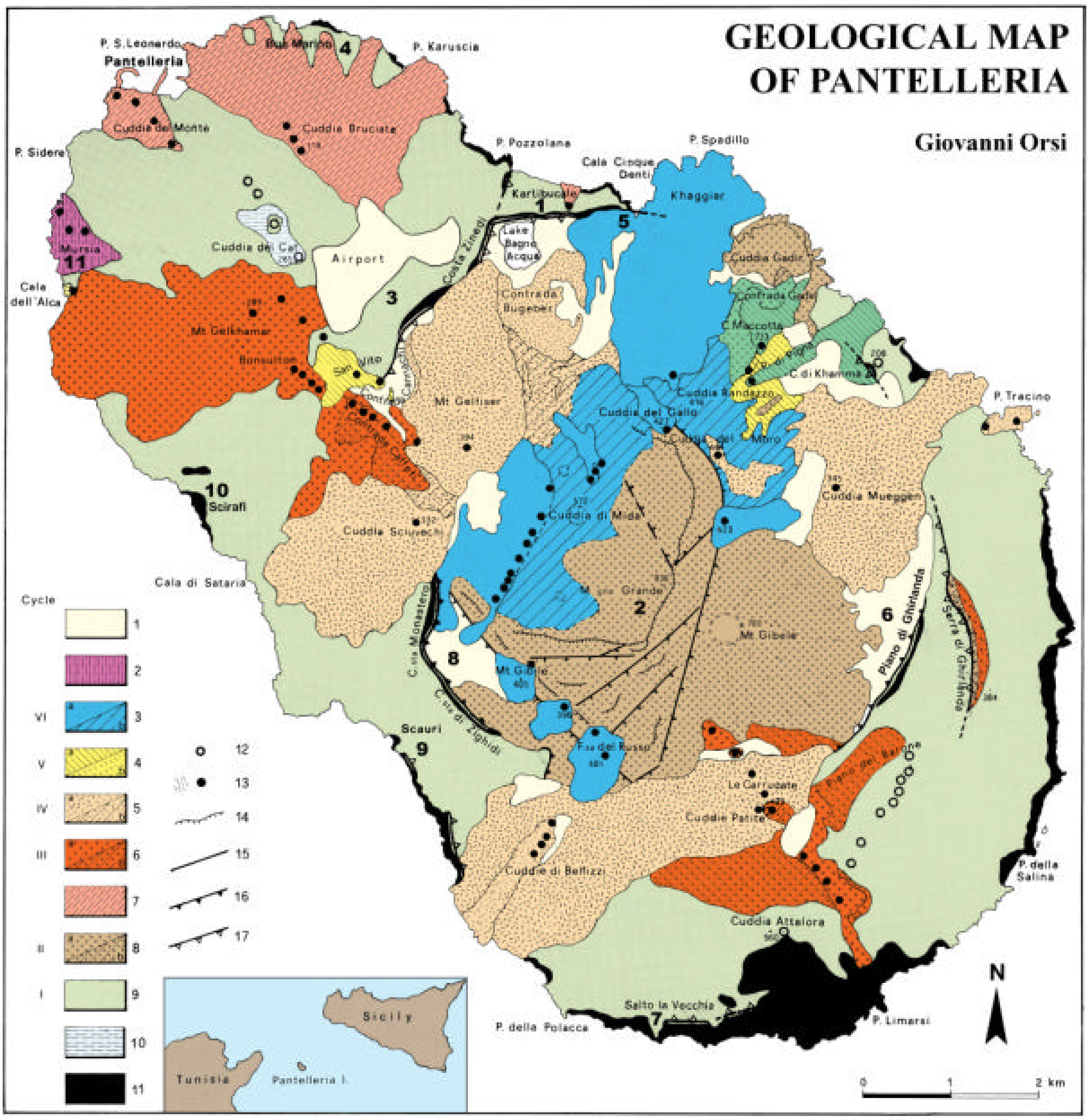


Figure 1 – Geological sketch map of the island of Pantelleria. 1, Alluvium; 2, Mursia basalts: lava flows and cinder cones younger than 10 ka; 3, volcanics of the VI silicic cycle (4-10 ka), a) lava flows and domes, b) pumice-fall deposits; 4, volcanics of the V silicic cycle (12-14 ka), a) lava flows and domes, b) pumice-fall deposits; 5, volcanics of the IV silicic cycle (15-20 ka), a) lava flows and domes, b) pumice-fall deposits; 6, volcanics of the III silicic cycle (22 ka), a) lava flows and domes, b) pumice-fall deposits; 7, Punta San Leonardo basalts (29 ka): lava flows and cinder cones; 8, volcanics of the II silicic cycle (35-29 ka), a) lava flows and domes, b) pumice-fall deposits; 9, volcanics of the I silicic cycle (50 ka): Green Tuff; 10, basalts older than 50 ka: lava flows and cinder cones; 11, silicic rocks older than 50 ka; 12, eruption vents older than 50 ka; 13, eruption vents younger than 50 ka; 14, top of escarpment of volcano-tectonic origin; 15, volcano-tectonic faults; 16, Monastero caldera (50 ka) rim; 17, La Vecchia caldera (114 ka) rim.

Numbers 1 through 11 indicate stops location of the field trip.

Working Group of the European Seismological Commission

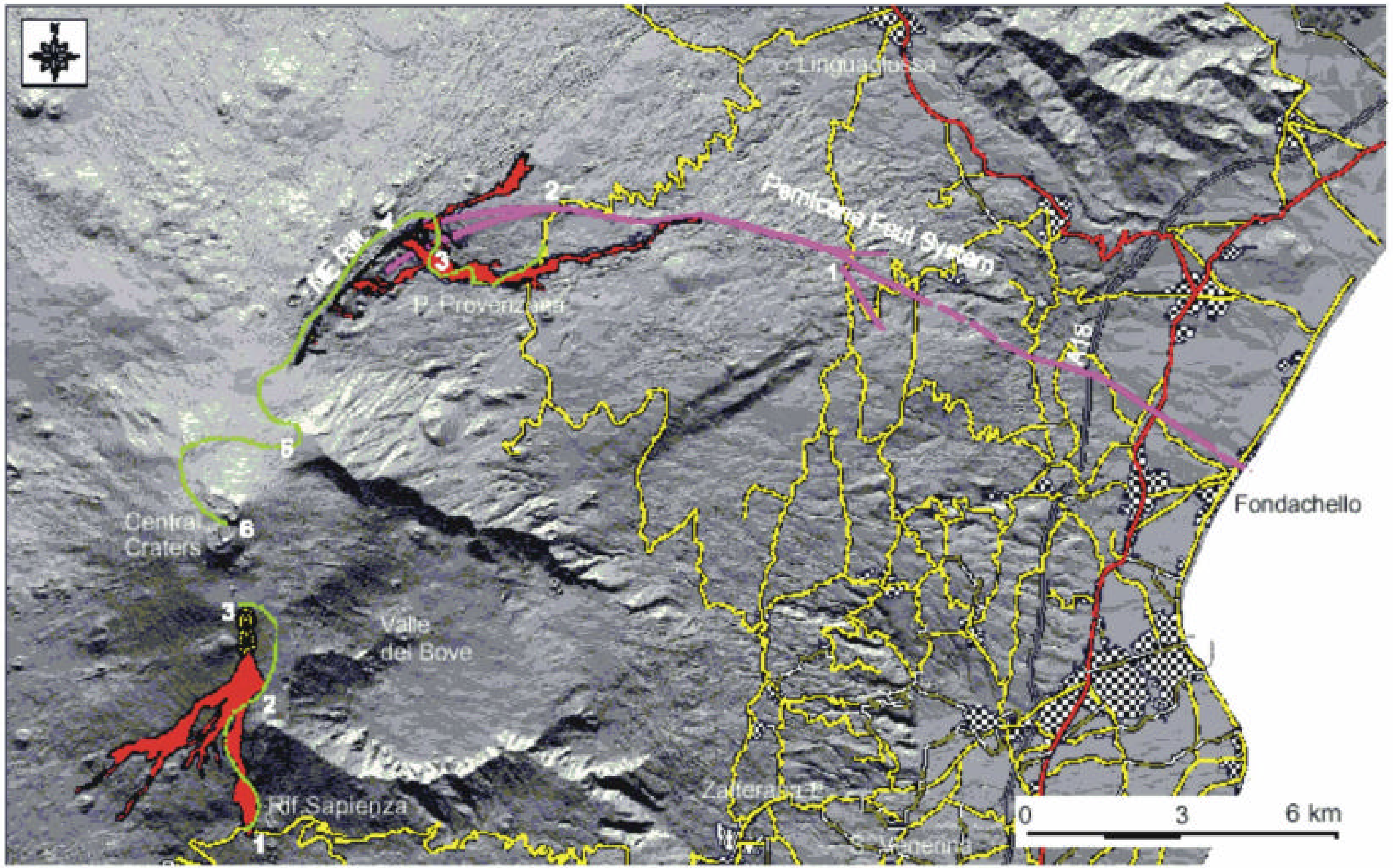
SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Post-workshop Field Trip
Geology and Vulcanism of Mt.Etna

Monday 29 September

Annual Workshop 2003, September
23 to 28, Pantelleria, Sicily

Theme:
"SEISMIC SIGNALS RELATED TO VOLCANIC UNREST"



Numbers mark location of the possible stops of the field trip, according to two different paths.

Barbano Maria Serafina
Department of Geological Science - University of Catania,
Corso Italia 55, 95129 - Catania – Italy
barbano@unict.it

Berrino Giovanna
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Napoli – Osservatorio Vesuviano. Via Diocleziano, 328. 80124 Napoli, Italy
berrino@ov.ingv.it

Borgström Sven
Istituto Nazionale di Geofisica e Vulcanologia - Osservatorio Vesuviano, Naples (Italy)
sven@ov.ingv.it

Carniel Roberto
Dipartimento di Georisorse e Territorio, Università di Udine, Italy
rcarniel@dgt.uniud.it

Falsaperla Susanna
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania; Piazza Roma, 2; 95123 Catania, Italy
falsaperla@ct.ingv.it

Formenti Yvan
Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England
formenti@earth.leeds.ac.uk

Garcia Alexander
Instituto Geofísico – Escuela Politécnica Nacional – Quito, Ecuador
agarcia@igepn.edu.ec

Graps Amara
Istituto di Fisica delle Spazio Interplanetario, Roma, Italy
amara@amara.com

Green David
Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England
dng@earth.leeds.ac.uk

Hellweg Peggy
Berkeley Seismological Laboratory, UCB, Berkeley, CA,USA
peggy@seismo.berkeley.edu

Jaquet Olivier
Colenco Power Engineering, Baden, Switzerland
olivier.jaquet@colenco.ch

Jones Josh
Department of Earth and Space Sciences, University of Washington, Seattle, Washington, USA
josh@ess.washington.edu

Langer Horst
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania; Piazza Roma, 2; 95123 Catania, Italy
langer@ct.ingv.it

Lesage Philippe
Laboratoire de Géophysique Interne et Tectonophysique, Université de Savoie, France.
Philippe.Lesage@univ-savoie.fr

Mattia Mario
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania; Piazza Roma, 2; 95123 Catania, Italy
mattia@ct.ingv.it

Neri Marco
Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Catania; Piazza Roma, 2; 95123 Catania, Italy
neri@ct.ingv.it

Neuberg Jürgen
Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England
J.Neuberg@earth.leeds.ac.uk

Orsi Giovanni
Osservatorio Vesuviano – INGV. Via Diocleziano 328, 80124 Napoli, Italy
orsi@ov.ingv.it

Powell Tanya
Dept. of Earth Sciences, University of Leeds, Leeds, W Yorkshire, LS2 9JT, England
tanya@earth.leeds.ac.uk

Rivalta Eleonora
Department of Geophysics, University of Hamburg
rivalta@dkrz.de

Roman Diana
Department of Geological Sciences, University of Oregon, USA
droman@newberry.uoregon.edu

Soosalu Heidi
Nordic Volcanological Institute, Reykjavík, Iceland
heidi@hi.is

Tenorio Virginia
INETER, Managua, Nicaragua
vtenorio.gf@ineter.gob.ni

Vinciguerra Sergio
Osservatorio Vesuviano- Istituto Nazionale di Geofisica e Vulcanologia, Napoli, Italy
sergio.vinciguerra@ct.infn.it

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The authors of the invited papers:

G. Orsi:
Geology and volcanism of Pantelleria

B. Behncke, G. Berrino, and R. Velardita:
Ground deformation and gravity changes on the island of Pantelleria in the geodynamic framework of the Sicily channel

A. Bonaccorso, O. Campisi, O. Consoli, G. Falzone, S. Gambino, M. Mattia, B. Puglisi, G. Puglisi, and M. Rossi:
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