Working Group of the European Seismological Commission

SEISMIC PHENOMENA ASSOCIATED WITH VOLCANIC ACTIVITY

Annual Workshop 2005

Quantifying volcanic activity

Saint-Claude, Guadeloupe, France

September 19 – 24, 2005

Organizing Committee

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the IAVCEI- IASPEI inter-association committee on Volcano Seismology

Program Outlook

	Morning	Afternoon	Evening
Mon 19	Arrival of the participants		**20:00** Icebreaker Welcome dinner
Tue 20	**09:00 - 11:30** Opening and Scientific session: La Soufriere de Guadeloupe volcano **11:30 - 13:30** Scientific session	**16:00 - 19:30** Scientific sessions	**22:00** White wine tasting session
Wed 21	**09:00 - 12:00** Visit to the Volcano Observatory	**15:00 - 19:30** Scientific sessions	**22:00** Scientific discussions...
Thu 22	**08:30 - 14:00** Field excursion to Bouillante geothermal field	**16:00 - 19:30** Scientific sessions	**22:00** Red wine tasting session
Fri 23	**08:30 - 17:00** Field excursion to Soufriere volcano		**19:30** Closure and goodbye dinner
Sat 24	Departure of the participants		

Practical Information

Lunches are planned on **Tue 20** at the hotel's *Lamazure* restaurant, on **Wed 21** at *Tamarinier* restaurant (Saint-Claude), on **Thu 22** at *Caprice des îles* restaurant (Baillif), and on **Fri 23** on la Soufrière (hotel packed meal for the field trip).

Dinners will be at the hotel's *Lamazure* restautant every day **from Mon 19 to Fri 23**.

Local time is **GMT-4**.

International phone code for Guadeloupe is **+590** (and NOT +33 like France).

Hotel Saint-Georges coordinates: rue Gratien Parize, 97120 Saint-Claude, GUADELOUPE. Phone **(0)590 80 10 10**, Fax **(0)590 80 30 50**, e-Mail **info@hotelstgeorges.com**

Scientific Program

Monday, September 19

20:00 Icebreaker and Welcome dinner

Tuesday, September 20

09:00 Opening

09:30 - 11:30 Scientific session: La Soufrière de Guadeloupe volcano

11:30 - 13:30 Scientific session : Latin-American volcanoes

16:00-19:30 Scientific sessions

Wednesday, September 21

09:00 - 12:00 Visit to the Volcano Observatory
F. Beauducel and C. Anténor-Habazac

15:00 - 19:30 Scientific sessions

22:00 Scientific discussions...

Thursday, September 22

08:30 - 14:00 Field excursion: Bouillante geothermal field
P. Jousset

16:00 - 19:30 Scientific sessions

22:00 Red wine tasting session

Friday, September 23

08:30 - 17:00 Field excursion to Soufriere volcano
G. Boudon, J.C. Komorowski and F. Beauducel

19:30 Closure and Goodbye dinner

Abstracts

Dynamical analysis of a highly energetic tremor phase during the 2002 eruption at Etna volcano, Italy

Fausto Barazza [1], Roberto Carniel [1] and Susanna Falsaperla [2]

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During the 95 days-long lava effusion at Mt. Etna that started on 26 October 2002, a phase was observed where although the VT seismicity was rather low (less than 5 events/hour, compared to hundreds per hour near the eruption onset), volcanic tremor was characterized by the most energetic radiation after the beginning of the volcano unrest.
In this talk we present the preliminary results of a dynamical analysis of the first part of this phase, spanning the period 10-19 November 2002. Spectral, dynamical and stochastic parameters are computed over 1 minute-long time windows, and their time evolution is examined in order to highlight coherent eruptive regimes and transitions between them. This period was in fact characterized by a phase of volcanic activity which was mostly effusive, interrupting the dominant effusive-and-explosive style of the 2002 eruption. It is worth noting that another phase with prevailing effusive activity occurred at a later stage of the 2002 eruption, although accompanied by a less energetic volcanic tremor. The choice of this particular period of the eruption, with such evident changes in the eruptive behavior, aims therefore at highlighting possible relations between volcanic system dynamics and eruptive style through the "simple" study of volcanic tremor, with benefits for the hazard mitigation, in this case at a relatively short timescale.

Comparison of seismic activity between three active volcanoes in Chile: Isluga, Llaima and Villarrica

<u>K. Bataille</u>, G. Hermosilla and R. Mora

Two broad band seismic stations were used to analyse the activity of volcanoes in Chile, that showed some degree ofunrest in recent years: Villarrica, Llaima and Isluga. These are located at latitudes of 39.42, 38.68 and 19.15 South along the Andes, and although are stratovolcanoes, with some differences on its chemical composition of erupted material, there is a remarcable difference on its seismic signature, as recorded at distances of 3-6 km from their crater. Villarrica volcano erupted in recent years in 1971 and 1984, has a lava lake emitting continuously gases with fluctuating intensity, has a characteristic seismic signature dominated by events related to the periods of increased gas emission. The spectrum of these events has predominant frequencies between 1 and 2 Hz, differing on each station, and has complex particle motion. There are very seldom records of high frequency events, where the source is distributed in a broad region between 3-5 km depth. Last eruption of Llaima volcano occurred in 1994, and recently there was a small explosion in 2003. The records for several months after this small explosion, showed a continuous signature of tremors without any high frequency event.
These tremors share remarcable well their spectrum within each station, implying that the source's dynamic is the dominant effect on the frequency content. The strength of the signal has decayed in time since the small eruption. Isluga's latest eruption was in 1913, but during 2002 began a period of unrest, increasing the fumarolic activity and earthquake felt at nearby towns. Its

records shows only high frequency events, with approximately 50 events per day. These events occurred up to 10 km deep. This is the most acid volcano of the three, and could be the reason for this behaviour. An understanding of the activity of these volcanoes require the deployment of a seismic network for a longer period of time.

Volcano-seismic signals and monitoring network on La Soufrière of Guadeloupe

S. Bazin, F. Beauducel, J-C Komorowski, A. Nercessian, G. Boudon, A. Saglio, C. Anténor-Habazac, A. Tarchini, B. Figaro, J-C Delmond, A. Lemarchand, C. Lambert and D. Mallarino

Observatoires Volcanologiques, Institut de Physique du Globe de Paris, France

P. Bernard

Equipe de Sismologie, Institut de Physique du Globe de Paris, France

B. Chouet

U.S. Geological Survey, Menlo Park, California, USA

The last phreatic eruption lasted 8 months in 1976-77 and presented very high seismic activity (16,000 events, 150 felt). After a short decrease, a phase of elevated activity associated with increased fumarolic activity started in 1992, and frequent volcanic seismic swarms are still being recorded (5 felt events since 1992). Events remain within 6 km below the dome and show no signs of rising magma. Presently, most of the seismic energy is released during swarms lasting several days up to two weeks and occurring few times a year since 1997. Although volcanic seismicity shows common features (shallow depth, low energy), several types of events with different characteristics occur at Soufrière volcano: few isolated volcanic-tectonic high-frequency events with impulsive P (VT-A), numerous imbricated emergent high-frequency events, no hybrid events, no tremor, sporadic long-period events with spindle shaped signal (resonant frequency near 4 Hz). The LP events could be generated by a resonant source or propagating-path effects. Preliminary processing (a dozen events recorded in the last 2.5 years) highlights a zone that could be interpreted as a plane of hydrothermally altered material within the dome. Overall, the shallow-depth low-energy seismic activity seems associated with the superficial hydrothermal system. The occurrence of seismic swarms does not show a simple correlation with rainfall. This points towards a temporal modification of superficial aquifers and their permeability by a process of local self-sealing. The Institut de Physique du Globe de Paris has been in charge of the monitoring of the Soufrière volcano since 1951. During the late 70s and moreover during the 90s, the seismic monitoring network was significantly upgraded. Presently, 12 telemetered short-period seismic stations (including three 3-components seismometers) are located within a 20-km radius of the summit. In 2003, four broadband seismometers (Guralp CMG-40T, 60 sec period) were installed near the dome.

The Mw 6.3 earthquake of Les Saintes (Guadeloupe) on November 21, 2004

F. Beauducel, C. Anténor-Habazac, S. Bazin, J.B. De Chabalier, A. Nercessian, N. Feuillet, E. Jacques, D. Bertil, G. Boudon, A. Lefriant, P. Tapponier, A. Hirn, J.C. Lépine, P. Bernard, J.C. Komorowski, G. King, OVSG team

Institut de Physique du Globe de Paris

On November 21, 2004, a shallow Mw 6.3 earthquake occured on a normal fault South-East of Les Saintes islands (Guadeloupe), at 15.75°N, 61.54°W, 14 km depth. It was the most important tectonic event in this area since 1897, and it caused one death and important damages at Les Saintes and North Dominica, a small tsunami (2-m runup) on Les Saintes as well as the nearest

shores of Guadeloupe and Dominica, and some landslides. The active but non-erupting Soufrière volcano, located about 40 km from the epicenter, has not shown developed any changes in activity (despite a reinforcement of its monitoring), excepted for superficial landslides on the edifice and it's immediate unstable surroundings, and minor localized ground cracks. We recorded more than 2000 aftershocks in the first 24 hours and a total amount of 24,000 aftershocks after 300 days. The main aftershock ML 5.7 occured 85 days after the main shock on February 14, 2005. It's epicenter was closer to the populated towns of Les Saintes. As of September 2005, the crisis was still going with a rate of 10 to 90 events per day. A large part of the events are localized at very shallow depths and still felt (or heard, as rumble) by the population, even small events of magnitude less than 2. We present here the evolution of aftershocks (in time, magnitude and space), and the first data and analyses of this event used to follow the crisis locally.

WEBOVS: Integrated Monitoring System Interface for Volcano Observatories

François Beauducel, Christian Anténor-Habazac, and Didier Mallarino
Observatoire Volcanologique et Sismologique de Guadeloupe, IPGP, Guadeloupe, FWI

Volcanological observatories have common needs and often common practical problems for multi disciplinary data monitoring applications. In fact, accessing to integrated data in real-time and measurements uncertainties estimation are keys for a strike interpretation, but instruments variety, data sampling and acquisition systems heterogeneity lead to difficulties that may check a crisis management. We have developed in the last few years an operational system that attempts to answer these questions, considering our 20 different networks and more than 200 permanent sensors installed in Guadeloupe. Based on a single computer server and a Web interface, the whole raw data are processed using automatic routines presently every minute for continuous seismology, and every 20 minutes for other slower acquisitions. Graphics are defined on preset moving time intervals mostly used for interpretation: last day, month, year, 10 years, all available data, and user defined. Numerical and graphical results are presented per station (calibrated data), per monitoring network (processed data), and the system is widely open to inter disciplines real-time modelling. Moreover, computers, stations and individual sensors states are checked automatically using simple criteria (files update and signal quality), and displayed as synthetic pages for technical control. This system leads to a real-time Internet access for integrated monitoring and becomes a strong support for scientists and technician's exchanges. It has been set up in Montagne Pelée and Piton de la Fournaise observatories, and is planed to be installed in Azores Volcanological Center.

Improvement of site effects estimation with Singular Spectum Analysis and possible applications in volcanic areas.

Roberto Carniel and Fausto Barazza
Dipartimento di Georisorse e Territorio, Università di Udine

Singular Spectrum Analysis (SSA) has a multidisciplinary range of applications, as it allows a generic time series to be decomposed into different components with decreasing mportance. Typical applications include denoising and data compression. SSA can also be used for a better characterization of spectral peaks highlighted by the Nakamura spectral ratio technique. In this talk we present this improvement of the classical Nakamura technique and we discuss possible applications in volcanic areas, in particular in the framework of the search for dynamical transitions in the time evolution of summarizing parameters characterizing volcanic tremor.

Combining numerical modeling and geophysical data to understand low frequency events on Montserrat

Marielle Collombet, Jurgen Neuberg, David Green, Lindsey Collier
School of Earth & Environment, The University of Leeds, United Kingdom

Characteristics of low frequency seismic events depend strongly on the magma properties. These properties vary both vertically and horizontally in the volcanic conduit during magma ascent toward the surface. Physical parameters such as viscosity, density, gas-content, shear and bulk modulus have been included in a 2D finite element model in order to better understand how the variations of each parameter can affect the conduit flow. Seismic data are used to constrain modeling. In return, numerical flow models provide conditions for possible trigger mechanisms of low frequency events.

Integration of R statistical engine into the MULTIMO application server web interface

Mauro Di Cecca, Marco Celotti and Roberto Carniel
Dipartimento di Georisorse e Territorio, Università di Udine

In the framework of the european project MULTIMO (Multidisciplinary monitoring, modelling and forecasting of volcanic activity) an application server based on Zope, MySQL and other fully open-source software was developed in order to store, browse and analyse geophysical time series recorded at an active volcano. In this talk we discuss the latest development of this project, aimed at integrating and exploiting the power of another open source GNU package, R.
R is a language and environment for statistical computing and graphics which provides a wide variety of statistical and graphical techniques. More important, its support by the open source community is growing, thanks to its high extensibility.
This makes its integration into the MULTIMO web application server an important task to achieve to give access to a wide set of new functionalities.

Active faulting controls volcanic activity in Guadeloupe

Nathalie Feuillet, P. Tapponnier, I. Manighetti, E. Jacques, B. Villemant, G. King
Observatoire Volcanologique de la Montagne Pelée - IPGP, Martinique

The Guadeloupe islands are cut by normal faults that accommodate oblique convergence between the North American and Caribbean plates. Such faults are responsible for part of the shallow seismicity and have produced M≥ 5 damaging earthquakes such as the M=6.4, 21 November 2004 one, south of Les Saintes. These normal faults cut the uplifted coral platforms Grande-Terre and Marie-Galante and the volcanic rocks of Basse-Terre. They extend offshore, as shown by the marine geophysical data acquired during the AGUADOMAR cruise in 1998, and form two families, at the scale of the northern part of the arc. The first one, composed of arc-perpendicular grabens, cuts the eastern part of the arc and results of a ~NS extension. The second one, composed of normal faults arranged in echelon, accommodates a left-lateral component of motion along the volcanic arc. The young "La Grande Découverte" volcanic complex of Basse-Terre, including the 1440 A.D. Soufrière dome, lies within the western termination of the Marie-Galante graben where

it connects to the Montserrat-Basse-Terre fault system. Such geometry, observed also in Montserrat, implies that faulting controls in part the emission of volcanic products in Basse-Terre. The ancient volcanic shoulders of the Marie-Galante graben buttress the active dome to the north and south, which may explain why major prehistoric sector collapses and pyroclastic avalanches have been directed southwestward into the Caribbean sea, or southeastward into the Atlantic ocean.

Pyroclastic flows in the islands of the Lesser Antilles : Coupling fields data – computer modelling data

Frédéric Dondin
Seismic Resarch Unit, UWI, Trinidad

The outer arc of the Lesser Antilles and its numerous islands are the result of the subduction of a part of the Atlantic plate under the Caribean plate. At the surface this process generate volcanic islands and a strong seismicity. Volcanoes of the Lesser Arc are explosive types and they are oftenly associated with lava domes. These volcanoes generate explosive eruptions because of a strongly viscous magma and these eruptions trigger off pyroclastic flows (Montagne Pelé in 1902, Soufriere Hills in 1997). When a gaz-solid mixture thrown out by a volcano collapse under its own load, vulcanologists name it pyroclastic flow. This type of flows can have a density more or less high that depends on the concentration of the solid part (incandescent products). These pyroclastic flows spread mostly under gravity effect along the volcano slopes and laterally of the lava dome.
A pyroclastic flow, thanks to its high speed (up to 300 m.s-1) and its large spread (several Km2), is extremely dangerous for population because it cans kill on a large scale (29000 deaths in 1902 in St-Pierre, Martinique). My Phd comes within the framework of a large research work that has been started since 1995 with the first eruptions of Soufriere Hills (Montserrat). A field cartography of one or two actives volcanoes of the Lesser Antilles with spatial pictures of the choosen volcanoes will permit us to estimate the volume of the pyroclastic flows deposits. Following these estimations, thanks to a numerical code we will try to simulate the flows that have generated these deposits. The main goal of this work is to try to draw up a dynamic map of pyroclastic flows hazards via SIG. This map will be adjust according to the eruption scenario. A further work will intend to adapt my results to the other volcanoes of the Lesser Antilles and to the other volcanoes that generate pyroclastic flows.

Ten years of extensometry at Soufrière of Guadeloupe: New constraints on the hydrothermal system

T. Jacob [1], F. Beauducel [2,3], J.G. David, J.C. Komorowski [3], G. Hammouya [2]
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[2] *Observatoire Volcanologique et Sismologique de Guadeloupe – IPGP*
[3] *Volcanologie group, IPGP, France*

Since 1995, the displacement field has been monitored on the lava dome's fractures at Soufrière of Guadeloupe volcano, using manual extensometry on 12 sites and five main radial fractures. In this study we analyse the data on four of the most important fractures: the North-west fracture, the North fracture, the 30th of August fracture and the 8th of July fracture, totalizing 7 stations. Three main trends are observed: (1) a period of extension from 1995 to 1999, (2) a period of contraction from 1999 to 2004, and (3) a new period of extension from 2004 until present. Given the small scale of these displacements, less than 2 cm, and given the real three dimensional context, we have used for modelling an elastostatic boundary elements code that takes into account 3-D topography, fractures and complex pressure source geometry: the mixed boundary element method (MBEM). Based on the hydrothermal activity of the volcano and recent results in electrical tomography, main source of displacements can be accounted by a hydrothermal reservoir undertaking pressure changes. Source overpressure value, geometry and location are inverted to simulate the complex observed deformation pattern. The best fit model for periods of extensions yields a shallow pressure source of ellipsoidal shape centered within the lava dome, at about 100-m depth, undergoing an overpressure rate of 0.21 and 0.48 MPa/yr for the two periods of extension respectively. At this given rate, if the extension trend remains constant in the future, the pressure in the superficial reservoir will exceed lithostatic pressure in less than ten years.

Geostatistical models for long term estimation of volcanic hazards

Olivier Jaquet
Colenco Power Engineering, Baden, Switzerland

Due to the difficulty of describing the complex spatial and temporal patterns inherent to volcanism, the use of solely deterministic models is not sufficient for long term estimation of volcanic hazards. In order to account of the intrinsic uncertainty of volcanism that occurs in space, time and with respect to event types and their intensity, the use of probabilistic models becomes quite natural for long term hazard assessment.
The motivation of this on-going work is driven by the necessity of investigating alternative probabilistic approaches for the estimation of volcanic hazards in relation to repository siting in Japan. In particular, the integration of additional sources of uncertainties linked to the distribution of volcanic events in space as well as to their occurrence need to be accounted for by the modelling. The concepts and the current geostatistical models of the proposed approach will be presented and then illustrated by a case study using data from the Tohoku volcanic arc.

Hydrothermal systems and broadband seismology : observations and 3D wave propagation modelling at Bouillante geothermal area, Guadeloupe

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[4] *United States Geological Survey, Volcano Hazards Team, Menlo Park, California, USA.*

Within the framework of sustainable development, hydrothermal systems offer a non-polluting long-term alternative as energy supply. Exploitation of geothermal energy is limited by drilling costs and by risks associated with possible hydrothermal/volcanic activity. This study aims at contributing to the surveying and monitoring of hydrothermal systems for a better understanding of the mechanical behaviour of rocks under fluid pressure.
BRGM has been involved for many years in the study of two geothermal systems, Soultz-sous-Forêt Hot Dry Rock (Alsace, Eastern France) and Bouillante hydrothermal system (Guadeloupe, West Indies). The French Geothermal Company (CFG) has been exploiting Bouillante hydrothermal system for several years for local power supply. In october 2004, CFG increased the extraction rate of the hydrothermal fluids to reach 10% of the electrical power supply needs of Guadeloupe Island.

Bouillante is therefore an ideal natural observatory to test, validate and improve geophysical and geochemical techniques for a better understanding of both structural and dynamical behaviour of hydrothermal systems under controlled depressurisation (there is no reinjection of cold fluid). Marine seismic and terrestial electrical surveys allowed BRGM to improve the knowledge of the 3D structure of Bouillante hydrothermal system. In order to catch potential changes in the hydrothermal activity due to pressure decrease within the fractured system, BRGM installed in July 2004 a network of six Güralp CMG-40T broadband stations at Bouillante. We present the network setup, observed signals and the methodology for processing data. Records mainly show signals associated to tectonic earthquakes, especially aftershoks of the M6.3 earthquake at Les Saintes Island (21 november 2004). We also present working progress in the modeling of seismic waves in a 3D complex viscoelastic medium with topography applied to Bouillante.

Reconstruction the eruptive activity of La Grande Découverte-La Soufrière volcano: implications for monitoring and future activity

Komorowski, J-C [1], Boudon, G.[1], Beauducel, F. [1,2], Caron, B. [1], Semet, M. [1], Le Friant, A. [1], Villemant B. [1]

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The volcanic island of Basse-Terre, which is part of Guadeloupe, consists of 7 main eruptive fields each composed of several volcanic centers. Based on current data, the Grande Découverte-Soufrière volcanic complex is the only centre to have been active in the last 10,000 years. The last magmatic eruption, which occurred about 560 years ago, was a complex eruption that had many similarities with the ongoing Soufrière Hills eruption on Montserrat. It culminated in the formation of the current Soufrière dome. All historical hydrothermal activity and the six phreatic explosive eruptions of 1690, 1797-98, 1812, 1836-37, 1956, 1976-77 AD have taken place from fractures and vents on this dome. La Soufrière of Guadeloupe is a well-monitored active volcano located within the Parc national de la Guadeloupe and just 5 km N of the town of Saint-Claude (population 10,000). In the last decade the volcano observatory has recorded a systematic progressive increase in shallow low-energy seismicity, a slow rise of temperatures of some acid-sulfate thermal springs closest to the dome, and, most noticeably since 1998, a significant increase in summit fumarolic activity associated with HCl-rich and H2S acid gas emanations. Permanent acid degassing from two summit high-pressure fumaroles has caused vegetation damage on the downwind flanks of the dome and required closure to the public of parts of the most active areas since 1999. No other anomalous geophysical signals have been recorded. Apart from the most likely phreatic eruptions, dome eruptions generating pyroclastic flows (7 in the last 15,000 years) and partial edifice-collapses generating debris avalanches and blasts (10 in the last 15,000 years) represent the major eruptive events most likely to occur in the future from the Soufrière dome area. Such events would directly threaten about 63,000 people which reside within 10 km of the volcano on top of the deposits from 8 edifice collapses in the last 8,500 years including those of at least 3 magmatic laterally-directed explosions. Such a magmatic reactivation would cause widespread destruction to a significant part of southern Basse-Terre, and require a total evacuation. The region and nearby islands could also be affected by ash fall and tsunamis.

Source model of the volcanic tremor at Arenal volcano, Costa Rica

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[5] *Institut de Recherche pour le Développement, France*

The main characteristics of volcanic tremor and explosion quakes at Arenal volcano are: 1) numerous regularly spaced spectral peaks; 2) frequency gliding in the range [0.9 - 2] Hz for the fundamental peak; 3) frequency jumps with either positive or negative increments; 4) tremor episodes with two simultaneous systems of spectral peaks affected by independent frequency gliding; 5) progressive transitions between spasmodic tremor and harmonic tremor; 6) lack of clear and systematic relationship between the occurrence of explosions and tremor. A type of explosion, followed by a long tremor-like coda, produces acoustic and seismic waves with identical frequencies and gliding.
We propose a source model for the tremor at Arenal in which intermittent gas flow through fractures produces repetitive pressure pulses. The repeating period of the pulses is stabilized by a feedback mechanism associated to standing or traveling waves in the magmatic conduit. The pressure pulses generate acoustic waves in the atmosphere and act as excitation of the interface waves in the conduit. When the repeating period of the pulses is stable enough, they produce regularly spaced spectral peaks by the Dirac comb effect and hence harmonic tremor. When the period stability is lost, because of failures in the feedback mechanism, the tremor becomes spasmodic. The proposed source model of tremor is similar to the sound emission process of a clarinet. Fractures in the solid or viscous layer capping the lava pool in the crater act as the clarinet reed, and the conduit filled with low velocity bubbly magma is equivalent to the pipe of the musical instrument. The frequency gliding is related to variations of the pressure in the conduit, which modify the gas fraction, the wave velocity and, possibly, the length of the resonator. Moreover, several observations suggest that two seismic sources, associated to two magmatic conduits, are active in Arenal volcano. They could explain in particular the apparent independency of tremor and explosions and the episodes of tremor displaying two simultaneous systems of spectral peaks.

Volcano Seismology in Central America

Philippe Lesage [1], Mauricio Mora [2], Wilfried Strauch [3], Demetrio Escobar [4], Otoniel Matías [5], Virginia Tenorio [3], Emilio Talavera [3], Angel Rodríguez [6], Guillermo E. Alvarado [2,7]

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[7] *Instituto Costarricense de Electricidad, Costa Rica*

We present an overview of the seismic activity of the thirty or so monitored and active volcanoes in Guatemala, El Salvador, Nicaragua, Costa Rica, and Panama. We shortly describe their monitoring seismic networks, which display a large diversity of technology and station density. We discuss some interesting aspects of the seismicity of the volcanoes, and we describe examples of pre-eruptive activity and early warnings that have been issued. Finally, we underline some issues that could justify detailed investigations either at the basic level or applied to the mitigation of volcanic hazard.

Methods for location of volcanic earthquakes at Montserrat Volcano Observatory

Richard Luckett and Venus Bass
Montserrat Volcano Observatory

Throughout the eruption of Soufriere Hills Volcano on Montserrat volcanic events have been located by MVO using a simple velocity model, adopted from the neighbouring island of Guadaloupe, and a damped least-squares algorithm without station corrections. Interpretation of these locations has been, and continues to be important to our understanding of the volcano's behaviour.

Here the reliability of the locations is investigated and the depths, in particular, found to be unstable with respect to minor changes in starting depth, velocity model and station distribution. Joint hypocentre determination and double-difference algorithms are investigated to see whether more reliable solutions can be consistently obtained and various programs and/or 1D velocity models are considered for use in regular analysis.

Seismic signals of Peruvian active volcanoes

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The seismic activity of three Peruvian volcanoes, the Sabancaya, the Ubinas and the Misti, has been studied in the last years.

After 200 years of a dormant stage the **Sabancaya** volcano (16º 13'S, 71º51'W, 5976 m) had a vulcanian eruption between 1986 and 1997, with moderate explosions rising plumes until 5 km above the crater. This eruption caught unprepared the Peruvian scientific community, which reacted after the beginning of explosions by setting up a temporal seismic array in July 1990 for a few months. This network was composed by four analogical 1 Hz stations which worked intermittently. A variety of seismic signals were recorded, like volcano-tectonic events, LP events, tremors, and explosions. Most of VT events were located in a large area situated East and North East of the volcano, where two strong earthquakes (5.4 and 5.0 mb respectively) occurred in 1991 and 1992. Harmonic tremor activity, which has been frequently observed, had predominant frequencies at 1.4 Hz.

The **Ubinas** volcano (16º 21'S, 70º54'W, 5672 m) is considered as the most active peruvian volcano; it has been reported 23 minor eruptions since 1550. After observing an increase of gas emission which begun at the end of 1996, a seismic network composed of 7 digital recorders was deployed on the volcano in 1998 during three weeks. Recorders were attached respectively to 5 short period and 2 broadband 3 components sensors. Typical VT and LP events were recorded as well as clear screw type events characterized by a long duration (more than 1 minute) and a sharp spectrum centered at 4.6 Hz. Screw events, probably associated with gas overpressure in the lava dome, were also observed the next years during some others short period time seismic monitoring.

The **Misti** volcano (16º 30'S, 71º41'W, 5822 m) is a strato-volcano rising over the city of Arequipa (800 000 ha) whose downtown is only 17 km far away from the Misti crater.Tens of pyroclastic flows and tephra falls were produced by vulcanian and sub-plinian eruptions in the last 50 ka. The last vulcanian deposits are dated between ca.1440-1470. The extent of the deposits show that an eruption even of low magnitude could affect severily the population of Arequipa. The first seismic data were collected on the Misti volcano during a two weeks experiment in April 1998. Two seismic recorders were set up respectively on the summit and the north flank of the volcano. Other short-period seismic experiments were conducted by IGP in 2000 and 2001. Records revealed superficial volcano-tectonic activity and the occurrence of screw type events. A permanent seismic monitoring network, deployed between 4200 and 5700 m asl was finally set up in 2005 through an agreement between IGP and IRD. This network is composed of 2 three-components and 3 vertical-components receivers. The seismometers have a natural frequency of 1 Hz. Data are transmitted by radio to IGP-Arequipa and processed using Earthworm package. As for many other "dangerous" andesitic volcanoes in the world, this network will be dedicated to observation, monitoring and scientific studies. First observations will be presented.

A photographic and didactic geological field trip by land, sea and air to new zealand volcanoes and geothermal areas: the Taupo volcanic zone

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New Zealand is located to the easternmost, NNE-SSW boundary of the Indo-Australian Plate, and is one of the best examples that can be found in our planet of a combined plate boundary. Volcanic activity in New Zealand occurs within the North Island and offshore to the north-east in the Kermadec Islands. The region by far the most frequently active is known as the Taupo Volcanic Zone (TVZ) which is in fact a prolongation of the Tonga-Kermadec volcanic arc. The TVZ occupies a narrow band 250 km long by 50 km wide which extends from the centre of the North Island to beyond the Bay of Plenty coast.

Spatial variations of b-values in the subduction zone of Central America

David A. Monterroso and Ota Kulhánek

Frequency-magnitude distribution along the Mid-American Trench (MAT) has been studied by means of 2345 earthquakes during the period 1964-1994. We used the regional MIDAS catalogue with a magnitude of completeness of 4.2. To resolve the b-value as a function of depth (one dimensional approach), we applied vertically sliding windows containing a constant number of events. To obtain more details in the b distribution, we projected catalogue hypocenters in three selected regions (approximately Guatemala and El Salvador, Nicaragua, Costa Rica), onto planes perpendicular to the trench. The b-values were calculated in sliding cylindrical volumes (two-dimensional approach) containing a constant number of earthquakes and centered at nodes of a 5 km x 5 km grid. The bvalue varies significantly along a large part of MAT. High b-values were identified in the upper part of the slab at depths of 80-110 km beneath Guatemala-El Salvador and at depths 130-170 km beneath Nicaragua. Anomalous (high) b-values in the lower part of the slab were located at depths of 50-90 km and 50-160 km beneath Guatemala-El Salvador and Nicaragua, respectively. Anomalies observed at the upper part of the slab may be related to dehydration and successive increase in pore pressure in the down-going lithosphere, which may generate volcanism above the anomalies in the upper part of the slab. Anomalies on the lower surface of the Wadati-Benioff zone are likely to be associated with high thermal gradients between the slab and mantle.

Low-frequency earthquakes in a wider volcanological context

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Linking observables like seismicity and ground deformation to the state of volcanic activity is the aim of any volcano monitoring program. Using examples from Soufriere Hills volcano, Montserrat, West Indies, it will be demonstrated how a detailed, simultaneous data analysis of seismic, infrasonic and tilt data can reveal changes in the volcanic system which are not directly observable. Such an approach utilises spectral methods and cross correlation techniques on the data side complemented by numerical methods to model physical processes in magma and their impact on observables, in the model side. In this way we will interpret two specific events in the eruptive history of Soufriere Hills volcano: A minor dome collapse on March 3rd 2004 as well as cyclic activity in June 1997.

Changes in local stress and volcanotectonic seismicity during the eruption of the Soufrière Hills Volcano

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The ongoing eruption of the Soufrière Hills Volcano, Montserrat, has been accompanied by significant high-frequency 'volcanotectonic' (VT) seismicity, although the level of VT seismicity has varied widely through the course of the eruption. Forward modeling of theoretical polarities and ground displacements for specified double-couple source geometries demonstrates that, despite relatively sparse seismic station coverage on Montserrat, unique and stable fault-plane solutions may be calculated for the VT earthquakes using standard methods. Following this, we repicked VT earthquakes recorded on the Montserrat Volcano Observatory digital seismic network and relocated them using a 1D velocity model. We also attempted to determine well-constrained double-couple fault-plane solutions for all relocated VT earthquakes. VT seismicity accompanying dome growth during 1996-1997 is characterized by small swarms lasting from a few hours to a few days, separated by periods of low-level VT activity, and by hypocenters extending over a wide depth range of 1-5 km BSL. In contrast, VT seismicity during a pause in the eruption in 1998-1999 is characterized by a steadier rate of seismicity occurring over a restricted depth range of 2.5-3.5 km BSL. Well-constrained fault-plane solutions for VT earthquakes indicate primarily oblique strike-slip events. For swarm earthquakes during the dome-growth period, fault-plane solution pressure (p-) axes are oriented approximately parallel and/or perpendicular to the inferred direction of regional maximum compressive stress around Montserrat. In contrast, fault-plane solution p-axes for earthquakes accompanying the pause in eruption have pressure axes oriented oblique to regional maximum compression. We hypothesize that the observed differences in earthquake rates, locations, and fault-plane solutions reflect differences in magma conduit dynamics during eruption and intrusion. Swarm earthquakes with fault-plane solution p-axes oriented perpendicular to regional maximum compression are thought to reflect local stresses induced by the inflation of the magmatic conduit system beneath Soufrière Hills.

Very long-period seismicity generated by slug ascent: a numerical investigation

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Seismic wave generation and propagation throughout volcanic regions is a complex and non-linear phenomenon controlled by the interaction of many processes. Seismicity generated by active or restless volcanoes can be classified into four broad categories, volcano-tectonic signals, explosions, low frequency and tremor. These seismic signals span a continuum from ultra-long period events with dominate periods of 100s of seconds through very-long period events to long period (LP) events, in addition volcano-tectonic signals. It is now well established that low frequency events and tremor are linked to fluid flow through cracks and conduits. This makes them useful in accessing the internal state of the volcanic plumbing system. To date, little work has been done to develop numerical models that include multi-phase fluids and the mechanical interaction with the surrounding rock including the complex internal structure of the volcano. To investigate the role played by gas slug ascent as a potential volcanic source mechanism we apply a discrete numerical method multi-phase fluid flow and for the mechanical coupling of a multi-phase fluid-rock system. The mechanical coupling of a multi-phase fluid-rock system allows us to model the seismicity caused by the pressure perturbations generated by the gas slug. We performed simulations of a fluid conduit embedded inside an elastic solid of different conduit geometries and fluid parameters and examined the associated seismicity. Our initial conclusions from the simulation indicate that the fluid viscosity, which controls the bubble rise time, is the dominant control on the frequency of the seismicity. Also, the conduit width plays an important role in the bubble rise time and hence the period of the seismic waves.

Long-term prediction of Hekla eruptions using geodesy and seismicity

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The volcano Hekla is located at the border between the Eurasian and American plates, at the junction of a transform (South Iceland seismic zone) and a ridge (Eastern volcanic zone). Hekla is an ENE-WSW trending ridge built up to the height of 1500 m a.s.l. by repeated eruptions on a narrow fissure zone. Hekla is one of the most active volcanoes in Iceland, as it has erupted at least 18 times during the last 1100 years. Since 1970 it has had a tendency of having small eruptions approximately once in a decade.

Hekla is notorious because of the short warning time of its eruptions, as no long-term or intermediate-term precursories have been observed for certain. During non-eruptive periods Hekla is virtually aseismic, and the eruption-related seismicity starts only 30-80 minutes before its onset, in the form of small volcano-tectonic earthquakes. Associated with the two latest eruptions in 1991 and 2000, a strain signal indicating a propagating intrusion was detected half an hour before the magma reached the surface.

Geodetic measurements, using both GPS and dry tilt techniques, have been conducted in the Hekla area for several years. Their results correlate well with activity at Hekla, indicating uplift when the volcano is inflating before an eruption, and deflation following an eruption. A high-quality time series of crustal deformation measurements exists, spanning the recent Hekla eruptions. When the uplift approaches the level observed at previous eruptions, the next eruption can be anticipated in the near future. Recent measurements indicate that the magma pressure is close to the critical level.

The few earthquakes at Hekla and in its immediate neighbourhood during the non-eruptive times are typically small (magnitude < 2) and few. They are not related to the volcanic processes of Hekla, but follow a similar distribution as the events of the South Iceland seismic zone to the west. We discovered that inter-eruption Hekla earthquakes tend to have a curious spectral content. Unlike earthquakes during the eruptions, they contain only low frequencies (< 5 Hz), although they otherwise have a tectonic appearance with distinct P- and S-wave arrivals. The frequency content of inter-eruption earthquakes is assumed to be caused by low stress drop in a weak, hot crust. During eruptions the stress is high at the volcano, and broad-spectrum (up to 15 Hz) events occur.

For many years after the 1991 Hekla eruption, low-frequency events were observed at the volcano. In February 1998 and July 1999 events with a broad spectrum were suddenly detected. Hekla erupted in February 2000, accompanied with broad-spectrum earthquakes. Since the year 2000 the events at Hekla proper have contained only low frequencies. However, broad-spectrum events have recently been recorded again, in September 2004 and March 2005.

Spectral content of Hekla earthquakes, if indicating the state of stress at the volcano, can be one key for understanding its eruptive pattern. However, the data record only covers one and a half eruption cycles. Geodetic methods combined with the seismic observations provide a more powerful tool for estimating the timing of the next eruption.

Results from the 2005 seismic experiment at the Torfajökull volcano, south Iceland – a pretaster

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Torfajökull is a large rhyolitic volcano massif with a 12-km-diameter caldera and a major high-temperature geothermal field. It is located in the neovolcanic zone in south Iceland, at a triple junction of the eastern rift zone, the transform zone and the intraplate volcanic flank zone of south Iceland. The most recent eruption at Torfajökull occurred about 500 years ago.

Persistent small-scale seismic activity is characteristic for Torfajökull. Two kinds of events are observed: high-frequency earthquakes in the western part of the caldera and low-frequency earthquakes in the south. High-frequency earthquakes are volcano-tectonic earthquakes with clear phases. They are small in size ($M_L < 3$) and occur typically in swarms. They are interpreted to be related to thermal cracking around a cooling magma chamber. Low-frequency events occur often in swarms, with alternating periods of activity and quiescence. They have emergent and unclear phases, and normally P-wave arrivals are small. Also the small size of these events (typically $M_L < 1$) makes locating them laborious. Low-frequency events have a narrow frequency band at 1-3 Hz.

A temporary network of thirty 3-component broadband Güralp 6TD instruments has been measuring local seismicity at Torfajökull since mid-June 2005, and will be in operation until end-September 2005. This project is a continuation of an experiment with a 20-station network in summer 2002. This time, several new stations are installed closer to the source area of the low-frequency seismicity. The principal aim of the more detailed survey is to illuminate the nature and source mechanism of the low-frequency events. As a by-product high-quality data on the high-frequency seismicity in the west is being gathered.

First preliminary locations of low-frequency events in 2005 point to origins between two small glaciers in the southern part of the caldera, in the area of hottest geothermal fields within the volcano. As experienced before, stations at distances of a few kilometres or more, record emergent signals consisting of low-frequencies and small P-wave arrivals. However, closer stations have some indications of higher frequencies and clearer phases. It may be possible that the low-frequency appearance is at least partly rather a path than a source effect. Our working hypothesis is that this seismicity is related to the existence of a shallow cryptodome in the southern part of the caldera.

New seismic broad band network for volcano monitoring in nicaragua

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Since 1993, Nicaraguan volcanoes have been monitored with short period seismic stations using analog data transmission. Soon afterwards, INETER used its new experience with seismic volcano monitoring, emitting several alerts for the possible eruption of the active volcanoes San Cristobal, Telica, Cerro Negro, and Concepcion. Decision making concerning the level of alert was based mainly on the evaluation of simple parameters such as: number of events per day, occurrence of long period tremor, and RSAM. The occurrence of lahars caused by heavy rains on the flanks of San Cristobal and Concepcion volcanoes were detected by seismic stations.

During operation the network presented numerous problems such as: radio interferences (spikes, noise, and interruptions), clipping in case of strong seismic events, and clipping due to strong tremor, which impeded the processing of data especially during ongoing eruptions.

To address these problems, in 2004 INETER installed seismic broad band equipment with digital data transmission at 12 stations situated near the active craters of volcanoes San Cristóbal, Telica, Cerro Negro, Momotombo, Masaya and Concepción. Each station has a Trillium 3-component seismometer, Earth Data digitizer, SeisComp data logger, Ethernet-wireless converter and high gain antenna, solar panels, and 12 V battery. The TCP/IP based wireless high speed data communication works in the 2.4 GHz band between stations and an Access Point and with 5.8 GHz on the wireless backbone which carries the data to the recording and processing center. The seismic stations have the capacity to connect additional seismic or other sensors or monitoring devices via USB or ethernet.

In this paper, we describe our first experiences and results with this new network.

Recent volcanic unrest at Concepción volcano and the August 2, 2005, Ms=6.3 earthquake near Ometepe Island

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At the end of July, 2005, Concepción volcano, situated at Ometepe Island in Lake Nicaragua, started to show increased activity. Volcano-seismic activity increased, there occurred some strong freatomagmatic explosions which launched volcanic ash up to 500 m above the crater rim. Ash fall was observed at Ometepe Island and near the town of Rivas, at distances of more than 20 km to the volcano.
On August 3, 2005, a magnitud ML=6.3 (NEIC) earthquake occurred near the volcano. The event was felt strongly allover Western Nicaragua and struck the villages on Ometepe Island with macroseismic intensity between VIII and VIII. Several houses were destroyed. This was the strongest seismic event in the Nicaraguan volcanic chain since the earthquake which destroyed the capital the country, Managua, in 1972.

Having in mind the increased activity of Concepción volcano both INETER volcanologists and the population of Ometepe Island assumed during the first hours after this event that this strong seismic activity could possibly be the precursor of a strong eruption. Nevertheless, epicenter determinations with data from Nicaraguan and Costa Rica seismic networks showed soon that the epicenters of the main event and most of the aftershocks were constrained southwest of Ometepe Island in Lake Nicaragua at distances between 15 and 30 km from Concepción volcano. So, an immediate eruption was estimated to be more unlikely. But, in the following days fissures occurred near Concepción volcano and the ash explosions continued.
To clarify the situation of the volcano the following work is going on: 1) Seismic data processing of the data of permanent and temporary seismic networks in Nicaragua and Costa Rica; 2) Evaluation of GPS measurements at several sites near the volcano; 3) Evaluation of COSPEC measurements; 4) Geological reconnaissance of surface fissures near the volcano.
Preliminary results of this work will be presented.

Coda Q tomography at Galeras Volcano, Colombia

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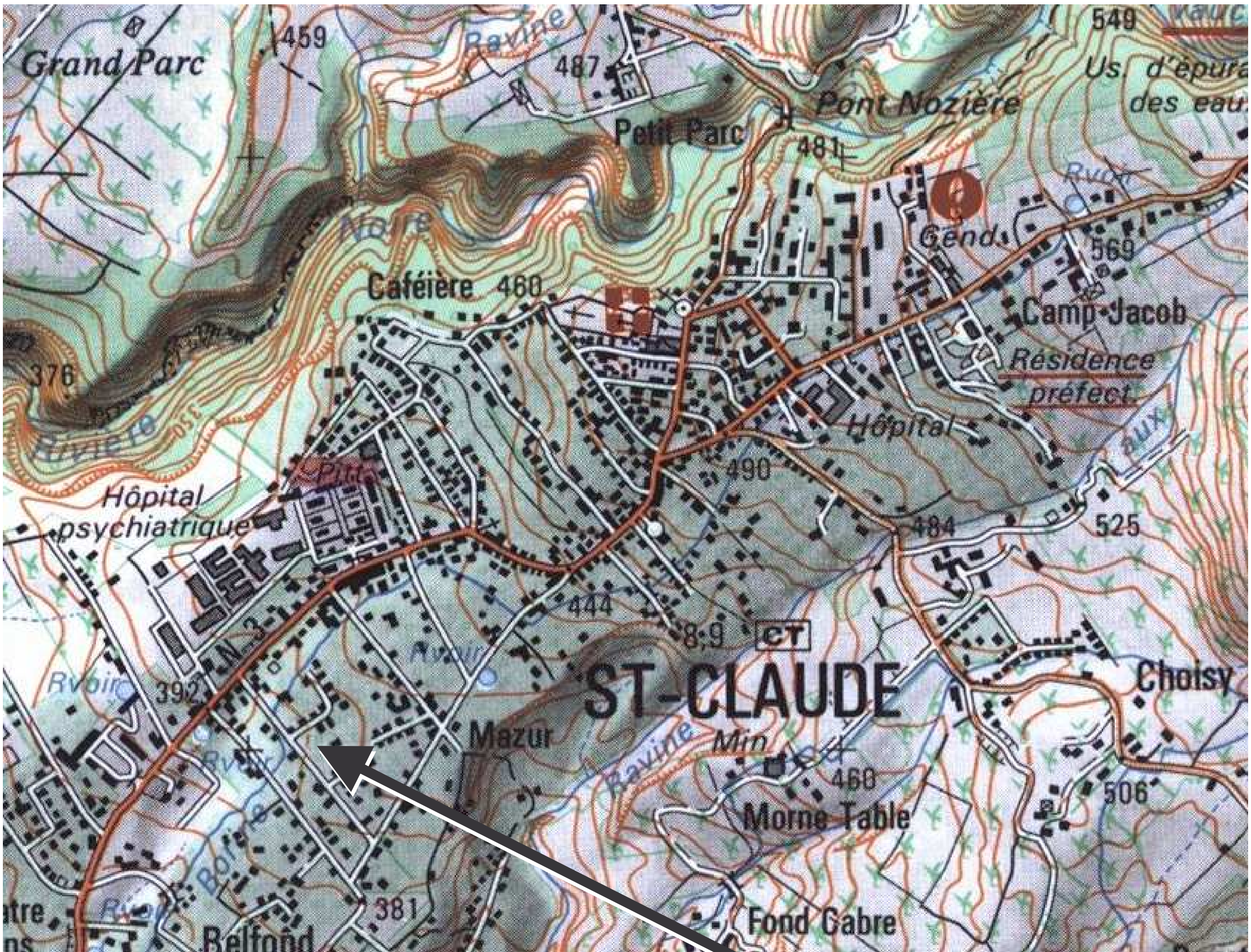
Spatial variation of coda Q was analyzed at Galeras volcano, located in the Andes of southwestern Colombia. The Qc value was calculated using the Single Backscattering (SBS) model working with seismograms filtered in frequency bands centered in 1.5, 3.0, 6.0 and 12.0 Hz. We estimated Qc values at 1 Hz and we used the estimated values as the mean attenuation that represents the total effect of simple scattering in an ellipsoidal volume. Then an inversion procedure was implemented to estimate the spatial variation of Qc as function of volume fractions. Synthetic tests in 2D and 3D allow us to extend the procedure with available data from the seismological network located at Galeras volcano.The inversion of 3623 Q values in a grid of 8x8x8 nodes associated to 435 earthquakes and 31 stations allowed us to resolve the presence of two attenuation anomalies which are assumed to be related to bodies of partially melted rocks located respectively at 4.0 km and 9.0 km from summit. These bodies would be responsible for Vulcanian type explosions as a consequence of mixture of shallow magma with deep basic magma. This shallow body seems to extend to the summit and may represent the presence of plugs and fluids that are constantly fed from the deeper body.



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