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Conveners:
Dr. Jürgen Neuberg, University of Leeds, UK
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Volcanoes: Too many questions and even more data?
Horst Rademacher

Many talks during our workshops deviate extensively from the original question under which the WG was founded: What can we learn about the processes inside a volcano from seismic measurements? I would like to give an "overview" presentation. I will try to summarize the experience with seismic measurements on volcanoes and point out the limitiations on getting information about the sources out of these data. I will then compare that to other forms of geophysical and gas - chemical measurements and ask, what constraints for our models we can get from them. And what constraints they can get for us from their models.

Latest developments of Soufriere Hills, Montserrat
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Unusually high seismic activity at the Katla volcano,south Iceland
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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. Katla 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 rises to 1500 m height and has a 10-km diameter caldera. A shallow magma chamber, with a bottom at the depth of 3 km, has been revealed by 2-D seismic shooting (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. The earthquakes in both of the places are volcanic in nature. They start with rather high frequencies, and the onset can be anything from clearly impulsive to emergent. The continuation of the signal consists of lower frequencies only. S-waves seem not to exist in most of the cases, especially not in the signals from Goðabunga.

Due to the nature of the Katla events it is somewhat difficult to estimate their magnitudes. However, they are seldom larger than M_L 4. It is worth noticing that the local population rarely feels Katla earthquakes, though inhabited areas are located quite near. The depths of the Katla events are difficult to be estimated, as well, but they seem to be shallow, within 0-5 km.

Katla has typically seasonal seismic activity – earthquakes concentrate to 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.

Since 1999 Katla has been showing signs of unrest. In July 1999 a small glacial flood lasting less than 24 hours was observed. It is possible that it was caused by an intrusion of magma or even a small subglacial eruption. So far this has not been followed by further eruptive activity. The seismicity in the year 1999, on the other hand, had the typical seasonal pattern and was not exceptional. During the year 2002 the seismic activity in the Katla area has risen dramatically. In this spring the earthquakes of the fall 2001 have not ceased to occur in a typical manner, but have continued throughout the year on a daily basis. Their magnitudes have been mostly below 2.5, but a M_L 3.3 event occurred in late April.

It is very much possible that the continuous activity in the Katla area is a sign of the next eruption being prepared, and thus the volcano has to be closely monitored. However, during the winter of 2001-2002 there has been exceptionally little precipitation and a thin snow cover in the district, which could enable the "glacial rebound" pattern to continue throughout the summer.

The MULTIMO project: an overview

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Fragmentation speed in explosive volcanism

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Bubble nucleation as trigger for dike initiation in the mantle

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Many xenoliths show evidence that they originate at depths of tens to hundreds of kilometers in the Earth's mantle. Limited reaction between xenoliths and the surrounding magma suggests short transport time, of the order of hours to days. The fast transport rates, as well as the physical size of the xenoliths indicates rapid magma ascent in dikes. This raises two difficulties: 1. How to initiate a dike in hot, ductile rocks? 2. How can the dike propagate fast enough?
We suggest that the mechanism for dike initiation involves the nucleation of bubbles in volatile-bearing magmas. At depth, the magma can segregate into channels that may coalesce into diapirs. However, initiation of cracks is surpressed by the high strength of the rocks (which increases with pressure) and the release of stresses by ductile flow of the hot rocks. Bubble nucleation from volatile supersaturated magmas may provide a mechanism for rapid pressure build-up and initiation of cracks.
We measured the supersaturation needed for nucleation of CO2 bubbles in basanitic melt. The basanite was saturated with 1.5 wt% CO2 at 1.5 GPa and 1350 C. CO2 bubbles were observed only after decompression by 0.2 GPa, or more. No new bubbles were observed after decompression by 0.1 GPa in four experiments.
Following segregation a volatile-bearing magma ascends slowly by viscously deforming the mantle rocks. As pressure falls it becomes saturated and finally reaches the critical supersaturation of 0.1-0.2 GPa. The newly nucleated bubbles are in equilibrium with the melt, and the excess gas pressure in the critical nuclei is compensated by surface tension. However, as bubbles expand the internal pressure overcomes the surface tension and the bubbles grow rapidly. Diffusion is very efficient while the bubbles are small and high gas pressure is maintained during the initial stages of expansion. When the bubbles grow to size of a few critical radii, surface tension becomes negligible and the gas pressure is exerted on the melt and the surrounding rock. The process is very rapid and the sudden pressure increase is

sufficient to overcome the strength of the rock and initiate a crack. Once formed, the crack can propagate and a dike is born. The exsolved volatile is also important for the propagation of the leading crack. As suggested in the past, volatile transport from the bubbles into the tip of the crack helps in maintaining pressure at the tip and ensures fast propagation of the dike.

Low-frequency earthquakes at the Torfajökull volcano, south Iceland, measured by a local network

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The Torfajökull central volcano in south Iceland is a large rhyolitic complex with a caldera, 12 km in diameter, and an outstanding high-temperature geothermal field. During the last 1100 years there have been two eruptions in the Torfajökull area, the latest at the end of the 15th century. Torfajökull is a source of continuous low-level seismicity, and the events fall into two distinct populations. High frequency tectonic earthquakes occur in the western part of the caldera and are interpreted to be expression of thermal cracking around a cooling magma chamber.

Low frequency volcanic earthquakes cluster into the southern part of the caldera and are possibly related to active magma. They are small in size, below magnitude 2, and it is quite difficult to obtain good locations for them. Their P-waves are characteristically emergent. The S-waves are typically somewhat clearer and their phase picks seem to fit more or less with the location. The low frequency events occur often in swarms, lasting from one to a few days and consisting of up to a couple of hundreds events per day. Typically the seismicity rises from rather low levels to its highest peak in a single day. Between the swarms occasional single events can occur, or it can be quiet up to a few weeks or months.

A network of 18 broadband 3-component Güralp 6TD seismometers has been deployed in the Torfajökull area in the summer 2002 to study more closely the low frequency earthquakes. This sort of activity has been rather modest during the operation of the network, but some events have been observed. No swarms have occurred so far. According to the preliminary analysis the recorded events have very similar appearance compared to what has been earlier observed by the more distant seismograph stations of the permanent Icelandic network. At every station of the Torfajökull network the records show only low frequencies. P-waves are mostly emergent, and S-waves rather distinct. However, in some of the seismograms S-waves may not exist. Preliminary locations of these events point to the southern part of the Torfajökull caldera.

Characteristics of seismic low-frequency events

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Numerical Modelling of Volcanic Seismic Signals

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Insights in magma processes using observation and modelling of low-frequency earthquakes at Montserrat

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Low-frequency earthquakes at Montserrat have a spectral frequency content ranging from 0.2 to 5 Hz. Among the possible models to explain their occurence, the complex wave-field generated by the propagation of seismic energy initiated in a rectangular container liquid conduit embedded in a homogeneous elastic medium.

In this work, we investigate effects of both wave intrinsic attenuation and topography on the characteristics of the synthetic low-frequency earthquakes obtained using a 2-D finite-difference formulation. We model intrinsic attenuation by the linear viscoelactic theory, and the topography is introduced using a mapping of the computational rectangular grid into a curved grid, which follows the topography.

This work bring new constrainsts on the frequency content of the source and hence hints of the source process of low-frequency earthquakes.

Seismic Attenuation in Bubbly Liquids
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Seismic parameters in different phases of volcanic activity in 1997
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During periods of harmonic tremor on Montserrat, gliding spectral lines have been observed. We have previously shown that these can be reproduced by repeated triggering of a similar event, using the dt=1/dw relationship, where dt is the time spacing and dw is frequency spacing. For this, the accuracy of dt must be precise, with a standard deviation of 2% or less. When the seismic events are further apart, they can be measured manually. This is very time consuming, so we wrote an Automated Event Classification Algorithm Program (AECAP), which finds and classifies events and writes seismic parameters to output files.

The seismic parameters include energy, dt, peak frequency, duration and percent energy below 2 Hz. We compare low-frequency event energy to the tilt cycles,k instead of the RSAM. This allowed us to compare the pressurisation with just the energy from these events. The comparison shows that in some cases they match nicely, with the seismics increasing after inflation, but peaking and deflating together. At other times, the seismic are time shifted to before or after the tilt cycles. The full relationship needs further investigation with different styles of tilt cycles.

Binning of some of the parameters show that peak dt ranges from 1.5-2.5 seconds in active periods and from 3.5-4.5 in quieter periods. Peak frequencies drop during busier periods, suggesting an increase in the lower frequency components. This has to be confirmed by looking at larger datasets and by making sure that the different types of seismometers do not affect the results.

Comparison between event duration and energy show 2 groups. One group had a linear trend on a logarithmic graph, which suggests a direct link between increase duration and increased energy. This may be remnant of the classification program, so must be investigated further. The other fits into a band, where no matter what the duration, the energy is within this band. This suggests that there is a specific energy reservoir that the event uses, but this can come out in an initial burst or be spread out over a longer event.

From seismograms to magma

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Tungurahua volcano: the June 2002 activity

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Automatic moment magnitude determination for tectonic events on Deception Island, Antarctica

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An automated algorithm for the determination of moment magnitude from the source spectrum was developed and tested with 151 tectonic events from the volcanic Deception Island, Antarctica. Both a converging grid search and genetic algorithm were tested in order to match the observed source spectrum with the synthetically computed spectrum assuming a simple omega^2 model. While both provide reliable results, it was found that the converging grid search is more cost effective. The method was found to give reliable magnitudes in the range $-1.1 < M < 2.1$. However, testing with other data sets showed that the same algorithm works for large earthquakes ($M > 7$). Due to the automation it is feasible to process large data sets and to obtain reliable source parameters.

Gas Monitoring at the Galeras Volcano, Colombia

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A monitoring system is described which is installed at the Galeras volcano, Colombia. Several gas components in the fumarolic exhalations (like CO2, Rn) as well as steam temperature and pressure are measured every 6 seconds and telemetered to the observatory. Unusual variations in these parameters are observed during a short period of increased seismic activity. At this stage of investigation, however, it is uncertain whether the variations observed are always linked with a seismic process. From monitored data we also conclude that ambient air can enter the fumarolic gas system which may be influenced by wind direction and speed.

Intensity attenuation law in the eastern flank of Mt. Etna

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The eastern sector of Etna volcano is crossed by faults trending NNW-SSE, locally called “Timpe”. Their significant activity is marked by both the geomorphological

evidences and the seismicity. Most of the sources of the shocks taken into account are associated to such tectonic structures. The earthquakes have a moderate magnitude ($M<4.5$) and very shallow depth ($h<3$ km). As a consequence of these peculiar features, the damage occurring, that sometimes is quite heavy, affects very small areas. Moreover, these characteristics imply that we cannot adopt the usual attenuation laws evaluated for regional size earthquakes.
Aim of present paper is to evaluate the peculiar attenuation law of the macroseismic intensity in the eastern flank of Mt. Etna. The macroseismic observations of local seismic events, reported in the database of Etnean earthquakes, were used as input data, taking into account 58 earthquakes having epicentral intensity $I_0 \geq 5\text{-}6$ and at least 11 site observations. The analysed data were tested performing linear regression analysis as well as exponential and logarithmic ones. The results pointed out that the best fit is achieved by adopting an exponential relationship like $I = a\, e^{-bx}$.
All the obtained relationships put however into evidence a strong dependence of the attenuation on both the maximum intensity and the hypocentral depth of the events.

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The Mediterranean precipitation teleconnection

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The relationship between Mediterranean precipitation and the North Atlantic and European sea level pressure fields has been studied using statistical techniques designed to investigate the variability within the 85 year long dataset. It is shown that the major winter precipitation variability is described by a see-saw fluctuation between the western and eastern Mediterranean, i.e. when precipitation is high in Portugal and Spain it tends to be low in Israel. The pressure fields associated with this precipitation teleconnection are dominated by the North Atlantic Oscillation, a north-south pressure variability pattern. However this pressure gradient alone does not provide a full explanation of the difference in precipitation between opposite ends of the Mediterranean basin.

The results of a canonical correlation analysis, coupled with a principal component analysis, show the major influence on precipitation in the western Mediterranean is the latitude of the high pressure system known as the Azores high. In the eastern Mediterranean two major influences on the precipitation are apparent. The presence of a depression close to Cyprus brings wet conditions, and the appearance of a high pressure system in west Kazakhstan produces meridional flow, blocking any westerly flow loaded with precipitation. This work shows remarkable consistency over large timescales. Features apparent in the statistical analysis of the 85 year long record can be identified in daily pressure maps chosen for particular events. Back trajectory analysis is used for visualisation of the moisture transport and confirms the findings of the statistical analysis.

Towards a user-friendly database for monitoring, analysis and forecasting

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The problem of archiving, accessing and performing analyses on data or information is very important in any field where lots of information are available, and especially when this information is not homogeneous. Our field of interest are volcanoes, with all their acquired (multidisciplinary) data and/or information. A user-friendly system is therefore necessary in order not to waste time searching where the data are, how to extract information and even how to load the raw data to perform analyses. In order to solve these problems, and to allow for additional features, a flexible and user-friendly database has been developed in the framework of the MULTIMO (Multi-disciplinary monitoring, modelling and forecasting of volcanic hazard) European project.
Our system consists of a collection of Open Source software such us Linux (operating system), Zope (web application server), MySql (relational database), Scilab (math engine) and any kind of programming language such as Python, C, Fortran etc. The choice of a relational database is due to its intrinsic modularity, the memory-saving characteristics and the possibility of adding new fields, or even new tables, without repopulating the entire database. Moreover, and especially, this choice allows for a wide range of possible cross queries.
All the data then become accessible through a web interface with automatic generated pages. We can apply built-in or user-defined queries, get information, draw graphs and even perform analyses using the scilab math-engine. New algorithms and analysis techniques can be added to our system in order to use them through the math-engine and, of course, these algorithms can be written in any possible language.
Researchers should be no more tied to a particular operating system or software when accessing data and information and applying analysis on them. All the low level problems should be left to the system and everything should be accessible with a simple user-friendly and platform-independent interface. The possible extraction and cross correlation of the data (and information) should be infact limited not by the software environment, but only by the fantasy of the researcher.

DEVIN : a simulator of volcanic events considered in terms of a stochastic punctual process

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Within the framework of the EU-project MULTIMO (Multi-disciplinary monitoring, modelling and forecasting of volcanic hazard), a software called DEVIN (Deducing Eruptions of Volcanoes In Near future) aiming at forecasting volcanic activity in the near future is currently under development. DEVIN is based on geostatistical concepts and allows the characterisation of the behaviour of time series recorded at active volcanoes. The functions of DEVIN used for the simulation of discrete and continuous variables are the following:

- Time behaviour analysis by variogram calculation.

- Time behaviour parametrisation by variogram modelling.
- Stochastic simulation for Monte Carlo forecasting and data reconstruction (i.e., gap filling).
- Kriging analysis for estimation of time components related to volcanic activity.
- Statistical analysis and visualisation of modelling results.

DEVIN is an open source software, running under Scilab, that applies specific routines written in C and Fortran in order to avoid time consuming computations. DEVIN is a tool which provides the possibility to model time behaviour as characterised from multi-parametric data sets. It, therefore, should reduce the uncertainty in forecasts of volcanic activity.

Identification and modelling of variable convective regimes at Erta Ale lava lake

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Between February 17 and 19, 2002, we collected a combined thermal and seismic data set for studying the persistent lava lake activity at Erta Ale volcano, Ethiopia. These data indicate that the lake cycles between periods characterized by low (~0.05 $m\ s^{-1}$) and high (~0.2 $m\ s^{-1}$) rates of convection, respectively. We use our measurements to constrain two models to explain such convection cycles. The first model relates variable convection rates to pulses in the rate at which magma is supplied to the lake. This model requires supply rates to cycle between high convection rate phases fed by a magma volume flux of 0.2 $m^3\ s^{-1}$ with a viscosity of 140 Pa s, and low convection rate phases fed by a magma volume flux of 0.03 $m^3\ s^{-1}$ with a viscosity of 3100-3600 Pa s. The second model assumes that supply to the lake is steady and that cyclic convection is set up by the generation of convective instabilities within the lake. In this case, cooling of the surface layer generates a slow moving, viscous convection cell at the lake surface overlying a faster moving convection cell of lower viscosity. Recharge of the lower cell, at the expense of draining degassed magma, increases the buoyancy of the lower layer to eventually trigger an overturn event. At this point the surface of the low viscosity cell extends to the lake surface and the high viscosity cell sinks to be drained from the lake.

The educational volcano seismic network

Angeles Llinares

Active buried faults in the eastern flank of Mount Etna (Italy): new evidence from seismotectonic and geochemical data.

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A multidisciplinary approach based on soil CO_2 gas measurements, macroseismic features of historical and recent earthquakes and geomorphological evidence has been used in order to constrain the geometry of a buried fault system located in the central part of the Etna's eastern flank. Here the tectonic pattern is not clearly associated with surface expression since it is concealed beneath a thick succession of Holocene and historical lava flows. In particular, two previously undetected faults have been suggested: the Dagala fault, a 4 km long tectonic structure that extends with WNW-ESE trend south of Petrulli and Dagala; the S. Venerina fault, that develops with NW-SE strike for 5 km between S. Venerina and the northern outskirts of Zafferana. Both faults seem to play a relevant role in the structural framework of the volcano since they connect the *Timpe* fault system with the volcano-tectonic depression of the Valle del Bove. The used approach may represent a valid tool for further detailed studies on other areas with similar seismotectonic and geochemical features.

Logical inference and conceptual uncertainty in estimating volcanic hazard

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Volcanological forecasts rely on the concepts that interpret the data. Strict evaluation of the concepts is essential for correct prediction of volcanic hazard. Unsaid assumptions, alternative interpretations and hidden contradictions herewith can be jointly termed as conceptual uncertainty, underlying all other known types of uncertainty (time, structural, metric, translation and others).
The procedures applied to eliminate it, such as "weighing" of opinions or poll, are highly intuitive and subjective. We suggest a logical assessment of statements involved in forecasting. It allows (i) verification of a statement for truth and satisfiability by reduction to normal forms, (ii) verification of a statement for deducibility from its premises by logical calculi (e.g., natural-sequential calculus of Gentzen (1939)), (iii) deduction of possible consequences from a statement by using the calculi and tautologies of propositional logic, (iv) construction of knowledge base of statement and its verification by means of logical calculi, (v) making consequences from a new added to the knowledge base, (vi) assessment of a set of statements for self-consistency by reduction to conjunctive normal form, (vii) transformation of a knowledge base into a logical model of volcanic phenomenon by means of predicate logic.
The measure of conceptual uncertainty is conceptual probability. It is inversely proportional to the length of inference of a statement from premises and hence to the number of propositional variables (simple statements) and number of logical connectives used to prove the statement. Complex definition of conceptual probability is being elaborated now to (i) more accurately account for the logical structure of inference, (ii) include the assessments of compatibility of a statement with various

logical models and (iii) that with different types of prior information. For recurring events, it will be comparable with statistically obtained probability. For rare, unique or hypothesized events this seems to be the only way of objective, bias-free and numerical probability assessment applicable in Bayes approach and event/probability trees. The suggested method can also be used for expert judgment assessment and governing scientific debate.

Explosion seismicity at the Soufriere Hills Volcano, Montserrat.

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Seismic signals associated with Vulcanian explosions at the Soufriere Hills volcano are typically monotonic, with a low frequency content. The initial low frequency phase is thought to be due to magma fragmentation and conduit flow, and both amplitude and duration have been correlated with observations of plume height and the duration of peak discharge. However, the signal can continue for up to two hours after the initial explosion and is accompanied by vigorous ash venting. This is too long to be caused by a single resonance since energy will rapidly decay from an open system. Instead a feedback mechanism may exist to allow the signal to decay gradually with time. Low frequency signals have also been associated with smaller explosions and gas venting eposides in early 1999. Pressure sensor data show that the source of these signals is not venting at the surface but must be inside the lava dome. In addition, some of these episodes are preceded by shifting spectral lines that may indicate a change in magma properties in the minutes leading up to the explosion. Analysis of three-component broadband data suggests a simple explosive source mechanism for the later explosions.