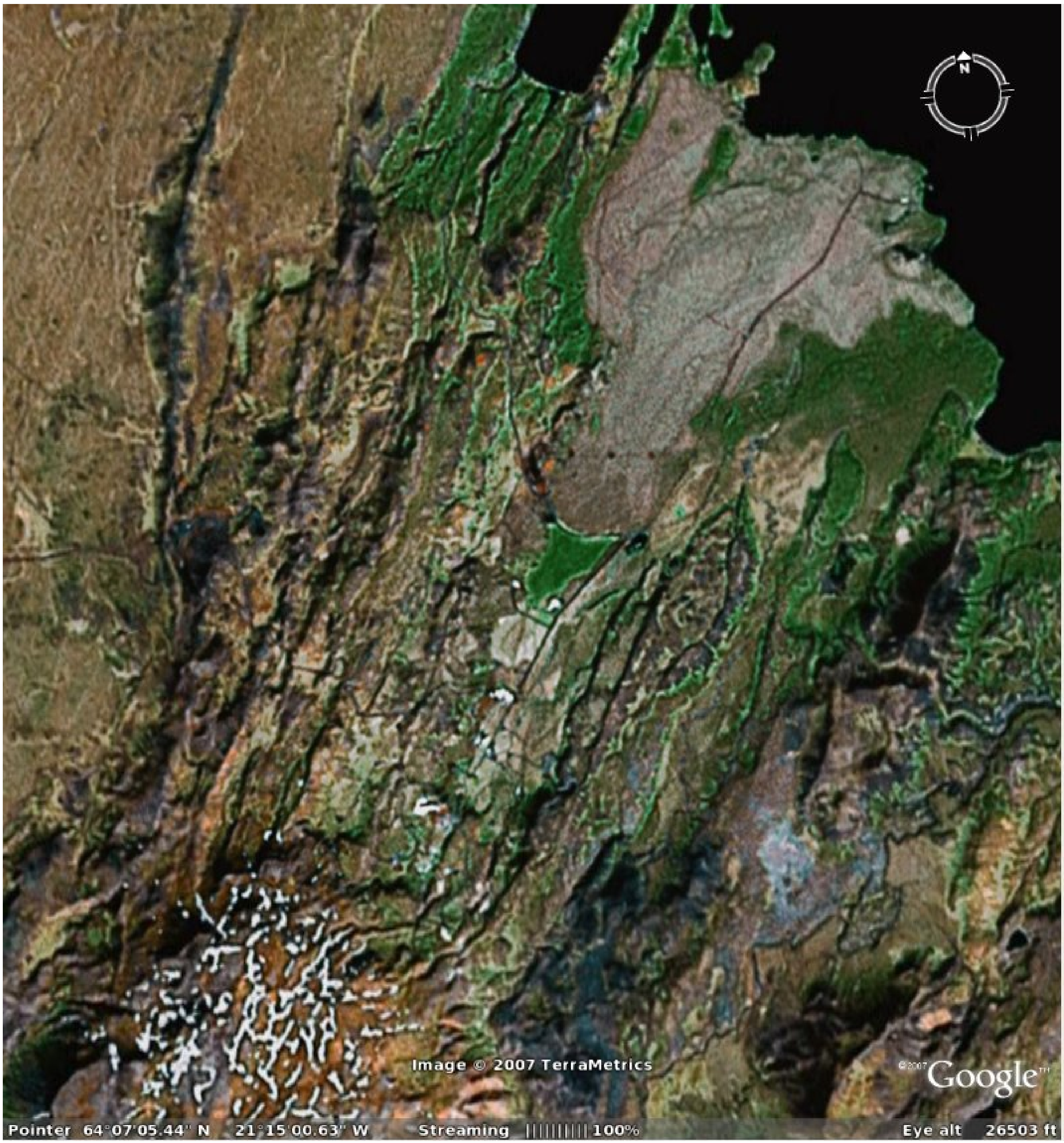
# "Hot and Cold: Seismicity associated with geothermal areas and ice-covered volcanoes"

**ESC Working Group "Earthquakes and Volcanoes"**
**Annual Workshop 2007, Nesbúð September 9 - 16**



## Monday:

**Monitoring structural volcanic changes in an objective way**
*Francesca Fattori Speranza , Roberto Carniel*

**Evidence for ground motion polarization on fractured lava of fault zones: observations on Mt. Etna volcano**
*Rigano R., Lombardo G.*

**Long-period earthquakes in Bouillante hydrothermal system**
*Philippe Jousset and Bernard Chouet*

**Rates of similar micro-earthquakes: comparison between Campi Flegrei and other volcanic areas**
*Jean Battaglia*

**The geothermal origin of the seismicity in the Timanfaya Volcano (Lanzarote) revealed by a self-potential continuous measurement**
*R. Ortiz. Dep. Volcanologia CSIC Spain*

**Estimation of volcanic hazard: towards more certainty in uncertainty**
*Olivier Jaquet, Susanna Falsaperla, Roberto Carniel*

**Imaging Seaward Dipping Reflectors at Oceanic Rift Zones**
*Robert S. (Bob) White & iSIMM Research Group**

## Wednesday:

**Low frequency coda decay: separating the different components of amplitude loss**
*Patrick Smith and Jurgen Neuberg*

**Conduit flow modelling to investigate possible sources of low-frequency earthquakes**
*April Janet Key*

*Dulce Vargas – Bracamontes*

**Effects of compressibility and shape on the volume budget of magma intrusions**
*Eleonora Rivalta*

**A seismic magma flow meter**
*Jurgen Neuberg*

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## Thursday:

**Preliminary observations of broad-band seismological records at Hengill geothermal system**
*Philippe Jousset, Knutur Arnason, Michael Weber, Hubert Fabriol, Benjamin François,*

*Halldor Stefansson and Steinunn Jakobsdottir.*

**Seismicity and structure of the Grímsvötn volcano under the Vatnajökull icecap, Iceland**
Bryndís Brandsdóttir, *Raimon Alfaro and Robert S. White*

**Project GODA2007 - Deployment of seismic stations on W-Mýrdalsjökull**
*Kristín Jónsdóttir, Reynir Böðvarsson, Roland Roberts, Steinunn S. Jakobsdóttir, Jósef Hólmjárn, Björn Lund, Pálmi Erlendsson*

**Location of Seismicity in the Mýrdalsjökull/Katla Volcano**
*Kristín Vogfjörð*

**Relocated earthquakes in Eyjafjallajökull between 1991 and 2006: Does deep seismicity indicate intruding material from below**
*Sigurlaug Hjaltadóttir*

**A magmatic origin for the 2007 micro-earthquake swarms at Upptyppingar, Iceland?**
*Matthew J. Roberts, Steinunn S. Jakobsdóttir, Gunnar B. Guðmundsson, Halldór Geirsson.*

**Waveforms of lower-crustal earthquakes near the Askja volcano at the north Iceland divergent plate boundary**
*Heidi Soosalu, Robert S. White, Clare Knox, Páll Einarsson and Steinunn S. Jakobsdóttir*

**Analytical and numerical modelling of surface displacement due to magma emplacement**
*Olivia Lewis & Jurgen Neuberg*

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# *Monitoring structural volcanic changes in an objective way*

Francesca Fattori Speranza[1], Roberto Carniel[2]

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It is well known that the occurrence of a tectonic event sufficiently close to a volcano and/or sufficiently energetic can trigger a change in its eruptive activity. Examples include Ambrym (Vanuatu), where tectonic earthquakes have triggered a significant increase of the permanent lava lakes activity; Teide (Spain), where local tectonic events change the characteristics of the seismic noise during the current phase of possible unrest; Tungurahua (Ecuador) and Villarrica (Chile), where an increase of volcanic activity was triggered by the occurrence of tectonic earthquakes. Timely identification of a change following an earthquake has of course serious implications in terms of hazard. However, little effort has been carried out so far to formalize the identification of these structural changes with a statistical approach. Moreover, this is only a particular case of the more general problem of identifying transitions between significantly different volcanic regimes at active volcanoes, at geothermal fields and/or dormant volcanoes.
In this work a statistical approach is applied to test for structural changes in volcanic tremor. We considered different fluctuation-type tests using the free source package strucchange in R language [Zeileis et al., J. Statist. Software, 2002].
Stromboli volcano is a particularly interesting case of study, because previous works [Falsaperla et al., J. Volcanol. Geotherm. Res., 2003] had suggested that tectonic events have no influence on volcanic activity, while most recent results [Carniel and Tarraga, Geophys. Res. Lett., 2006] has suggested that they can have it. Other test cases currently under study include Ambrym volcano in Vanuatu and Nisyros geothermal field in Greece.

*Working Group of the European Seismological Commission*

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# *Estimation of volcanic hazard: towards more certainty in uncertainty*

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When performing volcanic risk assessments, the volcanic system constitutes the dominant source of uncertainty. Uncertainty is mainly related to imperfect knowledge of non-linear volcanic processes, to space-time variability of distribution and intensity for volcanic events and to a limited amount of information. Therefore, the estimation of volcanic hazard is generally performed using a probabilistic formalism. Geostatistics provides operational tools and probabilistic models for the characterisation and the estimation of volcanic hazard over the short as well as the long term. A methodology using geostatistical tools was developed which enables the analysis of multi-parametric data sampled over time at active volcanoes. Such a probabilistic approach provides valuable information for the identification of precursors potentially, leading to the onset of eruptive activity. Recent efforts to develop a geologic repository in Japan have sparked the development of a specific stochastic model for improving uncertainty characterization with respect to long-term forecasts. Applications to the Etna volcano and the volcanic arc of Tohoku illustrate the proposed methodology and models. Finally some conceptual thoughts are proposed for the development of data assimilation methods tailored to the estimation of volcanic hazards. Such methods born in the meteorological sciences are likely to reduce forecast uncertainty, especially when large amounts of data become available at the dawning of a volcanic crisis.

# Evidence for ground motion polarization on fractured lava of fault zones: observations on Mt. Etna volcano

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Abstract

During local and regional earthquakes, a systematic polarization of horizontal ground motion is observed at two seismological stations near the Tremestieri fault. The study area is located a few kilometers north of Catania, on the southeastern flank of Mt. Etna volcano. Spectral amplitudes recorded at these stations show a significant amplification around 4 Hz when compared with those of a reference station installed on massive lavas in the city of Catania. The amplification has a directional character. At one station, a ten meter from the fault scarp, the 4-Hz peak of conventional spectral ratios exceeds a factor of 10 along the N40°E direction whereas the amplification of orthogonal motions is about 5. The other station, about 200 m away from the fault scarp, shows a similar directional effect even though the amplification is smaller.

A conventional polarization analysis using the eigenvectors of the covariance matrix confirms the very stable directional effect enhancing the approximately NE-SW elongation of the horizontal motion at the two stations. The effect is evident during the entire seismogram and independent of source backazimuth as well as distance and depth of earthquakes. The angle of polarization found for the two stations is not parallel to the fault strike making not convincing an explanation in terms of fault-trapped waves. The same polarization is observed in ambient noise as well.

The similar behaviour of earthquakes and ambient noise allowed us to use microtremors for investigating ground motion polarization properties along and across the Tremestieri fault zone with a high spatial resolution. The result is a stable polarization of horizontal motion in the entire area, interesting a broad frequency band. To check whether this ground motion property is recurrent and understand a possible role of fault orientation and stress directions, the ambient noise measurements were repeated on other mapped faults of the Mt. Etna area, the Moscarello and Pernicana faults. The latter, in particular, is characterized by different strike and fracture orientation. For these faults also, the results of horizontal polarization analysis indicate a systematic tendency of the ambient noise to be polarized with prevalent direction not parallel to the fault strike.

Tests were made to check if the observed polarization was source and time dependent. Results obtained from simultaneous measurements at two mobile stations at different time and

at different azimuth from the probable tremor source location, allowed us to rule out such hypothesis. Moreover, the ambient noise polarization on Mt. Etna faults persists too far away from the fault trace, excluding an effect limited to a narrow low velocity zone hosted between harder wall rocks.

In our opinion results obtained could find an explanation in the complex local stress field, and they appear consistent with findings coming from recent studies of velocity anisotropy in the Mt. Etna area.

Long-period earthquakes in Bouillante hydrothermal system.

Philippe Jousset and Bernard Chouet

We present evidence of sustained Long-Period (LP) seismicity at the Bouillante geothermal field, Guadeloupe, French Antilles. More than a year's worth of records from a permanent broadband seismometer reveal the existence of small repetitive superficial LP events (amplitudes, 1-5 10-6~ms$^{-1}$); average repeat time, 15 - 40~s; frequencies, 0.5 - 10~Hz). To locate these earthquakes, we use the repetitive property of the source and sample ground motion with a second roving broadband seismometer recording for 20~minutes at each of 19 sites distributed within an area of 1X1~km near the permanent station. Using this approach we identify events recorded by the permanent station that are also recorded at some of the temporary stations. We locate these events by using four complementary techniques, namely, first-arrival phase picks, amplitude analyses (using both temporal and spectral amplitudes), polarity analyses using particle motions, and waveform inversion. The location of LP events coincides with an area where hydrothermal activity is manifested in anomalous He-gas emission on land, and sporadic 3-10-s-long submarine bursts of uncondensable gas at sea. This hydrothermal activity occurs along a major tectonic feature crossing southern Guadeloupe. These observations suggest that bubble cavitation may be the source of the LP events.

**Preliminary observations of broad-band seismological records at Hengill geothermal system.**

Philippe Jousset, Knutur Arnason, Michael Weber, Hubert Fabriol, Benjamin François, Halldor Stefansson and Steinunn Jakobsdottir.

We present preliminary observations from the broadband seismological network set-up from June 2006 till October 2006 at Hengill volcano area.
The Hengill geothermal system is located in volcanic centres (up to 2000 m depth), within a triple junction between the Reykjanes Peninsula oblique rift, the West Volcanic Zone and the South Iceland Seismic Zone. Intense seismic activity has been recorded since 1990 by the South Iceland Lowland network. In addition, with the use of temporary seismological networks, Hengill volcanic system has been intensively studied, including tomography and anisotropy and seismicity patterns studies.
Cooling, mostly due to natural heat loss, and consequential thermal contraction and cracking in the heat source, are thought to be responsible for the continuous small-magnitude earthquake activity in this area. This mode of earthquake induction was suggested following the observation that many of the earthquakes have merely non-double couple focal mechanisms with large explosive components. Tectonic earthquakes have generally a double couple source mechanism, as they correspond to strike-slip motion only. When fluids are involved, tensile and explosive components of the moment tensor are involved, which are representative of non-double couple mechanisms. The mechanism responsible for the non-double couple in Hengill seismicity may be fluid flow into newly formed cracks.
Recent studies in volcano-seismology have suggested that long period (or low-frequency) earthquakes, i.e., 0.2-5 Hz are due to the interaction between fluid and solid, and are best observed by using network of broadband seismometers. Within the framework of the European project Integrated Geophysical Exploration Technologies (I-GET, 6$^{th}$ PCRD network), a network of 7 broadband seismological stations was set-up in summer 2006 in order to record broadband characteristics of the seismicity at Hengill geothermal area. Our network recorded at least 300 earthquakes in the period June 2006 to October 2006. Our present study aims at analyzing the high-quality, high-dynamic records of ground motion in this area and at relating the inferred source mechanisms to the exploitation of the geothermal system.

Bryndís Brandsdóttir(1), Raimon Alfaro(2) and Robert S. White(2).
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Seismicity and structure of the Grímsvötn volcano under the Vatnajökull icecap, Iceland.

Local, regional and teleseismic earthquake data recorded on a temporary array of 40 seismometers across western Vatnajökull icecap during the summer of 1998 have provided a three-dimensional image of the shallow crustal structure of the Grímsvötn central volcano. Microearthquake activity at depths of 1-4 km along the Grímsvötn caldera rim coincided with inflation of a shallow magma chamber beneath the caldera, which culminated in a 0.1 $km^3$ eruption in December 1998. As observed within other volcanic systems in Iceland the Grímsvötn seismicity diminished markedly with diminished magma pressure following the eruption. Tomographic inversion of the 1998 earthquakes define the extent of a low-velocity body beneath Grímsvötn with a volume of ~20 $km^3$ extending to ~3 km below the surface. This low-velocity body is flanked by high velocities under the caldera rim. Delays in the P-wave arrival times through the Grímsvötn caldera from regional and teleseismic earthquakes and from two detonations ~150 km east of Grímsvötn are 0.10-0.15 s greater than the delays through the uppermost 3-4 km of crust shown by local earthquake arrivals. This suggests the presence of a further low-velocity body at depths greater than 3-4 km beneath Grímsvötn, presumed to be due to the presence of melt. Using the distribution of local seismicity and shear wave attenuation we estimate the maximum lateral extent of the region containing partial melt to be 7-8 km E-W and 4-5 km N-S. P-wave delays require a thickness of less than 1 km of pure/high percentage partial melt, assuming a sill-like magma chamber.

**Conduit flow modelling to investigate possible sources of low-frequency earthquakes.**

April Janet Key

University of Leeds, now at University of Cambridge.

The trigger mechanism of low-frequency earthquakes on Montserrat, West Indies, has been proposed to be the brittle fracture of magma within a dyke or conduit. Brittle failure can occur under conditions of the glass transition, when the product of shear strain rate and viscosity exceeds a critical stress value. Conduit flow models were developed to investigate what effect geometric changes along the length of a conduit have on the shear strain rate of magma flowing through the conduit. The geometric changes were considered in both 2D and 3D, and all models with changing geometries showed increased shear strain rates compared to those that did not change with depth. The largest increases were generated by models with changes in the cross sectional area of the conduit, perpendicular to the flow direction. The shear stresses reached in these flow models could plausibly generate brittle failure of magma. The majority of the seismic energy produced by the brittle failure is trapped within the conduit, forming the low-frequency coda of the observed seismic signal. This resonance was modelled for a conduit that has a changing cross-sectional area with depth. The amplitude spectrum of the synthetic seismograms generated by the resonance model is consistent with the frequency range of low-frequency earthquakes detected at Soufriére Hills Volcano, Montserrat.

# Rates of similar micro-earthquakes: comparison between Campi Flegrei and other volcanic areas

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The precise relocation of micro-earthquakes using waveform cross-correlation is an efficient tool for defining the spatial characteristics of seismogenic structures in volcanic areas. To be applied and to provide meaningful results, the technique requires, however, the presence of sufficient amounts of similar events. We examined about 870 earthquakes recorded below the Campi Flegrei (CF) caldera by a temporary digital network during the end of the 1982-1984 bradiseismic crisis. The classification of these earthquakes indicates a surprising low amount of similar events, especially according to the clustered aspect of the seismicity. The relocation technique, allows only to identify 3 elongated patterns that may be interpreted as small faults which are dipping inward toward the center of the caldera. To determine up to which point this low similarity rate is unusual, we examined the rates for several data sets coming from various volcanic areas: Hawaii, Mount Pinatubo (Philippines), Guagua Pichincha (Ecuador) and Piton de la Fournaise (Reunion Island). The results show for all areas, percentages of similar events significantly higher than for CF and indicate that the low rate observed there is not just a matter of low detection threshold or network characteristics. At CF, most of the seismicity appears to be diffuse and generated along very small fractures rather than along well defined fault structures. The low similarity rate is in good agreement with a seismicity generated in a highly micro-fractured medium by overpressure in the geothermal system which is assumed by some authors as being at the origin of the bradiseismic crisis. In this context looking at the amounts of similar earthquakes appears as a possible technique to distinguish seismicity induced by geothermal activity from seismicity induced by tectonic constraints.

The geothermal origin of the seismicity in the Timanfaya Volcano (Lanzarote) revealed by a self-potential continuous measurement.

R. Ortiz. Dep. Volcanologia CSIC Spain

The electric field in Timanfaya Volcano presents great variations correlated with the seismic activity and precipitations. Geothermal fluids ascend through the fractures to the surface point when they expand and mix with air depositing salts as result. The system is sealed in this form, and pressure increases until is capable of break the cap and open conduits initiating a new cycle of sealing. Interaction with this process the diary humidity in the superficial lapilli would explain the great amplitude of diurnal oscillation of the electric field and attenuation after seismic swarm. Increase of the seismic activity has been observed as well systematically after 15 days of the main precipitations. The seismic activity of Timanfaya National Park is a consequence of the gasses circulation mechanism responsible of the superficial geothermal anomaly, and this fluid circulation is the result of the interaction of oceanic waters, meteoric waters and deep volcanic gases forming all a geothermic system.

The last part of the talk is coauthored by M. Tarraga and R. Carniel.

# Waveforms of lower-crustal earthquakes near the Askja volcano at the north Iceland divergent plate boundary

Heidi Soosalu[1], Robert S. White[1], Clare Knox[1], Páll Einarsson[2] and Steinunn S. Jakobsdóttir[3]

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Askja is one of the volcanic systems comprising the mid-Atlantic plate boundary in north Iceland. It has a nested caldera system, dissected by a swarm of eruptive and extensional fissures. Askja had its latest, minor eruption in 1961. The surroundings of Askja are a known area of persistent small-scale seismicity (below magnitude 3). We operated a network of 20 Güralp 6TD broadband seismometers in the area during July–August 2006 and combined with the data of the Icelandic national seismic network, SIL, detected over 1800 local earthquakes during this period.

The majority of the earthquakes were located 10–20 km to the NE of the volcano massif of Askja, beneath the mountains of Herðubreið and Herðubreiðartögl, at depths of 2–7 km. These events favour the deeper end of this range, marking the thickness of the brittle upper crust, with a slight deepening towards the north-east, away from Askja. Another conspicuous cluster of earthquakes is in the south-eastern part of the nested caldera system of Askja, at depths of 2–5 km and is apparently related to geothermal activity.

We discovered unexpectedly a new type of earthquake in the Askja area: lower-crustal events concentrated at depths of 13–27 km, with one event as deep as 34 km. This is near the base of the crust, or possibly even in the upper mantle, as the crustal thickness in the Askja area has been estimated to be approximately 30 km.

The lower-crustal events are distinctly different in appearance to the “ordinary-looking” upper-crustal earthquakes, with emergent P- and S-phases and low frequency content with a peak around 2-3 Hz. They typically occur in swarms of short duration, up to a few minutes, with several subsequent events. Appearance of arrivals is somewhat site-specific, as some sites may display initially also higher frequencies, but not all. Some sites show consistently rather distinct arrivals with few later reverberations while the same events merge into continuous tremor at other sites. There seems to be a correlation between depth and the frequency content: deeper events tend to be dominated with lower frequencies than shallower ones.

The lower-crustal earthquakes appear to be a persistent feature, as during the short measuring period of two months, we detected over 100 such events. As they are difficult to locate and are small in magnitude, only the two largest ($M_L$ 1.4 and 1.0) were detected by the more distant SIL network. We propose that this seismicity is related to magmatic movements within the north Iceland plate boundary. The deep events show that even though the Icelandic lower crust is hot and ductile, earthquakes can and do occur there.

# Imaging Seaward Dipping Reflectors at Oceanic Rift Zones

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Riftward-dipping basalt flows were first explained by interaction between rifting and the extrusion of basalt flows from observations of the neovolcanic zones in Iceland in an elegant model proposed by G. Palmason (A continuum model of crustal generation in Iceland, *J. Geophys*, vol. 47, pp. 7–18, 1980). The idea was then applied to the rifting and extensive basalt flows that occurred at volcanic continental margins to produce arcuate seaward dipping reflectors (SDR). SDRs are now recognised widely from volcanic margins around the world.

In this talk I will show examples of spectacular SDRs that were produced by the Iceland mantle plume as it interacted with the rifting that occurred as the North Atlantic broke open at 55 Ma. I will also show the change in morphology of the SDRs that occurred as the mantle thermal anomaly decreased and the rift subsided from being subaerial to below sea level. Controlled source seismic methods allow us to image the basalt flows at depth beneath the surface. Using state-of-the-art seismic reflection acquisition (12,000 metre streamer, 48-gun low-frequency source), we have also for the first time been able to image the sills that intrude the lower crust beneath the extrusive lavas, from which the basalts were formed by differentiation of the primary magmas.

One of the keys to imaging successfully through basalts is to tune the source and the receiver to the frequency pass-band of the sequence of basalts through which the seismic signal has to pass. Recent work measuring the seismic attenuation of basalts drilled in north Rockall Trough and in the Faroes demonstrates that stacked lava flows are highly attenuative: the effective Quality Factor is typically in the range 15–25. Synthetic seismogram modelling studies show that the attenuation is almost entirely due to scattering within the basalt sequence, due to the numerous interfaces at the tops and bases of weathered lava flows, each with high impedance contrasts. The consequence of this high attenuation is to markedly reduce the amplitude of the high-frequency components of the signal. This attenuation also affects seismic signals from deep earthquakes beneath the neovolcanic rifts in Iceland.

*The iSIMM (integrated Seismic Modelling and Imaging of Margins) research group comprises N.J. Kusznir, R.S. White, P.A.F. Christie, A.M. Roberts, D. Healy, R. Spitzer, H. Lau, A. Chappell, J.D. Eccles, R. Fletcher, N. Hurst, Z. Lunnon, C.J. Parkin, A.W. Roberts, L.K. Smith and V.J. Tymms.

Analytical and numerical modelling of surface displacement due to magma emplacement

by
Olivia Lewis & Jurgen Neuberg

The analysis of surface displacements produced as a result of magma migration can yield valuable information about the size, shape, location and pressurisation of magma reservoirs. The Mogi model remains a standard tool in volcano deformation despite several limitations that cast doubt on the validity of its use in volcanic areas. We study two of these limitations linked to the key assumptionsof (i) a point source in a half space, and (ii) perfect linear elasticity and the superposition principle.
We will demonstrate that there are significant discrepancies between numerical and analytical models when more than one Mogi source is employed to model a magma reservoir.

A seismic magma flow meter

by
Jurgen Neuberg

The development of our conceptual model of magma rupture as a trigger mechanism for low-frequency earthquake swarms, as well as the accompanying deformation patterns will be summarised and several source mechanisms and radiation patterns at the focus of a single event will be discussed. We investigate in detail the accelerating event rate and seismic amplitudes during one swarm, as well as over a time period of several swarms. The seismic slip vector will be linked to magma flow parameters resulting in estimates of magma flux for a variety of flow models. On the basis of these models we will discuss the underlying question whether processes in a magma reservoir or conditions near the surface control magma properties and magma ascent.

TITLE: Low frequency coda decay: separating the different components of amplitude loss.

AUTHORS: Patrick Smith and Jurgen Neuberg

ABSTRACT:
Low frequency seismic events, characterised by slowly decaying harmonic codas, have been observed on many volcanoes worldwide and are considered key tools in volcanic monitoring and eruption forecasting. Quantifying the effects of attenuation in a gas-charged magma is critical in attempts to model the generation and propagation of low-frequency events, such as those observed on Soufrière Hills Volcano, Montserrat, where our model for their generation is a resonating conduit system triggered by brittle failure of the melt at the conduit walls.

An ongoing aim of our research is to be able to relate the amplitude of low-frequency events at the surface to the amount of slip at the source, in order to use the seismicity as a tool for extracting a magma flow/ascent rate. An essential requirement of this concept is an understanding of energy losses in the system, and in particular how the amplitude decay of the observed signal is related to the combination of intrinsic attenuation in the magma and elastic parameter contrasts between the magma and volcanic edifice.

The basis of this study is a finite-difference model, which models the seismic wave-field associated with low-frequency events in a viscoelastic medium. Attenuation is quantified via the quality factor Q, and the attenuative behaviour of the magma as a function of frequency is modelled by parameterising the material as an array of Standard Linear Solids. The apparent or coda Q of the synthetic signals is calculated for a range of intrinsic input Q values for the model, as well as for a range of elastic parameter contrasts. The preliminary results allow us to begin separating out the different contributions of amplitude loss, in order to develop a quantitative relationship between source and surface amplitudes.

Eleonora Rivalta, Paul Segall

# Effects of compressibility and shape on the volume budget of magma intrusions

Inversion of surface deformation data of dike intrusions at Kilauea volcano (1997), Izu Ilands (2000), and Afar (2005), shows that dike volumes exceed by far volume loss at magma chambers. We investigated whether we have necessarily to appeal for deep sources, not discernible from data, or rather compressibility and shape effects can explain volume increase. We considered an initial situation with a magma chamber, and a final situation with a chamber and a dike, formed after magma output from the chamber. We applied mass conservation and hydrostatic equilibrium to the system. We obtained that the ratio between dike volume and volume change at chambers r_v is equal to 1+4*\mu*\beta/3, where \mu is rock rigidity and \beta is magma compressibility. Typically, \beta*\mu is significant, so that aproximately 1<r_v<5 .

**A Magmatic Origin for the 2007 Micro-Earthquake Swarms at Upptyppingar, Iceland?**

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Micro-seismicity is common within the rifting zones that intersect Iceland. However, between February and August 2007, anomalous swarms of tectonic earthquakes – amounting to at least 3,350 epicentres – have been detected over a 36 $km^2$ area near to Upptyppingar (16.2° W; 65° N), which forms part of the Kverkfjöll volcano system, extending from the northern flank of the Vatnajökull ice cap. Using results from the SIL seismic network, we summarise the spatial and temporal changes in ongoing seismicity that began in February 2007; additionally, we consider the processes underlying the escalated activity. Besides displaying spatial clustering, the Upptyppingar micro-earthquakes are noteworthy because: (i) they concentrate at focal depths ranging from 15 to 18 km; (ii) the swarms comprise earthquakes <2 in magnitude; and (iii) several of the swarms originate at focal depths exceeding 18 km. Each swarm has been confined to a small surface area and focal depths have remained mostly consistent, both within and between swarms. Spatially, different parts of the affected region have exhibited seismicity at different times, with swarm sites alternating between distinct areas. Curiously, few earthquakes have been detected at shallow depths within the zone of unrest. A likely reason for the sustained clustering of earthquakes near to Upptyppingar is inflow of magma into the base of the crust; such a hypothesis would account for the depth, intensity, and duration of the swarms. Based on observations elsewhere in Iceland, a candidate explanation is the emplacement of a dyke. Interestingly, the up-surge in seismicity from the Upptyppingar region coincides with the ongoing formation of a 2,000 GL reservoir for water, located 21 km south-east of Upptyppingar. Nevertheless, the possibility of induced seismicity remains unclear.

## Location of Seismicity in the Mýrdalsjökull/Katla Volcano

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Since installation of the Icelandic national digital seismic network (SIL) in 1991 over fourteen thousand earthquakes have been recorded in the Katla volcano, which is covered by the Mýrdalsjökull ice cap. Most of the seismicity is on the western flank of the volcano, near Goðabunga and only a about one fifth is located within the caldera itself. Although improving through time, location accuracy of most events has not been good. This is due to noisy conditions at the nearest seismic stations, emergent onsets of arrivals, high attenuation along some paths and, during the first half of the recording period, sparcity of recording sites. With the increasing number of staions located within 30 km distance, lateral location accuracy has improved somewhat, but vertical locations have remained higly inaccurate, with the majority of the events stuck at the surface. The main reason for this being the SIL velocity model, which is used for location of all seismicity in Iceland. Better velocity models have been obtained for many regions (Vogfjord et al., 2002), but have yet to be installed for use in day-to-day operations of the network. The model suitable for south Iceland improves locations in the nearby volcano Eyjafjallajökull, but in the Katla volcano it performs no better than the SIL velocity model.

A large portion of the events in the volcano have a long source-time-function and are dominated by low frequencies, 0,2-3 Hz on the predominantly Lennartz-5s seismic stations. Some events however, especially in the caldera, have a short duration and could lend themselves to be relocated with relative location mehtods with a more appropriate velocity model. A 2D velocity model was obtained for Katla in 1994 by tomographic inversion of travel times on a N-S profile crossing the caldera (Ó. Gudmundsson et al.) and a 3D model was published in 2007 (Jónsdóttir et al.) based on tomographic inversion of travel times from earthquakes in the Eyjafjallajökull and Katla volcanoes to the stations of the SIL network.

The thermal output of Katla has been monitored since 1999 through mapping of variations in ice couldrons on the ice surface above the caldera (M. T. Gudmundsson et al., 2007). In an attempt to look for a temporal relation between seismicity and cauldron development in and around the volcano's caldera, selected events from within the caldera are relocated using a double-difference method in a more appropriate velocity model. As with the initial locations in the SIL velocity model, when using the south Iceland model the events also stay confined to the near-surface. However, better results are obtained using a combination of the lower part of the south Iceland model and and a 1D approximation to the center of the 2D profile from 1994. The events move away from the surface and become fairly uniformly distributed in depth down to about 15 km. Starting with these new locations and repeating the relocation process, the events remain stable at their locations.

Some aspects of the character of the events and event distribution in the caldera in time and space will be discussed.

# Relocated earthquakes in Eyjafjallajökull between 1991 and 2006: Does deep seismicity indicate intruding material from below?

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Earthquakes within the Eyjafjallajökull volcano, recorded by the Icelandic SIL network from 1991 until August 2006, have been relocated using a double-difference location method. The method uses cross correlation of similar wave forms to determine relative times of waves from events to stations with increased accuracy, and then inverts these relative travel times for an improved location. This approach increases location accuracy to such a degree that fault patterns, if present, become resolvable.
In this study we suggest, that the pipe-like pattern of earthquakes observed below the volcano indicates a feeding channel through the crust.

During the observation period, three main swarms occurred: in 1994, 1996 and 1999. An intrusive episode at Eyjafjallajökull in 1994 was modelled by Pedersen et al. (2004) using InSAR data. They suggested that the more than15 cm of deformation seen in the InSAR data was caused by a sill intrusion at 4.5 -6.0 km depth, and that maximum deformation occurred south of the summit crater. The InSAR data constrain the timing of deformation between March 1993 and June 1995. Seismicity in Eyjafjallajökull can tighten these constraints to be in 1994, when seismic activity increased significantly.  In May and June that year, approximately 150 events were recorded under the northern edge of the postulated intrusion, which is also the northern edge of the ice cap. The relocated hypocenters form a horseshoe-shaped cluster between 9 and 11 km depth, well below the sill intrusion.

In 1999 another swarm took place in Eyjafjallajökull. The activity increased at the beginning of July, remained high until the end of August, and increased again between November and May the following year, when the seismicity gradually decreased. Crustal deformation was observed in 1999 and 2000 by dry-tilt and network GPS measurements (Sturkell et al., 2003).  Additionally InSAR data showed more than 20 cm of deformation, with a maximum just south of the edge of the ice cap. Using this data, Pedersen and Sigmundsson (2006) suggested that the uplift and heightened seismicity was caused by a sill intrusion at 6.3 km depth. As during the previous intrusive episode in 1994, most of the activity in 1999 was situated at the northern margin of the ice cap and the intrusive sill. The relocated main cluster is also similar in shape to the one in 1994: crescent-shaped facing south, at the same depth interval, and below the suggested intrusion. Two smaller distinct clusters were also observed in 1999. One situated at 6 km depth about 2.5 km west of the main activity, the other at 10 km depth, 2 km to the south. A third small cluster, observed in 2006, was located at 16 km depth to the north, beneath the Steinsholtsjökull valley glacier.

Between the two intrusion episodes, yet another seismic swarm took place in 1996, from February until mid-April.  These events were at greater depths,  between 20 and 23 km, just above the crust-mantle boundary. No crustal deformation was observed during the period of this activity, possibly because of its greater depth. The seismicity could indicate a  period of opening caused by intruding material from below, feeding the sill intrusion three years later, in 1999. Such deep seismic activity is uncommon in Iceland and has only been observed under the Heimaey fissure that erupted in 1973 (Westman-islands), and during the last year at Upptyppingar (northern volcanic zone).

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