### V12C-10 1605h

## Origin of Enriched Geochemical Signatures in Continental Arc Rocks by Antithetic Subduction of Continental Lithosphere

Allen F. Glazner[1] (919-962-0689; afg@unc.edu)

Mark T. Brandon[2] (mark.brandon@yale.edu)

[1]Univ. of North Carolina, Dept. of Geological Sciences, CB 3315, Chapel Hill, NC 27599-3315, United States

[2]Yale University, Dept. of Geology and Geophysics, New Haven, CT 06520-8109, United States

The source materials for magmas in continental arcs are not well known. Magmas are typically assumed to be derived from the subducted slab, subducted sediment, and mantle wedge, but some continental arcs have isotopic signatures that are inconsistent with these sources. For example, a large volume of the Sierra Nevada batholith consists of rocks that have initial Sr ratios of about 0.706-0.708 and $\epsilon_{Nd}$ values ranging from -3 to -8. Late Cenozoic volcanic rocks erupted through the batholith, and their entrained xenoliths, have similar isotopic compositions. These characteristics are inconsistent with derivation from only the sources above and are most easily explained by derivation from enriched continental lithospheric mantle. However, there was never enough lithospheric mantle under the arc to produce the observed volume of enriched arc rocks; mass balance fails by one or two orders of magnitude, and lithosphere cannot flow by viscous processes to provide material to the arc.

A possible solution to this problem lies in kinematic mass balance of the arc system. In many continental arcs (e.g., Cenozoic Andes, Mesozoic northern Cordillera and Sierra Nevada), thrust faults have carried the arc at least 100-200 km toward the craton. This motion requires moving a comparable amount of sub-detachment lower crust and mantle toward the arc and produces a tremendous cross-sectional balance problem. Geologic field studies and geodynamic modeling indicate that this antithetic subduction feeds continental lithosphere into the convecting mantle wedge where it can contribute to magma genesis. This process provides a large volume of enriched and probably fertile continental lithospheric mantle to the arc system and may account for the unusual geochemical signatures of some arc rocks.

### V12C-11 1620h

## Growth and Evolution of the Accreted Talkeetna Arc, South-Central Alaska: Solutions to the "Arc Paradox"

Matthew Rioux[1] (1-805-893-7999; rioux@geol.ucsb.edu)

James Mattinson[1]

Bradley Hacker[1]

Marty Grove[2]

[1]University of California, Santa Barbara, Department of Geological Sciences University of California, Santa Barbara, Santa Barbara, CA 93106, United States

[2]University of California, Los Angeles, Department of Earth and Space Sciences University of California, Los Angeles, Los Angeles, CA 90095, United States

The accreted Talkeetna arc, exposed in the Chugach Mountains of south-central Alaska, represents a cross section from the Moho to surficial volcanic deposits of a Jurassic intra-oceanic arc. We are using SIMS and partial dissolution-TIMS U/Pb zircon analyses of plutonic rocks in the Talkeetna arc to study how island arcs grow, evolve, and morph into continental crust.

Our partial dissolution analyses (PDA), following the chemical abrasion technique developed by Mattinson (2000, 2001a, 2001b), used high-T (800°C) annealing of radiation damage, followed by successive acid digestions of grain populations, to generate reproducible high precision ages. Low-T (160-170°C) "clean-up" digestions typically showed signs of Pb loss, consistent with removal of discordant zircon, whereas high-T (>170°C) and residue steps gave concordant age plateaus. Repeat analyses of samples showed similar dissolution patterns and ages agreed within two sigma errors.

The SIMS and TIMS U/Pb zircon analyses from the Talkeetna arc yielded ages of 184.3 ± 0.4 Ma, 185.0 ± 0.4 Ma, 186.6 ± 0.4 Ma, 192.4 ± 2.9 Ma, 193.2 ± 0.4 Ma, and 198.6 ± 0.4 Ma, indicating that the arc was active from ∼184-199 Ma. Previous $^{40}Ar/^{39}Ar$ hornblende cooling ages for the arc range from ∼175-182 Ma, suggesting a total arc lifespan of ∼20 My. This is consonant with fossil ages within arc volcanic rocks that range from early Sinemurian to upper Toarcian (∼180-202 Ma) and biochronology that bounds arc growth between Late Triassic and early Bajocian (∼169-206 Ma). Intermediate to felsic plutonic rocks in the Talkeetna Mountains intrude the volcanic carapace of the arc, but were not previously considered to be part of the Talkeetna arc. Our new SIMS and TIMS ages of 163.9 ± 3.6 Ma, 170.0 ± 4.2 Ma, 171.3 ± 5.1 Ma, 175.6 ± 0.4 Ma, 180.8 ± 2.7 Ma, and 183.8 ± 2.1 Ma, overlap the ages reported above for the Chugach Mountains, suggesting that portions of the intermediate plutonism could be related to the Talkeetna arc.

Our new age data from the Talkeetna and Chugach Mountains may explain the apparent paradox of intermediate continental crust being produced by the accretion of mafic intra-oceanic arcs. The lifespan of the Talkeetna arc, combined with Raleigh-Taylor instability modeling by Jull and Kelemen (2001) and thermobarometry on lower crustal garnet gabbronorites (Mehl et al., 2001), suggests that the lower crust of the Talkeetna arc could have become convectively unstable, and sunk into the asthenosphere prior to accretion. The removal of mafic lower crust would drive the bulk arc composition toward more continental values. Additionally, previously unrecognized intermediate arc plutonic rocks in the Talkeetna Mountains would lead to a more intermediate composition for the Talkeetna arc and also help solve the arc paradox.

### V12C-12 1635h

## Zircon U-Pb And Biotite 40Ar/39Ar Ages Of Kohistan Lower Crustal Tonalite And Their Implications For The History Of Continental Collision

Takashi Nakajima[1] (81-298-61-3957; tngeoch.nakajima@aist.go.jp); Ian Stuart Williams[2] (61-2-612-55164; ian.williams@anu.edu.au); Hironobu Hyodo[3] (81-86-252-3161; hhyodo@rins.ous.ac.jp); Kazuhiro Miyazaki[1] (81-298-061-2390; kazu-miyazaki@aist.go.jp); Sakae Sano[4] (81-89-927-9443; sano@edserv.ed.ehime-u.ac.jp); Allah Baksi Kausar[5] (92-51-9255139; kausar@geolab.is.sdnpk.org)

[1]Geological Survey of Japan, Institute of Geoscience, 1-1-1 Higashi, AIST Central-7, Tsukuba 305-8567, Japan

[2]Resarch School of Earth Sciences, Australian National University, Australian National University, Canberra, ACT 0200, Australia

[3]Okayama University of Science, 1-1 Ridai-cho, Okayama 700-0005, Japan

[4]Geological Survey of Japan, Ehime University, Faculty of Education, 3 Bunkyo-cho, Matsuyama 790-8577, Japan

[5]Geoscience Laboratory, Geological Survey of Pakistan, Shazad Town, Islamabad 000, Pakistan

The Kohistan block in northern Pakistan exposes a crustal cross section through an ancient oceanic island arc, comprising garnet pyroxenite, garnet granulite, banded amphibolite, norite gabbro, metasediment and metavolcanics. The Dasu Tonalite intrudes the lower crustal Kamila Amphibolite. The tonalite is foliated and folded concordantly with the host amphibolite, indicating syn-tectonic intrusion, and contains abundant magmatic epidotes, indicating high-P crystallization.

The Dasu Tonalite is extremely poor in K2O (0.6-0.9 wt.% for SiO2 64-70%) and has a low initial 87Sr/86Sr (0.7037-0.7038, similar to the associated lower crustal amphibolite and granulite), consistent with juvenile granitic magma free of contamination by recycled upper crust.

The Dasu Tonalite gave SHRIMP zircon U-Pb ages of 97.6+/-1.0 Ma and 98.0+/-1.1 Ma on two samples, and biotite 40Ar/39Ar ages of 69.7+/-0.7 Ma and 69.7+/-0.9 Ma. The euhedral shape and lack of overgrowth or resorption features in CL images of the zircons suggest a simple magmatic history starting at ca. 98 Ma with no evidence for a later major thermal event.

The large discrepancy between the U-Pb and Ar-Ar ages might record the deep crustal residence time of the Dasu Tonalite. The tonalite magma was probably generated and crystallized at ca. 98 Ma, then remained in the lower crust at a temperature of about 700C (which is given by geothermometry of the intercalating Kamila amphibolite), cooling down to ca.300C at 69.7Ma. 69.7Ma is a cooling age during the process of exhumation of the Kohistan arc caused by the Indian collision.

### V12C-13 1650h

## $^{238}U$-$^{230}Th$ Disequilibrium in Zircon and $^{87}Sr/^{86}Sr$ Variations in Plagioclase as Recorders of Magmatic Processes in a High-Silica Rhyolite: Taupo Volcano, New Zealand

Bruce L.A. Charlier[1] (b.l.a.charlier@durham.ac.uk)

Jon P. Davidson[1] (j.p.davidson@durham.ac.uk)

Colin J.N. Wilson[2] (C.Wilson@gns.cri.nz)

Jacob B Lowenstern[3] (jlwnstrn@usgs.gov)

[1]B.L.A. Charlier, Dept. Geological Sciences, University of Durham, Durham DH1 3LE, United Kingdom

[2]C.J.N. Wilson, IGNS Ltd, Private Bag 2000, Taupo 2730, New Zealand

[3]J.B. Lowenstern, USGS, 345 Middlefield Road, Menl Park 94025, United States

The processes involved in, and the timescales over which large bodies of silicic magma are generated and stored in the crust are addressed here by studies of the Oruanui eruption (530 $km^3$ magma), the latest caldera-forming event (26.5 ka) at Taupo volcano (Taupo Volcanic Zone, New Zealand). The eruption was mildly zoned, dominantly 73-76% $SiO_2$, but was non-systematically tapped. Here we report ($^{238}U$-$^{230}Th$) disequilibrium data on whole rocks and zircon by TIMS on bulk samples and SHRIMP-RG on single crystals and show that the Oruanui magma contained a suite of zircons with a bimodal age distribution. The dominant population yields a weighted mean age of 35.4±3.6 ka (10 ka in excess of the eruption age, which includes zircons actively crystallising in the Oruanui magma at the time of eruption), versus a smaller age population yielding a weighted mean age of 91.5±8.8 ka (65 ka in excess of eruption age). We believe that these data indicate that accessory phases such as zircon record episodic growth histories, where the older age population represents crystals relating to an earlier magmatic episode(s).

In addition, we present preliminary $^{87}Sr/^{86}Sr$ microanalysis data for feldspar crystals separated from the Oruanui rhyolite. High resolution electron microprobe traverses and Normarski imaging reveal a growth history punctuated by magmatic events that are manifested as unconformities and inclusion rich zones within the crystals. The opaque feldspar cores have $^{87}Sr/^{86}Sr$ of 0.70550, whereas rims are 0.70562, the latter being compatible with the whole-pumice values for Oruanui rhyolite. These variations are accompanied by changes from ∼An30 at the rim (in equilibrium with the host pumice) to ∼An65 in the core. However, some feldspars show a much more complex crystallisation history, where Sr isotope variations within the grains are far outside values seen in the whole-pumices. We interpret these variations and the age spectrum of the zircons to represent open system processes in the generation of the Oruanui rhyolite.

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# V21A MCC: Hall C Tuesday 0830h

## Statistical Analysis of Data Recorded on Active Volcanoes: Advancements and New Perspectives I Posters *(joint with S)*

***Presiding:*** **s Falsaperla,** Istituto Nazionale di Geofisica e Vulcanologia**; S Malone,** University of Washington

### V21A-1163 0830h POSTER

## Search for a Possible Triggering Effect Between Tectonic Earthquakes and Swarms at Volcanoes

John J Sanchez[1] (907-474-7309; jjalaska@giseis.alaska.edu)

Stephen R McNutt[1] (907-474-7131; steve@giseis.alaska.edu)

[1]Geophysical Institute, University of Alaska Fairbanks, 903 N. Koyukuk Dr., Fairbanks, AK 99775, United States

We searched for possible relationships between earthquake swarms at volcanoes and tectonic earthquakes nearby, using the Global Volcanic Earthquake Swarm Database (GVESD). From the GVESD we extracted a sample of 358 swarms with reported start dates. The durations of these swarms are in the range 15 minutes to 4.6 years and they occurred at 93 volcanoes around the world. Then we used the NEIC earthquake database to search systematically for earthquakes with magnitude >6 and distance <1000 km from the volcano, occurring in the ten years before the swarm start date. The relation between tectonic earthquakes and swarm start dates was analyzed by plotting the number of earthquakes, their magnitudes, and their distances to the volcano versus delta T, the time difference between earthquake occurrence and swarm start date. The time distribution of precursor earthquakes was divided into bins of 6 months and 1 month and all distributions were tested for significance of peaks in the number of earthquakes, magnitudes, or distances. For 50 randomly selected swarms with durations less than 120 days we found only one peak in the number of precursor earthquakes that appears to be statistically

significant. This peak occurs in the 4th month bin before the swarm start dates.

We also tested for smaller time scales and for earthquakes after the swarm start dates. We constructed plots of the number of earthquakes, magnitude, and distance to the volcano dividing the time axis in bins of 1 day and extending the search range up to one month after the swarm start dates. A peak in the number of precursor earthquakes occurs at the 15th day bin before the swarms start, but the peak is not significant as estimated using the t-test. The results are somewhat surprising considering that the group of precursor earthquakes includes events that are large (M=7.9), nearby to the volcanoes, and relatively close in time to the swarm start dates. Recent well-documented cases for triggering of seismicity at volcanoes in Alaska indicate that the triggered swarms are small and short (e.g. 17 events in 13 hours at Katmai). This suggests that most swarms in the GVESD may be too large or long lasting. Those likely to be triggered may be too small to be reported. Future studies would benefit from knowledge of the initial conditions at the volcanoes. This would help to determine whether there is some magnitude-distance threshold that the tectonic earthquake needs to overcome to trigger a volcanic swarm.

## V21A-1164 0830h POSTER

### Update of the Eruptive Activity at Mt. Etna: Multidisciplinary Evidence of Magma Refilling

Sonia Calvari[1] (+39 095 7165800; calvari@ct.ingv.it)

. INGV-CT WHOLE SCIENTIFIC STAFF[1]

[1]Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Catania, Piazza Roma 2, Catania 95123, Italy

Following the July-August 2001 flank eruption, Mt Etna volcano did not show any significant eruptive activity for several months. The new supply of fresh magma within the volcano was detected since December 2001 by gravimetry and especially by ground deformation, which showed a general trend of inflation of the whole volcano. The mass of gas-rich magma entering the system has been localised at 3-4 km b.s.l. The refilling of new magma caused growing stress within the volcanic pile. In turn, stress accumulation triggered sudden release and a diffuse seismicity in the upper crust (0 to 5 km depth) of the eastern and southwestern flanks of the volcano. This behaviour has been observed on Etna a number of times, and most recently before the last flank eruption. It is commonly recorded several months before flank eruptions. Refilling of the shallow feeding system became evident in March 2002, when lithic ash was emitted from Bocca Nuova, one of the four summit craters of the volcano. Ash emission interested also NE-Crater in April, with ash becoming increasingly richer in the juvenile component. Between June and August, Strombolian activity resumed at NE-Crater, with bombs falling well outside the crater rim. Several pulses of gas-rich magma entering the system have been detected by COSPEC measurements of SO2 gas flux and FTIR measurements of the SO2/HCl ratio. Thermal surface measurements and structural surveys have shown the gradual but limited expansion of a field of fractures along a N-S direction between NE-Crater and SE-Crater for a total length of 4 km.

URL: http://www.ct.ingv.it

## V21A-1165 0830h POSTER

### Process of Magma Migration at Mt. Etna, Italy, Evidenced by Mapping the b-value Anomalies (July 17 - August 9, 2001 Lateral Eruption)

Arianna Lisi[1] (0039-06-51860535; lisi@ingv.it)

Maura Murru[1] (0039-06-51860412; murru@ingv.it)

Caterina Montuori[1] (0039-06-51860404; montuori@ingv.it)

[1]Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, Rome, RM 00143, Italy

Abstract. During the period July 17 - August 9, 2001 a very intense eruption occurred in the upper southern flank of Mt. Etna in Sicily (Italy). The seismicity from August 1999 to August 2001 has been studied in order to map the intrusive process inside the volcano edifice by positive anomalies in the frequency-magnitude distribution (b-value) of earthquakes. The dataset, collected by the permanent network of System Poseidon, spread out over eastern Sicily, contains 1207 events with $Md \geq 1$, concentrated in the upper 15 km of the crust within a volume of about 7 km radius. We have analyzed the b-value as a function of space and time, using a dense grid with $0.005^{\circ}$ spacing sampling the 50 nearest earthquakes which occur in a maximum radius of 3 km. By this technique we find out, in the period November 5, 2000 - July 11, 2001 (when intense swarms occurred) a highly significant b-value positive anomaly (b = 1.86 ± 0.11) respect to the background value (0.72 ± 0.08). This anomaly, with an approximately NE-SW trend in agreement with earthquake alignment, located at 4 ± 2 km depth in the southern flank, has been correlated with a dike emplacement. The increase of b-value observed during this period may infact reflect the increasing fracture density due to the intrusion activity. In the period July 12 - 18, 2001, preceding the eruption, the volume of high b anomaly migrated to 1 - 2 km depth in combination with another very intense swarm. The excellent correlation of these results with the high Vp - body revealed by tomographic images confirms the analysis of b-values as a very useful support in the resolution of volcanoes' feeding conduits and their migration in time.

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## V21A-1166 0830h POSTER

### Application of Multivariate Statistics and Polarization Analysis in the Study of Volcanic Tremor Data at Stromboli Volcano, Italy

Susanna Falsaperla[1] (39-095-7165845; falsaperla@ct.ingv.it)

Horst Langer[1] (39-095-7165828; langer@ct.ingv.it)

Joachim Wassermann[2] (49-331-977-5411; jowa@geo.uni-potsdam.de)

[1]Istituto Nazionale di Geofisica e Vulcanologia, Sez. Catania, P.zza Roma, 2, Catania 95123, Italy

[2]Institut fuer Geowissenschaften, Postfach 601553, Potsdam 14415, Germany

The continuous monitoring of seismic signals recorded on Stromboli, Italy, since 1985 has allowed to gain insight on this peculiar volcanic system. The spectral analysis of the persistent volcanic tremor along with the polarization analysis have highlighted an internal dynamics which evolves in long time spans of the order of months. According to previous studies, we demonstrate that the slow evolution of the internal changes can be followed with the application of techniques of multivariate statistics.

In this note, we considered two unsupervised classification methods, i.e., the Principal Component Analysis and the Cluster Analysis. In particular, the Cluster Analysis allows us to identify three different clusters of spectra, according to the spectral amplitude of the signal and its frequency content. We present an overview of the results obtained from the application of statistical analyses we carried out from 1990 to 1999. For the most recent years, we combine these results with those of polarization analysis, considering azimuth and incidence angle of the seismic signal. Our interpretation of the overall data takes into account the relationships with volcanic activity using the images of a permanent video camera of INGV, which monitors the active craters 24 hours a day.

Cyclic changes of the spectral features of tremor along with the incidence angle lead us to highlight seismic sources acting at different depth within the volcano feeder. This finding has important consequences for the understanding of: i) changes of intensity of Strombolian activity visible at the surface, and ii) the processes of lateral intrusion of magma, such as that inferred from the data recorded in 1997 and 1998.

## V21A-1167 0830h POSTER

### Analysis of Seismic Broad-Band and Acoustic Signals at Stromboli Volcano.

Alessandro N. Pino[1] (+39.06.51860478; pino@ingv.it)

Maurizio Ripepe[2] (+39.055.2757479; maurizio@ibogfs.df.unibo.it)

[1]INGV- sez.Roma, via di Vigna Murata, 605, Roma 00143, Italy

[2]Dip. Scienze della Terra, Universita' di Firenze, Via LaPira, 4, Firenze 50121, Italy

Stromboli volcano is well known among volcanologists to be in a moderate and continuous explosive state. For this reason in the last years, it has been object of several geophysical experiments. Explosions have been recorded using optical and infrared videocameras, pressure sensors, thermal radiometers and broad-band seismometers. The combined use of these different sensors allows to better constraint the dynamical process and provides new experimental evidence to support a dynamical model based on the gas flux model. Seismic activity generated by the volcanic activity is not well explained in terms of dynamics of the source process. In the last years, experiments with a large number of broad-band seismometers have evidenced new features of the seismic source. Moment tensor inversion describes the explosive process as characterized by a volumetric source associated with a single force. Laboratory experiments indicate that when the gas rises along the conduit fluid moves downwards inducing a strong decompression. Models based on the single force best explain small strombolian explosion as well as large volcanic eruption. We provide new experimental data to demonstrate that the seismic low-frequency signal is mainly linked to the gas flux during the explosion. Source is shallow and is dominated by a strong contraction. Low-frequency seismic signal can be converted in gas flux rate and thus contribute to quantify the explosive process in terms of gas quantity, gas velocity and gas overpressure.

## V21A-1168 0830h POSTER

### Array Tracking of Infrasonic Sources at Stromboli Volcano

Emanuele Marchetti[1] (0039.055.2757479; marchetti@geo.unifi.it)

Maurizio Ripepe[1] (0039.055.2757479; maurizio@ibogfs.df.unibo.it)

[1]Dipartimento di Scienze della Terra, Universita' di Firenze, via G. La Pira 4, Firenze 50121, Italy

Infrasonic array represents a major tool in monitoring the activity of explosive volcanoes and could easily track the position of the source of the sound produced by volcanic activity. On volcanoes such as Stromboli the possibility to control the evolution of the explosive activity at each single crater, is believed to be crucial for a correct risk assessment. Explosions were recorded at Stromboli by a small aperture (120 m) infrasonic array at ∼ 350m from the 3 active craters. A grid searching technique based on semblance allows a fine location of the explosive vents. The location of the sound source lead to define, by stacking the infrasonic signals, the main characteristics of the acoustic wavefield produced by each crater. The NE crater produces short (<1 s) and strong (∼ 40 Pa) acoustic waves, while explosions at the SW crater generate a sharp low-pressure (∼16 Pa) onset followed by a long (∼ 15 s) acoustic coda. These acoustic waves reflect the eruptive styles observed during the experiment. Activity at the NE crater was characterised by short-lived (4-5 s) explosions, highly energetic and with a large amount of scoria. The explosions at the SW crater were long lasting (10-20 s) and rich in cold volcanic ash. We found that, in spite of the longer coda, the acoustic waves of the two craters show very similar onsets indicating that the source process is the same at the two craters. The duration of the explosion is mainly a function of the gas overpressure, which directly controls the gas jet velocity. High gas overpressure will produce large pressure perturbations in the atmosphere, but the duration of the explosion itself will be short. However, low regimes of gas overpressure will generate long living explosions with small acoustic amplitude as in the case of fountain-like explosions. The correlation of the acoustic waveforms with eruptive styles is the evidence that mass discharge rate is controlling the acoustic emission of the infrasonic coda. We suggest that the long acoustic coda can be associated to the mass discharge rate and reflects fluctuations of a sustained pressure release.

## V21A-1169 0830h POSTER

### The Permanent Seismo-Acoustic-Thermal Station at the Summit of Stromboli: Insights Into the Long-Term Dynamics of Explosive Activity

Maurizio Ripepe[1] (+39.055.2757479; maurizio@ibogfs.df.unibo.it)

Andy J.L. Harris[2] (+1.808.956.3157; harris@pgd.hawaii.edu)

Dave A. Rothery[3] (1908.652124; D.A.Rothery@open.ac.uk)

Emanuele Marchetti[1] (+39.055.2757479; marchetti@steno.geo.unifi.it)

[1]Dip. Scienze della Terra, Universita' di Firenze, via LaPira, 4, Firenze 50121, Italy

[2]University of Hawaii; HIGP/SOEST, 2525 Correa Road, Honolulu, HI 96822, United States

[3]Dept. of Earth Sciences, The Open University, Milton Keynes MK7 6AA, United Kingdom

Stromboli volcano is characterized by a persistent, moderately explosive activity. This behavior is interrupted once or twice a year by stroger explosions that present a serious risk to turists who gather to watch the activity. Simultaneous thermal, infrasonic and seismic measurements have revealed strong temporal links between variations in degassing and explosive activity. These results indicate that degassing, and thus explosive activity, cycles between contrasting states. These cycles consist of week-long periods of strong and weak

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levels of degassing activity, which are associated with marked changes in the style of activity. During May 2002, we installed a permanent station 250 meters from Stromboli's active craters in order to track changes between vigorous and weak states. The station includes a vertical short-period (Mark 1s) seismic sensor, a pressure sensor and 3 thermal sensors. The pressure sensor consists of a pre-amplified condenser microphone, with a sensitivity of 46 mV/Pa, in the 1-20Hz infrasonic band. The 3 thermal sensors are Omega infrared thermometers with a sensitivity of 1 mV/°C, in the range between -40 and 1200°C. Each thermal sensor is installed in weather-and-gas-proof Pelican cases and is targeted through a thermally transparent selenium-germanium-arsenic window onto a single crater. The 15° degree field of view of each thermal sensor allows us to monitor the activity over most of the crater terrace. Signals are converted to 16 bits digital data at 18ms sampling interval. Digital data are radio-transmitted from the summit to the recording site in the Laboratory of Geophysics of the University of Firenze, using an asynchronous serial protocol at 9600 baud rate. We plan soon to telemeter the data to a networked computer in Stromboli village. From there data will be downloaded via the web for analysis. We use thermal signal and delay time statistics collected by this system to define cycles of activity, with the aim of achieving a fuller understanding of conduit processes and eruption triggers.

## V21A-1170 0830h POSTER

### Analysis and Modelling of Tornillo Parameters Beneath Tongariro Volcano, New Zealand

Mike T Hagerty[1] (+64-4-570-4537; m.hagerty@gns.cri.nz)

John Haines[2] (haines@esc.cam.ac.uk)

Johanna George[2] (jmg51@cam.ac.uk)

[1]Institute of Geological and Nuclear Sciences, 41 Bell Road South Gracefield, Lower Hutt 30-368, New Zealand

[2]Cambridge University, Bullard Laboratories Madingley Road, Cambridge CB3 OEZ, United Kingdom

Low-frequency, quasi-monochromatic seismic events called tornillos have been recorded beneath Tongariro Volcano, New Zealand, for over one year as part of our routine volcano surveillance. As the waveforms and characteristics are similar to those recorded at Galeras Volcano in Colombia, where tornillos have been found to precede small to medium-sized eruptions, we are monitoring them closely. We have compiled a one year time series of measurements of tornillo properties e.g., peak frequencies and amplitudes, peak widths, number of events per day.

The resulting series show some interesting trends. The dominant frequency peak (near 1.2Hz) systematically increased from the beginning to the middle of 2001, before decreasing to its lowest values during September and October, 2001. The low values of frequency are coincident with a peak in the number of tornillo events per day and a decrease in the width of the 1.2 Hz peak width.

We attempt to model the tornillo events with a crack containing a viscous fluid embedded in an elastic solid. Because of their extremely low phase velocities (c∼1 km/s), we assume that the tornillos consist primarly of S waves. Most existing resonator models result in a predominantly P wavetrain in the far-field. Here we present a new model by solving the dispersion equations assuming total internal reflection of P waves within the crack, and transmission into the solid of S waves only.

Taken together, the changes in the tornillo parameters (decreased frequency and increased quality factor, Q) suggest an increase in the gas volume fraction of the magmatic fluid, resulting in an increase in tornillo production. Although the increase in tornillo activity in 2001 did not end in eruption, the systematic changes in the tornillo parameters provide an indication of the evolution of the magmatic system.

## V21A-1171 0830h POSTER

### Seismicity Rate and Volcano Dynamics at Piton de la Fournaise Volcano (Indian Ocean)

Marielle Collombet[1] (marielle.collombet@obs.ujf-grenoble.fr); john bob Grasso[1] (grasso@obs.ujf-grenoble.fr); valerie Ferrazzini[2] (feraz@ipgp.jussieu.fr); P. Bachelery[2] (bachel@iremia.univ-reunion.fr); Jean-Louis Cheminee[2] (chemine@ipgp.jussieu.fr); Jean-Claude Delmond[2]; Hugues Delormes[2] (delorm@ipgp.jussieu.fr); Alfred Hirn[2] (Hirn@ipgp.jussieu.fr); Philippe Katherine[2] (katerine@ipgp.jussieu.fr); P. Kowalski[2] (Kow@ipgp.jussieu.fr); Jean-Claude Lepine[2] (Kow@ipgp.jussieu.fr); Louis-Philippe Ricard[2] (Kow@ipgp.jussieu.fr); Thomas Staudacher[2] (staudacher@ipgp.jussieu.fr); Philippe Toachy[2] (Kow@ipgp.jussieu.fr); Jean-Paul Toutain[2] (Kow@ipgp.jussieu.fr)

[1]lgit, bp 53, grenoble 38041, France

[2]Ovpf, plaines des cafres, bourg murat 97418, France

Using the daily seismicity rate that is one of the primary observation on most volcano observatories, date and time of eruption on Piton de la Fournaise (PdF) are difficult to foresee except within a few hours from the surface lava flow. When using superposed epoch analysis to average the seismicty rate before the 15 eruptions of the April 1988 - September 2001 period, we find an increase of seismicity rate 10-15 days from the eruption time. During the last 6 days, the daily seismicity rate diverges as $(t_e - t)^{-\alpha}$, $t_e$ being the eruption time. This behavior is statistically significant when comparing the observation to the results from a randomised seismicity catalog on the 1988-2001 period. This average behavior argues for pre-eruptive processes to occur 10-15 days from eruption time even if this pattern is not recovered individualy for each eruption. The power-law acceleration of seismic rate when approching the eruption time mimics the increases of Acoustic Emission rates that are reported before failure for a wide range of materials, including crustal earthquakes. This volcano sismicity acceleration, that maps damage of storage capability of the volcano edifice, possibly argues for the eruption to be the end product of a damage process that last for 10-15 days on PdF volcano, for the studied period.

## V21A-1172 0830h POSTER

### Unusual Hybrid Earthquakes at Shishaldin Volcano, Alaska

Jacqueline Caplan-Auerbach[1] (907-474-6014; jackie@giseis.alaska.edu)

Tanja Petersen[1] (907-474-6171; tanja@giseis.alaska.edu)

Stephen R. McNutt[1] (907-474-7131; steve@giseis.alaska.edu)

[1]Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr., Fairbanks, AK 99775-7320, United States

Since it last erupted in April 1999, Shishaldin volcano (Alaska) has exhibited an extremely high level of background seismicity with hundreds of small earthquakes occurring each day. Most of the recorded events are low frequency (1-2 Hz), with hypocentral locations at shallow depths (0-3 km) beneath the summit. On March 13 2002, however, following several days of relative quiescence, a sequence of hybrid earthquakes began. Each hybrid event consists of a high-frequency (4-7 Hz) signal, followed by a low frequency (1-2 Hz) portion. Unlike hybrid events detected at other volcanoes, the timing between the high and low frequency phases changes dramatically over the course of hours. In some cases the low frequency portion follows immediately after the high frequency precursor, while at other times there may be as much as a 15 second delay between the two phases. In March and April 2002, there was a strong degree of variability in the delay time between high and low frequency phases. In May and June, however, the system appeared to stabilize, with episodes of low-frequency phases occurring at fixed times (approximately 10-12 seconds after the high-frequency precursor). The high frequency waveforms are extremely similar, suggesting a fixed, repeating source. Neither phase exhibits clear S-waves, and both have extended codas. We propose that the hybrid events represent the excitation of two fluid bodies within the edifice and that vibrations set up within the first reservoir trigger resonance in the second. The large variability in delay time between the two phases suggests that the triggering mechanism itself moves at variable speed. Furthermore, the fact that the delay time can be as much as 15 seconds for two sources within the volcanic edifice requires that at times the trigger moves extremely slowly. Possible triggering mechanisms include seismic energy moving through a foam layer, or direct transport of energy via a rising gas bubble. Both mechanisms require a large amount of gas in the system, consistent with observations of a ubiquitous steam plume at Shishaldin's summit.

## V21A-1173 0830h POSTER

### Temporal Distribution and Rates of Repetitive Low-Frequency Earthquakes at Shishaldin Volcano, Alaska

Tanja Petersen[1] (907-474-6171; tanja@giseis.alaska.edu)

Jacqueline Caplan-Auerbach[1] (907-474-6014; jackie@giseis.alaska.edu)

Stephen R. McNutt[1] (907-474-7131; steve@giseis.alaska.edu)

[1]Alaska Volcano Observatory, Geophysical Institute, University of Alaska Fairbanks, 903 Koyukuk Dr., Fairbanks, AK 99775-7320, United States

Since the 1999 eruption of Shishaldin volcano, Alaska, the network monitoring its seismic activity has recorded a continuously high background level. We observed up to ∼700 low-frequency (1-2Hz) earthquakes per day with M $\geq$ 0.5 originating beneath the summit within the volcanic edifice, although 300-500 events per day are more typical. The event sizes vary but the vast majority of events are below M=1.0 and the largest event has a magnitude of 1.8. The events which meet a certain selection criteria show episodes of increased numbers higher than any other monitored volcano in Alaska. Some of the events have similar waveforms, which may represent a repeating source process. They can be classified as distinct families segregated by differences in waveform. The dominance of a given family lasts for a time period of several days to months until it gradually decreases. Some of the observed event families are characterized by a later phase interpreted to be a ground-coupled airwave. These events occurred in September–October 1999 (up to 26 per day), from December 1999 through February 2000 (up to 213 per day), in May–June 2000 (up to 73 per day) and from July–September 2000 (up to 93 per day). Other events are hybrid in nature, starting in March 2002. In August 2002, some of the hybrid events (up to 33 per day) show an airwave phase. A waveform cross-correlation technique has been applied to extract individual low-frequency event types. Using the rates and magnitudes above, we estimate that Shishaldin has been producing the equivalent of one M=3.0 to 3.5 earthquake per day. This rate is far higher than that for any other monitored volcano in Alaska, exceeding most by 3 to 4 orders of magnitude. Even though details of the physical processes acting at Shishaldin are not known, this is a significant energy release at one of the most active volcanoes in Alaska.

## V21A-1174 0830h POSTER

### Erta Ale Lava Lake: Identification and Modelling of Variable Convective Regimes

Roberto Carniel[1] (39-0432-558749; carniel@dgt.uniud.it)

Andrew J.L. Harris[2] (1-808-956-3157; harris@higp.hawaii.edu)

Josh Jones[3] (1-206-543-5255; josh@ess.washington.edu)

[1]Universita' di Udine, Dip. Georisorse e Territorio Via Cotonificio, 114, Udine, UD 33100, Italy

[2]HIGP/SOEST University of Hawai'i, 2525 Correa Road, Honolulu, HI 96822, United States

[3]Dept.Earth & Space Sciences, University of Washington, Box 351310, Seattle, WA 98195-1310, United States

After more than twenty years without access to Erta Ale volcano, field campaigns are once again feasible. Between February 15 and February 20, 2002, a combined thermal and seismic data set was recorded at Erta Ale volcano, Ethiopia, to study activity of the persistent lava lake. Analysis of continuous tremor and thermal fluctuations suggests that lava lake activity, as recorded by temperature variations, is related to seismic energy and spectral content. When we compare these parameters at timescales of minutes to hours, we find that correlations range from good to poor. However, these two parameters do not significantly correlate on timescales of a full day. Both thermal and seismic data indicate that the lava lake exhibits cyclical behavior between 20 to 80 minute periods characterized by low (∼0.05 $ms^{-1}$) and high (∼0.2 $ms^{-1}$) rates of convection, respectively. We use our measurements to constrain two models to explain these 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 $m^3s^{-1}$ and low convection rate phases

fed by a magma volume flux of 0.03 $m^3 s^{-1}$. 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 increases the buoyancy of the lower layer, and eventually triggers 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. We find that the second model, whereby cyclic convection is generated by processes acting within the lake, is more plausible.

## V21A-1175 0830h POSTER

### Long-lasting Dike Intrusion in the 2000 Eruption of Miyake-Jima Volcano: Creep or Chamber deflation?

Koshun Yamaoka[1] (+81-52-789-3034; yamaoka@seis.nagoya-u.ac.jp)

Takeshi Kudo[2] (+81-572-66-2233; kudo@tono.jnc.go.jp)

Masahi Kawamura[1] (+81-52-789-3040; kawamura@eps.nagoya-u.ac.jp)

Naoyuki Fujii[1] (+81-52-789-3035; fujii@seis.nagoya-u.ac.jp)

[1]Res. Cntr for Seismology and Volcanology, Nagoya University, 1 Furo, Chikusa, Nagoya 4648602, Japan

[2]Tono Geoscience Center, Japan Nuclear Cycle Development Institute, 1-63 Yamanouchi, Meiseicho, Mizunami 5096132, Japan

The model for the 2000 intrusive event between Kozu-jima and Miyake-jima volcano, Japan, was reinvestigated. After the sudden earthquake swarm in Miyake-jima volcano, a dike intrusion of large volume lasting for two months was detected by the nation wide GPS network (Geonet). We extracted the step-wise displacement of the GPS station by fitting a function which represents a step, a linear trend and an annual sinusoidal variation. The displacements due to the dike intrusion were detected with stations in the area with a radius of about 200km. The displacement we obtained shows a distribution that is consistent with the idea that the source is located near Miyake-jima volcano.

The displacement apparently indicates that a dyke of large volume was intruded between Miyake-jima and the neighboring Kozu-jima volcano. However, the displacement cannot be reproduce solely by the dike even with some earthquakes associated with the intrusive event. Therefore, Yamaoka et al. (2000) and Nishimura et al. (2001) introduced an aseismic creep near the dike tip opposite to Miyake-jima. The magnitude of the creep that is required corresponds to M7 which is anomalously large. As there is no evidence which support such a large aseismic creep, we tried to explain the deformation with another model.

We, here, introduced a deflation model, which is well know as Mogi model, instead of creep source. We searched for the optimum values for the model with parameter search. We assumed a vertical dike with the length of 20km centerred at the middle of earthquake swarm region. We searched for the azimuth, the depth of the top, the depth extent of the dike and the tensile dislocation for the dike. For the deflation source we assumed that it locates beneath the dike between the depth of 15km and 40km. The optimum solution we obtained for the dike is 42 degree for the azimuth, 2.5 km for the top depth, 14km for the depth extent and 6m for the tensile dislocation. These values correspond to the volume expansion of 1.7km3. For the deflation point source, we obtained the deflation volume of 2.1km3 at the depth of 30km. This model also explains the regional and local pattern of displacement detected by GPS network.

## V21A-1176 0830h POSTER

### A source migration of low frequency earthquakes during the 2000 activity of Miyake-jima volcano, Japan

Tomokazu Kobayashi[1] (+81-3-5841-5697; tkoba@eri.u-tokyo.ac.jp)

Takao Ohminato[1] (+81-3-5841-5767; takao@eri.u-tokyo.ac.jp)

Eisuke Fujita[2] (+81-298-58-1004; fujita@bosai.go.jp)

Yoshiaki Ida[3] (81-792674941; yida@sci.himeji-tech.ac.jp)

[1]Earthquake Research Institute, 1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan

[2]National Research Institute for Earth Science and Disaster Prevention, 3-1, Tennodai, Tsukuba, IBA 305-0006, Japan

[3]Himeji Institute of Technology Global Tectonics, School of Science, 2167 Shosha, Himeji, HYO 671-2201, Japan

The volcanic activity of Miyake-jima started at 18:30 (JST) on June 26, 2000 with large ground deformation and earthquake swarms. The seismic activity started at the southern part of the island. The hypocenter distribution migrated northwestward and slipped away out of the island by early in the morning, June 27. Low frequency (LF) earthquakes with dominant frequencies of 0.2 and 0.4 Hz were first observed in the afternoon of June 27. The LF activity lasted till the first summit eruption on July 8.

Earthquake Research Institute of Tokyo University and National Research Institute for Earth Science and Disaster Prevention deployed 3 CMG-3T and 4 STS-2 broadband seismometers in the island. More than 300 LF earthquakes are detected during the period from June 27 to July 8. Most of the LF events whose dominant frequency is 0.2Hz occurred before July 1, while LF events with dominant frequency of 0.4Hz mainly occurred after July 2.

We determine hypocenters of these LF events by using the following technique. For each LF event, we assume a source location on a grid point in a homogeneous half-space. A reference station is chosen among all the stations. The cross correlation coefficients are computed between the waveform of the reference station and those of other stations. Then, the coefficients for all the stations are summed. In the same manner, summations of the coefficients are computed grid by grid. A grid point that gives the maximum value of the sum of the coefficients is regarded as the best estimate of the source location of the LF event under consideration.

The result shows that hypocenters of LF events are spread over the southern to western part of the island and they migrate from south to the west day by day. Hypocenter migrations associated with volcanic activity have been often reported but usually for short period events. This is one of remarkable cases in which a migration of earthquakes with dominant frequencies as low as 0.2 and 0.4Hz are clearly observed.

## V21A-1177 0830h POSTER

### Mechanisms of Groundwater Level Changes at Volcanoes

Sarah E. Albano[1] (sealbano@u.washington.edu)

Norio Matsumoto[3] (n.matsumoto@aist.go.jp)

Christopher G. Newhall[2] (cnewhall@ess.washington.edu)

Naoji Koizumi[3] (koizumi-n@aist.go.jp)

Tsutomu Sato[3] (sugar@ni.aist.go.jp)

[1]Department of Earth and Space Sciences University of Washington, Box 351310, Seattle, WA 98195-1310, United States

[2]United States Geological Survey Department of Earth and Space Sciences University of Washington, Box 351310, Seattle, WA 98195, United States

[3]Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, AIST Tsukuba Central 7, 1-1-1 Higashi, Tsukuba, Ibaraki 305-8567, Japan

Groundwater level changes associated with eruptions have been observed at Mayon Volcano, Philippines and Usu and Miyake-jima Volcanoes, Japan. Possible mechanisms include strain, uplift or subsidence of the ground surface, boiling away of recharge and changes in the permeability of the aquifer. These mechanisms may work alone or in combination. In order to use such information for eruption forecasting, the specific mechanisms should be determined.

By studying the tidal response of the aquifers and comparing the data with GPS data a previous study showed that crustal deformation can account for the water level changes in deep confined aquifers at Usu. Another study showed localized opening of fractures caused changes in unconfined aquifers six months prior to the eruption. Groundwater level monitoring can be an inexpensive supplement to more precise, but expensive, monitoring systems such as strainmeters and GPS.

Anecdotal evidence at Mayon indicates that the shallow unconfined aquifer water level 8 km from the summit dropped several meters prior to the 1993 eruption. In order to determine the mechanisms responsible for the groundwater level change, MODFLOW is being used to model the groundwater system. The water level change at Mayon was probably caused by a combination of enhanced permeability and rainfall pattern changes. Opening of fractures in the indurated lahar deposits making up the aquifer would increase the permeability. Since the radial distance at which strain changes from dilatation to compression depends on the depth of the source, these water level changes help constrain the estimated depth of intrusion.

Hourly groundwater level measurements of an unconfined aquifer at Miyake-jima show tens of centimeters rises and drops during seismic activity and the caldera forming event in 2000. The water level changes over time are consistent with uplift and subsidence of the ground surface. In systems similar to Miyake-jima hourly water level measurements can be used to supplement GPS data that is collected on a daily basis.

While groundwater level changes in unconfined aquifers are not sufficient to make eruption predictions or restrain models on their own, they can be an inexpensive supplement to more precise deformation data.

## V21A-1178 0830h POSTER

### Deformation monitoring of the new lava dome from 2001-2002 at the Colima Volcano

RAMIREZ RUIZ JUAN JOSE[1] (312-31-61134; ramirez@cgic.ucol.mx)

SANTIAGO JIMENEZ HYDYN (312-31-61134; hydyn@cgic.ucol.mx)

ALATORRE CHAVES ELISEO (312-3161134; eliseo@cgic.ucol.mx)

[1]JUAN JOSE RAMIREZ RUIZ, LIBERTAD No. 242 COLONIA MAGISTERIAL, COLIMA, COL 28020, Mexico

The emplace of the new lava dome at the Colima volcano began in may 2001. It occur afther a still phase of some months denoting the end stage of the 1997-2000 unrest. The lava dome appear without seismicity before and during this extrusion. The deformation parameter monitoring by a system of three electronic inclinometer located around the volcano edifice shows variations that indicate the process of extrusion. The Colima volcano is one of the most active volcanoes Mexico with most than 30 explosive activities in the last 500 years. During the last 500 years the volcano has displayed a cyclic eruptive pattern with alternate explosive and effusive episodes with a period of 100 year. The last big activity occurred in 1913 with an activity of type subplinian-stombolian. Here we show the deformation monitoring of the last extrusion of the lava dome from 2001- 2002 and the correlation with the seismicity and sulphur dioxide emission (SO2) of the gas fumarole. We correlate this parameter before, during and afther the occurrence of this lava dome to describe its evolution.

## V21A-1179 0830h POSTER

### Modelling Long Term Ground Deformation by a Submerged Archaeological Site: the Case of Basiluzzo Island (Aeolian Island, Italy)

Andrea Tallarico[1] (tallarico@geo.uniba.it)

Michele Dragoni[2] (dragoni@ibogfs.df.unibo.it)

Marco Anzidei[3] (anzidei@ingv.it)

Alessandra Esposito[3] (esposito@ingv.it)

[1]Dipartimento di geologia e Geofisica, Universita' di Bari, Via Edoardo Orabona,4, Bari, BA 70125, Italy

[2]Dipartimento di Fisica, Universita' di Bologna, Viale Berti Pichat, 8, Bologna, BO 40127, Italy

[3]Istituto Nszionale di Geofisica e Vulcanologia, Via di Vigna Murata, 605, Roma, RM 00143, Italy

By means of a roman-age submerged wharf, dated 2000 $\pm$ 50 a BP, we modelled the volcanic source which produced the long term vertical deformation of Basiluzzo island, located in the volcanic arc of the Aeolian island (Italy). This is the first attempt to model crustal deformation through a submerged archaeological structure. Nowa-days the top of the wharf, which can be considered as a non conventional levelling benchmark, is located near Punta Levante, at an average depth of 3.20 $\pm$ 0.10 m be-low a.s.l., and it is still in good conservation. Its present location is due to combined effect of sea level uprising, volcanic and tectonic activity occurred since its building. Taking into account the architectural features of the wharf and that the mean sea level uprising for the Mediterranean sea has been estimated in 0.45 m during the last 2000 years, was estimated a total subsidence of 3.75 $\pm$ 0.10 m, at a rate of 1.87 $\pm$ 0.05 mm/a. Our model, considering the Earths crust as a Maxwell body, aims to propose a possible mechanism to explain the long term subsidence on scale of time of thousand years, of a volcanic area, such observed in Basiluzzo island. We can suppose that the observed crustal deformation is mainly due to the slow cooling of a magmatic source located under Basiluzzo dome which underwent to a progressive solidification and a subsequent volume reduction, during the last 50000 years.

## V21A-1180 0830h POSTER

### What Drives a Restless Caldera? Insights From 20 Years of Gravity-Height Data on the Campi Flegrei, Italy

Joachim H Gottsmann[1] (+44-1908-659776; j.gottsmann@open.ac.uk)

Giovanna Berrino[2] (berrino@ov.ingv.it)

Hazel Rymer[1] (h.rymer@open.ac.uk)

Glyn Williams-Jones[3] (glynwj@higp.hawaii.edu)

[1]The Open University, Dep. of Earth Sciences Walton Hall, Milton Keynes MK7 7BL, United Kingdom

[2]INGV - Osservatorio Vesuviano, Via Diocleziano 328, Naples 80124, Italy

[3]Hawaii Institute of Geophysics and Planetology, SOEST, University of Hawai'i at Manoa 2525 Correa Rd., Honolulu, HWI 96822, United States

We have analyzed changes in gravity and ground height between 1981 and 2001 in order to obtain *gravity-height change* ($\Delta g/\Delta h$) *gradients* during unrest at the Campi Flegrei caldera (CFc), Italy. $\Delta g/\Delta h$ gradients during *inflation* and *deflation* are interpreted in terms of sub-surface mass redistribution, density changes or some combination of these. Within the context of a new model, we show that $\Delta g/\Delta h$ gradients obtained from precise gravity-deformation surveys provide valuable contributions to i) determination of the driving mechanism of caldera unrest, ii) forecasting eruptive volcanic activity and iii) assessment of associated hazards. At the CFc, the detailed evaluation of the temporal variations of $\Delta g/\Delta h$ gradients enables the effects of shallow hydrothermal processes to be separated from those of deeper-seated magmatic processes and thus facilitates the identification of magma dynamics within the reservoir. Our analysis suggests that the 1.8 m inflation of the CFc between 1982 and 1984 was caused by the replenishment of the magmatic system beneath the caldera. Thermal relaxation of the magma reservoir associated with some degree of mass loss provides a plausible explanation for the overall pattern of slow deflation since 1984. Large $\Delta g/\Delta h$ gradients associated with short terms of minor inflation of the caldera since 1984, however, appear to represent shallow localized mass/density changes within the hydrothermal system(s) beneath the caldera. For a number of other restless calderas, we report end-member $\Delta g/\Delta h$ gradients that provide a framework from which to infer when these calderas develop from a state of unrest to a state when eruptive activity *must* be anticipated.

## V21A-1181 0830h POSTER

### Are There Regional Differences in the Distribution of Volcanic Gas Emission Into the Atmosphere During the Last Century?

Martina Magdalena Halmer (+49 (0)431-6002128; mhalmer@geomar.de)

GEOMAR -Research Center for Marine Geosciences, Wischhofstrasse 1-3 Abt. Vulkanologie, Kiel 24148, Germany

The statistical asymmetry of volcano distribution is the reason why latitude, altitude of the volcano, tectonic setting and season of the year have a significant influence on the quantity of volcanic gas emissions, especially those reaching the stratosphere, in high dependence on. The evaluation of the geographic distribution of volcanic gas emissions results in a ratio of 4:5 (N:S) in the tropics ($0^{\circ}$-$30^{\circ}$) (frequency of eruptions from northern [N] to southern [S] hemisphere). We found ratios of 1.5:1 for N:S in the latitudinal interval $30^{\circ}$-$40^{\circ}$, 2:1 (N:S) in $40^{\circ}$-$50^{\circ}$, and 5:1 (N:S) between $50^{\circ}$-$60^{\circ}$. The eruption frequencies in the polar latitudes (60-90) result in a N:S ratio of 1:1. All eruptions that emitted gas into the atmosphere during the past century are included in the ratios. The ratios are very similar for those eruptions that injected their gas directly into the stratosphere. Volcanoes between the 50th and 60th latitude generally can inject gas more frequently into the stratosphere. We calculated a ratio of 5:4 (N:S) for stratospheric eruptions. Volcanoes between $30^{\circ}$ and $40^{\circ}$ (ca. 2 eruptions/a reaching the stratosphere; N and S) and also between $40^{\circ}$ to $50^{\circ}$ (ca. 2 eruptions/a; N and S) contribute less to the stratospheric gas input. Approximately 20 percent of volcanic plumes of all subaerial eruptions are able to reach the stratosphere.

URL: http://www.geomar.de/∼mhalmer

## V21A-1182 0830h POSTER

### Investigating Statospheric Loss Rates of Volcanic SO2

Jeremy M. Shannon[1] (906-487-3098; jmshanno@mtu.edu)

Gregg J.S. Bluth[1] (906-487-3554; gbluth@mtu.edu)

A. J. Prata[2] (Fred.Prata@csiro.au)

[1]Michigan Tech University, 1400 Townsend Dr., Houghton, MI 49931, United States

[2]CSIRO Atmospheric Research, PB 1 Aspendale, Victoria 3195, Australia

Explosive volcanism is the predominant pathway for sulfur species to enter the stratosphere. The most important species is sulfur dioxide (SO2) which subsequently converts to sulfuric acid (H2SO4) aerosol particles. The aerosol particles have relatively long lifetimes in the dry, stable stratosphere and have potential consequences for both climate and atmospheric chemistry. The aerosol particles can reflect incoming solar radiation, but can also absorb outgoing radiation. Also, the surfaces of aerosol particles catalyze other chemical reactions by providing a surface for additional reactions to take place. To better understand and constrain these effects, it is necessary to examine the chemical fate and transport of volcanogenic SO2 emplaced in the stratosphere.

Since 1978, detection and quantification of stratospheric SO2 from explosive eruptions have been predominantly accomplished with the Total Ozone Mapping Spectrometer (TOMS). To date, over 100 eruptions have been detected. However, to study the fate and transport of volcanic SO2, the cloud must be generated from a discrete event and be observable for multiple days. Although the TOMS database contains many detected events, only infrequent, powerful eruptions produce large SO2 clouds that reach the stratosphere and have multiple-day lifetimes. Thus, SO2 loss rates in the stratosphere have been difficult to study with TOMS for lack of sufficient statistical data. More recently, an SO2 retrieval algorithm has been developed for the Tiros Operational Vertical Sounder (TOVS) suite of instruments. TOVS data cover nearly the same 24 year period as TOMS, and provide valuable validation and comparison information.

In this study, we begin a comparative analysis of the available multiple-day SO2 clouds observed by TOMS and TOVS throughout their 24 year record. SO2 clouds from explosive eruptions have been chosen and processed using the latest algorithms. These eruptions include Mt. St. Helens (1980), El Chichon (1982), Cerro Hudson (1991), Mt. Pinatubo (1991), and Mt. Spurr (1992). We examine the influence of total erupted tonnage, latitude, eruption altitude, and meteorological conditions on the SO2 loss rates calculated for each eruption. Preliminary results show that e-folding times are proportional to altitude and total mass, but inversely proportional to temperature.

## V21A-1183 0830h POSTER

### Continous Monitoring of Diffuse Soil Degassing on mt. Etna (Italy)

Sergio Gurrieri[1] (390916809438; peppo@pa.ingv.it)

Gaetano Giudice[1] (ggiudice@pa.ingv.it)

[1]Istituto Nazionale di Geofisica e Vulcanologia, V.Ugo La malfa 153, Palermo 90146, Italy

Mt. Etna is an active volcano located in the Southern region of Italy, its last eruption was in July 2001. Periodical surveys on this volcano were carried out since 1989 in order to measure diffuse CO2 flux from soil. The acquired data suggest a strong dependance of peripheral soil gas emissions from volcanic activity. In particular, rapid decreases of diffuse emissions were observed before the onset of the eruption 1989 and 1991-1993 and very low values were also observed during all the eruptive phases. These data were interpreted as an increase of the gas drainage capability of the eruptive vents to the detriment of the peripheral areas (Giammanco et al.1995).

According to these observations a soil gas network was designed in order to acquire more information on volcanic activity. The whole project consists of 15 remote stations located on the South and East side of the volcanic edifice where periodical surveys highlighted the highest values of diffuse soil gas emissions.

Each remote stations of the gas network is able to measure CO2 and CH4 fluxes from soil according to the method proposed by Gurrieri & Valenza (1988). Moreover, the stations are also equipped with several sensors to measure soil water content (which gives indirect information of soil permeability variations with rainfall) and the atmospheric parameters: pressure, temperature, relative air water content, rainfall, wind speed and wind direction.

A very low correlation has been found between soil degassing and atmospheric parameters in areas characterised by strong soil gas emissions. This seems to be due to the volcanic trend at the measuring time, which totally overlapped the flux variations induced by atmospheric variations.

URL: http://www.pa.ingv.it

## V21A-1184 0830h POSTER

### Geochemical Precursors to a Minor Explosive Eruption at Masaya Volcano, Nicaragua

Hayley J Duffell[1] (+44 1223 333464; hjd26@cam.ac.uk)

Clive Oppenheimer[2] (co200@cam.ac.uk)

David M Pyle[1] (dmp11@esc.cam.ac.uk)

Bo Galle[3] (bo.galle@ivl.se)

Mike R Burton[4] (burton@ct.ingv.it)

[1]Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge, CB2 3EQ, United Kingdom

[2]Department of Geography, University of Cambridge, Downing Place, Cambridge CB2 3EN, United Kingdom

[3]Department of Radio and Space Science, Chalmers University of Technology, Gothenburg S-412 96, Sweden

[4]Istituto Nazionale di Geofisica e Vulcanologia, 2 Piazza Roma, Catania 95125, Italy

A small explosive eruption at Masaya volcano on 23rd April 2001 was preceded by a change in plume gas ratios and fluxes measured by open path Fourier transform spectroscopy (FTS) and other spectroscopic techniques. Between April 2000 and April/May 2001 the $SO_2$/HCl molar ratio increased from 1.8 to 4.6, and the $SO_2$ flux decreased from 11 to 4 kg $s^{-1}$. These changes are interpreted to be the result of scrubbing of water-soluble magmatic gases by a rejuvenated hydrothermal system. The increased magmatic-hydrothermal interaction may have been caused by a sequence of M5 earthquakes with epicentres about 7 km from the volcano in July 2000, altering the fracture permeability close to the magmatic conduit, leading, in a few months, to the phreatic eruption in 2001.

## V21A-1185 0830h POSTER

### The Use of Chemical Traps to Determine Metal and Halogen Flux From Mt. Erebus, Antarctica

Lois J Wardell[1] (505-835-5994; wardell@nmt.edu)

Philip R Kyle[1] (505-835-5995; kyle@nmt.edu)

Dale Counce[2] (counce@ees-mail.lanl.gov)

[1]New Mexico Institute of Mining and Technology, 801 Leroy Place, Socorro, NM 87801, United States

[2]Los Alamos National Laboratories, EES-1, Los Alamos, NM 87545, United States

Volcanic emission rates of As, Sb, Pb, Hg, Se, Cl, and F were determined at Mt. Erebus, Antarctica, based on chemical traps using 4M NaOH solutions. The trace element emission rates were determined using the species to S ratios in the solutions with independently determined SO2 emission rates measured by correlation spectrometer. At Mt. Erebus, metal flux values for Pb = 2x10-3 and Hg = 6x10-4 kgs-1 were determined. Fluxes for Cl, F, As, Se and Sb (0.32, 0.13, 2.3x10-4, 1.2x10-4, and 1.0x10-5 kgs-1, respectively) agreed within error limits for values determined by the LiOH impregnated filter method (Zreda-Gostynska et al., 1997), which demonstrates the utility of the chemical trap method. The traps were effective under extreme environmental conditions typical at Mt. Erebus. Using a simple box model, the estimated average concentration of Pb in snow distributed over the entire Antarctic continent is 6.1 ngkg-1. This implies that the Pb flux from Mt. Erebus is sufficient to account for Pb concentrations in snow and ice samples from South Pole and Dome C that were previously attributed to anthropogenic sources (Rosman et al., 1994).

## V21A-1186 0830h POSTER

### Temperatures of Thermal and Slightly Thermal Springs on Mount Hood, Oregon, Apparently Unperturbed by the Magnitude-4.5 Earthquake on June 29, 2002

Manuel Nathenson[1] (1-650-329-5292; mnathnsn@usgs.gov)

Robert H. Mariner[1] (1-650-329-4507; rmariner@usgs.gov)

[1]U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025, United States

On the basis of water chemistry, three distinct hydrothermal systems have been identified on Mount Hood. Swim Warm Springs has a series of vents with

temperatures ranging from 9° to 25°C with temperatures determined by mixing of thermal and nonthermal water. The hottest feature was 25.6° to 26.2°C in 1976-78, 25°C in 1997, and 24.7°C in 2001. The hot-water component is interpreted to have a source water that boiled from 187°C, re-equilibrated at 96°C, and then mixed with nonthermal water to produce the range of compositions found in various springs. The Meadows Spring is a slightly thermal spring with measured temperatures of 4.8°, 6.1°, 6.6°C in 1997, 1999, and 2001 related to mixing of thermal and nonthermal water. The hot-water component is interpreted to have a source water that boiled from 223°C, re-equilibrated at 94°C, and then mixed with nonthermal water to produce the range of compositions found in the spring over several years. Both systems contain water from precipitation at high elevation. The summit fumaroles have gas-geothermometer temperatures generally over 300°C, indicating that they are not the steam discharge from the Swim and Meadows hydrothermal systems. Field measurements in July-August, 2002, after the magnitude-4.5 earthquake of June 29, 2002, showed that the highest-temperature vent at Swim Warm Springs was 25.7°C, similar to values found in other years. Measurements on a hot afternoon and a cool morning yielded temperatures of 25.7° and 25.2°C, indicating that this low-flow feature is subject to some solar heating. The Meadows Spring was 6.3°C, consistent with its previous behavior of mixing. The lower temperature indicates that there is a variability associated with unknown hydrologic factors rather than confirming an apparent trend of continuously increasing temperatures for the 1997-2001 period. The Crater Rock fumarole was 89°C, similar to previous measurements. Post-earthquake measurements of spring temperatures show no obvious effect of the 6-km-deep earthquake on the Swim, Meadows, and Crater Rock hydrothermal systems. However, the lack of any surficial effects does not preclude the possibility of change at depths below that sampled by the springs.

## V21A-1187 0830h POSTER

### Probabilistic Modeling of Tephra Dispersion using Parallel Processing

Thea Hincks[1] (t.hincks@bristol.ac.uk)

Costanza Bonadonna[1] (co_bonadonna@hotmail.com)

Laura Connor[2] (laura.connor@netscape.net)

Charles Connor[2] (cconnor@chuma1.cas.usf.edu)

Steve Sparks[1] (steve.sparks@bris.ac.uk)

[1]Department of Earth Sciences, Wills Menorial Building University of Bristol, Bristol BS81RJ, United Kingdom

[2]Department of Geology, University of South Florida, Tampa, FL 33549, United States

Numerical models of tephra accumulation are important tools in assessing hazards of volcanic eruptions. Such tools can be used far in advance of future eruptions to calculate possible hazards as conditional probabilities. For example, given that a volcanic eruption occurs, what is the expected range of tephra deposition in a specific location or across a region? An empirical model is presented that uses physical characteristics (e.g., volume, column height, particle size distribution) of a volcanic eruption to calculate expected tephra accumulation at geographic locations distant from the vent. This model results from the combination of the Connor et al. (2001) and Bonadonna et al. (1998, 2002) numerical approaches and is based on application of the diffusion advection equation using a stratified atmosphere and particle fall velocities that account for particle shape, density, and variation in Reynolds number along the path of decent. Distribution of particles in the eruption column is a major source of uncertainty in estimation of tephra hazards. We adopt an approach in which several models of the volcanic column may be used and the impact of these various source term models on hazard estimated. Cast probabilistically, this model can use characteristics of historical eruptions, or data from analogous eruptions, to predict the expected tephra deposition from future eruptions. Application of such a model for computing a large number of events over a grid of many points is computationally expensive. In fact, the utility of the model for stochastic simulations of volcanic eruptions was limited by long execution time. To address this concern, we created a parallel version in C and MPI, a message passing interface, to run on a Beowulf cluster, a private network of reasonably high performance computers. We have discovered that grid or input decomposition and self-scheduling techniques lead to essentially linear speed-up in the code. This means that the code is readily adaptable to Bayesian updating for application in near-real time in volcanic crises. Conditional probability maps of expected tephra accumulation are compared with deposits resulting from eruptions of the Soufriere Hills Volcano (Montserrat), Cerro Negro volcano (Nicaragua). This code is freely distributed and open-source.

URL: http://www.cas.usf.edu/~cconnor/parallel/tephra/tephra.html

## V21A-1188 0830h POSTER

### Modelling the Effects of Magma Properties, Pressure and Conduit Dimensions on the Seismic Signature

Susan Sturton[1] (susan@earth.leeds.ac.uk)

Jürgen Neuberg[1] (locko@earth.leeds.ac.uk)

[1]School of Earth Sciences, University of Leeds, Leeds LS2 9JT, United Kingdom

A finite-difference scheme is used to model the seismic radiation pattern for a fluid filled conduit surrounded by a solid medium. Seismic waves travel slower than the acoustic velocity inside the conduit and the propagation velocity is frequency dependent. At the ends of the conduit the waves are partly reflected back along the conduit and also leak into the solid medium. The seismometer signal obtained is therefore composed of a series of events released from the ends of the conduit. Each signal can be characterised by the repeat time of the events and the dispersion seen within each event. These characteristics are dependent on the seismic parameters and the conduit dimensions.

For a gas-charged magma, increasing the pressure with depth reduces the volume of gas exsolved, thereby increasing the seismic velocity lower in the conduit. From the volume of gas exsolved, profiles of seismic parameters within the conduit and their evolution with time can be obtained. The differences between a varying velocity with depth and a constant velocity with depth are seen in the synthetic seismograms and spectrograms. At Soufriere Hills Volcano, Montserrat, single hybrid events merge into tremor and occasionally gliding lines are observed in the spectra indicating changes in the seismic parameters with time or varying triggering rates of single events. The synthetic seismograms are compared to the observational data and used to constrain the magnitude of pressure changes necessary to produce the gliding lines. Further constraints are obtained from the dispersion patterns in both the synthetic seismograms and the observed data.

## V21A-1189 0830h POSTER

### Software for Preliminary Location Shallow Explosions, at Colima Volcano, Mexico

Pablo J Gonzalez Mendez[1,2] (+49 304224153; polkesi@yahoo.es)

Eliseo Alatorre[3] (+52 312 31000; eliseo@cgic.ucol.mx)

Tonatiuh Dominguez[3] (tonatiuh@cgic.ucol.mx)

Carlos Navarro-Ochoa[3] (naoc@cgic.ucol.mx)

Mauricio Breton Gonzalez[3] (mauri@cgic.ucol.mx)

[1]Faculty of Sciences. Department of Geology, Granada University, Campus de Fuentenueva, s/n, Granada 18071, Spain

[2]Faculty of Geosciences. Department of Geophysical, Free University, Malteser Str., 74-100, Berlin 12249, Germany

[3]Colima Volcanological Observatory. Universidad de Colima, Av. Gonzalo Sandoval, 444, Colima, Col 28045, Mexico

The Colima Volcano (19.51°N, 103.61°W) had been considered, historically, the most active volcano in Mexico, located in west side of Trans Mexican Volcanic Belt, this stratovolcano has andesitic activity: explosive eruptions of sub-plinian type, with generation of piroclastic flows and fall deposits, and effusive eruptions that generated block-lava domes and flows. The most recent eruption is a sample for this, it was erupted since May of 2001, with generation of summit dome and little lava flows. Result of comparison between the pictures from visual monitoring network and explosive events of low magnitude recorded in RESCO (State of Colima Seismic Network), we observed that surface expression of explosive events and its seismic record had a variable temporal delay. This fact motivated us to define the zone where this dynamical process takes place (the zone where the pressure of gasses contained into bubble overcomes confined pressure for the magma and that had seismic and visual expressions). Particles movement and spectral analysis of seismic records show that each explosive event is composed of body and surface waves, moreover, shock waves are also observed for near stations. From Arrival times of these phases and group velocities, we obtained a multilayer structural model for more proximal region to the volcano that satisfied our observations. We plotted a Wadatis Diagram for body and surface waves and added a simple correction to obtain the origin time. A simple PC program for location of these explosive events was implemented. A small correlation between explosive events and tremor volcanic duration for the tremors which occurred during the months of April, May and early June of 2002 was also observed. Location of the source of the small explosions is another tool of surveillance that could be added to those which are already been carried out in Colima, since temporary or space variations of these sources could inform from physical changes in the behavior of the volcano.

## V21A-1190 0830h POSTER

### A Numerical Simulation of Magma Motion and Seismic Wave Radiation Associated with a Volcanic Eruption

Takeshi Nishimura[1] (+81-22-217-3948; nishi@aob.geophys.tohoku.ac.jp)

Bernard Chouet[2] (chouet@usgs.gov)

[1]RCPEV, Tohoku Univ., Aoba-ku, Sendai 980-8578, Japan

[2]USGS, Middlefield, Menlo Park, CA 94025, United States

We apply the finite difference method to calculate the magma motions and seismic wave radiation associated with a volcanic eruption. Our model consists of a cylindrical reservoir and narrow cylindrical conduit embedded in a homogeneous crust. A lid caps the vent and a plug blocks the flow of magma between the chamber and conduit. The magma reservoir is overpressurized prior to the eruption. The sudden removal of the plug triggers the transfer of magma from the chamber to the conduit, and an eruption occurs when the pressure at the conduit orifice exceeds the strength of the lid capping the vent. The exit pressure remains fixed to the atmospheric pressure throughout the eruption. Magma dynamics is expressed by the equations of mass and momentum conservations in a compressible fluid, in which the vesiculation process associated with depressurization is accounted for by a constitutive law relating pressure and density. Seismic waves are calculated from the equations of elastodynamics. The fluid and solid are dynamically coupled by applying the continuity of wall velocities and normal stresses across the conduit and reservoir boundaries. Free slip is allowed at the fluid-solid boundary. Our numerical simulations show that (1) the removal of the plug generates a compression wave which propagates up the conduit, and a rarefaction wave which propagates into the chamber; (2) a high-amplitude pressure pulse occurs at the lid when the magma impinges the lid, causing the failure of the lid; (3) the magma reservoir gradually deflates, and (4) superimposed on the reservoir deflation are decaying long-period oscillations caused by acoustic resonance in the reservoir. Magma motions are detected as (1) seismic signals prior to an eruption; (2) large-amplitude Rayleigh waves excited by the rupture of the lid; and (3) a gradual subsidence of the crust and (4) periodic oscillations of the seismic waves. These characteristics of the simulated seismic wave field are often observed at volcanoes such as Sakurajima, Tokachi, and Popocatepetl. The strength of the lid plays an important role in shaping up seismic waveforms associated with Vulcanian eruptions.

## V21A-1191 0830h POSTER

### Quantitative Vent Discrimination at Stromboli Volcano, Italy

April McGreger[1] (919 962-0695; mcgreger@email.unc.edu)

Jonathan M. Lees[1] (919 962-0695; jonathan.lees@unc.edu)

[1]Department of Geological Sciences, University of North Carolina, Chapel Hill, NC 27599-3315, United States

Explosion activity at Stromboli Volcano in May, 2001, was especially intense with numerous vents erupting with repose times of a few minutes. Broadband seismic and infrasonic acoustic recordings captured this activity over a period of 10 days during the 2001 multidisciplinary STROBE Experiment. During this period the Stromboli vents appear to have consistent seismic and acoustic source signatures, based on cross correlation cluster analysis and frequency response of the multivariate time series. Cross correlation of the ground displacement response to explosions from specific craters, such as the NE crater, form dense waveform clusters, while displacement waveforms from other craters, such as the SW crater, exhibit slightly weaker clustering. This suggests a more complicated source mechanism operating at the SW crater. Infrasonic arrays allow for the recovery of source origin locations and times, which confirm that the clusters of events are associated with specific vents or, more generally, craters. Detailed analyses of eruptions reveal a correlation between impulsive acoustic waveforms, i.e. the bursting of a single bubble, and shorter, simpler ground displacement responses. Furthermore, similar degassing mechanisms from vents of the NE crater and the Central crater (hornito), show common characteristics in their displacement waveforms. The cross-correlation cluster analyses is a statistical means to develop an understanding of the near surface conduit of multi-vent volcanoes. Combined with other statistical techniques (Settle and McGretchin, 1980), thermal monitoring (Harris et al.,

V

1996), and infrasonic monitoring (Braun and Ripepe, 1993, etc.), the clustering of the broadband recordings of events by cross-correlation analysis provides a valuable tool for developing and testing physical models of the near surface volcanic system operating at Stromboli, and other multi-vent systems. An automated cross correlation cluster procedure provides a mechanism for the analyses of massive continuously recorded datasets where handpicking may be onerous.

### V21A-1192 0830h POSTER

### Information fusion techniques applied to eruption forecasting

Marcus Bursik[1] (mib@geology.buffalo.edu)

Galya Rogova[2] (rogova@rochester.rr.com)

Justin Deming[1] (deming@geology.buffalo.edu)

[1]Department of Geology University at Buffalo, 876 Natural Sciences Complex State University of New York, Buffalo, NY 14260, United States

[2]Center for Multisource Information Fusion, State Unversity of New York, Buffalo, NY 14260, United States

We are assembling a relational database of information on past eruptions of the Mono-Inyo volcanic chain, eastern California. The most fundamental tables within the database contain information on locations at which pits were dug through the volcanic stratigraphy, or at which data were collected on a dome or lava flow. The locations include both those at which new data were collected as well as those in the literature.

Our working hypothesis is that the database will prove useful for unraveling the complex recent volcanic history of the Mono-Inyo chain. The chain consists of an assortment of domes, craters and flows that stretches for 50 km north-south, subparallel to the Sierran range front fault system. Almost all eruptions within the chain probably occurred less than 50,000 years ago. Because of the variety of magma and eruption types, and the migration of source regions in time and space, it is nontrivial to discern patterns of behaviour.

The database allows us to extract the features diagnostic of particular tephra layers, domes or flows. The diagnostic features include depth in the section, layer thickness and internal stratigraphy, mineral assemblage, major and trace element composition, tephra componentry and granulometry, and radiocarbon age.

At the present time, the database can be queried to show all layers of a particular depth, composition, age, etc., using standard statements of the Structured Query Language (SQL). Our goal is to automate the query and report process so that all location data can be queried simultaneously to produce derived tables containing maximum likelihood estimates of vent location, eruption type and eruption age. By statistical analysis of the information in the derived tables, we may be able to produce estimates of future vent locations and times of eruption.

URL: http://www.volcano.buffalo.edu/mmvz

### V21A-1193 0830h POSTER

### Systematic analysis of volcanic ashclouds over a large range of scales using integrated satellite sensors

Gerald Ernst[1] (Gerald.J.Ernst@bristol.ac.uk)

Matthew Watson[2] (watson@mtu.edu)

Gregg Bluth[2] (gbluth@mtu.edu)

Willaim Rose[2] (raman@mtu.edu)

David Schneider[3] (djschneider@usgs.gov)

[1]CEGF, Earth Sciences, University of Bristol, Wills Memorial Building, Queen's Road, Bristol BS8 1RJ, United Kingdom

[2]Michigan Technological University, 1400 Townsend Drive, Houghton, MI 49931, United States

[3]Alaska Volcano Observatory, USGS, Anchorage, AK 99501, United States

Volcanic ashclouds pose increasing hazards to air traffic. To enable accurate detection, tracking, and ultimately nowcasting (ie. near-real-time tracking and short-term forecasting), it is becoming increasingly important to be able to retrieve, in addition to information on SO2 (and aerosols) and ash (ice) mass, and ash (ice) size, key information such as cloud peak height, average height and height of the leading cloud edge, intensity changes, lateral and downwind spreading, ash/gas separation, evidence of microphysical changes (eg. mixed-phase aggregation), duration and cloud thickness. Here, we have systematically examined radar data and satellite data from a variety of sensors in combination with field and meteorological information (eg. balloon soundings) for a number of ashclouds covering a large range of spatial and temporal scales, as well as a large range of eruption intensity and meteorological conditions. We illustrate that the analysis of detailed surface features such as the overshoot geometry, cloud top gravity waves and cloud top or cloud edge Kelvin-Helmholz (K-H) shear billows can supply key additional information, compared to previous studies. We document that the overshoot size allows extraction of an independent estimate of cloud-top average height, that the number and characteristics of gravity waves allow to derive another independent estimate of column height as well as information on the height difference between peak and neutral buoyancy heights (Ht-Hb). These estimates are compared with estimates of cloud edge height extracted using the shadow method and also comparisons with wind profiles data, and also lead to the identification of ash/gas separation in some cases. The gravity waves can be understood by analogy with fluid mechanics modelling of mixed region collapse in a stratified fluid. Conditions for the development of K-H billows are also considered and we show how they can be used to identify the transition from the gravity-advection flow phase and the advection-diffusion phase of spreading. We also discuss their potential use in deriving ashcloud thickness from the quasi-2D satellite images. This, together with the information from ash-gas separation and gravity waves, enables to extract 3D information from quasi-2D satellite images. Implications of this work for generic understanding of processes in ashclouds and for aircraft safety are briefly discussed.

## V21B MCC: Hall C Tuesday 0830h

### Volcanic Gases Posters

***Presiding:*** **L Jaffe,** University of California, San Diego

### V21B-1194 0830h POSTER

### The Effects of Persistently Degassing Volcanoes on the Natural Environment as Exemplified by Kilauea, Masaya and Poás Volcanoes.

Glyn Williams-Jones[1] (glynwj@higp.hawaii.edu)

Luke Flynn[1] (flynn@higp.hawaii.edu)

Andrew J.L. Harris[1] (harris@higp.hawaii.edu)

Barbara Gibson[2] (bgibson@hawaii.edu)

Peter J. Mouginis-Mark[1] (pmm@higp.hawaii.edu)

[1]HIGP/SOEST, University of Hawai'i at Manoa, 1680 East-West Rd, POST 602, Honolulu, HI 96822, United States

[2]Department of Geography Environmental Studies, University of Hawai'i at Hilo, 200 W. Kawili St., Hilo, HI 96720, United States

While the effects on the global environment of large volcanic eruptions have been frequently studied, there has been little work on the impact of lower tropospheric emissions from persistently degassing volcanoes. In contrast to large volcanic eruptions which may have a short term but hemispheric/global effect (through injection of gas and ash into the stratosphere), persistently degassing volcanoes can have significant long-term (years to decades), local and regional effects. To examine these effects, we consider 3 persistently active degassing systems: Kilauea (USA), Poás (Costa Rica) and Masaya (Nicaragua). These volcanoes are characterized by $SO_2$ emission rates ranging from 100s to 1000s metric tonnes per day, and have emitted acid gases into the troposphere for extended periods of time. Masaya, for example, has degassed approximately the same amount of $SO_2$ (21 Tg) over a period of 140 years as the 1991 eruption of Mount Pinatubo injected into the atmosphere in just a few hours. The extended degassing at Kilauea, Masaya and Poás impacts on commercial agriculture and has led to attempts to mechanically mitigate the hazard through capping of the active crater at Masaya and flooding to reinstate the acid crater lake at Poás. In order to investigate the environmental effects of persistent degassing, we use remote sensing data (Landsat ETM+, IKONOS) with NDVI band ratio algorithms to delineate poorly vegetated areas downwind of each volcano. These data are incorporated, through a GIS, with DEM and various ground truth data (soil pH, dry deposition rates, precipitation acidity, etc). Extremely distinct zones of vegetation kill off are noted that correlate with changes in topography. It appears that sharp topographic changes allow the gas plume to decouple or couple with the ground, hence lessening or increasing its impact at any down wind location. This integrated study of degassing at persistently active volcanoes may aide in limiting the effects on human populations and agriculture downwind of such systems through improved land use management.

### V21B-1195 0830h POSTER

### Soil $CO_2$ and $H_2$ Efflux Distribution Along the North-South Rift Zone at Tenerife, Canary Islands

M. C. Hernández[1]; S. M. Dionis[1]; D. de la Rosa[1]; I. Galindo[2]; J. M. L. Salazar[2]; P. A. Hernández[2]; N. M. Pérez[2] (nperez@iter.rcanaria.es)

[1]Universidad de La Laguna, Avda. Astrofisico Fco. Sanchez, Tenerife, La Laguna 38206, Spain

[2]Environmental Research Division, ITER, Granadilla, Tenerife, Canary Islands 38611, Spain

Volcanic activity at Tenerife is mainly concentrated along three major volcanic rift-zones of NE-SW, NW-SE, and N-S directions as well as in the central part of the island where the Teide stratovolcano located. The goal of this study is to evaluate diffuse $CO_2$ and $H_2$ degassing through the N-S volcanic rift-zone and compare these results with those observed for the NE and NW rift-zones.

Surface degassing surveys were performed along the NW and NE rift-zones during the summer of 2000 and 2001, respectively. From July 18 to August 16, 2002, a new survey was performed along the N-S rift-zone covering an area of 352 $Km^2$. Soil $CO_2$ efflux reached values up to 44 $g m^{-2} d^{-1}$. Soil gas samples were collected at a 40 cm depth to estimate soil $H_2$ efflux by means of multiplying $H_2/CO_2$ ratio times soil $CO_2$ efflux. Soil $H_2$ efflux reached values up to 25 $mg m^{-2} d^{-1}$. The total output of diffuse degassing rate from the study area was estimated about 412 $t d^{-1}$ for $CO_2$ and 290 $Kg d^{-1}$ for $H_2$. The NW rift-zone surface degassing survey covered an area of 72 $Km^2$ and showed rates of 283 $t d^{-1}$ and 74 $Kg d^{-1}$ for diffuse $CO_2$ and $H_2$ degassing, respectively. The NE rift-zone degassing survey covered an area of 210 $Km^2$ and showed rates of 685 $t d^{-1}$ for $CO_2$ and 65 $Kg d^{-1}$ for $H_2$. If surface degassing rates are normalized by areas in order to compare these results among the major Tenerife's rift-zones, similar diffuse $CO_2$ degassing rates are osberved for the NW and NE rift-zones, but they are three times higher than the osberved for N-S rift-zone. In the case of $H_2$, similar diffuse $H_2$ degassing rates are osberved for the NW and N-S rift-zones, but they are three times higher than the observed for NE rift-zone. These results suggest that a shallower hydrotermal system is affecting more the NW than the others major rift-zones at Tenerife island.

URL: http://www.iter.es

### V21B-1196 0830h POSTER

### Diffuse Helium Degassing at Cumbre Vieja Volcano, La Palma, Canary Islands

E. Padron[1] (eleazar@iter.rcanaria.es)

L. Fuentes[2]

J. M. L. Salazar[1]

P. A. Hernandez[1]

N. M. Perez[1]

[1]Environmental Research Division, ITER, Granadilla, Tenerife, Canary Islands, Granadilla 38611, Spain

[2]Faculty of Chemistry, University of La Laguna, Av. Astrofisico Fco. Sanchez, La Laguna 38206, Spain

La Palma (730 $Km^2$) is the northwestern most island of the Canarian archipelago. Cumbre Vieja (<1 Ma) is situated in the southern part of La Palma, and is the most active basaltic volcano in the Canaries where the most recent eruption occurred in 1971, *Teneguia* volcano. The main structural features of Cumbre Vieja (220 $Km^2$) are three major volcanic rift-zones of N-S, NE, and NW orientations. Diffuse $CO_2$ degassing studies is becoming a useful geochemical tool for volcano monitoring (*Hernandez* et al., 2001). Since (1) helium is an ideal geochemical indicator because it is chemically inert, physically stable, sparingly soluble in water under ambient conditions and almost non-adsorbable, and (2) helium-3 is the best fingerprint for magmatic activity and reach levels up to 9.6 Ra at La Palma (*Perez* et al., 1994), the goal of this study is evaluate the use of diffuse helium emission for volcano monitoring of Cumbre Vieja.

Diffuse degassing survey of 619 sampling sites was carried out from July 19 to August 13, 2002, at Cumbre Vieja volcano. Soil $CO_2$ efflux measurements were performed by means of a portable NDIR sensor and according to the accumulation chamber method. At each sampling site, soil gas samples were collected at 40 cm deep using a metallic probe and analyzed for $^4He$ and $CO_2$ contents by means of a Omnistar QMS within 24 hours. Spatial distribution of soil gas helium expressed as ($\Delta$He = $He_{soil atmosphere}$ - $He_{air}$) showed that relatively high $\Delta$He values (> 1,800 ppb) occurred in the summit zone of Cumbre Vieja along the N-S rift-zone, suggesting a deep origin for the degassing through this major structure. Soil He efflux was estimated by