V41C-11 1120h

Tertiary Chemical Structure of the Afar Plume: Evidence From Primitive Mafic Lavas From Turkana, N. Kenya

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The East African Rift System is an ideal location for investigating the link between tectonism and magmatism during rift evolution. Geochemical studies in this region provide insight into plume-driven rift processes, including documenting the chemical structure of the sub-lithospheric mantle. The structure and chemistry of the Oligocene Afar plume were categorized by Pik et al. (1999) and Marty et al. (1996) in Ethiopian flood basalts of the northern rift. Plume influences have also been noted in Quaternary samples of the Afar/Red Sea region (Barrat et al. 1993) as well as at Turkana, N. Kenya (Furman et al., 2001).

We use new data on primitive (6-28 wt. % MgO) mafic lavas of Tertiary age from Turkana to investigate possible temporal and spatial evolution of the sub-lithospheric source region(s) beneath the East African Rift. Preliminary data suggest a plume influence in the source region for Tertiary Turkana mafic lavas. For example, most primitive lavas have La/Nb greater than 0.6 and Ba/Nb values between 3 and 20. Furthermore, Zr/Nb ratios from the Turkana suite demonstrate that incompatible trace element signatures in this area are spatially controlled; Zr/Nb values in central Turkana mafic lavas (about 5.5) are significantly higher than those observed 40 km to the south (around 2.5). La/Nb ratios also show spatial control, with values in the north ranging from 0.75-0.85 and those in the south ranging 0.45-0.7. These data imply consistent, latitudinal spatial heterogeneity in the Turkana source area.

U/Th ratios of the Turkana Tertiary suite overlap mafic Turkana Quaternary samples, suggesting a common, sub-lithospheric source component. Geochemical differences between Turkana and Ethiopian HT2 flood basalts (Pik et al. 1999) in the Tertiary may reflect the chemical structure of the Afar plume, or may imply a more complex scenario of melt segregation and transport within the lithosphere. The geochemical and isotopic data from Turkana basalts are thus an important part of a comprehensive interpretation of the dynamic East African Rift System and will enable us to constrain temporal and spatial chemical structures of the Afar plume.

References cited: Barrat et al. 1993, GCA, 57, 2291-2302 Furman et al. 2001, EPSL, submitted Marty et al. 1996, EPSL, 144, 223-237 Pik et al. 1999, GCA, 63, 2263-2279.

V42A MC: Hall D Thursday 1330h

Conduit Processes During Explosive Basaltic Eruptions I *(joint with P, S, T)*

Presiding: **J Sable,** SOEST

V42A-0983 1330h POSTER

Consequences of Dynamic Limits to Eruption Speeds Orthogonal to the Direction of Flow in Basaltic Volcanic Eruptions

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In sustained explosive volcanic eruptions, the vertical velocity of gas and entrained pyroclasts may exceed Mach 1 relative to the speed of sound in the erupting fluid. This commonly occurs when the vent geometry allows the fluid to be pressure-balanced with the atmosphere, and many eruptions have been shown to have had sustained eruption velocities of up to at least Mach 4. This includes some basaltic eruptions, such as the plinian phases of eruptions at Tarawera.

The dynamics of the transition from sub-sonic to supersonic flow place lower and upper limits on the lateral spreading rate of a subsurface supersonic gas-pyroclast mixture. If the volcanic fluid is in contact with the conduit walls, the gradient of the walls must be greater than a lower limit controlled by both the speed of sound in the erupting gas-pyroclast mixture and the wall friction factor: the walls must form a de Lavalle nozzle. The upper limit to the spreading rate of the mixture is equal to the inverse of the speed of sound of the erupting fluid. For eruptions that are supersonic at the vent, this can significantly affect near-vent conditions, resulting in significantly over-pressured (choked) eruptions in circumstances where pressure-balanced eruptions might be expected.

This helps to explain discrepancies between observed and modelled vent radii in many volcanic eruptions. Application of the constraint also helps with problems in model continuity between sub-surface volcanic dynamics and eruption plume dynamics, as the same constraint applies to volcanic jets above the surface.

V42A-0984 1330h POSTER

Nucleation Rates of Bubbles in Magmas

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The formation of gas bubbles in magmas drives explosive volcanic eruptions. Bubbles form in response to gas supersaturation by first nucleating and then growing. Studies of bubble nucleation in magmas have focused on whether it is homogenous or heterogeneous. Homogenous nucleation involves random clustering of gas molecules in a melt into stable entities, whereas heterogeneous nucleation involves clustering on preexisting surfaces. For either mechanism, however, little work has focused on the nucleation rate. Therefore, here we investigate experimentally these rates in magmas.

Experiments were performed on natural rhyolitic glasses. These were hydrated at high temperatures and pressures, and then isothermally decompressed rapidly to lower pressures, where they were held for varying lengths of time before quenching. Specially designed pressure vessels enable quenching within a couple of seconds. Quenched samples were analyzed for the sizes and number densities of bubbles that nucleated as a result of the lower pressure. Control experiments were run to ensure that no small bubbles nucleated before decompression. Bubble size distributions allow us to determine the variation in nucleation rate with time, and estimate the size distribution of nucleated bubbles.

Initial experiments were run at 800° C and various hydration pressures. Pressure drops were such that the same percent supersaturation was achieved. Results show that the rate of bubble nucleation is insensitive to water content in the range of 4-6 wt.%. Nucleation was heterogeneous, with bubbles nucleating on Fe-Ti oxide microlites. Almost all bubbles nucleated within 45 seconds, although a few nucleated up to 120 seconds. The peak nucleation rate occurred between 10 to 15 seconds, and was 2.5-3.5x10^6 cm^{-3} s^{-1}. Even in the shortest runs, all bubbles are 0.5 m or larger, suggesting that the critical size water bubbles is about that size. These results indicate that bubble nucleation is very fast, and can be considered instantaneous compared to growth rates. Further work will explore nucleation rates as a function of supersaturation pressures.

V42A-0985 1330h POSTER

On the Fragmentation Front in Conduit

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Vesiculation and fragmentation of magma in the conduit are the most fundamental processes to characterize explosive eruption. The interval from the vesiculation front to the fragmentation front critically controls the size distribution of pyroclasts and hence the style of eruption. The vesiculation process has been extensively investigated through experimental and model-simulational approaches. As for the fragmentation process, on the other hand, its physical basis is still not well-understood. In the above context, the movement of the fragmentation front is an important subject to be clarified. In this poster, we present a simple model which demonstrates how the fragmentation front is formed and how it moves. The model assumes mixture of gsolidh particles and ggash particles, each having contrasting values of density and compressibility. The initial state is compressed state of all particles. After removing externally-constrained pressure, particles begin to move driven by the forces due to the compression and mutual collision, exchanging the momentum between ggash and gsolidh particles. 2D numerical integration on this particles system clearly shows formation of quasi-shock front, which, we consider, corresponds to the fragmentation front. Non-linearity of the compressibility of ggash phase and cross-over of the continuous phase(pressure-sustaining phase) actually control the formation of the fragmentation front. Its propagation velocity is characterized by considering effective gHugonioth of this system.

V42A-0986 1330h POSTER

Numerical modelling of 2D solid/fluid interactions in explosive volcanic regimes using finite volumes: magma and multiphase flow dynamics induced by seismic elastic waves.

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In many volcanoes like the Popocatepetl, it is not well known if seismicity induces explosive eruptions, or inversely if the dynamics induces seismicity, or how both mechanisms trigger each other. In order to understand this mechanisms we numerically simulate, at greater scales than in laboratory, the behaviour of highly viscous magmas submitted to an incoming PSV wave involving high stresses. For that purpose we use a finite volume scheme of second order with a semi implicit algorithm in time for the fluid and a classical velocity/stress formulation at the second order to describe the elastic waves. The magma is considered as compressible and consists in a high viscous fluid and volatile gases. The gas fractions are computed following a power state law of the pressure. The disturbance of the fluid by the wave causes the pressure to increase and the gas to exsolve. The magma is then submitted to a convection behaviour and can arise through the conduit till reaching a certain depth which defines the location of fragmentation of the mixture. These simulations allow us to conclude that, depending on the magnitude of the wave, a viscous compressible fluid like a magma can be highly disturbed and differ strongly then from the quasistatic and acoustic behaviour classically taken into account in classical modelling of waves travelling through acoustic fluid/elastic solid structures. Depending on the Reynolds number, from laminar to turbulent, the fluid can not any longer be assumed incompressible, irrotational and non viscous. Inversely, when the magma has reached the fragmentation depth in the conduit, the fluid becomes multiphasic with specific exit velocities, pressures, temperatures, particle fractions. It is modelled with one particle phase and one gas phase interacting with drag forces and heat exchange terms. With a similar algorithm as described before, we show that the flow can be expelled at shock speeds and produce travelling elastic waves in the ground through the conduit walls. We show the pattern of the recorded waves at the free surface and their associated spectra.

V42A-0987 1330h POSTER

Sound Propagation in an inhomogeneous two-phase system: the influence of the gas bubble concentration on the sound source model.

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Volcanic explosions produce pressure perturbations in the atmosphere (infrasound) which are not contaminated by path effects as for the seismic wavefield and contain useful and direct informations on the source dynamics. Recently, many dynamical models of the explosive process are based on the analysis of the acoustic field. We have analyzed the acoustic wave field in terms of elastic wave propagation in a two-phase medium where the viscosity and compressibility are spatially inhomogeneous. At low pressure ($<$10 MPa) the magma can not be considered as an homogeneous medium, but has to be treated as a mixture of fluid magma and gas bubbles. Gas bubble nucleation starts when the pressure of the system drops below the supersaturation level (a few hundreds of meters for H_2O in basaltic magmas) and increases towards the surface, reaching its maximum value at the magma-air interface. Such a variation is non-linear with depth and is particularly strong at shallow depth. With the decrease of depth the density of the mixture and the sound velocity drop drastically while the shear viscosity of the mixture increases. We calculated the propagation of an elastic wavefield generated by an explosive source embedded in the magma column as function of the void fraction

increase in the magma. Large gas bubble concentrations (>70%) prevent the elastic wavefield to propagate suggesting that or the source is shallow or it is characterized by a high pressure drop. We propose a source model which explain the infrasonic wavefield in terms of a shallow unsteady pressure front.

V42A-0988 1330h POSTER

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The independent component analysis (ICA) on low frequency events recorded at Stromboli volcano reveals that these signals can be viewed as the superposition of three independent components in three different frequency bands. The first two are mainly composed of body waves coming from a direction in a range of 30°:30° around the crater area. Such a result is a clear indication that the whole signal, in these frequency bands, comes from the source area. The last independent component is, on the contrary, dominated by other kinds of waves coming from many different directions, suggesting that it is mainly composed of noise. On the base of such results we propose a simple model for strombolian explosion quakes based on a non linear self-sustained oscillator which exhibit the same dynamical characteristics of the experimental signal. The first few seconds of this one are exactly reproduced integrating the equations of the non linear oscillator, while the rest of the signal are qualitatively reproduced introducing random fluctuations of a parameter of the model.

V42A-0989 1330h POSTER

3-D modeling of ground deformation by conduit pressurization at Soufrire Hills volcano, Montserrat (B.W.I.)

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Dome growth at the Soufrire Hills volcano between 1996 and 1998 was frequently accompanied by repetitive cycles of earthquakes, ground deformation, degassing, and explosive eruptions. In particular, high-resolution tiltmeters recorded in real-time 6-14 h inflation cycles up to 20 microrad at two stations near the dome. These tilt data were used in eruption forecasting since peak rockfall and pyroclastic flow activity occurred with deflations. The cyclic ground deformation was ascribed to pressurization of the conduit magma beneath the degassing plug. The pressure source has been previously modeled as a point source or finite line source in an elastic medium without considering the topography of the volcano.

Using the finite difference code FLAC3D, we modeled the edifice as an elastic medium in three dimensions by integrating surface topography from Montserrat DEMs. We use the available tilt and geodetic data to constrain the geometry and the pressure distribution of the source and the properties of the edifice model. We analyse the effect of the edifice shape as compared to flat free surface models as well as the influence of varied pressure source geometries, pressure distributions, depths and conduit location. Results are compared with previous studies based on analytical models of point or line source and numerical models of conduit pressurization.

V42A-0990 1330h POSTER

Inferences on magma uprising at Mt. Etna (Italy) by seismic and GPS ground deformation data

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In this work, we analyse both the space-time evolution of seismic activity and ground deformation (by GPS data measurements) affecting Mt. Etna during the last thirteen years, with particular attention to the years following the 1991-1993 lateral eruption. After a short period of deflation following this eruption, ground deformation measurements indicate that during 1994-2000 the entire edifice underwent a marked inflation, which preceded the recent July-August 2001 lateral eruption.

Careful analysis of the spatial pattern of the seismic energy release, since the second half of 1996, evidences some strict relationship to the GPS ground deformation behaviour, and both strongly support a link between magma-related mass changes at depth and associated stress and strain variations. This observed stress-strain pattern is clearly influenced by the regional tectonic and the NNW-SSE trending fault zone which plays a relevant role in the recent volcano dynamic, until the July-August 2001 lateral eruption. Our observation suggests that there has been no major magma reservoir inside the upper crust (depth < 10 km) or within the volcanic pile but that high-level storage occurred in dykes, not concentrated in a specific area, with their position variable in the time. Moreover, the comparison between seismic and ground deformation data suggests that during the period of observation a transfer of different magma pulses from the volume located at depth in the western flank occurred toward the central area of the volcano.

V42A-0991 1330h POSTER

Eruptive Products and Processes: Mt. Etna, Sicily, 2001

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The dramatic eruption on the southern flank of Etna in July and early August 2001 was the most significant activity at the volcano in a decade. The eruption produced both vigorous strombolian activity, that built a number of prominent new scoria cones, and lava effusion. Texturally, the eruptive products are remarkably varied. Lavas erupted from vents near the summit are monotonous Hawaiites, typical of Etna's most recent products.

Ejecta from lower flank vents are petrologically and texturally distinct. In particular, they contain a prominent xenolith assemblage, principally comprising blocks of a white, friable arenite. The blocks are porous, have frequently been invaded by and reacted with the host melt, and show signs of having vesiculated on approach to the surface. Centimetre-scale magmatic enclaves are also common in these ejecta, and range in texture from coarse glomerocrysts to vesicular gabbroic inclusions. These eruptive products bear a remarkable textural similarity to the materials erupted during the 1892 activity of Etna's southern flank. Did these two eruptions share a common plumbing system? Or have they been tapped from the same reservoir, rejuvenated by the intrusion of primitive magma from depth?

We report the results of ongoing work that is aimed at characterising the 2001 eruptive products in detail; and of the continuing investigations into the links between FTIR measurements of Cl and S degassing during the eruption, the state of the erupted, degassed, products and of analogue experimental modelling of gas-melt separation in basaltic magma systems.

V42A-0992 1330h POSTER

Doppler Radar Sounding of Volcanic Eruption Dynamics at Mount Etna

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Based on the UHF wind profiler technique, a medium power (100 W) pulsed Doppler radar has been specifically developed for the sounding of explosive volcanic jets. Named Voldorad (Volcanological Doppler Radar), this radar can operate at medium distance (∼0.5 - 4 km) from the active vent and is compact enough to be easily set up on a volcano. The last version of the radar is housed in one unit (∼60x60x60 cm) and its total weight is ∼50 kg. A PC is used for real-time monitoring and data storage. The radar antenna is a 2*2 array of 24 elements Yagi antenna (9° beamwidth) set up on a tripod which is steerable in azimuth and elevation. A pulsed signal (typical duration 0.75 μs) is transmitted every 100 μs with a wavelength of 23.5 cm. After amplification and filtering, the received signal is digitized. Each digitized sample corresponds to a received echo at a selected time (i.e. selected range), thus defining the so-called range gates. The Doppler spectrum is then computed for each gate. Three parameters characterizing the ejecta can be deduced from this spectrum: reflectivity, mean velocity and maximum velocity of the jet particles.

We present results from experimental campains at Mount Etna during strombolian activity of the SE crater in October 1998 and July 2001. Quasi-continuous and powerful echoes were observed in the central gates, on either side of the jet axis, whereas echoes of side gates were weaker and more intermittent. The temporal variations of the radar signal were analyzed at two time scales. First, the time variations of reflectivity appear to be a good indicator of the long-term evolution of the eruption and also follow the overall trend of the tremor signal. Secondly, detailed analysis of the radar signal (typical integration time ∼64 ms) reveals 5 s periodic outbursts during fountain activity. Moreover, the maximum velocity of the jet particles estimated from Doppler spectra might represent the velocity of the finest particles directly entrained by gas.

V42A-0993 1330h POSTER

A Seismoacoustic Experiment During the July August 2001 Eruption at Mt. Etna Volcano (Italy)

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On July 13, 2001 a summit paroxysmal eruption (with strong strombolian activity and lava overflows) occurred at the SE Crater of Mount Etna volcano. It was , coincident with the start of an intense earthquake swarm. During the following three days, more than 2500 earthquakes were recorded, and a dry-fracture field began to open on the higher southern slope of the volcano Another paroxysmal eruptive episode occurred at the SE Crater on July 17, while a few hours later the higher part of fracture field (2995 m a.s.l) became eruptive, producing mild strombolian activity and a lava flow extending to SSE. During the same day, also a second part of the fissure became eruptive (a large pyroclastic cone formed at 2700 m a.s.l.) and a major lava flow was produced. On the morning of July, 18 a M=2.7 seismic event accompanied the opening of a third eruptive vent at about 2100 m a.s.l. This fissure in the following days produced mild to intense strombolian activity and emitted lava flows that slowly advanced southward. On the evening of 18 July, a further eruptive vent opened at about 2550 m a.s.l., along the same fracture system. This vent was the main explosive one, producing powerful phreatomagmatic explosions with huge ash columns, turning to strombolian activity and lava fountains in the following days, and then producing again phreatomagmatic explosions. The eruption ended on early August 10. On August 3, a seismoacoustic array, composed by three stations, has been deployed at few hundreds of meters from the vent located at 2100 m a.s.l.. A fourth station was installed much closer to the summit craters, at the site Torre del Filosofo (TDF), coupled with a thermal-infrared sensor. All seismo-acoustic stations were equipped with three-components (5 seconds) seismometers and one acoustic sensor, sensitive in the infrasonic band between 1 and 20 Hz. The thermal-infrared sensor (a Omega

thermometer) was sensitive in the band between 8-14 microns. The array recorded infrasonic waves coming from both vents located at 2100 and 2550 m a.s.l. Each vent showed a different infrasonic signature according to the different strombolian and phreato-magmatic activity. The analysis of the time delays between seismic, infrasonic and infrared onsets has evidenciated that the explosions at both craters were sub-sonic. The explosive source in both vent is relatively shallow. Time delays between the infrared and infrasound onsets recorded for the crater located at 2550 m a.s.l. indicate that the source is ca. 200 m below the crater rim. The source mechanism of seismic signals relating to the strombolian activity at the vent at 2100 m a.s.l. shows a strong decompression at the source.

V42A-0994 1330h POSTER

Origin of the 1974 Eruptions of Kilauea Volcano, Hawaii, by Magma Mixing: Evidence From Mineral Chemistry, and Crystal Size Distributions

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Three distinct episodes of eruption from Kilauea volcano, Hawaii, during July, September, and December of 1974 exhibit a pattern of westward migration, from the upper East Rift Zone, across the summit of Kilauea, and down the volcanos southwest flank. Lockwood et al. (1999) suggest that the 1974 eruptions were initiated by intrusion of "new," more mafic magma into a shallow conduit system in which more differentiated basalt resided. Crystal size distribution and mineral chemistry data presented here, together with whole-rock data presented in Lockwood et. al, show that lavas associated with each episode are characterized by progressive chemical and petrologic changes that are consistent with the suggestion that the lavas originated by magma mixing in the conduit system.

All of the lavas from 1974 are tholeiitic basalts and contain a typical mineral assemblage for Hawaiian basalts, including olivine, plagioclase, clinopyroxene and FeTi oxides. Lavas from the July eruption are characterized by a wide range of MgO, from 6.7-10.9 wt. %. The total mode of the three most abundant phases, plagioclase, olivine, and clinopyroxene, is ~18 (vol.) %, with plagioclase making up ~90% of all phenocrysts. Plagioclase has an average An content of 70.3, olivine has an average Fo content of 80.7, and clinopyroxene is characterized by $Wo_{39.3}En_{49.6}Fs_{11.2}$. CSD analysis documented a maximum crystal size of 1.26 mm for plagioclase, and 1.33 mm for olivine. CSD slopes calculated from ln number of crystals vs. crystal size are -2.73 for plagioclase and -0.95 for olivine. September lavas are more homogeneous, with MgO wt. % of 7.2-7.5. Phenocryst mode is ~18%, with plagioclase making up ~50% and olivine ~30% of the phenocryst population. The average An content for plagioclase is 64.1, the average Fo content for olivine is 79.7, and clinopyroxene is characterized by $Wo_{34.7}En_{49.3}Fs_{16.0}$. Crystal size distribution analysis documented a maximum crystal size of 0.58 mm for plagioclase and 1.02 mm for olivine. Calculated CSD slopes are -13.32 for plagioclase and -4.83 for olivine. Lavas from the final episode in December include some of the most mafic magmas to erupt from Kilaueas summit since 1959, with MgO wt. % of 12.5 to 15.6. The phenocryst mode is ~20% with olivine constituting ~90% of all crystals. The average An content of plagioclase is 64.2, the average Fo content of olivine is 84.6, and clinopyroxene is characterized by $Wo_{30.1}En_{53.6}Fs_{16.3}$. Crystal size distribution analysis determined a maximum crystal size of 0.22 mm for plagioclase and 2.62 mm for olivine. The calculated CSD slopes are -21.88 for plagioclase and -1.10 for olivine.

These data show that the July lavas are the most differentiated, have the highest abundance of plagioclase, and for a constant growth rate, have the longest crystal residence times. In contrast, the December lavas are the most mafic, have the highest proportion of olivine, and have the shortest residence times. Lavas erupted in July therefore represent more differentiated magma that resided in the conduit, December lavas have the largest component of the newest, most mafic magma that was intruded into the system and may have catalyzed the eruption, and September lavas are a mixture of the two.

V42A-0995 1330h POSTER

Magma's Degassing Process Verified by Conduit Drilling at Unzen Volcano

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Drilling into a hot conduit of the 1991-95 dacite lava dome is carried out in the Unzen Scientific Drilling Project (USDP), a part of which is a joint project with ICDP starting in 2002. The target depths are shallower than 1.3 km under the summit. Swarm of low-frequency earthquakes occurred in this depth during eruption, and petrological studies suggest fragmentation-anealing of magma there. Rock samples corrected by drilling will clarify the degassing efficiency mechanism and its evolution history.

The dome lava of the 1991-95 eruption at Unzen had changed its vesicularity and crystallinity of the groundmass with time, showing their good correlation with its effusion rate. The vesicularity reflects the degree of degassing, while the crystallinity does that of undercooling induced by decompression. The latter is strongly linked to degassing during ascent. The temporal chemical variation of plagioclase microlite rims is harmony with the crystallinity change, whereas that of amphibole microlite rims is not. As amphibole stability in the Unzen melt is limited in the water pressure larger than 0.5 kbar, different degrees of degassing (crystallization) occurred only in the shallow depth. Ineffective-degassing mainly due to magma's fast ascent creates over-pressurization of magma vesiculated. The 1991-95 itself was effusive, but the initial-eruption style was rather violent. Over-pressurization probably was high at first and decreased with time. If such magmas were successively frozen (quenched) on the conduit wall, the temporal change of over-pressurization can be read by measuring water contents in glass and crystallinity of the conduit-margin samples.

Sulfur dioxide flux during eruption, in harmony with the lava effusion rate, may suggest a possibility that degassing occurred principally using the crater. Fragmented or microcrack-networked material on the conduit wall may be responsible for the effective degassing to the crater. Unzen volcano has developed in a fracture-dominated circumstance, characterized by an active graben. Water-abundant nature just below the summit may also favor to create the above structure. Results of drilling on flanks at this volcano in this project revealed that the eruption activity began with explosive eruption of pumice-flows ca. 50 ka, graded into a moderate style of eruption, and, now, is characterized by the lava dome eruption. Historical change in degassing efficiency of magma may be caused by temporal variation of the above circumstance.

V42A-0996 1330h POSTER

Sulfur-rich melt inclusions in pyroxene phenocrysts of Unzen 1993 dacite: Evidence for excessive volatile supply from mafic magma

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In the latest Unzen eruption during 1991-1995, excess volatile supply has been pointed out based on comparison of bulk SO_2 contents of the magma (130-450 ppm) estimated from SO_2 flux by COSPEC measurement and magma extrusion rate [1] with S contents of melt inclusions (MI) in quartz and plagioclase phenocrysts and matrix glass (< 50 ppm) [2]. In order to reveal the source of excessively supplied volatile, we carried out the microanalysis of MI in pyroxene phenocrysts in 1993 dacite clast.

Major compositions for coarse calcic and low-Ca pyroxene phenocrysts in 1993 dacite were $Wo_{35}En_{55}Fs_{10}$ and $Wo_4En_{84}Fs_{12}$, respectively. Pyroxene geothermometer [3] yielded 900-980°C for typical pairs of the small grains and 1000-1100°C for large ones. Elemental profiling on a large calcic pyroxene (~500 μm) showed high-Al_2O_3 core (~3.5 wt%), suggesting derivation from Al_2O_3-rich less-evolved magma. We found that MI especially in the most Al_2O_3-rich calcic pyroxene core have relatively less SiO_2 (67-68 wt%) and much higher S (600-870 ppm) contents than those in other phenocrysts (SiO_2 = 72-76 wt%; S < 80 ppm). The S-rich MI in pyroxene shows negative correlation in SiO_2 vs. Al_2O_3, K_2O, and S plots, suggesting that MI entrapment could have occurred during magma differentiation by mixing between S-rich less evolved and S-poor evolved magmas.

These results suggest that the pyroxene MI could be a likely proxy of volatile source for the latest Unzen eruption. Based on a mass-balance calculation, bulk SO_2 content of extruded magma based on COSPEC results (< 450 ppm) could be explained by mixing between ~70% of near S-free dacitic and ~30% of S-rich mafic magmas.

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V42A-0997 1330h POSTER

Three-dimensional Seismic Velocity Structure around Usu Volcano, Japan

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Three-dimensional P- and S-wave velocity structures around Usu volcano, Japan, are investigated using traveltime data of earthquakes by which eruptive activity in 2000 was accompanied, in order to clarify magma plumbing system and background structure. The velocity inversions are started from three-dimensional initial structure which is constructed from density structure inferred from gravity measurements around the volcano, as well as usual one-dimensional initial structure. As a result, (1) a low velocity region is detected at a depth of 6 km beneath Usu volcano, and (2) a lateral velocity gradient from southern coast of Lake Toya to coast of Uchiura bay at depths from 2-4 km. The low velocity body may be due to a magma chamber, because precursory earthquakes of the 2000 eruption initiated at the top of the body and distributed to shallower depths, and few earthquakes occurred at the body. The body can be shallower one of two magma chambers which are inferred from petrological study. The lateral velocity gradient is consistent with deepening of high density and high apparent resistive layer toward Uchiura bay which is interpreted as due to deepening of Pre-Tertiary layer. The precursory earthquakes and earthquakes after the beginning of the eruption mainly occurred within or at the uppermost part of the high velocity area which implies that locations of earthquake occurrence are largely restricted by the structure.

V42A-0998 1330h POSTER

Long-period (12sec) Volcanic Tremor Observed at Usu 2000 Eruption: Seismological Detection of a Deep Magma Plumbing system

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Mt. Usu is a dacitic stratovolcano located in southwestern Hokkaido, Japan, and has erupted repeatedly (in 1910, 1943-45, and 1977-78). In the end of March 2000, after twenty some years of quiescence, Usu volcano began its activity with an intensive earthquake swarm. After several days of the earthquake swarm, on March 31, 2000, the eruption began at the northwest foot of the volcano.

We have installed five broadband seismometers around the volcano, and detected long period (12 sec) tremors (hereafter called LPTs) which are continually emitted from the volcano. Although these LPTs are continually observed at an interval of a few minutes, there exist no corresponding surface activities such as eruptions. The source of these LPTs are located relatively deep at a depth of 5 km, and their amplitude variation well correlates with the uplift rate of the eruption area. We thus attribute these LPTs to the flow induced vibration of a magma chamber and its outlet located around the source region of the LPTs. The estimated moment tensor for LPTs shows a reversed polarity for the isotropic and CLVD components. This is consistent with a combination of a deflating spherical

source and an inflating crack which opens northwestern direction toward the eruption site.

The volumetric magma flow rate may be estimated from the observed RMS amplitude of LPT through a seismic moment rate, and turns out to be around $3 \times 10^5 m^3$ per day. Geodetic observations report the volume change of the order of $10^7 m^3$ within the first few days. It appears that the volume flow rate estimated from LPTs is about one order of magnitude smaller than that of the actual flow rate. This may be reasonable if we consider that through seismic waves we are observing a fluctuating part of the magma flow. This may be the first seismological detection of dynamics of a main magma plumbing system beneath volcanos directly related to eruption activities.

V42A-0999 1330h POSTER

Volcano acoustic activity associated with the eruption of Mt. Usu, 2000 - Mud-pool Strombolian -

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There was intense acoustic activity associated with the eruption of Mount Usu, which began on March 31, 2000. Repeating phreatic explosions generated many isolated infrasonic signals, which were observed at plural acoustic stations. During the periods when acoustic activity was high, infrasonic pulses as many as 200 were identified every 10 minutes. Source location of infrasonic signals could be well identified from the records of the low frequency microphone network. Two active craters, Nishiyama craterlets and Konpirayama craterlets, are clearly distinguished by sound source determination analysis though distance between them is around 1 km. To investigate the transition of acoustic activity from April to June, 2000, we contrive a method to detect arrival and amplitude of infrasonic signals automatically. The number of automatically identified infrasonic signals exceeds 1.46 million during three months. It seems that there is a good correlation between acoustic activity and seismic signal amplitude. Patterns of acoustic activity and infrasonic pulse shapes observed at Usu volcano are very similar to those of observed at Stromboli volcano, Italy. We name the acoustic activity accompanied with phreatic explosion that scatters a lot of clods 'mud-pool Strombolian type'. Phreatic explosion excites not only infrasonic pulse but also seismic signal observed before the arrival of infrasonic pulse. Existence of Rayleigh wave phase with large amplitude suggests that the seismic wave is excited at a shallow part.

V42A-1000 1330h POSTER

Magma plumbing system of 2000 eruption of Miyakejima volcano, Izu-Mariana arc, Japan

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The 2000 Miyakejima eruption has been very unique among 13 historic eruptions since 1469 A.D, and its activity has continued now. The activity had been detected as westward migration of the magma since June 26, part of which erupted from submarine craters at the western flank of the volcano on the next day. After that, eruption has continued at the summit to form a summit caldera since July. Based on both the temporal variations in the historic ejecta and petrology of the 2000 ejecta (scoria of June 27 from submarine craters and volcanic bombs of August 18 from the summit caldera), we discuss its magma system and explain the sequence of the 2000 eruption. Most of the historic ejecta show evidence for magma mixing. In order to identify end-member magmas, we focus on the assemblage and compositional relationship of crystal clots in a single sample, suggesting that many of the historic ejecta are mixing products of basaltic and andesitic magmas. The magma system during the historic activity has been derived from two magma storage systems; deep sheeted basaltic and shallower andesitic ones. In many cases, the basaltic magma injected into the shallower andesitic one to form mixed magma, whereas andesitic magma also rarely erupted alone without extensive injections of the basaltic magma. The basaltic magma has differentiated gradually since 1469 AD, and its magmatic temperature has decreased from 1220 to 1180 C. On the other hand, the andesitic magma has become more mafic (magmatic temperature; from 1050 to 1100 C), possibly due to repeated injections of the basaltic magma. In conclusion, just before the 2000 eruption, it has been estimated that the basaltic magma has been least mafic, and that andesitic one to be most mafic. The scoria from 2000 submarine craters is aphyric, basaltic andesite, whereas the volcanic bombs from the summit are porphyritic basalt. Whole-rock chemistry and mineral compositions of these magma suggest that both magmas are quite similar to two types of magmas (shallower andesitic and deeper basaltic magmas) possibly existed in magma storage systems beneath the volcano. In addition, no evidence for magma mixing is recognized in these ejecta. Therefore, we could interpret the sequence of the 2000 eruption as follows: Shallower andesitic magma had moved westward, and part of the magma erupted at submarine. Then, deep sheeted basaltic magma ascended to fill the shallower space formed by migration of the andesitic one, and has erupted from the summit. Furthermore, considering continuous discharge of SO2 since August, it could be also suggested that another basaltic magma distinct from the historic one has ascended. In conclusion, it should be emphasized that historic magma plumbing system since 1469 AD must be completely destroyed during the 2000 eruption. We believe that the activity of Miyakejima volcano has progressed to a new phase.

V42A-1001 1330h POSTER

Magma migrations and caldera formation revealed by tilt observation during the 2000 Miyakejima volcano eruption, Japan: (1) dike intrusions and (2) tilt-steps with 50-s pulse waves

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Miyakejima volcano, central Japan, has been experiencing an enormous seismic swarm, crustal deformation and emission of volcanic gases since June 26, 2000. The NIED (National Research Institute for Earth Science and Disaster Prevention) Miyakejima volcano observation network has continuously and successfully monitored the volcanic activities, mainly by the borehole-type seismometers and tiltmeters, and broadband seismometers. The 2000 Miyakejima volcano eruption is characterized by four stages in the first two months: the first stage: the dike intrusion and migration from the southeastern to the western part of the volcano (June 26 June 27 1200 LT), the second stage: the shrinkage of the volcanic body (June 27 1200 LT July 7), the third stage: episodic summit eruption and summit crater collapse (July 8 August 18) and the fourth stage: episodic summit eruption and volcanic-gas emission (August 18 -). In this presentation, we focus on two significant phenomena among many suggestive volcanic activities, that is (1) dike migration during the first stage and (2) tilt-steps with 50-s pulse wave, associated with caldera formation at the summit area during the third stage. (1) dike intrusions and migrations were revealed by the analyses of tilt-data observed at the five stations in the island. We applied the tensile crack-opening models by Okada [1985] to recognize temporal and spatial tilting changes. The results suggested that the magma began to climb up toward the summit with the dip angle about 60- 70 degrees, reaching almost the ground surface, but the magma did not erupted. After that, the magma intruded vertically toward the western frank of the volcano and furthermore, moved toward western-off the island, causing the huge seismic swarms, those were never recorded. (2) the tilt-steps with 50-s pulse waves were observed during the third stage. This stage began after the first summit eruption at July 8 1841LT, interpreted to be due to the first summit collapse. The tilt-steps with 50-s pulse waves occurred intermittently once or twice per day on average, but none of their events were synchronized with the summit eruption except the first tilt-step on July 8 1841 LT. Analyses of tilt and broadband seismic data show that the tilt-steps with the 50-s pulse waves were caused by the opening of sill-like tensile cracks oriented in a SE-NW direction with a dip-angle of 20 degrees, at a depth of 7-8 km. Each volumetric change ranges 10^6-10^7 m^3. This source can be interpreted to be thermal two-phase flow instabilities and the caldera formation may be due to the result of this perturbation of stress-field of volcanic body.

V42A-1002 1330h POSTER

Mechanism of Caldera Collapse during the Miyakejima 2000 Eruption, Japan

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A circular collapsed caldera was formed at the summit of Miyakejima Volcano during the 2000 eruption. The collapsed caldera appeared on July 8, 2000 with minor phreatic eruption. The formation of the collapsed caldera followed 12-days seismic activity beneath and western off the volcano, suggesting the evacuation of magma from the reservoir to westward. The initial scale of the caldera was about 1.0 km in diameter, 150 m in depth, and 5.6 10^7 m^3 on July 9. Growth of the caldera continued about 1 month with seismic swarm associated to the continuous intrusion of magma in the northwestern off of the volcano, and the final scale of the caldera reached 1.6 km in diameter, 450 m in depth, and 6 10^8 m^3 in volume. The growth rate of the caldera kept nearly constant ratio about 1.4 10^7 m^2/day. Major phreatomagmatic eruptions occurred intermittently after the growth of the caldera, producing a total of about 1.6 10^{10} kg (1.1 10^7 m^3) of volcanic ash, from middle of August to September. Volume of the eruptive materials is only 1.1 % of the volume of the caldera. The eruptive materials contain about 25 wt % of juvenile materials of basaltic scoria, suggesting the ascending of new magma to the stoping column.

Structure of the caldera floor shows the subsidence of the caldera floor with circumferential faults, suggesting the subsidence with columnar plug on the magma reservoir. Landslides from the caldera wall enlarged the outline of the caldera during subsidence of the floor and the final outline of the caldera wall was much larger than the subsidence area indicated by the circumferential faults. The final outline of the caldera is much larger than the area of the stoping column indicated by the circumferential faults on the caldera floor during its growth. The oval area about 600-700 m across (2.8-3.8 10^5 m^2) surrounded by circumferential faults in the caldera floor may represent the horizontal scale of the stoping column. Subsidence of the stoping column consumed the whole volume of the caldera, which was 1.6 km across and 450 m depth. Ratio between the area of the stoping column (2.8-3.8 10^5 m^2) and the final volume of the caldera (6 10^8 m^3) suggests that the stoping column may have subsided 1.6-2.1 km into the reservoir. The averaged rate of subsidence of the stoping column was 40-53 m/day, during 40 days of the subsidence from July to August.

V42A-1003 1330h POSTER

Mechanisms for Basaltic Plinian Volcanism: A Quantitative Study of the Products of the 122BC Eruption of Mount Etna

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The 122BC eruption of Etna volcano, Sicily, is one of the few known examples of basaltic Plinian volcanism. The eruption had two Plinian phases, each of which was preceded and followed by periods of weak phreatomagmatic activity. The main goal of this study is to investigate the mechanisms that permit basaltic magma to erupt in Plinian fashion. Several possible mechanisms have been proposed, including: (1) delayed onset of vesiculation leading to rapid runaway vesiculation at high levels in the conduit; (2) interaction between the magma and the conduit walls; and (3) degassing-induced microlite crystallization and consequent effects on magma rheology. An additional goal is to examine possible reasons for the abrupt changes in style and intensity that occurred during the eruption: why did a Plinian plume form, then cease, twice? One hypothesis to explain the slowing and stopping of the Plinian phases is constriction and eventual blockage of the conduit through buildup of relatively degassed magma along the sides of the conduit.

Quantitative studies of pyroclasts are used to constrain the ascent and degassing history of the magma. Systematic measurements for samples at different stratigraphic levels within the Plinian units show that distributions of bulk clast densities, and hence vesicularities, changed with time. Early in each Plinian

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phase, a uniform population of low-density, microvesicular pumice clasts was ejected; later, the clast population became progressively more dense and less uniform, displaying a broader and in some cases bimodal density distribution. In addition to these bulk density studies, the size, shape, and distribution of vesicles have been observed and quantified through computer-aided analysis of images obtained with petrographic and scanning electron microscopes. The combined results from these techniques provide insight about the rates and timing of degassing and vesiculation processes that preceded fragmentation of the 122BC basaltic magma.

V42A-1004 1330h POSTER

Textural Characterization of 1912 Novarupta Pyroclasts: Understanding Fluctuations in Eruptive Style and Intensity

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The eruption of Novarupta on June 6-8, 1912 was the largest eruption of the 20th century, producing c. 11km^3 of ignimbrite and c. 17km^3 of plinian fall deposits. The Plinian fall deposits are divided into 8 units formed during three episodes (I through III) of sustained eruptive activity interrupted by two short breaks of up to several hours in duration. After 60 hours explosive volcanism ended, replaced by dome growth and disruption. Lack of caldera collapse at the vent has preserved proximal eruption products which help to reveal a complex, pulsatory pattern to Novarupta volcanism even within the three episodes of sustained eruption.

The deposits at Novarupta thus enable us to examine the questions: 1. What causes powerful explosive eruptions to pause and, ultimately, to stop, and 2. What drives intervals of pulsating unsteadiness, on a shorter time scale, in the eruption? By measuring clast density and crystal content and performing image analysis on samples that span the transitions between each eruptive pause and shifts in intensity, the range of textural features from individual stratigraphic levels can be quantified and the processes that create the features can be ascertained.

Density data from juvenile pumices show that there is an abrupt decrease in density/increase in vesicularity at the break between episodes I and II and a gradual change in density/vesicularity toward the close of episode III. Image analysis data include vesicle size distributions (VSDs) measured on clasts from samples that extend over changes in eruption activity. These VSDs help to quantify the role of ascent-driven changes in the physical state of the volumetrically dominant dacitic magma, which influenced the dynamics of the explosive eruption. In addition, the effects of phenocrysts on apparent values of bulk vesicularity were investigated by combining data from density measurements for individual clasts and glass/crystal separates.

V42A-1005 1330h POSTER

Explosive Volcanism: Understanding the Transition between Plinian and Phreatomagmatic Activity in the 79 AD Vesuvius Eruption, Italy

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This study focuses on the cause of the abrupt transition from the stable sustained Plinian phase (EU2, EU3) to discrete phreatomagmatic explosions generating highly destructive pyroclastic density currents (EU4-EU8) during the 79 AD eruption of Vesuvius, Italy. Density data for clasts from these phases shows that the density (and vesicularity) ranges within samples widen significantly at the EU2/EU3 contact rather than at the EU3/EU4 boundary. From the density samples of 100 clasts we selected subsets of 10 clasts that represent the mean values of density/vesicularity and the density/vesicularity minima and maxima in each sample to quantify the vesicle and crystal populations of each clast. Our goal in this characterization is to establish the range of textural features within individual clasts and within stratigraphical units before and after the key transition, and to link the textural features to changing processes in the volcanic conduit. Preliminary results show that the processed pumices from the phonolitic white EU2 and phono-tephritic gray EU3 Plinian fall phases show a pronounced contrast in bubble shapes, number densities and crystal content. EU2 pumices show a narrower range in vesicle textures, and are characterized by a low percentage of microlites, mainly leucite, the dominant phase in all the 79AD samples, and have very thin glass walls. The mean and most dense pumices show zones of deformed vesicles. The EU3 pumice are instead characterized by a wider range in vesicle textures, they contain a high percentage of microlites, vesicles are generally equant and vesicle walls are thicker than in EU2. Although of the same chemical composition as EU3 pumice, EU4 fall pumice (emplaced after the change in eruptive style) show different vesicle textures. They have only a high content of crystals in common with the EU3 pumice, but the vesicle size distributions of the EU4 pumices are more similar to those of EU2.

V42A-1006 1330h POSTER

Heat Transport and Groundwater Flow on the Summit of Kilauea Volcano, Hawaii

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In active volcanoes the potential for advective heat distribution from the summit towards the flanks depends on the amount of heat supplied to the system by the underlying magma, the amount of water recharged into the system and the permeability structure of the edifice. High resolution temperature logs, geophysical techniques and water level measurements in deep drill holes on or near volcanic summits provide an opportunity to analyze the role of circulating groundwater in distributing heat within the edifice. Where temperature-gradient inversions are measured, the high-temperature sections are commonly assumed to represent lateral flow of hot fluid through thin aquifers embedded between low-permeability zones. Inverse modeling of such temperature profiles can provide estimates of groundwater flow rates, heat fluxes, and the time that has elapsed between the onset of hydrothermal flow and the temperature measurement.

We propose two contrasting groundwater flow models to interpret the complex temperature profiles from a deep well on the summit of Kilauea volcano, Hawaii. The first is a confined lateral-flow model with a continuous flux of hydrothermal fluid. The second is a transient-flow model in which slow conductive cooling follows a brief advective heating event. Numerical simulation results for both models are sensitive to the initial conditions, and with realistic initial conditions it takes between 750 and 1,000 simulation years for either model to match the measured temperature profiles. With somewhat hotter initial conditions results are consistent with the onset of a hydrothermal plume approximately 550 years ago, coincident with the initiation of caldera subsidence. We believe that the transient flow model is more consistent with geochemical data from the hydrothermal system and more appropriate for this highly dynamic environment. This model implies that thermal perturbations may last for thousands of years after hydrothermal flow has essentially ceased.

V42A-1007 1330h POSTER

Mixing of Magmatic Volatiles With Meteoric Groundwater in the Summit of Kilauea Volcano, Hawaii

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Water samples were collected from the only deep well (Keller Well-NSF Well) on the summit of Kilauea volcano, Hawaii. The well was drilled in 1973 to a depth of 1262 m, but sat idle until 1998 when a drilling rig was used to remove mud and renew access to the hydrothermal system at a location very close to summit fumarolic activity. The chemistry and isotopic composition of fluid samples collected in 1998-2001 differ significantly from those of samples collected before 1998 and reported in previous studies.

The water from the well is rich in sulfate and has a near-neutral pH. The major element chemistry differs significantly from seawater composition and from that of hydrothermal fluids from Kilauea's east rift zone. The well water has a low chloride concentration relative to typical magmatic-hydrothermal fluids and a high sulfate to bicarbonate ratio (approximately 4:1). Based on the S/Cl mass ratio and on carbon and helium isotopes in the well fluids, summit fumaroles and the parental Kilauea magma, we conclude that the hydrothermal fluids sampled from the well formed by condensation of magmatic volatiles into shallow, mainly meteoric groundwater. The oxygen and deuterium isotopic composition indicate that the meteoric component was recharged on the eastern margin of the caldera. Steam condensation and gas dissolution beneath the crater formed an acidic fluid that dissolved the host basalt at high temperatures. The hydrothermal fluid was then modified by cooling and precipitation of secondary minerals along a flow path away from the crater towards the well.

Geochemical modeling based on fluid chemistry and geothermometry suggests that the well fluids equilibrated with an assemblage of secondary minerals at temperatures between 90 and 140°C. The C/S ratios in the well water, the parental magma, and the gas plume emanating from the caldera indicate that most of the sulfur degassed from the magma is scrubbed by groundwaters beneath the summit. However, based on the mean sulfate concentration in the well water and on the estimated mean annual water recharge in the caldera region, we conclude that the sulfate concentration in groundwater beneath Kilauea's summit must be an order of magnitude higher than that found in the well water.

V42B MC: Hall D Thursday 1330h

Volcanic Degassing

Presiding: **J Witter,** University of Washington

V42B-1008 1330h POSTER

Investigating Errors in Static COSPEC Measurements of Volcanic SO2 Plumes

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Correlation spectrometer (COSPEC) measurements of sulfur dioxide (SO2) from active volcanoes are collected using both airborne and ground-based methods. Utilizing both methods for volcano monitoring is useful because a more robust data set is produced, comparisons can be made between the different techniques, and environmental conditions or logistics can inhibit the use of either method. However, a number of errors are unique to the static method that make fixed-position measurements less reliable than airborne measurements. Among these are increased path lengths, variable plume geometries, and inconsistent background conditions.

We use COSPEC measurements collected at Soufriere Hills Volcano, Montserrat to investigate shortfalls in static COSPEC measurements. The data consist of five scans collected from a fixed position in February 2001 in which a clinometer was used to measure scan rotational speed. Data collected at Soufriere Hills are ideal because 1) helicopter and static measurements are both collected on a near-daily basis, and 2) static measurements are consistently lower than airborne measurements. Plume geometry and viewing angle are investigated as causes of underestimation of static SO2 measurements. Constraining errors associated with fixed-position scanning makes static COSPEC measurements more accurate and dependable, especially important when conditions prohibit airborne surveys.