

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 densities, 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. 11km³ of ignimbrite and c. 17km³ 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 Pheatomagmatic 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 pheatomagmatic 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 phonolithic 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.

V42B-1009 1330h POSTER

H₂O Emission Rate of Volcanic Plume During the 2000-2001 Miyakejima Volcanic Activity

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Immediately after the onset of the eruption of last year, Miyakejima has effused a large amount of volcanic gases from its summit crater. In order to obtain the basic data about the volcano-hydrothermal system, we observed the volcanic plume and estimated H₂O emission rate from the summit crater.

A temporarily observation was made from a patrol ship on September 19, 2000 and then continuous observation has been conducted at Ako district of Miyakejima since October 25, 2000. Infrared thermal image and video image of the plume were recorded in digital tape at 2 seconds intervals in minimum. At the same station, air-temperature, humidity and atmospheric pressure were recorded at 30 minutes intervals. By pursuing the light and shade patterns of the infrared thermal images or video images, we measured the rising velocity of the plume. From the temperature distribution of the plume, which was obtained by the infrared thermal image, we measured the width and mean temperature of the plume at an arbitrary height.

When the clear image of the plume was taken, we conducted analysis. From the observation data: plume rising velocity, plume width, plume mean temperature and meteorological conditions, H₂O emission rate of the plume was estimated using the conservation law of mass and energy (Fukui, 1995). The result was the underestimation because the mean temperature was evaluated at the plume margin.

The average H₂O emission rate from October 2000 to February 2001 was 400ktons/day, which was one or smaller than that observed on September 19, 2000 (2000kton/day). The average sulfur dioxide emission rate at the same period was 40ktons/day (Kazahaya et al, 2001). Because the glass inclusion analysis indicated that the melt in the magma had 1.4wt% H₂O and 0.2wt% SO₂ content (Saito et al, 2001), the H₂O degassing rate from the intruded magma was estimated to be 280kton/day. The H₂O emission rate decreased to the value near the degassing rate after October 2000, suggesting that the ground water surrounding the intruded magma had been exhausted by the progress of the volcanic activity and the plume was mainly constituted by the H₂O degassed from the intruded magma.

V42B-1010 1330h POSTER

Comprehensive COSPEC measurements to measure SO₂ conversions in moist tropical atmosphere, Santa Ana, El Salvador

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Santa Ana is an andesitic stratovolcano (summit 2381 m) in western El Salvador which has not erupted magma since 1920. Santa Ana's summit crater lake temperature and gas emission rates increased between May and September 2000 prompting further investigation. On February 8 and 9 2001, SO₂ emission rates were measured using a COSPEC instrument at a) Cerro Verde (2030 m elevation), as stationary position observing the plume ca. 2 km from the vent and b) from a vehicle traveling in the Santa Ana-Sonsonate highway (some 5-8 km from the vent). The resulting fluxes were 3.657 kg s⁻¹ (316 t d⁻¹) and 2.476 kg s⁻¹ (214 t d⁻¹) respectively. Using a wind speed of 7.5 m s⁻¹ these results yield a range of loss rates from 5 x 10⁻⁴ to 1 x 10⁻³ s⁻¹, similar to plumes of similar altitude (1-3 km) observed at Etna and Montserrat. We will further constrain this loss rate by analysing other data taken at a variety of azimuthal angles (effective distances from the plume) taken on February 8. We will also use the overall experience to plan a field survey for Santa Ana which can focus on quantifying SO₂ conversion rates, to take advantage of the unusually good geometry there for ground-based COSPEC measurements.

V42B-1011 1330h POSTER

Anomalous Diffuse CO₂ Emission Changes at San Vicente Volcano Related to Earthquakes in El Salvador, Central America

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San Vicente or Chichontepeque (2,180 m a.s.l.) is a composite andesitic volcano located 50 Km east of San Salvador. Its paired edifice rises from the so-called Central Graben, an extensional structure parallel to the Pacific coast, and has been inactive for the last 3000 yrs. Fumaroles (98.2) and hot spring waters are present along radial faults at two localities on the northern slope of the volcano (Agua Agria and El Infernillo). CO₂ is the most abundant component in the dry gas (>90%) and its mean isotopic composition ($\delta^{13}\text{C}(\text{CO}_2) = -2.11 \text{‰}$ and $^3\text{He}/^4\text{He}$ of 6.9 Ra) suggests a magmatic origin for the CO₂. These manifestations are supposed to be linked to a 1,200 m depth 250 reservoir with a CO₂ partial pressure of 14 bar extended beneath the volcano (Aiuppa et al., 1997).

In February 13, 2001, a 6.6 magnitude earthquake with epicenter about 20 Km W of San Vicente damaged and destroyed many towns and villages in the north area of the volcano causing some deceases. In addition, two seismic swarms were recorded beneath the northeastern flank of the volcano in April and May 2001. Searching for any link between the actual seismic activity and changes in the diffuse CO₂ degassing at San Vicente, an NDIR instrument for continuous monitoring of the diffuse CO₂ degassing was set up at Agua Agria in March 2001. Soil CO₂ efflux and several meteorological and soil physical variables were measured in an hourly basis. Very significative pre-seismic and post-seismic relationships have been found in the observed diffuse CO₂ efflux temporal variations related to the May 2001 seismic swarms. A sustained 50% increase on the average diffuse CO₂ efflux was observed 8 days before the May 8, 5.1 magnitude earthquake. This pre-seismic behaviour may be considered a precursor of the May 2001 seismic swarm at San Vicente volcano. However, about a three-fold increase in the diffuse CO₂ efflux was also observed after the intense seismicity recorded on May 8-9. These preliminary results suggest that changes in the fluid pore-pressure within faults/fractures associated to the volcanic roots may be triggering, enhancing and responding (aperture and closure of fractures) to the local seismicity in the area of San Vicente volcano.

V42B-1012 1330h POSTER

Acid Gas Emissions Measured by COSPEC, Volatile Trap, and Filter Pack at Volcán Villarrica, South Chile

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Volcán Villarrica is a basaltic andesite stratovolcano 170 km SE of Temuco, Chile. Villarrica has been characterized by continuous degassing from a summit lava lake since 1985. We present new measurements of the flux of SO₂, HCl, and HF from Villarrica using correlation spectrometry (COSPEC) combined with the method of volatile traps and filter packs.

COSPEC measurements yielded an average SO₂ flux of 460±260 tons/day SO₂. This is greater than, but within error of, the 260±170 tons/day SO₂ measured by us last year. We assume H₂S emission is negligible.

Volatile trap and filter pack measurements were made at the summit crater. To test for diffuse degassing on the flanks of the volcano, we conducted a soil

CO₂ flux survey. Using an accumulation chamber configured with a continuous infrared CO₂ gas analyzer, we found diffuse degassing of CO₂ to be undetectable. We assume flank degassing of other gases is similarly low.

Four volatile traps (6N KOH solution in a plastic beaker) were deployed at the active crater on three occasions for periods ranging from 8 to 13 days. Acid gas species were absorbed into the alkaline solution and the relative concentrations of SO₄, Cl, and F were obtained by ion chromatography. Volatile traps yielded an average SO₂/HCl ratio of 5.9±1.2 and HCl/HF ratio of 4.1±0.7. This compares with an average SO₂/HCl ratio of 9.3±2.6 and HCl/HF ratio of 3.0±0.4 obtained with volatile traps in the 2000 field season.

Twenty-three gas measurements were made using filter packs during eight summit days. Using a small vacuum pump we filtered the gas through a series of three paper filters each impregnated with a saturated sodium bicarbonate solution. Total filtration time varied from 3 to 46.5 minutes. Filtration time was chosen so that nearly all of the acid gases were absorbed by the first two filters in the filter stack. Relative concentrations of the acid gas species (SO₄, Cl, and F) absorbed onto the filter paper were obtained by ion chromatography. Measurements of the acid gas species with filter packs yielded an average SO₂/HCl ratio of 4.5±0.7 and HCl/HF ratio of 7.8±1.6.

The volatile trap method is based on the assumption that the proportions of acid species absorbed into the alkaline solution are the same as those in the volcanic gas. Simultaneous collection of gas data using volatile traps and filter packs allows for a comparison of the two methods and an evaluation of this assumption. Filter packs yielded lower average SO₂/HCl ratios but higher average HCl/HF and SO₂/HF ratios. These results imply that the KOH solution in the volatile traps may not absorb S-gases and Cl as readily as it does F.

Using gas ratios from filter pack measurements, we calculate average HCl and HF fluxes from Villarrica summit crater of 102±42 tons/day and 13±3 tons/day, respectively. These values may be higher if H₂S emission is significant.

V42B-1013 1330h POSTER

Diffusive Soil Degassing of Radon and Carbon Dioxide at San Miguel Volcano, El Salvador, Central America

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San Miguel volcano is located 15 km to the Southwest of San Miguel City (population 300,000) and lies on the southern fault of the Central American graben at an intersection with NW-SE faults. The composition of San Miguel lavas varies from olivine-pyroxene basalts for the older lava flows to more andesitic compositions for the more recent products. This volcano have been degassing and having small ash emission since the late nineteen eighties. During December 1999 and January 2000, radon gas concentrations (pCi/l) in soils were measured using a Pylon AB5 radon monitor, and flux of CO₂ (g/m²/day) was determined using the accumulation chamber method at 205 sampling stations. High gas emission inside the crater did not allow measurements to be taken in that region. CO₂ fluxes throughout the soils of the volcanic edifice show low values compared to other active volcanoes of the world, suggesting that San Miguel is degassing preferentially throughout the summit region. CO₂ fluxes range from less than 1 to 14 g/m²/day, with an average value of 5.6 g/m²/day. Radon concentrations range from 2 to 833 pCi/l with an average value of 110 pCi/l. Thoron concentrations range from 20 to 2178 pCi/l with an average value of 362 pCi/l. These values are comparable to radon concentrations found in other active volcanoes (e.g. Cerro Negro, Connor et al., 1996). CO₂ flux, radon and thoron concentrations show higher values to the northwest and northeast faulted regions. Some anomalies seem to be related to the contact region between the older and more recent lava flows. Thoron/radon ratios show high anomalies aligning in the NW-SE direction where faulting also occurs. These results suggests that low permeability rocks forming the volcanic edifice of San Miguel volcano do not allow large fluxes of magmatic CO₂ to be discharged throughout the soils. Higher permeability at faults and contacts allow slightly larger fluxes of CO₂ and radon and thoron concentrations.

V42B-1014 1330h POSTER

Diffusive Soil Degassing of Radon and Carbon Dioxide at Ilopango Caldera, El Salvador, Central America

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Ilopango Caldera lies 10 Km east of San Salvador, El Salvador and holds Ilopango Lake, the largest body of fresh water in El Salvador. There is currently no observed fumarolic activity within the caldera system. However, the last eruption occurred in 1880. In November - December, 1999, radon gas concentrations (pCi/l) were measured using a Pylon AB5 radon monitor, and flux of CO₂ (g/m²/day) was determined using the accumulation chamber method at 106 sampling stations around the lake, along and across the caldera walls. Gas samples were also collected to determine the isotopic composition of C in CO₂. CO₂ fluxes did not show high values characteristic of other volcanic systems, values ranged from 0.7 to 9.2 g/m²/day with an average value of 3.9. These values are similar to the low values of the background population observed in nearby San Salvador volcano. Highest values are observed to the east and west of the lake. Isotopic values for C in soil gases do not show an important magmatic component. Radon concentrations present three distinct populations with the highest values occurring to the southwest. Thoron concentrations are higher close to the caldera walls than inside the caldera due to the possible higher rock fracturing in that region. Measurements taken in March 2001, after the January 13 and February 13, 2001 earthquakes did not show significant variations in CO₂ fluxes. However, radon concentrations varied due to the high seismicity that lasted several months after these earthquakes. These results suggest that the magmatic system of Ilopango Caldera is not emitting high fluxes of CO₂ to the atmosphere throughout the caldera soils. Subaqueous emissions of CO₂ have not been evaluated. However, subaqueous hydrothermal discharges have not been identified at this calderic lake.

V42B-1015 1330h POSTER

Soil-gas Emanation in Long Valley Caldera, California

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Over five hundred soil-gas emanation measurements have been made within the Long Valley Caldera over the past two years. Data derived from these measurements provides clear evidence regarding the nature and spatial extent of outgassing within the region. Identification of anomalous zones of emanation has been accomplished by statistically evaluating individual concentration measurements relative to all data collected in a given survey area. The mean of these measurements is considered to represent the background soil-gas flux for that particular area. Any individual value exceeding the mean plus one standard deviation represents a location where anomalously high emanation occurs, while values less than the mean minus one standard deviation represent areas of anomalously low emanation.

In each of the individual areas surveyed thus far, all recorded values fall into one of three distinct statistical populations, representing either anomalously high, anomalously low, or background emanation. Twenty one percent of all radon concentration values obtained during the course of this study are anomalously high, and eleven percent are anomalously low. Twenty five percent of carbon dioxide measurements yielded anomalously high values, and eleven percent yielded anomalously low values.

Results generated thus far indicate that the majority of outgassing in the region as a whole occurs through relatively narrow networks of northwest-southeast trending fractures. Anomalously high degrees of outgassing occur where the majority of fractures within a given network remain unsealed, while below average outgassing occurs in regions that contain a high percentage of sealed fractures. The paucity of sealed fractures in a given area is thought to be related to its having experienced relatively recent and/or frequent deformation. Thus, the most significant emanation anomalies found so far exist in association with

fractures within and along the rim of the caldera's resurgent dome.

A comparison of background emanation values derived from measurements made in several areas containing surface manifestations of recent geothermal activity suggests that soil-gas emanation measurements may also be useful in helping to constrain the nature and extent of hydrothermal activity within the caldera region.

V42B-1016 1330h POSTER

Determination of Dissolved Helium Isotope Ratio in Ground-Waters From Volcanic Areas: a new Method Based on gas-Water re-Equilibration Utilizing the Head-Space Technique

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He and carbon isotopes composition gives useful clues on the origin of fluids and the chemical and isotopic processes that affect deep gases during their rise towards the surface. He isotopic composition is largely utilized to reveal the different origins of fluids because of the low reactivity and solubility of this gas in the waters. Here, a new method to determine dissolved helium isotope ratio in groundwaters from volcanic areas is presented. This method is based on the achievement of He equilibrium conditions between a dissolved gas phase and a host gas (N₂). Ultrapure N₂ is introduced upon collection in the field in a water-filled glass flask (100-250cc), hermetically sealed. After shaking in ultrasonic bath for 10 minutes, an aliquot of the separated gas phase is removed from the flask for MS analysis, thus avoiding any fractionation of ³He and ⁴He isotopes. ³He/⁴He ratios are measured using a modified double collector mass spectrometer (VG 5400-TFT). Helium abundances are also calculated by scaling the He partial pressures in each sample to He air-standard measured by a QMS (VG Quartz). Using the helium partitioning coefficient it is possible to calculate the amount of gas originally dissolved in the water. Analytical results highlight that, at equilibrium conditions, the helium concentration in the gas phase is positively correlated with the water/host-gas ratios, whereas the ³He/⁴He ratio is independent on water/host-gas ratios. The method was tested both on air-saturated-waters and on thermal-waters from volcanic areas. The results highlight the good reproducibility (~5%) and accuracy (~3%) of the helium isotope ratio measurements. The proposed method is a useful tool for determining the helium isotopic ratios on those volcanic systems where a free gas phase is not available.

V42B-1017 1330h POSTER

Groundwater at Mayon, Volcano

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Around Mayon Volcano, Philippines, anecdotal evidence and rainfall normalized spring discharge data suggest that the water table 8 km from the summit of the volcano drops prior to eruptions. Residents report that they had to deepen their shallow wells in 1993 (some before and others following the eruption). In some cases they had to dig as far as 5 meters deeper to reach the water table. Significant decreases in spring discharge were recorded prior to the 1999 phreatic explosions and explosive eruption in 2000. A lesser decrease in spring discharge was recorded prior to the 2001 explosive eruptions. The cause of the observed correlation is not yet understood. Mechanisms consider include decrease in rainfall and boiling away of groundwater due to magmatic intrusion. Dilatation of the volcano may cause an increase in pore pressure, opening of cracks, and inflation of the ground surface that would all result in lower water table levels and decreases in spring discharges. Lack of significant hydraulic precursors prior to the 2001 eruptions may be due to a sustained state of inflation following the eruption of 2000.

To better understand the relationship between changes in the volcanic system and changes in the groundwater system surrounding Mayon, instruments were installed about eight kilometers from the summit immediately following the explosive eruption of 26 July 2001. Parameters monitored include rainfall data, water levels in four shallow wells, discharge in the main

river basin, and spring discharge. The aquifers at eight kilometers are predominantly poorly sorted lahar flow deposits. Characterization of these highly permeable aquifers has been conducted. Preliminary data include porosity ranges, hydraulic conductivity estimates, and response to rainfall. Water samples have been collected that are intended for geo-chemical analysis to determine if the water is predominantly meteoric or magmatic in origin. Numerical modeling of the system using the above mentioned parameters is planned. We expect to determine what the magnitude of strain produced by the intruding magma would have to be for the lowering of the water table that was observed in 1993, 1999, and 2000. This strain will then be compared with the expected strain from volcanic intrusion to determine if strain alone could be responsible for the changes to the groundwater system.

V42B-1018 1330h POSTER

Seasonal variations in geochemistry of the hyperacidic Ijen Crater Lake, East Java, Indonesia

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Kawah Ijen is a typical crater lake in a tropical climate where there is a balance between the volume of atmospheric precipitation and the level of water in the lake. The crater lake has a regular oval form (600 × 1000 m²), is 180 m deep, and contains about 36 million m³ of turquoise-green colored water (pH ~ 0.2). The water contains extremely high Cl, SO₄, F concentrations, the maximum values being about 2,500 mg/kg, 80,000 mg/kg and 1,300 mg/kg respectively. Twenty-four samples of lake water taken during August 1996 (dry season) show most major elements to be homogeneously distributed throughout the lake at this time to a depth of 165 m within a standard deviation of less than 10%. Homogeneity is most likely due to thorough mixing driven by thermal convection. However, iron and sulphur do not behave in the same way showing variations up to 14% variation. Monthly monitoring of surface water (1997-2001) shows temporal fluctuations in acidity (pH 0 ~ 0.6) and water level, concentrations of major elements, temperature (20 ~ 45°C). Between 1976-1996, the water level varied by ~ 15 m; and from 1997-2001 by ~ 10 m. The onset of the wet season may coincide with an episodic decrease, a spike, in major element concentrations up to 70% of their dry season value. This spike occurs annually at the lowest temperature and highest degree of dilution, indicates of the influence of rainfall. However, volcanic gases entering beneath the lake bottom may have added to these temporal changes in the lake especially during phreatic eruptions. Shallow earthquake records do not indicate correlations between seismic activity and chemical changes in the lake. Temporal variations of lake surface temperature show good agreement with major element variations in surface water. Crater lake surface water collected at three points on August 1996, March 2001, May 2001 revealed that the surface water was homogenous in the dry and rainy season within a standard deviation below 7%. The geochemical and seasonal variations in the lake are important in assessing the environmental impact of acidic water that drains in to the Banyupahit-Banyuputih River, particularly in the Asembagus area (40 km from the lake) where the water is used for irrigation. The fluoride level in the 55 well water samples was high. In 50% of the samples it was above the 1.5 mg/kg limit recommended by the World Health Organization (WHO). Ratios of B/F, B, E/SO₄ as conservative elements indicate that Banyuputih River contaminates the groundwater.

V42B-1019 1330h POSTER

Magmatic and hydrothermal controls on trace element output at active volcanoes as recorded by spherules of sulfur in acid crater lakes

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Volcanic crater lakes are a major site of condensation for volatile elements and associated trace elements produced by magmatic activity. Spherules of solid native sulfur up to several mm in diameter with sulfide inclusions (mainly corroded FeS) are common in the dense acidic waters of magmatically active lakes. They were most likely produced as hot gas (e.g. H₂S or SO₂) was released at the bottom of the lake creating turbulence in pools of liquid sulfur. Analysis of the spherules presents a new opportunity to estimate the magmatic output of a poorly studied group of trace elements including Se, Te, As, Sb and Hg that often present a major environmental hazard in volcanic areas.

Sulfur spherules and acid lake waters were sampled from three active subduction-related volcanoes with differing stages of activity and degassing rates. Poás in Costa Rica hosts a highly dynamic crater lake with respect to volume and chemical composition. In contrast, the crater lakes at Kawah Ijen, East Java and Kawah Putih, West Java were more stable during the last 10 years but show some seasonal variations. Major and trace elements were determined *in situ* using electron microprobe and laser ablation ICP-MS techniques.

Spherules are highly enriched in trace elements including Se (400-4000 µg/g), Te (500-800 µg/g), Sb (1-18 µg/g) and As (30-510 µg/g). The internal chemical homogeneity of the spherules supports rapid formation. Changes in lake chemistry may account in part for large differences in trace element content between samples from each volcanic center. Lower As/S and Sb/S ratios at Poás correspond to higher temperatures that promote an enhanced release of HCl vapor from the lake surface. Recycling of hydrothermal acid brines into the lake may also have affected these trace element ratios. High Se/S and Te/S ratios cannot be explained by mixing between mantle and shallow sources and probably reflect additional sulfur loss due to degassing of the magmatic source.

V42B-1020 1330h POSTER

Volatiles in Basaltic Glasses from the Easter-Salas y Gomez Seamount Chain and Easter Microplate: Implications for Geochemical Cycling of Volatile Elements

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We present H₂O, CO₂ and Cl concentrations in 66 basaltic glasses from the Easter Microplate (EMP) and Easter-Salas y Gomez Seamount Chain (ESC) system in the Southeastern Pacific. The EMP-ESC system is characterized by binary mixing between a depleted MORB source and an incompatible element and radiogenic isotope enriched plume source, with channeling of plume material toward the ridge crest centered at ~27°S on the east rift of the microplate. Water concentrations on the EMP are highest on the east rift at ~27°S and become progressively lower to the north and south, following the spatial pattern of other geochemical tracers. EMP basalts have not lost H₂O to degassing, but have assimilated variable quantities of a Cl-rich hydrothermal component. In contrast, some seamount basalts have lost water by shallow degassing, but very few have gained Cl, indicating little assimilation of Cl-rich materials. Several seamount glasses from the ESC may have assimilated a hydrous component, e.g., serpentinized harzburgite, during magma ascent through the lithosphere. Based on samples unaffected by shallow processes, the main plume component has H₂O/Ce of ~210 ± 20 and is neither preferentially enriched nor depleted in H₂O relative to other similarly incompatible elements. The depleted MORB source has a H₂O/Ce of ~150 ± 10. Estimated mantle volatile concentrations for the Salas y Gomez plume are 590 ± 40 ppm for H₂O and 26 ± 2 ppm for Cl. The most depleted source region for the Easter Microplate basalts

has 64 ± 20 ppm H₂O and 1.8 ± 0.6 ppm Cl. The coupled behavior of H₂O and Cl with similarly incompatible elements suggests that the volatiles are juvenile, representative of a component common to mantle plumes, with minor contribution from recycled lithospheric components.

V42B-1021 1330h POSTER

H₂O and CO₂ contents of basaltic glasses from Mauna Kea volcano, Hawaii

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In 1999, the Hawaii Scientific Drilling Project recovered 3098 meters of drill core from Mauna Loa and Mauna Kea volcanoes on the island of Hawaii. Using FTIR spectroscopy, we measured H₂O and CO₂ concentrations in 145 basaltic glasses from the Mauna Kea section of the drill core. All glass samples are from submarine units (hyaloclastites, pillow basalts, intrusives, and massive basalts) at depths of 1103-3096 mbsl (meters below sea level). The analyzed samples contain 0.06-0.84 wt% H₂O and <20-106 ppm CO₂. With one exception, hyaloclastites (1103-2889 mbsl) are degassed (0.06-0.16 wt% H₂O, <20 ppm CO₂); one deep sample (2860 mbsl) contains 0.67 wt% H₂O and 43 ppm CO₂. Pillow basalts define two groups: degassed pillows (0.09-0.15 wt% H₂O, <20 ppm CO₂) shallower than 2132 mbsl, and undegassed pillows (0.16-0.75 wt% H₂O, <20-85 ppm CO₂) deeper than ~2236 mbsl. Intrusive units contain 0.57-0.79 wt% H₂O and 53-106 ppm CO₂ and generally have volatile contents equal to or greater than the volcanic units into which they have intruded. The 11 massive basalts (1126-2502 mbsl) measured have a range of H₂O contents (0.09-0.84 wt%), but only one sample had a CO₂ content (27 ppm) above background. Comparing measured OH and H₂O in all of the samples to experimentally determined water speciation in rapidly quenched basaltic glasses (Dixon 1995) suggests that several pillow basalts have elevated molecular H₂O contents. However, many of the samples with high molecular H₂O are near intrusive units, suggesting that the molecular H₂O content was elevated during interaction with fluids heated by the nearby intrusions. If eruption depths correspond to the pressures at which liquids with the volatile contents of the pillows would be vapor-saturated, then the deepest pillow basalts were erupted at ~1600 mbsl. Combining the present depths of these pillows (~3100 mbsl) with a subsidence rate of 2.5 mm/year (Moore 1996), leads to an estimated eruption age of ~600,000 years for the deepest recovered pillow basalts. Although CO₂ concentrations in our samples were modified on degassing during ascent and eruption (and thus reflect eruption pressures), the measured range of H₂O contents over limited depth intervals cannot be explained by degassing. In the section from 2236-2424 where the glasses trend toward "transitional" basaltic compositions, H₂O correlates positively with K₂O, but in strongly tholeiitic sections H₂O is decoupled from K₂O. These results suggest that the sources of the basalts are heterogeneous with respect to H₂O and that these heterogeneities are decoupled from variations in incompatible elements such as K₂O. Moore, J.G., B.L. Ingram, K.R. Ludwig, and D.A. Clague, Coral ages and island subsidence, Hilo drill hole, *J. Geophys. Res.*, 101, 11599-11605, 1996. Dixon, J.E., E.M. Stolper, and J.R. Holloway, An Experimental Study of Water and Carbon Dioxide Solubilities in Mid-Ocean Ridge Basaltic Liquids. Part I: Calibration and Solubility Models, *J. Petrol.*, 36, 1607-1631, 1995.

V42B-1022 1330h POSTER

Fractional Crystallization as a Control on Magma Degassing

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A relationship between major element fractionation due to magma crystallization and volatile element fractionation due to magma degassing is known for MORB

glasses such that fractionated volatiles are trapped in fractionated glasses. Marty and Zimmerman [1999] developed a model whereby CO₂ content of a magma increases during fractional crystallization due to its' incompatible behavior. When CO₂ content exceeds solubility, bubbles evolve and are lost. As a result, crystallization increases degassing. Insoluble noble gases are lost more rapidly during degassing than soluble ones. SHe/SAr (where S is the solubility) = c,10, therefore the He/Ar ratio increases rapidly with fraction of gas lost. In addition, He/Ar is a useful parameter with which to examine degassing as the starting 4He/40Ar is relatively well constrained at between 2 and 4 from U+Th/K constraints.

The model is a two stage process. Initially, magma is intruded into the crust at a given pressure with a specific CO₂ content. If CO₂ content exceeds CO₂ solubility at that pressure, then the 'excess' CO₂ (i.e. that above the solubility) is degassed, and the He/Ar ratio increases according to: C_i/C_j = (C_i/C_j)_o F (S_i/S_j) (C = concentration of i or j, S = solubility, F = fraction of CO₂ degassed). Note He/Ar fractionation at this stage is not accompanied by magmatic crystallization. The magma then crystallizes, increasing CO₂ content of the melt such that CO₂ now exceeds its' solubility limit, causing more CO₂ to be degassed and increasing He/Ar once more.

The noble gas composition of a crystallizing, degassing magma was computed assuming CO₂ is incompatible. CO₂, He and Ar solubilities were assumed to be constant. The models show that the He/Ar fractionation primarily depends on initial CO₂ content and pressure of fractionation, not magma chemistry. For example, increasing initial CO₂ content by 40% can increase He/Ar by a factor of 8.

Marty and Zimmerman argue that 40Ar/36Ar of oceanic basalts is determined by Ar in local crustal rocks that is assimilated by ascending magmas (evolved lavas have low 40Ar/36Ar). The models developed here show it is possible to generate the range in 40Ar/36Ar in basaltic glasses by adding a near - constant atmospheric Ar contaminant; because magmatic Ar - predominantly 40Ar - is efficiently lost from the magma, the 40Ar/36Ar is controlled by extent of gas loss, not assimilation.

Marty, B., and L. Zimmerman, *Geochim. Cosmochim. Acta*, 63, 3619-3633, 1999.

URL: <http://www.gps.caltech.edu/~peteb>

V42B-1023 1330h POSTER

The Application of H₂O-CO₂ Solubility Models to the Development of a Realistic Volatile Evolution Model for Crystallizing Magma

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Magmatic systems cannot be accurately modeled by assuming a pure volatile phase of H₂O or CO₂. As such, researchers have focused on determining the solubility of a binary H₂O-CO₂ fluid. Holloway and Blank¹ assumed Henrian mixing behaviour to model experimental results for the H₂O-CO₂ fluid up to 0.2 GPa. Papale² derived a more complex model depicting non-Henrian behaviour of the fluid up to 1 GPa. Here is presented a technique by which these and future fluid solubility models can be used to examine volatile phase behaviour in a dynamic, crystallizing magma. This graphical technique uses a three dimensional environment with dissolved H₂O and dissolved CO₂ concentrations as the x and y-axes and composition forming the z-axis, thus expanding the compositionally constant conditions used in previous studies of volatile solubility. Temperature is also a variable since a crystallizing magma cools. However, temperature effects are taken into account along the composition axis as each compositional step is fixed at its liquidus temperature. Through this three-dimensional space, a saturation surface plane is formed using an H₂O-CO₂ solubility model to calculate the saturation surface at each composition-temperature step. Using the initial magma volatile content as a starting point, a line can be drawn through the three dimensional space representing the path of the volatile composition in the melt as the composition of the liquid fraction of the magma changes. As crystallization proceeds, the volatile trend may intersect the saturation plane at which point a free volatile phase is generated, the composition of which is defined by the X^{fluid}_{H₂O} value at the intersection point as given by the model used to generate the saturation plane. Continued crystallization will result in further changes in both the melt and free volatile compositions. Using this process, the characteristics of the dissolved volatiles and free fluid may be determined at any point during crystallization. This methodology can be adapted to more complex situations, such as open and partially open systems, pressure changes, the crystallization of a hydrous or carbon-bearing phase, the inclusion of volatile oversaturation effects on bubble nucleation and, where a solubility model exists, the possible application to systems containing other volatiles.

The technique provided here is a useful and realistic approach for the examination of volatiles in real magmas that evolve compositionally with time.

¹Holloway, J.R. and Blank, J.G. (1994) Application of experimental results to C-O-H species in natural melts. In Mineralogical Society of America Reviews in Mineralogy, 30, 187-230

²Papale, P. (1999) Modeling of the solubility of a two-component H₂O + CO₂ fluid in silicate liquids. American Mineralogist, 84, 477-492

V42C MC: Hall D Thursday 1330h
Volcanology: Monitoring and Risk
Presiding: R Scandone, University of Rome III

V42C-1024 1330h POSTER

The Evaluation of Volcanic Risk of Campi Flegrei (Italy)

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The volcanological history of Campi Flegrei suggests that the emplacement of pyroclastic flow and surge characterizes the most frequent eruptions occurred from different vents scattered over a 150 km² wide caldera. The evaluation of volcanic risk in volcanic fields is complex because of the lack of a central vent. To approach this problem, we subdivided the entire area of Campi Flegrei into a regular grid and evaluated the relative spatial probability of opening of vents basing on geological, geophysical and geochemical data. We evaluated the volcanic risk caused by pyroclastic flows basing on the formula proposed by UNESCO (1972) $R = H \times V \times Va$, where H is the hazard, V is the vulnerability and Va is the value of the elements at risk. The product $H \times V$ was obtained by performing simulations of type eruptions centered in each cell of the grid. The simulation is based on the energy cone scheme proposed by Sheridan and Malin (1983), hypothesizing a column collapse height of 100 m for eruptions of VEI=3 and 300 m for eruptions of VEI=4 with a slope angle of 6°. Each simulation has been given the relative probability value associated with the corresponding cell. The vulnerability linearly decreases with the distance from the vent. We made use of the GIS software ArcView 3.2 to evaluate the intersection between the energy cone and the topography. The superposition of the areas invaded by pyroclastic flows (124 simulations for VEI=3 and 37 for VEI=4) was used to obtain the relative vulnerability map of the area. The relative volcanic risk map is obtained by superimposing the urbanization maps.

V42C-1025 1330h POSTER

Summary of the historical eruptive activity of volcn de Colima, Mexico 1519-2000

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Volcn de Colima (103°37'W, 19°30'N) has had significant eruptive activity over the last 5 centuries, leading to its designation as the most active volcano in Mexico. This activity has manifested itself through a variety of eruptive processes, culminating in explosive events rated VEI 4. Much of our knowledge of the earlier volcanic events is from non-scientific writings and as such is only an interpretation of sometimes ambiguous information. The most recent eruptions of the 19th and 20th centuries are, however, well documented scientifically allowing for more detailed understanding of these events. Numerous cities and towns, numbering up to 390,000 persons, are at risk from hazards posed by a Plinian or Subplinian eruption. Pyroclastic flows accompanying the 1818 and 1913 eruptions reached distances of 15 km, strong ash fell over 30 km distance, and lesser ash falls reached many hundreds

of kilometers. It is to be remembered that at present there are a number of towns within Colima and Jalisco States that could be seriously affected by such an eruption: pyroclastic flows, ash falls, and lahars being the major threats. Although the historical record does not permit forecasting the start of such activity, it gives abundant evidence that this style of volcanism will no doubt occur in Colima's future.

V42C-1026 1330h POSTER

Stability Evaluation Of Previous Volcanic Edifice Collapse At Pico De Orizaba Volcano, Mexico, Using Geotechnical Techniques

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Pico de Orizaba volcano has collapsed twice during its geologic evolution (Carrasco-Nuñez, 1997). The initial stage of evolution for this volcano is known as the Torrecillas cone that collapsed 0.21 Ma b.p., and the related deposits formed the Jamapa avalanche which traveled eastward 75 km. A second, superimposed constructional stage is the Espoln de Oro cone that also ended with a collapse 20 000 years b.p., forming the Tetelzingo avalanche-lahar that traveled 85 km. Samples from the remains of old summit cores and their corresponding collapse deposits were collected and tested in order to obtain strength parameters of altered rock from old volcanic edifices. Hydrothermal alteration and variations of strength of the two avalanche deposits were correlated with the strength values and alterations from the in situ corresponding sources. Strength values: Hoek and Brown's parameters, Uniaxial Compressive Strength (50-300 kPa), cohesion (480-2000 kPa), angle of friction (6°- 35°); and degree of alteration give insights of rock mass quality and maximum intact rock strengths of the edifice rock mass. These values provide the upper limits for numerical model input parameter values for evaluation of flank stability. Rock strength from numerical model of previous failures can be compared with those obtained for the rock mass and intact rock of the actual edifice. This would permit the assessment of future avalanche hazards.

URL: <http://www.scs.unr.edu/~aline/current.html>

V42C-1027 1330h POSTER

Development of the cosmic-ray muon detection system for probing internal-structure of a volcano

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Very high energy cosmic-ray muons penetrating through a mountain enable us to probe internal-structure of volcanoes by using the cosmic-ray muon energy spectrum and the range-energy relation of muons. An improved cosmic-ray muon detection system comprising two segmented detectors with multiplicity cut of the soft components of cosmic ray was developed. The result of the test measurement for the volcano Mt. Asama will be presented.

URL: <http://nerv.riken.go.jp>

V42C-1028 1330h POSTER

Intracaldera Lake Shorelines in the Taupo Volcanic Zone, New Zealand: Long-Term Versus Short-Term Deformation Trends

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Taupo Volcanic Zone is a region of active arc volcanism, deformation, and seismicity developed in association with rifting behind the Hikurangi subduction zone at the south end of the Tonga-Kermadec Trench. At Taupo volcanic center, a major ~26.5 ka caldera system (now occupied by a large lake) cuts across the Taupo Fault Belt, a zone of late Quaternary extension and normal faulting. Short-term (<20 years) vertical deformation rates from geodetic and lake-leveling techniques reveal complex and episodic deformation trends, linked in part to local seismicity, overprinting a broader regional pattern. Medium-term deformation trends, defined relative to a paleolevel formed by a highstand shoreline developed within ~15 years of the 1.8 ka Taupo eruption are broadly similar to these historic patterns. However, warping and offsetting of a highstand shoreline developed in the immediate aftermath of the 26.5 ka Oruanui eruption indicates rather different long-term deformation trends. Relative offsets on the 26.5 ka shoreline are only double those of the 1.8 ka shoreline, despite it being 15 times older, except where subsidence has been concentrated on a single, highly active fault. The 26.5 ka shoreline reaches its highest elevation in the middle of an inferred graben in the Taupo Fault Belt: extrapolation of short-term deformation rates at this site would place it below modern lake level. The inference is that the Taupo Fault Belt immediately north of Lake Taupo is largely isostatically compensated, with short-term patterns (years to centuries) of episodic uplift and subsidence cancelling out over longer time periods (tens of thousands of years). Long-term subsidence is instead apparently focused to the east, in the actively deforming, little-faulted Taupo-Reporoa Basin, which hosts a lacustrine succession stretching back 300 ka. Usage of short-term patterns to indicate long-term deformation trends, or to demonstrate caldera unrest at Taupo volcanic center is inappropriate, as such patterns may simply represent elastic responses to continued horizontal extension across the Taupo Volcanic Zone, made manifest by the presence of Lake Taupo as a horizontal datum.

V42C-1029 1330h POSTER

Precise Repicking and Relative Relocation of Volcanic Earthquakes at Soufriere Hills Volcano Reveals Distinct, Stationary Sources for Early Earthquake Swarms

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We have performed automatic, waveform correlation-based phase repicking and a multi-tiered method of clustering to isolate distinct families of repeating seismic events at Soufriere Hills Volcano, Montserrat, for July, 1995 - February, 1996. 75 large clusters of similar events have been identified. These clusters correspond to times of significant swarming activity at the volcano. Families segregated by waveform differences tend also to be separated from one another in time, and each spans at most a few days.

Earlier families are volcano-tectonic in nature and represent brittle failure in association with pre-eruptive activity near the summit crater. Hypocenters could not be estimated for these events due to poor signal/noise ratio at most stations; however, repeatability of waveforms at the summit station suggests a consistent source region within each of these clusters. Rapid attenuation with distance indicates extremely shallow depths, and we interpret these events as occurring very near the volcano edifice.

Later clusters can be located with traditional earthquake location methods. These events coincide temporally with observed dome extrusion. They are characterized by high-frequency onsets exhibiting mixed first motions, followed by long period codas of tens of seconds' duration. These volcanic hybrid event swarms occur within discrete source regions of at most a few hundred meters' diameter. Some clusters are spatially