

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

V21A-1192 0830h POSTER

Information fusion techniques applied to eruption forecasting

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

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

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

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

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

V21A-1193 0830h POSTER

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

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Volcanic ashclouds pose increasing hazards to air traffic. To enable accurate detection, tracking, and ultimately nowcasting (ie. near-real-time tracking and short-term forecasting), it is becoming increasingly important to be able to retrieve, in addition to information on SO₂ (and aerosols) and ash (ice) mass, and ash (ice) size, key information such as cloud peak height, average height and height of the leading cloud edge, intensity changes, lateral and downwind spreading, ash/gas separation, evidence of microphysical changes (eg. mixed-phase aggregation), duration and cloud thickness. Here, we have systematically examined radar data and satellite data from a variety of sensors in combination with field and meteorological information (eg. balloon soundings) for a number of ashclouds covering a large range of spatial and temporal scales, as well

as a large range of eruption intensity and meteorological conditions. We illustrate that the analysis of detailed surface features such as the overshoot geometry, cloud top gravity waves and cloud top or cloud edge Kelvin-Helmholtz (K-H) shear billows can supply key additional information, compared to previous studies. We document that the overshoot size allows extraction of an independent estimate of cloud-top average height, that the number and characteristics of gravity waves allow to derive another independent estimate of column height as well as information on the height difference between peak and neutral buoyancy heights (Ht-Hb). These estimates are compared with estimates of cloud edge height extracted using the shadow method and also comparisons with wind profiles data, and also lead to the identification of ash/gas separation in some cases. The gravity waves can be understood by analogy with fluid mechanics modelling of mixed region collapse in a stratified fluid. Conditions for the development of K-H billows are also considered and we show how they can be used to identify the transition from the gravity-advection flow phase and the advection-diffusion phase of spreading. We also discuss their potential use in deriving ashcloud thickness from the quasi-2D satellite images. This, together with the information from ash-gas separation and gravity waves, enables to extract 3D information from quasi-2D satellite images. Implications of this work for generic understanding of processes in ashclouds and for aircraft safety are briefly discussed.

V21B MCC: Hall C Tuesday 0830h Volcanic Gases Posters

Presiding: L Jaffe, University of California, San Diego

V21B-1194 0830h POSTER

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

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While the effects on the global environment of large volcanic eruptions have been frequently studied, there has been little work on the impact of lower tropospheric emissions from persistently degassing volcanoes. In contrast to large volcanic eruptions which may have a short term but hemispheric/global effect (through injection of gas and ash into the stratosphere), persistently degassing volcanoes can have significant long-term (years to decades), local and regional effects. To examine these effects, we consider 3 persistently active degassing systems: Kilauea (USA), Poás (Costa Rica) and Masaya (Nicaragua). These volcanoes are characterized by SO₂ emission rates ranging from 100s to 1000s metric tonnes per day, and have emitted acid gases into the troposphere for extended periods of time. Masaya, for example, has degassed approximately the same amount of SO₂ (21 Tg) over a period of 140 years as the 1991 eruption of Mount Pinatubo injected into the atmosphere in just a few hours. The extended degassing at Kilauea, Masaya and Poás impacts on commercial agriculture and has led to attempts to mechanically mitigate the hazard through capping of the active crater at Masaya and flooding to reinstate the acid crater lake at Poás. In order to investigate the environmental effects of persistent degassing, we use remote sensing data (Landsat ETM+, IKONOS) with NDVI band ratio algorithms to delineate poorly vegetated areas downwind of each volcano. These data are incorporated, through a GIS, with DEM and various ground truth data (soil pH, dry deposition rates, precipitation acidity, etc.). Extremely distinct zones of vegetation kill off are noted that correlate with changes in topography. It appears that sharp topographic changes allow the gas plume to decouple or couple with the ground, hence lessening or increasing its impact at any downwind location. This integrated study of degassing at persistently active volcanoes may aid in limiting the effects on human populations and agriculture downwind of such systems through improved land use management.

V21B-1195 0830h POSTER

Soil CO₂ and H₂ Efflux Distribution Along the North-South Rift Zone at Tenerife, Canary Islands

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Volcanic activity at Tenerife is mainly concentrated along three major volcanic rift-zones of NE-SW, NW-SE, and N-S directions as well as in the central part of the island where the Teide stratovolcano located. The goal of this study is to evaluate diffuse CO₂ and H₂ degassing through the N-S volcanic rift-zone and compare these results with those observed for the NE and NW rift-zones.

Surface degassing surveys were performed along the NW and NE rift-zones during the summer of 2000 and 2001, respectively. From July 18 to August 16, 2002, a new survey was performed along the N-S rift-zone covering an area of 352 Km². Soil CO₂ efflux reached values up to 44 gm⁻²d⁻¹. Soil gas samples were collected at a 40 cm depth to estimate soil H₂ efflux by means of multiplying H₂/CO₂ ratio times soil CO₂ efflux. Soil H₂ efflux reached values up to 25 mgm⁻²d⁻¹. The total output of diffuse degassing rate from the study area was estimated about 412 td⁻¹ for CO₂ and 290 Kgd⁻¹ for H₂. The NW rift-zone surface degassing survey covered an area of 72 Km² and showed rates of 283 td⁻¹ and 74 Kgd⁻¹ for diffuse CO₂ and H₂ degassing, respectively. The NE rift-zone degassing survey covered an area of 210 Km² and showed rates of 685 td⁻¹ for CO₂ and 65 Kgd⁻¹ for H₂. If surface degassing rates are normalized by areas in order to compare these results among the major Tenerife's rift-zones, similar diffuse CO₂ degassing rates are observed for the NW and NE rift-zones, but they are three times higher than the observed for N-S rift-zone. In the case of H₂, similar diffuse H₂ degassing rates are observed for the NW and N-S rift-zones, but they are three times higher than the observed for NE rift-zone. These results suggest that a shallower hydrothermal system is affecting more the NW than the others major rift-zones at Tenerife island.

URL: <http://www.iter.es>

V21B-1196 0830h POSTER

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

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La Palma (730 Km²) is the northwestern most island of the Canarian archipelago. Cumbre Vieja (<1 Ma) is situated in the southern part of La Palma, and is the most active basaltic volcano in the Canaries where the most recent eruption occurred in 1971, *Teneguia* volcano. The main structural features of Cumbre Vieja (220 Km²) are three major volcanic rift-zones of N-S, NE, and NW orientations. Diffuse CO₂ degassing studies is becoming a useful geochemical tool for volcano monitoring (Hernandez et al., 2001). Since (1) helium is an ideal geochemical indicator because it is chemically inert, physically stable, sparingly soluble in water under ambient conditions and almost non-adsorbable, and (2) helium-3 is the best fingerprint for magmatic activity and reach levels up to 9.6 Ra at La Palma (Perez et al., 1994), the goal of this study is evaluate the use of diffuse helium emission for volcano monitoring of Cumbre Vieja.

Diffuse degassing survey of 619 sampling sites was carried out from July 19 to August 13, 2002, at Cumbre Vieja volcano. Soil CO₂ efflux measurements were performed by means of a portable NDIR sensor and according to the accumulation chamber method. At each sampling site, soil gas samples were collected at 40 cm deep using a metallic probe and analyzed for ⁴He and CO₂ contents by means of an Omnistar QMS within 24 hours. Spatial distribution of soil gas helium expressed as (ΔHe = He_{soil atmosphere} - He_{air}) showed that relatively high ΔHe values (> 1,800 ppb) occurred in the summit zone of Cumbre Vieja along the N-S rift-zone, suggesting a deep origin for the degassing through this major structure. Soil He efflux was estimated by

multiplying soil CO_2 efflux times $\Delta He/\Delta CO_2$ ratio at each sampling site. Taking into consideration the spatial distribution of estimated soil He efflux and the volcanic area, the total output of diffuse He emission is estimated about 59 Kg/d for Cumbre Vieja volcano. Monitoring these results could be useful for the volcanic surveillance.

URL: <http://www.iter.es>

V21B-1197 0830h POSTER

Continuous Monitoring of Diffuse Gas Emission From Teide Volcano, Tenerife, Canary Islands

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Teide volcano (3,717 m a.s.l.) is located in the central part of Tenerife island, at the intersection of three major volcanic rift-zones. Low temperature fumaroles (81-85°C) occur in the summit cone, where significant amounts of diffuse CO_2 degassing have been measured about 400 of tons per day (Hernandez et al., 1998; Gonzalez et al., 2001). Chemical and isotopic composition of these gases show a mixing of CO_2 -rich deep-seated gas and atmospheric air. In order to improve the volcanic surveillance program of Teide volcano, a geochemical station for continuous monitoring of the diffuse degassing was installed at the summit (3,575 m a.s.l.) in April 1999.

Soil CO_2 and H_2S efflux (WEST Systems, Italy), soil temperature, soil water content, rainfall, and meteorological variables (wind speed and direction, barometric pressure, air temperature and air humidity) are continuously measured in an hourly basis and real-time radio-transmitted to ITER facilities 25 Km far. Soil gas composition, collected at 70 cm deep, as well as $^4He/^{40}Ar$, $^4He/CO_2$, $N_2/^{40}Ar$, and $^{40}Ar/^{36}Ar$ ratios are also routinely measured using an Omnistar quadrupole mass spectrometer (QMS). Teide geochemical station is also integrated by an electrostatic-type SARAD alpha detector, which allows measuring ^{222}Rn and ^{220}Rn from its radioactive progeny, ^{214}Po , ^{216}Po and ^{218}Po hourly. Diffuse degassing at Teide volcano is dominated by a large and variable CO_2 content (<66.7%V) and CO_2 efflux <29 Kg $m^{-2} d^{-1}$. Despite the air-like $^{40}Ar/^{36}Ar$ (<310) and N_2/O_2 (~3.4) ratios, the $^4He/^{40}Ar$ ($9.3 \cdot 10^{-4}$) and $^4He/CO_2$ ($2.6 \cdot 10^{-5}$) ratios showed the contribution of deep-seated derived gas. Soil gas ^{222}Rn content has a median value of 1.18 KBq m^{-3} and is quite variable depending on the meteorological conditions at the observation site (wind speed, barometric pressure and soil water content). These promising results are a relevant key within the geochemical monitoring program for the seismic-volcanic surveillance at Tenerife island.

URL: <http://www.iter.es>

V21B-1198 0830h POSTER

Anomalous Changes of Diffuse Hydrogen Emission from Poas Volcano, Costa Rica, Central America: a Premonitory Geochemical Signature of Volcanic Unrest?

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Poas volcano is a large basaltic-andesite stratovolcano located in the Cordillera Central in Costa Rica. The summit of Poas consists of three nested calderas and an active crater located between two older cones: Von Frantzius to the north and Botos cone to the south. This active crater contains a hot and acidic crater lake, and host an active hydrothermal system. The purpose of this work is to study and evaluate the spatial distribution of diffuse H_2 at the surface environment of Poas volcano during the period 2000-2002.

Diffuse H_2 degassing surveys have been yearly performed at Poas volcano since the year 2000 covering an area of 3.4 Km^2 . Soil gas H_2 concentration ranged from 0.6 to 4.1 ppmV, from 0.4 to 1,910.3 ppmV, and from 0.8 to 7,059.2 ppmV for the 2000, 2001 and 2002 surveys, respectively. Statistical-graphical analysis was

applied for the soil gas H_2 concentration data observed for three surveys. Two populations were observed for the 2000 survey, while three were observed for 2001 and 2002 surveys. Most of the study area showed background soil gas H_2 concentrations for the 2000 (0.6 ppmV), 2001 (0.7 ppmV), and 2002 (4.1 ppmV) surveys. Peak mean values of soil gas H_2 content were just observed for the 2001 (15.2 ppmV) and 2002 (340.1 ppmV) surveys. Peak soil gas H_2 concentration values were mainly observed inside the main crater, but the anomalous H_2 area for the 2002 survey is larger than the 2001 survey. These data suggest an increasing trend of soil gas H_2 concentration at Poas. The observed secular variation of the spatial distribution of diffuse H_2 emission was closely related to fumarole activity changes inside the main crater during the last three years. These results might suggest that diffuse H_2 emission could be a premonitory geochemical signature of volcanic unrest at Poas.

URL: <http://www.iter.es>

V21B-1199 0830h POSTER

Surface Pressure Gradient and Carbon Dioxide Degassing Survey at Cumbre Vieja Volcano, La Palma, Canary Islands

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La Palma (730 Km^2) is one of the youngest island of the Canarian archipelago. Recent volcanic activity is concentrated on the southern part of the island, where Cumbre Vieja volcano (220 Km^2) has been constructed during the last 1 Ma reaching an elevation of 1,898 m above sea level. Six historical eruptions had occurred at Cumbre Vieja, and the most recent event took place in the southern part of the volcano (Teneguía volcano, 1971). The main structural features are three major volcanic rift-zones of N-S, NE, and NW orientations. Since fumarolic activity is absent at Cumbre Vieja, coupled surface pressure gradient and carbon dioxide degassing monitoring could be potential geophysical and geochemical tools for its volcanic surveillance.

Surface pressure gradient and carbon dioxide degassing survey of 619 observation sites was carried out from July 19 to August 13, 2002, at Cumbre Vieja volcano. Pressure gradient measurements were performed by means of a Setra 239 Model pressure transducer, and soil CO_2 efflux measurements were performed by means of a portable NDIR sensor according to the accumulation chamber method. At each sampling site, soil gas samples were collected at 40 cm deep using a metallic probe and analyzed for CO_2 contents by means of an Omnistar QMS within 24 hours. Surface pressure gradient ranged from -36 to 90 Pam^{-1} . Soil CO_2 efflux ranged from negligible values to 1,300 $gm^{-2}d^{-1}$, and soil gas CO_2 content ranged from 0.03 to 1.1 %V. Statistical graphical analysis showed two different populations for the CO_2 efflux data and their mean values are 1.4 and 52 $gm^{-2}d^{-1}$, respectively. For this 2002 survey, the total output of diffuse CO_2 emission was estimated about 1,340 td^{-1} , which lies within the range of previous surveys (1,250-2,500 td^{-1}). Spatial distribution of the data showed an excellent agreement between surface pressure gradient and CO_2 degassing at Cumbre Vieja, where the highest observed values were detected in and around the volcanic vent related to the most recent eruption at Cumbre Vieja volcano.

URL: <http://www.iter.es>

V21B-1200 0830h POSTER

Soil Volatile Hg, As, B and NH_3 Distribution Prior the 2001 Eruption at Usu Volcano, Japan

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Usu volcano is one of the most active volcanoes in Japan, and eight major eruptions have been recorded at this volcano since 1963. It is located in the southwestern part of Hokkaido. The volcano is a post-caldera cone of Toya caldera, and composed of a somma volcano with a parasitic scoria cone and a number of lava domes and pyroclomes. A regular repetition of the eruptions of Usu at an interval of 30-50 years in later historic times is an important aspect for the surveillance and monitoring of this volcano. The most recent one occurred in March 31, 2000.

A soil volatile Hg, As, B and NH_3 survey of 150 sampling sites was carried out at Usu in September 1998, 18 months prior the 2000 eruption. Soil samples were collected at 40 cm depth to avoid the soil organic rich layer. Soil samples were air dried and sieved (< 2mm). Hg, As and B measurements were performed by means of ICP in soil extractions whereas NH_3 was measured by means of ISE. Soil As, B, Hg and NH_3 contents ranged from 91.5 to 12,442 ppb, 75.4 to 1667 ppb, 6.4 to 3,090 ppb and from 0.1 to 46.4 ppm, respectively. Median values for As, B, Hg and NH_3 were 2,151 ppb, 433 ppb, 123 ppb and 4.9 ppm, respectively. Highest values of As, B and NH_3 were spatially well correlated and mainly identified at the summit and northern slope of Usu volcano as well as near by the site of the March, 2000 eruption. Soil mercury distribution did not show any spatial correlation with the main geological and hydrothermal features at the studied area. Distribution of soil As, B and NH_3 anomalies at Usu were also spatially well correlated with high values of soil CO_2 efflux (Hernandez et al., 1998), suggesting a common origin for these discharges. These results indicate that deep perturbation of the Usu volcanic-hydrothermal system on the surface environment has been responsible for the observed spatial distribution pattern of soil volatiles.

URL: <http://www.iter.es>

V21B-1201 0830h POSTER

Helium and Carbon Isotope Systematics of Springs in the Separation Creek Drainage System, Three Sisters area, Central Oregon Cascades.

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In response to recent and on-going uplift in the Separation Creek drainage system, 5 km west of South Sister volcano in the central Oregon Cascades (e.g. Wicks et al., 2001), a hydrogeochemical monitoring project was initiated by the U.S. Geological Survey in the summer of 2001. When compared to existing literature data, we found no significant changes in the helium isotope composition of hot springs located in the vicinity of South Sister volcano, but outside the area of uplift. Nor were there significant changes in fluid chemistry or conductivity of cold springs within the area of uplift. For the latter group, there are no pre-uplift helium or carbon isotope data. Therefore, the implications of the strong magmatic helium and carbon isotope signals measured in two of these samples and their possible relationship to the recent uplift could not be evaluated (Van Soest et al., 2001; Evans et al., 2002).

Within the scope of the hydrogeochemical monitoring project, a detailed survey of cold springs in the Separation Creek drainage area was planned for the spring, summer and fall of 2002. Preliminary results for spring 2002 samples suggest a relationship between helium isotope composition and distance from South Sister volcano, but not the center of uplift: $8.6R_A$ at 3 km (from a sample nearest the youngest erupted volcanics), $7.4R_A$ at 5 km (near the center of uplift), $7.0R_A$ at 10 km, $6.8R_A$ at 18 km, and $5.2R_A$ at 25 km from South Sister volcano. The last value is from the hot spring closest to the area of uplift for which there is pre-uplift data and it suggests a constant helium isotope ratio over time (1982-present). The new carbon isotope results confirm the existence of a mixing relationship between deep abiogenic (magmatic) carbon and shallow biogenic carbon that was apparent in the 2001 samples. The carbon isotope results appear to correlate with the Cl and conductivity anomalies in the springs. At this time, whether a similar correlation exists for

the helium isotope data remains unclear. To date there is no clear evidence that links the geochemical data to the recent and on-going uplift, but work currently in progress may shed more light on this issue.

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Wicks, C. Jr., Dzurisín, D., Ingebritsen, S. E., Thatcher, W., Lu, Z., and Iversen, J. Magmatic activity beneath the quiescent Three Sisters volcanic center, central Oregon Cascade Range, USA, inferred from InSAR. *Eos Trans. AGU* 82(47), Fall Meet. Suppl., Abstract G31C-0155, 2001.

V21B-1202 0830h POSTER

Spatial and Temporal Variations of Diffuse Carbon Dioxide Emission From Cerro Negro Volcano, Nicaragua, Central America

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Cerro Negro is a basaltic cinder cone that has erupted 22 times since its birth in 1850. It is part of a group of four young cinder cones NW of Las Pilas volcano. Cerro Negro's most recent activity was on 5 August 1999 when erupted ash clouds at heights of about 7 km. In December 1999, three months after the eruption, a surface flux survey was carried out at Cerro Negro. Soil CO₂ efflux values ranged from 0.5 to 35,000 gm⁻²d⁻¹ and the total diffuse CO₂ output was estimated about 2,800 td⁻¹. Soil temperature reached values above 300°C on the NE flank of the volcano (Salazar et al., 2001). The goal of this study is to evaluate how diffuse CO₂ degassing rate at Cerro Negro changes through its eruptive cycle and improve its volcano monitoring program.

From February 26 to March 11, 2002, a new diffuse CO₂ degassing survey was carried out at Cerro Negro. Sampling distribution was similar to the 1999 survey covering an area of (0.6 Km²). Diffuse CO₂ emission rates for the 2002 survey showed a wide range of values from 0.3 to 26,500 gm⁻²d⁻¹. Most of the study area showed soil CO₂ efflux values above 110 gm⁻²d⁻¹, and the highest CO₂ efflux rate was observed in the Northeastern sector of the crater. Soil temperature was also recorded during the survey, and the highest value was observed in the NE flank reaching temperatures up to 450°C. The total diffuse CO₂ output for the 2002 survey was estimated about 280 td⁻¹, which is one order of magnitude lower than the estimated for the 1999 survey. This significant temporal variation on diffuse CO₂ emission rate seems to be clearly related to the eruptive cycle of Cerro Negro. If we consider that the statistically eruptive cycle for Cerro Negro is less than a decade, it is obvious that the December 1999 survey was performed within its post-eruptive period, while the recent 2002 survey was carried out two years and a half after the most recent eruption of Cerro Negro, within its inter-eruptive period. These results suggest that diffuse CO₂ degassing monitoring at Cerro Negro could be a potential geochemical tool for its volcanic surveillance.

URL: <http://www.iter.es>

V21B-1203 0830h POSTER

Diffuse CO₂ Degassing at Masaya Volcano, Nicaragua

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Volcanic gas emissions from a lava lake at Masaya volcano, Nicaragua, have been repeatedly measured over the past several decades. However, the extent and nature of diffuse degassing associated with the volcano are relatively unknown. We conducted a preliminary soil CO₂ flux and temperature survey (August, 2002) at two sites along a NE-trending lineament, located on the NE flanks of Masaya. At the first site, located ~3.5 km NE of the inactive Masaya crater and adjacent to the Comalito cinder cone, we made 209 measurements of soil CO₂ flux (25 to 41,711 g m⁻²d⁻¹) and temperature (30 to 80 °C) within a 7175 m² area. CO₂ fluxes belong to three populations of low, medium, and high flux. Total CO₂ emission rate from this area is estimated to be 20 t d⁻¹. At the second site (844 m²), located ~0.75 km NE of Masaya crater, we made 133 measurements of soil CO₂ flux (9 to 39,488 g m⁻²d⁻¹) and temperature (27 to 62 °C). These fluxes constitute low and high flux populations. Total CO₂ emission rate is estimated to be 2.5 t d⁻¹ from this area. CO₂ fluxes belonging to medium and high flux populations at both study sites are distributed along linear trends approximately parallel to the existing structures. Autocorrelation analysis shows that soil CO₂ fluxes and temperatures at these study sites are moderately to well spatially correlated, with direction of anisotropy oriented approximately parallel to the structures. A positive correlation between soil CO₂ flux and temperature is observed. Our results suggest that large quantities of heat and CO₂ may be advectively transported with steam along highly permeable fractures from depth to the atmosphere. Assuming comparable emission rates along the length of the lineament, diffuse CO₂ degassing may significantly contribute to total CO₂ emission from Masaya volcano.

V21B-1204 0830h POSTER

Secular Variations of Soil CO₂ Efflux at Santa Ana-Izalco-Coatepeque Volcanic Complex, El Salvador, Central America

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The Santa Ana-Izalco-Coatepeque volcanic complex (2,365 m elevation), located 40 Km west of San Salvador, consists of the Coatepeque collapse caldera (a 6.5 x 10.5 Km elliptical depression), the Santa Ana and Izalco stratovolcanoes, as well as numerous cinder cones and explosion craters. The summit of the Santa Ana volcano contains an acid lake where hot springs, gas bubbling and intense fumarolic emissions occur. A volcanic plume, usually driven by the NE trades, may be seen rising up to 500 m from the summit crater of the Santa Ana volcano. The goal of this study is to provide a multidisciplinary approach for the volcanic surveillance by means of performing geochemical continuous monitoring of diffuse CO₂ emission rate in addition to seismic monitoring.

Temporal variations of soil CO₂ efflux measured at Cerro Pachó dome, Coatepeque caldera, by means of the accumulation chamber method and using a CO₂ efflux continuous monitoring station developed by WEST Systems (Italy). From May 2001 till May 2002, CO₂ efflux ranged from 4.3 to 327 gm⁻²d⁻¹, with a median value of 98 and a quartile range of 26 gm⁻²d⁻¹. Two distinct diffuse CO₂ degassing periods have been observed: (1) an increasing trend from May to July 2001, and (2) a stationary period from November 2001 to May 2002. The increasing-trend period may be due to the anomalous plume degassing at the Santa Ana volcano during 2001 and soon after the January and February 2001 earthquakes. Temporal variations of CO₂ efflux during the second period seem to be coupled with those of barometric pressure and wind speed at different time scales, though most of the variance is contained at diurnal and semi-diurnal frequencies. These observations can help to explain the existence of a persistent behavior (Hurst exponent, H=0.934 ± 0.0039) within the diffuse CO₂ degassing phenomena. However, further observations are in progress to understand the long-term memory of diffuse CO₂ degassing at the Santa Ana volcanic complex.

URL: <http://www.iter.es>

V21B-1205 0830h POSTER

Continuous Monitoring of Diffuse CO₂ and H₂S Degassing Rates at Masaya Volcano, Nicaragua, Central America

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Masaya lies 20 km SE of Managua and is one of Nicaragua's most unusual and most active volcanoes. It is a basaltic-andesitic caldera and forms a basin 11.5 x 6 Km in diameter whose long axis is oriented to the northwest, parallel to the Quaternary volcanic chain. It is known to have been active since the Spanish arrival in the 16th. Since its reactivation in 1993 is going through a significant degassing process with a stable volcanic plume releasing to the atmosphere about 3,000 td⁻¹ of CO₂ (Horrocks et al., 1999).

The total output of diffuse CO₂ emission has been previously estimated about 28,800 td⁻¹ by a diffuse CO₂ degassing survey carried out in December 1999. This data imply that diffuse/plume CO₂ degassing ratio at Masaya is about 9.6 (Pérez et al., 2000). Peak values of soil CO₂ efflux (> 1,600 gm⁻²d⁻¹) were identified at El Comalito as well as in other specific caldera sites. To study and monitor secular variations of diffuse degassing rates at Masaya, a continuous monitoring station for soil CO₂ and H₂S efflux measurements developed by WEST System (Italy) was installed at El Comalito on March 15, 2002. Diffuse CO₂ and H₂S degassing rates as well as several meteorological parameters are measured in an hourly basis and radio-transmitted to the National Park facilities. Soil CO₂ efflux ranged from 12.6 to 16,012 gm⁻²d⁻¹ and showed a median of 4,300 gm⁻²d⁻¹. Soil H₂S efflux ranged from 11.6 to 703 mgm⁻²d⁻¹ and showed a median of 41.2 mg m⁻²d⁻¹. Soil temperature ranged from 60.5 to 77.6°C and showed a median of 75.8°C. A sharp increase of CO₂ efflux rate from median value to 9,290 gm⁻²d⁻¹ was detected in July 18, 2002. CO₂ efflux reached background values by September 2002. This acute increment on CO₂ efflux is not correlated with high frequency minor fluctuations related to meteorological variables. On the contrary, major secular variation of H₂S efflux rate is strongly affected by rainfall. A larger observation time-span is needed to understand the influence of the volcanic and meteorological activity on the observed soil CO₂ and H₂S efflux time series at Masaya volcano.

URL: <http://www.iter.es>

V21B-1206 0830h POSTER

Precursory Diffuse CO₂ Emission Signature of the January 2002 Short-term Unrest at San Miguel Volcano, El Salvador, Central America

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San Miguel is one of the most active volcanoes in El Salvador and rises from near sea level to 2,132 meters. San Miguel has erupted at least 29 times since 1699 and its historical eruptions consisted mainly of relatively quiescent emplacement of lava flows or minor explosions that produced modest tephra falls (Mayer-Abich, 1956). In January 2002 a short-term volcanic unrest characterized by a gas-and-steam plume containing a little ash rising with a mushroom-like profile a few hundred meters above the summit crater occurred at San Miguel volcano (BGVN 27:02, 2002). In addition, an anomalous microseismicity pattern, about 75 events between 7:30 and 10:30 hours, was also observed on January 16, 2002. This style of increased seismicity and gas emission is within the range of normal activity at San Miguel according to SNET, since intermittent periods of vigorous steam-and-gas emission have been commonly reported in recent years (BGVN 27:02, 2002).

Continuous geochemical monitoring of diffuse CO₂ degassing is performed on the eastern flank of San Miguel volcano since November 24, 2001, to provide a multidisciplinary approach for San Miguel's volcanic surveillance program. At the observation site, the

background mean of the diffuse CO₂ emission rate is about 16 gm⁻²d⁻¹, but a 17-fold increase, up to 270 gm⁻²d⁻¹, was detected on January 7, nine days before the January 2002 short-term unrest at San Miguel. This observed anomalous changes on diffuse CO₂ degassing rate might be related to a sharp increase of CO₂ pressure within the volcanic-hydrothermal system of San Miguel since meteorological fluctuations cannot explain this observed significant increase of diffuse CO₂ emission nine days before the short-term unrest at San Miguel volcano on January 16, 2002.

V21B-1207 0830h POSTER

Anomalous Change of Diffuse CO₂ Emission Rates at San Salvador volcano, El Salvador, Central America: a premonitory geochemical signature of magmatic and/or tectonic reactivation?

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San Salvador volcano is located towards the southern part of the Central American graben. The most recent magmatic activity was mainly focused on the volcano NW flank forming monogenetic explosion craters, cinder cones, and lava flows. Flank vents continue to erupt at a rate of once every 82 yrs with the last eruption in 1917 (Sofield, 1999). The city of San Salvador, with a population 1.7 million located at the skirts of the volcano, will be at high risk if an eruption occurs. The purpose of this work is to provide a multidisciplinary approach for the volcanic surveillance by means of introducing geochemical continuous monitoring of diffuse CO₂ and H₂S emission rates.

Soil CO₂ and H₂S efflux are continuously monitored at Cerro La Hoya, which is located at San Salvador volcano southern flank, by means of a soil gas efflux continuous monitoring station. Since Nov.11, 2001, until Aug.30, 2002, about 6,800 observations of soil gas efflux and meteorological measurements had been recorded. Soil H₂S efflux values were negligible during this period. On the contrary, two distinct diffuse CO₂ degassing periods have been observed: (1) a stationary period from Nov. 11 to Dec. 27, 2001, and (2) a clear increasing trend period from Dec. 28, 2001, up to date. From Nov.11 to Dec.27, 2001, CO₂ efflux showed an average of 700 gm⁻²d⁻¹ peaking values up to 1,194 gm⁻²d⁻¹. From Dec.28, 2001, to Aug.30, 2002, CO₂ efflux showed an average of 7,435 gm⁻²d⁻¹ peaking values up to 45,285 gm⁻²d⁻¹. Soil temperature showed similar average and peak values for both periods. It is quite evident that this anomalous change of CO₂ efflux rate at San Salvador is not driven by meteorological fluctuations. Therefore, this anomalous change of diffuse CO₂ emission should be related to an increase of CO₂ pressure in the volcanic-hydrothermal system. This increase of fluid pressure could be related to subsurface strain/stress changes, which might be taking place due to either magmatic or tectonic reactivation in the study area.

URL: <http://www.iter.es>

V21B-1208 0830h POSTER

Time-Series Analysis of Volatile Chemistry At Poas Volcano, Costa Rica

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Shallow hydrothermal processes can affect the composition of gases sampled at the surface of the earth. Poas volcano in Costa Rica is an ideal location to quantify these effects as it has numerous fumaroles, and interactions between rising volatiles and its acid crater

lake are well documented (Rowe et al., Bull Volc, 1992). In addition, Costa Rica has extreme wet and dry seasons thus allowing study of seasonal changes in gas chemistry through time-series data.

Vapor condensates and thermal waters can yield information on vapor-fluid interaction through δD and $\delta^{18}O$ analysis. The condensates form a trend subparallel to the meteoric water line, indicating mixing between magmatic vapor and meteoric water ($y=6.20x-17.12$). Water from the crater lake shows extreme ^{18}O enrichment ($\delta D=-30.63\text{‰}$, $\delta^{18}O=1.48\text{‰}$) due to water-rock exchange and possibly the contribution of primary water from degassing magma.

Complementary gas data on fumaroles at Poas reinforce these findings. Monitoring over the period Jan-July 2001 revealed increasing outlet temperatures (76° to 108°C), increasing relative proportions of sulfur (1.1 to 7.9 mmol/mol) and decreasing SO₂/H₂S ratios (5.4 to 2.6). Increasing outlet temperatures trigger the remobilization of elemental sulfur, resulting in decreased SO₂/H₂S ratios. In the past, decreasing SO₂/H₂S ratios at Poas have accompanied increases in volcanic activity (Rowe et al., 1992). Concurrently during the 2001 sampling interval, the level of the crater lake dropped 4 meters, and the acidity of the crater lake increased (pH=2 in January to 0 in July). These changes indicate increasing addition of magmatic gases to the hydrothermal system. Analysis of redox conditions in terms of H₂, CH₄, and CO indicates that at depth the hydrothermal system is vapor phase, and at shallower levels the system is two-phase (vapor and liquid coexisting as a result of vapor condensation). During the rainy season, Poas hydrothermal system is dominated by a liquid phase, even at shallow levels. Using fumarole chemistry and redox allows time series analysis of chemical changes due to seasonality and volcanic activity.

V21B-1209 0830h POSTER

Sediment Underplating Beneath Central America: Insights From N-He, $\delta^{15}N$ Systematics of Volatile Discharges in Nicaragua

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We investigated N-isotope systematics and geochemistry of gases emitted from fumarolic and geothermal sources along the Nicaraguan volcanic front. The goals of this study are: 1) to quantify the contributions from different reservoirs to the volatile output along the volcanic front; 2) to map along-arc variations in sediment contribution to magmas.

We report relative abundances of N₂, Ar, and He, as well as N isotopes, for geothermal fluid samples from Nicaraguan volcanoes. Samples from Masaya, Tipitapa, Xiloa, Momotombo geothermal wells, Cerro Negro, and San Cristobal (from SE to NW) have N₂/He ratios in the range 1,600-25,000 typical of arcs. The southernmost sample, Volcan Mombacho, has N₂/He = 144, consistent with upper mantle derivation (N₂/He ~ 150). N isotopes identify sources for the geothermal gases. A positive $\delta^{15}N$ value indicates N contribution from subducted hemipelagic sediment ($\delta^{15}N = +7\text{‰}$). The upper mantle, in contrast, is characterized by a $\delta^{15}N = -5\text{‰}$. Samples from Masaya, Xiloa, a Momotombo well, and Cerro Negro have $\delta^{15}N = +1.2, +4.9, +2.1, \text{ and } +4.9\text{‰}$, a strong sediment signature. The sample from Mombacho has a $\delta^{15}N = +0.5\text{‰}$, indicative of mantle nitrogen.

These Nicaraguan data contrast with reported N₂-He - $\delta^{15}N$ systematics of central Costa Rica, where gas discharges sample primarily mantle wedge volatiles (Zimmer et al., AGU 2001, Fischer et al., Science 2002).

Most Nicaraguan samples have N₂/He and $\delta^{15}N$ values that indicate subduction of hemipelagic sediments, as is typical of other arcs. In Costa Rica and southern Nicaragua (Mombacho), underplating prevents hemipelagic sediments from reaching the zone of melting and results in low N₂/He and negative $\delta^{15}N$ values. Southern Nicaragua represents the transition from sediment underplating (in the south) to sediment subduction (in the north). The N-systematics are therefore consistent with other geochemical indicators (Ba/La, ¹⁰Be, e.g.) showing significant sedimentary contribution to Nicaraguan volcanic output.

V21B-1210 0830h POSTER

Tracking Sediment Subduction Along the Sangihe Volcanic Arc, Indonesia Using Volatile Chemistry and N-isotopes

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We report the first data on volatile emissions from the Sangihe Volcanic Arc to trace sediment subduction. The Sangihe Arc is part of an unusual tectonic setting where the Molucca Sea Plate subducts beneath both the Sangihe and Halmahera Arcs, resulting in oblique arc-arc collision. The northern parts of Sangihe and Halmahera are fused, while the south has not yet collided. Collision has resulted in sediment obduction onto the facing arcs, decoupling it from the oceanic plate below. To study the geochemical effects of collision, we collected gases at eight locations along Sangihe Arc at fumaroles and hot springs. Our results complement CO₂-He systematics of the same samples (Jaffe et al., this volume).

Gas samples were analyzed for major volatiles and N isotopes. Typical N₂/He for subduction zones are 1000-25,000, while MORB and OIB are lower (10-100) due to the lack of sediment-derived N input. Most Sangihe samples have N₂/He that deviate from the subduction signature (330-2825). The N isotopic ($\delta^{15}N$) value of air is 0‰/‰ by definition, -3 to -5‰/‰ in the upper mantle, and +7‰/‰ in marine sediments. $\delta^{15}N$ values for Sangihe samples range from -7 to +2‰/‰. Variations in N₂/He ratios and $\delta^{15}N$ data (tracers of hemipelagic sediment) correlate with latitude, with values decreasing to the north suggesting that subduction of hemipelagic sediment is less significant in the north than the south. The N₂-He systematics suggest that arc-arc collision, more advanced in the north (where N₂/He=537 and $\delta^{15}N=-7\text{‰}$ at Ruang Volcano), has caused the sediment package to become less coupled to the underlying ocean crust. The higher values in the south (N₂/He=1977 and $\delta^{15}N=+2\text{‰}$ at Ambang Volcano) suggest that sediment is still subducting there, as the collision is less developed. Alternatively, sediment composition may vary along strike of the arc, with hemipelagic and carbonate-rich sediments subducted in the south and north, respectively.

V21B-1211 0830h POSTER

Helium and Carbon Systematics of the Sangihe Arc, Indonesia: Tracing Volatile Sources in an Arc-Arc Collision

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The Sangihe and Halmahera arcs in northeastern Indonesia are presently colliding, forming the worlds only extant example of an arc-arc collision. We report the first helium and carbon isotopic and relative abundance data from the Sangihe Arc volcanoes as a means to trace magma origins in this complicated tectonic region. Gas chemistry and N-isotopes from the same localities are reported in a companion paper (Clor et al., this volume).

There is a distinct regional pattern in He and CO₂ variations along the north-south strike of the Sangihe Arc. The two northernmost volcanoes (Auw and Karangetang) have ³He/⁴He ≤ 6.4R_A (where R_A = air ³He/⁴He), CO₂/³He > 30x10⁹, and $\delta^{13}C \geq -2.0\text{‰}$. In contrast, the southern volcanoes along the arc (Ruang, Lokon, Mahawu) have ³He/⁴He ≥ 7.0R_A, CO₂/³He < 7x10⁹ and $\delta^{13}C < -3.0\text{‰}$. The southern volcanoes, therefore, sample volatiles more typical

of island arc volcanoes. Resolving the CO₂ into component structures (mantle-derived, plus slab-derived organic and limestone CO₂ - following the approach of Sano and Marty, *Chem. Geol.*, 1995), the northern volcanoes contain higher than average slab-derived limestone contributions. For example, limestone-derived CO₂ makes up > 90% of the total CO₂ at Karangatang and ~98% at Awu. These values compare with an average limestone contribution of ~65% in the southern Sangihe arc and ~73% in other arcs worldwide.

We are investigating possible reasons for the enhanced limestone contributions in the northern Sangihe arc. The sedimentary melange wedge is thickest in the north (up to 15km) - where the arcs initially collided. The greater availability of sediment may result in a greater input of subducted sediment, thereby providing enhanced dilution of mantle wedge C inputs. Alternatively, subducted sediments may be more carbonate-rich in the northern segment of the arc. This may reflect obduction of shallow, organic-bearing sediments onto the over-riding plate, leaving only pelagic carbonates to contribute to arc magma sources. Finally, the large carbonate flux may reflect enhanced contributions from sediment fluids and/or melts in the northern arc. Central Mindanao (Philippines), just north of Awu, contains post-collisional, slab-derived melts (adakites) attributed to thermal rebound of previously depressed isotherms upon termination of subduction (Sajona et al., *Lithos*, 2000). Similar thermal processes could be occurring at the northernmost extensions of the active Sangihe arc as a result of the reduced rate of subduction.

V21C MCC: 106 Tuesday 0830h

Melt Inclusions: What Do They Tell Us? I (joint with OS)

Presiding: A Kent, Danish Lithosphere Center/Oregon State University; **P Wallace**, University of Oregon

V21C-01 0830h

Insights into the architecture of basaltic magmatic systems from melt inclusion studies

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Studies of melt inclusions from basaltic lavas are often aimed at elucidating the nature of mantle source(s) and/or the processes responsible for melt generation. However, melt inclusions also provide unique insights into the architecture of basaltic magma systems, and melt inclusion compositions can potentially constrain the nature, timing, location and rate of the processes which control magma transport, melt aggregation, fractionation, mixing, assimilation and eruption. They are particularly powerful when a complete suite of elements is analysed for and when used in concert with the host lava suite. The availability of large integrated inclusion and host lava datasets covering a range of geodynamic environments (e.g. MORB, IOB, CFB, IAB) also offer the potential to compare and contrast differences in magmatic architecture related to external tectonically-driven factors, such as magma production and upwelling rates, lithospheric and crustal thickness differences and the eruption environment.

Examples of the utility of this approach come from MORB and CFB. Melt inclusions from slower-spreading MOR have been shown to preserve a greater diversity of melt inclusion compositions than inclusions from faster spreading segments. New data from the SWIR extends this observation to ultra-slow spreading centres, which have inclusions that preserve an extraordinary degree of magmatic diversity ($K_2O/TiO_2 = 0.01$ to 2.8, $[La/Sm]_N = 0.15$ to 2.0). Overall this observation is consistent with the wider variety of compositions preserved within the less-vigorous and transient magmatic systems that occur at slower upwelling rates. In CFB, the occurrence of mantle-derived trace element variations and those resulting from crustal contamination within the same inclusions, along with the observation that primitive melts may contain highly contaminated inclusions, show that very limited amount of melt aggregation and fractionation occurs within CFB melt systems prior to entering the continental crust. CFB melt transport systems must be able to efficiently

transport diverse melts to the crust with little opportunity for aggregation and mixing.

V21C-02 0845h INVITED

The Reliability of Olivine-Hosted Melt Inclusions: Making Ultracalcic Liquids With a CaO Pump.

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Geochemical evidence demonstrates that the extraction of silicate melt from residual peridotite is an efficient process, and that near-fractional partial melting of peridotite in the oceanic upper mantle occurs over a range of pressure-temperature conditions. Silicate melts included in olivine phenocrysts are isolated from most magma chamber process and, therefore, may preserve geochemical information relating directly to the processes of peridotite melting and melt transport in the upper mantle. Unusually CaO-rich (ultracalcic) melt inclusions, with compositional characteristics (CaO 14 wt%; CaO/Al₂O₃ 1.0 by weight) that are rare in the global mid-ocean ridge basalt (MORB) population, suggest the involvement of exotic lithologies in mantle melting. However, results from modeling carried out using new experimental determinations of the diffusivity of CaO demonstrate that equilibration of olivine phenocrysts occurs over relatively short timescales. Further, the systematically low Na₂O contents of ultracalcic melt inclusions suggest that their high CaO content may result from diffusive equilibration following magma mixing.

Diffusive equilibration of the CaO content of an olivine-hosted melt inclusion following magma mixing depends upon both the systematics of olivine/melt partitioning and diffusivity. The olivine/melt partition coefficient for CaO increases with increasing Na₂O in the melt. If, following magma mixing, an olivine finds itself floating in a melt with increased Na₂O, but CaO comparable to the melt from which it crystallized, its CaO content will increase. Further, if the olivine contains a melt inclusion with low Na₂O, the CaO increase of the host olivine will be magnified, producing a CaO "pump". Rapid diffusivity of CaO in olivine allows this process to occur over relatively short timescales. Because Al₂O₃ is likely to be relatively immobile, the CaO/Al₂O₃ will be fractionated. At 1225 °C a 200 μm melt inclusion centered in a spherical host olivine 2 mm in diameter will retain its original concentration of CaO for only ~10 years after magma mixing, after which it increases rapidly. Complete equilibration of the inclusion with the external melt requires ~70 years.

V21C-03 0900h INVITED

The Common Occurrence of Melt Inclusions With Exotic Major-Element Compositions in High-Fo Olivine Phenocrysts: A Result of Localised Wall-Rock Assimilation?

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Melt inclusions (MI) hosted by high-Fo olivine phenocrysts from various tectonic settings commonly have unusual major and trace element compositions, unlike any lavas, whereas MI in more evolved olivine phenocrysts are usually compositionally similar to the host lavas. Anomalous MI often have high CaO contents and CaO/Al₂O₃ values, whereas SiO₂ contents are either lower or higher than those in lavas. In some cases, particularly in subduction-related magmatic suites erupted through a thick arc crust, all MI in high-Fo olivines have anomalous compositions, whereas in other suites anomalous and 'normal' MI can be found in a single sample. In samples with dominant anomalous MI, high-Fo olivines usually contain a large number of MI of variable sizes, often > 100 microns. In contrast, in samples with MI of 'normal' compositions, many high-Fo olivines are devoid of inclusions, however when present, inclusions are small and few. The above differences in the size and abundance of 'normal' and anomalous MI imply differences in the rate of crystallisation, with anomalous MI corresponding to faster cooling rates. The fastest cooling rates of a primitive magma are expected at the margins of a magma body where it is in contact with the wall rocks. Interaction of such magmas with cooler wall-rocks will cause localised rapid

cooling, facilitating crystallisation at the margins of the magma and also trapping of MI by the growing phenocrysts. The compositions of these MI are likely to record the processes of partial dissolution of the wall rock and mixing of the resulting melt with the primitive magma, and have no bearing on magma generation processes. On the other hand, inside the magma body, far away from the reaction zones, slow cooling rates do not favour trapping of MI, and 'normal' MI are much less common. The population of MI in high-Fo phenocrysts is thus naturally biased towards anomalous compositions, whereas in the macro system these reaction processes are far less important. Large abundant 'normal' MI are found in high-Fo olivine from magmatic suites (eg, boninites, low-Ti arc tholeiites, komatiites) where crystallisation occurred at shallow depths during ascent and was accompanied by degassing, resulting in rapid crystallisation.

V21C-04 0915h

LILE enrichment in MORB melt inclusions: evidence for upper-mantle autometasomatism.

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After corrections for host plagioclase interaction, primitive melt inclusions from Central Indian Ridge basaltic lavas have compositions that can be accounted for by fractional crystallisation of an olivine, clinopyroxene and plagioclase assemblage. Correcting for this fractional crystallisation, the melt inclusions are also found to be depleted in phosphorus, titanium and iron, relative to their matrix glasses. Furthermore, phosphorus and titanium concentrations correlate inversely with sodium and potassium, an effect that is incompatible with either mantle partial melting processes or diffusion between melt inclusions and their external magma. Instead, it is concluded that the melt inclusions were formed from melt increments derived from the depleted shallow mantle melting column during which fusion was promoted by a hydrous fluid carrying sodium and potassium. We suggest the fluid originates during early dehydration melting of the mantle column and is transported rapidly to shallower levels. The common occurrence of similar enrichment in depleted basaltic magmas, melt inclusions and upper-mantle peridotites indicates that this is a globally significant process.

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Melt Inclusions Record Extreme Compositional Variability in Primitive Magmas at Mauna Loa Volcano, Hawaii

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Melt inclusions carry potentially unique information about magmatic processes and the compositional evolution of erupted lavas. Major element compositions of olivine-hosted melt inclusions in submarine tholeiitic picrites from the southwest rift zone of Mauna Loa volcano have been studied to examine the compositional variability of primitive magmas feeding the world's largest volcano. Approximately 600 naturally quenched inclusions were examined from 8 samples with 3-25 vol% olivine phenocrysts and 9-22 wt% MgO. Olivine compositions ranged from Fo91-Fo82. The inclusions show a continuous variation in FeO contents from near-magmatic values (9 to 11 wt%) in the most evolved olivines to extremely low values (3.5 to 7.0 wt%) in the most primitive olivines. This appears to reflect a complex magmatic history for these crystals involving extensive re-equilibration of melts trapped by early formed phenocrysts with their host olivine. Extreme compositional variability also characterizes incompatible elements that would not be affected by equilibration with the host olivine. Inclusions trapped in relatively primitive olivines (Fo88-91) show a large range of K₂O contents (0.1 to 2.1 wt%), whereas inclusions in more evolved olivines converge on whole