per mil) show composition inbetween. A depth profile through a 70Ma old Fe-Mn crust revealed steep gradients for Mo concentrations (300ppm to 400ppm within 2 Myr), precluding post-depositional homogenisation of Mo. In contrast, the Mo isotopic compositions are uniform throughout the entire 70 Myr profile (-3.2 +/- 0.1 per mil relative to 98Mo/95Mo MOMO). We conclude, that a constant Mo isotopic composition must be assumed for ocean water during the last 70 Myr.

V22D-10 1605h

Thallium Isotope Variations in Seawater and Ferromanganese Deposits

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We have conducted an in-depth investigation of Tl isotope variations for a comprehensive suite of hydrogenetic ferromanganese crusts, diagenetic Fe-Mn nodules, hydrothermal manganese deposits and seawater samples. The natural variability of Tl isotope compositions in these samples exceeds the analytical reproducibility ($\pm 0.05^{o}/_{oo}$) by more than a factor of 40.

Hydrogenetic Fe-Mn crusts have $\epsilon^{205}Tl$ of +10 to +14, whereas seawater is characterized by values as low as -8 ($\epsilon^{205}Tl$ represents the deviation of the $^{205}Tl/^{203}Tl$ ratio of a sample from the NIST SRM 997 Tl isotope standard in parts per 10^4). This $\sim 2^{o}/_{oo}$ difference is thought to result from the isotopic fractionation that accompanies the adsorption of Tl onto ferromanganese particles. An equilibrium fractionation factor of $\alpha = 1.0021$ is calculated for this process.

Ferromanganese nodules and hydrothermal manganese deposits have variable Tl isotope compositions that range between the values obtained for seawater and hydrogenetic Fe-Mn crusts. The variability in $\epsilon^{205}Tl$ in diagenetic nodules appears to be caused by the adsorption of Tl from pore fluids, which act as a closed-system reservoir with a Tl isotope composition that is inferred to be similar to seawater. Nodules with $\epsilon^{205}Tl$-values similar to seawater are found, if the scavenging of Tl is nearly quantitative. Hydrothermal manganese deposits display a positive correlation between $\epsilon^{205}Tl$ and Mn/Fe. This trend is thought to be due to the derivation of Tl from distinct hydrothermal sources. Deposits with low Mn/Fe and low $\epsilon^{205}Tl$ are produced by the adsorption of Tl from fluids that are sampled close to hydrothermal sources. Such fluids have low Mn/Fe ratios and high temperatures, such that only minor isotope fractionation occurs during adsorption. Hydrothermal manganese deposits with high Mn/Fe and high $\epsilon^{205}Tl$ are generated by scavenging of Tl from colder, more distal hydrothermal fluids. At such conditions, adsorption is associated with significant isotope fractionation, and this produces deposits with higher $\epsilon^{205}Tl$-values coupled with high Mn/Fe.

V22D-11 1620h

Advances in Mg and Fe Isotope Cosmochemistry

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Our recent multi-collection inductively coupled plasma-source mass spectrometry (MC-ICPMS) studies of Mg and Fe isotope ratios in meteoritical materials (Galy *et al.* 2000, Science 290, 1751; Zhu *et al.* 2001, Nature 412, 311; Young *et al.* 2001, Geochim. Cosmochim. Acta, in press) demonstrate the potential of these new isotope systems. Taken together, the studies show that rock-forming elements other than O were well mixed in the early solar system, and that pressures during melting to form chondrules were higher than conventional astrophysical estimates. These conclusions place severe constraints on explanations for the elemental compositions of rocky planets and asteroids.

Mass-dependent fractionation results in two distinct fractionation laws that manifest as distinct slopes in three isotope space. The slopes of equilibrium fractionation lines, or more correctly the exponent in the $\alpha_{2,1} = \alpha_{3,1}^{\beta}$ fractionation law where $\alpha_{2,1}$ is the isotope fractionation factor for isotopes 2 and 1, is $\beta = (1/m_1 - 1/m_2)/(1/m_1 - 1/m_3)$ for isotope masses $m_1 < m_2 < m_3$. Kinetic fractionation lines produce shallower slopes approaching $\beta = \ln(m_1/m_2)/\ln(m_1/m_3)$ where the values for m_i can be reduced masses or even molecular masses, depending upon the process. MC-ICPMS measurements can be used to distinguish these two mass fractionation laws in natural materials.

Highly precise measurements of $^{56}Fe/^{54}Fe$ and $^{57}Fe/^{54}Fe$ in a diverse sampling of meteoritical materials show that Fe in all bodies of the solar system came from a single reservoir. The data span limited ranges in $\epsilon^{56}Fe$ and $\epsilon^{57}Fe$ (16 and 23, respectively). Despite the limited range, the precision of the data (approx. ± 0.6 ϵ) is sufficient to distinguish between equilibrium exchange and kinetically controlled mass fractionation of Fe isotopes. The three-isotope slope defined by the meteorite data is 0.678 ± 0.004. The slope predicted for equilibrium exchange of these Fe isotopes is 0.6786 while the slope for kinetic fractionation is 0.6726. Good agreement between the measured slope and the predicted equilibrium slope suggests that not only was there a single Fe reservoir in the early solar system, but that variability in Fe isotope ratios reflects equilibration. In the case of chondrules, this may suggest that an approach to exchange equilibrium between vapor and liquid, requiring high vapor pressures of Fe, was responsible for precluding Fe volatilization.

Measurements of $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg$ in components of chondrites suggest a canonical $\delta^{25}Mg$ (relative to SRM 980) of about 1.6 ± 0.1 $^{o}/_{oo}$. Whole chondrules from the Allende CV3 meteorite show a limited range in $\delta^{25}Mg$ with values from 1.6 to 2.6 $^{o}/_{oo}$. First results from a novel ultraviolet laser ablation MC-ICPMS method for measuring Mg isotope ratios *in situ* together with *in-situ* laser ablation oxygen isotope ratio data show that the heterogeneity in $\delta^{25}Mg$ is in part a consequence of inheritance from refractory mineral grains with high $^{25}Mg/^{24}Mg$ and low $\Delta^{17}O$ and not volatilization. Therefore, the Mg isotope data, like the Fe data, suggest that Allende chondrules grew at pressures high enough to prevent loss of Mg by volatilization at temperatures above the solidus.

V22D-12 1635h

Cu and Zn Isotopes as New Tracers of Early Solar Nebula and Asteroidal processes

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Cu and Zn isotopic variations are now identified in extra-terrestrial samples, as has been the case for terrestrial samples (1). The main parameters which may cause these variations are : redox state, temperature, biological activity (Earth), and volatility (extra-terrestrial samples). We report data for meteorites from various groups and classes, including carbonaceous chondrites, ordinary and diffentiated chondrites (iron meteorites, SNC and HED). All analyses have been duplicated (from powder aliquot to final measurement). Values are expressed as relative deviations from NIST and JMC standards for 65Cu/63Cu and 66Zn64Zn, respectively (deltas in permil). Carefull chemistry and MC-ICP-MS measurements allow an overall precision of +/-0.04 permil.

I- Carbonaceous Chondrites A very important feature is that each group seems to exhibit a specific isotopic signature : Cu gets isotopically lighter from CI to CM to CO to CV, spanning an overall range of 1.5 permil. Zn shows a reverse order, getting heavier from CI to CM to CO. Zn in CV chondrites (whole rock) seems more variable. This order is the same as that observed for trace elements. Cu and Zn isotopic compositions are generally correlated to trace element content from one group to another, particularly those of similar volatility (e.g. Mn for Cu; Ge for Zn). Cu and Zn isotopic signatures exhibit remarkable relationships with Oxygen isotopes. Each group is well identified. Cu is linearly correlated with Oxygen, whereas Zn-O data display strong curvature : the difference in shape can be related to the nearly constant Cu content in all groups, and by the decreasing Zn content from CI to CO. Since Oxygen variations (from CV to CI) are thought to reflect progressive interaction of liquid water with initial solid (asteroid), Cu isotopic variations may also reflect this progressive alteration process. It may be so for Zn too, although its more volatile character might play a role.

II-Allende Progressive leaching experiments have been conducted on various powder aliquots : HF-HCl cold(#1), HF-HCl hot(#2), HF-HNO3(#3) hot under pressure. Results show clearly that different Zn (and Cu) isotopic signatures (are preserved in early components. We stress that these are NOT anomalies for Zn : three isotopic ratios (66, 67 and 68 vs. 64) agree perfectly with a mass-dependent process. In particular Zn gets systematically lighter from the "volatile" compounds (#1) to the refractory ones (#3). The rough correlation between O and Zn isotopes in these compounds could imply that Zinc, like Oxygen, experienced interaction between gaseous and solid states (e.g. spinels) at high temperatures.

III- Iron Meteorites Non magmatic irons do not show much variation (less than 1 permil in range for both elements). On the other hand, meteorites from the IAB-IIICD group show not only large variations (3.5 permil in Zn), but also a negative correlation between Cu and Zn isotopes : this could be interpreted as a mixing between two endmembers, one of them being strongly fractionated in Zn isotopes. Fractionation of such extent (+3.7 permil) could reflect either volatilization during impact melting, or alteration on the parent body.

Data available indicate that Cu and Zn isotopes are potentially important tracers for studying : 1- early solar nebula processes (e.g. high and low-T compounds exhibit different isotopic signatures); 2- meteorite parent body evolution (e.g. Cu and Zn isotopes correlate remarkably well with Oxygen isotopes in a well-established order : CV-CO-CM-CI).

References (1)Marechal C., Telouk P. and Albarede F. (1999) Chem. Geol., 156, 251-273.

V22E MC: 305 Tuesday 1330h

Understanding Volcanoes Through Multiparameter Measurements and Their Interpretation: Martinelli Memorial II

Presiding: **M Calvache,** Observatorio Vulcanologico de Pasto**; J Neuberg,** School of Earth Sciences

V22E-01 1330h INVITED

Dike Emplacement Triggering the 2001 Etnas Flank Eruption

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On 12 July a seismic swarm in the upper southern flank of Etna, between La Montagnola and the summit craters, heralded the start of a new flank eruption. The emplacement of a new feeder dyke, occurred while the summit of the volcano was still the site of persistent eruptive activity, was confirmed by a number of data, spanning from seismicity, ground deformation, petrology, volcanology, geomagnetism, gravity, tectonics and gas geochemistry. The dike emplacement was marked by the seismic swarm composed by more than 2500 events mostly concentrated in the few days preceding the opening of the eruptive fissures. Ground deformation data from permanent GPS and tilt networks showed marked variations in concomitance with the seismic swarm. The deformation pattern inferred the dike penetration. Magnetic data revealed a sharp and intense decrease in the total geomagnetic field on the upper southern flank, and an increase on the upper northern flank. The Serra La Nave continuously-running gravity station (southern slope of the volcano; 1740 m elevation) recorded a sudden gravity increase, starting on 12 July. The result on the surface was the opening of a 6-km-long field of fractures that intersected the summit of the volcano from north (Valle del Leone: 2600 m a.s.l.) to south (Rifugio Sapienza: 2100 m a.s.l.). Four eruptive fissures opened between 17 and 19 July on the south and north flanks of the volcano, from the SE Cone down to 2600 m, producing small lava flows. These formed the upper fissure system. An additional vent opened on 18 July at 2100 m elevation on the south flank producing a large lava flow that spread south towards the village of Nicolosi and traveled 6.5 km. Explosive activity, increased by the intersection of the feeder dike with a shallow aquifer, since 19 July gave rise to a new cone just north of Montagnola at 2550 m elevation. This new cone built up as a result of alternating phreatomagmatic and magmatic explosive and effusive activity. The new cone at 2550 m and the 2100 m vent formed the lower fissure system. Petrology of tephra and lava flows, and SO2/HCl ratios of magmatic gases measured by FTIR, evidenced a marked chemical distinction between the upper and lower fissure systems related to the two distinctive plumbing systems. The eruption ended on 9 August with a gradual reduction in the effusion rate and a marked decrease of the SO2 flux from the four summit craters.

V22E-02 1345h

Multiparameter Measurements at Montserrat and their Interpretation: Honoring the Memory of Bruno Martinelli

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Bruno claimed we cannot make worthwhile predictions about a volcano's activity without understanding the physical processes occurring inside it, and this requires the joint interpretation of measurements of many different phenomena. Current well-documented volcanism at Soufriere Hills Volcano exemplifies this philosophy. Extrusions are (and were) unsteady and accompanied by oscillating patterns of ground deformation, seismicity, and gas exhalation. Deformations on the short term were best expressed by tiltmetry, with inflations and deflations at periods from 3 to 30 hours indicating shallow pressure changes in magma. Earthquake swarms or tremor occurred about the conduit when a critical magma pressure was exceeded. The oscillations of rapid extrusion of magma or explosions indicate instability in the magma flow, which we suggest results from viscosity changes induced by degassing and microlite crystallization. Increased viscosity of shallow degassed magma causes flow stagnation; conduit pressure then builds as detected by tilt and seismicity, and then is released as the plug yields and a slug of magma is extruded. The viscosity is dependent on volatile content of magma, and within an elastic magma-and-conduit system, oscillatory flow is produced for a critical range of input flow rates. Thus at Montserrat unstable flow was recognized only after July 1996 after a substantial increase in eruption rates. Slower, generally steady extrusion had occurred earlier between November 1995 and July 1996. The short-term oscillations were used to forecast times, near or just after the pressure peak, when dome collapse and associated nuees ardentes were most likely, or when vulcanian explosions were likely to occur. Likewise, longer-period patterns over 6-7 weeks were recognized, involving nearly steady extrusion after several weeks of strongly oscillating, high pressure flowage. These patterns, due to periodic rebuilding of magma chamber pressurization and high conduit input flow rates, were also useful in hazards mitigation; e.g., a forecast was made in August 1997 for the occurrence of dome collapse and explosive eruptions one month later, and a large event in late December 1997 was anticipated similarly. Lava flow to the surface from Feb 1998 to Nov1999, but the resumed flow has oscillated with cyclic seismicity indicating pressurization, and with gas flux (and extruded lava) lagging behind the pressure peak. The Montserrat data and analogues elsewhere suggest that oscillatory flow is a fundamental mode of behavior at silicic volcanoes, and recognition and understanding of it allows improved short- and medium-term forecasts of timing and eruption style.

V22E-03 1400h

Continuous Gas and Temperature Monitoring on Merapi Volcano, Indonesia

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A set of devices consisting of a gas chromatograph and an alpha scintillometer especially designed to monitor high-temperature volcanic gases was successfully operated over several weeks at the fumarole-area of the Merapi summit, Indonesia. The gas temperature is being continuously registered every minute since July 2000 using a special temperature sensor. The complete unit operates automatically and is remote controlled by radio link.

The continuous gas measurements at Merapi volcano have shown that the concentrations of the gases and temperatures in the Merapi fumaroles vary relatively strongly. Concentration of CO_2 and the gas temperature increase periodically every three to four hours with a simultaneous decrease in water content. This oscillation is probably a result of a regular stronger degassing of the magma. On the other hand during and after strong rain fall higher water concentrations and drastic drops in fumarolic temperature were observed. The fumarolic system, however, takes a considerable long time, sometime even up to a few days, before returning to its original temperature level. This is a result of deep circulating meteoric water within the volcanic edifice. Hereby, the magmatic gases are cooled and diluted i.e. the ratio of magmatic gas to meteoric water shifted to smaller values. During the dry season (May to August) rainfall is seldom and the fumarolic temperature is constant at a relatively high level (450°C), however, in the wet season (October to April), the temperature is generally lower and comparatively variable.

The time series of gas concentrations and temperature data allow for a correlation with activity and seismic data. Fumarole temperatures are positively correlated with the occurence of shallow volcanic quakes.

The results of our investigations show that, in addition to volcanic activity, the gas emission temperatures in volcanic fumaroles are also largely influenced by meteorological parameters. Only a comprehensive and combined interpretation of all available chemical, geophysical and meteorological data allow for an evaluation of individual parameters and their relevance for the assessment of volcanic risk.

V22E-04 1415h

Determination of Mass-Changes at Merapi Volcano, Indonesia, by Repeated Microgravity Measurements (1997-2000)

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The monitoring of active volcanoes gets more and more important, as the population density in dangerous regions grows. A better knowledge of the inner structure and the internal processes of volcanoes would facilitate statements about expected eruptive masses.

For this purpose a combined Gravity- and GPS-network was installed 1997 at the Indonesian high-risk volcano Merapi. Until summer 2000 five repetition campaigns have been carried out. The appearing signals are significant and increase towards the summit region. From the residual gravity-changes the anomale mass is determined. This gives a first estimation about the mass-changes around Mount Merapi.

This work is part of the interdisciplinary German-Indonesian MERAPI project.

V22E-05 1430h

The Aseismic Zone Inside Merapi Volcano: Evidence for a Magma Chamber?

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Merapi volcano (Central Java, Indonesia) is one of the most active and dangerous volcanoes of the world. Due to endangerment of more than one million people in its surrounding Merapi has been classified as a high-risk volcano and included into the list of 16 Decade Volcanoes by IAVCEI. In cooperation with research institutions in Indonesia and Germany, an interdisciplinary research program was established in 1994 coordinated by the Volcanological Survey of Indonesia and the GeoForschungsZentrum Potsdam. The MERAPI project (Mechanism Evaluation, Risk Assessment, Prediction Improvement) is supposed to contribute to the development of prediction and warning strategies on different time scales and at different stages of the volcano's activity. For a better understanding of volcanic processes, both geophysical experiments and geological studies were carried out to get a clue on magmatic evolution, magma fragmentation, eruptive mechanisms, and emplacement mechanisms of the flows, as well as the overall structure of the volcano edifice.

Volcano seismological investigations have located high microseismic activity in the upper part of Merapi, in general during dome growing phases, as well as volcanic quakes in the lower part. In the central part of the cone an aseismic zone was detected and proposed as an effect of a magma chamber. However, no supporting evidence was found by geophysical structure investigations, with high resolution DGPS, and tiltmeter deformation monitoring at the flanks of Merapi. During the observation time detected deformation at the flanks corresponding to volcanic eruptions are very small and can be correlated with one explosive event (January 1997) only. During eruptions enlarged deformation can only be observed at the upper most summit part, and due to loading effects of pyroclastic deposits on the flanks. Furthermore, deformation modeling indicates that at the moment Merapi works on a relative low pressure level which leads to moderate eruptions as happened during project time.

V22E-06 1445h

Pressure Sensor Data Reveal New Details of the 1999 Eruption of Shishaldin Volcano, Alaska

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New data from a pressure sensor, along with seismic and satellite data enable us to perform a detailed analysis of the 1999 eruption of Shishaldin volcano, Alaska. The eruption was well monitored by a 6-station seismic network and frequent satellite passes, but visual observations were minimal. Consequently, we relied on satellite imagery and seismic tremor to interpret the chronology and behavior of the eruption. To refine our interpretation of the 1999 eruption we investigate acoustic data recorded on a pressure sensor 6.5 km north of Shishaldin. Four types of acoustic signals were identified, representing different types of eruptive behavior. A low-frequency (1-5 Hz), pulsating signal correlates with strong thermal anomalies in GOES and AVHRR satellite imagery and is interpreted as signifying lava fountaining. On April 19, 1999, the fountaining signal is replaced by a monotonic hum that builds in amplitude for >13 hours. At 1936 UTC on April 19, the humming frequency declines and the 2.3 Hz signal abruptly ends. This cessation of the humming signal coincides with a dramatic increase in seismic tremor amplitude, previously believed to represent the onset of a Subplinian eruption. Pressure sensor data, however, suggest that the main Subplinian phase begins six minutes later. At this time, the pressure sensor recorded a 20-minute broadband signal, over which several low-frequency bursts are superimposed. The final acoustic phase detected by the pressure sensor is a series of discrete pulses, interpreted as gas explosions. The strongest explosions, recorded on April 23rd, were associated with a small, ash-poor plume and strong seismic tremor. In time series, these events are similar to gas explosions observed at a number of other volcanoes. However, the Shishaldin events are of lower frequency (1-2 Hz) and are 1-2 orders of magnitude ($\sim$100 Pa at 7 km) larger than explosions observed at Stromboli, Arenal, and Karymsky volcanoes. The frequency of the gas explosions allows us to put constraints on the size of Shishaldin bubble bursts and the amount of gas released during the eruption. The 1999 eruption of Shishaldin shows that pressure sensors can serve as an excellent complement to traditional means of monitoring remote volcanoes.

V22E-07 1500h

Precise Hypocenter Distribution of Seismic Signals Associated with the 2000 Volcanic Unrest of Mount Bandai, Northeastern Japan

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We precisely determine hypocenters of volcanic earthquakes and tremor and compare their distribution with 3-D seismic structure and low resisitivity zones of the volcano to understand the 2000 volcanic unrest of Mount Bandai, Japan. Many volcano tectonic earthquakes (VT), volcanic tremor and very long period events (VLP) have been recorded by our broad band seismic network closely deployed around the volcano since April 2000. VT earthquakes are characterized by high frequency (>10Hz) signals with clear onsets of P and S phases, and volcanic tremor by long coda having a frequency ranging from a few Hz to more than 10 Hz. Waveforms of VLP consist of very long period (about 10s) signals preceded by short period (less than 1 s) signals. Absolute locations of their hypocenters are precisely determined by using the 3-D seismic structure that is obtained from P-wave arrival times of about 290 seismic stations for eight active sources that was conducted in 1997 as a national project of the program of prediction for volcanic eruptions. The results show that: hypocenters of VT earthquakes are concentrated in two clusters at a depth of 0-2 km beneath the summit and the northwestern area of the volcano; hypocenters of the volcanic tremor and the source of the short period signals of VLPs are located in a gap of the two clusters of volcano tectonic earthquakes. Since the gap of VT earthquakes is very close to a low resistivity zone detected by magnetotelluric soundings, we infer that volcanic tremor and the short period signals of VLPs are very closely related with magmatic fluid (hot water and/or magma) activity at the shallow part of the volcano. On the other hand, very long period signals of the VLPs are located at 5 km beneath the north-northwestern flank, which is more than 2 km far from the short period source of VLPs. These results imply that the activity of the shallow part of the volcano is dynamically related with inflation and deflation motions of the VLP source.

V22E-08 1535h

Magma plumbing system inferred from absolute hypocenter determination in Iwate volcano, Japan, using 3D velocity structure derived from active seismic survey

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Absolute locations of volcanic earthquakes are indispensable for understanding magma plumbing system and forecasting the volcanic eruption. Based on the 3D velocity structure from the active seismic survey at the Iwate volcano, Japan in October 2000 [Hamaguchi et al., 2001, in the poster session of this symposium], we obtain precise hypocenters of volcanic earthquakes and discuss the 1998 volcanic unrest with relations to the structure.

The data set is the P- and S-wave travel times of volcanic earthquake around the Iwate volcano in 1998. Since the 3D structure of the volcano is obtained for only P-wave, S-wave velocity is assumed to keep the relation of Vp/Vs as 1.66. The weights of P- and S-times are 1.0 and 0.05, respectively. The hypocenters are searched with the downhill simplex method [Press et al., 1992] until the variation of the weighted residuals at each iteration becomes less than 1 ppm which is the criteria of convergence. Travel times are calculated with the pseudo-bending method [Um and Thurber, 1989; Zhao et al., 1992]. The average residual of the initial hypocenters calculated by the 3D structure was 0.2 s. That of the final became 0.08 s.

Seismic activity started in the central part of the high P-wave velocity column beneath the western caldera of the volcano in February 1998. Low-frequency earthquakes (LF) with predominant frequency of 2 - 5 Hz occurred at the western tip of the high-velocity body around 0 km depth in March 19 and terminated after 8 days. This activity suggests that magmatic fluid accumulates in the western tip of the high-velocity region. Another LF occurred just beneath the crater lake in the western caldera locating the top of the high-velocity body from March to August. These LF earthquakes are located just beneath the ground surface suggesting that the activity of fluid reaches the surface. In April to July, the activity of volcano-tectonic earthquakes (VT) with predominant frequency more than 10 Hz reached its climax in the western tip of the high-velocity region. The VT activities may be triggered by the fluid accumulated at the western tip. As mentioned above, the absolute hypocenters and detailed 3D velocity structure reveal clearly the magma plumbing system in the Iwate volcano.

V22E-09 1550h

Monitoring and Modelling Diffuse Gas Emission From Volcanic Areas. An Interdisciplinary Approach to Assess Hydrothermal System Evolution

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Periodic monitoring of diffuse degassing in various volcanic areas has shown the importance of this phenomenon through which volcanoes are capable of releasing important quantities of mass and energy. Collection and analysis of emitted gas allow to draw important considerations on the origin of the gas and on the current state of evolution of the volcanic system. Based on chemical equilibria, it is possible to infer the gas origin, to establish P,T conditions characterizing the source area, and to hypothesize the phase distribution within the hydrothermal system. Chemical composition and physical conditions of the circulating fluid depend on the nature of magmatic degassing, on the presence and nature of shallower fluids, and on the type and degree of interaction between these two components. Diffuse degassing at the surface, however, does not depend only on these relevant aspect of the hydrothermal system: the specific nature of the porous matrix, through which circulation takes place, plays in fact a major role in determining the state and evolution of fluid flow.

Numerical modeling of the non-isothermal and multi-phase flow of water and carbon dioxide through a porous medium was performed to assess the importance of subsurface structure and fluid composition on the evolution of hydrothermal circulation. Modeling results are coupled with data from geochemical monitoring to improve our understanding of diffuse degassing processes and to provide a wider perspective for the interpretation of monitoring data.

Preliminary results emphasize once more how rock physical properties, and their variation throughout the underground succession, represent a primary parameter controlling fluid composition, physical conditions and phase distribution within the hydrothermal system. Modeling data suggest that better constrains on the porous matrix characterizing a given hydrothermal system should be sought to ensure an effective volcanic hazard evaluation based on gas monitoring at the surface.

V22E-10 1605h

CO2 Degassing at Kilauea Volcano: Implications for Primary Magma, Summit Reservoir Dynamics, and Magma Supply Monitoring

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We report a new CO2 emission rate of 8,500 tons/day (t/d) for the summit of Kilauea Volcano, a result several times larger than previous estimates. It is based on 12 experiments on three occasions over four years constraining the SO2 emission rate and the average CO2/SO2 of emissions along the 5.4-km summit COSPEC traverse (by COSPEC, NDIR CO2 analyzer, and CP-FTIR). The core of the summit plume is at ground level along the traverse and gives average CO2/SO2 values that are representative of the overall summit emission, even though CO2 and SO2 variations are commonly uncorrelated. CO2 and SO2 concentrations exceed background by 200-1,000 ppm and 1-7 ppm respectively. Nighttime measurements exclude Park auto exhaust as a source of CO2. The summit CO2 emission rate is nearly constant (95% confidence interval = 300 t/d), despite variable summit SO2 emission rates (62-240 t/d) and CO2/SO2 (54-183). Including other known CO2 emissions on the volcano (mainly from the Pu‘u ‘O‘o eruption) gives a total emission rate of about 8,800 t/d. Thus summit CO2 emissions comprise 97% of the total known CO2 output, consistent with the hypothesis that all primary magma supplied to Kilauea arrives under the summit caldera and is thoroughly degassed of excess CO2. A persistent large CO2 anomaly of 200-1,000 ppm indicates the entry to the summit reservoir is beneath a km^2-area east of Halemaumau. The bulk CO2 content of primary magma is about 0.70 wt%, inferred from the CO2 emission rate and Kilauea's magma supply rate (0.18 km^3/y [Cayol et al., Science, 288, 2343, 2000]). Most of the CO2 is present as exsolved vapor (3.6-11.7 vol%) at summit reservoir depths (2-7 km), making the primary magma strongly buoyant. Magma chamber replenishment models show that robust turbulent mixing of primary and reservoir magma prevents frequent eruption of buoyant primary magma in the summit region. The escape of 90-95% of the CO2 from the summit reservoir provides a potential proxy for monitoring the magma supply rate. Streaming CO2-rich vapor causes fractional degassing of H2O and SO2 from reservoir magma, but scrubbing minimizes summit SO2 emissions.

V22E-11 1620h

High Temporal Resolution Measurements of Volcanic gas Composition Using FTIR on Stromboli Volcano, Italy

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Fourier transform infrared spectroscopy, when used in passive mode over a short pathlength, allows the measurement of most gases present in volcanic plumes whilst allowing the operator to remain at a safe distance from active vents. The simultaneous measurement of oxidation pairs such as carbon monoxide and carbon dioxide allows thermodynamic calculations to be performed that constrain the ultimate equilibrium pressure and temperature of the volcanic gas.

Recently we performed high temporal resolution (sampling CO_2, CO, COS, SO_2, HCl and HF every 4 seconds) FTIR measurements on Stromboli volcano as part of a co-ordinated multi-parameter measurement campaign which brought together seismic, acoustic, radiometric and radar instruments in simultaneous measurement of the volcanic activity.

We observed that during explosive degassing significantly different chemical compositions were measured compared with those determined during passive degassing. Thermodynamic calculations suggest that the explosive degassing has a source at greater depth than passive degassing. This is consistent with the collection or growth of bubbles at depth prior to the explosions. These results and calculations are compared with simultaneous observations from acoustic, seismic, radiometric and radar sensors.

V22E-12 1635h

Sulphur budget at Pos volcano

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Pos volcano has been extensively studied over the last 15 years. Both geochemical and geophysical data have been integrated in order to develop a better understanding of the volcanic processes occurring there. A major feature at Pos is the presence of a well-developed hydrothermal system and an acidic crater lake. Between 1995 and 2001, the consistency of parameters such as lake level, temperature and composition, ground deformation, micro-gravity, river and gas flux and composition, can help to estimate the total sulphur budget of the magmatic system. Sulphur from the magma enters a brine which feeds the Rio Agrio on the west flank of the volcanic edifice. The extreme acidity of the hydrothermal system (pH 0-0.5) enhances the permeability of the summit area (loss of 1650 m3.y-1 in this zone; Rowe et al., 1992). The lack of ground deformation suggests that most of the voids are filled by mineral deposition in order to maintain the yield strength of the volcanic deposits. Previous studies show that the calculated precipitation of liquid sulphur at equilibrium, largely exceeds the deposition amount required to maintain a lower porosity. Based on the constant lake level, temperature and chemistry, as well as the calculated sulphur input and output in

the lake between 1995 and 2001, an annual budget of approximately 11x103 tonnes of magmatic S entering the lake is required. COSPEC measurements for March 2001give minimum SO2 flux of 40 t/d. This flux is of the same magnitude as the flux measured by Andres et al. in 1991. Assuming that this flux was relatively constant during the last 6 years (consistent with visual observations), it implies a mean annual S output of 7200 tonnes as SO2(g). As it is extremely difficult to remove SO2 from a hydrothermal system (Symonds et al., 2001), the total SO2 budget must come from the magma. The corresponding volume of degassed magma is 3.9x10-3 km3 per year. The negligible volume of degassed magma, required to insure a balance of the sulphur budget, can be either recycled at depth by convection in the conduit or accreted within the edifice (consistent with low micro-gravity variations due to magma movement since 1995; Rymer et al., 2000). Therefore, the magma feeding at Pos volcano appears to be in low steady state regime.

V22E-13 1650h

Proximal Ignimbrite Geometry on Santorini, Greece Using Ground Penetrating Radar

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Ground penetrating radar (GPR) surveys on Santorini, Greece, are used to constrain the 3-dimensional geometry of the near-surface pyroclastic deposits produced by the 3.6 ka caldera-forming Minoan eruption. Specifically, the results elucidate deposit structures at the south end of the island. More than 2.4 km of radar survey data were collected at a measurement spacing of 0.5-1.0 m, using the common offset reflection method (3 m offset) and radar frequencies of 50 and 100 MHz. Imaging depths of the raw data were typically small (<10 m) due to noise introduced by a local aviation radar facility which was in line-of-sight of most of the field survey. Most noise was removed by the application of standard radar signal processing techniques, allowing imaging to depths of 20-30 m, greater than the typical thickness of the Minoan eruption package. Survey lines were run between deposit exposures to ensure direct correlation between the observed depositional units and the geophysical data. This approach allows characterization of the radar signature of each deposit and facilitates subsurface mapping where exposures are absent. The phase 1 Plinian pumice is defined in the radar profiles as a unit with near constant thickness and little internal structure. The phase 2 surge and phase 3 massive tuff have similar radar propogation properties so the contact is poorly-defined by GPR, but the data reveal the cross-bedded internal structure of the surge allowing it to be mapped. The radar characterizations of the units and their contacts are continuous over the survey area, creating a well-defined image of the eruption package geometry over a 2-km-wide proximal segment of the volcano slope. The results show that the depositional package of airfall, surge deposits, massive tuff and ignimbrite is surprisingly uniform in thickness, except in minor paleo-lows where it thickens. In addition, each unit in the survey area is approximately uniform in thickness. The geometrical uniformity changes near the paleo-coast location, where the depositional package dramatically thickens as it crosses a line of low, coast-parallel paleo-sea cliffs. Observations of the deposits at the current coastline, outboard of the paleocliffs, suggest that the increase in thickness is due dominantly to a sudden thickening of the phase 4 pyroclastic flow deposit. This geometry contrasts with previous models, based on interpolation between outcrops. These proposed that the deposits of phases 2 and 3 thin gradually with distance from the caldera rim while phase 4 gradually thickens. The GPR results suggest that the flows were more energetic than the previous model implied, and too energetic to bulk deposit in the subaerial, proximal area. Most of the mass of pyroclastics swept down the slope and into the sea, leaving behind only thin veneers. The velocity reduction caused by a combination of the phase 4 flow thickening as it passed over the ancient sea cliffs, and by entering the sea, caused the flow to switch to a strongly depositional mode resulting in a thickened deposit. An implication of these results is that most of the Minoan pyroclastic flow deposits on Santorini, apart from those near and on the outer coast, were emplaced aggradationally.

V31A MC: Hall D Wednesday 0830h

Understanding Volcanoes Through Multiparameter Measurements and Their Interpretation: Martinelli Memorial III

Presiding: **P Hellweg,** UC Berkeley; **N M Perez,** Inst Technol Renewable Energies

V31A-0928 0830h INVITED POSTER

The Evolution of the State of Mt. Etna Volcano in the last ten Years Inferred Through Multidisciplinary Investigations

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In the last 30 years the eruptive activity of Mt. Etna has occurred near annually. After the 1991-1993 eruption, the most important lateral eruption in the last three centuries both in terms of duration (473 days) and lava erupted (ca. 235.106 m3), the volcano has not shown its activity through lateral eruptions but, since 1995, through frequent summit eruptive phenomena as vigorous strombolian activity, more than one hundred spectacular lava fountains, and lava flows from the summit craters. The last lateral July-August 2001 eruption occurred after this intense summit activity about ten years later the previous 1991-1993 lateral eruption. In this work we present multidisciplinary investigations conducted during these ten years preceding the 2001 eruption. The different disciplines and monitoring techniques (volcanological observations, seismology, ground deformation, petrology, gravimetry, geochemistry, geomagnetism) allowed us to obtain a knowledge of the state of the volcano and to evaluate its evolution. The positive gravity anomaly, the ground deformation inflation, the seismicity pattern and the SO2 flux indicate that from 1994 an intrusive process interested a crust volume at 2-5 km b.s.l. under the summit crater area. This volume probably represents an intermediate storage zone. From the second half of 1996 to 1997 the recharge process of the volcanic system was particularly intense, as evidenced by the maximum value of the gravity anomaly, the continuous increasing of the areal dilatation, the increasing of the cumulative seismic strain release pattern, the increasing of the SO2 mean flux. The chronology of these phenomena, together with a strong seismic swarm occurred in the western flank on January 1998, suggested magma migration towards the upper part of the plumbing system. This is confirmed by the composition of the erupted products from the summit craters that became progressively more primitive. Also previous eruptions, such as the 1989 and 1991-1993, showed analogous phenomenal pattern culminating with the eruptive phases. From 1998 the intensification of the summit craters activity, which indicated re-alimentation and strong tension accumulation, has been preceded by a decrease of the gravity anomaly and accompanied by a decrease of the SO2 mean flux, and by a partial attenuation of the areal dilatation and of the cumulative seismic strain release trends. Moreover, a slow and continuous increase in the total geomagnetic field observed on the north flank of the volcano and the absence of significant anomalies at the south supported a possible demagnetisation in the summit area. Different observations indicated that the tension accumulation did not appear equilibrated by the energy discharge occurred through the lava flow summit eruptions (February-November 1999; January-June 2001) and through the several tens of strong explosive events which took place at the summit craters during the 1998-2001 before the July 2001 eruption.

V31A-0929 0830h POSTER

Intrusive Mechanisms Evidence Occurred During January-April 2001 at Mt. Etna and Preceding the July 2001 Eruption

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In this work we show seismological and ground deformation evidence for the intrusive phase which prepared the July 17- August 10, 2001 lateral eruption at Etna. The analysis performed on the seismicity and ground deformation measurements, during the eight months preceding the eruption, highlighted a strict relationship between seismic strain release at depth and surface deformation. This joint analysis provided strong constraints on the magma rising mechanisms. The axes of maximum compression, obtained by the analysis of fault plane solutions, showed an orientation predominantly orthogonal to the N-S direction which is in agreement with the surface displacements measured by the permanent GPS network. The inferred orientation of the compressive axis of focal mechanisms and the deformation pattern suggested that both the seismicity and the deformation were caused by the same stress source due to the initial magma intrusion of a near-vertical dyke oriented about N-S. The source appears to be shifted by a few kilometres south of the summit region. The analysed period, which preceded the July 2001 eruption, was mainly marked by the occurrence of a strong seismic swarm on April 20-24, 2001, composed by more than 250 events (Mmax = 3.6) with prevalent dextral shear mechanisms in the western flank. The swarm showed a ca. NE-SW earthquake alignment which, in agreement with previous cases, can be interpreted as the response of the medium to an intrusive process along the ca. N-S volcano-genetic trend. These mechanisms, leading to the July 17- August 10, 2001 lateral eruption, are analogous to the ones observed some months before the 1991-93 lateral eruption and, more recently, in January 1998 before the February-November 1999 summit eruption.

V31A-0930 0830h POSTER

Seismic Evidences of Magma Intrusion at Intermediate Depth Before the July-August 2001 Mt. Etna (Italy) Eruption.

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Several authors investigated the seismic behavior before Mt. Etna eruptions and some models were proposed in order to explain peculiar features of seismicity before flank eruptions. In particular, stress and strain fields seem to modify their orientation due to the action of magma overpressure. Recently, about 40 seismic stations boosted the Mt. Etna permanent network and permitted to study with great detail seismicity occurred before July-August 2001 eruption. More than 2600 earthquake occurred in about 8 months prior the seismic swarm that heralded the lateral eruption and pointed out a change of the dynamic condition acting on the volcano, starting from November 5, 2000. Seismicity in the period November 2000 June 2001 was characterised by the occurrence of several relevant seismic swarms. The epicentres of events spread in a wide area covering mostly of the southern and eastern part of the volcano and delineate two main alignments. A NNW-SSE epicentres alignment builds up gradually and was composed by earthquakes occurred clustered and sparsely in time. A clear NE-SW alignment was also defined mainly by the occurrence of a 4 days swarm. A peculiar feature of the earthquakes spatial pattern is the depth distribution. Under the eastern part of the volcano the seismicity is confined in the depth range 1 6 km b.s.l., in the western part hypocentres are distributed in two volumes under 5 km and upper 2 km b.s.l., respectively. This pattern defines two volumes affected by few earthquakes. These volumes correspond to crust portions where magma reservoirs were located by previous works. On the basis of a fault plane solutions analysis, we observe relevant rotation of maximum compressive axis at very short distance, indicating a local stress source elongated in NNW-SSE direction at about 5 - 6 km depth under the summit craters. Analyses on the space distribution of b value outline that the NNW-SSE epicentres alignment shows the higher value. We suggest that in the investigated period a migration of a magmatic mass occurred through out a major geological barrier located in coincidence of the local stress source detected. Furthermore the NNW-SSE earthquakes alignment is interpreted as the fragile response of the medium to the eruptive dyke early intrusion phases.