

Continuous monitoring studies using on-site species-selective sensors are a rapidly evolving part of the gas studies effort for the eruption.

The Pu'u 'O'o-Kupaianaha eruption has also provided an opportunity to study hazards associated with long-term environmental effects of volcanic emissions. Beginning in mid-1986, when activity changed from episodic fountaining to continuous effusion, volcanic air pollution, known locally as vog, became an unfortunate part of everyday life for Hawai'i residents and visitors. Since then, Kilauea has on average released about 1,600 tonnes of SO<sub>2</sub> per day, roughly 6,000 times the daily amount judged by the EPA to classify an emitter as a major industrial source. The emissions are converted by oxygen, moisture and sunlight to a mixture of gases and sub-micron acidic particles capable of being drawn and retained deep in the lung.

When the northeasterly trade winds, which prevail more than 75% of the year, are disrupted, emissions build up in east, rather than west Hawai'i. The acidic nature of vog causes unquantified respiratory effects, rapidly corrodes metal objects, damages crops, degrades domestic water quality and has been linked to decreased rainfall in downwind areas on the island of Hawai'i. Unlike the *mostly episodic* nature of earthquakes and lava flows that have become the signature of hazards during the eruption, volcanic air pollution has been a *nearly continuous* albeit low-level hazard since 1986. Depending upon wind direction, some portion of the island and its 150,000 residents are affected. During trade wind disruptions, Oahu, 300 km northwest, is impacted as well.

Vog buildup in east Hawai'i degrades air quality for residents and also for some of Hawai'i National Park's 2.3 million annual visitors. The emissions have taken at least one life directly, and asthma deaths island-wide, probably caused in part by Kilauea's large SO<sub>2</sub> emissions, exceeded predictions by 300 percent after the eruption became continuous. Health care professionals, scientists and educators are currently working with the community to define vog's health effects. While this hazard evaluation proceeds, the USGS, in collaboration with the National Park Service, has developed a real-time system to inform and advise park visitors and employees when vog levels, as approximated by ambient SO<sub>2</sub> concentration, exceeds preset levels.

## V62D MCC: 132 Saturday 1530h

### Hawaiian Volcanism (*joint with T*)

**Presiding:** K H Rubin, University of Hawaii

## V62D-01 1530h

### Magnetotelluric Investigations of the Kilauea Volcano, Hawaii

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A collaborative effort between Lawrence Berkeley National Laboratory, Sandia National Laboratories, Electromagnetic Instruments and the USGS Hawaiian Volcano Observatory has undertaken a three-dimensional (3D) magnetotelluric (MT) study of the Kilauea volcano in Hawaii. The survey objectives are 1) to produce a high quality 3D MT data set over the central caldera and the eastern and southwestern rift zones, 2) to use this data set to drive the continued development of new 3D MT inversion algorithms and 3) to integrate existing gravity, seismic and electrical data with the new MT data to provide an improved understanding of the internal structure of the volcano. Data acquired over the currently active eastern rift zone are compared to that from the now dormant southwest rift zone. The first phase of data collection acquired 6 sites in February 2002 with a second phase acquiring 30 sites in August 2002. The survey was designed to make use of multiple remote reference sites and multi-station robust processing techniques with as many as eight acquisition systems operating simultaneously. Excellent quality data was obtained even in the harshest conditions, such as those encountered on the fresh lava flows of the eastern rift zone, where electrical contact resistances were extremely high.

Most sites, which required helicopter access, were recorded with only electric (E) fields to reduce weight

and setup time. Certain helicopter sites had magnetic (H) data and were processed with and without local H data demonstrating the validity of using remote H fields with local E fields for impedance calculations. 3-D inversion of the data assuming the data to be local impedance is compared to 3D inversion that explicitly models the locations of the measured E and H fields. Selected two-dimensional (2D) lines of sites are inverted with 2D algorithms and compared to previously obtained electrical structure from transient EM soundings.

Early one-dimensional inversion of a site located near the caldera shows a conductor at 5km depth, which is consistent with the depth to magma as shown by seismic monitoring experiments. In addition, a shallower conductor at about 1km depth is indicated and is being investigated as a possible indicator of shallow magma. The site near the caldera was occupied in February and again in August 2002, giving a time-lapse view of the resistivity structure. Three dimensional modeling of the entire island of Hawaii shows that the coastal effects of the sea-land interface on the MT data is greatly reduced compared to the effects observed at continental boundaries where the interface is more 2D in nature.

## V62D-02 1545h

### Submarine geology of South Kona landslide complex: investigation using ROV Kaiko

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KR01-12 cruise of Japan Marine Science and Technology Center using ROV KAIKO and its mother ship R/V KAIREI were carried out around Hawaii islands in the early fall of 2001. During this cruise, two dives of ROV KAIKO were made on western submarine flank of the island of Hawaii: South Kona landslide complex (K210: proximal part of the south Kona landslide, K211: distal block of the landslide). One single channel seismic reflection line was collected from vicinity of the above dive sites. These areas have never been systematically studied using submersible due to the bad sea state and /or the depth of outcrops. Valuable information about the submarine geology and in situ rock samples from western franks of the island of Hawaii were obtained.

K211 site is one of the distal landslide block and can be divided into 3 geological units from bottom to top: picritic sheet lava and hyaloclastite, volcanoclastic deposit with picritic breccia, muddy breccia with highly vesiculated of basalt. On the other hand, rocks recovered from K210 are composed mainly of aa clinker and aa lava which are highly vesiculated and reddish in color. The rocks from K210 is similar to the upper part of K211 in their bulk rock chemistry. Based on the geological and bulk rock chemistry, rocks recovered from both sites should be erupted subaerially. It suggests that these landslide blocks were composed subaerial portion of the paleo-Mauna Loa volcano.

## V62D-03 1600h

### Evolution of the Hawaiian Plume: Evidence from Submarine Haleakala Volcano (Hana Ridge), Hawaii

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Hana Ridge is the submarine portion of the east rift zone of Haleakala Volcano, Hawaii. At 140 km long, Hana Ridge is the longest submarine rift zone in the Hawaiian Island chain and has developed a complex morphology compared to other Hawaiian rift zones, such as Puna Ridge. The main ridge comprises two or three subparallel or subadjacent ridges with distinct morphological expressions related to sequential accretionary stages of the shield-building phase of Haleakala volcano. In order to investigate the geochemical evolution of Haleakala shield-building, we sampled several sections of Hana Ridge on six dives with ROV Kaiko and Shinkai 6500 submersible, both operated by JAM-STEAC, in 2001 and 2002.

We report new geochemical data for basalt samples from these six dives on Hana Ridge. All the recovered rocks are primitive tholeiites and picrites and more

than half of them, those obtained in the deeper portions of the ridge, are picrites. Major and trace elements of the submarine Hana ridge rocks are similar to modern Kilauea and unlike Honomanu series lavas. Our results indicate that the mantle plume source for the Haleakala shield has changed over time from Kilauea-like compositions (high La/Sm, low Zr/Nb) in the submarine lavas to Mauna Loa-like compositions (lower La/Sm, higher Zr/Nb) in the subaerial Honomanu shield lavas. Moreover, the submarine stages show a gradual, but irregular, trend from higher to lower La/Sm with decreasing water depth (inferred to be decreasing age). We infer that Haleakala volcano originally had typical Hawaiian tholeiite magma compositions whose source material was similar to present-day Kilauea volcano and that the magma source became more Mauna Loa-like during growth of Haleakala volcano.

## V62D-04 1615h

### Understanding the Thermal and Rheological Evolution of Deep Submarine Lava Flows in the North Arch Volcanic Field

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The North Hawaiian Arch Volcanic Field is a 24,000 km<sup>2</sup> region of relatively young submarine volcanic landforms located 100-300 km north of Oahu and Kauai, centered on the flexural arch created by the Hawaiian Islands. In HAWAII-MRI acoustic imagery, individual lava flows are resolvable due to the large backscatter contrast between the young lavas and the pelagic sediments they overlie. In the southern portion of the volcanic field is a well-surveyed flow that provides an excellent location to apply a numerical model to investigate thermal and rheological evolution during flow emplacement. This flow was emplaced on slopes that average 0.35° in MRI bathymetry and is typically less than 1 km wide, yet attains a length of approximately 45 km from an inferred fissure source.

FLOWGO, a thermo-rheological model used to determine how far lava will flow in a channel in the subaerial regime, has been modified for the submarine environment, allowing measured lava flow parameters to help constrain the model for submarine applications. Adaptations for the submarine environment include recognizing that the dominant heat-loss mechanism switched from radiative in the subaerial environment to convective in the deep submarine environment, where we calculate the convective heat transfer coefficient appropriate to the seafloor. By fitting the model output to measured flow dimensions, we find that the only way to obtain the observed length is for the flow to have had extremely effective thermal insulation. If the layer of insulation moved with the flow, the insulation was most likely a cool, thick crust insulating a molten core or a tube roof if the crust was stationary. The model also indicates flow emplacement may have been associated with effusion rates of 10<sup>3</sup> m<sup>3</sup> s<sup>-1</sup>.

Several model input variables, such as vesicularity, crystallinity and slope, were obtained from flow samples obtained during submersible dives and from sidescan and bathymetry from sonar surveys. Repeated model runs were performed to determine the sensitivity of the model to all input parameters. The results show that reasonable variation in factors other than crust cover and temperature have very little impact in our results.

## V62D-05 1630h

### Relatively Recent Volcanism on Oahu, Hawaii: New U-series and Paleomagnetic Age Constraints on the Hanauma Bay Eruption

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The Koko Rift Zone (KRZ), eastern Oahu, is generally regarded as among the youngest volcanic features on the island. Previous workers have suggested that the 9 or 10 vents of this rift erupted near-simultaneously. However, K-Ar data in the literature (32-39 ka vs 320 ka) provide only general guidance on the youthfulness of these eruptions. We present new age constraints

on KRZ volcanism using deposits of the phreatomagmatic eruption that produced Hanauma Bay (a popular snorkeling spot) and spatially associated lava flows. Numerous continuous basaltic ash units within the walls of Hanauma crater contain lithic fragments of well-preserved coral reef, beach rock, and marine mollusks, indicating that the eruption occurred in a near shore environment.  $^{238}\text{U}$ - $^{234}\text{U}$ - $^{230}\text{Th}$  dating of coral clasts in the deposit demonstrates that the eruption breached reef of MIS stage 7 age ( $200 \pm 30$  ka), thereby ruling out the K-Ar age of 320 ka. U-series nuclides in normal MIS 7 coral lithics are indistinguishable from those in the island encircling Waianae Reef of the same age. However, U-series components in some originally aragonitic coral clasts were offset during the eruption when the rims recrystallized to calcite.  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{234}\text{U}/^{238}\text{U}$  and Sr and U concentration indicate chemical mixing with host basaltic ash during this event, from which potential ages of the eruption can be constructed using isochron methods. More modeling of the data remains to be done but our preliminary estimate places the eruption at less than 100 ka. This result is consistent with new data on paleointensity and paleomagnetic secular variation within the lava flows exposed in or around the crater. This U-series dating approach should prove useful for eruptions in the locales where carbonate bioclast lithics are present in the deposits.

**V71A MCC: Hall C Sunday 0830h**

**The Big Score: Twenty Years of Research on the Pu'u 'O'o - Kupaianaha Eruption, Kilauea Volcano, Hawai'i II Posters (joint with G, H, S, T)**

**Presiding: J Kauahikaua, U.S. Geological Survey; M O Garcia, University of Hawaii**

**V71A-1250 0830h POSTER**

**Tracking Multiple Tremor Sources Below Kilauea's Summit**

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Various tremor sources, shallow as well as deep, are commonly observed below the island of Hawaii. Eruption tremor is almost constantly and continually present since the onset of the Pu'u 'O'o east rift zone eruption 20 years ago. Its source is found at shallow depth below the eruption crater. Indirectly related to the ongoing eruption, tremor is also recorded below the summit of Kilauea about 15 kilometers away from the eruption site.

Time-frequency transforms (sgram) are automatically processed in real-time at the Hawaii Volcano Observatory via the Earthworm system for several seismic stations situated in Kilauea's summit area. This processing indicates the presence of marked spectral peaks, sometimes common to several stations. It also emphasizes changes in tremor spectral content and cyclic behaviors. During small eruption crises, changes in the signal relative amplitude at the different stations suggest the presence of several tremor sources.

We locate the sources using seismic amplitude distributions corrected for the site effects. Amplitudes are calculated in several frequency bands and spatial amplitude distributions across the summit area are usually smooth and coherent. We search for the source of those distributions by approximating the decay of the amplitude as a function of the hypocentral distance. The application of our location method to tremor recorded between March and August 2001 indicates the presence of at least two shallow sources whose locations are persistent with time. In the case of a small crisis that occurred in April 2002, we distinguish two main sources of activity, with a first deeper one triggering the activation of a second shallower source. Those results suggest the possibility of using tremor for mapping fluid transport below Kilauea volcano.

**V71A-1251 0830h POSTER**

**The Shallow Magmatic System of Kilauea Volcano**

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Geodetic leveling and Global Positioning System (GPS) measurements image a deflating magma reservoir in the southern part of Kilauea caldera. This reservoir, centered about 3.5 km below ground level, has been slowly deflating ( $\sim 2.5 \times 10^6 \text{ km}^3$  per year) since the beginning of the Pu'u 'O'o eruption. Electronic borehole tiltmeters reveal a secondary, much shallower magma chamber located just east of Halemaumau Crater at about 750 m below ground level. This secondary reservoir produces episodic deformation events, many of which share striking similarities that suggest a corresponding similarity of process.

The self-similar episodic events are characterized by a three-phase deformation pattern. In the first phase, tiltmeters surrounding Kilauea caldera record slow deflation centered at the Halemaumau magma reservoir that persists for about 24 hours. The second phase begins as the slow deflation abruptly gives way to rapid inflation, again centered at the Halemaumau reservoir. The inflation is short-lived, lasting about 20 minutes. In the final phase, tiltmeters record exponentially decaying deflation, lasting from 8 to 20 hours, that brings the final tilt close to pre-event levels. The seismicity during these events is dominated by bursts of volcanic tremor coincident with the onset of the second (inflationary) deformation phase.

We interpret these events as arising from an interruption in magma supply. At the onset of the interruption, deflation begins at the summit as magma continues to exit the system through flank vents at Pu'u 'O'o. When the interruption ends, rapid inflation ensues as the accumulated and over-pressurized magma below the locus of interruption surges up into the shallow magma system.

Several significant inferences follow from this interpretation of the episodic deformation events. First, from the duration of the initial deflation and from its size, we estimate the magma supply rate into the shallow system to be ( $\sim 5 - 10 \times 10^5 \text{ m}^3$  per day). Second, from the instantaneous volumetric inflation rate and the lag time between inflation at the summit and inflation at Pu'u 'O'o cone, we calculate the approximate radius of the connecting magma conduit to be 2 m. Finally, from the style and timing of the deformation and seismicity, we conclude that the conduit from Kilauea summit to Pu'u 'O'o probably begins at the shallow Halemaumau magma reservoir rather than at its deeper counterpart in the south caldera.

**V71A-1252 0830h POSTER**

**Continuous GPS Monitoring of Deformation at Kilauea Volcano During the Latter Half of the Pu'u 'O'o eruption.**

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The installation and development of a continuous Global Positioning System (GPS) network on Kilauea Volcano, Hawaii, has significantly improved the quality and resolution of deformation data for the volcano. The continuous GPS monitoring network of 17 stations on Kilauea was installed from 1995 onward in a collaborative project between the Crustal Deformation Group at Stanford University, the Hawaiian Volcano Observatory (HVO), and the University of Hawaii, Hilo.

Continuous GPS measurements made on Kilauea between 1996 and 2001 show a long-term signal of nearly constant velocity with respect to the Pacific Plate. The horizontal component of velocity is characterized by south- to southeastward motion of all stations, with maximum rates of up to 8 cm per year occurring on the south coast of Kilauea. The vertical component shows uplift of nearly 3 cm per year on the south flank and highlights an area of rapid subsidence (4.5 cm per year) in the southernmost part of Kilauea's summit caldera.

Combined with campaign GPS data from annual surveys made between 1990 and 1996, there is now a 12 year record of GPS for Kilauea. Using the new, high quality data set from the continuous GPS network we are able to model the deformation of Kilauea with greater confidence and to test and refine past models for deformation. For example, Owen et al. (2000) give a deformation model for Kilauea estimated from campaign GPS data. This model consists of two dislocations representing a basal decollement structure, two dislocations representing a deep rift system, and one point source for a summit magma chamber. We compare the predicted velocities from this model to the station velocities from the continuous GPS. Owen et al.'s model fits the recent data reasonably well, but there are significant disagreements. First, it fails to account for the uplift south of the east rift zone (indeed, it predicts subsidence). Second, it overestimates the amount of subsidence in the south caldera while also underestimating the horizontal velocities in the same area. Finally, their model does not well represent the velocities, both horizontal and vertical, at the stations lo-

cated along the western and eastern edges of the network.

Using non-linear optimization techniques, we have refined the details of Owen et al.'s model to see if the gross character of that model can be preserved without significantly violating the new continuous GPS data. Moreover, we have explored alternative, considerably simpler, deformation models that depart from the coupled decollement/deep rift zone hypothesis. Early results suggest that the simpler models, consisting of a single dislocation plane, can fit the data equally well.

Owen, S., P. Segall, M. Lisowski, A. Miklius, R. Denlinger, and M. Sako. Rapid deformation of Kilauea volcano: GPS measurements between 1990 and 1996. *J. Geophys. Res.* **105**, 18,983-18,998, 2000.

**V71A-1253 0830h POSTER**

**Magma Reservoir Processes Revealed by Geochemistry of the Ongoing East Rift Zone Eruption, Kilauea Volcano, Hawaii**

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Geochemical data were examined for a suite of 1,000 near-vent lava samples from the Pu'u 'O'o-Kupaianaha eruption of Kilauea, collected from January 1983 through October 2001. Bulk lava and glass compositions reveal short- and long-term changes in pre-eruptive magma conditions that can be correlated with changes in edifice deformation, shallow magma transfer and eruptive behavior. Two decades of eruption on Kilauea's east rift zone has yielded  $\sim 2 \text{ km}^3$  of lava, 97% of which is sparsely olivine-phyric with an MgO range of 6.8 to 9.6 wt%. During separate brief intervals of low-volume, fissure eruption (episodes 1 to 3 and 54), isolated rift-zone reservoirs with lower-MgO and olv-cpx-plg-phyric magma were incorporated by more mafic magma immediately prior to eruption. During prolonged, near-continuous eruption (e.g., episodes 48-53 and most of 55), steady-state effusion is marked by cyclic variations in olivine-saturated magma chemistry. Bulk lava MgO and eruption temperature vary in cycles of monthly to bi-annual frequency, while olivine-incompatible elements vary inversely to these cycles. However, MgO-normalized values and ratios of highly to moderately incompatible elements (HINCE/MINCE), which nullify olivine fractionation effects, reveal cycles in magma chemistry that occur prior to olivine crystallization over the magmatic temperature range that is tapped by this eruption (1205-1155°C). These short-term cycles are superimposed on a long-term decrease of HINCE/MINCE, which is widely thought to reflect a 20-year change in mantle-source conditions. While HINCE/MINCE variation in primitive recharge magma cannot be ruled out, the short-term fluctuations of this signature may require unreasonably complex mantle variations. Alternatively, the correspondence of HINCE/MINCE cycles with edifice deformation and eruptive behavior suggests that the long-term evolving magmatic condition is a result of prolonged succession of short-term shallow magmatic events.

The consistent limits of repeated MgO and temperature variation imply end-member magma conditions that are regulated by open-system recharge of the shallow magmatic plumbing system. The low-end of MgO variation (7 wt%) approaches the low-pressure multiphase cotectic, which is maintained by open-system replenishment of a persistent magma reservoir. The high-temperature end-member (10 wt% MgO) is probably regulated by olivine fractionation in a zone of turbulent mixing between primitive recharge magma (15 wt% MgO) and resident cotectic magma. The highest temperature magmas are associated with eruption pulses that occur in response to intrusive events at the summit and initiate short-term increases of HINCE/MINCE. Subsequent changes toward lower magmatic temperatures are associated with periods of overall summit deflation, relatively low-level effusion, and frequent eruptive pauses. The long-term trends can be explained by episodic mixing of chemically uniform recharge melt with diminishing proportions of pre-1983 summit magma (maintained at cotectic conditions). Decreasing HINCE/MINCE may signify that a greater proportion of recharge magma is being diverted directly to Pu'u 'O'o with minimal summit interaction or that the mass ratio of those mixing end-members has changed due to a depleted summit chamber (or both). The coincidence of long-term summit deflation since the 1982 summit eruption suggests that shallow processes related to summit reservoir depletion may be responsible for decreasing HINCE/MINCE and Pb isotopes in post-1982 steady-state eruption products. Magma derived from a uniform mantle-source, after having flushed out older resident magma, may now completely occupy the shallow magmatic plumbing system.