V11F-08 1205h

The Protracted History of Magmatic Evolution Recorded by Zoning in Allanites

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Compositional zoning in crystals provides a detailed but nevertheless ambiguous record of melt differentiation in magma chambers because the duration and absolute timing represented by the zoning stratigraphy are essentially unknown. Using a novel marriage of *in situ* compositional and isotopic analyses of zoning in allanite, we unravel the magmatic history recorded by single crystals and resolve the duration and ages of differentiation in the voluminous rhyolitic magma chamber that produced the 75 ka Youngest Toba Tuff (YTT), Indonesia. Detailed electron probe traverses reveal that allanites from the most-evolved portion of the YTT magma chamber (75 wt.% SiO_2) are strongly zoned in composition and single crystals may zone to compositions that match those for allanites from the *least-evolved* (69 wt.% SiO_2) rhyolite reported by Chesner and Ettlinger (1989). Low MnO/MgO, high La/Nd, and greater concentrations of Mg, La, & Ce are characteristic of less-evolved allanite zones, and normal zoning produces trends to higher MnO/MgO, lower La/Nd, and higher concentrations of Mn & Th. Most allanites have similar patterns of oscillatory zoning punctuated by resorbed boundaries and mantled by a near-rim section of normal zoning recording episodic mixing with hotter, less-evolved melts and subsequent growth from more-evolved melts. The core-to-rim differentiation history revealed by these single allanites represents a time scale of up to 150 ky that continued up to the time of eruption, as determined by ion probe ^{238}U-^{230}Th dating. Nonetheless, no single allanite composition is associated with a specific time interval in the magmatic evolution. In fact, compositional variability increases by up to a factor of three within ca. 35 ky of eruption, suggesting an episode of increased crystal and/or melt mixing relatively close to eruption. The magnitude of MnO/MgO and La/Nd variations, as well as parental melt compositions predicted by the zoning, fall within the ranges reported for erupted YTT glasses, suggesting the allanites record interactions between a diversity of melts related by the 40-50% fractionation calculated by Chesner (1998). Our results demonstrate that minerals like allanite can record a complex differentiation history of fractionation and episodic mixing, which in the case of the YTT allanites represents protracted residence and crystallization in a voluminous magma chamber.

V11G MCC: 3006 Monday 1020h

The Growth and Collapse of Hawaiian Volcanoes II *(joint with OS, T)*

Presiding: **B Eakins,** U.S. Geological Survey**;** **E Takahashi,** Tokyo Institute of Technology

V11G-01 1020h

Spreading Flanks of Ocean-Island Volcanoes: Similarities and Differences at Mauna Loa and Kilauea, Hawaii

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Submarine-flank deposits of Hawaiian volcanoes are widely recognized to have formed largely by gravitationally driven volcano spreading and associated landsliding. Observations from JAMSTEC submersibles (Japan Marine Science and Technology Center) show that prominent benches at mid-depths on flanks of both Mauna Loa and Kilauea consist of volcaniclastic debris derived by landsliding from nearby shallow submarine and subaerial flanks of the same edifice. Both volcanoes have mid-slope benches that record the same general processes of slope failure on varying scales, followed by modest compression during continued volcano spreading, even though they record development during different stages of edifice growth. Massive slide breccias from the mature subaerial tholeiitic shield of Mauna Loa underlie the frontal scarp of its South Kona bench. Outboard of the South Kona bench are large slide blocks, containing mixed subaerial and submarine Mauna Loa rocks, that appear to constitute a distal facies of the same large landslide event(s). The dive results also suggest that volcaniclastic rocks at the north end of the Kona bench, interpreted by others as distal sediments from older volcanoes that were offscraped, uplifted, and accreted to the island by far-traveled thrusts, alternatively are a largely coherent stratigraphic assemblage deposited in a basin behind the South Kona bench. In contrast, the Hilina bench developed as Kilauea volcano has spread seaward, in part riding piggyback on the still active south flank of Mauna Loa. The Hilina bench is underlain by coarse volcaniclastic sediments derived largely from submarine-erupted pre-shield alkalic and transitional basalts of ancestral Kilauea. The south flank of Kilauea is thus far not associated with any massive slide deposits comparable to the distal blocks of the South Kona slide complex.

V11G-02 1040h

North Kona Slump: a Recent Giant Submarine Landslide in Hawai'i

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Four Giant Submarine Landslides (GSLs) scar the west flank of Mauna Loa and adjacent Hualalai, two volcanoes of the Big Island of Hawai'i. Other than the Alika 2 slide (120 ± 10 ka), the ages of the GSLs are only poorly known. From sidescan sonar and multibeam bathymetry the South Kona GSL is older than Alika 1, and Alika 1 older than Alika 2, but where North Kona fits into this sequence is unclear. Because Alika 2 levees appear to cross the North Kona debris field, North Kona has been assumed to be more than 130 ka. More recent mapping, however, suggests that the apparent right levee of the Alika 2 debris avalanche may actually be the deformation front at the base of North Kona. Farther north, the North Kona Slump truncates the entire sequence of drowned terraces (18–430 ka) descending the submarine slope of Hualalai. A shallower terrace, previously undescribed, traverses the slope of Hualalai between 100 and 150 m depth. The terrace is probably the drowned reef from the 4 to 6 ka Holocene high stand; whether it has been disrupted by the North Kona Slump is unclear. Morphologically, the North Kona Slump is very similar to the currently-active Hilina Slump of Kīlauea. Indeed, a magnitude 6.5 earthquake in 1929 may indicate that the North Kona Slump is itself still active. The initial North Kona failure apparently occurred near the beginning of the Holocene Transgression, a timing supporting the hypothesis that large flank failures of oceanic island volcanoes have a climate trigger.

V11G-03 1055h

Development of the Waianae slump and Kaena Ridge, Hawaii

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New ROV and submersible dives offshore of Waianae volcano, Oahu, provide evidence pertaining to the size and shape of the volcano's edifice as well as timing of its collapse to form the Waianae slump. Two JAMSTEC dives, K205 and S707, ascended the base of the slump and collected volcaniclcastic sandstones and pillow lavas that are relatively unfractionated (5.5 to 8.6 wt% MgO in glass), low-S (<300 ppm) tholeiites. These magmas likely erupted subaerially early during the volcano's shield stage, and correlate with subaerial Lualualei Member lavas. The dives are 70 km apart and their samples' compositional similarities suggest that the entire Waianae slump was derived from a single volcano. A single hyaloclastite sample from dive K205 contained abundant moderate-S (220 to 520 ppm) transitional basaltic glass grains, indicating shallow submarine eruption perhaps early during or before the volcano's shield stage. These transitional compositions do not overlap with the volcano's well-studied post-shield alkalic phase. MBARI dive T326, on a shallow portion of the slump, collected tholeiitic hyaloclastites, but glass grains are systematically higher in alkalis (2.7 to 3.8 wt% Na_2O + K_2O) and are more fractionated (5.5 to 6.7 wt% MgO) than glasses found at the slump's base. These shallow samples correlate compositionally with late shield-stage subaerial Kamaileunu lavas. None of the collected slump samples correlate with subaerial post-shield lavas. We suggest that the lower, largest portion of the slump formed during or just after the volcano's main shield building stage. A second mass-wasting event could have occurred during or after the latter portion of the shield stage, forming the upper, rotated block ascended by dive T326. MBARI dive T325 ascended a small shield atop the submarine Kaena Ridge northwest of Oahu, and encountered abundant basaltic beach cobbles and a single aa flow, all tholeiitic. Kaena Ridge may have formed as the subaerial northwest rift zone of Waianae volcano. Two additional MBARI dives along the northern flank of Kaena Ridge (T327 and T328) collected hyaloclastite fragments that contain rare alkalic glasses; these may be derived from late-shield or post-shield Waianae.

V11G-04 1110h

Rethinking the Standard Model of Kilauea's South Flank Deformation

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Over the last two decades, a standard model of deformation at Kilauea's south flank has emerged. Consisting of two main structures, the model includes a 9 to 10 km deep basal decollement, which slips steadily at 10 to 20 cm/yr, and a deep east rift zone, which opens at an equal rate. The two parts of the model are fundamentally interdependent in that they represent Kilauea's south flank as a large, mobile block that is, in the long run, decoupled from the rest of the island. Several recent papers have taken this model at more or less face value. Thus, the conclusions of these papers are conditional on whether or not the model is correct. Evidence is accumulating that it is not. First, a deep, rapidly opening east rift zone predicts significant subsidence within the rift zone and significant uplift on Kilauea's south flank. Continuous GPS receivers in these areas observe neither. Second, a recent pressurization of the east rift zone in early 2002 produced a deformation field inconsistent with a deep source. Either there are two, decoupled magmatic systems in the east rift zone, or there is a single system that extends to only a few kilometers depth. Third, a recent seismic tomography experiment sought to resolve the deep magmatic system in the east rift zone. It was unable to do so. Fourth, two episodes of aseismic fault slip have occurred in the last three years (the first in November 2000, the second in July 2003). These "silent earthquakes," which are unmistakable in the continuous GPS record, are occurring on a structure that is no more than 4 or 5 km deep. If this structure is the so-called decollement, then the decollement is much shallower than previously thought. A much shallower decollement requires significantly lower slip rates to explain observed secular deformation. Lower slip rates eliminate the need for a deep east rift zone as a "decoupler." Fifth, the standard model of south flank deformation fails to explain - indeed, even to address - the two most strikingly active structures on Kilauea: the Hilina and the Koa'e fault systems. We offer an alternative model of south flank deformation consisting of persistent creep on a hypothesized listric extension of the Hilina normal fault system. Not only is this model much simpler than the standard model, but it seems to make more sense mechanically. In the long term, we argue, the Hilina fault system behaves as a gravity-driven mass transport system, which moves both aseismically and in large earthquakes. We do not suggest that our alternative model for south flank deformation is a panacea or that it completely explains magmatic-tectonic interactions on Kilauea. Rather, we argue that our model is a more realistic starting point for future discussion about the origin of south flank deformation.

V11G-05 1125h INVITED

The Hilina Slump: Consequences of Slope Failure and Volcanic Spreading Along the Submarine South Flank of Kilauea Volcano, HI

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Kilauea volcano is the type locale to study the dynamic interplay between slope failure and volcanic spreading; this was recognized very early by Jim Moore and colleagues. New geophysical data and seafloor mapping in the area now better resolve the dramatic history of Kilauea volcano. In this seismically active setting, the interface between the oceanic crust and volcanic edifice accommodates seaward sliding of the south flank of Kilauea, probably rooted along Kilauea's East Rift Zone. Present day displacement of the south flank is punctuated by intermittent movement of the Hilina slump, defined by a set of arcuate normal faults that break the flank just downslope of Kilauea's summit. Analysis of recent multichannel seismic (MCS) data and high-resolution bathymetry over the submarine slopes of Kilauea volcano reveals that the active slump has a relatively shallow detachment, 3-5 km deep, comprises largely slope sediments, and is restricted to the upper northwestern portion of the mobile south flank. Offset morphologic features along the marginal ridge known as Papa'u seamount, constrain measurable downslope displacement of the slump to 3 km, directed oblique to its western boundary. The MCS data also reveal the buried scar of a large-scale slope failure to the northeast of the submarine Hilina slump, which is the probable source of thick deposits of volcaniclastic breccias presently contained within the frontal midslope bench. The midslope bench developed as the mobile south flank of Kilauea plowed seaward into and offscraped the landslide debris, trapping a broad basin above the landslide scar. Uplift and backtilting of young basin fill indicate recent, and possibly ongoing, bench growth. The Hilina slump now impinges upon this frontal bench, a buttress that may tend to reduce the likelihood of future catastrophic detachment of the landslide.

V11G-06 1145h

Rapid Mass Wasting Following Nearshore Underwater Volcanism on Kilauea Volcano

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The rapid mass wasting of shallow submarine basalts was documented during SCUBA dives (with extensive underwater video and photography) along the flanks of Kilauea volcano, Hawaii during the Ki'i lava entry of the current eruption (19°20.4'N, 155°00.0'W). Lava entered the ocean at this site from mid-February to late March 1990, with several pauses. Dives on 19-20 March 1990 confirmed the widespread formation of lava pillows, as well as channelized lava flows, at this site over a water depth range of 20-40 m. Visual observations suggested that the resulting volcanic deposits were generally stable, despite the steep incline of the seafloor (∼40 degrees). (The pre-eruptive seafloor slope was ∼14 degrees.) However, dives on 2 April 1990 revealed that nearly all of these relatively large submarine volcanic features had been subject to mass wasting, as the offshore area had been transformed into a debris field composed of material ranging in size from fine sand to boulder fragments. This generally featureless seascape extended uniformly to beyond the visual range of divers (∼60 m water depth). High resolution side-scan bathymetry and imaging indicate that steeply sloped talus fields extend down the flanks of Kilauea in this area to abyssal depths, implying a possible linkage between coastal submarine volcanism and deep-water deposits. This work, combined with other observations at Kilauea, also suggests that coastal submarine volcanism may not generally result in the accumulation of stable rock formations.

V11G-07 1200h

Megatsunami Generation From Giant Submarine Landslides on Oceanic Islands: New Insights Gained From the Hawaii Evidence and Modeling

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High-elevation marine gravels on the Hawaiian islands of Lanai and Molokai either mark uplifted shorelines or are deposits from massive tsunamis. The subsidence history of those islands has been too ambiguous to differentiate these causes, leading to controversy over the deposit's origins and to confusion over the impacts, or even the existence of megatsunamis generated from giant submarine landslides (GSL) mapped offshore. U-series ages of these deposits that correlate with sealevel high stands have added to the confusion. Landslide tsunami simulations have now advanced to the point where the tsunamigenic potential of GSLs can be affirmed. We show that megatsunamis are a sufficient explanation for the observed pattern of debris height of calcareous marine deposits on the southeast Hawaiian islands. Further, our tsunami simulations, using the Alika GSL as example, can be used to reduce the considerable uncertainty in subsidence history of the different Hawaiian islands. Modeled runups of 800 m occurred directly landward of the Alika 2 slide on west Hawaii and were up to 300 m on west Lanai, in agreement with previous deposit estimates there (Moore & Moore, 1984, 1988). Recently, we rediscovered calcareous marine deposits on Kohala volcano on Hawaii island, where continuous subsidence is well established from its stairway of submerged reefs. On Kohala, we found a marine fossiliferous basalt boulder conglomerate from 1.5 to 61 m above present sea level exposed at the coast and up to 1 km inland. U-series dates of corals from the deposit are approximately the same age, 100 to 120 ka, as the giant Alika 2 landslide from nearby Mauna Loa volcano, directly dated using sediment stratigraphy (McMurtry et al., 1999). The present depth of the 120-ka shoreline implies that the deposit was left by a tsunami whose runup at 6 km inland exceeded 490 m. For the late Pleistocene, large volcanic failures and exposed marine deposits both correlate foremost with sea level high stands, and in particular with the onset of interglacial conditions that are reflected in Hawaii by the apex ages of the lowstand fringing reefs. We show that such large volcanic failures inevitably generate megatsunamis, and we conclude that persistent climate effects during sea level high stands eventually unleash large volcanic failures and megatsunamis amongst the Hawaiian islands and perhaps all volcanically active oceanic islands, with invariable propagation toward the continental coasts.

V11H MCC: 2010 Monday 1020h

U-Series in Continental Environments: Soils, Rivers, and Groundwaters I *(joint with H)*

Presiding: **B Bourdon,** Institut de Physique du Globe de Paris**; F Chabaux,** Université de Strasbourg**; D Porcelli,** University of Oxford

V11H-01 1020h

High Precision Measurements of 235U/238U Isotopic Fractionations Resulting From Uranium Reduction Induced by Zero Valent Iron

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Uranium is a widespread natural and anthropogenic contaminant in surface and subsurface waters. Like several other inorganic contaminants, uranium is mobile under oxidizing conditions but may be immobilized by chemical reduction. U(VI) moves with groundwater as (UO2)2+ and as soluble complexes with carbonate, phosphate, and fluoride. In many groundwater systems, uranium undergoes chemical reduction to U(IV), which is insoluble and immobile. Therefore, understanding the extent of reduction is essential for predicting the mobility of uranium in groundwater. Mass dependent isotopic fractionations of redox sensitive contaminants frequently found in groundwater (including chromate, selenate, and nitrate) have proven exceptionally useful for estimating the rate and extent of reduction and immobilization. Until recently, however, analytical limitations have prevented these techniques from being applied to heavier redox sensitive elements, such as uranium. The advent of highly sensitive multi-collector inductively coupled plasma mass spectrometers (MC-ICP-MS) enables high precision measurements of previously undetected variations in many elements. Laboratory reduction experiments with zero valent iron (ZVI) were performed in a controlled environment to test the hypothesis that uranium isotopes, specifically 235U/238U, behave similarly to other redox sensitive contaminants and produce a mass dependent fractionation during the transformation between valence states. Because of the large abundance differences between 235U and 238U, initial experiments used U500, an enriched uranium standard with approximately equal parts 235U and 238U. Results suggest that the highly sensitive MC-ICP-MS distinguishes 235U/238Uvariations to approximately + 0.02per mil. Measured isotopic fractionations between the 235U/238U of the initial and final experimental solutions (70% reduced) are approximately 1.1 per mil, and increase with decreasing concentration. Measured variations in 235U/238U suggest that uranium isotopic ratios could also prove to be valuable indicators of contaminant immobilization and paleoenvironmental conditions.

V11H-02 1035h

Isotope Fractionation of Uranium in Low-Temperature Environments

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Uranium is the heaviest naturally occurring element. It has three isotopes, ^{238}U, ^{235}U and ^{234}U, and two redox states, U(IV) and U(VI). Large isotopic fractionations have been previously documented for $^{234}U/^{238}U$ that are attributed to lattice damage and subsequent preferential leaching and oxidation at the α-recoil site. However, fractionation between ^{235}U and ^{238}U is not expected due to the small $\sim$1% difference between the masses of these two isotopes. It is therefore usual to assume $^{238}U/\ ^{235}U$ is constant in the terrestrial environment and equal to 137.88. Stable isotope fractionation is normally restricted to the light and intermediate mass elements due to relatively large mass differences of several percent. Recently, however, thallium, a heavy element with stable isotopes at masses 203 and 205, has been shown to display large, permil-level $^{205}Tl/^{203}Tl$ variability (Rehkamper et al., 2002, Earth Planet. Sci. Lett. 197, 65). Given their similar redox chemistries, it is not unreasonable to propose that $^{235}U/^{238}U$ may show similar variability in certain terrestrial environments. We have developed experimental protocols for the precise measurement of $^{235}U/^{238}U$ by multiple-collector ICPMS (MC-ICPMS) and have analyzed a suite of samples formed in a range of low- and high-temperature environments. Using a Nu Instruments NuPlasma MC-ICPMS, we are able to resolve variations in $^{235}U/^{238}U$ at the 0.5 ϵ level (2σ; 1 ϵ = 1 part in 10,000) on sample sizes comprising 30 ng of uranium. Data can be acquired on smaller 4 ng samples with 1-2 epsilon 2σ uncertainties. High quality U measurements are possible because we have used a high-purity ^{233}U-^{236}U double spike to internally monitor the large (percent-level) but essentially constant instrumental mass bias effects that are inherent to plasma source mass spectrometry. The natural variability in $^{235}U/^{238}U$ shown by the analyzed samples is 13 ϵ units and exceeds the analytical reproducibility by more than an order of magnitude. Reproducible compositions both heavier and lighter than our terrestrial standard are observed. Importantly, the largest excursions are observed in old samples that can not have been disturbed by anthropogenic contamination. The observed variability in $^{235}U/^{238}U$ indicates that uranium isotopes may offer the potential to monitor redox processes during the transition between U(IV) and U(VI) oxidation states. Our observations will also impact on U-series and U-Th-Pb applications in geochemistry, paleoclimatology and cosmochemistry, which currently assume invariant $^{235}U/^{238}U$ in all terrestrial and extraterrestrial environments.

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