origins of those components. Radiogenic isotope data suggest mid-ocean-ridge basalts (MORBs) also contain variable amounts of recycled crustal materials within their mantle sources, suggesting that oxygen isotope data might be similarly useful in constraining their abundances and origins. We present new high-precision laser-fluorination analyses of fresh MORB glasses for the Australian-Antarctic discordance (AAD; n=11) and the 9-10° N region of the East Pacific Rise (EPR; n=23). When combined with previous measurements in the same lab, we now have a dataset of 130 geographically and geochemically diverse MORBs, representative of much of the global range of physical and chemical properties of mid ocean ridge spreading centers. Within a given geographically (e.g., mid-Atlantic ridge) or compositionally (e.g., NMORB) restricted subset, there are relationships between δ^{18}O and other geochemical properties that can be attributed to the varying influence of recycled crustal materials. However, as a whole, MORB from all different areas spans a restricted range in δ^{18}O (5.2-5.8$^{o}/_{oo}$), and subsets of the data each have a similar range and similar mean composition (of 5.45-5.54 $^{o}/_{oo}$). This low variance in δ^{18}O places upper bounds on the influence of recycled crust in producing the other geochemical distinctions among MORBs. For example, there is no systematic difference in the amount of recycled crust sampled during different degrees of partial melting (e.g., low-degree melting of anomalously cold mantle beneath the AAD compared to other locations), different spreading rates, or within the different ocean basins (Indian vs. Pacific vs. Atlantic). These observations suggest that 1) at the scale sampled by MORB melting, all MORB source regions preserve oxygen-isotope heterogeneity, and 2) this heterogeneity is due to the presence of similar and small (<10%) percentages of recycled crustal material. In particular, the fact that δ^{18}O across the AAD shows no difference between Indian and Pacific MORB suggests that the MORB source in both ocean basins contains a similar average amount of recycled crust, and if the distinction in radiogenic-isotope composition (e.g., Sr, Pb) is due to the presence of pelagic sediment in the Indian mantle, it cannot be present in abundances greater than 1-2%

V52D-08 1525h

High Precision Osmium Isotope Evidence From Chondrites for Late Accretion and Evolution of the Earth's Mantle

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Prevailing models for early differentiation in terrestrial planets call for magma oceans generally concurrent with core formation. Consequently, extraction of a metal-rich core must have resulted in strong depletion of the silicate portion of Earth in highly siderophile elements (HSE), including Re, Os, and Pt. Efficient degassing of a magma ocean could leave the interior of the Earth depleted in volatiles. A result of such processes is that subsequent late accretion may be necessary to replenish both volatiles and HSE to their estimated and measured bulk silicate Earth concentrations. If one type of material was the supplier, then late accretion material should be volatile-rich, and have Os isotope compositions and HSE concentration ratios similar to the Earth's mantle. At present, such type of material is not known. Alternatively, if different types of materials led to volatile and HSE replenishment, then volatile-poor material could supply HSE during late accretion. The Os isotopic compositions of the Earth's mantle can provide a fingerprint for the type of material accreted. Thus, tracing mantle evolution over Earth's history is critical to constraining the Os isotopic composition of the earliest terrestrial mantles, and hence the types of materials present during late accretion. To address the issues surrounding late accretion and terrestrial mantle evolution, volatile-rich carbonaceous, and volatile-poor enstatite and ordinary chondrites, were measured for high-precision Os isotopic compositions. These data combined with those from previously published data for abyssal peridotites, new data for 2.7 Ga Pyke Hill komatiites, show the following. The Earth's primitive upper mantle has evolved with Pt/Os and Re/Os ratios similar to those in enstatite and ordinary chondrites, suggesting that late accretion materials that replenished HSE in terrestrial mantles were volatile-poor. Different materials are therefore required to re-seed the interiors of terrestrial planets with volatiles. These volatile-rich materials must essentially be depleted in HSE.

V52E MCC: 2010 Friday 1340h

The Changing Shapes of Active Volcanoes: Volcano Geodesy II *(joint with G)*

Presiding: **M P Poland,** U.S. Geological Survey**; A V Newman,** Los Alamos National Laboratory

V52E-01 1340h

2002 and 2003 Gravity and GPS observations in Yellowstone's Upper Geyser Basin

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Here we present 10 days of continuous relative gravity and global positioning system [GPS] campaign data from 2002 and 5 days of GPS campaign data from 2003 collected in Yellowstone's Upper Geyser Basin. These data confirm the persistence of the crustal deformation first detected in absolute gravity measurements from 2000 and 2001 and GPS observations from 2001 in the Upper Geyser Basin. The magnitude of the oscillatory microgravity fluctuations is on the order of +/- 4-6 microGals, on the timescales of hours to tens of hours. The crustal deformation inferred from the GPS is on the order several cm of vertical motion and is corroborative of the apparent inflation and deflation interpreted from the gravity measurements. The 2002 continuous gravity data provides a higher resolution of the temporal gravity signal with 1 minute averages versus the 1 hour and 15 minute sets from the 2000 and 2001 absolute gravity data. In the 2002 and 2003 campaigns we tried to test the breadth of the crustal deformation signal with spatially broadly distributed GPS campaign measurements. The 2003 GPS campaign sites span the length and the width of the 3.2 km x 0.8 km Upper Geyser Basin.

V52E-02 1355h

Co-eruptive deformation of Nyiragongo and Nyamulagira volcanoes, Africa, from radar interferometry

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Nyiragongo and Nyamulagira volcanoes are located in the western branch of the East African Rift in the Democratic Republic of Congo. On January 17, 2002, an eruption at Nyiragongo stratovolcano sent lava flows into the city of Goma (population 500,000), 18 km south of the summit. About 13% (4.5 km^2) of the city was destroyed and several dozen people were killed. Although the extrusion of lava on the flanks ended by January 18, intermittent volcanic activity at the summit of Nyiragongo continued through 2002 and 2003. The region experienced a second major eruption of lava on July 25, 2002, from the Nyamulagira shield, 14 km northwest of Nyiragongo. Radar interferometry results derived from RADARSAT-1, ERS-1, and ERS-2 data do not indicate significant deformation in the area between early 1997 and January 14, 2002, except for subsidence of a lava flow that erupted on the north flank of Nyamulagira in 1989-1991. Interferograms spanning January 14 to February 13, 2002, show a broad pattern of fringes across the rift valley in addition to closely spaced fringes in the vicinity of Goma. After February 13, 2002, little deformation is apparent until the July-August 2002 time period, when fringes suggesting uplift characterize the summit of Nyamulagira. From August 2002 until February 2003 no noteworthy deformation is evident, despite the occurrence of several large (M > 5) tectonic earthquakes. We believe that radar interferograms covering the January 2002 eruption of Nyiragongo volcano reveal a broad rifting event accompanied by shallow dike intrusion. The temporal characteristics of the displacement field indicate the event occurred in a relatively brief period of time with little precursory or post-eruptive deformation. Inflation of Nyamulagira volcano in July-August 2002 may be the result of dike intrusion from a shallow reservoir that fed the July 25, 2002, eruption. The results suggest that the eruption of Nyiragongo on January 17, 2002, may have been driven by an episodic rifting event, while the subsequent eruption of Nyamulagira occurred without accompanying tectonism. Since 1997, minor eruptive activity at Nyiragongo, including the reemergence of a lava lake, has not been associated with significant deformation.

V52E-03 1410h

Anelastic Deformation on Montserrat

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GPS measurements at Soufriere Hills volcano on Montserrat show that displacements that occurred since 1995 are irreversible. Displacements measured between June 1996 and June 1997 (Shepherd et al., 1998) are re-interpreted using a three-dimensional Boundary Element Method (3D BEM) for elastic medium. Using a spherical source model, it is shown that the source of the displacements is located at the base of the dome (350 meters below the dome summit in 1997), therefore these displacements could be created by the dome weight. Further models show that the weight of the dome on the crater floor only accounts for 14 percent of the measured displacements. We have then assumed that the dome was fed by a vertical cylindrical conduit so that increase in the dome volume increases pressure in the conduit. We find that this pressure could explain the GPS observations if the conduit radius was 350 meters in diameter. In 1996 and 1997, tiltmeters recorded cyclic deformations of the edifice (Voight et al, 1999). Two tiltmeters operated simultaneously at different distances from the summit allowing determination of the source depth. Assuming these deformations are created by the pressurization of a portion of a cylindrical conduit in an elastic medium and using again a 3D BEM, we show that this source is located at 900 meters depth below the dome summit. Scaling the conduit diameter so that the elastic rock matrix does not fail, the measured tilt amplitudes are explained by a conduit diameter larger than 100 meters. These interpretations of Montserrat deformations lead us to estimate a conduit diameter much larger than the 30 meter-diameter estimated from geological and petrological interpretations (Devine et al., 1998). This paradox can be explained if the conduit size estimated from the deformations corresponds to a "pseudo-pressurized-conduit" made of a central cylindrical conduit where magma is flowing, embedded in a visco-plastic cylindrical medium where stresses are close to hydrostatic so that magma pressures are transmitted to the surrounding elastic rock matrix. This explanation is compatible with the geological and petrological interpretations as these methods provided the conduit diameter required to transport magma to the surface. This anelastic rheology is particularly relevant to studies of the stability of the edifice and further risk assessments.

V52E-04 1425h

Interpretation of Gravity Gradients Produced by Magmatic Intrusions Using Elastic- and Viscoelastic-Gravitational Deformation Models

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A method for the computation and interpretation of time-dependent potential and gravity changes and gravity gradients produced by magmatic intrusions in a layered elastic- and viscoelastic-gravitational medium is presented. The model assumes a plane medium geometry, which consists of welded layers overlying a half-space. Every layer or the bottom half-space can be considered either elastic or allowed to relax. The intrusion is treated as a point source and can be located in any of the layers or in the half-space. The model allows to compute geometric and orthometric vertical displacements as well as surface, free-air and Bouguer free-air corrected gravity changes. We can compute the corresponding gravity gradients. We present several examples of theoretical computations and study different types of geometric and orthometric gravity gradients. The results show that these gradients can be an useful tool to obtain information on the dynamics of the injection and post-injection processes, in particular detecting new magma intrusion or changes in the depth of the source. We also present the results of the application of the methodology to Mayon volcano, Philippines, and to Campi Flegrei, Italy.

V52E-05 1440h

Inference of Magma Chamber Geometry at Sierra Negra Volcano, Galapagos Islands, Using a 3D Boundary Element Method With Pressure Boundary Conditions and InSAR Observations

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We present a new way of implementing a 3D boundary element method with uniform pressure boundary conditions. Uniform opening dislocations have often been used to infer surface deformation due to subsurface processes such as slip on fault planes or magmatic processes under volcanoes. These models require displacement discontinuities as input parameters and quantify the displacement and stress fields at observation points in the continuum. We use the linear relationship between displacement discontinuity and stress to derive a boundary element method subject to uniform pressure boundary conditions. Application of this method to synthetic aperture radar interferometry (InSAR) data over Sierra Negra shows agreement with previous results in terms of maximum sill opening. Amelung and Jonsson et al. [2000, Nature] successfully used a sill model with spatially varying opening boundary conditions. We have improved the model by applying the physical constraint of uniform pressure on the wall of the sill. Given the model geometry, in particular, the periphery of the sill, the pressure boundary condition determines the opening at each model element. Thus the number of degrees of freedom in the problem is reduced by the number of model elements. Determining which elements open, and are thus subject to the pressure boundary condition, is a non-linear problem. We adopt a Bayesian Monte Carlo approach to estimate the sill geometry. The probability that an element either opens or remains closed is assumed to be a Gaussian random variable centered on the peak of the radar range change measured in our interferogram. Elements beneath the largest range change are most likely to be open, those far away least likely. The Monte Carlo estimation is run for an arbitrary time, and the best fitting model is chosen.

V52E-06 1455h

Distributed Source Model for Deformation Caused by Magma Reservoirs

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Volume and pressure changes in magma reservoirs cause inflation or subsidence at the surface. The changes can be caused by accumulation, withdrawal or crystallization of magma. Deformation models are used to determine parameters like location, depth, extent and shape of the reservoir. In most models today, overly simple predefined source geometries are used. These may not only give an unrealistic image of the source shape, but also mislead when interpreting the underlying deformation processes. We present a model of distributed deformation sources that inverts for the volume strain in discrete subsurface units. The deformation sources consist of centers of dilatation and double forces. Solutions are sought that minimize a residual norm weighted by the data covariance and a regularizing functional that requires the source volume to be spatially compact. Compactness is realized by penalizing locations in the model space proportional to their distance from a target location. This compactness criterion distinguishes the modeling from the commonly used approach of spatial smoothing which would smear the source out over an unrealistically large volume, implying a magma body too dispersed to be viable over long time periods. To interpret the estimated distribution of point sources in terms of a physical model, we seek closed surfaces surrounding the sources on which the normal stress is constant, and the shear stress vanishes. These surfaces then represent an equivalent magma pressure increase or decrease in a magma chamber of uniform pressure. To define the absolute size of a magma body, additional constraints are needed. The modeling algorithm is applied to deformation data from Long Valley caldera between 1985 and 1999, which experienced nearly 1 meter of uplift during that time period. We find an inflation source with a center depth of about 8 km, and with a vertical extent of about 4 km. The total volume increase over the 14 year time period is 0.06 km3. We compare our results with those obtained from simple spherical and ellipsoidal models.

V52E-07 1510h

Stress changes during the rapid deformation of Miyakejima volcano on 26-27 June 2000

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Deformation often signals the occurrence of magmatic processes within volcanoes, such as the intrusion of new magma bodies and inflation or deflation, of existing bodies. Stress change induced by magmatic activity can drive propagation of dike and earthquake activity. Conversely, by relieving stresses from previous intrusive processes, can establish stress states favorable to new or continued intrusion. In this research we have modeled stress transfer effects during the dikes intrusion sequence in Miyakejima volcano on 26-27 June 2000. On 26-27 June 2003, a kinematic GPS analysis of data from the the Miyakejima volcano captured a fast developing event in unprecedented spatial and temporal detail. Initial ground deformation toward east and upward was observed in the southeastern part of the volcano at 18:00 on 26 June 2000, almost simultaneous with earthquake swarms. Some time after 21:30 on 26 June the displacements at these sites turned from eastward to westward. Three hours later the displacement rates increased gradually at GPS sites in the western part of Miyakejima as the seismicity migrated and approached the west coast, and reached a climax with the submarine eruption at 09:00 on 27 June 2000. The non linear inversion of GPS data leads to an interpretation that the 18:00, 26 June earthquake swarm was caused by a dike intrusion near the Oyama crater. Starting from 21:30 this dike deflated and a new dike intruded near the west coast. Following the propagation of this dike to the offshore, a spherical source began deflating in the southwest of Oyama crater. This research attempts to identify and delineate stress interactions and to develop a consistent model of magmatic processes in Miyakejima volcano.

URL: http://www.seis.nagoya-u.ac.jp/~irwan/myk062000.html

V52E-08 1525h

Towards a 4D Viscoelastic Model for Deformation of the Long Valley Caldera 1997 Inflation Episode

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We investigate the effects of viscoelastic rheologies and non-spheroidal sources on time-dependent deformation for a large silicic volcanic body. We focus on surface deformation at Long Valley caldera for the 1997 inflationary episode, but the methods developed here should apply to similar systems elsewhere. We begin with the model in Newman et al. (J. Volc. Geoth. Res., 2001), a spherical magma chamber encased by a 1-km thick viscoelastic shell ($\mu = 5$ GPa, $\nu = 0.25$, $\eta = 10^{16}$ Pa-s – similar to a 600 degree rhyolite at 5% wt. water) in an elastic half-space ($\mu = 5$ GPa, $\nu = 0.25$) and extend it to include ellipsoidal geometries that better represent magmatic sources. The data include 2-color EDM baselines, 3-D continuous GPS, and temporally limited but spatially dense synthetic aperture radar interferograms. All models fit a source at similar location and depth to the inflation source identified by Langbein et al. (JGR, 1995) for the 1989 inflation episode, indicating the source has not migrated significantly in that 8 year period. Though this technique is unable to uniquely identify the source volume, allowing for significant uncertainty in magma pressure changes, all models that include a modest (500 m thick) viscoelastic shell require only a fraction of the pressure required by purely elastic models (~20-70 MPa rather than 400+ MPa). This is significant because the lithostatic load at 6 km depth is only ~160 MPa and magma pressures that far exceed it would predict eruption.

V52F MCC: 3008 Friday 1600h

Melt Formation and Migration

Presiding: **M Jellinek,** University of Toronto**; A Stracke,** Max-Planck-Institut für Chemie, Abteilung Geochemie

V52F-01 1600h

Experimental Investigation of the Partially-Hydrated Solidus of KLB-1

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It is important to study the effects of the presence of trace amounts of water, found in nominally anhydrous minerals, on mantle melting by more accurately determining the position of the peridotite solidus as a function of trace water content at upper mantle pressure and temperature conditions. The specific effects of trace water on melt productivity and the composition of liquids in equilibrium with mantle minerals can be examined using experimental methods. However, there is a lack of experimental data with regard to the trace water contents associated with the mid-ocean ridge basalt source mantle (50 to 500 parts per million H_2O) as opposed to fully saturated or nominally anhydrous conditions. The complex speciation of H_2O dissolution in silicate liquids makes it difficult to extrapolate from either dry or saturated runs into this slightly hydrous regime. The challenges to accurate experimental measurement of the "partially hydrous" peridotite solidus include control of initial and final water contents and characterization of extremely small melt fractions. An experimental protocol has been developed to minimize external water contamination. This includes a rigorous drying sequence to eliminate adsorbed water from the system. Our double capsule assembly utilizes a hematite "hydrogen-getter" in order to discourage hydrogen diffusion into the sample during the run. Time-series experiments using an anhydrous glass of albite-orthoclase eutectic composition constrain the amount of water entering the system from the environment. We found that no more than 280 ppm can contaminate the system during run durations of up to 72 hours using this assembly at P = 1.9 GPa and T = 1350°C. Peridotite melting experiments were performed using the piston-cylinder device at 2.0 GPa. The sample material is a mix compositionally equivalent to the fertile spinel peridotite KLB-1 comprised of a synthetic component commensurate to the pyroxene plus spinel portion in addition to natural KLB-1 olivine material. The olivine component was doped with H_2O in water-saturation experiments, allowing the accurate representation of peridotite composition as well as allowing for a trace amount of H_2O. The incorporation of water as measurable structurally bound hydroxyl within the olivine enables the aggressive drying protocol to remove additional adsorbed water while still permitting a pre-determined amount of water to remain in the system. In order to determine precisely the position of the solidus and to evaluate near-solidus melt productivity, a method is required by which the presence of a very small degree of melt (<1%) can be recognized. Simple observation of the presence or absence of glass or quench material may not be sufficient at such low melt fractions. To this end, analyses of the incompatible elements Na and Ti in clinopyroxene grains have been performed using a trace element protocol on the EPMA. The onset of melting is demonstrated by the sudden drop in concentration of the element in the clinopyroxene, allowing a more accurate estimation of the position of the solidus than had been previously measured. A preliminary estimate for the position of the anhydrous solidus of KLB-1 at 2.0 GPa is between 1325-1350°C. Applying a similar method with a more incompatible tracer (e.g. H or K) is expected to reveal the slightly hydrated solidus.

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