normal fault. The distinction between exhumation-dominated and tectonically-dominated mountain fronts is best quantified by analyses of a new metric we call the drainage basin volume to drainage basin area ratio (V-A ratio) as well as the gradients of first-order streams. Drainage basin volume and area are calculated by constructing topographic envelope maps from 10 m resolution digital elevation models (DEM). The envelope maps are pinned by the watershed divide and cover the maximum elevations in each drainage basin. Subtracting the original DEM from the maximum elevation envelope map produces a topographic residual map from which area and volume data can be obtained. The erosionally exhumed Sierra Nacimiento has a mean V-A ratio of 88 m while the tectonically active Taos Range has a mean V-A ratio of 140 m. Similarly, there are systematic differences in the gradients of first order streams measured both in the range block and approximately 5 km of adjacent piedmont. Streams were defined and subsequently Strahler ordered by a flow accumulation threshold of 250 water-equivalent grid cell units. First order stream channel long profiles were extracted from the DEM at 30 meter increments and gradients were calculated by a FORTRAN program. Gradients of first order streams in the exhumation-dominated Sierra Nacimiento have a mode of 6.8 degrees, significantly less than the 17.7 degrees for Taos Range first order streams. Furthermore, in the Taos Range first-order stream gradients steepen with increasing activity on the range-front fault. The distinct V-A ratio and stream gradient populations hint at an important change in the processes shaping hillslopes and low-order channels that is supported by the lack of slope-clearing landslides in the Sierra Nacimiento landscape and the presence of such landslides in the Taos Range. Slopes on Sierra Nacimiento are not steep enough to landslide and here, creep processes following a linear diffusion law dominate. In contrast, landsliding is present in the Taos Range where creep processes following a non-linear diffusion law are dominant. The signatures of distal base level fall are low V-A ratios accompanied by low modal channel gradients. Tectonically active mountain fronts have both high V-A ratios and high modal channel gradients.

T22E-05 1700h

Position of the Topographic Divide as a Measure of Tectonics, Steady-State, and Bulk Rock Strength

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The fractional position of the topographic divide relative to local base-levels defines the first-order shape of mountains over a wide range of length-scales, from spur-ridges to entire mountain ranges. We propose that the fractional position is a sensitive measure of the relative roles of tectonics, local base-levels, and bulk-strengths of rocks exposed on adjacent flanks of the range. In the absence of tectonics and in a homogenous lithology and climate, the fractional position of a steady-state divide is given by $D = F/(F+R)$ where F and R are the reliefs of adjacent flanks of the range. Departures from the predicted value indicate that one or more of the stated conditions is invalid. In cases where the topography is being generated over an active thrust, for example, the divide position expresses the relative role of tectonics. Examples from the Siwalik Hills, along the southern margin of the Himalaya, suggest that base-level is the primary control over the first-order shape of the emerging ranges. This means that attributes of the topography cannot be simply linked to the state of active faulting, but must be made with some reference to the geological history of marginal base-level changes. In cases where tectonics and differences in bedrock bulk strength can safely be disregarded, departures from the value of D speak to the response time of landscapes that are adjusting to recent changes in base-level. Such changes may be induced by climate change or to significant base-level changes (e.g., eustatic) that have subsequently migrated to the local region. In the absence of all external forcings (tectonics and climate), departures from D measure directly the difference between the bulk-strength of rocks exposed on adjacent flanks of a range. This measure is at a length-scale previously unavailable and may be of use in landscape evolution models and in landslide hazard analyses. All of this is predicated on the assumption that mean slopes measured from the topographic divide to local base-levels are ideally equal, which is a straightforward result if slopes are generated via landslides and debris flows. We propose and show supportive evidence that this is also the case where fluvial erosion is primarily responsible in the generation of range slopes.

T22E-06 1715h INVITED

What are the links between landslide distributions, topographic relief and erosion rates?

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If we wish to understand the pattern and rates of erosion in mountains, we need to understand the coupling between hillslope failure events and the evolution over time of hillslopes. There must be a link of some kind between the process that triggers the landslides and the morphology of the hillslopes sculpted by them. This link presumably determines the size, frequency and location of landslides, in combination with runoff and channel erosion processes, and together they determine the flux of sediment into the channel network. Unfortunately, it is very difficult to quantify the patterns and rates of landslide erosion, in part because individual landslides occur on scales (of area and volume) that are wildly variable, from failures a few meters across to several kilometers in size, and in part because the timing and location of landslides is complex. These problems make both data acquisition and mathematical analysis very challenging. Nevertheless, many landslide maps and inventories now exist, and with the advent of widely available digital elevation data, there is an excellent opportunity to study both in tandem. We present an analysis of several dozen landslide inventories and show that the size (planform area) distribution of landslides has more or less the same shape regardless of geographical location, bedrock lithology, or trigger mechanism. Each distribution has a heavy, power-law tail, with a similar exponent in most data sets. In some very good inventories the full shape of the distribution can be estimated with confidence, along with the modal average landslide size. We present a theoretical model that links these observations to the morphology of the landscape on which they were triggered. The model predicts a probability distribution for landslide sizes that matches very well our observations. The result is quite promising: it makes a simple link between hillslope failure and hillslope geometry, and it suggests that, in combination, high-resolution data for both may be able to tell us something about the physical parameters that drive landslide erosion and landscape evolution.

URL: http://geomorph.ldeo.columbia.edu

T22E-07 1730h

Tracking tectonism with terraces: new methods, new insights in the Gulf of Evvia, central Greece

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Coastal terraces are typically the preferred geomorphic marker to calibrate crustal deformation along tectonically active coastlines. Their elevation with respect to a horizontal reference datum - typically sea level - provides a measure of net uplift (or subsidence), whilst their dislocation or tilting can constrain the 3-D deformation field. Such tectonic interpretations, however, rest on the reliable identification, characterisation and measurement of the terraces themselves. To aid extraction of the topographic attributes of terraces from DEMs, we have developed an algorithm that rapidly and consistently delimits the spatial extent of terrace surfaces based on user-defined individual 'seed points'. The extracted topographic attributes can then be manipulated by standard structural geological 3-D visualisation techniques to inform tectonic analyses. We illustrate the methodology with a case study from the northern Gulf of Evvia, Greece. Here, on the Arkitsa headland of the gulf's western shore, a staircase set of topographic benches are carved into the uplifted tip of a major active normal fault, the Kamena Vourla fault. In the field the benches are observed to be multiple unconformable wave-cut platforms, though individual surfaces are locally faulted in places. A 10 x 10m DEM of the headland, extracted photogrammetrically from scanned air-photos, served as the testbed for the terrace delimitation algorithm. The algorithm computed a terrace map which, when combined with the digital topography, defined the altitude, slope and aspect data for each terrace fragment. The data indicate that the terrace fragments conform to two discrete populations that locate either side of a largely ignored transverse lineament, the Livanates fault. Structural reconstruction of pre-deformation terrace geometries track the differential uplift and tilting of terraces across the Livanates fault. Our tectonic interpretation proposes that this fault is an important 'release' structure to the main Kamena Vourla fault, and that this release fault has been operating at most since the penultimate interglacial period.

T22E-08 1745h

Tectonics from topography: Methods, Application, and Limitations

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Empirical observations from fluvial systems across the globe reveal a consistent power-law scaling between channel slope and contributing drainage area. Theoretical arguments for both detachment and transport limited erosion regimes suggest that rock uplift rate should exert first-order control on this scaling. Here we describe in detail a method for exploiting this relationship, in which topographic indices of longitudinal profile shape and character (stream profile concavity and steepness indices) are derived from digital topographic data. Key data handling steps include sub-sampling at uniform vertical intervals to recover contour crossings in source vector data and to more evenly distribute data in log(S)-log (A) space. In addition, we test several approaches to further smoothing data to improve the noise-signal ratio. These tests reveal that stream profile concavity and steepness indices are not sensitive to the various smoothing options considered, but that smoothing does greatly improve one's ability to recognize scaling breaks otherwise hidden in the noise. The stream profile data can then be used to delineate breaks in scaling which may be associated with tectonic boundaries. In the San Gabriel Mountains, CA, analyses of USGS 10m, USGS 30m, SRTM 30m, ASTER 30m, and SRTM 90m DEMs differ in detail, but overall yield similar results. The description of the method is followed by three case studies from varied tectonic settings. The case studies illustrate the power of stream profile analysis in delineating spatial patterns of, and in some cases, temporal changes in, rock uplift rate. Owing to an incomplete understanding of river response to rock uplift, the method remains primarily a qualitative tool for neotectonic investigations; we conclude with a discussion of research needs which must be met before we can extract quantitative information about tectonics directly from topography.

T31A MCC: 3007 Wednesday 0800h

Izu-Bonin-Mariana Arc Processes and Progress I *(joint with S, V)*

Presiding: **S Klemperer,** Stanford University**; J Gill,** University of California, Santa Cruz

T31A-01 0800h INVITED

Constructing a dynamically and geologically consistent hypothesis for the initiation of Izu-Bonin-Mariana subduction

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The Izu-Bonin-Mariana (IBM) subduction zone, though now mature, is an excellent location for studying intra-oceanic subduction initiation largely because drilling of its fore-arc basement provides constraints on the tectonic and magmatic history during initiation. The timing of uplift and subsidence of the overriding plate, recorded on topographic ridges of the West Philippine Basin, constrain the strength of interplate coupling during initiation. Arc volcanism during the first 10 My of subduction at IBM occurred at a rate much higher than typical of mature arcs, and over an area that was exceptionally broad (200 km) compared to present arcs (50 km in width). The early arc was dominated by boninitic volcanism, uncommon in mature arcs, as it requires a high degree of partial melting of a clinopyroxene-poor source that is depleted in basaltic components (but presumably enriched in volatiles) and lies on an abnormally steep geothermal gradient. We are studying the dynamics of subduction initiation with numerical methods that allow for simultaneously modeling multiple styles of deformation, from elastic plate bending to plastic failure at plate boundaries to viscous flow in the deeper mantle. Our methods allow us to address the previously studied problem of determining the magnitude of driving and resisting forces in unprecedented detail, and to monitor the evolution of these interacting forces. Perhaps more importantly, though, we are developing means for extracting a variety of predicted constraints from these models, such as topography, gravity, and melting characteristics. With such model predictions, we will address whether the unique character of early IBM volcanism a general feature of incipient subduction, or whether extenuating circumstances, such as the influence of a mantle plume, are required to explain the observations.

T31A-02 0820h INVITED

Changes in Lava Compositions and With Time From the Eocene Through the Miocene for the Mariana Forearc

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We are investigating the evolution of volcanism in the Mariana arc from the initiation of subduction of the Pacific plate beneath the Philippine plate in the Eocene through the Miocene. The oldest lavas in the Mariana fore-arc region are a ca 49 Ma tholeiite to boninite sequence from DSDP sites 458 and 459. These tholeiites have NMORB-like REE, HFSE, and Th concentrations, but are enriched in LIL elements, Pb, and U. The capping boninite-series glasses have similar slab-derived trace element abundance patterns, but lower and flatter REE contents (1-2 x PUM). $^{40}Ar/^{39}Ar$ ages obtained on boninite series lavas from Guam stretch back to 44Ma. These lavas have U-shaped REE patterns and HREE concentrations about 3-8 x PUM. La/Nb decrease and Hf/Sm increase with increasing Ba/La for both the DSDP and Guam lavas. Pb isotope values plot within fields defined by Pacific plate lavas and volcanogenic sediments (Meijer, 1976, GSA Bull., v. 87; Pearce et al., 1999, J. Petrol., v. 40). Hf and Pb isotopic compositions change consistently with Hf/Sm and Ba/La ratios for lavas from the DSDP sites, but not for those from Guam. The data suggest either that little of the Pb in these lavas was derived from subducting sediments, or that the contrast in Pb isotopes between lavas from Guam and slab fluids was inconsequential. The source of the DSDP site lavas was similar to a Pacific or transitional Pacific-Indian Ocean MORB-source. Fluxed melting at high-P generated the tholeiites. Boninites were generated at low-P by continued fluxed melting. The mantle source for the boninite-series lavas from Guam was less depleted. Progressive fluxed melting here apparently occurred with less mantle upwelling. In both locations, the variations in La/Nb and perhaps the Hf/Sm ratios appear to be related to changes in the residual mantle source mineralogy with progressive melting. Rhyolites erupted on Saipan at 45- 46 Ma are unusually high in silica for an oceanic island arc setting. These lavas are enigmatic in that they have trace element and isotopic compositions similar to those of Oligocene (36-32 Ma) mature arc andesites and dacites from forearc sites. Pb isotope values for all of these lavas plot along a trend that stretches from the NHRL toward Pacific siliceous sediments, with the rhyolites plotting at the least radiogenic end of the array. Basalt dikes with ages of ca. 41 Ma cut the boninite series lavas in Guam. These basalts have trace element patterns of typical arc tholeiites, and mark the first appearance of relatively normal mafic arc lavas in this system. Pb isotope compositions for these samples indicate that siliceous sediment also makes its first appearance at this time. A second stage of normal arc volcanism began on Guam and Saipan at about 14 Ma, after spreading in the Parece Vela Basin ceased. These lavas have incompatible trace element and isotopic ratios that are remarkably similar to those of the modern Mariana arc. In conclusion: lavas from DSDP sites 458 and 459 were apparently generated from upwelling mantle that rushed in behind the newly subducting Pacific lithosphere (see Stern and Bloomer, 1992, GSA Bull. v. 104; Hall et al., 2003, EPSL, v. 212). The transition from an upwelling mantle wedge to relatively normal mantle counterflow and P-T distributions in the mantle wedge apparently required several million years of subduction and cooling of the corner of the mantle wedge. The compositions of the mantle (Pacific to Indian) and the subducted components (basaltic to silicic sediment) both changed with the mantle convection regime.

T31A-03 0840h

Sedimentation rate curves as a key to understand the evolution of arc and backarc basin -Arc type and Basin type-

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The deepsea cores recovered from about 50 drilling sites in the Philippine Sea, equally distributed in marginal basins, remnant arcs, present arcs and other tectonic settings, during the DSDP/IPOD/ODP offer significant geotectonic information. Sediment accumulation rates, lithologic changes and frequency of tephras were examined in the light of the recent advanced nannofossil biostratigraphy of the sediment on these cores. Sediment accumulation rate curves of these drill sites were classified into two major types, A and B types, respectively. A type has rapid accumulation rates just above the arc basement and then shows a decreasing pattern. In contrast, B type has rather constant accumulation rate throughout the cores. Sediments from the rapid sediment accumulation rates imply volcanogenic debris flow and volcaniclastic turbidite sequences derived which were derived from arcs that represent an activity of magmatic arc consisting of tholeiitic and calc-alkalic volcanic rocks. On the contrary, sediments from the low sediment accumulation rates imply mostly biogenic materials instead of volcaniclastic materials. This may mean the termination of intense arc volcanism. Frequency of volcanic ash layers deduced from these cores has maxima just after the rapid sediment accumulation stage of A type curves. As for the remnant arcs such as the Kyushu-Palau and the Daito Ridge, tephra maxima exist at both late Eocene to early Oligocene time and the present arc such as the Izu-Bonin Arc, there are two major maxima at Eocene-Oligocene and Pliocene-Pleistocene time, respectively. Explosive volcanism may take place when oceanic arc develops as shallow as the pressure compensation level (PCL). If this is the case, we may draw the volcanic history of oceanic island arc. At the incipient stage of arc evolution the style of volcanism is quiet resultant formation of pillow lavas and hyaloclastite. On the contrary, the intense volcanism takes place with formation of marine tephra layers at the explosive stage, and at the subaerial stage, large amount of tephras are emitted from the summit of the volcanoes. No volcanisms were happened instead continuous rapid subsidence of the arc at the remnant stage. These stages of the evolution of oceanic island arc are quite similar to those of the volcanic islands such as the Hawaiian volcanoes.

T31A-04 0855h INVITED

Seismic Structure of the Izu-Ogasawara (Bonin)-Mariana Oceanic Island Arc

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The formation and evolution of the Izu-Ogasawara-Mariana arc located at the eastern rim of the Philippine Sea plate is associated with the Pacific plate subduction. The arc system is most likely created in an entirely oceanic environment. Basic information required to understand how an oceanic crust transforms to an island arc crust clearly includes the seismic velocity models. Due to recent advance in marine seismological investigation technology, we are now able to map the whole crustal-scale arc structure in two-dimensional views by utilizing many digital ocean bottom seismographs spaced only several kms apart over hundreds of kms in horizontal distance range. Powerful airgun shooting allows depth coverage down to the uppermost mantle depths. The striking features of the seismic velocity model from this area were first obtained in 1992 from a survey across 32.25 deg N, which suggested formation of tonalitic rocks in the arc middle crust and a thick >7km/s lower crust beneath the rift center. Since then, a number of investigations were conducted in the area to better understand the significance of these features. We will show preliminary results from recent Japanese investigations, which possess similar features of the above model. From north to south, the entire arc system is experiencing different tectonic conditions at different latitudes. At the northern end the Izu arc is colliding with the Honshu arc. The Izu part is in the rifting stage after the cessation of the opening of the Shikoku Basin. There is ongoing back-arc opening in the Mariana Trough along the Mariana arc. How these different stages manifest their formation processes in seismological models and observations is a fundamental problem for understanding the plate subduction dynamics. We are planning to obtain more comprehensive seismic velocity models from this area in order to relate the structure to evolution and dynamics of the arc system.

T31A-05 0915h

Possibility of existence of serpentinized material at the Izu-Bonin subduction plate boundary around 31N using Q structure by FDM-simulation

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At the Izu-Bonin subduction zone (IBSZ), there is a chain of serpentine seamounts at the forearc slope of trench axis, and few large earthquakes occurred at shallow depth (<100km) in spite of many large ones at greater depth (>400km). To elucidate these characteristics we carried out a seismic refraction-reflection study at the forearc slope of the IBSZ around 31N using 22 OBSs and chemical explosives and airguns as seismic sources in 1998. As the results of forward and travel-time inversion modeling of the study, P-wave velocity structures were obtained along E-W and N-S survey lines which is perpendicular to and parallel to the trench axis, respectively (Kamimura et al., 2002). The result of E-W line (transect a summit of serpentine seamount) suggests presence of a low velocity zone just above the subducting Pacific plate, and this zone connects to the Torishima Serpentine Forearc Seamount. The interpretation of the result was: dehydration of hydrated oceanic crust supplies water to the mantle wedge, and peridotites of the mantle wedge were serpentinized. The serpentinized peridotites have moved between the oceanic slab and the overriding island arc crust and were diapiring into the serpentine seamount. The serpentine on the plate boundary might act as a lubricant and decrease seismic activity along the subduction zone, and this can explain the characteristics of seismicity of IBSZ. In order to evaluate Q structures of

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the above low velocity zone on the subducting slab, we calculated synthetic waveforms using FDM (Finite Difference Method) with elastodynamic formulation (E3D code, developed by Dr. Shawn Larsen) and the P-wave velocity 2D structure of Kamimura et al. (2002). The E3D uses staggered grid, and 2nd order and 4th order approximation in time and space, respectively. Grid spacing of the calculation is 30 m in x and z, and 1.5 msec in time. Five-Hz and 0-phase Ricker wavelet pressure source was used. Several structure models are used for comparison. One model has no low-Q zone, another one has low-Q zone only just below the serpentine seamount. Other models have low-Q zones just below the serpentine seamount and above the subducting slab, horizontal width of the low-Q zone are different one another. Comparing synthetic waveforms and observed data, we can conclude that there must be a low-Q zone just below the serpentine seamount and on the subducting oceanic slab. The low-Q zone on the slab has ca. 80 km wide east to west and connects to the serpentine seamount. It is very important to understand where serpentinites of the seamounts came from to explain the characteristics of seismicity at the IBSZ. In this presentation we are going to explain an interpretation that serpentine moved through the plate boundary and reached just below the serpentine seamount, using an existence of the low-Q zone. Kamimura, A., Kasahara, J., Masanao S., Hino, R., Shiobara, H., Fujie, G., Kanazawa, T., 2002. Crustal structure study at the Izu-Bonin subduction zone around 31°N: implications of serpentinized materials along the subduction plate boundary, Physics of the Earth and Planetary Interiors, 132, 105-129.

T31A-06 0930h

Geodynamic and Seismic Characterization of Mantle Flow in the Izu-Bonin Subduction System

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The goal of this study is to provide new constraints on mantle flow in subduction zones as inferred by patterns of seismic anisotropy. In particular, we are implementing improved methods of interpreting seismic anisotropy measurements in terms of lattice-preferred orientation (LPO) induced by mantle flow. In this study, we focus on the dynamics of the Izu-Bonin (IB) subduction system, which contains a plate geometry that can be approximated to first order by 2D mantle flow models. This simple configuration, combined with recent new measurements of shear wave splitting in the region [Anglin and Fouch, this session], provides an important opportunity to evaluate the role of water on flow and strain development in a hydrated mantle wedge. Current and previous observations of seismic anisotropy in the IB mantle wedge, suggest convergence-parallel fast polarization directions, consistent with models of deformation in a "dry" mantle system. However, the IB mantle wedge is most likely hydrated, and some models of deformation in a hydrated mantle predict convergence-orthogonal fast polarization directions. This dichotomy thus provides an ideal setting in which to test hypotheses regarding the effect of water on mantle flow, strain, and seismic anisotropy. To this end, we use a finite element approach to calculate kinematic models of flow in the mantle wedge. We use these flow models to calculate LPO in the mantle wedge following the method developed by Kaminski and Ribe [EPSL, 2001] that incorporates the combined effects of intracrystalline slip and dynamic recrystallization on textural development. We utilize the resulting textures to predict shear wave splitting for a range of seismic raypaths by solving the Christoffel equation for each increment of a raypath and integrating the resulting predicted shear wave splitting experienced by each ray. A significant advantage of this approach is the ability to provide more appropriate representation of a range of mantle mineralogies, resulting LPO development, and predicted shear wave splitting for regions within the mantle flow model. While our current modeling efforts utilize an isoviscous mantle rheology, we are developing more appropriate models with temperature-dependent rheologies and hydrated mantle conditions. In addition, we will examine the role of water on LPO development and predicted shear wave splitting. Finally, we will compare the range of results of predicted shear wave splitting with shear wave splitting measurements currently in progress.

T31A-07 0945h

Mantle Seismic Anisotropy in the Izu-Bonin Subduction System

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The objective of this study is to determine the location and extent of seismic anisotropy within the Izu-Bonin (IB) subduction system to constrain mantle flow dynamics in the region. Of particular importance is an improved understanding of the role of water in strain development and seismic anisotropy in hydrated mantle. The IB system is a key location in which to evaluate this problem as it presumably contains a hydrated mantle wedge and is a viable candidate for relatively simple 2D mantle flow. However, the dearth of seismic stations in IB presents significant challenges in measuring shear wave splitting in the region. We therefore apply a unique approach for imaging mantle seismic anisotropy to provide new constraints on patterns of strain and mantle flow in the IB system. We apply an analysis technique that determines residual splitting between teleseismic S and sS for intermediate- and deep-focus events. In this method, we estimate receiver-side anisotropy by applying particle motion analysis to teleseismic S. To limit the receiver-side anisotropic effect on the sS waveform, we use the resulting splitting parameters (fast polarization direction and relative delay time) from the S phase to apply particle motion corrections to the sS phase. We then evaluate shear wave splitting in sS to provide an estimate of seismic anisotropy recorded by sS within the upper mantle on the source side of the raypath. In our current dataset, we have examined residual sS splitting in waveforms in which no discernible splitting is evident on teleseismic S, thus limiting the potential effect of receiver-side upper mantle anisotropy on sS. Preliminary results from analysis of several source-receiver pairs exhibit fast polarization directions oriented E-W (i.e., convergence-parallel) and splitting times ranging from 1.75 s to 2.75 s. These results are consistent with the limited body of existing shear wave splitting analyses of local S phases for northernmost regions of the IB mantle wedge; however, splitting times from the current study are roughly double those estimated by previous work, as expected given the extended path length of sS relative to local S within the mantle wedge. While we emphasize that these results are preliminary, analysis of our dataset will continue to provide new constraints on the lateral and depth distribution of seismic anisotropy beneath the Izu-Bonin region.

T31B MCC: 3005 Wednesday 0800h

Causes and Consequences of Lateral Heterogeneity in the Earth's Mantle I *(joint with S, V, MR, DI)*

Presiding: **C Lithgow-Bertelloni,** University of Michigan; **L Stixrude,** University of Michigan

T31B-01 0800h INVITED

The Production and Destruction of Chemical and Lithological Heterogeneities in the Mantle

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Gast, Tilton and Hedge first showed that Earth's mantle was isotopically heterogeneous in 1964. Since that time, work on the isotopic taxonomy of Earth's mantle has delineated 5 chemical species (domains): DMM (depleted MORB mantle), FOZO (Focus zone depleted mantle), HIMU (high U/Pb mantle), EM1 and EM2 (enriched mantles). Despite decades of debate, the mode of formation and placement of these domains in the mantle is still contentious. DMM is certainly the upper mantle, and FOZO is likely the deep mantle. The "Standard Model" of Hofmann and White ascribes the other three domains to subduction and long-term storage of the oceanic lithosphere, followed by recycling to surface hotspots via plumes. The HIMU and EM domains reflect mantle containing ocean crust and/or sediment components. The challenge is to translate the arguably miniscule isotopic heterogeneities of this isotopic zoo into a macroscopic view of the mantle. What is the variability in major element composition? What are the scale-lengths of these heterogeneities? Are there mafic lithologies as well as peridotitic lithologies? Do these heterogeneities imply bulk chemical and thermal variations that are important in seismological and dynamical studies of the mantle? The Standard Model creates heterogeneities in both lithology (eclogite and peridotite) and chemistry (mafic and ultramafic) on only 10-km scale lengths. Can these survive mixing, stirring and storage for billions of years? Can they be imaged tomographically? Do they provide dynamically significant chemical or thermal buoyancy? Is the Standard Model even operative? One weakness of this model is its requirement for arbitrary and ad hoc chemical processing during subduction of the lithosphere, in order to provide the right protoliths for evolution of the mantle zoo. We have probed this weakness using the classic example of an EM2 mantle domain, the Samoa hotspot. Basalt with the most extreme Sr (0.7089) in the oceans shows a very smooth trace element pattern with only slight negative anomalies at Ti and Ba. This spidergram is inconsistent with the standard model that invokes a sediment component to explain the enrichment of the EM2 mantle source. Furthermore, it is highly unlikely that any chemical processing during subduction would "smooth out" the typically jagged spidergram of oceanic sediment. We propose instead that EM2 mantle represents the bottom, not the top, of the oceanic lithosphere. The enriched character results from a metasomatic melt/rock reaction process involving small-degree partial melts percolating up from underlying partially molten asthenosphere. This causes the lower regions (tens of kilometers?) of all oceanic lithosphere to become trace-element enriched as a matter of course; subduction and long-term storage then generates the EM2 isotope signature, and recycling in plumes/hotspots provides us the witness. The model EM2 source will have a major element composition inconsequentially different from that of DMM mantle, but with a heat production some 10 times higher (11 pW/kg versus 0.9 pW/kg).

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Constraints on Mantle Flow Through Joint Inversions of Seismic and Geodynamic Data

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Recent progress in global seismic tomography is yielding three-dimensional (3-D) images of mantle structure with greatly improved resolution on length scales ranging from a few hundred to several thousand kilometers. All seismic models agree on several large scale structures although seismic models from different groups still differ in many regions indicating issues of resolution remain. Furthermore, there is still debate on fundamental questions concerning the nature of mantle flow and chemical reservoirs in the mantle. Even as seismic models of the mantle improve, it is likely debate will remain concerning their interpretation in terms of mantle layering. Mantle flow has an observable signature in several geophysical fields including global gravity anomalies, plate motions, and dynamic surface topography. Given a density field of the mantle and a mantle viscosity structure, these geodynamic observables can be computed by calculating the instantaneous flow in the mantle. The dynamic response functions relating a given density anomaly to a given geophysical observable depend upon the existence of any chemical or phase change boundaries that impede vertical mass transport across the mantle. With knowledge of the three-dimensional variation in mantle density, we may thus discriminate among models with and without flow boundaries at different depths in the mantle using global geodynamic surface observables. Using various scalings between seismic velocity and density, we present joint inversions for 3D seismic velocity (density) mantle structure, plate motions, global free-air gravity anomalies, global dynamic surface topography, and dynamic ellipticity of the core-mantle boundary for a layered and un-layered mantle. The mantle flow models employ new mantle viscosity profiles that are optimized for each inversion. The seismic data consist of over 40000 S, multi-bounce S, ScS, multibounce ScS, SKS, and SKKS travel times. The joint inversions to date indicate that whole mantle flow is favored over a model with a barrier to flow near 660 km depth. We will also present results showing how these joint inversions can explicitly test the hypothesis of a negative or null correlation between anomalies of density and seismic shear velocity in the bottom half of the lower mantle. Such hypothesis tests provide insight on the relative importance of thermal and chemical contributions to lower-mantle density and seismic anomalies.