poles, those with ages from 32 Ma to 81 Ma, are determined from skewness analysis of 1563 crossings of marine magnetic anomalies due to seafloor spreading. They reveal the APW of the Pacific plate over this time interval with an accuracy and age-resolution far superior to other data sets. The skewness-only portion of the path indicates northward motion of the Pacific plate with 3 main swings in declination, clockwise from 81 Ma to 68 Ma, counterclockwise from 68 Ma to 40 Ma, and clockwise from 40 Ma to the present. The older two poles are from combinations of data types. There is no significant motion of the pole from 125 Ma to 88 Ma, but there is a sudden large counterclockwise shift of the pole in the brief interval from 88 to 81 Ma. This large and rapid shift of the pole is strongly supported by paleocolatitude data from azimuthally unoriented vertical cores of igneous rock obtained by deep sea drilling. In a reference frame attached to the Pacific hotspots, the spin axis lay near 80N, 160E during mid-Cenozoic time (32-40 Ma), near 80N, 210E during early Cenozoic time (55-68 Ma), and near 75N, 170E during Campanian and early Maastrichtian time (73-81 Ma). Thus, there was modest motion of the spin axis from 81 Ma to 32 Ma (or younger) with larger swings before and after. The most recent shift, sometime during the past 32 Myr, has been about 10 in arc length. A bigger shift of about 20 arc length occurred from 88 to 81 Ma, near the end of the Cretaceous normal polarity superchron. The largest difference between Pacific hotspot APW and Atlantic hotspot APW occurs for 73 to 81 Ma. The poles available from this time interval for the continents are highly scattered and some are likely biased. Overall there is good agreement between the two sets of curves, with the Indo-Atlantic hotspot APW path resembling a smoothed version of the Pacific hotspot APW path. The substantial overlap of confidence regions for the 125 Ma poles indicates no significant net motion between Pacific hotspots and Indo-Atlantic hotspots for the past 125 Ma. Within uncertainties, however, such motion could be as much as 9 mm/yr for the combined effect of the two paleomagnetically observable degrees of freedom. These results indicate that motion between Pacific and Indo-Atlantic hotspots is small enough that the hotspot reference frame is useful for estimating true polar wander.

U52A-05 1150h

Three Potential Description of the Dynamics of Rotating Fluid Bodies

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The oscillatory dynamics of a rotating, inviscid, stratified and compressible liquid body is simplified by an exact description in terms of three scalar fields which are constructed from the perturbations in pressure, gravitational potential and the dilatation. We show that this scheme has several advantages over the conventional approach of using the displacement (velocity) vector field, and that it provides a reliable method for computing normal modes of a fluid body. We will also discuss the geophysical and astrophysical applications of this approach.

U53A CC: 517 A Friday 1330h

The Importance of Water and Melt in Mantle Dynamics: Developing Constraints From Interdisciplinary Studies I

Presiding: **B Holtzman,** University of Minnesota**; C Hall,** California Institute of Technology

U53A-01 1330h

The influence of melt on the LPO, seismic properties and dynamics of mantle plumes

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Patterns of seismic anisotropy are indicators of both deformation mechanisms and melt distribution in the mantle and, as such, are primary sources of information on mantle flow dynamics. Recent experimental constraints on the influence of melt distribution on lattice preferred orientation (LPO) of deformed partially molten rocks impact interpretations of seismic anisotropy data, based on 3 observations: i) In melt-free samples deformed at low differential stresses, olivine a-axes (seismic fast direction) align in the shear direction; ii) when melt is present and pockets align due to stress, olivine a-axes form girdles; iii) when melt segregates into melt-rich networks, the resulting partitioning of strain and modification of stress fields cause alignments of a-axes 90° to the shear direction. Here, we propose tests for the presence of melt-modified fabrics based on 1) field observations in the Oman ophiolite and 2) published seismic observations from the Iceland hotspot. Plume-like structures provide good test sites because of strong 3-D gradients in flow and melt production, but to what extent can small-scale diapiric flow provide insight into the dynamics of large-scale plumes? 1) In the Semail Massif, frozen mantle flow structures suggest the presence of small scale (< 10 km diameter) diapiric flows. Although direct evidence of melt (frozen pockets) are rare, abundant evidence for large fluxes of melt in the area exist, including significant weakening of mantle rocks that enabled small-scale diapiric flow. In olivine LPOs from this region, increasingly strong maxima develop with increasing distance from the center of the diapir, though in preliminary results, the effects of melt as observed in our experiments are not obvious. 2) In large-scale plumes, the third mechanism (shear-normal a-axes) may develop. In SKS splitting observations of upper mantle beneath Iceland (e.g., Li and Detrick, EPSL, 2003), fast directions tangential, as opposed to radial, to the plume center are often observed. In deforming partially-molten mantle, effects of melt geometry on seismic anisotropy must be considered and compared to the effects of LPO. We propose a model involving melt segregation, strain partitioning, and olivine a-axis rotation to explain these tangential fast-directions in plumes.

U53A-02 1345h INVITED

Rock-Physics Constraints on Seismic Wave Behavior in Upper-Mantle Material

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Seismic waves sample upper mantle material that has undergone - and is undergoing - large-scale plastic deformation ± partial melting ± strain-effected phase separation: the waves are a 10-100 kPa, 10^{-7} strain, 10^{-3} -1 Hz "tickling" of material that is otherwise responding to a thermodynamic condition that includes a relentless deviatoric stress (σ) in the range 1-100 MPa. Thus, seismic wave velocities, velocity anisotropy and intrinsic attenuation reflect the combined structural and thermodynamic state of the sampled material. Interpreting the seismic signature depends on knowledge garnered from experimental studies. Careful experimental studies of the impacts of temperature (T; e.g., [1]), water fugacity (f_{H2O}; e.g., [2]) and partial melting (e.g., [3]) on steady-state viscosity of olivine aggregates, including the impact of steady-state flow on the development of fabric (lattice preferred orientation) in olivine, have begun to address conditions giving rise to anisotropy. The attenuation picture is less clear: the relationships amongst thermochemical/mechanical potentials (e.g., T, P, f_{H2O}, σ) and accumulated, large plastic strain that give rise to fabric may not be first-order in the attenuation response; rather, the structures of high- and low-angle grain boundaries (e.g., olivine-olivine) and solid-state phase boundaries (e.g., olivine-orthopyroxene), the nature of electrochemical ionic segregation to these boundaries, the spatial density of these boundaries and the interaction of these boundaries with lattice dislocations is suggested by experiment to be important [e.g., 4]. [1] M. Bystricky et al., Science, 290, 1564 (2000). [2] H. Jung and S.-i. Karato, Science, 293, 1460 (2001). [3] B.K. Holtzman et al., Science, 301, 1227 (2003). [4] K.M. McMillan et al., J. Mater. Sci. 38, 2747-2754 (2003).

U53A-03 1405h

Searching for Earth's Lost Oceans: A Planetary Odyssey in Mineral Physics

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The oceans cover more that 7 percent of the surface area but compose only 0.025 percent of the mass of the Earth. The nominally anhydrous silicate phases thought to compose the upper 660 km of Earth can incorporate more than ten times this much H. Hydrogen is thus a very poorly constrained compositional variable in the Earth. In order to evaluate the possibility of there being a very large reservoir of H in the interior we have conducted experiments to measure the effect of H incorporation on the physical properties of these minerals. At depths less than 410 km, olivine can incorporate 2000 ppm, and possibly as much as 8000 ppm, H_2O by weight at pressures above 10 GPa. Clinopyroxene can incorporate a similar amount of H as hydroxyl, and petrologic evidence in natural high-pressure samples suggests it may incorporate 5000 ppm or more. In the subducting basaltic slab after all hydrous phases break down, the pyroxene can carry down 0.1 to 0.2 percent H_2O by weight of the slab. If the ultramafic portion below the crustal portion becomes hydrated, the olivine can carry as much or more water into the interior. Based on neutron and X-ray diffraction studies, H is incorporated in these mineral principally by the 2H for Mg mechanism, meaning that H become a much more compatible element at pressures above 10 GPa. Using single crystal X-ray diffraction, we have measured the effect of hydration on compression of ringwoodite to 12 GPa. Using powder diffraction and synchrotron radiation we have measured compression to 50 GPa. Using GHz ultrasonic measurements of P and S-wave travel times, we observe a reduction of P-wave velocity equivalent to an increase in temperature of 600° C and on S-wave velocity of 1000° C. Throughout most of the Transition Zone (TZ), hydration has a larger effect on velocity than does temperature within reasonable ranges of these parameters and a much larger effect than do other compositional variables such as Mg/Fe ratios. In tomographic images of the TZ in regions distant from active subduction, red is more likely to mean wet' than it is to mean hot'. Observed seismic velocities in the TZ are consistent with a pyrolite composition with 0.5 to 1.0 percent by weight H_2O, but not consistent with dry pyrolite compositions. This would allow for Transition Zone storage of two to three times the amount of water currently in the hydrosphere.

U53A-04 1420h

The effect of water on the $P2_1/c$ to $C2/c$ high-pressure phase transition in $MgSiO_3$-clinopyroxene: implications for the mantle X-discontinuity

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The presence and distribution of hydrogen in Earth's mantle has intriguing implications for the geochemical evolution of liquid water on the planet. Bell and Rossman (1992) showed that pyroxenes of upper mantle origin typically contain 200 to 500 wt ppm H_2O. It is possible that in regions of lherzolitic or depleted harzburgitic mantle, the phase transition of Ca-poor orthoenstatite (OEN) to high-clinoenstatite (HCEN) may result in an observable seismic discontinuity at around 300 km-depth (Woodland, 1998). We devised a simple experiment to test the effect of water on the transition pressure of the $P2_1/c$ low-clinoenstatite (LCEN) to the high-density $C2/c$ HCEN in situ. A single crystal of dry $MgSiO_3$ LCEN was placed adjacent to a second crystal of LCEN containing approximately 500 wt ppm H_2O in a diamond-anvil cell. Raman spectroscopy was used to track the Si-O-Si bending vibrations from the pyroxenes, which display a characteristic doublet between 600 and 750 cm^{-1} for the $P2_1/c$ structure, or a singlet for the C2/c structure (Ross and Reynard, 1999). On compression, the phase transition from LCEN to HCEN occurred at 7.9(1) GPa for the dry LCEN, but at only 5.8(1) GPa for the wet LCEN.

On decompression, the hysteresis of the phase transition was reduced from 3 GPa for the dry sample, to 1.5 GPa for the hydrous sample. We studied upper-mantle discontinuity structures below the western U.S., South America, and in the Tonga subduction zone using receiver functions calculated from P-to-S converted arrivals. Within each region, there are multiple reflectors between 100 and 300 km depth, but their depths vary and not all of them are present at each station. In the western US, there is a sporadic and relatively weak reflector varying in depth between about 250 and 300 km depth. In S.A. along the Andean belt, a moderate to strong arrival is observed at around 290-300 km-depth, but below the craton strong arrivals appear at 245-280 km depth. At Tonga, the strongest reflector occurs at around 100 km depth, with only weak evidence for arrivals from 300 km. Mantle discontinuity structure in the upper 300 km of the mantle is considerably more complicated than for the transition zone, but if the effect of water on the LCEN to HCEN transition pressure observed in these experiments is comparable to that for OEN to HCEN in the mantle, any corresponding seismic discontinuity would be shifted to lower depths by about 40-60 km, or, extinguished altogether by widening of the divariant loop in the (Mg,Fe)SiO_3 system.

U53A-05 1435h

Incorporation of Hydrogen and Aluminum in Perovskite: A First Principles Investigation

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The incorporation of water into nominally anhydrous silicates is associated with mechanical weakening and lowered melting points such that even small amounts of water in mantle minerals can serve as a significant volatile reservoir in the planet. Experimental attempts at water incorporation in $MgSiO_3$-perovskite have met with varied success, with little agreement in solubility or the frequency of the OH band. Here we present first principles, pseudopotential calculations of fully relaxed structures on $MgSiO_3$-perovskite with aluminum and hydrogen substitutions. We find three symmetrically distinct stable arrangements for the location of hydrogen in the unit cell given the coupled substitution of Si^{4+} for Al^{3+} + H^+ in perovskite. These three stable hydrogen locations have OH bond lengths of 1.09Å, 0.96Åand 0.99Åat 0 GPa, and less than 2 kJ/mol difference in the energy distinguishing each arrangement. These multiple substitutions with small energy differences may explain the variable OH frequencies found for hydrated perovskite, with sensitivity to the synthesis conditions. This substitution is associated with a 2.2% softening of the equation of state for structure containing 3.1 mol% H_2O and Al_2O_3, comparable to recently reported results for softening in SiO_2-stishovite containing 2.1 mol% H_2O and Al_2O_3 [Panero and Stixrude, 2004]. We calculate that the enthalpy of solution of Mg^{2+}+Si^{4+}=$2Al^{3+}$ is slightly less than the Si^{4+} for Al^{3+} + H^+ reaction, but both solution enthalpies are generally independent of pressure between 0 and 100 GPa. Further, we confirm previous theoretical results that aluminum incorporation with oxygen vacancies is not favored ($2Si^{4+}+O^{2-}=2Al^{3+}+V_O^{**}$). Assuming ideal entropy of solution, at 2000 K we find Mg-perovskite saturated in aluminum and water to contain 0.13 wt% H_2O.

U53A-06 1450h

Oxygen Fugacities of Lavas From Iceland and Implications for Mantle Redox States.

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The oxygen fugacities of magmas provide information about the redox states of their mantle source regions. In principle, it is possible to use oxygen fugacities for magmas erupted in different tectonic environments to map variations in the redox state of the underlying mantle. Published data have been interpreted to indicate that the mantle source of MORB is reduced relative to that of OIB. In fact, oxygen fugacities calculated from analyzed Fe_2O_3/FeO for some OIB fall in the range of those for MORB (ΔQFM=0.402 to -1.305). For example, ΔQFM=0.188 to -1.212 for Hawaii, and ΔQFM=0.293 to -0.881 for Loihi. This suggests that the mantle source of at least some OIB is similar to that of MORB. To further compare the redox states of OIB and MORB mantle source regions, we have calculated oxygen fugacities for lavas from various volcanic centers on Iceland from the compositions of coexisting olivine and glass. Iceland lies across the Mid-Atlantic Ridge, but magmatism is thought to be related to the presence of a mantle plume. Hence oxygen fugacities for plume-derived magmas may be compared with those of magmas erupted along the nearby MAR. For the latter, oxygen fugacities calculated from olivine-glass pairs agree with those calculated from analyzed Fe_2O_3/FeO (ΔQFM=-0.562 to -2.212). Calculated oxygen fugacities for Icelandic lavas fall within this range (ΔQFM=-0.107 to -2.088), and broadly agree with those calculated from mineral equilibria for volcanoes such as Thingmuli. This confirms that oxygen fugacities for some OIB are virtually identical to those of MORB. The major implication of this study is that there is no evidence that the redox states of the mantle sources of OIB and MORB are substantially different. It follows that if OIB are derived from deep mantle plumes, there is no evidence that the redox state of the lower mantle differs from that of upper mantle. However, if the redox states of the lower and upper mantle are indeed different, this difference is not recorded in the oxygen fugacities of magmas erupted from these sources.

U54A CC: 517 A Friday 1530h

The Importance of Water and Melt in Mantle Dynamics: Developing Constraints From Interdisciplinary Studies II

Presiding: **W R Panero,** University of Michigan**; S D Jacobsen,** Carnegie Institution of Washington

U54A-01 1530h

Numerical Modeling of Melt Generation and Migration in Subduction Zones

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Using a two-phase flow model, we investigate the generation and migration of melt in the mantle wedge of a subduction zone. Our model consists of a deformable solid matrix, and melt that flows through the matrix. It allows for compaction and decompaction of a partially molten rock. We solve the equations of conservation of mass and momentum for the solid matrix and the melt, heat transport, and advective transport of the depleted mantle rock in a subduction model that extends to the bottom of the upper mantle. It is thought that transport of water from the slab to the mantle wedge can lower the melting temperature to around 1000 C. We investigate the generation of melt in the presence of dry, as well as, wet peridotite. We do not study the actual mechanism of water transport. We simply assume that such flux of water exists and affects the dry peridotite. We then study the amount of melt generated and its migration under varying parameters such as slab age, velocity and dip, viscosity, etc. We assume that water can flow to a maximum distance of 100 km from the surface of the slab. We also study batch and fractional melting conditions. We use the melting curves for dry and wet peridotite obtained by Iwamori et al. (EPSL, Vol. 134, 1995). The results show that voluminous melt production is possible only for wet peridotite and reasonable thermal evolution models. Both batch and fractional melting result in the melting of wet peridotite and the differences are, for the most part, of second order. The movement of the melt is governed by its vertical upwelling, and the wedge flow that works to keep the melt close to the slab. As a result, the melt has a tendency to accumulate near the corner of the mantle wedge. The models show a wide variety of melt flow behavior, ranging from circulating motions in the wedge, to entrainment of a significant part of it into deep mantle. In constant-viscosity models the melt is able to reach to the surface, whereas in models with temperature-dependent viscosity, it accumulates under the rigid lithosphere.

U54A-02 1545h INVITED

Estimates of Water Concentrations in the Mantle

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This talk will review estimates of mantle water concentrations as determined by studies of mantle-derived melts. A major uncertainty in the earth's water cycle is the effect of subduction and recycling of hydrated lithosphere on deep mantle water concentrations. There is general agreement that the earth accreted "wet" and that post-accretion influx of water to Earth from comets is limited to <∼20%. A minimum value of ∼1000 ppm H_2O in the primitive mantle can be estimated by adding exosphere water (ocean, atmosphere, and crust) to the depleted mantle, assuming that this water comes from degassing of half the mantle and that the depleted mantle has ∼100 ppm H_2O. Lower values of primitive mantle water (330 ppm for the Pacific and 430 ppm for the north Atlantic) are obtained by calculating the value required to produce a smooth depletion trend for highly incompatible elements in MORB. A similar phenomenon noted for Pb has been interpreted as preferential partitioning of Pb into the exosphere during subduction. I suggest that the same is true for water. Water concentrations in various mantle end-member components support this hypothesis. Mantle plumes enriched in recycled lithosphere (EM1, EM2, LOMU, and HIMU; H_2O/Ce<=100) have lower ratios of water to similarly incompatible elements than plumes dominated by the common plume component (FOZO; H_2O /Ce=210 to 300). High H_2O /Ce in FOZO plumes cannot be derived from recycled lithosphere; therefore, a significant amount of water must be juvenile, left over from planetary accretion. Thus, dehydration during subduction effectively partitions water into the exosphere (mantle wedge, crust, ocean, atmosphere) resulting in time-integrated depletion of water relative to other incompatible elements in recycled (deeply subducted) lithosphere and sediments and, ultimately, the majority of the mantle. Entrainment of hydrated suprasubduction zone mantle (0.025 to ∼2 wt% H_2O) may lead to water enrichments in the upper ∼400 km, as evidenced by seismic tomography. Mantle below this depth is likely to be quite dry (<0.08 wt%), regardless of the existence of high pressure hydrous phases observed in laboratory studies.

U54A-03 1605h INVITED

Lateral Variation in Upper Mantle Viscosity: Role of Water

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Differences in the viscosity of the earth's upper mantle beneath the western US (10 18-10 19 Pa-s) and global average values based on glacial isostatic adjustment and other data (10 20-10 21 Pa-s) are generally ascribed to differences in temperature. We compile geochemical data on the water contents of western US lavas and mantle xenoliths, compare these data to water solubility in olivine, and calculate the corresponding effective viscosity of olivine, the major constituent of the upper mantle, using a power law creep rheological model. These data and calculations suggest that the low viscosities of the western US upper mantle reflect the combined effect of high temperature and high water concentration. Our model is compatible with temperature estimates in the western US based on P-wave seismic tomography, but not with S-wave seismic tomography, suggesting that the latter could be biased to high values by the presence of fluid and/or partial melt. The high water content of the western US upper mantle may reflect the long history of Farallon plate subduction, including flat slab subduction, which effectively advected water into the upper mantle as far inland as the Colorado Plateau.

U54A-04 1625h INVITED

Seismic Attenuation Constraints on Temperature and Water Content of the Mantle Wedge

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TThe mantle wedge in subduction zones produces arc volcanism, receives devolatilized fluids from subducting slabs, and controls the coupling between the earth's surface and descending plates. Still, few constraints exist on either its temperature (T) or water content, which together control melting and wedge viscosity. We show here new advances in the use of