

the average composition of the matrix in the DM, which consists of small length-scale subreservoirs (<15km). Thus, FOZO is not the lower mantle, there is no need for revision of the size of the DM, and it is still possible to have an Earth with a chondritic Sm/Nd ratio. Our model, which allows both for averaging of source heterogeneities during sampling as well as homogenization of source heterogeneities owing to mantle mixing through time, yields a new understanding of the isotopic variability in ocean basalts.

U51A-03 0920h INVITED

Recent progress and future challenges in mineral physics

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Unraveling the physical behavior of earth materials at mantle and core conditions remains a major challenge and pre-occupation of mineral physics. This endeavor has had an important impact on our understanding of Earth's thermal structure, chemical composition, origins, evolution, and dynamics. A review of recent progress revolves around three themes: 1) our increasingly sophisticated ability to interpret seismological observations in terms of spatial variations in temperature, composition, and phase 2) the discovery of unanticipated material behavior at extreme conditions and their possible impacts on seismological and geodynamical models and 3) the prospects for constructing "mineralogical" earth models that are largely independent of and complementary to geodynamical and seismological earth models. Progress in mineral physics continues to be driven by rapid technological advances in our ability to generate and control extreme conditions in the laboratory, to probe samples under these conditions with a rapidly expanding array of probes, and to predict material behavior from first principles quantum mechanical calculations. We argue that continued progress in our understanding of earth will require, in addition to the characterization of individual mantle and core phases, a new generation of semi-empirical thermodynamic models of the mantle that encompass the essential multiphase equilibria and physical properties. The study of non-equilibrium properties remains a major challenge for a number of reasons, the most fundamental of which is that they depend on a far greater number of variables than do equilibrium properties. Our current knowledge of attenuation and its possible relationship to viscosity is highlighted as an area where fundamental questions remain.

U51A-04 0945h INVITED

Seismic Anisotropy and Global Geodynamics

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For many years, seismic anisotropy was often neglected, mostly because of the inherent heavy mathematical and computational tools needed to describe and model its effects on seismic waves. However, it is not a second order effect and it turns out that it is a good marker of large scale deformations. Seismic anisotropy is reflecting some inherent organization of the matter, contrarily to isotropy. The uppermost mantle down to 410 km is the depth range where the existence of seismic anisotropy is now widely recognized and well documented. Azimuthal variations have been found for body waves and surface waves in different areas of the world. The application of seismic anisotropy to geodynamics in the upper mantle is straightforward, if we assume that fast-polarization axis of mineralogical assemblages (primarily of α -olivine) is in the flow plane parallel to the direction of flow. Seismic anisotropy in the mantle is therefore reflecting the strain field prevailing in past (frozen-in anisotropy) for shallow layers or present convective processes in deeper layers. From the global geodynamics point of view, seismic anisotropy makes it possible to define the root of continents and to investigate the coupling between the lithosphere and the rest of the mantle and more generally to gain insight into mantle convection. Oceans are the areas where Plate tectonics applies almost perfectly. In the Pacific ocean, the map of the azimuthal anisotropy at 100 km shows that it is very large along spreading ridges with a large asymmetry for the East Pacific rise. The direction of anisotropy is in very good agreement with plate motion. The anisotropy is large as well in the middle of the Pacific plate, but it can be observed that there is a line of very small azimuthal anisotropy almost parallel to the EPR and another one between EPR and Tonga-Kermadec subduction zone. These linear areas of small anisotropy were coined Low Anisotropy Channel by Montagner (EPSL, 2002). They are presumably related to cracking within the Pacific plate and/or to secondary convection within and below the rigid lithosphere, predicted by numerical and analog experiments.

These new features provide strong constraints on the decoupling between the plate and asthenosphere. The existence and location of these LACs might be related to the current active volcanoes and hotspots (possibly plumes) in Central Pacific. LACs, which are dividing the Pacific Plate into smaller units, might indicate a future reorganization of plates with ridge migrations in the Pacific Ocean. Below continental lithosphere, it is also observed significant azimuthal anisotropy which is reflecting asthenospheric flow. Some recent results beneath the eastern Africa will be presented and also show that this flow is highly perturbed by the presence of the Afar hotspot upwelling and might induce upwellings (with babyplumes) and downwellings at large distance (several thousands kilometers) from Afar. For filling the gap between grain scale modeling and large scale anisotropy measurements, there is now a real need for making more quantitative comparisons between seismic anisotropy and numerical modeling. Gaboriet al. (EPSL, 2003) calculated the convective circulation in the mantle by converting perturbations of S-wave velocity into density perturbations. This kind of modeling enables to calculate the strain tensor and to test different hypotheses for the prevailing mechanisms of alignment, by comparison with anisotropic seismic data. In conclusion, the scientific potential of seismic anisotropy is enormous and largely unexploited. It provides a new dimension in the investigation of processes of our dynamic Earth.

U52A CC: 517 A Friday 1030h

Frontiers and Challenges in Deep Earth Dynamics II

Presiding: A M Forte, Universit du Qubec Montral; G A Houseman, University of Leeds

U52A-01 1030h

A New Three Dimensional Spherical Model of the Mantle General Circulation

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We describe a new Navier-Stokes solver for modeling convection in the Earth's mantle that supports three-dimensional spherical geometry, a choice of Dirichlet and Neumann boundary conditions, discontinuities in background density and viscosity, and lateral variations in viscosity. The solver is based on a finite volume formulation with collocated pressure and velocity. Spectral methods, used in simulations of the mantle by Glatzmaier in [1], were not selected because they were not well-suited to handling viscosity fields with arbitrary spatial dependence. Finite element methods, used by Baumgardner in [2], were not selected because the assembly of discretized equations is simpler under finite volume; this is important when the viscosity field changes over time due to temperature dependence. The numerical grid is based on the projection of an icosahedron onto the sphere. On this basis, we have developed a number of techniques for evaluating derivatives required by finite volume discretization as well as a data structure for representing quantities that exhibit discontinuities at certain depths. The new solver has been used to compute the pressure, velocity, and stress fields arising from a density heterogeneity model delivered by seismic tomography. When the viscosity is a function of radius only, we present comparisons of the pattern of geoid anomalies predicted by the solver to that from an independent code based on generalized spherical harmonics by Pari and Peltier [3]. [1] Glatzmaier, G. A., GAFD 43, p. 223 [2] Baumgardner, J. R., J. Statistical Physics 39(5-6), p. 501 [3] Pari, G. & W. R. Peltier, JGR 100 #B7, p. 12,731

U52A-02 1050h

Coupling numerical models of mantle convection with energy and entropy balance models in the core: Implications for the evolution of the Earth's core and magnetic field

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Recent studies of energy and entropy balances in the core constrain the power requirements for magnetic field generation and the age of the inner core (e.g. Buffett, 2002, Labrosse et al., 2001, Labrosse, 2003, Nimmo et al., 2004). These studies suggest that the change of entropy in the core needs to be positive during the entire period the geodynamo operated. The geodynamo efficiency is determined by the redistribution of heat and mass in the core and is ultimately controlled by the rate at which the mantle removes heat from the core. In the previous analyses the heat flow at the core-mantle boundary was either prescribed or determined from parameterized schemes of mantle convection. We couple heat flows predicted by numerical models of mantle convection with energy and entropy balance models to determine the age of the inner core and the available power to drive the dynamo. The entropy and energy balances are studied for various degrees of layering in the mantle and highly temperature dependent mantle rheology. In addition, we explore the consequences different rates of internal heating in the core and mantle have on the thermal and magnetic evolution of the Earth and its core.

U52A-03 1110h

Superplumes and the Viscosity Structure of the Mantle

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Seismological studies indicate the existence of large upwelling regions of complex structures in the lower mantle. A mantle flow model with only a few strong upwellings is an alternative to conventional convection models with respect not only to pattern of the flow but also to heat transport and mixing properties. By two- and three-dimensional numerical models we demonstrate that a significant increase of the viscosity with pressure in the lower mantle leads to a focusing of buoyancy into strong upwellings from the core-mantle boundary. This phenomenon is further enhanced by a thermal expansion coefficient which decreases with pressure. Besides pressure, the viscosity of the mantle material will strongly depend on temperature. Combining the effects of temperature and pressure-dependent viscosity, generates a significant viscosity maximum in the lower mantle. Pressure dependence let the viscosity increase from the upper to the lower mantle, temperature dependence, however, compensates this effect at greater depth. The spatiotemporal evolution of plumes is likewise influenced: While a purely pressure-dependent viscosity creates single plumes, additional temperature dependence leads to plume-clusters, characterized by instabilities at the core-mantle boundary, which are centered around a strong upwelling flow. These plumes generate a complex flow pattern at the base of the mantle.

U52A-04 1130h

Apparent Polar Wander of the Pacific Plate and Pacific Hotspots: Implications for True Polar Wander and Hotspot Fixity

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Whether the apparent polar wander (APW) path of the Indo-Atlantic hotspots is a record of true polar wander could be tested from a detailed APW path of the Pacific plate, the motion of which can be estimated relative to the hotspots independently of reconstructions in the Atlantic and Indian Ocean basins. Such an APW path has previously been lacking because of the difficulty in obtaining fully oriented paleomagnetic samples from oceanic plates. We present an APW path for the Pacific plate and for the hotspots of the Pacific basin. Our Pacific plate APW path from 125 Ma to the present is based mainly on the analysis of the skewness of marine magnetic anomalies due to seafloor spreading and is determined with better accuracy and resolution from 32 Ma to 81 Ma than is the APW path of any continent. Our path is defined by eleven paleomagnetic poles from non-overlapping age windows. Nine of these

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 paleolatitude 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 Semai 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_{H_2O} ; 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_{H_2O} , 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 than 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, H₂O 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 H₂O 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 pyrolytic composition with 0.5 to 1.0 percent by weight H₂O, but not consistent with dry pyrolytic 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 P₂₁/c to C₂/c high-pressure phase transition in MgSiO₃-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 H₂O. 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 P₂₁/c low-clinoenstatite (LCEN) to the high-density C₂/c HCEN in situ. A single crystal of dry MgSiO₃ LCEN was placed adjacent to a second crystal of LCEN containing approximately 500 wt ppm H₂O 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 P₂₁/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.