high crossing the mapped trace of the Calaveras Fault on the western edge of the San Ramon Valley, near Crow Canyon. This anomaly is associated with Miocene Neroly Sandstone that outcrops west of the fault in the Las Trampas Ridge Anticline, suggesting that the sandstone is continuos without appreciable offset across the mapped fault trace into the subsurface of San Ramon Valley. Therefore, Neogene offset on the NCF must terminate at or south of the latitude of Crow Canyon, and slip previously inferred for the NCF must be assigned to other structures in the region. The amount of slip previously assigned to the NCF varies between 28 km and 80 km. Recent palinspastic reconstructions (Graymer and others, 2002) indicate that most of the right-slip offset is taken up by the Palomares-Miller Creek-Moraga-Pinole fault system to the west. Others (Unruh and Lettis, 1998) suggest that slip is transferred from the NCF by means of multiple folds and small displacement faults west of the Calaveras Fault. The 2003 Working Group on California Earthquake Probabilities suggests that slip on the NCF is transferred across the Mt. Diablo antiform onto the Concord Fault. This transfer of slip would be a right step in a right lateral system, which should produce extensional features at this step. However, only compressional structures exist between the NCF and Concord Fault. The lack of extension at this right step, combined with little or no late Neogene offset on the NCF indicate that the proposed Concord-NCF right step is either a very young tectonic element or does not exist at all.

T21A MCC: 3007 Tuesday 0800h

New Views of the Structure and Composition of the Deep Earth II

(joint with GP, S, V, MR, DI)

Presiding: **D L Farber,** Lawrence Livermore National Laboratory**; J Badro,** University Paris VI - Institut de Physique du Globe

T21A-01 0800h

Tangent Cylinder within the Outer Core and the Constraints from Normal-Mode Data

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Recently, the tangent cylinder within the outer core has received a renewed interest as a structure that may explain observations of seismic waves travelling through the core. This is an important issue, not only because seismically detectible heterogeneity within the outer core has implications to its dynamics, but also because inferences of inner core anisotropy depends upon outer core structure. Instead of using travel time measurements, we rely mainly upon normal-mode splitting data to investigate the velocity and density difference between regions within and without the tangent cylinder. The lateral heterogeneity within the Earth, such as the tangent cylinder, is observed in seismic spectra as the splitting of normal-mode resonance peaks. Because isolated modes are standing waves, splitting measurements of these modes are only sensitive to even-degree structure. This limitation does not affect the investigation of the tangent cylinder, since this structure consists only of spherical harmonics at even degrees. In addition, biasing of data due to uneven coverage is less prominent in splitting data than in travel-time measurements, hence the normal-mode data are better suited to study large-scale structure. The normal-mode data are divided into subsets based upon their sensitivity to different parts of the Earth. Inversions of these data sets with various model parametrisations are performed to obtain and test the robustness of the strength of the tangent cylinder. The resulting ranges of velocity and density heterogeneity within the cylinder are then used to analyse the effects on travel-time measurements and on inner-core anisotropy.

T21A-02 0815h

Upper Mantle and Transition Zone Geochemical Heterogeneity: Seismic Constraints on the 80% Peridotite Solution

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The size of mantle geochemical heterogeneities spans from the length-scale of grains to the thousands of km lateral length-scales associated with subducted slabs. Grain-scale heterogeneities are difficult to probe remotely, while the large-scale heterogeneities associated with recent subduction have been extensively investigated. At intermediate length-scales, observational evidence is accumulating that abundant mantle heterogeneities exist in the 10 to 100 km size range: such sizes of heterogeneity may be associated with either moderately stirred ancient subduction, or with regional magmatic events. The ability to seismically detect such intermediate-sized features hinges on their type of mineralogic heterogeneity, and thus the velocity- or impedance-contrasts of such regions with the normal background of upper mantle peridotite. Two distinct types of mineralogic heterogeneity can be seismically detected in the upper mantle: (1) assemblages bearing free silica, such as occurs in many eclogites at pressures above about 2 GPa; and (2) at depths less than 300 km, highly garnet-enriched assemblages. Abundant amounts of eclogite can be detected through the observation of seismic discontinuities generated by phase transitions within their silica component: such eclogite could be generated through remixing of subducted oceanic crust or delamination of basaltic lower crust. At depths less than 300 km, garnet-rich zones have substantially higher seismic velocities than those of coexisting peridotite: such garnetite zones may be generated by magmatic processes, and have been documented to occur beneath the Pitcairn hot-spot chain. In the case of both silica and garnet-enrichment, seismic observations indicate that, within different geodynamic environments, geochemical heterogeneities can be detected at the 10 to 100 km length scale. Such detections provide critical constraints on regional deviations from a peridotite-only mantle, and thus on the nature and length-scale of mantle heterogeneity.

T21A-03 0830h

Large Scale Anisotropy in D" from Global Waveform Inversion

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The Earth's core-mantle boundary is both a thermal and chemical boundary layer between the silicate mantle and the fluid iron outer core. The mantle-side region (D") is also a mechanical boundary layer for the convection of the mantle, leading to intense deformation. This strain field can lead to detectable seismic anisotropy, either through the alignment of anisotropic crystals or of layers (or inclusions) of materials with strongly contrasting elastic properties (Karato, 1998; Kendall and Silver, 1996). Anisotropy in D" is observed in several regions using Sdiff or ScS (Vinnik et al., 1989; Kendall and Silver, 1996; Lay et al., 1998). However, these studies only sample limited areas of D". A global picture of long-wavelength anisotropic D" structure would clearly aid both dynamic flow modeling and mineral physics interpretations. Therefore, we have adapted a global tomography approach (Li and Romanowicz, 1996) to develop a 3D global model of mantle radial anisotropy using three component time-domain waveforms of surface and body waves. The model is parameterized by isotropic V_S and ξ ($\xi = V_{SH}^2/V_{SV}^2$), a measurement of radial anisotropy in shear velocity. In our model, D" is characterized by a strong degree 0 signature of positive $\delta \ln \xi$ ($V_{SH} > V_{SV}$), similar to the uppermost mantle in previous anisotropic models such as PREM. The 3D isotropic velocity imaged in D" is consistent with earlier tomographic models of V_S in this depth range (Masters et al., 1996; Mégnin and Romanowicz, 2000), and is characterized by a strong degree 2 component representing a fast ring surrounding two low velocity features ("superplumes") beneath the central Pacific and Africa. For ξ in D", the degree 0 component dominates, but the regions that deviate most from this structure correlate well with the locations of the superplumes. We see reduced $\delta \ln \xi$ under the central Pacific, Africa, and the south Atlantic, including patches with negative values ($V_{SV} > V_{SH}$). The observed anisotropy in D" is consistent with a boundary layer dominated by horizontal flow, while emphasizing the unique character of the two superplume regions. Our results also suggest similar relationships between anisotropic signature and flow prevail in the uppermost and lowermost mantle.

T21A-04 0845h INVITED

Extreme Short Scale Variations in D" Topography Beneath the Pacific Ocean Just West of Central America

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In this study we use a wavefield migration technique to infer D" reflectance and topography in a densely sampled region just west of Central America beneath the Cocos plate. High quality broadband waveforms from seismic networks in California of 13 deep focus South American earthquakes are instrument and source wavelet deconvolved to displacement, aligned on ScS as a reference phase, then studied for coherency of energy between ScS and S. A search for potential lowermost mantle reflector locations is achieved by migrating the wavefield for each earthquake to each node of a 3D grid of potential reflector locations, with spacing every 1 deg laterally and 10 km vertically (with ranges: -2 to 18 deg N; -100 to -80 deg E, 2200 to 2888 km depth). Grouping our data into densely sampled latitudinal bins resulted in 41 clusters of bounce points between 0 and 15 deg N. The migrated images for all bounce point clusters show an abrupt increase in velocity that is thickest to the north in our study area (up to 300 km and greater) and dramatically reduces to as thin as 100 km thick in the south. We also see evidence for the main positive velocity increase being underlain by a negative velocity discontinuity in the northern half of our study region, though this feature is not visible in all migrations. These results are compatible with the general picture from simpler 1D studies (which indicate a thicker high velocity D" layer to the north beneath the neighboring Central American and Caribbean than that to the south) but demonstrate increased complexity at shorter scale lengths. The thickening of the D" layer to the north coincides with inference for higher velocities there implied by ScS-S and S-SKS differential travel time residuals. Evidence for out of plane reflections is also visible in some migrated images. Such strong topographical variations (200 km change over several hundred km laterally) are likely intimately coupled to overlying mantle currents related to subduction, such as localized flow complexities or being near the edge of a larger scale downwelling. These results, including the less well-constrained mid-D" velocity decrease, will be compared to larger scale velocity heterogeneity and gradients as inferred from tomography, as well as recent ultra-low velocity zone results.

URL: http://garnero.asu.edu/research/earthslowermantle.html

T21A-05 0900h

Phase relations and phase transformation kinetics of the subducted oceanic crust and the seismic reflectors in the lower mantle

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We determined phase relations in dry and hydrous mid-ocean ridge basalt (MORB) at high pressure and temperature by in situ X-ray diffraction study together with conventional quenching experiments. In the lower temperature range around 1000-1100C at 20-30 GPa, we observed CaMg-cubic perovskite phase both under the dry and wet conditions. However, quenching experiments with a long duration revealed that the cubic perovskite is metastable, and it eventually decomposes into two perovskites. The metastable cubic perovskite might exist in the cold slabs. The phase boundary of the perovskite appearance in the wet MORB has a positive slope, and is about 1 GPa lower than that in the dry MORB (Hirose and Fei, 1998). The results presented above suggest that water can play an important role in slab dynamics near the 660 km discontinuity. The density relations between the basalt and peridotite implies that there is no density crossover between the basalt and the underlying peridotite layers in the wet slabs along the cold slab geotherm, resulting in higher density of the basalt layer throughout the transition zone and the lower mantle compared to the peridotite portion of the slabs. Thus, the hydrated slabs

can penetrate effectively into the lower mantle. We also conducted a kinetics study of garnet-postgarnet transformation (Kubo et al., Nature, 2002), and found that the transformation rate is sluggish resulting in metasltable garnet in the dry and cold oceanic crust. On the other hand, our experiments on the in situ X-ray diffraction in MORB indicated that water enhances the reaction kinetics significantly. Therefore, the garnet-postgarnet transformation completes in the wet and cold subducted slabs. Recently, the seismic reflectors have been reported in the upper part of the lower mantle (e.g., Kaneshima and Helfflich, 1998; Niu et al., 2002). The seismic reflectors might be explained by the subducted oceanic crust in the lower mantle. Niu et al. (2002) reported that the seismic reflectors have characteristic properties, i.e., an increase in the density, nearly constant Vp, and a decrease of Vs in the reflectors. Recent mineral physics data on high pressure minerals in the oceanic crust including NAL phase and CF phase (Ono, 2002; Vanpeteghem et al, 2003) may provide information on the state of the oceanic crust in the lower mantle. Our preliminary analysis suggests that the change in physical properties of the seismic reflectors can not be accounted for by a simple chemical change from the lower mantle peridotite to the oceanic crust of the perovskite lithology with or without metastable garnet. Additional mechanisms are needed to explain a decrease of Vs in reflectors suggesting anelastic effects such as a possible existence of fluid or melt.

T21A-06 0915h INVITED

A watered-down primordial lower mantle

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For more than a decade, conflicting evidence between seismic tomography and isotope geochemistry of rare gases has thwarted the construction of a unifying convection model and blurred our vision of lower mantle chemistry and mineralogy. All body wave models vividly depict lithospheric plates penetrating the 660 km discontinuity such as the Farallon and the Tethyan plates. In contrast, the presence of helium with a high $^{3}He/^{4}He$ ratio and, even more, of solar neon in OIB attests to the presence of undegassed material at depth. Current models of tracer redistribution by convection do not resolve this conflict and are limited to the description a whole range of regimes with variable extent of layering. We addressed this problem through the residence time distribution theory, which shows that the time different parcels of mantle survive extraction and degassing from a well-stirred mantle is exponentially distributed. Whole mantle mixing only destroys the primitive signature of the average lower mantle (at the scale of the global reservoir) but leaves some small parcels untouched since terrestrial accretion. From available isotopic data, we assess that the lower part of a unhindered convective mantle may contain several percent primordial material. If the 660 km discontinuity is a partial hindrance to vertical mixing, this proportion is significantly higher. The most likely texture of the lower mantle is an intricate layering of material recycled from the surface and primordial material while its chemical composition is geochemically enriched with respect to the upper mantle. This simple concept accounts for the coexistence of the primordial character of rare gases, the recycled character of lithophile-element isotope compositions in OIB, the apparent lack of ^{142}Nd anomalies, and the missing component inferred from a number of geochemical systems. The marble cake incorporates different ingredients at different depths: mostly residual mantle and recycled oceanic crust at the top and more oceanic plateaus and primordial material at the bottom.

T21A-07 0930h

High-Pressure Brillouin Measurements on Single-Crystal Ferropericlase, (Mg0.94Fe0.06)O: Implications for Earth's Lower Mantle

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The determination of accurate compositional models of Earth's interior from observed seismological data requires knowledge of the elastic properties of candidate phases under conditions approaching those of Earth's interior. Ferropericlase, (Mg,Fe)O, is expected to coexist with silicate perovskite in Earth's lower mantle (660 C 2900 km depth), and will therefore have a major influence on all properties in this region of the Earth. However, the effect of iron on the single-crystal elasticity of MgO at high-pressures is still poorly constrained. In this contribution, we present the single-crystal elastic properties of ferropericlase, $(Mg_{0.94}Fe_{0.06})O$ [hereafter referred to as Fe6], measured by Brillouin scattering on a sample compressed to 13.3(4) GPa with a diamond anvil cell. Within the uncertainties, we find that at room-pressure the bulk modulus of Fe6 is unchanged from MgO, but that the shear modulus of Fe6 is about 7% less than that of MgO. Furthermore, the elastic anisotropy of Fe6 is about 10% greater than that of MgO at room-pressure, in excellent agreement with results obtained using gigahertz ultrasonic interferometry on the same sample [1]. Our measurements also allow us to assess the effect of iron on the pressure derivatives of the sound velocities and elastic moduli of MgO. Results indicate that 6 mol% Fe in MgO does not significantly affect the pressure derivatives of the aggregate elastic properties of ferropericlase compared to MgO. At the highest pressure obtained in this experiment, the elastic anisotropy of Fe6 is close to that of MgO. In light of these new high-pressure measurements on Fe6 and other recent measurements on Al-bearing $MgSiO_3$ perovskite [2], implications for the mineralogy of Earth's lower mantle will be discussed. *References:* [1] S.D. Jacobsen *et al.* (2002) J. Geophys. Res., 107, 2001JB000490 [2] J.M. Jackson *et al.* (2003) Geophys. Res. Abstr., 5, EGS-AGU-EUG Joint Assembly, France, EAE03-A-12122.

T21A-08 0945h

Compositional Effects of Trace Element Partitioning Between Mg-Silicate Perovskite and Silicate Melt

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Models for the accretion of the Earth propose the existence of a deep magma ocean that may have extended to depths corresponding to the present day lower mantle. Crystallization and fractionation of such a deep magma ocean could lead to chemical differentiation and stratification within the Earth. While it seems that the upper part of Earth's mantle has been rehomogenized by subsequent mantle convection it is possible that chemical layering may have survived in the lower mantle causing a chemical and geophysical signature. In this study we present new experimental data on trace element partitioning between Mg-silicate perovskite (Mg-pv) with various compositions and coexisting silicate melt. High pressure melting experiments have been performed in Re and graphite containers in a multi-anvil apparatus between 25-27 GPa and temperatures up to 2573 K. Starting materials were synthetic pyrolite compositions with varying aluminum contents and a CI chondrite model composition, both doped with a selection of trace elements at the 100-500 ppm concentration level. Trace elements in crystals and quenched melt were analyzed by secondary ion mass spectroscopy. Mg-pv is found to have an affinity for four-valent high field strength elements (Ti, Zr, Hf) with a tendency for higher mineral-melt partition coefficients ($D^{Mgpv/melt}$) with increasing Al content of the solid phase. Large ion lithophile elements (LILE) and rare earth elements (REE's) are found to be incompatible in Mg-pv except for Lu for which the $D^{Mgpv/melt}$ value also increases with increasing Al content. We consider possible effects on the crystal chemistry of Mg-silicate perovskite as a function of major element concentration and discuss the question to what extend perovskite fractionation into a hidden reservoir in the deep mantle could have occurred without disturbing chondritic element ratios preserved in the residual upper mantle

T21B MCC: 3005 Tuesday 0800h

Development of Fault Systems Through Time: Process and Rates I

Presiding: **J M Bull,** Southampton Oceanography Centre**; P Cowie,** Edinburgh University

T21B-01 0805h INVITED

Fault and Rift evolution - All Features Great and Small

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It has been recognised for some time that oceanic ridges propagate and that the process involves the transfer and concentration of stored elastic energy to the site where new rift is being created. Together with flexure associated with volcano loading and subduction, the evidence that oceanic lithosphere has long-term elastic strength seems convincing. Data demonstrating long-term strength and propagation-like behaviour for continental lithosphere has taken longer to collect. For the Gulf of Aden and two major faults (the Altyn Tagh and North Anatolian faults) the evidence now appears to be convincing. Over periods of many millions of years these fault have evolved in a way most simply explained if the continental lithosphere, like that of the oceans, is elastic overall. However, while the propagation of continental faulting or rifting is similar to that observed in engineering materials, there are important differences. A central tenant of traditional fracture mechanics is that big cracks grow at the expense of smaller ones, which therefore are unimportant. This is not true for the Earth, as demonstrated by the scale distribution of faults and earthquakes. Damage or breakdown zones also appear to be larger than those in engineering materials and to scale with the length of the associated fault. Finally, unmodified concepts of Critical Stress Intensity Factor cannot applied to the evolution of faulting in the Earth. Recent studies of long-term fault growth sheds new light on this problem. The cumulative slip profiles of such faults appear to be triangular and can only be explained by the development of large damage zones off the main fault, that incorporate macro- rather than micro-scale fissuring. Such triangular faults or cracks cannot behave like elliptical (or modified elliptical) ones since the stress intensity factor at their tips is zero. Hence, large faults are not favored with respect to small ones, and in the absence of interactions, all faults are equally likely to extend. Although these faults do extend, this consists of a process of linkage. The highly irregular slip profiles of long-term faults is consistent with this view.

T21B-02 0825h

Controls on Growth Rates of Normal Faults

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A recent model of fault growth suggests that many faults establish their lengths rapidly and for much of the duration of deformation grow principally by the accumulation of displacement. For faults consistent with this model we investigate the factors controlling displacement rates and average recurrence intervals using the lengths and displacement rates for 274 normal faults from 4 extensional regions. Our analysis of the evolution of fault systems on geological time scales (i.e. 60 kyr to 7 Myr) suggests a broad positive correlation