an inland fault in Hispaniola is explained by different stress distributions in the forearc of the two segments due to the change from oblique slip on the subduction interface in Puerto Rico to dip slip in Hispaniola. The observations and modeling suggest that seismic hazard to Puerto Rico from oblique subduction and from subduction-induced forearc strike-slip earthquakes is much smaller than previously assumed, but hazard to Hispaniola remains high.

T42D MCC: 3007 Thursday 1340h

Deformation Mechanisms: From the Lab to the Lithosphere II *(joint with V, MR)*

Presiding: **I Katayama,** Yale University**; D L Goldsby,** Brown University

T42D-01 1340h

Viscosity of a molten mantle: experimental data for liquid peridotite.

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The debate surrounding Earth evolution accompanied by a largely molten magma is increasingly reliant on the results of models for physico-chemical processes in such a scenario. To date, the primary emphasis in the physical characterisation of molten peridotite has been the determination of a PVT equation of state with contributions from shock-wave and buoyancy studies. Determinations or other melt properties are largely lacking. The viscosity, in particular, has received too little attention. Here, the Newtonian viscosity of molten peridotite has been determined experimentally at superliquidus and supercooled conditions. The high temperature determinations were obtained using a concentric cylinder technique employing constant high-speed deformation. The low temperature determinations have been obtained from the analysis of the glass transition in scanning calorimetric traces and conversion via published shift factors into viscosity data. These latter measurements were made possible by the experimental synthesis of peridotite glass using a splat-quenching device. Taken together the superliquidus and supercooled data provide the first quantitative description of the viscosity of molten peridotite. The temperature-dependence of the viscosity of molten peridotite is extremely non-Arrhenian. As a result, molten peridotite, despite having an extremely low viscosity near its liquidus temperature, exhibits a very high glass transition temperature. The extrapolation of viscosity in terms of temperature is of central importance to the application of these data to nature. The viscosity data presented here cover over 12 log units of viscosity and 800K. As a result, this data set provides a robust basis for the extrapolation of melt viscosity to the even higher temperatures expected to exist where molten peridotite is or was present in the mantle. Further influences on the viscosity of peridotite, such as volatiles and pressure, are expected to play a relatively minor role. Extrapolated values of these peridotite viscosity data are compared with those estimated for non-silicate liquids at pressure-temperature conditions for a molten mantle in the Earth.

T42D-02 1355h

Effects of Temperature and Water on Deformation Microstructures of Olivine

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Recent studies in our laboratory have shown that water and stress have important effects on deformation microstructures of olivine including lattice preferred orientation and recrystallized grain-size (Jung and Karato, 2001a,b). These findings provide us with different interpretations of the geodynamic significance of seismic anisotropy, particularly in subduction zones. However, these initial studies were limited to a narrow temperature range (~1500-1600K). Theoretical considerations suggest that in addition to water content and stress, temperature is likely to modify these microstructures. Temperatures in some parts of subduction zone upper mantle are likely significantly lower than ~1500 K. Consequently, it is crucial to extend these previous studies to lower temperatures and compare these results with microstructures of naturally deformed peridotites from collision zones which were likely deformed at low temperature conditions. We conduct deformation experiments in simple shear at lower-temperature (to 1273 K). An olivine single crystal was sandwiched between alumina pistons cut at 45^o from the compression direction, and surrounded by a mixture of talc and brucite that acts as a water source. Shear strain was measured by the rotation of a strain marker, and the microstructures of olivine samples were investigated by a scanning electron microscope with an electron backscatter diffraction (EBSD) technique. Even at a temperature as low as ~1273 K, samples were totally recrystallized at small strain (~0.8). The recrystallized olivine grains show a fabric which is different from any of the known fabrics. We tentatively interpret this as caused by the combination of inherited fabric and deformation- (+ recrystalllization-) induced fabric involving the activity of the b=[001]. The details of fabrics and its variation with temperature, stress and water content will be reported together with a comparison with the fabrics in naturally deformed peridotites under low temperature (and "wet" ?) conditions.

T42D-03 1410h

Dislocation Microstructures in Deformed Olivine Displaying the C-type and B-type Fabrics

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Because seismic anisotropy in the upper mantle is commonly a result of lattice preferred orientations (LPOs) of minerals as a result of mantle flow, seismic anisotropy is used to probe fabrics and therefore flow directions in the mantle. Jung and Karato, (2001) have shown that the fabrics developed in experimentally deformed olivine are dependent on H2O fugacity and stress, suggesting that olivine fabric in the upper mantle can provide a means of probing H2O content and stress. Olivine fabrics, known as B-type and C-type, occur in olivine deformed under high H2O fugacity and high stress. In order to extrapolate these experimental deformation fabrics to the mantle, one must understand how H2O changes the mechanisms of plastic deformation in olivine. Experimentally deformed olivine samples with C-type and B-type fabrics have been examined by TEM to determine dislocation microstructures, core structures and active slip systems. In the C-type sample, we examined a relatively large olivine grain with its b axis normal to the TEM foil and the a and b axes approximately 45^o from the slip direction. Tilt boundaries along (100) and (001), consisting of edge dislocations with b = [100] and b = [001], respectively, indicate that the dominant slip systems are (001)[100] and (100)[001]. HRTEM imaging of the b = [100] and b = [001] edge dislocations along [010] shows no dissociation for b = [100], whereas the b = [001] dislocations are dissociated into 1/2[-101] and 1/2 [101] partial dislocations separated by 3 nm along the (-101) plane. The C-type fabric, which occurs in wet olivine deformed at low stress, results from the domination of the (100)[001] slip system over the (010)[100] slip system that produces the A-type fabric. Based on the abundance of b = [001] edge dislocations, we infer that the presence of hydrogen in olivine reduces Peierls stresses for glide of b = [001] screw dislocations in (100). The more complicated microstructures in the B-type sample will be presented at the meeting.

T42D-04 1425h

Effect of Mineral Reaction on the Deformation of Plagioclase-Olivine Aggregates

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There have been many studies that have described the relative timing of deformation and metamorphism in natural rocks, but there are few studies that have analysed the interrelationship of the processes that produce simultaneous deformation and chemical reactions. We studied the physical and microstructural relationships between the processes of deformation and chemical reaction by performing simple shear deformation experiments on plagioclase-olivine aggregates. Our study shows that deformation and reaction processes are strongly related by a mutual positive feedback, and point out possible mechanisms for shear localization in the upper mantle lithosphere during subduction and extension. Shear deformation experiments were carried out on dry plagioclase-olivine mixtures (4-10 μm grain sizes, ±50-50 vol.% olivine-plagioclase ratio) in a Griggs apparatus under a constant applied shear strain rate of $\sim 5*10^{-5}s^{-1}$ at 900°C and 1.0-1.6 GPa confining pressures. We have studied the plagioclase-olivine deformation in presence and absence of reaction by choosing plagioclase to be of labradorite (An60) and anorthite (An92) composition. At 1.0-1.6 GPa confining pressures, the anorthite-olivine samples react to spinel-pyroxene bearing assemblages, whereas the labradorite-olivine samples do not. Labradorite and anorthite are expected to have fairly similar deformation behaviour. *Effect of reaction on deformation:*
In the absence of reaction, labradorite-olivine mixtures are so strong at the chosen experimental conditions that they hardly deform plastically. In contrast, anorthite-olivine mixtures deformed at the same temperature and strain rate react during deformation, producing a stress maximum (~375 MPa) followed by a significant stress decrease. Regardless of the chosen confining pressure, reacting samples commonly weaken towards a shear stress of ~275 MPa. The plagioclase-olivine reaction strongly reduces the grain size of the samples (down to 0.1 μm), and causes a transition from grain size insensitive (dislocation) creep of plagioclase and olivine to diffusion accommodated grain boundary sliding of the reaction products, even though the newly formed minerals (e.g. pyroxene, spinel) are mechanically stronger than the original minerals. *Effect of deformation on reaction:*
The plagioclase-olivine reaction progress is greatly enhanced by differential stress and/or crystal plastic strain. At 1.5 GPa, hydrostatic experiments of 168 hours show less than 30% reaction progress, whereas in the deformation experiments (~58 hours) the reaction goes to completion.

T42D-05 1440h

DEFORMATION OF SERPENTINITE AND ITS IMPLICATIONS FOR THE ASEISMICITY AND SEISMIC LOW VELOCITY ANOMALY IN SUBDUCTION ZONES

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Recent seismic data suggest that a low velocity layer up to ~ 7 km thick exists at the top of the subducting slab in many subduction zones (Abers, 2000). Both P and S-wave velocities are consistently 5-7 % lower than the surroundings. There are also observations of a distinct low seismicity zone in the Japan Trench (Fujie et al., 2002) and even an aseismic zone in central Oregon (Brocher et al., 2003). We have investigated a possible cause of these observations by deforming a natural serpentinite at the pressures of 1.0 - 3.4 GPa and the temperatures of 923 - 1023 K. We conducted triaxial deformation experiments at a constant strain rate using a Griggs-type apparatus. Oxygen fugacity was buffered by Ni/NiO. We find that under conditions where serpentine is dehydrating during deformation, Mode-I cracks are commonly observed in serpentine as well as in relict olivine. A similar phenomenon (Mode-I cracks) may occur at the top of the subducting slab due to the deformation of a hydrated mantle wedge above a dehydrating subducting slab. We propose that such aligned Mode-I cracks, which fill with water as they open, may result in the low seismic velocity in subduction zones (i.e. Alaska, the Aleutians, Kuriles, Honshu, the Marianas, and Nicaragua). We also find that deformation of the serpentinite under a differential stress display faults and localized shear zones, delineated by ultra fine-grained solid reaction products, formed as byproducts of antigorite dehydration. We observe this phenomenon under all conditions tested. A distinct low seismicity zone in the Japan Trench region, aseismicity beneath central Oregon, and other aseismic

zones in mantle wedges may be attributable to "super-plastic" flow under low stresses within the ultra-fine-grained dehydration products in dehydration-induced fault zones. Abers, G. A. Earth Planet. Sci. Lett., 176, 323-330 (2000). Fujie, G. et al., Geophys. Res. Lett., 29, 7 (2002). Brocher, T. M. et al., Geology, 31, 267-270 (2003).

T42D-06 1455h

HIGH TEMPERATURE DEFORMATION OF OMPHACITE IN ECLOGITE: IMPLICATIONS FOR SUBDUCTED LITHOSPHERE

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Omphacite is a major component mineral in subducted oceanic crust at depth. It often develops strong lattice preferred orientation and dominates the flow properties and seismic anisotropy in eclogite. Investigation on the rheology of omphacite is important for a better understanding of geodynamic problems associated with eclogite in subduction zones. The high temperature deformation behavior of polycrystalline omphacite ($Di_{58}Jd_{42}$) is being studied at temperatures of 1300-1500 K, a confining pressure of 3 GPa, and strain rates of 10^{-4}/s to 10^{-5}/s. We obtained a power-law creep for the high temperature deformation of omphacite with n=3.1, Q=289 KJ/mol, and a preexponential factor of $10^{-1.2}$MPa^{-n}s^{-1}. These results show that the creep strength of omphacite falls between its two end members of solid solution (diopside and jadeite), which supports the previous arguments that sodic pyroxene could be significantly weaker than other pyroxenes (enstatite and diopside). A steady increase of flow strength is also observed after adding garnet. Eclogite reconstituted from powders of 50% garnet ($Pry_{21}Alm_{18}Gro_{61}$), 40% omphacite ($Di_{58}Jd_{42}$), 10% quartz shows strength about 3 times that of polycrystalline omphacite. These data are consistent with observations of extensive deformation of omphacite in eclogite at low peak metamorphism temperatures during deep subduction and exhumation. These preliminary results also suggest that strain will concentrate into omphacite-rich domains within the subducting zones.

T42D-07 1510h

Nanoindentation Creep of Quartz, Olivine, and Calcite, with Implications for Rate and State Friction Laws

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A hallmark observation from friction experiments on rocks is that the coefficient of friction increases linearly with the log of time of quasi-stationary contact. This increase in friction, or *state* in the rate- and state-variable friction laws, is usually attributed to an increase in real area of contact between rough surfaces caused by deformation of highly stressed contacts. This behavior is typically explored in slide-hold-slide (SHS) friction experiments at ambient temperature. Despite the importance of the evolution of the state variable for determining conditions for which earthquakes may nucleate, contact-scale deformation mechanisms in rocks remain unknown. In an effort to identify these deformation mechanisms, nanoindentation creep experiments were conducted on single crystals of quartz, olivine and calcite at room temperature and constant loads of 50 to 250 mN. The amount of creep in a typical nanoindentation creep test is indicated by the increase in indentation area with time, determined from the measured displacement of indenter into the specimen and the well-characterized geometry of the indenter tip. A major limitation of such tests, that displacements are difficult to discern from thermal noise, was eliminated by employing *continuous stiffness* techniques. A 45-Hz oscillation in displacement of 2 nm amplitude was imposed on a diamond Berkovich indenter held at otherwise constant load for times comparable to those in SHS tests, up to $5{\times}10^4$ s. By analyzing the resulting specimen response with a frequency-specific analyzer, a nearly continuous measure of the contact stiffness, proportional to contact area, was obtained. Thus, contact area is determined over times too short for significant thermal drift. Changes in area with time from indentation tests were compared with those inferred from complementary SHS tests on quartz, olivine and calcite rocks conducted in a high pressure rotary-shear apparatus. The contact area between indenter and specimen increased linearly with log time for each mineral, in qualitative agreement with the linear increase in area with log time inferred from SHS tests. However, the rate of fractional area increase from nanoindentation tests is much larger than inferred from SHS tests, by factors of 2, 5, and 10 for quartz, olivine, and calcite, respectively. This discrepancy may indicate that contact stresses in the two tests are the same, but that area formed during the hold in SHS tests is partially destroyed during reloading after the holds, as demonstrated for acrylic plastic and glass (*Dieterich and Kilgore*, 1994). Alternatively, the difference may indicate that contact stresses in rock friction experiments are significantly less than determined from indentation tests.

T42D-08 1525h

Nature and Origin of Cataclastic Bands in Well Cemented Quartz Arenite

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Cataclastic bands are a common structure in well-cemented quartz arenites deformed at low temperatures (<250°C). These structures have been interpreted to originate by cataclasis with or without recrystallization. However, recent studies of samples from the Tuscarora and Oriskany sandstones from the Appalachian Valley and Ridge province suggest dilation was more important than shear in the formation of these bands. The cataclastic bands consist of sharply to diffusely-bounded tabular bodies ranging in thickness from 50 μm to a few cm filled with quartz having a uniform 5 μm grain size. In some cases, wall-parallel displacement can be demonstrated, but in others, the displacement is purely dilational. Two-phase, aqueous fluid inclusions in vuggy cores found in some bands yield homogenization temperatures of 140-170°C. FTIR data from traverses across cataclastic bands show a marked decrease in water content within the bands compared to nearby wall rock grains, and also suggest the presence of submicroscopic sheet silicates (mica or clays). In cathodoluminescence the bands are uniformly dark in contrast to brighter luminescing wall rock grains indicating either complete reconstitution of original wall rock or introduction of new phases. Rather than cataclasis, the fine grained texture in the bands is believed to result from rapid crystal growth in a dilating fracture with variable, but small amounts of shear. Despite the fine grained texture, the presence of sheet silicates suggests that these bands may have acted as a fluid conduit, not a permeability barrier.

T42E MCC: 2002-2004 Thursday 1700h

Birch Lecture

Presiding: **P Segall,** Stanford University

T42E-01 1710h INVITED

Splitting, Stretching and Spreading of Lithosphere

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That lithospheric plates diverge across relatively narrow zones has been accepted since the late nineteen sixties. Thus, in surprise many that several basic features of continental rifts and oceanic spreading centers were first observed in the last few years. Several of these new findings concern the distribution of molten or frozen magma along segments of present or past divergence. One view that the observations reinforce is that tectonic processes often cannot be understood without accounting for magmatism. This talk highlights the impact of new observations on how we think about the processes of faulting and magmatism from the plate tectonic scale to the scale of individual faults and magma chambers.

T51A MCC: 3007 Friday 0800h

Analysis of Plate Boundary Deformation Using Stress and Strain Rate Data in Tandem I *(joint with G, S)*

Presiding: **S Miyazaki,** Stanford University**; K Wang,** Geological Survey of Canada

T51A-01 0800h INVITED

A Thermo-Mechanical Model of the San Andreas Fault System in Central and Northern California

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The San Andreas Fault System (SAFS) in central and northern California is a family of sub-parallel strike-slip faults that accommodate the transform motion between the Pacific and the North America plates. We present here a fully coupled numerical thermo-mechanical model of the SAFS as it evolved over the past 20 Myr following the northward migration of the Mendocino triple junction. The strike-slip displacements and fault perpendicular compression (over the last 5 Myr) are implemented as side boundary conditions in the upper 20 km of the 100 km deep model box, other parts of the side boundaries and bottom boundary being free for material flow. The model employs realistic visco-elasto-plastic rheology and allows for spontaneous generation of faults. The modeling replicates the evolution of multiple strike-slip faults, the overall eastern migration of the San Andreas fault itself from the western edge of the Coast Ranges near Cape Mendocino to the eastern edge in central California, the variation of heat flow in the Coast ranges along and across the SAFS as well as high angle (60-80°) between the direction of the maximum horizontal stress and the local fault orientation in the upper crust. The modeling shows that the key conditions for such behavior are the cooling (and strengthening) of the lithosphere following passage of the triple junction which causes ductile deformation at depth to migrate eastward with time and the drop of frictional strength at high strain in the upper crust which results in a small number of major transform faults to develop, rather than a broad distribution of such faults. Our modeling suggests that the major faults in the SAFS in Central and Northern California must have been weak during most of the 20 Myr period over which it evolved.

T51A-02 0820h

Seismic Versus Aseismic Deformation in Iran Inferred from GPS and Seismicity Data

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The present tectonic of Iran results from the north-south convergence between the undeformed shield areas