The rates of grain coarsening are under investigation for stoichiometric dolomite ($CaMg(CO_3)_2$) and magnesite ($MgCO_3$) annealed hydrostatically at temperatures to 800°C and pressures P_c to 400 MPa, and results are compared with rates of grain coarsening for calcite ($CaCO_3$). Dense, fine-grained aggregates of the three carbonates were produced by first cold pressing (P_c = 300 MPa) and then hot isostatically pressing (HIP) powders at T = 600°C, P_c = 300 MPa for durations of 5 days (for dolomite and magnesite) and 9 hours (for calcite), following procedures similar to those of Olgaard and Evans (1988). The initial dolomite powder consisted of crushed and sized (< 2 μm) natural material while reagent grade calcium and magnesium carbonates were used, respectively, to produce calcite and magnesite specimens. Sequential heat treatments at T = 300°C, P_{CO2} = 0.1 MPa and T = 600°C, P_{CO2} = 20MPa were required to dehydrate the magnesium carbonate and eliminate oxides remaining after dehydration. Initial grain sizes of the HIP specimens were 1.4 μm, 1.1 μm, and 17 μm for $CaMg(CO_3)_2$, $MgCO_3$, and $CaCO_3$, respectively. Grain growth of dolomite is much slower than either the rates of calcite or magnesite; assuming normal grain growth, its rate constant K at T = 800°C, P_c = 300 MPa is 3 orders of magnitude smaller than that of calcite and smaller than that of magnesite by a factor of 30. Self-diffusion of Mg across magnesite grain boundaries is apparently slower than diffusion of Ca across calcite grain boundaries, and combined rates of Mg and Ca diffusion across dolomite grain boundaries are slower yet. Given that Mg and Ca of dolomite are fully ordered ahead and behind of advancing grain boundaries, the low grain boundary mobility of dolomite may be explained by larger diffusional jump distances than are involved in grain growth of the end-member carbonates.

T41B-06 0930h

Grain Boundary Microstructures of Wet and Dry Recrystallizing Marble

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We analyzed 2D grain boundary maps of samples of marble that were deformed at high temperature with and without added water. Our aim was to relate the grain boundary geometry of wet and dry marble to the observed mechanical behavior, and to obtain criteria that can help interpretation of natural calcite rocks in terms of the influence of water on their deformation.
We made use of cylindrical samples of pure white, microporous Carrara marble that were axially compressed in a gas medium deformation apparatus at temperatures (T) ranging 600-1000°C, a constant confining pressure of 300 MPa and strain rates around 10^{-5} s^{-1}. Samples were jacketed in sealed Pt-capsules with or without the addition of 0.4-2.1 wt% water. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) and Light Optical Microscopy. Traced grain boundary maps were made from ultra thin sections of samples, and were quantitatively analyzed using Image Analysis techniques.
The strength of water-added samples was found to be slightly less than of dry samples at all temperatures investigated (weakening 40% at T=600°C, decreasing to ~10% at higher T), with one exception at T=800°C. Microstructurally, the samples showed grain flattening and twinning at T=600°C and development of new grains by dynamic recrystallization at higher T, dominated by grain boundary migration. Grain boundaries in wet samples showed isolated or locally continuous remnants of fluid pockets in SEM. Quantitatively, the mean grain size and grain size distribution were found to only marginally vary between dry and wet samples. Average roundness of grains in wet recrystallized samples is systematically better than in dry samples. The fractal dimension D for the relationship between grain diameter d and grain perimeter P (expressed $P \sim d^D$) for wet samples is systematically lower than for dry samples. Thus, grain boundaries in wet-deformed samples have less irregular shapes than in dry samples. Average grain aspect ratios of deformed samples were compared to strain ratios calculated on the basis of the imposed bulk shortening. The results demonstrated that wet samples did not track the bulk strain to the same extend as dry-deformed samples, indicating higher grain boundary mobility in the wet samples. We suggest that the small difference in strength between the wet and dry marble was caused by an enlarged contribution of grain boundary sliding mechanisms to the overall creep, governed by limited grain shape modification by fluid-enhanced dynamic recrystallization. Analysis of naturally deformed calcite rocks might benefit from quantification of the grain diameter-perimeter fractal dimension, but only if relative changes from the same geological setting are used.

T41B-07 0945h

The Influence of Grain Boundary Fluids on the Recrystallization Behavior in Calcite: A Comparison of "dry" and "wet" Marble Mylonites

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Carbonate rocks are able to accumulate large amounts of strain and deform crystal-plastically even at low p-T conditions and thus, marble sequences are often the site of strain localization in the upper crust during late-stage deformation in mountain building processes. In this study we sought to identify the effect of fluids on grain boundary morphology and recrystallization processes in marble mylonites during shear zone evolution, as fluids play a major role in the flow behavior of many rock materials during deformation (e.g. quartz, olivine, halite, feldspar). We compared calcite marble mylonites from two geological settings: (a) Schneeberg Complex, Southern Tyrole, Italy and (b) Naxos Metamorphic Core Complex, Greece. The shear zones of the selected areas are suitable for comparison, because they consist of similar lithology and the marble mylonites resemble each other in chemical composition. In addition, calcite-dolomite solvus geothermometry and TEM observations indicate similar p-T conditions for the shear zones formation. However, the two settings are different in the availability of fluids during the shear zone evolution: In the Schneeberg mylonites, both the alteration of minerals during retrograde metamorphism of neighboring micaschists and the existence of veins suggest that fluids were present during mylonitization. The absence of these features in the Naxos samples indicates that fluids were not present during deformation of these mylonites. This difference is also supported by the signature of stable isotopes. Microstructural investigations using optical and scanning electron microscopes on broken and planar surfaces did not indicate major differences between wet and dry mylonites: Grain boundaries of both types of samples display pores with shapes controlled by crystallography, and pore morphologies that are similar to observations from crack and grain-boundary healing experiments. Grain size reduction was predominantly the result of subgrain rotation recrystallization. However, the coarse grains inside the wet protomylonites (Schneeberg) are characterized by intracrystalline shear zones. With the exception of the intracrystalline shear zones, there were no obvious microstructural signatures that were obvious indicators of the presence of fluids, at least for these two field examples.

T41C MCC: Level 1 Thursday 0830h

Structure and Dynamics of the Oceanic Upper Mantle I Posters *(joint with OS, S, V)*

Presiding: **J Korenaga,** Yale University

T41C-0223 0830h POSTER

Imaging the transition between the region of mantle melt generation and the crustal magma chamber beneath southern East Pacific Rise with short-period Rayleigh waves

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Beneath the southern East Pacific Rise resides a crustal magma chamber confined to the immediate vicinity of the rise axis, yet the mantle melt-production region is broad (>200 km wide) and asymmetric. Short-period (10-20 s) Rayleigh waves propagating along the rise from regional earthquakes provide a means of probing the transition from the asymmetric melt production region to the rise-centered crustal magma chamber. Low velocities beneath the rise act as a waveguide for surface wave energy. We model this complex wave propagation with a Gaussian beam representation as part of our non-linear inversion for velocity structure. Rayleigh wave results are generally similar to those of our previous Love wave study and show an asymmetry low-velocity zone in the mantle that is present at the crust-mantle interface, or Moho, and increases in width and asymmetry downward. The lowest mantle velocities are located beneath the rise at the Moho; thus, beneath the rise there is a gap in the high-velocity "lid" at the top of the mantle indicating a gap in the lithosphere. In addition there are lower asthenospheric velocities beneath the Pacific plate than the Nazca plate. The transition from the broad upwelling region to the narrow crustal magmatic system occurs over a 15 km depth interval at the top of the mantle. The low-velocity region is much wider in the Rayleigh wave solution than the Love wave solution, indicating that seismic anisotropy is present. One explanation, that requires further quantitative analysis, is that horizontal alignment of olivine in the upper 100 km increases with increasing distance from the rise axis, which retards the increase in Rayleigh wave velocity while advancing the increase in Love wave velocity. Our observations indicate higher temperatures and greater melt production beneath the Pacific plate. East of the rise melting appears to abruptly shut off at shallow levels, perhaps due to a component of downward mantle flow. We suggest that melt percolates upwards, increasing in concentration, until reaching a permeability barrier beneath the lithosphere, it then moves up along the lithosphere to accumulate at the Moho beneath the rise.

T41C-0224 0830h POSTER

Oceanic Crustal Structure North Of The Kane Fracture Zone From 87-147 Ma

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The 2001 Far-Offset Active-source Imaging of the Mantle (FAIM) experiment was conducted along an 800-km-long transect in the western Atlantic. This transect extends along a plate kinematic flow line which lies on 87-147 Ma lithosphere. The primary objective of this experiment is to image upper-mantle layering associated with Mid-ocean ridge (MOR) processes by recording and modeling direct P-wave phases propagating through the mantle. The main transect of the experiment consisted of 7 pairs of ocean-bottom seismometers (OBSs) spaced 80-120 km apart. Shots were spaced 1 km apart. These data also provide constraints on oceanic crustal thickness at each OBS pair location, and thus a history of MOR melting and melt-extraction processes over a 60-m.y. time-span. Crustal structure observations are relevant to the primary objective of this experiment in that MOR processes expressed in mantle structure should have some corollary in the crust. Crustal models based on travel-time fit and comparison with synthetic seismograms indicate an abrupt change in crustal thickness near the center of the transect, with average crustal thickness of 6.8 km below the western portion of transect and 5.8 km below the eastern portion. These differences in crustal thickness are consistent with the long-wavelength gravity field and with a apparently abrupt change in spreading rate from 18 mm/yr in the west to 7 mm/yr in the east. The crustal thickness change is also correlated with dramatic changes in basement morphology and mantle P-wave propagation. Smooth and rough basement are overlying thicker and thinner crust, respectively. In the west (thick crust), mantle P-wave phases are absent or have very weak amplitudes implying a weak or negative upper-mantle velocity gradient. In the east (thin crust), mantle P-wave phases have strong amplitudes, suggesting a positive upper-mantle velocity gradient. This correlation between crustal thickness and upper-mantle velocity gradient may be related to differences in melt retention at the MOR, suggesting a strong sensitivity of MOR processes to small changes in spreading rate for slow spreading systems.

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T41C-0225 0830h POSTER

Hunting for Ocean Island Moho: The Snipe Bites Back.

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Previous studies of oceanic crust in the Pacific using seismic refraction have modeled average properties of the plate, neglecting regions of abnormal topography (White et al. 1992). Subsequent refraction studies (eg. Mutter and Mutter, 1993) have shown that, though the average thickness of the Pacific crust follows White et al.'s 7.1 km, it ranges in thickness from 2-37 km in anomalous regions. We investigate crustal structure underneath Rarotonga (Cook Islands), Tahiti (Society Islands), and Christmas Island using multi-taper correlation (MTC) receiver function (RF) methods in conjunction with data from Global Seismic Network (GSN) stations (RAR, PPT, XMAS respectively). 415 teleseismic P coda comprise our data set, of which 166 were recorded at RAR, 182 at PPT, and 67 at XMAS. Robust receiver functions to 2.5 Hz are computed at each station, at a broad distribution of back-azimuths and epicentral distances. We find that the crust and upper mantle under these islands are significantly more complex than a simple oceanic lithosphere model predicts, and that this structure is very similar from one island to the next. We observe Ps conversions arriving at less than 0.5-s delay that we attribute to conversions from the base of the volcano. We also see three conversions arriving at roughly 1, 2, and 3 seconds delay. Several mechanisms could explain our results, including crustal underplating, partial serpentinization of the upper mantle, topographic scattering, and partial-melt phenomena. We also consider the possibility that this structure is broadly associated with the Pacific superswell, because the North Pacific stations POHA (Hawai'i Island) and WAKE (Wake Island) exhibit markedly different receiver functions. Mutter, C.Z. and J.C. Mutter, Variations in thickness of layer 3 dominate oceanic crustal structure, Earth Planet. Sci. Lett., v117, 295-317, 1993. White, R.S., D.P. McKenzie, and R.K. O'Nions, Oceanic crustal thickness from seismic measurements and rare earth element inversions, J. Geophys. Res., v97, 19683-19715, 1992.

T41C-0226 0830h POSTER

Azores Hotspot Deep Signature

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The Azores archipelago occupies a lateral branch of the Mid-Atlantic ridge near the triple junction of 3 large tectonic plates, the North American, the Eurasian and the African plates. The tectonic setting is even more complex due to the existence of the Azores hotspot and to the hotspot-ridge interaction. But the hotspot origin at depth as a plume and its lateral extent are controversial subjects. High-resolution tomographic models, through the mapping of low velocity and anisotropy anomalies, can provide an important hint to evaluate the depth and lateral extent of mantle plumes. Therefore, we investigate the Azores deep seismic structure as seen on recent global and regional studies. The mapping of S-wave negative velocity anomalies in the different models reveals that the anomaly right beneath the Azores seems to be confined in the upper 200km. Considering the time evolution of a plume, this low velocity anomaly might be the signature of a present-day dying plume, that created the Azores plateau 20Ma ago. In the model from Silveira and Stutzmann (2002), the negative velocity anomaly beneath the Azores archipelago seems to be connected to a deep anomaly further at the South. This deep anomaly ($\sim$ 28^{o}N/26^{o}W, 200-400km) is in the middle of the bunch of Azores, Great Meteor, Madeira and Canary hotspots, and might be related to a plume originating either in the transition zone or in the lower mantle. This single deep plume is located too far from the Azores archipelago for being responsible of the Azores plateau formation. But, due to the lithosphere geometry, this single plume might feed at present day Azores, Great Meteor, Madeira, Canaries and Cape Verde hotspots and therefore be at the origin of the present day volcanism. The diverging azimuthal anisotropy around this point below lithosphere is confirming a unique origin of these hotspots.

T41C-0227 0830h POSTER

Azimuthal Anisotropy Across the Pacific

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We present maps of the 2ψ component of azimuthal anisotropy across the Pacific Ocean for Rayleigh wave group velocities at periods ranging from 20 sec - 150 sec. The fast axis directions and relative amplitudes at large scales (> 1000 km) across the Pacific are robust to ad-hoc choices of smoothing and damping, but the absolute amplitude of azimuthal anisotropy remains poorly determined. At long periods (100 - 150 sec), anisotropic fast axes align approximately parallel to current plate motions, but at short periods (20 - 50 sec) fast axes diverge from current plate motion directions in the western Pacific and align more closely with the local paleo-spreading direction. This behavior provides evidence that anisotropic fabric in the deep lithosphere and asthenosphere evolves with the plate and is able to conform with contemporary plate motions. In the shallow lithosphere, however, anisotropic fabric appears to be "frozen in" and remains representative of the conditions at the time of formation of the lithosphere. In addition, the amplitudes of azimuthal anisotropy decrease with lithospheric age at periods between 50 and 150 sec. This may be the effect of a process or processes that disrupt azimuthal anisotropy in the central Pacific, such as plumes or lithospheric instabilities (small-scale convection).

T41C-0228 0830h POSTER

The Cooling Oceanic Lithosphere as Constrained by Surface Wave Dispersion Data

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The tremendous improvement in resolution capabilities of global surface wave phase velocity maps now encourage us to search for anomalies that are caused by mantle plumes. On the other hand, the implications of even large–scale anomalies in such maps are still not well understood. One such anomaly is caused by the cooling oceanic lithosphere. Some studies investigate the cooling effects by fitting thermal models to the 3–dimensional mantle models resulting from tomographic inversions. The inversion of surface wave data for structure at depth is nonunique and the model often depends on the techniques applied. We prefer to compare the dispersion data directly with predictions from thermal models. Simple cooling models produce a signal that is roughly proportional to the square root of age. This signal is typically much smaller than the one caused by other lateral heterogeneity within the Earth's crust and upper mantle. In a careful analysis we are able to extract clear, roughly linear trends, in all major oceans. We explore the parameter space by fitting cooling half space as well as cooling plate models to the data. In the Pacific ocean, our data are inconsistent with standard parameters that are used to fit the observed bathymetry, and perhaps surface heat flux data. Instead of an initial temperature of 1350 deg C in the cooling half space model our data require a lower temperature (around 1200 deg C) to be well fit, especially the Love wave data. Regarding the cooling plate model, our data seem to require a thicker lithosphere to be well fit (135 km instead of the 'standard' 100 m). We observe similar trends for the other oceans investigated: the Indian ocean, the South and the North Atlantic oceans. For the Indian ocean in particular, a crust correction (removing the predictions caused by crustal structure including water depth and sediment thickness) is crucial to obtain an internally consistent dataset. For the Atlantic ocean, a large signal remains unexplained. An age–dependent signal is also apparent in the SS-S and PP-P body wave datasets. However, a comprehensive analysis is somewhat hampered for two reasons: 1) the uneven sampling of the data does not allow us to analyze trends in some oceans (e.g. South Atlantic Ocean); 2) the signal in the oldest parts of the oceans appear "too fast". We suspect that we observe effects that are deeper–rooted than the lithosphere–asthenosphere system (e.g. subducting slabs). The surface wave dispersion maps contain an intriguing oscillating signal that is particularly strong for Rayleigh waves in the Pacific ocean. This signal is symmetric to the EPR and we speculate that this is caused by current convective processes or by processes at the time when the plates were formed.

URL: http://mahi.ucsd.edu/Gabi

T41C-0229 0830h POSTER

Vp/Vs Tomography of the Central Lau Spreading Center and Tonga Volcanic Arc

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Previous 3D P-wave tomography of the Lau Basin from the Labatts experiment shows a >100 km deep slow velocity anomaly beneath the arc, above and paralleling the slab, and an asymmetric slow velocity anomaly beneath the Central Lau back-arc spreading center (CLSC) with nearly all of the anomaly to the west of the axis [Zhao et al., 1997]. These anomalies may be indicative of the melt structure beneath the arc and back-arc or alternatively could reflect higher temperatures or a combination of the two in these regions. To distinguish between the two effects, we jointly use S-waves with the P-waves since P and S-wave velocities are affected to different degrees by temperature and the presence of melt. Because the back-arc region strongly attenuates S-waves, we focus on 2D inversions beneath the array rather than attempt a 3D inversion that is only sparsely constrained by S-waves, and also solve for Vp/Vs rather than directly solve for Vs. The Vp/Vs structure exhibits several distinct anomalies. As expected, the subducting slab has a low Vp/Vs (with fast Vp), consistent with the cold downgoing plate. The CLSC has a strong asymmetric Vp/Vs anomaly as well as an asymmetric Vp anomaly, probably indicating that melt is mostly present west of the axis. There is no obvious anomaly beneath the volcanic arc, but could be due to poor resolution and/or ray coverage in the uppermost wedge. The models also exhibit a couple of curious anomalies: one with slow Vp and low Vp/Vs (fast Vs relative to Vp) beneath the western Lau remnant arc and the other with fast Vp and high Vp/Vs (fast Vp, slow Vs) below the slab. The latter anomaly involves arrivals almost exclusively observed at the island of Niue, oceanward of the trench. As the models improve we will be able to better detail the robustness of each of the observed anomalies and map out significant variations within the sub-arc and back-arc mantle.

T41C-0230 0830h POSTER

Effect of Water on the Rheological Behavior of Fe-rich Olivine

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The influence of water content on the rheological properties of Fe-rich olivine was investigated in order to better understand the influence of hydrogen on the creep behavior of mantle rocks. Triaxial compressive creep experiments were performed on fine-grained samples of Fo$_{50}$ and Fo$_{50}$ + water. Samples were fabricated from a mixture of powders of San Carlos olivine, Fo$_{90}$, and synthetic fayalite, Fo$_0$. The resulting Fo$_{50}$ material was ground into powders of <10 μm, cold-pressed into a Ni capsule, and hot-pressed at 300 MPa and 1533 K for 2 to 12 h. Two drops of water were added for the Fo$_{50}$ + water sample, which was then hot-pressed using a telescoping can to prevent the water from escaping. The final grain size of the resultant sample was 24-36 μm for dry Fo$_{50}$ and 24-45 μm for the Fo$_{50}$ + water sample. Samples were then deformed in a gas-medium apparatus at a confining pressure of 300 MPa and temperatures between 1223 and 1473K. The samples were deformed both in the diffusional and dislocation creep regimes, characterized by stress exponents of $\sim$1 and $\sim$3.5, respectively. Samples of Fo$_{50}$ deformed at a water fugacity of $\sim$300 MPa creep at a rate $\sim$15 times faster than samples of Fo$_{50}$ deformed under anhydrous conditions. This enhancement in strain rate is a factor of 2-3 greater than the enhancement in rate for Fo$_{90}$ aggregates deformed under similar conditions. The greater reduction in the viscosity of Fo$_{50}$ than in the viscosity of Fo$_{90}$, in going from anhydrous to hydrous conditions, is consistent with the observation that hydrogen solubility (and thus the degree of water weakening) increases with increasing iron content in olivine. Hence, rocks with increased iron content such as those believed to constitute the mantle of Mars may be considerably weaker under hydrous conditions than their counterparts within the mantle of Earth.

T41C-0231 0830h POSTER

Olivine Friction at the Base of the Seismogenic Zone

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The frictional properties at the base of the seismogenic zone in oceanic lithosphere are fundamental to our understanding of oceanic earthquake processes. While the composition of the oceanic lithosphere is probably the simplest and most well constrained of any seismogenic region on Earth, few data on its frictional properties exist. We are investigating the strength and sliding stability of olivine aggregates at temperature and effective pressure conditions close to those at the base of the seismogenic zone on a typical transform fault. We have conducted triaxial compression tests on dry olivine powder (38 – 60 μm particles) at effective pressures of $P_{\mathrm{eff}} = P_c - P_f = 50$, 200, & 300 MPa using argon as a pore fluid medium, temperatures of $T = 800^\circ$C & 1000°C, and strain rates of $\dot{\epsilon} = 3 \times 10^{-5}$ & 3×10^{-4}. For all experiments, strain became localized on faults and strain-rate steps showed velocity-weakening behavior. Stick-slip events were observed at all temperatures up to 1000°C, with a greater tendency towards instability (i.e. more stick-slip events) at the higher strain rate. By contrast, previous laboratory work by Stesky et al. (1974) found stable sliding for olivine at temperatures above 200°C. Our experiments are consistent with seismic data, which find that earthquake hypocenters regularly occur to temperatures well above 200°C, regularly to near the 600°C isotherm.

T41C-0232 0830h POSTER

The Anisotropic and Rheological Structure of the Oceanic Upper Mantle From a Simple Model of Plate Shear

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We have developed a channel flow model that dynamically couples plate motion and mantle stress with a composite rheology (diffusion creep and dislocation creep) to study rheological and anisotropic structures of the oceanic upper mantle. A semi-analytic approach is used to solve for mantle stress and viscosity, allowing fast calculations and exploration of a wide range of rheological parameters. Mantle stress in our model is due to shearing by a moving plate. By comparing mantle stress to a transition stress for dislocation creep, we identify regions where either diffusion creep or dislocation creep is active. Deformation by dislocation creep results in mineral fabric that may be responsible for observed seismic anisotropy. Our study suggests that there is an important relation between plate motion, seismic anisotropy, mantle viscosity, and transition stress. Using laboratory results for rheological parameters, we find that dislocation creep exists only in a layer at certain depths in the upper mantle. For plate velocity of 10 cm/yr, asthenospheric viscosity of 10^{19} Pa-s, and asthenospheric transition stress of 0.1 MPa, our model predicts a 200 km thick dislocation creep layer, which is broadly consistent with the observations of seismic anisotropy. For plate velocity of 10 cm/yr and asthenospheric transition stress of 0.1 MPa, the asthenospheric viscosity needs to be greater than $5x10^{18}$ Pa-s to produce any dislocation creep deformation, and the asthenospheric viscosity needs to be larger for slower plate motion or larger transition stress. Slower plate motion leads to a thinner dislocation creep layer, which may partially explain the observed asymmetry in anisotropic structure in the East Pacific Rise.

T41C-0233 0830h POSTER

On the Small-Scale Morphology of Asthenospheric Flow

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We investigated the interaction of small-scale cold instabilities dripping from a cooling lithosphere with a shear flow confined in the asthenosphere, using analog experiments. Rayleigh numbers ranged between 10^4 and 10^8. The fluids were either polymer solutions (constant viscosity), sugar or corn syrups (viscosity depending on temperature), or wax (phase transition). When cooling away from the ridge, the thickening lithosphere becomes thermally unstable and develops small-scale convective instabilities at its bottom. For sufficiently fast asthenospheric flow, these instabilities are sheared and remain trapped in the asthenosphere, following a helicoidal path aligned with the direction of plate motion. A phase diagram and scaling laws for the flow characteristics were determined. The observed helicoidal pattern could explain some geophysical observables such as small wavelength lineations in the terrestrial gravity field, or seismic anisotropy anomalies under the Pacific plate. Moreover, the distance from the ridge at which the small-scale instabilities form depends on the underlying mantle temperature: for a hotter mantle, they are generated closer to the ridge. Therefore, in the case of a ridge-centered plume, the hot temperature anomaly due to the plume triggers small-scale instabilities almost at the ridge. The heat transfer out of the mantle is accelerated, and the thickening of the lithosphere away from the ridge is delayed. Therefore, a groove at the bottom of the lithosphere may be expected along the track of a ridge-centred hotspot.

T41C-0234 0830h POSTER

3-D numerical simulations of mantle flow beneath mid-ocean ridges

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Small-scale perturbations in the oceanic geoid aligned with the seafloor spreading direction have been observed in the Pacific Ocean. One explanation is to attribute these anomalies to small-scale convection.
3-D analogical and 2-D numerical experiments of the cooling of an oceanic lithosphere show that, at young ages, the material flows at the base of the lithosphere along the isotherms topography of the lower part of the lithosphere. After 20 to 70 Myrs, cold downgoing instabilities develop at the base of the lithosphere. Small-scale convection can then be observed superimposed on the large-scale circulation. With a strongly temperature and pressure dependent viscosity, large wavelength topography, thermally stable, is observed at the base of the lithosphere.
We perform 3-D numerical simulations using a Newtonian rheology with a viscosity depending strongly on temperature in a cartesian box. To avoid any influence of the boundary conditions on the convective cells evolution, we use an aspect ratio of 6x3x1. A constant horizontal velocity of 2 or 4 cm/yr is applied at the surface of the box to mimick the plate motion. Two kinds of ridge geometry have been modelled: (A) a ridge perpendicular to the plate motion, and (B) a ridge with transform faults along the spreading center with a mean ridge orientation strongly oblique to the plate motion. Different 3-D flow geometries have been observed. For case (A), we first observed a series of downgoing instabilities parallel to the ridge axis at young ages and then a series of downgoing instabilities nearly perpendicular to the ridge axis. At old ages, an irregular small-scale flow dominates. But this flow pattern is time-dependent, since for a caracteristic time greater than 200 Myrs, depending on the surface velocity value, ridge-perpendicular downgoing instabilities become the preferred form. For case (B), the flow at the base of the lithosphere appears nearly perpendicular to the mean orientation ridge and is oblique to the plate velocity direction. Morever downgoing instabilities initiating at each transform fault then become perpendicular to the mean ridge axis. The thermal state does not evolve with time, contrarily to case (A).
We then compare some variables issued from cases (A) and (B) like the heat flow evolution with time, the onset time of instabilities at the base of the lithosphere, and the main strain direction generated by the flow. The latter could explain oceanic surface-wave velocities anisotropy showing fast velocity directions perpendicular to the ridge axis, which does not correlate simply with plate motion direction.

T41C-0235 0830h POSTER

On the Relationship Between Rheology and Sublithospheric Small Scale Convection

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Sublithospheric small scale convection (SSC) has been proposed to explain the deviation in oceanic topography and heatflow from the cooling half-space model for oceanic plates spreading away from the mid-ocean ridge. The dynamics of this SSC process have been previously studied in several numerical and laboratory experiments. The process of SSC is the rheology of lithosphere and mantle. Studies with an Newtonian Arrhenius rheology show that the lithospheric age at the onset of SSC τ_c is related to the Rayleigh number Ra, and rheological activation energy E^* as $\tau_c \sim \mathrm{Ra}^{-0.68} E^{*0.74}$. In the presence of shearing due to plate motion, longitudinal rolls, and not transverse rolls, are the preferred mode of instability, and a moderate dependence of Richter roll onset time on the amount of shearing exists. We further elaborated the rheological influence by exploring the effects of non-Newtonian rheology, in which the deformation rate is related to the ambient stress to the power n. In that case, shearing by plate motion couples to the effective viscosity through the stress-dependence of the rheology. We use a numerical 2-D longitudinal-roll model with imposed background shearing to determine the relationship between τ_c and the rheological parameters for the general case of non-Newtonian rheology, and results are tested against 3-D models with plate motion. For models with different rheological stress-dependence n, but with a comparable mantle viscosity, a higher n gives a significant reduction in the onset of SSC. Thermal structure of lithosphere above SSC can be compared to the cooling halfspace model, which leads to a 'thermal age' that due to SSC may deviate from the real plate age . We found that numerical models of SSC reproduce the 'thermal age' revealed from a seismic surface wave tomography model. This strongly supports the existence of SSC, and provides constraints on the rheological parameters of the upper mantle.

T41C-0236 0830h POSTER

Deriving seismic anomalies and electrical conductivities from mantle convection models: effects of melting and water content

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Physical properties of rocks depend on several physical and compositional quantities which are often taken as homogeneous or neglected for simplicity or because they are not known well enough. We take the temperature, depletion, melt content, and water content distributions of 3D numerical convection/melting models of a ridge-centered plume and apply a combination of theoretical and empirical models for the effects of temperature, depletion, melt content and H^+ resp. OH^- content (extended after Kreutzmann et al., submitted paper, 2003) to derive seismic anomalies and electrical conductivities for well-defined water-free and water-bearing systems. We find that for both seismic and electrical observables, several factors apart from temperature play an important role, e.g. the presence of melt, but in particular the water content has a very strong impact on the magnitude and shape of seismic anomaly and conductivity patterns in the deeper, unmolten parts of the models, thus confirming predictions by Karato (1990, 1998). Assuming a higher water content for the plume than for the background mantle, the effect of water leads to a stronger low-velocity anomaly in the unmolten mantle which would be misinterpreted as a very hot plume if the effect of water were neglected altogether. On the other hand, the stiffening effect of dehydration on rheology in the melting zone

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reduces the upwelling rate of a plume and decreases its melt production, so that nonetheless a strong thermal anomaly is needed to generate the thickened crust of islands located above plumes, such as Iceland. In the shallower parts, the disappearance of water results in a convergence of the anhydrous and hydrous models, and other factors, e.g. porosity or depletion, are important, although to a lesser extent. In parts of the partially molten plumehead the low-velocity and high-conductivity anomalies are drastically reduced, so that they may be invisible for seismic or electromagnetic methods.

T41C-0237 0830h POSTER

Dynamic Topography and Edge-Driven Mantle Convection

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The topological rise of Bermuda is enigmatic in that simple hot spot plume theories do not provide a clear explanation for its elevation. The broad elongated NE-SW swell exceeds its expected value by ∼800-1000 m, while approximately 1000 km southeast of Bermuda there exists a negative anomaly of 600 m. The rise also manifests in a geoid anomaly with a maximum value of 6-8 m; the peaks of the topography and geoid anomalies approximately coincide. It has been suggested that the anomalies may be the consequence of ‘edge-driven convection’ (EDC), which is essentially upper mantle small-scale convection driven by the thermal gradient at a continent-ocean lithospheric discontinuity. In this study we use a numerical model to consider how EDC may influence the evolution of surface topography at a passive continental margin. We simulate an idealized plate margin by defining strong plates with a step-like thickness/temperature discontinuity at the continent-ocean boundary. Experiments are conducted with lateral velocities imposed on the lithosphere to consider how the character of EDC and associated topography may change with relative plate motions. The models demonstrate that a time-dependent EDC roll develops with downwelling flow at the lithosphere discontinuity and an upwelling beneath the oceanic lithosphere. This convection cell induces a localized subsidence at the plate boundary and uplift further outboard on the oceanic plate. The magnitude of dynamic topography is controlled by the geometry and thermal profile of the plate discontinuity, and the material rheologies. The aspect ratio of the EDC cell changes depending on the direction of the plate motion (i.e., continent- or oceanward) and consequently this alters the style of surface topography. The results demonstrate the behaviour of an alternative mechanism for intraplate oceanic topography anomalies that do not readily conform to simple hotspot models.

T41C-0238 0830h POSTER

Laboratory experiments on the interaction between on-axis plumes and segmented ridges

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Observational and modeling studies suggest that plume dispersal in the upper mantle is strongly influenced by plate driven mantle flow associated with spreading ridges and the presence of a sloping rheological boundary layer (RBL) at the base of the lithosphere. Questions remain as to how (or if) transform offsets in mid ocean ridges effect the dispersion of plume material. We examine the essential physical aspects of the case of a thermal plume rising beneath a segmented ridge system in a series of three-dimensional laboratory experiments. The working fluid is a glucose solution, with a temperature dependent viscosity. Divergent plate driven flow is modeled using Mylar sheets that are coupled to, and pulled in opposite directions across, the fluid surface. Buoyantly driven flow is produced using a circular resistance heater located at the base of the fluid. We consider cases when the plume rises beneath the center of a ridge segment and when the heater is located beneath a ridge-transform corner. The effect of a sloping RBL is modeled by cooling the fluid surface using dry ice. For the cases with plumes beneath segment centers, results show that long term patterns in along-axis plume dispersion are governed by the initial flattening and spreading of the plume head at the ridge. Plume heads produce a pocket in the RBL, which is subsequently filled by flow through the plume tail. Results show that transport of plume material in the vicinity of a ridge-transform offset is distinct from that which arises in the case of a ridge without any offset. This is due both to differences in RBL morphology and the pattern of plate driven upwelling associated with the presence of a transform boundary. The transform offset deflects the rising plume and, for cases of slow spreading rates and relatively weak plumes, blocks the flow of plume material to the distant ridge axis.

T41C-0239 0830h POSTER

Plume-Transform Interactions at Ultra-Slow Spreading Ridges: Implications for the Southwest Indian Ridge

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We explore a potentially important variable in controlling ridge-hotspot interaction, the effect of transform offsets in limiting along-axis flow of plume material. We focus on the Southwest Indian Ridge (SWIR), where the "transform damming" effect is likely to be pronounced because of both long offset lengths and large contrasts in lithospheric thickness across the transform faults due to the ultra-slow spreading rate. We investigate the degree to which transform faults affect axial asthenospheric flow by performing a series of three-dimensional (3D) numerical experiments with simplified channel-flow geometry and extrapolating their results to the SWIR. 3D mantle viscosity structure for a ridge-transform- ridge system is determined based on temperature- and pressure-dependent viscosity laws. We consider six transform lengths, spanning 0 to 250 km in increments of 50 km. We then calculate the 3D viscous flow in response to an along-axis pressure gradient corresponding to a ridge-centered hotspot. Modeling results predict that transform faults affect along-axis asthenospheric flow in two important ways. First, transforms reduce along-axis flux. The longer the transform offset, the greater the reduction in across-transform flux relative to the zero-offset case. Second, transforms deflect shallow asthenospheric along-axis flow. The predicted transform damming effect is most pronounced for a viscosity structure that is strictly pressure- and temperature-dependent. Flux reduction effects could be less significant for viscosity laws that additionally consider dehydration, melting, and change in deformation mechanism. This model predicts that the waist width of an on-axis plume is dependent not only on such previously-explored factors as buoyancy and spreading rate, but also on the geometry of ridge segmentation. Along the SWIR, axial flow driven by the Marion plume is likely curtailed by the long-offset Andrew Bain and Discovery II fracture zones, severely limiting its lateral extent.

T41C-0240 0830h POSTER

Iceland, the Scotian Basin, and the Farallon Slab: Dynamic Topography of the North Atlantic

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Upwelling or downwelling flow in the Earth’s mantle is thought to elevate or depress the earth’s surface on a continental scale. Direct observation of this “dynamic topography” has been elusive, however, because it is obscured by isostatically-supported topography caused by near-surface density variations. We calculate the non-isostatic topography of the North Atlantic by correcting seafloor depths for the isostatic effects of lithospheric cooling and sediment loading. We also predict dynamic topography of the North Atlantic seafloor using a model of mantle flow driven by tomographically-inferred mantle densities. Predicted and observed topography fields show several similar features, suggesting that these features have a dynamic, rather than isostatic, origin. We show that anomalously high topography near Iceland and the Azores can be predicted dynamically, but that only the Icelandic high has an upper mantle origin, which suggests a different dynamic origin for these hotspots. The Scotian Basin, an anomalously deep area off the coast of Nova Scotia, may be associated with the downwelling component of edge-driven convection at the continental boundary. Finally, we find that seafloor west of the Mid-Atlantic Ridge is an average of 0.5 km deeper than it is to the east. About 50-80% of this topographic difference can be explained by dynamic topography associated with downwelling of the Farallon slab, which is currently situated in the lower mantle beneath the east coast of North America. The fact that a whole mantle flow model underpredicts the North Atlantic dynamic topography while successfully predicting the geoid (60% variance reduction) may suggest additional complexity for mantle flow. One possibility is that upwelling flow experiences stronger layering, and thus produces less dynamic topography, than slab-induced downwelling flow.

T41C-0241 0830h POSTER

Two Time-Scales of Pulsation of the Iceland Plume Inferred From Magnetic Anomalies of the North-Atlantic

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We have shown previously [Abelson and Agnon, EPSL, 1997, 2001] that small offsets 2nd-order MOR segments, oblique to spreading direction, may indicate a strong influence of a nearby hotspot. We term this anomalous plan-view-geometry of the ridge axis as a planform anomaly (PA). The PA-hypothesis was successfully tested on the ridge-plume system around Iceland, where ancient planforms of the Kolbeinsey Ridge (KR) and the Reykjanes Ridge (RR) are recorded by magnetic anomalies north and south of Iceland, respectively. The magnetic fabric off-KR axis displays variations between normal planform (orthogonal & segmented) and PA in the past 10 Myr. The PA recurrences of the KR correlate with the plume pulses previously inferred by the V-shaped ridges around RR, suggesting that PA records episodes of strong influence of Iceland on KR. Accordingly, the inferred time-scale of cycles of plume pulsation is 5 Myr. On the other hand, the magnetic fabric around the RR displays variations between normal planform and PA in a time-scale of 30 Myr. The fluctuations between PA and normal planform are made by twist of the 2nd-order segments while preservation of obliquity of the general trend of the ridge on 30° to spreading direction. From this magnetic record two major pulses of enhanced plume activity are inferred since the formation of the oceanic crust (anomaly #24). The first pulse is between 54 Ma to 39 Ma, compatible with thick igneous crust (18-9 km). The second pulse starts some 20-24 Ma, consistent with the disappearance of off-axis scars (i.e., disappearance of 2nd-order discontinuities along the RR). This long pulse is accompanied with the emergence of the Iceland Plateau. Between the two long pulses, a period of segmented and orthogonal planform suggests a significant decrease of the plume activity between anomalies #17 (38.1-36.6 Ma) to anomaly #6 (20.1-19 Ma), consistent with the deeper seafloor bathymetry. The inference of the PA-pulse linkage and the two time-scales of pulsation may assist in the detection of the plume structure and dynamics. For instance, we suggest that the short-time scale pulsation is due to fluctuations in the flux of plume material, supported by a pinch-and-swell structure of a vertical anomaly of seismic velocity. This structure implies ascent velocity of 4 cm/y for 5 Myr interval between pulses.

T41C-0242 0830h POSTER

Interaction of the Iceland Plume and the Mid-Atlantic Ridge: the Effect of Detailed Ridge Geometry and Mantle Flow

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The interaction of the Iceland plume with a global mantle flow field is investigated in 3D numerical mod-

els. The approach consists of two steps. First the large-scale mantle flow field is calculated in a global model, in the whole mantle. This global and robust flow field serves as a background flow in the regional model, in which the interaction of the mid-Atlantic ridge and the Iceland plume is calculated. A time-dependent model of the large-scale mantle flow field was obtained by using paleogeometries of the Atlantic and Eurasian plates reconstructed from magnetic anomalies and by advecting density anomalies backward in time. The motion of the plume source on the bottom of the model box is calculated according to the distortion of an initally vertical plume conduit in the large-scale mantle flow field. In the regional model the changing large-scale flow field and the moving plume source are introduced as time dependent boundary conditions. In this way, the interaction of the Iceland plume and the mid-Atlantic ridge is investigated in a 3D model containing detailed ridge geomtery. Results with time independent boundary conditions show that the large-scale mantle flow field controls the development of the plume. In the regional model the plume is tilted to the north in the upper mantle, which is also shown by seismology. However, the northward channeling of the plume material in the model does not explain the geochemical anomalies, which show an increased plume influence south of Iceland. Simulations with time dependent boundary conditions (time dependent ridge geometry and plume source position) modify this channelling of plume material and give a more precise view of plume-ridge interaction.

T41C-0243 0830h POSTER

The Dynamics of Slab detachment: Process Initiated by Melting of Subducted Crust

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It is well recognized that slab detachment or breakoff is a realistic geological process, as shown by recent tomographic imaging [1]. Using 2-D upper-mantle model with an area of 660 km deep and 2000 km wide we have investigated with a finite-difference and marker numerical technique the multi-resolutional character of thermomechanical phenomena related to this complex geological process. We have used up to 50 million markers on a shared-memory computer for delineating the complex multiscale structures in the composition, viscosity, accumulated strain, shear heating, and other field variables. Our experiments show that this process can be initiated by slab weakening due to the thermal relaxation of the slab and related melting of the subducted oceanic crust. The melting propagates within the subducted oceanic crust at the top of the slab occurring at the restricted depth interval of 100 to 200 km defined by the non-linear dependence of wet solidus temperature of the oceanic crust with pressure. The detachment process is self-accelerating due to the strain and thermal erosion focussing and strong thermal feedback from the shear heating. Slab detachment develops around 10% faster with viscous dissipation included, thus showing the importance of shear heating in this process. Detached slab rapidly fall down having a tendency of coherent rotation. This may produce near horizontal relatively cold slab fragments laying on denser mantle at 660 km discontinuity. Influence of a temperature- and pressure-dependent thermal conductivity for the process of thermal relaxation of the slab is significant. Overall 20% increase in thermal conductivity of mantle produce 20% decrease in timescale of detachment. This support the idea that breakoff process is mainly driven by focussed thermal erosion with timescale linearly dependent on heat conductivity. Rapid changes in topography and significant volcanic activity due to the massive melting of subducted oceanic crust during the slab detachment process are plausible consequences of this vigorous geodynamic scenario.
[1] Levin, V., Shapiro, N., Park, J. and M. Ritzwoller, Seismic evidence for catastrophic slab loss beneath Kamchatka, Nature, 418, 763-767, 2002.

T41C-0244 0830h POSTER

Slab Dynamics and Non-Newtonian Rheology in the Upper Mantle

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One of the fundamental aspects of plate tectonics and mantle convection in the Earth is one-sided subduction of plates at trenches with apparent slab dips ranging from 30° to 90°. While this aspect of plate tectonics is not often reproduced in large scale mantle convection simulations, the importance of slab dip to the thermal structure of the slab-wedge system has lead to numerical models of slab thermal structure, which fix the slab dip at a specified value and impose one-sided subduction.Understanding the balance of forces that lead to the range of observed slab dips can provide constraints on the viscosity structure of the shallow mantle and the importance of phase changes in modifying the buoyancy forces driving subduction. We present 2-D, time-dependent, finite element models of thermal convection exploring the dependence of slab dynamics on the viscosity structure and phase changes in the upper mantle. The viscosity structure evolves in time and is defined by a composite rheology which is temperature, pressure and strain-rate dependent, including both diffusion (Newtonian) and dislocation (non-Newtonian) flow laws and a yield criterion at low temperatures. The plate boundary within the lithosphere is included as a narrow shear zone with low viscosity. We find that slab dynamics are strongly dependent on the assumed boundary conditions and proximity of the subduction zone to the side boundaries.Flat slab subduction and/or two-sided subduction often occurs for models in which the viscosity is not strain-rate dependent. The strain-rate dependence of viscosity can lead to weak regions that cut through the full thickness of the subducting lithosphere within the subduction zone, producing steeply dipping slabs.

T41C-0245 0830h POSTER

On the Curvature of Oceanic Arcs

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The key feature of plate tectonics is the subduction of cold oceanic plates into a hot convective mantle. These subducting plates, as seen from the surface, mostly portray a distinct concave arc shape at the trench with respect to the leading edge of subduction. The origin of arc curvature is not yet understood. A common belief is that it is probably an effect of the Earth's sphericity. However, the spherical effect of the Earth creates convex, long-wavelength arc shapes. We thus investigate whether concave arc curvature can be explained by: (1) Exogenic feedback between the migrating lithosphere and the secondary induced mantle flow, (2) Endogenic heterogeneities within the lithosphere itself, e.g. owing to differences in cooling ages of the plate at the trench. Although both mechanisms create concave arcs, for isolate subduction systems, only the endogenic effects are sufficient to explain the magnitude of observed arc curvature. We compare our results to the Aleutian and Sandwich arcs. Our method is based on a novel 3-D numerical tool. We model the subduction process as a solid (lithosphere) - fluid (mantle) interaction. Two different numerical methods are used to solve for the constituents: Implicit Finite Element (FEM) for the lithosphere and Implicit Boundary Elements (BEM) for the mantle. The methods are chosen on the basis of a critical isotherm allowing a fluid mechanical approximation of the full continuum-mechanical problem above 1200 K. Thus the calculus of an approximate average drag effect is feasible through semi-analytical methods. This approach extends the 2-D setup of Funiciello et al., (JGR, 2003) into 3-D by adding the BEM solution. The BEM method builds on the stokeslet theory as a semi-analytical solution for the mantle drag. It shows that the drag mainly depends by the integration of the singularities at the lateral extremities of the slab.

URL: http://www.sg.geophys.ethz.ch/geodynamics/gabriele/

T41C-0246 0830h POSTER

Blob Tracing Models for the Central Mexican Volcanic Belt

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The numerical model of steady state temperature and velocity fields in the mantle wedge of the Central Mexican Volcanic Belt (CMVB) is used to compute a dynamic model of buoyant blob tracing in the non-newtonian mantle wedge velocity field. Considering that the main component of the volcanic material is generated by the melting processes on the subducting plate surface, a dynamic model simulating the motion of detached blobs in a viscous mantle wedge flow was developed. The blob's motion is determined by the action of drag, mass, and buoyancy forces in the mantle wedge velocity field. The blobs of the realistic diameter of 0.2 - 2.0 km show very different trajectories only at very low wrapping viscosity (1015 Pas). The blob rise time which is necessary to reach the bottom of the continental crust is from 0.04 up to 12.5 million years depending on the plume diameter and surrounding viscosity.

T41D MCC: Level 1 Thursday 0830h

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

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

T41D-0247 0830h POSTER

Dislocation Creep in Magnesium Calcite

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To investigate the effect of dissolved Mg on plastic deformation of calcite, we performed triaxial deformation experiments on synthetic calcite with varying amount of Mg content. Mixtures of powders of calcite and dolomite were isostatically hot pressed (HIP) at 850°C and 300 MPa confining pressure for different intervals (2 to 20hrs) resulting in homogeneous aggregates of high-magnesium calcite; Mg content varied from 0.07 to 0.17 mol%. Creep tests were performed at differential stresses from 20 to 160 MPa at 700 to 800°C. Grain sizes before and after deformation were determined from the images obtained from scanning electron microscope (SEM) and optical microscope. Grain sizes are in the range of 5 to 20 microns depending on the HIP time, and decrease with increasing magnesium content. Both BSE images and chemical analysis suggest that all dolomite are dissolved and the Mg distribution is homogeneous through the sample, after 2 hrs HIP.

At stresses below 40 MPa, the samples deformed in diffusion region (Coble creep), as described previously by Herwegh. The strength decreases with increasing magnesium content, owing to the difference of grain size. At stresses above 80 MPa, the stress exponent is greater than 3, indicating an increased contribution of dislocation creep. The transition between diffusion to dislocation creep occurs at higher stresses for the samples with higher magnesium content and smaller grain size. Preliminary data suggests a slight increase in strength with increasing magnesium content, but more tests are needed to verify this effect. In a few samples, some strain weakening may have been evident. The activation energy in the transition region (at 80 MPa) is ∼ 200 KJ/mol with no dependence on magnesium content, agreeing with previous measurements of diffusion creep in natural and synthetic marbles.

URL: http://www.agu.org˜lilixu

T41D-0248 0830h POSTER

The Effect of Humidity and Particle Characteristics on Friction and Stick-slip Instability in Granular Fault Gouge

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