magnetic anomalies. It consists of a frontal prism and margin wedge upper plate underlain by a bend-faulted lower plate. The frontal prism maintains its modest width and taper in equilibrium with local conditions through feedback from subduction zone dip, friction along the decollement, and material strength. The prism elevates fluid pressure in the subducting plate forcing pore fluid into fractures above the plate interface thrust that hydrofract the underside of the upper plate margin wedge. Beneath the base of the slope, upper plate fracturing is aided by the up-and-down riffling over subducting topography. Progressive fracture and upward fluid migration shift the zone of least strength upward. The interplate thrust seeks the zone of least strength and shifts with the upward migrating fluid thereby detaching underlying upper plate material and transferring it to the lower plate. This process may begin at the seismogenic zone and progress updip to the landward part of the frontal prism. Beneath the lower slope fluid pressure and fracturing weaken the upper plate so that its strength decreases to the level of the subducting sediment. The model we propose can be tested with deep scientific ocean drilling.

T41B MCC: 3007 Thursday 0800h

The Structure and Physical Properties of Grain Boundaries in Rocks I *(joint with V)*

Presiding: **A M McCaig,** University of Leeds**; O Schenk,** Aachen University

T41B-01 0805h INVITED

Synthetic Grain Boundaries in Rock Forming Minerals

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A grain boundary may be defined as the zone separating two crystals differing in crystallographic orientation, composition, or dimension of the crystal lattice. In polycrystalline, multiphase materials, grain boundaries or phase boundaries are present in many different configurations forming three-dimensional networks very much like the networks of liquid films that A constitute foams. Physical properties of rocks, as for example, strength, electrical conductivity and diffusivity are largely controlled by grain boundary properties. Most of our present knowledge on grain boundaries stems from studies of metals and alloys. Likewise, the structure and properties of grain or phase boundaries in ceramics consisting of complex ionic and covalent compounds are well investigated. However, relatively little is known about the structure and physical properties of grain boundaries in rocks. For example, grain boundary diffusivity and mobility depend on orientation, and they are different for low and high angle grain boundaries. We successfully synthesized bicrystals of rock-forming minerals with defined grain boundaries to investigate their physical properties. We used the direct bonding technique to avoid plastic deformation of the grain boundary region. We synthesized quartz, periclase (MgO), forsterite and feldspar bicrystals. In addition, we successfully produced a forsterite bicrystal directly from a melt using the Czochralski method. For each direct bonded bicrystal two oriented mineral single crystals were joined at room temperature and annealed at 400°C for one week. All bicrystals were cut in two parts and one part was annealed further at 0.9 T_m for 48h. Specimens were prepared for investigation in the transmission electron microscope (TEM) using the focused ion beam (FIB) technique. High-resolution TEM studies reveal similar grain boundary structures produced at 400°C and at 0.9 T_m between undisturbed crystals. This suggests that bonding of bicrystals was effective at or below 400°C. Common structural elements of the synthetic grain boundaries encompass dislocations, steps and disconnections.

T41B-02 0825h INVITED

The Effect of Magnesium on Diffusion in Calcite Under Static and Deformational Conditions

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In order to test the influence of solute impurities on diffusion creep and static grain growth, synthetic calcite aggregates with variable Mg contents were tested. The synthetic marbles were produced by HIPing different mixtures of dry calcite and dolomite powders at 1123K for 2 hours. During the HIP, chemically induced grain boundary migration occurred via a combination of diffusion processes and chemically induced grain boundary migration. After HIP, creep tests were performed at 300 MPa and temperatures in the range of 923-1123K. Creep experiments on aggregates with small grain sizes show that the strength of calcite aggregates correlates inversely with dissolved Mg content at flow stresses below 40 MPa. However, under static conditions, grain growth rates decrease with increasing Mg content. Thus, the inverse correlation between strength and Mg content appears to arise from suppression of grain size with increasing Mg content, i. e., the effect of Mg on strength is indirect through an extrinsic control of calcite grain size, rather than an extrinsic control on grain boundary diffusion rate during deformation. Creep tests in the diffusion creep field for samples with identical grain size, but with variable Mg content, revealed no dependence of strength on the Mg content. The creep tests seem to indicate that the rate controlling step during self-diffusion is not affected by changes in the Mg concentration. It is possible that solid solutes are segregated to the calcite grain boundaries and that impurity drag affects the boundary mobility, but not the self-diffusion rate.

T41B-03 0845h

Rapid Diffusion of Ca Along Migrating Grain Boundaries in Calcite

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Grain boundary diffusion is an important process at moderate to high homologous temperatures and one that has the potential to redistribute isotopes and other chemical species over significantly greater length scales than volume diffusion alone. When the grain boundaries are moving, this redistribution can be greatly enhanced because the incorporation of tracers into the grain interiors is not limited by the short length scale of volume diffusion, as it is in the case of static boundaries. An experimental charge consisting of a layer of fine (< 5 μm) calcite powder containing 25% ^{44}Ca-enriched calcite (98% ^{44}Ca compared with the natural abundance of 1.95%) was sandwiched between cylinders of single crystal calcite and Carrara marble and hot isostatically pressed at 900 °C 200 MPa for 10 hours. Examination of the experimental run products using the SEM in orientation contrast mode shows that during the experiment the fine calcite layer underwent static recrystallization followed by normal grain growth. The resulting mean grain size was 60-80 μm. The single crystal also statically recrystallized in a 5 mm wide layer immediately adjacent to the powder layer. The resulting grain size was 100 μm to 1 mm. The driving force for this latter recrystallization was the small amount of strain energy introduced during the initial pressurization of the charge as the powder layer compacted. There were no noticeable changes in the Carrara marble layer, which retained its initial grain size of about 150 μm. Isotopes ^{44}Ca and ^{40}Ca were imaged using the Cameca ims4f microprobe at Edinburgh University, and ion beam traverses were also made with an estimated effective beam diameter of 5 μm. Combined images of ^{44}Ca/(^{44}Ca+^{40}Ca) reveal extensive but very heterogeneous zoning of ^{44}Ca in the recrystallized single crystal, and relict cores of ^{44}Ca-enriched calcite in recrystallized grains in the powder layer. On the whole the powder layer homogenised to a composition of 22-24% ^{44}Ca, and provided a fairly fixed composition source of ^{44}Ca to diffuse into the recrystallizing single crystal. Penetration into the single crystal along mobile grain boundaries was extensive, with zones of up to 8% ^{44}Ca present locally at > 300 μm from the tracer layer. Complex isotopic zoning patterns are interpreted to result primarily from variations in boundary migration velocity. There is good evidence that parts of the original single crystal have been swept by multiple grain boundaries, and that some boundaries reversed migration direction. Mishin and Razumovski (1992) developed an analytical model for the concentration (C) of tracer in a grain behind a grain boundary that is moving parallel to an interface beyond which there is a constant composition source of tracer. They found that the gradient reaches a steady state given by $d(\ln C)/dx = (V/D_{GB}\delta)^{0.5}$, where V is the velocity of migration, D_{GB} the grain boundary diffusion coefficient and δ the grain boundary width. Although our grain geometries are more complex and our ion probe profiles are not ideally located, it is possible to estimate maximum values for $d(\ln C)/dx$ parallel to moving boundaries and minimum values for V based on the width of compositional zones and the duration of the experiment. We estimate **minimum** values for $D_{GB}\delta$ of 10^{-18} m^3/s, about 500 times greater than the value reported by Farver and Yund (1996) in static grain boundaries.

T41B-04 0900h

Diffusion-Controlled Reaction rim Growth Studied in Thin Films Down to the Nano Scale

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Grain boundaries play a crucial role for diffusion in polycrystalline materials. Diffusion through polycrystalline rims of enstatite-rich pyroxene was studied in pulsed-laser deposited thin films [1] by the rim growth method. The starting samples consisted of layers of isotopically doped (^{18}O, ^{29}Si) olivine $fo_{90}fa_{10}$ (c. 500 nm thick) and pyroxene $en_{90}fs_{10}$ (c. 100 nm thick) on a polished quartz surface. Annealing experiments were performed at temperatures between 1000 and 1200 °C at fO_2 of 10^{-10} bar. Layer thickness and composition were measured by Rutherford Back-Scattering (RBS) and TEM using Focused Ion Beam preparation methods. O and Si isotope profiles were measured by SIMS depth scanning. The miniaturization of the layer assembly allows one to study growth at lower temperatures than previously possible and avoids large extrapolations to natural conditions. During the experiments the enstatite layers thicken by rates for ΔX^2 of 700 to 50000 nm^2/h at the chosen conditions. An activation energy of 398±30 kJ/mol was derived. The rim growth rates are slightly slower than expected from an extrapolation of high temperature data (1350-1450 °C) [2] but yield the identical activation energy, suggesting that rim growth over the entire temperature range is controlled by the same diffusion mechanism and that this is valid down to the nano scale. At 1000 °C enstatite rim growth in our dry experiments is slower by about 4 orders of magnitude than in high pressure experiments at 7 [3] resp. 10 kbar [4] in the presence of small amounts of H_2O. The isotope concentration profiles reveal that Si acts as a slow diffusing component compared to O. Effective diffusion coefficients D_{eff} for Si were derived from the SIMS profiles using a moving boundary diffusion model. $D_{eff}{}^{Si}$ in the dry polycrystalline enstatite rims is 2-3 orders of magnitude smaller than in polycrystalline olivine under similar conditions [5]. At 1000 °C $D_{eff}{}^{Si}$ is 4 orders of magnitude smaller than in enstatite rims during hydrous high pressure experiments [6]. Ref.: [1] Dohmen et al. (2002) Eur J Miner 14: 1155-1168; [2] Fisler et al. (1997) Phys Chem Minerals 24: 264-273; [3] Yund (1997) Contrib Miner Petrol 126: 224-236; [4] Milke et al. (2001) Contrib Miner Petrol 142: 15-26; [5] Farver & Yund (2000) Geophys Res Letters 27, 2337-2340; [6] Abart et al (2002) J Conf Abs 7, 4

T41B-05 0915h

Grain Growth Kinetics of Dolomite and Magnesite

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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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