Melt-rock and fluid-rock interactions in serpentinized abyssal harzburgites (Mid-Atlantic Ridge, ODP Leg 209)

N. Jöns1, W. Bach1, M. Rosner1,2, T. Schroeder3

1Fachbereich Geowissenschaften, Universität Bremen, Klagenfurter Straße, 28359 Bremen, Germany
2present address: Bundesanstalt für Materialforschung und -prüfung, 12205 Berlin, Germany
3Faculty of Science and Mathematics, Bennington College, Bennington VT05201, U. S. A.

At slow- and ultraslow-spreading mid-ocean ridges, abyssal peridotites are commonly exposed at the seafloor. Peridotite-seawater interaction leading to serpentinization influences the rheology, density and chemistry of the oceanic lithosphere. In addition, serpentinization reactions are the cause for increased methane and hydrogen concentrations, which fuel microbial activities at ultramafic-hosted hydrothermal systems. An almost complete lithological and hydrological history of the oceanic lithosphere can best be reconstructed by examination of different generations of veins. These veins are representative for an enormous spectrum of processes, from high-temperature melt impregnation in the deep lithosphere to seawater alteration at ambient pressures and temperatures.

We examined drillcore samples from the Mid-Atlantic Ridge (ODP Leg 209). The sample localities are north and south of the prominent 15°20’N Fracture Zone; Site 1270 is in proximity to the ultramafic-hosted Logatchev hydrothermal vent field. Here, abyssal peridotite is exposed along low-angle detachment faults. At Site 1270, four holes were drilled near the top of an exposed long-lived normal fault (Kelemen et al. 2004; Schroeder et al. 2007). Samples are strongly serpentinized peridotites with abundant gabbroic intrusions. Our study focuses on serpentinites that are crosscut by strongly deformed shear zones. These shear zones feature a distinct mineralogy and are of schistose appearance. Therefore, they are frequently referred to as “fault schists” (e.g., Boschi et al. 2006b).

Chlorite-amphibole-bearing veins are found within shear zones. There has been considerable debate about the formation mechanism of such chlorite- or, in other cases, talc-bearing fault schists. Some authors propose that these lithologies form from an ultramafic protolith under conditions of extremely high fluid/rock ratios, whereas others identify gabbroic melt impregnation veins as the likely protolith (e.g., Escartín et al. 2003; Bach et al. 2004; Boschi et al. 2006a, b). Veins examined in this study consist of porphyroclasts of brownish magneisohornblende in a matrix of fibrous chlorite (X_Mg = 0.82–0.95). Hornblende (X_Mg = 0.86–0.96; TiO_2 = 1.7–2.4 wt.%; Al_2O_3 = 6.9–9.6 wt.%) crystals are slightly deformed with needles of actinolite/tremolite (X_Mg = 0.85–0.93; TiO_2 = 0.00–0.08 wt.%; Al_2O_3 = 0.8–2.9 wt.%) growing in pressure shadows (Figure 4). No talc has been identified. Zircon and apatite are common accessory mineral phases. From major and trace element geochemistry as well as mineralogy we conclude that the chlorite-amphibole veins represent alteration products of former plagiogranitic melt impregnations (Jöns et al., in press). Ti-in-Zircon thermometry (Watson and Harrison 2005; Ferry and Watson 2007) yields temperatures of ca. 820 °C for the crystallization of the precursor melt, which is in agreement with a plagiogranite. To provide a model for fluid flow through the detachment fault system and to examine the fluid-rock interactions necessary to produce the alteration assemblage observed, we performed reaction path modeling using the EQ3/6 software package. The model predicts rodigritzerization assemblages for hydrous alteration of a pure plagiogranite. In contrast, a mechanical mixture of plagiograniitic and harzburgite, which is likely to be present on a shear zone, is able to act as a model protolith for the observed chlorite-amphibole assemblage. The model also shows that serpentine directly adjacent to altered plagiogranite veins as part of the equilibrium assemblage. To explain the co-occurrence of shear zones and chlorite-amphibole schists, we propose the following model: shear zones enable seawater to enter the oceanic crust. At greater depth and higher temperatures, the fluids might get in contact with gabbro intrusions, lower the gabbro solidus and allow partial melting and thus plagiogranite formation. During cooling under hydrous conditions, the original plagiogranite mineralogy breaks down to form a chlorite-bearing assemblage at temperatures of ca. 400–500 °C. At such temperatures olivine of the surrounding harzburgites and dunities is still stable, leading to strain localization around the altered melt veins. During further cooling, these shear zones act as effective fluid pathways for serpentinization of the host peridotites.

Figure 4: (a) Serpentinite showing the co-occurrence of chlorite-amphibole-bearing veins and shear zones. The latter is crosscut by picrolite veins. (b) Porphyroclast of magnesiohornblende in a matrix of chlorite. Fine-fibrous actinolite/tremolite is growing around magnesiohornblende.
Peridotite host rocks are almost completely serpentinized dunites or harzburgites, with less than 10 vol.% of the primary minerals being preserved. Relics of olivine are locally found in mesh textures, where they are largely replaced by secondary serpentine minerals; in shear zones, fine-grained recrystallized olivine is locally present. Both generations are Mg-rich with $X_{Mg}=0.87-0.90$. Orthopyroxene is only rarely preserved. It is Mg-rich ($X_{Mg}=0.91-0.93$), contains some aluminium ($Al_{2}O_{3}=1.2-3.8$ wt.%) and mostly replaced by serpentine in bastite textures. Another primary mineral phase is chromium-bearing (Cr/[Cr+Al]=0.47-0.55) spinel, which is generally rimmed by magnetite. By far the most common secondary mineral is serpentine. In mesh textures after olivine it is more magnesian ($X_{Mg}=0.93-0.97$) than in bastite pseudomorphs after orthopyroxene ($X_{Mg}=0.88-0.92$). Notably, brucite is not present as a secondary mineral phase after olivine, demonstrated by means of XRD, optical and electron microscopy. This is in accordance with reaction path modeling, which shows that high aSiO$_2$ values imposed to the fluid by the nearby plagiogranitic material inhibit brucite formation in the serpentinites.

In addition, the whole-rock chemistry of serpentinites is changed in vicinity of melt veins: compared to an average peridotite, a strong enrichment in rare earth elements, strontium and potassium is found, whereas cobalt and nickel were apparently lost. These chemical changes can in part be explained by slight mechanical mixing of peridotite and plagiogranite on the shear zone, but must also result from fluid flow on the detachment fault. The latter is evidenced by whole-rock oxygen isotope data of altered plagiogranite veins ($\delta^{18}O=+3.0-4.2$ ‰ SMOW) and adjacent serpentinites ($\delta^{18}O=+2.6-3.7$ ‰ SMOW). Compared to values of unaltered peridotites ($\delta^{18}O=+5.5$ ‰ SMOW) and serpentinites more distal from melt impregnations ($\delta^{18}O=+3.2-5.2$ ‰ SMOW; Alt et al. 2007), these comparatively low values indicate an intense influx of seawater-derived fluids in the detachment fault system.

Serpentine minerals in shear zones record both melt-rock and fluid-rock interaction processes. Lithological inhomogeneities due to formation of plagiogranitic or gabbroic veins at high temperatures remain the locations of intense fluid flow even during cooling to greenschist- or subgreenschist-facies conditions. These major fluid pathways allow for initiation of serpentinization at different crustal levels and contribute to cooling of the oceanic crust.


