Serpentine and serpentinization: A link between planet formation and life

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Ultramafic rocks, composed mainly of olivine and pyroxenes, are a major component in the lithosphere of early terrestrial planets, where they formed by direct crystallization of mantle-derived magmas on the planet’s surface or by partial crystallization as cumulates from a magma ocean. On modern Earth, ultramafic rocks are commonly exposed near and along slow- and ultraslow-spreading ridges (e.g., Dick et al., 2003), along magma-poor passive margins (e.g., Boillot et al., 1980) and in tectonically active zones in mountain belts. The way that ultramafic rocks alter into serpentine is central to a variety of processes at the interface between the solid earth, the hydrosphere, the atmosphere, and the biosphere.

There are three main serpentine polymorphs—chrysotile, lizardite, and antigorite—whose stability fields are dependent on both thermodynamic and kinetic parameters (e.g., Evans, 2004). Serpentine contains ~13 wt% H₂O and is thus an important player in the global subduction zone water cycle and for inducing flux melting in the mantle wedge beneath subduction-related magmatic arcs (Ulmer and Trommsdorff, 1995). Growing appreciation of peridotite exposure on the seafloor and its interaction with seawater controlling low-temperature hydrothermal systems has led to new insights into how serpentine forms, how water is incorporated into serpentine minerals, and how important serpentinization might be as an energy source for anaerobic microorganisms.

Experimental investigations, field studies on Alpine peridotite and serpentinites, dredging and drilling results from mid-ocean ridges and active venting systems, and theoretical calculations have shown that serpentinization produces H₂-rich fluids, alkaline solutions, and Fe-Ni alloys (Früh-Green et al., 2004; Sleep et al., 2004). Water in contact with peridotite minerals, mainly olivine and pyroxenes, is reduced to form molecular hydrogen and concomitant oxidation of iron. Hydrogen released during serpentinization is of vital importance for the emergence of life because it acts as an energy source for metabolism (Corliss et al. 1981; Kelley et al. 2005; Russell, 2007), but may, at high temperatures, also be combined with CO₂ for the abiotic formation of organic compounds such as hydrocarbons and fatty acids through Fischer-Tropsch--type synthesis (Holm and Charlou 2001; Russell 2007). However, the efficiency of these processes depends on the concomitant formation of magnetite and Fe-Ni alloys, which act as catalysts to enhance production of hydrogen, methane, and higher hydrocarbons.

Between 1995 and 2001, two fundamental discoveries—the existence of planets outside of the solar system, and the existence of low-temperature hydrothermal fields—have propelled research efforts in serpentinization processes that are now recognized as probably the most important metamorphic hydration reactions for explanations of the origin of life. Ever since humans recognized the unique physical and chemical environments on Earth relative to other planets of the solar system, they were plagued by the question of whether there are similar conditions in other stellar systems of the universe. This curiosity has been partially satisfied with the first key discovery of exoplanets by Mayor and Queloz (1995), and later discoveries of many other stellar systems with celestial bodies similar to our solar system planets.

The second key discovery came with the advent of the new millennium and the discovery of the Lost City ultramafic-hosted hydrothermal system on the Atlantis Massif at 30°N, ~15 km west of the Mid-Atlantic Ridge, which is associated with serpentinization (Kelley et al., 2001). Coupled with the knowledge that the undifferentiated crust of terrestrial planets such as Mars and the early Earth is largely composed of mafic and ultramafic rocks (Longhi et al., 1992), these observations have led to an increased interest in the origin of life, both terrestrial and extraterrestrial, especially since the discovery of exoplanets (Mayor and Queloz, 1995). This has fueled a new interdisciplinary research direction called astrobiology, and recent efforts on Mars pointed out the importance of serpentinization on Mars in the formation of molecular hydrogen and methane (Oze and Sharma, 2005; Schulte et al., 2006). Clearly, understanding serpentinization of ultramafic rocks is one of the pillars in linking life sciences with solid earth processes, and may be the fundamental process for prebiotic and biotic environments on extraterrestrial planetary bodies.

It is thus no surprise that research on serpentinization has substantially increased over the past years, but the fundamental question of why low-temperature serpentinization is related to oxidation, and high-temperature serpentinization is not, has not seriously been debated. The answer to this contentious question is as important as it is simple—it ultimately depends on the Fe-Mg lattice diffusion in olivine. Evans (2010, p. 879 in this issue of Geology) makes the point that magnetite and molecular H₂ production depend on the temperature of serpentinization, and ultimately on the Fe-Mg lattice diffusion in olivine. A fundamental observation is that the Fe-Mg distribution coefficient (Kd) between serpentine and olivine in thermodynamic equilibrium is less than 1 (Trommsdorff and Evans, 1972). The manner in which iron and magnesium can be balanced during serpentinization is twofold and is intrinsically linked to the achievement of thermodynamic equilibrium. For a constant magnesium number (Mg#) of olivine, which is usually the case at temperatures <300 °C because of extremely sluggish Fe-Mg diffusion in olivine, serpentine + magnetite + molecular hydrogen, and in some cases brucite, and Fe-Ni-Co alloys are formed. Ferric iron is mainly stored in magnetite, and, at low temperatures of 100–200 °C, to some degree in lizardite. Magnetite is thus largely the consequence of the Mg-rich nature of serpentine. In a higher-temperature regime, above 400 °C, Fe-Mg diffusion is orders of magnitude faster, and above ~600 °C, thermodynamic equilibrium is achieved, and olivine will adapt its Mg# to lower values than mantle olivine, according to the Fe-Mg distribution coefficient between olivine and coexisting minerals (e.g., Müntener et al., 2000). The consequence is that little magnetite is formed if olivine coexists with antigorite, and this might be the principal difference to distinguish between ocean floor serpentinization and mantle wedge serpentinization, as pointed out by Evans (2010).

One of the obvious follow-up questions that emerge from Fe-Mg diffusion in olivine and its role for serpentinization and hydrogen production is both important and more difficult to answer: Is the proposed mechanism of “sluggish low-T Fe-Mg lattice diffusion in olivine” (Evans, 2010, p.881) equally important for the reaction of peridotite with anion-rich or CO₂-rich fluids? Natural carbonation of tectonically exposed peridotite during subaerial weathering and sub-seafloor alteration by the formation of carbonates such as magnesite (CaCO₃), calcite (CaCO₃), or dolomite (CaMg(CO₃)₂) is a significant sink for CO₂, and has recently gained much
attention as a potentially important natural process for the long-term storage of CO₂. Away from mid-ocean ridges, drilling into the magma-poor passive margins of Newfoundland-Iberia (Ocean Drilling Program legs 103, 149, 176, and 210) demonstrates that carbonate-serpentinite associations (also known as ophiocarbonates) build up the interface between tectonically exhumed serpentinized mantle and the post-rift sedimentary cover (e.g., Tucholke and Sibuet, 2007). However, the mass fraction of carbonates and serpentinites that formed during exposure on the seafloor, relative to the mass fraction that formed later under a thick pile of post-rift sediments, is poorly constrained. Serpentinitization is, as carbonation, an exothermic reaction that leads to heat production (Fyfe, 1974). If these processes are active while deep margins are buried by sediments, the heat flow could be substantial, and lead to contemporary maturation of hydrocarbons in marine settings in areas far from mid-ocean ridges.

Much progress has been made over the past few years in unraveling the details of the mechanisms by which serpentinitization progresses (McCollom and Bach, 2009). Recent approaches to determine the influence of dissolved CO₂ on serpentinitization rates include hydrothermal experiments (Jones et al., 2010). The results indicate that ferrous iron is more rapidly incorporated into carbonates than in oxidized to form carbonates and serpentinites that formed during exposure on the seafloor, cover (e.g., Tucholke and Sibuet, 2007). However, the mass fraction of tectonically exhumed serpentinized mantle and the post-rift sedimentary accretions (also known as ophicarbonates) build up the interface between rocks and life.

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