



Invited review article

Serpentine in active subduction zones

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ABSTRACT

Serpentinization is a key phenomenon for understanding the geodynamics of subduction zones in the 10–200 km depth range. Serpentine is a major water carrier, and their rheological properties have a strong influence on deformation partitioning and seismicity at depths. I review experimental investigations that have been conducted on serpentines, with emphasis on the large body of data acquired over the past decade. Determinations of physical properties at the pressure and temperature conditions of subductions allow interpreting geophysical data in active subduction in terms of mineralogy and petrology, and to link the presence of serpentinites with deformation and fluid circulation. The fluid budget can be partially constrained from geophysical data. Elasticity data provide a quantitative basis for mapping serpentinization in the mantle wedge and slab from seismic tomography. Anisotropy suggests the existence of thin serpentinite channels above the plate interface, that account for mechanical decoupling inferred from down-dip limit of the seismogenic zone and heat flow. Strain-rate dependent rheology of antigorite serpentine is consistent with stable deformation of this thin layer or channel over timescales ranging from those of the seismic cycle to those of thermal equilibration and exhumation of high-pressure rocks, and with the geological record of subduction-related deformation. Circulation of serpentinizing fluids depends on the permeability structure, and is imaged by electrical conductivity tomography. It could be controlled by fracturing in the undeformed cold nose of the mantle wedge, and by plastic deformation along the plate interface. Fluid migration mechanisms are similar to those inferred from petrological and geochemical data on exhumed serpentinites. Estimation of the fluid budget associated with serpentine formation will rely on numerical simulations for which coupling of kinetics of hydration and dehydration at scales ranging from grain size up to faulting pattern needs to be established, especially for water cycling to the transition zone in the core of the slab.

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1. Introduction

Serpentinites form by the interactions of water with ultrabasic and basic rocks at two major geodynamic sites: At mid-oceanic ridges (Bonatti et al., 1970; Cannat, 1993; Christensen, 1972; Miyashiro et al., 1969), where intense hydrothermal alteration is fueled by temperature gradients associated with magmatic activity and extensive fracturing of the crust; and at subduction zones, where serpentinitization occurs in the subducting mantle in association with slab-bending faulting (Ranero et al., 2003), and in the overlying mantle wedge where fluids from the dehydration of the subducting slab move upwards (Barriga et al., 1992; Maekawa et al., 1993; Peacock, 1993).

Serpentinitization is an essential geodynamical process because it drastically changes the physical and mechanical properties of mantle and oceanic crustal rocks. Fully serpentinitized peridotites have densities down to $2.6\text{--}2.7 \cdot 10^3 \text{ kg/m}^3$ or lower, and are as buoyant as the continental crust. Geological and experimental observations led to the early recognition that they form highly deformable zones, and that they are associated with and can localize deformation at major faults and plate boundaries (Coleman, 1971; Hess, 1955; Raleigh and Paterson, 1965; Scarfe and Wyllie, 1967). Serpentinitization is also essential for understanding of the water cycle, because serpentinites store up to 12–13 wt.% water in a solid form that can be subducted to great depths (Scambelluri et al., 1995; Ulmer and Trommsdorff, 1995).

The influence of serpentine and serpentinitization on subduction zone geodynamics has been studied with petrological, geodynamical, and geophysical approaches (Hyndman and Peacock, 2003; Hyndman et al., 1997; Stern, 2002). Exhumed terrains provide petrological records of the subduction history that can be tied to the processes taking place at the time when subduction was active, and the role of serpentinites in both subduction (Strating and Vissers, 1991) and exhumation has been emphasized (Guillot et al., 2009; Hermann et al., 2000; Mizukami and Wallis, 2005; Schwartz et al., 2001). Numerical simulations of increasing complexity provide a dynamical picture of mass and water transfer in subduction, where serpentine physical properties play a major role (Gerya et al., 2002; Iwamori, 1998; Rüpke et al., 2004; van Keken et al., 2011).

Geophysical surveys of subduction zones have greatly improved with the installation of temporary or permanent high-density networks of geophysical stations. These networks provide increasing amounts of information on the physical properties of materials at depths and on the dynamics of active subduction zones (Table 1). This includes spectacular tomographic images of seismic properties (Abers et al., 2009; Audet et al., 2009; Bostock et al., 2002; Kawakatsu and Watada, 2007; Matsubara et al., 2009; Nakajima et al., 2009b), real-time measurements of active tectonics at intermediate timescales from tremors to slow slip (Obara, 2002; Radiguet et al., 2011; Rogers and Dragert, 2003; Subarya et al., 2006), and electrical conductivity tomography (Ichiki et al., 2009; Matsuno et al., 2010; Soyer and Unsworth, 2006; Worzewski et al., 2011).

Interpretation of geophysical signals in terms of the nature of rocks, their relation to subduction geodynamics, and input data for numerical simulations relies on laboratory measurements of mineral and rock transformation and properties under the conditions of pressure and temperature of the crust and mantle. The role of serpentine in subduction processes has stimulated a large body of experimental studies over the last decades. Current ideas on the potential presence of serpentine in subduction are summarized in Fig. 1. I review here these results, and outline some consequences for

our understanding of active subduction geodynamics as probed by geophysical observation.

2. Thermodynamic and elastic properties of serpentines

2.1. Serpentine varieties and high-pressure stability

Serpentines are phyllosilicates based on the stacking of tetrahedral–octahedral sheets bonded by hydroxyl groups, and their structures have been reviewed in details elsewhere (Wicks and O'Hanley, 1988). Lizardite is the simplest structure with stacking of flat layers; antigorite has a corrugated structure with regular inversion of layers along one in-plane direction. Sheets define the basal plane of crystals, and the anisotropic properties of serpentine and phyllosilicates. Other varieties are derived from these two with topologies akin to the carbon nanotubes and fullerenes (Baronnet et al., 2007), of which the major nanotube variety is the asbestos chrysotile with rolled sheets (Yada, 1967).

The metamorphic or magmatic origin of serpentine has long been debated in spite of early recognition that it forms during alteration of olivine rocks by slow water infiltration (Bonney, 1877). After the experimental demonstration that serpentine could not have a magmatic origin because of decomposition to anhydrous phases near 500 °C (Bowen and Tuttle, 1949), the stability field of serpentines was investigated to moderate pressure of a few kilobars (Kitahara et al., 1966), and then with the aim of unraveling the complex stability relationships of serpentine varieties like antigorite and chrysotile (Evans et al., 1976). Phase relationships in the hydrated ultrabasic rock systems have been summarized, and a thermodynamic dataset established (Berman, 1988; Chernosky et al., 1988). These studies demonstrated a relatively

Table 1

Summary of physical properties of antigorite serpentine.

Thermodynamic properties for molar composition $\text{Mg}_{48}\text{Si}_{34}\text{O}_{85}(\text{OH})_{62}$
Free enthalpy of formation (Connolly, 2005)
$\Delta G_0 = -66132.44 \text{ kJ.mol}^{-1}$
Entropy (Connolly, 2005)
$S_0 = 3591 \text{ J.mol}^{-1}.\text{K}^{-1}$
Molar volume (Connolly, 2005)
$V_0 = 175.48 \text{ cm}^3$ (density at ambient conditions $\rho_0 = 2.62 \text{ g.cm}^{-3}$ for common natural composition)
Heat capacity (Connolly, 2005)
$C_p(T) = c_1 + c_2 T + c_3/T^2 + c_5/T^{1/2} \text{ J.mol}^{-1}.\text{K}^{-1}$, where $c_1 = 9621$, $c_2 = -0.091183$, $c_3 = -35941600$, $c_5 = -83034.2$
Thermal expansivity (Connolly, 2005)
$\alpha = 4.7 \cdot 10^{-5} - 4.710^{-4}/T^{1/2} \text{ K}^{-1}$
Equation of state, third order Birch–Murnaghan parameters (Hilalret et al., 2006a, 2006b; Nestola et al., 2010)
$K_0 = 62.9 \text{ GPa}$, and $K'_0 = 6.1$
Elastic constants (Bezacier et al., 2010a)
$C_{11} = 208.1(5.4) \text{ GPa}$, $C_{22} = 201.6(4.8) \text{ GPa}$, $C_{33} = 96.9(0.9) \text{ GPa}$, $C_{44} = 16.9(0.1) \text{ GPa}$, $C_{55} = 18.4(0.1) \text{ GPa}$, $C_{66} = 65.5(0.6) \text{ GPa}$, $C_{12} = 66.4(1.1) \text{ GPa}$, $C_{13} = 16.0(0.8) \text{ GPa}$, $C_{23} = 4.9(1.6) \text{ GPa}$, $C_{15} = 5.5(0.3) \text{ GPa}$, $C_{25} = -3.1(0.3) \text{ GPa}$, $C_{35} = 1.6(0.1) \text{ GPa}$, $C_{46} = -12.1(0.2)$
Power-law rheology (Hilalret et al., 2007)
$\partial \epsilon / \partial t = A \sigma^n \exp\{[E + PV]/RT\} \text{ s}^{-1}$, where $\partial \epsilon / \partial t$ is the deformation rate, σ the stress, $\ln A = -86$, $n = 3.8$, $E = 8.9 \text{ kJ.mol}^{-1}$, and $V = 3.2 \text{ cm}^3$
Thermal conductivity, k , and diffusivity, K (Osako et al., 2010)
$k = 2.4 + 0.07P$
$K = k/\rho C_p$, where ρ is density
Electrical conductivity (Reynard et al., 2011)
$\sigma = A \exp(E/RT) \text{ S.m}^{-1}$, $A = 400 \text{ S.m}^{-1}$ (maximum value), $E = 115 \text{ kJ.mol}^{-1}$
P and T are pressure and absolute temperature, respectively.

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