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Deformation mechanisms of antigorite serpentinite at subduction zone conditions determined from experimentally and naturally deformed rocks

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ABSTRACT

We performed deformation-DIA experiments on antigorite serpentinite at pressures of 1–3.5 GPa and temperatures of between 400 and 650 °C, bracketing the stability of antigorite under subduction zone conditions. For each set of pressure–temperature (P–T) conditions, we conducted two runs at strain rates of 5×10^{-5} and 1×10^{-4} s^{-1}. We complemented our study with a sample deformed in a Griggs-type apparatus at 1 GPa and 400 °C (Chernak and Hirth, 2010), and with natural samples from Cuba and the Alps deformed under blueschist/eclogitic conditions. Optical and transmission electron microscopies were used for microstructural characterization and determination of deformation mechanisms. Our observations on experimentally deformed antigorite prior to breakdown show that deformation is dominated by cataclastic flow with observable but minor contribution of plastic deformation (microkinking and (001) gliding mainly expressed by stacking disorder mainly). In contrast, in naturally deformed samples, plastic deformation structures are dominant (stacking disorder, kinking, pressure solution), with minor but also perceptible contribution of brittle deformation. When dehydration occurs in experiments, plasticity increases and is coupled to local embrittlement that we attribute to antigorite dehydration. In dehydrating samples collected in the Alps, embrittlement is also observed suggesting that dehydration may contribute to intermediate-depth seismicity. Our results thus show that semibrittle deformation operates within and above the stability field of antigorite. However, the plastic deformation recorded by naturally deformed samples was likely acquired at low strain rates. We also document that the corrugated structure of antigorite controls the strain accommodation mechanisms under subduction conditions, with preferred inter- and intra-grain cracking along (001) and gliding along both a and b. We also show that antigorite rheology in subduction zones is partly controlled by the presence of fluids, which can percolate within the exhumation channel via deformation-induced interconnected porosity.

1. Introduction

Subduction zones host numerous processes that impact the dynamics and geochemical evolution of the Earth (see Tatsumi and Kogiso, 2003; Hirth and Guillot, 2013). In this context where tectonic stresses dominate, the peculiar rheological properties of serpentinites focus the interest of the scientific community (see Reynard, 2013 for a review). Indeed, serpentinites are believed to be an important component of the subducting slab owing to the hydrothermal alteration of the oceanic lithosphere (Mevel, 2003; Garth and Rietbrock, 2014). Additionally, serpentinite are present in the mantle wedge due to fluids rising from the dehydrating lithosphere, as inferred from the low seismic velocities (Hyndman and Peacock, 2003) and the high Poisson's ratio (Kamiya and Kobayashi, 2000) of the mantle wedge. These inferences from geophysical observations are supported by field evidence in paleo-subduction zones (Guillot et al., 2009) or serpentine mud volcanoes (Fryer et al., 1999). Understanding how serpentinites deform

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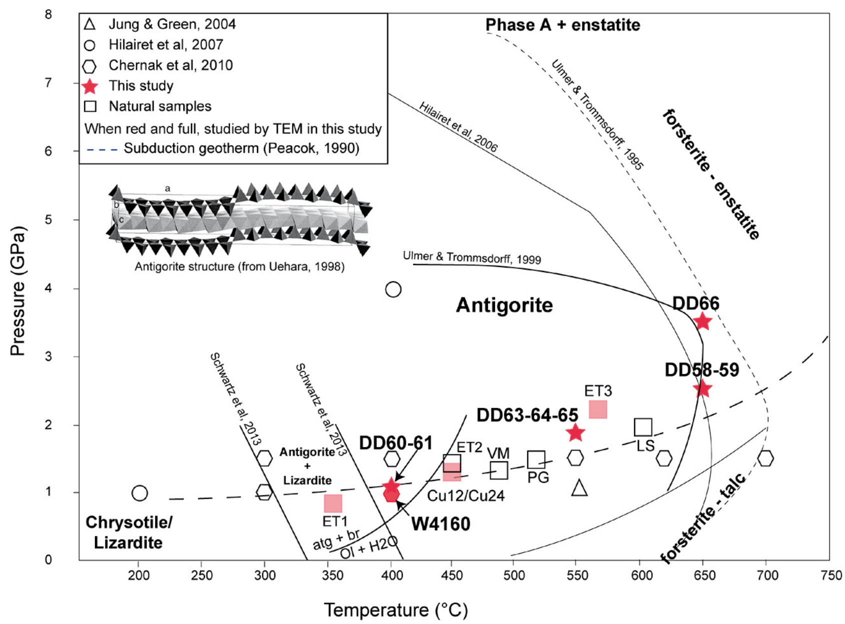

Fig. 1. P–T diagram plotting the experimental conditions reported in this study and from previous experimental works. Curve limiting the thermal stability of antigorite are reported from Ulmer and Trommsdorff (1999) and Hilairet et al. (2006). We also reported the curve from Ulmer and Trommsdorff (1995) which is widely used in the literature but is incorrect (see Ulmer and Trommsdorff, 1999). We also plotted the metamorphic conditions undergone by natural samples (ET1, 2 and 3 correspond to Erro Tobbio metamorphic stages from Hermann et al., 2000; VM, PG and LG stand for Vizzo Mozzo, Passo Gallarino and Lago Superiore units described by Schwartz et al., 2000) as well as experimental conditions from previous studies. Insert illustrates to the corrugated crystal structure of antigorite (dark silicate tetrahedra and light magnesian octahedra).

in subduction zones, particularly in the exhumation channel that overlies the subducting slab (Hilairet and Reynard, 2009), is of prime importance to understand decoupling between the downwelling slab and the overriding plate (Wada et al., 2008), exhumation of high-pressure rocks (Guillot et al., 2001; Agard et al., 2009), controls on fluids pathways (Padrón-Navarta et al., 2010) and, more generally, the mantle wedge dynamics (see van Keken, 2003 and references therein). Also, when dehydration occurs at depth, serpentine embrittlement is believed to trigger seismicity (Dobson et al., 2002; Hacker et al., 2003; Jung and Green, 2004; Peacock, 2001; Garth and Rietbrock, 2014). The fate of the dehydration fluids is also of great importance as they affect the properties of mantle rocks such as their rheology and melting temperature and impact the geochemical budget of elements that are recycled in the subduction zone (Deschamps et al., 2013; Marchesi et al., 2013).

Serpentine minerals (1:1 hydrous phyllosilicates) display three main structural varieties: lizardite (flat), chrysotile (tubular), and antigorite (corrugated). In subduction zones, antigorite is the stable variety (Ulmer and Trommsdorff, 1995) and its rheological behavior has been probed by numerous studies, yielding diverging results or interpretations. Some experimental studies document deformation in the (semi)brittle regime (Escartín and Hirth, 1997; Jung and Green, 2004; Chernak and Hirth, 2010), while at similar deformation conditions other studies suggest that deformation operates in the plastic regime (Hilairet et al., 2007). As models of mantle wedge dynamics and fluid transport feed from these experimental data, it is necessary to better constrain the precise mode of deformation of antigorite within the subduction zone. We thus conducted experiments with a Deformation-DIA apparatus, at strain rates and total strains similar to those reported in previous studies, and coupled this study with the investigation of naturally deformed samples. To facilitate the comparison, we conducted experiments under P–T conditions similar to the metamorphic conditions experienced by serpentinites from the Alps and Cuba (Fig. 1). The microstructures of the samples described in this study were investigated with optical and transmission electron microscopy (TEM) to determine deformation mechanisms. Microstructural observations are indeed the key way to infer the strain accommodation processes of minerals, particularly for phyllosilicates (Shea and Kronenberg, 1992). Investigating field and laboratory samples is essential to constrain the application field of experiments, which necessarily lack the complexity of natural systems. Furthermore, differences between experimental and natural microstructures should highlight the effects of processes not active in experiments.

2. Materials and methods

2.1. Experimental deformation

2.1.1. Experimental device

The D-DIA high-pressure experiments were carried out at the Bayerisches Geoinstitut (Bayreuth, Germany). The D-DIA can generate pressures up to 10 GPa at high temperatures (up to 2000 °C), and then deform the sample. Further description of the device can be found as supplementary material and in Wang et al. (2003). We increased pressure with a rate of 0.02 GPa/min. At high pressure, temperature was increased with temperature ramping up between 50 and 100 °C/min. At high P–T, the sample was annealed for a couple of hours to remove the eventual deformation-induced structures acquired during cold compression. After annealing, the samples were deformed at strain rates of 1×10^{-4} s^{-1} and 5×10^{-5} s^{-1}. Total time at high temperature is ranging between about 180 to 240 min. After quench, special care was taken to unload the sample and prevent brittle deformation structures during decompression. Experimental conditions are presented in Table 1 and Fig. 1. Pressure and temperature conditions reflect the HP-LT conditions experienced by natural serpentinites from the Monviso and Erro Tobbio Massif in the Alps (Scambelluri et al., 1995; Schwartz et al., 2000; Angiboust et al., 2011) (Fig. 1). They also compare well to experiments by Chernak and Hirth (2010) conducted in a Griggs-type apparatus; Chernak and Hirth (2010) sample W1460, deformed at 1 GPa and 400 °C was provided by the