Earth and Planetary Science Letters 421 (2015) 1–12

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Role of pore fluid pressure on transient strength changes and fabric development during serpentine dehydration at mantle conditions: Implications for subduction-zone seismicity

Brooks Proctor*, Greg Hirth

Brown University, Department of Earth, Environmental and Planetary Sciences, 324 Brook St., Box 1846, Providence, RI 02912, USA

ARTICLE INFO

Article history:
Received 25 September 2014
Received in revised form 20 March 2015
Accepted 24 March 2015
Available online 8 April 2015
Editor: J. Brodholt

Keywords:
dehydration embrittlement
serpentine
olivine
pressure-solution
semibrittle flow

ABSTRACT

To further investigate the dehydration embrittlement hypothesis and its possible link to subduction-zone seismicity, we conducted deformation experiments on antigorite serpentinite in a Griggs-type apparatus at conditions below and above antigorite stability. Temperature ramps (crossing the antigorite thermal stability) were used in conjunction with a new experimental method that allows fluid produced during dehydration reactions to be drained, partially drained or undrained. During temperature ramps, weakening coupled with transient slip initiated at ∼650 °C, coincident with the predicted phase transition of antigorite to olivine and talc at ∼1 GPa. The weakening-rate and steady-state strength were dependent on drainage conditions; undrained samples weakened over a few minutes and supported the lowest shear stress (∼50 MPa), while drained samples weakened over a few hours and supported the highest shear stress (∼210 MPa). The coefficient of friction (shear stress over normal stress) in drained samples decreased from ∼0.4 to ∼0.16 after the temperature ramp. The strengths of samples that were first annealed at 700 °C for ∼12 h, then deformed, were similar to those observed in the temperature ramp experiments. Strain localization along fractures occurred in all samples during temperature ramping, regardless of the drainage conditions. However, microstructural observations indicate deformation by ductile mechanisms at higher strain under both undrained and drained conditions. The rheology and microstructures suggest dehydrating serpentinite deforms via semibrittle flow with grain-scale ductile deformation more active at high pore fluid pressures. Our results suggest that earthquakes in serpentinized mantle do not nucleate as a direct result of unstable frictional sliding along fractures generated at the onset of dehydration reactions.

1. Introduction

In subduction zones there is a strong correlation between the location of intermediate-depth earthquakes (50–200 km) and the predicted thermal stability of hydrous minerals, suggesting a link between dehydration reactions and seismicity (e.g., Hacker et al., 2003; Abers et al., 2013). Earthquake hypocenters are typically observed along parallel trending planes within the subducting crust and mantle giving rise to the double Benioff zone (e.g., Brudzinski et al., 2007). The overall distribution of these earthquakes is highly dependent on the thermal structure; in older (cold) lithosphere, earthquakes primarily occur within the subducting crust and deep within the mantle, whereas in younger (hot) lithosphere, earthquakes primarily occur within the mantle near the slab Moho (Abers et al., 2013).

Intermediate-depth earthquakes are commonly attributed to dehydration embrittlement, a phenomenon in which rocks containing hydrous minerals undergo brittle fracturing during prograde metamorphism (e.g., Raleigh and Paterson, 1965; Murrell and Ismail, 1976; Green and Houston, 1995; Kirby et al., 1996; Davies, 1999; Hacker et al., 2003; Peacock, 2001; Jung et al., 2004; Milsch and Scholz, 2005). Since its initial discovery, dehydration embrittlement has been almost exclusively explored (experimentally) with serpentine, a mineral that likely occurs within seismically active regions of the subducting mantle (e.g., Hacker et al., 2003; Hyndman and Peacock, 2003; Reynard, 2013; Hirth and Guillot, 2013). Other hydrated rocks within the subducting crust that are associated with seismicity (e.g., lawsonite blueschist) are generally assumed to exhibit similar behavior (e.g., Abers et al., 2013).

Despite numerous studies that have documented dehydration embrittlement in serpentinite, it remains unclear if and how

---

* Corresponding author.
E-mail address: brooks_proctor@brown.edu (B. Proctor).

http://dx.doi.org/10.1016/j.epsl.2015.03.040

this phenomenon generates earthquakes (e.g., Gasc et al., 2011; Chernak and Hirth, 2011; Reynard, 2013). The nucleation problem is two-fold; (1) we need to understand how strain becomes localized during metamorphism and (2) whether continued frictional sliding along the localized zone is unstable (e.g., Kanamori and Broadsky, 2004; Scholz, 1998). As described below, existing experimental observations on serpentinite give conflicting observations on both strain localization and unstable fault slip during dehydration reactions.

There are many physical models to explain the link between serpentine dehydration and seismicity. The classic dehydration embrittlement model assumes simple Mohr–Coulomb failure caused by increasing pore fluid pressure (Raleigh and Paterson, 1965; Murrell and Ismail, 1976); pore fluid is generated from the dehydration reaction and fluid pressure increases because the reaction has a positive volume change. The distribution of earthquake hypocenters in both hot and cold subduction zones appears to support this model (Abers et al., 2013). However, the experiments by Jung et al. (2004), at confining pressures (P_c) as high as 6 GPa, demonstrated that partially serpentinized samples also fracture when the reaction volume is negative. Under similar conditions, Dobson et al. (2002) and Jung et al. (2009) recorded acoustic emissions during dehydration, which they interpret to indicate unstable slip accompanied by fracture. Furthermore, unstable sliding was observed at dehydration conditions in experiments conducted on antigorite, the high-pressure serpentine polymorph, with a constant pore fluid pressure and at $P_c = 100$ MPa (Takahashi et al., 2011). Together, these studies support the hypothesis that earthquakes can nucleate directly as a result of the promotion of unstable frictional sliding on fractures produced via dehydration.

Conversely, a second body of work illustrates stable frictional behavior of dehydrating serpentinite (Rutter and Brodie, 1988; Arkwright et al., 2008; Rutter et al., 2009; Chernak and Hirth, 2010, 2011; Gasc et al., 2011). Based partly on these observations, several alternative mechanisms have been proposed to generate intermediate (and deeper) depth subduction zone earthquakes (cf., Hacker et al., 2003); for example via dynamic weakening of fine-grained reaction products via superplastic flow (e.g., Schubnel et al., 2013), thermal runaway within fine-grained olivine shear zones (Kelemen and Hirth, 2007; Prieto et al., 2013), plastic faulting (Renshaw and Schulson, 2013), unstable slip promoted by stress concentrations at the edge of weak zones created during dehydration (Brantut et al., 2012), or simply by fluid migration out of the region of dehydrating serpentinite into overlying mantle rocks that may exhibit unstable frictional behavior (e.g., Arkwright et al., 2008).

The conflicting hypotheses surrounding the link between dehydration embrittlement and seismicity are in part due to the complicated nature of the mechanical behavior and reactions involved (e.g., Hacker et al., 2003; Wong et al., 1997; Brantut et al., 2011), as well as the extreme pressures at which they occur in the Earth (>1 GPa). Our ability to explore processes that occur at high pressures is limited by the deformation apparatus and procedures used during experiments (e.g., constant stress vs. constant strain-rate; general shear vs. axial compression), each with their own limitations (e.g., Tullis and Tullis, 1986; Jaeger et al., 2007). One drawback of high confining pressure deformation machines (e.g., D-DIA, Griggs Rig, Multi-anvil) is a lack of pore fluid pressure control. For this reason many studies have used lower confining pressure machines (<500 MPa) (e.g., Rutter and Brodie, 1988; Arkwright et al., 2008; Rutter et al., 2009; Takahashi et al., 2011; Brantut et al., 2012). The results are then extrapolated to higher pressure with the assumption that the effective pressure predominantly controls the rheology, and thus that the magnitude of the sample pressure (or depth) is irrelevant. To date this assumption remains untested.

In this study we provide a novel experimental method to vary the pore fluid pressure in a Griggs Rig deformation apparatus – a task not previously accomplished at confining pressures as high as ~1 GPa. We use this method to explore how pore fluid pressure affects transient weakening during dehydration at mantle pressures, following the approach employed by Chernak and Hirth (2011). These tests allow us to further constrain the rheology of dehydrating serpentinite and the possible link between dehydration embrittlement and seismicity.

2. Experimental methods

2.1. Starting material and sample preparation

Experiments were conducted on an antigorite-rich serpentinite (ATG) collected near Rochester, Vermont that is composed of ~90% antigorite, 5–8% magnetite and minor amounts of magnesite, sulfides and oxides determined by X-ray diffraction and petrographic analysis (Proctor et al., 2014). The serpentinite was first crushed into a fine-grained powder, sieved to a grain-size of 37–53 μm, washed in distilled water to remove ultra fine-grained particles and dried on a hot plate at ~100 °C. The powder was next cold-pressed at room temperature into a ~1.1 mm thick gouge zone between two alumina or yttria-stabilized zirconia (Y-zirconia) pistons cut at 45 degrees, then hot-pressed at 400 °C at a confining pressure of ~1 GPa for 12 h prior to deformation.

2.2. Deformation apparatus and sample assembly

Experiments were conducted in solid confining media Griggs-type triaxial press (see Tullis and Tullis, 1986 for details). The sample was encased in an assembly that rests within a cylindrical pressure vessel. The outer assembly components are shown in Fig. 1A. We designed three versions of the inner assembly components to accommodate fluid that is generated within the sample at high temperatures (Fig. 1B, 1C and 1D). In the undrained assembly (Fig. 1B), the sample is confined between two solid Y-zirconia pistons cut at 45 degrees and encased in a 0.25 mm thick silver tube or jacket. The jacket is cut long enough such that the outer pistons partially fit into the ends of the tube (Fig. 1B). This overlap keeps the pistons aligned during the initial sample loading. Platinum disks separate the inner shear pistons from the outer pistons and become mechanically welded to the jacket forming an impermeable chamber during the initial hot pressing of the sample at 400 °C and 1 GPa confining pressure. The partially drained assembly (Fig. 1C) is similar to the undrained assembly except that the inner shear pistons are alumina and have a hollow core (1.6 mm diameter) creating an upper and lower cylindrical reservoir. The reservoirs are filled with either ~200 μm diameter Y-zirconia microspheres or 200–400 μm diameter glass carbon microspheres (Fig. 1E and 1F). The drained assembly is further modified to vent fluid out of the pressure vessel (Fig. 1D). In this assembly the lower Pt disk is removed and a ~2.5 mm thick split (i.e., with a vertical cut) alumina disk is added below the lower hollow shear piston, and the lower piston is replaced with a hollow alumina piston. The split alumina disk allows only fluid to pass from the upper shear piston to the lower piston. The Ag jacket is extended to cover the disk and overlap the lower outer piston. Because there is no lower welded seal, to prevent salt from potentially leaking into the jacket and drainage system, a portion of the inner salt cylinder is replaced with a soft-fired pyrophyillite "can," which prevents salt from migrating into the jacket. The can is machined such that the jacket is seated within a notch on the inner side. The solid tungsten carbide (WC) base plug is replaced with a WC plug that has a matching (1.6 mm diameter) drainage hole (Fig. 1A). The plug rests