Earth and Planetary Science Letters 474 (2017) 138–147

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

# Faulting of natural serpentinite: Implications for intermediate-depth seismicity

Julien Gasc[a,*], Nadège Hilairet[b], Tony Yu[a], Thomas Ferrand[c], Alexandre Schubnel[c], Yanbin Wang[a]

[a] GeoSoilEnviroCARS, Center for Advanced Radiation Sources, The University of Chicago, 5640 S. Ellis Avenue, Chicago, IL 60637, USA
[b] Unité Matériaux et Transformations, UMR 8207 – CNRS – Université de Lille-ENSCL-INRA Bat. C6, 59655 Villeneuve d'Ascq, France
[c] Laboratoire de Géologie, UMR8538 – École Normale Supérieure, 24 rue Lhomond, 75005, Paris, France

ARTICLE INFO

*Article history:*
Received 10 December 2016
Received in revised form 26 May 2017
Accepted 8 June 2017
Available online xxxx
Editor: J. Brodholt

*Keywords:*
high pressure
acoustic emission
serpentinite dehydration
intermediate depth earthquakes
synchrotron x-ray diffraction
deformation-DIA

ABSTRACT

The seismic potential of serpentinites at high pressure was investigated via deformation experiments on cored natural serpentinite samples, during which micro-seismicity was monitored by recording Acoustic Emissions (AEs). Deformation was performed at pressures of 3–5 GPa, using a Deformation-DIA device, and over a wide range of temperatures, both within and outside antigorite's stability field. Below 400 °C, serpentinite deformation involves "silent" semi-brittle mechanisms, even in cases where strain localization is observed. At high temperature (i.e., above 600 °C), despite conditions propitious to dehydration embrittlement (i.e., fast strain rates and reaction kinetics), joint deformation and dehydration lead to ductile shear, without generation of AEs. Brittle behavior was observed in a narrow temperature window ca. 500 °C. In this latter case, AEs are consistently observed upon faulting and extremely sharp strain localization is observed in recovered samples. The resulting microstructures are consistent with the inverse ductile-to-brittle transition proposed by Proctor and Hirth (2016) in antigorite. This may therefore be a source of seismicity in subducting slabs at mantle pressures and temperatures from 500 to 600 °C. However, the acoustic signal observed here is orders of magnitude weaker than what is obtained at low PT conditions with brittle failure, consistently with low radiation efficiency of serpentinite faulting (Prieto et al., 2013) and suggests that other mechanisms are responsible for large intermediate-depth earthquakes. In fact, the present results are in line with a recent study (Ferrand et al., 2017), that suggests that intermediate earthquakes are likely induced by mechanical instabilities due to dehydration in partly hydrated peridotites.

## 1. Introduction

The origin of intermediate-depth earthquakes, which occur at depths of 60–300 km in subducting slabs, remains enigmatic. Although increasing pressure (P) and temperature (T) conditions are expected to promote ductile deformation of rocks, earthquakes are recorded as deep as 700 km (Cahill and Isacks, 1992). In many cases, intermediate-depth earthquakes (i.e., occurring between 60 and 300 km) delineate two distinct Wadati–Benioff (WB) planes (Brudzinski et al., 2007). The lower plane has been shown by several studies to coincide with the dehydration of antigorite, which occurs at pressures of 1–5 GPa (Dorbath et al., 2008; Hacker et al., 2003; Yamasaki and Seno, 2003).

In fact, the release of fluids upon serpentine breakdown was long considered a possible triggering mechanism, via dehydration embrittlement. In particular, the dehydration of antigorite (the Mg-rich variety of serpentine stable at high PT) was considered as a good candidate to explain lower WB plane seismicity. Raleigh and Paterson (1965) first demonstrated that the rheology of serpentinites is strongly affected by the onset of dehydration. According to the fluid-embrittlement hypothesis, dehydration kinetics with fast fluid production rates do not allow the rock to relax plastically and therefore lead to hydrofracturing (Chollet et al., 2011; Eggler and Ehmann, 2010; Perrillat et al., 2005). However, fast fluid production rates do not necessarily imply strain generation and fracturing. At conditions where the volume change of the reaction is nil or negative (i.e., at 2 GPa or above for antigorite), dehydration can theoretically result in pore pressure reduction and models based on fluid overpressure fail to explain how fluid embrittlement can take place at high pressures (Miller et al., 2003; Nishiyama, 1989). Brittle behavior was nevertheless documented

---

* Corresponding author.
*E-mail address:* gasc@gm.univ-montp2.fr (J. Gasc).

http://dx.doi.org/10.1016/j.epsl.2017.06.016
0012-821X/© 2017 Elsevier B.V. All rights reserved.

**Table 1**
Experimental conditions and results. Errors on stress, strain and strain rate are given in parentheses as one standard deviation.

| | $P$ [GPa] | $T(1)$ [°C] | $\sigma$ [GPa] | $T(2)$[a] [°C] | $\dot{T}$ [°C s$^{-1}$] | $\dot{\varepsilon}$[b] [s$^{-1}$] | Final $\varepsilon$ [%] | $\dot{T}/\dot{\varepsilon}$ [°C] | # HP-HT AEs | Deformation microstructures |
|---|---|---|---|---|---|---|---|---|---|---|
| S1 | 3 | 230 | – | – | – | 1.0E−4 (3.9E−6) | 51.9 (2.0) | 0 | 0 | conjugated faults |
| S2 | 5 | 240 | 1.11 (0.10) | – | – | 4.5E−5 (9.9E−7) | 40.1 (0.3) | 0 | 1 | anastomosed fractures |
| S3 | 3 | 400 | 0.83 (0.06) | – | – | 1.0E−4 (8.3E−6) | 16.1 (0.3) | 0 | 1 | distributed (+ inherited compression fault) |
| T1 | 3 | 450 | 0.90 (0.04) | 500 | 3.1E−2 | 6.3E−5 (1.7E−6) | 49.0 (0.3) | 4.9E+2 | 8 | conjugated faults |
| T2 | 3 | 450 | – | 500 | 2.7E−2 | 9.6E−5 (5.3E−6) | 52.6 (2.9) | 2.8E+2 | 5 | conjugated faults |
| T3 | 3 | 500 | – | – | – | 8.5E−5 (4.9E−6) | 50.8 (2.9) | 0 | 8 | conjugated faults |
| T4 | 3 | 550 | – | – | – | 1.2E−4 (1.0E−5) | 58.7 (4.8) | 0 | 9 | conjugated faults |
| T5 | 3 | 550 | 0.52 (0.02) | – | – | 2.0E−4 (5.3E−6) | 56.4 (0.4) | 0 | 4 | conjugated faults |
| D1 | 3 | 470 | 0.71 (0.20) | 610 | 2.1E−1 | 1.2E−4 (1.0E−5) | 47.2 (0.3) | 1.7E+3 | 1 | distributed |
| D2 | 5 | 410 | 1.16 (0.16) | 720 | 8.2E−1 | 4.7E−4 (1.4E−4) | 31.7 (0.3) | 1.7E+3 | 0 | distributed |

[a] Highest temperature reached at the end of stage 2.

[b] S1, T2, T3 and T4 were performed without XRD. Stress could therefore not be determined and strain rate was estimated from the final axial strain observed on the recovered sample.

at 1–6 GPa, i.e. by Jung and Green (2004) and Jung et al. (2004), who proposed a mechanism that involves separation of the dehydration fluid and solid reaction products to allow local positive volume change and mode I crack propagation despite high pressures (>2 GPa). Acoustic Emission (AE) recording constitutes an efficient way to identify brittle failure at high pressure. Dobson et al. (2002, 2004) recorded AEs between 1.5 and 8.5 GPa associated with brittle faulting of dehydrating antigorite samples and Jung et al. (2009) also recorded AEs when increasing pressure and temperature beyond the antigorite stability field limit.

More recent experimental studies challenge this classic fluid-embrittlement theory by showing that faulting of serpentinites, related to dehydration, occurs in an aseismic manner. This was shown by the absence of both associated acoustic signal (Gasc et al., 2011b) and mechanical unstable behavior, i.e., stick slip (Chernak and Hirth, 2011) and seems in good agreement with recent results from Okazaki and Hirth (2016). Antigorite presence may still be related to intermediate earthquakes. Other studies proposed indeed that earthquakes may arise in thermally stable antigorite, which undergoes an inverse – and possibly seismogenic – ductile-to-brittle transition with increasing temperature (Chernak and Hirth, 2010; Proctor and Hirth, 2016), thus explaining the occurrence of the lower WB plane intermediate-depth earthquakes.

In order to address the paradox raised by these contradictory experimental results, and assess the seismogenic potential of both dehydrating and stable antigorite, we extend here the work of Gasc et al. (2011b) by using an improved version of the AE experimental setup. This state-of-the-art AE recording setup is in use on the deformation-DIA (D-DIA) press at the beamline 13BM-D of the Advanced Photon Source, Argonne National Laboratory, where stress, strain and reaction advance can be measured in situ. Ten deformation experiments were carried out on cored natural serpentinite samples, both outside and within the stability field of antigorite.

## 2. Experimental details

*Data collection setup and starting materials*

2.1 mm in diameter and 2–3 mm long samples were cored from a serpentinite block from Patrimonio (Corsica, France). This material has already been used in (Gasc et al., 2011b); it is mainly composed of antigorite with minor amounts of magnetite (Fe–Ni oxide; see supplementary material, Fig. S1). The mean grain size is ∼10 μm. The samples were cored at 45° with respect to a visible macroscopic foliation. No LPO could be detected in the XRD patterns collected at ambient conditions, prior to the experiments. However, texture development is observed upon the compression stage, before deformation is performed (see results section for details).

The samples were fitted in a Boron Nitride (BN) sleeve and sandwiched between two densified $Al_2O_3$ cylinders that served as pistons during the deformation. Two 5-μm thick gold foils were placed between the samples and the pistons to monitor the length of the sample on the X-ray radiographies. Two samples (T2 and S3) were cut in half, normal to the axial principal stress direction, prior to the experiment and an additional gold foil was placed in between the two halves as a strain marker. A graphite sleeve was used as a furnace for resistive heating. No thermocouple was used here; temperature was inferred from previously calibrated power-temperature relations. Temperatures mentioned in the present study should therefore be considered with caution and are not used for quantification. However, temperature estimation is not a key aspect of the present study since we do not attempt to provide information about the stability temperature of antigorite but to investigate the rheology of the samples whether or not experiencing dehydration, which can be monitored using XRD.

A total of ten samples were deformed in the D-DIA at pressures of 3 or 5 GPa. Experimental conditions are listed in Table 1. Six experiments were conducted with the use of in situ synchrotron radiation. The present setup has proved to be extremely efficient at collecting rheology data at pressures up to ∼15 GPa (Wang et al., 2003, 2010). For these on-line experiments (6 out of 10), full Debye X-ray diffraction (XRD) rings and X-ray radiographies of the sample were collected alternatively in situ with a time step of 6–13 min. XRD data were used for stress and lattice preferred orientation (LPO) quantification as well as for phase identification, whereas radiographies were used to determine the axial strain (i.e., whole sample shortening) of the sample. Lattice strains were extracted from the (0 0 1), (1 0 2) and (16 0 1) *hkl* reflections of antigorite. Stress was then obtained using the elastic constants of Bezacier et al. (2010) and by averaging the stress values, $t(hkl)$, returned from these *hkl* planes (see Hilairet et al., 2007, supplementary material). For off-line experiments (namely S1, T2, T3 and T4; see Table 1), stress could not be determined and strain (and strain rate) was estimated from the length of the recovered samples.

In all experiments, the acoustic signal was monitored in order to identify brittle mechanisms possibly associated with deformation and/or dehydration reactions of antigorite. The AE setup used here consists in an improved version of the one used in Gasc et al. (2011b). More information can be found in the supplementary material (Figs. S2, S3 and S4). Six piezoelectric transducers (PZT) are used here on the rear of the anvils. Thanks to their center frequency, the transducers are sensitive to fractures propagating over distances corresponding typically to grain or sample sizes (typically from 1 μm to 1 mm) and thus constitute a powerful tool to track brittle deformation mechanisms in the sample. Acoustic Emissions (AEs), in the form of triggered data, were monitored