Potential link between antigorite dehydration and shallow intermediate-depth earthquakes in hot subduction zones

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Abstract

The distribution of earthquakes at intermediate depths corresponding to pressures <2 GPa in several hot subduction zones (such as Cascadia and southwestern Japan) coincides with the breakdown of antigorite to forsterite and talc; thus, this reaction may have triggered these earthquakes. However, previous studies have overlooked the potential significance of this reaction. Here, we performed a series of time-dependent dehydration experiments on antigorite at a pressure of 200 MPa and a temperature range of 300–650 °C. The results show that dehydration is controlled by a heterogeneous nucleation and growth mechanism and has an activation energy of 354 ± 24 kJ/mol. The formation of fine-grained forsterite and large talc crystals is consistent with kinetic results indicating Avrami exponents \( n = \sim 1.4−1.1 \) and \( \sim 2.7 \), respectively. Fluid production rates at 600 and 650 °C are \( 2.54 \times 10^{-6} \) and \( 4.69 \times 10^{-5} \) mol m\(^{-2}\) s\(^{-1} \), respectively, which are much faster than those of mantle deformation, causing high fluid pressure in hot subducting mantle but not necessarily embrittlement. We emphasize the role of kinetic mechanisms in controlling the grain sizes of reaction products, which likely determine the mechanical behavior of serpentinized fault zones. Superplasticity or velocity weakening of fine-grained forsterite and velocity weakening of antigorite by water and/or talc may be responsible for earthquake nucleation and propagation in a heterogeneous system, which can be either dehydration products within a serpentinized fault zone or the mixture of antigorite fault and surrounding peridotite in hot subduction zones (<2 GPa).

Keywords: Antigorite, talc, forsterite, kinetic mechanism, subduction zone, shallow intermediate-depth earthquakes

Introduction

Serpentine is a main hydrous phase in oceanic plates and the most abundant water-bearing mineral in altered ultramafic rocks (Hyndman and Peacock 2003), with water contents up to \( \sim 13 \) wt% (Schmidt and Poli 1998; Shao et al. 2014, 2021, 2022; Ulmer and Trommsdorff 1999). There are three main forms of serpentine: chrysotile, lizardite, and antigorite (Rinaudo et al. 2003). Among them, antigorite is persistent in subduction zones to a depth of \( \sim 200 \) km and is thus called high-temperature serpentine (Ji et al. 2013; Reynard 2013; Reynard et al. 2007; Shao et al. 2014). Previous studies have shown that the temperature stability field of antigorite, from 1 to 5 GPa, is close to the iso-therm of the lower plane of a double seismic zone (DSZ) (e.g., Abers et al. 2013; Peacock 2001; Yamasaki and Seno 2003); which means that the hypocenter distribution of intermediate-depth earthquakes in the subducted mantle fits the distribution of antigorite. However, a recent study by Ferrand (2019) suggested that many of the upper-plane earthquakes actually appear in the uppermost mantle, as clearly observed in northern Chile.

Therefore, antigorite dehydration is commonly used to explain the seismic activity in the entire DSZ (Dobson et al. 2002; Omori et al. 2004; Peacock 2001).

In a pioneering study by Raleigh and Paterson (1965), seismogenic faulting was claimed to be triggered within the dehydrating antigorite itself due to fluid overpressure. This is the original model of so-called “dehydration embrittlement,” which is possible only when the Clapeyron slope of serpentine dehydration reaction is positive (i.e., \( P < \sim 2 \) GPa). However, several experimental studies on syndeformational antigorite dehydration have found that antigorite is weakened but deforms aseismically (Chernak and Hirth 2010, 2011; Gasc et al. 2011, 2017; Okazaki and Hirth 2016; Proctor and Hirth 2015; Shao et al. 2021), which might be comparable to slow earthquakes occurring in hot subduction zones (e.g., Chernak and Hirth 2010; French et al. 2019; Okazaki and Katayama 2015). Some studies have improved the model and considered that seismogenic faulting should occur in more brittle surrounding rocks rather than the dehydrating antigorite itself (e.g., Brantut et al. 2017; Ferrand et al. 2017). For example, Ferrand et al. (2017) proposed dehydration-driven stress transfer (DDST) to generate earthquake events in fresh peridotite at the edge of antigorite-rich zones.

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