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The influence of hydrous phases on the microstructure and seismic properties of a hydrated mantle rock

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ABSTRACT

To better understand the microstructural evolution of a “serpentinized” mantle rock and the influence of various hydrous phases on the seismic properties of the mantle wedge, we have conducted the detailed microstructural analyses of a sample of tremolite–chlorite–antigorite schist collected from the Moses Rock dike (central part of the Colorado Plateau). We performed differential effective media (DEM) modelling to study the effect of three hydrous phases forming two-phase aggregates with olivine, considering the crystallographic preferred orientation (CPO) of each phase and the shape ratio of the hydrous phases. We have demonstrated that in a partially serpentinized peridotite, the olivine CPO characteristic of [100](010) dislocation glide is still preserved, and the high-temperature asthenospheric flow is preserved with a foliation normal to that of antigorite schist. The transformation of olivine into antigorite occurs predominantly (~75%) by the relationship (100)ol || (001)atg with [001]ol || [010]atg, with the (010)ol || (001)atg and [001]ol || [010]atg relationship observed in areas of weak antigorite CPO. Chlorite results from the phase transformation of olivine in a relatively static environment, as shown by the correlation between the olivine–chlorite CPOs with (100)ol || (100)ch, (010)ol || (001)ch and (001)ol || (010)ch. The fluid percolation that caused the localized metasomatism and partial hydration of the mantle occurred possibly along trans-lithospheric shear zones. The presence of chlorite induces the most important drop on the P-wave velocities and may help to explain some local low velocities in the fore-arc mantle wedges, but is unlikely to be of global importance due to its very high Vp/Vs ratio ~ 1.9. On the other hand, antigorite is the only phase that causes important modification on the propagation directions of P and S-waves, and the only phase to explain the polarization of the fastest shear waves parallel to the subduction trench.

1. Introduction

Many of the key-processes that occur in subduction zones are linked to hydration/dehydration metamorphic reactions, which are of extreme importance to our understanding of the dynamics of subduction zones (e.g., Hacker et al., 2003a, 2003b; Hirth and Kohlstedt, 2003; Kneller et al., 2005; Van Keken et al., 2002). The hydration of the lithospheric mantle may occur in different environments, such as: (i) slow spreading ridges where “mantle rocks” are actually part of the oceanic crust, (ii) along faults and fracture zones where mantle rocks behave in a brittle manner and (iii) in the fractures due to the bending of the subducting plate, locally leading to the hydration of the mantle rocks (e.g., Escartín et al., 1997; Faccenda et al., 2009; Hyndman and Peacock, 2003).

In the last few years, antigorite, lizardite, chrysotile (serpentine group) have been receiving increasing attention as the direct expression of hydration of the upper mantle and the water cycle in the deep Earth (e.g., Boudier et al., 2010; Christensen, 2004; Hacker et al., 2003a, 2003b; Hirauchi et al., 2010; Hyndman and Peacock, 2003; Katayama et al., 2009; Nishii et al., 2011; Soda and Takagi, 2010). Although they are important phases because they may store ~13 wt.% of water (e.g., Bromiley and Pawley, 2003) and therefore represent an important water reservoir in mantle rocks, they are not the only hydrous phases in subduction zones. Talc, amphiboles, chlorite, brucite and clinohumite are some of the hydrous minerals commonly associated with alteration of peridotites at different P–T conditions. Many of these phases, when present in altered peridotites, may dramatically change the physical properties of the hydrated mantle (e.g., Mainprice and Ildefonse, 2009). Nevertheless there are relatively few papers that address the modifications of the physical properties in the mantle wedge caused by different hydrous minerals (e.g., Christensen, 2004; Connolly and Kerrich, 2002; Hacker et al., 2003a, 2003b; Hyndman and Peacock, 2003; Mainprice and Ildefonse, 2009; Mainprice et al., 2008; Peacock and Hyndman, 1999). Besides acting as a chemical-softening reaction usually facilitating the deformation accommodation during the dynamic processes related to the subduction, the presence of these phases may change

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the elastic properties of the mantle wedge, and by consequence, their anisotropic seismic properties (e.g., Hirauchi et al., 2010; Katayama et al., 2009; Mainprice and Ildefonse, 2009; Nishii et al., 2011). As an example, the distribution of seismicity along the subduction zones seems to result from the dehydration processes and embrittlement of the subducted hydrated oceanic crust (e.g., Green, 2007; Kawakatsu and Watada, 2007; Kita et al., 2006). The water released during this process then migrates and is recycled in the mantle where it controls the deformation and partial melting in the mantle wedge (e.g., Hilairet et al., 2007; Hirauchi et al., 2010). Some of these hydrated phases can be stable over pressure and temperature conditions at depths of up to 100 km (Fumagalli and Poli, 2005; Iwamori, 2004; Ohtani et al., 2004; Schmidt and Poli, 1998, also see Fig. 2 of Mainprice and Ildefonse, 2009).

To better understand the microstructural evolution of a "serpentinized" mantle rock and the role of hydrous phases in altering the seismic properties of the mantle wedge, we have conducted the detailed analysis of a rare sample of tremolite–chlorite–antigorite schist. Although the assemblage of olivine + antigorite + chlorite + tremolite is common in the hydrated mantle rocks in subduction zones (e.g., Hirauchi et al., 2010; Mizukami and Wallis, 2005), the study of partly transformed rock preserving a significant fraction of the original olivine network (~40%) within ~60% of the new hydrous phases is exceptional. Previous studies presented in the last few years make use of completely transformed aggregates in which it is not possible to observe the relationships between the protolith (mantle) mineralogy and the transformed (hydrous) phases (e.g., Katayama et al., 2009; Nishii et al., 2011; Soda and Takagi, 2010). In addition, this study presents results of a microstructural study of all hydrous phases present rather than just antigorite, which allows an analysis of the impact of each mineral on the modification of physical properties in the mantle wedge.

2. Geological setting

The sample of tremolite–antigorite–chlorite schist studied here (MR-1) was collected from the Moses Rock dike, which is exposed in the central part of the Colorado Plateau (Fig. 1) and belongs to the Navajo Volcanic Field (NVF), with eruptive ages between 25 and 31 Ma. The NVF is located in the "Four Corners" (SW of USA — Fig. 1) and is dominated by potassic, mica-bearing lamprophyres.

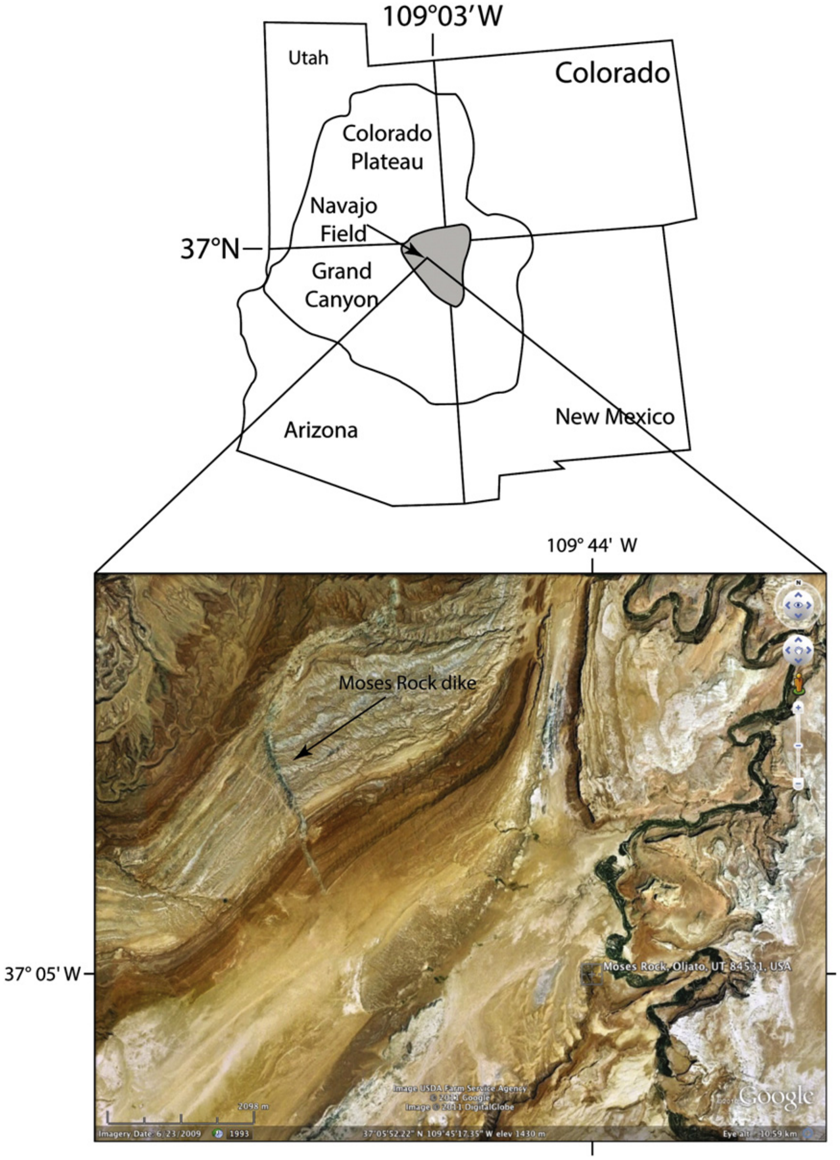

Fig. 1. Location of the study area within the Navajo Volcanic Field in the Colorado Plateau region with the Google Earth satellite image showing the Moses Rock dike running from NW–SE and crosscutting sedimentary sequences.
Location map modified from Smith and Griffin (2005).