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Elastic and electrical properties of serpentinite dehydration at high temperature and high pressure

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Abstract

P-wave velocities (V_P) and electrical conductivities (σ) in serpentinite, collected from Ailaoshan orogenic belt, Yunnan province, China, were measured at 2.0–3.5 GPa and high temperature with the pulse transmission–reflection combined method and impedance spectroscopy by the means of a multi-anvil pressure apparatus, the YJ-3000 press. V_P decreased and σ increased markedly at temperature higher than about 560 °C. It is argued that the onset of the dehydration of serpentine is the main cause for V_P decreasing and σ increasing. Combining the present experimental data with the results of previous experiments, we were led to speculate that the formation of the low-velocity layer between the subducted slab and mantle wedge is closely related to the dehydration of serpentine.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Among the hydrous minerals, such as amphibole, chlorite, talc, mica, and serpentine, which may be carried into the lower crust and upper mantle by the subduction slab, serpentine may be the most abundant. Previous studies have examined the relationship between the dehydration of serpentine and the fate of the subducted slab with serpentine, serpentinitized basalt, or a material similar to the MgO–SiO₂–H₂O system as the starting material [1–8]. However, many of the experiments were carried out at pressure less than 1.0 GPa, preventing confident extrapolation of results to upper-mantle conditions. Furthermore, only one physical parameter (elastic wave velocity or electrical conductivity) was determined in their experiments; therefore, the origin of the low-velocity layer and the highly conductive layer must be discussed separately.

The work described in this paper was conducted to measure P-wave velocities (V_P) and electrical conductivities (σ) in serpentinite at 2.0–3.5 GPa and up to 1365 °C with the pulse transmission–reflection combined method and impedance spectroscopy. These data were then

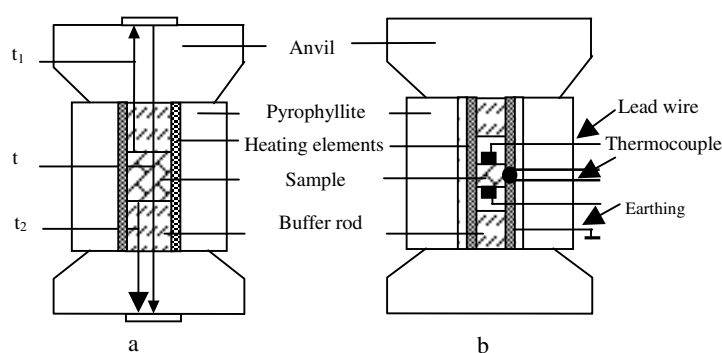


Figure 1. The set-ups of the sample assemblies. (a) For V_P -measurement; (b) for σ -measurement.

used to elucidate the origin of the low-velocity layers and highly conductive layers in the subducted zone, simultaneously.

2. Sample and experimental method

The sample was collected from an ultrabasic rock body occurring in Ailaoshan orogenic belt, in Yunnan province. The rock is massive and black in colour. The mineral composition of the rock includes serpentine (95% by volume), magnetite (5% by volume) and a few clay minerals [9]. Serpentine, which are mainly lizardite as determined by x-ray diffraction analysis, are fibrous and show pseudomorphs of olivine or orthopyroxene. The major oxides of the rock are SiO_2 : 40.46, TiO_2 : 0.01, Al_2O_3 : 0.70, Fe_2O_3 : 6.00, FeO : 1.60, MnO : 0.11, MgO : 35.20, CaO : 0.11, Na_2O : 0.08, K_2O : 0.01, H_2O : 15.80, P_2O_5 : 0.02.

All experimental samples were ground into cylinders, about 12 mm in diameter and 8 mm in length for V_P -measurement, and about 8 mm in diameter and 3 mm in length for σ -measurement. Before the experiments, the samples were cleaned in acetone; this was followed by ultrasonic cleansing in distilled water, then baking at 100 °C for at least 12 h to eliminate absorbed water.

The experiments were performed in a multi-anvil pressure apparatus, the YJ-3000 press, at the Institute of Geochemistry, Chinese Academy of Sciences, Guiyang, China. The details of the apparatus were described elsewhere [10]. The sample assemblages for V_P - and σ -measurements are shown in figure 1. The experimental processes for V_P and σ were given by Liu *et al* and Zhu *et al* in detail [11, 12], respectively.

3. Results

The values of V_P for the serpentinite at 2.0–3.0 GPa are illustrated as a function of temperature in figure 2. At 2.0 GPa, V_P decreases with increasing temperature at a small rate from 6.17 km s^{-1} at room temperature to 6.13 km s^{-1} at a temperature less than 580 °C. In the temperature range of 580–1030 °C, V_P decreases rapidly from 6.11 to 5.66 km s^{-1} . At temperature higher than 1030 °C, V_P decreases slowly again. The variation of V_P with temperature at 3.0 GPa is similar. At 3.0 GPa, V_P starts to drop sharply at a temperature of 570 °C.

Figure 3 shows the typical impedance spectra in $Z'-Z''$ complex planes at 3.5 GPa and 370–560 °C. The results at 2.5 GPa are similar. It can be seen that the values of both the real and

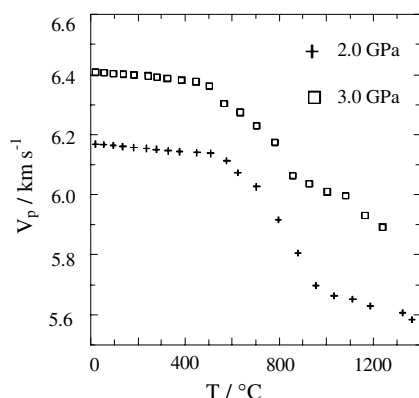


Figure 2. V_p in serpentinite as functions of temperature at 2.0–3.0 GPa and up to 1365 °C.

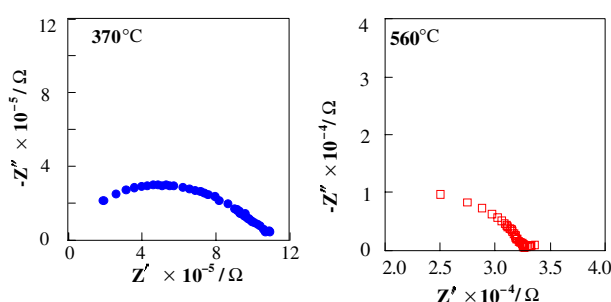


Figure 3. $Z'-Z''$ impedance spectrum planes for serpentinite at 3.5 GPa and various temperatures.

imaginary parts decrease with increasing temperature. The impedance data are analysed with a complex nonlinear least-squares method to obtain the resistance (R). Then, σ is calculated from $\sigma = (d/s)/R$, where d is the thickness of the sample, s the section area of the electrodes (figure 4). The electrical conductivities of serpentinite at 3.5 GPa are 0.2 log units higher than at 2.5 GPa at temperatures less than 560–575 °C. At higher temperatures, the difference between them disappears.

4. Discussion and conclusions

Previous studies at pressure less than 2.0 GPa indicated that V_p for serpentinite decreased significantly only at temperatures above the dehydration [4, 5]. Hence, we infer that the reason for V_p decreasing sharply in this work is serpentine dehydration. We speculate that at 2.0 and 3.0 GPa, the temperatures of serpentine dehydration are about 580 and 570 °C, respectively.

On the other hand, the relationship between $\log \sigma$ and $1/T$ shows that $\log \sigma$ against $1/T$ can be well fitted by the Arrhenius equation: $\sigma = \sigma_0 \exp(-\Delta E/kT)$, where σ_0 is the pre-exponential factor, T absolute temperature, k Boltzmann constant, and ΔE activation energy (figure 4). The slopes, i.e. ΔE , are broken at about 560 °C at 2.5 GPa, and 575 °C at 3.5 GPa, which is roughly in agreement with the dehydration temperatures of serpentinite at the same pressures [2, 3], implying that the conductance mechanism changes from one type to another.

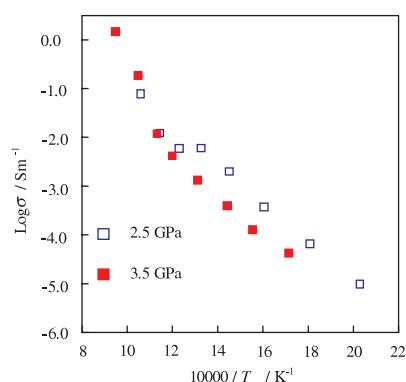


Figure 4. $\log \sigma$ versus $1/T$ at 2.5 and 3.5 GPa for serpentine.

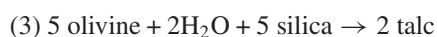
σ increases more rapidly with temperature over this range of temperature. It is most likely that dehydration causes the increase of σ .

According to present work, serpentine brought by the subducted slab to a depth of 60–100 km in the subduction zone would dehydrate at temperature higher than 600 °C and form a low-velocity highly conductive layer at the top of the subduction slab. So far, field seismic and magnetotelluric investigations have not confirmed such a layer. Only a low-velocity layer of 2–10 km thickness at a depth of 60–150 km between the subducted slab and mantle wedge have been revealed by seismic observations [13–15]. The discrepancy between experiments and seismic observations could be attributed to two factors. Firstly, the content of serpentine in the oceanic crust, as proved by Carlson and Miller [16], is so small that the effect of serpentine dehydration is constrained to a limited region. Secondly, in comparison with geological timescales, the time required for the reaction of serpentine dehydration is very short and the reaction involving production of water and minerals should go to completion easily. Therefore, the low-velocity highly conductive layer would not be detected by the seismic and magnetotelluric investigations.

The low-velocity layer between the subducted slab and mantle wedge would not have been formed by the dehydration of serpentine directly. However, its formation would be closely related to the dehydration of serpentine. As revealed by previous experiments, the dehydration reaction of serpentine at high pressure has two steps [2–4]:

- (1) 5 serpentine \rightarrow 12 olivine + 2 talc + 18 H₂O (at about 600–700 °C and 2.0–3.5 GPa);
- (2) olivine + talc \rightarrow 5 enstatite + H₂O (at >800 °C and 2.0–3.5 GPa).

Serpentine is dehydrated in the pressure–temperature conditions at a depth of 60–100 km in the subduction zone and forms the olivine + talc + H₂O assemblage. However, the pressure–temperature conditions in the mantle wedge peridotite immediately above the downgoing slab lie on the high-temperature side of estimated slab–surface geotherms in which talc can be stable [17–19]. Hence, water produced by serpentine dehydration, together with water and silica stored in sediments, reacts with olivine to produce talc in step (3):



and forms the low-velocity layer between the downgoing slab and the mantle wedge at a depth of 60–100 km [20].

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