Sound velocities and elastic constants of iron-bearing hydrous ringwoodite

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Abstract

The sound velocities and single-crystal elastic constants of Fo89 hydrous ringwoodite (γMg2Fe2SiO6) containing ∼10,000 ppm by weight (1 wt.%) H2O have been determined from seven separate pure-mode travel-time measurements using gigahertz ultrasonic interferometry. The experiments feature a new Yttrium–Aluminum–Garnet (YAG) P-to-S conversion shear buffer rod (BR), capable of producing pure ultrasonic shear waves with known polarization in the region of 0.5–2.0 GHz. To our knowledge they are the first such single-crystal ultrasonic measurements on a high-pressure phase recovered from the multi-anvil press. The cubic single-crystal elastic constants of hydrous Fo89 ringwoodite at ambient conditions are (in GPa): c11 = 298 ± 13, c44 = 112 ± 6, and c12 = 115 ± 6. Hydration of Fo89 ringwoodite to 1 wt.% H2O reduces the adiabatic bulk (K0s = 176 ± 7 GPa) and shear (G = 103 ± 5 GPa) moduli by about 6 and 13%, roughly equivalent to raising the temperature at room pressure by 600 and 1000 ◦C, respectively. Assuming a linear trend with hydration, we calculate that P- and S-wave velocities are reduced by about 40 m/s for every 1000 ppm weight (0.1 wt.%) H2O added to Fo89 ringwoodite.

P- and S-wave velocities of the lower transition zone in PREM are consistent with a hydrated ringwoodite-rich composition.

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Keywords: Hydrous ringwoodite; Elastic properties; Hydrogen in the transition zone; Gigahertz ultrasonic interferometry

1. Introduction

The hydrogen content of Earth’s interior is arguably one of the most poorly constrained geochemical variables, and the total H2O content of the planet is probably unknown within an order of magnitude. Whether or not there are even small amounts of H (100’s ppm) as hydroxyl in the dominant phases of the upper mantle and transition zone has major implications for our understanding of Earth’s evolution and chemical budget (e.g. Dixon et al., 2002; Drake and Rafter, 2002). Just one-tenth of 1 wt.% (1000 ppm by weight) H2O in wadsleyite β-(Mg,Fe)2SiO4 and ringwoodite γ-(Mg,Fe)2SiO4 in the volume of Earth’s transition zone between 410 and 660 km depth is equivalent to about 800 m of liquid water across the surface of the Earth (Smyth, 1994).

Natural olivine from mantle-derived xenoliths normally contains anywhere from zero to about 140 ppm by weight H2O (Bell and Rossman, 1992; Ingrin and...
Skogby, 2000), although hydration experiments show that olivine can incorporate up to 2000 ppm weight H₂O at 13 GPa and 1100 °C (Kohlstedt et al., 1996). Of the phases expected to occur in Earth’s upper mantle or transition zone, wadsleyite and ringwoodite have the potential to contain by far the most H₂O (Bolfan-Casanova et al., 2000). However, these laboratory hydration experiments provide only upper bounds for the actual hydration state of Earth’s mantle. Therefore, quantifying the effects of hydration on the thermoelastic properties of wadsleyite and ringwoodite with likely mantle Fe-contents is of particular importance to building more robust models that are based on both mineral physics and seismology (e.g. Chen et al., 2002; Smyth and Frost, 2002).

Iron-free ringwoodite is known to incorporate up to 2.8 wt.% H₂O, resulting in a large volume of hydration of about 4.58 Å³ or 1.8% (Sasaki et al., 1982; Yusa et al., 2000). Under isothermal compression, the bulk modulus (K₀) of this hydrous ringwoodite was determined to be 148 ± 1 GPa, or about 20% lower than for nominally dry pure-Mg ringwoodite with K₀ = 182 ± 3 GPa (Meng et al., 1994). The single-crystal elastic constants of hydrous Mg-ringwoodite containing ~2.2 wt.% H₂O were measured by Brillouin scattering (Inoue et al., 1998), resulting in aggregate bulk and shear moduli, K₀ = 155 ± 4 GPa and G₀ = 107 ± 3 GPa. These values are about 16 and 10% lower than for nominally dry Mg-ringwoodite with K₀ = 184 ± 2 GPa and G₀ = 119 ± 2 GPa (Weidner et al., 1984) or K₀ = 185 ± 3 GPa and G₀ = 120 ± 2 GPa (Jackson et al., 2000).

The single-crystal elastic constants of Fo89 nominally anhydrous ringwoodite were measured to 16 GPa at room temperature, and to 923 K at room pressure by Sinogeikin et al. (2001). The resulting zero-pressure aggregate moduli are: K₀ = 188 ± 3 GPa, G₀ = 120 ± 2 GPa, with pressure derivatives 4.1 ± 0.3 and 1.3 ± 0.2 for the bulk and shear moduli, respectively.

Our main objective here is to report the sound velocities and cubic single-crystal elastic constants of Fo89 hydrous ringwoodite containing approximately 10,000 ppm weight (1 wt.%) H₂O. The samples were synthesized in the 5000 ton multi-anvil press at Bayerisches Geoinstitut, and are characterized by electron microprobe, Mössbauer spectroscopy, single-crystal X-ray diffraction, high-resolution TEM, and FTIR spectroscopy (this study and Smyth et al., 2003a). Pure ultrasonic shear waves of near-optical wavelength are produced by P-to-S conversion inside a new single-crystal buffer rod (BR) made of Yttrium–Aluminum–Garnet (YAG). The new buffer rod is more durable than our prototype MgO conversion buffer rod (Jacobsen et al., 2002), and has already been coned and tested on the diamond anvil cell for future ultrasonic shear-wave experiments at high pressures and temperatures. In this study we report the bench-top elasticity of ringwoodite micro crystals as thin as ~30 μm. The samples are among the thinnest ever studied with ultrasonic interferometric methods, also marking to our knowledge the first time single-crystal ultrasonics has been used to measure the elasticity of a high-pressure phase synthesized in the multi-anvil press. Both P- and S-wave travel times can now be routinely measured in single-crystal samples of any optical character, making gigahertz ultrasonic interferometry a powerful compliment to Brillouin spectroscopy for determining the anisotropic elastic constants of high-pressure minerals or metals of importance to both the Earth and materials sciences.

2. Experimental

2.1. Sample synthesis and characterization

Deep-blue colored Fo89 hydrous ringwoodite single crystals were synthesized in the 5000 ton multi-anvil press at Bayerisches Geoinstitut for diffraction (Smyth et al., 2003a, 2003b) and ultrasonic studies. Starting materials of San Carlos olivine plus brucite, quartz, and FeO (for about Fo89 plus 3 wt.% H₂O and slight excess silica) were compressed in an 18 mm edge-length MgO octahedron to 20 GPa and heated at 1400 °C for approximately 5 h. Run products were dominantly ringwoodite, plus minor amounts of stishovite and quench glass. The ringwoodite crystals are exceptionally large, measuring up to 800 μm (equant) in size. Microprobe analysis gives a Mg/(Mg + Fe) ratio ranging from 88.5 to 89.2 (Table 1), with an average of 45 wt.% MgO and 40 wt.% SiO₂, resulting in ~1.7 Mg atoms and ~1.0 Si atom per four oxygen. Mössbauer spectroscopy indicates that approximately 10% of the iron is in the ferric state (Smyth et al., 2003a). Therefore, excluding...
hydrogen, the formula of the ringwoodite samples is approximately (Mg,Fe)H₂O (wt.%) Cell volume (Å³) ρ (g/cm³) Reference

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mg/(Mg + Fe)</th>
<th>H₂O (wt.%)</th>
<th>Cell volume (Å³)</th>
<th>ρ (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ringwoodite</td>
<td>1</td>
<td>0</td>
<td>525.30</td>
<td>3.55</td>
</tr>
<tr>
<td></td>
<td>0.91</td>
<td>0</td>
<td>526.20</td>
<td>3.70</td>
</tr>
<tr>
<td>Hydrous ringwoodite</td>
<td>1</td>
<td>2.2</td>
<td>527.24</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>0.89</td>
<td>1.0</td>
<td>530.80</td>
<td>3.65</td>
</tr>
</tbody>
</table>

Three separate samples were prepared for the ultrasonic experiments. Potential crystals were pre-checked optically and then oriented with X-rays on a four-circle diffractometer. We constructed a level stage for directly transferring oriented micro crystals from the four-circle goniometer to a glass slide. Once the orientation matrix for a crystal is obtained, the reciprocal orientation matrix for a crystal is obtained, the reciprocal translation of the goniometer can move the desired vector [u,v,w] into the vertical, where the z-translation of the goniometer can move the oriented crystal onto the glass slide. We use an acetone soluble UV-curing epoxy to rapidly fix the oriented crystal to the slide, held parallel to the goniometer table. In this way, the crystal orientation can be maintained to well within ±1°. Three crystals were double polished with [1 0 0], [1 1 1], and [1 1 0] perpendicular to the plates, referred to here as hring 1 0 0, hring 1 1 1, and hring 1 1 0, respectively (Table 2). Finally, the [0 0 1] and [−1 1 0] directions were located in the [1 1 0] plate using a precession camera so that both pure-shear polarization modes could be measured in the [1 1 0] propagation direction. Sample thickness measurements were carried out using two different digital micrometers, resulting in lengths of 47, 52, and 31 μm for the [1 0 0], [1 1 1], and [1 1 0] plates, respectively. The various thickness measurements were reproducible and consistent to 1 μm.

Unit-cell parameters for the ringwoodite samples were measured by the eight-position centering of ~20 reflections, giving an average cell volume of 530.80 ± 0.05 Å³. Thus, compared to nominally dry Fo90 ringwoodite (Sinogeikin et al., 1998) hydration to 1 wt.% H₂O is associated with a positive volume of hydration of about 4.6 Å³, or about 1%.

Our spectra show a dominant absorption band at ~3160 cm⁻¹, which is typical for hydrous ringwoodite, showing broad absorption in the region of 3750–2750 cm⁻¹ (Fig. 1) and indicate that all three samples contain (within uncertainty) the same amount of hydrogen. Our spectra show a dominant absorption band at around 3160 cm⁻¹, with an additional shoulder around 3580 cm⁻¹. These assignments could correspond to...
those at 3120 and 3695 cm$^{-1}$, respectively, observed by Bolfan-Casanova et al. (2000) in pure-Mg hydrous ringwoodite, with shifts due possibly to the iron-content of our samples. For lack of a specific (ringwoodite) calibration, we used the method of Paterson (1982) to estimate the average water content of the samples, resulting in about 9960 ppm weight (1 wt.%) H$_2$O, or about 161,000 H/10$^6$ Si.

Combining the microprobe, Mössbauer, and FTIR data results in the formula, Mg$_{1.7}$Fe$_{0.22}$H$_{0.16}$SiO$_4$, with about 10% of the iron the ferric state. Therefore, the calculated density of this hydrous Fo89 ringwoodite is 3.651 $\pm$ 0.005 g/cm$^3$.

2.2. Ultrasonics

We recently produced pure ultrasonic shear waves over a broad bandwidth (0.5–2.0 GHz) by P-to-S conversion inside a single-crystal acoustic buffer rod (Jacobsen et al., 2002). The resulting high-frequency shear is of suitable wavelength ($\sim$1–10 $\mu$m) and has a known polarization direction for elasticity measurements on single-crystal samples as thin as 20–30 $\mu$m in length, on the bench or in the diamond anvil cell. The new technique takes advantage of an orthogonal P-to-S conversion inside an oriented YAG single-crystal buffer rod, illustrated in Fig. 2a. Incident P-waves are produced by a ZnO sputtered thin-film transducer. Using Snell’s Law, $V_p^{[100]}$, and $V_s^{[100]}$ to calculate the angle incidence ($\iota$), we force the conversion to occur at exactly 90°. This allows for both the incident P-wave and reflected S-waves to travel in pure-mode directions of the cubic single-crystal buffer rod, as well as allowing for the symmetric return of the wave (labeled PSSP in Fig. 2) for detection at the source transducer. In this way, delay-line acoustics are carried out in the usual way (Spetzler et al., 1993).

Ultrasonic travel-times are measured using interferometric methods, described in more detail by Spetzler et al. (1993). Briefly, a pulse generator is used to gate a continuous RF signal, resulting short ($\sim$100 ns) phase-coherent tone bursts that are introduced to the sample via a buffer rod (Fig. 2). The impedance contrast at the BR-sample interface produces a reflection, which is interfered with an echo produced at the far end of the sample, either by lengthening the width of the input signal, or by carefully delaying two tone bursts such that the first sample echo overlaps with the second BR echo (see Jacobsen et al., 2002 for a standard, thick-sample echo train). In this case, the samples are so thin (and associated travel times so short, 10–20 ns) that the sample echoes cannot be separately resolved in time (see inset of Fig. 3a). Therefore, we measure simply the amplitude of the interfered tone burst where there is only first-order interference.

Fig. 1. Unpolarized FTIR spectra from the three Fo89 hydrous ringwoodite crystals used in the ultrasonic study.
Fig. 2. The new P-to-S conversion ultrasonic shear-wave buffer rod. (a) In schematic, showing the GHz P-wave source transducer, the orthogonal P-to-S conversion, and back reflections from the tip of the buffer rod (PSSP) and from the far end of the sample. The buffer rod is sharpened for placement in the cone of a diamond anvil cell. For bench-top measurements, the sample is gently weighted by an optically aligned glass rod (shown at right). (b) A pulse echo train from the buffer rod resulting from a single sine wave input signal. The echo labeled PSSP1 results from one round trip through the buffer rod. Many PSSP echoes are observed, illustrating the high efficiency of the conversion and precision of the facet orientations. The round trip within the sample is considerably shorter than the width of each burst and can, thus, not be resolved separately. Each echo is about 100 ns in duration and the frequency of the sine wave within them is 1200 MHz. Therefore, there are over 100 cycles per burst. The structure within the bursts (observed here) results from aliasing inherent in the display of a digitizing oscilloscope.

between the sample and the first buffer rod echo. The resulting interference pattern contains maxima (and minima) produced each time there is an integer number (or half-integer for minima) of wavelengths in the round-trip (Fig. 3a). Acoustic coupling between the sample and the buffer rod is achieved by either direct (dry) contact or with wet and cured glue thin-films, but in all cases a weight of a few grams is applied through an optically aligned glass rod (shown in Fig. 2a).

Fig. 3a shows an example of a shear-wave interference pattern measured from 600 to 1200 MHz for the [1 1 0] ringwoodite sample, vertically polarized (T_v), i.e. [0 0 1]. The complex BR and overlapping sample echo are also shown, indicating at what positions the uninterfered and interfered amplitudes were measured. The resulting travel-time data calculated from each f_{max} and f_{min} are shown in Fig. 3b. In this way, we determined seven different pure-mode phase velocities from compression wave travel times in the [1 0 0], [1 1 1], and [1 1 0] directions, and shear-wave travel times in the [1 0 0] and [1 1 1] directions, plus both shear polarizations (T_h and T_v) for the [1 1 0] propagation direction as given by Brugger (1965), and listed in Table 2.
3. Results and discussion

Measured P- and S-wave travel times were used to calculate ultrasonic wave velocities (Table 2) and the single-crystal elastic constants of Fo89 hydrous ringwoodite, compared to other ringwoodite studies in Table 3. Substitution of plane wave solutions into the equations of motion (e.g. Brugger, 1965) gives the $c_{11}$ elastic constant directly from

$$\rho V_{P}^{2} = 298 \pm 13 \text{ GPa},$$

where the propagation of error is calculated using standard Gaussian methods. Although travel-times can be routinely measured on
Table 3
Single-crystal and aggregate elastic properties of ringwoodite and hydrous ringwoodite

<table>
<thead>
<tr>
<th></th>
<th>Ringwoodite</th>
<th>Hydrous ringwoodite</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>γ-Mg$_2$SiO$_4$</td>
<td>γ-Mg$<em>2$Fe$</em>{10}$Si$<em>6$O$</em>{16}$</td>
</tr>
<tr>
<td>ρ (g/cm$^3$)</td>
<td>3.59</td>
<td>3.70 ± 0.05</td>
</tr>
<tr>
<td>ρ (g/cm$^3$)</td>
<td>3.469</td>
<td>3.61 ± 0.05</td>
</tr>
<tr>
<td>c$_{11}$ (GPa)</td>
<td>327 ± 4</td>
<td>329 ± 3</td>
</tr>
<tr>
<td>c$_{44}$ (GPa)</td>
<td>126 ± 2</td>
<td>130 ± 1</td>
</tr>
<tr>
<td>c$_{12}$ (GPa)</td>
<td>112 ± 3</td>
<td>118 ± 2</td>
</tr>
<tr>
<td>t$_{4}$ (GPa)</td>
<td>0.113</td>
<td>0.149</td>
</tr>
<tr>
<td>K$_0$ (GPa)</td>
<td>184 ± 2</td>
<td>188 ± 3</td>
</tr>
<tr>
<td>G (GPa)</td>
<td>119 ± 2</td>
<td>119 ± 2</td>
</tr>
<tr>
<td>V$_P$ (km/s)</td>
<td>9.79</td>
<td>9.69 ± 0.02</td>
</tr>
<tr>
<td>V$_S$ (km/s)</td>
<td>7.77</td>
<td>6.78 ± 0.04</td>
</tr>
</tbody>
</table>

*Anisotropy factor $A = (2c_{11} + c_{12})/c_{44}$ - 1.

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micro-crystals to a few parts in 10$^5$, the rather large uncertainty in the elastic constants are dominated by the much larger uncertainty in the thickness measurement, in this case ±1 μm. There are two ways of obtaining $c_{44}$ directly; from $V_c^{[100]}$ we obtain $c_{44} = 112.5$ GPa, and from $V_p^{[110]}$ polarized [0 0 1] we obtain $c_{44} = 112.7$ GPa, in perfect agreement. Given $c_{11}$ and $c_{44}$, we have four remaining equations for obtaining $c_{12}$ (listed in Table 2), resulting in 115, 118, 110, and 116 GPa, also showing good internal consistency. We use for all subsequent calculations the average value, $c_{12} = 115.6$ GPa. Despite the rather large reported uncertainties resulting from correct propagation of uncertainty in the length, we note that the internal consistency among the seven independent equations determined from three different crystals is much better. For example the standard deviation in the mean for $c_{12}$ using the four independent equations is only 3 GPa, or about half the reported uncertainty.

Another way of approaching this calculation is to solve all seven equations simultaneously by least-squares. Using a standard over-determined least-squares inversion with data matrix [$\phi$], we obtain $c_{12} = 297$, $c_{44} = 112$, and $c_{11} = 116$ GPa, in excellent agreement with the (preferred) direct approach.

The single-crystal elastic constants of various ringwoodite samples with and without Fe and water are listed in Table 3. We obtain for the (VRH averaged) aggregate bulk and shear moduli, $K_{0R} = 176 ± 7$ GPa and $G_{0R} = 103 ± 5$ GPa, corresponding to isotropic bulk sound velocities $V_P = 9.26 ± 0.20$ and $V_S = 5.31 ± 0.13$ km/s. The bulk sound velocities for hydrous Fo$_{90}$ ringwoodite are about 4.4 and 6.5% slower (for P and S, respectively) than for dry Fo$_{90}$ ringwoodite (Sinogeikin et al., 1998). Thus, hydration of ringwoodite appears to have a larger effect on S-wave velocities than P so hydration should increase the ratio $V_P/V_S$ in the Earth, an important seismic parameter. We calculate $V_P/V_S = 1.74 ± 0.04$ for our hydrous sample, compared to $V_P/V_S = 1.706 ± 0.002$ for dry Fo$_{90}$ ringwoodite (Sinogeikin et al., 1998). Although the ratio $V_P/V_S$ for our sample has a rather large uncertainty due to propagation of the uncertainty in length (around 2%), we note that uncertainties in the ratio $V_P/V_S$ for the various measured crystallographic directions are much lower (around 0.5%) because $V_P/V_S = (2l/n p)/(2l/n s) = \eta/l$, where $l$ is the sample length and $n_p$ and $n_s$ are the P-wave and S-wave travel-times, respectively. Using travel times and associated uncertainties found in Table 2, we calculate $(V_P/V_S)^{[100]} = 1.64 ± 0.01$, $(V_P/V_S)^{[110]} = 1.83 ± 0.01$, $(V_P/V_S)^{[111]} = 1.68 ± 0.01$ for shear vertically polarized ($T_s$) and $(V_P/V_S)^{[110]} = 1.86 ± 0.01$ for shear horizontally polarized $(T_h)$.

Compared to dry iron-bearing ringwoodite (Sinogeikin et al., 1998), the $c_{11}$ elastic constant of hydrous Fo$_{90}$ ringwoodite is reduced from 329 to 298 GPa (or 9.4%), and the $c_{44}$ elastic constant is reduced from 130 to 112 GPa (or 13.8%). In contrast, the $c_{12}$ elastic constant is statistically identical to that measured for nominally dry ringwoodite with or without iron. Consequently, the anisotropy factor
$A = \left[ (2c_{24} + c_{12})/c_{11} \right] - 1$ is reduced from 0.149 to 0.138 or about 7.4%.

Hydration of Fo$_{90}$ ringwoodite to 1 wt. % H$_2$O reduces the bulk ($K_{0S} = 176 \pm 7$ GPa) and shear ($G_{0} = 103 \pm 5$ GPa) moduli by about 6 and 13%, respectively, compared to nominally dry iron-bearing ringwoodite (Fig. 4). Our value for the adiabatic bulk modulus is in relatively good agreement with the isothermal value, $K_{0T} = 169 \pm 3$ GPa, measured in a companion paper of this volume (Smyth et al., 2003b). Using the temperature derivatives of the moduli $\partial K_S/\partial T = -0.021$ and $\partial G/\partial T = -0.016$ measured for dry Fo$_{90}$ ring...
woodite (Sinogeikin et al., 2001), we estimate that at room pressure hydrating FeO–90 ringwoodite to 1 wt.% H$_2$O is roughly equivalent to raising the temperature by about 600 and 1000°C. From the adiabatic moduli and density, we calculate bulk sound velocities (in m/s): $V_p =$ 9260 and $V_s =$ 5310. Anchoring these data to the dry Fo$_{90}$ ringwoodite data from Sinogeikin et al. (1998), we obtain a rough linear estimate for the elastic moduli and velocities FeO–90 ringwoodite as a function of water content:

$$K_H = 188 - 0.0012C_{H_2O} \text{(GPa)}$$

$$G_H = 119 - 0.0016C_{H_2O} \text{(GPa)}$$

$$V_p = 9690 - 0.042C_{H_2O} \text{(m/s)}$$

$$V_s = 5680 - 0.036C_{H_2O} \text{(m/s)}$$

where $C_{H_2O}$ is the water concentration in ppm H$_2$O by weight (1000 ppm weight = 0.1 formula wt.% H$_2$O).

Hydrating FeO–90 ringwoodite to 1 wt.% H$_2$O reduces its density from 3.70 to 3.65 g/cm$^3$, or about 1.4%. The bulk $P$- and $S$-wave velocities are reduced by 4.3 and 6.3%, respectively, thus, reducing the impedance ($\rho V$) by 5.8% for $P$-waves and 7.6% for $S$-waves. For comparison, the effect of adding 10% Fe to dry ringwoodite is to increase the impedance by 3.2% for $P$-waves and 2.4% for shear waves. Without adiabatic moduli for wet wadsleyite, we cannot speculate on the potential impedance contrast between wet–wet versus dry–dry wadsleyite–ringwoodite mantle discontinuities. However, between this study and existing isothermal compression data for hydrous Mg-wadsleyite (Yusa and Inoue, 1997), hydrous Mg-ringwoodite (Yusa et al., 2000), and Fo$_{90}$ hydrous ringwoodite (Smyth et al., 2003b), a larger picture is emerging on the relative magnitude of effects that hydration has on the elasticity of high-pressure silicates.

If the effects of relatively small amounts of water (on the order of one-tenth of 1 wt.%) are still large enough at the $P$-$T$ conditions of Earth’s transition zone to affect seismic velocities more than the likely range of Fe/Mg ratios or temperature gradients away from subduction zones, then water should be considered a very likely compositional variable able to produce lateral velocity variations and topography on the discontinuities as observed by seismic tomography.

Duffy and Anderson (1989) used the relatively low $P$- and $S$-velocities of the transition zone in PREM (Dziewonski and Anderson, 1981) to infer that the mantle in that region could not contain more than about 50% of an olivine-stoichiometry phase, i.e. ringwoodite or wadsleyite. Consideration of the effects of hydration of ringwoodite on velocities removes this constraint so that the $P$- and $S$-velocities of the lower transition zone in PREM are consistent with a hydrated ringwoodite-rich composition. Further, it is interesting to note that the current results indicate a strong effect of hydration on $V_p/V_s$, raising the value from 1.706 for dry to 1.744 for this hydrated ringwoodite at ambient conditions. If these results are confirmed in future studies at elevated pressures and temperatures, it may be possible to distinguish hydration from high temperatures in the transition zone of the mantle.

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