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# Experimental determination of the effect of $H_2O$ on the 410-km seismic discontinuity

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**Abstract**

Due to the high solubility of $H_2O$ in the mineral wadsleyite it has been recognized that the presence of $H_2O$ in the mantle could influence the pressure and pressure interval of the olivine to wadsleyite phase transformation that is generally considered to be the cause of the 410-km seismic discontinuity. We have performed multianvil experiments in the $Mg_2SiO_4$–$H_2O$ system in order to quantify the expansion of the wadsleyite stability field as a result of the presence of $H_2O$. At 1200 °C we find that the wadsleyite stability field expands to lower pressures by approximately 1 GPa under $H_2O$-rich fluid-saturated conditions. At 1400 °C the expansion is approximately 0.4 GPa and no expansion can be detected at 1600 °C. A thermodynamic model based on recent $H_2O$ solubility measurements and crystallographic observations predicts an expansion of the wadsleyite stability field that is in good agreement with the experimental results. When these results are combined with phase relations in the $Mg_2SiO_4$–$Fe_2SiO_4$ system it can be shown that significant effects on the pressure and pressure interval of the olivine to wadsleyite transformation, i.e. on the depth and width of the 410-km discontinuity, are only expected at lower than ambient mantle temperatures (<1400 °C) and for $H_2O$ concentrations that are substantially greater than 0.2 wt.%. Areas of the mantle where the 410-km discontinuity appears to occur over a depth interval of over 20 km can only be explained if the temperature in these regions is at or below 1200 °C and water concentrations are close to the level where olivine would become $H_2O$ saturated (i.e. >0.5 wt.%). The presence of ferric Fe in the mantle, however, may also play a role in the broadening of the 410-km discontinuity that is as yet unquantified.
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*Keywords:* 410-km discontinuity; mantle; transition zone; wadsleyite; $H_2O$; high pressure

## 1. Introduction

The isochemical phase transformation of (Mg, $Fe)_2SiO_4$-olivine to the higher pressure polymorph wadsleyite is considered to cause the discontinuity in seismic velocity that occurs at approximately 410-km [1,2]. Wood [3] first proposed that this transformation has the potential to be strongly influenced by the presence of $H_2O$ in the mantle. This arises from the fact that wadsleyite has an enormous capacity to accommodate hydroxyl ($OH^-$) in its structure (up to 3.3 wt.% $H_2O$), which results in a preference of $H_2O$ for wadsleyite over olivine [4–6] at equilibrium. The solution of $H_2O$ as hydroxyl should raise the configurational entropy of wadsleyite and consequently expand its stability field with respect to olivine, making it stable at lower pressures than in dry systems.

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Even in dry systems the olivine to wadsleyite transformation occurs over a pressure, i.e. depth, interval because both phases are binary solutions and Fe–Mg exchange takes place. The presence of $H_2O$ causes an additional degree of freedom, which should lead to a further broadening of the transformation interval. Based on the available measurements [4,6] Wood [3] assumed $H_2O$ would partition between wadsleyite and olivine in a ratio of approximately 10:1. Therefore, even if olivine has an initial $H_2O$ concentration of only 0.02% (200 ppm), at the pressure where wadsleyite first starts to form from olivine it would have an $H_2O$ concentration of approximately 0.2%. Using a solution model, Wood [3] calculated that 0.2% $H_2O$ in wadsleyite would expand its stability field to lower pressure by approximately 0.25 GPa or 7 km in comparison to a dry system. The presence of $H_2O$ broadens the olivine to wadsleyite transition because it lowers the pressure where wadsleyite first appears in the mantle but does not significantly change the pressure where olivine disappears in the transformation. This means that if 0.02 wt.% $H_2O$ is present in the mantle it not only expands the wadsleyite stability field by 7 km but also broadens the transformation interval by approximately the same distance. Many seismic studies of short period reflected and converted waves have proposed that the "410" is a relatively sharp discontinuity with most of the velocity increase occurring over a depth interval of 4 km or less [7–9]. Wood [3] proposed that this was inconsistent with a mantle containing more than 0.02% $H_2O$.

These predictions were to some extent confirmed by experiments under hydrous conditions performed by Smyth and Frost [10] who observed the $(Mg,Fe)_2SiO_4$ olivine–wadsleyite transformation to be approximately 10 km broader than the dry transition at 1400 °C. Another study performed at 1200 °C with slightly higher $H_2O$ contents, however, observed a depression of the transformation but a sharpening of the transformation interval [11].

Recently van der Meidje et al. [12] observed the thickness of the 410-km discontinuity beneath the Mediterranean to vary between 20 and 30 km, which is significantly broader than previous observations but using the model of Wood [3] could be accounted for by the presence of approximately 0.07 wt.% $H_2O$ (700 ppm) in the mantle. On the other hand, recent studies have shown the solubility of $H_2O$ in wadsleyite to be lower than previously assumed at typical transition zone temperatures [13], while the solubility of $H_2O$ in olivine is apparently higher [14,15]. The higher values for olivine are mainly due to the use of a new calibration [16] for measuring olivine $H_2O$ contents using Fourier-transform infrared spectroscopy (FTIR). For both phases $H_2O$ solubilities appear to rise with temperature to a maximum at approximately 1200 °C but drop off quite sharply at higher temperatures as significant hydrous melting occurs. Based on these new data Hirschmann et al. [17] used the model of Wood [3] to show how the lower solubility of $H_2O$ in wadsleyite at ambient mantle temperatures would reduce the effect of $H_2O$ on the olivine to wadsleyite transformation.

Another important observation, is that the $Fe^{3+}/\Sigma Fe$ contents of $H_2O$-saturated $(Mg,Fe)_2SiO_4$ wadsleyite synthesised in platinum capsules can be up to 44% and up to 96% in gold–palladium capsules [18]. Ferric Fe also partitions preferentially into wadsleyite over olivine and also influences the position and width of the olivine–wadsleyite phase transformation [19]. In Fe- and $H_2O$-bearing systems it is therefore necessary to also control oxygen fugacity, hence isolating the influence of $H_2O$ alone on the wadsleyite stability field becomes much more difficult. The primary way to overcome this is to exclude Fe completely from the system and examine the effect of $H_2O$ on the $Mg_2SiO_4$ transition.

In Fig. 1 the model of Wood [3] has been used to calculate a phase diagram in the Fe-free system showing the forsterite to wadsleyite transformation. The diagram has been calculated assuming that wadsleyite is saturated with only 1 wt.% $H_2O$ but already shows an

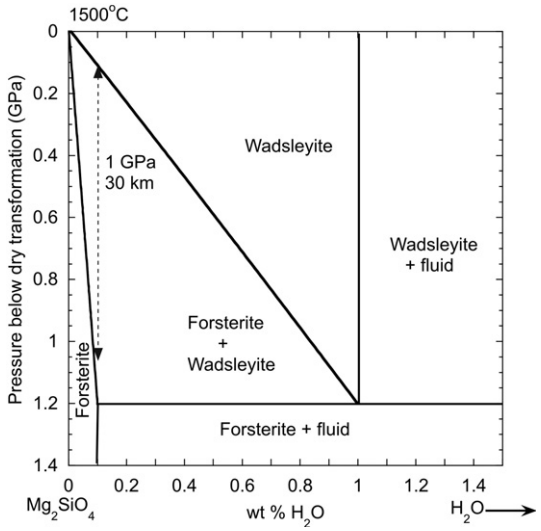


Fig. 1. The $Mg_2SiO_4$ forsterite–wadsleyite transformation as a function of $H_2O$ content calculated using the model of Wood [3]. The partitioning of $H_2O$ between forsterite and wadsleyte is assumed to be in the ratio 1:10 as in [3]. The diagram is calculated assuming saturation of wadsleyite by only 1 wt.% $H_2O$ whereas wadsleyites with over 3 times this $H_2O$ content have been reported [5]. The vertical arrow indicates the degree of broadening predicted for a mantle $H_2O$ content of 0.1 wt.%.

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