The Effect of H_2O on the 410-km Seismic Discontinuity

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Science Paper (1995)

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Background

- Seismic discontinuities at 410 km and 660 km ------ important jumps in mantle density and P, S wave velocity.
- 410 km and 660 km discontinuities -----phase transitions (ol (α)→$_{410\ km}$ wa(β) → sp(γ) →$_{660km}$ Pv + Mw)
- Seismological constraints on the phase transition zones: sharp and with small depth intervals (660-km ~ 5 km, 410 –km < 10 km)
- Divariant loop (two phases coexisting area) in phase diagram from α→β : sharp 410 km discont. with a maximum interval of 8 km.

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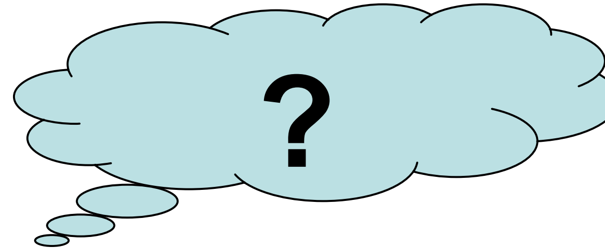
Please see:

Wood, B. J. "The effect of H2O on the 410-kilometer seismic discontinuity." *Science* 268 (1995): 74-76.

Fig. 1. Phase diagram (2) for Mg_2SiO_4-Fe_2SiO_4 at 1773 K (close to mantle temperature) and at 10 to 18 GPa. For an observed mantle Fe/(Fe+Mg) ratio of about 0.1, the transformation from olivine [α-$(Mg,Fe)_2SiO_4$] to β-$(Mg,Fe)_2SiO_4$ takes place through an interval of about 0.25 GPa where both phases coexist. This should result in an apparent seismic discontinuity spread over a 7-km depth interval.

Problems



- **Basic Assumption** in phase transition calculation: the chemical system of the Earth is MgO – FeO – SiO_2 and **other components (e.g. H_2O) have no effect on the phase transformations.**
- **New evidences about H_2O :** (1) H_2O is structurally bounded in the nominally anhyrous minerals of the Mantle including olivine; (2) H_2O is much more soluble in the β phase than in olivine α .
- **This Paper will show** : (1) strong preference of H_2O for β phase; (2) very low concentration of H_2O in the mantle greatly affect the width of the transition interval; (3) implications for the correlation between seismic observations and phase relations

H_2O Effect on 410-km Discont.

- **Smyth** proposed β phase could be a large host for H_2O below 410 km from energy viewpoint of chemical reaction.
- **New experiments** evidence: (1) a solubility up to 3% H_2O (by weight) in the β phase ; (2) a partitioning of H_2O between β phase and olivine of great than 10:1 → H_2O in favor of β phase.
- Chemical Equilibrium containing H_2O:

$$\underset{\beta\ \text{phase}}{3Mg_2SiO_4} + \underset{\text{Pyroxene}}{MgSiO_3} + H_2O = \underset{\beta\ \text{phase}}{Mg_7Si_4O_{14}(OH)_2} \qquad (1)$$

- **Chemical potentials calculation**

$$\mu^{\beta}_{Mg_2SiO_4} = \mu^{0}_{Mg_2SiO_4} + RT\ln[X^2_{Mg}\gamma_{Mg}(1 - X_{OH})^{0.5}] \quad (2)$$

$$\mu^{\beta}_{Fe_2SiO_4} = \mu^{0}_{Fe_2SiO_4} + RT\ln[X^2_{Fe}\gamma_{Fe}(1 - X_{OH})^{0.5}]$$

$$\mu^{\alpha}_{Mg} = \mu^{0}_{Mg_2SiO_4} + RT\ln[X^2_{Mg}\gamma_{Mg}(1-X_{OH})^4/(1-0.5X_{OH})^4] \quad (4)$$

Phase relations for partially hydrated (500 ppm H_2O) olivine and β phase

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Fig. 2. The calculated effect of 500 ppm H_2O (by weight) on the $\alpha+\beta$ region of Fig. 1; β-$(Mg,Fe)_2SiO_4$ appears at a pressure 0.6 GPa lower (16 km higher in the mantle) than in the anhydrous case, and the $\alpha+\beta$ loop is expanded from 7 to 22 km.

Effects of H_2O contents (0 → 1000 ppm in olivine) on the olivine - β phase transformation

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Fig. 3. The olivine–β-phase transition interval for initial H_2O contents of olivine of 0, 200, 500, and 1000 ppm. Addition of H_2O elevates the point at which β-$(Mg,Fe)_2SiO_4$ appears (shifts it to lower pressure) and broadens the transformation interval. Given a seismically determined transformation interval of $<$10 km, the maximum H_2O content of upper mantle olivine at a depth of 400 km is constrained to about 200 ppm.

H_2O Effect on 660-km Discont.

- Phase transformation from γ → Pv + Mw at 660 km is also sensitive to **H_2O** content.
- If H_2O partitioning between two phases is 10:1 in favor of either, the transformation interval must be broadened.
- If H_2O favors Pv → trans. interval would be broadened to lower pressure.

  If H_2O favors γ → trans. interval would be broadened to higher pressure.

- Observed width of discont. < 5 km will be consistent only with < 1000 ppm H_2O in γ phase if the discontinuity is isochemical.

Implications for the correlation between seismic observations and phase relationships

- Seismic results: H_2O may be released from subducting lithosphere in two depth interval (<100 km and 300 → 500 km).
- Nolet and Ziehuis: from 300 to 500 km, the low S-wave velocities above an ancient subduction zone could only reasonably be accounted for by the weakening of the shear modulus because of the presence of H_2O or small amounts of hydrous partial melt.
- Author’s suggestion: further seismic experiments on the nature of 410 and 660 km discont. in the ‘wet’ region of subduction zone. (elevation and broadening of these discont. ???) (If yes, isochemical changes; if no, combined phase and bulk compositional changes)

- Structurally bound H_2O contents in lower pressure mantle minerals: garnet < xenoliths (olivine)<< pyroxene
- Olivine is a more important host for H_2O at 410 – km disconti. than it is the shallow mantle because

  (1) the proportion of pyroxene declines with depth as it dissolves into garnet with depth, i.e., a H_2O rich mineral replaced by a H_2O poor mineral.

  (2) data on natural samples: a stronger pressure effect on H_2O in olivine than in pyroxene. Bell et al. argued that olivine is the major reservoir for H_2O below 200 km.

  (3) experimental results: H_2O content of pyroxene similar to that of olivine at 14 GPa.
- Structurally bound H_2O may explain the apparent breadth of transition interval (~ 0.5 GPa > 0.25 GPa with 0 H_2O) in experiments, perhaps due to that it's impossible to exclude H_2O from these high pressure experiments.

- **Is there any other minor elements affecting the olivine - β** phase transition ?

Recent experiments show no evidence! →

The effect of **H_2O is the most important!**

The effect of water on the 410-km discontinuity: An experimental study Smyth & Frost 2002 GRL

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Please see:
Smyth and Frost. "The effect of water on the 410-km discontinuity: An experimental study." *Geophysical Research Letter* (2002).

Anhyrous system:
0.4 GPa ~ 12 km
Hydrous system
~ 1.3 GPa (40 km)

Figure 1. Plot of experimental results at 1400°C. Solid symbols represent olivine and open symbols wadsleyite. Gray symbols and boundaries represent the hydrous experiments and black the anhydrous.