

The Lehmann Discontinuity Due to Dehydration of Subducted Sediment

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Abstract: Recent high-pressure experiments have led to the conclusion that water release from subducted sediments lying under continents in subduction regions occurs at about 220 km depth. This dehydration reaction is in good agreement with the seismological signature of the discontinuity indicating that sediment dehydration causes the Lehmann discontinuity in the upper mantle.

Keywords: Lehmann discontinuity, high pressure, water, dehydration, 220 km, sediment.

1. INTRODUCTION

The Lehmann discontinuity was first observed in Europe and North America from seismic refraction studies beneath continents [1, 2]. The discontinuity is characterized by the following features: (1) The depth of the seismic discontinuity is around 220 km depth. (2) A regionally varying negative seismological Clapeyron slope (dP/dT) of the discontinuity depth has been estimated [3]. (3) The discontinuity has not been detected everywhere at around 220 km depth [4]. It is observed under continents more than twice as often as under oceans [5], and the largest amplitudes of this discontinuity appear beneath the continents [6]. (4) An increase in the compressional or shear wave velocity and in seismic reflections from around 220 km depth has been reported [7, 8]. (5) A seismic transition from anisotropic to a more isotropic state occurs at depths corresponding to the Lehmann discontinuity [9, 10].

The phase transitions of (Mg,Fe)SiO₃ pyroxene [11, 12] and silica (SiO₂) [13, 14] were reported at high pressures corresponding to the depth of the Lehmann discontinuity. These transitions seemed to be candidates for the origin of the discontinuity. However, both models have serious flaws, and from the view point of the mineralogy, those characteristic features of this discontinuity could not be explained by previous models.

The dP/dT slope of the mineralogical phase transition is one of the important features to understand the structure of the mantle. This slope can be expressed using differences of entropy and volume at the transition ($dP/dT = dS/dV$). The seismological Clapeyron slope can be estimated using the depth of the discontinuity and the relative seismic velocity perturbation taken from a tomographic model [3].

(Mg,Fe)SiO₃ pyroxene is one of the major minerals present in the pyrolite mantle, which has a typical upper mantle composition. If the phase transition of pyroxene causes the seismic discontinuity, this would be observed everywhere in

the upper mantle, whereas most observations are under continents. It is therefore impossible to explain the local occurrence of the discontinuity using this concept.

In the case of the silica phase transition, if the coesite-stishovite transformation occurs at 220 km depth, the temperature of the upper mantle would be about 800 K; far too low a typical temperature for this depth. Although both phase transitions have a positive Clapeyron slope, such a negative seismological Clapeyron slope has been reported [3]. It is, therefore, difficult to explain the origin of the discontinuity simply by mineral transition.

The relationship between the seismic discontinuity and chemical boundaries in the mantle has often been discussed [15]. Chemical change induces a different mineral assemblage. As the physical properties of rock are influenced by each constituent mineral, the seismic discontinuities can be a reflection of a chemical boundary. There is no clear evidence, however, that such a boundary exists at 220 km depth in the upper mantle [16, 17].

Karato [18] proposed that the change of deformation mechanism from dislocation creep to diffusion creep caused the Lehmann discontinuity. The diffusion creep is due to transport of matter by self-diffusion through the grains of a polycrystal. In the case of the dislocation creep, dislocations are carriers of plastic deformation in solids. Olivine shows a pressure-induced change in its deformation mechanism. This seems to occur between 240 and 380 km depth. This variation is due to differing parameters of grain size, temperature, water fugacity, and strain rate. This model can explain a velocity jump at the depth of the deformation mechanism change. However, if the mechanism change causes the seismic discontinuity, this would be observed everywhere, because olivine is a major mineral present in the upper mantle. As most observations of the Lehmann discontinuity are local, this hypothesis cannot be accepted.

In this paper, it is proposed that the Lehmann discontinuity is a consequence of the dehydration of subducted sediment. The proposal is made on the basis of high-pressure experiments using a multianvil press. This new model can explain all the characteristic features of the discontinuity such as depth, seismological Clapeyron slope, locality of observation and the velocity jump.

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2. EXPERIMENTAL WORKS

We conducted experiments with hydrous sediment. Samples were contained in Au₇₅Pd₂₅ capsules and the temperature was varied between 1073 and 1673 K, while a pressure of 6-15 GPa was applied using the multi-anvil press. A synthetic gel was used to produce a reactive and homogeneous starting material. We confirmed that the gel starting material quickly achieved a nearly equilibrium state in the multi-anvil experiments [19]. The typical pelite composition was used as the sediment [20]. Sediment with 6 wt% H₂O was produced from synthetic dry gel and reagent-grade Al(OH)₃ as the maximum H₂O content stored in the sediment composition was less than 6 wt%, our experiment was a water saturated condition. It is known that the natural subducted sediment has a considerable variation of chemical composition. Compositional changes of experimental starting material can change the mineral proportions of hydrous minerals. The influence of compositional change in sediments was discussed in our previous study [21]. The average composition of continental crust is sufficiently close to the sediment composition so that the phase relationships of the sediment composition may be generally applicable to that of continental crust. Details of the experimental procedure and results are described elsewhere [21].

Garnet ((Ca,Fe,Mg)₃(Al,Fe)₂Si₃O₁₂), clinopyroxene ((Ca,Fe,Mg)_{2-x}(NaAl)_xSi₂O₆), and silica (SiO₂) phases were present in all of the experiments. Three hydrous phases were observed at temperatures below 1573 K. The stable crystalline hydrous minerals consisted of phengite ((K,Na)Al₂(Si₃Al)O₁₀(OH)₂) below 8 GPa, topaz-OH (Al₂Si₄(OH)₂) from 9-12 GPa, and phase egg (AlSiO₃(OH)) above 12 GPa (Fig. 1). The breakdown boundaries of topaz-OH and phase egg show a positive Clapeyron slope. In contrast, the breakdown reaction of phengite gave a negative slope at about 7 GPa corresponding to 220 km depth. In the case of most high-pressure hydrous mineral, such as alphabet phases, the stability limit in response to temperature is not high [22]. However, the upper temperature limit for phengite is greater than 1473 K. This phase is thus likely to be stable within average adiabatic mantle conditions.

Water-saturated experiments show that the maximum water content in subducted sediment is ~2 wt% H₂O, because phengite, which includes ~4 wt% H₂O, constitutes ~50 wt% of the assemblage. In the case of the continental composition, the water content is estimated to be a half of the sediment composition [21]. When this material reaches the dehydration boundary of phengite (Fig. 1), most water is released from the sediment. This is not pure H₂O because it is known that a large amount of silicate is in solution at high pressure and temperature corresponding to typical upper mantle conditions [23-26]. The solubility of silicate components in water and the solubility of water in silicate melt increase with increasing pressure [e.g., 27-29]. Recently, the complete miscibility between silicate melt and water has been directly observed [26, 30]. According to previous experimental studies, the complete miscibility occurs at ~100 km depth. Therefore, the volume of released water (fluid) including silicate components is therefore greater than 2 wt% estimate made in the previous study [21]. Below ~1200K, topaz-OH is stable in the sediment. A certain amount of water released from phengite breakdown is stabilized in topaz-

OH. The volume of fluid released in low temperature locations typified by the subduction zone is therefore less than in a normal mantle geothermal region.

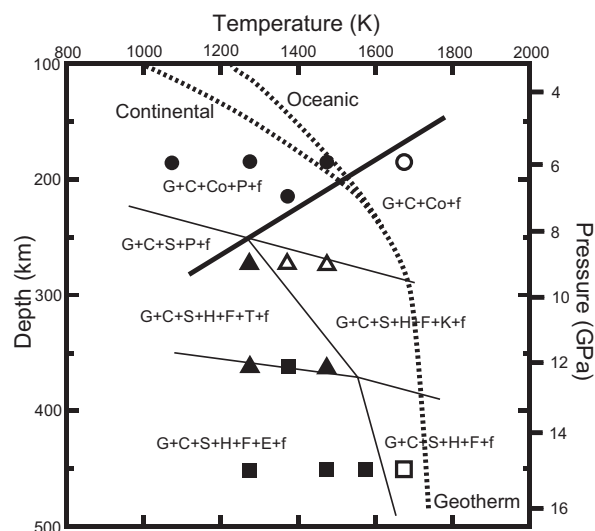


Fig. (1). Experimental constraints on the dehydration of subducted sediment. Symbols represent observed phase assemblages. Thin lines represent the inferred boundaries of phase relation of sediment [21]. Abbreviations of phases are as follows: G, garnet; C, clinopyroxene; Co, coesite; S, stishovite; K, kyanite; H, K-hollandite; F, Fe-Ti oxide; P, phengite; T, topaz-OH; E, phase egg; f, fluid. The thick line represents the dehydration boundary of phengite. The dashed lines represent typical geotherms under oceanic and continental crust. The geotherms intersect with the phengite dehydration boundary at ~220 km depth.

3. ORIGIN OF LEHMANN DISCONTINUITY

The physical properties of water in the upper mantle are distinctly different to those of silicate minerals. It seems nevertheless difficult to explain the origin of the Lehmann discontinuity by water alone. As the volume of the subducted sediment is likely to be very small and the volume of the released water from the sediment is also negligible, the influence of water itself on the discontinuity is not considered important. One interesting feature of water is its percolation into the surrounding rocks. When the dehydration occurs, water can migrate upwards by permeable flow because of the large density difference between the fluid and the surrounding rock. During the migration, the physical properties of the surrounding rock in contact with the water can change.

The solubility of water in olivine is less than 0.1 wt% at pressures corresponding to 220 km depth [31]. In contrast, ~1 wt% water can be released from the subducted sediment. A large amount of water can not be dissolved into olivine. Consequently, the dehydrated water from the subducted sediment is sufficient to wet the grain boundary in the mantle rock. A small amount of water in the grain boundary can induce the creep deformation of olivine.

Above ~220 km depth the deformation mechanism of olivine is dislocation creep, which gives a preferred orientation to the crystals. Seismological observations show that the shallower upper mantle has a strongly anisotropic structure [10, 32]. It is known that the seismic anisotropies here result

from the preferred orientation of olivine [33, 34]. When the olivine-bearing rock is exposed to water, the diffusion creep dominates. Water enhances the change in the deformation mechanism [18]. After this change, the seismic behavior of the rock becomes isotropic and the preferred orientation of olivine will disappear. As there is a difference in seismic velocity between the anisotropic and isotropic layers, the velocity jump of vertically traveling seismic waves is observed at around 220 km depth.

When the oceanic crust sinks at the subduction zone, the sediment accumulated on the ocean floor is dragged into the mantle. However, a certain amount of subducted material is likely to separate from the descending slab, because the sediment has buoyancy at a depth of less than 300 km because its density is less than that of the surrounding mantle rock [35]. As most subduction zones locate around and beneath continents, the separated sediment stagnates under the continent. According to geochemical arguments (see [36] for a comprehensive review), the original materials of many hot spot magmas include the subducted sediment component. The EM II component in mantle endmembers is considered to reflect recycled sediments. This indicates that the subducted sediments are likely to stagnate at many locations in the mantle.

In the water-free condition, the typical transition depth of the deformation mechanism estimated by previous study is greater than 220 km [18]. On the other hand, the transition depth moves to upper region in the wet condition. From a view point of thermodynamics, the hydrous mineral, phengite, is stable in the subducted sediment at depths shallower than ~220 km. The subducted sediment can contain a significant amount of water for geological time scale. In the

upper mantle, the dominant upwelling flow occurs at the mid-oceanic ridges and the hot spots. In contrast, the dominant downwelling flow occurs at the subduction zones. The lateral flow is dominant at other regions, such as under the continent and the oceanic floor. The stagnated sediments separated from the subducted slabs can be transferred to widespread regions in the upper mantle, especially under continents, by such lateral flows. If the sediment descends by secondary convective flow in the upper mantle and intersects the dehydration boundary of phengite, the released water migrates into the surrounding mantle rock and the sharp boundary between the anisotropic and the isotropic structure is formed at around 220 km depth (Fig. 2). The Lehmann discontinuity is likely to be due to this boundary corresponding to the change in the deformation mechanism of olivine. As this exists only in regions of stagnated sediment, the local detection of the discontinuity is consistent with the hypothesis of sediment dehydration. The most characteristic features of the Lehmann discontinuity, such as 220 km depth, negative seismological Clapeyron slope, local detection, seismic velocity jump, and the anisotropic to isotropic transition can be reasonably explained. Further seismological studies to verify our model will be welcomed.

The Lehmann discontinuities often accompany the X-discontinuities observed at deeper depth (~300 km) [3, 37-39]. The dehydration of subducted sediment can not explain the origin of the X-discontinuity, because of the inconsistency for the depth. However, the depth of the mineralogical phase transition of silica in the subducted sediment agrees with that of the X-discontinuity. Silica phases, coesite and stishovite, constitutes ~20 wt% of the assemblage of subducted sediments at high pressures [21]. This transition in-

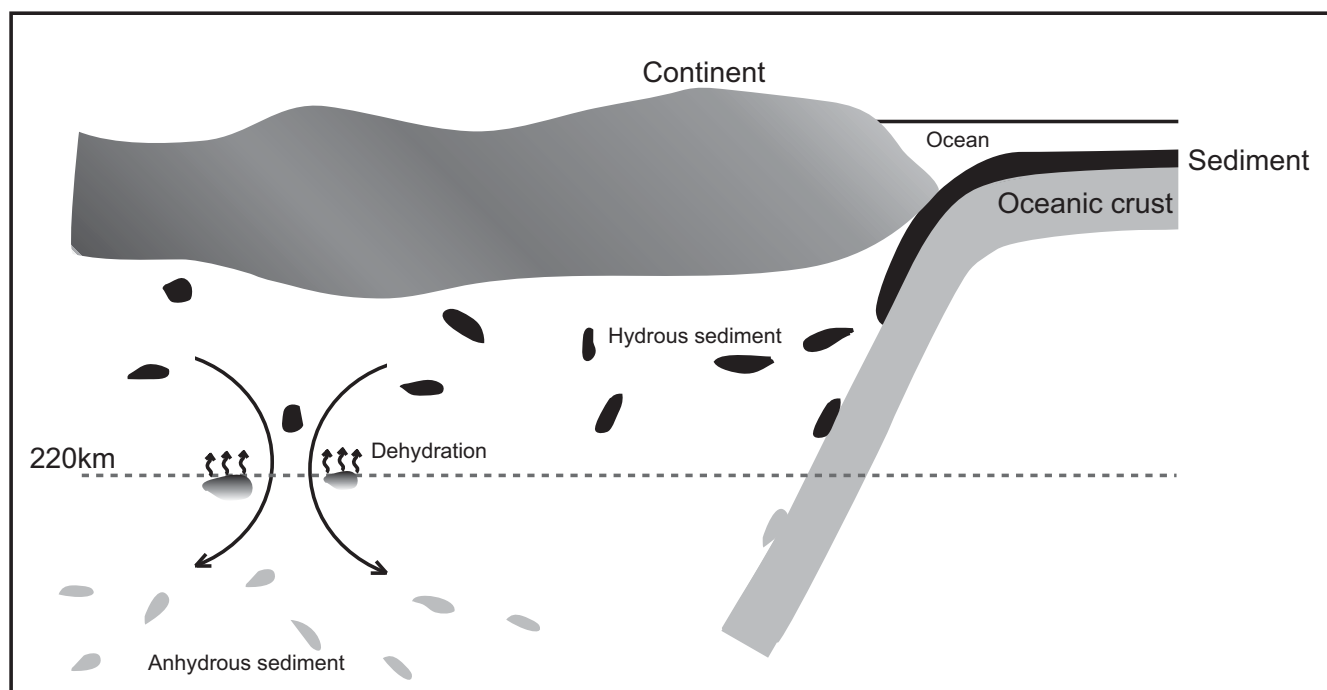


Fig. (2). Model showing dehydration of subducted sediment in the upper mantle. The hydrous sediment decoupled from the subducted slab stagnates at shallow depth under the continent. When the sediment descends into the deep mantle along the mantle convection, the pressure-induced dehydration of phengite occurs at ~220 km depth. The dehydrated water migrates upward and enhances the change in the deformation mechanism of olivine. The Lehmann discontinuity is likely to be due to this sharp boundary of deformation mechanism change.

duces the significant change in various physical properties of rock including the seismic velocity. This hypothesis can explain why the X-discontinuities are often observed with the Lehmann discontinuities.

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