5. Stress Fields in Slabs Penetrating into the Lower Mantle, and Rheology and Composition of the Lower Mantle

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Abstract: Focal mechanisms of deep-focus earthquakes show compressional stress fields in the deepest part of upper mantle slabs. We examine mechanisms to realize the stress fields using numerical models of slabs interacting with a phase and/or a chemical boundary. The compressional stress field implies that compositional density difference greater than 2% exists at the 660 km discontinuity, or that viscosity increases by a factor larger than a few tens and linear-law rheology dominates the flow mechanism in the lower mantle.

Key words: Slab penetration; rheology of the lower mantle; mantle convection.

Introduction. The fate of subducted slabs is one of the most important issues of mantle dynamics. Recently we understood how slabs interact with the 660 km discontinuity (the upper mantle-lower mantle boundary) by 3-dimensional seismic tomographic studies.^{1),2)} Cold slabs temporarily accumulate above the 660 km discontinuity, and form large melanges called a megalith.³⁾ After some time, the slab with the megalith starts to penetrate into the lower mantle, because the 660 km discontinuity cannot support the large negative buoyancy of the megalith any longer. These processes of slab penetration can be explained by interaction of cold descending flow of the mantle convection with the spinel-perovskite phase transition with a negative Clapeyron slope.^{4),5)}

The stress fields in the slabs inferred from focal mechanisms of deep-focus earthquakes give important information to consider the interaction of the slab with the 660 km discontinuity. Down-dip compressional stress is commonly observed in deep subducted slabs near the 660 km discontinuity.^{6),7)} This observations were previously interpreted as an evidence indicating that the slab cannot penetrate into the lower mantle.⁷⁾ However, tomographic studies showed that some slabs are obviously penetrating into the lower mantle.^{1),2)} We should consider mechanisms to consistently explain these apparently incompatible observations. In this study, we examine mechanisms to realize compressional stress fields in the deepest part of the upper mantle slabs penetrating into the lower mantle using time-dependent numerical models simulating an interaction of the slab with the 660 km discontinuity.

Models and numerical methods. The slab is modeled as a sinking thermal and mechanical boundary layer. The 660 km discontinuity is taken as a phase or a chemical boundary or a combination of both. The mantle is approximated as a viscous fluid in the 2-dimensional rectangular box with the height and the width of 1500 km. The phase and chemical boundary is initially at the depth of 650 km. Typical values of the mantle properties are employed. We assumed that initial conditions are the same as those of Christensen and Yuen.⁸⁾

Temperature- and stress-dependent rheology is employed to achieve subducting and

plate-like behavior of the cold thermal boundary layer. Temperature (T) dependence of the viscosity is taken as a virtually step-like function⁸⁾ to avoid complications of the viscosity variations as

$$\eta_{\text{New}} = \eta_0 + \frac{\eta_L + \eta_0}{2} \tanh \left[\frac{T - T_{\text{tr}}}{\beta} \right] \quad (1)$$

where η_L is the viscosity of the lithosphere ($T < T_{\text{tr}}$), η_0 is the viscosity of the mantle under the lithosphere ($T > T_{\text{tr}}$) at zero stress. The rheology combined with a linear law and a power law is employed to introduce stress dependence. The viscosity is defined by a function of second invariant of strain rate tensor $\dot{\epsilon}$ as

$$\eta = \left[\frac{1}{\eta_{\text{New}}} + \left(\frac{\dot{\epsilon}^{n-1}}{\eta_{\text{New}} \sigma_{\text{tr}}^{n-1}} \right)^{1/n} \right]^{-1} \quad (2)$$

where n is stress exponent. Power-law rheology is dominant when the stress is higher than the assumed transition stress σ_{tr} . In this study, the values of $\sigma_{\text{tr}} = 35$ MPa/K and $n = 3$, which are applicable to olivine's rheological properties, are used. In some numerical calculations, we employed a linear law ($n = 1$) as the rheological law of the lower mantle.

Stress fields in the slabs penetrating into the lower mantle. We assume in the first series of numerical simulations that the rheology of the lower mantle is the same as that of the upper mantle, i.e., η_0 does not increase with $n = 3$. An example of the calculated results is shown in Fig. 1. In this case, the 660 km discontinuity is assumed to be a pure phase boundary with the Clapeyron slope of -4.5 MPa/K. This is the most negative value with which slabs can penetrate into the lower mantle. The slab penetration occurs with forming a megalith in this case. The stress field of the upper mantle slab becomes tensional. A compressional stress field is not realized because of the large negative buoyancy of the megalith.

We have performed numerical calculations with the varying value of the Clapeyron slopes (0 to -6 MPa/K) and the compositional density difference (0 to 6%). The results are summarized in the phase diagram shown in Fig. 2 (Note the rheological condition used here). The compositional density difference between the upper and the lower mantle should be greater than 2% for down-dip compressional stress fields to prevail in the deepest part of the upper mantle slab. Tensional stress fields are always realized in the

Fig. 1. A snap shot of a sinking slab interacting with a pure phase boundary. Each column shows stream lines plotted in steps of 50 non-dimensional units, isotherms in 160 K intervals and the phase boundary, and isolines of the logarithm of viscosity in 0.5. Denser stream lines in the descending thermal boundary layer toward the deeper mantle mean a tensional stress field in the slab.

Fig. 2. Domain diagram for the stress field in the deep part of upper mantle slabs and the penetration depth without the viscosity increase in the lower mantle and the superplasticity. Circles and diamonds show the penetration depth (open circles: >800 km, diamonds: $800\text{--}200$ km, closed circles: <200 km). Symbols P and T mean that the stress field is compressional or tensional, respectively. The megalith is formed under the condition indicated by symbols M.

cases in which slab penetration occurs with forming a megalith (Note that the slab cannot penetrate into the lower mantle when the megalith is formed by the buoyancy due to the compositional density difference). This does not seem to be consistent with seismological observations.

Effects of superplasticity of the slab penetrating into the lower mantle. We examine the effects of superplasticity by the phase transition⁹⁾ at the 660 km discontinuity in the next series of numerical simulations. The superplasticity might be considered as a mechanism to realize the compressional stress field in the upper mantle slab because a slab losing the mechanical strength by the superplasticity does not pull down the connecting upper mantle slab. The superplasticity is modeled by reducing the viscosity of the materials which have experienced the phase transition at the 660 km discontinuity by 5×10^{20} Pa·s with $n=1$. It is assumed that the superplasticity becomes extinct 10 m.y. after the materials experience the phase transition.

The results are summarized in the phase diagram (Fig. 3) similar to Fig. 2. Superplasticity slightly reduces the critical values of the Clapeyron slope and the chemical density difference at the 660 km discontinuity which acts as an impediment of sinking slabs. A megalith is not formed because a barely penetrated slab flows sideward along the phase boundary. The negative buoyancy of the slab without a megalith does not become large enough for the slab penetration under the nearly critical condition.

The stress fields in the upper mantle slab near the 660 km discontinuity, which is penetrating into the lower mantle, is not changed by the superplasticity. The reason is as follows. Superplastic slabs descend with their velocities depending on the force balance of

Fig. 3. Domain diagram for the stress field in the deep part of upper mantle slabs and the penetration depth with the superplasticity of the penetrated slab and no viscosity increase in the lower mantle. See Fig. 2 for detailed explanation.

the density anomaly with the viscosity in the lower mantle. We here assume that the viscosity of the superplastic slab (5×10^{20} Pa·s) is approximately as high as that of surrounding lower mantle (5×10^{20} – 1×10^{21} Pa·s). In this case, the viscous stress of the descending superplastic slab is still large to pull the connecting upper mantle slab. If the viscosity in the superplastic slab is significantly reduced to be about 10^{19} Pa·s, the compressional stress field is realized. It is, therefore, difficult to consider the superplasticity as a mechanism to generate the compressional stress field in the deepest part of the upper mantle slab. However, this conclusion does not always deny that the superplasticity occurs in the penetrated slab, but suggests that another mechanism is required to realize the down-dip compressional stress field in the upper mantle slab.

Effects of the viscosity increase and change of rheological mechanism at the 660 km discontinuity. The compressional stress field in the upper mantle slab has not been obtained in the models without compositional layering. We now examine the effects of the viscosity increase at the 660 km discontinuity. The slow descent of the megalith or the slab in the lower mantle is probably required for the slab to realize the compressional stress field, and might be caused by larger viscosity in the lower mantle. The effect of the viscosity jump has already been shown by the numerical modeling¹⁰⁾ with simple stratified viscosity but with no phase boundary. The effect of the viscosity increase at the 660 km depth is examined using the model including the pure phase boundary with the Clapeyron slope of -4.5 MPa/K. We especially notice a creeping mechanism of the lower mantle, which appears in stress dependence of the viscosity. Stress exponent n is taken to be 3 (a cubic-power law) in the upper mantle and 3 or 1 (a linear law) in the lower mantle. Viscosity increase is introduced by the procedure that η_0 in Equation (1) increases by a factor of 10 or 100.

Calculated results with the viscosity increase by a factor of 100 show that the compressional stress field in the upper mantle slab is not realized when the lower mantle

Fig. 4. Effects of viscosity increase and change of rheological mechanism at a phase boundary on the interaction of sinking slabs with the pure phase boundary. The viscosity at the zero stress increases by a factor of 100. The stress exponent of the lower mantle viscosity is taken at 3 (a) or 1 (b). Stream lines are plotted in steps of 100 (a) or 50 (b) non-dimensional units. The other contour intervals are the same as those of Fig. 1. Stress fields in the slabs (tensional (a) or compressional (b)) are perceived in the patterns of stream lines (denser (a) or coarser (b) toward the deeper mantle).

has power law rheology (Fig. 4a), though the averaged viscosity of the lower mantle is rather high. The reason is as follows. The viscosity of the lower mantle is sufficiently high before the slab penetration because the flow stress is not high. The amount of the stagnated slab in this case, therefore, becomes much larger than that in the case of no viscosity increase at the phase boundary. After starting penetration, the viscosity beneath the megalith is drastically reduced by power-law rheology as the flow stress rises. The slab with the large megalith rapidly drops in the lower mantle, so the upper mantle slab is strongly pulled by the lower mantle slab. A tensional stress field is generated in the upper mantle slab in this case.

The viscosity in the lower mantle cannot be reduced by the slab penetration in the case of linear rheology. Therefore, the slab penetrates slowly and the compressional stress field in the deep part of the upper mantle slab is generated, when the viscosity of the lower mantle is sufficiently high. A tensional stress field is obtained in the case of viscosity increase by a factor of 10. In the case of viscosity increase by a factor of 100, the viscosity is large enough that the compressional stress field is successfully realized (Fig. 4b).

Discussion. The compressional stress fields in the upper mantle slab near the 660 km discontinuity are realized under the following conditions. One is that there exists compositional density difference between the upper and the lower mantle larger than about 2%. Another one is that the viscosity increases at the 660 km discontinuity at least by a factor of a few tens and that linear-law rheology dominates the flow mechanism in the

lower mantle. In both the cases, resistive force against the slab penetration is sufficiently large, and the slab-pull force due to the density anomaly of the lower mantle slab or the megalith has little influence on the descending velocity of the upper mantle slab. The buoyancy force due to the depression of the phase transition does not significantly affect the stress field of the upper mantle slab after the slab starts to penetrate into the lower mantle. The reason is that the slab with the high viscosity cannot be deformed by such a local force. More regional force as mentioned above can realize the compressional stress field. Mechanism of deep focus earthquakes indicate that the slab sluggishly penetrates into the lower mantle and the break of the barrier at the 660 km discontinuity is not catastrophic.

The conclusion of this study may be indefinite because of the following reasons. We might be observing slabs in the transient state before starting to penetrate into the lower mantle. However, the compressional stress field is also observed in the slabs penetrating into the deep region of the lower mantle, for example, the slab subducting from the Java trench.³⁾ The model used in this study might not simulate a realistic slab because the slabs in the models are completely vertical along the side free-slip boundary of the model. Real slabs descend with shallower angles and there is no free-slip boundary in the mantle. We have checked this point. Although we could simulate only slabs with a rather steep angle, the subduction angle does not seem to change the stress field in the slab penetrating into the lower mantle; at least the boundary condition does not affect it.

One of our conclusions that linear-law creep (diffusion creep) occurs in the lower mantle is consistent with a recent laboratory experiment on a polycrystalline perovskite.¹¹⁾ However, Karato and Li¹¹⁾ also pointed out that the viscosity in the lower mantle is possibly lower than that of the mantle transition zone. This point does not agree with our conclusion. Our study suggests that such a viscosity model cannot explain the compressional stress field without the compositional density difference at the 660 km discontinuity.

A simple penetration model such as slabs interacting with a phase boundary cannot explain the compressional stress field in the deep upper mantle slab inferred from the mechanism of the deep focus earthquake. Therefore, this observation provides us one of important constraints to consider the structure of mantle convection. We need more precise study on seismological observations, high-pressure experiments, and numerical experiments to understand the interaction of the subducting plate with the 660 km discontinuity.

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