Numerical Simulation of the Thermal Convection and Subduction Process in the Mantle

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The aim of this project is to make up a comprehensive model of the dynamics and evolution of the Earth's mantle, and to simulate phenomena related with subduction. (1) With the global modeling in Earth-like spherical shell geometry, we made systematic research on the convection patterns for the wide range of Rayleigh numbers with phase transitions. The experimentally and seismologically plausible value of Clapeyron slope for 660 km phase transition is not enough to reproduce slab stagnation at transition zone. By introducing both the viscosity increase in the lower mantle, and yield stress near the surface, the 660 km phase transition acts as a barrier for the vertical flow. Then the flow pattern in the upper mantle is decoupled from the flow in the lower mantle, and "stagnant slabs" are successfully formed. (2) With the regional modeling focusing on subduction process, we made systematic research on the form of stagnant slab by setting both the velocity of subducting plate and that of trench migration. These simulations succeeded in reproducing wide variety of the stagnation styles, which is comparable to the images from seismic tomography.

Keywords: mantle convection, subducting slab, plate tectonics

1. Introduction

The Earth's mantle is composed of solid rocks but it flows like a viscous fluid in a geologic time scale. This convective flow of the mantle is emerging as the motion of tectonic plates on the Earth's surface. The motion of surface plates causes earthquake, volcanism and mountain building at the plate margins. And as the mantle flow transports the heat from the hot interior, the whole of the Earth has been cooling through its history. Hence, mantle convection is the key process for understanding the activity and evolution of our planet.

We can see the internal structure of the Earth's mantle by seismic tomography. It illustrates the behavior of slabs, that is, subducted plates in the mantle. Some of the slabs stagnate in the mantle transition zone while the others penetrate into the lower mantle (Fig. 1). Because slabs are the downwelling portions of the mantle convection, the mechanisms to generate the various styles of subducted slabs in the mantle transition zone are important to understand the structure and dynamics of the mantle. We have been studying the process of stagnation and penetration of slabs, and succeeded in simulating both behaviors and clarifying the conditions for slab stagnation. Our two-dimensional model can reproduce the general behavior of slabs under natural setting, but it has limitations in applying for specific subduction zones of the Earth. Three-dimensional structure is essential for some subduction zones especially located in western Pacific region. Figure 1 is the structure of the mantle relating to the subduction around the Pacific Ocean from global tomography [1]. There are wide variation of the subduction style, some is stagnant around the transition zone, and other is penetrating to the lower mantle.

2. Global model: The effect of viscosity layering and yield stress for the slab stagnation

The cause of slab stagnation has been discussed in relation to the post-spinel transition across the 660-km discontinuity. The negative Clapeyron slope of this phase transition tends to resist against straightforward falling of slabs into the lower mantle. We presented the results of the numerical simulation of the mantle convection in three-dimensional spherical shell, which incorporates the 660 km endothermic phase transition. The spatial resolution is about 15 km on the Earth's surface. We carried out systematic calculations by varing Rayleigh number, and the value of the Clapeyron slope at the 660 km depth with isoviscous mantle. Figure 2 is the extended version of our regime diagram of the convection patterns. In the range of Ra > 10^5, as the absolute value of the Clapeyron slope increases, the pattern of the convec-

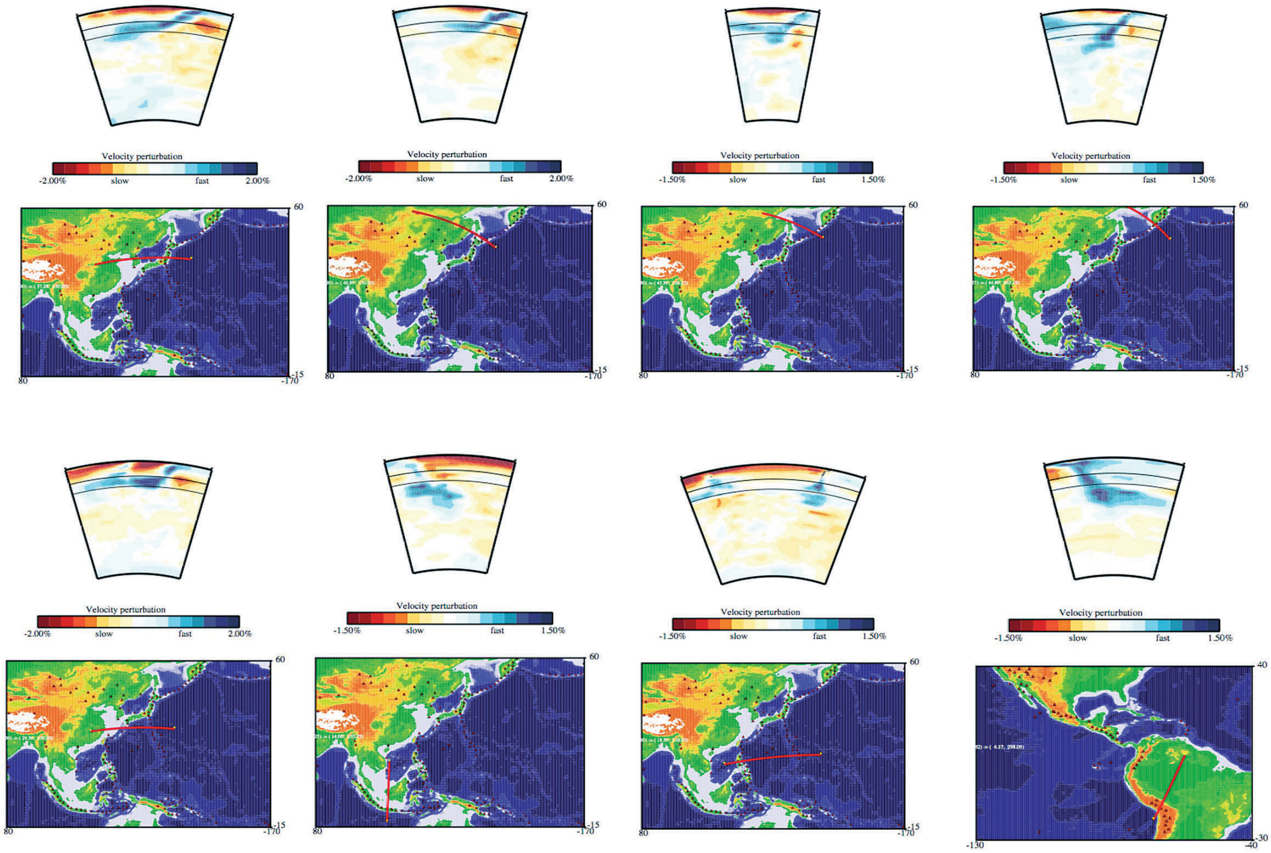


Fig. 1 Cross sections of seismic tomography for subdcution around Pacific Ocean (drawn by the dataset GAP-P1 [1]). The P-wave velocity anomalies are shown from surface to core-mantle boundary. Red lines on the maps show the location of each cross section. The wide variety of the subduction style is observed.

tion changes from the whole layer convection to two-layered one. There is a transition phase between the whole layer convection and the two-layered one, in which the convection becomes intermittently.

The recent experimental values of the Clapeyron slope are in a range from –2 to –0.5 MPa/K for dry ringwoodite, and < –2 MPa/K for wet ringwoodite (summary in [2]). On the other hand, the estimated Clapeyron slope by seismological observations is in a range from –3.5 to –2 MPa/K [3, 4]. This suggests that the transition zone contains some amount of water. These ranges are also shown in Fig. 2. These estimated values of Clapeyron slope are located near the boundary of "intermittent" and "whole layer" convection regime, and the effect of phase transition is weak for large-scale slab stagnation. In our previous regional two-dimensional modelings, we showed that viscosity increase in the lower mantle and the temperature dependence of viscosity are also important for slab stagnation. Hence, we introduced viscosity layering and plate-like structure into our global modeling. Figure 3 (a) is the setting of the viscosity factor to the reference value, and lower mantle viscosity is 40 times larger than the upper mantle. The viscosity also depends on temperature, and the material has large viscosity at cold portion. We introduced yielding of the material that acts near the surface, and then the

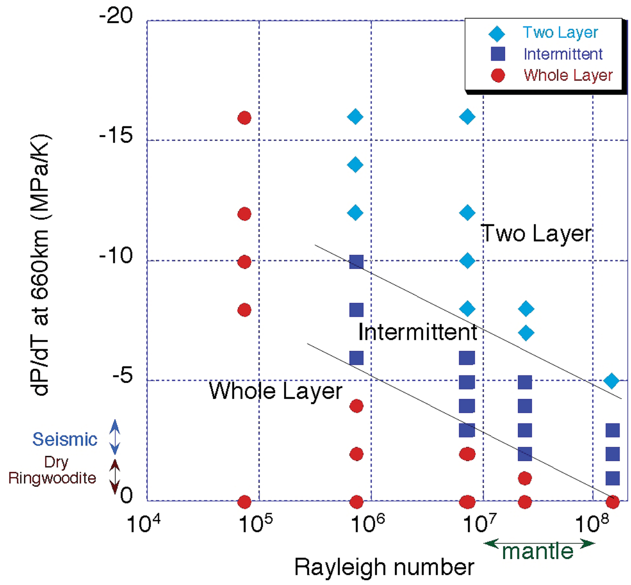
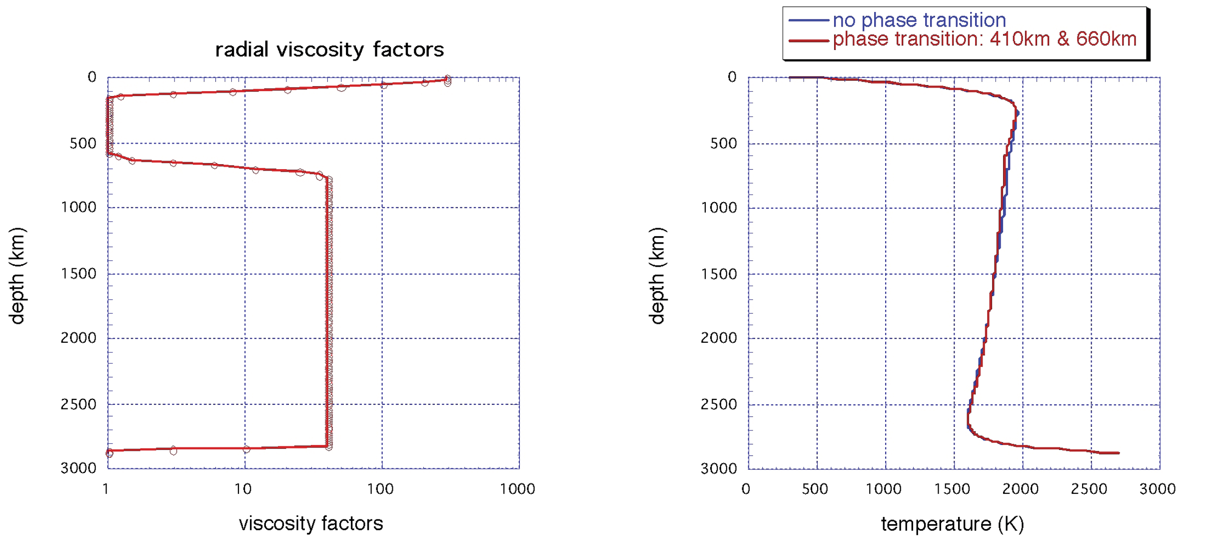


Fig. 2 The regime diagram of the convection patterns for isoviscous spherical shell. This is the extended version of our result reported in ES annual report 2005.

deforming and subducting portion is very localized and plate-like behavior is reproduced. The yield stress is set to 80 MPa from the result of [5] to realize plate-like one.

Here we compare the results with and without 660 km



(a) radial viscosity factors (b) horizontally averaged temperature

Fig. 3 (a) (b) Horizontally averaged temperature at each depth with and without 660 km phase transition. There exist small difference between the two cases.

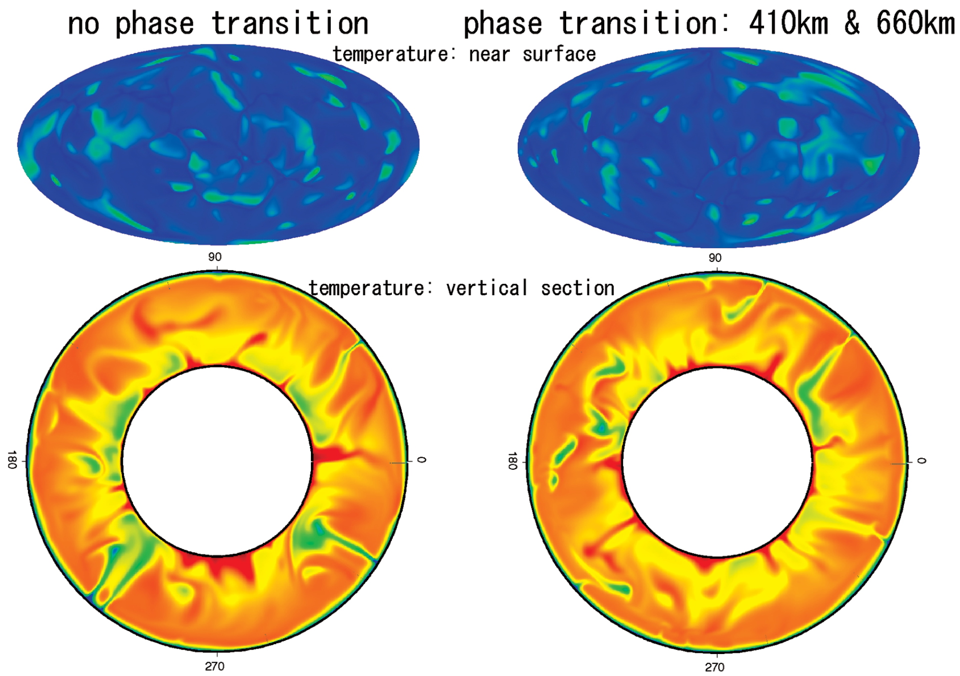


Fig. 4 Snapshots of the convection in spherical shell with depth- and temperature-dependent viscosity (Ra = 2 $\times 10^7$). Left; no phase transition. Right; phase transition at 410 km and 660 km. Top; temperature just below the surface. Bottom; temperature cross-section along a meridian. There exist small difference for the typical wavelength of the surface pattern between the two, but large difference for the vertical cross section. In case of phase transition, stagnant slabs are observed at the transition zone and the flow patterns for the upper and lower mantle are decoupled to some extent.

phase transition. We set the value of Clapeyron slope for 660 km as –2.5 MPa/K (plausible value from seismology), and 0 MPa/K (no phase transition). In the case of –2.5 MPa/K, the phase transition at 410 km depth is also introduced with Clapeyron slope +2.5 MPa/K. The Rayleigh number calculated by the reference viscosity is Ra = 2 $\times$ 10^7 for these simulations. Figure 3 (b) is the horizontally averaged temperature profile, and you can see that there is a little decrease of temperature around the transition zone in relation to phase transition. The effect of phase transition is not so large on average temperature profile, but the flow pattern is much different. Figure 4 shows the convection pattern by temperature, left: no phase transition, right: with phase transition. With phase transitions, the flow pattern in the upper mantle is decoupled from the flow in the lower mantle. The time-scale for the flow in the upper mantle is shorter than that of the lower mantle because of its lower viscosity. Trenches at the surface move with the time scale of the upper mantle flow, and the penetrated slab in the lower mantle is anchored for a while. Then the structures like "stagnant slabs" are formed. With the sufficient time integration, we can conclude that 660 km phase transition plays important role for reproducing stagnant slabs. Without phase transition, the stagnant structure emerges at the beginning of the simulation, but it settles to be vertically continuous flow pattern after several hundred million years.

3. Regional model: Dynamic behaviors of subducting slabs, toward three-dimensional modelings

We are developing three-dimensional numerical models of mantle convection in order to study the formation and the dynamic behaviors of stagnant slabs. A time-dependent thermal convection of Boussinesq fluid in a rectangular box of 1320 km height and 7920 km width is considered. We have included both the exothermic olivine to spinel and the endothermic spinel to perovskite phase transitions at around 410 and 660 km depths from the top surface, respectively. The viscosity of mantle material is assumed to be exponentially dependent on temperature and pressure (or depth). We also take into account the effects of the sudden increase in viscosity at the 660km depth. The computational domain is divided into the "oceanic" and "continental" regions on the left-hand and right-hand sides, respectively. The plate subduction is imposed by applying different kinematic boundary conditions to the top surface of the "oceanic" and "continental" sides. The initial distribution of temperature in the "oceanic" region is set by a half-space cooling model moving at a uniform velocity, while that in the "continental" region is characterized by a thinner thermal boundary layer than the "oceanic" side in order to enhance the negative buoyancy of the "oceanic" plate at the "trench axis". We also included a thin layer of weak "lubricating" material along the top surface of the "oceanic plate" in order to accommodate a strong shear deformation along the "plate boundary". The lubrication at the plate boundary is modeled by applying maximum yield strength in the regions with the weak materials which are advected along with the subduction of "oceanic plate". The numerical calculations is performed by using the multigrid-based numerical code ACuTEMan [6, 7] designed for large-scale three-dimensional experiments. In this numerical code, the motion of highly viscous and incompressible fluid is iteratively solved for the primitive variables (velocity and pressure). The advection of "lubricating" material is calculated by the CIP-based semi-Lagrangian conservative scheme developed by [8]. We have employed non-uniform mesh divisions between the "oceanic" and "continental" sides and between the upper and lower mantle, in order to resolve the dynamic behavior of subducted slabs as much as possible.

In addition, we take into account the effect of trench migration, by extending the approach by [9] to the three-dimensional models. Here we assume the subduction below an actively overriding continent with an ocean-ward velocity $-\mathbf{V}_{tr} = (-V_{tr}, 0, 0)$ with respect to the deep mantle. Although the reference frame in subduction models is usually fixed to the deep mantle, we choose a "continental reference frame" here, which is fixed to the top surface of the overriding "continental" plate, for reasons of computational convenience. To this end, we use a simple Galilean coordinate transformation: a no-slip boundary condition is imposed on the continental surface while at the bottom and inflow boundary, a velocity $\mathbf{V}_{tr}$ is imposed, describing again the relative motion between continent and deep mantle. The motion of "oceanic" plate is, on the other hand, driven by a fixed velocity V_{pl} along the top surface. A horizontal flow and hydrostatic pressure are prescribed on the vertical right-hand side boundary. These define the flow to be "developed", i.e. with a zero horizontal velocity gradient, as in one-dimensional channel flow.

We show in Fig. 5 the snapshots taken from preliminary two-dimensional calculations with different values of the velocities of subducting plate V_{pl} and overriding plate V_{tr}. In these calculations, the viscosity of the lower mantle is assumed to be 10 times higher than that of the upper mantle. The comparison of the cases presented in Fig. 5 clearly indicates that the importance of the motion of overriding plate on the formation of stagnant slabs. Figure 5 also shows that the larger V_{tr} tends to pinch off the subducting plates at a shallow depth. This may come from the fact that the modeled "oceanic" plate is rather weak due to the exponential dependence of viscosity on temperature.

We do believe, nevertheless, the importance of the present work toward the three-dimensional numerical models of subducting slabs. Almost all of the earlier studies of plate subduction had been performed by two-dimensional models, by making good use of stream-function formulation. Although this formulation is proved to be significantly robust against numerical difficulties such as sharp and strong viscosity variations, its application is in principle limited to two-dimensional models. In other words, one needs to employ the formulation with primitive variables in order to pursue three-dimensional models. Moreover, we need to rely on the multigrid strategy which is crucial for the rapid solution of large-scale elliptic problems, despite of the difficulty of multigrid technique with handling the sharp viscosity variations. In this study we have demonstrated that some of numerical difficulties described above could be overcome by some extent. We expect that this study mark the important

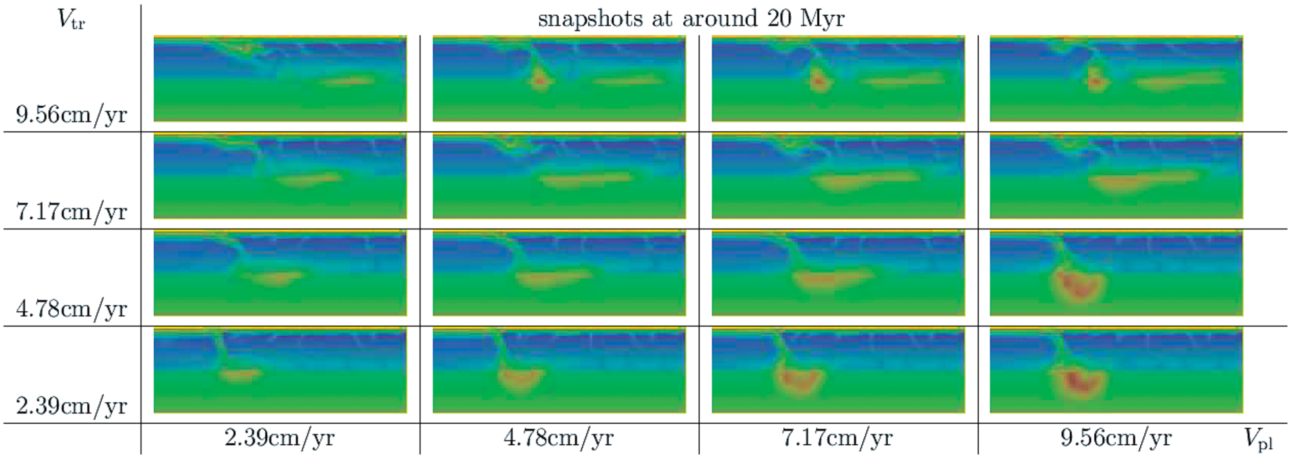


Fig. 5 Snapshots of behaviors of cold subducting plates obtained by time-dependent calculations with different values of the velocities of subducting plate V_{pl} and overriding plate V_{tr}. Shown are the distribution of viscosity. The regions in red stands for higher viscosity, while those in blue for lower viscosity.

step toward the truly three-dimensional dynamical modelings of stagnant slabs.

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マントル対流と沈み込み過程の数値シミュレーション

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地球のマントルは岩石から成り固体である。しかし地質学的な時間で見るとマントルは流体として振る舞い、ゆっくりと動いている。その流れによりプレート運動が生じて地震や火山という現象を引き起こし、更に長い時間スケールでは日本列島のような島弧やヒマラヤのような大山脈を作り出す原動力となっている。よってマントルの動きをモデル化することは地球の進化を考え、自然現象による我々の生存圏への影響を理解する上で極めて重要である。本プロジェクトでは目的に応じて二つのモデル化とその研究を行なっている。一つは地球全体の進化過程を明らかにするために三次元球殻という形状の影響を考慮したマントル全球対流モデルである。そしてもう一つは地震や火山現象の直接的原因であるプレートの地球内部への沈み込み過程を捉えるためにこの部分に特化した領域モデルである。地震波トモグラフィーによると、沈み込んだプレートの延長と考えられる構造（スラブ）がマントル遷移層の深さまで到達し、地球上の多くの場所ではそのまま遷移層に滞留している。これらはスタグナントスラブと呼ばれる。日本列島も含めた西太平洋域の地下にはスタグナントスラブが広域に存在し複雑な形態を示している。我々はこれまでに、二次元モデルによりスラブが滞留する条件を明らかにし、スラブの形状の時間発展を再現することに成功している。それによるとスラブの滞留およびその後の崩落には、マントル構成鉱物の相転移、下部マントルでの粘性率の急激な増大、粘性率の温度依存、プレートのレオロジー、海溝の後退、というそれぞれが重要な役割を果たしている。本年度は三次元の全球モデルにこれらの効果を組み込んだ計算を系統的に実行した。660kmの深さに相当する相転移には最新のデータによる値を用い、下部マントルの粘性率を上部マントルより大きく設定し、さらに粘性の温度依存性とともにプレートのレオロジーとして地表面付近での降伏現象を組み込んだ。これにより表面ではプレートテクトニクスで想定されるように局在化した沈み込み領域が自然に形成され、実際の地球に見られるような長いスケールのプレートと片側沈み込みに相当する薄い下降流の再現に成功した。長時間の積分から、マントル遷移層での鉱物の相転移と粘性急増の両者の効果で、沈み込んだスラブは一旦滞留して崩落するということを繰り返すことが明らかとなった。このような現象を過去の研究よりも2桁程度高いレイリー数領域（ほぼ地球マントルに相当）まで確認した。

キーワード：マントル対流, 滞留スラブ, プレートテクトニクス