Numerical Simulation of the Mantle Convection and Subduction Process

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The internal structure and the evolution of the mantle have been inferred by the geophysical and the geological observations. The seismic tomography reveals the large scale flow of the mantle convection, and it also illustrates some ancient slabs are stagnant in mantle transition zone. Our 2-D models made clear the conditions for realizing "stagnant slab". We got the following important results; (1) the trench backward motions have an essential role to generate the stagnant slab around the 660 km phase boundary, (2) when the viscosity jumps at the 660 km phase boundary is a factor of 10, the stagnant slab is easily formed at the relatively gentle Clapeyron slope, -2 MPa/K. On the other hand, recent high pressure and temperature experiments suggest a new phase transition around the bottom of the mantle. We made systematic study on the role of this new phase in 3-D spherical shell models. The results suggest (3) if the density jump relating to the transition is as small as supposed at present, it may not modulate the convection of mantle so much.

Keywords: mantle convection, plate motion, subduction zone, stagnant slab, phase transition

1. Introduction

The Earth's mantle is composed of silicate rocks. The mantle acts like a highly viscous fluid on long time scale and as a heat engine; it flows slowly to transport the heat from the hot interior to the cool surface. This convective flow in the mantle is observed as the motion of tectonic plates on the Earth's surface. The motion of surface plates in turn causes earthquake, volcanism and mountain building at the plate margins. Thus, the mantle convection is the origin of the geological and geophysical phenomena observed at the Earth's surface.

Seismic tomography enables us to "see" the internal structure of the mantle. It illustrates the behavior of slabs, that is, ancient surface plates subducted in the mantle (review by [1]). Some of the slabs stagnate in the mantle transition zone while the others penetrate into the lower mantle. Because the slab is an expression of downwelling flow in the mantle convection, the mechanisms to generate the various styles of subducted slabs in the mantle transition zone are important to understand layering structure of the mantle convection. It is also very important for our life to understand the nature and behavior of "subduction" and "stagnant slab", because the Japanese Islands locate at the subduction zone, and slab stagnation are widely observed below the East Asia.

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. To this goal, we have been developing numerical models which are consistent with the observations such as seismic tomography and geological evidence. The research of this project is divided in two subgroups, according to the nature of phenomena to be considered. First subgroup deals with 2-D regional mantle flow in rectangular geometry with discrete mechanics in generating plate-like surface motion to model the stagnant structure of subducting slabs above the 660 km phase boundary, which is consistent with seismic tomography models (section 2). Second subgroup deals with 3-D global mantle flow in spherical shell geometry, and aims at understanding the large spatial scale dynamics and long-term evolution of the Earth (section 3).

2. Regional modeling for subduction zone and stagnant slab

Recent seismic tomography models have revealed various morphology of subducting plate. In particular, significant flattening and stagnation of slabs around the 660 km phase boundary are observed in some areas beneath the Western Pacific subduction zones. To reproduce the stagnant slabs in numerically modeled mantle convection in 2-D rectangular geometry, we have performed calculations of the mantle convection with various controlling parameters related to physics of the 660 km phase transition, trench retreat velocity, dip angles of slabs, and the viscosity contrast between the upper and the lower mantle.

2.1 Case of the self-consistently moving plate

In this section, we have attempted to produce slab evolution from the subduction initiation to the penetration into the lower mantle with freely moving surface plate without imposed velocity boundary condition for the plate ([2], [3]). The trench can also freely migrate as well as the plates. We focus on the rheological effects of the slab in the transition zone and the lower mantle. We assume Arrhenius-type temperature dependence of the viscosity and the yielding of the slab. We also introduce temperature and pressure dependence of a thermal expansion coefficient. Our results are summarized as Fig. 1 shows.

Because the slab has high viscosity, the slab memorizes the past deformation. This has an important role to determine the slab structures in our simulation. In the case with the free trench migration, the stagnant slab is formed with a shape like the cross section of spoon. The tip of the stagnant slab is suspended above the 660 km phase boundary by the slab strength. When the viscosity reduction is induced by the slow grain growth, the curvature of the stagnant slab becomes smaller. The stiffness of the slab has also important effects to generate the stagnant slab with weaker Clapeyron slope because the horizontally wide plate descends slower than vertically long plate. A horizontally lying slab beneath the 660 km phase boundary is formed when a thermal expansion coefficient has temperature and pressure dependence, or when the viscosity jump by 10 to 30 times at the 660 km phase transition.

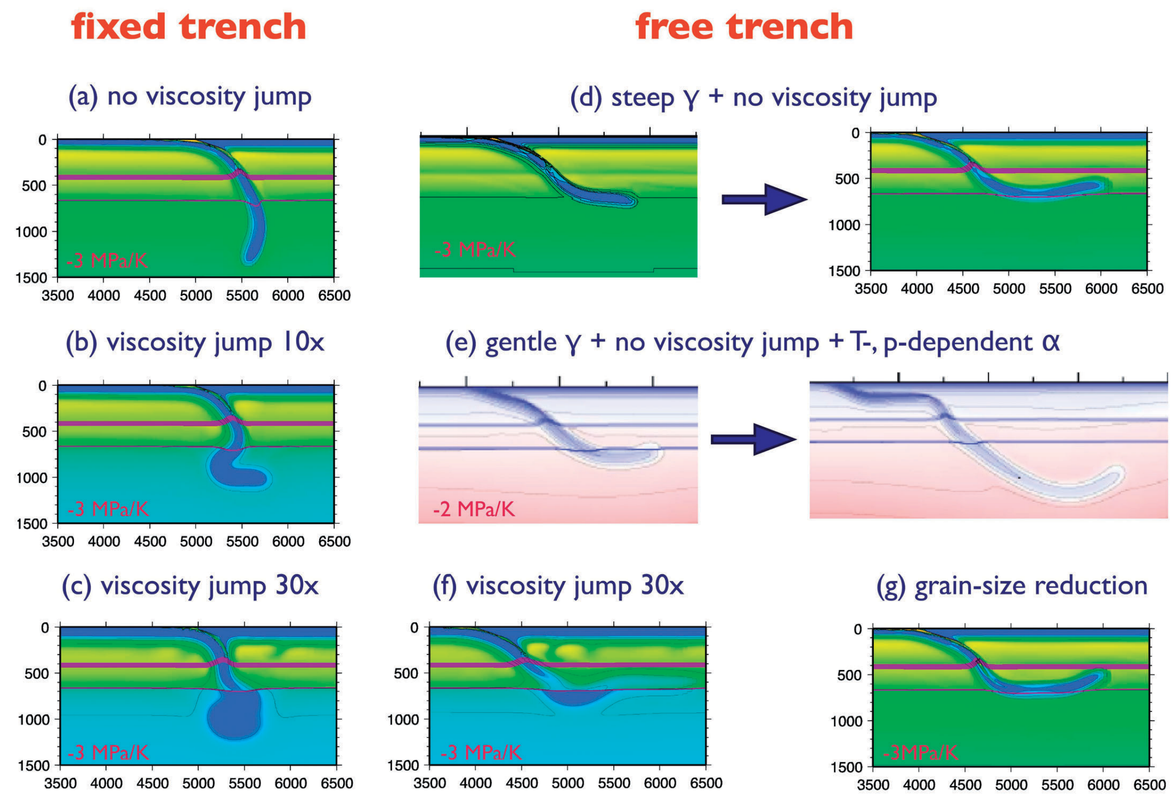

Fig. 1 Styles of the subducted slab interacting with 410 and 660-km phase transitions. The overriding plate is fixed in the Cases (a) to (c) and freely movable in the Cases (d) to (g). The Clapeyron slope of the 660 km phase transition is set to be -3 MPa/K except Case (e) with -2 MPa/K. The additional features are as follows. Case (a): no viscosity jump, Case (b): viscosity jump by 10 times at 660 km phase boundary, Case (c): viscosity jump by 30 times, Case (d) no viscosity jump, Case (e): temperature- and pressure- dependent thermal expansivity and no viscosity jump, Case (f): viscosity jump by 30 times, Case (g): grain size reduction with the 410- and 660-km pahse changes and no viscosity jump.

In the case with a stagnant slab with high viscosity, the subducted slab keeps to stay on the 660 km phase boundary without avalanche when the Clapeyron slope is as steep as -3MPa/K. When the stagnant slab has viscosity as low as ambient mantle because of the grain size reduction in the whole slab, the stagnant slab finally penetrates into the lower mantle. When the viscosity jumps at the 660 km discontinuity by a factor of 10 to 30, the stagnant slab is more easily formed at -2 MPa/K. In this case, the slab also finally drops into the lower mantle. These can be explained by shorter growth time of Rayleigh-Taylor type instability with lower viscosity contrast between the slab and the ambient mantle. This may explain that the younger subduction zone (e.g., Izu-Bonin, Tonga) seems to have stagnant slabs and older subduction zone does penetrating slabs (Japan, Kuril, Java, and America).

The viscosity jump seems to be essential to generate stress filed in the transition zone slab resembling that obtained by the seismic observation. In the case with no viscosity jump, a couple of compressional and tensile stress always appears in the location with strong stress. The viscosity jump at 660 km phase boundary is needed to generate stress field of down-dip compression in the transition zone stab. The viscosity jump, however, slows the motion of the surface plate.

2.2 Case of the plate-like surface boundary condition

In order to systematically investigate the effects of trench retreat velocity, dip angles, and the high viscous lower mantle on the stagnation of subducting slabs, we have used a 2-D Cartesian model with imposing plate-like velocity condition at the surface boundary. We have searched conditions for slab stagnation under the assumption of the relatively gentle Clapeyron slope, which is obtained from recent high pressure experiments. The results show that slabs tend to stagnate above the 660 km phase boundary with increasing the absolute value of the Clapeyron slope, the viscosity contrast at the phase boundary, trench retreat velocity, and decreasing an initial dip angle. Stagnant slabs can be realized in realistic ranges of parameters obtained from geophysical observations by the combination of buoyancy force, high viscosity of the lower mantle, and trench retreat. We found that low dip angle of a descending slab at the bottom of the upper mantle plays an important role to stagnate the slab. There are two regimes for slab stagnation: buoyancy-dominated regime and viscosity-dominated regime. In the viscosity-dominated regime, it is possible for slabs to stagnate above the 660 km boundary even if the value of the Clapeyron slope is 0 MPa/K.

We have investigated conditions that can realize slab stagnation by changing the value of the Clapeyron slope in the range of -3 to 0 MPa/K, the viscosity contrast between the upper and lower mantle in the range of 0 to 40, and velocity of trench retreat in the range of 1 to 3 cm/yr. Dip angles of 45° are compiled for trench migration velocity of 1, 2, and 3 cm/yr (Fig. 2). We obtain several findings from our numeri-

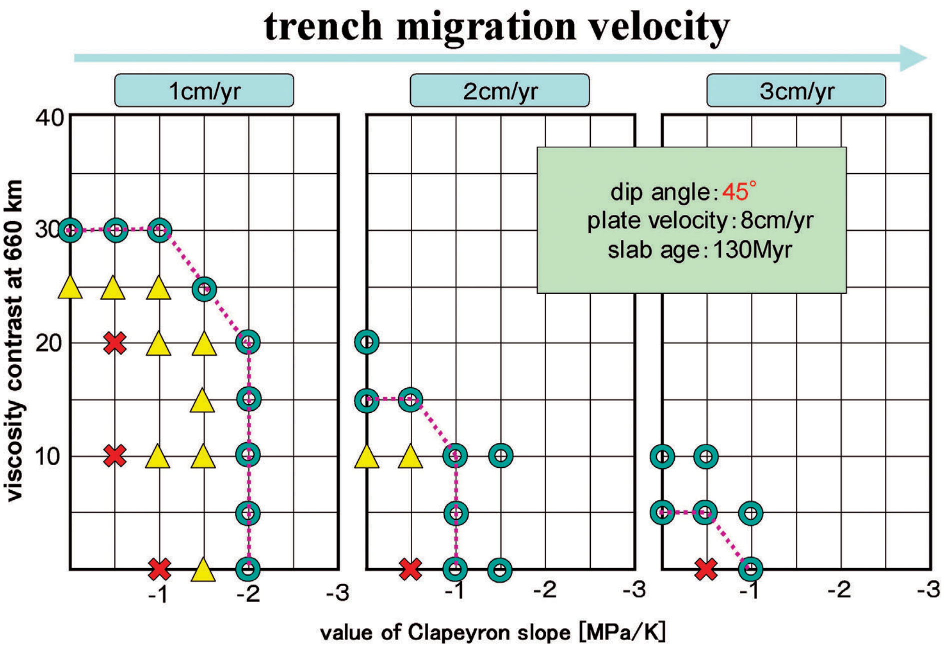

Fig. 2 A compilation of calculated results. For each figure, horizontal and vertical axes denote the value of the Clapeyron slope and the value of viscosity jump between the upper and lower mantle, respectively. Results which show slab stagnation horizontally over a long distance are represented by circles, and results which show slab penetration into the lower mantle are represented by crosses, and the other results which show stagnation temporarily before descending into the lower mantle or stagnation below the 660-km discontinuity are represented by triangles. The dashed line indicates the critical boundary between slab stagnation and slab penetration. Initial dip angle is 45°. The left, middle, and right figures demonstrate the results for the trench retreat velocities of 1, 2, and 3 cm/yr, respectively.

cal experiments: (1) When the effect of trench retreat is considered, slabs tend to be easier to flatten dramatically. (2) The faster trench retreat velocity is or the higher viscosity of the lower mantle is, the more easily slabs can flatten. (3) When the trench retreats, if the viscosity of the lower mantle is higher than a certain value, slabs can stagnate above the 660 km phase boundary, even if the value of the Clapeyron slope is 0 MPa/K, for which positive buoyancy force does not act upon slabs. (4) Average slab viscosity in the mantle transition zone decreases with increasing trench retreat velocity.

3. Global model to see the effects of PPV phase transition

The post-perovskite (PPV) phase is a newly discovered phase of mantle material, and the pressure-temperature condition of the transition corresponds to the deepest part of the mantle. This transition may be the origin of D" layer which is seismically observed undulated structure at the bottom of the mantle, and it could also control the large-scale mantle flow, moreover, the long term evolution of the Earth.

We carried out systematic numerical simulations of mantle convection including a phase transition near the core-mantle boundary, to clarify how that type of transition can affect on the thermal state in the mantle. We calculate time-dependent thermal convection of infinite Prandtl number fluid in a three dimensional spherical shell. Compressible fluid is treated to consider the effect of latent heat. Other two phase transitions, which are exothermic one at a depth of 410 km and endothermic one at a depth of 660 km, are also included. To simplify the model and to save the calculation resources, the temperature- and pressure- dependencies of viscosity and other physical properties are ignored. Both internal and basal heating are considered. We performed thermal convection with the approximate Rayleigh number to 10^8. We assume the negative or positive Clapeyron-slope of the PPV phase transition, though the experimental and theoretical studies indicate that this transition is exothermic (positive Clapeyron-slope) one. In addition, the depth of the phase boundary should play an important role, so we calculate two cases as follows: the PPV phase boundary exists inside of the bottom thermal boundary layer of mantle convection (Case 1; e.g. Fig. 3), and above that layer (Case 2).

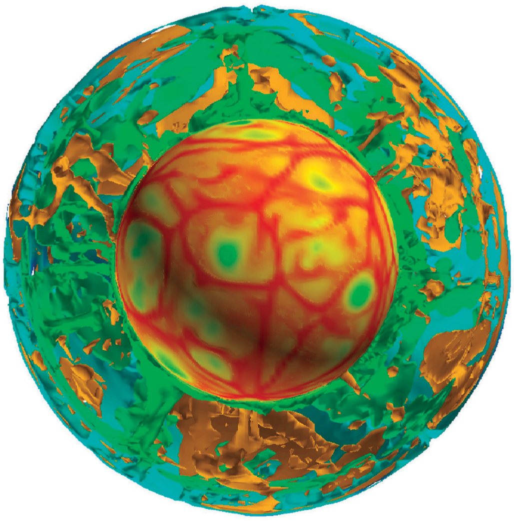

Fig. 3 Mantle convection in 3-D shell geometry with phase transitions at the depth of 410 km, 660 km, and 2750 km. Temperature anomaly is shown for each depth. The endothermic phase transition at 660 km prevents vertical flow motion, and stagnant structures are formed at the depth. The value of Clapeyron-slope for PPV transition is +8 MPa/K, and Rayleigh number is 10^7 in this case.

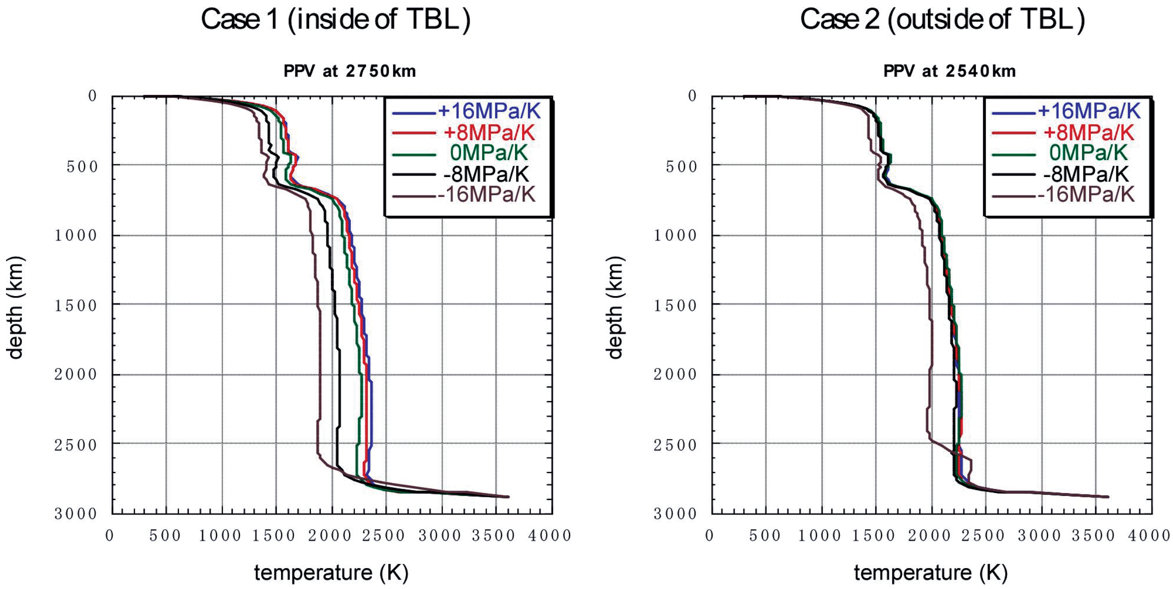

Fig. 4 Horizontally averaged temperature profiles (Ra~10^7). Case 1: PPV phase transition zone exists inside of the thermal boundary layer. Case 2: outside of the thermal boundary layer. These are the results with several values of Clapeyron-slope for PPV phase transition. Phase transitions at 410 km and 660 km are also introduced. For the smaller value of the Clapeyron-slope, the bottom thermal boundary layer is thicker, and the mean temperature of the mantle is lower.

When the PPV phase transition zone exists inside of the thermal boundary layer, the mean temperature of the mid-mantle rises a little with the increase of Clapeyron-slope with positive values. When it exists above the thermal boundary layer, the temperature field does not depend on Clapeyron-slope except for extreme negative value (Fig. 4). The convection flow patterns show similar dependence on Clapeyron-slope. With positive values of the slope, every pattern in Case 1 and 2 has almost the same spatial scales at the depth of mid-mantle. With extreme negative value, a thin separated convection layer is formed at the bottom in Case 2, and then the characteristic spatial scale of mid-mantle drastically changes. At present, the value of Clapeyron-slope and the density jump with PPV phase transition in the Earth is supposed to be around +8 MPa/K and +1 % respectively ([4], [5]). Our results of numerical simulations show that though the existence of PPV phase transition zone slightly modifies the structure of the bottom boundary layer, it has little impact on the global convection structure in the mantle.

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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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地球のマントルを構成するのは固体の岩石である。しかし地質学的な時間で見るとマントルは流動していてそれがプレート運動として地表に現れ、プレートの境界で地震や火山という現象を引き起こす。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因となっている。プレートは海溝より地球内部に沈み込んでいるが、沈み込んだ後のマントル内での挙動が地震波トモグラフィーにより描き出されている。それによれば沈み込み帯から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横たわっている。これらはスタグナントスラブと呼ばれる。日本列島も含めた東アジア地域はスタグナントスラブの上方に位置している。そのため、どのようにしてスタグナントスラブが形成されてきたのか、さらに将来このような構造はどうなっていくのか、という問題は我々が生存している場の理解にとって重要である。我々は、沈み込み帯に着目したリージョナルモデルで、海溝の後退、大規模粘性変化、プレート構造と複雑レオロジー、などを統合したシミュレーションを実行し、沈み込んだスラブが自発的に横たわる一連の過程を再現することに成功するとともに、スタグナント構造生成の条件を明確化した。一方、地球深部のような高温高圧化でのマントル構成鉱物の性質が実験を中心として調べられてきた。最近、マントル最下層の条件で今まで知られていなかった相への転移が発見され、ポストペロフスカイト(PPV)と名づけられた。この新たな相転移はその性質によっては従来のマントル対流像に大幅な修正を迫る可能性があり、我々はグローバルモデルによりマントル最下層に相境界が存在する場合の対流の振る舞いを広いパラメータ範囲について調査した。

今年度の重要な成果は以下のようにまとめられる。

(1) 地表に見られる海溝の後退はマントル遷移層でのスタグナントのプロセスと一体のものであり、両者の時間的な対応関係を明らかにした。
(2) スタグナントスラブが形成される条件を明確化した。特に、下部マントルの粘性が一桁程度大きければ、上下マントルでの相転移のクラペイロン勾配に関わらずスタグナント構造は容易に形成されることが分かった。
(3) マントル最下層での相転移の存在は条件次第では対流パターンや熱輸送量を大きく変化させるが、現在見積もられているPPV相転移に関わる密度変化量は影響を与えるには小さいものであることが分かった。

キーワード：マントル対流, プレート運動, 沈み込み帯, スタグナントスラブ, 相転移