論文内容の要旨

論文題目 Numerical Simulation with a Finite Element Method for the Development of Mechanical and Thermal Structure in Subduction Zones

（有限要素法を用いたプレート沈み込み帯の
力学的－熱的構造発達シミュレーション）

氏　名　　鹿倉　洋介

Topography in plate subduction zones is formed as the result of interaction between the internal crustal processes such as igneous activity and tectonic deformation due to plate subduction and the external surface processes such as erosion and sedimentation controlled by climate and environment. The internal processes cause surface uplift and subsidence, while the external processes even the Earth's surface through mass transfer from highlands to lowlands. Therefore, we can regard the internal and external processes as active and passive processes, respectively. In the present paper we focused on the internal crustal processes in plate subduction zones.

In numerical simulation for the development of mechanical and thermal structure in plate subduction zones, the following points are essential: 1) rational representation of plate-to-plate interaction, 2) realistic modeling of rheological structure, and 3) interaction between mechanical and thermal processes. For the first point, we rationally represented the plate-to-plate interaction by the increase of tangential displacement discontinuity (fault slip) at plate interfaces. For the second point, we modeled the realistic rheological structure of subduction zones with a finite element method (FEM). As to the third point, we constructed a mechanical-thermal interaction model by combining a thermal FEM model for temperature changes due to thermal diffusion and advection with a mechanical FEM model for internal velocity fields due to plate subduction through a temperature-dependent constitutive equation prescribing rheological properties of materials.

In Chapter 2, first, we developed a mechanical FEM model to compute the long-term internal velocity fields for a simple subduction zone, which is modeled by an elastic continental plate and an elastic oceanic plate descending into an underlying viscoelastic half-space. The steady plate subduction is represented by the steady increase of tangential displacement discontinuity at the interface between the continental and oceanic plates (Matsu'ura & Sato, 1989). The most direct way to obtain the internal velocity fields is to solve a boundary value problem for the elastic-viscoelastic composite medium in the time domain, but it is very difficult even in the simple case. In order to avoid the difficulty in computation, we applied the corresponding principle of linear viscoelasticity (Lee, 1955; Radok, 1957) and the equivalent theorem (Fukahata & Matsu'ura, 2006) to the elastic-viscoelastic problem, and reduced it to a simple elastic problem, which is directly obtained from the original elastic-viscoelastic problem by regarding the underlying viscoelastic half-space as the elastic half-space with a normal bulk modulus and a very small rigidity. Then, we can use a standard elastic FEM to construct a mechanical model for computing long-term internal velocity fields due to steady plate subduction in a realistic situation. In the construction of the mechanical FEM model, we represented the tangential displacement discontinuity at the plate interface with the split node technique (Melosh & Raefsky, 1981). The negative and positive buoyancy effects related to surface uplift and subsidence were incorporated into the stress-free conditions at the Earth's surface (Williams & Richardson, 1991). When we decrease the rigidity of the underlying elastic half-space to zero, the computational instability called "volumetric locking" arises. We resolved this computational instability by using the selective-reduced integration scheme (Hughes, 1980).

Next, with the mechanical FEM model we computed the internal velocity fields due to steady plate subduction. We took a 2000 km (horizontal) x 500 km (vertical) fine-mesh model region composed of 800x500 elements as shown in Fig. 1, where the blue thick solid line indicates the split nodes to represent tangential displacement discontinuity (fault slip) at the plate interface. In order to suppress boundary echoes we added a broad coarse-mesh region surrounding the fine-mesh model region. The right side of the total model region is set to be horizontally fixed but vertically free, the base to be vertically fixed but horizontally free, and the left side to be free both for horizontal and vertical displacements. Therefore, the computed results represent the velocity fields relative to a remote reference point fixed to the continental plate. The traction free conditions at the upper surface were modified to incorporate the negative and positive buoyancy effects related to surface uplift and subsidence. From numerical computations we found the following. In the case of a horizontally layered model, the long-term internal velocity fields calculated from the FEM model almost completely agree with those from analytical expressions by Fukahata & Matsu'ura (2006). The pattern of velocity fields in

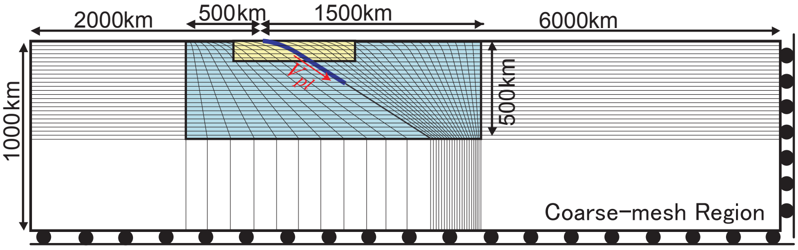

Fig. 1 The FEM model used for numerical computation.

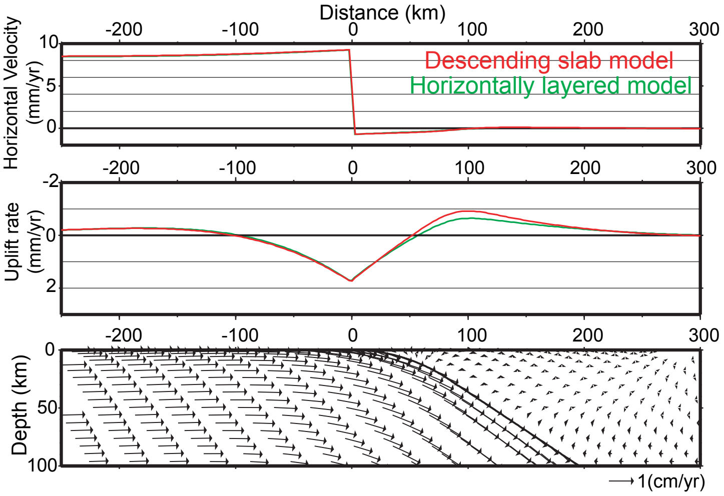

Fig. 2 Internal velocity fields for a descending slab model.

the case of a descending slab model are similar to that in the case of the horizontally layered model, if the thickness of plates is the same in both models, as shown in Fig. 2. A significant difference between these two models is in uplift rates on the overriding plate: the maximum uplift rate for the descending slab model is much faster than that for the horizontally layered model. Then, we examined the effects of the thickness of descending slab on surface velocity patterns. The results are shown in Fig. 3. If the descending slab is thicker, the uplift zone in the overriding plate and the subsidence zone around the trench become broader, and the uplift and subsidence rates become faster. If the overriding plate is thicker, the subsidence pattern around the trench does not change significantly, but the uplift pattern in the overriding plate changes notably. These results are consistent with geophysical observations in subduction zones.

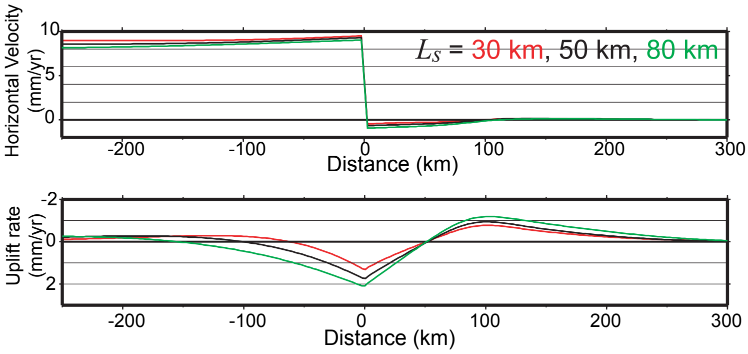

Fig. 3 The effects of the thickness of descending slab.

In Chapter 3, first, we developed a thermal FEM model to compute temperature changes due to thermal diffusion and advection. In the development of the thermal FEM model, we considered three sources of advection; the subduction of the cold oceanic slab, the mantle flow induced by slab subduction, and the vertical deformation of the overriding plate. With the thermal FEM model we computed temporal change in thermal structure for given internal velocity fields. The computed results in Fig. 4 show that the third source is less effective in heat transfer, but crucial in geomorphic development in plate subduction zones. Next, combining the thermal FEM model

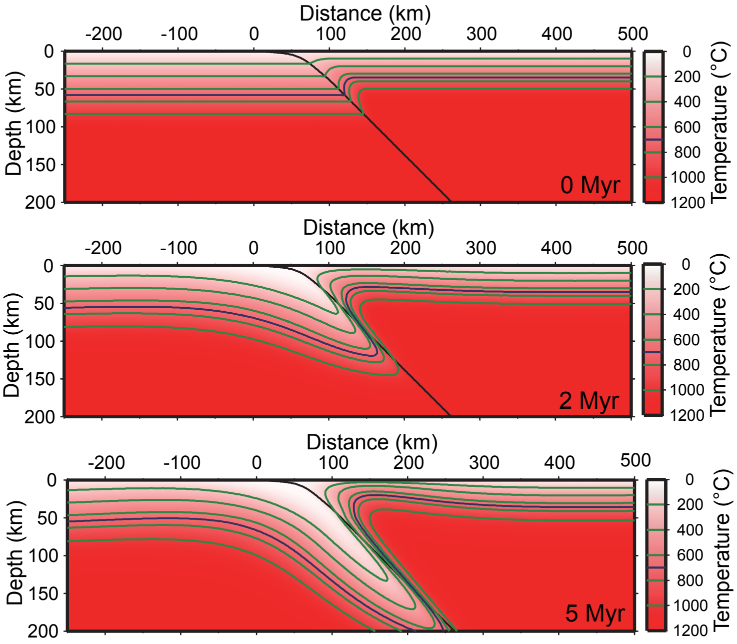

Fig. 4 Thermal structure change due to steady plate subduction.

with the mechanical FEM model, we constructed a mechanical-thermal interaction model. In this model the mechanical-thermal interaction is described through a temperature-dependent constitutive equation prescribing rheological properties of materials; that is, the temperature-dependence of the mantle viscosity (Courtney & Beaumont, 1983). With the mechanical-thermal interaction model, we numerically simulated the development of mechanical and thermal structure in a plate subduction zone. In this simulation, at a certain time step, we compute internal velocity fields due to plate subduction. Then, by using the computed internal velocity fields, we evaluate temperature changes due to thermal diffusion and advection, and update the boundaries between the lithosphere and the asthenosphere to compute internal velocity fields at the next time step. Through the numerical simulation with such a computation algorithm, we revealed the evolution process of mechanical and thermal structure in the plate subduction zone over a span of 5 Myr. In each diagram of Fig. 5 we show the surface uplift rate (top) and the mechanical and thermal structure development (bottom) together with internal velocity fields. In the early stages of plate subduction (0-2 Myr), the cooling of the mantle wedge leads to the thickening of the continental lithosphere near the plate boundary and increases the uplift rates of the lithosphere beneath the island arc. Then, as time goes on, the thinning of the lithosphere beneath the island arc proceeds, and the uplift rates further increase there. This simulation result indicates that the mechanical-thermal interaction is crucial to understand the geomorphic evolution in plate subduction zones.

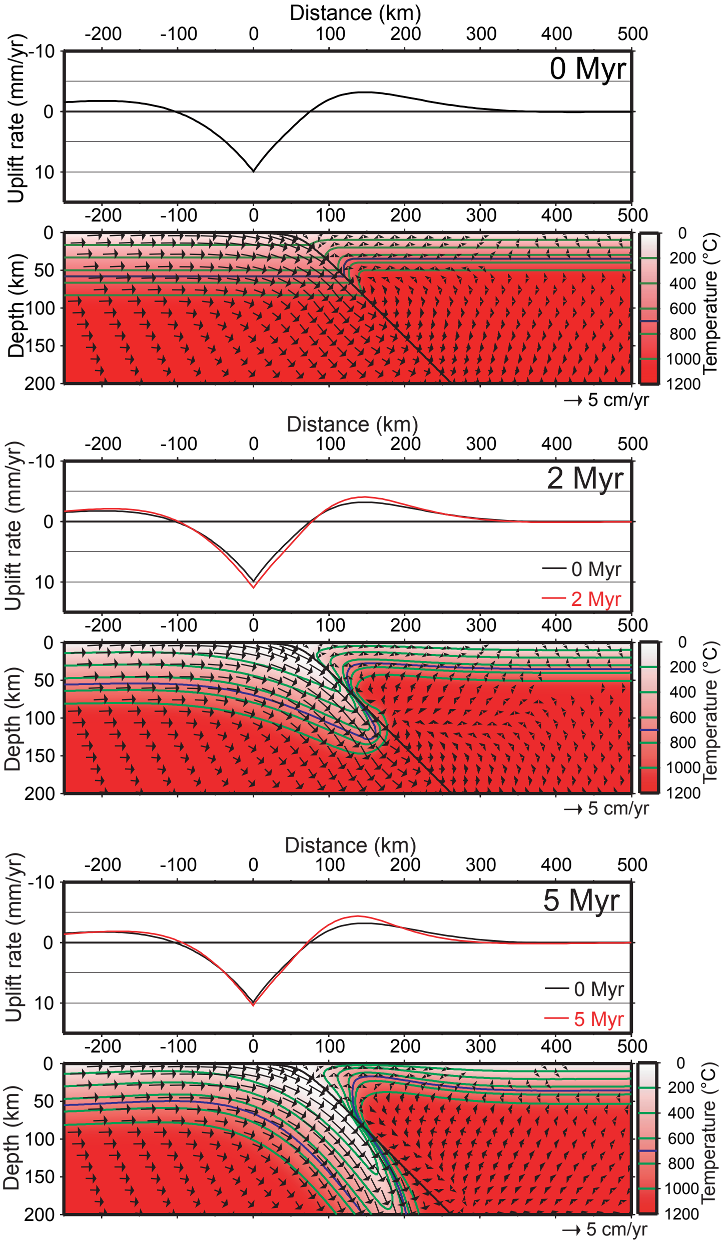

Fig. 5 The development of mechanical and thermal structure.