Experimental study of the transition time of convection patterns and its application to the Wilson cycle

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Abstract: We studied the influence of the inhomogeneous boundary conditions on the convection pattern and the response of the pattern to the change of these conditions. These are the idealized models for drifting continental tectospheres at the surface of the Earth. Continental tectosphere acts as a thermal insulator and it can regulate convection upwelling region to come below it. We investigated the transition time of convection patterns and found out that it is much longer than the flow circulation time under some conditions. The Earth satisfies this condition at present; hence we can explain the time scales for aggregation and breakup of continents.

Key words: Mantle convection; continent; Wilson cycle; laboratory experiment.

Introduction. The Earth’s mantle occupies more than eighty percent of the volume of the Earth and controls various phenomena. It is, therefore, very important to investigate mantle dynamics in order to understand the Earth’s present state and its evolution. The main component of mantle dynamics is mantle convection. One of the most interesting features of convection is that it has ascending regions and descending regions, so that it acts as a pattern. The distribution and motion of the continents and the oceans at the surface of the Earth are considered to be closely related to the pattern of mantle convection. Another important feature of convection is that it can transport heat much more quickly than conduction can. This is important in studying the Earth’s thermal history.

Many studies have been made of mantle convection (see Peltier (ed.); Schubert et al.). One effective method is to study the characteristics of convection as a physical problem. Mantle convection differs from simple Rayleigh-Bénard type convection. For example, it includes the effects of plates and slabs, temperature-pressure dependent viscosity, internal heating, phase changes, partial melting, and non-Newtonian rheology. It is necessary to determine how each effect acts on the convective motion, and to estimate the roles they play in mantle dynamics.

Here, we consider the effect of heterogeneity of a boundary condition. Seismology has revealed the structure of continental plates is different from that of oceanic plates, to the depth of several hundred kilometers. Old continents have thick roots in the upper mantle, whereas oceanic plates do not. These continental roots are named the “tectosphere” and are considered to be composed of lighter material than the surrounding mantle, because such continents have been drifting at the surface of the Earth for billions of years. The roots under the continents are separated from the mantle's convective motion. In mantle convection, oceanic plates play the role of thermal boundary layers. However, such continental roots are unnaturally thick for thermal boundary layers for mantle convection, and behave as thermal insulators (e.g., Lenardic et al.). Therefore, mantle convection can be modeled as convection with an upper boundary condition that is thermally heterogeneous.

Several studies have been made of the problem of convection with heterogeneous boundary conditions. Gurnis and Zhong and Gurnis carried out numerical simulations of convection containing continent-like mobile rafts, and they reproduced behavior of rafts that was similar to the Wilson cycle of continental aggregation.

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and breakup. Their ranges of Rayleigh number and continental width were limited, so that further studies with wider parameter ranges are required. Guillou and Jaupart\textsuperscript{15} studied convection with a partially insulated boundary using laboratory experiments, and they revealed that in the stable state, convection cells are long sideways with an uprising region under the insulator. Their parameter ranges were sufficient for considering the Earth’s mantle, but they did not study enough about the process of pattern transition. Here, we discuss how convection patterns adjust to the change in boundary conditions when the location of an insulator changes, and how long it takes to achieve equilibrium or a stable state. The transition process is important for understanding the relationship between continents and mantle convection, particularly in relation to continental drift and the Wilson cycle.

**Method of the experiment.** The apparatus we used for studying convection is shown in Fig. 1. The tank is made of acrylic plates of 8 mm thickness. The size of the tank is 30 mm \times 200 mm \times 80 mm. The flow patterns generated by this experiment are approximately two-dimensional. The upper and lower boundaries are made of copper plates, and circulating water keeps each copper plate at constant temperature horizontally. The accuracy of the temperature control of upper and lower boundaries is 0.5 K, and the horizontal temperature difference is less than 0.1 K for each boundary. Silicon oil and water are used for the working fluids.

Temperature-sensitive micro-encapsulated liquid crystals were used for visualizing the temperature field and the flow field of the convection (e.g., Dahi, and Gharib\textsuperscript{14}). The color of the liquid crystal changes from red to green, to blue, as the temperature rises. A K-type thermocouple was used to measure the actual temperature, and we determined a transform equation for converting the liquid crystal color to temperature. The accuracy of the temperature indicated by the color of the liquid crystals is about 0.5 K for 10 K of temperature difference. The size of the encapsulated liquid crystals is about 30 micrometers, so they have little influence on the flow, and instantly reflect the surrounding fluid temperature.

To simulate the thermal effect of a continent, a thermal insulator was pasted to part of the upper boundary. We use a type of sponge, which holds small air bubbles in its pores and works as a thermal insulator. Its thermal conductivity is almost equal to that of air. The thickness of the sponge was 1.5 mm. This is much thinner than the thickness of the convecting layer, so its mechanical effect on the flow is negligible. The sponge was regarded as the continental crustosphere, and we simulated continental drift by changing the position of the sponge. The sponge was fixed to a certain place on the upper boundary. To simulate continental drift, we picked up the upper cooling tank, changed the location of the sponge, and quickly reset in the tank. The time taken for this manipulation was short enough to not disturb the original
flow pattern. We achieved Rayleigh numbers ranging from $10^3$ to $10^6$ for simple Rayleigh-Bénard convection, and observed transient states with the insulator at Rayleigh numbers ranging from $10^3$ to $10^7$.

**Results.** *(1) Convection with a homogeneous boundary condition – stable state.* First, we describe the results of the experiment with a homogeneous boundary condition, that is, a constant temperature boundary condition. Many studies of convection have been made with this type of boundary condition, and we were able to check that our results are consistent with them. This has shown that our apparatus works well for studying convection. The range of Rayleigh numbers for these experiments was from $10^3$ to $10^6$.

The convection pattern changes from steady to unsteady and to turbulent as the Rayleigh number increases. Each of the typical patterns observed using the liquid crystals are shown in Fig. 2. The structure of the convection cells, in particular, the thermal boundary layers and up- and down-flow regions of convection, are clearly visible. The spatial interval between upwelling and downwelling is approximately equal to the layer depth for steady convection, but becomes shorter as the Rayleigh number increases. At higher Rayleigh numbers, turbulent convection is reorganized into large-scale circulation, and an apparently steady pattern exists in the tank. We do not discuss this further here.

We measured the upwelling and downwelling velocity of the convection by tracing the motion of the particles. Upwelling and downwelling velocities are almost the same. The velocity is proportional to about a 1/2 power of the Rayleigh number when fitted in a Rayleigh number range of $10^3$ to $10^6$.
(2) Convection with a heterogeneous boundary condition – stable state. In these experiments, we pasted a sponge onto some part of the upper boundary layer, and it worked as a thermal insulator. The important results are as follows: For the Rayleigh number range investigated, the thermal insulator regulated the convection pattern with the upwelling region rising below it. In the steady convection regime, the uprising part of the convection cell occupies the area beneath the insulator. The aspect ratio of the cell under the insulator becomes longer sideways. The neighboring cells also get a little longer sideways. In the unsteady convection regime, the cells under the insulator are stabilized and elongated steady cells exist. In the turbulent convection regime, uprising plumes combine under the insulator and downgoing plumes are rarely generated under it, such that a quasi-steady pattern exists in the turbulent flow under the influence of the insulator. The aspect ratios of the convection cells are related to the size of the insulator and Rayleigh number. For each Rayleigh number, we varied the size of the sponge and measured the cell size formed beneath it. If the horizontal scale of the insulator is longer than the thickness of the thermal boundary layer, the insulator has an influence on the convection pattern and the uprising region is located below it. As the size increases, the cell below it also gets wider. The increase in cell size is linearly proportional to the increase in the size of the insulator when the insulator is small, but for a large insulator, the cell size saturates at a certain value according to the Rayleigh number. For the same size of insulator, the cells become wider for the higher Rayleigh numbers. For higher Rayleigh numbers, the cell size also saturates at a larger value. These results can be compared with that of Guillou and Jaupart.\textsuperscript{(3)} Our results are essentially consistent with theirs, but there are some differences at longer insulator sizes. They did not observe a saturation of the cell size. We believe that this is because of a difference in the geometry between the tank used here and that used by Guillou and Jaupart.\textsuperscript{(3)}

(3) Convection with a heterogeneous boundary condition – transient state. In this section, we describe the reaction of the convection pattern when the location of the insulator changes. In this experiment, we try to simulate the continental drift. The uprising region of the convection pattern exists below the insulator in the equilibrium or stable state, as mentioned in the previous section. We moved the insulator to the downgoing region and observed the pattern transition. The insulator is fixed to the upper boundary in this system and convection flow cannot move it. When the insulator is placed away from the uprising region, the pattern is not in a stable state and changes itself to achieve equilibrium.

At every Rayleigh number in our experiment, the convection pattern changed with the influence of the insulator. Sponge size was fixed to about one third of the layer thickness. In the steady convection regime for lower Rayleigh numbers, the transition occurs with the uprising and downgoing region moving sideways. Fig. 3 shows the transition process of this regime. The uprising region quickly moves to the edge of the insulator and then slows down below it. We defined the pattern transition time in this regime as the time taken to move to the edge of the insulator. In the turbulent convection regime for higher Rayleigh numbers, pattern transition occurs in a different way. After changing the place of the insulator, the original pattern generated under the influence of the insulator becomes weaker and disappears. The pattern temporally seems truly turbulent like the convection under a homogeneous boundary condition. Then a new pattern is generated under the influence of the insulator at the new site, and incoherent uprising plumes are generated below the insulator to achieve the stable state. In this convection regime, we defined the pattern transition time as the time taken to form the new uprising region. Fig. 4 shows the pattern transition time ($T_{tr}$) as defined below, in relation to Rayleigh number. The time is nondimensionalized by the thickness of the layer $d$ and thermal diffusivity of the fluid $\kappa$. In the same figure, we plot the uprising time ($T_{up}$), which is the time required for the flow to pass from the bottom to top of the layer and is calculated by the measurement of the velocity at each Rayleigh number. As shown in the figure, transition time is inversely proportional to Rayleigh number. This Rayleigh number dependence is more marked than that of the flow velocity. Hence, in the case of lower Rayleigh numbers, the pattern transition time is much longer than the time taken for the flow to circulate through the convection cell. But in the case of higher Rayleigh numbers, the pattern change is as fast as the velocity of the flow.

Discussion and application to the Earth. The important results from our experiments are as follows: (1) The thermal insulator controls the upwelling region so that it resides below it, even if the size of the insulator is same as the thickness of the thermal boundary layer. (2) The shape of the convection cell becomes elongated sideways as the insulator gets longer. (3) If we change the location of the insulator, the convection pattern changes gradually, and eventually attains a new state of
equilibrium. (4) The time required to attain the equilibrium state is inversely proportional to the Rayleigh number \( (T_m \propto \text{Ra}^{-1}) \), and this dependence is steeper than that of the circulation time \( (T_m \propto \text{Ra}^{-1/3}) \).

Results (1) and (3) indicate that the expected horizontal scale of a continent is several hundred kilometers in order to regulate the convection pattern if it has a thick tectosphere. Therefore, many of the cratons that are present at the surface of the Earth are large enough to gather uprising plumes. However, it is necessary for the craton to be fixed at a certain point for a long time to regulate the convection pattern. Result (4) indicates that a continent drifting by convective flow cannot regulate the convection pattern, because the drifting speed is faster than the pattern transition speed. On the other hand, this means that continents can move together to a downwelling region, and consequently, a supercontinent may be formed in the time \( T_m \) (Fig. 5, left). This is a mechanically stable state for the convection pattern, and the supercontinent is fixed at a point for a while. Then, the continents' insulating effect causes an upwelling region of the convection pattern to move below it after the passage of \( T_m \) (Fig. 5, right). This upwelling may cause the continent to breakup, and a new stage in the Wilson cycle may start. In this scenario, it is essential that \( T_m \) is much longer than \( T_m \), which is clarified by our experiments. If we assume that the Rayleigh number of the present Earth's mantle is \( 10^7 \), the equation in Fig. 4 indicates that the transition time of the mantle convection pattern \( (T_m) \) is about 400 million
years, which is longer than the circulation time $T_{\text{circ}}$ (about 100 million years). These time scales are consistent with geological evidence. The approximate period of the Wilson cycle is considered to be 400 or 500 million years.

Concerning result (2), seismological studies have revealed horizontally long wavelength structures in the lower mantle, and the locations of the low seismic wave velocities correspond to Africa and the South Pacific.\cite{15,16} Africa is located at the center of the last supercontinent, and there are many hot spots in these low velocity regions.\cite{17,18} The large horizontal scale in the mantle may be attributed to the insulating effect of continents, and the low velocity (that is, high temperature) region under Africa is a vestige of the supercontinent Pangaea. The breakup of Pangaea occurred around 200 million years ago, and our experiments show that the general convection pattern can survive for this time scale.

Further, our results indicate that the pattern transition speed is comparable to the convective flow speed in the higher Rayleigh number range. If we go back in Earth’s history, it is believed from geological evidence that supercontinents did not exist in the Archean. This can be attributed to a higher Rayleigh number for the mantle at that time. In that case, the convection pattern changes as fast as the velocity of the flow, and consequently, the continents could not come together, and a supercontinent was unable to form.

References


