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EXPRESS LETTER

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Tectonic plates in 3D mantle convection model with stress-history-dependent rheology

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Abstract

Plate tectonics is a key feature of the dynamics of the Earth's mantle. By taking into account the stress-history-dependent rheology of mantle materials, we succeeded in realistically producing tectonic plates in our numerical model of mantle convection in a three-dimensional rectangular box. The calculated lithosphere is separated into several pieces (tectonic plates) that rigidly move. Deformation of the lithosphere caused by the relative motion of adjacent plates is concentrated in narrow bands (plate margins) where the viscosity is substantially reduced. The plate margins develop when the stress exceeds a threshold and the lithosphere is ruptured. Once formed, the plate margins persist, even after the stress is reduced below the threshold, allowing the plates to stably move over geologic time. The vertical component of vorticity takes a large value in the narrow plate margins. Secondary convection occurs beneath old tectonic plates as two-dimensional rolls with their axes aligned to the direction of plate motion. The surface heat flow decreases with increasing distance from divergent plate margins (ridges) in their vicinity in the way the cooling half-space model predicts, but it tends towards a constant value away from ridges as observed for the Earth because of the heat transport by the secondary convection.

Keywords: Mantle convection, 3D numerical model, Plate tectonics, Stress-history-dependent rheology

Introduction

One of the most challenging issues in studies of the Earth's mantle dynamics is to self-consistently produce tectonic plates in three-dimensional numerical models of mantle convection. The lithosphere develops along the surface boundary, when the viscosity strongly depends on temperature (Weertman 1970). The lithosphere produced in this way, however, behaves as a stagnant lid that develops on top of the convecting mantle (Ogawa et al. 1991; Moresi and Solomatov 1995). To allow the lithosphere to be further divided into several pieces (tectonic plates) that rigidly move, it is necessary to introduce plate margins, where the mechanical strength is much lower than that of the surrounding tectonic plates in the lithosphere. In the Earth, plate margins develop when a stress higher than the rupture strength of the lithosphere is induced there by, for example, Large Igneous Provinces (Coffin and Eldholm 1994). Once formed, plate margins persist, even after the stress is reduced below the rupture strength. Indeed, various geophysical and tectonic observations (Kanamori 1980; Zhong and Watts 2013; Gao and Wang 2014) show that mechanically weak plate margins persist in the lithosphere at stress levels lower than those for mechanically strong plate interiors. This stress-history-dependent behaviour of the lithosphere is thought to play a crucial role in plate tectonics (Bercovici 1998; Zhong et al. 1998; Ogawa 2003). Here, we present a three-dimensional model of mantle convection to examine how a stress-history-dependent rheology exerts control over the dynamics of the lithosphere.

Methods

The model of mantle convection with tectonic plates was calculated with the ACuTEMan code (Kameyama et al. 2005; Kameyama 2005) as thermal convection of an incompressible Newtonian fluid with an infinite Prandtl number in an internally heated three-dimensional

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rectangular box with an aspect ratio of 4 × 4 and a height of 3000 km. The temperature on the surface boundary is fixed at 0° C, whereas the other boundaries are insulating. All of the boundaries are impermeable and shear-stress free. The viscosity strongly depends on the temperature, and the lithosphere develops as the coldest and most viscous part of the cold thermal boundary layer along the surface. The viscosity is also a two-valued function of stress in a range from σ_m (the strength of mechanical coupling at the plate margins) to σ_p (the rupture strength of the lithosphere) (Ogawa 2003). The viscosity takes a high (or "intact") value for the plate interior when the stress is sufficiently low, but it drops to a low (or "damaged") value for the plate margins as the stress increases and exceeds σ_p; the viscosity remains low, even when the stress is reduced below σ_p as long as it is higher than σ_m (see the Additional file 1 for more detail). Which of the two values the viscosity takes in the stress range is determined by whether or not the material has experienced a stress higher than σ_p in the past, and this memory of stress-history persists for an indefinitely long period of time as long as σ stays in the range from σ_m to σ_p. We stored this information of stress history, which is transported by convection, in a scalar quantity called damage parameter (Bercovici et al. 2001; Ogawa 2003). The persistent memory of stress-history of our model is different from the memory assumed in some earlier models (e.g., Bercovici 1998; Foley et al. 2014) that fades away with a decay time of several hundred million years. This persistent memory is the reason why a more plate-like behaviour of the lithosphere is produced in our model. The viscosity for plate interiors is $\eta_p = 10^{27}$ Pa s, whereas that for plate margins is 3.2×10^{23} Pa s along the surface boundary. We also assume $\sigma_p = 200$ MPa, a value somewhat lower than earlier estimates (Kohlstedt et al. 1995; Watts and Burov 2003; Jain et al. 2017), and $\sigma_m = 67$ MPa.

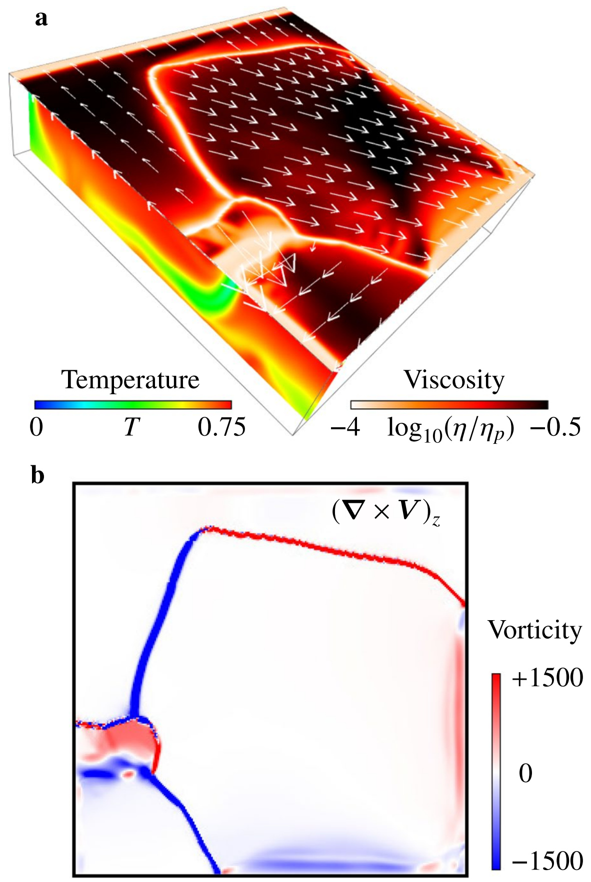

Fig. 1 The overall three-dimensional structure of thermal convection obtained in our numerical model with stress-history-dependent rheology. **a** The distribution of temperature T in a vertical cross section and that of viscosity η (colour) and velocity $\boldsymbol{V}$ (arrows) on the surface. The value of η is normalised by η_p, the viscosity of intact material at the surface. **b** The distribution of the vertical component of vorticity $(\nabla \times \boldsymbol{V})_z$ on the surface

Results

The lithosphere simulated in our model is rifted into several highly viscous pieces (tectonic plates) separated by narrow plate margins where the viscosity is substantially lower than that in the plate interiors (Fig. 1a). Each of the plates rigidly moves (see the arrows for velocity vector $\boldsymbol{V}$ in Fig. 1a), and the deformation of the lithosphere caused by relative motion between adjacent plates is accommodated in the narrow plate margins. The cold plates sink into the mantle at convergent plate margins (subduction zones) where $\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} < 0$ holds (see the temperature distribution on the vertical section presented in Fig. 1a). The vertical component of the vorticity field $(\nabla \times \boldsymbol{V})_z$ takes a large value in the plate margins except in the subduction zones (Fig. 1b); $(\nabla \times \boldsymbol{V})_z$ is somewhat large over the entire small plate along the west side in Fig. 1b too, implying that this plate rigidly rotates. As far as the authors know, Fig. 1b is the first example where $(\nabla \times \boldsymbol{V})_z$ takes a significant value in narrow plate margins in 3D numerical models of thermal convection where tectonic plates spontaneously develop (Tackley 2000; Bercovici et al. 2015).

The plate motion induces lateral variation in the surface heat flow (Fig. 2a). The heat flow decreases with increasing distance L from the divergent plate margins (ridges) in their vicinity. The almost linear dependence of $1/(\text{heat flow})^2$ on L observed in Fig. 2b is consistent with a prediction from the cooling half-space model of tectonic plates (Sclater et al. 1980) because L is almost proportional to the surface age because of the calculated stable plate motion in our models (see below).

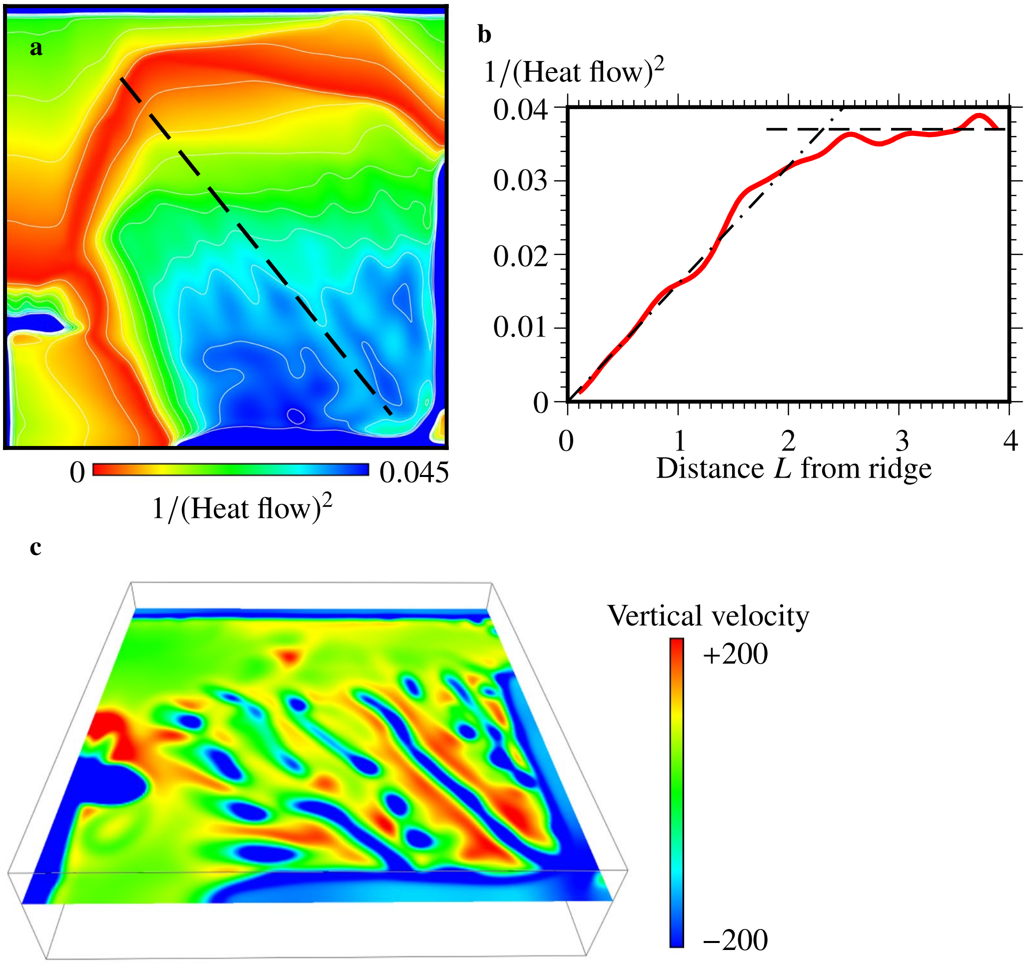

Fig. 2 The lateral variations in the surface heat flow and convecting flow structure. **a** The distribution of the inverse square of the surface heat flow shown in both colour and white contour lines. **b** The plot of the inverse square of heat flow at the surface as a function of the distance *L* from the divergent plate boundary (ridge) along a horizontal track indicated by the dashed line in **a**. Also shown by the dash-dotted line is the theoretical prediction from the half-space cooling for small *L*, while by the dashed line is the deviation from it for large *L*. **c** The distribution of vertical component of velocity V_z on the horizontal plane at the height of $z = 0.672$

Away from ridges, the value of 1/(heat flow)^2 deviates from the linear dependence and tends towards a constant value (Fig. 2b). Figures 2a and c show that the deviation is due to heat transport by the secondary convection that occurs beneath old plates: The distribution of the vertical component of velocity on the horizontal plane at $z = 0.672$ plotted in Fig. 2c shows that the secondary convection indeed occurs in the form of two-dimensional rolls whose axes are aligned in the direction of plate motion. The convection rolls extend to the depth of about 1000 km. The secondary convection also induces a stripe pattern in the surface heat flow (Fig. 2a). The onset and pattern of secondary convection beneath old oceans are consistent with a prediction from earlier laboratory (Parsons and McKenzie 1978; Richter and Parsons 1975) and numerical (van Hunen et al. 2003; Huang and Zhong 2005) experiments of thermal convection beneath moving plates. Such stripe patterns may be identified in the future by high-resolution tomographic studies of the upper mantle beneath old parts of large oceanic plates such as the Pacific and Indian plates.

The time evolution of the velocity distribution along the surface presented in Fig. 3 shows that the tectonic plates produced in our model move rather steadily on the non-dimensional time scale of 0.01 (or about 3 billion years). Plate A, for example, moves to the south-east, whereas plate B moves to the north, and the ridge between them exists throughout the presented time span. The velocities of these plates do not change so wildly, although the rigid rotation of plate A observed in Fig. 3a

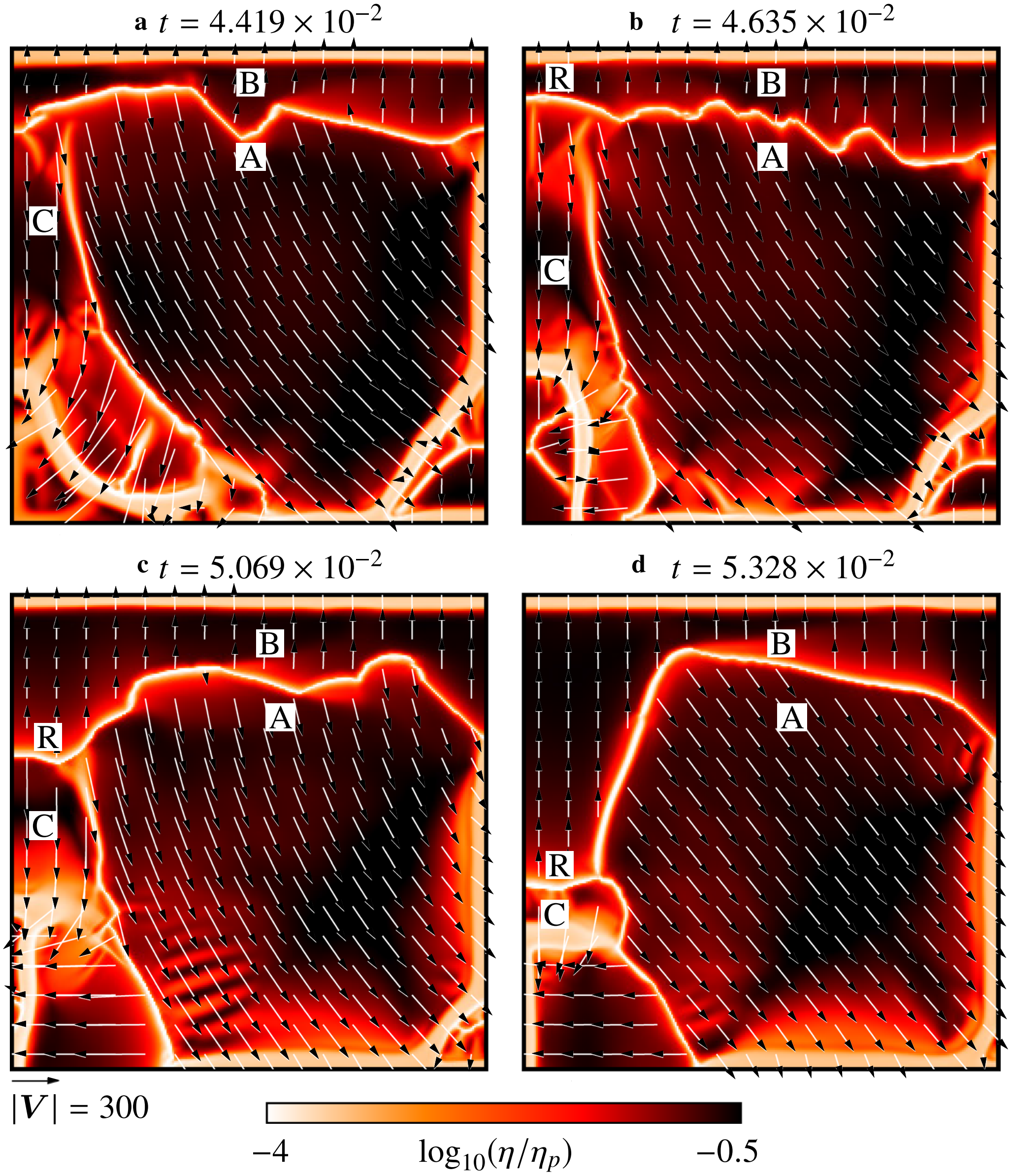

Fig. 3 The time evolution of the surface plate motions. Snapshots of the distributions of viscosity η (colour) and velocity $\boldsymbol{V}$ (arrows) in a horizontal plane along the surface at the elapsed times indicated in the figure. The values of η are normalised by η_p, the viscosity of intact material at the surface

stops by $t = 5.328 \times 10^{-2}$. The plate margins move in accordance with the plate motion. Ridge R (Fig. 3b), for example, moves to the south in frames (b) to (d) because the southward motion of plate C is much faster than the northward motion of plate B.

Plate margins persist in our calculation because the lithosphere remembers the location of existing plate margins owing to the assumed stress-history dependence of the viscosity. The margins do not spontaneously disappear; they disappear only when they merge with each other or with the sidewalls of the convecting box owing to the advection by tectonic plates.

An interesting feature of the modelled tectonic plates shown in Fig. 3 is that the ridges are just simple narrow bands but the subduction zones are more diffuse. Besides, fragments of plates (micro-plates) are often formed along subduction zones (see the area around the southwest and southeast corners of the convecting box). This feature arises because high stress tends to be induced around subduction zones by plate motion. This feature is also observed for the Earth (Gordon et al. 1998). In Fig. 3 we could not find a clear relationship between formation of micro-plates and the curvature of plate margins, as opposed to the suggestion by Mallard et al. (2016).

Discussion

Our model of tectonic plates shown in Figs. 1 to 3 indicates that a stress-history-dependent rheology that allows the lithosphere to "remember" the location of plate margins is crucial for plate tectonics to stably operate over geologic time (Zhong et al. 1998; Gurnis et al. 2000). It is difficult to produce stable plate motion together with a large value of $(\nabla \times \boldsymbol{V})_z$ in narrow plate margins in numerical models where the viscosity depends only on the instantaneous stress (Moresi and Solomatov 1998; Tackley 2000). An example is the yielding model; the lithosphere is intact and its viscosity is high when the stress is less than a threshold, called the yield strength, but it is ruptured and its viscosity is reduced as the stress reaches the threshold. In the yielding model, however, plate margins often spontaneously disappear or migrate at a velocity much higher than the plate velocity as the stress field evolves with time in the lithosphere. Stable motion of tectonic plates separated by narrow plate margins is difficult to produce, even in some models where the viscosity in the lithosphere does depend on its stress history over the past several hundred million years (Foley et al. 2014). See the Additional file 1 for more discussion.

The stable plate motion produced in our model is important for understanding the global-scale heterogeneity of the Earth's mantle revealed by tomographic studies. The large low shear velocity provinces (LLSVPs) develop on the core-mantle boundary away from the slab graveyards where subducted slabs have accumulated over the past several hundred million years (Richards and Engebretson 1992; Cottaar and Lekic 2016). The same feature is observed for numerical models of the evolution of thermo-chemical piles on the core-mantle boundary where the Earth's plate motion in the past is given as the mechanical boundary condition on the surface (Zhang et al. 2010). If plate margins jump and/or migrate so wildly and plate velocity varies with time as strongly as observed in some numerical models where the rheology depends on instantaneous stress rather than stress-history, regions such as LLSVPs and slab graveyards would not have developed (Nakagawa and Tackley 2014). Stable plate motion produced in our model opens a way to self-consistent numerical modelling of the development and evolution of large-scale structures in the Earth's mantle throughout its history. It is important to further extend our model to three-dimensional spherical geometry of the mantle in future exploration.

Conclusions

In this study we have realistically produced for the first time tectonic plates in our model of thermal convection of three-dimensional mantle, by assuming a stress-history-dependent rheology for mantle materials. The tectonic plates calculated in our model show the following five features: (i) rigid motion of cold and stiff plates (both translation and rotation), (ii) accommodation of relative motion of adjacent plates in narrow plate margins, (iii) stable tectonic motions over several billion years, (iv) decrease in surface heat flow in the vicinity of divergent plate boundaries in a way consistent with the prediction from the half-space cooling model, and (v) deviation of the surface heat flow from the half-space cooling model away from divergent plate boundaries. We believe that our model opens a way to self-consistent numerical modelling of development and evolution of large-scale structure in the Earth's mantle in its history.

Supplementary information

Supplementary information accompanies this paper at https://doi.org/10.1186/s40623-020-01195-1.

Additional file 1. Additional Materials for "Tectonic plates in 3D mantle convectionmodel with stress-history-dependent rheology".

Abbreviation

LLSVPs: The large low shear velocity provinces.

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Authors' contributions

T.M. performed numerical simulations, analysis of simulation data, and prepared the manuscript. M.K. developed the numerical simulation code ACuTEMan and prepared the manuscript. M.O. prepared the manuscript. All authors discussed numerical simulation results. All authors read and approved the final manuscript.

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Availability of data and materials

The data that support the findings of this study are available upon reasonable request to T.M. (email: miyagoshi@jamstec.go.jp).
The numerical code ACuTEMan is available upon request to M.K. (email: kameyama@sci.ehime-u.ac.jp).

Competing interests

The authors declare no competing interests.

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