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A three-dimensional numerical model of tectonic plates that develop due to a stress-history dependent rheology

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Model description

We present a self-consistent numerical model of tectonic plates in convecting mantle modeled by an internally heated 3D rectangular box that is cooled from the surface. The viscosity strongly depends on the temperature T, and the lithosphere develops along the surface boundary as a layer of a highly viscous fluid. The viscosity also depends on stress-history in the lithosphere: When the stress σ is sufficiently low (the point A in Fig. 1), the viscosity takes a high value for plate interiors. As σ increases and exceeds a threshold σ_p that corresponds to the rupture strength of the lithosphere, the viscosity drops to a low value for plate margins. When σ is decreased below σ_p, the viscosity remains low provided that $\sigma > \sigma_m$ holds, where σ_m ($< \sigma_p$) is the coupling strength at plate margins (the point A'). The viscosity is a two-valued function of σ in the stress range between σ_m and σ_p, and which of the branches a lithospheric material chooses is determined by whether or not the material has experienced stress σ higher than σ_p in the past. This stress-history dependence of the viscosity induces the plate-like regime of the lithosphere shown in Figs. 2 and 3.

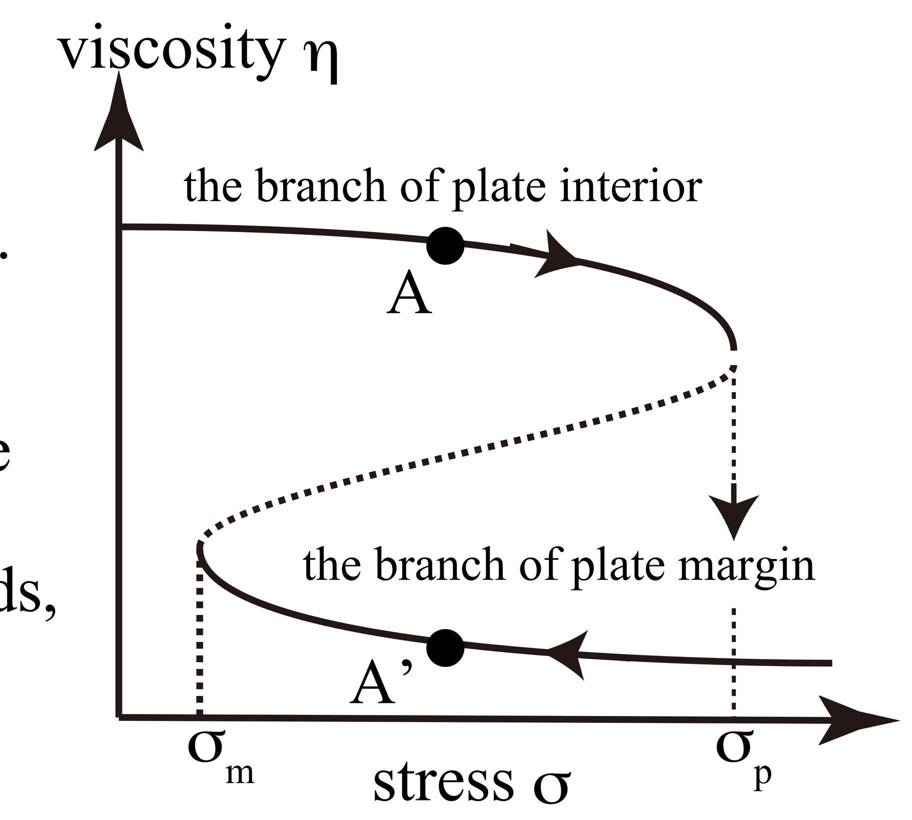

Fig. 1

Snapshots of the calculated plate motion

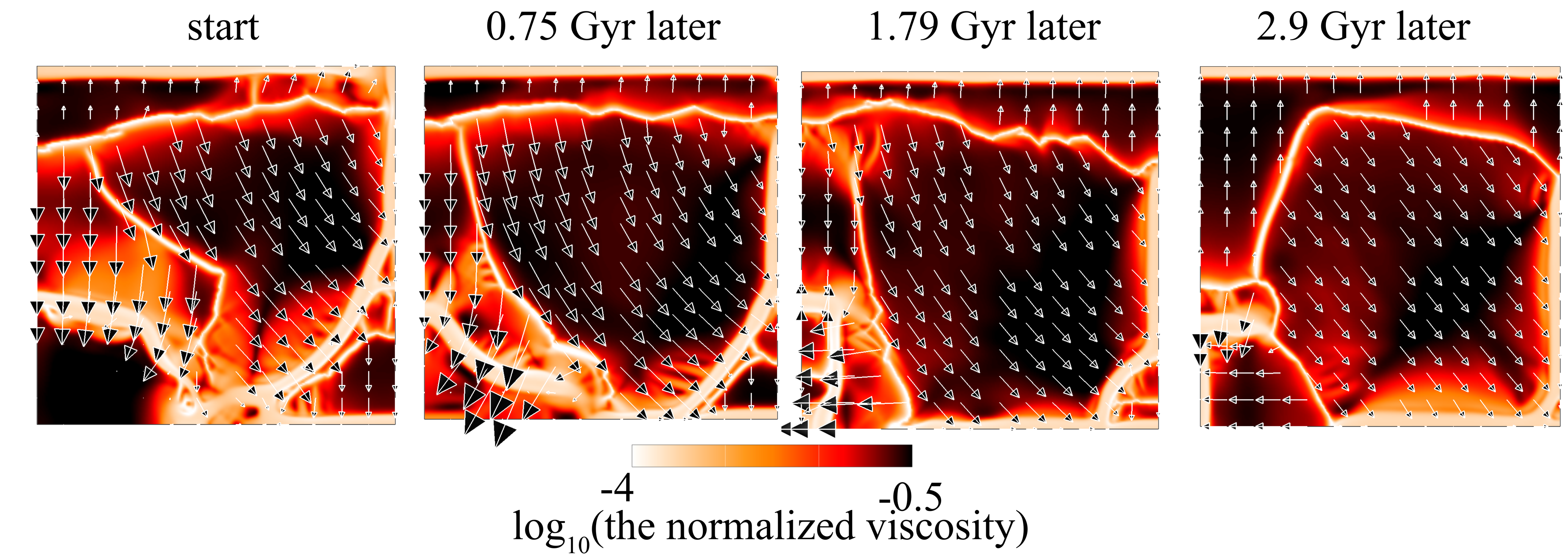

Fig. 3. Several highly viscous domains in the lithosphere, or plates, are separated by soft and narrow plate margins. The plates stably move, and the plate margins persist for billions of years.

A typical flow pattern of convection in the plate-like regime

Fig. 2. (a) A convection with tectonic plates occurs in a 3D rectangular box. (b) The vertical component of the vorticity (rot $\boldsymbol{U}$)$_z$ takes a large value at the narrow plate margins. (c) The heat flow decreases with increaing distance from the spreading center in its vicinity, but becomes flattened out away from the centers owing to the secondary convection shown in (d). (d) The distribution of the vertical component of the velocity U_z on a horizontal plane shows that a secondary convection occurs in the form of two-dimensional rolls with their axes aligned in the direction of the plate motion beneath the older part of a plate.