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Yield Stress of Plate Boundary and Viscosity of Asthenosphere: Constraints from Plate Spin Motion

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Although more than 40 years have passed since the advent of plate tectonics and some essential problems remain unresolved, such as the generation of plate tectonics from mantle convection, the recent progress in theoretical studies has revealed several important factors to generate plate tectonics, in particular importance of the rheological properties of lithosphere and asthenosphere (e.g., Solomatov and Moresi, 1996; Tackley, 2000; Bercovici, 2003). While numerical simulations quantitatively estimate the rheological properties necessary for generating plate tectonics (e.g., Solomatov and Moresi, 1997; Tackley, 2000; Richards et al., 2001), it is difficult to verify the result from the observational data. In this study, by analyzing the spin motion of the plates comprehensively, we have successfully obtained the relationship between yielding stress of lithosphere and viscosity of asthenosphere, in which dynamic equilibrium of spin motion and the plate size are key as will be explained below.

First, we divide observed plate motions into two components: spin motions and straight motions. For plates without a slab, spin motion of a plate is a result of dynamic equilibrium between the driving force from neighboring plates via the plate boundary associated with shear stress and the resistive force of mantle drag via the bottom area associated with flow and viscosity of asthenosphere. Consequently, we have found that the small plates, or microplates, rotate relatively fast and the large major plates rotate much slower, indicating that there is a critical size between the small plates and the large ones at which plate boundary cannot transmit the motions from one plate to another because shear stress increases with the plate size and accordingly exceeds the yielding stress along the plate boundary. Our analysis suggests a critical diameter (scale or size) of 1000 km, above which spin motion suddenly drops.

For the equation of dynamic equilibrium in spin motion of a plate 1000 km in diameter, using the yielding stress obtained by a numerical simulation, about 10 ˜ 200 MPa (Tackley, 2000), we obtain a reasonable range of viscosity of asthenosphere, approximately 1 x 10ˆ19 ˜ 1 x 10ˆ21 Pa s, which means that the observational constraint is consistent with the results from numerical simulations for generation of plate tectonics. Note that the yielding stress given by numerical simulations represents the critical stress to deform an intact part of lithosphere instantaneously, rather than a part of the former plate boundary; therefore, we should use the lower value of yielding stress for our theory, which leads to the soft asthenosphere, e.g., 1 x 10ˆ19 ˜ 1 x 10ˆ20 Pa s, and implies a mechanism to soften mantle just below the plates, such as melting, as suggested by some authors (e.g., Kawakatsu et al., 2009).

For future works, in order to clarify the nonlinear mechanism to soften lithospheric boundaries, including the effect of grain size and water, a comparative study to investigate the difference between the boundary along a small plate, where plate motion transmits linearly, and that along a large plate, where softening occurs, will be useful to understand the origin of plate tectonics.

Keywords: plate tectonics, plate boundary, asthenosphere, viscosity, rheology, plate spin motion