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Plate tectonics simulations using reduced viscosity contrasts – The simple approach?

L. Noack and D. Breuer
DLR, German Aerospace Center, Institut für Planetenforschung, Germany (lena.noack@dlr.de)

In the last decades, more and more studies focussed on the simulation of plate tectonics for Earth and other terrestrial planets inside and outside the solar system. But only the recent development of new robust codes (e.g. GAIA [1] or RHEA [2]) and the usage of super-computers shifted the investigation of planetary mantles into more realistic regimes.

One of the problems that many codes still cannot handle is the large viscosity contrast (global or local cell-to-cell contrasts) expected for terrestrial planets and the viscosity is typically simplified [3]. On Earth, the expected contrast varies with 10 or more orders of magnitude. On planets with higher mantle temperatures (e.g. as can be expected for young super-Earths), this viscosity contrast may be even higher with steeper viscosity gradients at the lower boundary of the lithosphere.

To solve this problem one can either use a larger nondimensional surface temperature in the Arrhenius viscosity law (or analogously a smaller activation energy) or linearize the exponent of the viscosity, leading to the so-called Frank-Kamenetskii approximation. Several codes use one of these two approximations to be able to simulate terrestrial planets and try to investigate the trend of the likeliness of processes like plate tectonics, depending on factors as surface temperature, internal heating, or mantle thickness.

However, our findings propose that the trends observed with these viscosity approximations differ from the ones obtained with the Newtonian Arrhenius law. The first observation is that the approximations lead more easily to plate tectonics than the Arrhenius law. In addition, the dependence of the critical yield stress (i.e. where the transition from plate-tectonics regime to stagnant-lid regime takes place) on the Rayleigh number strongly differs, and the plate tectonics regime is much more easily obtained than for the Arrhenius viscosity. The difference increases with planetary radius.

Note, that a more realistic rheology using a mixed Newtonian/non-Newtonian viscosity law including an elastic surface regime is expected to further differ from the Newtonian Arrhenius law.

References

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[2] G. Stadler et al. (2010), Science, 329(5995), 1033-1038.
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