CONSTRAINTS ON LITHOSPHERIC STRESSES AND SUBDUCTION INITIATION FROM STEADY-STATE CONVECTION: APPLICATION TO TERRESTRIAL PLANETS.

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Introduction: The initiation of subduction is extremely difficult due to the high strength of the lithosphere and is believed to be the major issue in the origin of plate tectonics [1]. Subduction initiation on the Earth is caused not only by the negative buoyancy of the lithosphere but also by the forces associated with plate movements already occurring elsewhere with weak zones favoring motions [2]. However for a one-plate planet, the very first episode of lid mobilization has to be caused by forces other than plate motions.

Sublithospheric convection has been proposed as a potential mechanism to cause lid failure [3, 4]. The stresses generated by convection may be sufficient to cause deformation in the lithosphere such that it becomes unstable and subducts. We investigate this mechanism and estimate the largest possible yield stress that the lithosphere should possess for lithospheric failure to occur.

Planetary mantles are likely to be multi-cell time-dependent convective systems which are more difficult to analyze and computationally challenging to study. Here we analyze steady-state solutions in single cells, which can be considered as part of the multi-cell system. The single-cell flow allows us a better control of convective solutions and a relatively simple analysis. We then apply our steady-state results to predict the critical yield stress for strongly time-dependent convection, and scale it to terrestrial planets to evaluate the possibility of plate tectonics on these planets.

Steady-state solutions: To initiate subduction from a stagnant lid, we consider the range of parameters in which convection is in the stagnant lid regime. We use the finite element code CITCOM to simulate convection in a box with 64*a* x 64 mesh, where *a* is the aspect ratio.

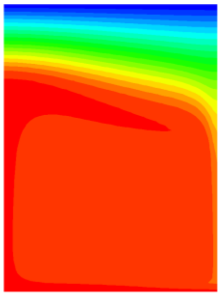

Fig. 1. Thermal structure of a convective cell in steady state.

The temperature field in Fig. 1 shows that the base of the thermal lithosphere has a slope dipping towards the downwelling end of the cell. The slope may be providing the gravitational pull that causes instability.

A very high stress layer close to the surface is developed under free-slip boundary condition (Fig. 2, top left). When a yield stress is present, this surface stress boundary layer will be the first to reach the yield stress, and the yielded (plastic) zone would develop from here.

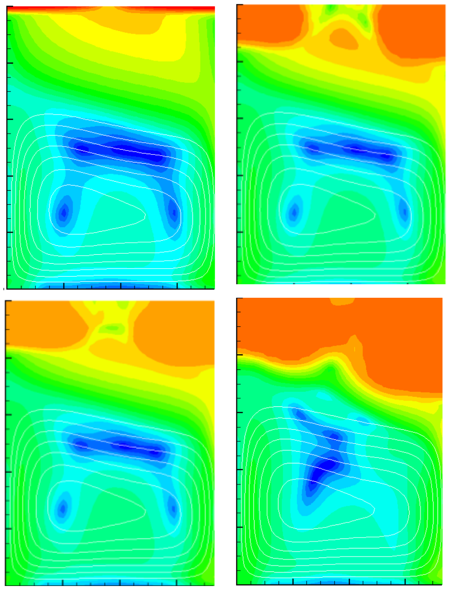

Fig. 2. Stress fields with infinitely large yield stress (top left), higher yield stress (top right), and lower yield stress (bottom left) imposed on the steady-state solutions. Bottom right figure shows the snapshot just before subduction, with the same yield stress as the bottom left figure.

Convection with yield stress: To simulate brittle failure of the lithosphere, we use a pseudoplastic rheology with a yield stress that can be defined by Byerlee's law: $\tau_y = \tau_0 + \tau' z$, where τ_0 is the cohesion and $\tau' = \mu\rho g$ is the yield stress gradient. Plastic yielding occurs when convective stresses exceed the yield value.

Critical yield stress. If the yield stress is small, it can be easily overcome and the lid can be substantially weakened and mobilized. The critical yield stress is defined as the largest possible yield stress that lid mobilization can still occur. The critical yield stress and the critical yield stress gradient can be parameterized in terms of Ra, *a*, and the Frank-Kamenetskii parameter which represent the viscosity contrast. We obtain preliminary scaling relations in this parameterization.

Time-dependent convection: To test the applicability of our scaling relationships to convection in larger aspect ratios and higher Rayleigh numbers at which the flow is strongly time-dependent, we apply our numerically obtained scaling law to estimate a critical

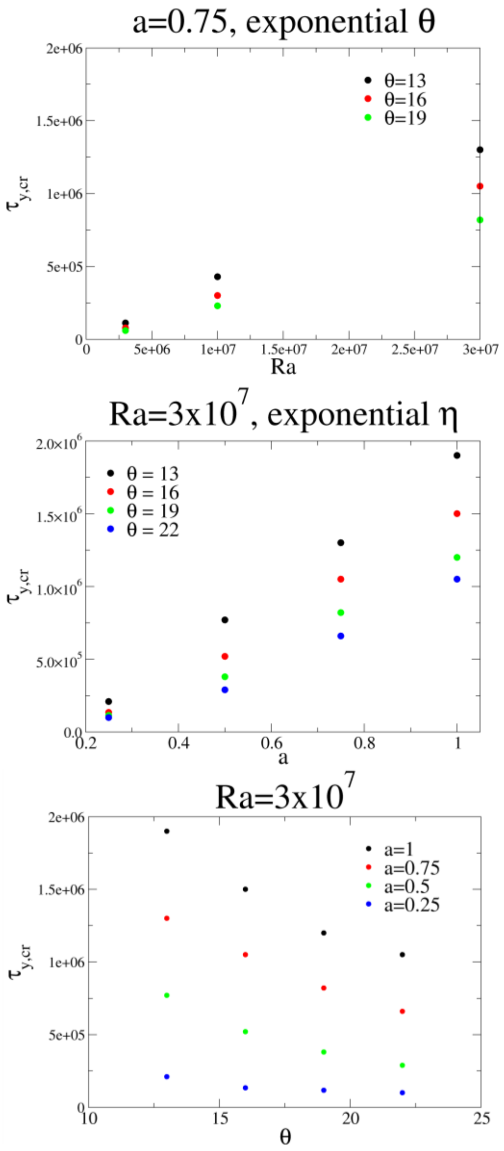

Fig. 3. Critical yield stress as a function of Ra (top), aspect ratio (middle), and Frank-Kamenetskii parameter (bottom).

yield stress for a range of cases in a 4x1 box with 512x128 resolution. Steady-state scaling relations suggest that the larger cells have higher critical yield stresses. Therefore in a long convective box with various sizes of sub-cells, the largest of them may be the first to become unstable and subduct (Fig. 4).

In strongly time-dependent convection, even if the lid stresses are not high enough to cause subduction right away, the convective cells may evolve to a configuration in which the lid stresses become sufficiently high to overcome the yield stress. The timing of mobilization may be a stochastic property that depends on initial conditions (Fig. 5).

Discussion: We apply our scaling laws to Earth, Venus, Mars, and Mercury. Our preliminary calculations suggest larger critical yield stresses and critical yield stress gradients than previous studies [4]. This may be due to the uncertainty in aspect ratio scalings. Further analysis on the variation of stresses in the lid has to be conducted to understand the mechanisms that affect the magnitude of critical yield stress.

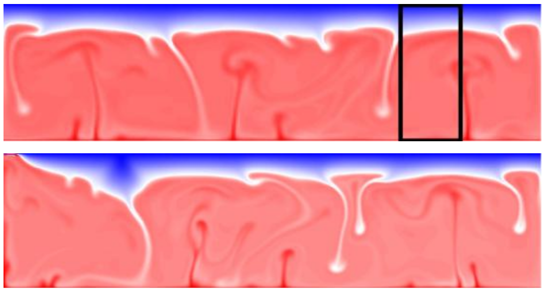

Fig. 4. A large convective cell tends to subdivide into smaller but more stable sub-cells which vary in size. Lower picture shows the snapshot right before subduction.

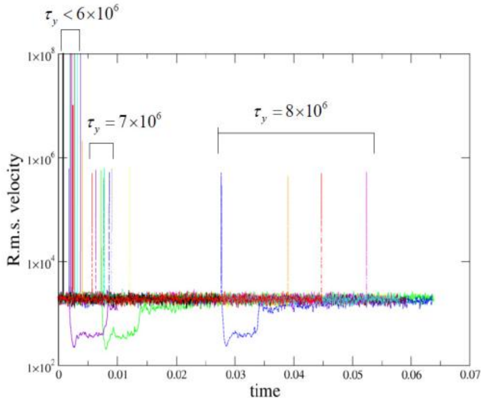

Fig. 5. Time of yielding with different yield stresses in cases with the same parameters but slightly different initial conditions corresponding to different time moments of the fluctuating convective system in a statistical equilibrium. The spikes in r.m.s. velocity represent the event of lid mobilization.

To obtain more robust scaling relations of critical yield stress, we have to study the stress structures with imposed yield stress to define the depth of plastic zone and to find a criterion for the lid to become unstable. A statistical study of yield stress and time of lid mobilization will be useful in defining a yield criterion for time-dependent convection.

The interpretation of the lithospheric strength in terms of yield stress is a simplification of the complex mechanics of lithospheric failure. In the future, it would be interesting to investigate the connections between the yield stress approach and other approaches such as those based on the damage theory [5].

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