Timing of plate tectonics initiation on a one-plate planet: Insights from numerical simulations of time-dependent convection

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How was the question of subduction initiation studied?

A lot of studies aimed to understand whether plate tectonics could happen, but they did not investigate the timing of plate tectonics initiation – *When does plate tectonics start under favorable conditions?*

The initial conditions and the evolution of the convection system may render the event of subduction initiation a random outcome.
What controls subduction initiation?

Two approaches to obtain scaling laws for subduction initiation:

1. Fix yield stress
2. Find parameters of convective system to start subduction

3. Find the yield stress (critical yield stress) at which subduction begins
4. Fix parameters of convective system
What controls subduction initiation?

Scaling relation for critical yield stress \((\text{Wong and Solomatov, 2015})\)

\[
\tau_{y,cr} \sim 2\alpha \rho g \left( \frac{E}{RT_i} \right)^{-1} \Delta T^{-0.03} \delta_0^{-0.4} l_{\text{hor}}^{1.8} d^{-0.4}
\]

Critical yield stress of the lithosphere may be higher than previously predicted as a result of random initial conditions and random changes in convective cell width.
Dynamics of time-dependent convection

- Changes in the dynamics of time-dependent convection are **random**
- Cell width varies with time
- Widest cell may initiate subduction
Dynamics of time-dependent convection

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Lid thickness evolution

Variation in lid structure is slow compared to the motions in the interior
Different lid structure from different initial states

Statistically steady-state convective solutions resulting from different initial conditions are slightly different.

For example, average lid thickness is slightly different among the solutions.
Time of subduction initiation

\[ \tau_y = 0.086 \]

\[ \text{Ra} = 3 \times 10^8, \quad \eta = \exp(-18.4T) \]
Time of subduction initiation

![Graph showing time of mobilization vs. τy]
Time of subduction initiation
Simulations are not long enough yet to determine at which yield stress the time of mobilization would be infinite (i.e., no subduction)
What controls the time of subduction initiation in a single cell?

\[ t = A \exp(B\tau_y) \]
What controls the time of subduction initiation in a single cell?

\[ t \sim \frac{\eta_{\text{eff}}}{\Delta \rho g \delta_{\text{lid}}} \]

\[ \tilde{t} \sim \frac{\Delta \eta}{R a_i \delta_{\text{lid}}} \]

\[ \Delta \eta \sim \exp[\theta(T_i - T_{\eta_{\text{eff}}})] \]

\[ \sim \exp \theta \left[ -\frac{dT}{dy} (\delta_{\text{lid}} - \delta_{\eta_{\text{eff}}}) \right] \]

\[ \sim A \exp B \tau_y \]
Subduction initiation – a random outcome?

- Random initial conditions
- Evolution of width of cells
- Subduction?
Conclusions

• An important question is how long does it take for plate tectonics to start under favorable conditions.

• The timing of plate tectonics initiation might be a random outcome of mantle convection, controlled by initial conditions and cell evolution.

• For a planet that has vigorous convection, plate tectonics may emerge either early, late or never in planetary history depending on the its early state and evolution.

• For the Earth, the yield stress has to be as low as \(~10\) MPa to reduce the viscosity contrast to at most \(~10^5\) to have plate tectonics initiated within its lifetime.