Exploring the Onset of Plate Tectonics on Terrestrial Planets Using Grain-Damage

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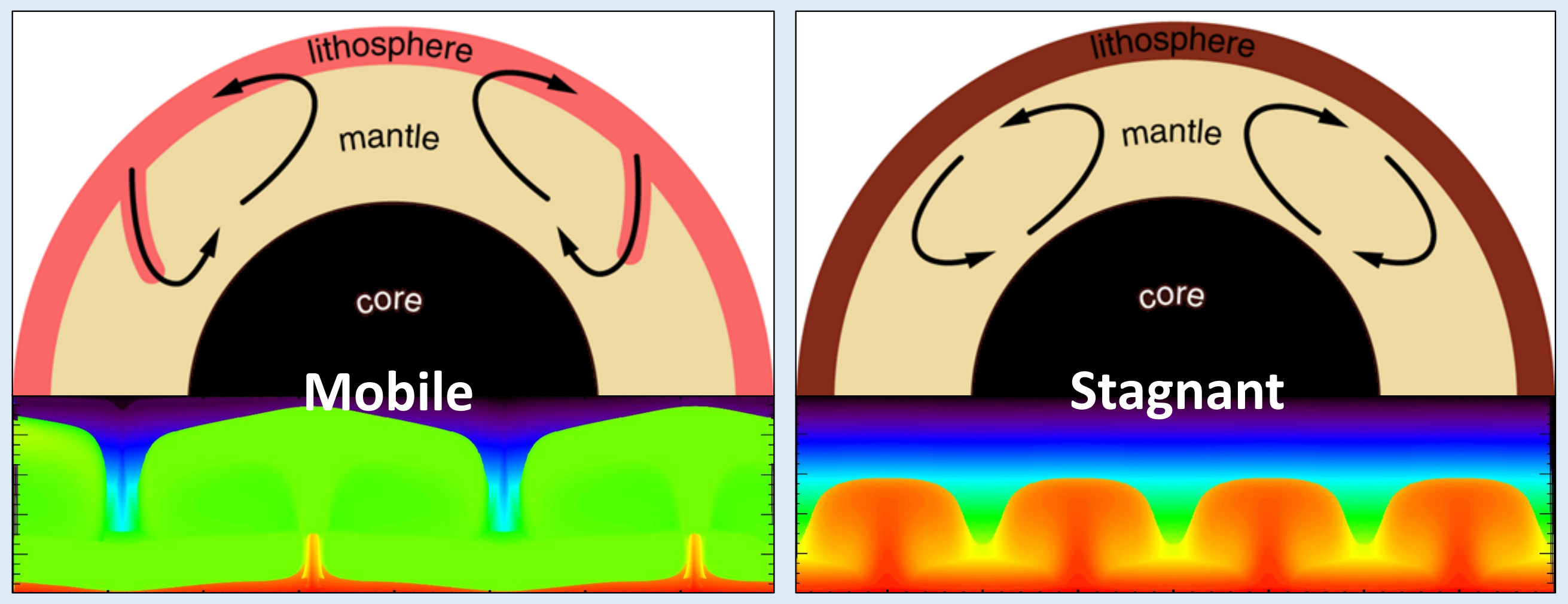
Introduction

One of the most important questions involving the recently discovered rocky exoplanets is whether they maintain the conditions that could potentially support life. Determining whether exoplanets have plate tectonics is an important aspect of assessing whether they could support life, since a mobile lid plays a critical role in buffering atmospheric CO_2 through the negative feedbacks involved in the carbonate-silicate cycle. Although stagnant lid planets may also be able to sustain a carbonate-silicate cycle that regulates their climate, planets with a mobile lid can likely sustain this cycle for longer periods of time and over a wider range of conditions.

Mobile vs. Stagnant Lids



For both mobile and stagnant lids, top) cartoons of the two modes of mantle convection from Katato & Barbot 2018, and bottom) temperature fields from two models with different viscosity activation energies. Mobile lids lead to a substantial exchange of material between the planet surface and interior, which is likely a key in maintaining a habitable world.

Although planets with stagnant lids might be able to regulate their climates, mobile lids likely sustain the carbonate-silicate cycle for longer.

Plate tectonics from a stagnant lid

On Earth, plate tectonics arises from shear localization in and weakening of a highly viscous lithosphere. However, the mechanism responsible for this weakening and localization is unknown and debated. Most studies employ a pseudoplastic yield stress mechanism, where the lithosphere "breaks" once stresses reach a critical level, the yield stress. However, an alternative mechanism, supported by observations of naturally formed shear zones on Earth, is a grainsize feedback loop, typically referred to as grain-damage.

Damage Theory

Grain-damage relies on a feedback between grain size reduction (DA/Dt) and a grain size dependent viscosity (μ_m). As deformation reduces the grain size, the material weakens, causing more deformation:

$$\frac{DA}{Dt} = D\psi \exp\big(\theta_v(1-T)\big)\, A^{-m} - H \exp(-\theta_h(1-T))\, A^p$$

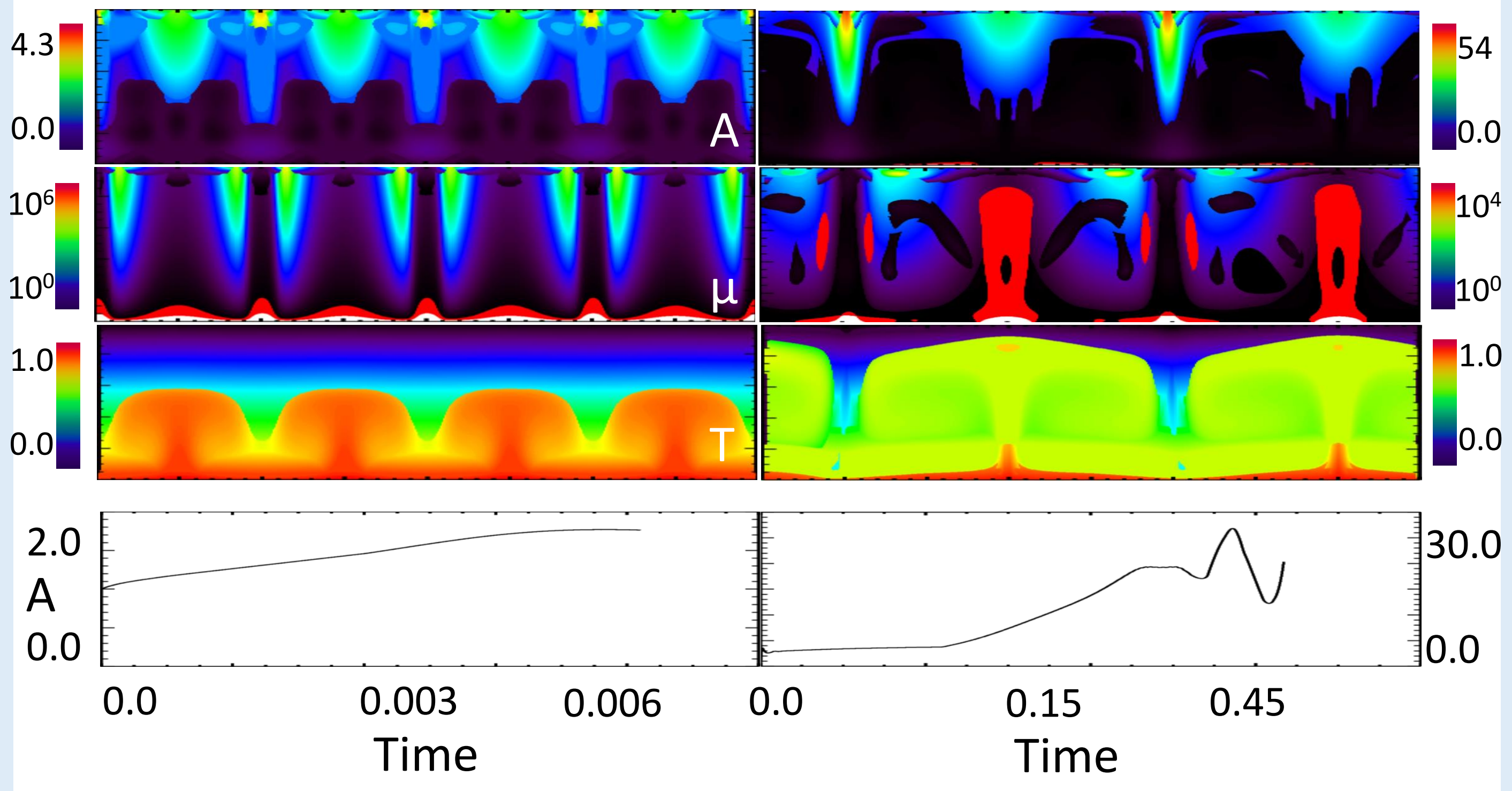
$$\theta = \frac{E\Delta T}{R(T_s + \Delta T)^2} \qquad D = \frac{f\mu_m \kappa}{\gamma A_0 d^2} \qquad H = \frac{h_m A_0^{p-1} d^2}{\kappa}$$

Simulations

- We solve the coupled convection and damage equations using a 2-D Cartesian finite volume
- We use the SIMPLER algorithm to solve the momentum equations and employ a multi-grid method for the diffusion terms in both the momentum equation and the temperature equation
- We perform numerical experiments with a 4 x 1 aspect ratio domain, with a resolution of 512 x 128
- We start all models with stagnant lid convection
- We vary initial Rayleigh number (Ra), damage number (D), viscosity activation energy, and healing activation energy

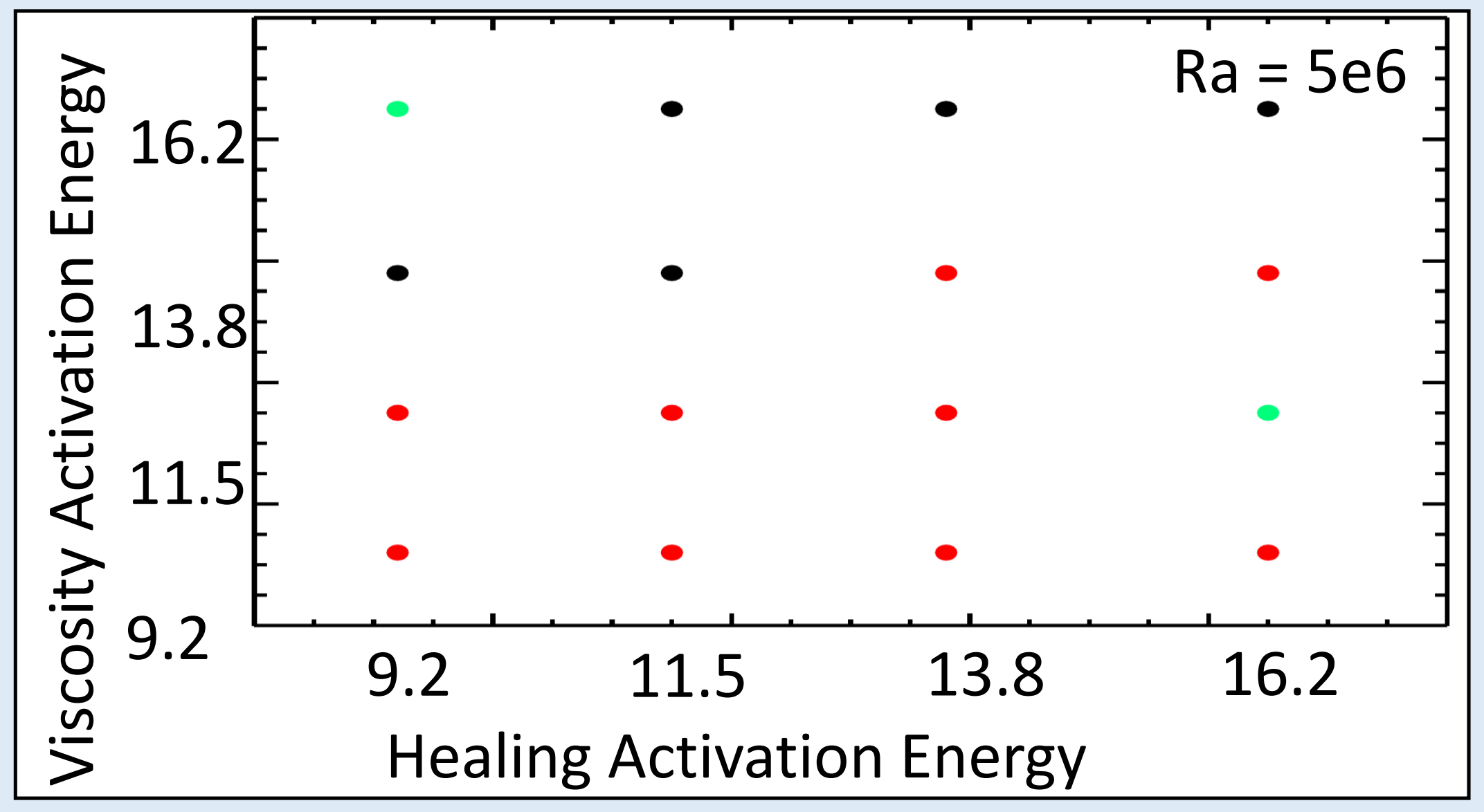
Grain-damage captures both dynamic localization and weak-zone memory, unlike a viscoplastic yield stress rheology which only produces instantaneous shear localization.

Planform of convection for stagnant vs mobile lids



Fineness field (A), viscosity field (μ), temperature field (T), and evolution of maximum fineness in lithosphere for models with stagnant (left) and mobile (right) lids.

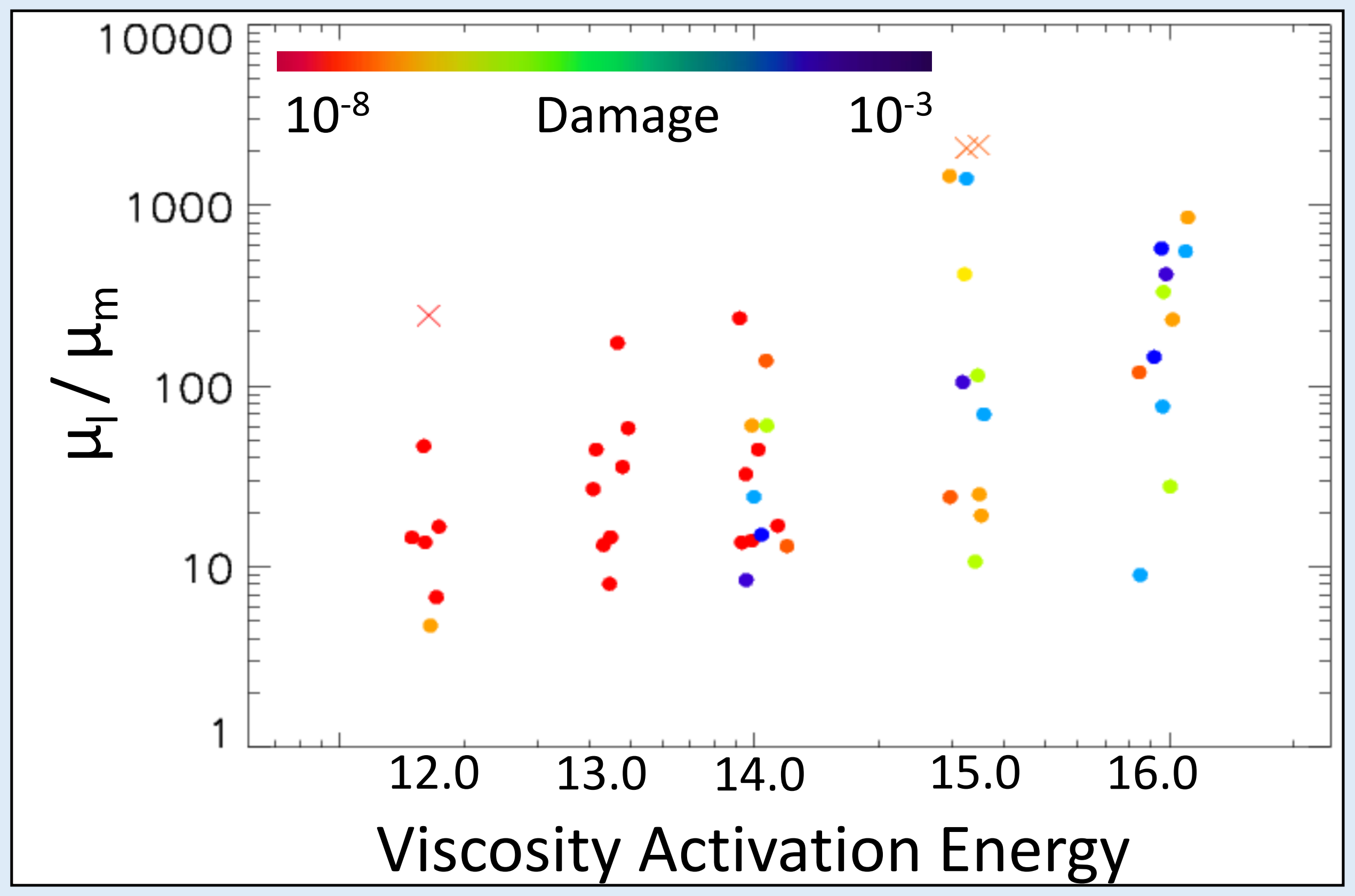
Mobile lids initiate with higher Ra and lower activation energies



Regime diagrams of one ensemble of models with Ra = 5e6 and D = 10^{-4} as function of viscosity and healing activation energies. Black = model remained stagnant, red = model went mobile, green = convection stopped or the solution could not converge.

The transition from stagnant lid to mobile convection occurs for larger viscosity activation energies as healing activation energy increases.

Mobile lids initiate at $\mu_l / \mu_m < 10^4$



The resulting viscosity in lithospheric shear zones scaled by that in the underlying mantle for all models. Circles indicate models that went mobile and crosses indicate models that stayed stagnant. The color indicates the damage number D, where blue models had increasing damage number.

The viscosity ratio between lithospheric shear zones and the underlying mantle must be reduced, via damage, to a critical threshold of ~10^4 for a mobile lid to initiate.

Summary and Conclusions

- We model mantle convection using grain-damage to better understand the transition from a stagnant lid to a mobile, plate-like lid.
- More damage is required for a model to go mobile for larger values of viscosity activation energy.
- Larger values of Ra lead to mobile lid being more likely to initiate.
- Smaller values of viscosity activation energy are required for a model to go mobile with smaller values of healing activation energy.
- The viscosity ratio between lithospheric shear zones and the underlying mantle must be reduced to ~10^4 for a mobile lid to initiate.

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