HEAT TRANSPORT IN THE HADEAN MANTLE: FROM HEAT PIPES TO PLATES. Duminda G. J. Kankanamge[1,2] and William B. Moore[1,2], [1]Department of Atmospheric and Planetary Sciences, Hampton University, Hampton, Virginia, USA (gjkduminda@gmail.com). [2]National Institute of Aerospace, Hampton, Virginia, USA (bill.moore@nianet.org).

Introduction: Plate tectonics is a unique feature of Earth and it plays a major role in transporting Earths internally generated heat. It also governs the nature, shape and the motion of the surface of Earth. The mechanism and the timing of the origin of plate tectonics on Earth has been difficult to establish observationally, therefore it is still an interesting subject, which is still under debate. The internal heat energy of the terrestrial planets was greater in the early stages of their histories than it is today [1].

In order to understand the behavior of the Earth under much higher heating rates, we turn to a contemporary example. Jupiter's moon Io is a rocky body experiencing very high heat production due to tidal dissipation resulting in a surface heat flow roughly 40 times Earth's [2]. Io transports heat from the interior to the surface by melt segregation resulting in extreme volcanism [3, 4], a mode of heat transport called "heat pipes". Recent studies [5] have proposed that, for roughly the first third of Earth's history, heat flow was sufficiently high that Earth's heat-loss and lithospheric dynamics were also dominated by the 'heat pipe' mode. When volcanism dominates the heat transport of a terrestrial body, hot magma moves through the lithosphere in narrow channels to erupt on the surface. Continuous burial of old, cooled flows results in a thick, cold, and strong lithosphere.

In this study, we numerically simulate the heat transport in the pre-plate tectonic Earth to understand the transition from heat pipe mode to plate tectonic behavior. These simplified numerical simulations of the flow of Earth's mantle include heat transport by melting and melt segregation (volcanism), Newtonian temperature-dependent viscosity, and internal heating. We investigate the influence of melt transport on the thermal structure and stresses of the lithosphere vary with initial conditions and yield stress for a given set of solidus function parameters. This report discuss our numerical model, simulation results and discuss how the convective stresses exceed the yield stress of a lithospheric lid producing overturn.

Model: We use STAGYY [6] to solve the equation of mass, momentum, energy and composition conservation for infinite-Prandtl-number Boussinesq flow in a 4×1, two-dimensional domain spanning the depth of the mantle. The system is made dimensionless by using the mantle depth, D, as the length scale, D^2/κ as the thermal diffusion time scale (κ, thermal diffusivity) and D^2H/k as the temperature scale (where H, k are the volumetric heat production rate and the thermal conductivity, receptively). The Newtonian, exponentially temperature-dependent viscosity (η) is used. We model the strength of the lithosphere by using a yield stress σ_y which modifies the constitutive equation as follows:

$$\sigma_{ij} = 2\frac{\sigma_\mathrm{y}^2\eta}{\sigma_\mathrm{y}^2 + \eta^2\dot{\varepsilon}^2}\dot{\varepsilon}_{ij} \equiv 2\eta_\mathrm{eff}\dot{\varepsilon}_{ij}. \quad (1)$$

Here σ_{ij} is stress, $\dot{\varepsilon}_{ij}$ is strain rate, η_eff is an effective viscosity and $\dot{\varepsilon}^2$ is second invariant of the strain rate tensor, and the effect of finite σ_y is to lower the viscosity to maintain an upper limit on the stress.

To keep the dynamics of melting and melt extraction isolated, we take a highly simplified approach to mantle compositional evolution. Composition is assumed to vary between the two end-members basalt and harzburgite. The variable C, which varies from 0 (harzburgite) to 1 (basalt), represents the fraction of basalt at each location. Melting is calculated in each grid cell at each time step. Basaltic melt is generated whenever the mantle exceeds a simple linearly pressure-dependent solidus [7]. Only the basaltic component can melt; once the composition reaches harzburgite, further melting is not permitted. The fraction of partial melt f that brings the temperature back onto the solidus, if sufficient basalt fraction is present. Melt is immediately extracted to the surface, and the column in which the melt was produced is advected downwards to conserve mass.

Results: We first investigate the influence of melt transport on the thermal structure and stress state of the lithosphere. We assume that heat is only produced in-

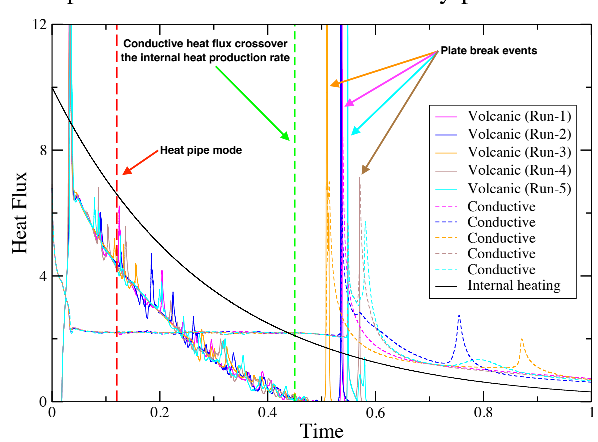

Figure 1: Heat flux as a function of time for Tsol0 = 0.8 and dTsol = 0.4 and $\sigma_\mathrm{y} = 3 \times 10^4$. Surface conductive heat transport (colored dashed) and surface volcanic heat transport (colored solid) are given for the five different initial conditions. The internal heat production rate in terms of an equilibrium surface flux is given by the black solid curve.

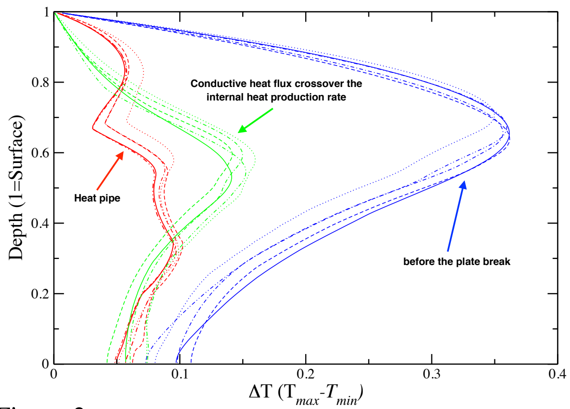

Figure 2: Maximum horizontal temperature difference profiles for heat pipe mode (red), when the conductive heat flow cross over the internal heat production (green) and just before the plate breaks (blue). Solid, dashed, dotted, dotted-dash and dotted-dotted-dashed curves show the results obtained from the five random initial conditions.

ternally and the volumetric heat production rate (H) is exponentially decaying through time from an initial dimensionless value of 10 with a dimensionless half life of 0.2 time units. Figure 1 shows the conductive heat flux, volcanic heat flux and the heat flow in equilibrium with internal heat production for five different initial conditions varying only in the random number seed given to determine the 2% temperature variations imposed at t=0. The system rapidly evolves through an initial transient into the heat pipe mode. During the heat pipe phase (up to about 0.25 time units), internal heat is mainly transported through volcanism, while the lithosphere transports a nearly constant amount of heat. As the heat pipe mode shuts off ($\sim$0.45 time units), internal heat is transported by conduction through the lithosphere. The transition to plate tectonic behavior is abrupt and always occurs after the cessation of heat pipe volcanism when conductive heat flux exceeds the internal heating and the mantle begins to cool. Plate breaks resulting from different initial conditions occur at slightly different times demonstrating that the timing of the plate break is sensitive to the initial conditions and not determined uniquely by the convective parameters.

Figure 2 demonstrates why plate tectonics does not occur during the heat pipe mode. Figure 2 shows the maximum horizontal temperature difference as a function of depth for the three different epochs indicated by vertical lines in Figure 1: In order to initiate plate-like behavior, the strength of lithosphere must be overcome by the convective stress. The convective stress scales with the amplitude of the temperature changes. During the heat-pipe mode, the temperature difference is suppressed by the limiting effect of the solidus, and therefore the buoyancy forces and the convective stresses are not large enough to overcome lithosphere strength. When the conductive heat flux exceeds the internal heat production rate, the temperature difference is greater than that of the heat pipe mode, but the buoyancy force is still not favorable for breaking plates. Finally when the heat pipe mode shuts off, the temperature difference and the buoyancy forces increase so that the convective stresses from the mantle overcome the lithospheric stress and the plate breaks. Figure 3 shows the time evolution of the temperature (left) and stress (right) distributions from heat pipe to plate break for one of the five simulations. The snapshots in the top-left show that, the development of cold and thick lithosphere during the heat pipe mode. Note the very flat isotherms caused by the capping of the temperature distribution by the solidus. Moving from top to bottom as heat-pipes shut off, we see the gradual development of significant slopes on the lithosphere's base until a break occurs. Snapshots in the right column show that the stress in the lid also gradually increases (from top to bottom) until breaking.

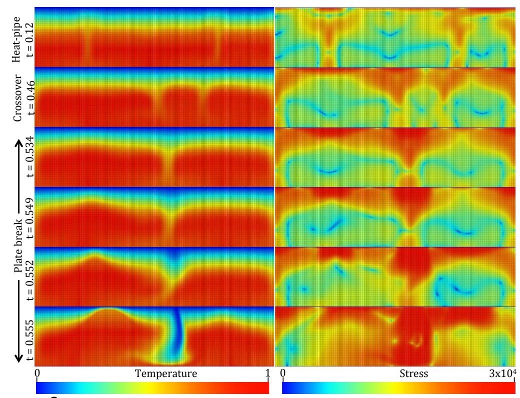

Figure 3: Snapshots of the temperature (left) and the stress fields (right) from heat pipe mode (top) to the plate break (bottom).

Conclusions: Our results demonstrate that heat pipes remove buoyancy from the actively convecting boundary layer at the top of the mantle, reducing convective stresses and therefore suppressing plate tectonics. This explains why Io displays no evidence of plate tectonic behavior despite its very strong internal heating. When the heat pipe mode shuts off, the solidus no longer exerts a dominant effect on the temperature distribution in the upper part of the convecting mantle and the convective stresses increase. Eventually they may overcome the strength of the lithosphere and break the plate, initiating plate tectonic behavior if the scaled yield stress is sufficiently low.

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