THERMAL EVOLUTION OF A ONE-PLATE PLANET WITH STABLE LAYERING IN MANTLE HEATING; INFLUENCE ON TIMING OF VOLCANIC, MAGNETIC, AND TECTONIC ACTIVITY.

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Introduction: Chemical fractionation during a planet's solidification from a magma ocean in its early history can produce heterogeneity in both bulk density and concentration of heat-producing elements (HPE). As a result, heterogeneity in heat production may be stabilized (e.g., by density or viscosity) against mixing over geologic timescales [1,2]. Such heterogeneity has been invoked to explain puzzling aspects of the thermal evolution of the Moon Mars, and Mercury, where final cumulates may sink to the core-mantle boundary and/or remain trapped near the surface [3-7].

We seek to identify the consequences of vertically layered heating with a numerical study of a simplified system, in which either the top or bottom of the mantle may concentrate heating that is stabilized against convection. We evaluate the influence of layering on the timing of the potential for volcanic and magnetic activity, and planetary expansion or contraction.

Methods: As a simple treatment of mantle evolution, we model 2D thermal convection with a Boussinesq approximation in the Stokes limit using Lattice-Boltzmann methods. The core is treated as a constant-temperature energy reservoir under the mantle as in [8]. Mantle physical properties apart from HPE concentration are held constant (e.g. viscosity, thermal diffusivity). In scenarios with a stabilized layer, heat transfer within the layer occurs only by conduction and heating is concentrated in it (zero elsewhere). In the mobile mantle, convective heat transfer is modeled in a rectangular domain with an aspect ratio of 1:8√2. As a simplified representation of a planet's thermal state at the end of magma ocean solidification, the core and mantle begin at a uniform hot temperature. A cold fixed surface temperature is imposed and temperatures and velocities are allowed to evolve for 5 Gy.

Parameter	Values
Rayleigh number, *Ra*	10^4, 10^5, 10^6
Mean initial heating, H_0	2, 4, 6, 8 *10^{-11} W/kg
Heated layer thickness, *d*	1/8, 1/4 system height
Core heat capacity, C_c	0.2 and 2 (normalized by mantle)

Results: In each scenario modeled (see table above), we identified four times to describe the evolution of the planet, illustrated for three reference cases in Figure 1: (A) the onset of mantle convection (first peak in mantle velocity), which provides the conditions for melting through adiabatic transport, (B) the time when the mantle has lost 20% of its initial heat, as a proxy for when the mantle potential temperature might be subsolidus everywhere, (C) the onset of core cooling, representing the earliest possible time of magnetic field generation, and (D) the onset of planetary cooling, as a proxy for the transition from planetary expansion to contraction. We define a window of potential decompression melting from time (A) to time (B); volcanism before (A) is possible but would require an energy source other than advected heat. We then compared this window to the timing of potential for magnetic field generation (C) and/or the transition from expansion to contraction (D). Figure 2 illustrates results from all scenarios, describing the relative timing of whole-planet and core cooling and the window between the onset of convection and a cold mantle in terms of three regimes, where cooling begins before, during, or after the window.

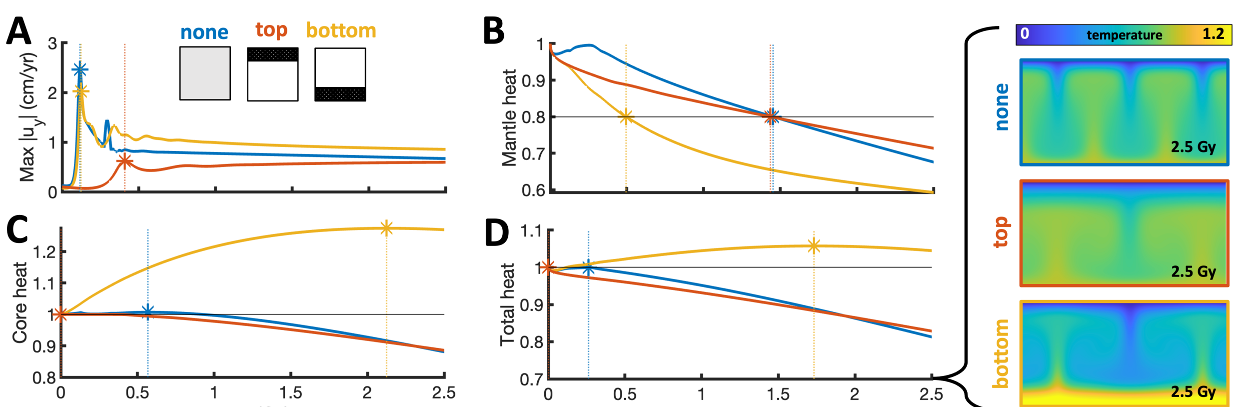

Figure 1. Evolution of mantle velocity (A) and mantle (B), core (C) and total (D) energy (each normalized by initial value) for a trio of reference cases (*Ra*=1e5, H_0=6e-11 W/kg, *d*=75 km, and C_c=2): no stabilized layer (blue) and heating sequestered at the top (red) and bottom (yellow). Right: snapshot of mantle temperature at 2.5 Gy.

As expected, homogenous mantle models produce early and vigorous convection, with the timing and magnitude of core and planet cooling determined by heat production and the mantle viscosity.

Sequestration of HPE at the top of the mantle delays mantle convection by reducing or reversing the driving temperature gradient across the mantle. At the same time, it permits early escape of radiogenic heat by virtue of the proximity of the heat's production to the surface, allowing relatively early cooling of the planet and, if heating is not too strong, the core as well.

A stabilized layer at the bottom of the mantle promotes convective instability and mantle cooling. Moreover, heating in that deep layer delivers energy to both the core and lower mantle. The consequence is that the window for decompression melting is very short in all but the most strongly heated, low-Ra cases. With moderate to strong heat production, simulations with deep heating exhibit a period of core and planet warming; the effect is more pronounced with a large core, whereas the mantle's early convective history is less affected by core size, leading to 1) the delay of cooling (as in [7]) until after the window of hot mantle convection for large cores, 2) but the onset of cooling during the window for small cores.

Discussion/conclusions: We infer the implications of our results for the interaction of observable geologic processes, with the caveat that real planetary histories may depart from predictions if a neglected process (e.g., stagnant lid development, heat piping) has a dominant effect. Unlike a **homogenous mantle**, for which our models predict that the onset of global contraction and magnetic field generation should occur during the volcanically active period, layering of heating results in a much wider variety of timing.

Our results suggest that in a planet with **HPE sequestered at the bottom of the mantle**, volcanism can be active early and begin in a state of lithospheric extension, with the transition to compression and the onset of magnetic field generation occuring during or after the volcanically active period, depending on the core size. If instead, **HPE are sequestered at the top of the mantle**, limited initial expansion and an early transition to contraction is expected. Decompression melting could be very delayed and would primarily occur in a state of lithospheric compression. Earlier volcanism would be possible if radiogenic heat could provide the energy necessary for melting instead, but the spatial distribution of melt generation could differ from convection-driven melting. An interesting extension of this work will be to predict the spatial and temporal planform of melt generation for comparison to observed volcanic deposits.

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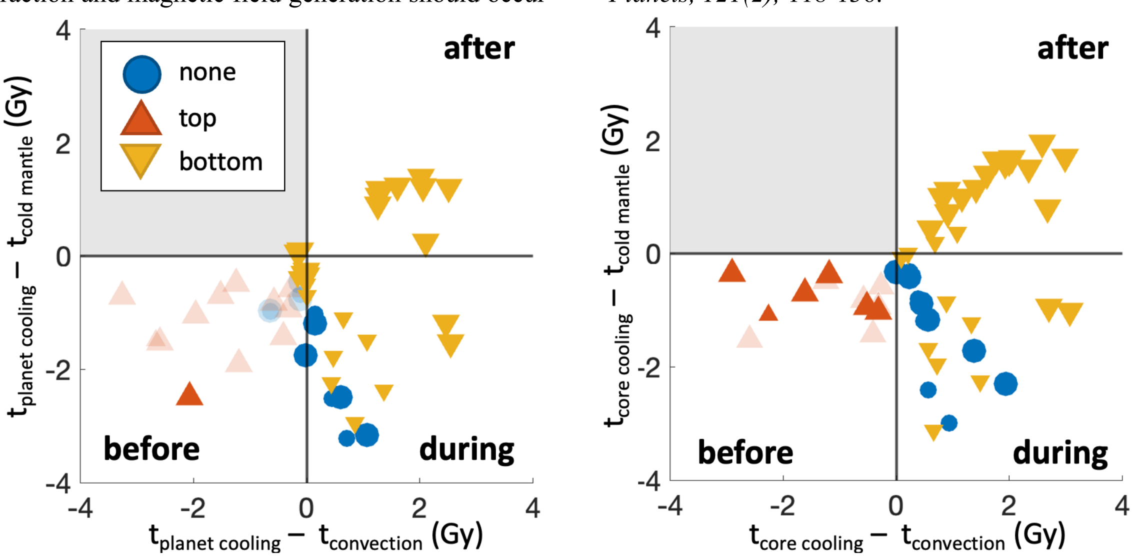

Figure 2. Relative timing of the window of potential for mantle melting (between the onset of convection and the mantle becoming too cold) and the onset of (left) planet cooling or (right) core cooling. The onset of cooling may be before, during, or after the window. Each symbol indicates one model; marker size indicates C_c and faded markers indicate runs where there is never warming, only cooling. Mantle configuration controls relative timing.