



# Penetrative Convection in Earth's Mantle: A Test Using Whole-Earth Geochemical Models

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## Abstract

The nature of mantle convection within the Earth remains one of the most important unanswered questions regarding Earth evolution. Two competing theories have been proposed; one backed primarily by geochemists invoking two separately convecting homogeneous upper and lower reservoirs, and the other backed primarily by geophysicists invoking a single incompletely stirred reservoir. The recently proposed Penetrative Convection Model offers a reconciliation of the two perspectives and is consistent with the first-order constraints provided by geochemists and geophysicists. The model suggests that the phase change occurring at 670 km depth serves to prevent some sinking slabs from mixing into the lower reservoir, but allows others to cross through the barrier and descend to the D" layer at the bottom of the mantle. Here we present whole-Earth geochemical models that apply the dynamics of the Penetrative Convection Model and follow the geochemical evolution of the upper and lower mantles. We constrain the amount of mixing that is required to develop the geochemical signatures observed in the two reservoirs today, and in particular, we show that the Penetrative Convection Model is consistent with observed geochemical variations seen in mantle-derived magmas around the globe.

## Introduction

Geochemists and geophysicists have long held a divided view of mantle circulation. Noting that the distribution of long-lived radioactive isotopes in mantle-derived samples indicate that several global mantle reservoirs have remained isolated from one another throughout much of Earth history, geochemists argued that the upper mantle and lower mantle are compositionally distinct and convect independently with little exchange of matter between them [e.g., DePaolo and Wasserburg, 1975; Hofmann, 1997]. The sharp seismic discontinuity at 660 km provided a likely candidate for a boundary between the two reservoirs because the thermodynamics of the phase change occurring at that depth offered a natural mechanism for inducing convective layering [Ringwood, 1969; Christensen and Yuen, 1984].

In contrast, geophysicists used seismic techniques to show that some down-going slabs penetrate the 660 km discontinuity [e.g., van der Hilst et al., 1997] and generally hold that convection in the mantle is single-celled and involves circulation that spans the entire silicate interior [e.g., Davies, 1984]. This view is supported by dynamic models of layered mantle convection that predicted a sizeable thermal boundary layer should exist between two stratified reservoirs, although no evidence for such a phenomenon is observed in seismic studies or as gravity and geoid anomalies. These dynamic models have challenged geochemical conceptualizations of mantle convection; indeed, the inability of geochemists to confront this challenge has left the status of the layered convection model in peril [Hofmann, 2003].

Here, we test a new model of mantle convection that incorporates aspects of both the geochemist's 'layered' and the geophysicist's 'whole-mantle' convection regimes. The model, termed 'Penetrative Convection' views the endothermic phase change at 670 km depth as filter for slab penetration, in which some slabs penetrate and others do not (depending on their thermal histories). The model considers elemental fractionation involved in the formation of both oceanic and continental crust, and seeks to match the chemical 'fingerprint' of magmas currently observed at spreading centers (that tap the upper mantle) and at hotspots (that tap plumes from D").

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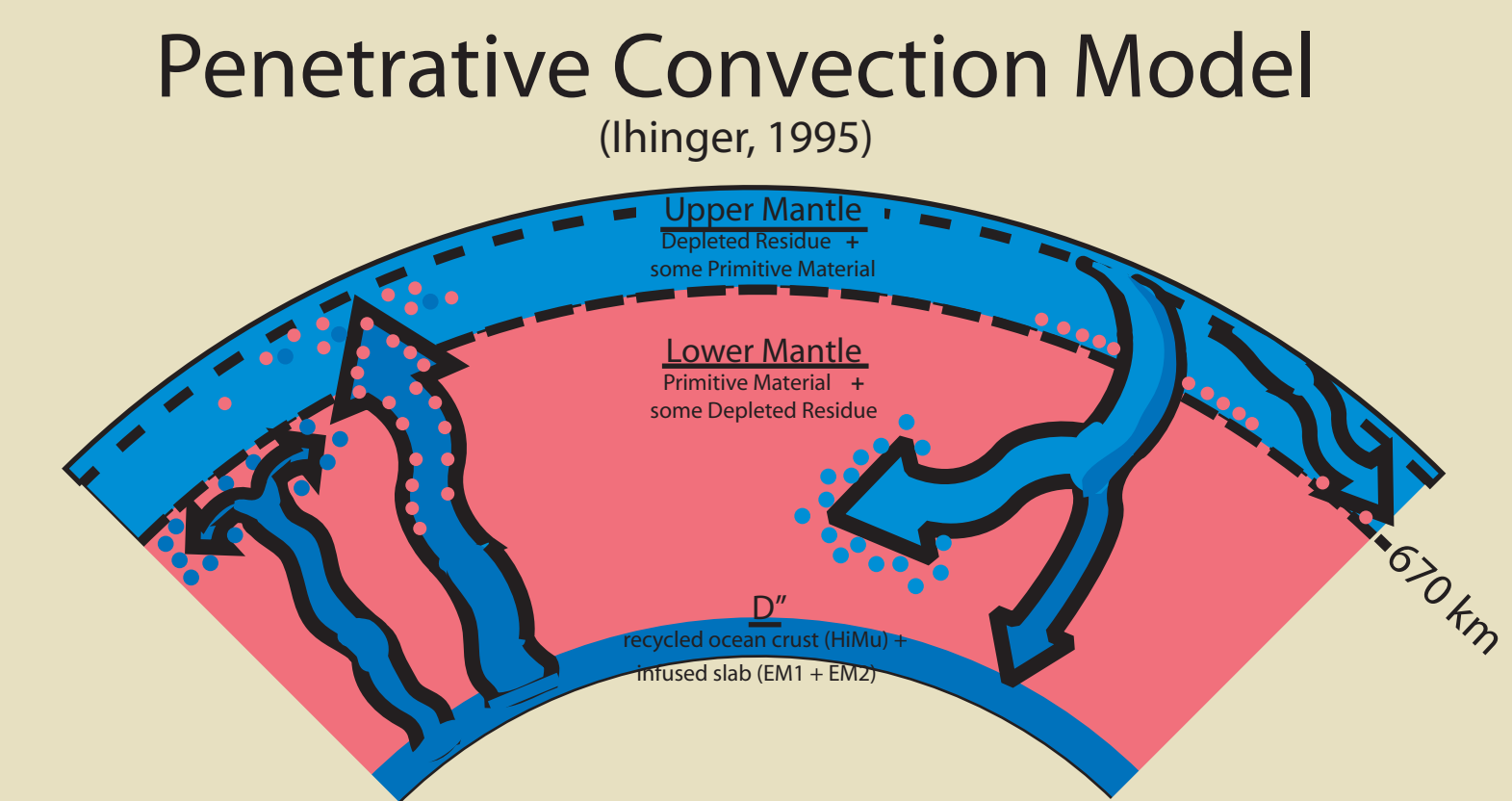
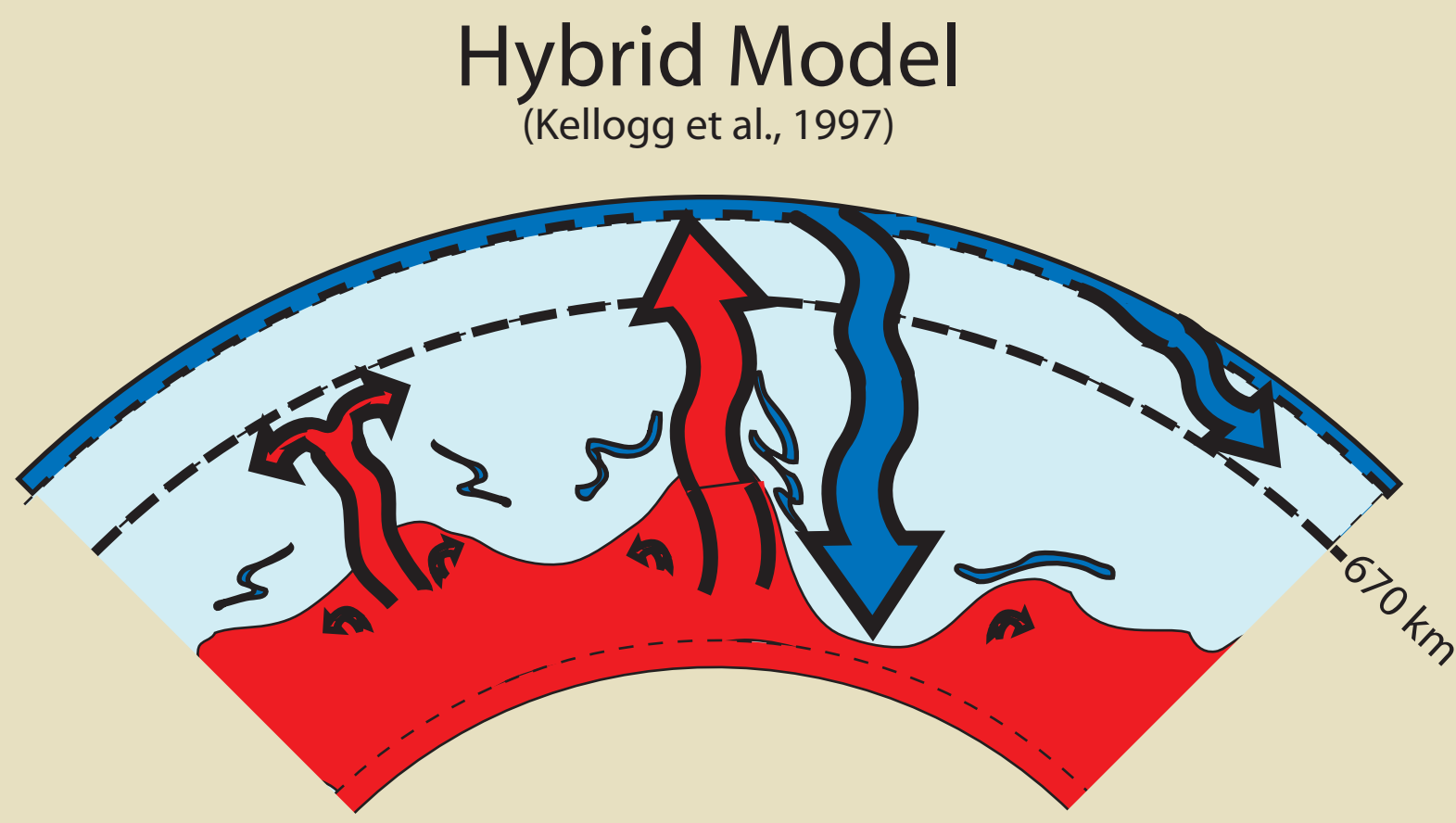
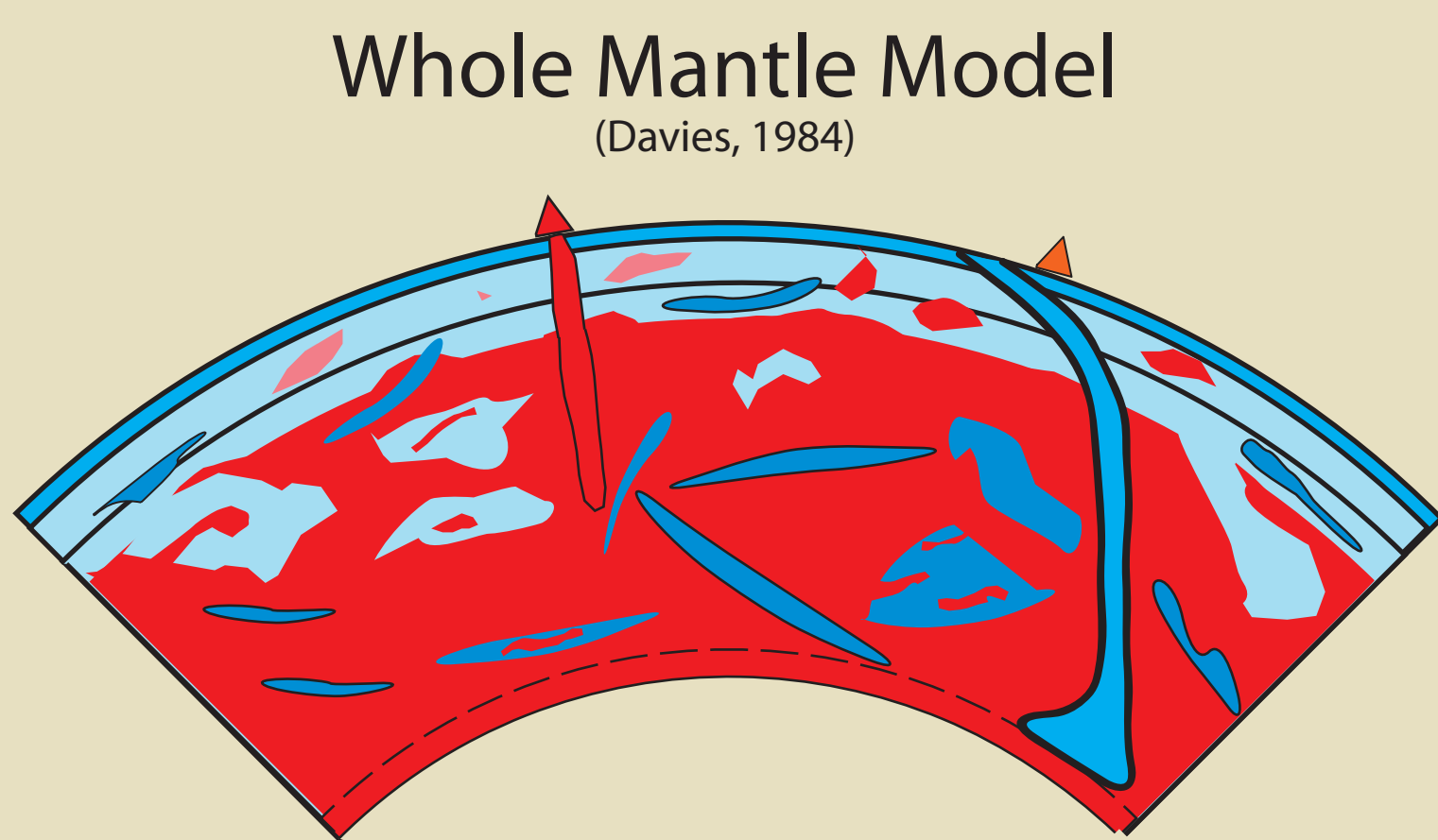
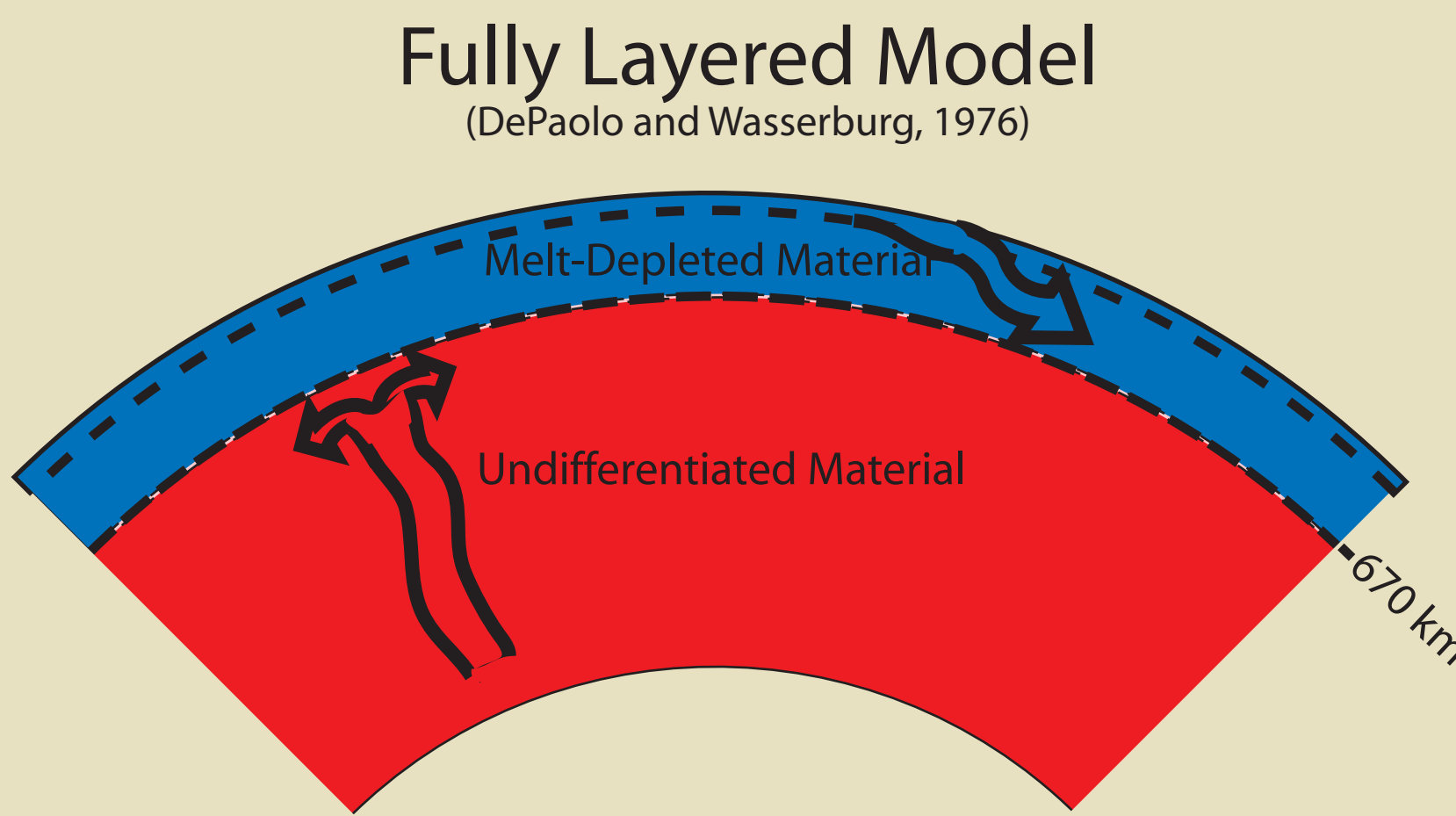
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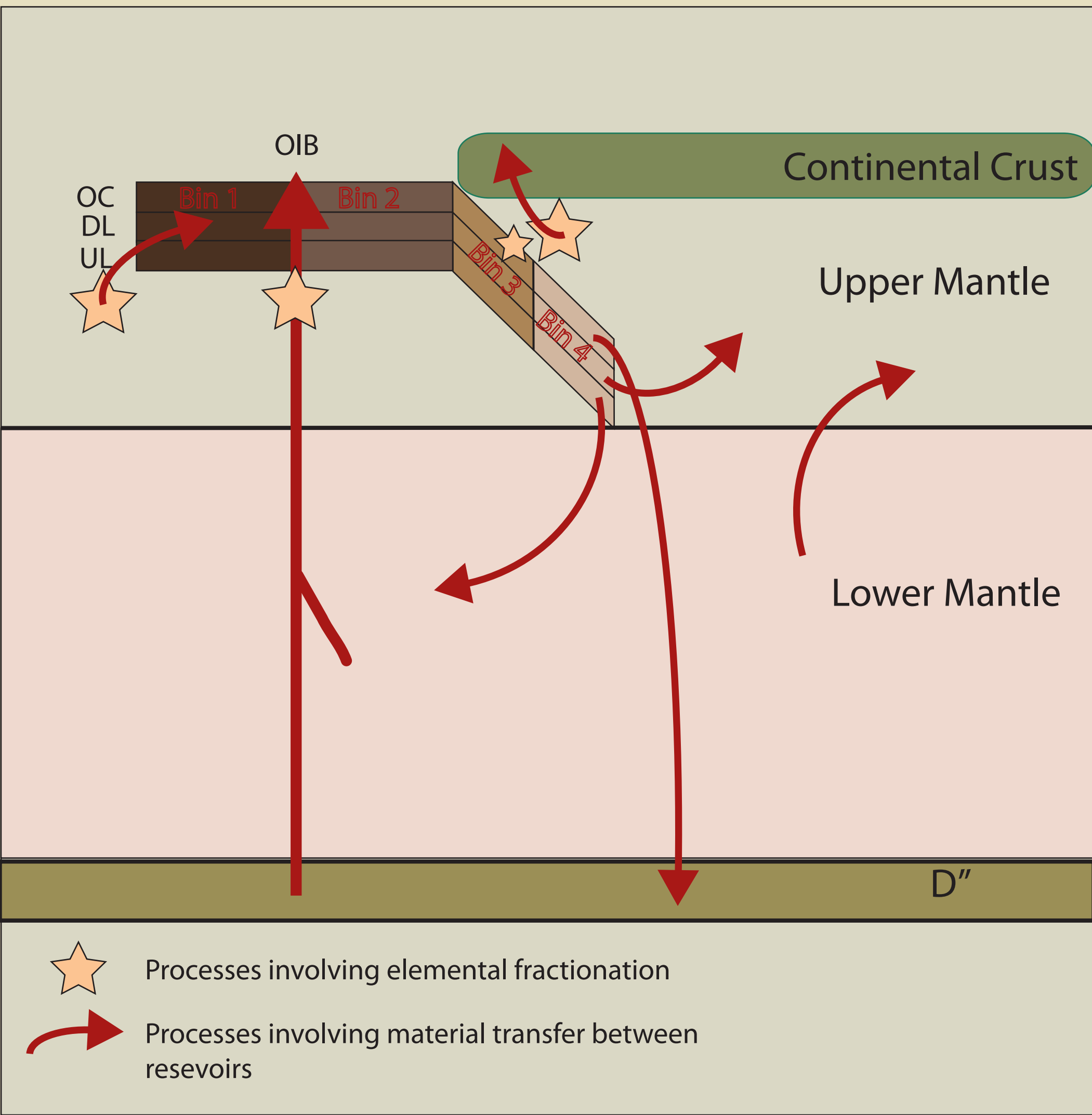
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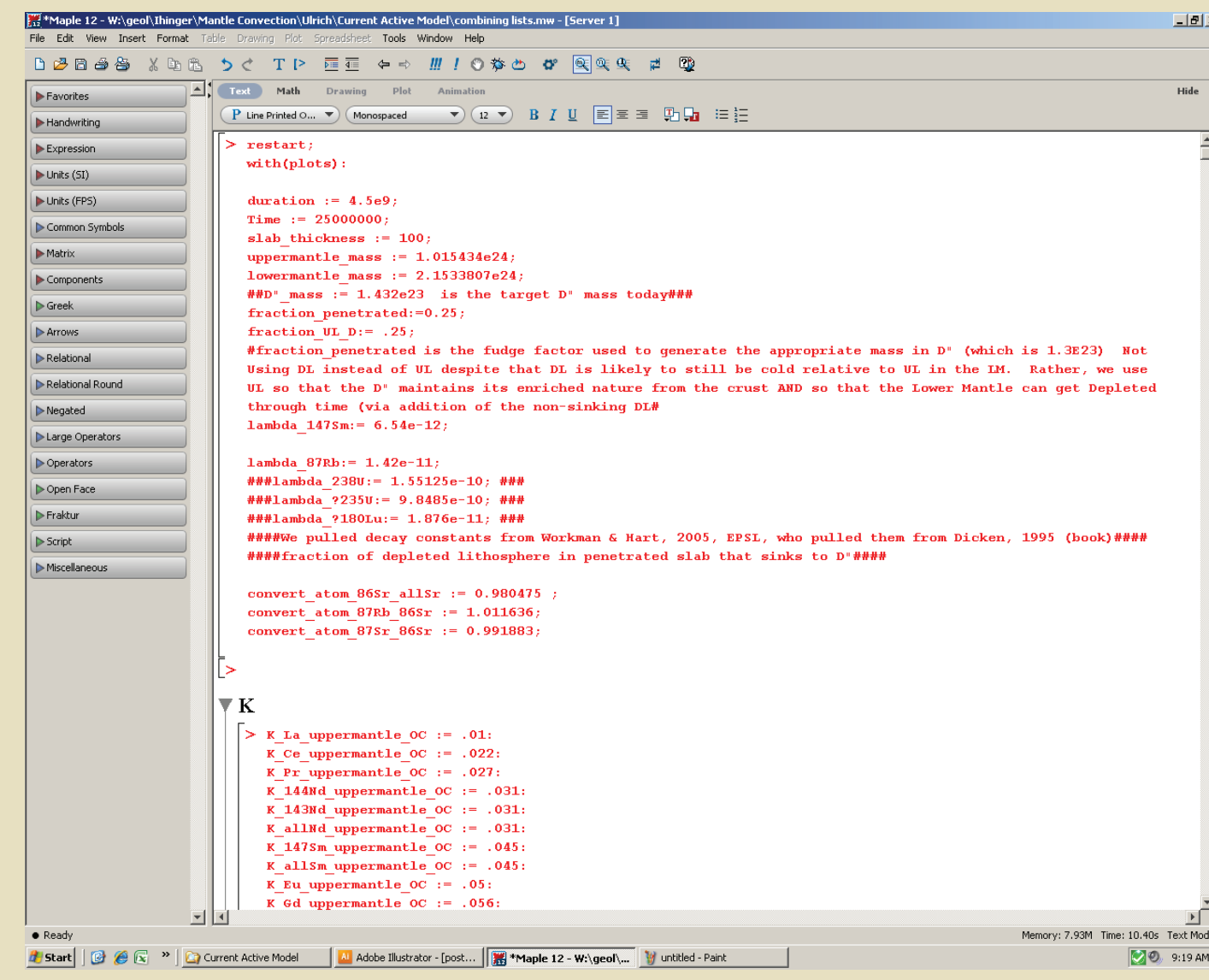
## Competing Models of Mantle Convection



## The Code

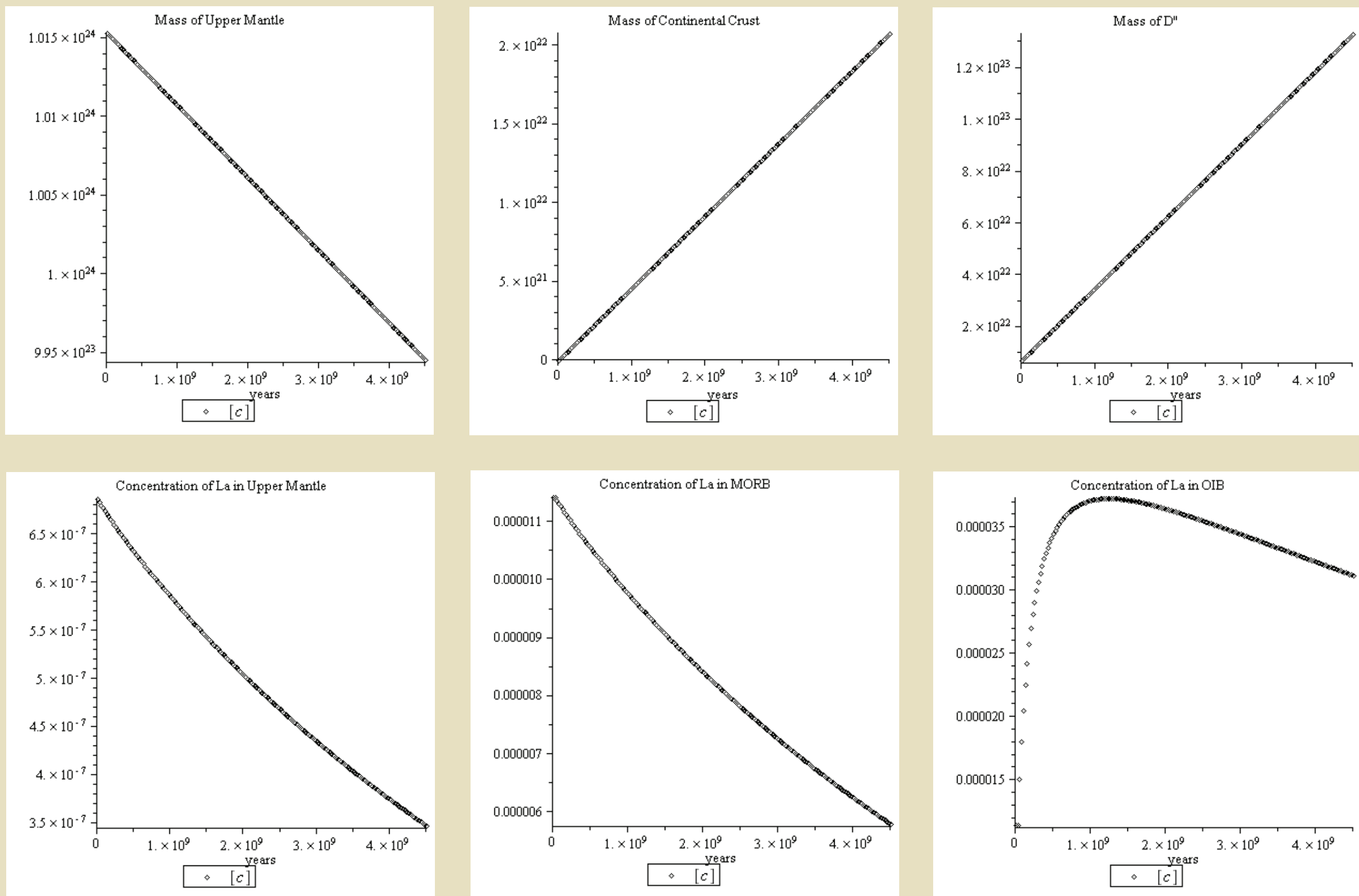


We use MAPLE 12 to model the fractionation and transport of trace elements between mantle reservoirs (UM, LM, D"). In this model, we control the percentage of slabs that penetrate below the 660 km phase boundary, and the percentage of Upper Mantle that is transported with Oceanic Crust to D".



### An Example Run:

25% Slab Penetration - 25% Entrainment

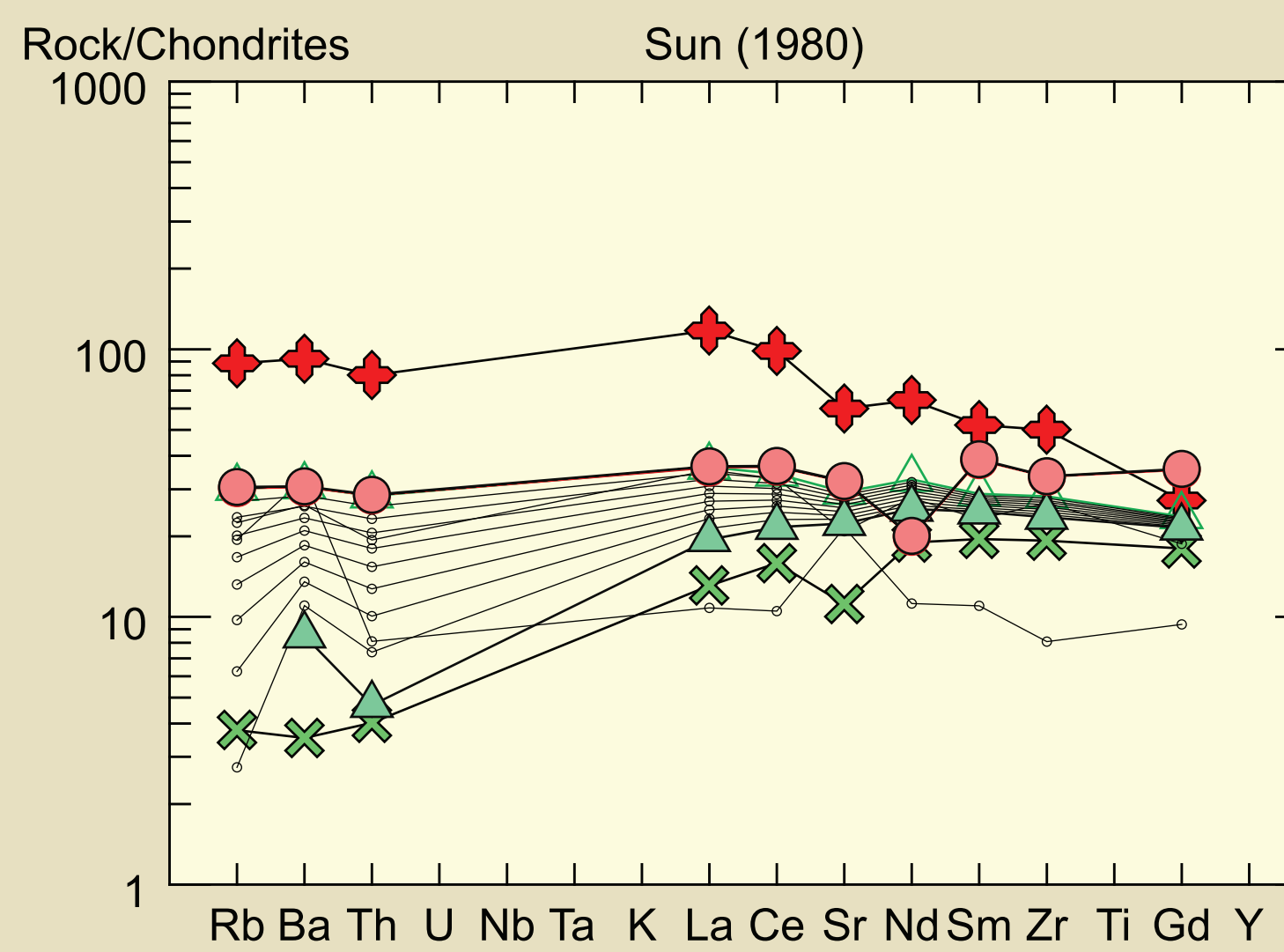


Geochemical observations suggest 1) the Upper Mantle is composed of a homogenized mixture of ~50% primitive, undepleted material with ~50% depleted residue from the formation of Continental Crust, and 2) the Lower Mantle is composed of a homogenized mixture of ~25% depleted material with ~75% undepleted material.

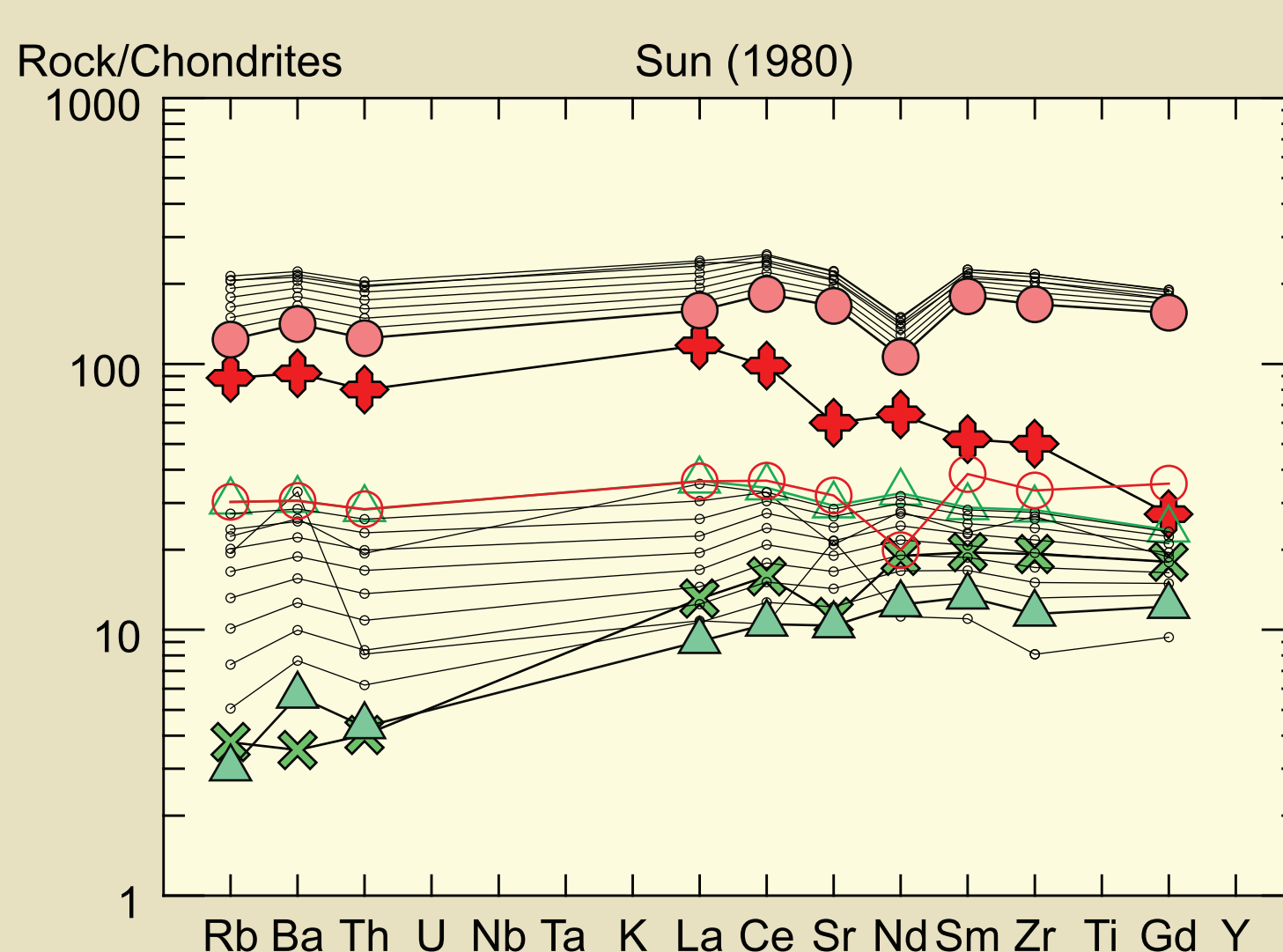
Fraction of the Upper Mantle mixed into the Lower Mantle: 0.277  
Fraction of the Lower Mantle mixed into the Upper Mantle: 0.508

## Results and Conclusions

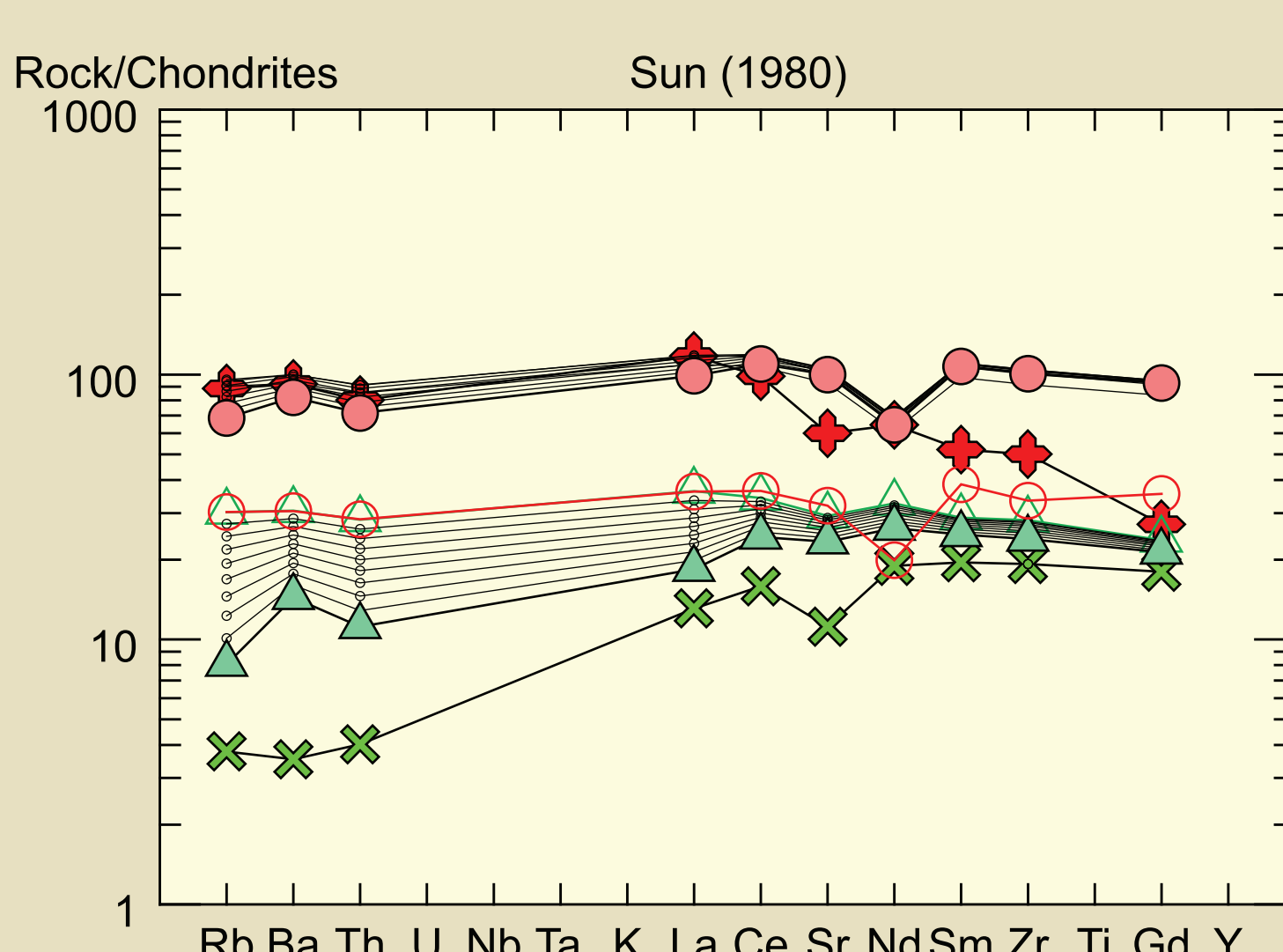
Fully Layered Model: Geochemists  
0% slab penetration and  
0% addition of UL to D"



Fully Convecting Model: Geophysicists  
100% slab penetration and  
0% addition of UL to D"



Best Fit Model: Penetrative Convection  
25% slab penetration and  
25% addition of UL to D"



**Key**

MORB: derived from Upper Mantle

- ✕✕ MORB: observed values (today)
- △△ MORB: model initial values (at 4.5 Gy)
- ▲▲ MORB: model final values (today)

OIB: derived from Lower Mantle + D"

- ◆◆ OIB: observed values (today)
- ◇◇ OIB: model initial values (at 4.5 Gy)
- OIB: model final values (today)

- Whole Earth modeling can track the geochemical evolution of large reservoirs within Earth through time.
- Models invoking either fully layered (geochemist's model) or fully mixing (geophysicist's model) upper and lower mantles cannot account for current geochemical observations of mantle-derived magmas.
- Our models suggest that ~25% of the slabs that have subducted through time have penetrated the phase transition at 670 km to generate the D" reservoir.