Mantle convection, plate tectonics and the thermo-chemical evolution of the Earth

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Mantle convection with plate tectonics and continental drift on Earth

Movie by:
Tobias Rolf, Antoine Rozel, Paul Tackley

https://gfd.ethz.ch
Convection is the key process
Here focus on the solid mantle

- Heat sources: radioactive heating (U, Th, K) & cooling from a hot/molten initial state
- Oceanic plates are part of this convection

F. Press & R. Siever
Early on: Magma Ocean
Geoneutrino relevance: Radiogenic heating rate is key

- Must be high according to conventional geophysical understanding of how mantle convection + Earth cooling work
- Geo/cosmo-chemistry estimates much lower
- How to reconcile?
- Where are the radioactive elements?
Geophysical estimates

Key result: Heat Flux (Nu) $\propto Ra^{1/3}$

$$Ra = \frac{\rho g \alpha \Delta TD^3}{\eta \kappa}$$

Turcotte and Schubert
For $\beta = 0.3$, radioactive heating must be $\sim 85\%$ of the total heat loss! (i.e. the Urey ratio = radioactive heating / total heat loss = 0.85)

Turcotte & Schubert: “..the cooling of the Earth is responsible for about 25% of the Earth’s heat loss, while 75% is attributable to radiogenic heating. There is little room for uncertainty in this conclusion”
More likely

Figure 12  Proposed breakdown of the present energy budget of the Earth. With continental lithosphere, mantle heat production, and core heat loss constrained, the mantle cooling rate is adjusted to fit the total energy loss.

from Jaupart et al. 2015 (Treatise on Geophysics)
Reasons why $\text{Nu} \sim \text{Ra}^{1/3}$ does not apply to Earth?

• The mantle is not constant viscosity => plates are stiff
  • Plate tectonics doesn’t scale like constant viscosity convection?
  • Change in tectonic mode as Earth cooled?
• Melting and crustal production
  • Change tectonic mode
  • Transport heat when plate tectonics not operating
• Grain-size evolution: viscosity does not decrease with increasing temperature
Grain-size evolution could change heat flux-Ra scaling

Can hotter mantle have a larger viscosity?

V. S. Solomatov

GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 9, PAGES 937-940, MAY 1, 1996

\[ \eta \propto d^m \exp(Q/RT) \]

\( d = \) grain size
Large \( \implies \) high viscosity
Small \( \implies \) low viscosity

A. Rozel @ETH is now observing this in fully dynamic models

Figure 2. Variation of the grain size during Earth’s evolution. The grain size can either decrease or increase during Earth’s cooling depending on the specific ranges of kinetic parameters. The cartoon shows the first case.
Why does Earth have plate tectonics?
The plate problem

- Viscous, T-dependent rheology appropriate for the mantle leads to a stagnant lid
- \( \exp(E/kT) \) where \( E \sim 340 \text{ kJ/mol} \)
- \( T \) from 1600 \( \rightarrow \) 300 K
- \( \Rightarrow 1.3 \times 10^{48} \) variation
- \( \Rightarrow \) STAGNANT (rigid) LID!

Only small \( \Delta T \) participates in convection: enough to give \( \Delta \eta \) factor \( \sim 10 \)
Stagnant lid convection
Strength of rocks

- Increases with confining pressure (depth) then saturates

Low-T deformation: Effect of P

Fig. 6. Effect of confining pressure on the strength of Sleaford Bay clinopyroxene tested in triaxial compression (S. H. Kirby and A. K. Kronenberg, unpublished data, 1978): (a) stress-strain curves, (b) ultimate strength or stress at 10% strain as a function of confining pressure.
Strength profile of lithosphere

Continental (granite): Shimada 1993

Oceanic: Kohlstedt 1995
Reminder:
Plastic yielding + T-dependent viscosity can produce
- mobile lid,
- episodic lid
- stagnant lid
depending on the yield stress.
Rayleigh number versus yield stress

\[ \tau_0 \leq 6.72 \times 10^{-4} \times Ra^{0.67} \times \frac{4 \times 10^7}{Ra} \]
Internal heating rate

Strength of the lithosphere vs convective stresses

Yield stress versus internal heating rate

Yield stress (MPa)

Internal Heating rate

- Mobile lid
- Rigid lid
- Prediction

H. van Heck & Tackley
Implications for terrestrial planet evolution

- Plate tectonics favoured at
  - higher mantle viscosity (lower Ra)
  - Lower internal (radioactive) heating

- Both predict transition **stagnant lid->plates** as planet cools.
Coupled convection models of mantle-crust-core evolution
Calculations of mantle thermo-chemical evolution over 4.5 Gyr

• Include melting->crustal production,
  • viscosity dependent on T, d, and stress,
  • self-consistent plate tectonics,
  • decaying radiogenic elements and cooling core,

Many papers by Takashi Nakagawa & me
Typical evolution over 4.5 Gyr
\[(\eta_{\text{ref}}=10^{20} \text{ Pa.s, } \sigma_y=30\text{MPa})\]

Mobile lid. Much chemical heterogeneity; basal MORB layer
With no basalt settling
Scaling between velocity, strain-rate, heat flux and viscosity (Rayleigh #)?

No clear scaling, unlike in simple convection

*Each dot in these graphs is one time step; quantities are volume-averaged*
Magmatic resurfacing transports a lot of heat for much of the evolution
Core evolution?

Nakagawa & Tackley, 2015 GCubed
Too-large inner core!
(very high early CMB heat flow)

Nakagawa & Tackley, 2015 GCubed
With prim. Layer + MORB

Nakagawa & Tackley, 2015
GCubed
Successful core evolution
Deep dense layer reduces core cooling

Nakagawa & Tackley, 2015 GCubed
Core: Summary

• If geodynamo driven by cooling + inner core crystallisation, favours primordial + recycled layer above the core-mantle boundary

• Other geodynamo driving mechanisms have been proposed recently (MgO or SiO₂ precipitation, libration) which would allow lower CMB heat flux.
Key questions:
Did Earth always have plate tectonics?

Box models assume it did

What was before plate tectonics?
Subduction doesn’t work on a hotter Earth

(van Hunen & van den Berg, 2008)
Subduction doesn’t work on a hotter Earth

ΔT = 250°C  
No subduction regime

ΔT = 175°C  
Pre-subduction regime

ΔT = 0°C  
Modern subduction regime

(Sizova et al., 2010)
Numerical and physical model

Melting-induced crustal production (MCP)

Temperature (K)

With MCP

Without MCP

Basaltic crust
Extrusive heat pipe magmatism

But probably most magmatism is intrusive

-> COLD, STRONG crust/lithosphere

-> WARM, WEAK crust/lithosphere

(picture from Moore & Webb 2013)

(picture from Cawood et al 2013)
Typical episodic evolution - extrusive
In comparison – 90% intrusive
Regime diagram

\[ \eta_0 = 10^{20} \text{ Pa} \cdot \text{s} \]

Extrusion rate (%)

Yield Stress (MPa)

Diogo Lourenco et al., submitted to G-Cubed
“Plutonic Squishy Lid” mode

Lourenco et al., submitted
PSL in early Earth

- weak **deformable** plates with low topography
- mantle-flows-driven orogeny
- magma-assisted crustal convection

(Sizova et al., in 2015)

No plate tectonics but not a rigid lid either!

-> **Plutonic Squishy-Lid tectonics**
PSL is relevant to Early Earth?

Elena Sizova
Lack of *plate* tectonics \(\neq\) lack of *tectonics*

Venus is tectonically and volcanically active

“Stagnant lid” \(\neq\) “Rigid lid”
Efficient cooling of rocky planets by intrusive magmatism

Diogo L. Lourenço\textsuperscript{1,2,*}, Antoine B. Rozel\textsuperscript{1}, Taras Gerya\textsuperscript{1} and Paul J. Tackley\textsuperscript{1}

Fig. 3 | Regime diagram of the tectonic regimes discussed in this work. Parameter space in terms of extrusion efficiency and partitioning of HPEs where the different tectonic regimes discussed in this work are expected, together with a brief discussion of them.
Fig. 2 | Surface heat loss, behaviour and internal state of a planet/moon in a plutonic squishy lid regime versus in a heat-pipe regime. The reference viscosity for these simulations is $10^{21}$ Pa s. a. Conductive, magmatic and total surface heat flow as a function of the eruption efficiency. b. Left, an illustration of the dynamics of a plutonic squishy lid. Right, a schematic representation of a typical upper mantle geotherm (solid blue line) and the solidus temperature curve for mixed mantle composition (red dashed line). Part. partitioning. c. Left, an illustration of a typical upper-mantle geotherm (solid green line) and, again, the solidus curve (red dashed line). Right, an illustration of the dynamics of a heat-pipe regime. d.e. Final temperature and basalt-euclogite distribution at 4.5 Gyr of the evolution of a plutonic squishy lid case with a $D_{\text{part}}$ of 1.0 and an eruption efficiency of 0% (d), and of a heat-pipe case with a $D_{\text{part}}$ of 1.0 and an eruption efficiency of 100% (e).
Summary: Reconciling geophysical models with low internal heating

• The Problem: Simple convection scalings require a Urey ratio (=internal heating/total heat loss) of ~0.8 due to $\text{Nu} \sim \text{Ra}^{1/3}$, but this is not possible with geo/cosmo-chemical estimates of internal heating.

• Solutions:
  • Complex mantle convection with yielding-induced plate tectonics & magmatism does not follow the standard $\text{Nu} \sim \text{Ra}^{1/3}$ law.
  • There was likely a different tectonic mode in early Earth (plutonic squishy-lid) with lower heat transport efficiency than scaled-backwards plate tectonics.
  • Grain-size evolution could have caused the early Earth viscosity to have been higher than expected.