Influence of magmatism on mantle cooling, surface heat flow and Urey ratio: Towards the possibility on geoneutrinos for deep Earth geodynamics

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Outline of talk

- **Introduction:** How much does heat transport from deep Earth’s interior.
- **Introduction:** Uncertainties of HPEs (Heat Producing Elements)
- Show the ‘trick’ of Urey ratio estimate.
- How does heat transport by magmatic effect work for the surface heat flow?
- Including early Earth condition.
- Various possibility of geoneutrinos - mantle and core dynamics
- Conclusions
Two issues on thermal evolution of the Earth

- Surface heat flow inferred from numerical mantle convection - obviously lower than the observational constraint.

- 20 TW from mantle convection modeling [Nakagawa and Tackley, 2010] but 39 TW for oceanic heat flow [Jaupart et al., 2007].

- Urey ratio - Usually higher value compared to constraints based on observations and experiments.

- 0.7 at maximum from simple mantle convection [Deschamps et al., 2010; Lenardic et al., 2011] but 0.21-0.49 from observational constraint [Jaupart et al., 2007].

- The amount of heat producing elements in the mantle - 10 to 30 TW from geochemical analyses [Lyubetskaya and Korenaga, 2007; McDonough and Sun, 1995] and geoneutrino [The KamLand Collaboration, 2011].
Heat Producing Elements (HPEs)

<table>
<thead>
<tr>
<th>Composition and radiogenic power</th>
<th>BM</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_u$ in ppb</td>
<td>4.1 ± 2.8</td>
</tr>
<tr>
<td>$A_{Th}$ in ppb</td>
<td>8.4 ± 5.1</td>
</tr>
<tr>
<td>$A_K$ in ppm</td>
<td>57 ± 30</td>
</tr>
<tr>
<td>Th/U</td>
<td>2.0</td>
</tr>
<tr>
<td>K/U</td>
<td>13,900</td>
</tr>
<tr>
<td>Power in TW</td>
<td>3.3 ± 2.0</td>
</tr>
<tr>
<td>Mantle Urey ratio</td>
<td>0.08 ± 0.05</td>
</tr>
</tbody>
</table>

Sramek et al. [2013]

Huge uncertainties - estimate of HPEs: uncertainties of Urey ratio.

$$U_r = \frac{H M}{Q_s}$$
Two different estimates on Urey ratio

Korenaga [2008]: Dehydration melting with the plate bending effect

Butler [2009]: Simple mantle convection with an endothermic phase transition
Prescriptions?

- Surface heat flow - uncertainty on mantle viscosity = possible to resolve in current numerical mantle convection modeling with some trick.

- Urey ratio - effects of plate-like behavior [e.g., Korenaga, 2008] and uncertainty on amount of heat producing material in the mantle = although such simple treatments are good, the Earth should be more complicated!

- Resolving such issues, we show prescriptions obtained from numerical mantle convection simulations including plate-like behavior and melt-induced differentiation.
How to generate the prescription.

- StagYY [Tackley, 2008] is used; 1024x128 with 4 million tracers.
- $T$, $z$, and yield stress-dependent viscosity: 120 MPa of yield stress at surface.
- Melt-induced differentiation: create oceanic crust and latent heat effect.
- Heat pipe approximation calculating heat transfer by magmatism.
- Three values of heat production rate (12.5 TW, 20 TW and 28.5 TW) at the initial are used.
- $T_m(t=0) = 1600$ K or $2500$ K; $T_{CMB}(t=0) = 6000$ K; CMB = Core-Mantle Boundary.
- Reference viscosity: measured at the center of convective region.
Example results

The upper mantle viscosity = $10^{20}$ Pa s - Consistent with PGR [Barnhoorn et al., 2011].

Strongly early differentiation in the higher initial mantle temperature but large-scale thermo-chemical anomalies in the deep mantle for both cases.

Nakagawa and Tackley [2012]
Effects of material differentiation?

- Including material differentiation - Mantle cooling is similar phase to the magmatic activity.

- Isochemical case - Mantle cooling is similar amount of radioactive heat production

- Early differentiation - drastically cooling down but similar temperature at 4.5 Gyrs

Nakagawa and Tackley [2012]
On influence to the Urey ratio

\[ Q = Q_s + Q_e \]
\[ Ur = \frac{H_m}{Q} = \frac{H_m}{Q_s + Q_e} \]
\[ Ur_c = \frac{H_m}{Q_s} \]
\[ Ur_e = \frac{H_m}{Q_e} \]
\[ Ur = \left( \frac{1}{Ur_c} + \frac{1}{Ur_e} \right)^{-1} \]

Total surface heat flow = 32 + 7 = 39 TW
Total Urey ratio - lower than the convective one because of eruptive heat flow.
Effects of amount of heat production rate

Textbook: 28.5 TW [Schubert et al., 2001]
BSE: 20 TW [McDonough and Sun, 1995]
BSE - C.C. = 20TW - 7.5TW [Rudnick and Gao, 2003]
Effects of mantle cooling and Urey ratio

Mantle cooling: Similar phase to peaks of magmatic heat flow. Total surface heat flow = 32 + Magmatic effect (TW).

Urey ratio: Magmatic heat flow decreases the convective one but still high Urey ratio for textbook case
→ dependent on the amount of heat production rate
= huge uncertainty for the Urey ratio!

Nakagawa and Tackley [2012]
Conclusion 1

- Surface heat flow (convective effect): 32 + Magmatic effect (TW) - Not very dependent on initial mantle temperature and heat production rate. Surface heat flow tends to be strong constraint?

- T-C structure: Not very different from each run - Present mantle structure is difficult to constrain the early Earth state.

- Magmatic heat flow: Important for explaining the mantle cooling effect.

- Urey ratio: strongly dependent on heat production rate. Because of huge uncertainty of heat production rate, the Urey ratio is not very strong constraint for understanding thermal evolution of Earth's mantle.

- Urey ratio: However, a reduction due to the magmatic effect, the Urey ration can be decreased up to 0.4 to 0.5.
Different scenario from early Earth

a. Early Earth
- Thick early crust
- Trapping near 660 km
- Upside-down differentiation
- Basal Magma Ocean
- Fresh melting of Fe-rich materials

b. Present day
- Thin oceanic crust
- Buoyant HZ in plume
- ULVZs
- Some MORB joins BAM
- pPv shaded

BAM: Present day thermo-chemical anomalies including early Earth and recycled material.

Tackley [2011]
Simplified initial condition for expressing the early Earth...

Primordial material layered above the CMB with 300 km thickness

Nakagawa and Tackley submitted (today!)
Preferred model: (0.75 %, 3.175 %)

Total amount of heat source in the mantle: 20 TW at the present time.

Nakagawa and Tackley submitted (today!)
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In a 3-D spherical shell...

Large-scale thermo-chemical structure in the core-mantle boundary

30 TW of surface conductive heat flow across the plate

5 to 8 TW of magmatic heat flow - 35 to 38 TW of total surface heat flow

CMB heat flow ~ 12 TW

Cooling rate of mantle ~ 300 K/4.5 Gyrs ~ 65 K/Gyrs
If geoneutrinos can map HPEs in a convecting mantle...

Mantle convection modeling can track the trace elements.

Using some tricks, it is possible to plot Th/U field observed by geoneutrinos?

Geodynamics modeling could be compared with some images of deep Earth’s interior generated by Geoneutrinos

Xie and Tackley [2004]
If geoneutrinos can image the outermost core...: A stably stratified layer below the CMB

**Pm = 0.5**

Weak field solution but dipolar field

(a) Pm = 1

(b) Pm = 0.5

(c) Dipole tilt

(d) Dipole strength ratio

Tilt angle - Unstable: fluctuate between 60 and 120 deg.
Strength of dipolar field: 40 % compared to total B at surface.

Nakagawa and Aubert to be submitted
Conclusion II

• Assuming the early Earth condition, the magmatism is still important for understanding mantle cooling and surface heat flow.

• The effect of primordial material, which may be enhanced for the HPEs compared to the ambient mantle, could be better results on a coupled Earth’s mantle and core.

• Geoneutrinos tomography - might interpret something related to the mantle and core dynamics from image taken from geoneutrino observations.
The END
Thank you for your attentions.