Isotopic Evolution of the Mantle with Self-consistent Plate Tectonics
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Background

Geochemical Observation
- Mantle heterogeneous on small and large scales (e.g., marble cake structure and Dupal anomaly).
- MORB is uniform while OIB is a mixture of DMM, HIMU, EMI and EMIL.
- OIB Basalt groups:
  - St. Helena group: Sr=0.7035, 206Pb/204Pb > 19.5
  - Kerguelen group: Sr high, low Nd & Pb
  - Society group: 207Pb/208Pb, 206Pb ratio > 18.6
- Hawaiian group

Noble Gas Constraints
- $^{3}$He/$^{4}$He observed at Loihi, Hawaii: 35 Ra, MORB: 8.4 Ra, where Ra=1.4x10^{-6}
- Mass balance requires ~50% 40Ar outgassing efficiency.

Issues to Address
- Mantle mixing will destroy heterogeneity, how can it survive for billions of years?
- Where are reservoirs HIMU, EMI, EMIL etc.?
- What/Where is high $^{3}$He/$^{4}$He reservoir?
- Can we match the Argon outgassing constraints?

Goals
- Combine the self-consistent lid behavior with a major and minor element geochemical evolution model using a convection code.
- Chemistry
  - Melting + crustal formation
  - Trace element tracking, radioactive decay, noble gases
- Physics: Self-consistent lid behavior (Tackley, 2000)- increasing yield strength leads to plate-like behavior (Earth), Episodic overturn (Venus?), rigid lid (Mars, Venus?).

Model

Chemical Model
- Major elements:
  - Simplified 2-component: crust and residue
- Melting occurs when T reaches solidus, melt instantly removed to form surface crust.
- Trace elements:
  - Track 207Pb, 206Pb, 204Pb, 143Nd, 144Nd, 147Sm, 235U, 238U, 3He, 4He, 36Ar, 40Ar, 40K, 232Th
- Initial concentrations represent after formation of CC 3.6 Ga ago
- Radioactive decay
- The trace element concentration is fractionated between the melt (Cm) and the residue (Cr).
- Noble gases 100% outgas on melting

A Two-stage Model
- Hofmann (1988) explained the complimentary chemical composition pattern between MORB and the continental crust
  - 1st stage: primitive mantle --> continental crust + residue
  - 2nd stage: residue 1 --> oceanic crust + residue 2
- Assume extraction of continental crust took place at ~3.6 Ga
- IMORB or hotspot melting extracts incompatible elements from the mantle.
- Oceanic or continental crust re-enters the mantle through subduction.

Physical Model
- Boussinesq
- Viscosity dependent on:
  - Temperature (factor 10^6)
  - Depth (factor 10)
- Stress (yielding gives different lid behaviors)
- Composition (different for basalt and residue)
- Mixed basal and internal heating (Ra=2.10^{6}, H=13)

Preliminary Results (3 representative cases)

Figure 1. Viscosity, composition, lead ratio and Helium ratio distribution after 3.6 billion years. In mobile lid case, regions of high Pb/207Pb/204Pb and He/4 are formed. High Pb/207Pb/204Pb patches develop from subducted oceanic crust, while high He/4 patches are anticorrelated with recycled crust regions. These cases are started from an initially homogeneous composition.

Figure 2. Heat flux as a function of time. Note the episodic behavior when YS = 960MPa, and the rigid lid behavior when YS = 2.4GPa.

Figure 3. Noble gas outgassing history. Top panel: low strength lithosphere, YS = 240MPa, mobile lid regime. Middle panel, high strength lithosphere, YS = 960MPa, episodic lid regime. Bottom panel, YS = 2.4GPa, rigid lid regime.

Figure 4. Lead ratio after the tracers have been injected for 3.6 billion years. Each point is one grid cell. Chemical density contrast is 2.5%. Top panel, YS=240MPa, the slope is ~0.16, and the corresponding heterogeneity age is 2.4 billion years. Middle panel, YS=960MPa, the slope is 0.27, the age is 3.3 billion years. Bottom panel, YS=2.4GPa, the slope is 0.13, and the age is 2.1 billion years.

Conclusion & Future Work

Findings
- In mobile lid and episodic lid case, crustal settling at base leads to HIMU signature. The age of the heterogeneity determined from the lead ratio is ~2 billion years. In rigid lid case, the crust rarely subducts, all heterogeneity is observed in the crust region.
- High He/4 patches develop, anticorrelated with recycled crustal regions. The lowest and highest He/4 ratio is consistent with the observations.
- In mobile lid case, noble gas outgassing is efficient (~80%). While in episodic lid or rigid lid case, it is less efficient (~30%).

Discussion and Future Work
- In mobile lid case, Ar/40 outgassing efficiency is 80%, much larger than the value (50%) required by the mass balance calculation. The high Ar/40 outgassing is due to too large a fraction of the mantle having undergone melting. A more realistic solidus and other physical parameters would fix this.
- More realistic physical model:
  - more realistic solidus (than present linear profile)
  - compressible reference state with depth-dependent properties
  - realistic depth-dependent density-composition relationship
  - more realistic rheology
  - cooling core and decreasing radiogenic isotope
- Improve chemical model to include variable major element chemistry allowing continental crust to form
- Apply to other planets (Venus Ar/40 outgassing, Mars)

References

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