The Deep Mantle Feeding Hawaiian Volcanism: New Perspectives on Old Models

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A Dynamic Earth
Ocean island lavas provide a “window” to the mantle, an otherwise virtually inaccessible reservoir.
Lavas as probes of the mantle’s composition:

Radiogenic isotopes (e.g., $^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$) and some trace element ratios are not changed between solid and melt.
Hotspot lavas reveal a heterogeneous mantle

Lavas erupted at hotspots are isotopically heterogeneous. 
Therefore:  The solid mantle sources of these lavas are heterogeneous.
Ocean island petrology/geochemistry: Probes of the Earth’s deep interior

The observation that the mantle is heterogeneous leads to some of the most important questions in the study of the deep Earth, and many of these questions remain unanswered:

Part 1: How are mantle heterogeneities formed, and what are they made of, how old are they?

Part 2: What was Earth’s starting point?

Part 3: Can we relate heterogeneities observed in lavas to mantle reservoirs at specific depths?
Part 1: How did the mantle become heterogeneous?

30-year anniversary of the Recycling hypothesis:
Crustal materials injected into the mantle at subduction zones, and this material is returned to the surface in upwelling mantle plumes.

Mantle plumes from ancient oceanic crust
Albrecht W. Hofmann * and William M. White *

Nature Vol. 296 29 April 1982
Sr and Nd isotope geochemistry of oceanic basalts and mantle evolution
W. M. White * & A. W. Hofmann *

- If so, what’s being recycled?
Recycling hypothesis

1. Oceanic plates (crust and sediment) enter the mantle at subduction zones,
2. They are returned to the surface in mantle upwellings (plumes?)
3. Crust and sediment are melted beneath hotspots.

Rivers contribute > 85% of ocean floor sediment
$^{87}\text{Sr}/^{86}\text{Sr}$ and $^{143}\text{Nd}/^{144}\text{Nd}$ data: Consistent with upper continental crust!

Jackson et al., *Nature*, 2007
Continental crust has unique trace element “fingerprints”

Jackson et al. (2007)
But what about the other components?

- **HIMU**: Recycled oceanic crust? Requires a lot of “fiddling” with the crust in the subduction zone. Niu & O’Hara (2003) suggest “metasomatism”.

- **EM1**: A real “dog’s breakfast” of proposed origins: Pelagic sediment, lower continental crust, sub-continental lithosphere, “metasomatism”, etc., etc.
**Paradox:** How can radically different subducted lithologies generate such similar trace element patterns in OIBs?

1. Exotic metasomatic components?
2. Exotic Phanerozoic sediments? Archaean, Proterozoic?
3. Archaean oceanic crust?
The community needs to make a concerted effort to look at $\Delta^{33}\text{S}$ in OIB.
Major element (lithological?) heterogeneity accumulates in the mantle owing to subduction over time

"HOLY GRAIL"
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Pinpointing specific major element compositions for the different isotopic reservoirs will allow experimentalists to better constrain source lithologies.
Mantle plumes: Are they hot or not?

Current petrological thermometers require that **olivine and orthopyroxene** co-exist in the mantle source of the melts.

Problem: Olivine may not always be a phase in the source of oceanic lavas.

**An olivine-free mantle source of Hawaiian shield basalts**

Alexander V. Sobolev¹ ², Albrecht W. Hofmann¹, Stephan V. Sobolev³ ⁴ & Igor K. Nikogosian⁵ ⁶
Summary Part 1

Why do we care what is melting (eclogite vs. peridotite) beneath Hawaii & other ocean islands?

Well, until we figure out what is melting beneath Hawaii, geochemists and petrologists can’t do simple things like calculate mantle melting temperatures with any certainty.

Without temperature estimates, it’s hard to argue for mantle plumes.

Without mantle plumes, we can’t easily cool the Earth.

How can we model the thermal evolution of the Earth without a good idea of present-day temperature variations?
Part 2: Where is home?

- Following accretion at 4.568 Ga, a deep terrestrial magma ocean...
- Siderophile elements (Fe-Ni) to the core, leaving behind the early (primitive) silicate mantle or BSE (bulk silicate Earth).
- From the primitive silicate earth, the crust (continental and oceanic) was extracted from the early **primitive mantle**.
- But what material accreted to make the Earth in the first place... and what is the bulk composition of the Earth?
- OIBs (and Hawaii) offer a window into deep mantle/time and the initial conditions for geochemical evolution of the Earth.
Home? Primordial helium in Earth’s mantle?

• Helium in the Earth’s mantle:
  - Two isotopes: \(^{3}\text{He}\) (lower abundance) and \(^{4}\text{He}\) (greater abundance)
  - U and Th decay to Pb via alpha decay (\(^{4}\text{He}\) nuclei production)
  - Little \(^{3}\text{He}\) produced in the earth (mostly primordial)
  - Therefore, \(^{3}\text{He}/^{4}\text{He}\) in the earth decreases with time.
  - Absolute \(^{3}\text{He}/^{4}\text{He}\) ratios in the solar system are small (10\(^{-3}\) to 10\(^{-8}\)), so we normalize to \(^{3}\text{He}/^{4}\text{He}\) ratio in atmosphere (Ra, 1.38x10\(^{-6}\)).

• The sun (solar wind) and the atmosphere of Jupiter have high \(^{3}\text{He}/^{4}\text{He}\). High \(^{3}\text{He}/^{4}\text{He}\) is thought to be primordial.
Starting composition of the Earth—Chondritic?

1.) Carbonaceous (C) chondrites ≈ Sun

2.) C-chondrites and Earth came from the same (homogeneous?) solar nebula, and the sun represents over 99.9% of solar system’s mass.

3.) Therefore, C-chondrites ≈ Earth (for the non-volatile, lithophile elements like Sm/Nd)

4.) $^{147}\text{Sm} \rightarrow ^{143}\text{Nd} + ^4\text{He}$ ($t_{1/2} = 106 \text{ Gyr}$)
   $^{146}\text{Sm} \rightarrow ^{142}\text{Nd} + ^4\text{He}$ ($t_{1/2} = 68 \text{ Myr}$)

5.) If the Earth is a C-chondrite, then Earth and chondrites have the same Sm/Nd & $^{143}\text{Nd}/^{144}\text{Nd}$ & $^{142}\text{Nd}/^{144}\text{Nd}$.

Comparison of solar-system abundances (relative to silicon) determined by solar spectroscopy and by analysis of carbonaceous chondrites (after Ringwood, 1979)
A paradox:
Primitive (high) $^3\text{He}/^4\text{He}$ lavas do not have primitive (chondritic) $^{143}\text{Nd}/^{144}\text{Nd}$

Jackson et al. (EPSL, 2007)
Implications from Neodymium-142

- **Discovery:** $^{142}\text{Nd}/^{144}\text{Nd}$ ratios in accessible modern terrestrial lavas are 18±5 ppm higher than O and C chondrites (Boyet & Carlson, ’05)

- There are two interpretations of the new data:

1. $^{142}\text{Nd}$ variation due to incomplete mixing of s-, r-, p-process nucleosynthetic products. $^{142}\text{Nd}$ variation has nothing to due with $^{146}\text{Sm}$ decay. Earth has chondritic Sm/Nd.

   OR....

2. $^{142}\text{Nd}$ variation due to $^{146}\text{Sm}$ decay. All modern accessible terrestrial samples evolved from a mantle reservoir with a Sm/Nd ratio ~6% higher than chondrites. $^{143}\text{Nd}/^{144}\text{Nd}$ is 0.5130!

(Boyet and Carlson, Science, 2005)
Paradox resolved?
Lavas with high $^3\text{He}/^4\text{He}$ have “primitive” (but not chondritic) $^{143}\text{Nd}/^{144}\text{Nd}

$^{143}\text{Nd}/^{144}\text{Nd} = 0.5130$ ($\varepsilon^{143}\text{Nd} = +7$)

Reservoir parental to modern terrestrial mantle

$\text{Loihi}$

Jackson et al. (EPRL, 2007)
How does this work?

1. \( \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_t = \left( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_0 + \left( \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_t (e^{\lambda t} - 1) \)

2. \( \left( \frac{^{142}\text{Nd}}{^{144}\text{Nd}} \right)_t = \left( \frac{^{142}\text{Nd}}{^{144}\text{Nd}} \right)_0 + \left( \frac{^{146}\text{Sm}}{^{144}\text{Nd}} \right)_t (e^{\lambda t} - 1) \)

3. \( \frac{^{146}\text{Sm}}{^{147}\text{Sm}} = \text{Constant} \)

4. If \( \frac{^{146}\text{Sm}}{^{144}\text{Nd}} \) increased by 6\%, then must also increase \( \frac{^{147}\text{Sm}}{^{144}\text{Nd}} \) by 6\%.

5. Therefore, if \( \frac{^{142}\text{Nd}}{^{144}\text{Nd}} \) of BSE is 18 ppm higher than chondrites, then BSE \( \frac{^{143}\text{Nd}}{^{144}\text{Nd}} \) is \( 7 \text{ EPSILON UNITS (!)} \) higher than chondrites....
Two problems with “hidden” reservoir hypothesis:

1. $^{146}\text{Sm} - ^{142}\text{Nd}$ and $^{182}\text{W} - ^{182}\text{Hf}$ systematics: How would a “hidden” reservoir remain completely hidden at the bottom of the mantle during a giant impact event?

\(^{142}\text{Nd}/^{144}\text{Nd}\) in OIBs:
There’s No Evidence for a Hidden Reservoir in the Deep Mantle

Jackson and Carlson (G-cubed 2012)
Bulk Silicate Earth (BSE)?
No hidden reservoir. So Bulk Earth isn’t chondritic? A growing clamor……

Evidence against a chondritic Earth
Ian H. Campbell1 & Hugh St C. O’Neill1

LETTERS

Super-chondritic Sm/Nd ratios in Mars, the Earth and the Moon
Guillaume Caro1, Bernard Bourdon2, Alex N. Halliday3 & Ghylaine Quitté4
Earth isn’t chondritic?

A growing clamor

Naming the Loch Ness monster

Recent publicity concerning new claims for the existence of the Loch Ness monster has focused on the evidence offered by Sir Peter Scott and Robert Rines. Here, in an article planned to coincide with the now-cancelled symposium in Edinburgh at which the whole issue was due to be discussed, they point out that recent British legislation makes provision for protection to be given to endangered species; to be granted protection, however, an animal should first be given a proper scientific name.

Better, they argue, to be safe than sorry; a name for a species whose existence is still a matter of controversy among many scientists is preferable to none if its protection is to be assured. The name suggested is *Nessiteras rhombopteryx*. 
Predicted non-chondritic mantle reservoir overlaps with high $^3\text{He}/^4\text{He}$ reservoir

Jackson et al. (EPSL, 2007)

$^{143}\text{Nd}/^{144}\text{Nd} = 0.5130$ ($\varepsilon^{143}\text{Nd}=+7$)

Reservoir parental to modern terrestrial mantle
Bulk Silicate Earth is FOZO?

- FOZO is a “common component” in the mantle: \( \text{FOZO=} \text{Focus Zone} \)

- FOZO has high \(^{3}\text{He}/^{4}\text{He}\) and \(^{143}\text{Nd}/^{144}\text{Nd}\) of \(~0.5130\)

- If Bulk Silicate Earth (BSE) isn’t chondritic, FOZO is probably our best bet.

After Hart et al., 1992
Interpreting ocean island volcanism: Enriched or Depleted?

- **Enriched:** $\varepsilon^{143}\text{Nd} < 0$
- **Depleted:** $\varepsilon^{143}\text{Nd} > 0$

**Diagram:**
- Number of Samples
- $^{143}\text{Nd}/^{144}\text{Nd}$
- Samples: Hawaii, All OIB Except Hawaii
- Chondritic Mantle
Interpreting ocean island volcanism: Enriched or Depleted?

![Graph showing Nd isotopes and sample distribution.

- **Hawaii** and **All OIB Except Hawaii**
- **Chondritic Mantle** and **Non-chondritic Mantle**

**ε^{143}Nd**:
- **Enriched**: ε^{143}Nd < +7
- **Depleted**: ε^{143}Nd > +7
Interpreting Hawaiian volcanism: Enriched or depleted?

In the chondritic reference frame, all Hawaii is depleted: $\varepsilon^{143}\text{Nd} > 0$

DePaolo et al., G-cubed (2001)
A “mostly enriched” Hawaiian plume?

But if BSE isn’t chondritic, then…..

DePaolo et al., G-cubed (2001)
Summary & Implications for Part 2:

- Still “early days” for a non-chondritic BSE…
- BSE is simply the high $\frac{^3\text{He}}{^4\text{He}}$ (FOZO) reservoir?
- How to extract continental crust from a mantle with $\frac{^{143}\text{Nd}}{^{144}\text{Nd}}$ closer to MORB than chondrites?! 
- BSE has been “under our noses” for for 30 years (i.e., Loihi mantle!), but the Boyet and Carlson (2005) $^{142}\text{Nd}$-discovery has only recently made this interpretation possible.
Part 3: Location of heterogeneities?

-- $^{129}$I $\rightarrow$ $^{129}$Xe (half life = 16 Ma).
-- $^{129}$I is effectively extinct after 5 of 6 half-lives (~100 Ma).
-- Therefore, all $^{129}$Xe/$^{130}$Xe variability in the mantle had to be made before 100 Ma after accretion of Earth (>4.45 Ga)!

How to preserve 2 distinct $^{129}$Xe/$^{130}$Xe domains for 4.45 Ga?
Baffin and West Greenland picrites plot near the Geochron

Jackson et al. (Nature, 2010)
Figure 1 | Reconstructed large igneous provinces and kimberlites for the past 320 Myr with respect to shear-wave anomalies at the base of the mantle. The deep mantle (2,800 km on the SIMEAN tomography model) is dominated by two LLSVPs beneath Africa and the Pacific. The 1% slow contour (approximating to the PGZs) is shown as a thick red line. 80% of all reconstructed kimberlite locations (black dots) of the past 320 Myr erupted near or over the sub-African PGZ. The most ‘anomalous’ kimberlites (17%)
Connecting high $^3$He/$^4$He to the deep mantle: Titanium, Tantalum & Niobium (TiTaN)
Ca-perovskite in peridotitic and basaltic systems shows negative Ti and Nb partitioning patterns compared to Th, U, and the rare earth elements (REEs).

Melt equilibrated with Ca-perovskite could have positive anomalies.
Summary & Implications of Part 3

- A confluence of experimental data and measurements of natural samples will allow us to connect deep reservoirs with isotopic “species” observed in surface lavas.
- Better understanding of deep Earth convection will help us determine how reservoirs are preserved (isolated) for 4.45 Ga.
In the span of 1 human life…

(oldest living person born in 1896)

- **Becquerel**
  - 1896. Discovered radioactivity accidentally. Phosphorescent U-salts exposed photographic plates

- **Curie**
  - 1903. Nobel Prize in physics in 1903 for their work on “radioactivity” – a term coined by Marie Curie.

- **Rutherford**
  - 1903-1910. Demonstrated existence of isotopes and that radioactivity follows an exponential law. Hypothesized that it might be used as a clock.

- **Soddy**
  - 1907. Dated first rock, acting on suggestion from Rutherford. Got ages from 400 to 2200 million years.
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100 years from now?
Geoneutrinos to “map out” mantle chemical heterogeneities

Sramek et al. (2012)
Looking ahead 100 years....

- We are on the cusp of making enormous headway in our understanding of the deep Earth.
- We will determine the composition of the Earth to be chondritic or to be “something else”.
- The composition, age and origin of mantle “species” (HIMU, EM1, etc) will be determined. A mantle “Darwin”.
- Location of deep Earth reservoirs will be related to isotopic species observed in lavas.