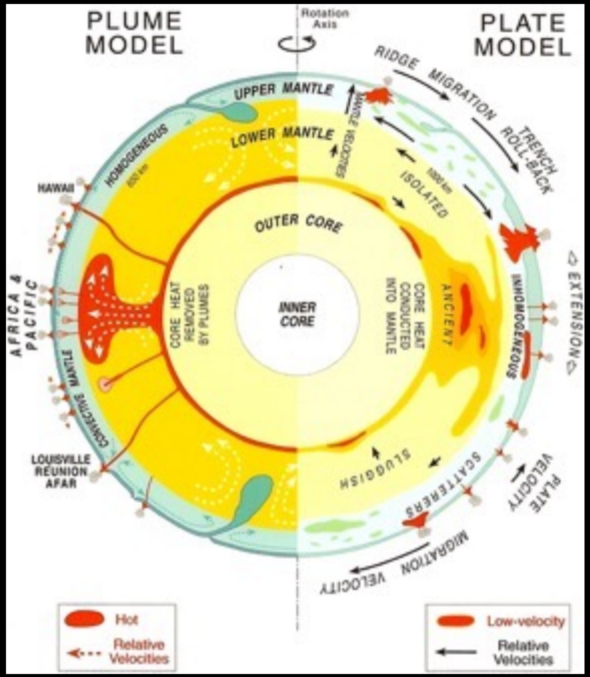
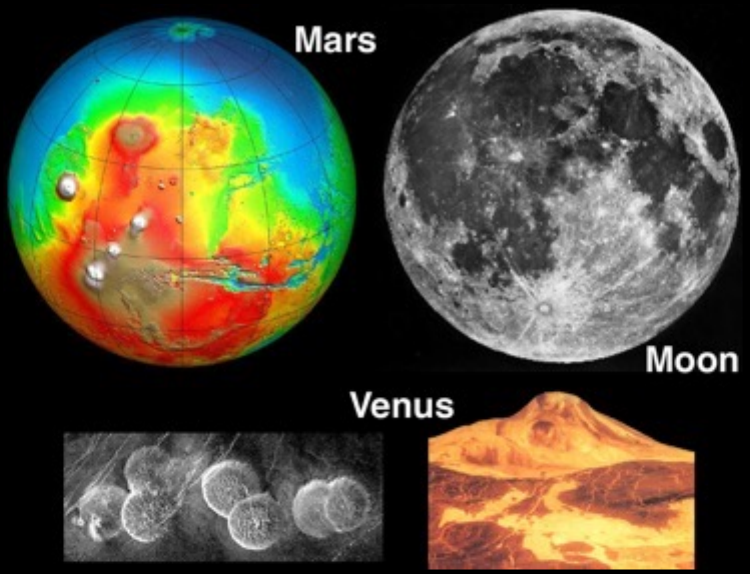
Frontiers of Technology, Exploring Earth's Seafloor and Beyond



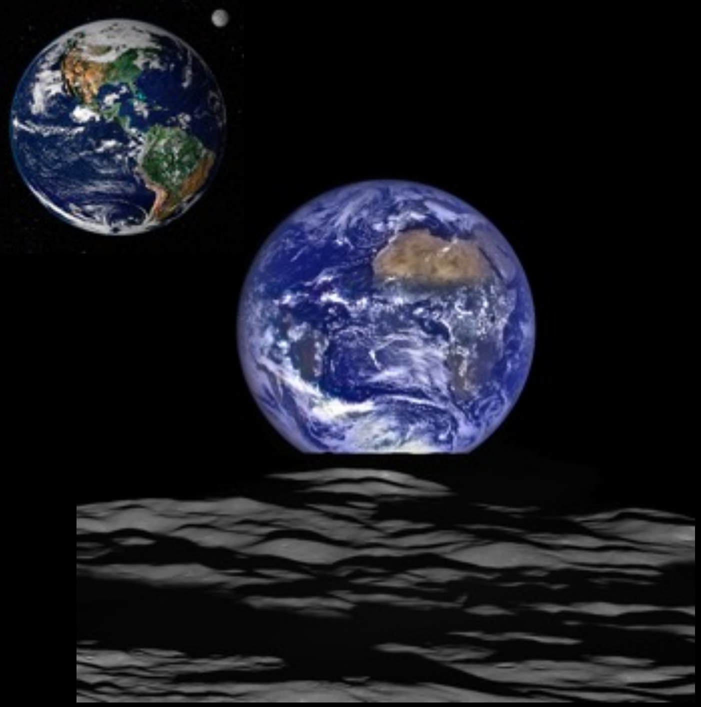
Clive R. Neal
@Prof_Clive_Neal

Plume Volcanism = Planetary Volcanism



Tohoku University Forum for Creativity: International Symposium, Frontier of Understanding Earth's Interior and Dynamics

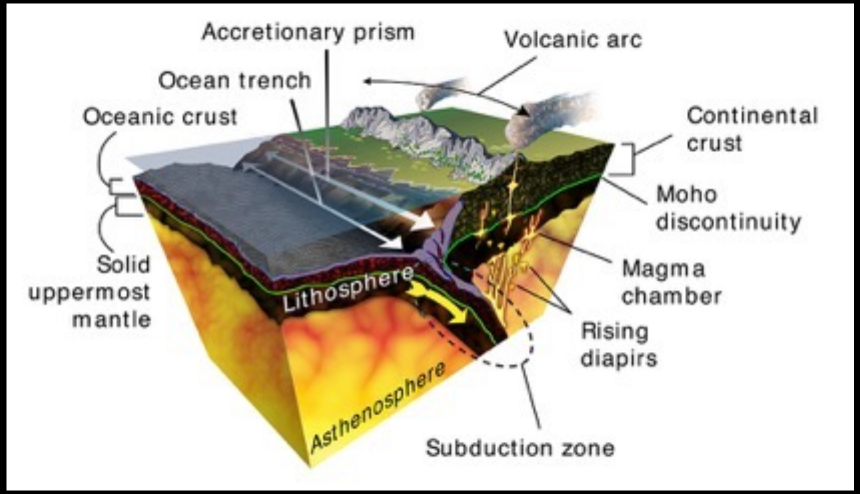
Earth is Unique

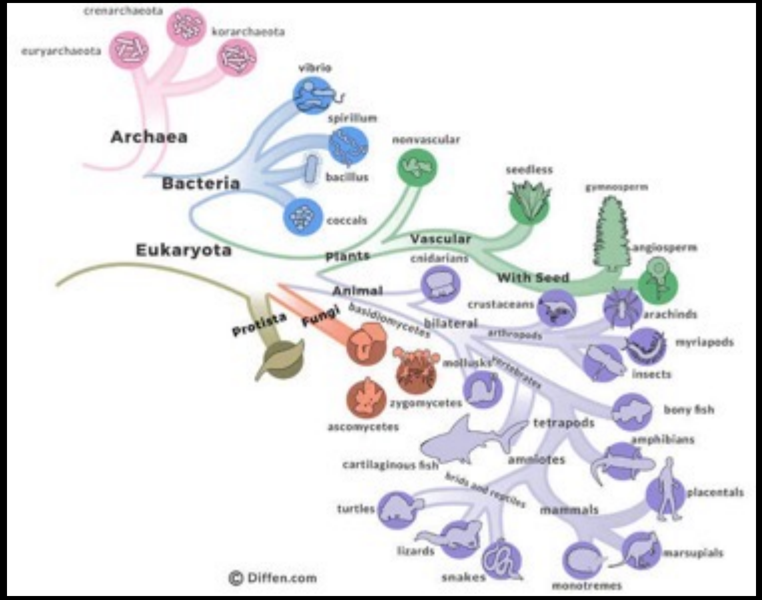


Water

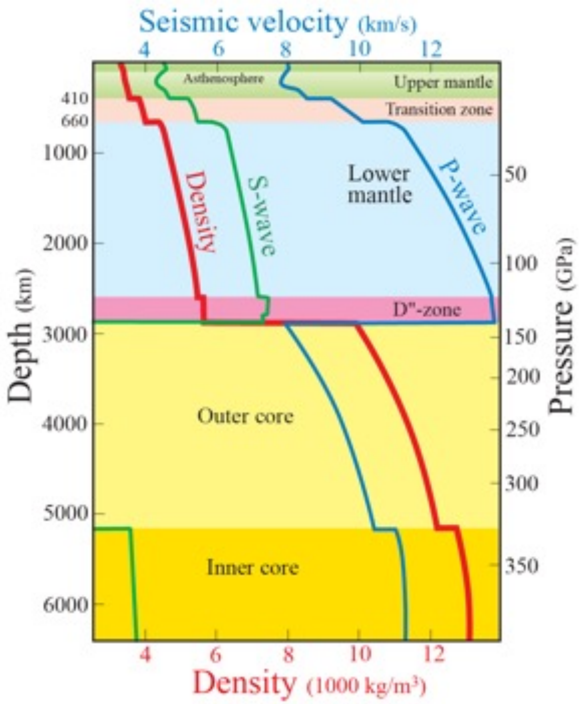
Life

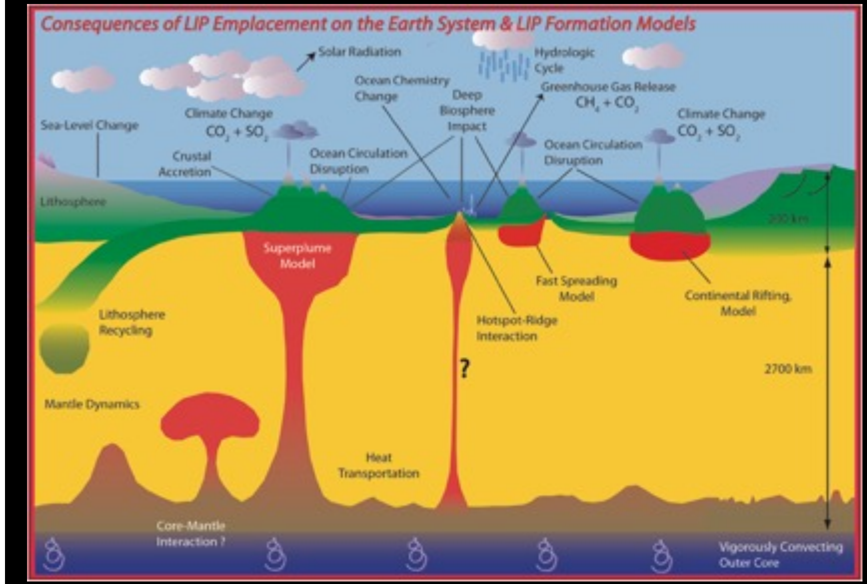
Plate Tectonics

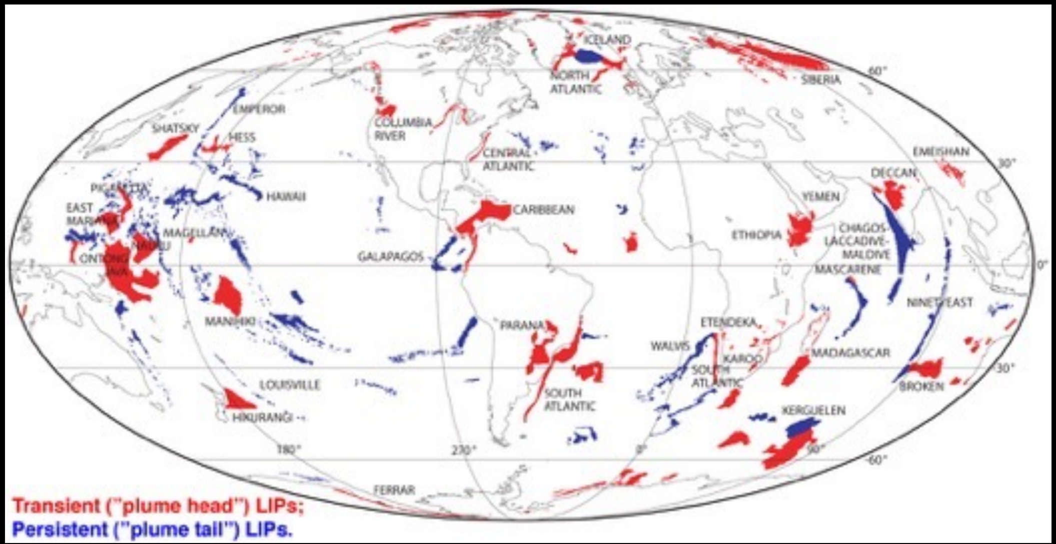




Plume Volcanism on Earth



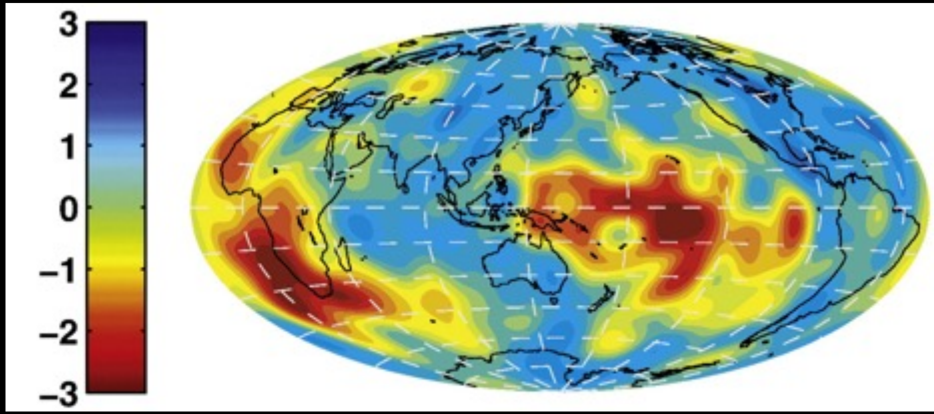




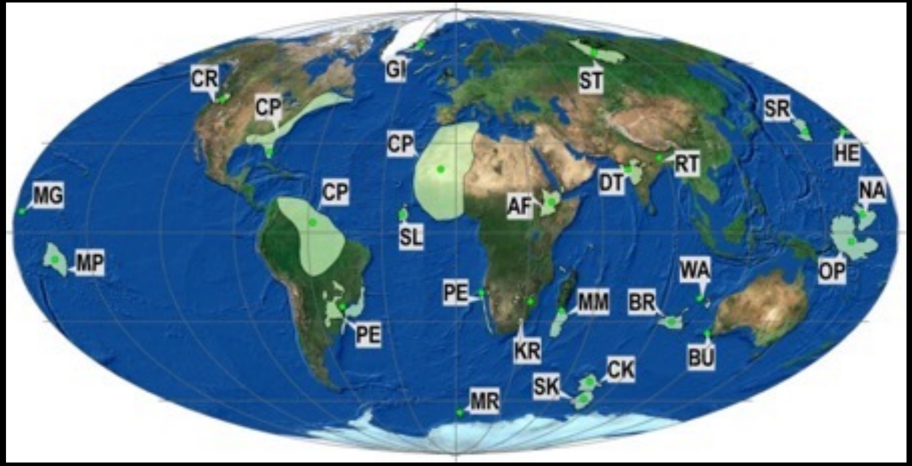
- Transfer of heat across a boundary
- Plume rise initiated by subducted material reaching the boundary
- Correlated with Large Low-Shear Velocity Provinces (LLSVPs) – thermochemical pile at CMB?

Large Low-Shear Velocity Provinces

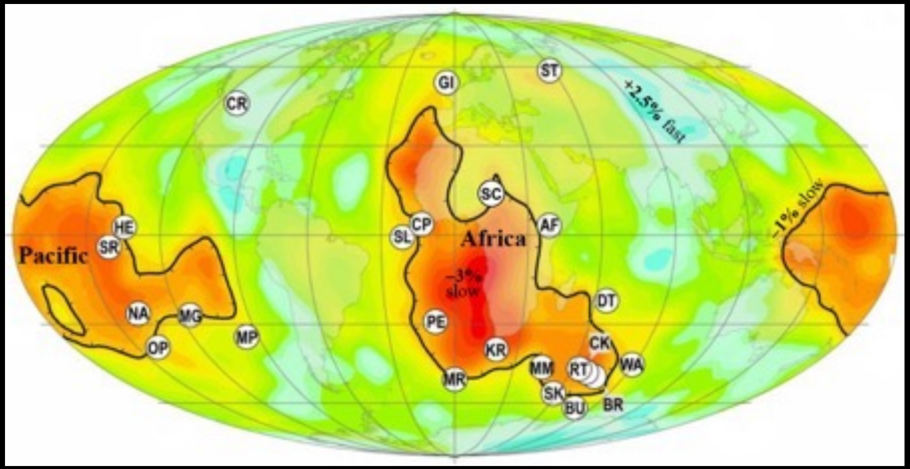
Two large antipodal LLSVPs **Africa** and **Pacific** (near equator - 180º apart)



Dziewonski et al. (2010) EPSL 299, 69-79



Large Igneous Provinces (LIPs)
- age span: 16-297 Ma
- irregular distribution



Paleogeographic relocation

- LIPs cluster near LLSVP margins
  - long-term stability, dense and hot

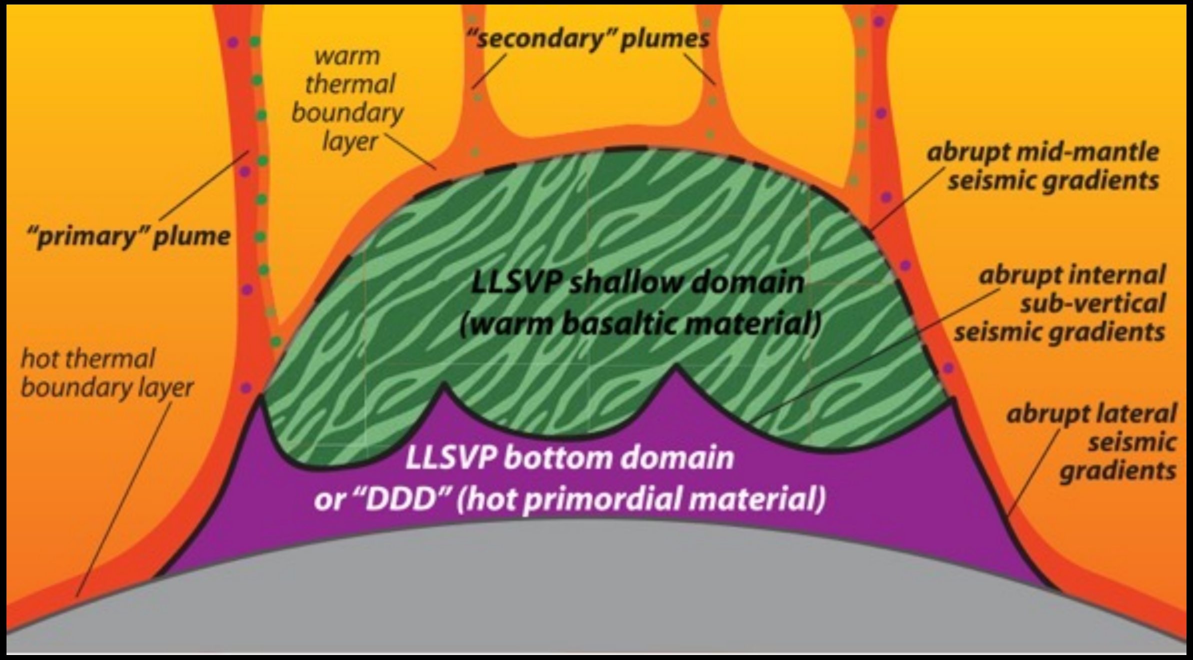
Burke & Torsvik, 2004, EPSL; Torsvik et al., 2006, GIJ; Burke et al. 2007, EPSL; Torsvik et al. 2008, EPSL; Torsvik et al. (2010, Nature)

Large Low-Shear Velocity Provinces

LLSVPs are compositionally subdivided into two domains:

- Primordial bottom domain near the core-mantle boundary
- Basaltic shallow domain that extends from 1100 to 2300 km depth.

Ballmer et al (2016) *Geochem. Geophys. Geosyst.*, **17**, 5056–5077, doi:10.1002/2016GC006605



- Double-layered piles exist for billions of of years if density differences of ~100 kg/m^3 exist.
- Short-lived "secondary" plumelets rise from LLSVP roofs and entrain basaltic material that has evolved in the lower mantle.
- Long-lived, vigorous "primary" plumes instead rise from LLSVP margins and entrain a mix of materials, including small fractions of primordial material.
- Consistent with the locations of hot spots relative to LLSVPs, and address the geochemical and geochronological record of (oceanic) hot spot volcanism.

Large Low-Shear Velocity Provinces

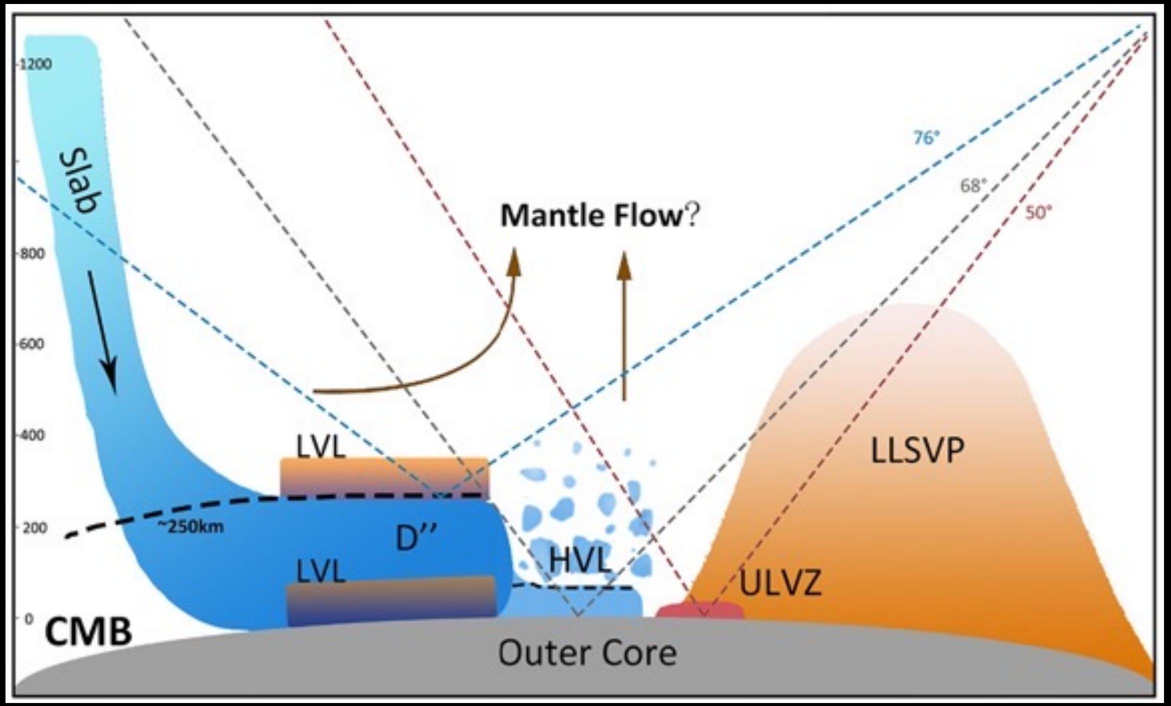
Possible LLSVP-material

Basalt-rich

- Separated from deep subducted lithosphere
  Niu (2018) *Geosci. Front*. **9**, 1265-1278
  Fan et al. (2022) *G3*, **23**, e2021GC009879
- Age of ~3-0 Ga

Peridotitic (or komatiitic) with elevated Fe/Mg-ratio

- Age of >3.0 Ga



Decomposition of Oxidized Mantle

Wang et al. (2021) Nat. Comm. https://doi.org/10.1038/s41467-021-22185-1

- Enrichment of Fe^{3+}-rich bridgmanite in a pyrolitic composition can explain the observed features of the LLSVPs.
- Presence of Fe^{3+}-rich materials within LLSVPs may have profound effects on the deep reservoirs of redox-sensitive elements and their isotopes.

Large Low-Shear Velocity Provinces

Possible LLSVP-material

Basalt-rich

- Separated from deep subducted lithosphere
  Niu (2018) *Geosci. Front.* **9**, 1265-1278
  Fan et al. (2022) *G3*, **23**, e2021GC009879
- Age of ~3-0 Ga

Peridotitic (or komatiitic) with elevated Fe/Mg-ratio

- Age of >3.0 Ga

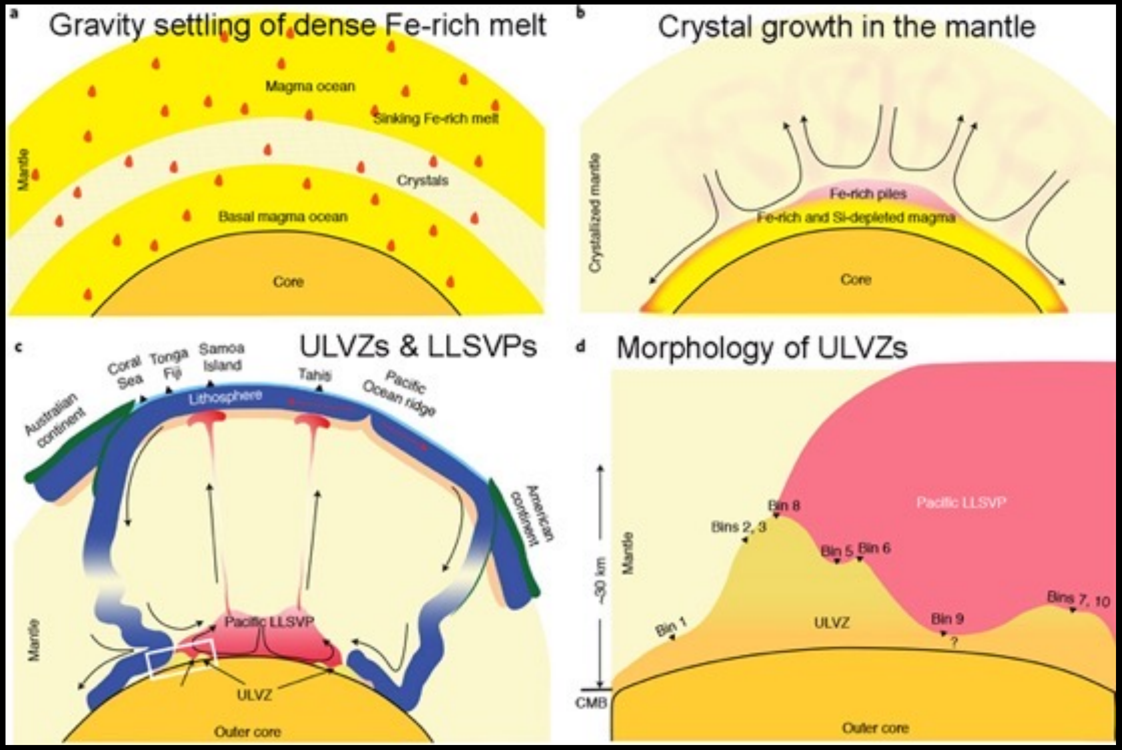
Primordial Magma Ocean Cumulates

Kreielkamp et al. (2022) *EPSL* **579**, 117357.
Pachhai et al. (2022) *Nat. Geosci.* **15**, 79-84.

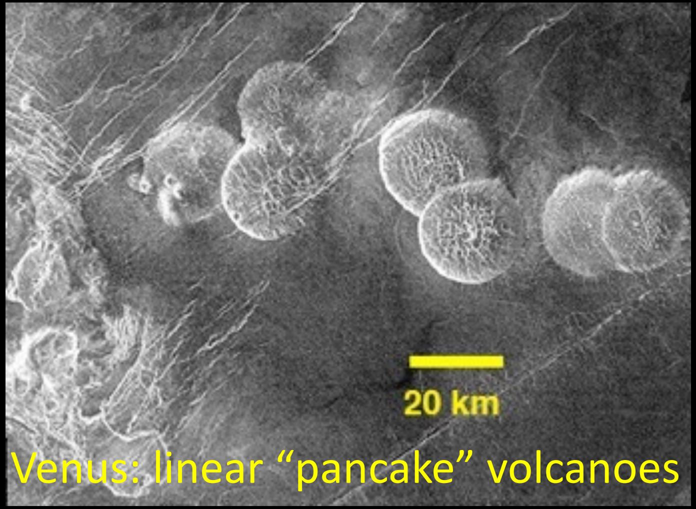
- Assumed to be compositionally dense leftovers from the magma-ocean phase that are formed to dense accumulations (piles) by mantle flow.

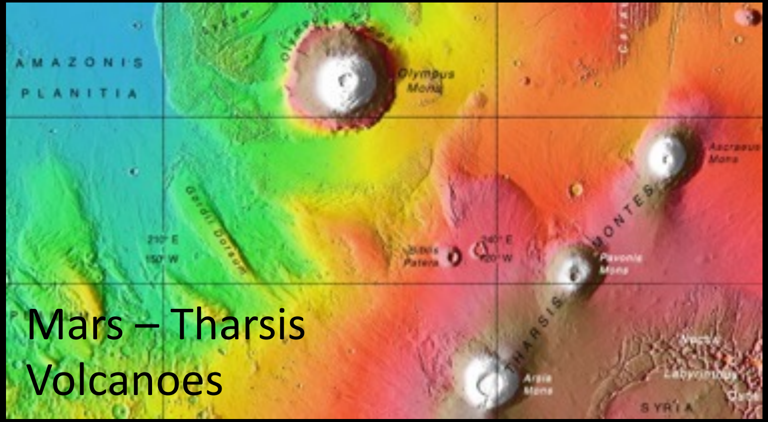
Schaefer & Elkins-Tanton (2018) *Phil Trans. Roy. Soc. A* **376**, 20180109.

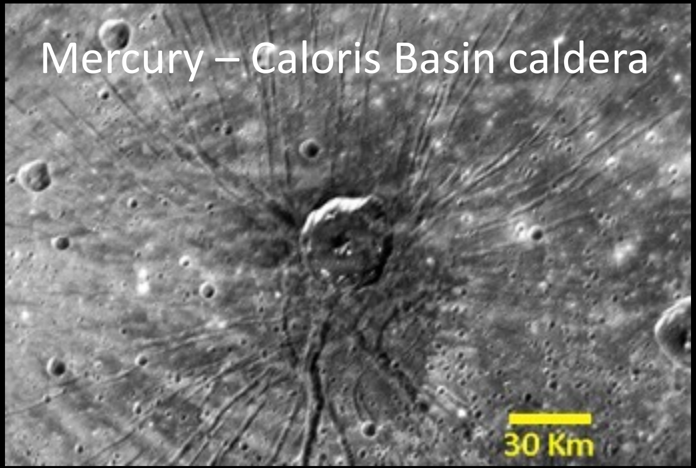
- Magma ocean crystallization leads to a massive mantle overturn that may set up a stably stratified mantle.
- Could lead to significant delays or total prevention of plate tectonics on some planets.

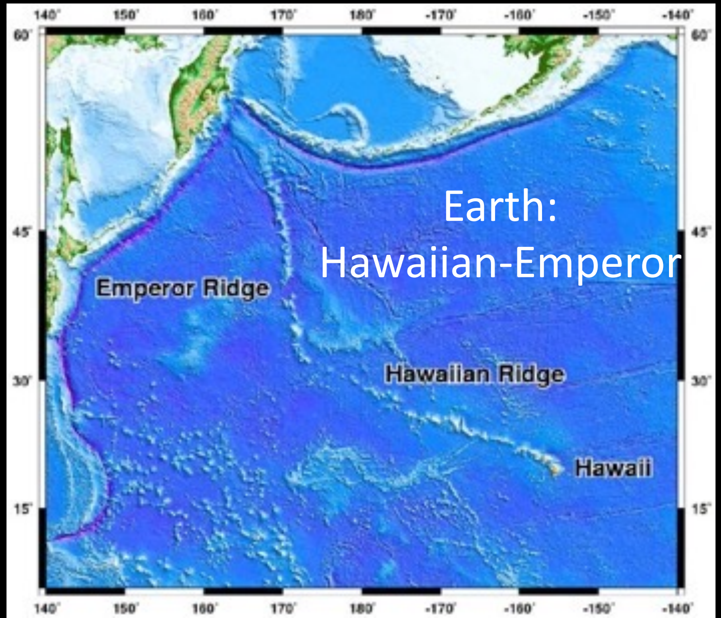


Solar System Volcanism





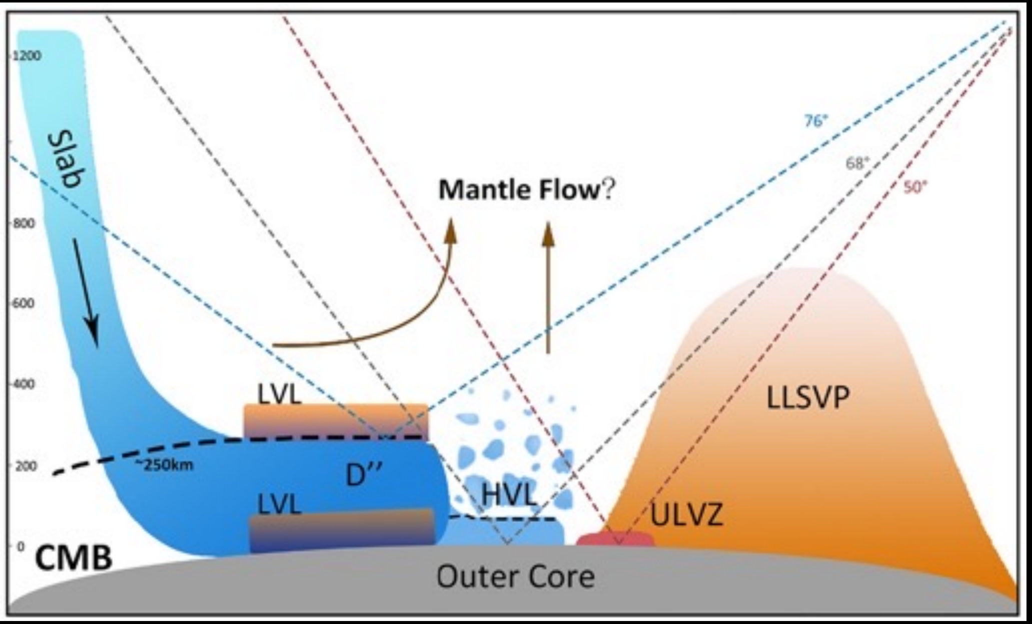




- Plate Tectonics & subduction-related volcanism is unique to Earth.
- Hot spot volcanism is seen throughout the planets of the inner Solar System.
- How is plume volcanism initiated without plate tectonics?

Origin of LLSVPs

- Suggests subducted material in LLSVPs are a secondary feature of LLSVPs IF these induce plume volcanism on other planetary bodies.



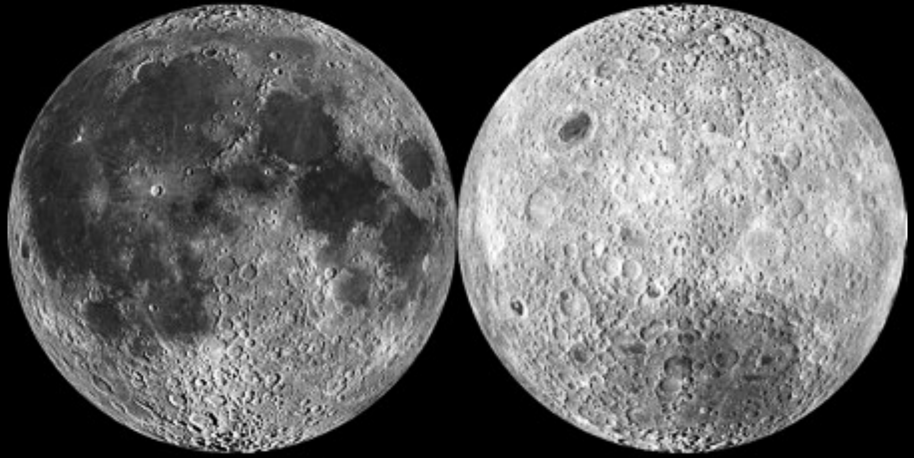
Hypothesis: LLSVPs represent evidence of the primordial differentiation of terrestrial planetary bodies through an initial magma ocean stage, and these are responsible for plume volcanism.

- Cannot be tested on Earth because of its size and long-lived heat engine.
- Difficult to test on other planets for the same reason.

The Moon is ideal for testing this hypothesis

Our Moon

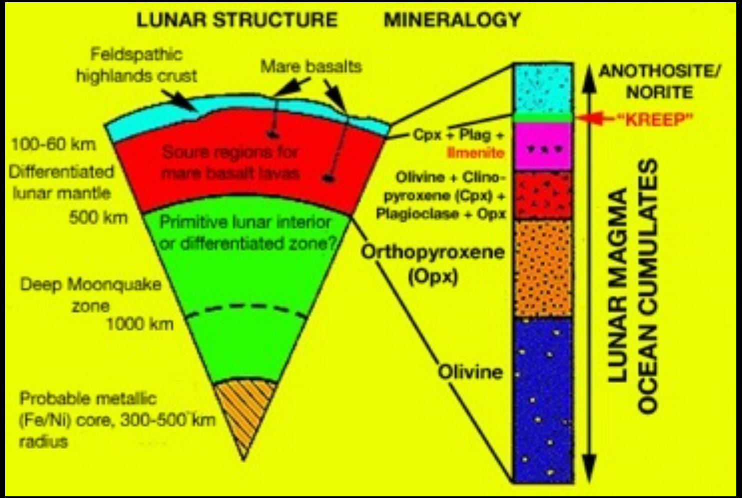
Near (left) **and far** (right) **sides of the Moon**

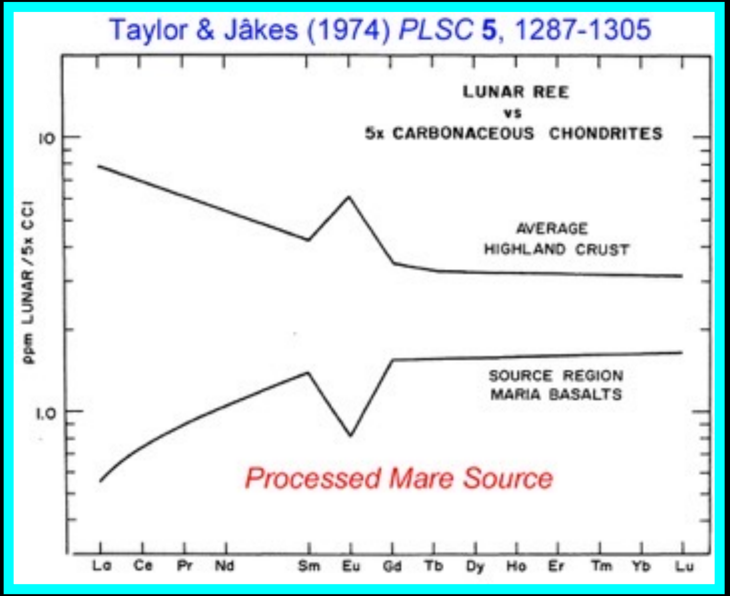


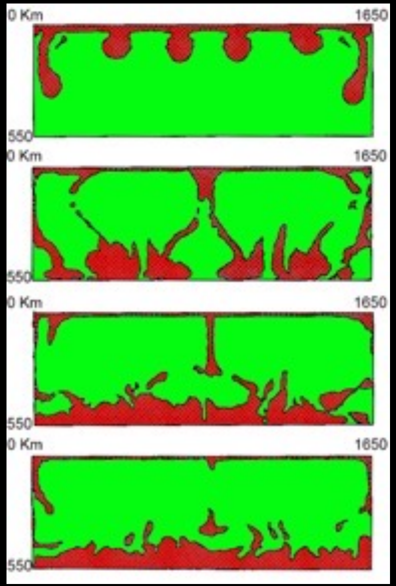
Taken by the Lunar Reconnaissance Orbiter

- Dark area = mare (flood) basalts.
- Mostly on the near side – crust is thinner.
- Derived from a mantle comprised of magma ocean cumulates.
- Crust = plagioclase flotation cumulates.

- Differentiated source for basalts:
- Olivine + Orthopyroxene early;
- Plagioclase Clinopyroxene + Ilmenite later;
- “KREEP” = last dregs.
- Density instability – overturn of the cumulate pile.







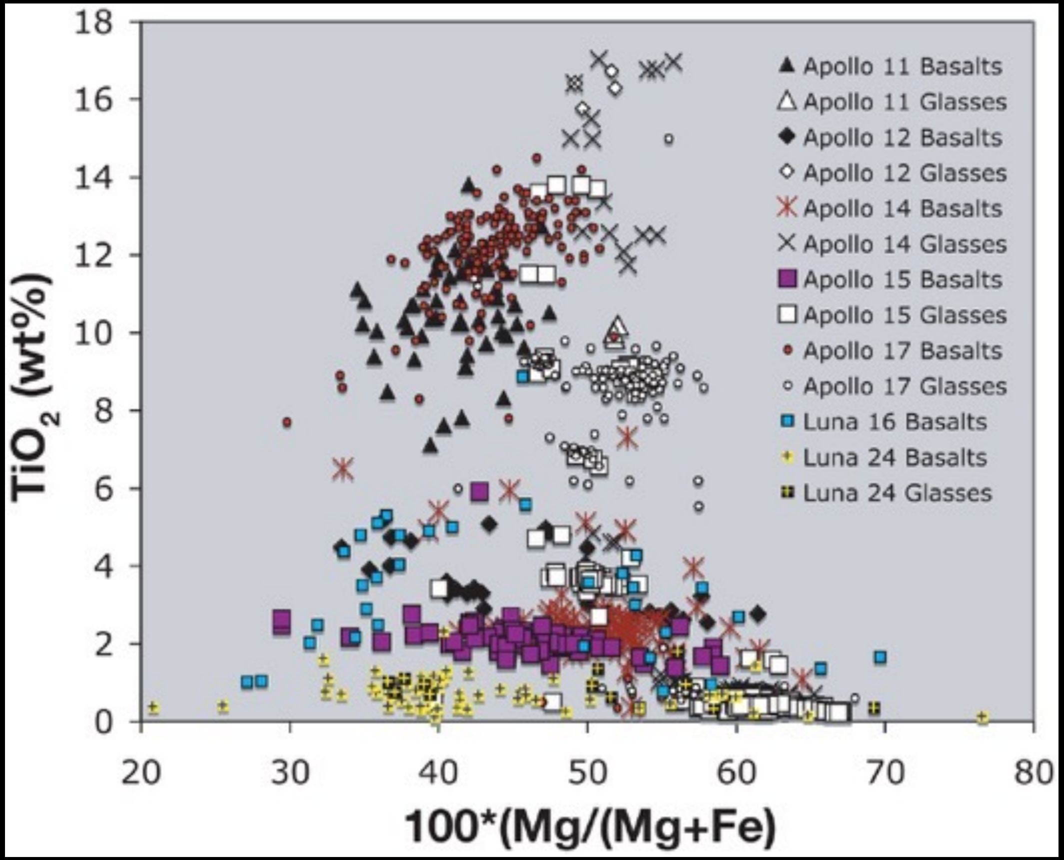
Cumulate Overturn

Spera (1992) *GCA* **56**, 2253-2266

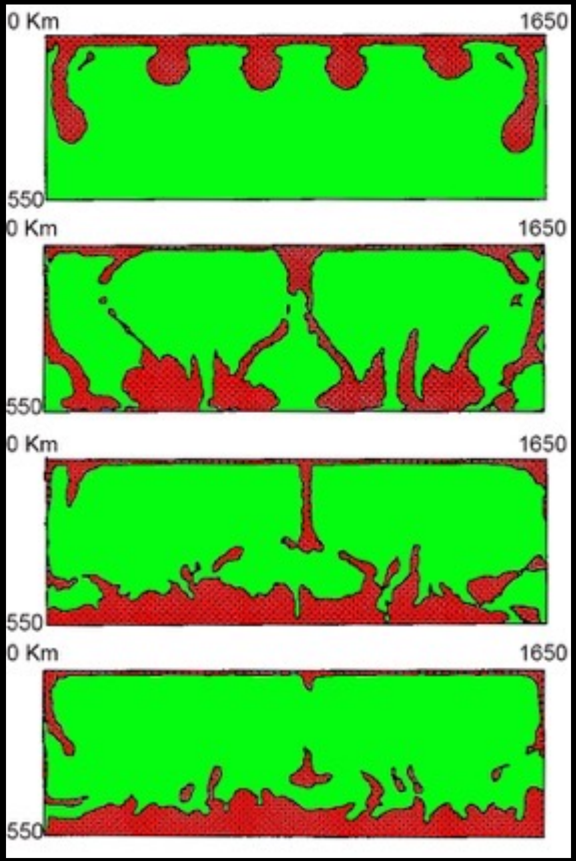
Our Moon

Basalts & Volcanic Glasses:

- Very Low-Ti (<1 wt.% TiO_2)
- Low-Ti (1-5 wt.% TiO_2)
- High-Ti (>5 wt.% TiO_2)

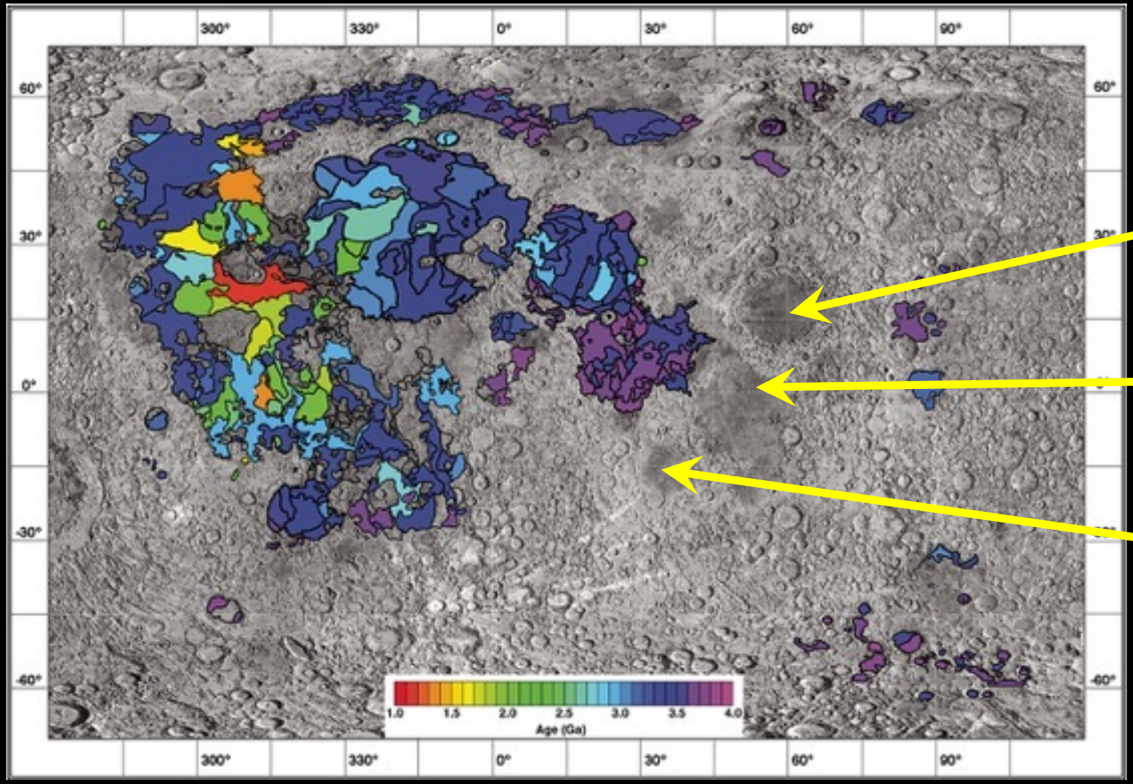


Cumulate Overturn



Spera (1992) *GCA* **56**, 2253-2266

Our Moon



Crisium = 3.42 Ga

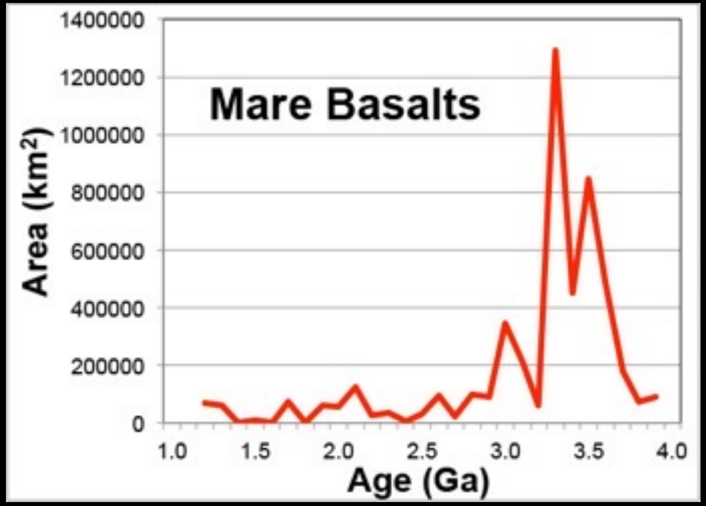
Nyquist et al., 1978, Mare Crisium, 631-656

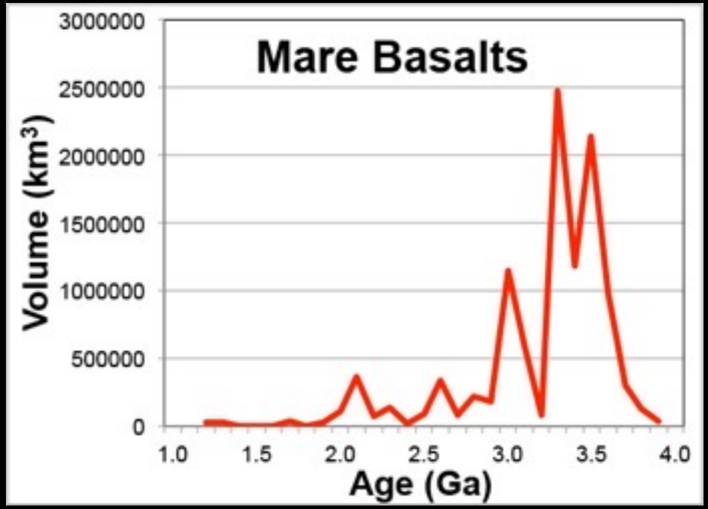
Fecunditatis = 3.62 Ga

Papanastassiou & Wasserburg, 1972, *EPSL* **13**, 368-374

Nectaris = 3.89 Ga

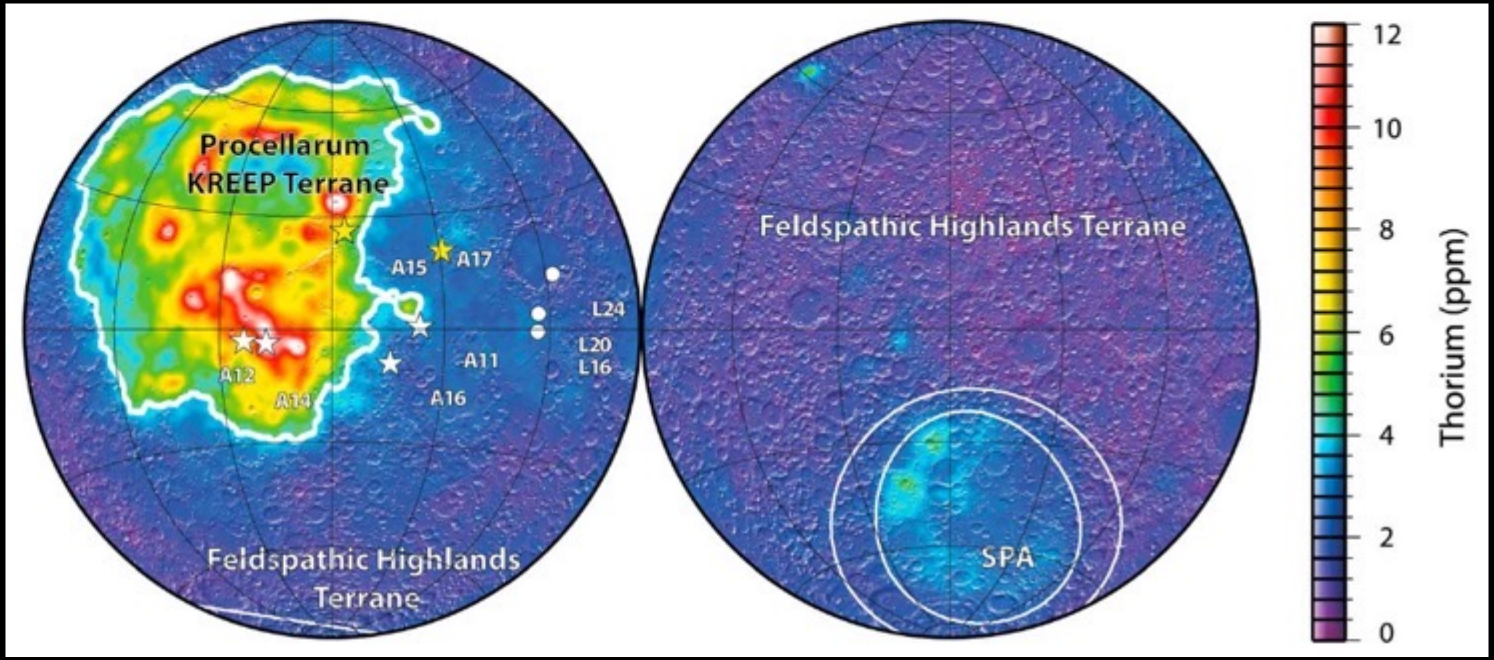
Stöffler & Ryder, 2001, *Space Sci. Rev.* **96**, 9-54



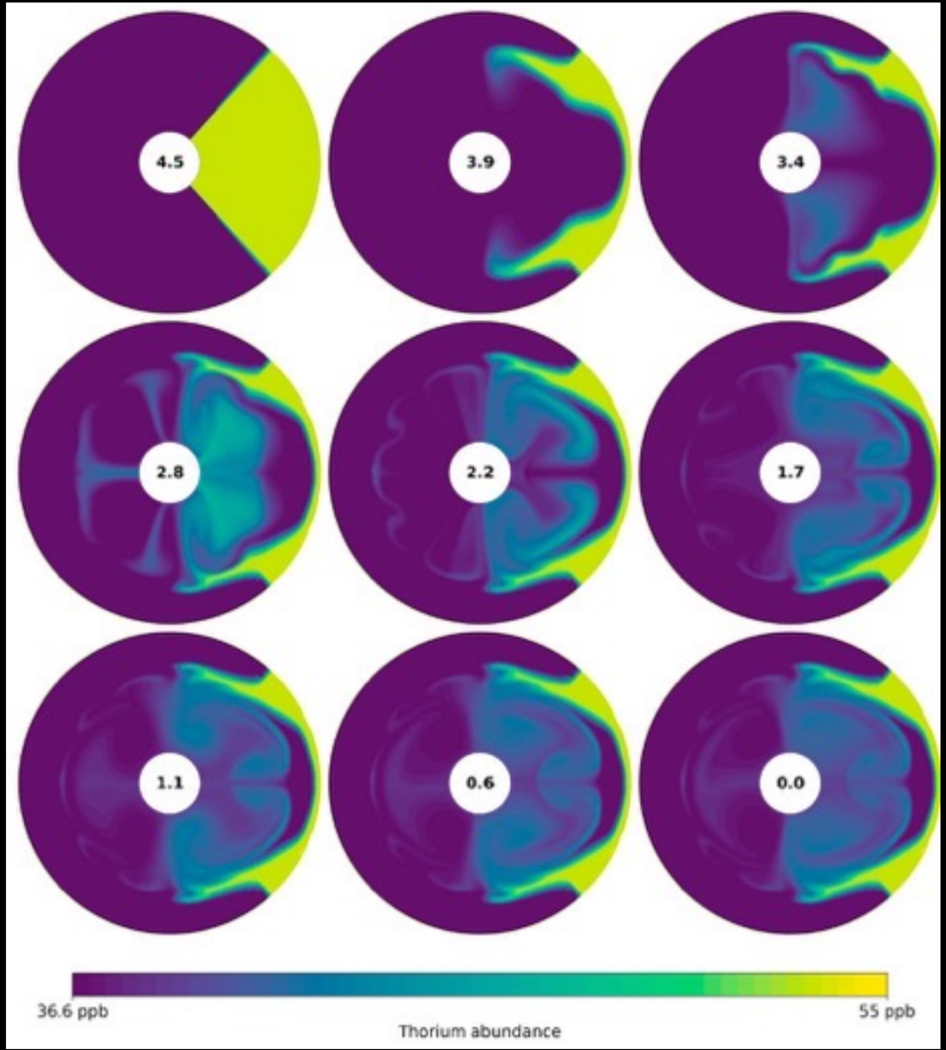


Hiesinger et al. (2011) *GSA Spec. Pap.* **477**, 1-51

Our Moon



Plume activity over the life of the Moon.



Th “hot spot” identified from the Lunar Prospector mission – does it extend to depth?

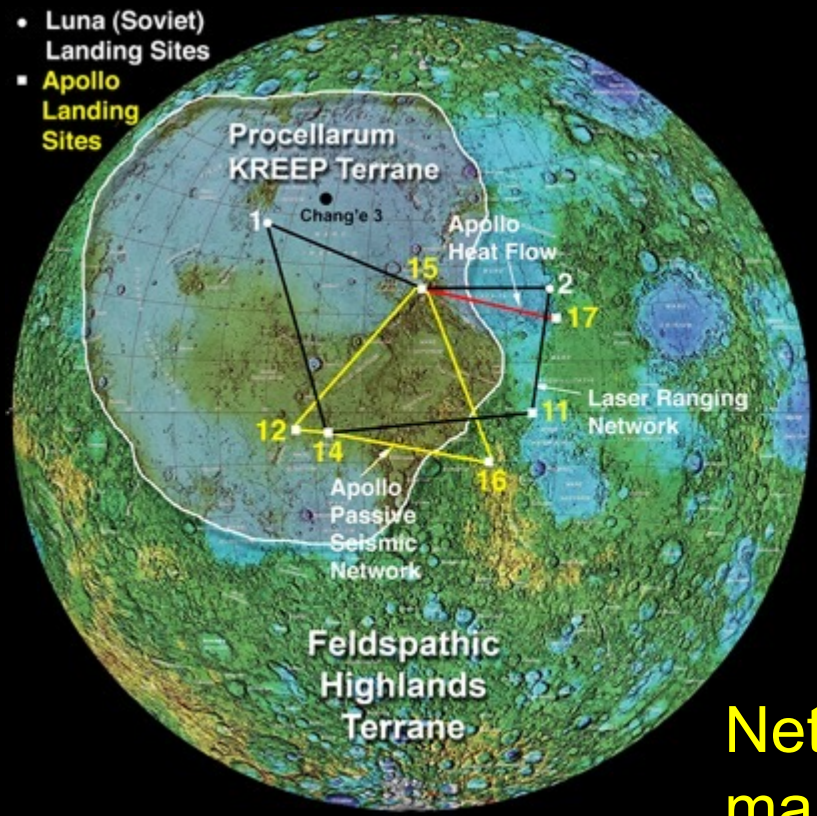
Youngest volcanics in the Th hot spot area: Procellarum KREEP Terrane.

Laneuville et al. (2018) *JGR Planets* **123**, 3144–3166,

Our Moon

Apollo detected 4 types of seismic events on the Moon.

Verification needed – Geophysical data

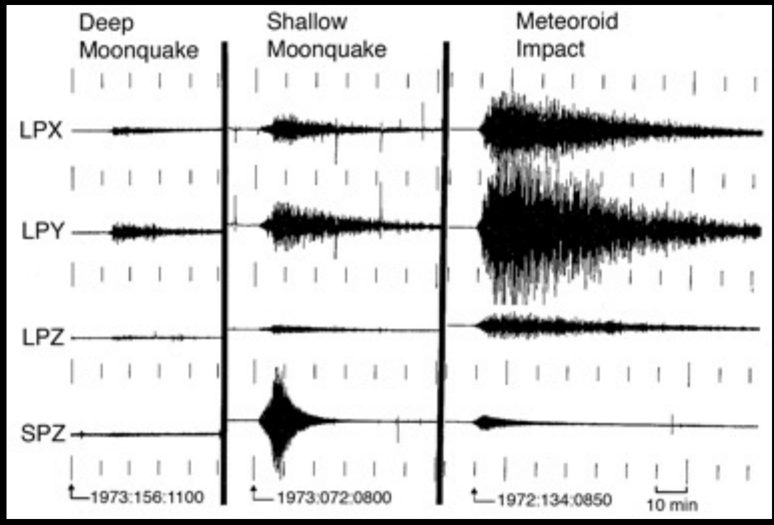


1) Thermal Moonquakes - Associated with heating and expansion of the crust. Lowest magnitude of all moonquakes.

2) Deep Moonquakes - 850-1,000 km. > 7,000 recorded. Originate from "nests" - >300 nests defined from Apollo seismic data to date. Small magnitude (< 3). Associated with tidal forces. Predominantly near side.

3) Meteoroid Impacts - >1,700 events representing meteoroid masses between 0.1 and 100 kg were recorded 1969-1977. Smaller impacts were too numerous to count.

4) Shallow Moonquakes - some > 5 magnitude. Exact locations unknown. Indirect evidence suggests focal depths of 50-200 km.



Network too close to detect deep mantle and core structure

Using the Moon to Explore the Origin of LLSVPs: Lunar LIPs

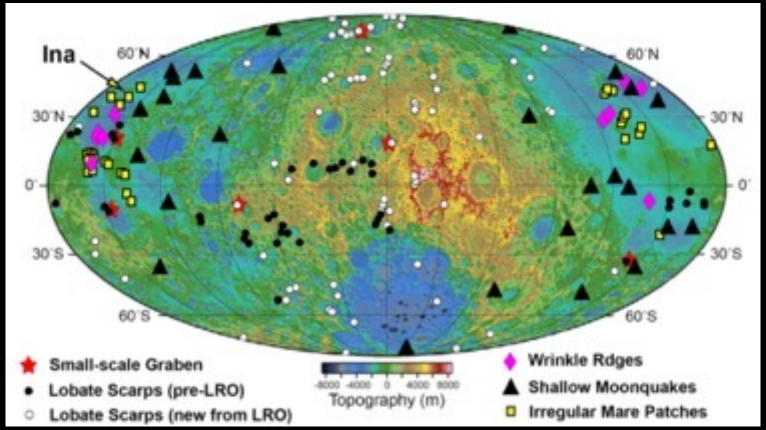
The Lunar Geophysical Network Mission

- High priority science in NASA's last two decadal surveys.
- Named medium-class mission in the New Frontiers line ($1-1.5 billion cost cap).
- Planetary Mission Concept Study funded in 2019 https://science.nasa.gov/science-pink/s3fs-public/atoms/files/Lunar%20Geophysical%20Network.pdf
- Globally distributed network of seismometers, heat flow probes, electromagnetic sounders, laser retroreflectors

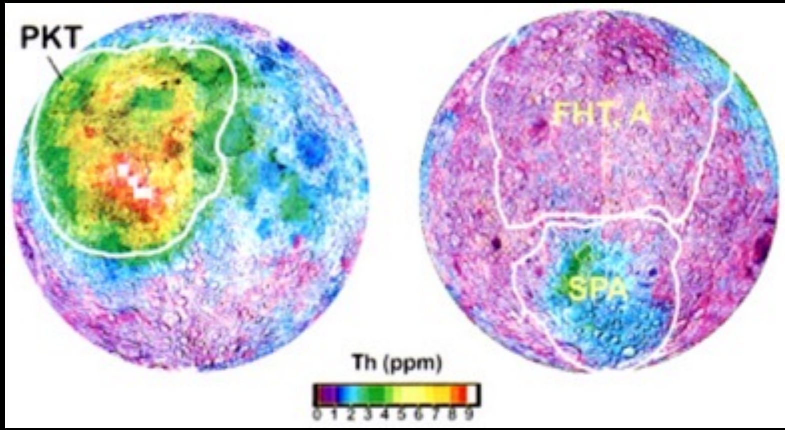
Using the Moon to Explore the Origin of LLSVPs: Lunar LIPs

Goal: To understand the initial stages of terrestrial planet evolution.

Objectives: Define the interior structure of the Moon.
Constrain the interior and bulk composition of the Moon.
Delineate the vertical and lateral heterogeneities within the interior of the Moon as they relate to surface features and terranes.
Evaluate the current seismo-tectonic activity of the Moon.



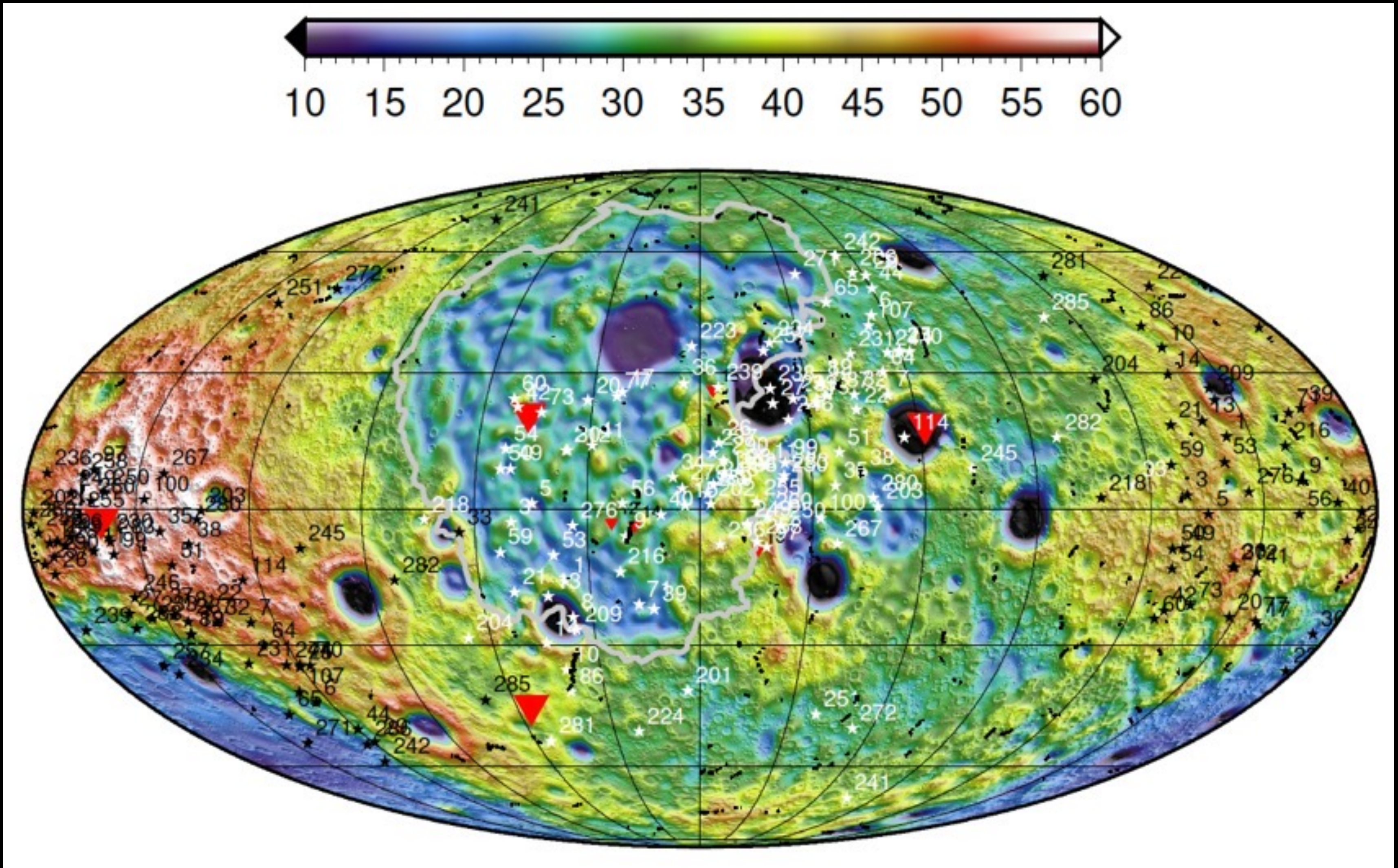
Watters et al. (2012) Nature Geosci.. 5, 181-185



Jolliff et al. (2000) J. Geophys. Res. 105, 4197-4216

Using the Moon to Explore the Origin of LLSVPs: Lunar LIPs

- 4 identical landers deployed globally.
- Communications satellite required for the far-side station.
- Sites chosen to maximize science return.



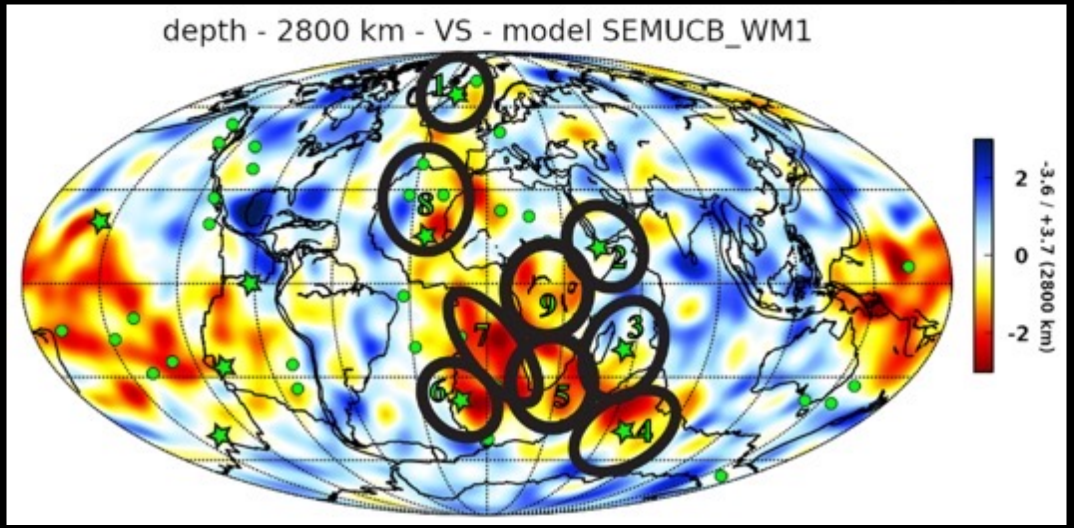
Landing sites for 4 geophysical stations:
Haviland et al. (2022) *Planet. Sci. Jour.* **3:40** (21 pp.)
https://doi.org/10.3847/PSJ/ac0f82

Summary

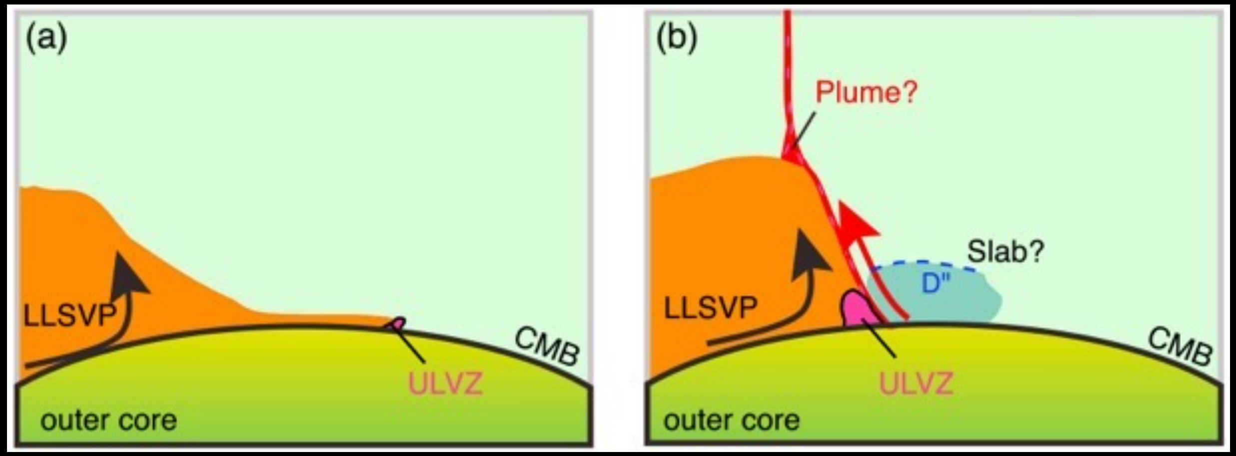
- Plume volcanism is the norm on rocky planetary bodies in the Solar System.
- On Earth, plume volcanism is associated with LLSVPs that contain accumulated subducted material.
- How is plume volcanism initiated on other planetary bodies?
- Ultimate origin of the LLSVPs is due to cumulates from initial planetary differentiation via a magma ocean – the Earth story is confused by subsequent accumulation of subducted material at the CMB.
- Test this on the Moon through the Lunar Geophysical Network mission:
  - Moon has experience plume activity (flood basalts, Th anomaly)
  - The lunar interior preserves the magma ocean cumulates from the initial differentiation (as see in mare basalt compositions).

Large Low-Shear Velocity Provinces

- LLSVPs contain well-separated, low-velocity conduits that extend vertically throughout the lower mantle.
- Each LLSVP is composed of a bundle of thermochemical upwellings probably enriched in denser than average material.
- The overall shape of the LLSVPs controlled by the distribution of subducted slabs.
- Position of thermochemical LLSVPs and individual upwelling dynamics should be time dependent.



Davaille & Romanowicz (2020) *Tectonics* **39**, e2020TC006265



Ultralow velocity zones (ULVZs) cluster along the edges of the LLSVPs.

- (a) ULVZ locates at the far edge of the LLSVP.
- (b) Steepened edge of the LLSVP may develop due to presence of subducted material.
- ULVZ may be driven towards the interior of the LLSVP, and develop a possible plume.

Sun et al. (2019) *GRL* **46,** 3142-3152