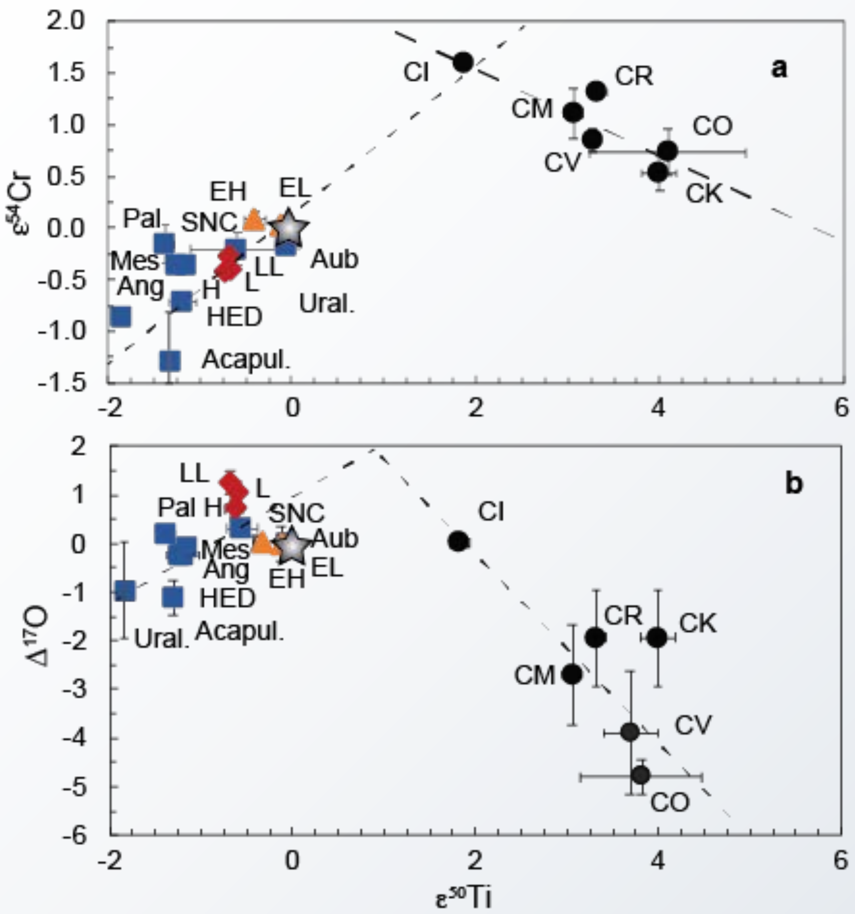
Deep Time, Deep Earth, Big Questions

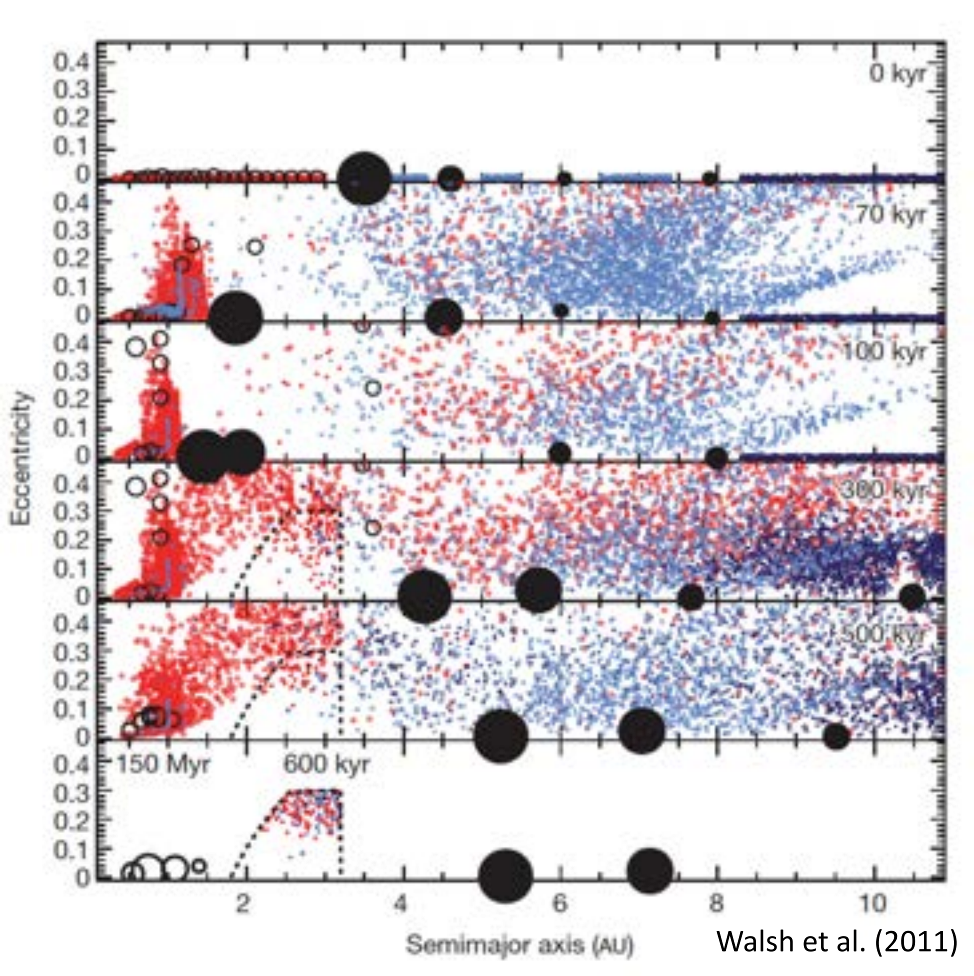
William White
Dept. of Earth & Atmospheric Sciences
Cornell University
Ithaca, NY USA
wmw4@cornell.edu

Big Questions, Big Debates

- Earth's formation & Composition
  - What was the Earth made from and what was the process?
- Continental crust formation through time
  - How much was created and how much destroyed?
  - Why is crust formation (or survival) punctuated in time?
  - Why is Archean crust different?
  - Why the change in the Neoproterozoic?
- When did modern plate tectonics begin?
- Why did O_2 of the Earth's atmosphere dramatically change in the Paleoproterozoic and again in the Neoproterozoic?
- What are the LLSVPs at the base of the mantle?
  - What are they made of?
  - How have they evolved through time?
- Does the deep mantle ultimately control the evolution of the Earth's surface or vise versa?

Solar System Formation



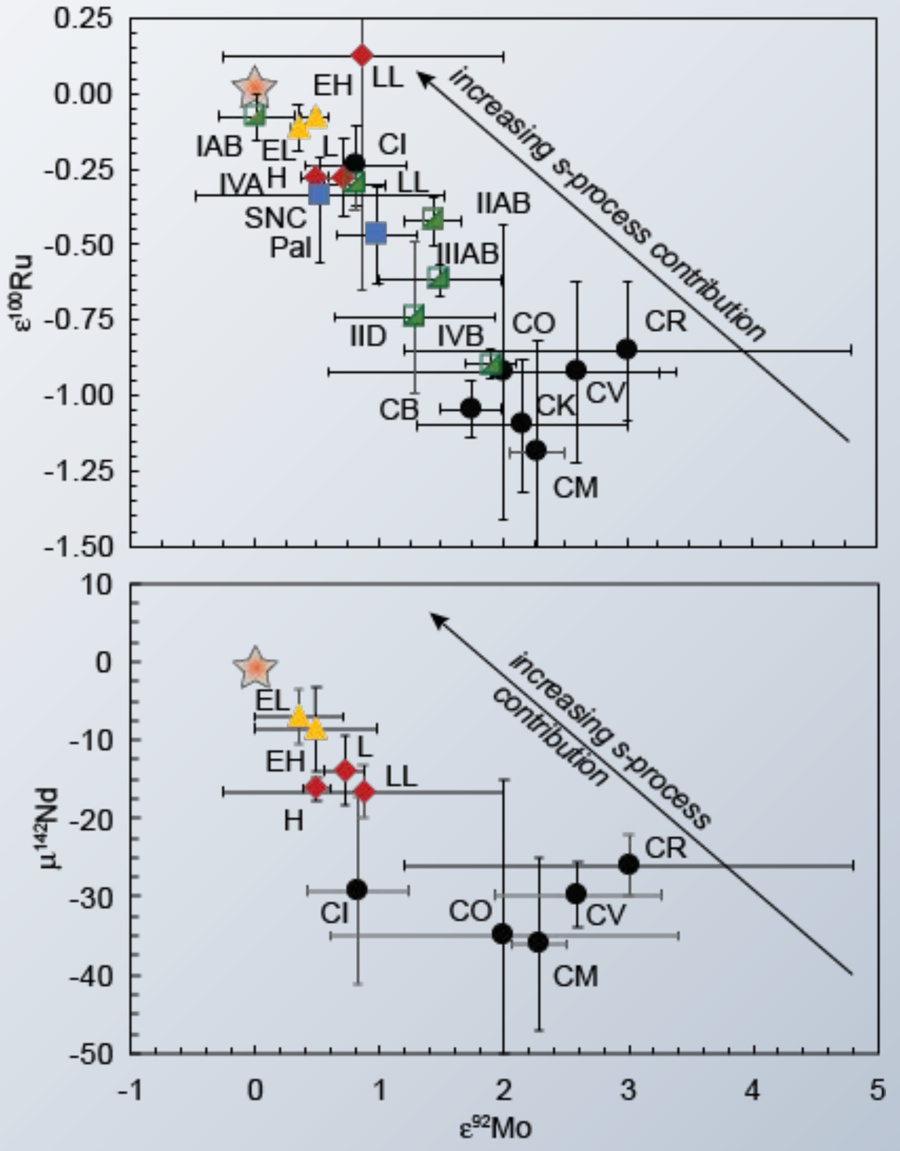


Grand Tack Model

Carbonaceous chondrites, such as Ryugu, are isotopically distinct, which reflects primary heterogeneity in material that formed the solar system, with the giant planets initially forming a boundary. The Grand Tack mixed CC material inward, supplying much of Earth's volatiles.

Earth's Formation

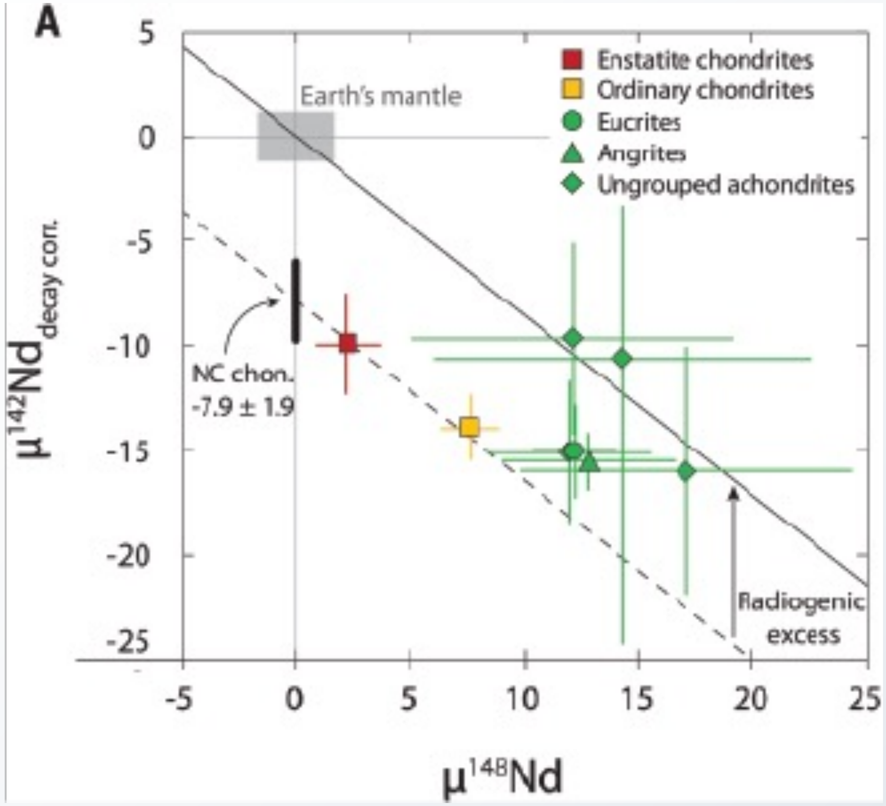
- The Earth is more enriched in s-process isotopes than all other analyzed bulk solar system materials and less like C. chondrites.
- *"Currently, no mixing model can account for the observed composition of the Earth using known materials"* – Metzger et al. Space Sci. Rev., 2020



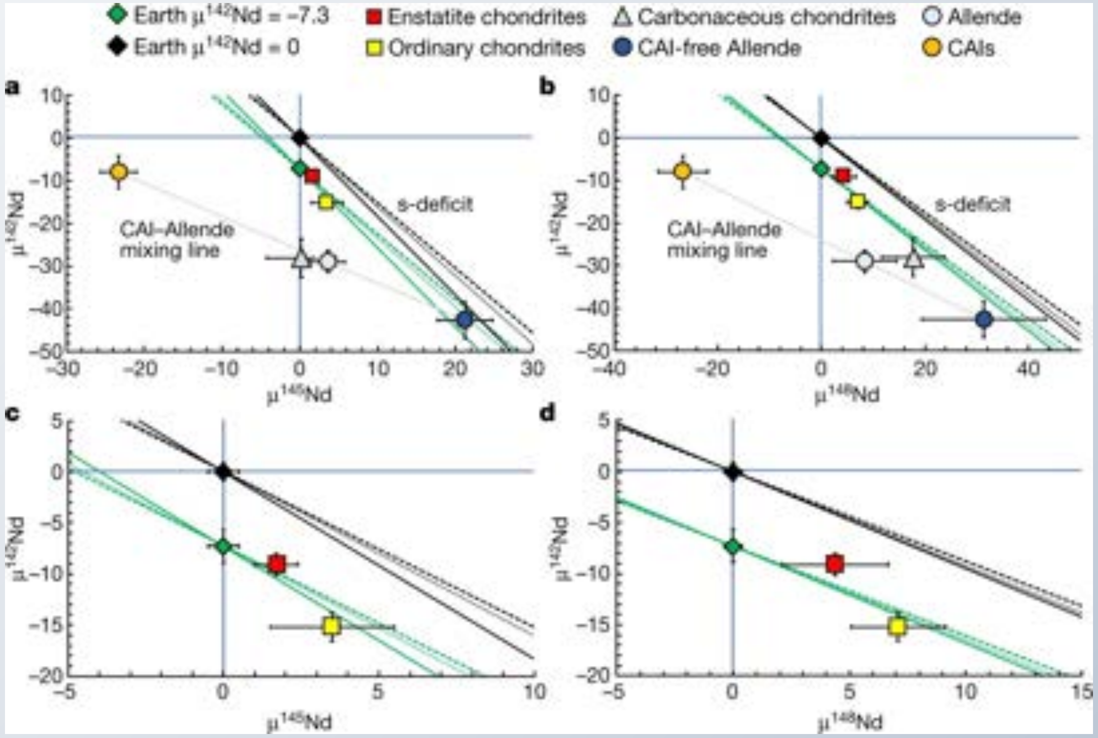
Possible missing inner solar system component?

Earth's composition

- ^{142}Nd produced by the extinct radionuclide ^{146}Sm.
- Excess terrestrial ^{142}Nd requires as higher than chondritic Sm/Nd ratio, implying a depletion in the Earth of refractory incompatible elements.

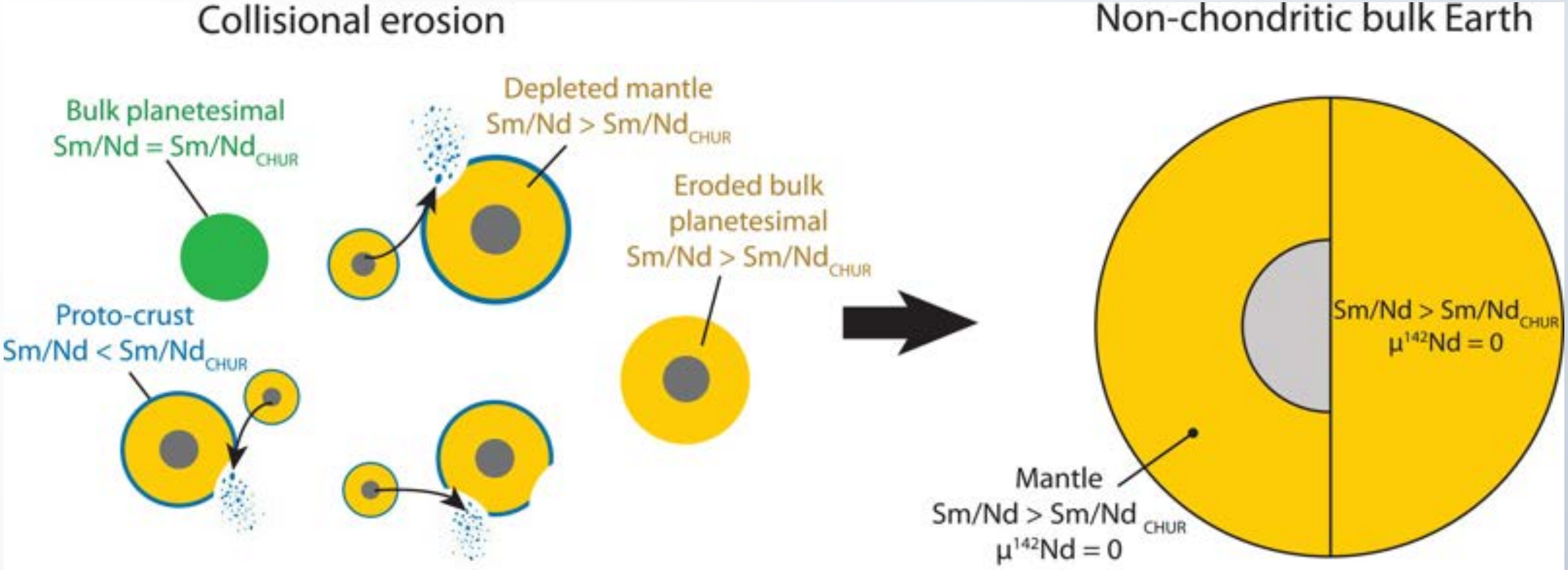


From Frossart et al. (2022)



From Johnston et al. (2022)

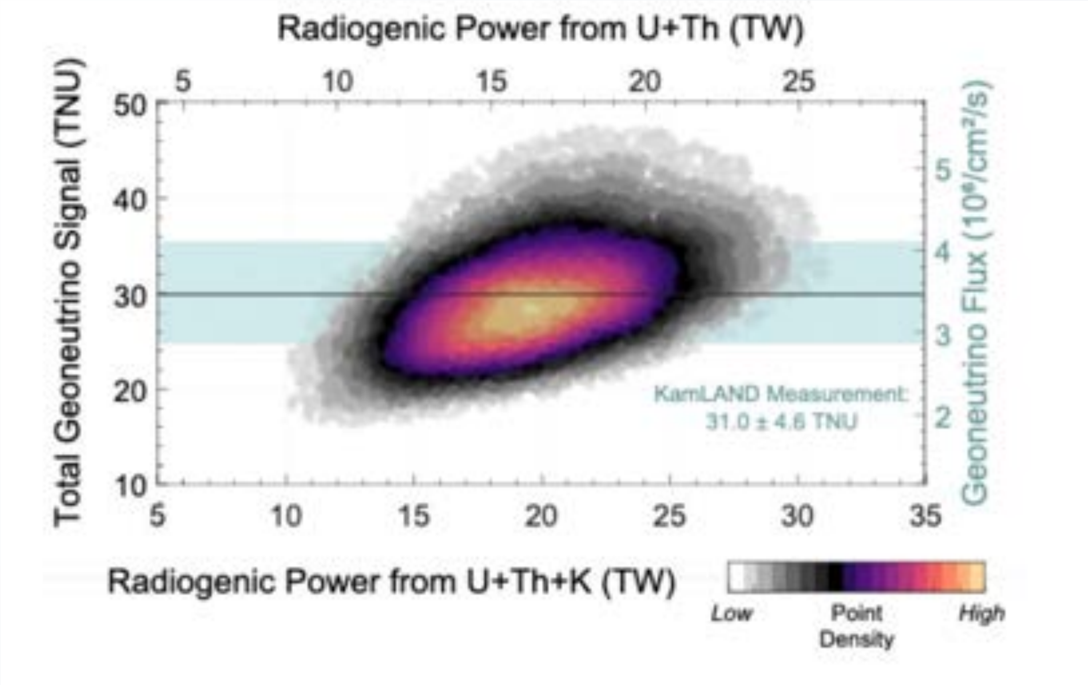
Collisional Erosion may be the cause



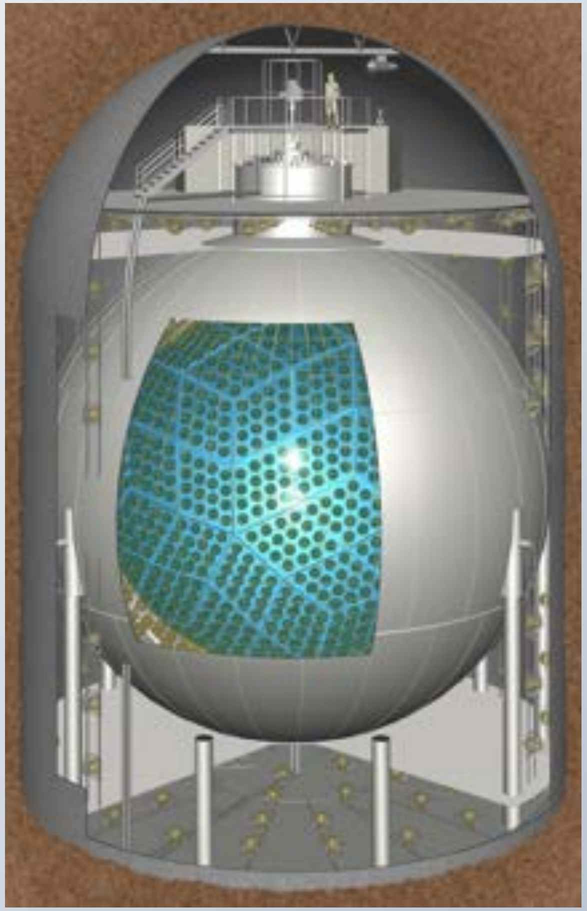
From Fossart et al. (2022)

This predicts a depletion of the Earth in heat producing elements U, Th, and K relative to chondritic values

Geoneutrinos may help us better constrain Earth's composition and heat production

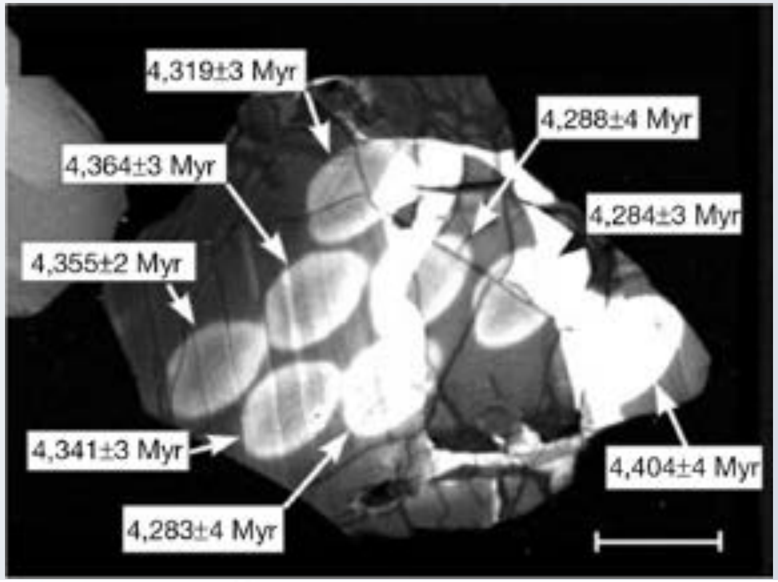


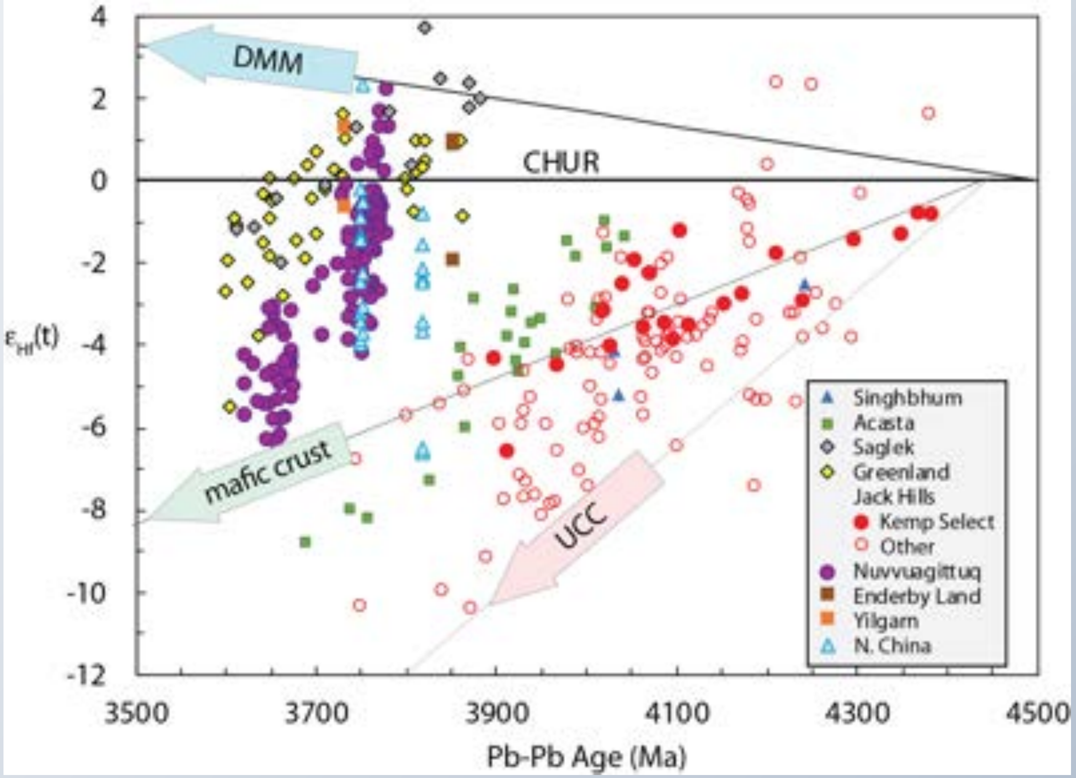
McDonough (unpublished)



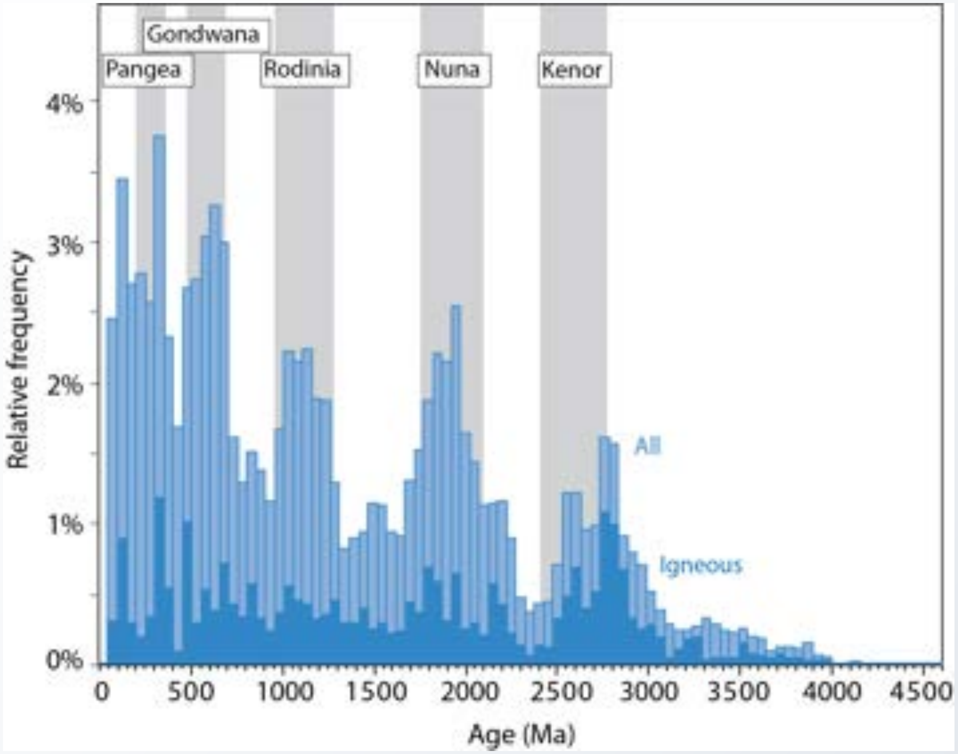
Crustal Evolution: Hadean

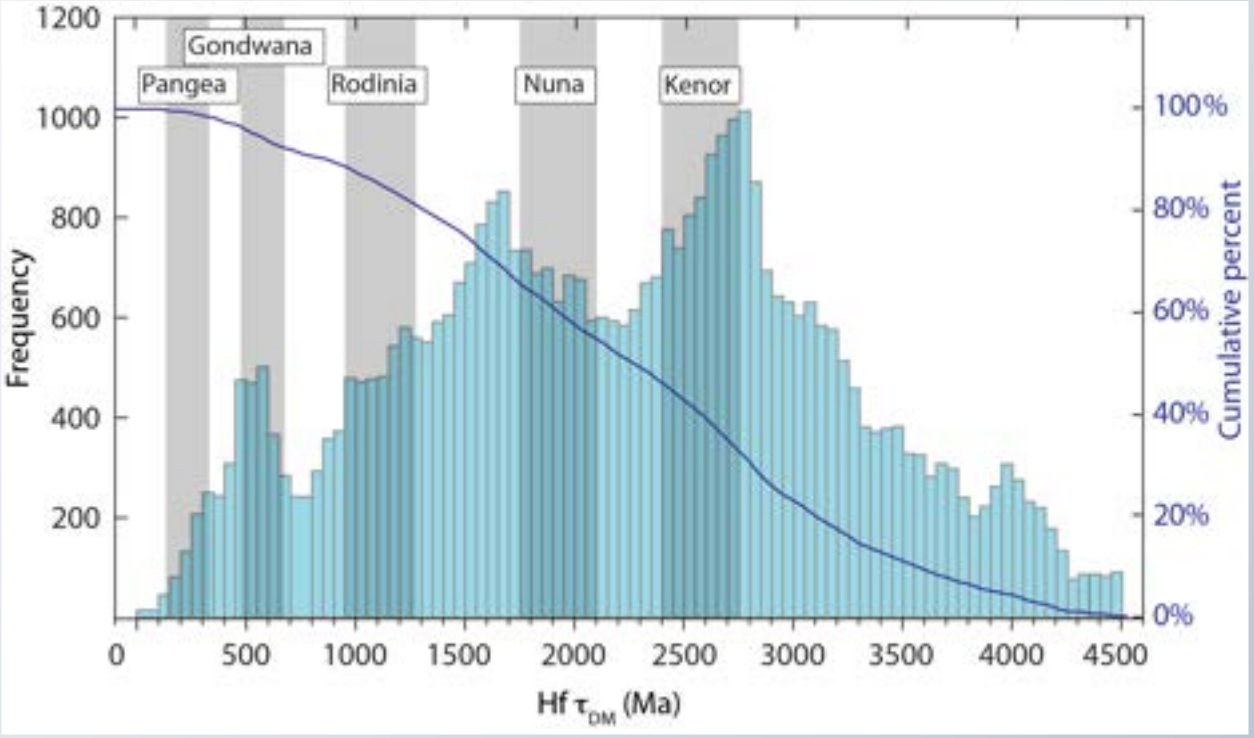
- *In situ analyses show that* zircons older than 4 Ga have now been found on nearly every continent, yet no >4 Ga crust exists.
  - Continental crust formation began in the Hadean.
- What happened to it?
  - Simultaneous *in situ* determination of Hf isotope ratios and Pb age help answer this.
  - It appears much of it was recycled into new crust.
  - *But how much existed and how much was recycled into the mantle remains unclear.*





Continental crust formation appears to have happened in pulses –why?

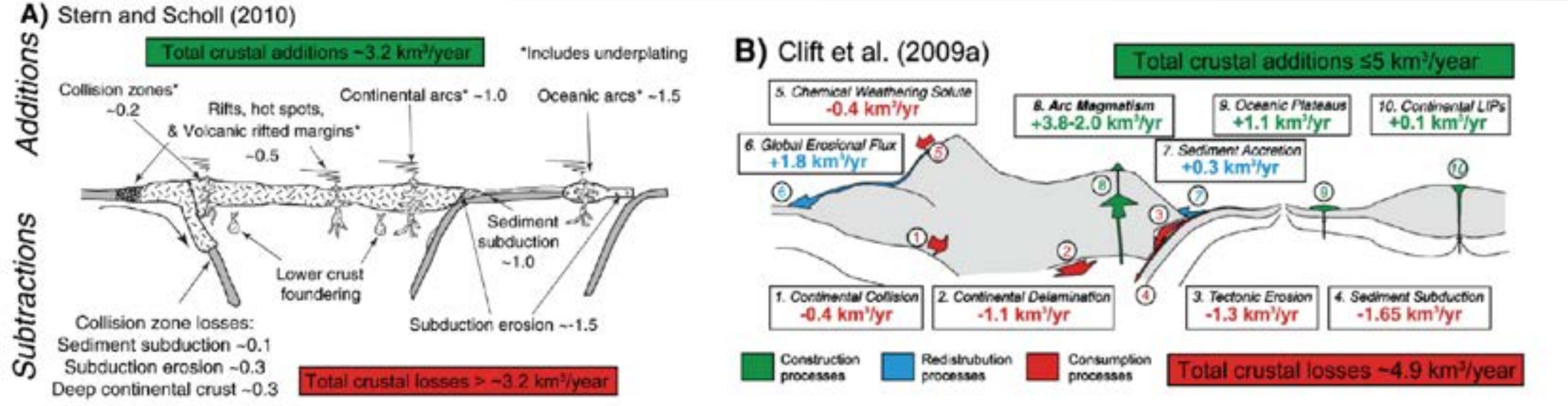




- Zircon ages suggest increasing crustal production over time.
- Does this reflect crust production or merely preservation?

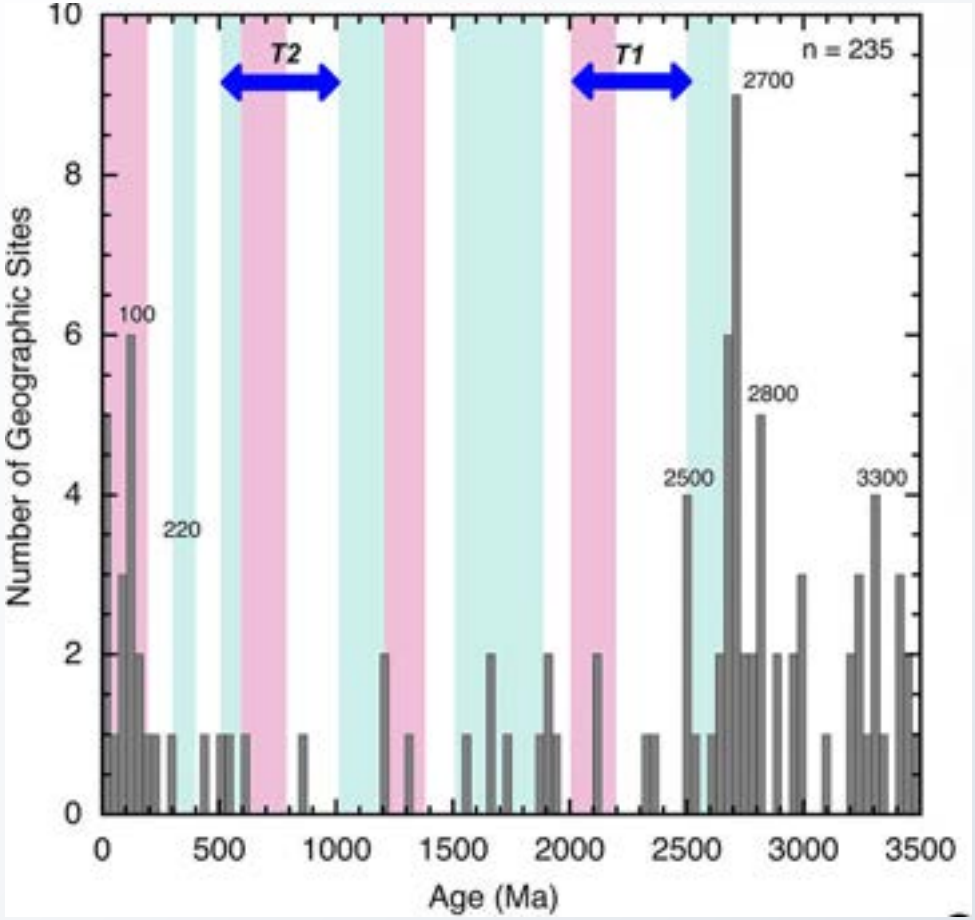
But Hf model ages suggest much of that crust formed from pre-existing crust; >50% formed in the Archean.

How much continental crust has been destroyed and recycled into the mantle?



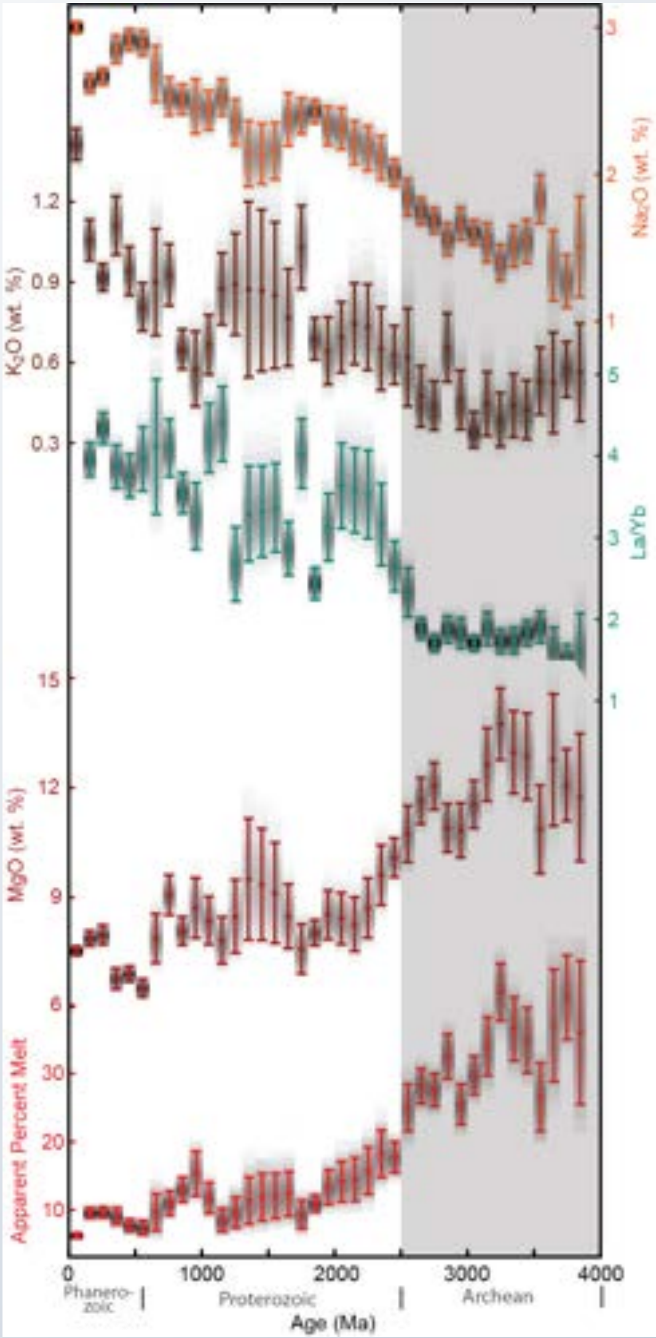
At present, the combined fluxes of sediment subduction, subduction erosion and lower crustal floundering appear to equal or exceed the rate of new continental crust production. Was this true in the past?

Archean crust is different. Why?



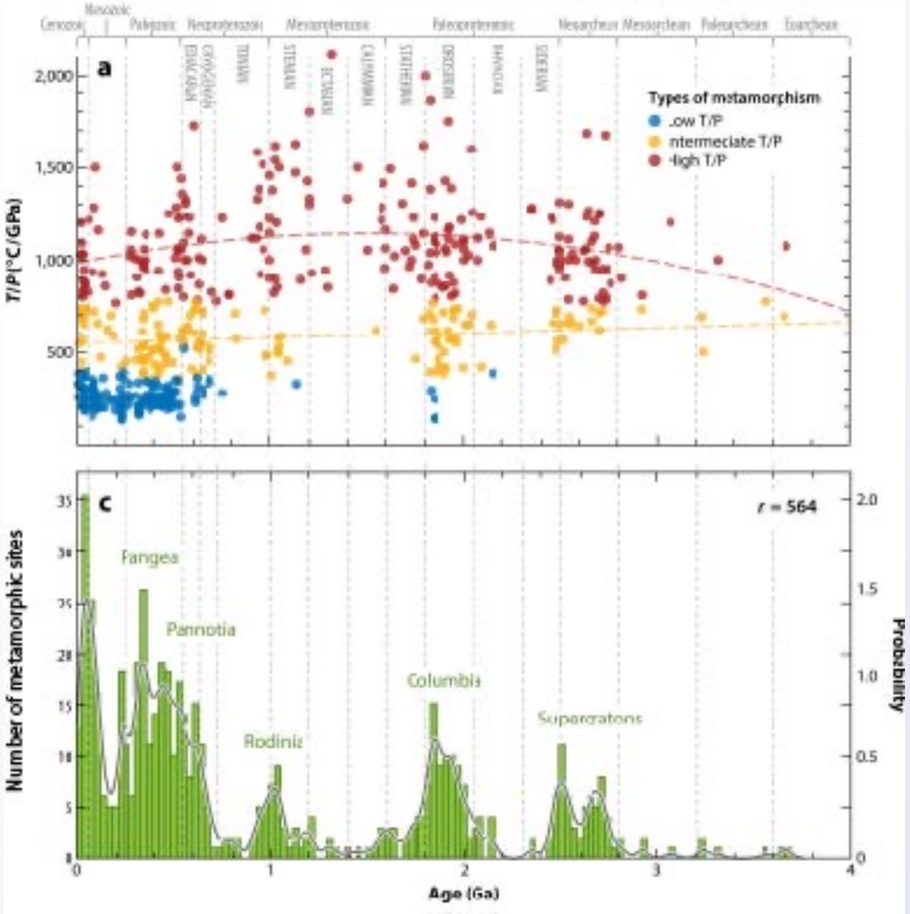
Secular distribution of tonalite-trondhjemite-granodiorite suites (TTG)

Condie (2021)

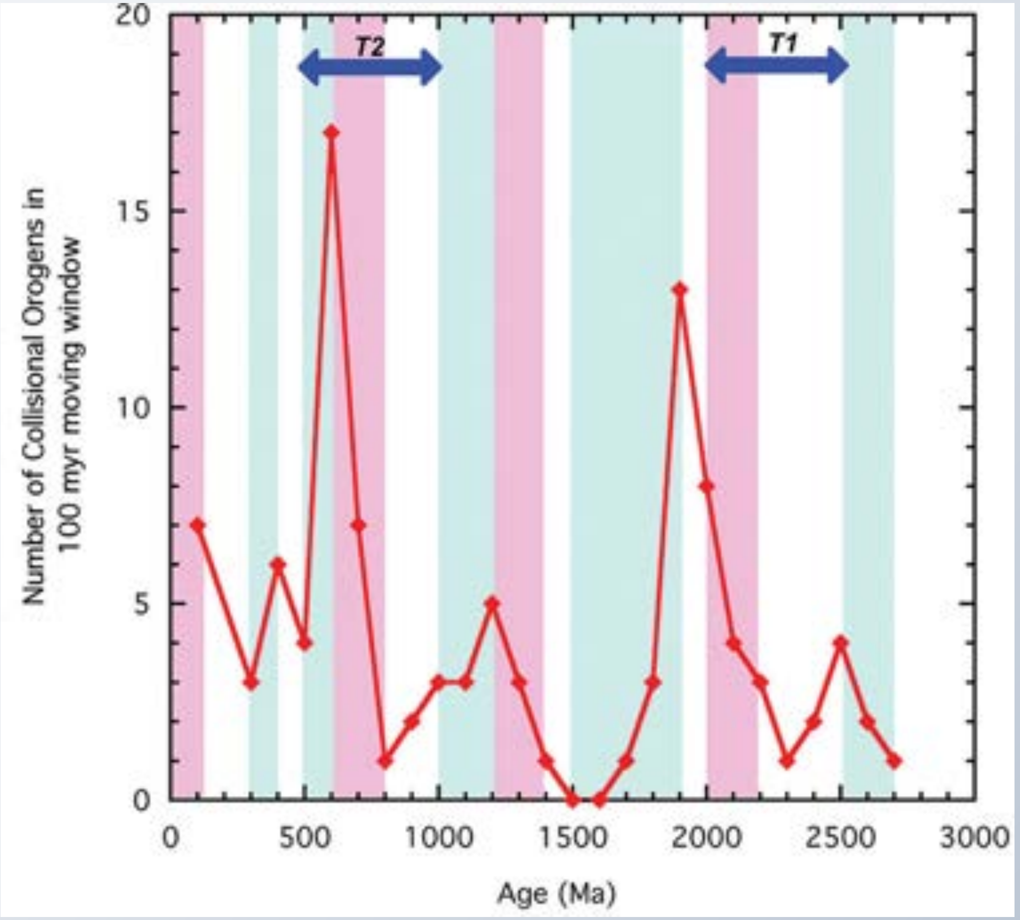


Keller & Schoene (2012)

A Tectonic Transition in the Neoproterozoic?



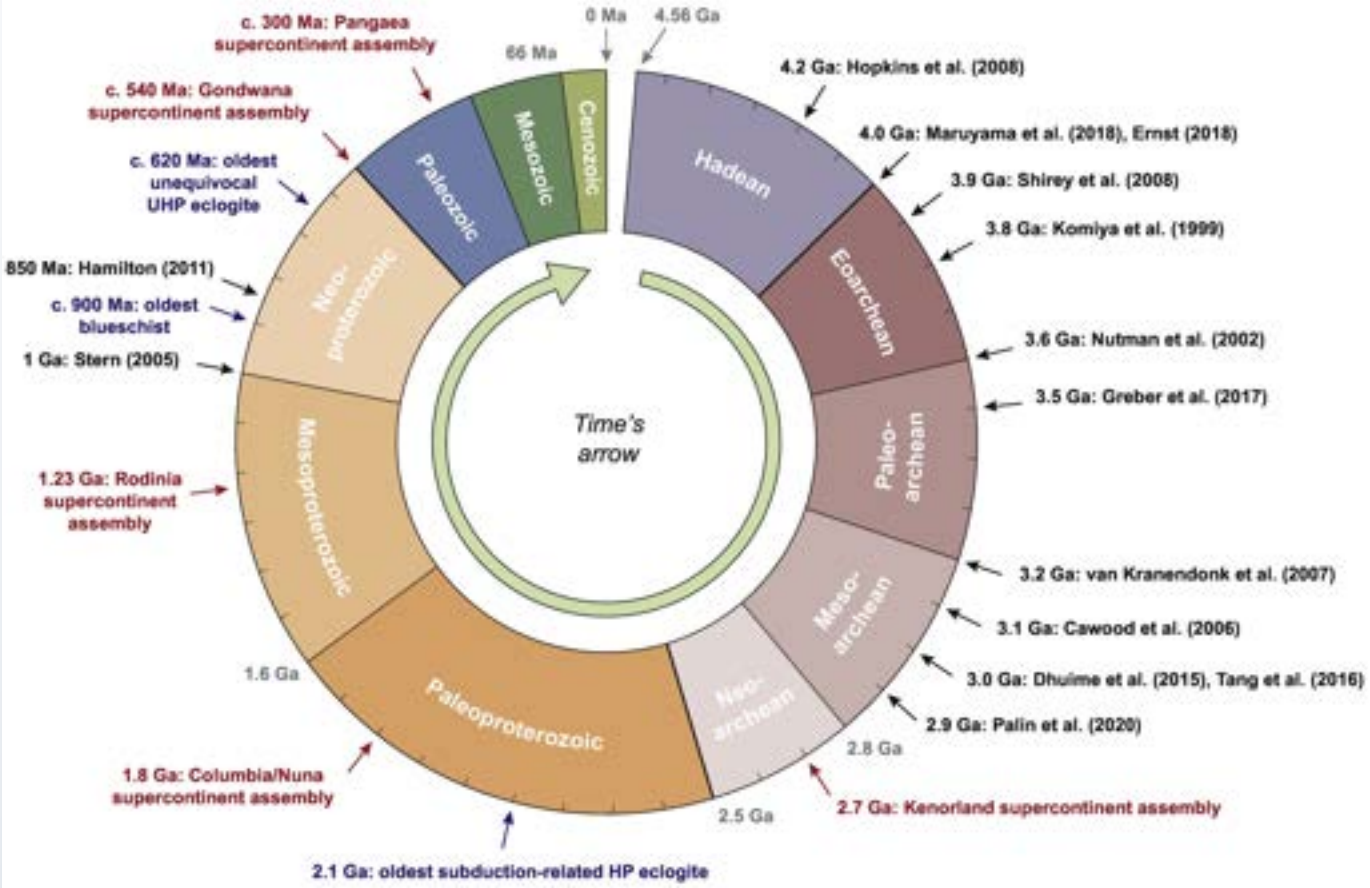
Brown et al. (2020)



Condie (2021)

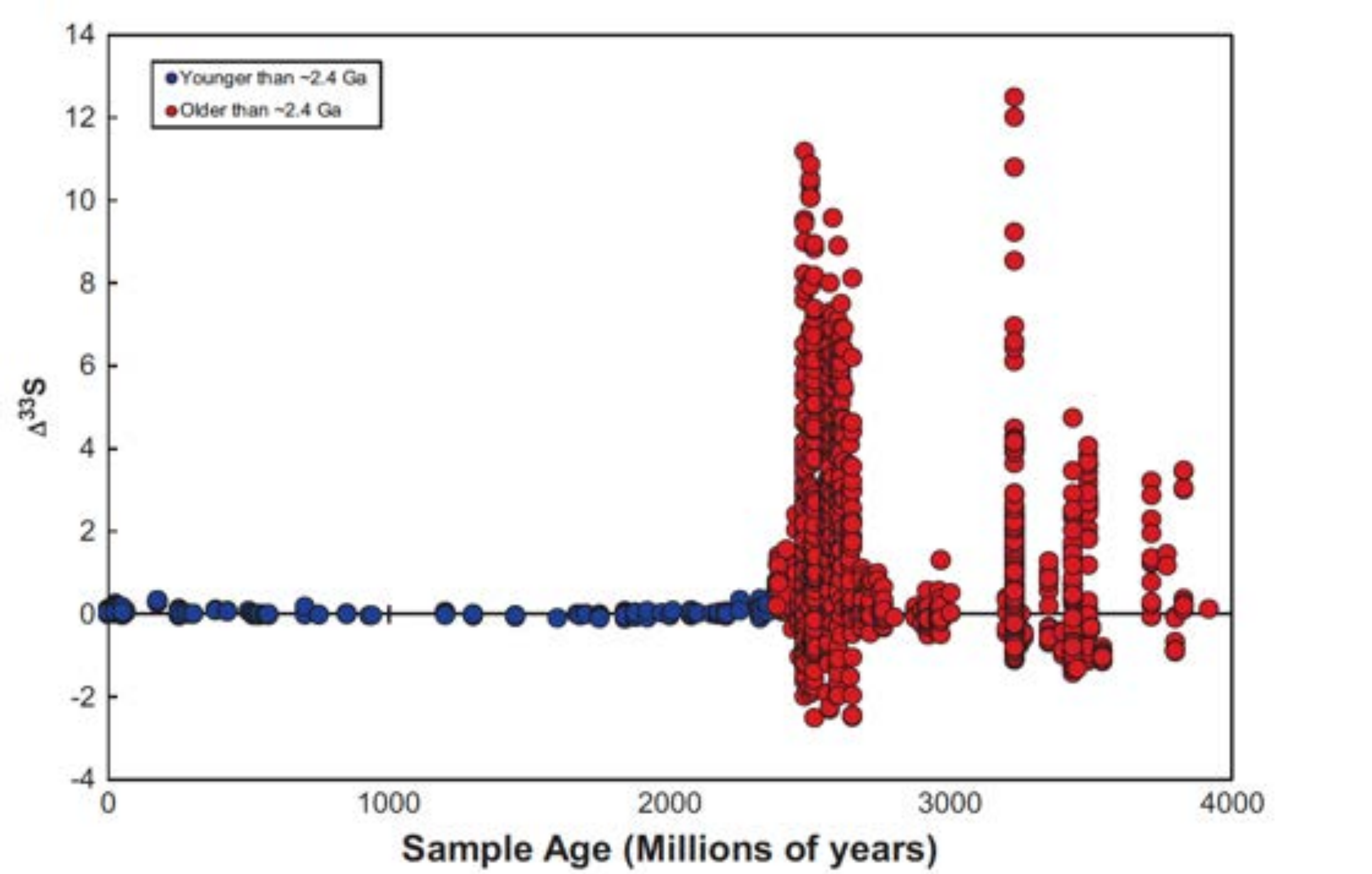
When did modern Plate Tectonics Begin?

- “Modern” means sheet-like upwellings and downwellings.
- There is no consensus, but most answers are either Archean or Neoproterozoic.
- Most nevertheless agree crust has been both created and destroyed since the Eoarchean.



Palin et al. (2020)

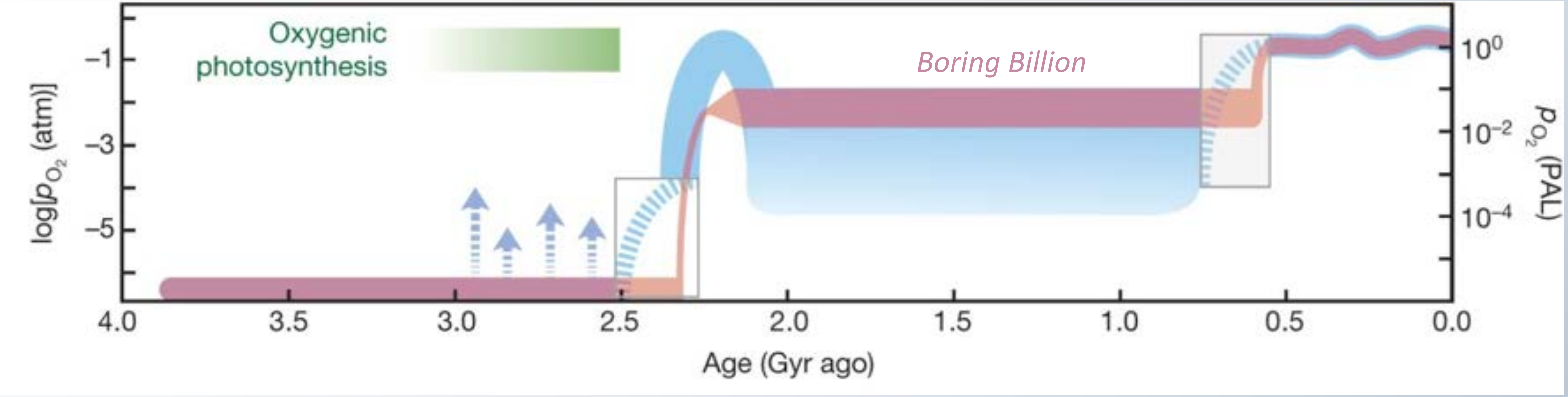
Dramatic change in S isotopes at ~2.4 Ga



Farquhar et al. (2014)

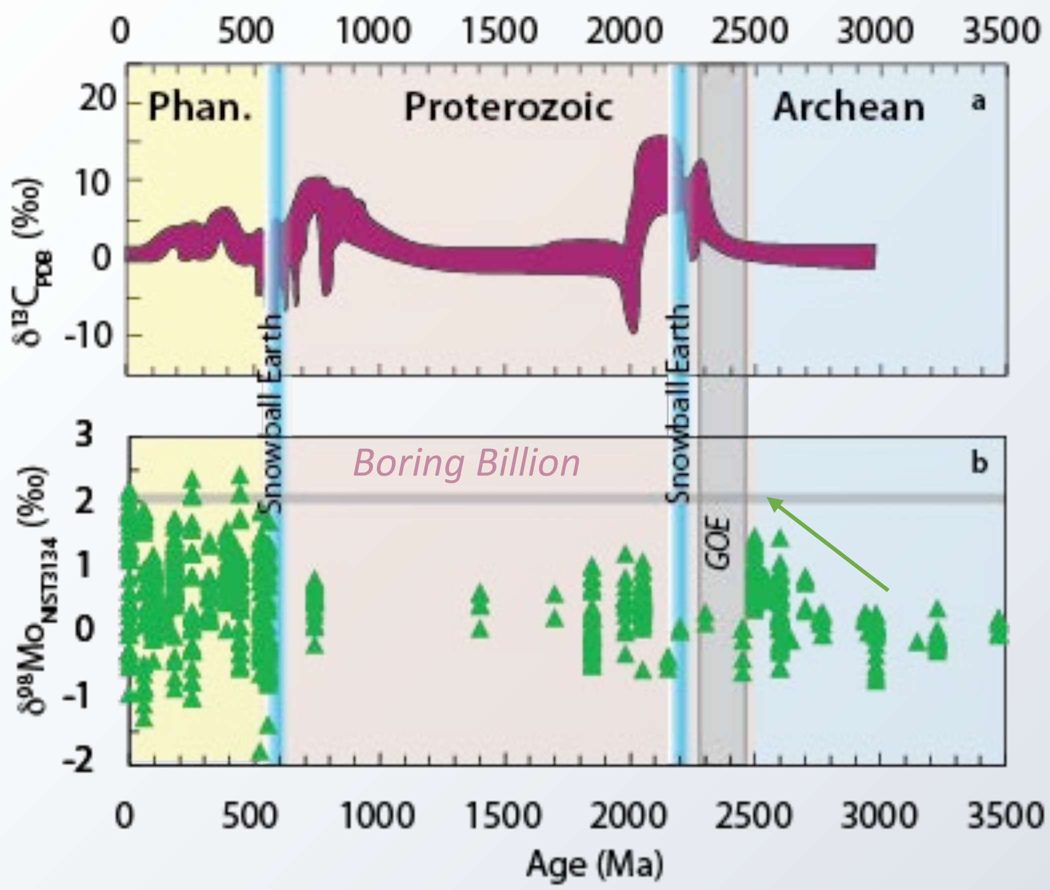
UV photolysis of SO_2 ended in the early Proterozoic

Why did O_2 of the Earth's atmosphere dramatically change in the Paleoproterozoic and again in the Neoproterozoic?



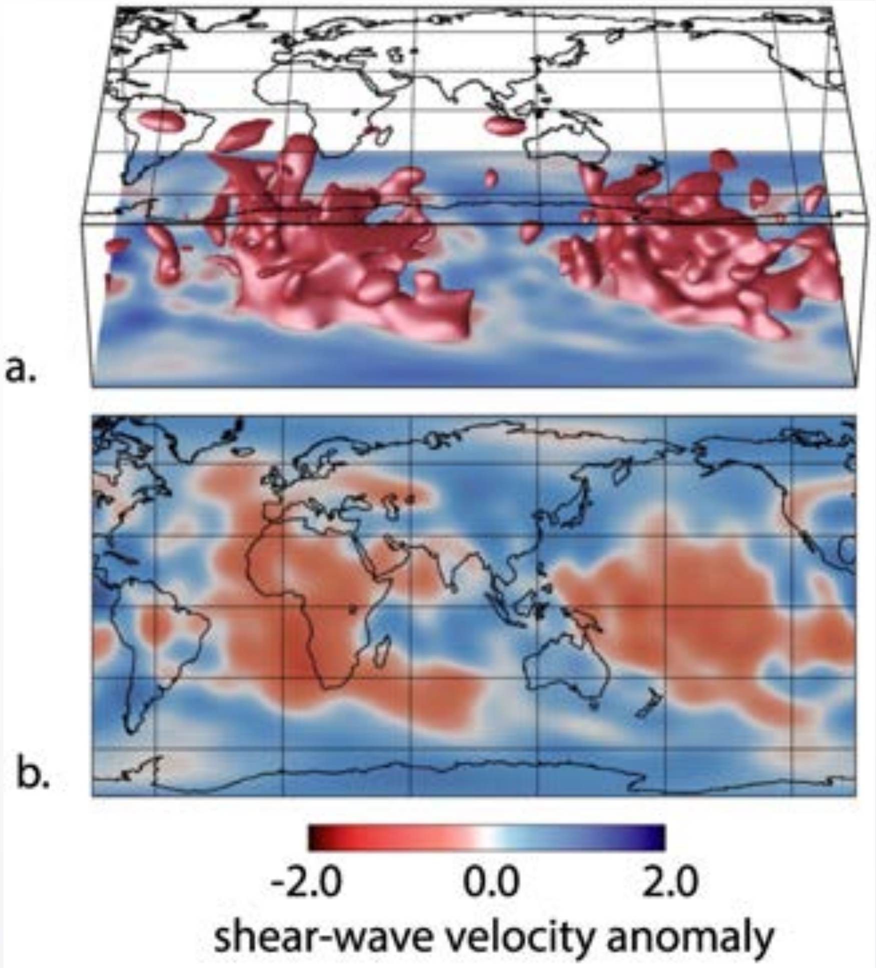
Lyons *et al. Nature* **506**, 307-315 (2014)

Atmosphere, Life, and Climate



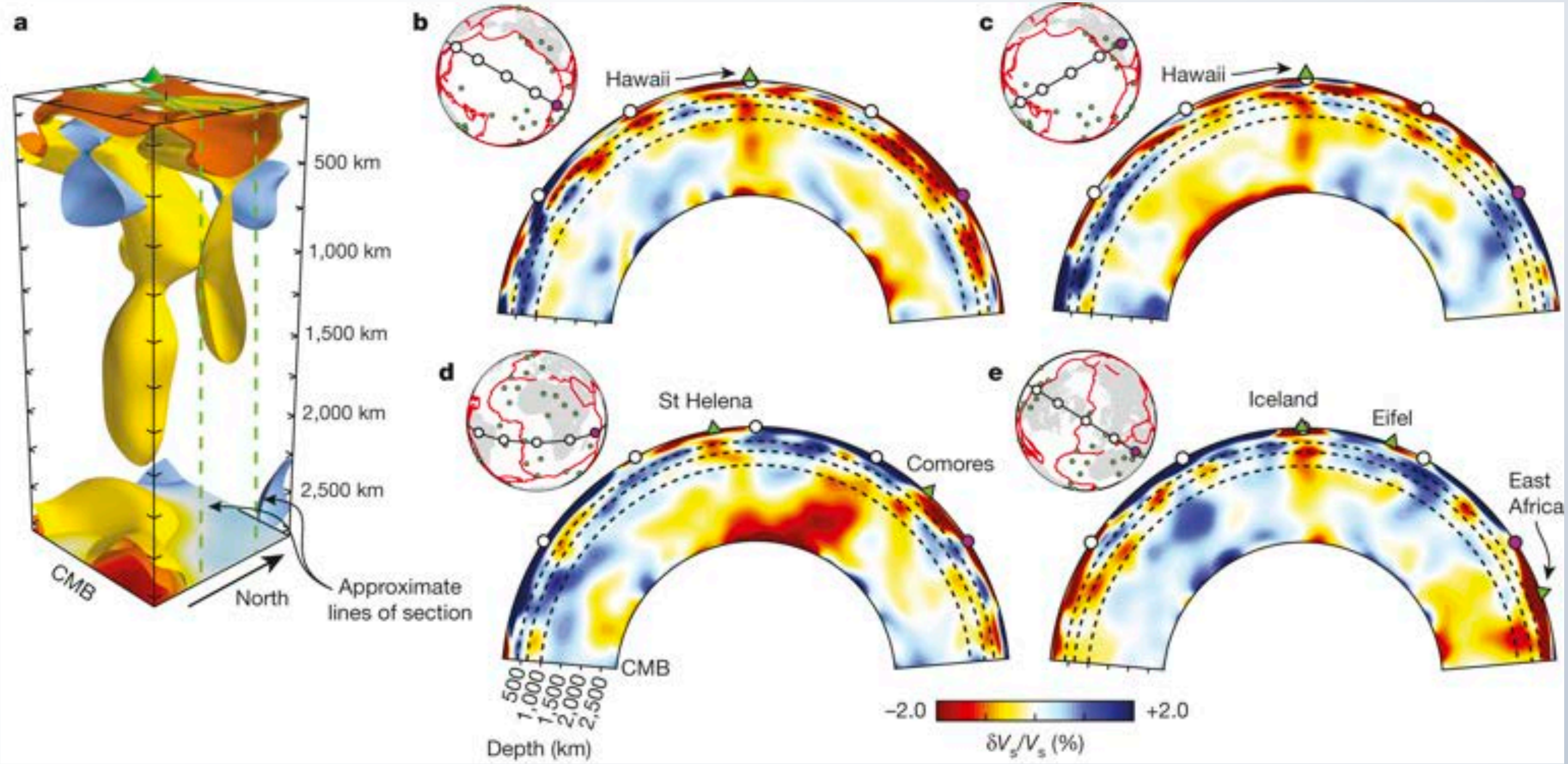
- *Rising δ^{98}Mo and isotopes of other redox-sensitive metals* indicate that the oceans were beginning to become oxidizing in the Neoarchean – photosynthesis began in the Archean.
- Oxidation state of the Earth's surface remained static until the Neoproterozoic (*boring billion*).
- First animal fossils appear at the end of the Neoproterozoic when O_2 rises again.
- Both events marked by extreme glaciations.

Large Low S-wave Velocity Provinces (LLSVPs) in the Deep Mantle



- Sharp boundaries require more than just thermal difference.
- Largest structures on the planet: occupy ~5% of mantle volume (10 times bigger than the continents)
- Rise as high as 1000 km above the core-mantle boundary.
- Approximately antipodal.
- What are they?
  - Primordial material (e.g., magma ocean residues)?
  - Subducted oceanic crust?
  - Something else?

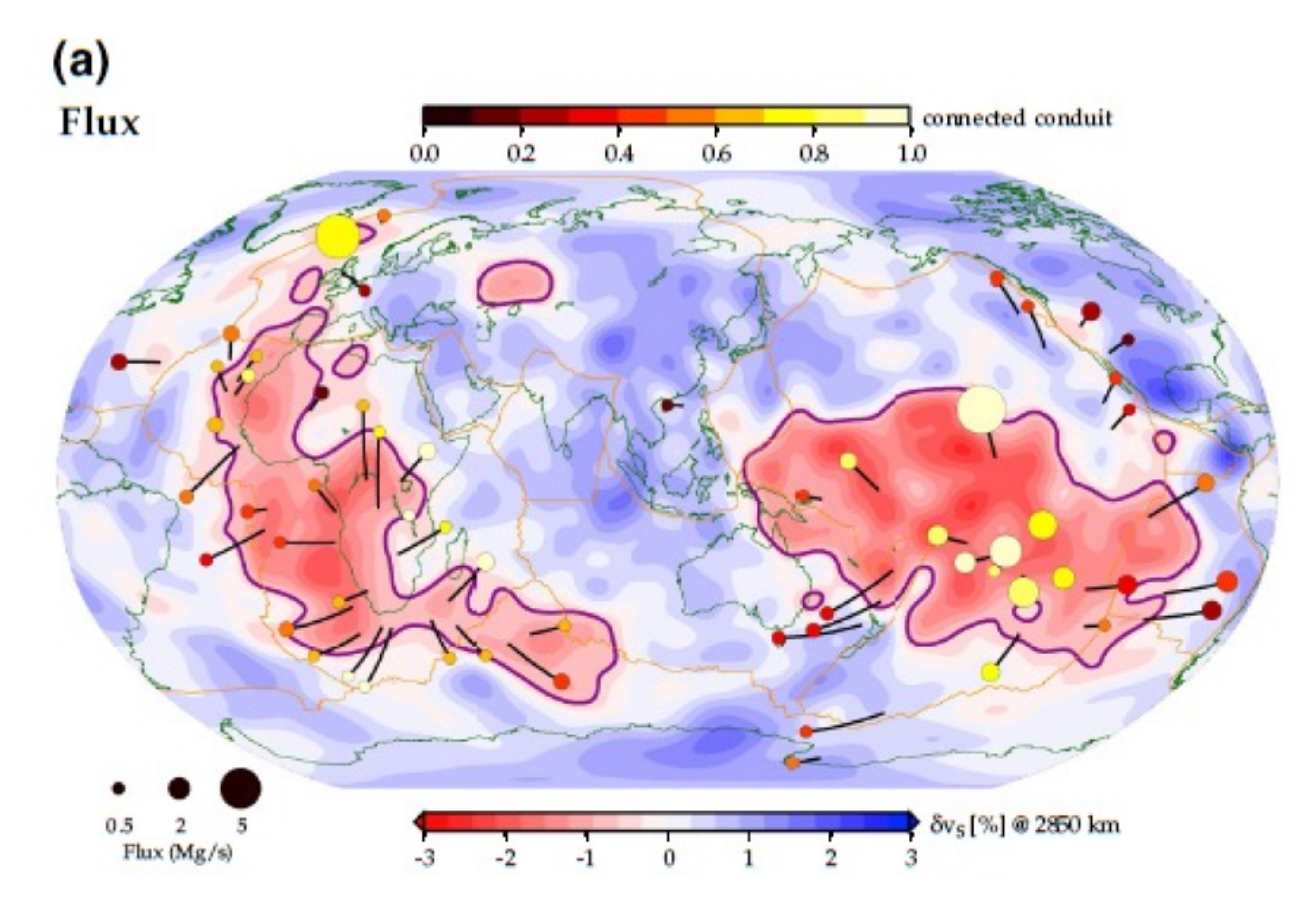
Mantle Plumes rise from LLSVPs



SW French *et al. Nature* **525**, 95-99 (2015) doi:10.1038/nature14876

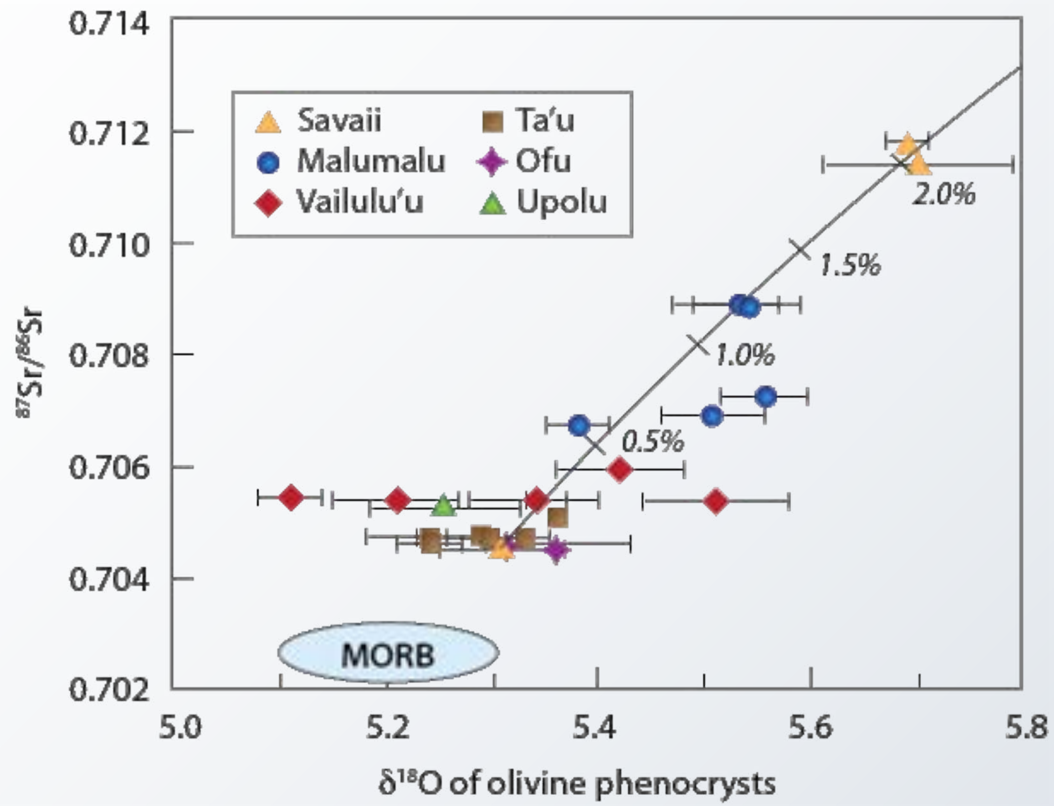
nature

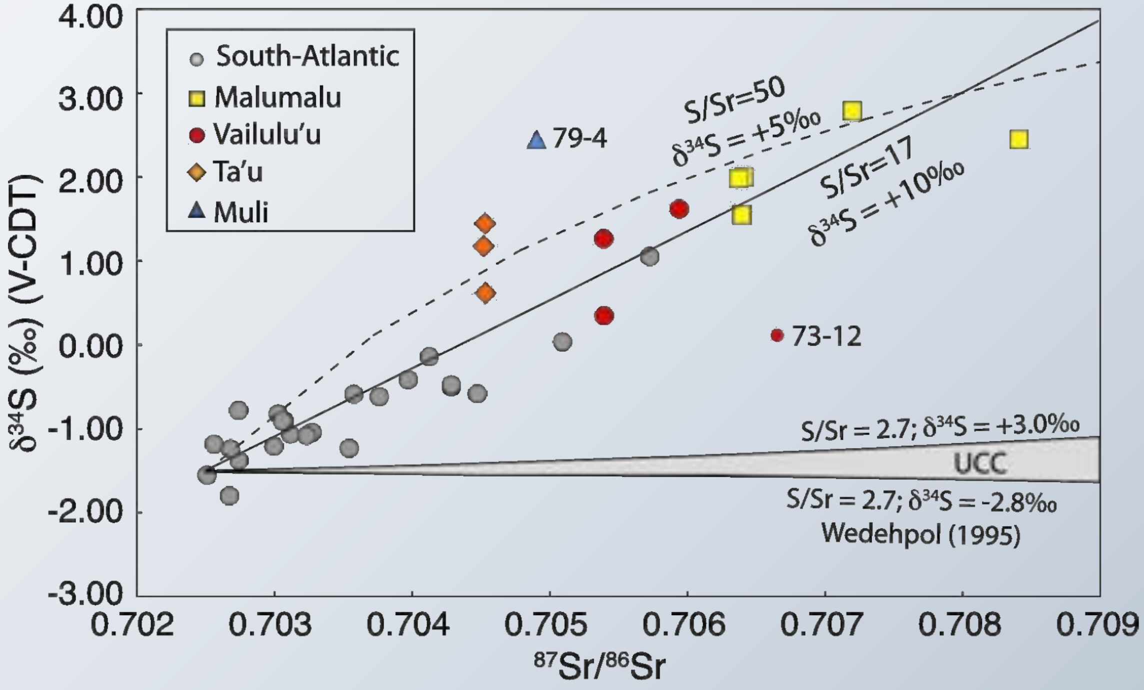
Many plumes rise from the edges of LLSVPs



Jackson et al. (2021)

Plumes contain material recycled from the Earth's surface



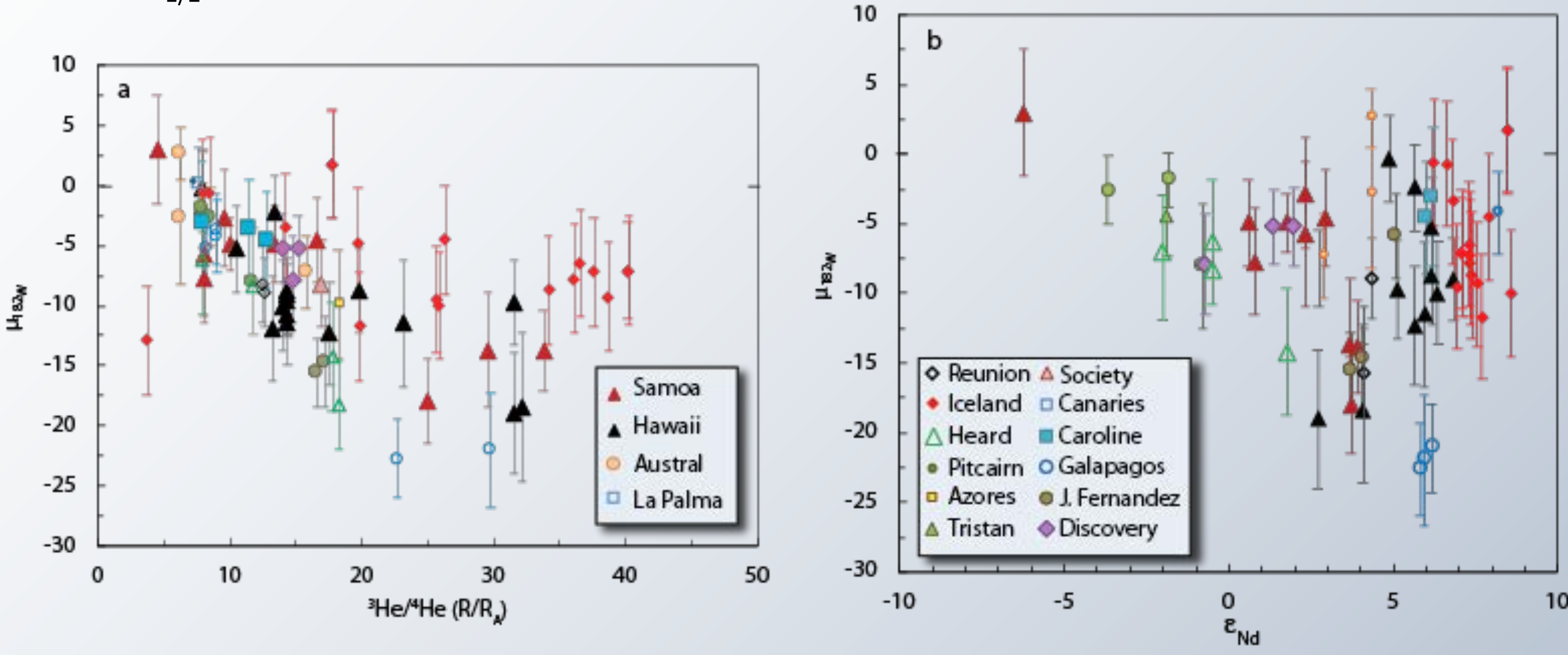


Correlations between radiogenic and stable isotopes establish the presence of recycled material in the Samoan plume.

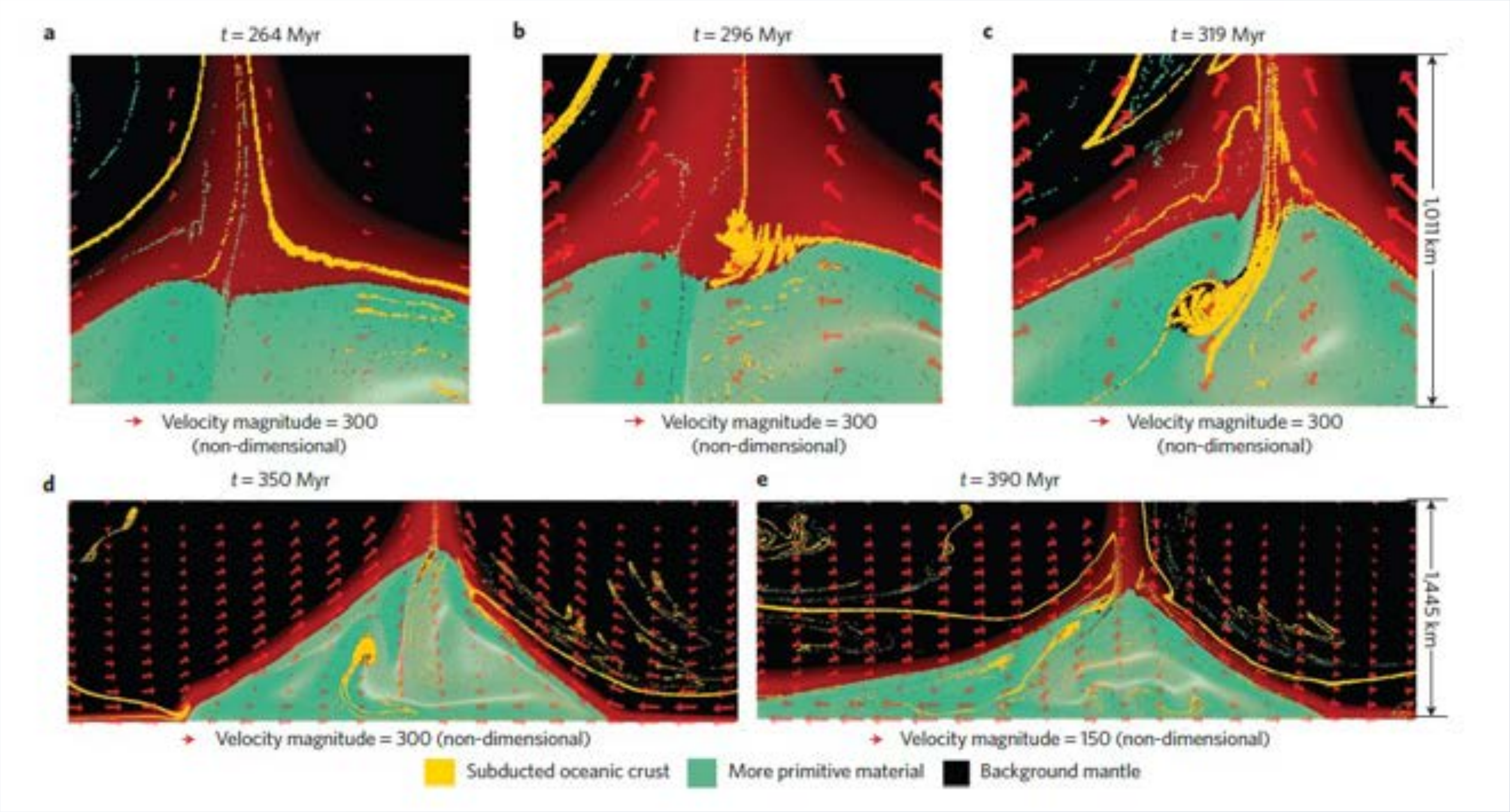
Plumes also contain an ancient primitive component

Extinct radionuclides: nuclides that existed in the early Solar System but have long since decayed away:

- $^{129}I \longrightarrow {}^{129}Xe$ $t_{1/2}$ = 15.7 Ma
- $^{244}Pu \longrightarrow {}^{131-136}Xe$ $t_{1/2}$ = 81.2 Ma
- $^{146}Sm \longrightarrow {}^{144}Nd$ $t_{1/2}$ = 103 Ma
- $^{182}Hf \longrightarrow {}^{182}W$ $t_{1/2}$ = 8.9 Ma

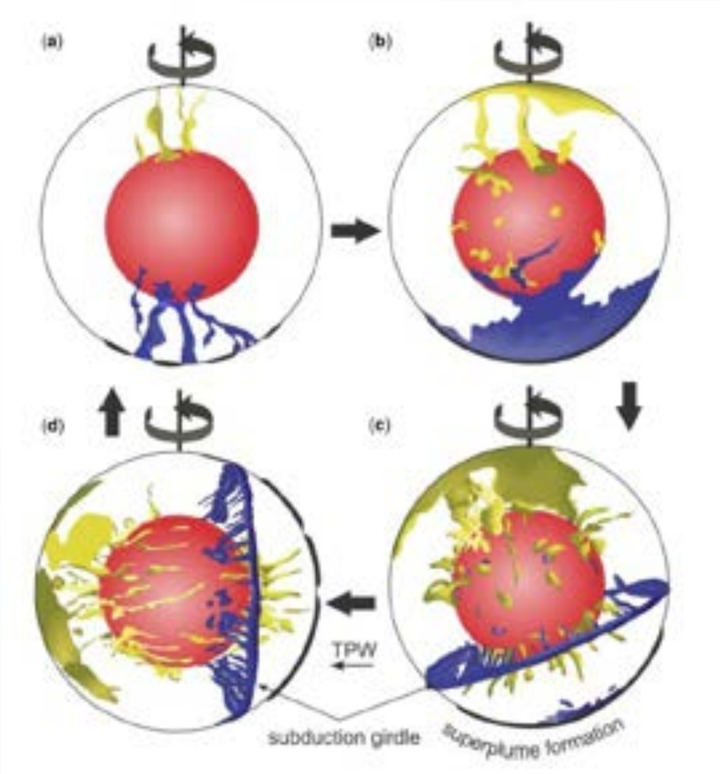


Can geodynamic models show how plumes can contain both?

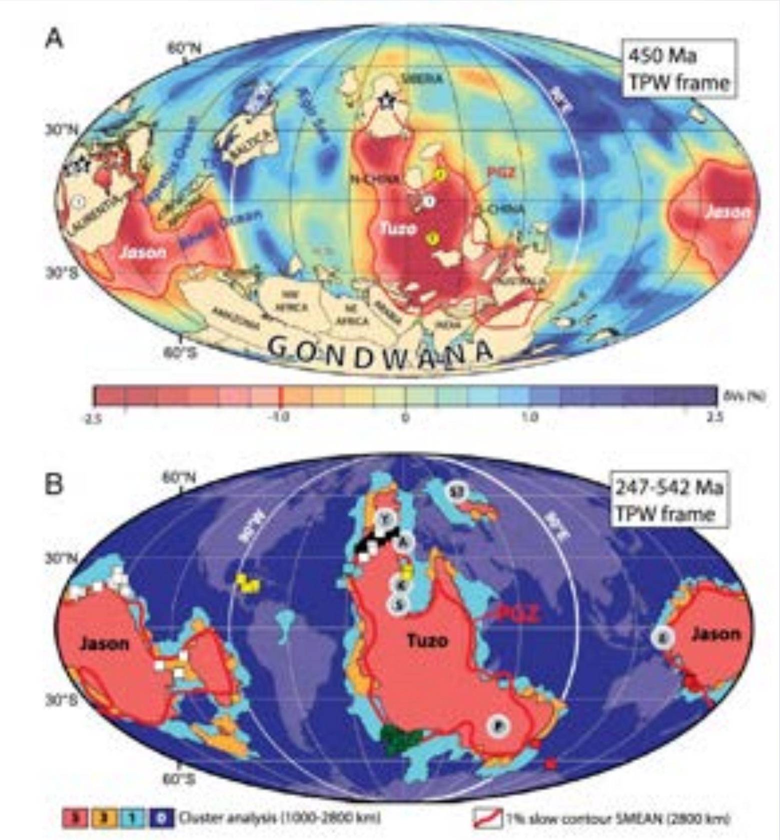


Li & MacNamera (2014)

Does plate tectonics organize LLSVPs or do LLSVPs organize plate tectonics?



Li & Zhong (2009) and Murphy et al. (2021) argued that supercontinent cycles control/produce LLSVPs.



Dziewonski et al. (2010), Torsvik et al. (2014) argue LLSVPs are fixed and have organized mantle flow throughout the Phanerozoic and probably longer.

Are tectonic transitions, the deep mantle, atmospheric O_2 (and therefore life) linked?

- Tectonism and magmatism supplies fresh rock for erosion, supplying critical nutrients, most notably phosphorus, to the oceans, enabling photosynthesis.
  - Phosphorite sediements first appear in the Paleoproterozoic and then do not reappear until the Neoproterozoic (Bekker & Holland, 2012).
  - Many (e.g., O’Niell et al., 2022) argue for reduced tectonism during the Boring Billion, limiting phosphorus supply until the breakup of Rhodinia around 800 Ma.

- Volcanism supplies reduced gases and minerals to the surface consuming atmospheric O_2.
  - Condie et al. (2008, 2022) argue a Paleoproterozoic magmatic lull allowed O_2 to rise in the GOE.
  - O’Neill & Aubach (2022) argue destabilization of deep oxidized mantle (formed during Earth’s magma ocean stage, by disproportionation of FeO during bridgmanite formation) carried to the surface by mantle plumes drove the GOE.

Conclusion: The deep and shallow Earth are intimately connected.

- The Earth has evolved in a very non-linear manner, including dramatic changes at the beginning and end of the Proterozoic, although the details are debated.
- The deep mantle contains the largest structures on Earth, LLSVPs, which generate mantle plumes.
- Material from the Earth’s surface is subducted into the deep mantle and may influence or create these structures, which also contain primordial material.
- Mantle plumes influence plate tectonics, break-up continents and provide fresh nutrients to the Earth’s biosphere.
- The deep and shallow Earth are intimately connected, but the details of these connections are still poorly understood at best.