Early Earth and the initiation of Plate Tectonics

Marek Zastąpiło

The initiation of Plate Tectonics?

Plate tectonics

Article Talk

From Wikipedia, the free encyclopedia

"Tectonic plates" redirects here. For the film, see Tectonic Plates (film).

Plate tectonics (from Latin *tectonicus*, from Ancient Greek τεκτονικός *(tektonikós)* 'pertaining to building')[1] is the scientific theory that Earth's lithosphere comprises a number of large **tectonic plates**, which have been slowly moving since about 3.4 billion years ago.[2] The model builds on the concept of *continental drift*, an idea developed during the first decades of the 20th century. Plate tectonics came to be accepted by geoscientists after seafloor spreading was validated in the mid-to-late 1960s.

Google

when did plate tectonics start???????

Grafika Wideo Wiadomości Książki Mapy Loty Finanse

Około 11 900 000 wyników (0,33 s)

around 2.8 billion years ago

Plate tectonics is generally thought to have become a well-established global process on Earth no earlier than around 2.8 billion years ago.

22 kwi 2020

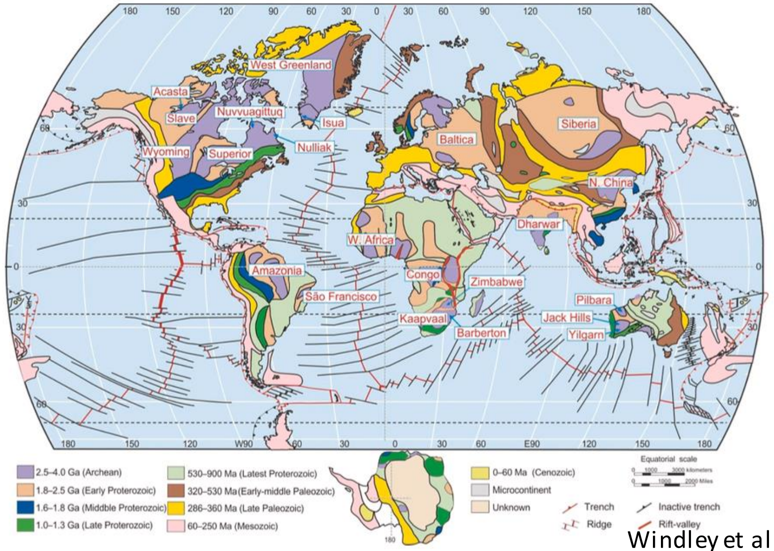
SN Science News

https://www.sciencenews.org › article › earth-plate-tecton...

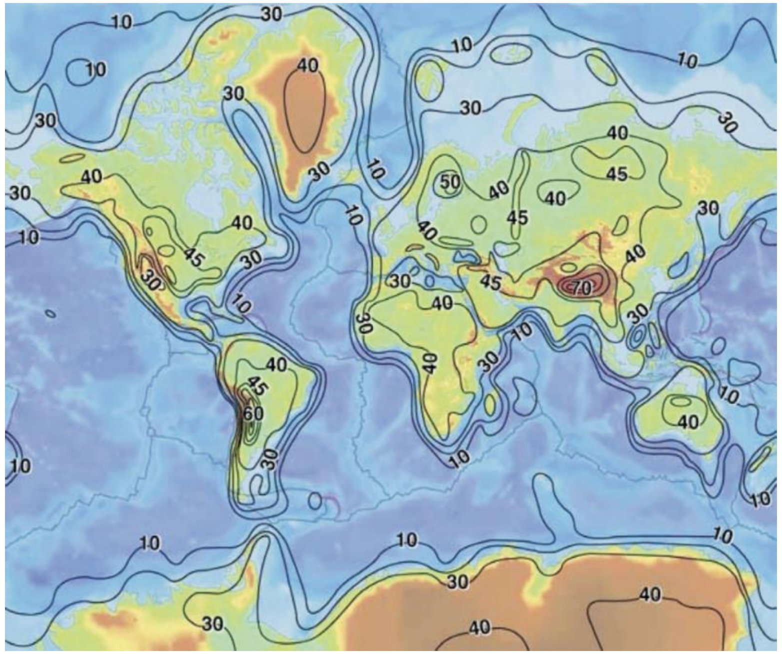
Earth's plate tectonics may have started earlier than we thought

The initiation of what exactly?

- Present-Day / "Modern" Plate Tectonics

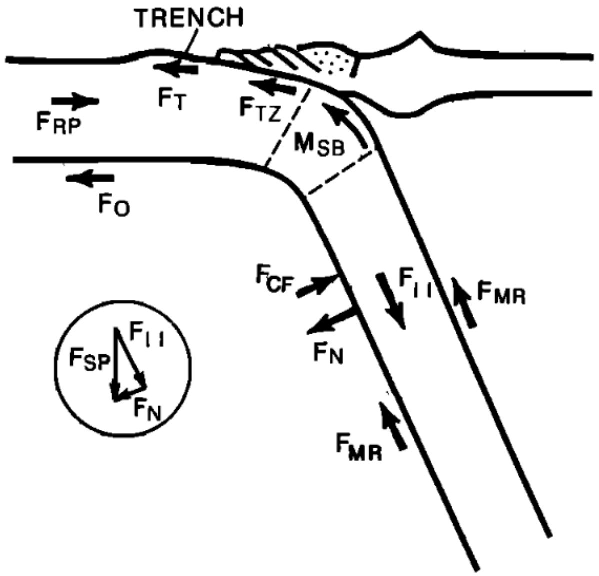


Windley et al. (2021)



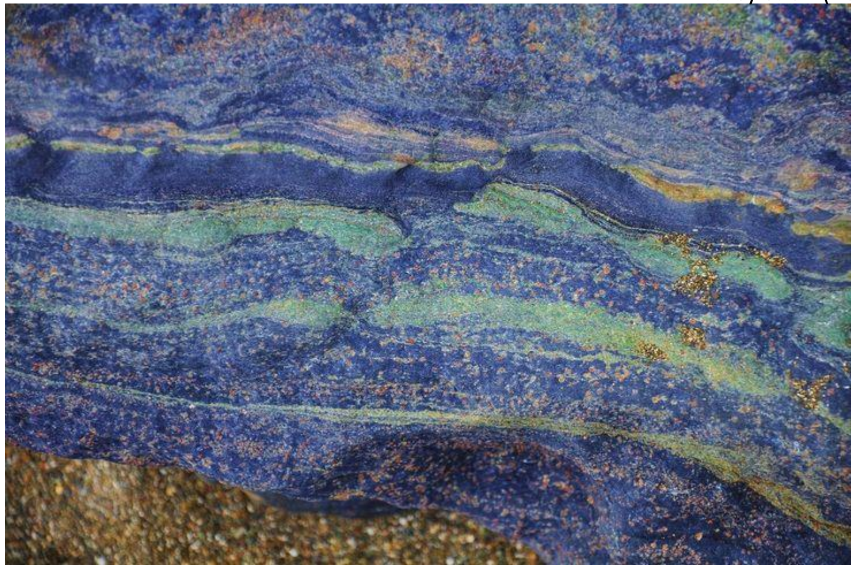
http://earthquake.usgs.gov/research/structure/crust/index.php

Bimodal distribution of crust types: Continental and Oceanic crust



W. Spence (1987)

Slab Pull and Ridge Push (& others) as main driving forces & recycling mechanisms



http://downtoearthquestions.blogspot.com/2013/08/brittle-ductile-deformation-in.html

Ultra-High Pressure (UHP) rocks – blueschists and eclogites

Excellent review paper

AGU ADVANCING EARTH AND SPACE SCIENCE

Reviews of Geophysics

COMMISSIONED MANUSCRIPT
10.1029/2022RG000789

Secular Evolution of Continents and the Earth System

Peter A. Cawood[1], Priyadarshi Chowdhury[1,2], Jacob A. Mulder[3], Chris J. Hawkesworth[4], Fabio A. Capitanio[1], Prasanna M. Gunawardana[1], and Oliver Nebel[1]

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Key Points:

- Long-term record of Earth evolution preserved in continental lithosphere
- Three main tectonic modes operated through Earth history: stagnant lid, squishy lid and rigid, active lid (plate tectonics)
- Stabilization of cratons at end of Archean marks transition to plate tectonics with supercontinent cycle controlling subsequent changes

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Understanding of secular evolution of the Earth system is based largely on the rock and mineral archive preserved in the continental lithosphere. Based on the frequency and range of accessible data preserved in this record, we divide the secular evolution into seven phases: (a) "*Proto-Earth*" (ca. 4.57–4.45 Ga); (b) "*Primordial Earth*" (ca. 4.45–3.80 Ga); (c) "*Primitive Earth*" (ca. 3.8–3.2 Ga); (d) "Juvenile *Earth*" (ca. 3.2–2.5 Ga); (e) "*Youthful Earth*" (ca. 2.5–1.8 Ga); (f) "*Middle Earth*" (ca. 1.8–0.8 Ga); and (g) "*Contemporary Earth*" (since ca. 0.8 Ga). Integrating this record with knowledge of secular cooling of the mantle and lithospheric rheology constrains the changes in the tectonic modes that operated through Earth history. Initial accretion and the Moon forming impact during the Proto-Earth phase likely resulted in a magma ocean. The solidification of this magma ocean produced the Primordial Earth lithosphere, which preserves evidence for intra-lithospheric reworking of a rigid lid, but which also likely experienced partial recycling through mantle overturn and meteorite impacts. Evidence for craton formation and stabilization from ca. 3.8 to 2.5 Ga, during the Primitive and Juvenile Earth phases, likely reflects some degree of coupling between the convecting mantle and a lithosphere initially weak enough to favor an internally deformable, squishy lid behavior, which

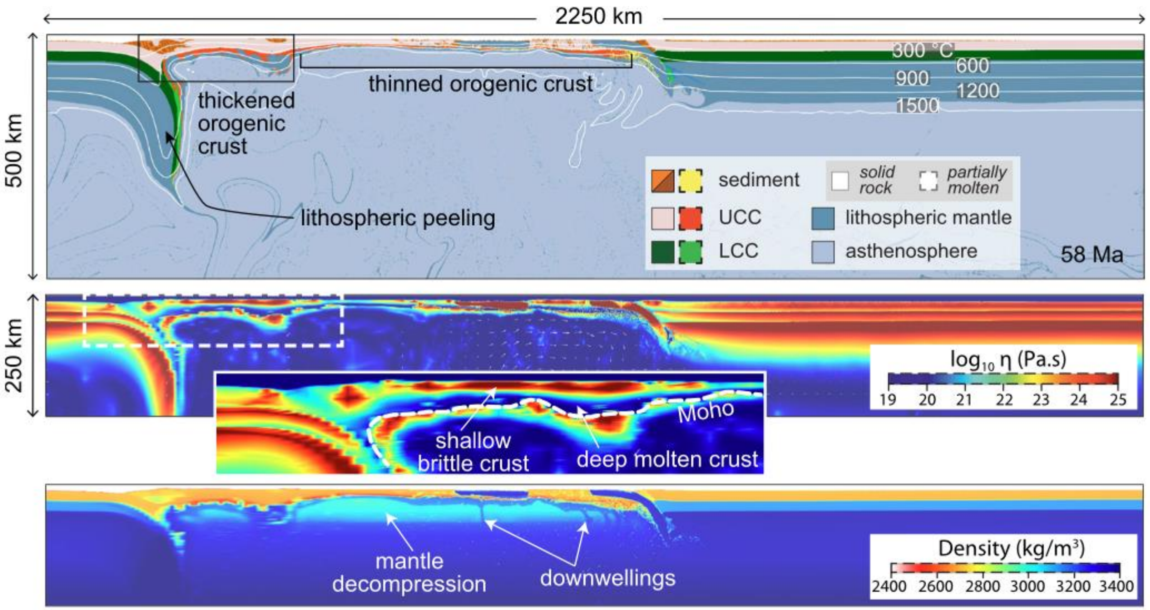
First, the methodology.

How do we study the Early Earth?

Field observations

(Wide group: geochemical proxies, occurrence of mineral deposits, facies changes in sedimentary successions, sedimentation rates and much more.)

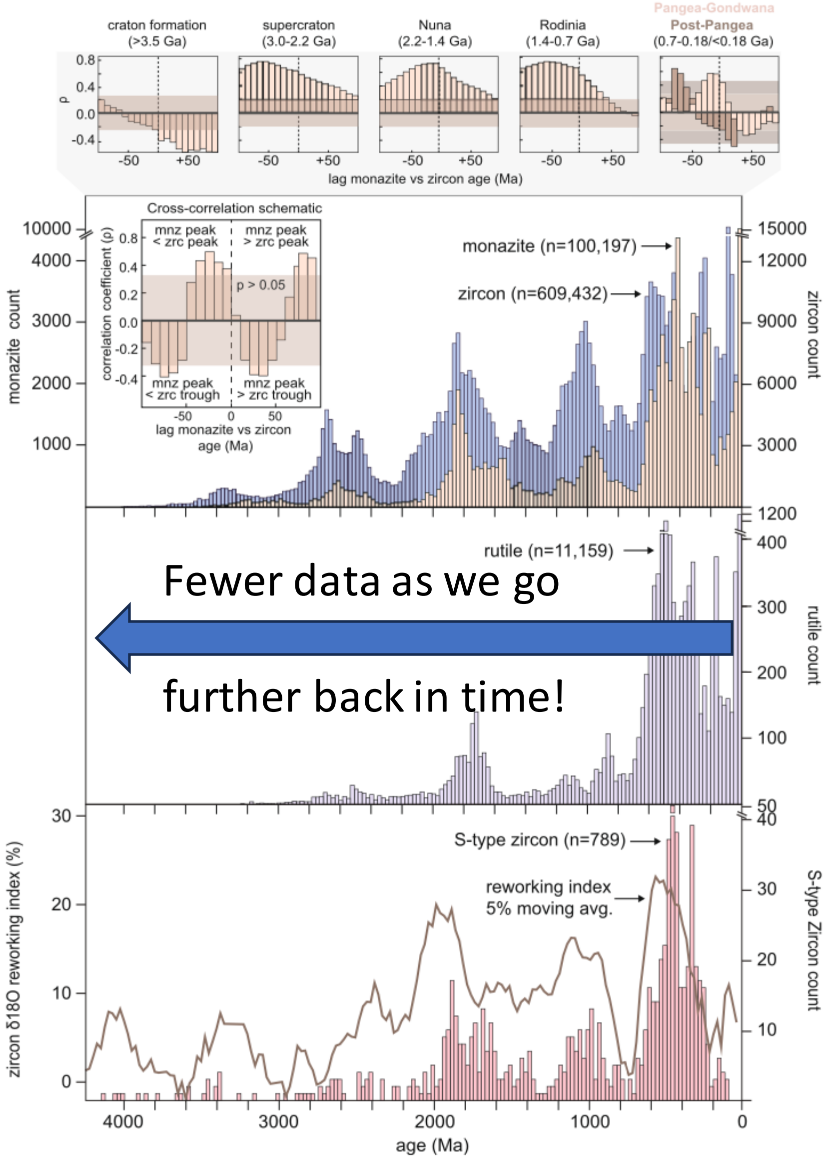
Will mention where applicable



Numerical models

Chowdhury et al. (2020), modified in Cawood et al. (2022)

Bias! Understanding the limitations of our dataset.



Cawood et al. (2022), taken from Mulder and Cawood (2022)

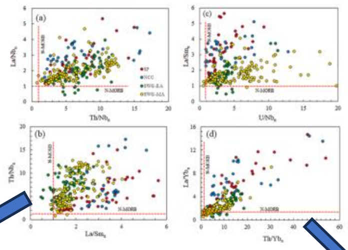
Histograms of global monazite and detrital zircon age distributions

Also, the relationship between the ages of detrital zircons and various indicators of tectonic activity (like the age of certain granites and metamorphic minerals) indicates that the continental crust's record is more about preserving evidence of past geological events rather than being a direct record of the creation of new continental crust.

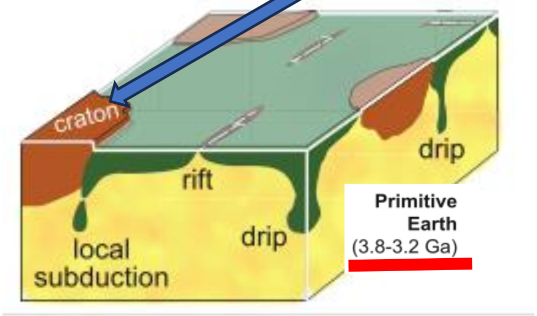
Bias! Understanding the limitations of our dataset.

"Proposed evidence for recycling of Archean lithosphere (e.g., Smart et al., 2016), and for geochemical signatures comparable to modern convergent plate margins (e.g., Windley et al., 2021), lies at the heart of many arguments as to the viability of Hadean-to-Archean plate tectonics. However, modeling studies have shown that these signatures are also consistent with non-plate tectonic modes; that is, lithospheric recycling need not be synonymous with subduction."

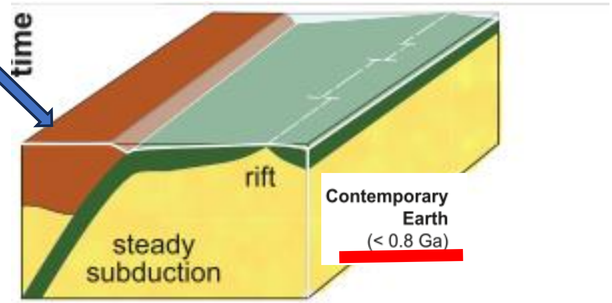
Cawood et al. (2022)



Windley et al. (2021)



Cawood et al. (2022)



Cawood et al. (2022)

= Different processes may produce similar geochemical signatures!

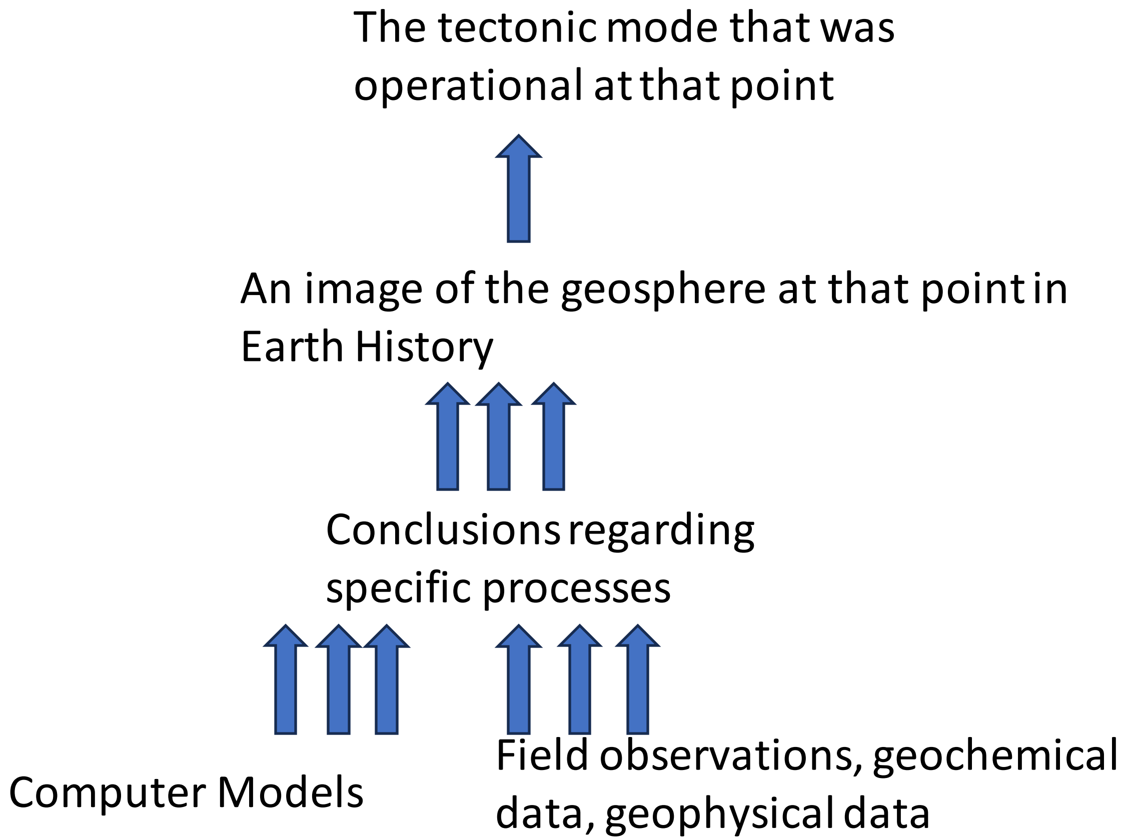
Caution! One last foreword

- We are talking about a set of tectonic modes that may have operated throughout Earth history
- = Large-scale processes
- = High level conclusions

7.3.2. Squishy Lid Mode

The period from ca. 3.8 to 2.5 Ga (i.e., during phases III and IV) marks the formation and stabilization of Earth's cratons. The beginning of this time range is marked by the preservation of granite-greenstone terranes and high-grade gneisses in the rock record, and after 3.2 Ga there was ongoing craton formation and also widespread stabilization of these associations leading to their long-term preservation. Voluminous mafic volcanism during greenstone belt formation and the concomitant production of TTGs with supra-chondritic Hf signature during ca. 3.8–3.2 Ga suggests significant input of mantle-derived, juvenile melts during this time-period (Figure 13; Mulder et al., 2021). These rock types eventually formed the cratonic crust and were shielded from the convecting mantle by a rigid layer of harzburgitic lithospheric mantle (cratonic keel). Formation of this continental lithospheric mantle during juvenile melt extraction was fundamental in ensuring the cratons' long-term preservation (Korenaga, 2006; Pearson et al., 2021). Studies of the cratonic mantle lithosphere reveal internal layering due to variations in the amount of melt depletion (Griffin et al., 2003; Yuan & Romanowicz, 2010). Furthermore, the numerical models of Perchuk et al. (2020) propose that this layering is a complex multistage process that occurs through the juxtaposition of depleted lithospheric mantle by spatially and temporally discrete processes (cf., Z. Wang et al., 2022). Importantly, the formation of these lithospheric keels likely marks the transformation of a lithosphere region undergoing intense plutonism and non-rigid, distributed deformation to a rigid and buoyant lithosphere (cratonic core) that is a prerequisite for plate tectonics. Coincident with increased rigidity is evidence after ca. 3.2 Ga for increased thickening of the lithosphere including geochemical data for increased depth of crustal melting in the production of TTG's, the evolving source of felsic magmatism from melting of mafic lower crust to TTG-like compositions for potassic granites (Moyen & Laurent, 2018; Moyen & Martin, 2012; Nebel et al., 2018), and evidence for continental emergence above sea-level at craton scale (Chowdhury, Mulder, et al., 2021; Reimink et al., 2020; W. Wang et al., 2021a). In addition, data from modeling proportions of juvenile versus evolved global detrital zircon populations as well as orogen specific studies (Dhuime et al., 2018; L. Gao et al., 2022a; S. Gao et al., 2002; X. Wang et al., 2021b) provide evidence for recycling and hence destruction of lithospheric mantle throughout the Archean (<3.8 Ga).

We interpret the rock association and geochemical changes commencing at 3.8 Ga to result from a sluggish/active-lid regime, involving some degree of coupling between the convecting mantle and the lithosphere resulting in



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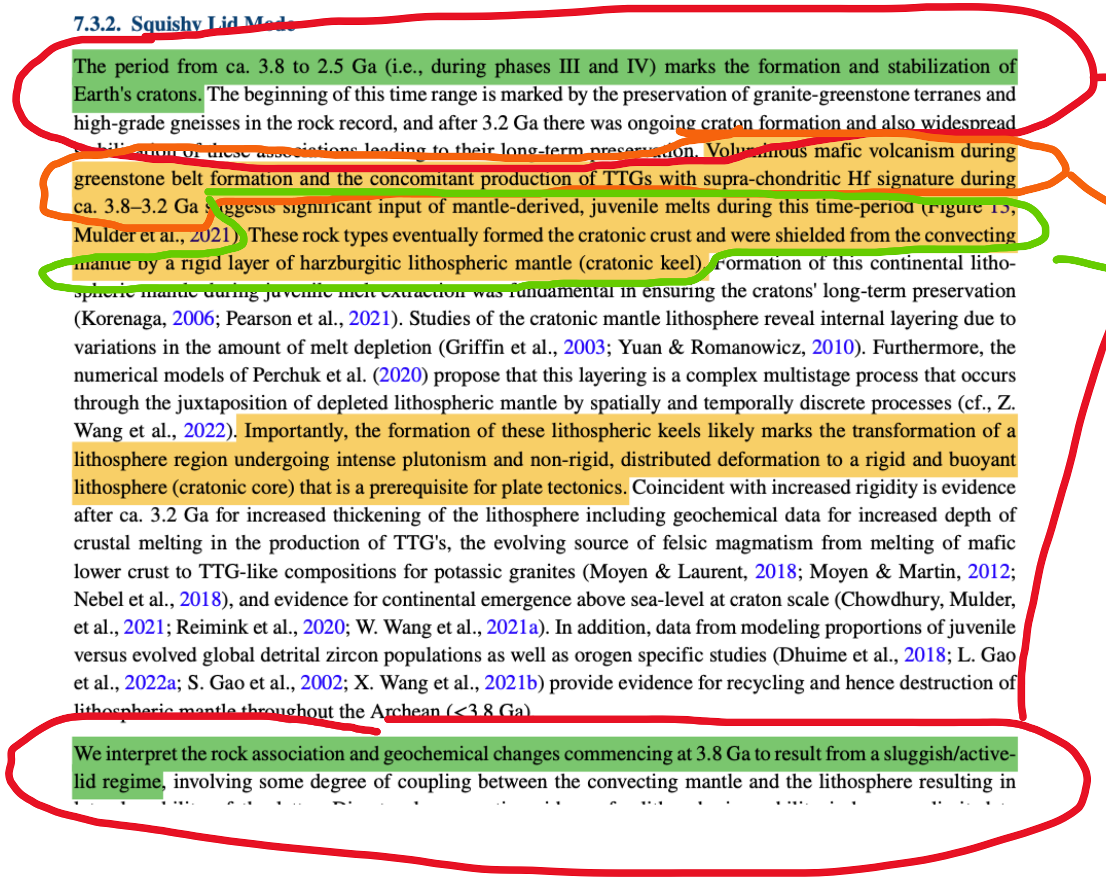

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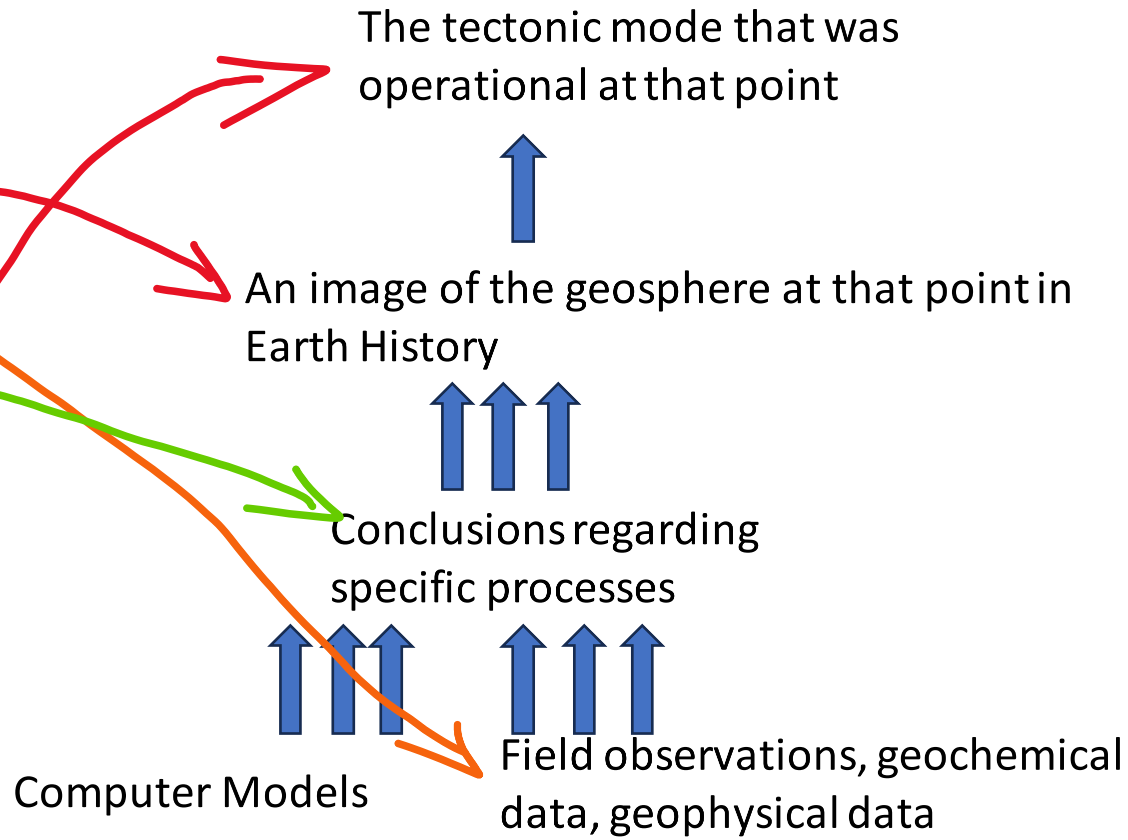
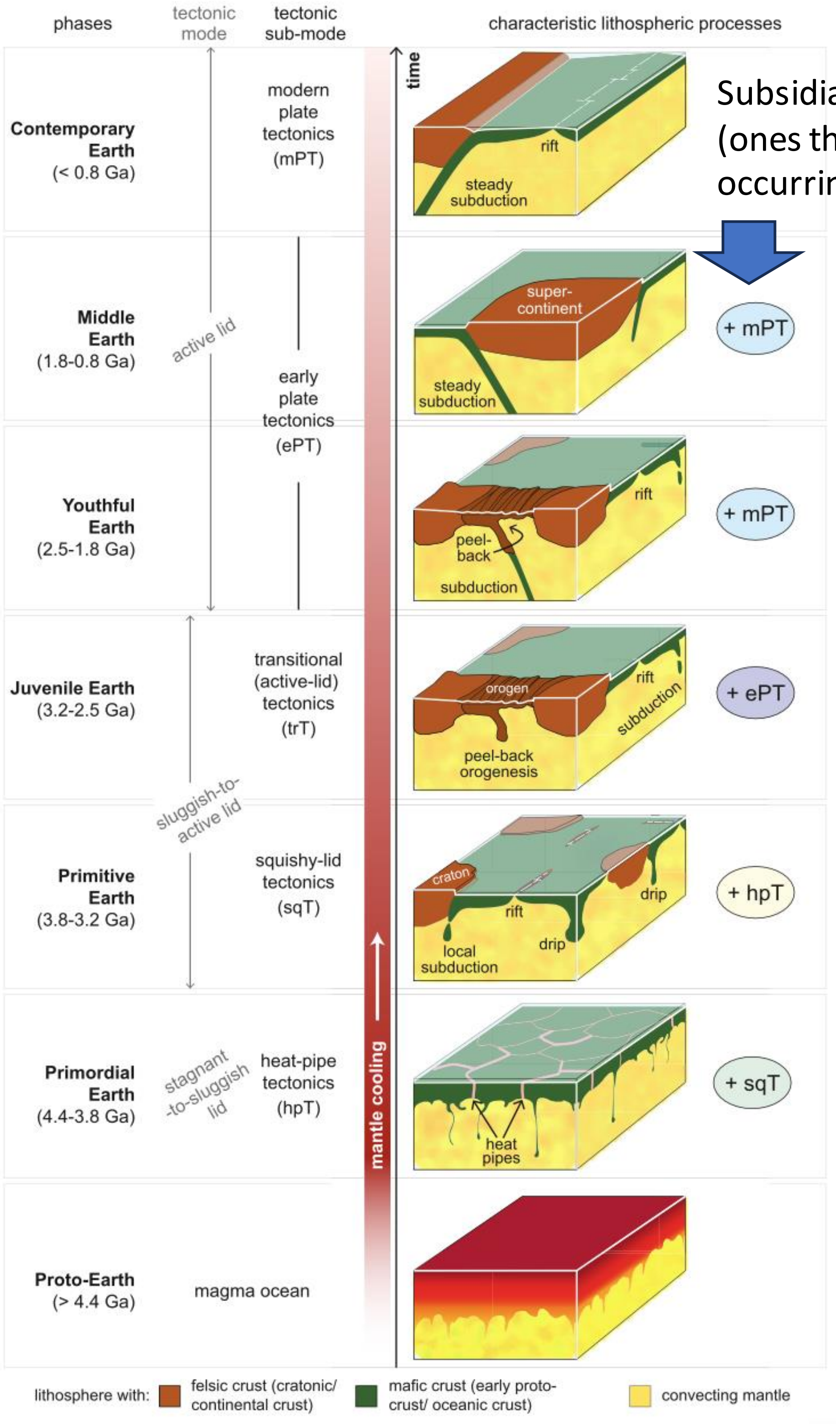


The Cawood et al. (2022) timeline

Subsidiary tectonic modes (ones that might have been occurring aside the main mode)



How far back can we look?

- "Event Horizon" = formation of Earth-Moon system after Theia impact (ca. 4.57–4.45 Ga)
- Oldest <u>detrital</u> zircons = 4.4 Ga (Jack Hills, Yilgarn craton, Australia)
- Oldest intact piece of continental crust = ca. 4.0 Ga (Acasta gneiss, Slave craton, Canadian Northwestern Territories)

https://www.nwtgeoscience.ca/file/ketchum-2006fieldschool2jpg

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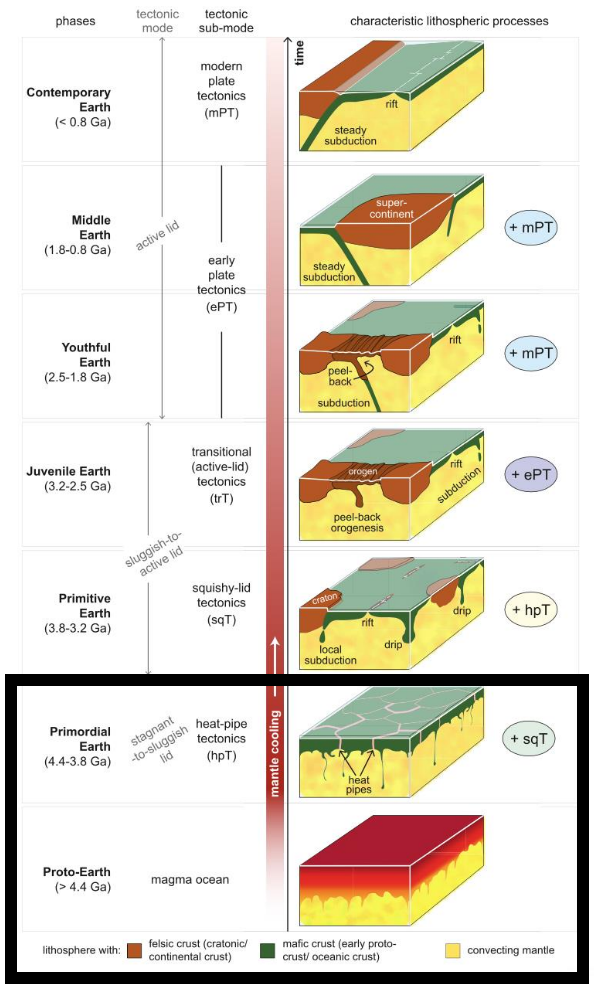
An impact melt origin for Earth's oldest known evolved rocks

Tim E. Johnson, Nicholas J. Gardiner, Katarina Miljković, Christopher J. Spencer, Christopher L. Kirkland, Phil A. Bland & Hugh Smithies

Nature Geoscience **11**, 795–799 (2018) | Cite this article



MANY conflicting theories.

nature communications

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Article | Open access | Published: 06 March 2020

An andesitic source for Jack Hills zircon supports onset of plate tectonics in the Hadean

Simon Turner, Simon Wilde, Gerhard Wörner, Bruce Schaefer & Yi-Jen Lai

Nature Communications **11**, Article number: 1241 (2020) | Cite this article

Hadean subduction zones????

RESEARCH ARTICLE | DECEMBER 16, 2021

Early Earth zircons formed in residual granitic melts produced by tonalite differentiation

Oscar Laurent; Jean-François Moyen; Jörn-Frederik Wotzlaw; Jana Björnsen; Olivier Bachmann

+ Author and Article Information

Geology (2022) 50 (4): 437–441. https://doi.org/10.1130/G49232.1 | Article history

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Partial melting of mafic crust due to late meteorite bombardment?

"Primordial Earth's" <u>many</u> tectonic modes:

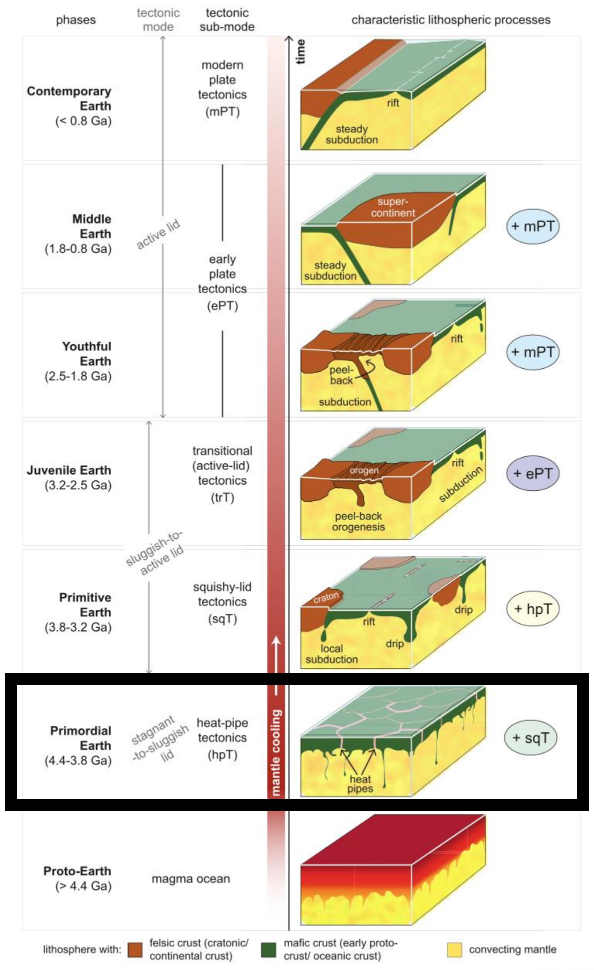
- Stagnant-lid tectonics
- Heat-pipe tectonics
- Sluggish-lid tectonics
- Squishy-lid tectonics

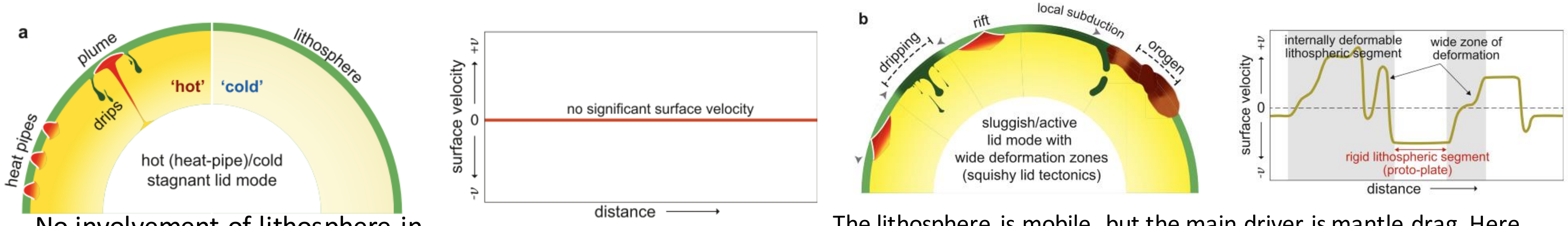
Sources of data:

- Very rare crustal remnants (a.k.a. Acasta Gneiss & co.)
- Detrital zircons within younger rocks
- Chemistries of younger igneous rocks whose protoliths were thought to have formed in the Archean

+ MANY models!

Cawood et al. (2022), Lenardic (2018), Richards et al. (2001)





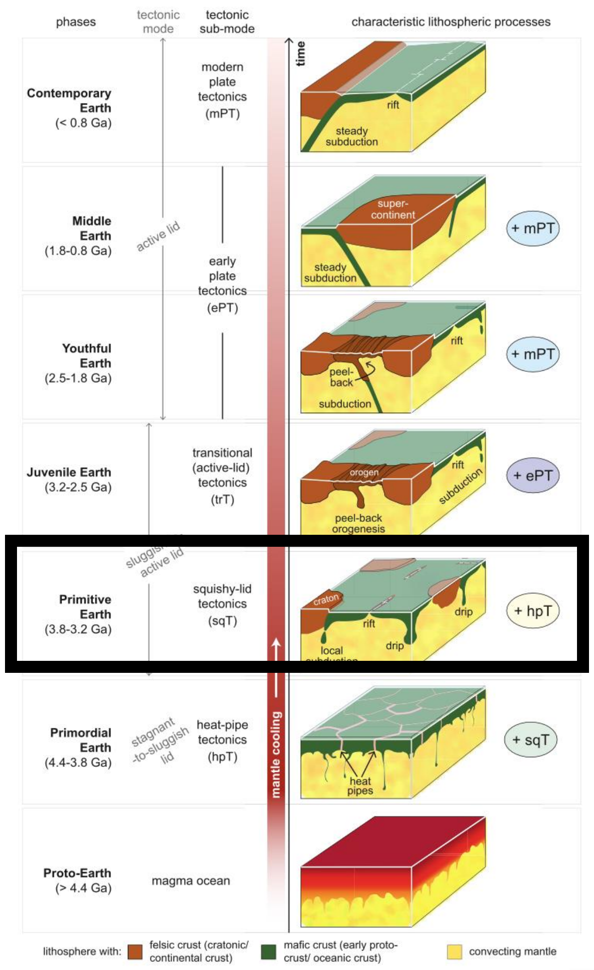
No involvement of lithosphere in mantle convection (laterally immobile lid on top of mantle)

The lithosphere is mobile, but the main driver is mantle drag. Here (Archean), "rigid lithospheric segments separated by wide zones of non-rigid, melt-impregnated lithosphere" = modern day Venus

BIG unknown!

The timing of development of Earth's bimodal hypsometry and whether it can be uniquely linked to a tectonic mode remain critically unresolved issues in unraveling secular evolution.

"Primitive Earth" - Squishy-lid tectonics.

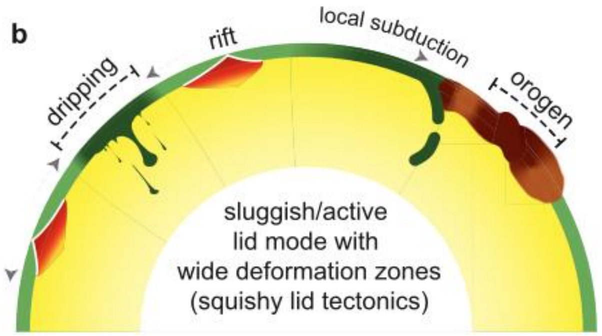


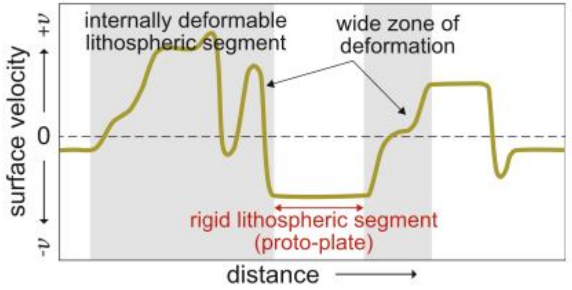
- Squishy lid tectonics & heat pipe tectonics.
- Formation of the first cratons & greenstone terranes.

Data & processes:

- Mafic & Tonalite-Trondhjemite-Granodiorite (TTG) volcanism = large input of mantle-derived melts.
- First of potassic volcanics = melting of TTG = increasing thickness of continents
- Modelling of detrital zircon populations = cratons being recycled
- Field evidence of continents emerging above sea level en masse
- (limited) Palaeomagnetic evidence for continental drift

Cawood et al. (2022), Lenardic (2018), Richards et al. (2001)





This is the time period when chemical signatures resembling present-day plate tectonics are produced.

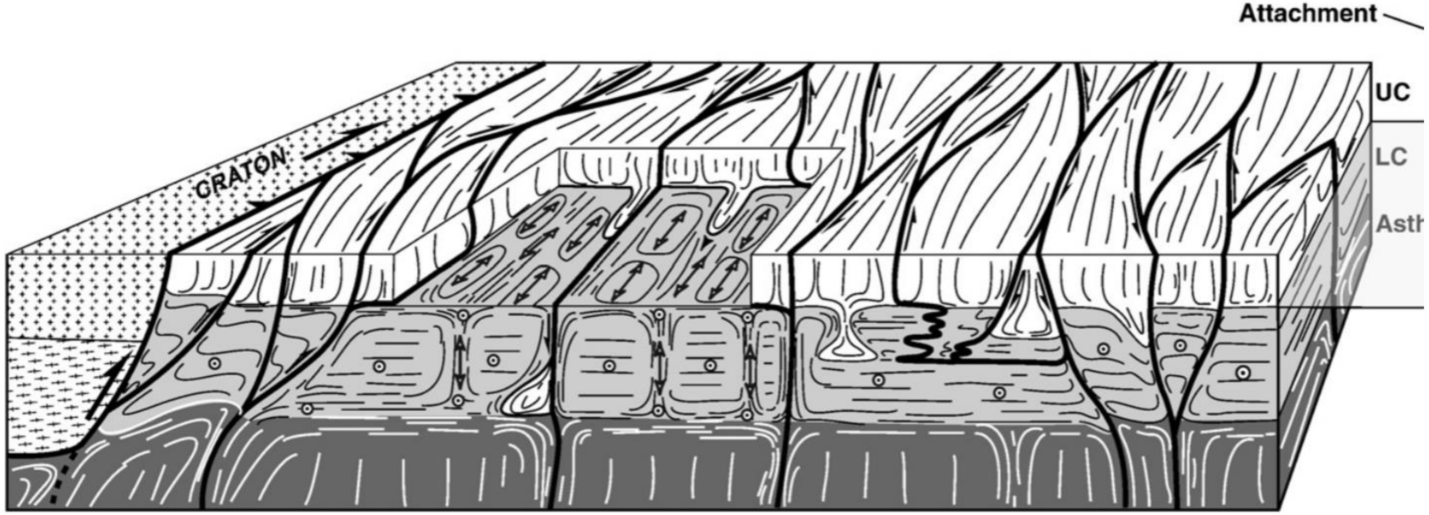
Recycling lithosphere ≠ mPT!

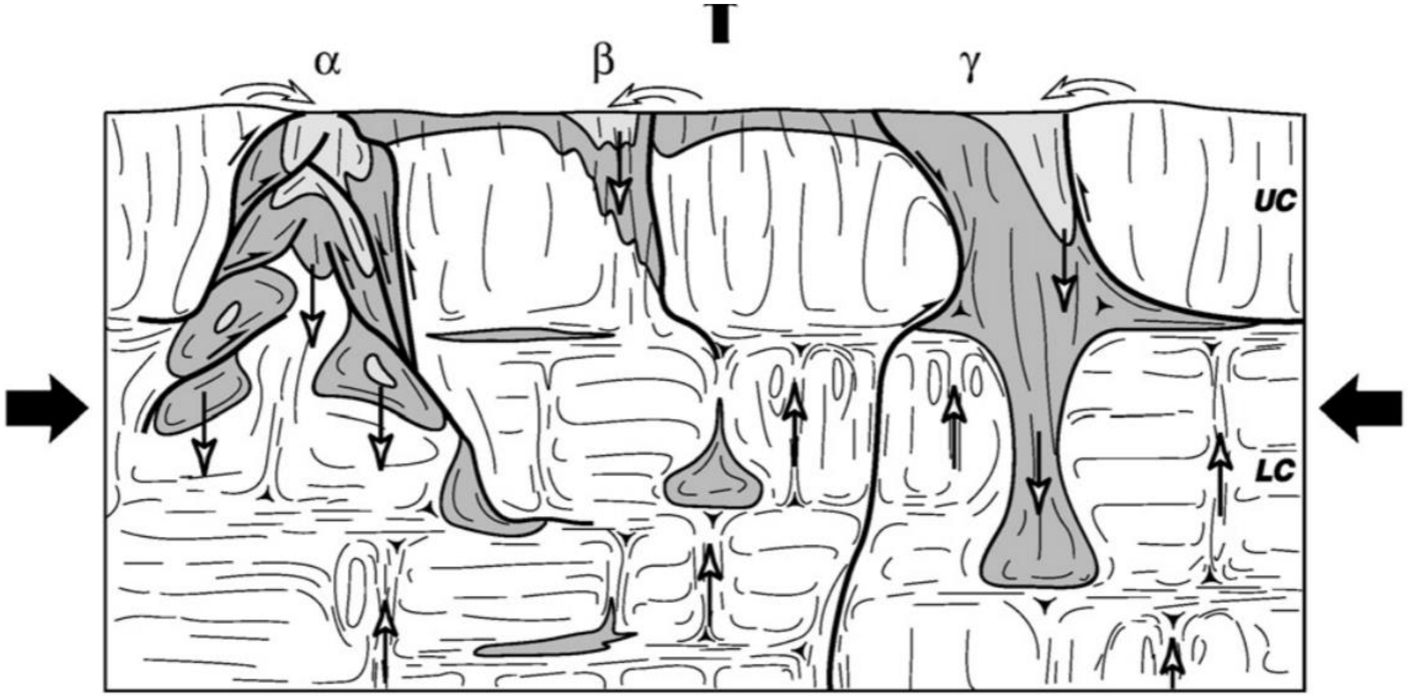
Done via drips, delamination

Small proto-plates separated by zones of hot & weak lithosphere

Squishy-lid tectonics up close

- Surface pattern and kinematics of "Ultra-hot orogens"



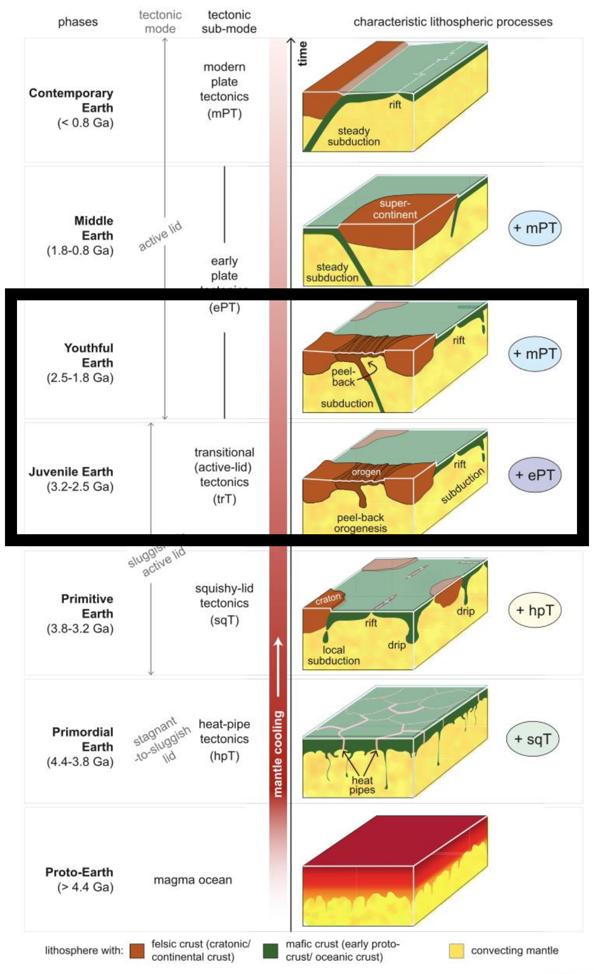


- Kinematics of <u>vertical</u> movement in "Ultra-Hot orogens"

Chardon et al., (2009)

Juvenile Earth. Is this Plate Tectonics yet? Not really.

- Reminder: We still haven't left the Archean! (4.0 Ga – 2.5 Ga)
- Transitioning to active-lid tectonics.

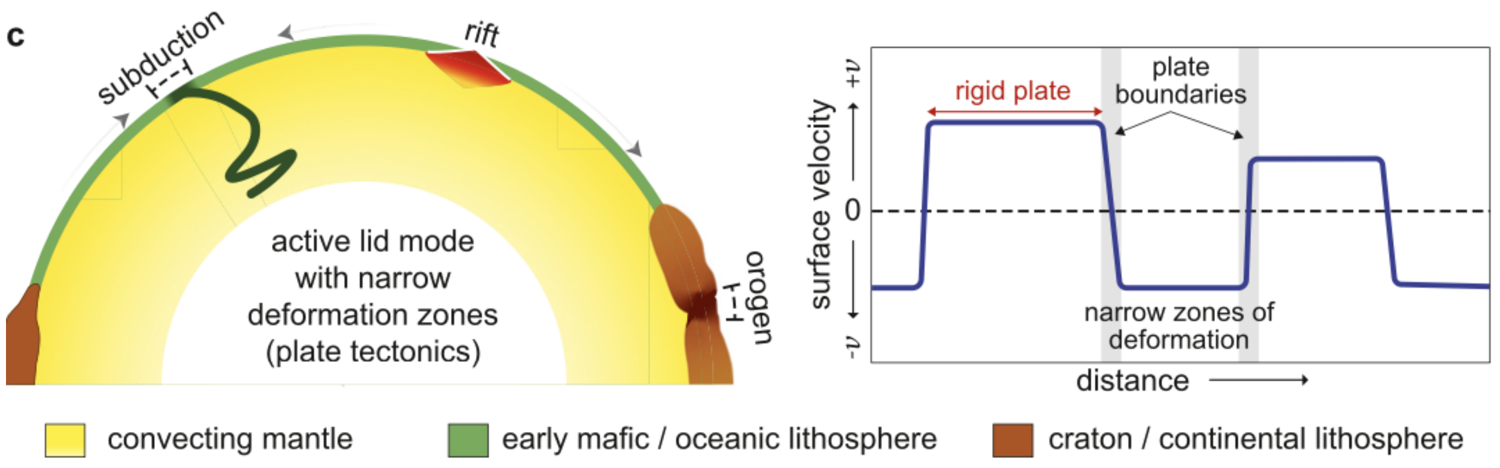


Data and processes:

- Field evidence – many first appearances:
  - Massive dyke swarms
  - Granulite-facies metamorphism
  - Linear, orogenic accretionary belts

The mantle is still much hotter than in our times = style of orogens much different (impeded by slabs breaking off and trench rollback)

Collisional processes dominated by lithospheric peeling.



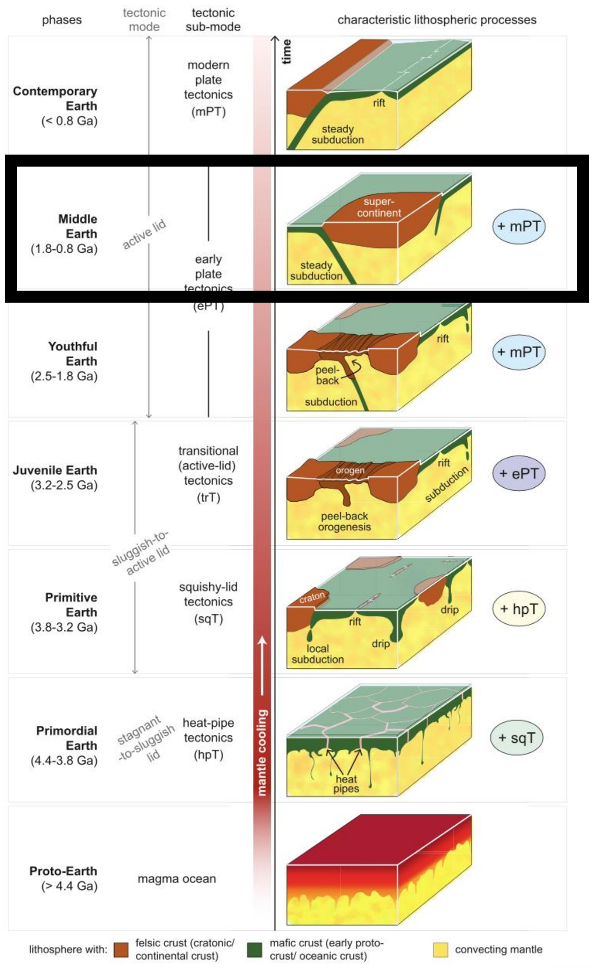
Active lid = deformation limited to plate boundaries ("stiff" continents)

"Middle Earth" Are we there yet?

Yeah, kinda!

- Supercontinental cycle – formation of Nuna and Rodinia
- Long-lived supercontinents?
  - Lots of A-type granites
  - No complete "subduction girdle" around Nuna periphery
  - No chemical signatures suggesting subduction
  - No mineral deposits associated with subduction
- BUT we have a large record of well-developed orogens!
  - Thin crust
  - HIGH heat flux (UHT metamorphism)

Modern plate tectonics possibly present in some places!

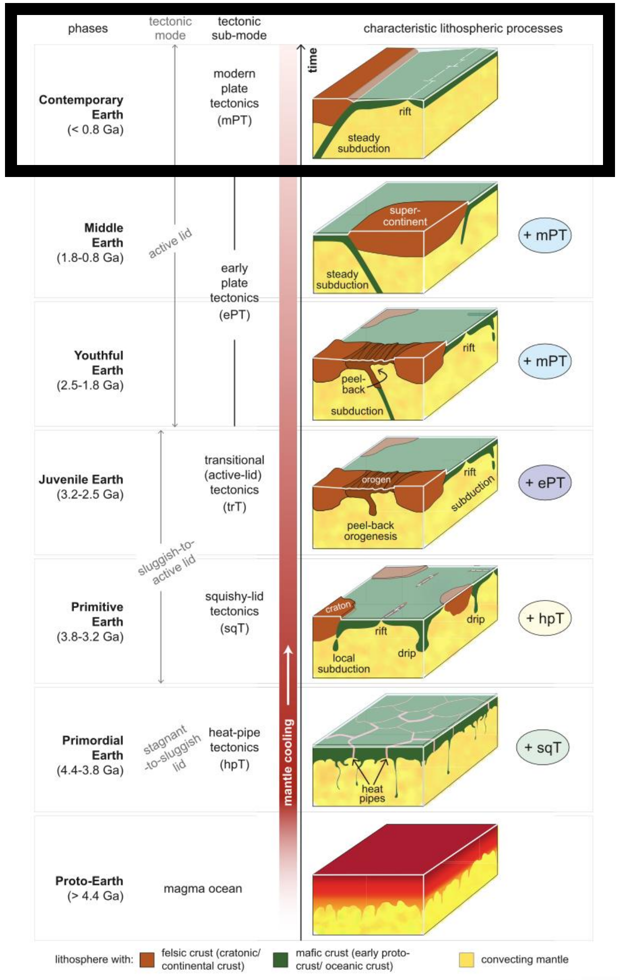


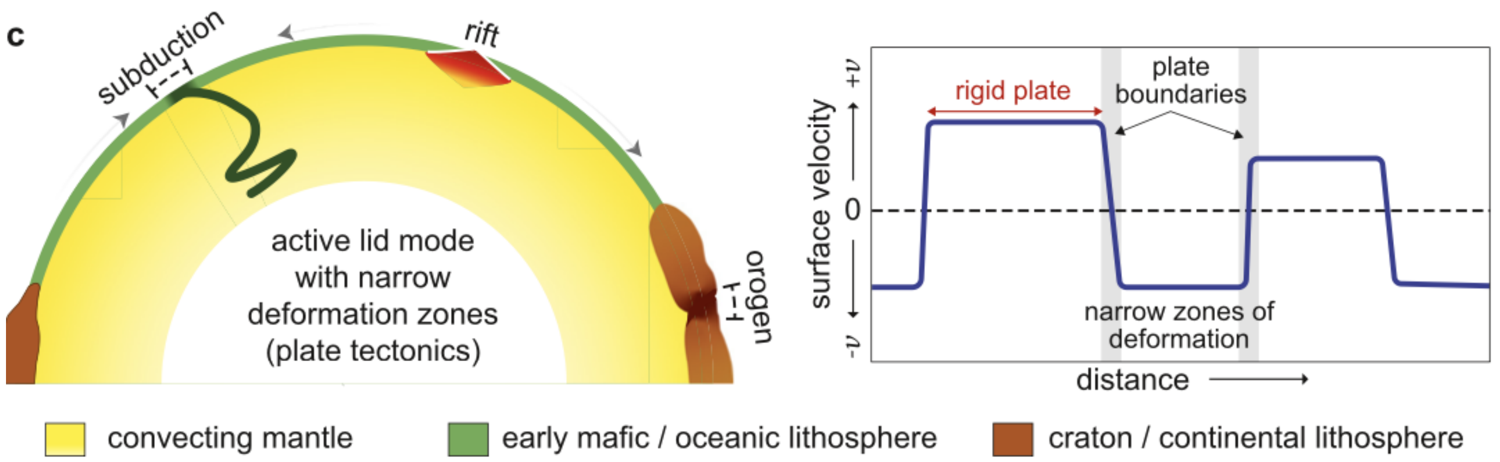
Explanations? :
- Supercontinent-induced thermal blanketing weakening the lithosphere?
- Mantle upwelling due to slab break-off / delamination softening the "typical"?
- Or BOTH? = Protracted Supercontinent cycle AND just a different style of plate tectonics?
  - Modern plate tectonic regime (Wilson cycle) but different orogenic style – orogens behaving differently

"Modern" Plate tectonics!

- How do we finally get here?

  - The mantle is finally cold enough – the subducting slab, weakened by bending, can finally withstand the mantle temperatures and NOT break off / delaminate!
  - Steady and continuous subduction commences.
  - Slab pull can now drive the subduction process!
  - UHP rocks form





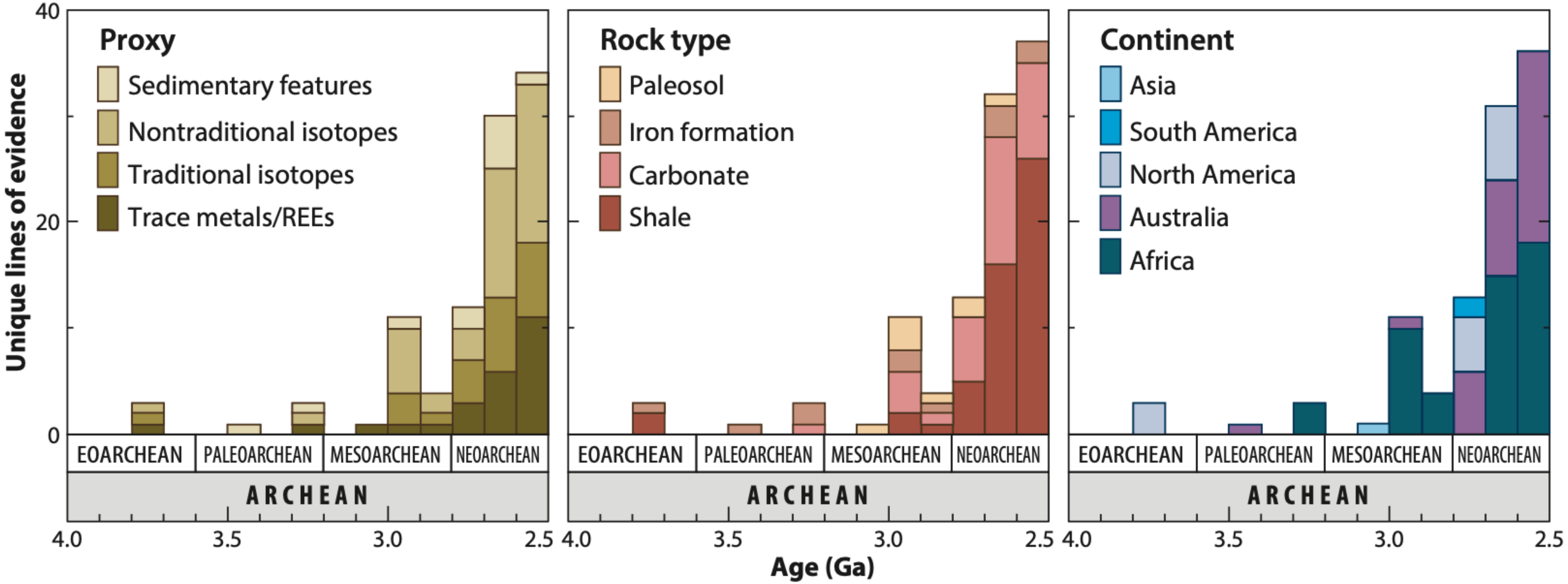
Last few words - thank you for your attention!

The evolution of the continental lithosphere and tectonics through time has direct implications for the surficial morphology of our planet and the Earth system as a whole.

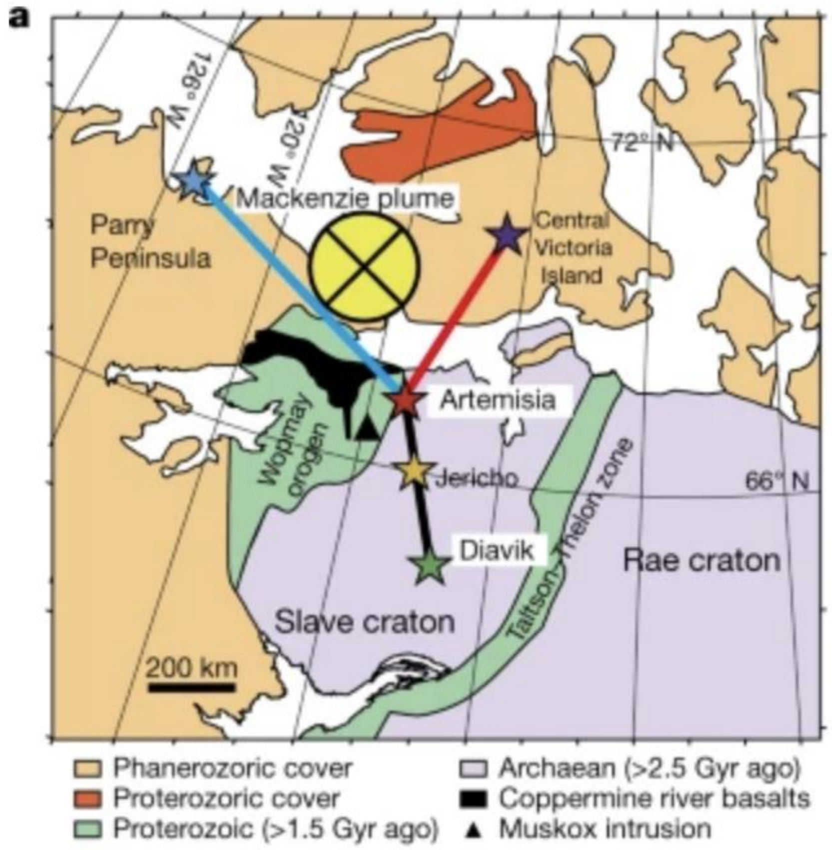
Cawood et al. (2022)

Plate tectonics and the beginning of life on Earth?

Ostrander et al. (2021)



First "whiffs" of oxygen coincide with the emergence of continents above sea level.



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Article | Published: 28 April 2021

Plume-driven recratonization of deep continental lithospheric mantle

Jingao Liu, D. Graham Pearson, Lawrence Hongliang Wang, Kathy A. Mather, Bruce A. Kjarsgaard, Andrew J. Schaeffer, Gordon J. Irvine, Maya G. Kopylova & John P. Armstrong

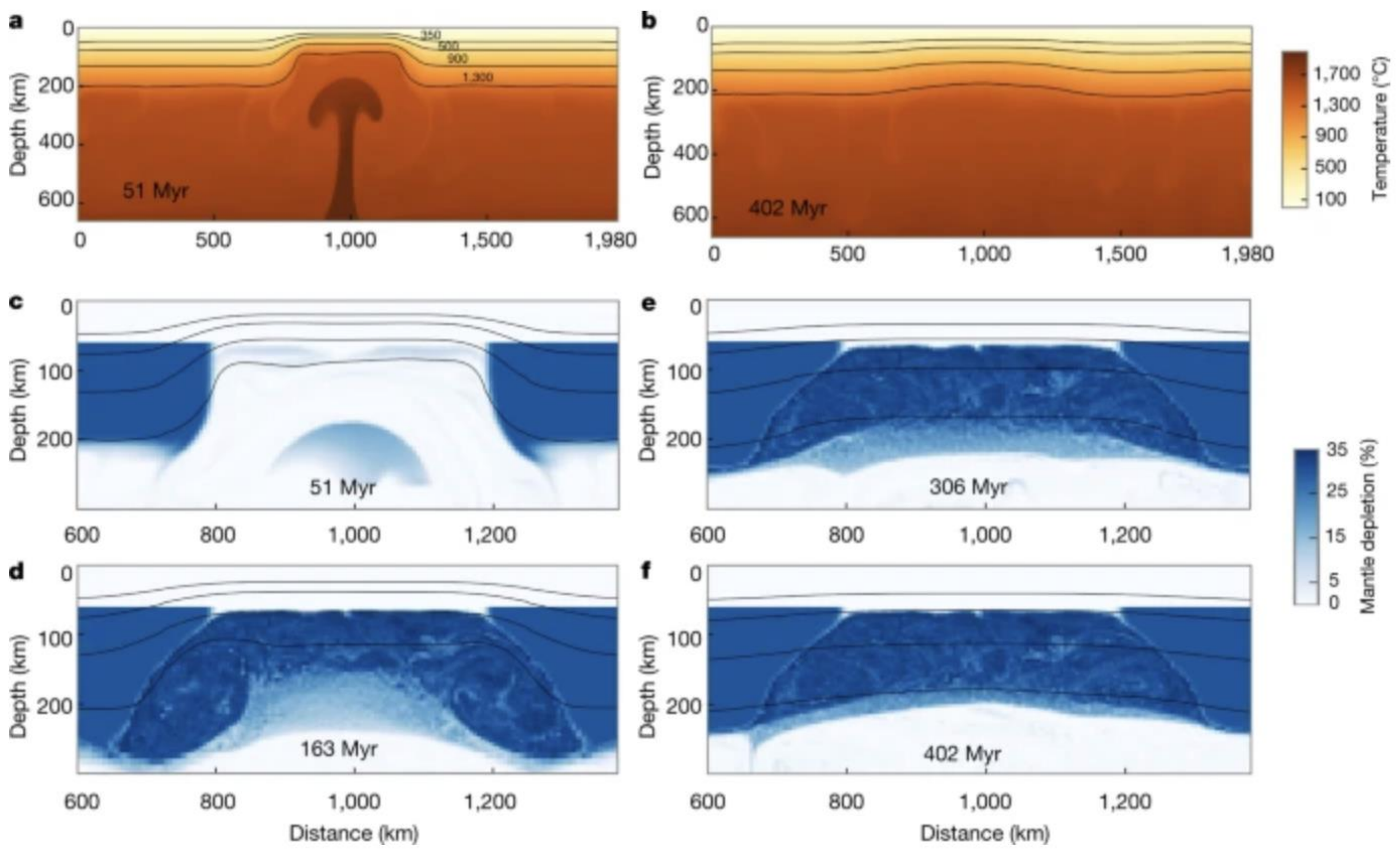
Nature **592**, 732–736 (2021) | Cite this article

Old(est) crust on top of (relatively) young mantle!

Thinning allows the production of melt and creates a trap for the upwelling buoyant and strong residues resulting from plume melting. The basal lithospheric topography, combined with the effects of plume melting, sets up a situation where the thin spot heals through the vertical accretion of these melting residues, specifically peridotite

And they modelled it!

Fig. 3: Numerical modelling of plume residues filling a thin spot between thick cratonic lithospheric roots.



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The presentation should be:

- An introduction to the topic
- Its methodology
- How this is used for studying the lithosphere (and possibly, the asthenosphere)