Continental lithosphere

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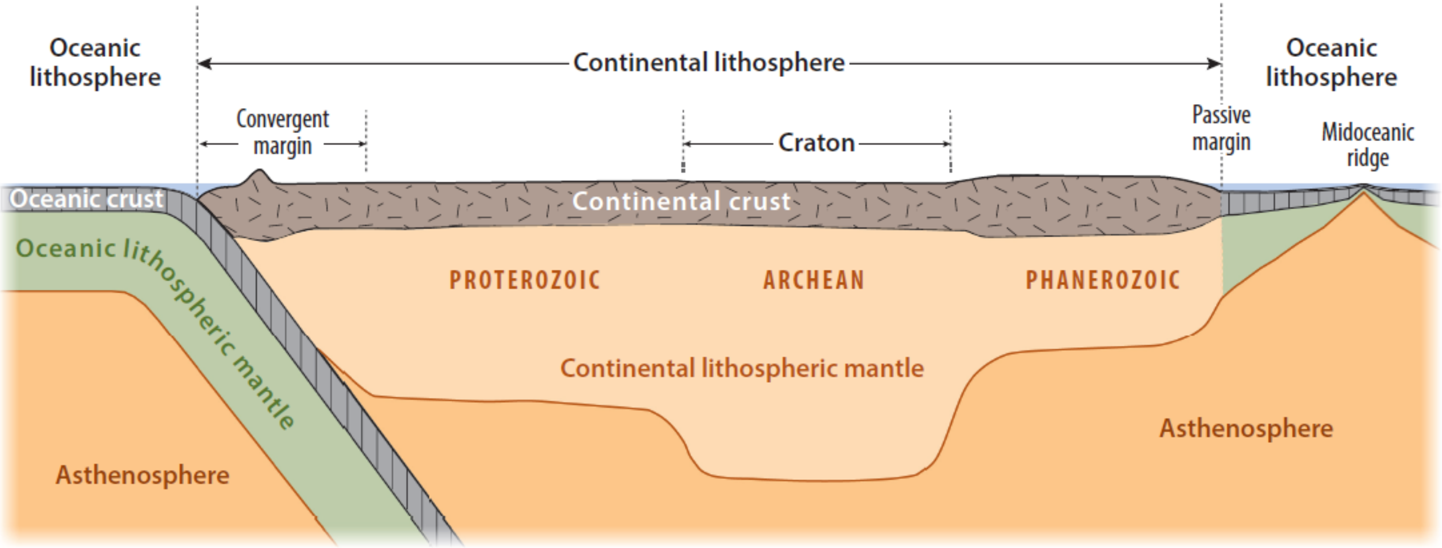
Current understanding of continental lithosphere

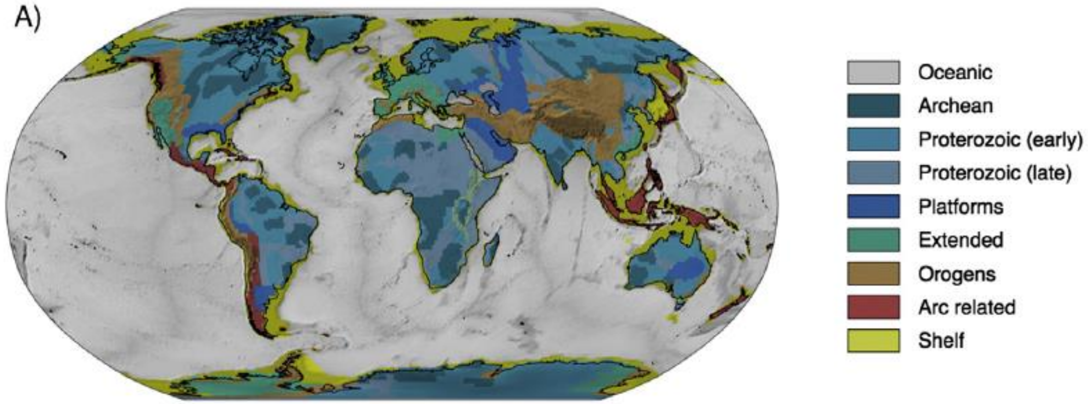
- Continental crust complex, less understood than oceanic lithosphere
- Continental crust is buoyant and challenging to destroy
- Rocks up to 4.2 Ga (oceanic crust 200 Myr), old rocks 3 Ga 5% of the crust
- New crust generated by volcanism and accretion in subduction zones
- Archean crust 200-250 km, dehydrated stable cratons
- Information gained from: seismic studies, geochemical studies, geodynamic modelling etc.
- Current lithosphere represents the sum of several tectonic processes
- Can use present day observations together with geodynamic modelling and geochemical analysis to get information on past earth



Characterization of continental lithosphere

- Can be characterized in many different manners
- Cratons and mountain chains mapped within the same regions in both models

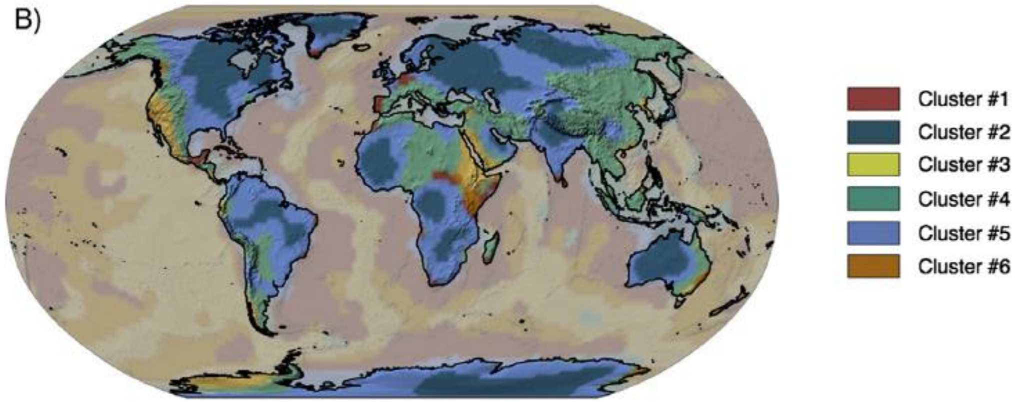
A)



Laske et al, 2012

Crust 1.0: Shallow geophysical observations and geological provinces

B)

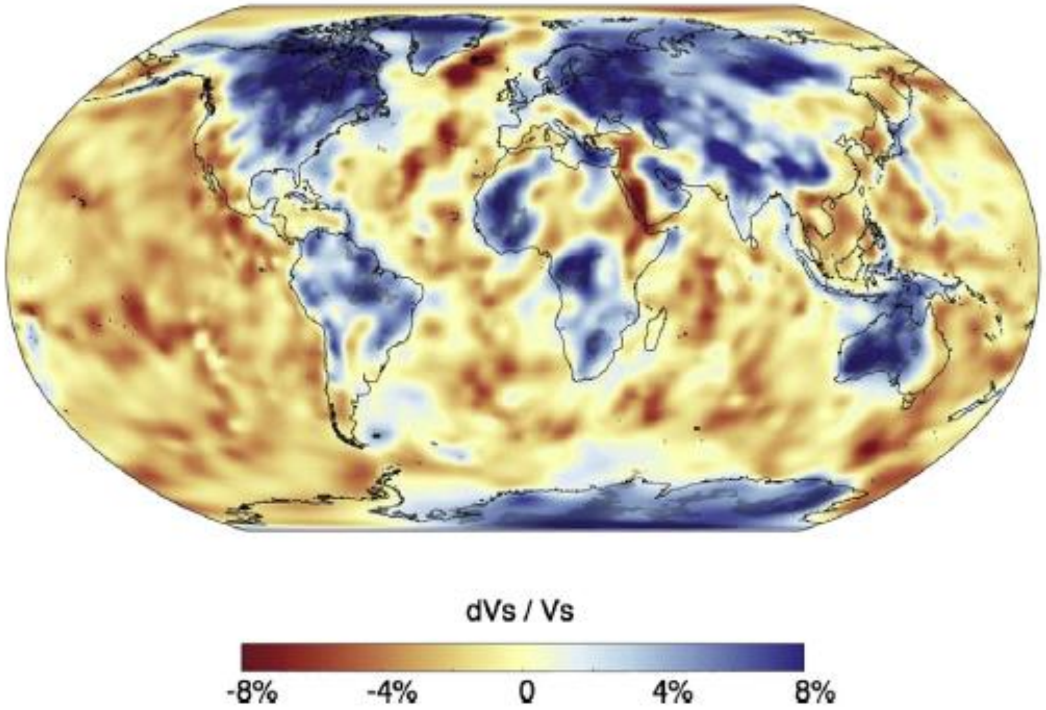


Lekic & Ramanovicz, 2011

Clustering based on tomography studies and seismic velocities

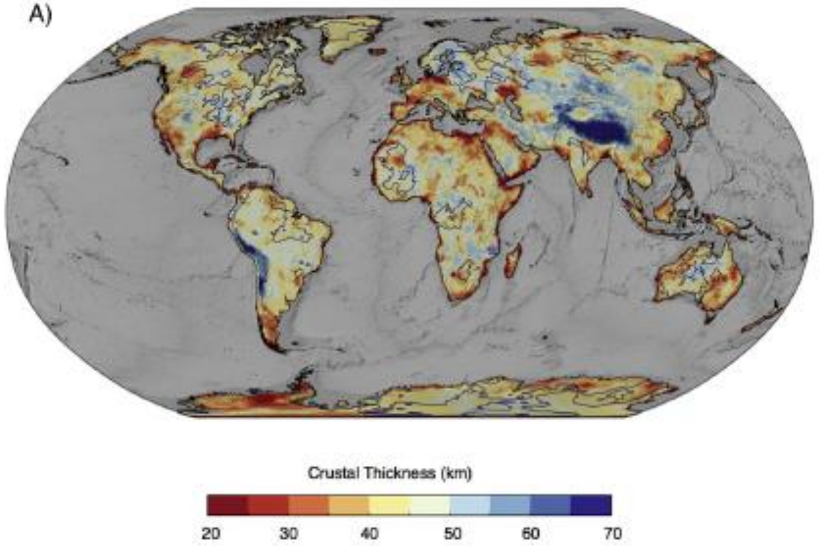
Seismic studies

- Global S-wave tomography study. Higher velocities associated with less tectonically active regions
- Regional studies show higher complexities

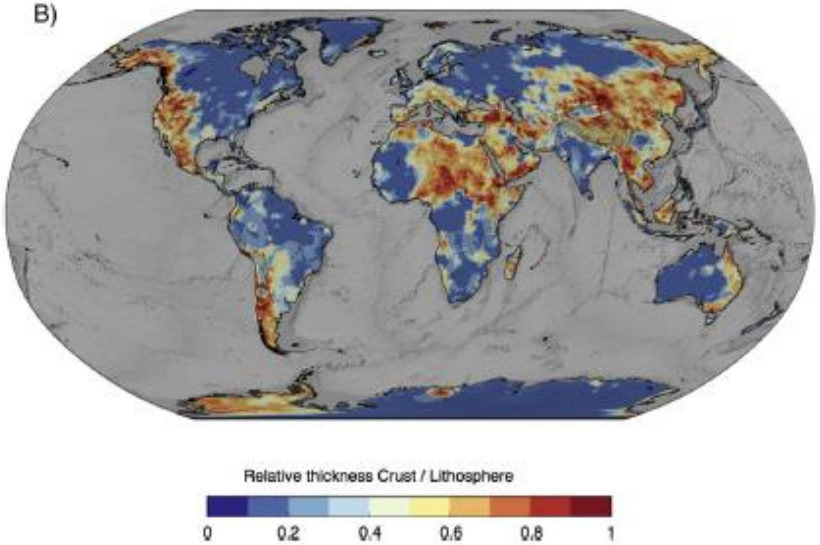


Surface wave tomography- depth 150 km

Thickness of continental lithosphere



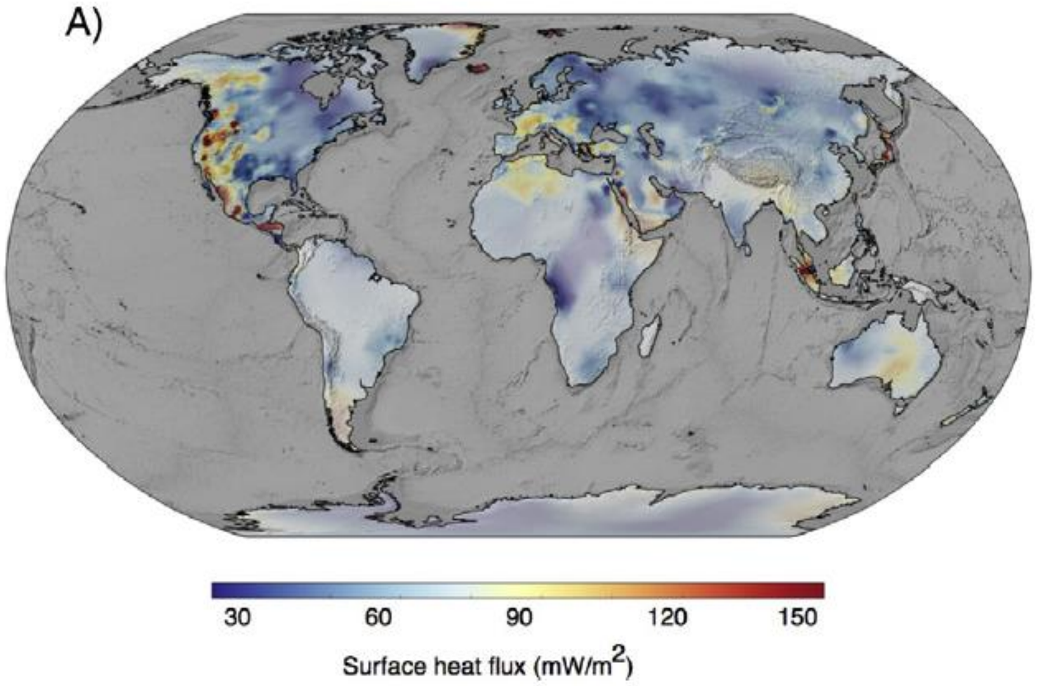
Crustal thickness: Mountain chains



Relative thickness: tectonically active vs. stable regions

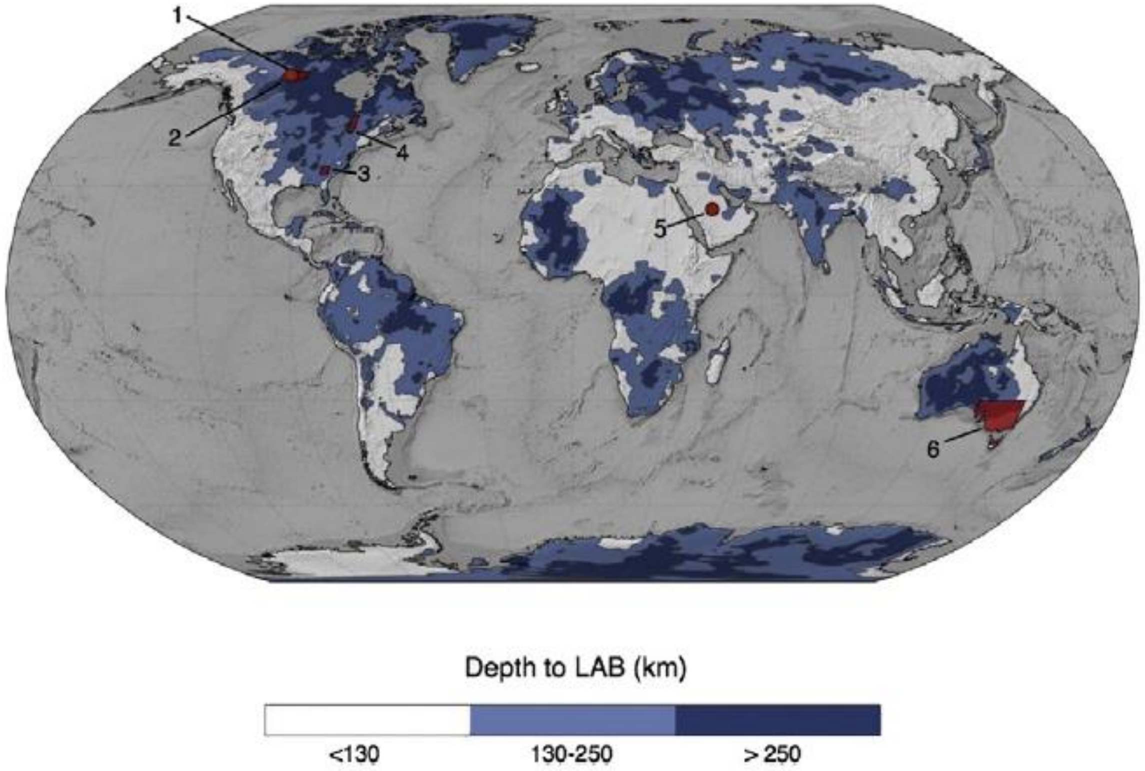
Heat flux

- Surface heat flux measurements
- As the earth cools, the average thickness of the thermal boundary layer increases
- Variations in thickness of thermal boundary layer, indicate variations in age (Time since last tectonic event)



Depth to LAB

- Dark blue, depth thicker than 250 km
- Red: Ancient accreted terrains preserved within the lithosphere
- Seismic studies, possible presence of tectonic boundaries or sutures in stable continents
- Base of LAB observed at different depths also within stable cratonic regions

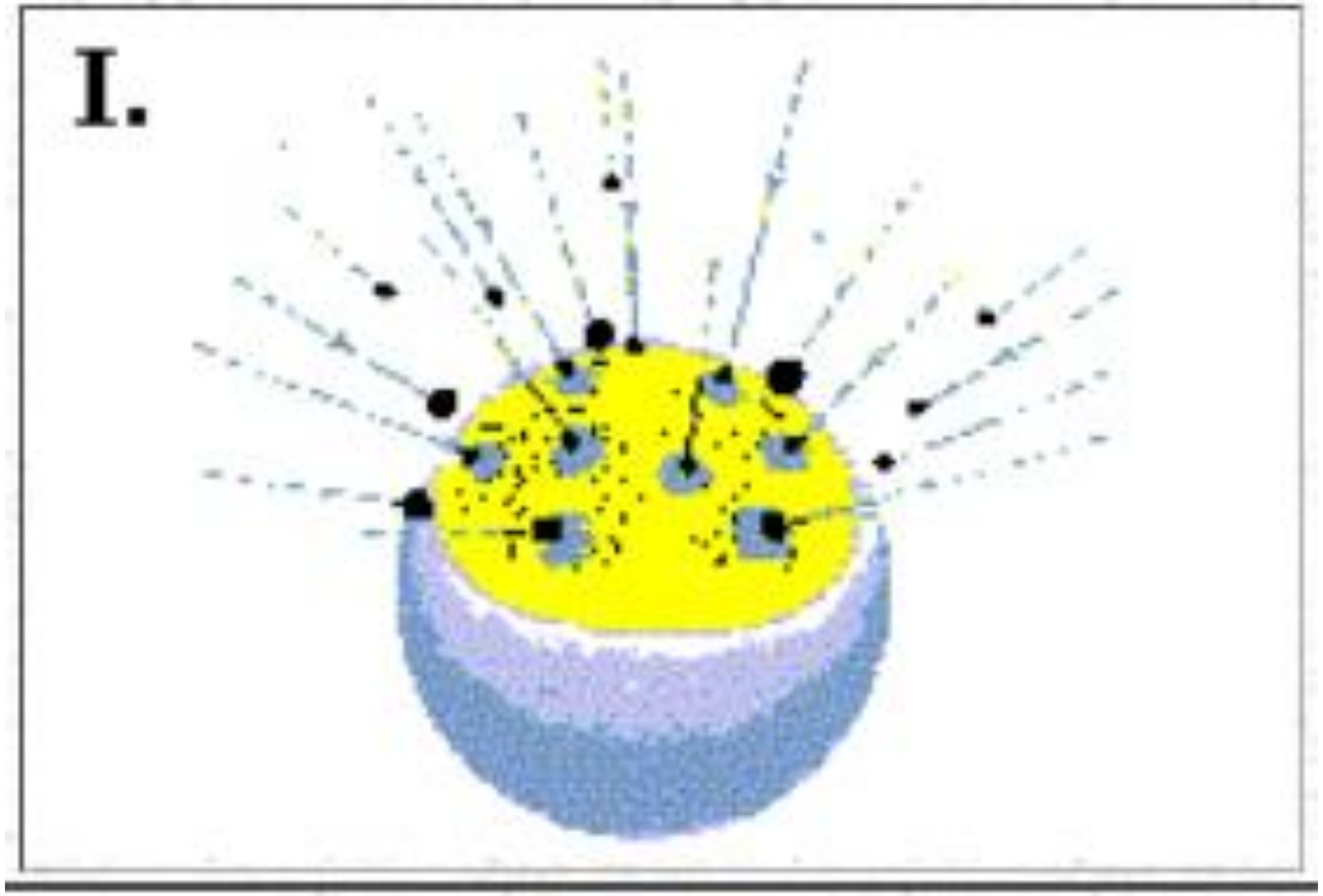


Formation of the continental lithosphere

- There is proposed 5 stages of the evolution of the Earth
- Stage 1 is the initial accration of the Earth
- Stage 2 generation of crust prior to 3.0 Ga in a preplate tectonic regime

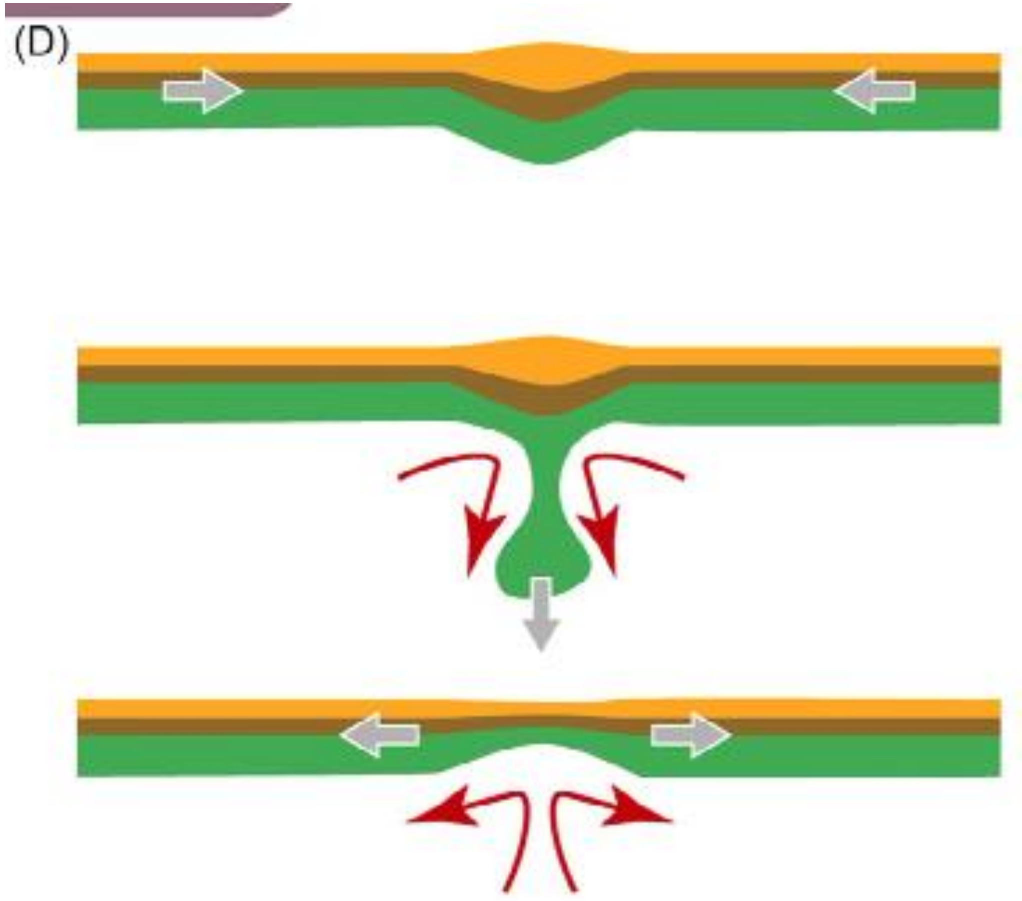
Stage 1

- Accretion of the Earth
- Development of a magma ocean
- Development of an undifferetiated mafic protocrust
- Gravitational field - Differensiation of the core and the mantle



Stage 2

- Apparent meteorite bombardment
- Collision between the proto-Earth and a body the size of Mars – resulting in the formation of the Moon
- This heavy bombardment ended at 3.9 Ga (Gomes et al. 2005)
- Mantle temperatures presumed to be 250 degrees higher than today
- Heat production was 3-6 times higher than than today
- There were zones of mantle upwelling and melting which caused lithospheric generation
- Recycling back to the mantle also occured as possibly lithospheric delamination



Magni and Király, 2019

First continental crust

- No known rock is older than 4.02 Ga, but zircons are dated to be 4.4 Ga.
- **Less than 7%** of the rocks preserved are older than 3.0 Ga.
- No lithosphere from that time, but inferred that there was and that the 3.0 Ga marks the stabilization of continental lithosphere that has survived
- The continental crust before 3.0 Ga was more mafic, and the distiction between continental and oceanic lithosphere was less clear
- This is indicated by the Rb/Sr ratios which are directly connected to the SiO_2. Rb readily incorprates in feldspars, which is one of the most common felsic minerals (high SiO_2)
- The Rb/Sr ratios of the crust are similar to that of the mantle at that time.
- First continental crust from initial magma ocean, was felsic magmas present, δO^{18} indicate that there was surface water aswell

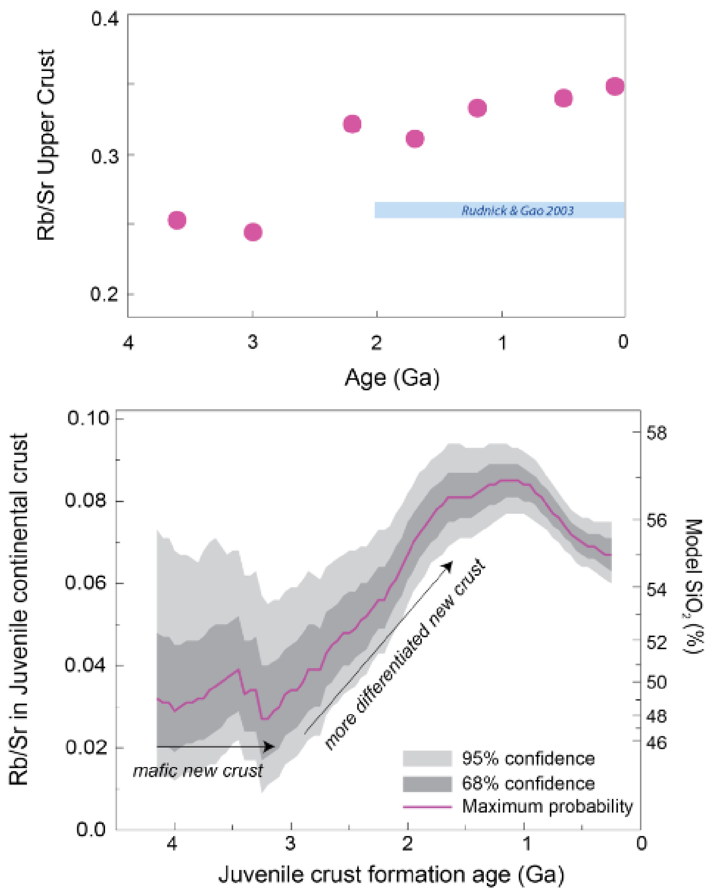


FIGURE 7 | Changes in the Rb/Sr ratios of the upper crust (map normalized) (Condie, 1993) and of juvenile continental crust (Dhuime et al., 2015) with time. The upper crust estimates of Rudnick and Gao (2003) is for average crust which has an age of ~2 Ga. The estimates of SiO_2 contents of juvenile crust are taken from the co-variation of Rb/Sr and SiO_2 in magmatic rocks (Dhuime et al., 2015).

More isotope data

- Rocks of Archean age tend to have lower topographic relief, but are underrepresented (Nd-model age figure)
- Nd-content of Earth's initial igneous rocks, are similar to those of chrondrites. (DePaolo and Wasserburg, 1976)
- The CHUR model. Chondrites are the earliest material that formed the solar system.
- The ratio between the radiogenic ^{143}Nd and non-radiogenic ^{144}Nd increases as compositon change from mafic to felsic.
- There was little recycling of volatiles as indicated by Xenon isotope data. As recycling of these materials are mainly driven by subduction (Peron and Moreira, 2018)

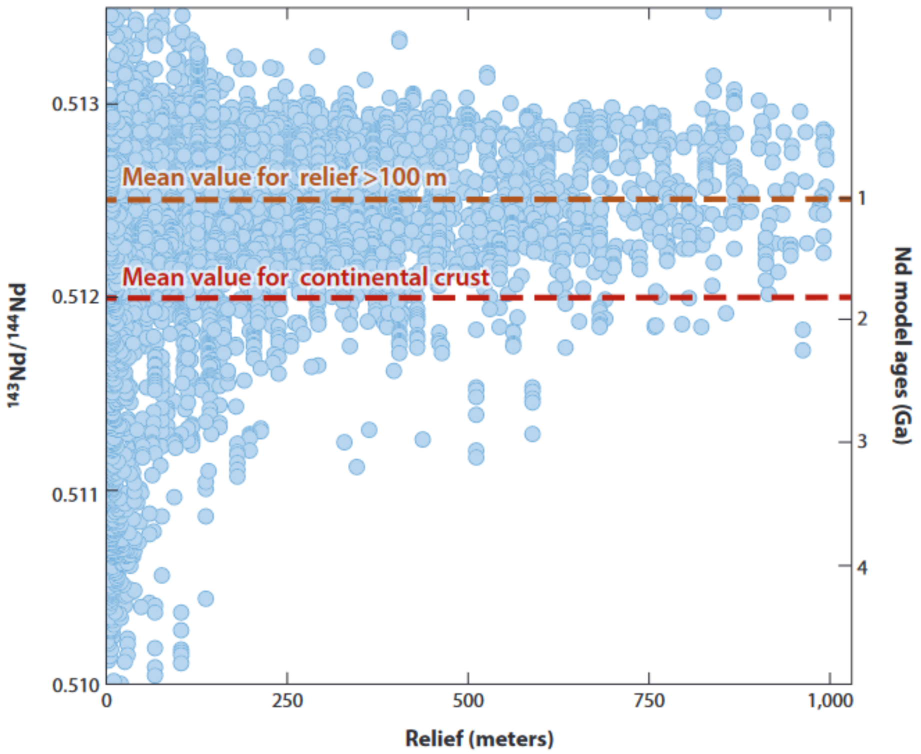
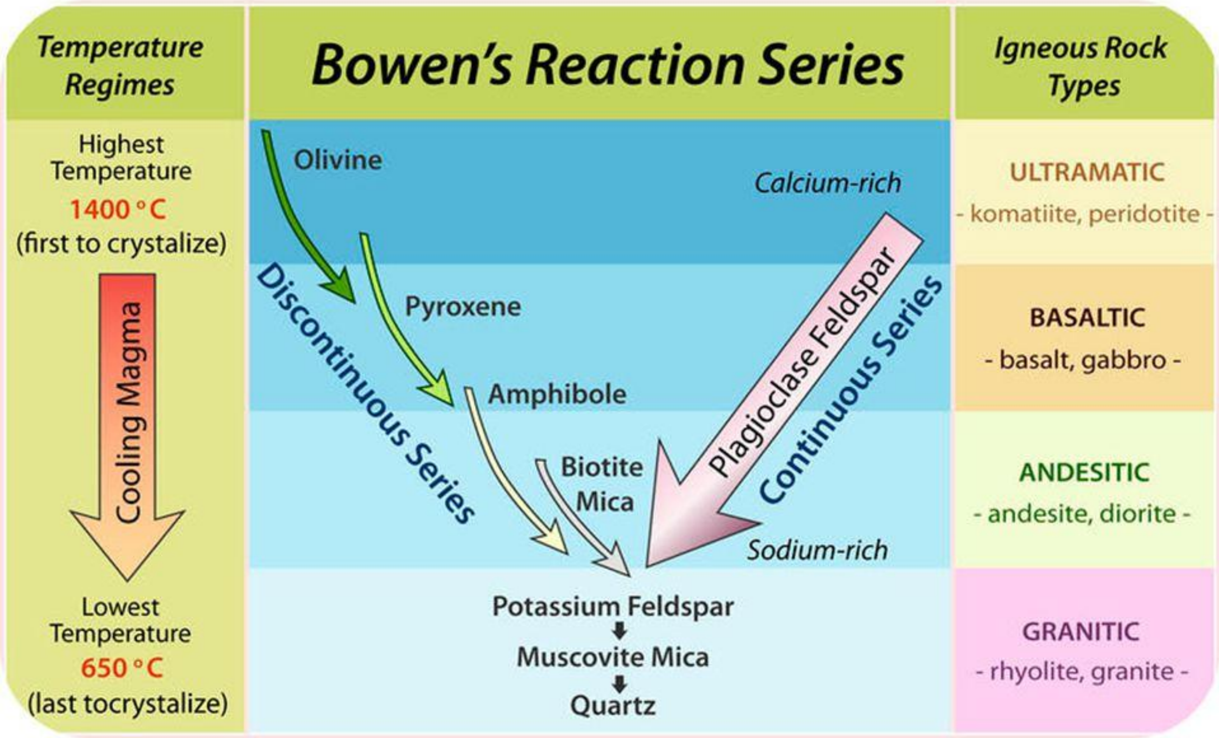


Figure 4

Present-day Nd isotope ratios for whole-rock samples plotted against topographic relief (Allan 2014). The average Nd model age for samples from areas of >100-m relief is ~1 Ga, whereas estimates of the average Nd model age for the continental crust is ~1.8 Ga from Condie & Aster (2010) and Chauvel et al. (2014).

More indications of a mafic crust

- Archean shales and glacial diamicities have high Ni/Co and Cr/Zr ratios comapred to younger sediments.
- These ratios correlate to MgO content in igneous rocks, which again is the main component of mafic minerals
- Based on this Tang et al. 2016 indicated
  that there was a decrease in MgO of the upper crust, from 15% at 3.2 Ga to
  4% by 2.6 Ga.



- Archean suits are bimodal in silica
- Bimodal distribution can be a feature of intraplate volcanism but does not occur in subductionrelated magmas
- Domes
- Pilbara Tarrane, Australia

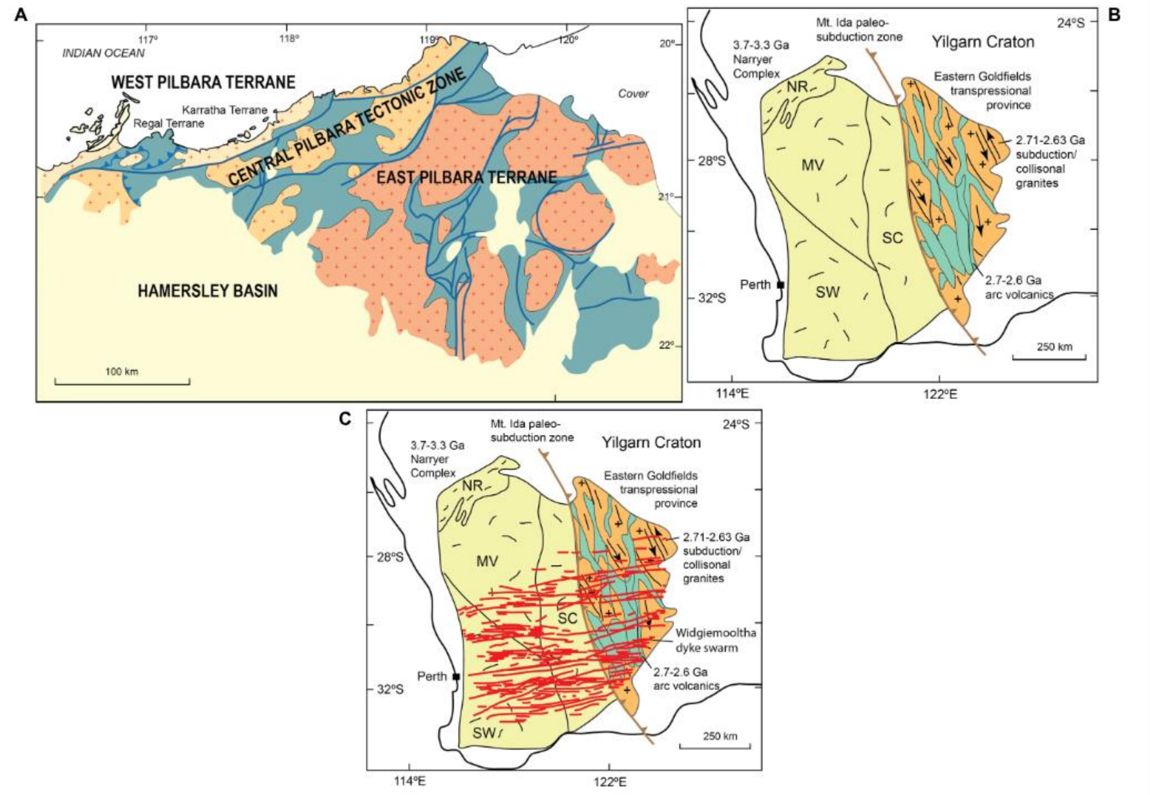
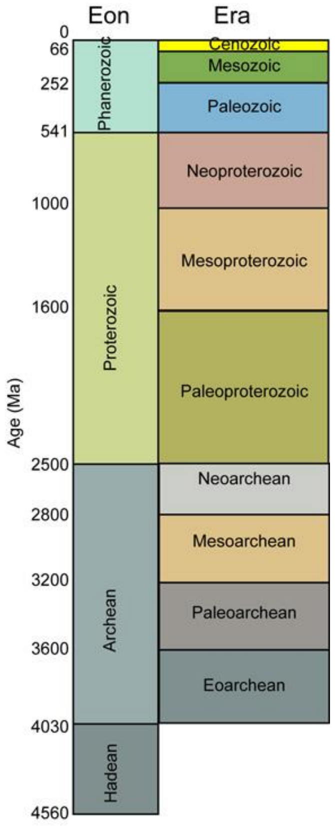
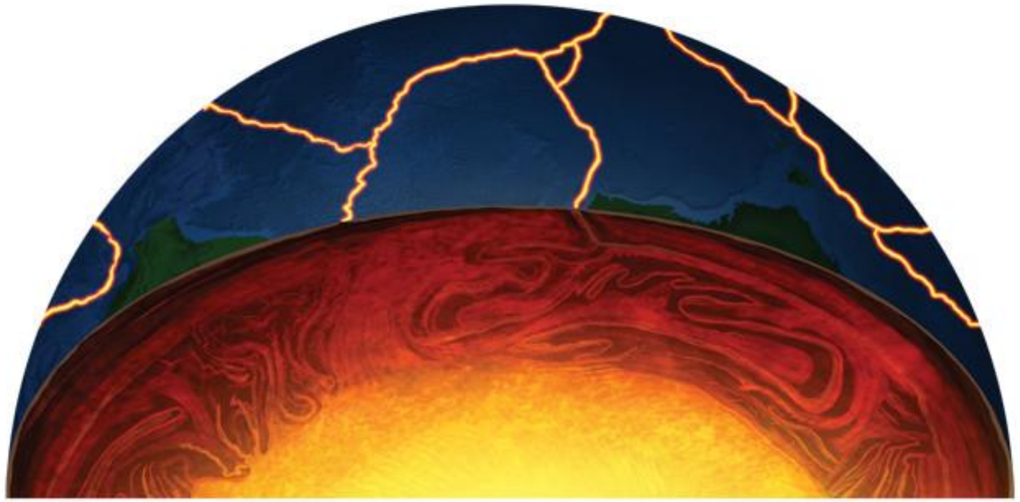


FIGURE 2 | The changing tectonic styles from 3.5 to 2.4 Ga in Western Australia. **(A)** A sketch map of the dome and basin terrain of Pilbara in NW Australia, after Hickman (2004) and Van Kranendonk (2010) **(B)** geological sketch map of the Yilgarn craton and the N-S trending mobile belts in the East Yilgarn (after Kusky et al., 2018), and **(C)** a map of the Widgiemooltha dyke swarm in the SW Yilgarn.

Onset of Plate Tectonics



- Earth is the **only known planet** where plate tectonics (PT) is active
- The lithosphere **broke into plates** and they began recycling into the mantle via subduction zones
- The forces of plate tectonics have repeatedly assembled supercontinents together and torn them apart - the **Wilson Cycle**
- There is still discussion over **when** PT may have become the dominant regime on Earth, and **how** it was established (development of PT → development of life)
- Different studies have concluded that plate tectonics started at times that range from **the early Hadean to 700 Ma** – **why such a long range?!**



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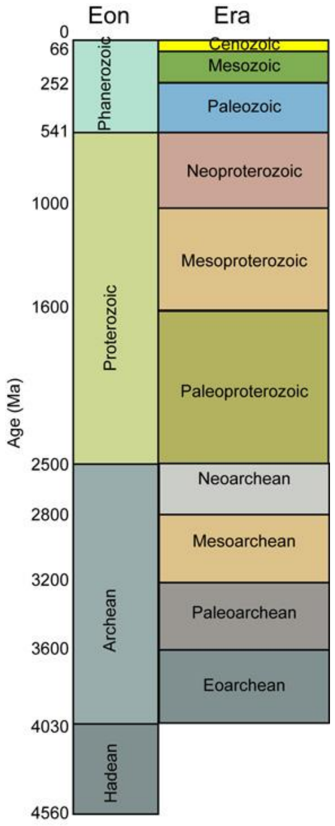
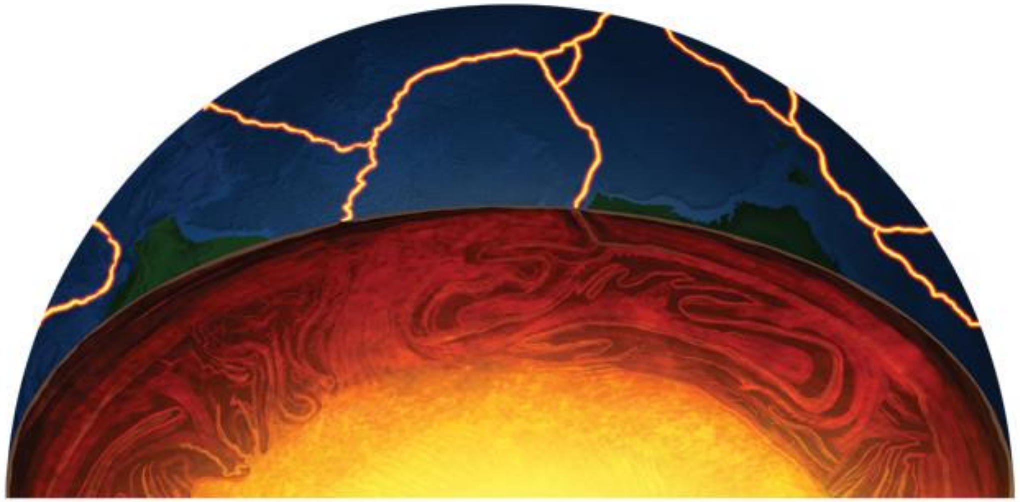


- differences in definition of plate tectonics

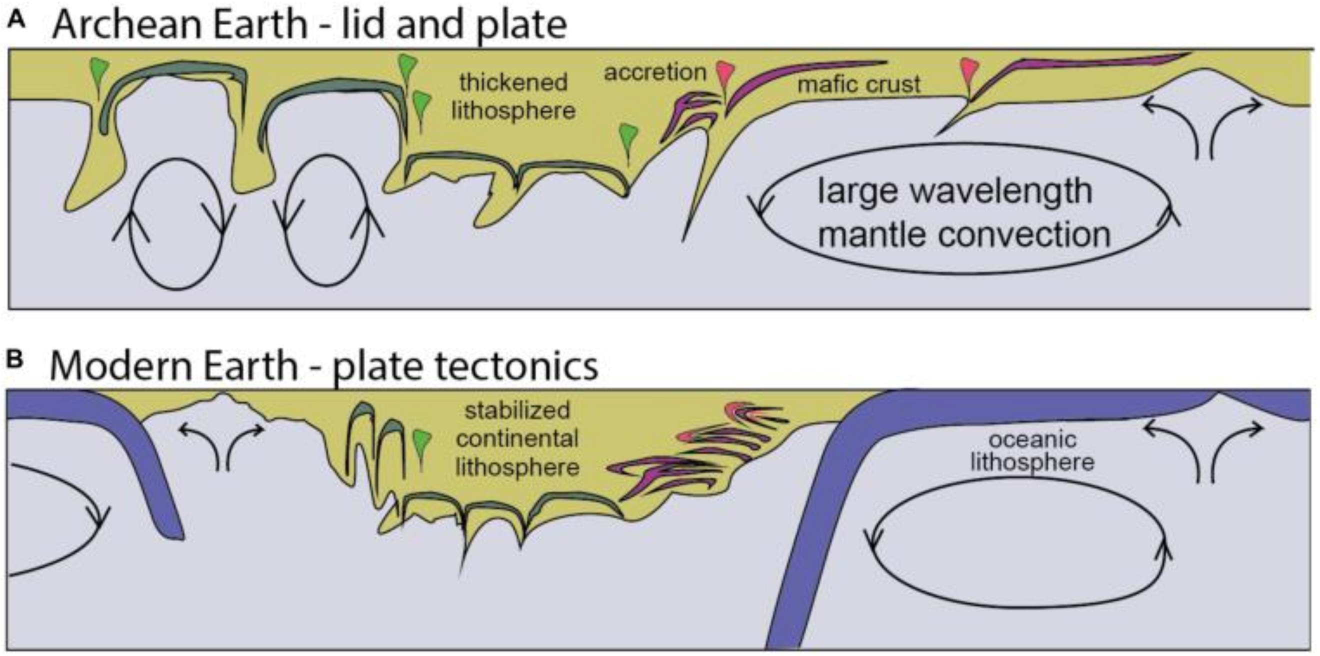
- different studies have regarded different pieces of evidence as pivotal



Archean Earth vs. Modern Earth

- PT emerged in response to **thermal cooling** of the mantle (mantle convection), and the consequent **increase in lithospheric strength and rigidity**
- **Heat production was 3–6 times higher** than at the present time (e.g. Pollack, 1997)
- **Archean Earth** - hotter mantle, weak lithosphere, shallow unstable “subduction”, stagnant lid PT
- The change from a nonplate tectonic Earth to plate tectonics dominated Earth was unlikely abrupt

PT was unlikely to have begun on Earth as a single global “event” at a distinct time, but rather that it **began locally and progressively became more widespread** through time (Condie and Kroner, 2008)



Hawkesworth et al. 2020

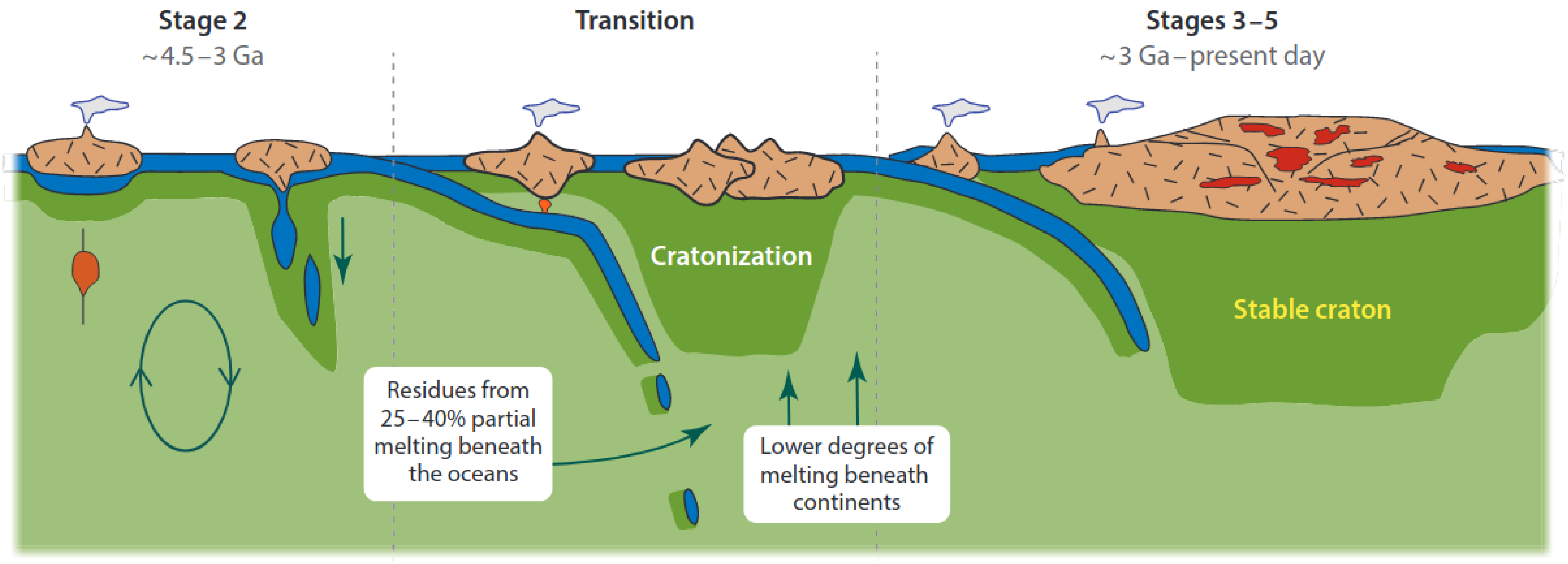


Figure 9

Schematic depiction of changing tectonic processes controlling the evolution of the lithosphere from an early Earth dominated by nonplate processes (stage 2) to one in which plate tectonics is the main mechanism for the generation and recycling of lithosphere (stages 3–5). These changes are a response to the secular cooling of the mantle and the consequent increase in lithospheric strength and rigidity. The mantle xenolith record suggests that they represent residues (from relatively shallow partial melting of hot mantle beneath the oceans), which subsequently accreted beneath continents. In contrast, the mafic crust that is the source of Archean tonalite-trondhjemite-granodiorites has relatively low Lu/Hf and Sm/Nd ratios, implying lower degrees of partial melting.

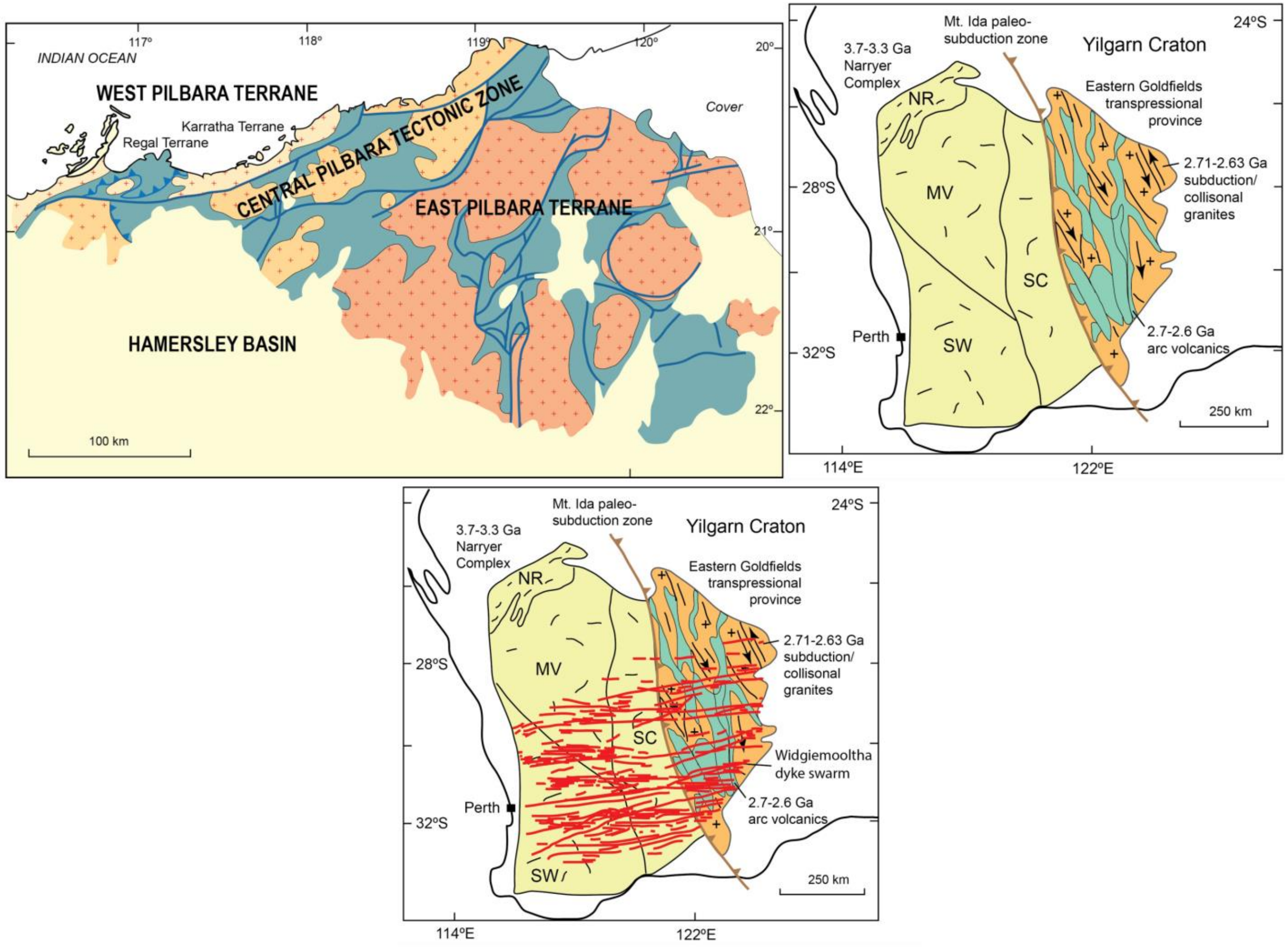
Hawkesworth et al. 2017

Geological Evidence for the Onset of Plate Tectonics

- Less than 7% of the **continental crust preserved today** is older than 3 Ga (Goodwin, 1996) → difficult to evaluate how representative that record may be of the processes that were **globally dominant** at that time
- Forces related to subduction → the **primary forces driving plate motion**
- Processes similar to subduction of lithosphere at destructive plate margins, can be triggered by **impacts and mantle plumes** (e.g. Gerya et al., 2015) → **not an evidence of PT!**
- The geological record reflects when the continental crust became rigid enough to facilitate plate tectonics, through the onset of **dyke swarms** and **large sedimentary basins**, together with **evidence for crustal thickening** and varying **rates of generation and destruction** of the continental crust

Strength of the Lithosphere

- Subduction of one plate below another requires a **certain rigidity in the crust**
- Some geological features reflect the strength of the lithosphere, e.g. regional **dyke swarms** at ~2.6 Ga, and the oldest **major sedimentary basins** at ~2.8 Ga
- Western Australia provides a good example of changing tectonic styles in the Archean and into the early Proterozoic
- The oldest dyke swarm in the area - the **Widgiemooltha dykes at 2.4 Ga**



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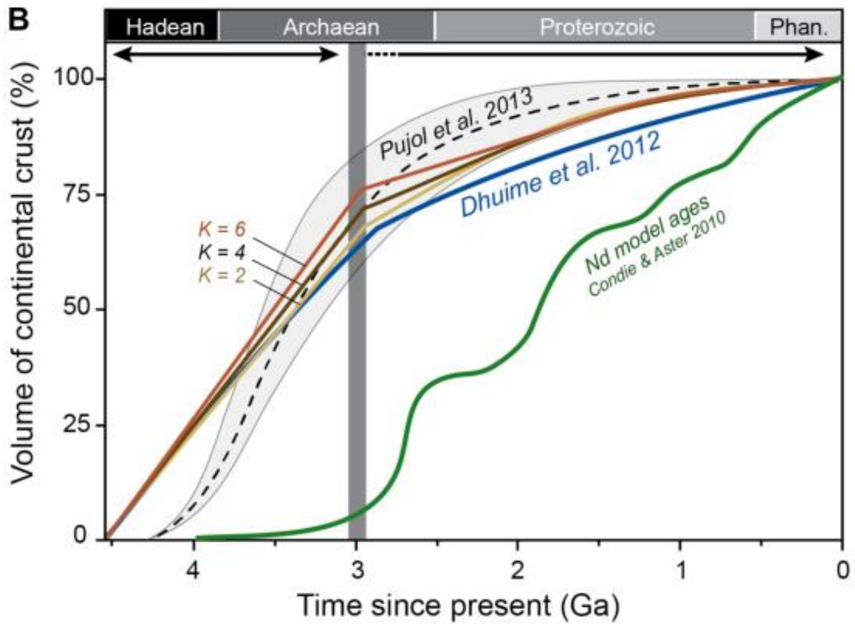
Growth of the Continental Crust

- 60 to 80% of the present day volume of continental lithosphere was established by ~3 Ga
- The development of PT is thought to **increase the rates at which continental crust is destroyed**, and that in turn will **reduce the rates of crustal growth**



Selected crustal growth curves suggesting that 60–80% of the present volume of the continental crust had been generated by 3 Ga, compared with the present day proportions of juvenile continental crust based on zircon crystallization ages in rocks with juvenile Nd or Hf isotope ratios (Condie and Aster, 2010).

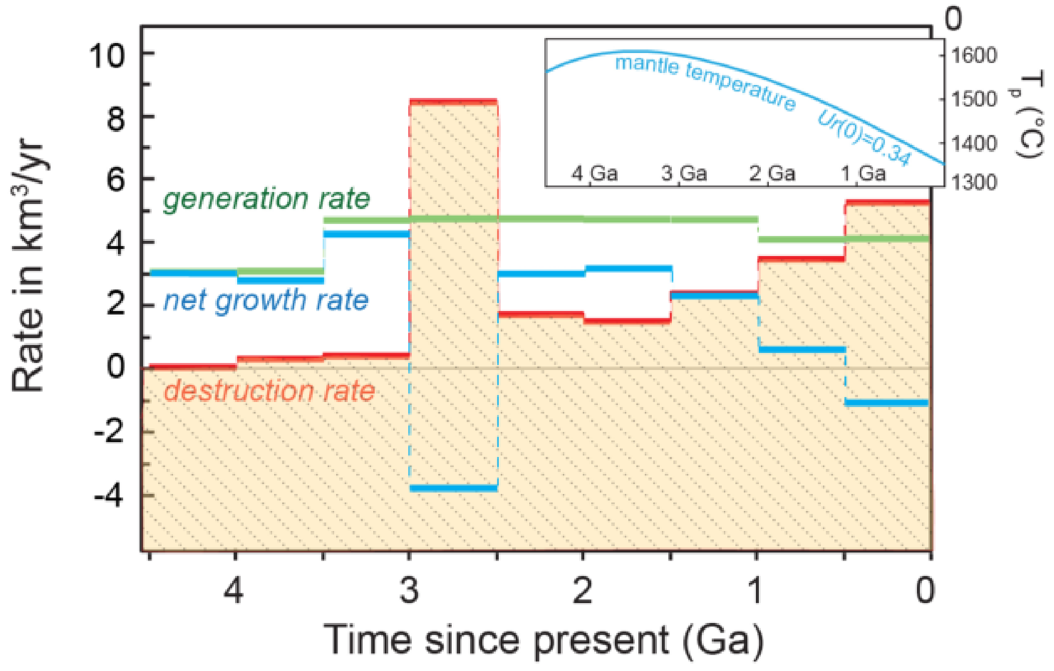


FIGURE 11 | A model for the changes in the volume and rates of generation and destruction of the continental crust through time (Dhuime et al., 2018). The model assumes that 60 to 80% of the present day volume of continental crust was established by 3 Ga, and seeks to reproduce the cumulative curve for the present day distribution of juvenile crust (Condie and Aster, 2010; **Figure 10**). The estimated rates of generation (green curve), destruction (red curve + shading) and net growth (blue curve) of the continental crust, are plotted in 500 Myr intervals. The inset shows the smooth evolution of the mantle temperature through time, after Herzberg et al. (2010), Korenaga (2013).

Onset of Plate Tectonics – When?

Onset of Plate Tectonics – When?

- **???**
- Change in crustal growth rates at ~3 Ga
- Dyke swarms from ~2.4 to 2.8 Ga
- Crustal thickness rising from ~3 Ga
- + The increased destruction of more differentiated crustal material…
- **Reflects the onset of widespread subduction and the associated plate tectonics at ~3 Ga (Hawkesworth et al. 2020)**

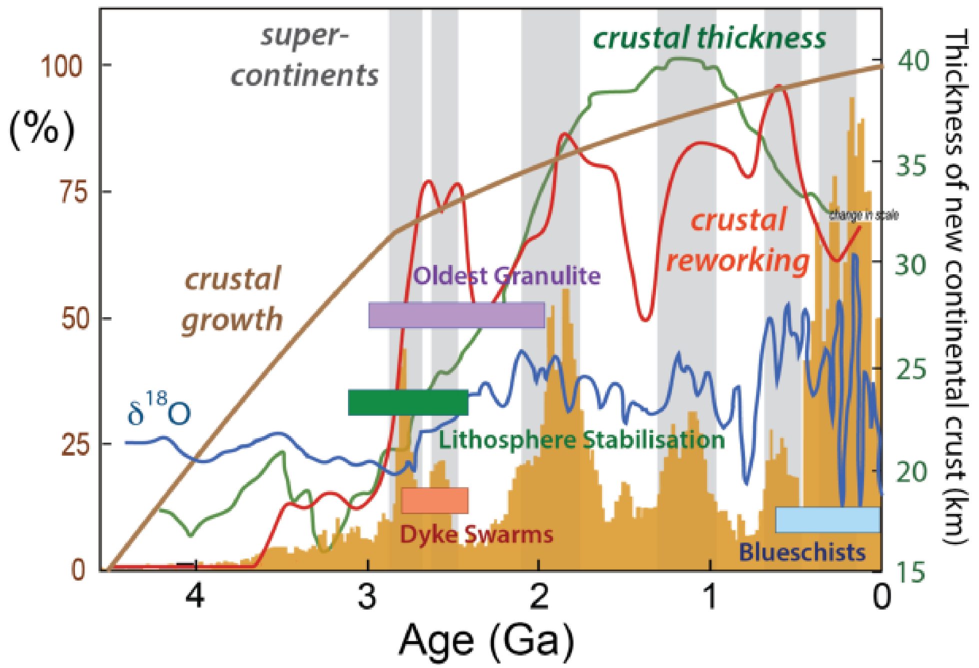
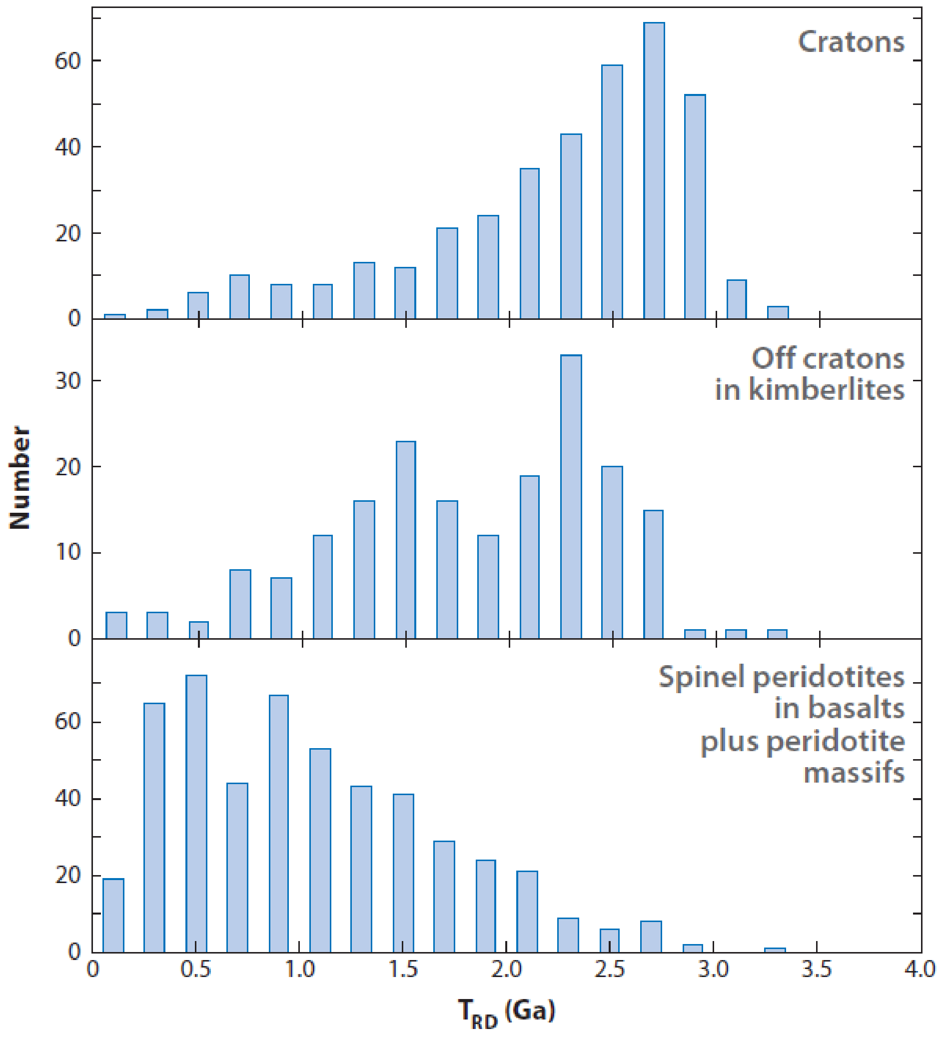
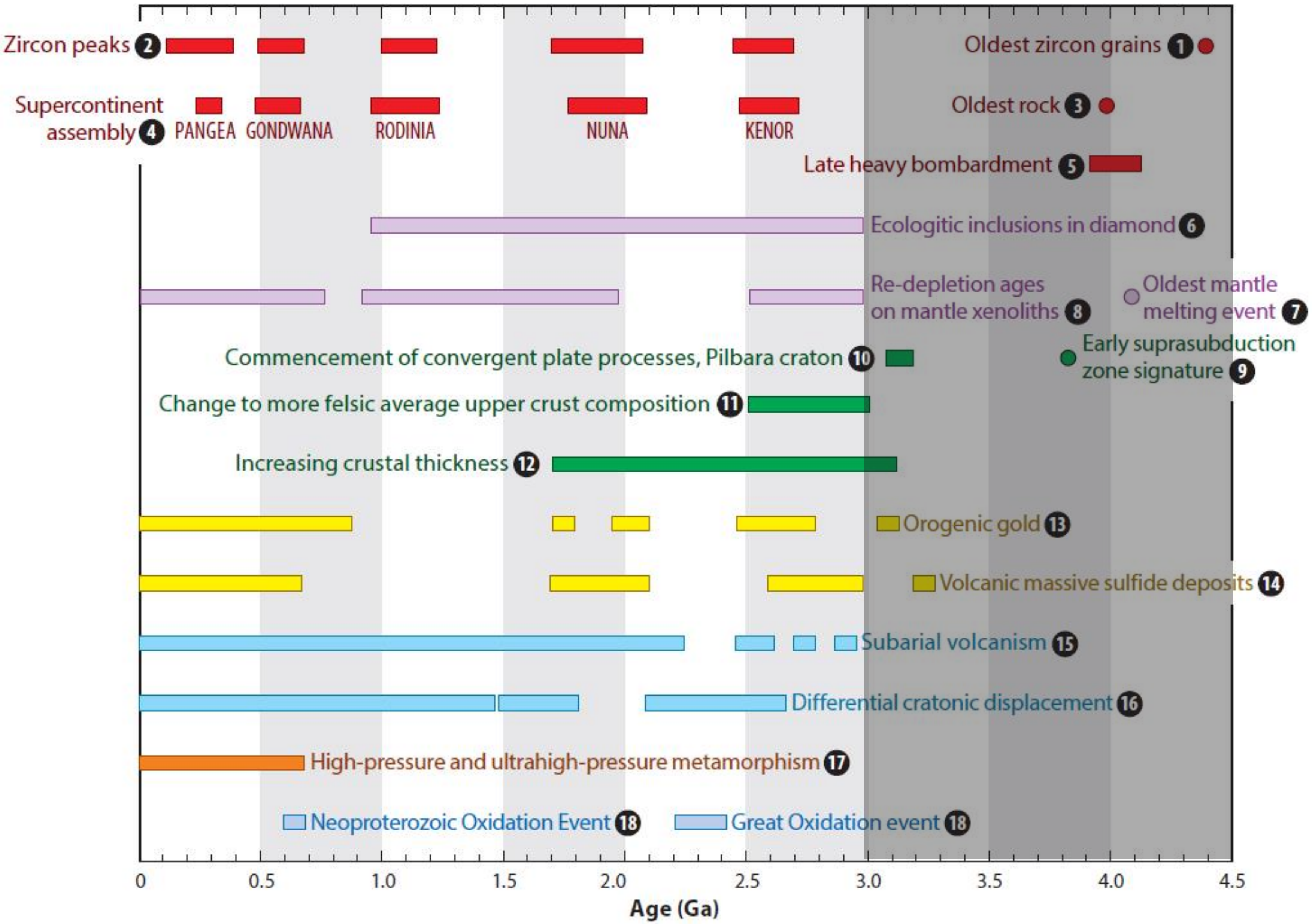


FIGURE 13 | A summary of some of the changes that appear to mark the end of the Archean. These include the development of supercontinents/supercratons, marked by vertical gray bars (Hoffman, 1996; Zhao et al., 2002; Bleeker, 2003; Cawood et al., 2013; Evans, 2013), stabilization of lithosphere and the oldest major dyke swarms (Cawood et al., 2018), the increase in the degree of crustal reworking as indicated by Hf isotope ratios in zircon (Belousova et al., 2010; Dhuime et al., 2012), the development of significant peaks in the age distribution of zircons (Campbell and Allen, 2008; Voice et al., 2011), a shift in the composition of juvenile crust from mafic to more intermediate compositions accompanied by an inferred increase in crustal thickness (Dhuime et al., 2015), and the step-up in the $\delta^{18}O$ values in zircons (Valley et al., 2005; Spencer et al., 2014).

Hawkesworth et al. 2020

→ Peak in Cratons at 3-2.7 Ga considered as the mark stabilization of the continental lithosphere

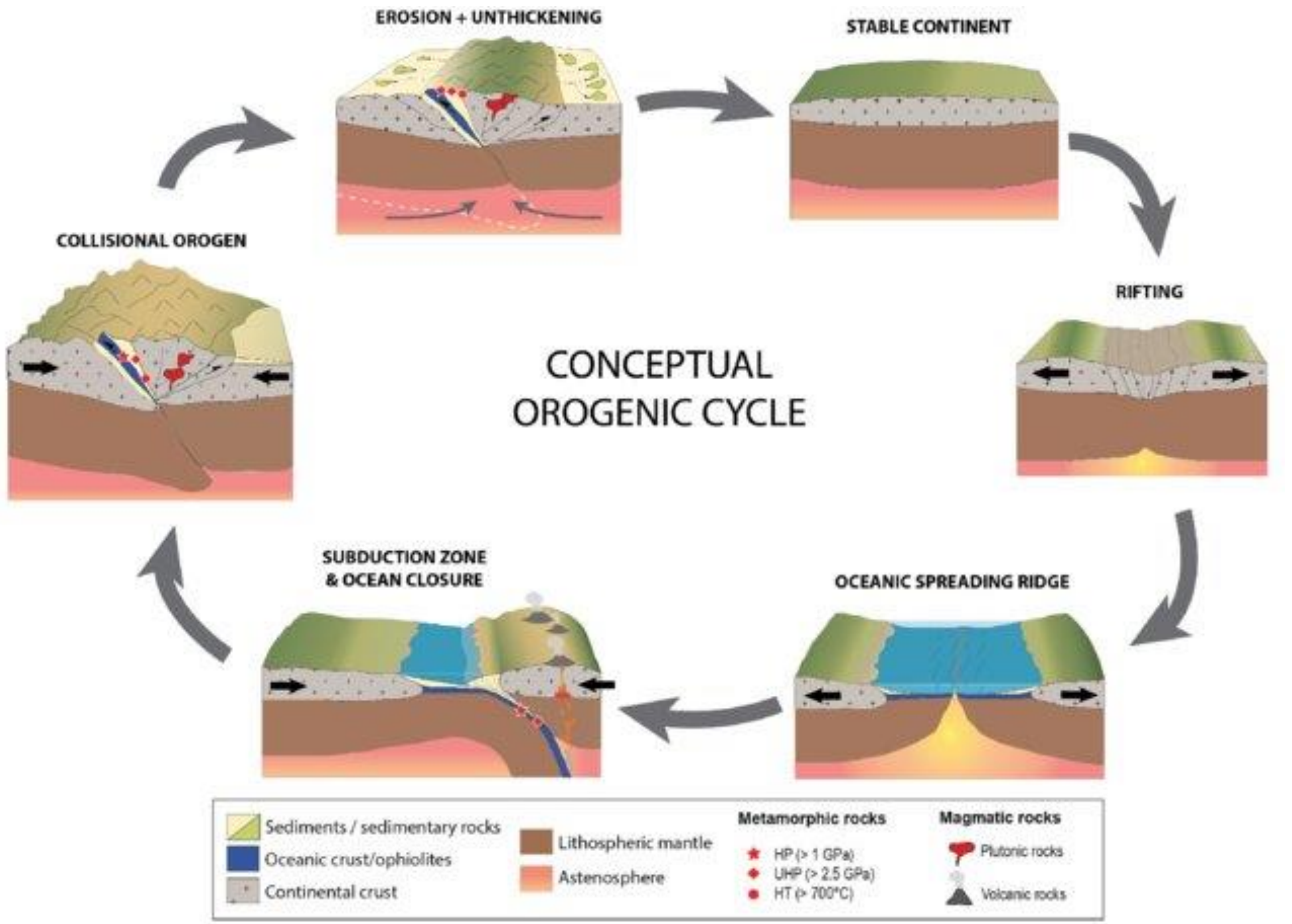




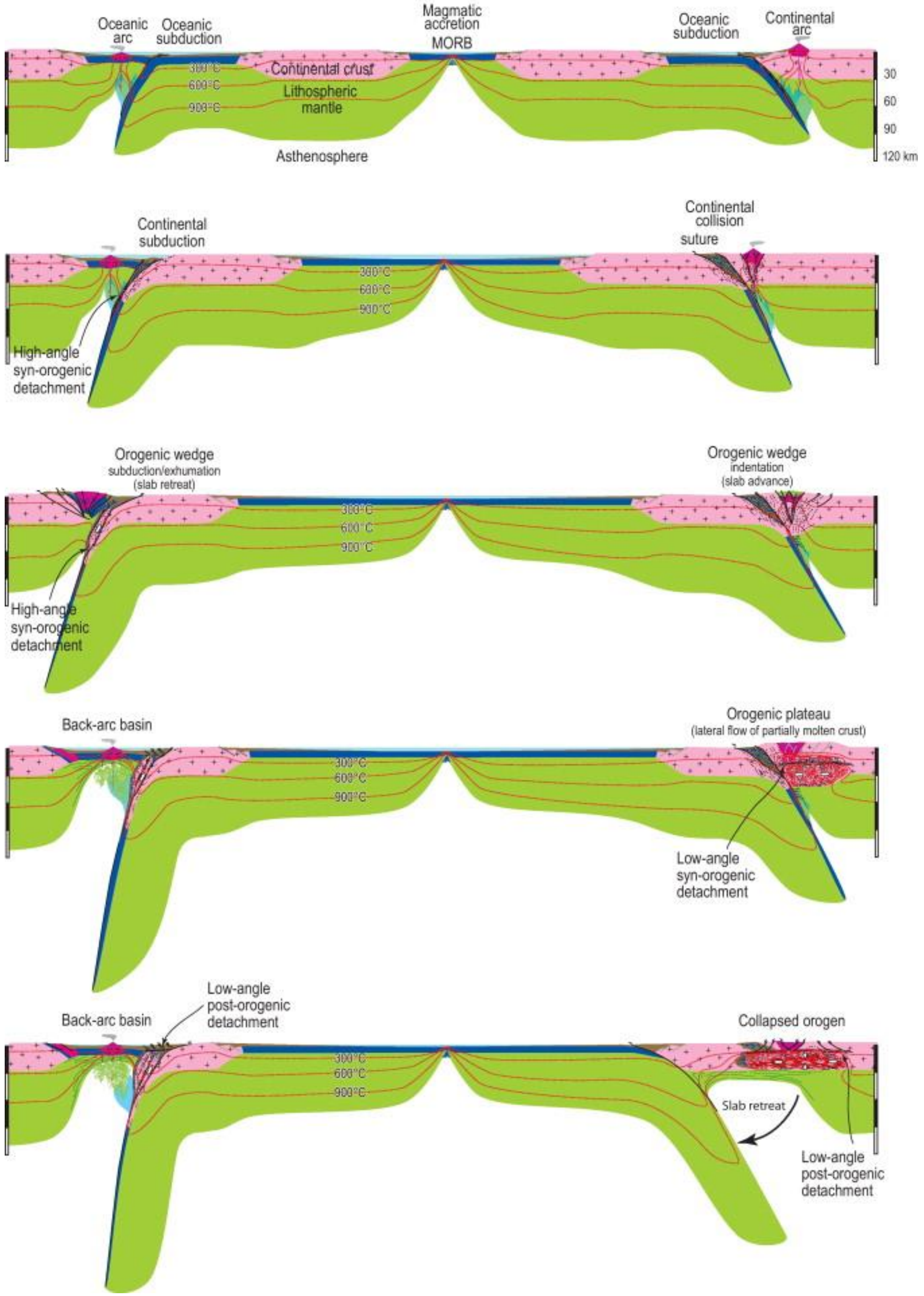
Hawkesworth, 2017

Orogenic cycles

- Sediment deposition
- Compression
- Crustal thickening
- Uplift
- Erosion

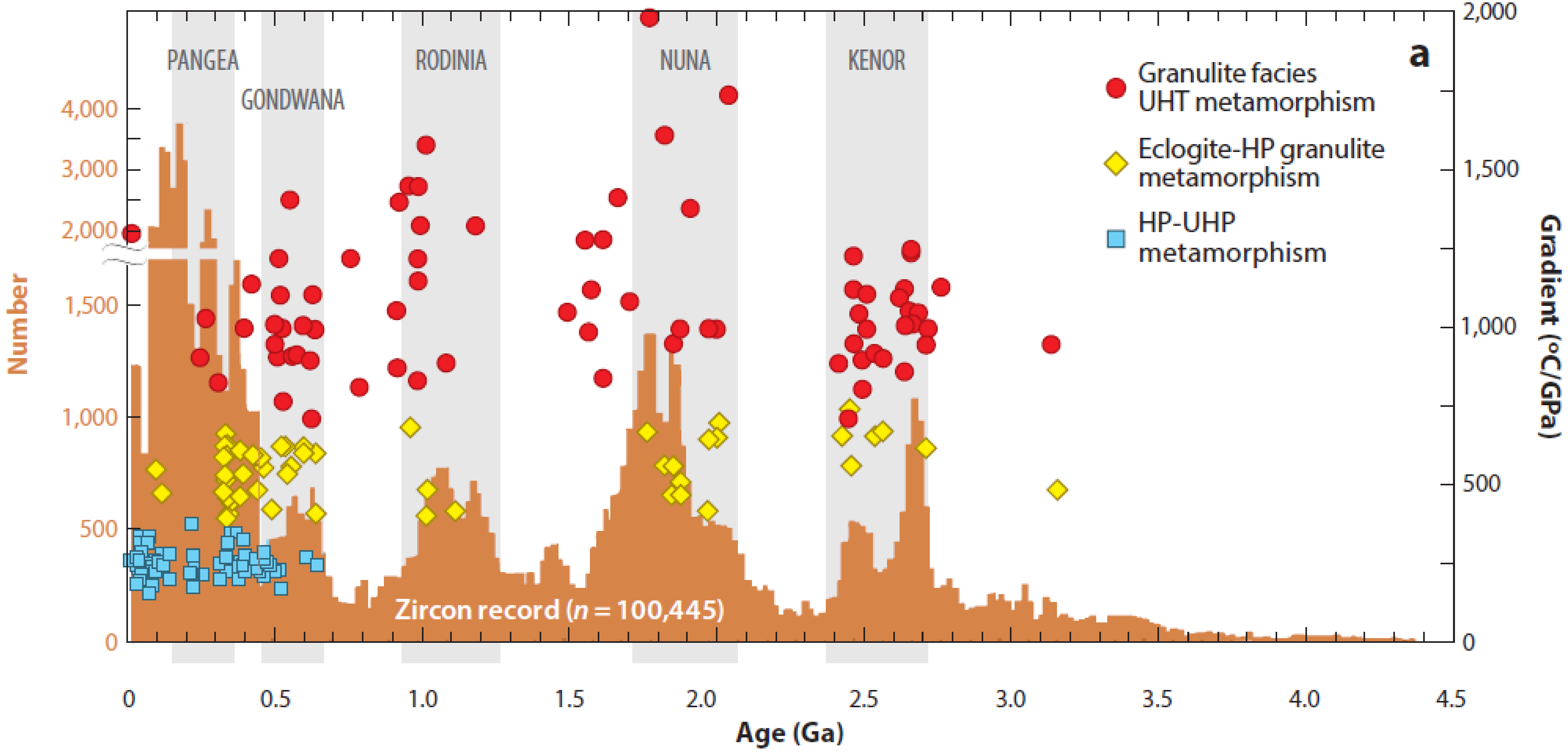


Francois et al., 2021



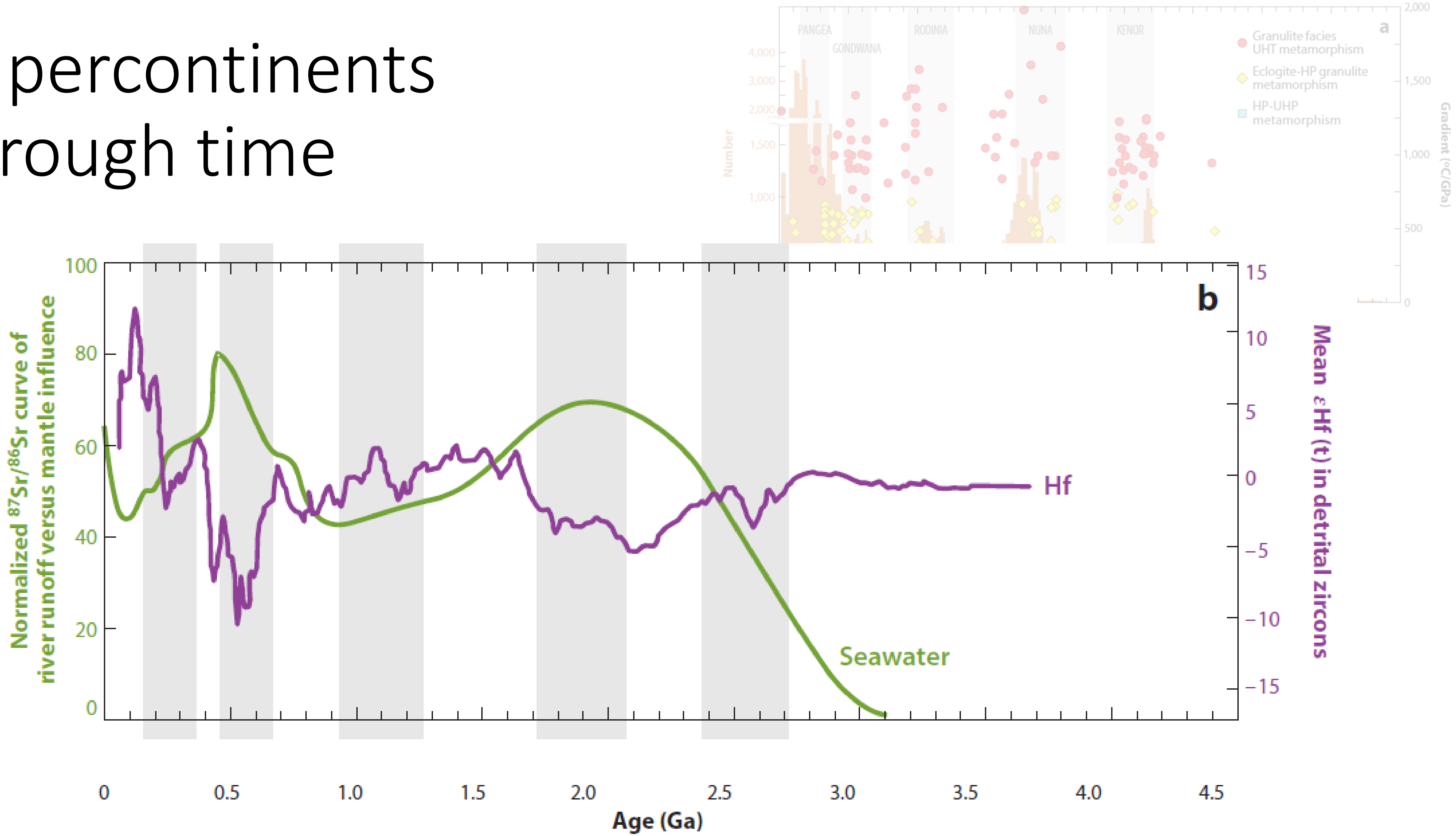
Vanderhaeghe, 2012

Supercontinents through time



Hawkesworth, 2017

Supercontinents through time



Hawkesworth, 2017

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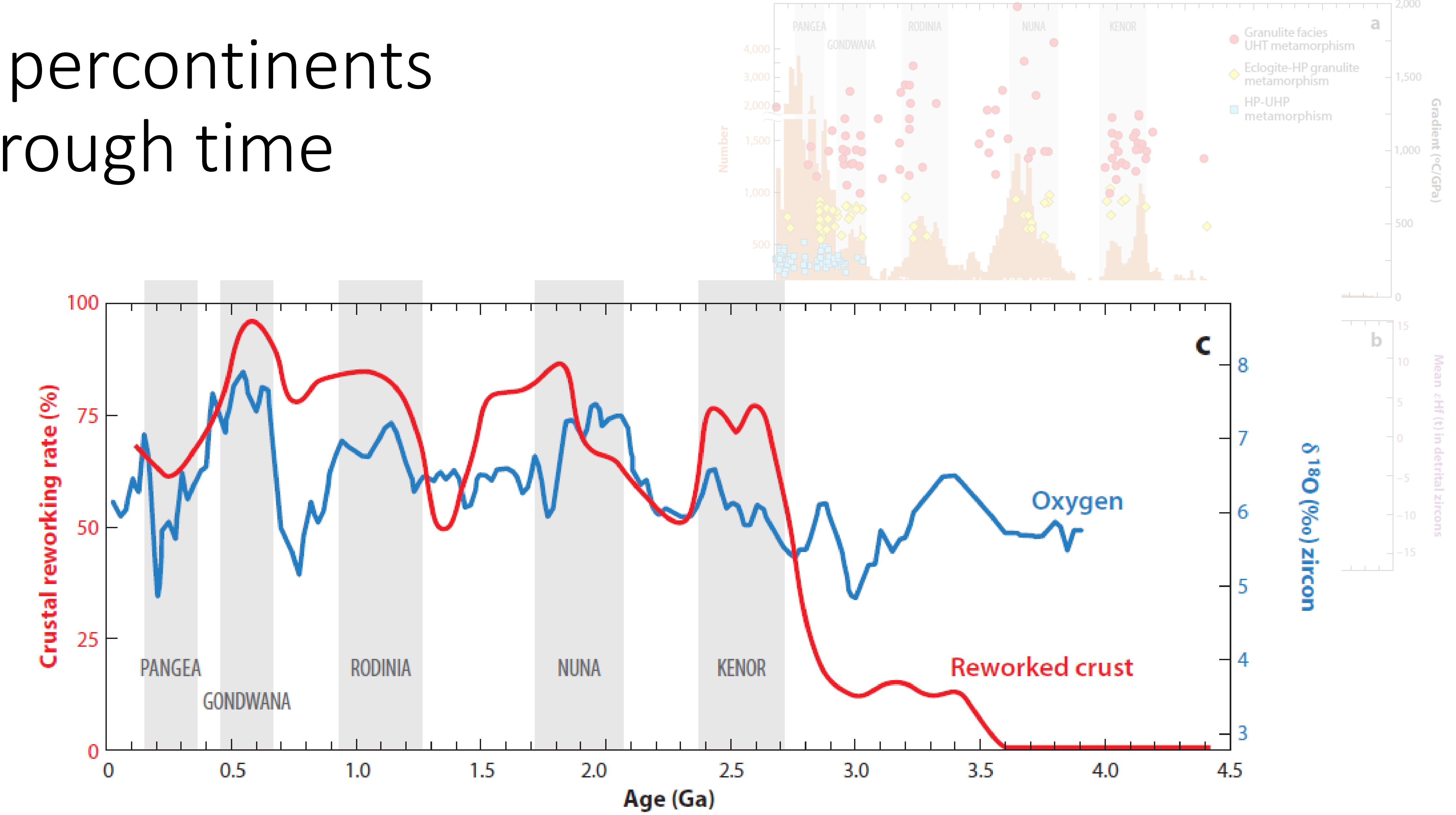
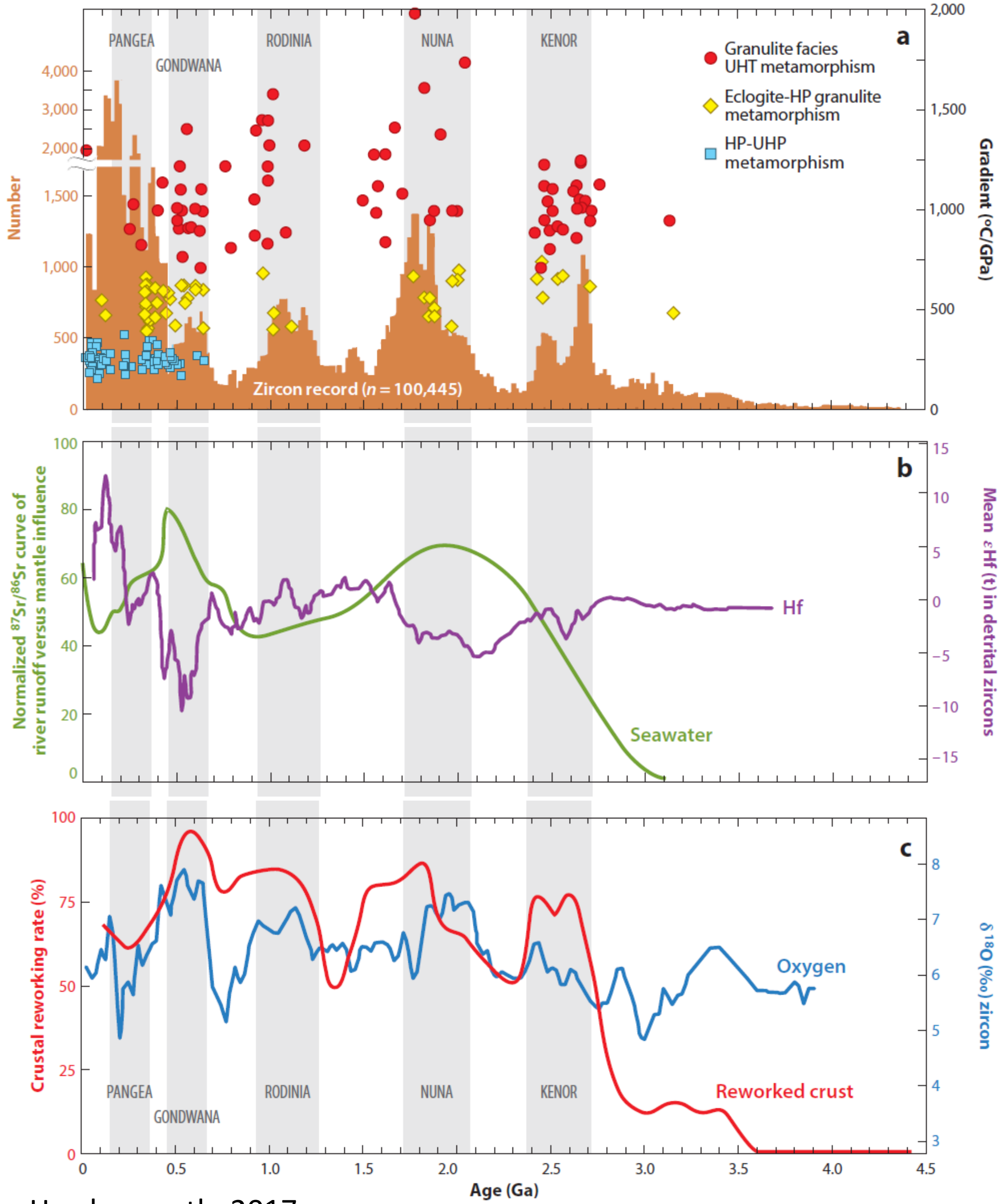


Hawkesworth, 2017

Supercontinents through time

→ Crustal growth and thickening a result of continental collisions



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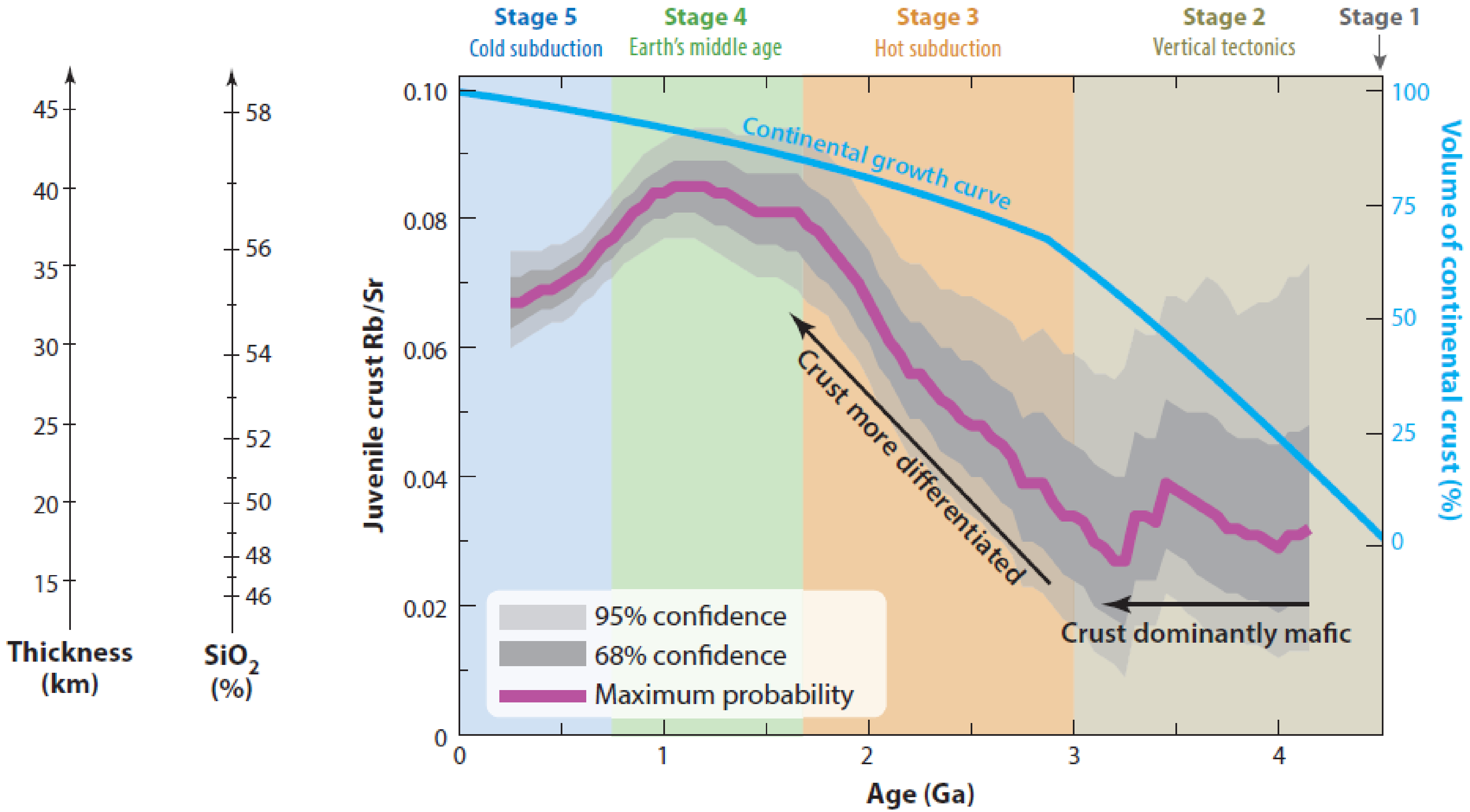
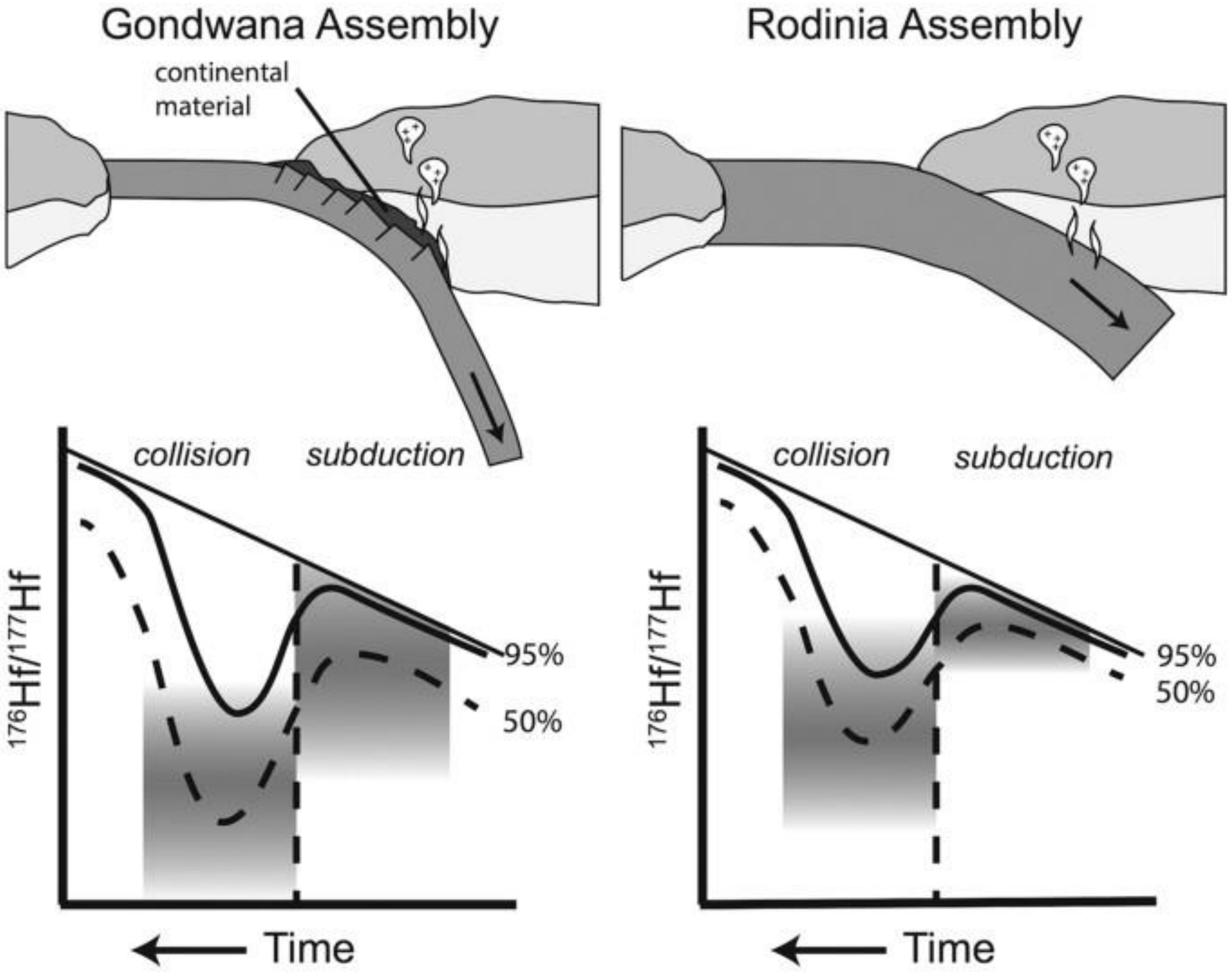
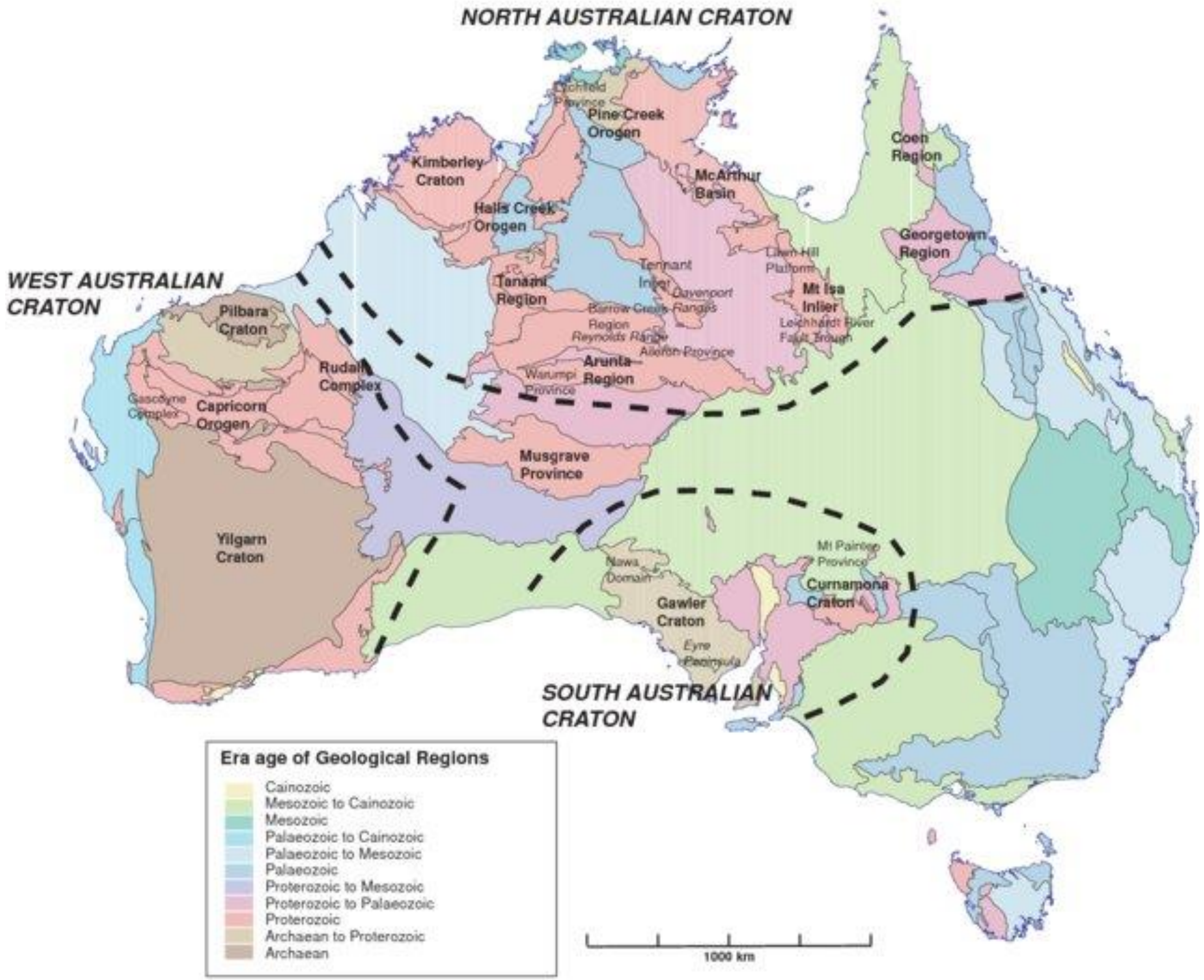


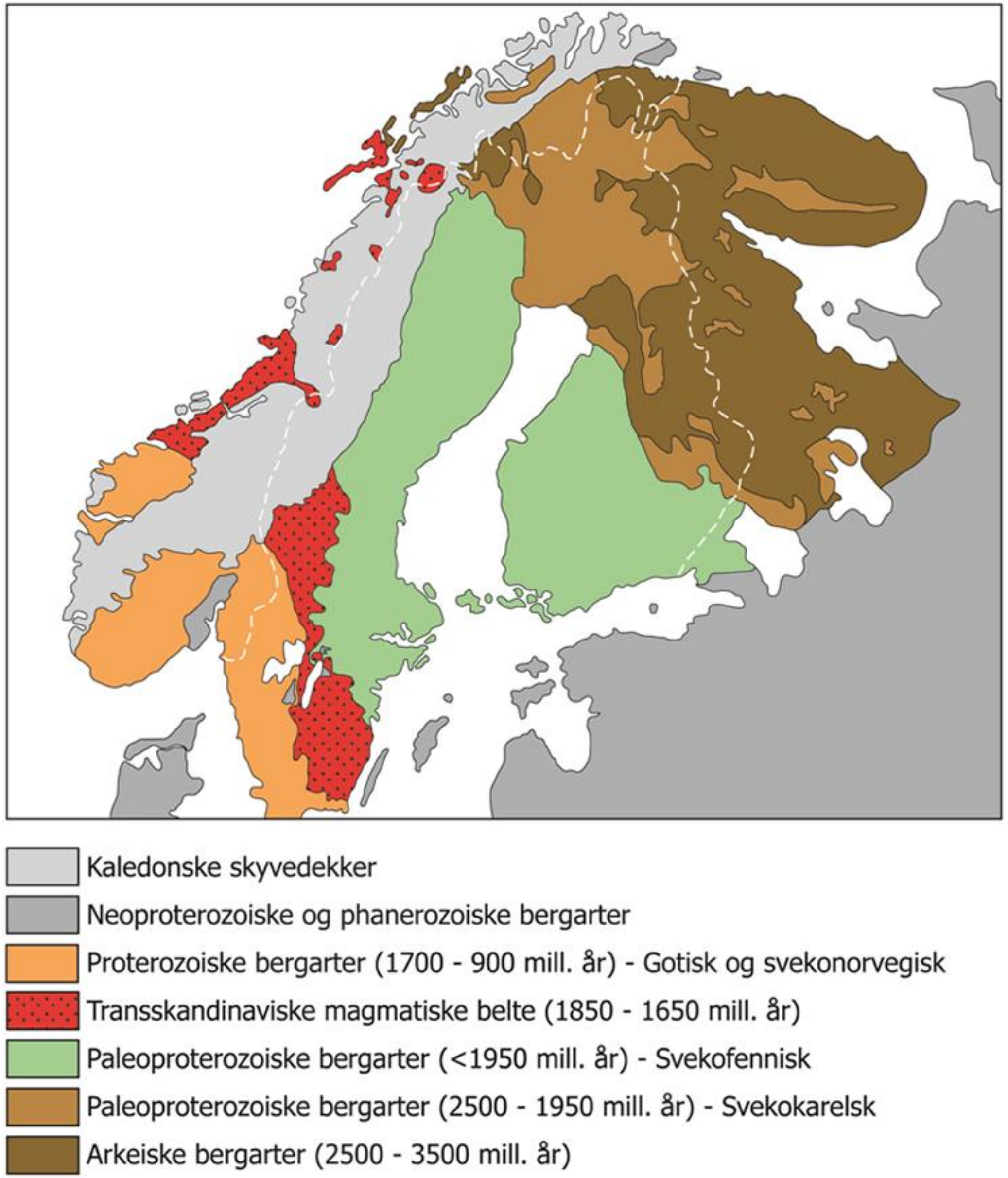
Hawkesworth, 2017



Gardiner et al., 2016



Geoscience Australia, 2007



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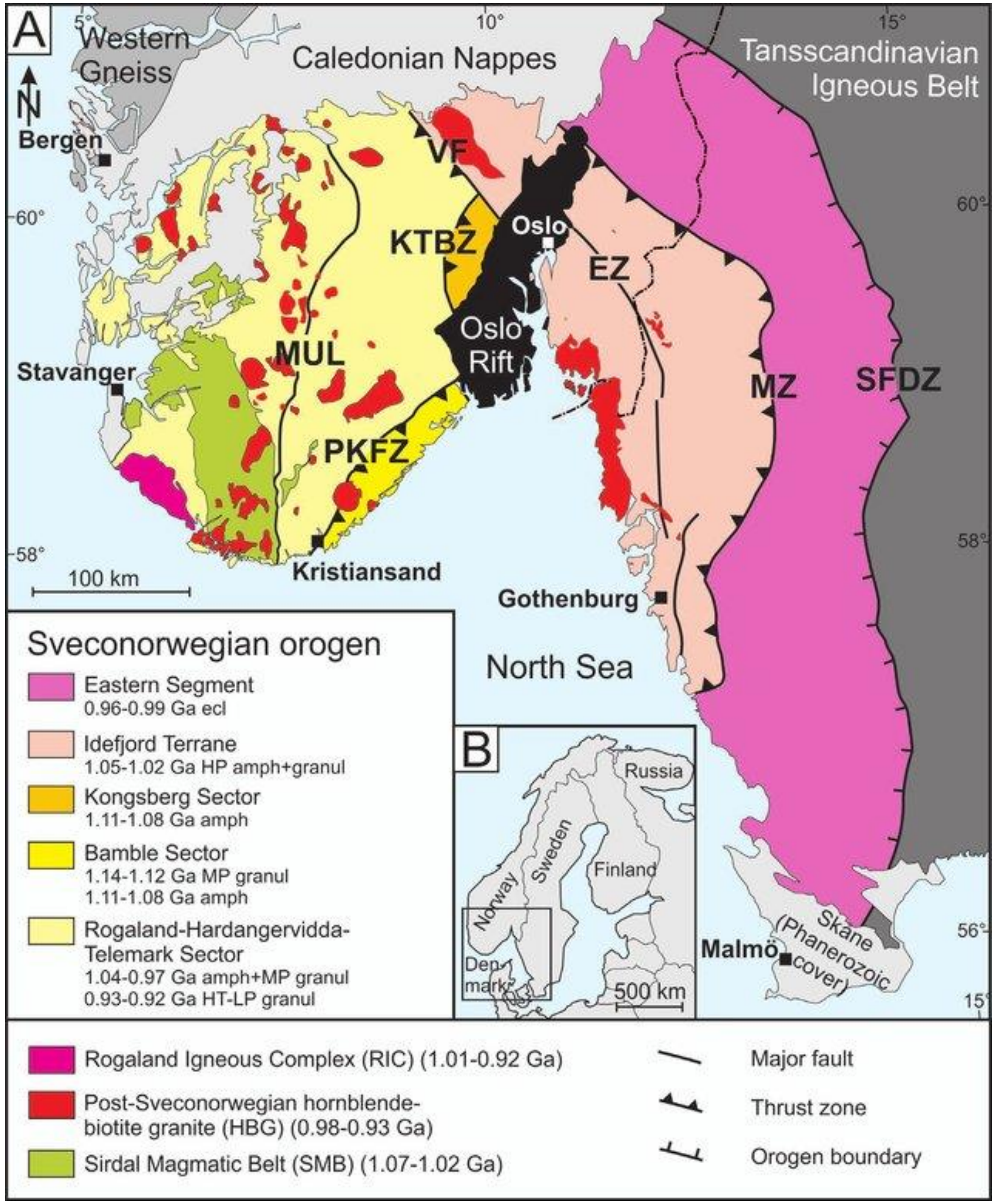

Müller et al. 2017

Future work

- Continue to conduct work on understanding the transition from early earth tectonics to modern plate tectonics
- Sutures/weaknesses often associated with reactivation in modern plate tectonics, why is this not the case for sutures/weaknesses observed in the cratonic crust?
- Developments in methods and data can improve our understanding
  - Geodynamics
  - Improve uncertainties associated with geochemical methods
- Continue to combine multiple sciences and methods to get answers