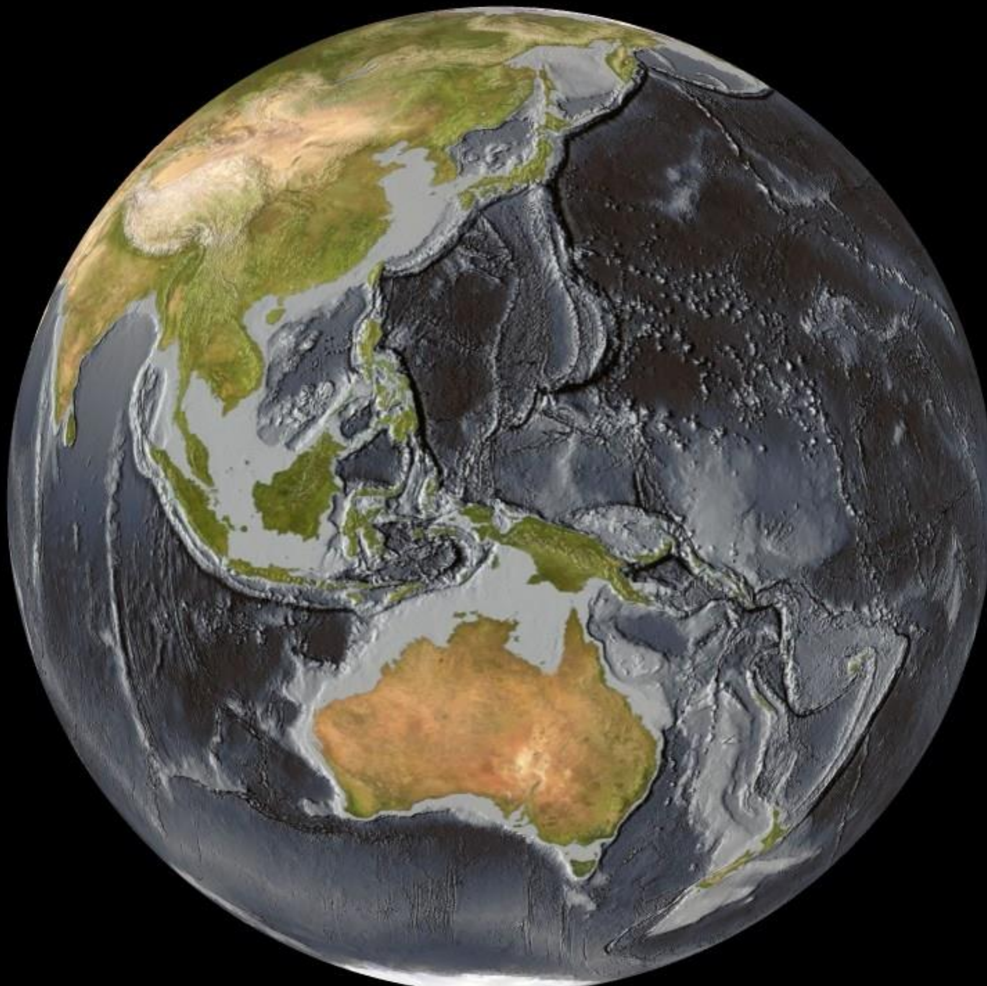
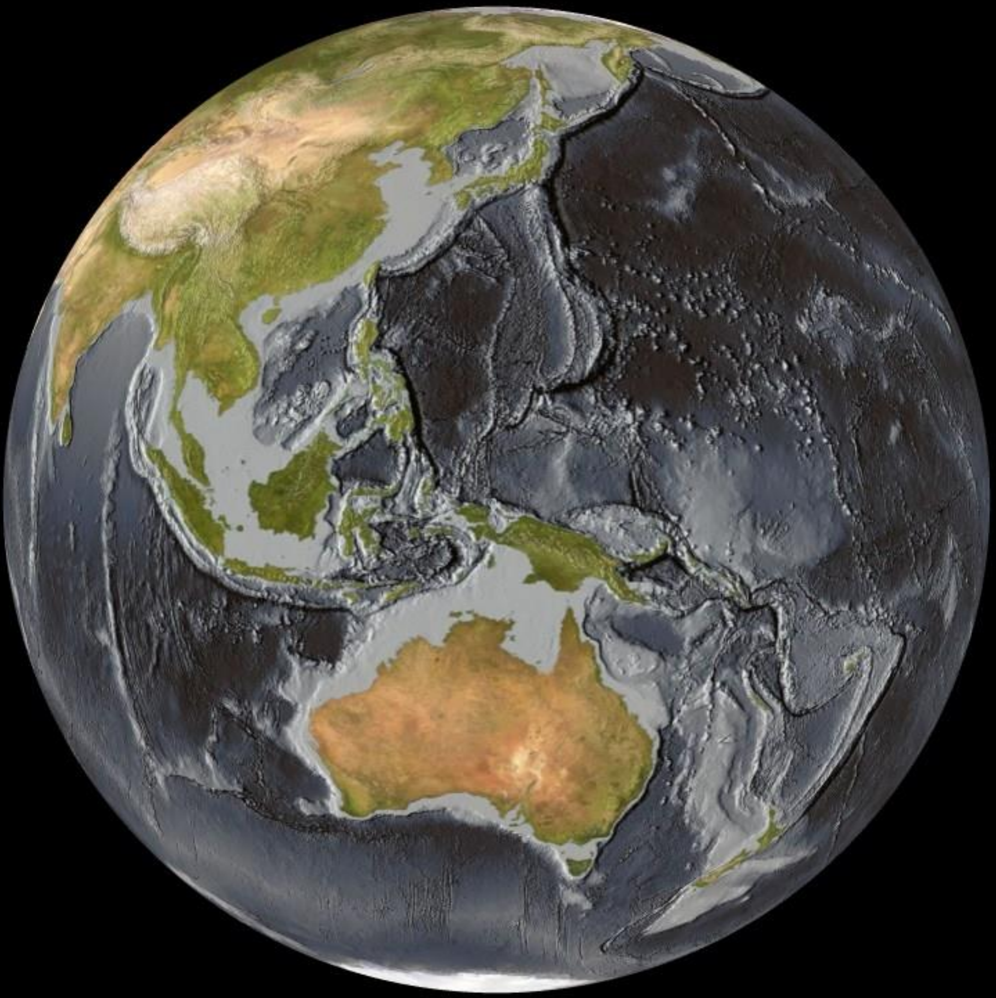
The geological record of plate tectonics



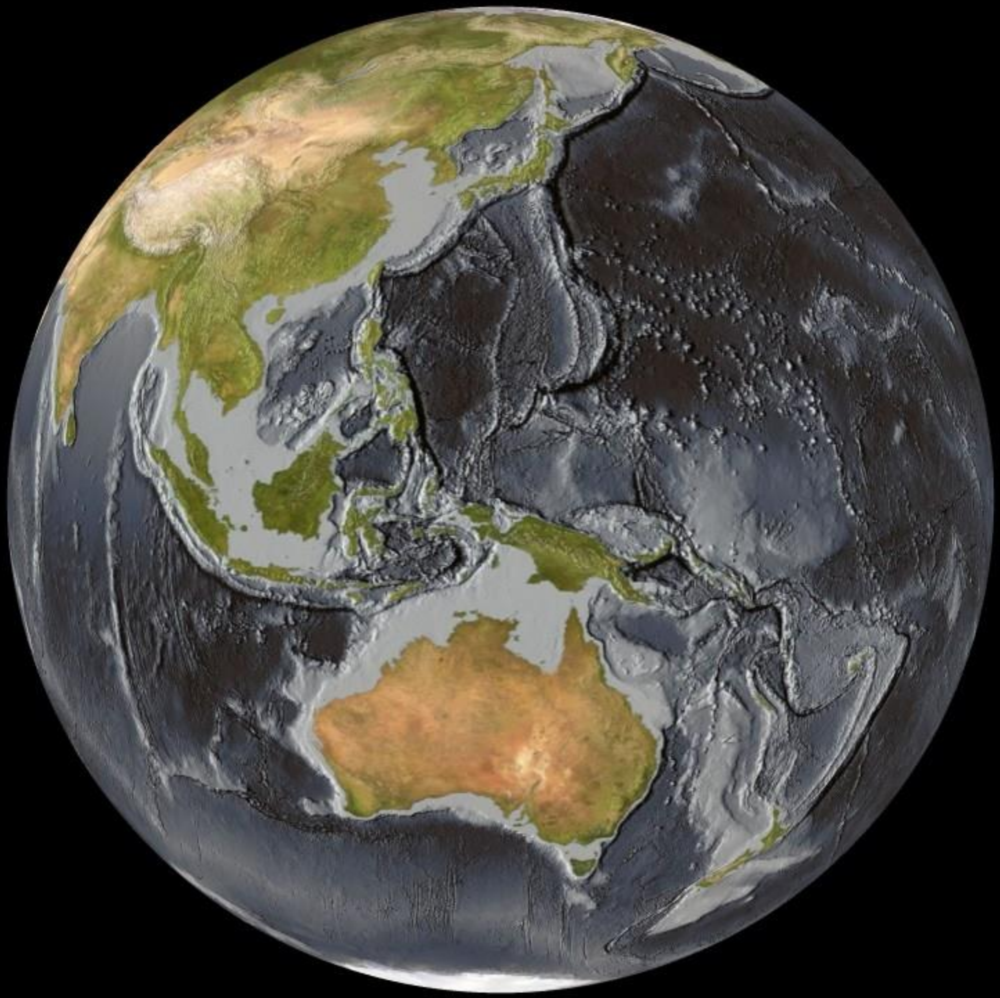
Francis A. Macdonald

UC Berkeley Dept. of Earth and Planetary Science

What makes Earth so special?

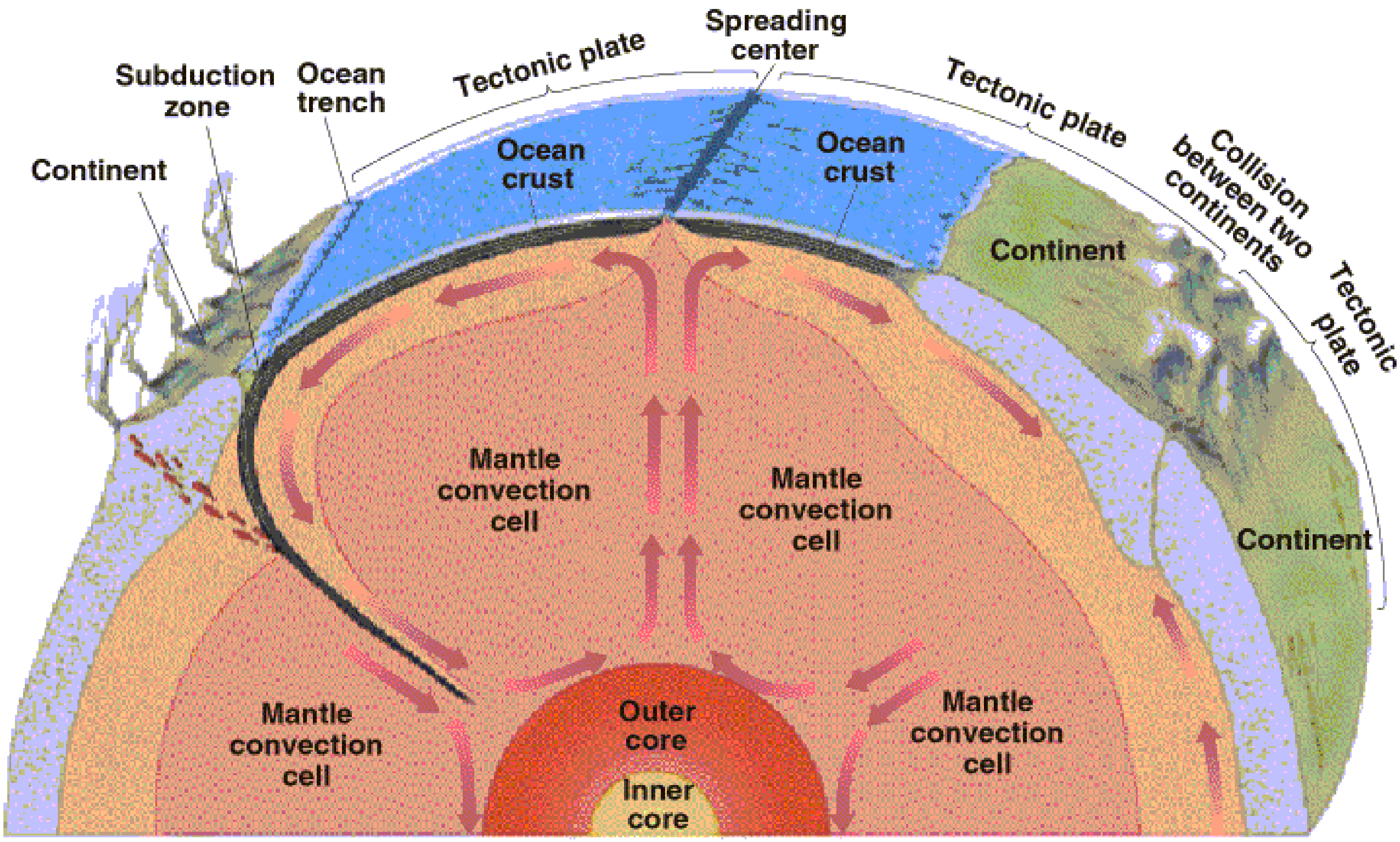


What makes Earth so special?



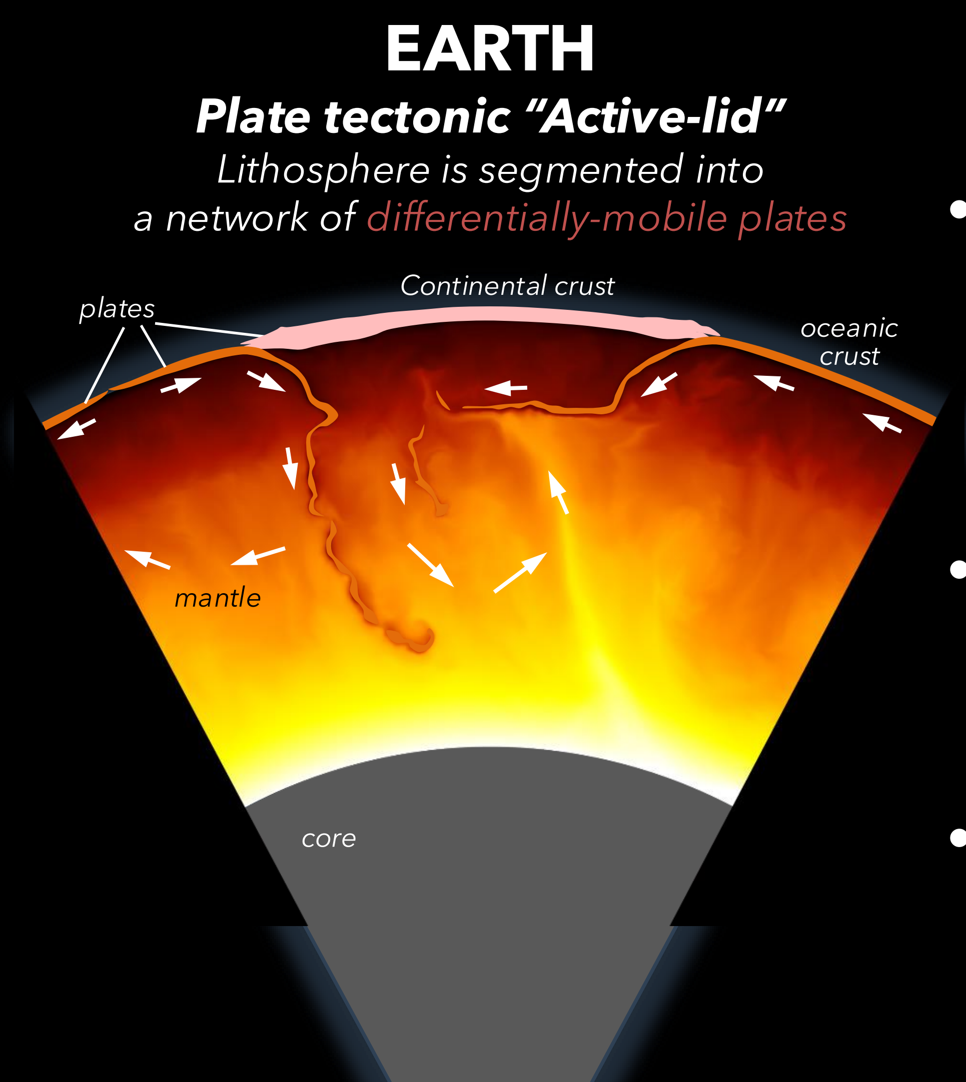
Ingredients for life: water, atmosphere, bimodal distribution of topography, geochemical cycles

Plate tectonics is the engine for geochemical cycling on Earth



Creates continents, oceans, volcanoes, mountains, rivers

Plate tectonics is the lateral motion of ridged crust on a sphere



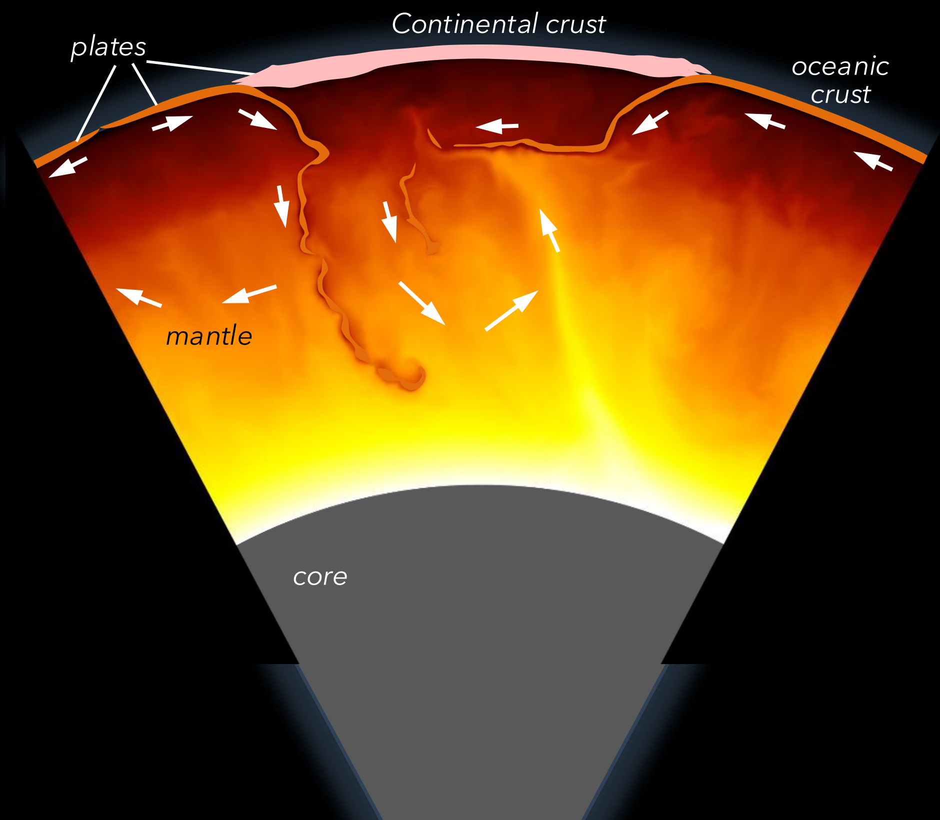
- Although the mantle is solid it can plastically convect
- Driven by heat loss and the buoyancy contrast between the continental and oceanic crust
- Subduction of dense oceanic crust below light continental crust= slab pull
- Once subduction starts it is difficult to stop

When and how did continents originate and tectonics begin?

EARTH

Plate tectonic "Active-lid"

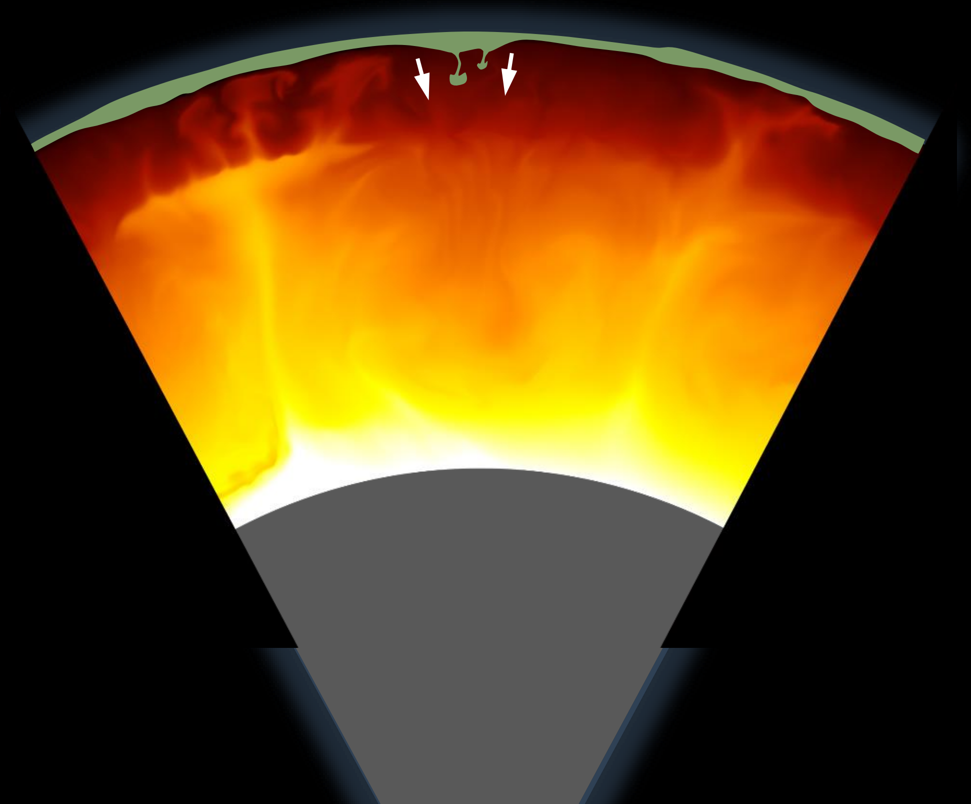
Lithosphere is segmented into a network of differentially-mobile plates



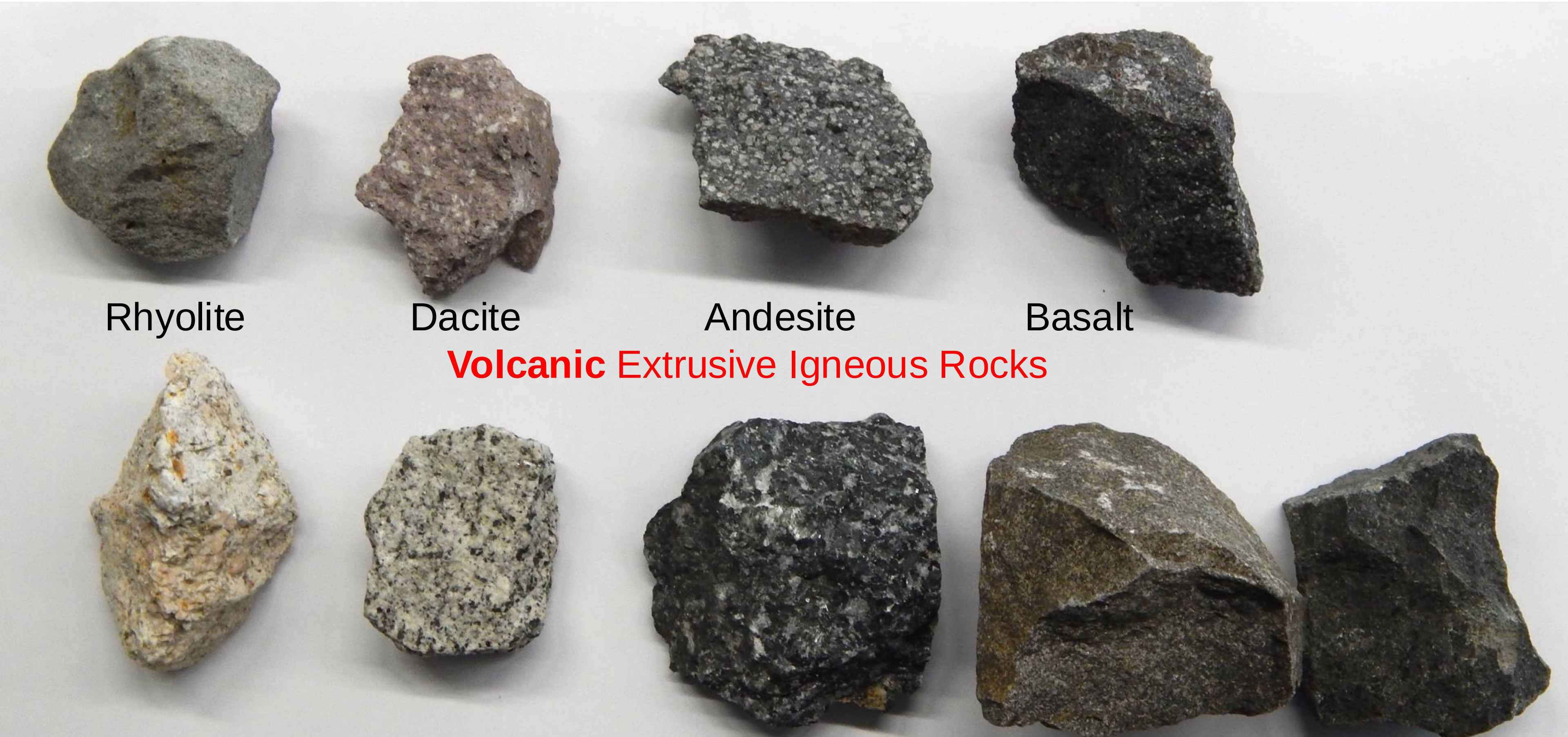
VENUS

"Stagnant-lid"

One global plate with limited horizontal mobility and/or distributed deformation



Continental crust is felsic, oceanic crust is mafic



Granite | Granodiorite | Diorite | Gabbro | Peridotite

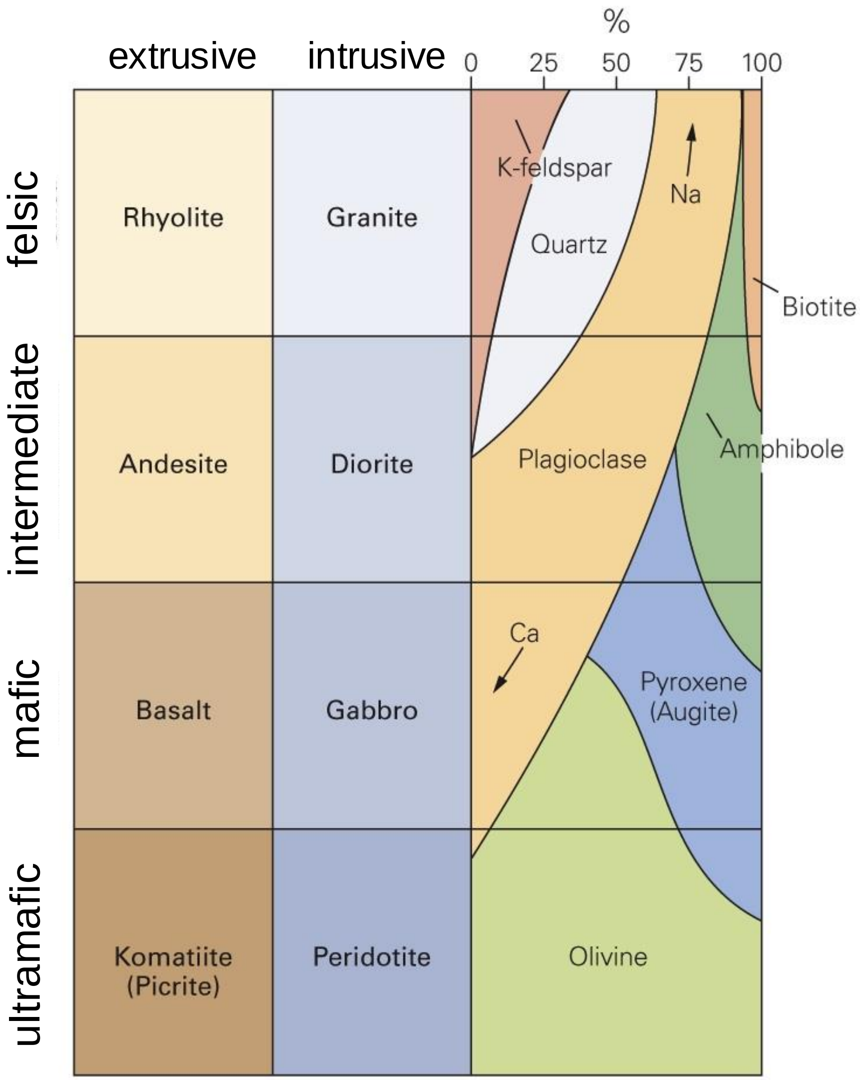
Plutonic Intrusive Igneous Rocks

Felsic (rich in Si) | Mafic (rich in Mg) | Ultra-mafic

Low melting temperatures → High melting temperatures

2.65 g/cm^3 Increasing bulk density (mass/volume) 3.3 g/cm^3

Continental crust is felsic, oceanic crust is mafic



Felsic

- high Si (70–75 wt. %), K
- lower Mg, Fe, Ca

Intermediate

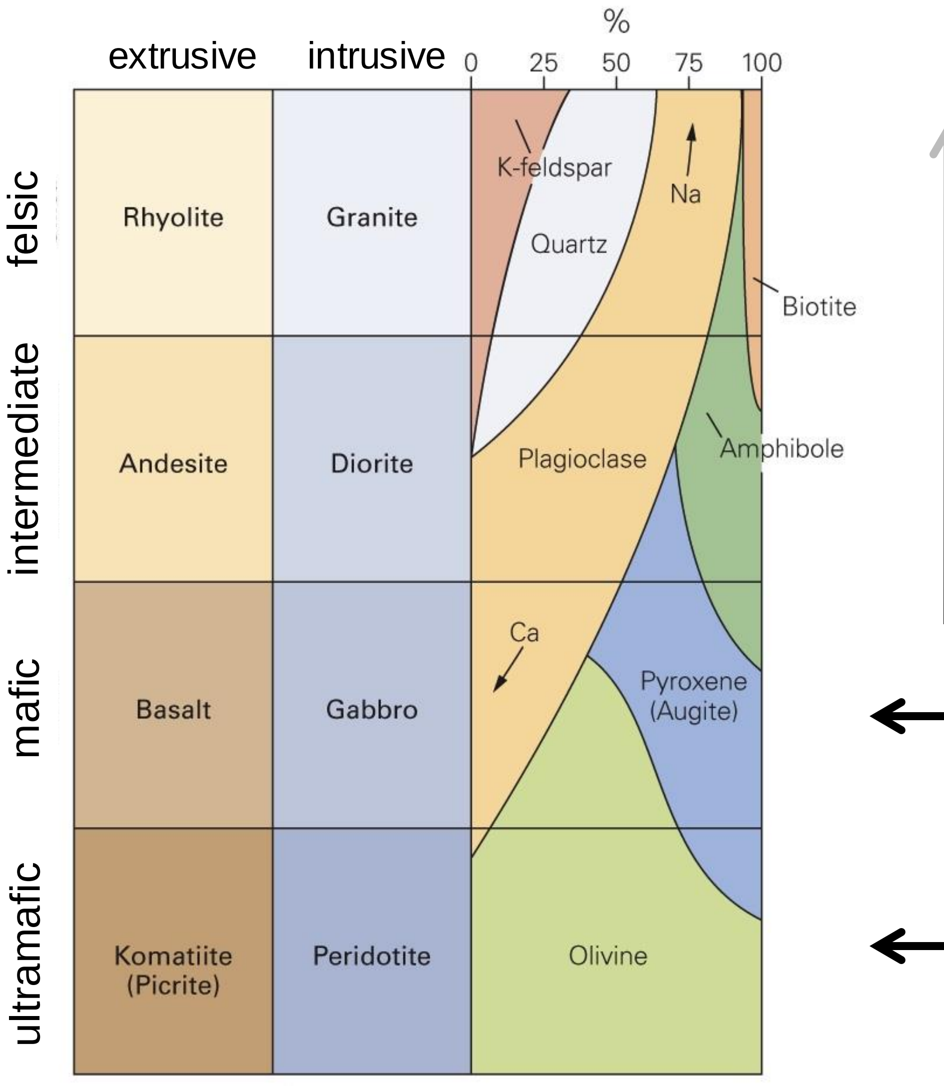
- Si (60 wt. %)

Mafic

- lower Si (50 wt. %), K
- Higher Mg, Fe, Ca

Marshak, 2016

Early Earth was undifferentiated ~ mantle



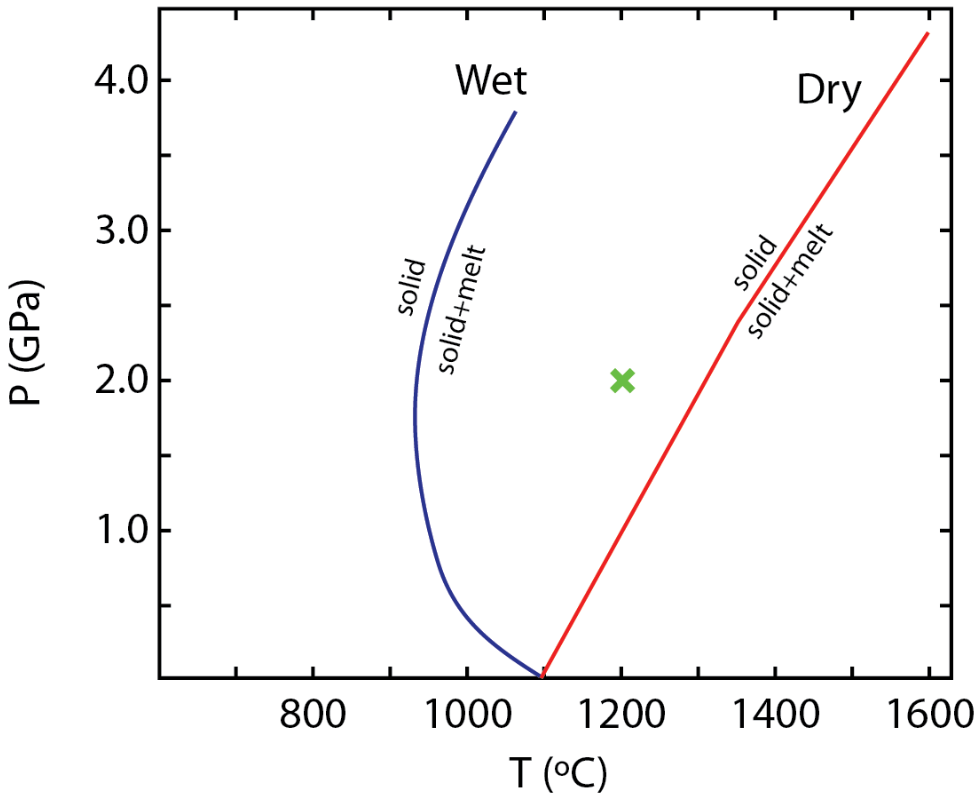
Differentiation (fractional crystallization, partial melting of crust)

Mantle melt

Mantle composition

Marshak, 2016

Mantle phase diagram

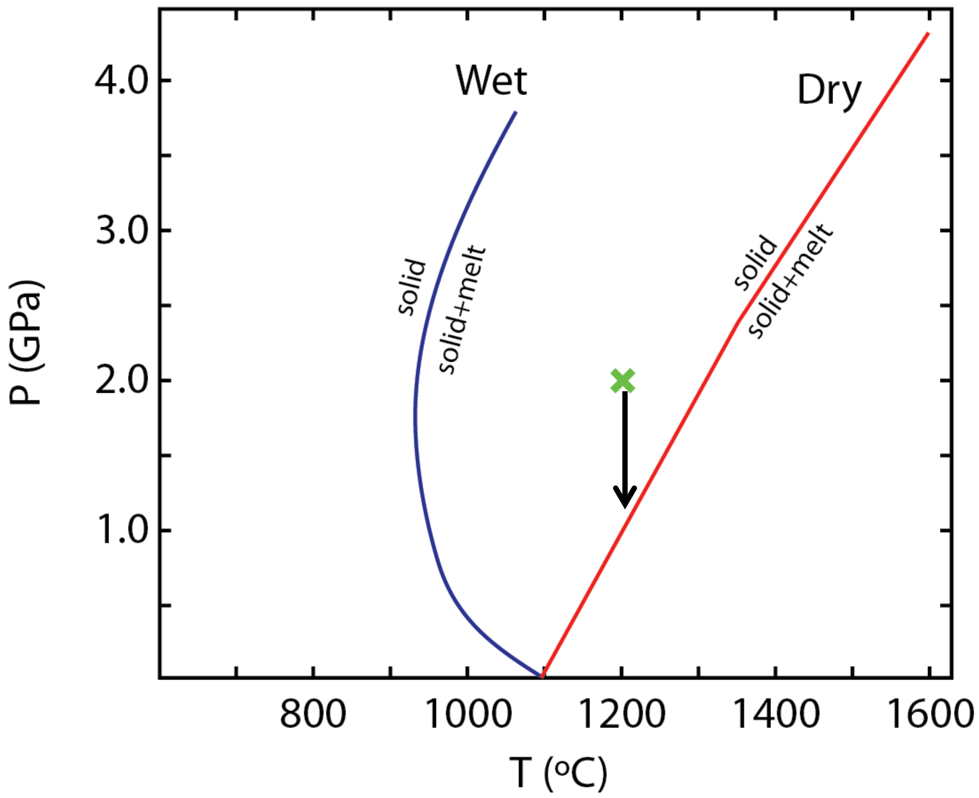


Juvenile magma on Earth is derived by mantle melting.

Solidus: the P and T where a rock either first melts or completely solidifies

Winter, 2009

Mantle phase diagram



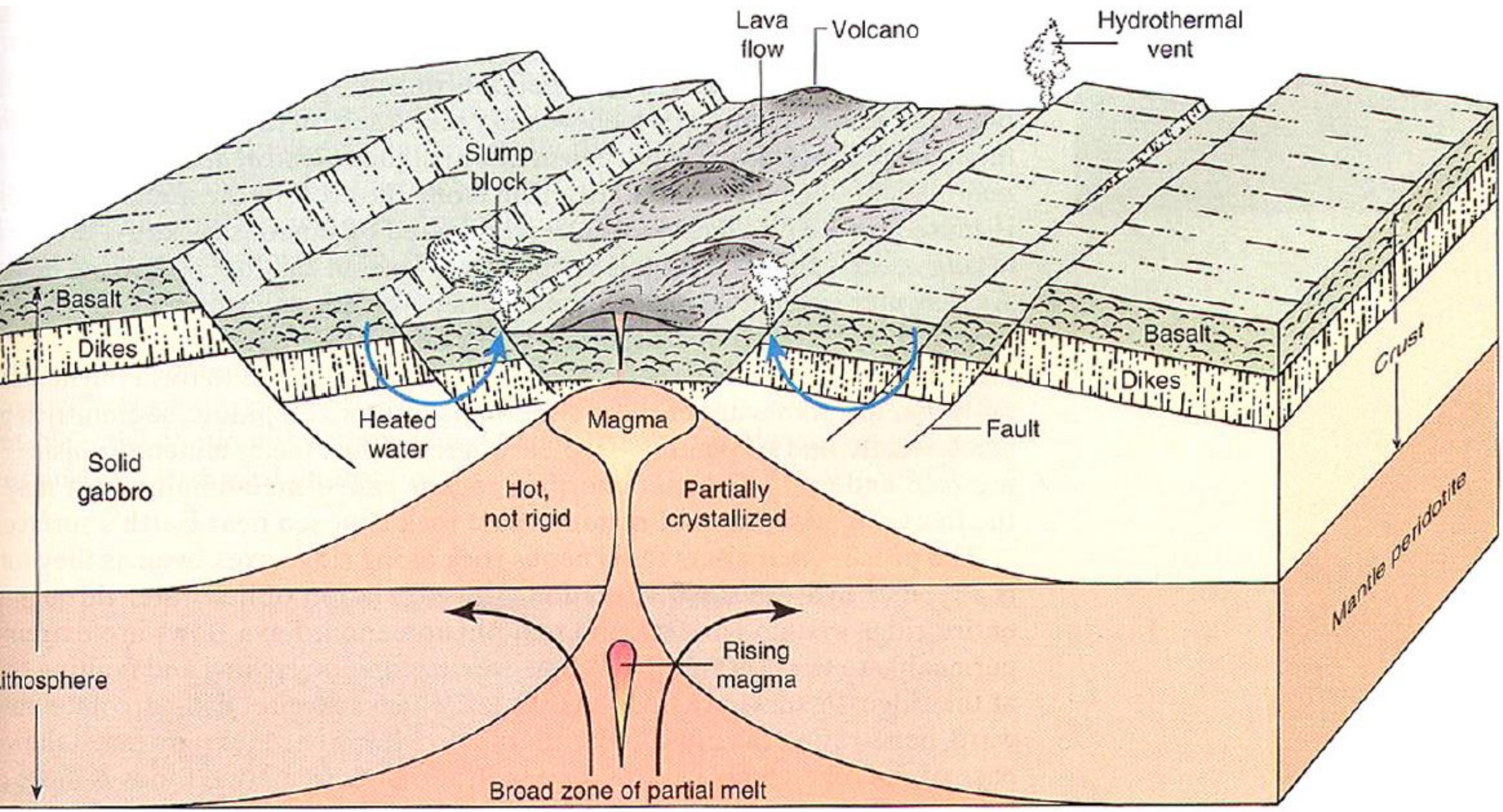
Ways to generate melt:

1. Decrease P

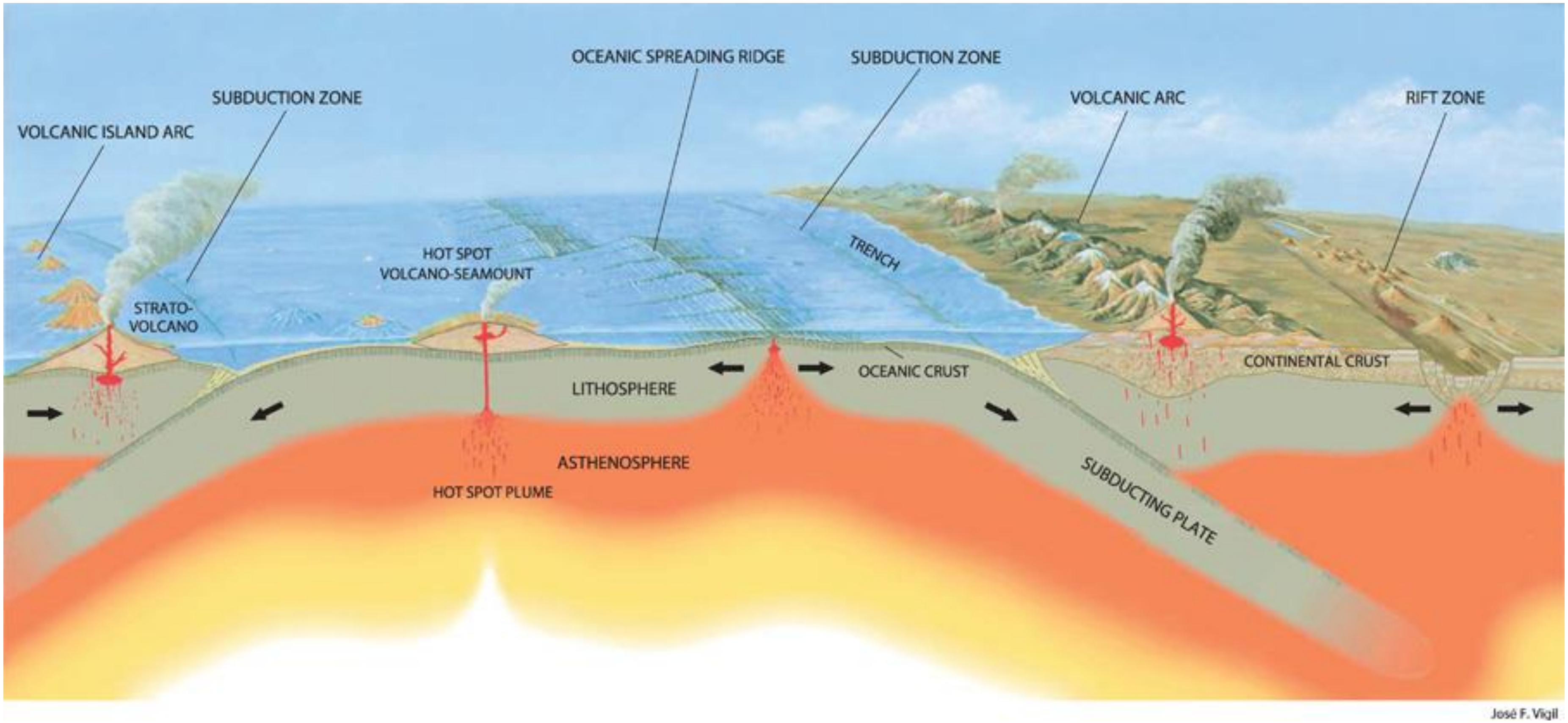
Winter, 2009

Formation of oceanic crust by decompression melting

Formation of oceanic crust by decompression melting



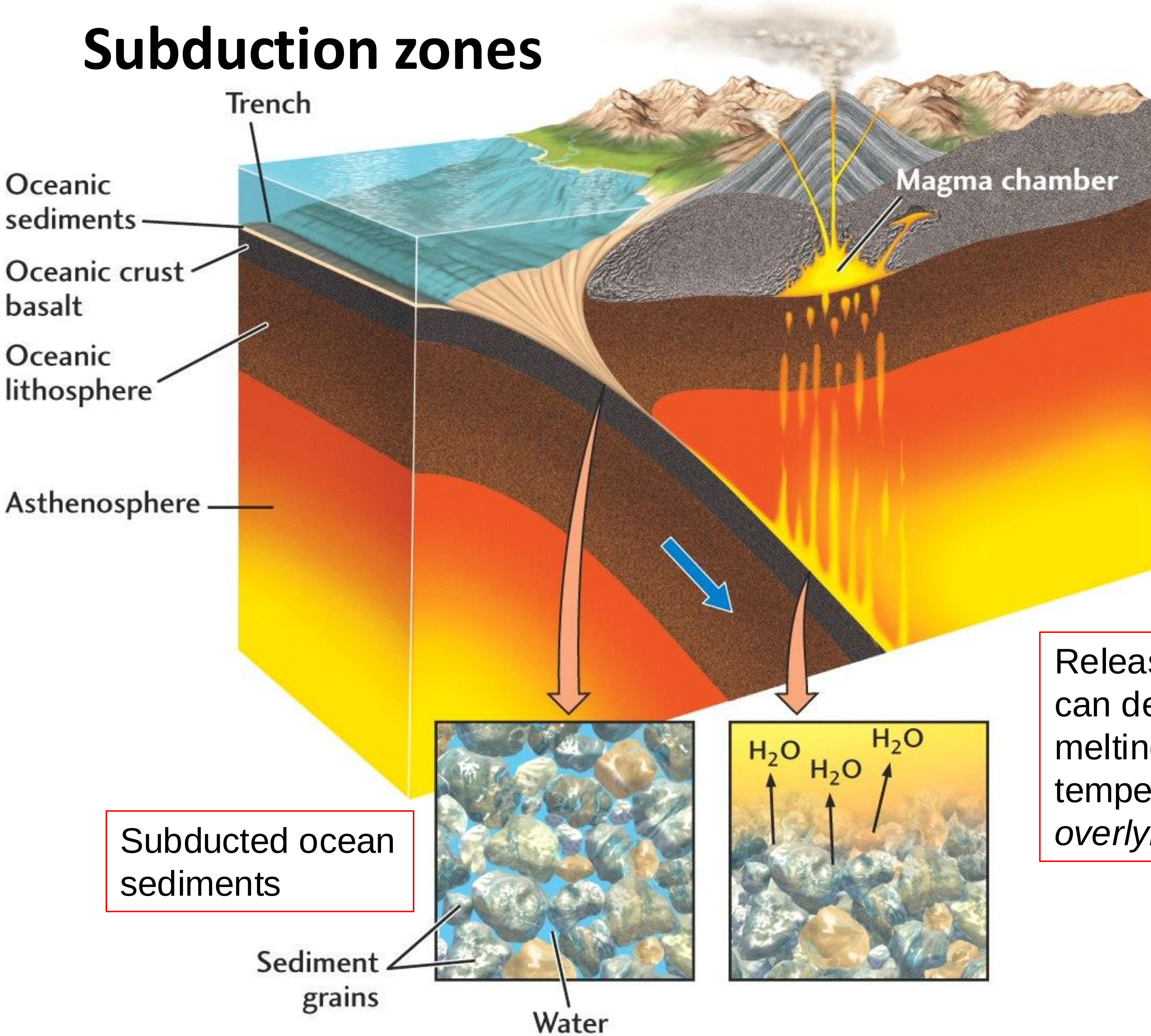
Tectonic settings for crustal formation



USGS; Marshak, 2016

Formation of continental crust by flux melting

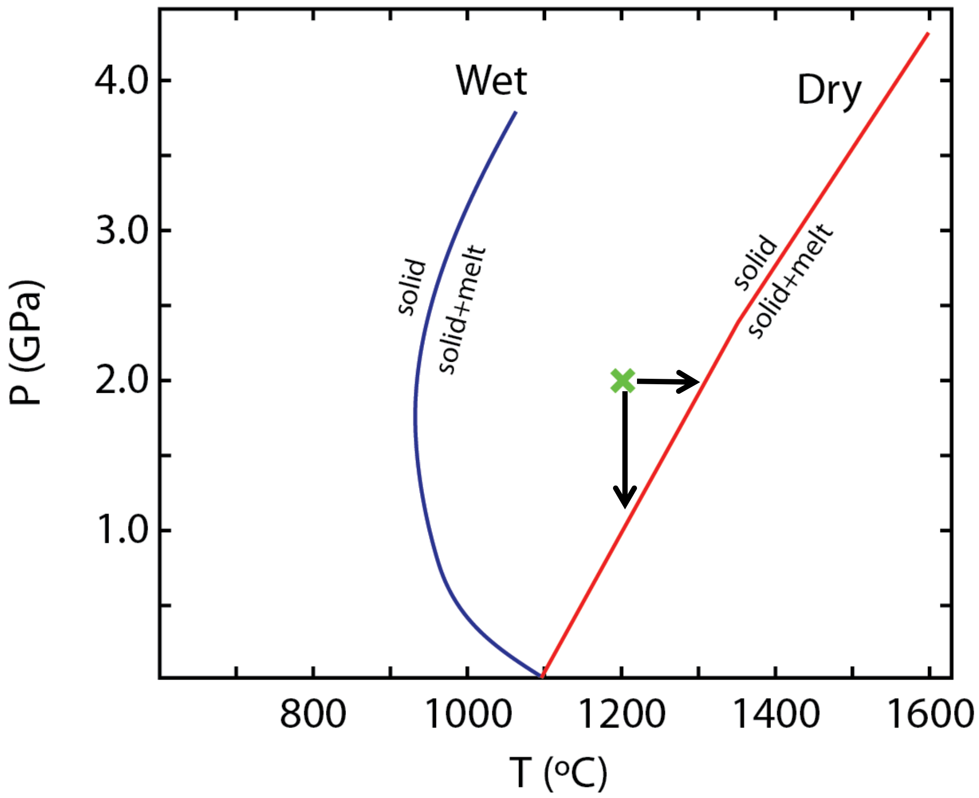
Subduction zones



Subducted ocean sediments

Release of water can decrease the melting temperature of *overlying* rocks

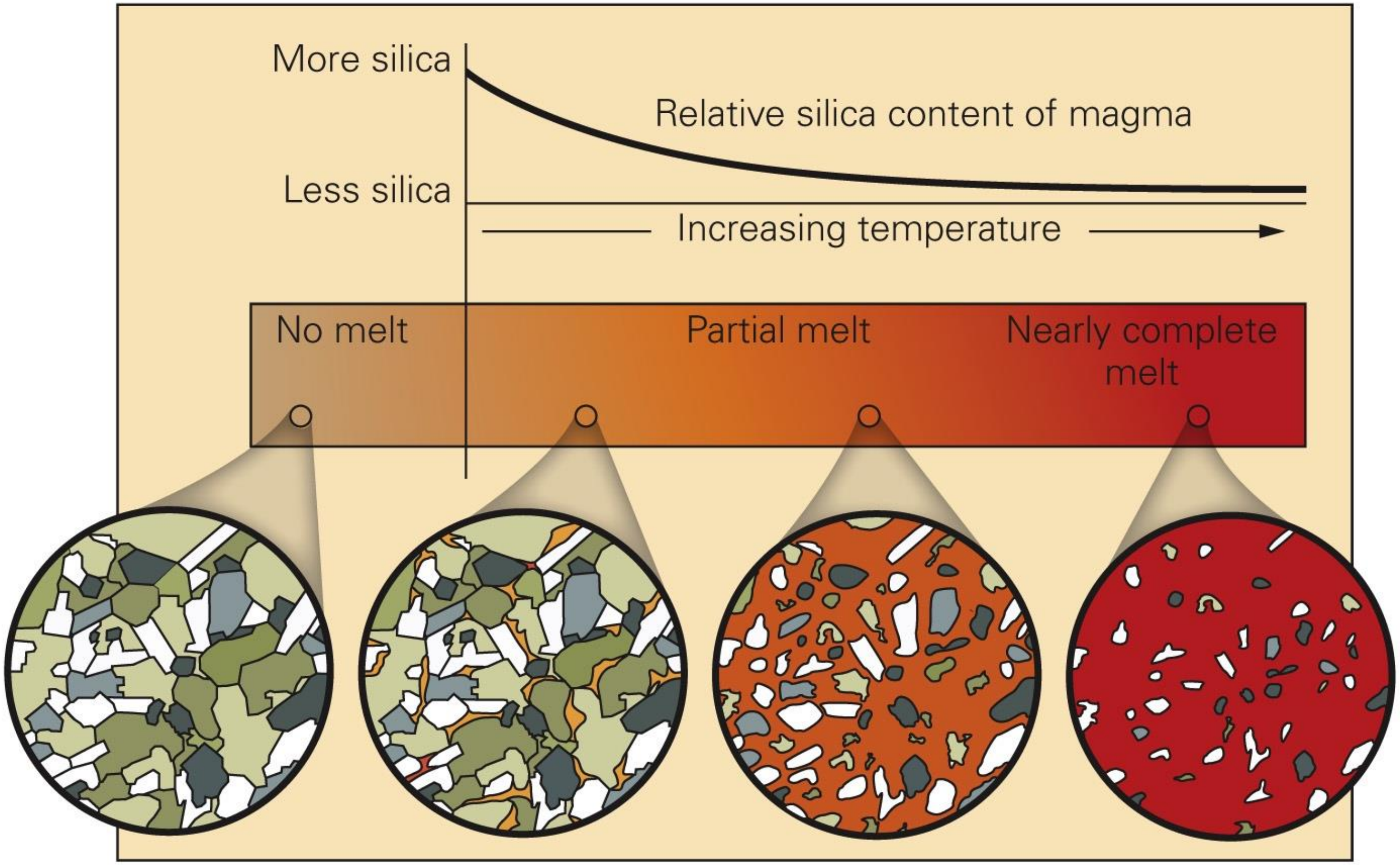
Mantle phase diagram



Ways to generate melt:
1. Decrease P
2. Increase T
3. Add H_2O

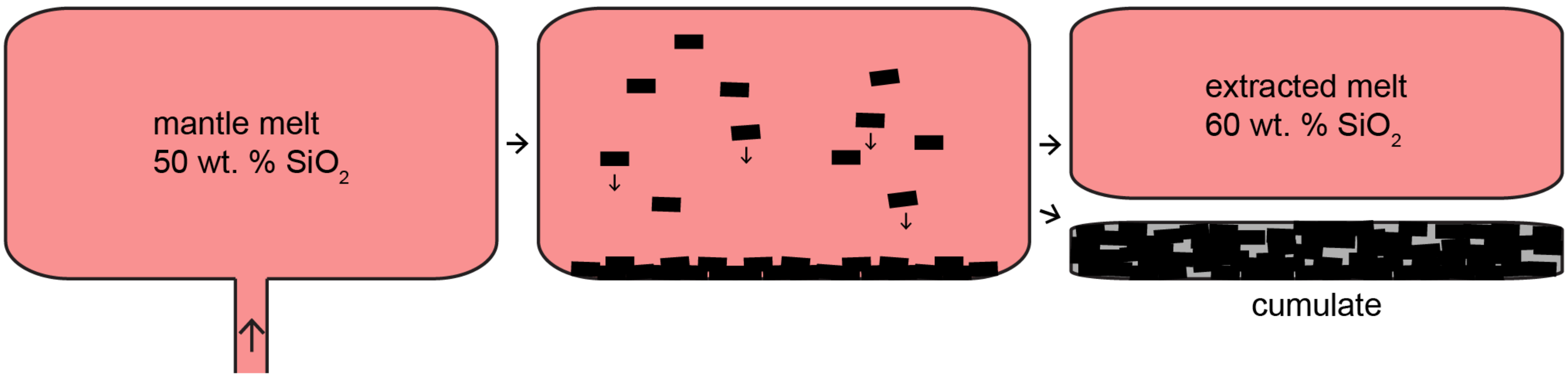
Winter, 2009

Differentiation of the crust: Partial melting



- When a rock is partially melted, the melt generated has higher SiO_2
- Partial melt of the mantle = basalt
- Partial melt of the crust = more felsic rock

Differentiation of the crust: Fractional crystallization



- Crystallizing minerals, with low SiO_2, are removed from the melt (e.g., olivine = 40 wt. % SiO_2)
- Mineral crystallization increases the SiO_2 content of the melt (i.e., makes the melt more felsic)

Differentiation of the crust

- Most mantle melts have a basaltic (mafic) composition
- Magmas evolve to more felsic compositions through additional differentiation

Plate tectonics and formation of continental crust

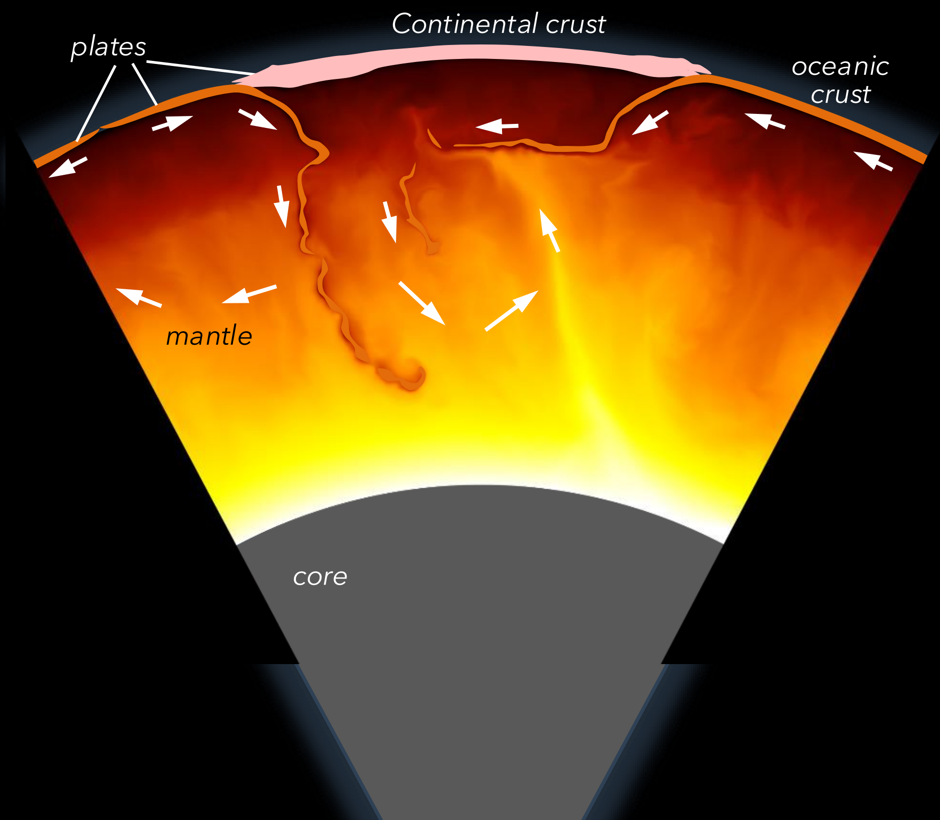
- Plate tectonics is lateral motion of rigid plates on a sphere driven by convection and buoyancy contrast between continents and oceans
- Although the mantle is a solid, it can plastically convect
- As the mantle rises it decompresses and melts
- Different minerals and rocks have different melting temperatures
- Initial differentiation from the mantle is due to partial melting and extraction of basaltic composition
- Flux melting and fractional crystallization leads to additional differentiation of the continental crust

When and how did continents originate and tectonics begin?

EARTH

Plate tectonic "Active-lid"

Lithosphere is segmented into a network of differentially-mobile plates



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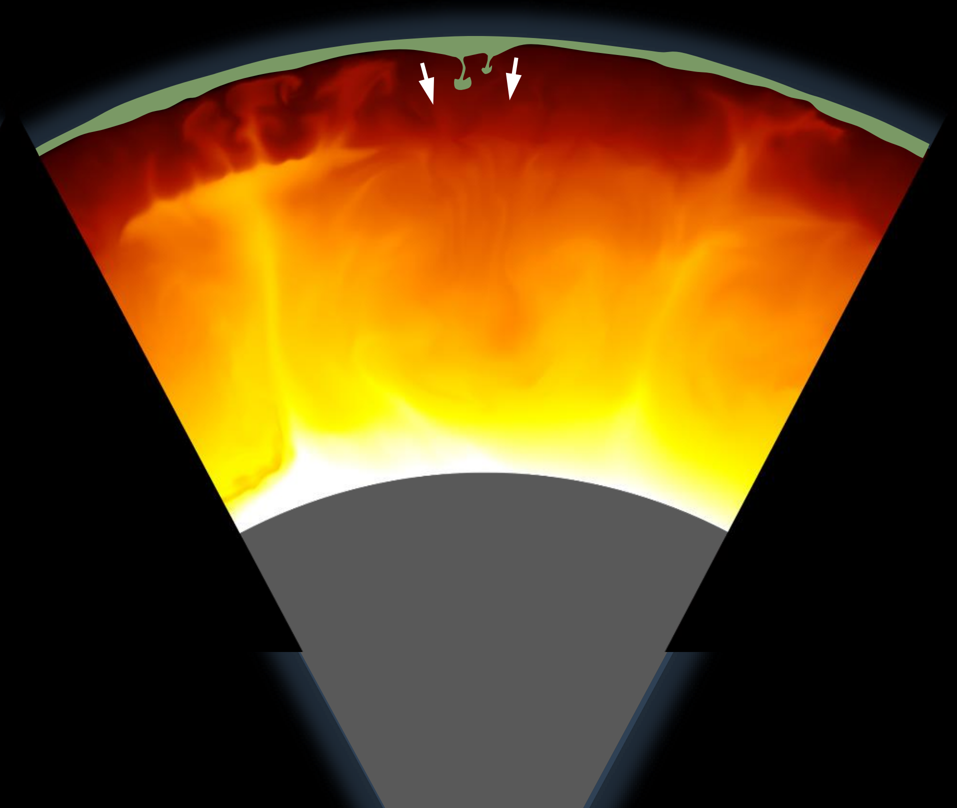
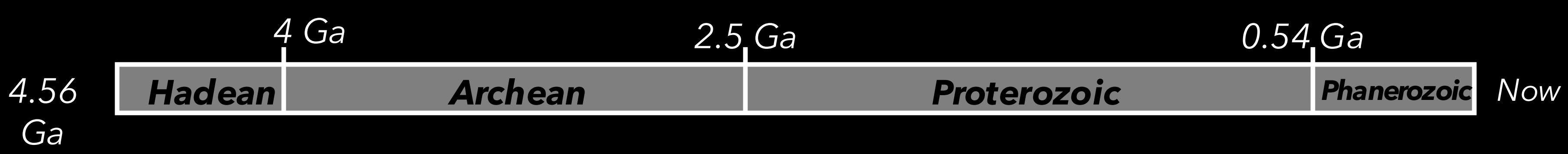
One global plate with limited horizontal mobility and/or distributed deformation



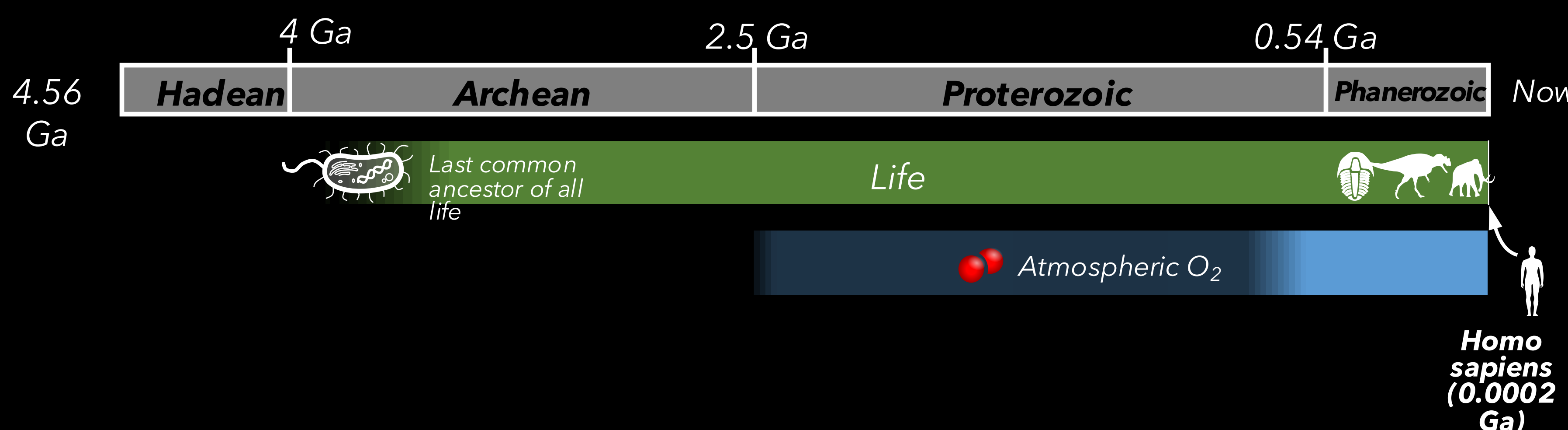
When and how did continents originate and tectonics begin?

What material do we have available to test theories about early Earth?

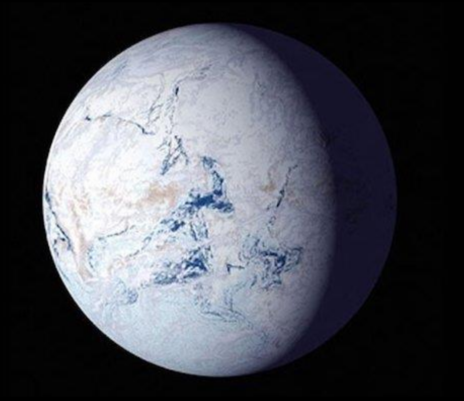
4.5 billion years (Ga) of Earth history, to scale

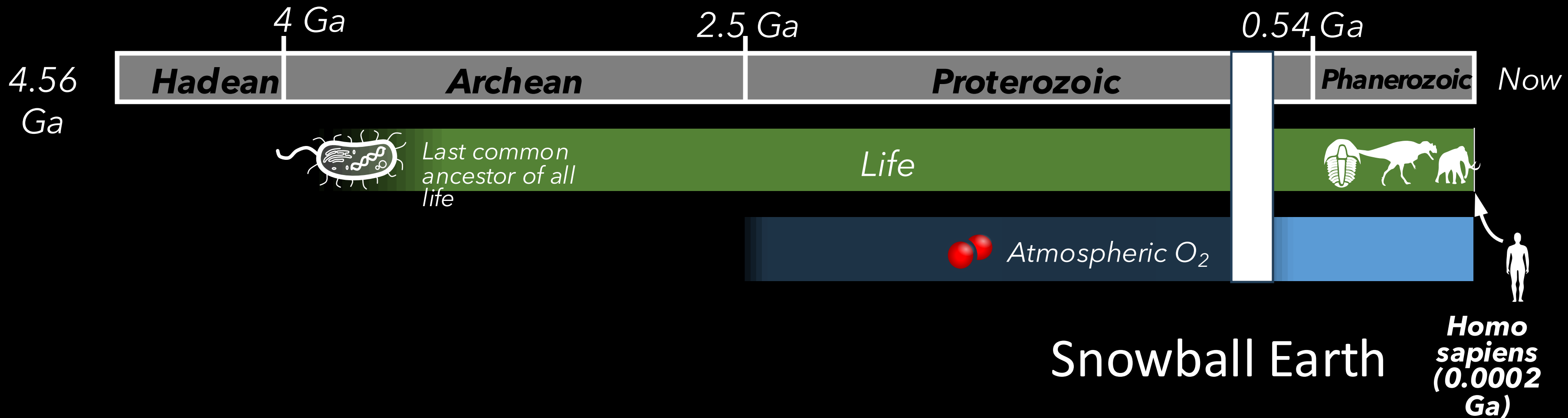


4.5 billion years (Ga) of Earth history, to scale



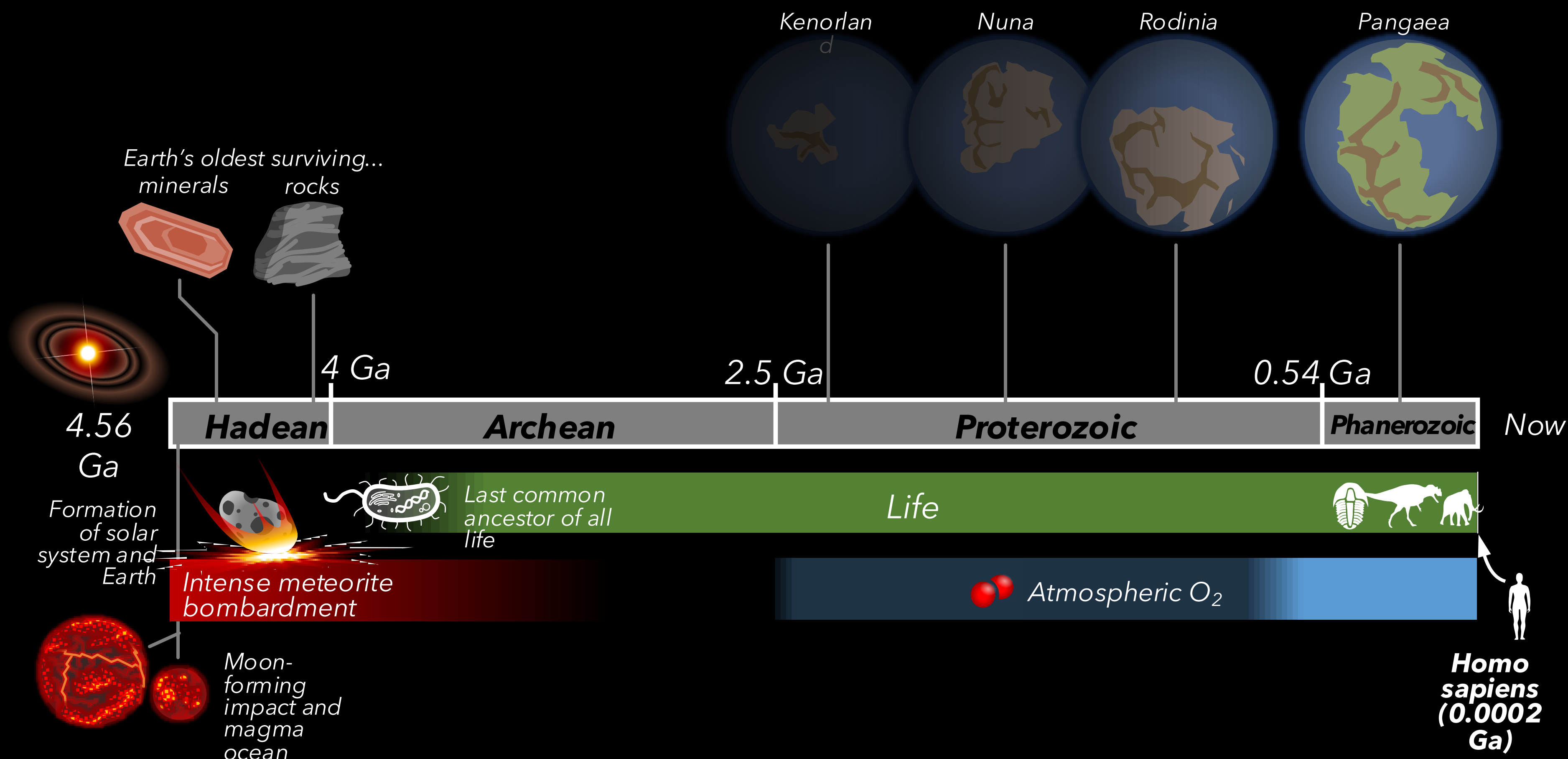
4.5 billion years (Ga) of Earth history, to scale



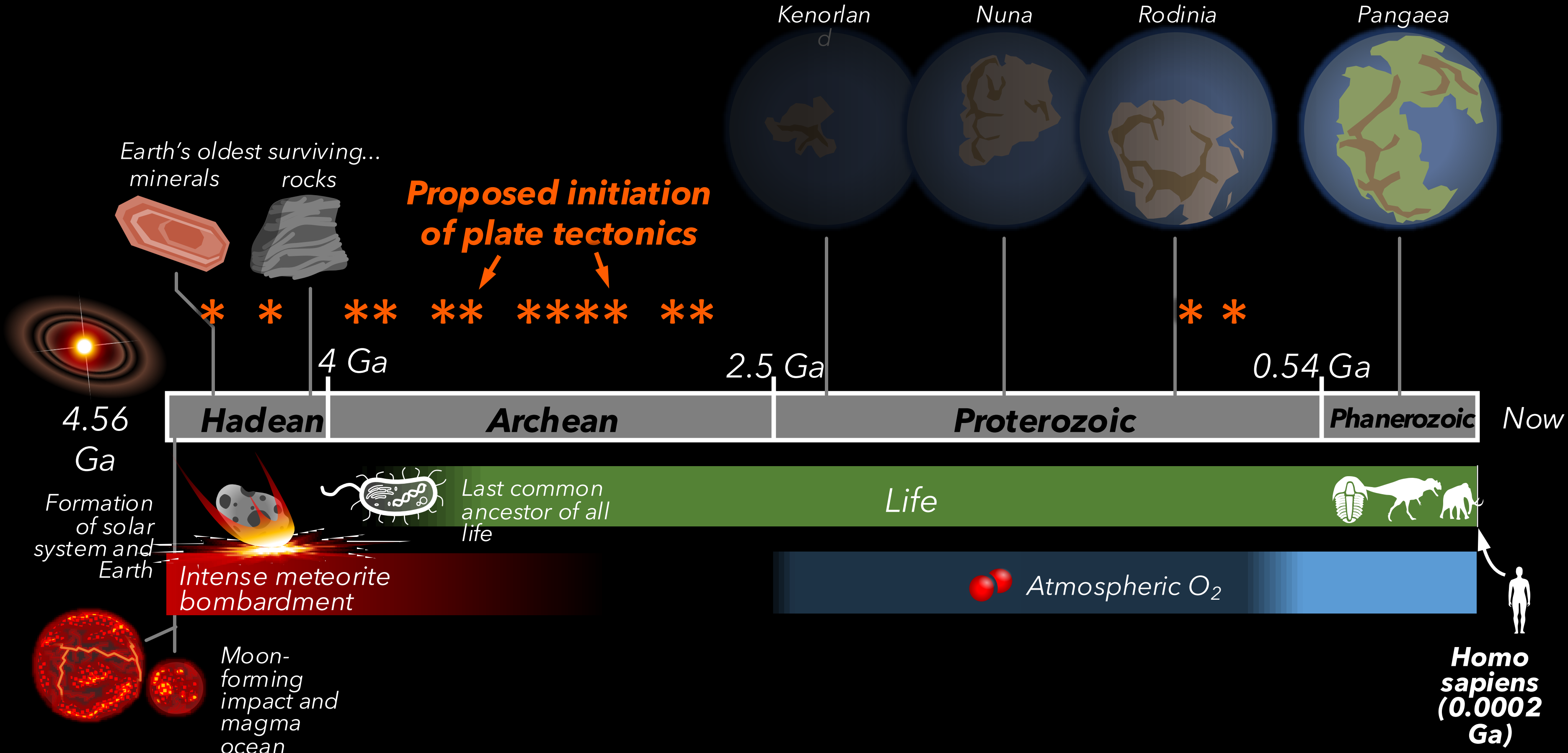


Snowball Earth

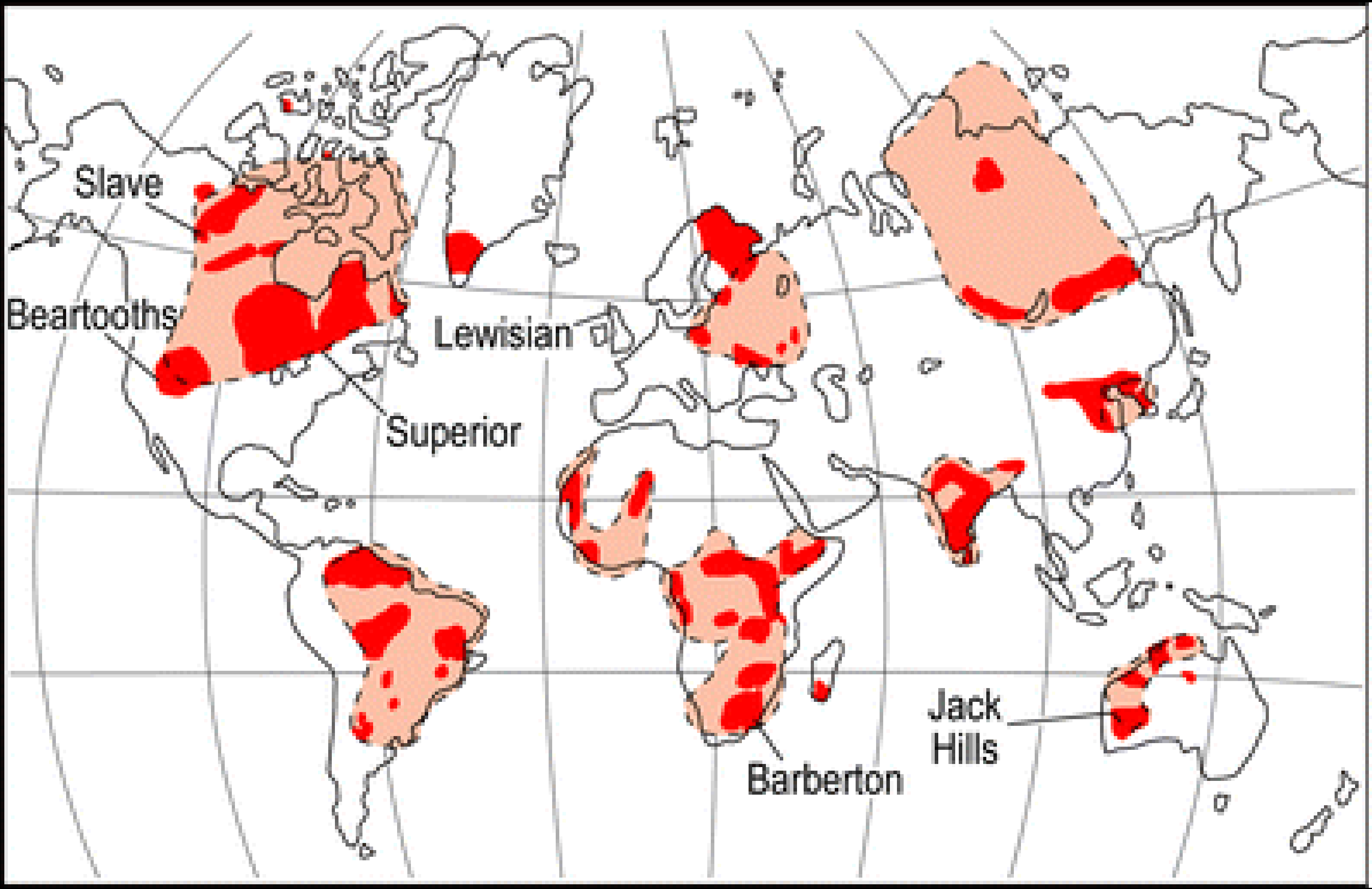
4.5 billion years (Ga) of Earth history, to scale



4.5 billion years (Ga) of Earth history, to scale



What do we have to work with?

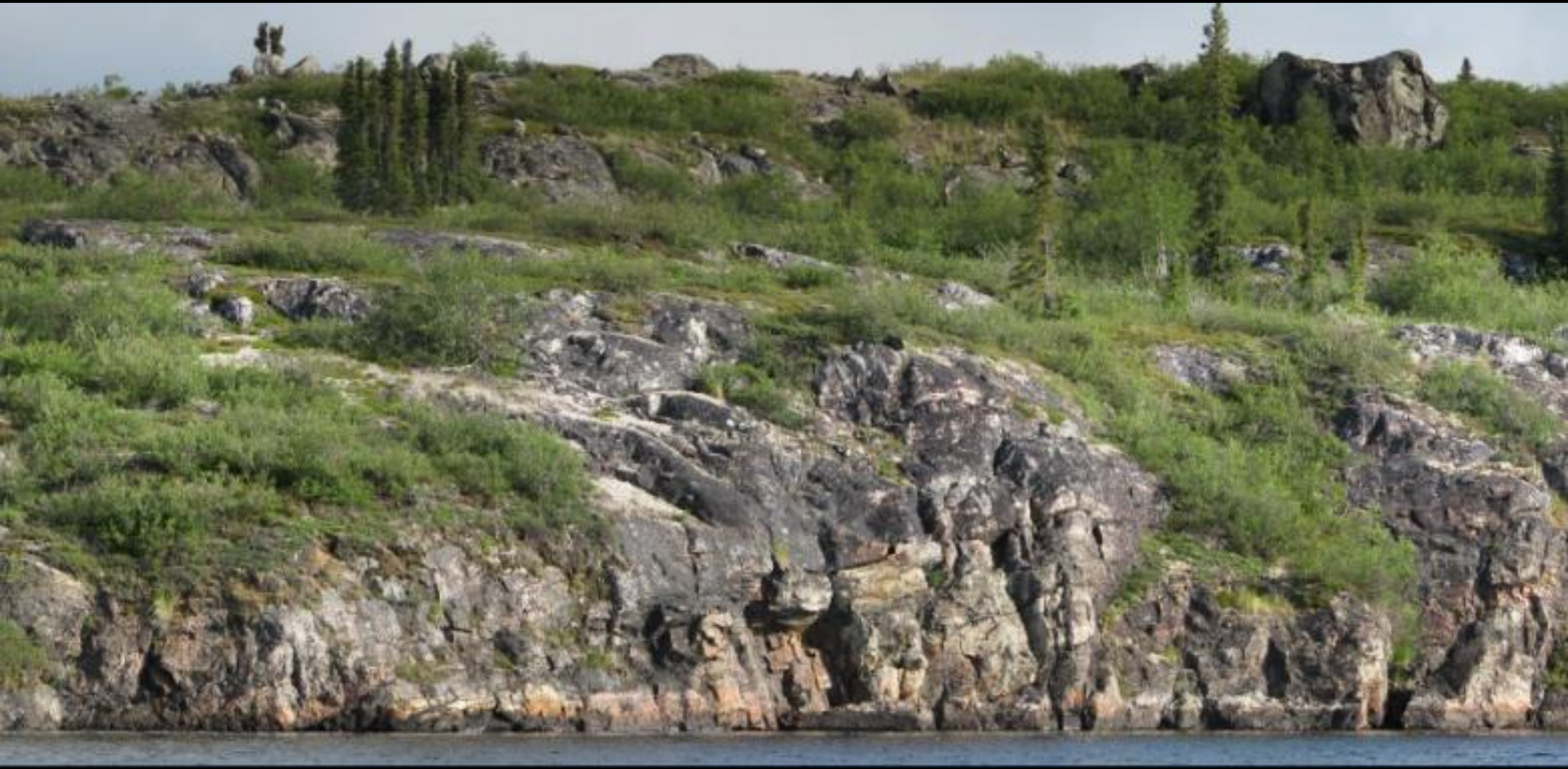


- Archean rocks (>2.5 billion years old) in dark orange

Oldest rocks are gneiss

- Acasta Gneiss on western margin of Slave craton, Northwest Territories, CA

Oldest rocks are gneiss

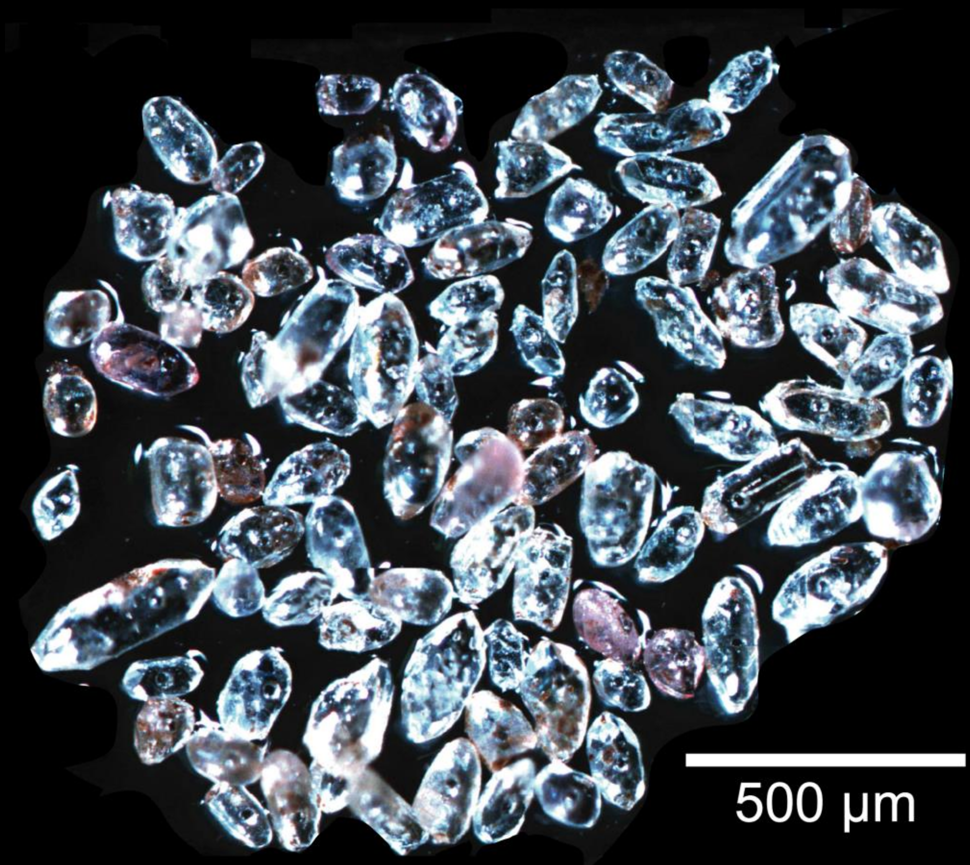


- Acasta Gneiss on western margin of Slave craton, Northwest Territories, CA
- Composition similar to Sierra Nevadas

Oldest rocks are gneiss

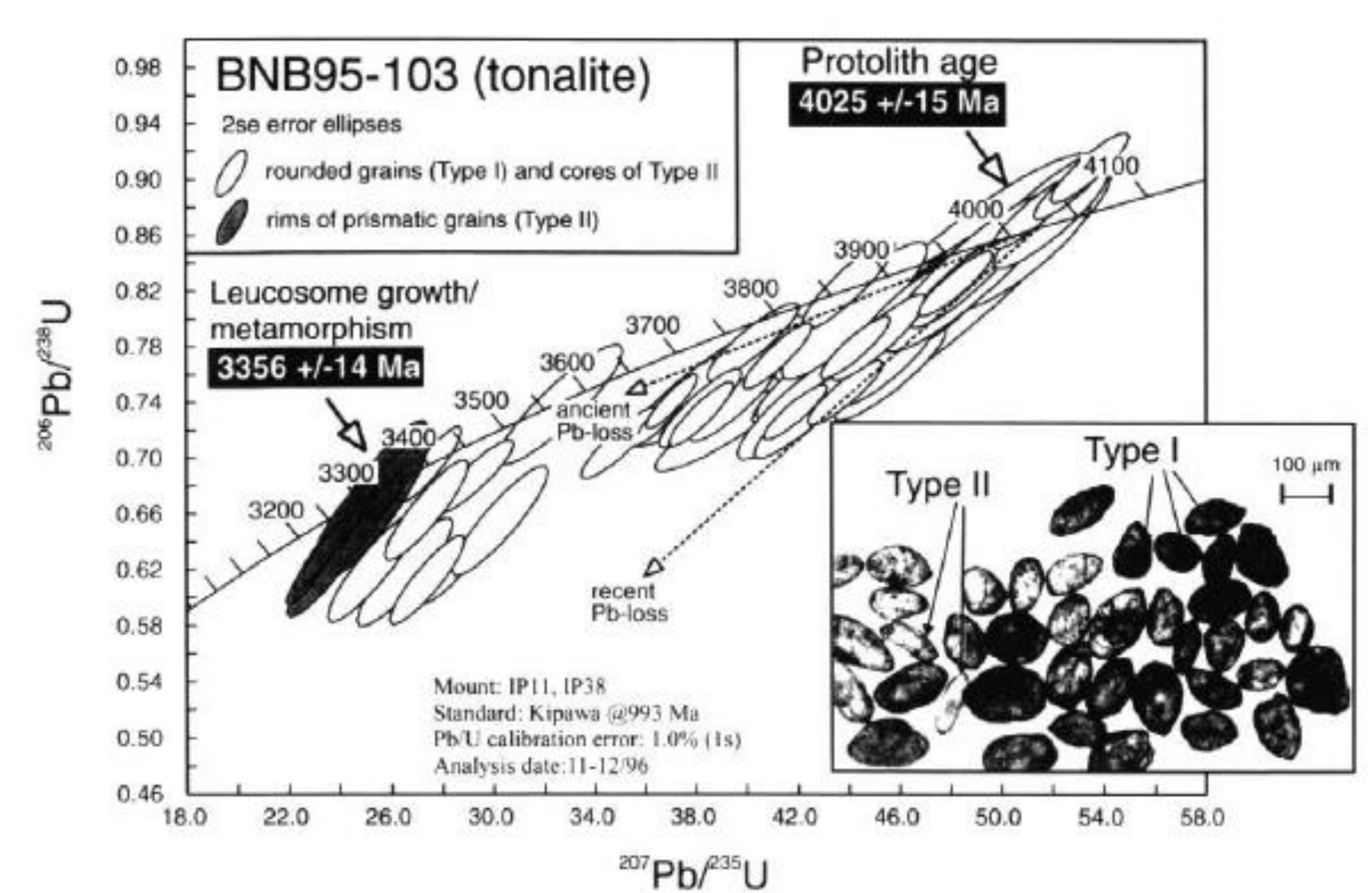
- Acasta Gneiss on western margin of Slave craton, Northwest Territories, CA
- Composition similar to Sierra Nevadas
- First dated at 4.01 Ga by Bowring et al., 1989 => continental nucleus

Acasta Gneiss zircon



Zircon ($ZrSiO_4$)

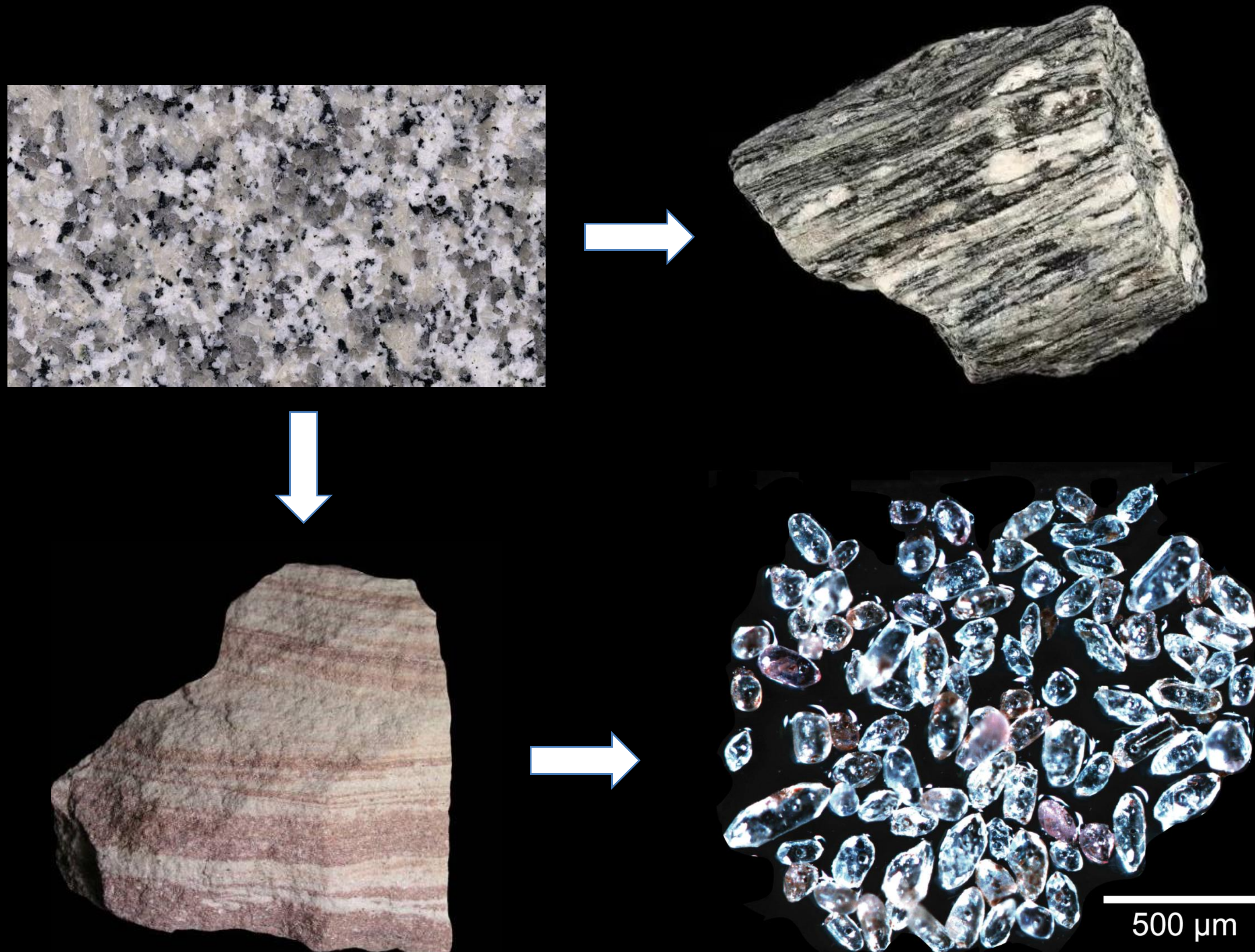
Acasta Gneiss zircon



Stern & Bleeker, 1998

- Tonalite (plag, >20% qtz, <10% K-spar, amphibole, pyrx.) with 4.03 Ga crystallization with T(Ti) = ~700 degrees C
- High grade metamorphism at 3.36 Ga on western margin of Slave craton

If we want to go older than 4.0 Ga the main archive is detrital zircon



Oldest minerals: Jack Hills, Australia

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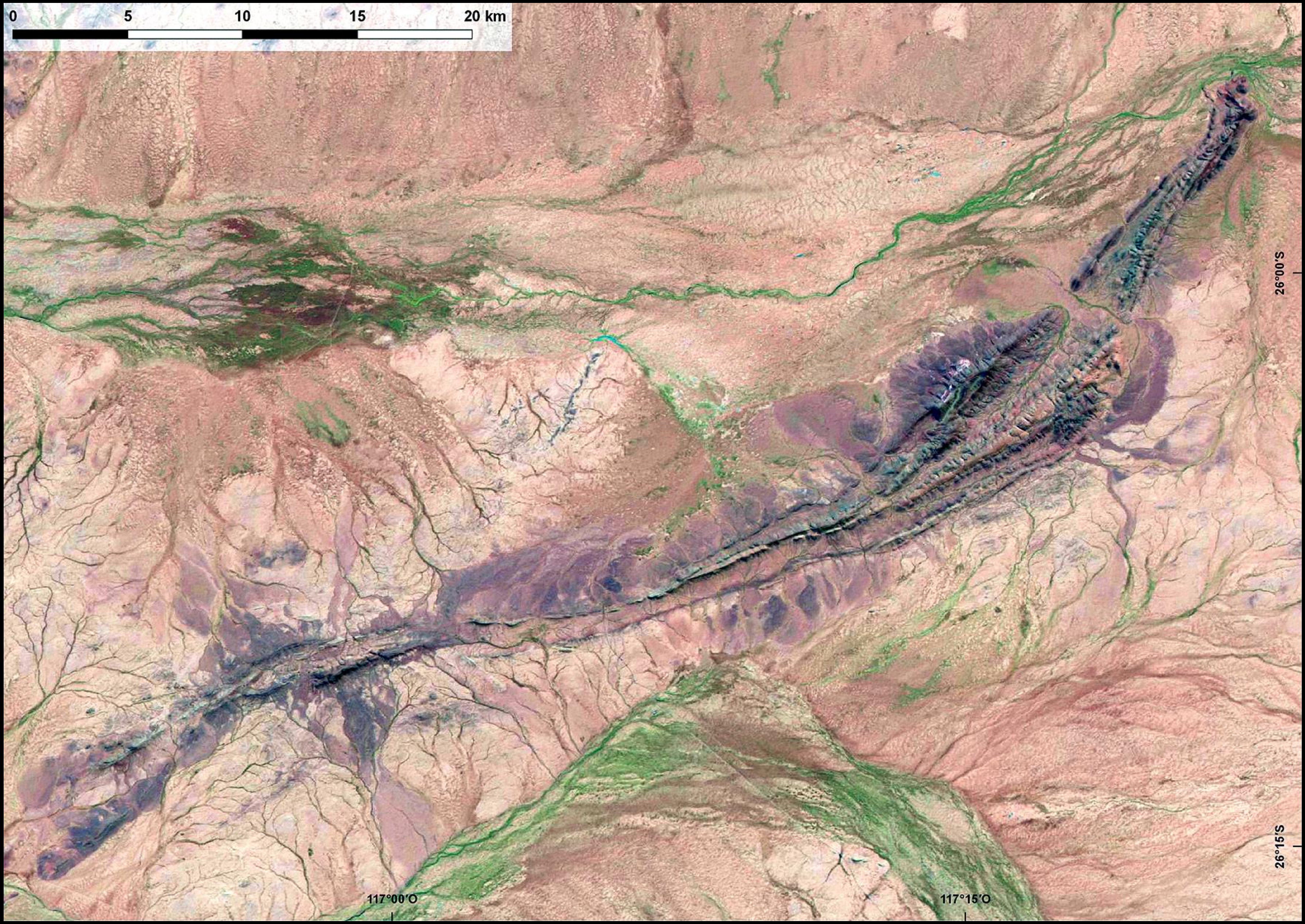
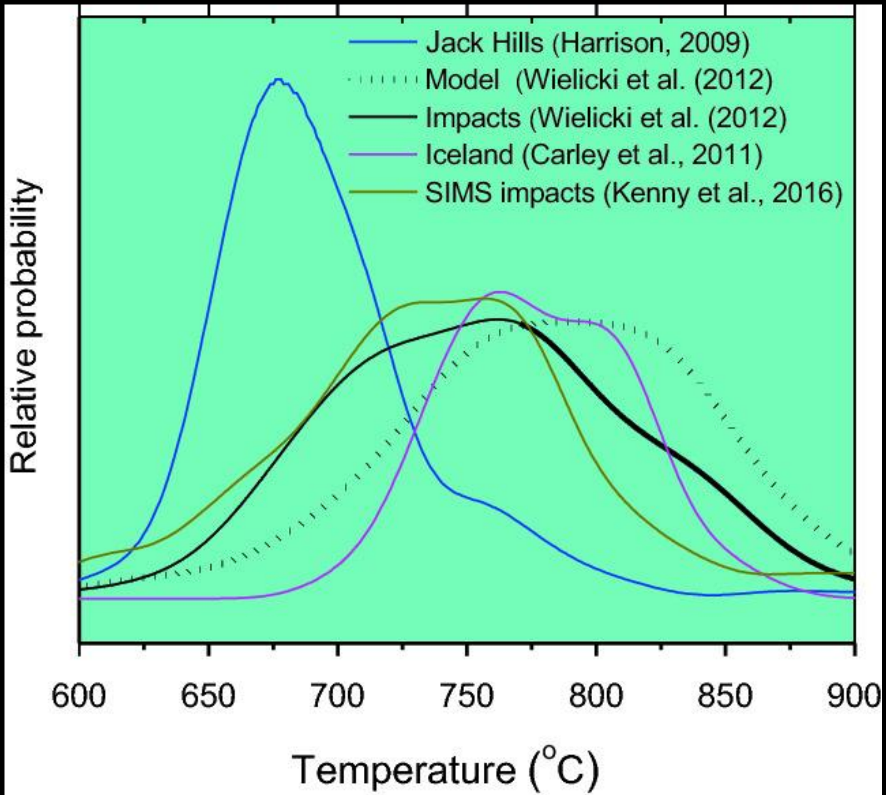


Oldest minerals: Jack Hills, Australia

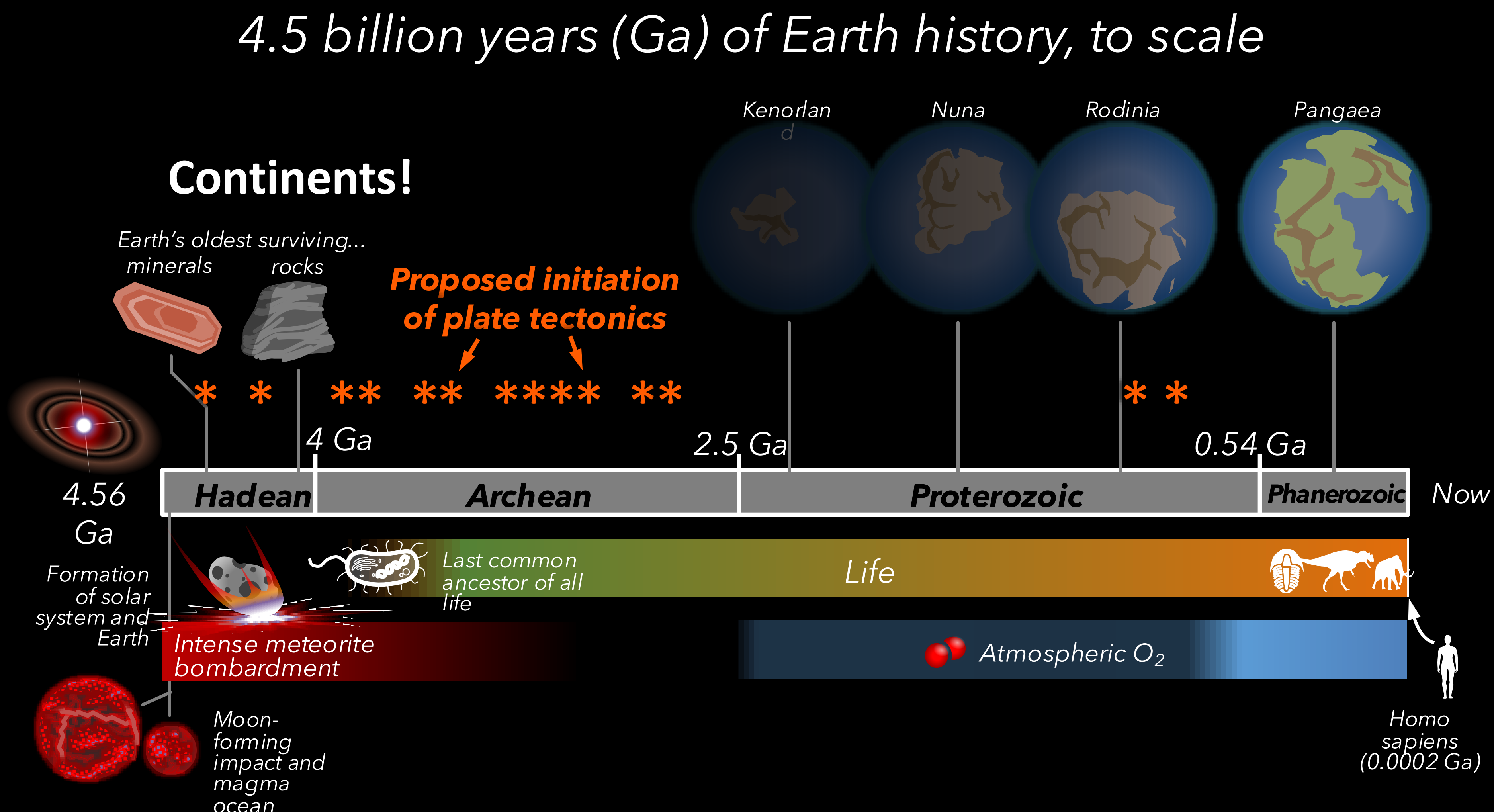
- 3.0 Ga sedimentary rocks with 4.3-4.0 Ga zircon grains

Oldest minerals: Jack Hills, Australia

- Fractionated Hf isotopes show formed from partial melting of crust (Valley et al., in prep.)
- Heavy O isotopes show that they formed in the presence of liquid water—i.e. subduction zone and not dry mantle melt
- Low T(Ti) consistent with arc magmatism geochemistry and liquid water by 4.3 Ga (Harrison, 2009)

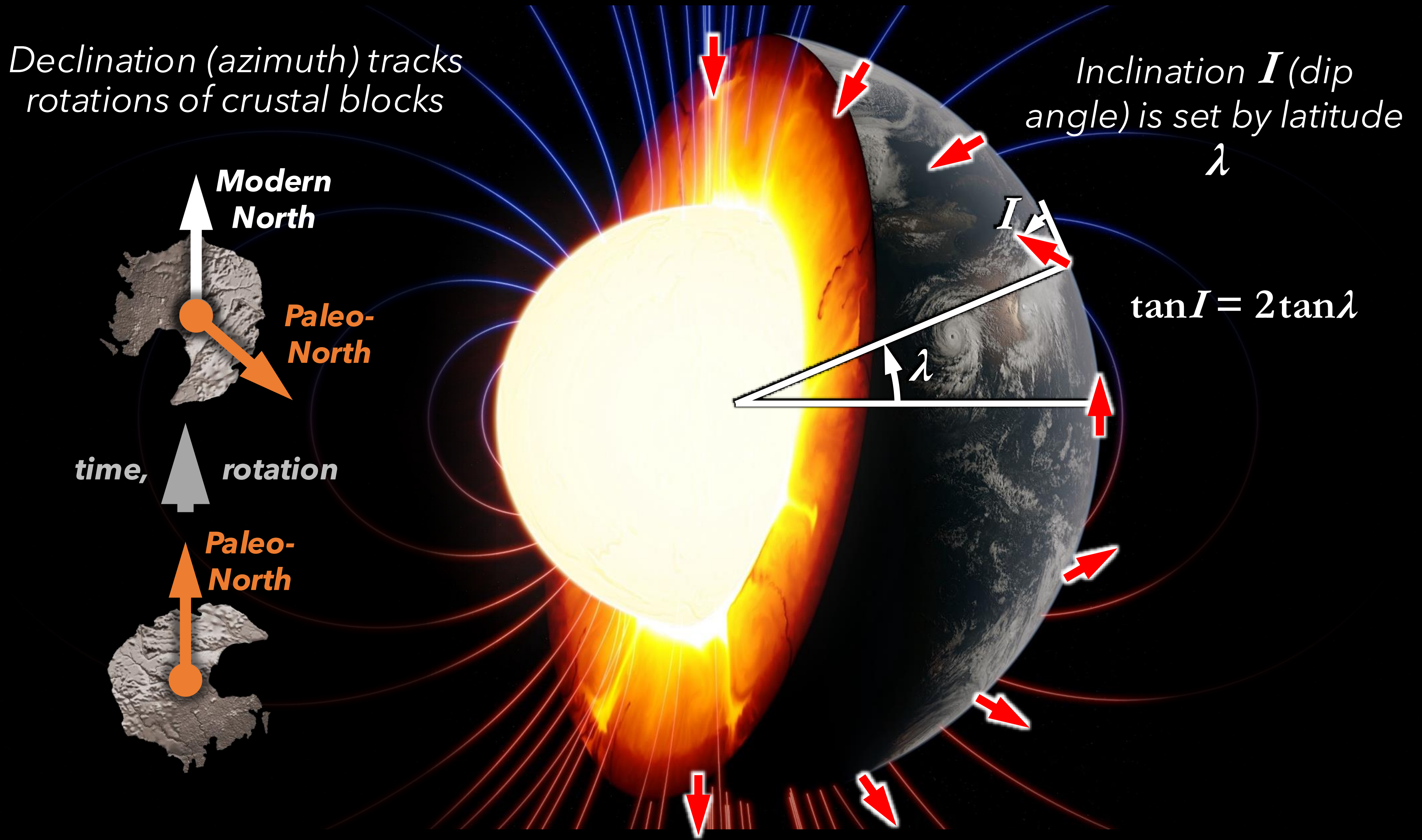


When and how did the continents and oceans originate? And when did tectonics begin?



- Oldest rocks and minerals have compositions consistent with forming in a wet, subduction zone, i.e. pieces of continents….what about plate motion?

We can measure plate motion with paleomagnetism



Slide from Alec Bernner

We can measure plate motion with paleomagnetism

Many iron-bearing minerals get magnetized
by the ambient magnetic field when they form.

If formed correctly and preserved well, these minerals stay magnetized for billions of years.

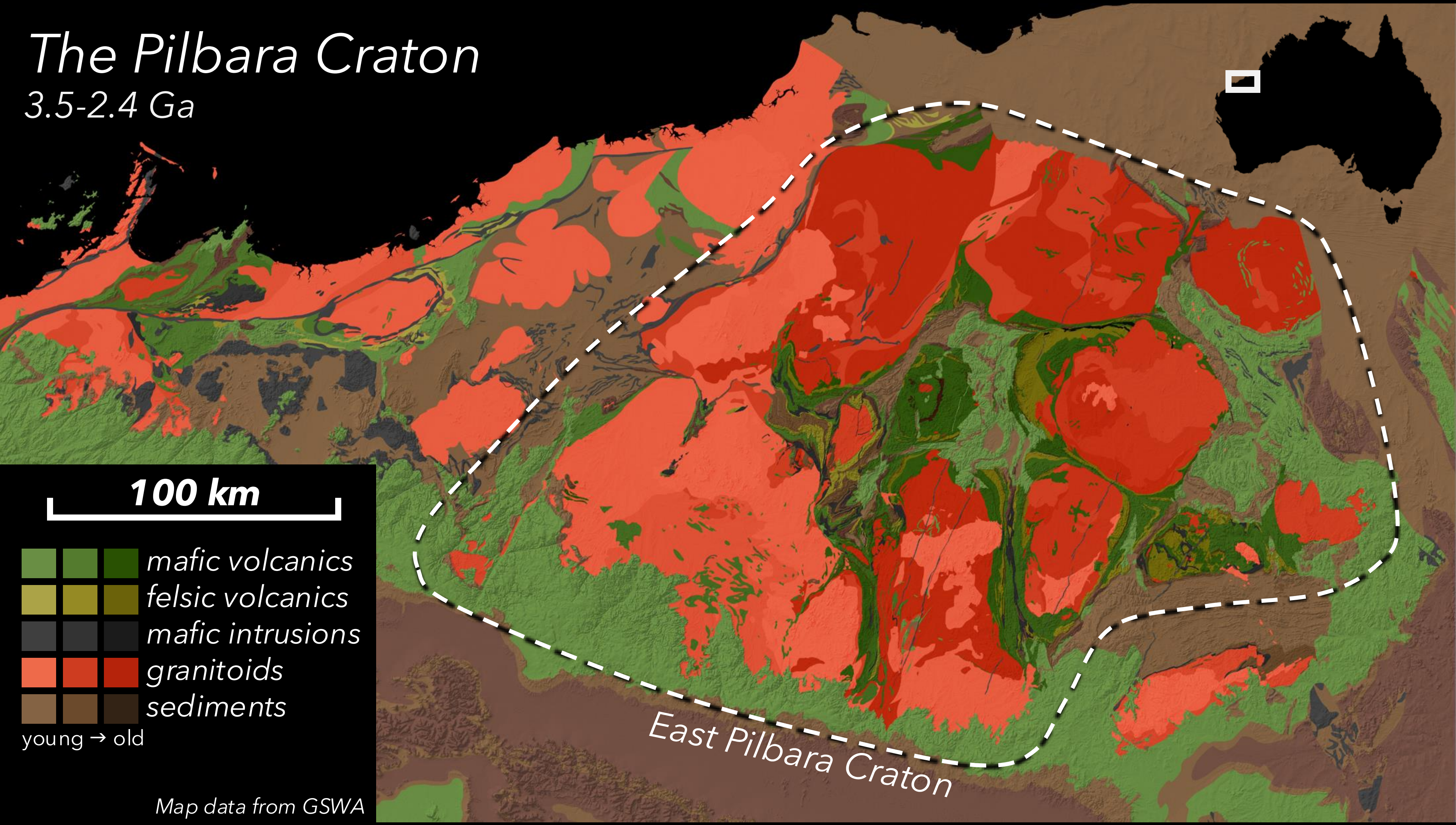
Almost all rocks contain these minerals.

Magnetite, $Fe^{2+}(Fe^{3+})_2O_4$
Cerro Huañaquino, Potosí, Bolivia

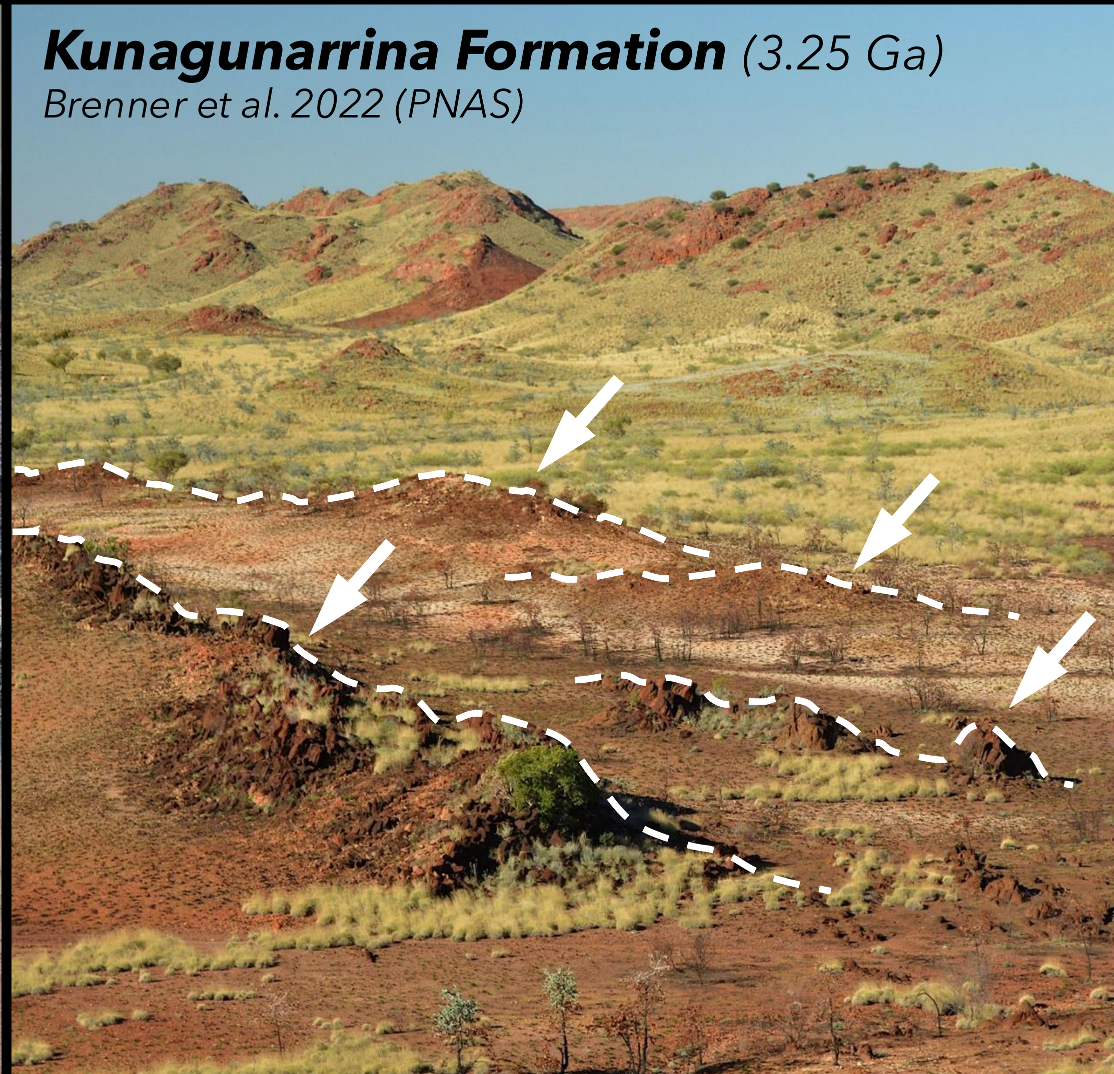
Hematite, $(Fe^{3+})_2O_3$
Barberton Greenstone Belt, South Africa

- Abundant magnetite in basalts

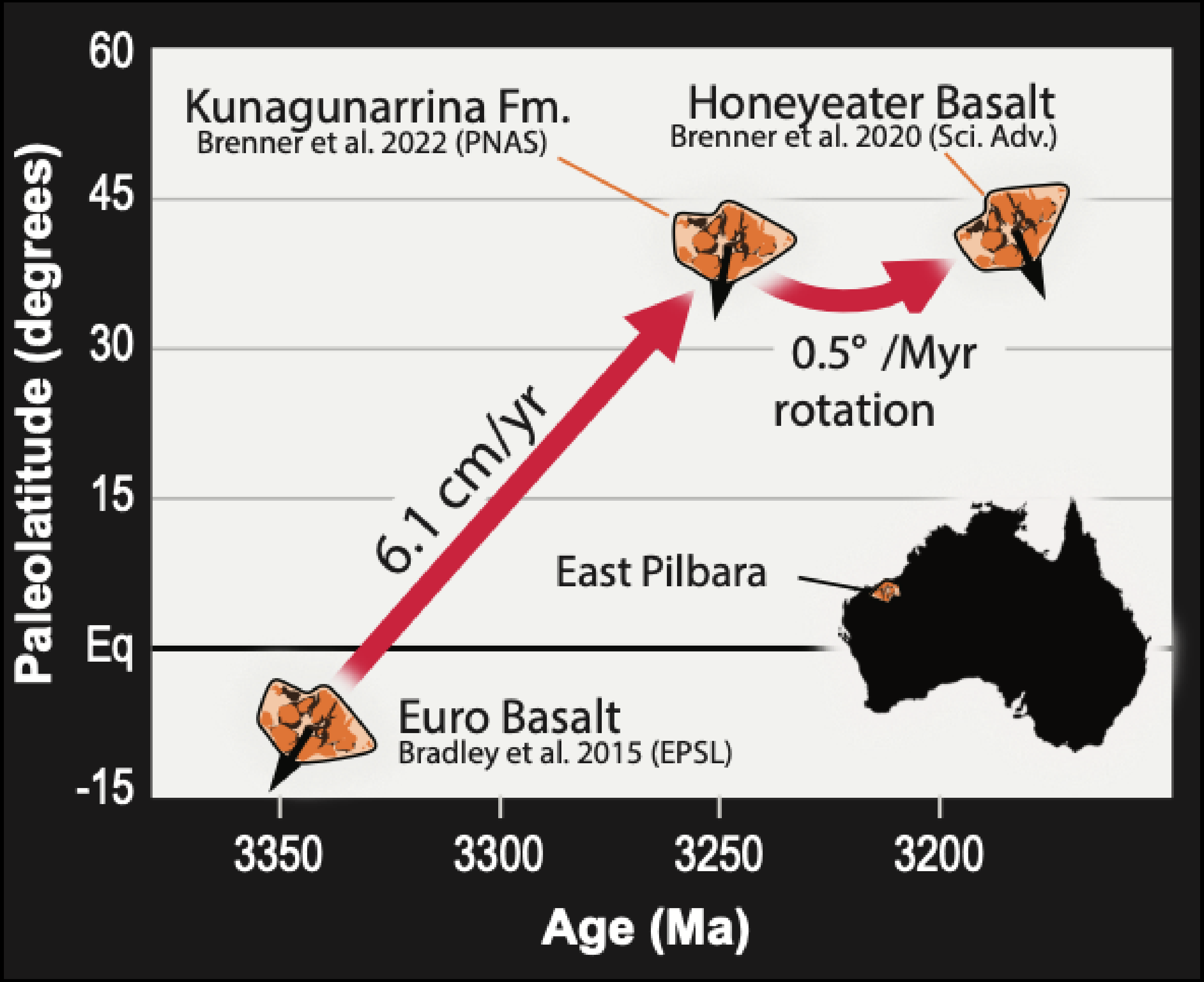
Old basalts in NW Australia



Old basalts in NW Australia



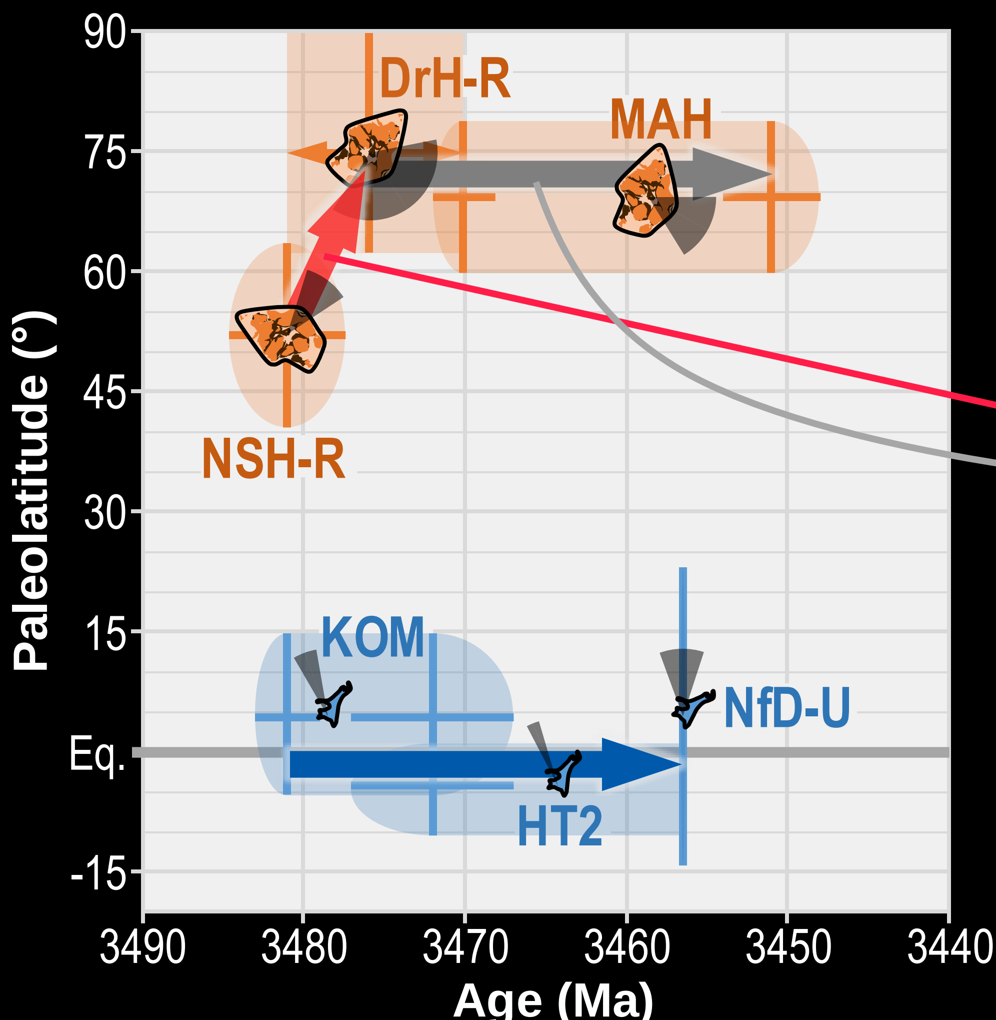
Paleogeographic reconstruction



The East Pilbara experienced motions fast enough to be compatible with plate tectonics

North Pole Dome *(3.49-3.35 Ga)*
Brenner et al. 2024 (G^3)

Differential motion between Australia and S. Africa



Paleogeographic reconstruction

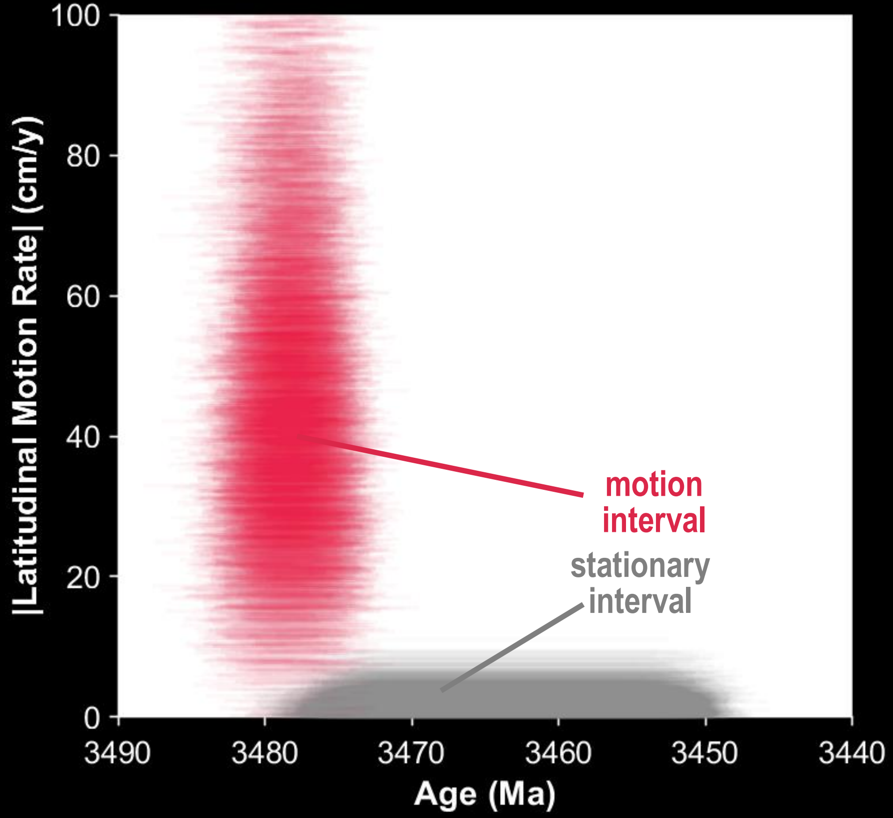
East Pilbara Craton (this work):
in motion at high latitudes
47^{+70}_{-36} cm/yr latitudinal motion,
then a ~25 Myr stationary period

Barberton Greenstone Belt:
no resolvable motions from 3481-3456 Ma

Biggin et al. 2011 (EPSL)
Roberts 2014 (thesis)
Usui et al. 2009 (G^3)
Yoshihara and Hamano 2004 (Prec. Res.)

Plate tectonic rates in the Archean

Motion rate history



Observables:

- *Rapid differential motion for several Myr, then…*
- *Motion ceases abruptly, then…*
- *Stationary for ~25 Myr*

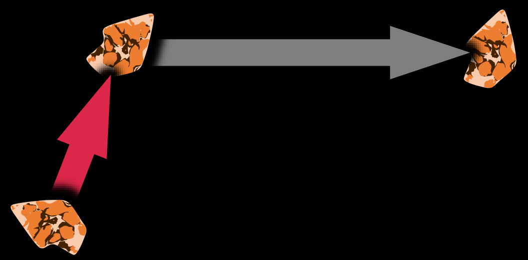
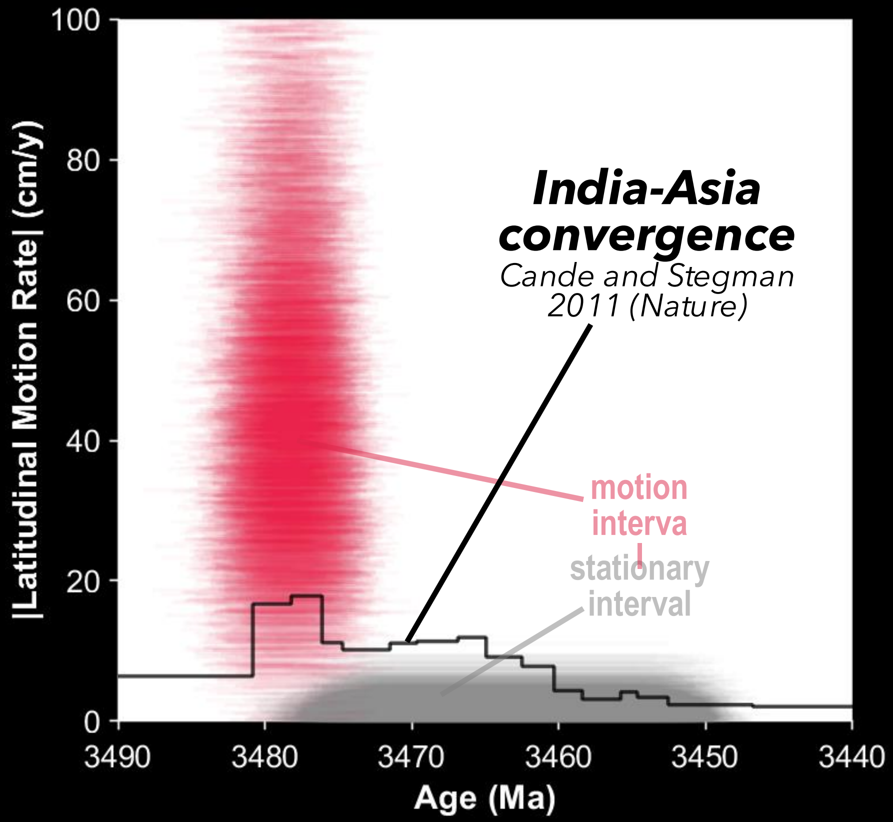
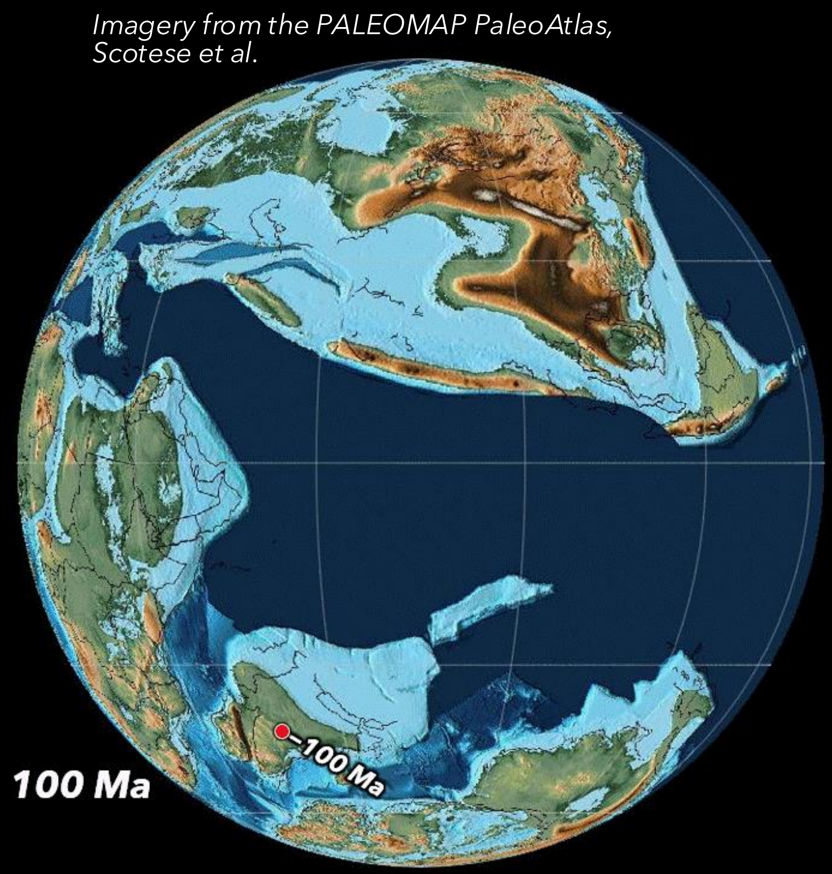


Plate tectonic rates in the Archean are similar to modern

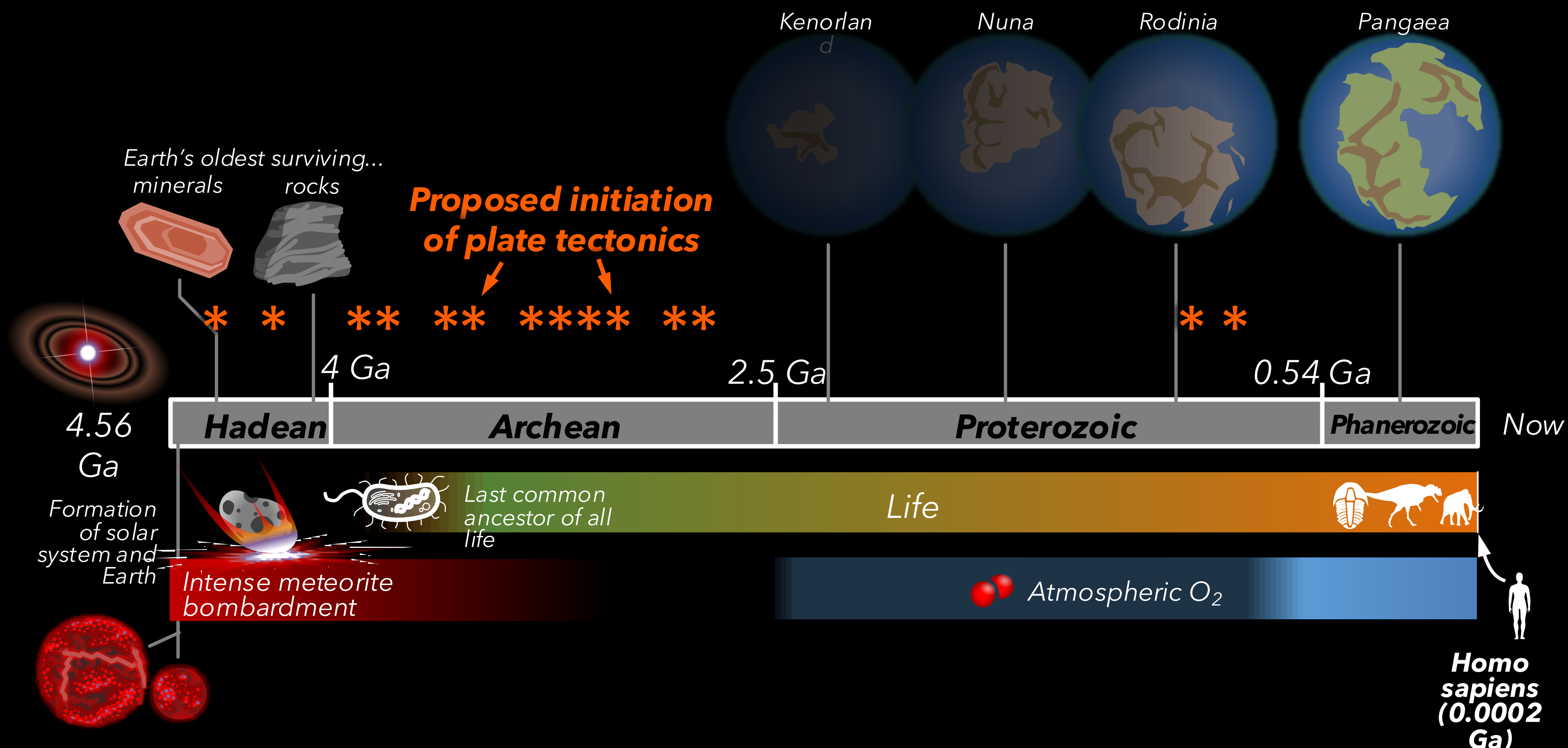




Modern rapid plate tectonics followed by slow down

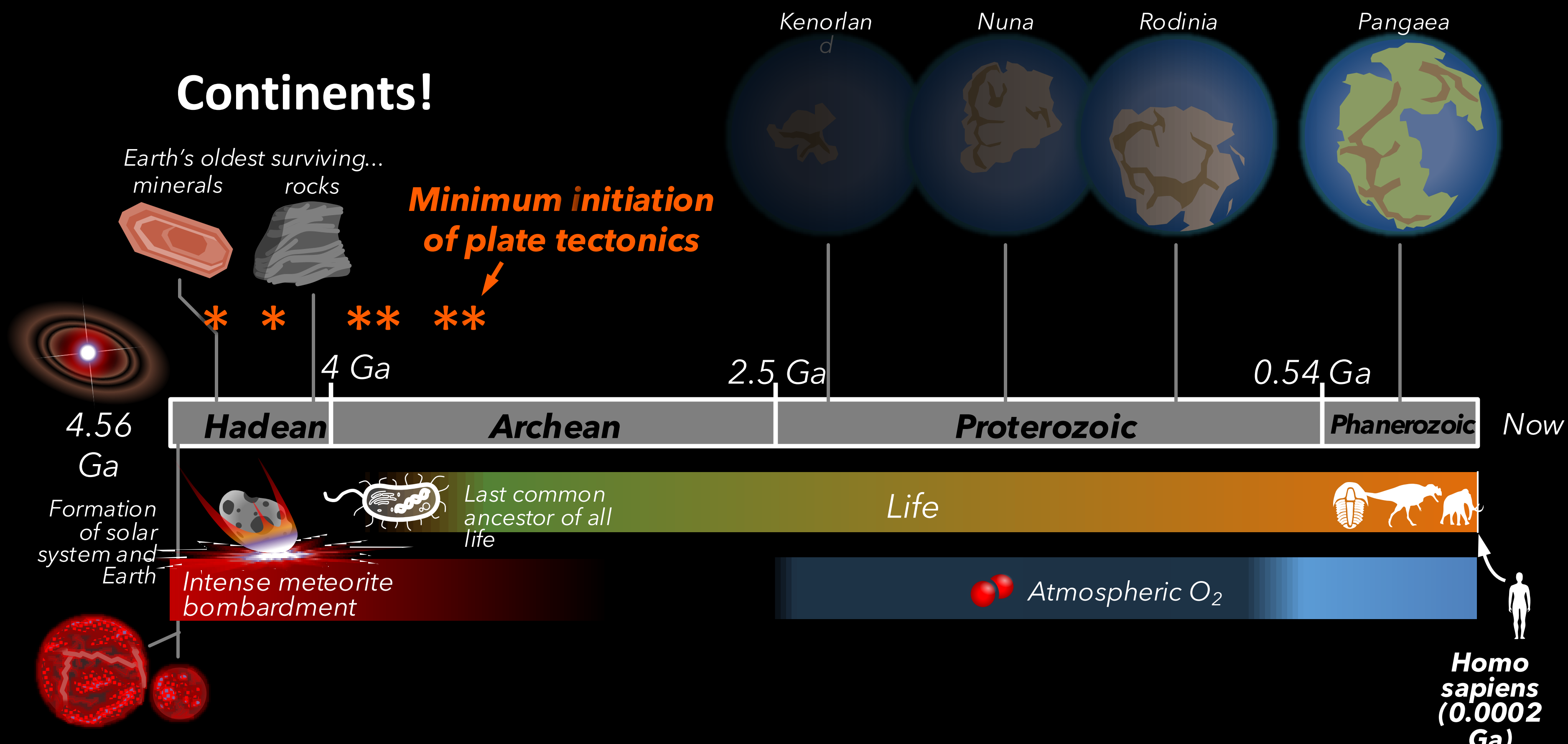
When and how did the continental and oceanic crust originate? And when did tectonics begin?

4.5 billion years (Ga) of Earth history, to scale



Oldest records geological records are consistent with plate tectonics

4.5 billion years (Ga) of Earth history, to scale



Ingredients for life by 3.48 Ga: water, atmosphere, bimodal distribution of topography, geochemical cycles

The geological record of plate tectonics

- Plate tectonics drives hydrological and geochemical cycles of bioessential nutrients through subduction, volcanic outgassing, erosion, and weathering

- Oldest rocks and minerals formed in a wet, subduction zone setting—i.e. continental nuclei by 4.3 Ga

- Oldest reliable paleomagnetic data is consistent with plate motion rates similar to the modern—i.e. plate tectonics by >3.48 Ga

- How was plate tectonics initiated on Earth? Why not Venus? Other questions?