The dynamics of subduction throughout the Earth's history

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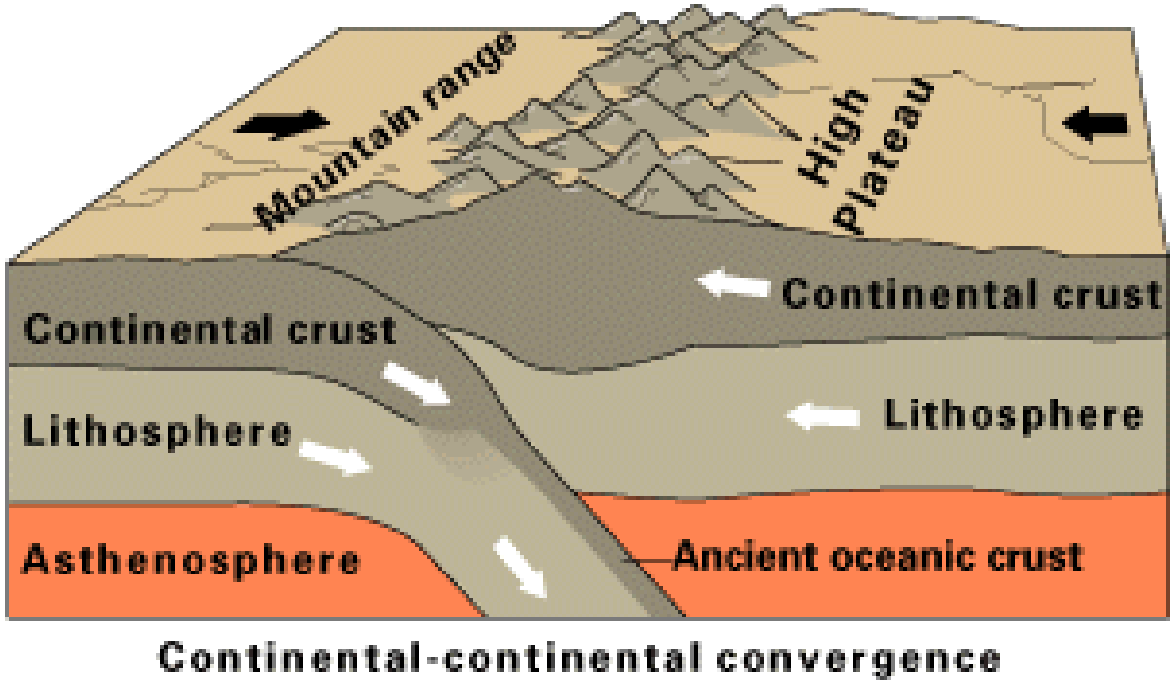
Thanks to: Jean-François Moyen (St Etienne, France)
Jon Davidson (Durham, UK)
Arie van den Berg (Utrecht, The Netherlands)

In this talk

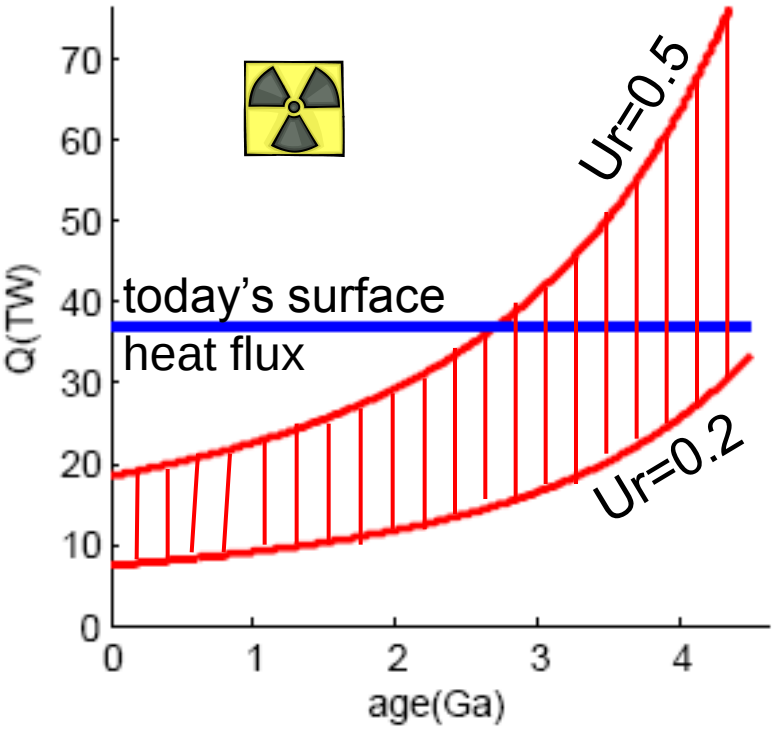


- Viability of early Earth subduction
  - Theoretical and numerical models
  - Observables
- Did subduction style change over time?

Surface tectonics and heat budget

- Today's (*deep*) surface heat flux Q = 36 TW or 80 mW/m^2:
  - 20-50% ('Urey ratio', Ur) from H = radiogenic heat
  - rest = Earth cooling
- Cooling Archaean Earth?

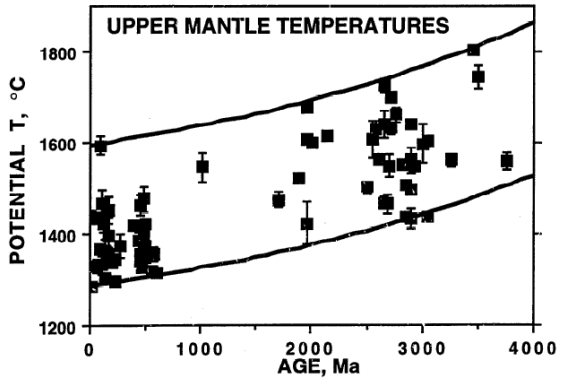
  → more efficient mechanism than modern plate tectonics

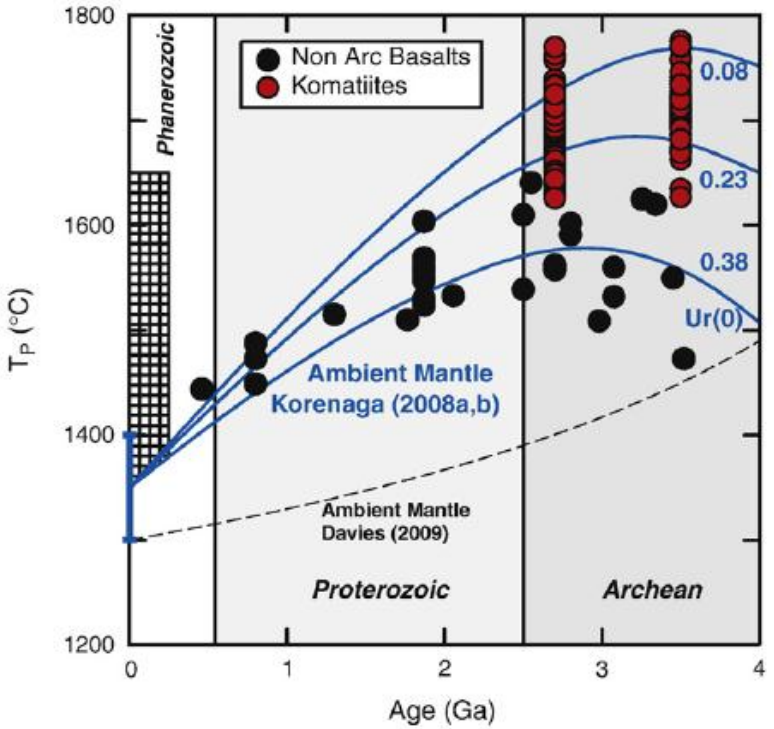


$$C\frac{dT}{dt} = H - Q$$

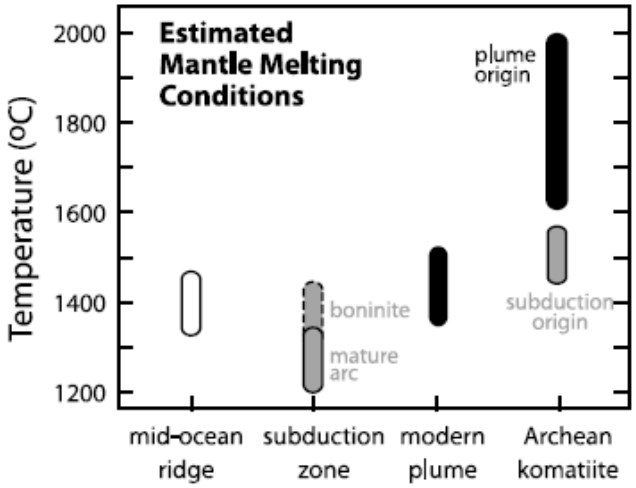
(Sleep, 2000; Turcotte and Schubert, 2002)

Archaean mantle was 100-300 K hotter





Significantly hotter Archaean mantle (Nisbet et al., 1993; Abbott et al., 1994)



Wet, slightly hotter Archean mantle
(Grove and Parman, 2004)

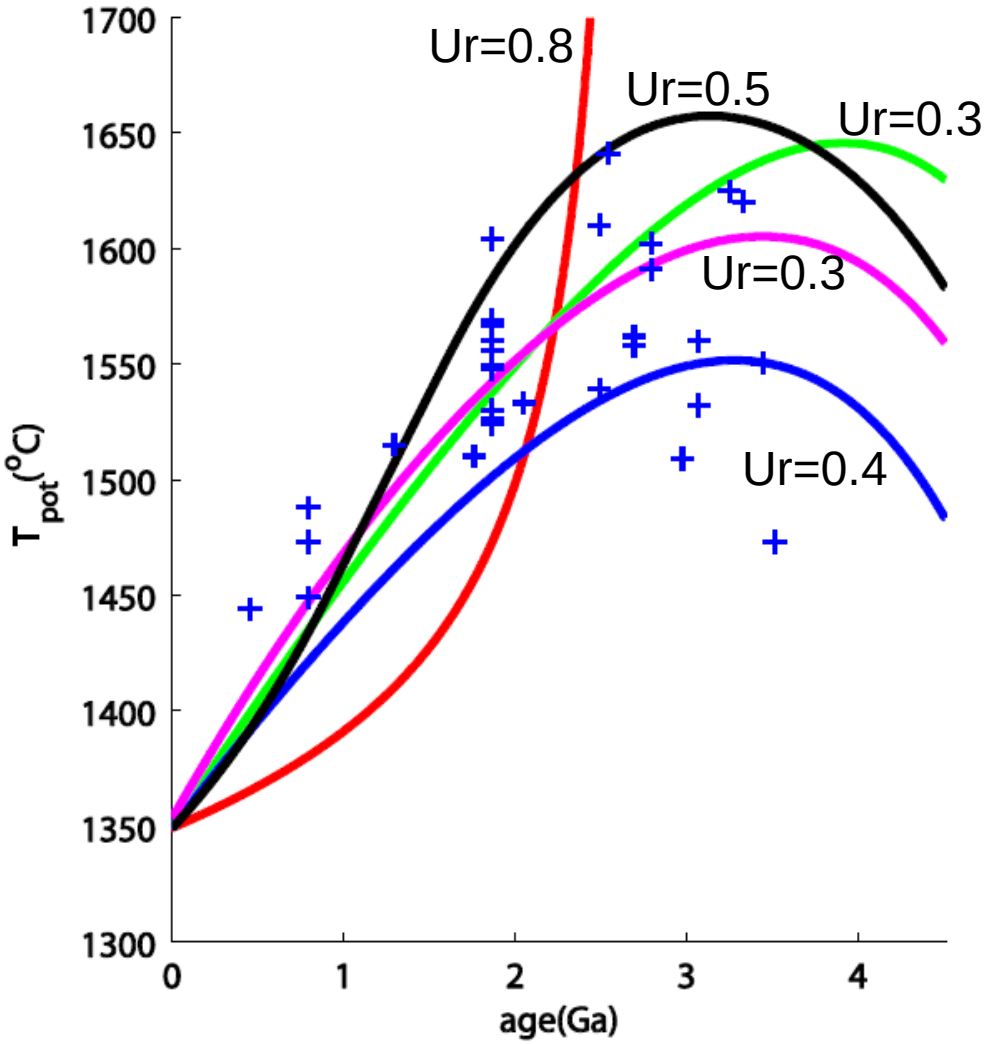
Peak temperature in Archaean?
(Herzberg et al., 2010)

Thermal evolution of the Earth

$$C\frac{dT}{dt} = H - Q$$

Models for heat loss Q:

- constant heat flow
- parameterized convection (convection-limited)
- strong plate (plate-limited)
- Weak, buoyant plate (convection/plate limited)



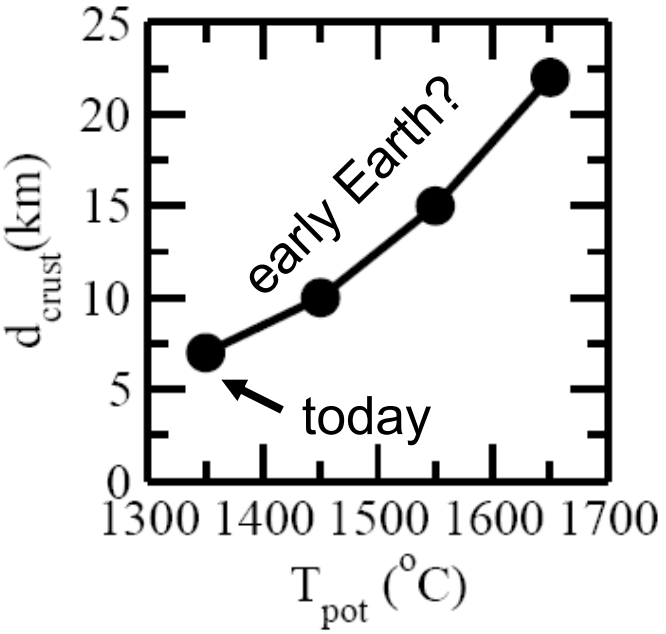
Parameterizations from (Korenaga, 2006; Labrosse & Jaupart, 2007; van Hunen and van den Berg, 2008; Davies, 2009). Data points from (Herzberg et al., 2010)

Consequences of a hotter mantle

1. BUOYANCY:

   More melting at mid-ocean ridges

   - thicker oceanic crust
   - thicker harzburgitic melt residue layer



2. STRENGTH:

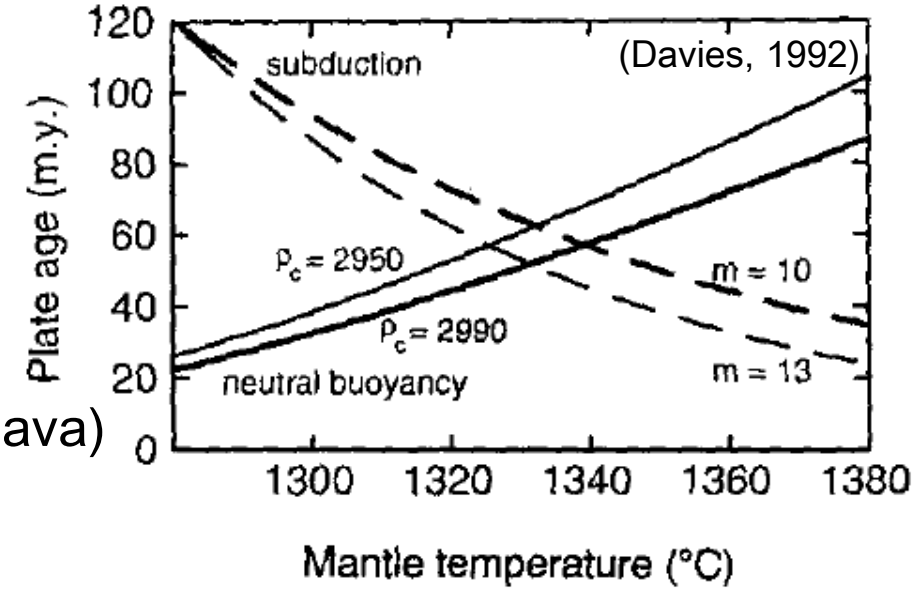
   Weaker plate and mantle material:

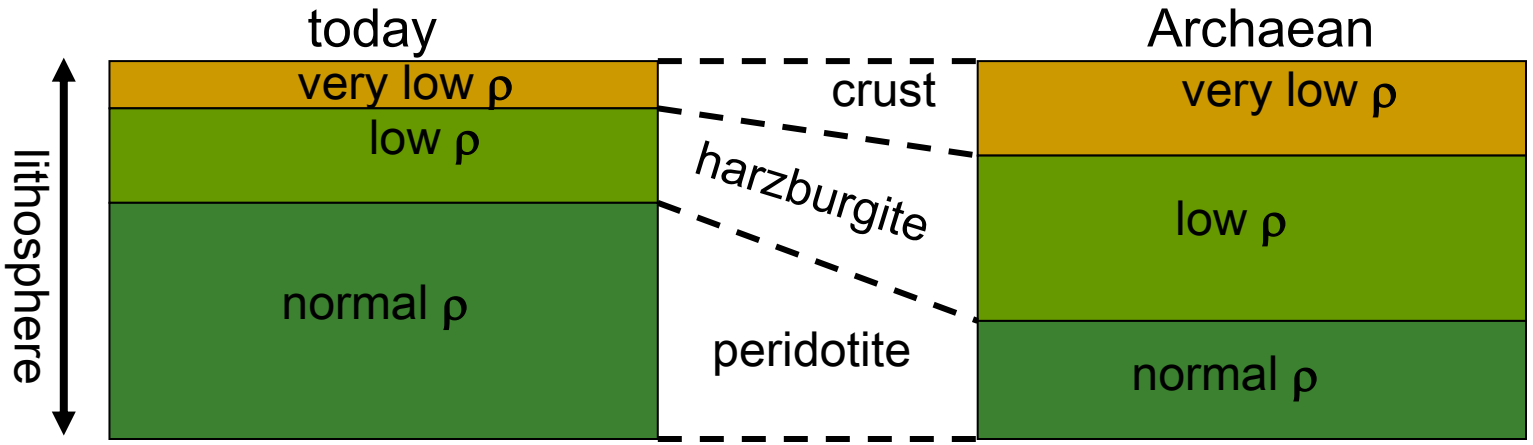
   - η = exp (T)
   - ~1 order of magnitude for every 100 K
   - Effect of dehydration strengthening?

(van Thienen & al., 2004)

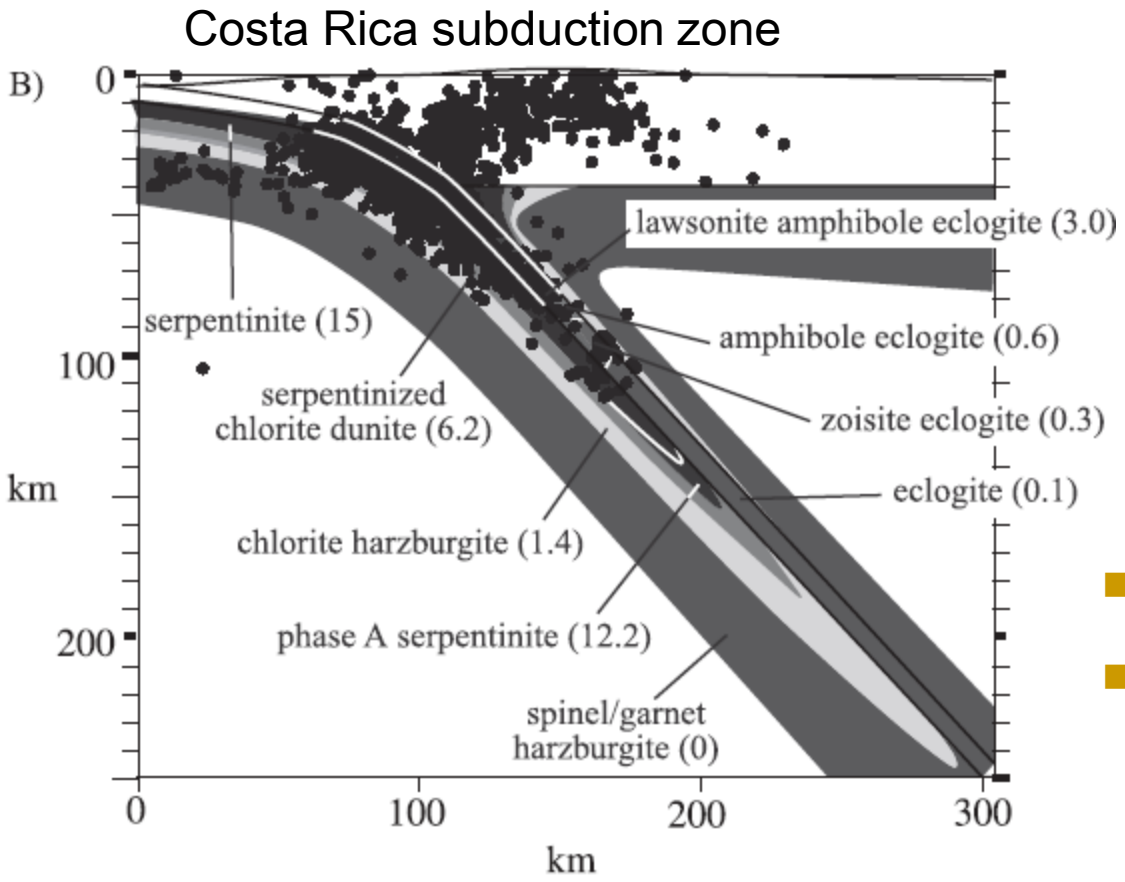
Buoyancy

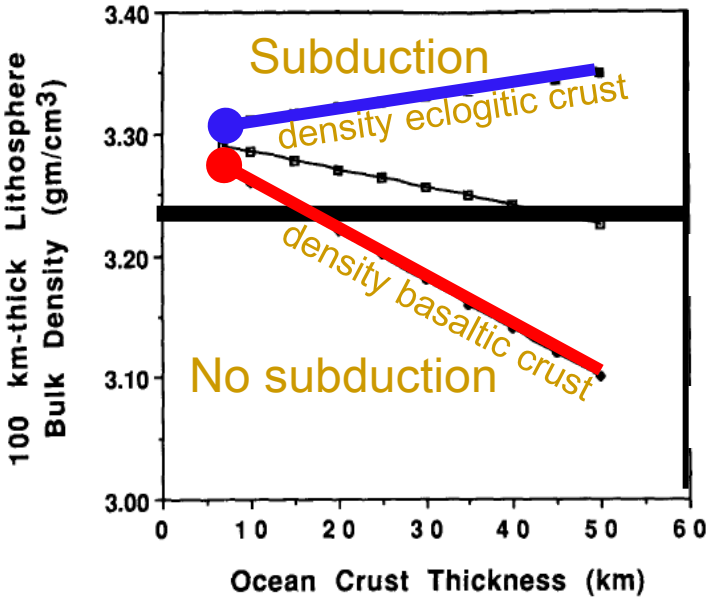
- more melting
- thick crust/residue
- low average density ρ
- no slab pull?
- no subduction? (Ontong Java)
- no plate tectonics?





Effect of basalt-eclogite transition?



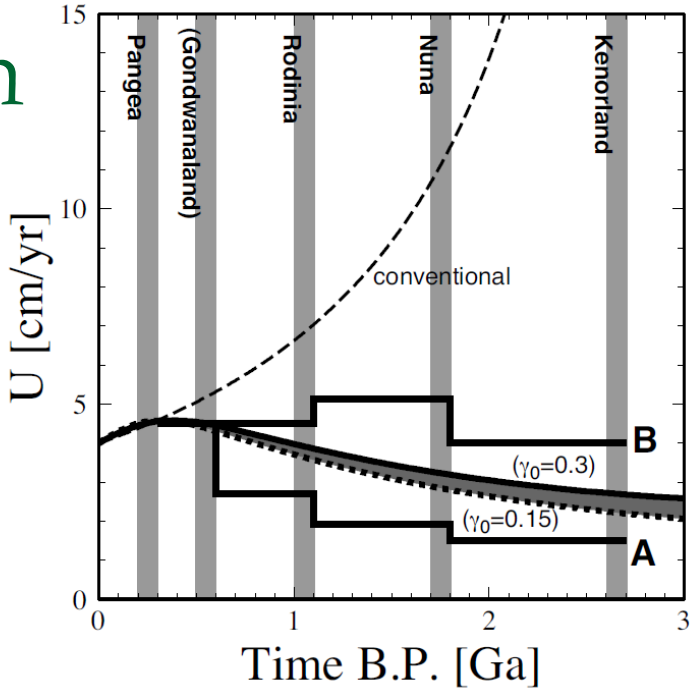


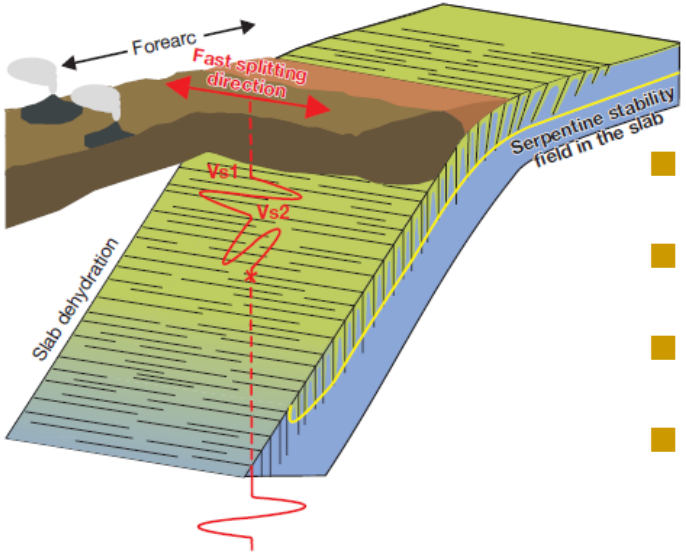
- Meta-stable basalt
- transition gradual

(Cloos, 1993; Hacker, et al., 2003)

Mantle and plate strength

- Depleted residue = dry = strong
- plate bending more difficult?
- slower Archaean plate motion?
- fits with supercontinent ages





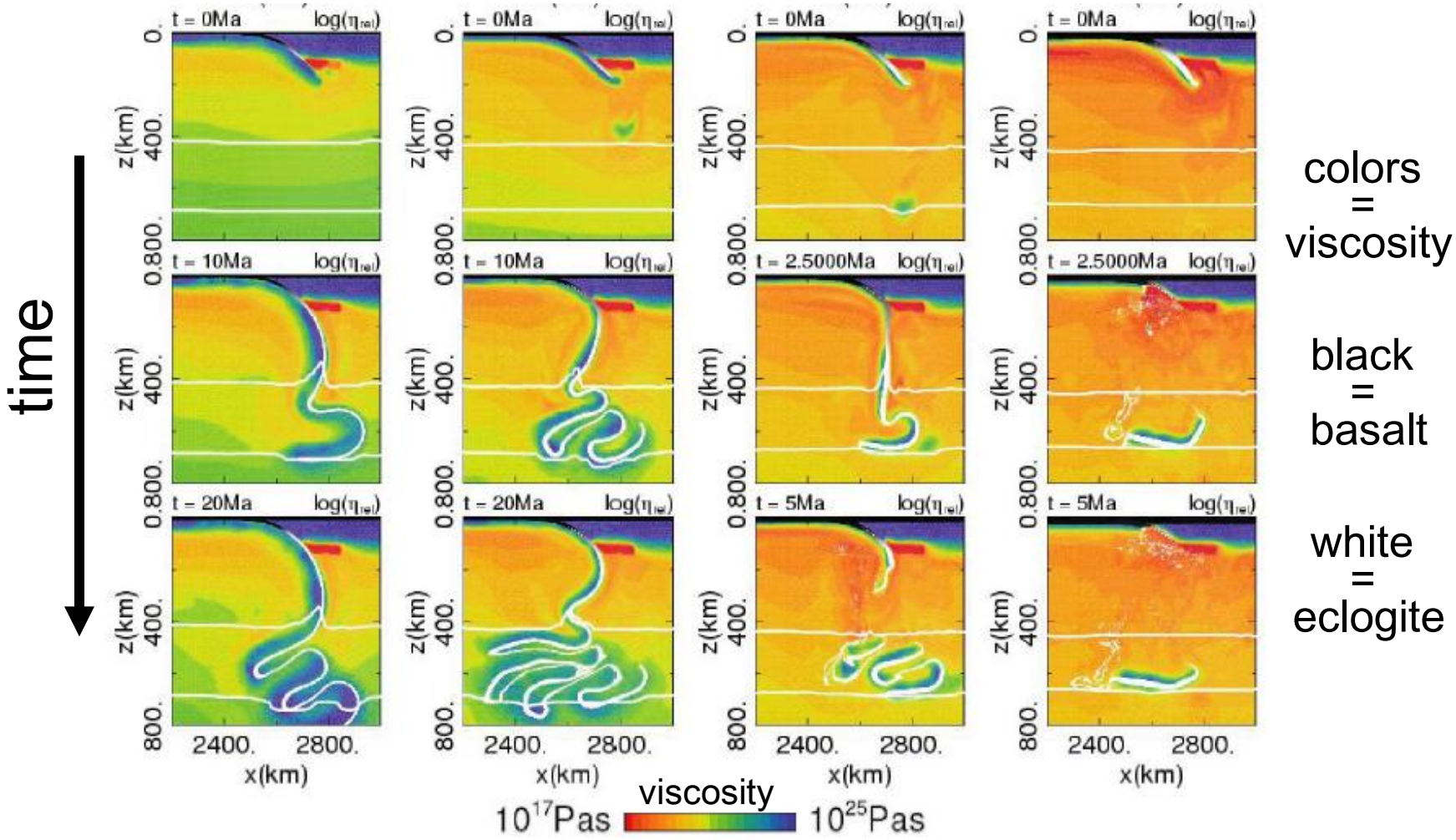
But:

- Before melting mantle isn't 'wet'
- Δ100 K → 1 order weakening
- viscosity $\eta_{crust} < \eta_{mantle}$
- plates bending induces faulting + rehydration

(Faccenda et al., 2008)

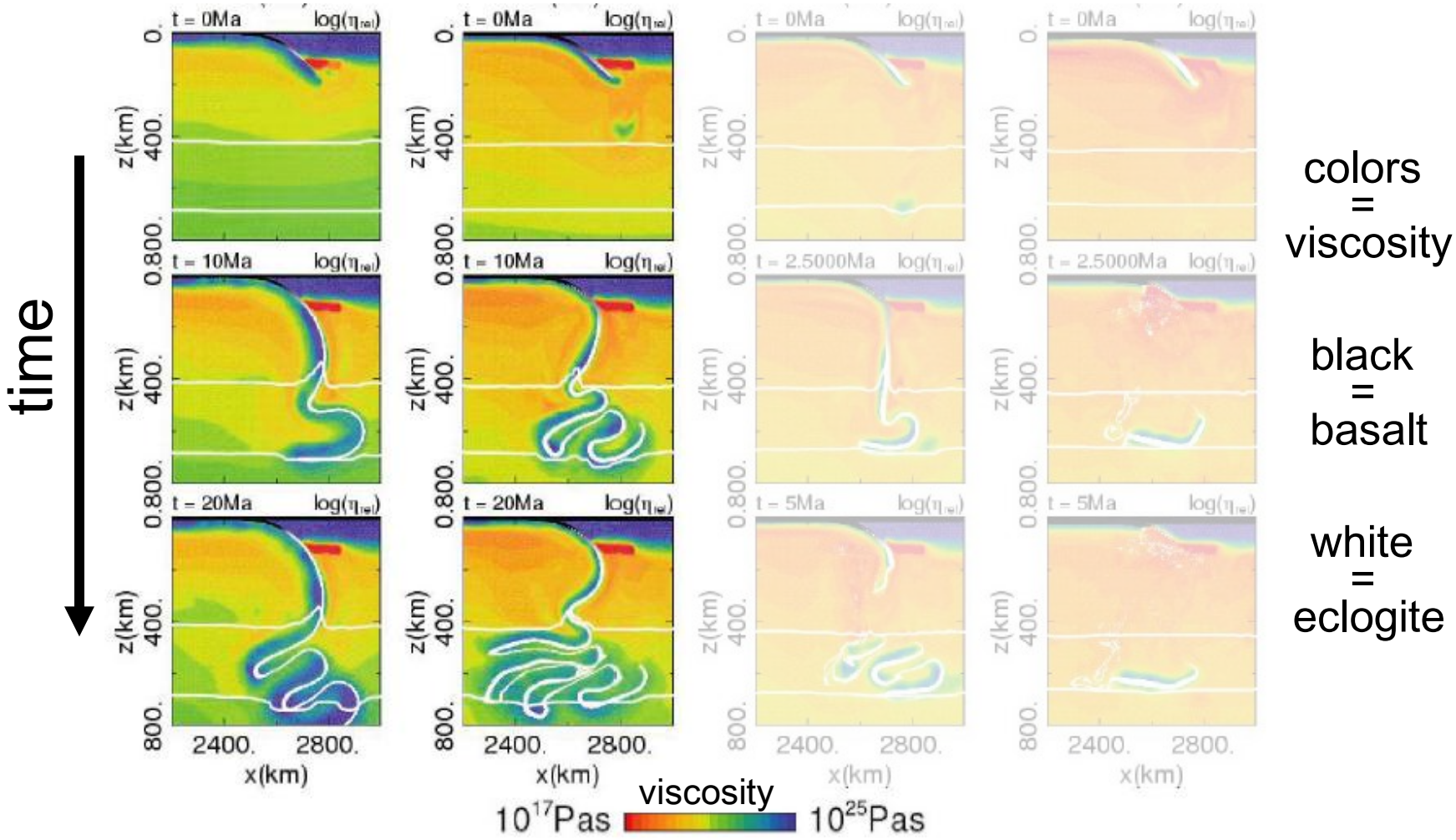
(Korenaga, 2006)

Geodynamical models



(van Hunen & van den Berg, 2008)

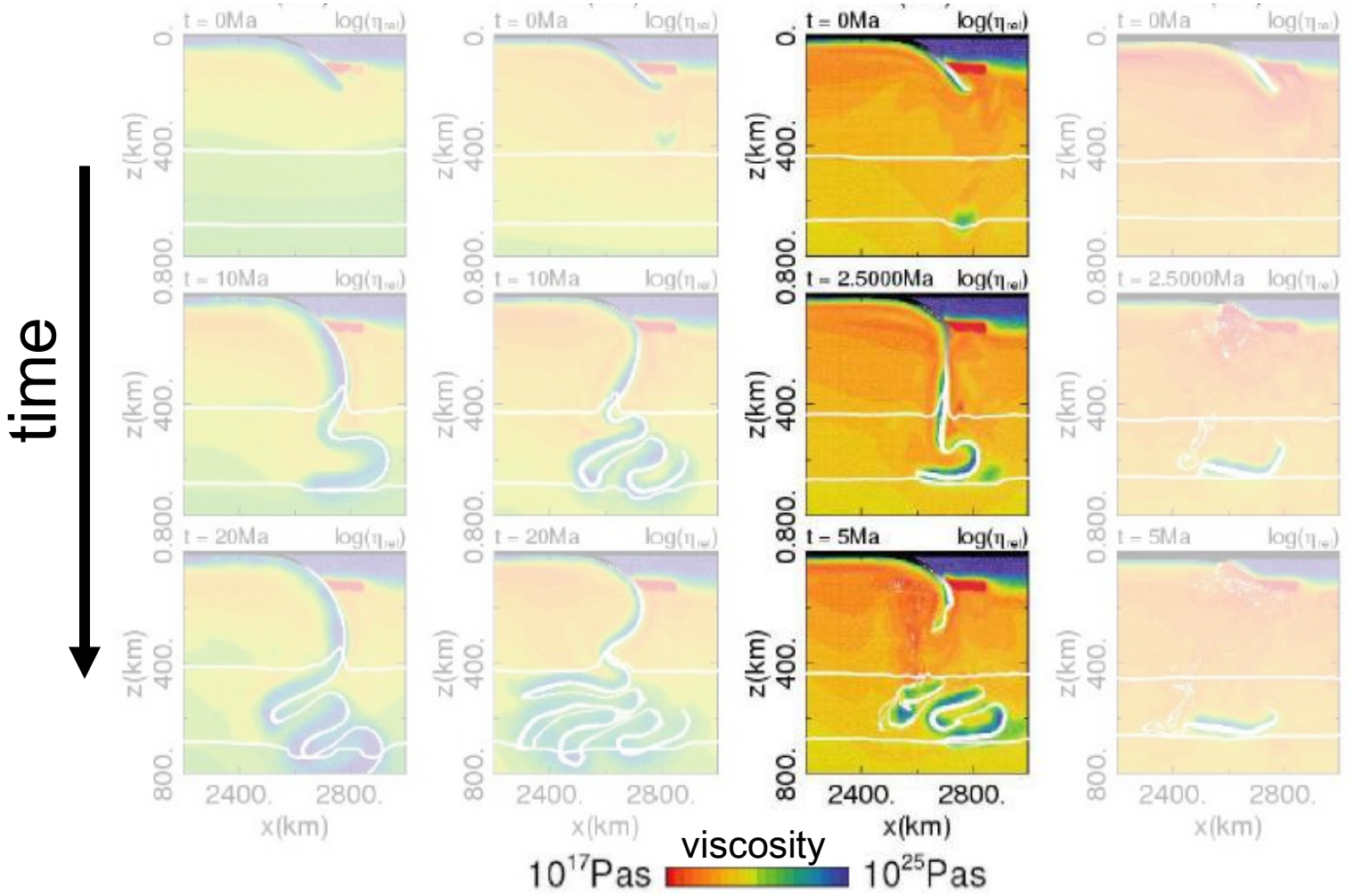
Geodynamical models



- For low T_{mantle} subduction looks like today's

(van Hunen & van den Berg, 2008)

Geodynamical models



colors = viscosity

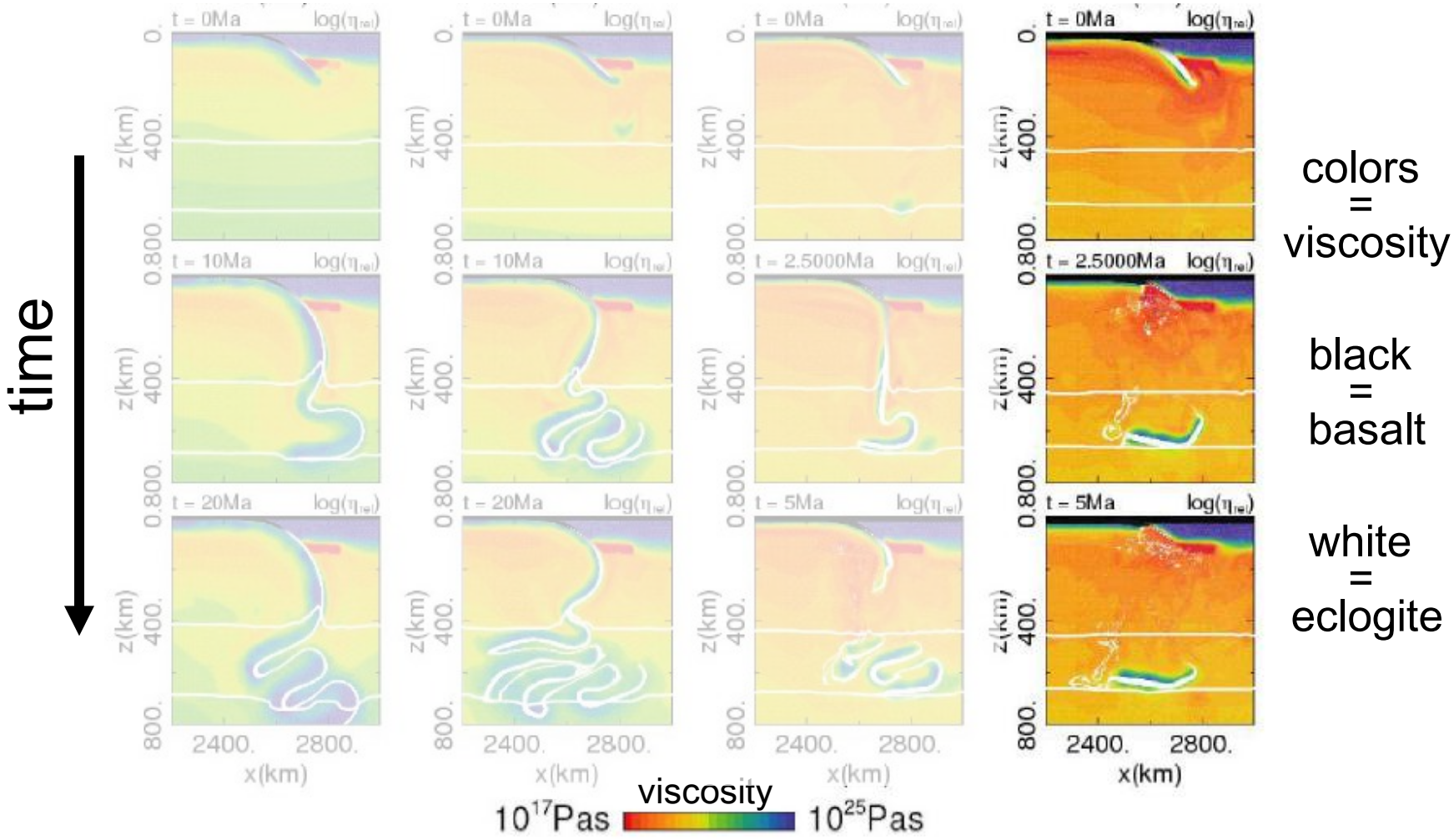
black = basalt

white = eclogite

- For higher T_{mantle} frequent slab break-off occurs …

(van Hunen & van den Berg, 2008)

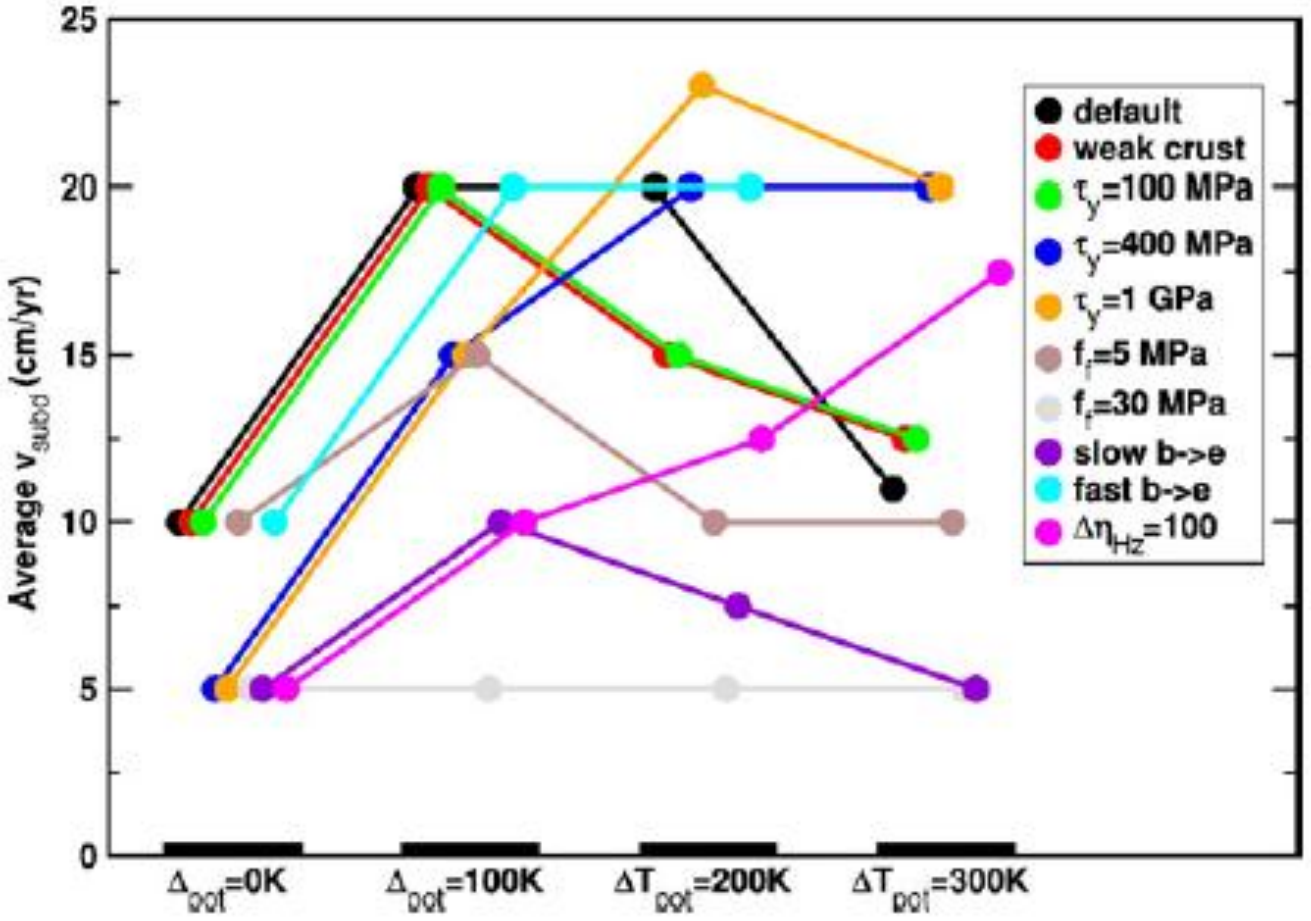
Geodynamical models



- … or subduction completely stops.

(van Hunen & van den Berg, 2008)

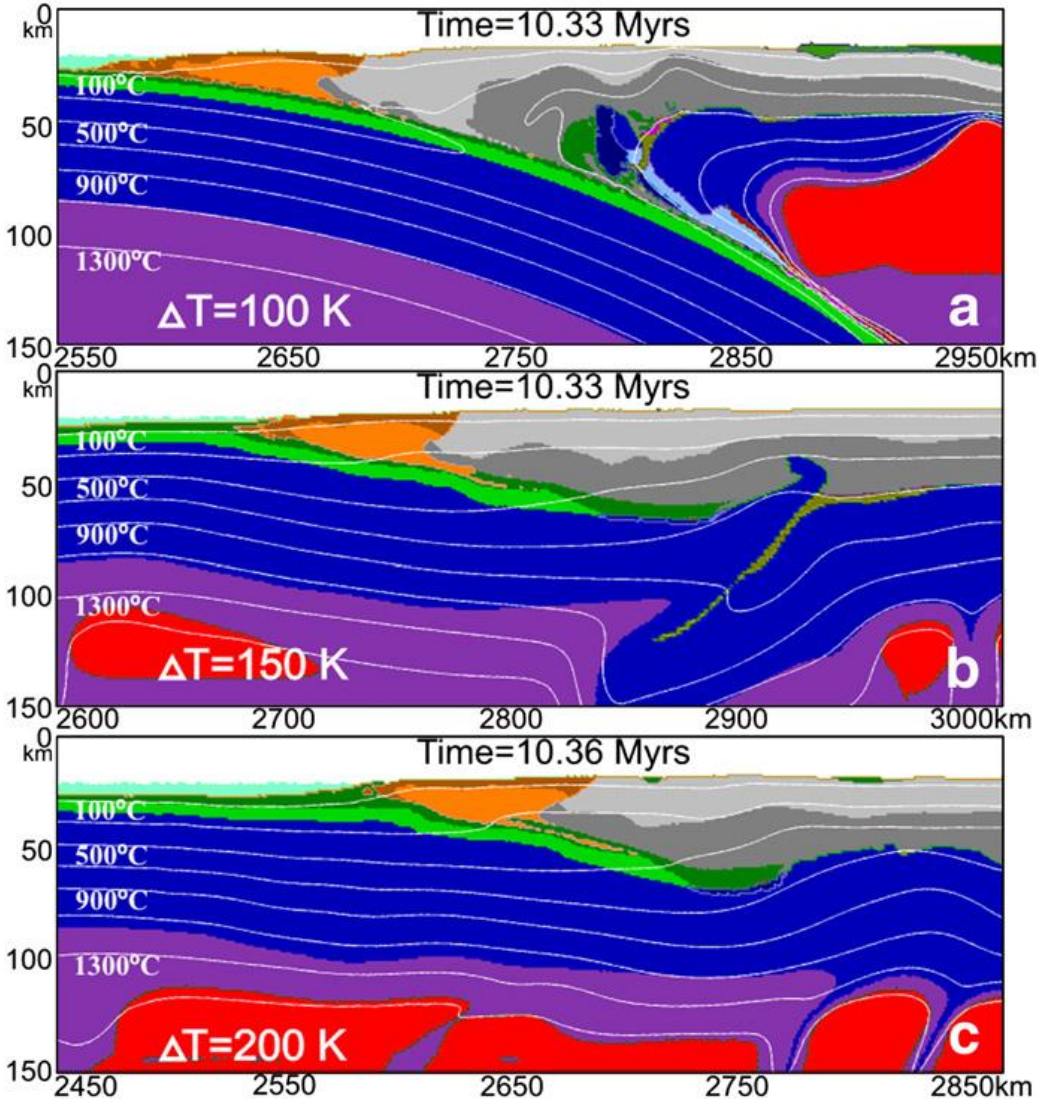
Uncertainty in models



(van Hunen & van den Berg, 2008)

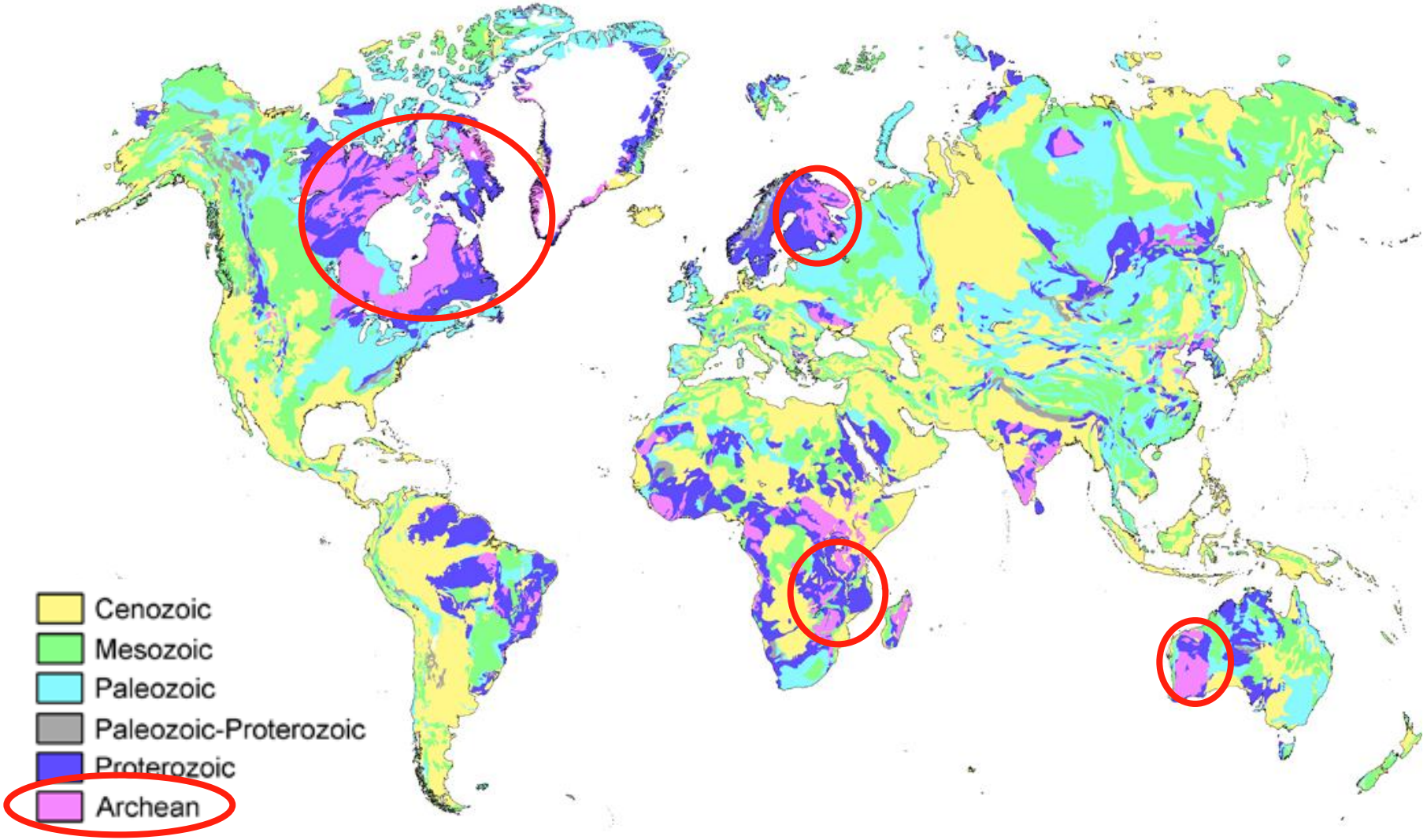
Geodynamical models

- modern subduction
- ‘pre-subduction’
- No subduction

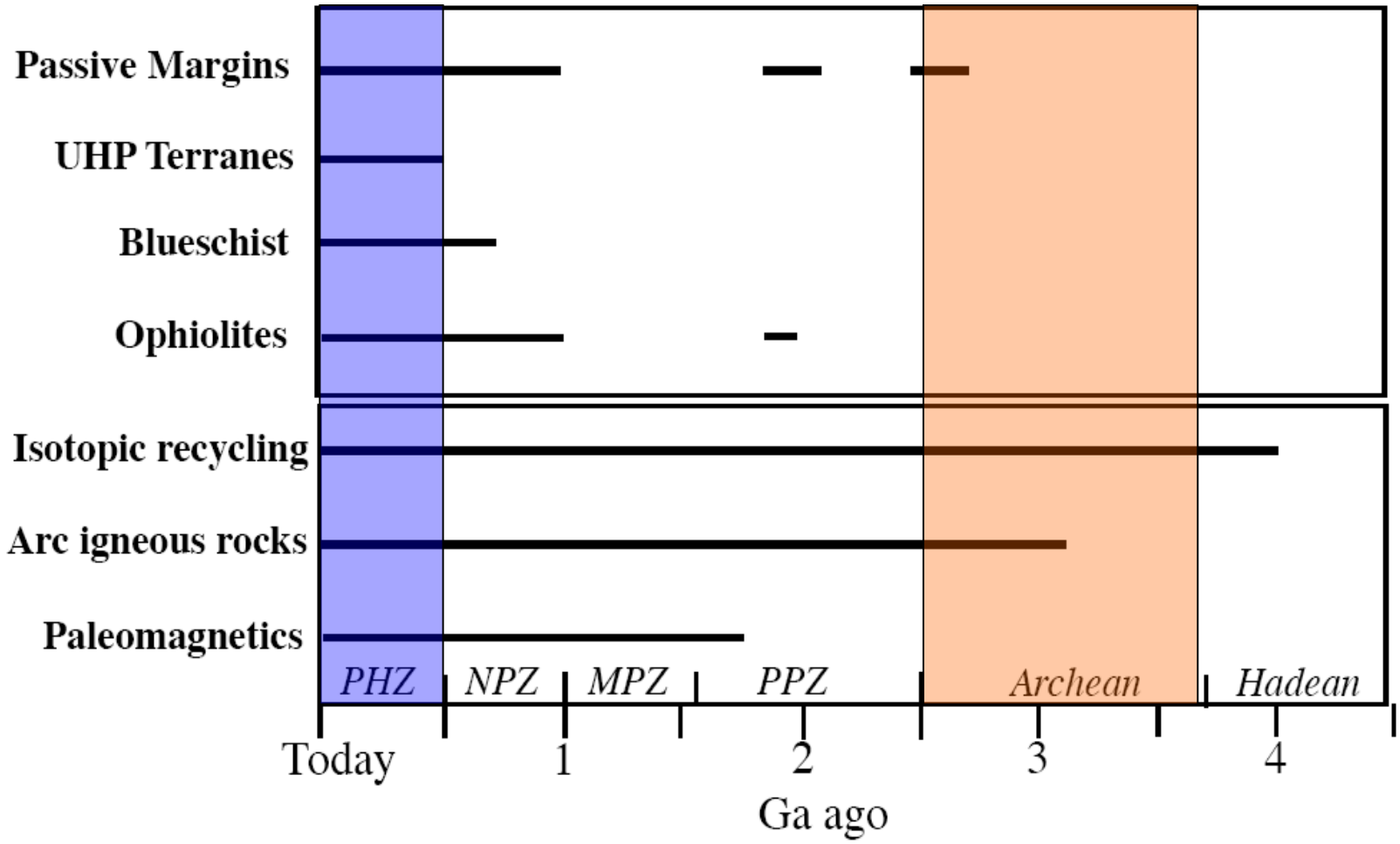


(Sizova et al., 2010)

Observations: Archaean terranes



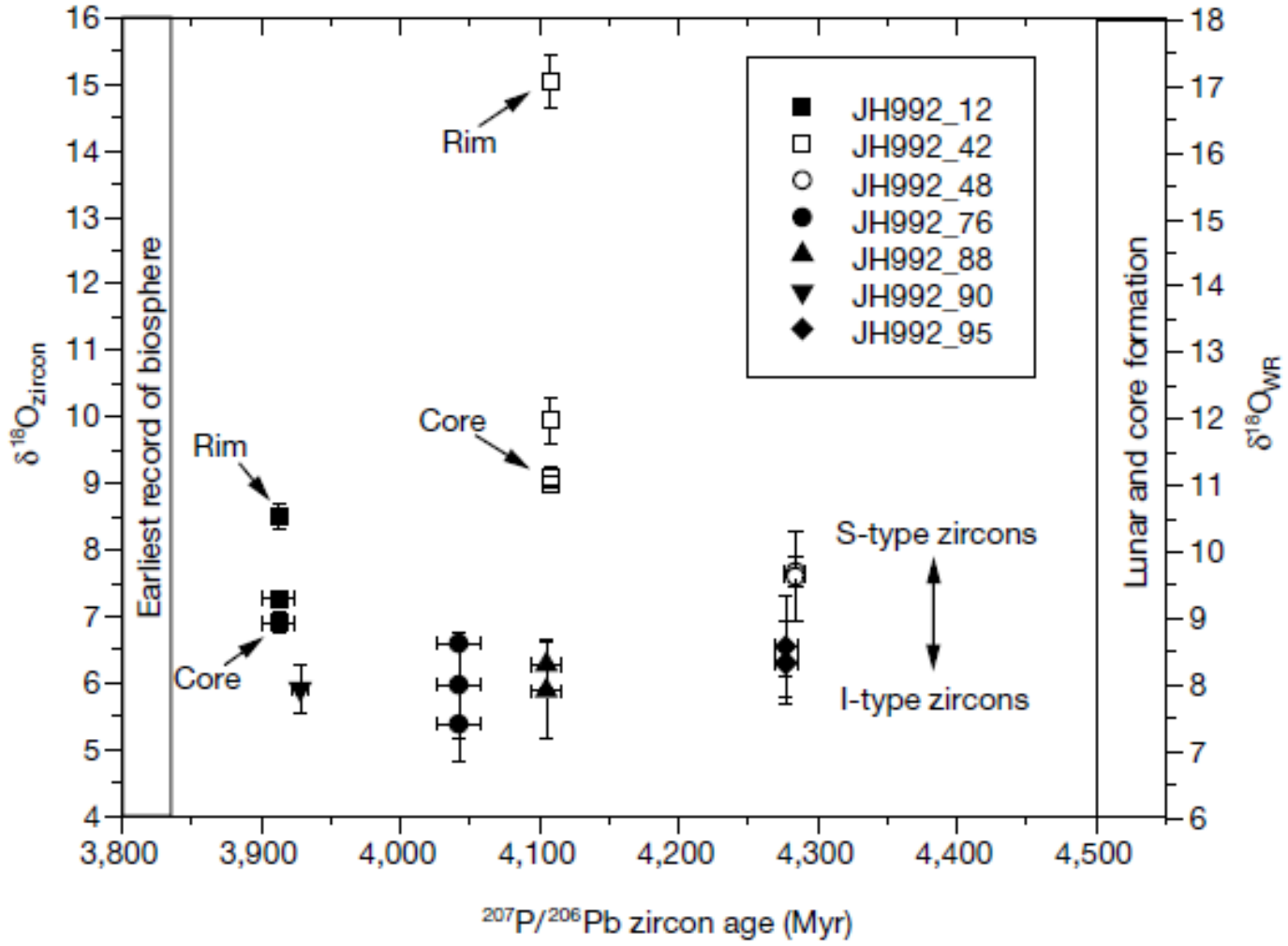
Key characteristics of plate tectonics?



No subduction in Precambrian?

(Stern, 2008)

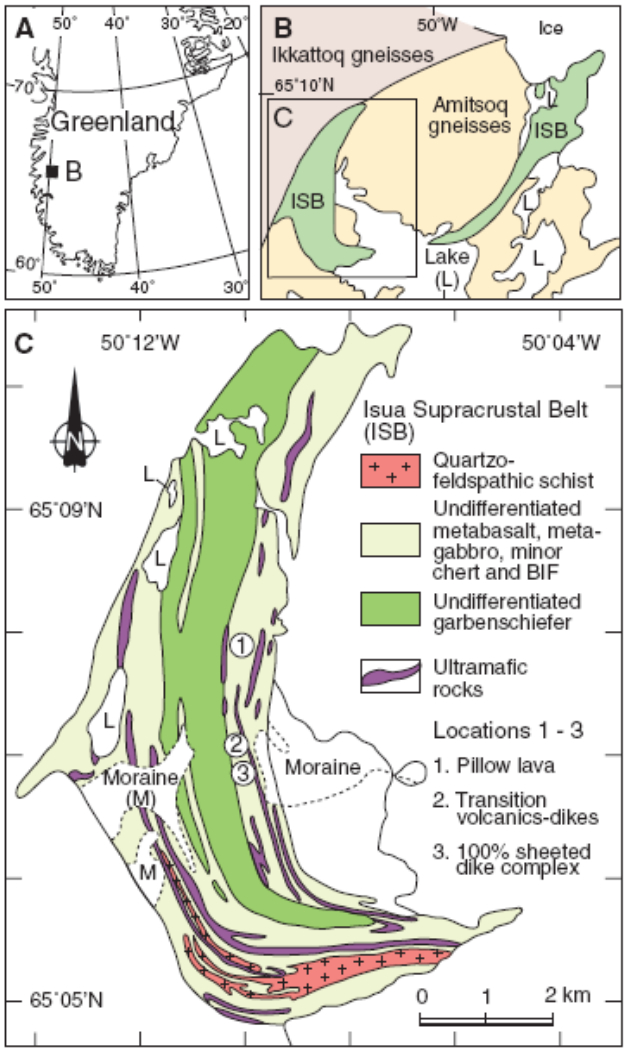
Zircons: recycled crust at ~4.3 Ga



(Mojzsis et al., 2001)

Oldest ophiolites

- Oldest ophiolite 3.7 Gyrs old?
- Oldest generally accepted ophiolites are ~2 Gyrs old (Jormua, Finland; Purtuniq, Canada)
- Ophiolites become wide-spread after 1.0 Gyrs ago

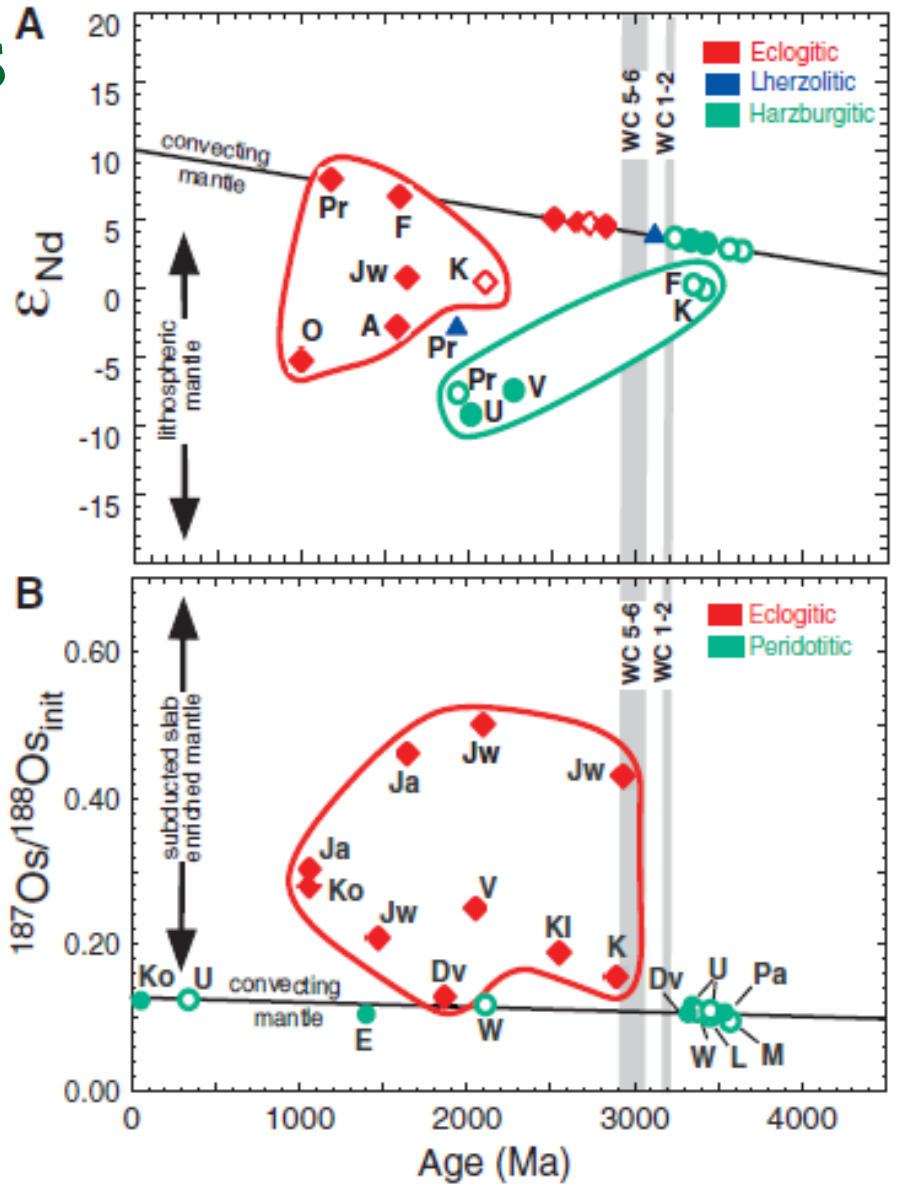


(Stern, 2005; Furnes et al., 2007)

Diamond inclusions

- > 3 Ga: peridotitic
- < 3Ga: eclogitic + peridotitic

→ Plate tectonics started ~ 3Ga

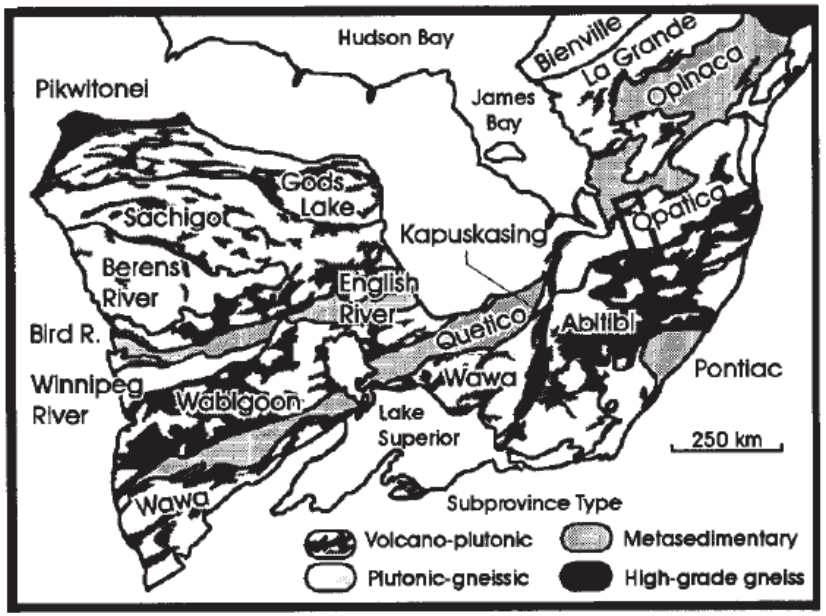


(Shirey & Richardson, 2011)

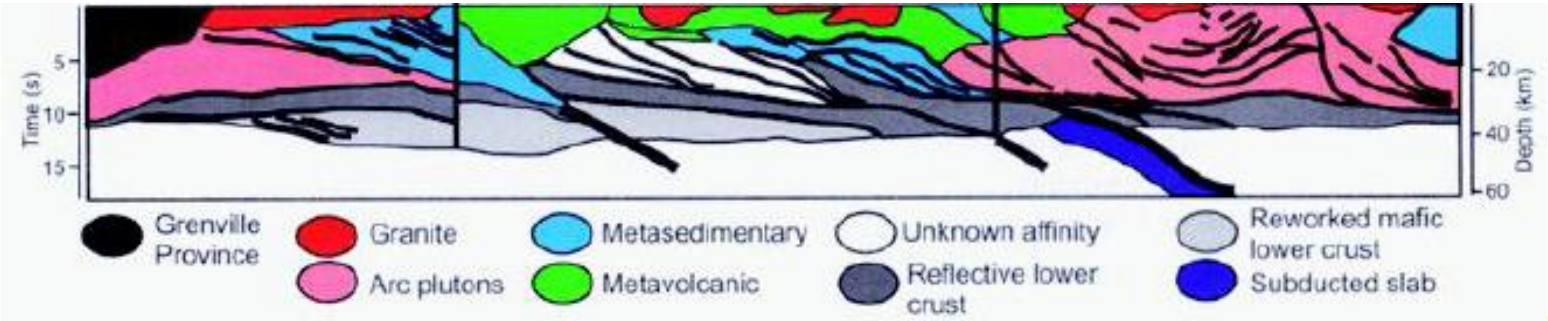
Structural observations

- Accreted terranes
- Low-angle reflectors

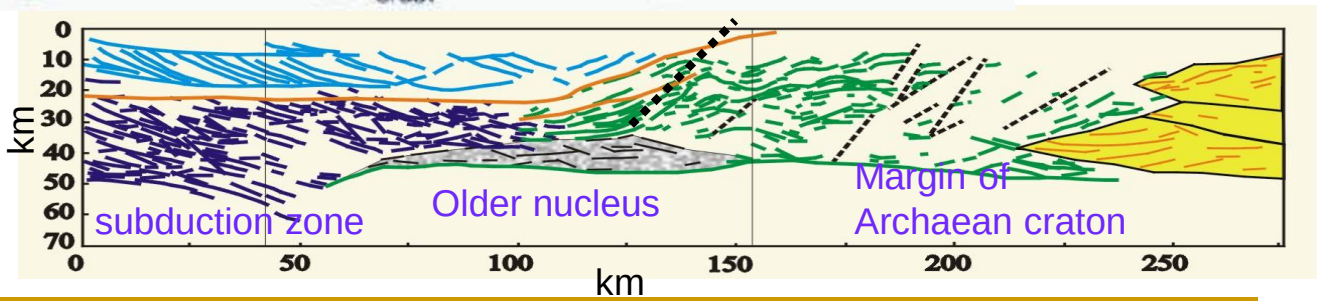
→ fossil subduction?



Superior Province



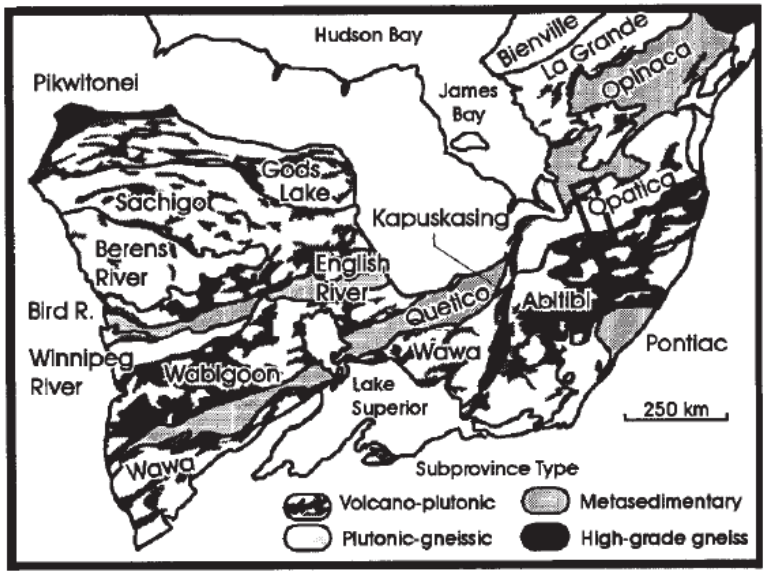
Fennoscandian Shield



(Calvert et al., 1995; Korja & Heikkinen, 2008; Benn & Moyen, 2008)

Linear features?

Abitibi, Superior Province



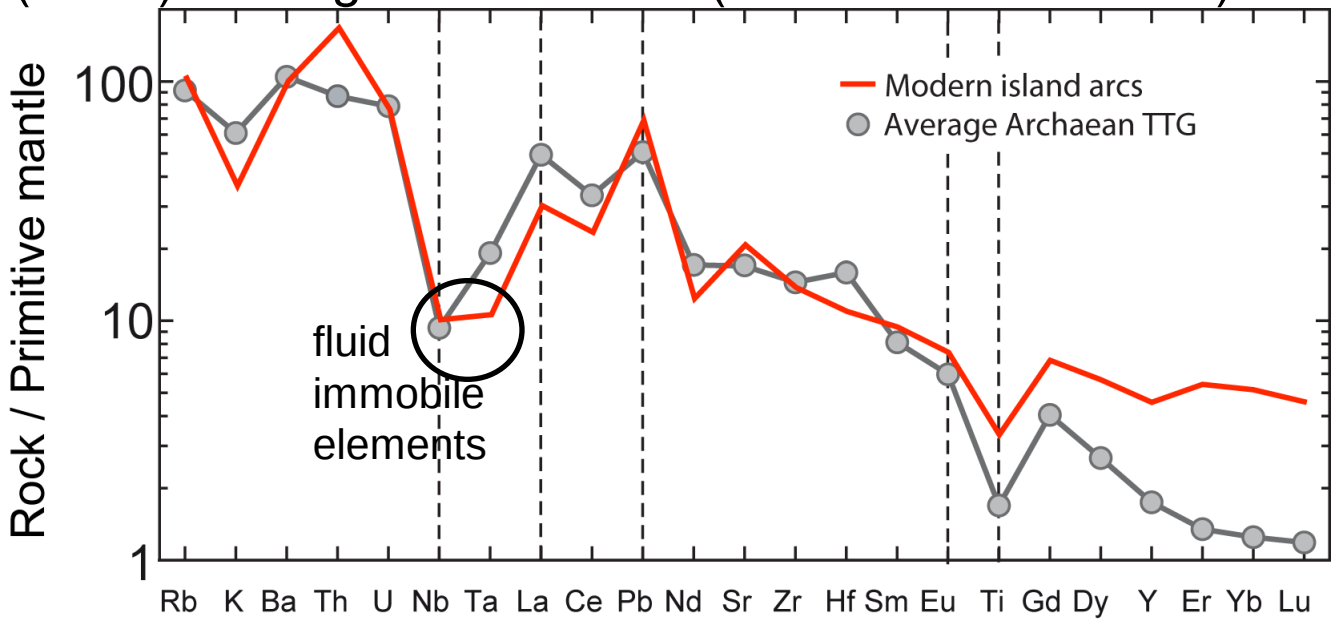
E-Pilbara, Australia

(Calvert et al., 1995, JF Moyen, pers.comm.)

Geochemical 'arc' signature

Bulk continental crust:

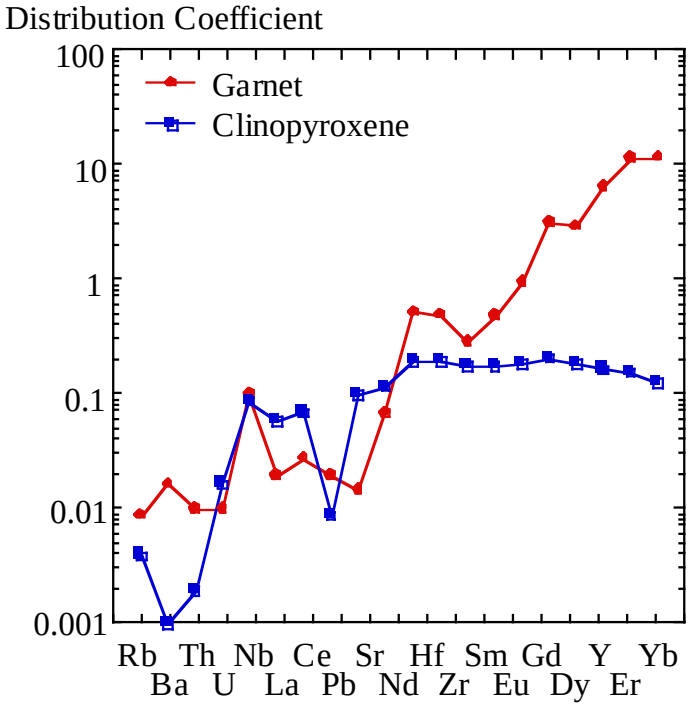
- Today: andesites
  - Formed in subduction zone
  - Mantle wedge hydration and -melting
- Archaean: tonalite-trondhjemite-granodiorite (TTGs)
  - (slab?) melting of mafic crust (like modern adakites)

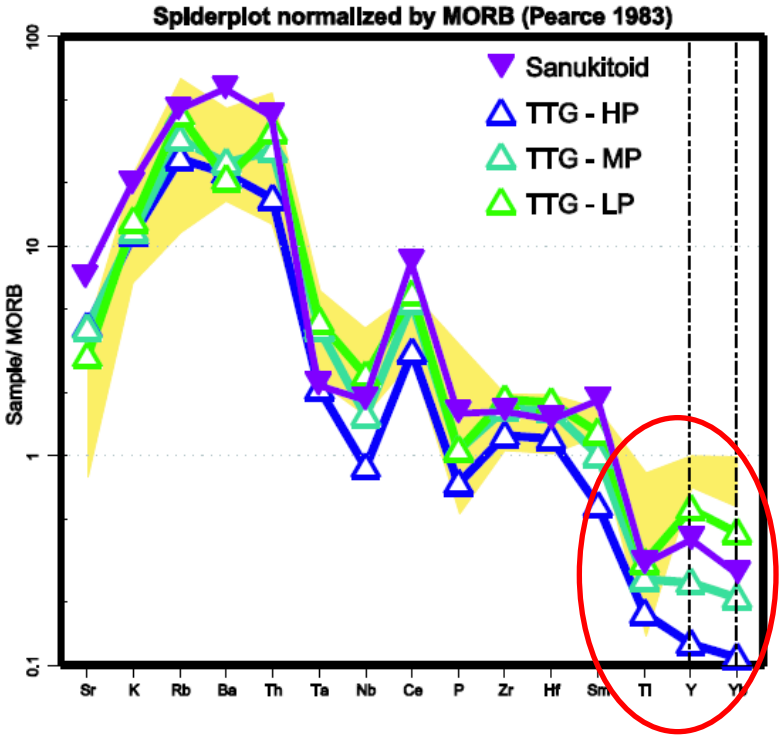


(Defant and Drummond, 1993; JF Moyen, pers.comm.)

Different types of TTGs

- HREE depletion indicates garnet in source.
- HP-TTG requires >18-20 kbar or >60 km.



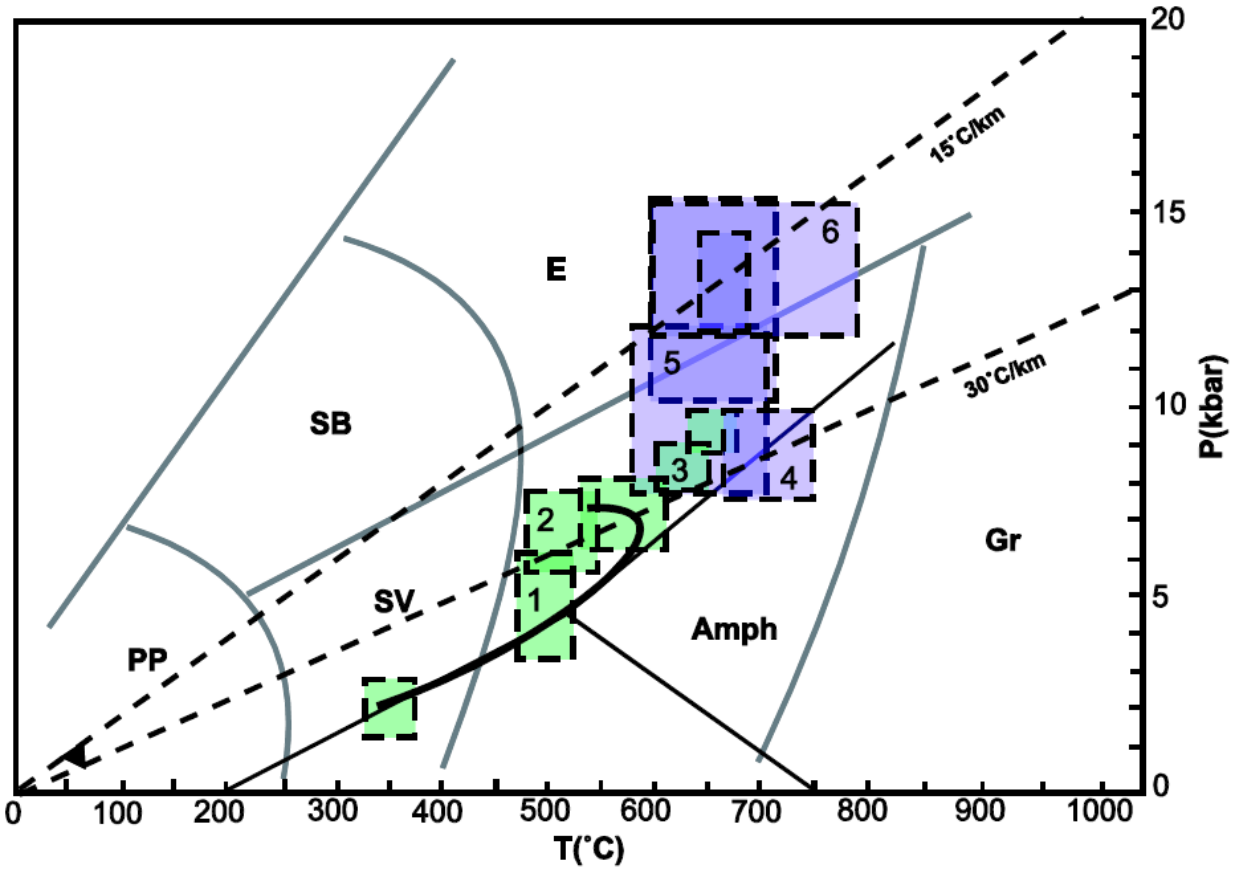


HREE depletion

(Rick Carlson, pers.comm.; Moyen et al., 2011)

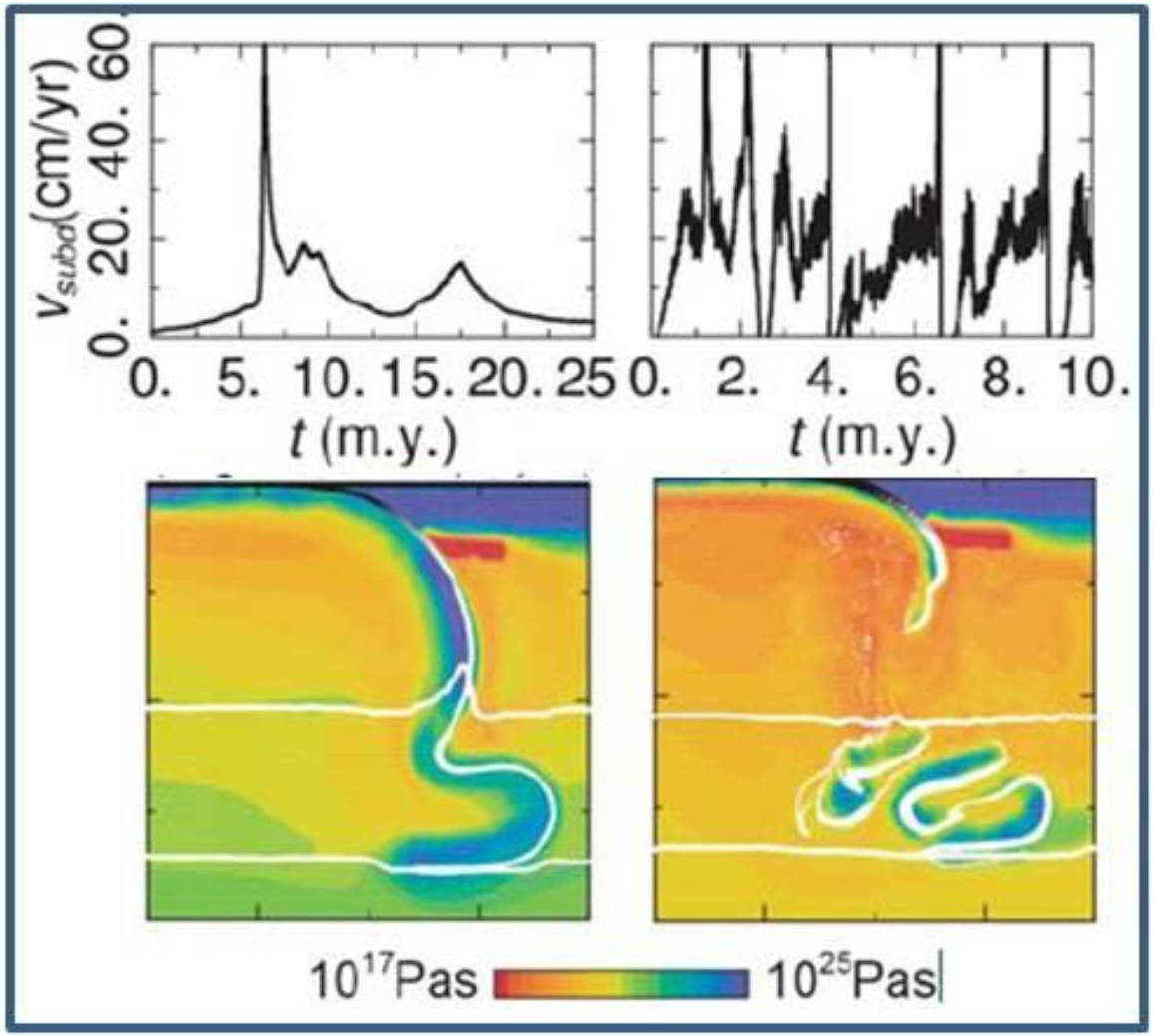
Subduction zone metamorphism

- low dT/dp – high dT/dp pairs typical for subduction
- Modern low dT/dp=5-8 K/km absent in Archaean
- But paired belts occur, shifted to higher geotherms.



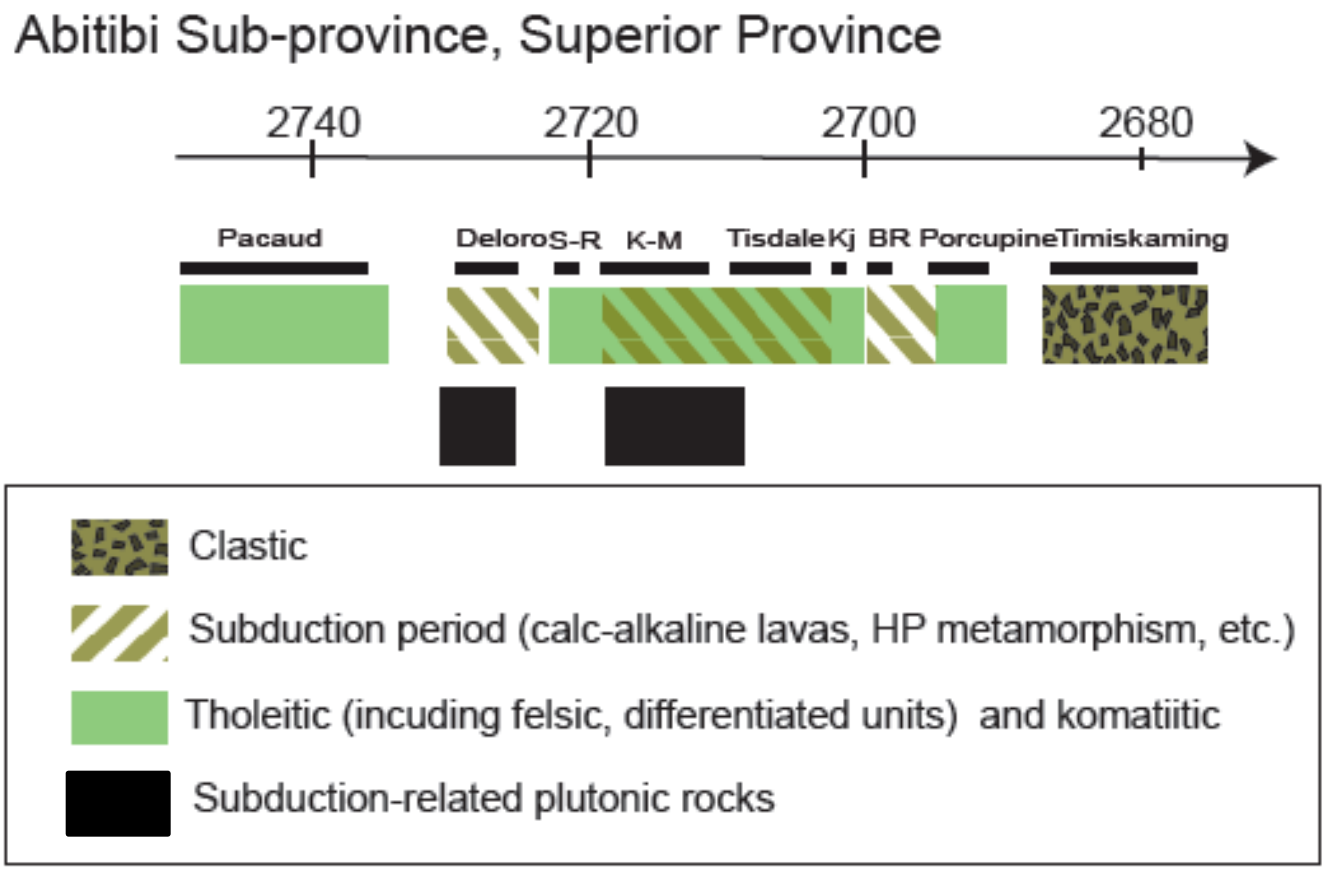
(plot courtesy of Gautier Nicoli; data from Stevens & Moyen, 2007; Lana et al., 2010; Saha et al., subm.)

Short-term episodicity in subduction?



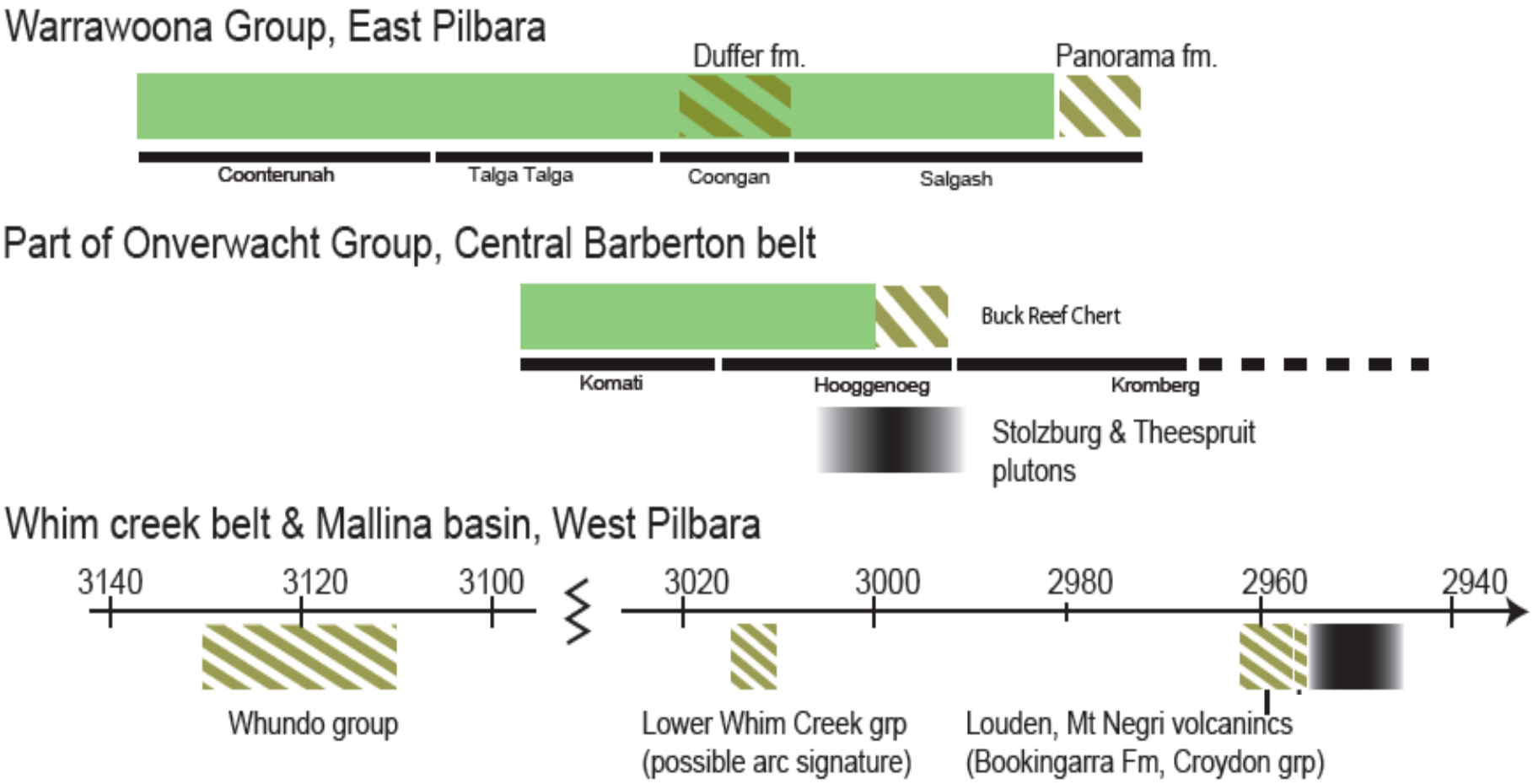
(van Hunen & van den Berg, 2008)

Episodic subduction in W-Abitibi?



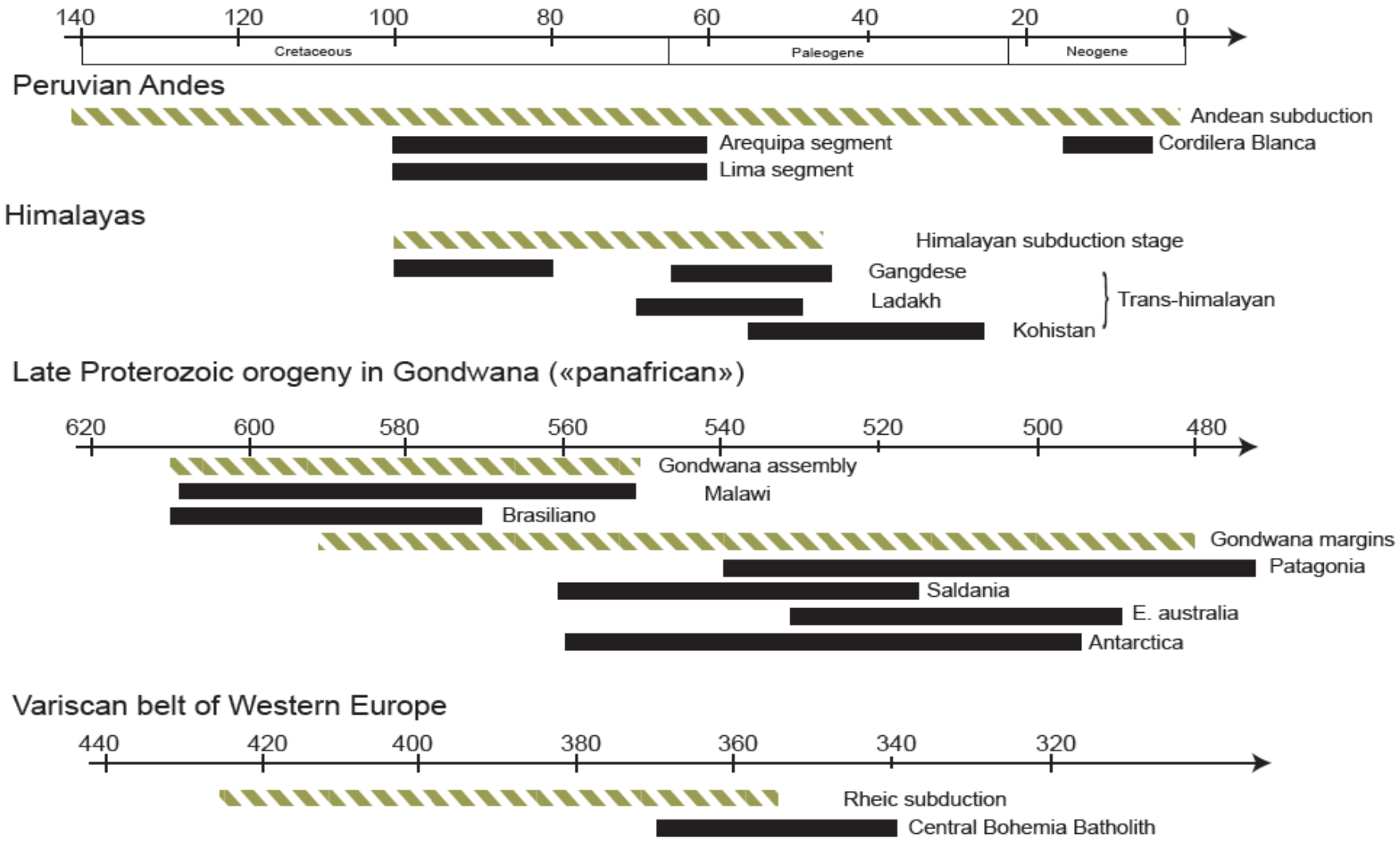
(Moyen and van Hunen, 2012)

Other Archaean provinces?



(Moyen and van Hunen, in prep.)

L.-Proterozoic/Phanerozoic subduction



Concluding remarks

Subduction evolution:

- Thermal evolution constrains surface tectonics
- Modern-style subduction viable for $\Delta T<200K$,
- perhaps not in hotter mantle
- Subduction recognized in rock record?:
  - Zircons (Hadean)
  - Ophiolites (Neo-Archean)
  - Structural geology / seismics (Neo-Archean)
  - Geochemistry of TTG (Archean)
- Potential changes in subduction style:
  - Episodic on Ma timescale?