The dynamics of subduction throughout the Earth's history

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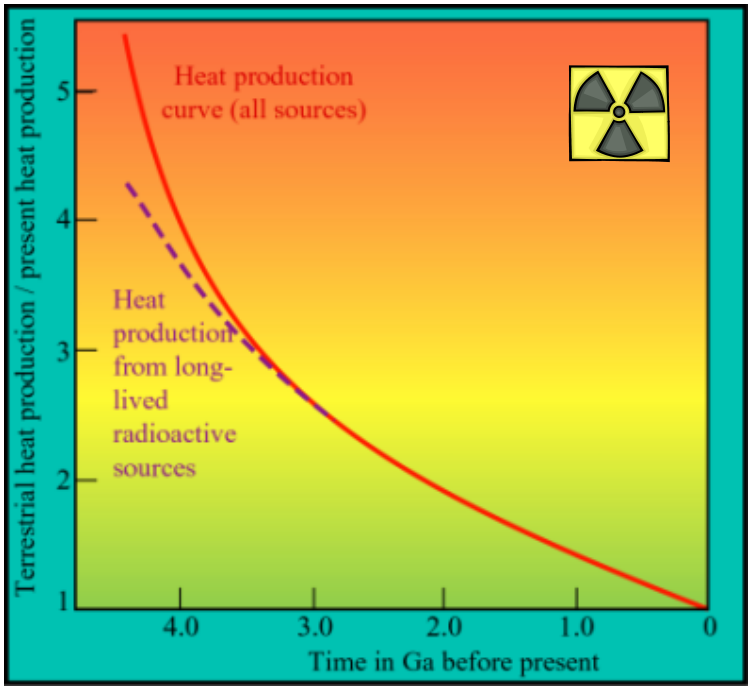
Jon Davidson (Durham)
Arie van den Berg (Utrecht)
Nico Vlaar (Utrecht)

In this talk

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

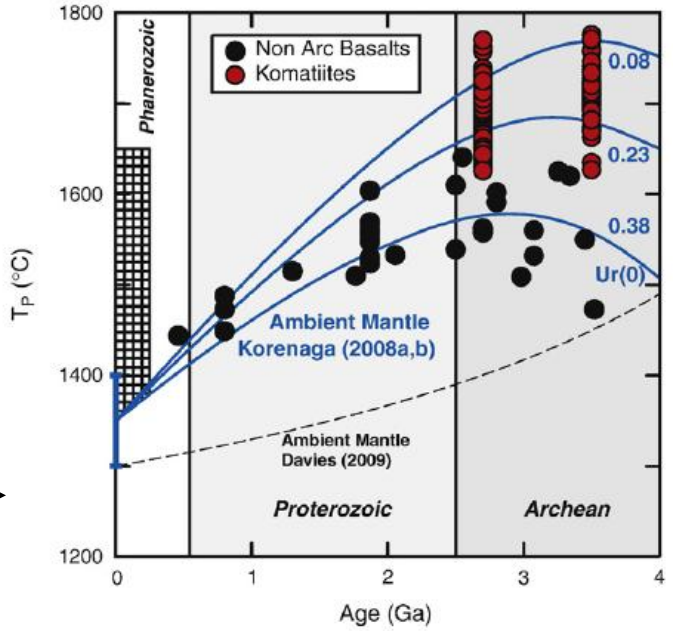
Dynamics of Archaean subduction

How was Earth different in the past?



1) Produced 3x as much radiogenic heat ←

2) was 100-300 K hotter →

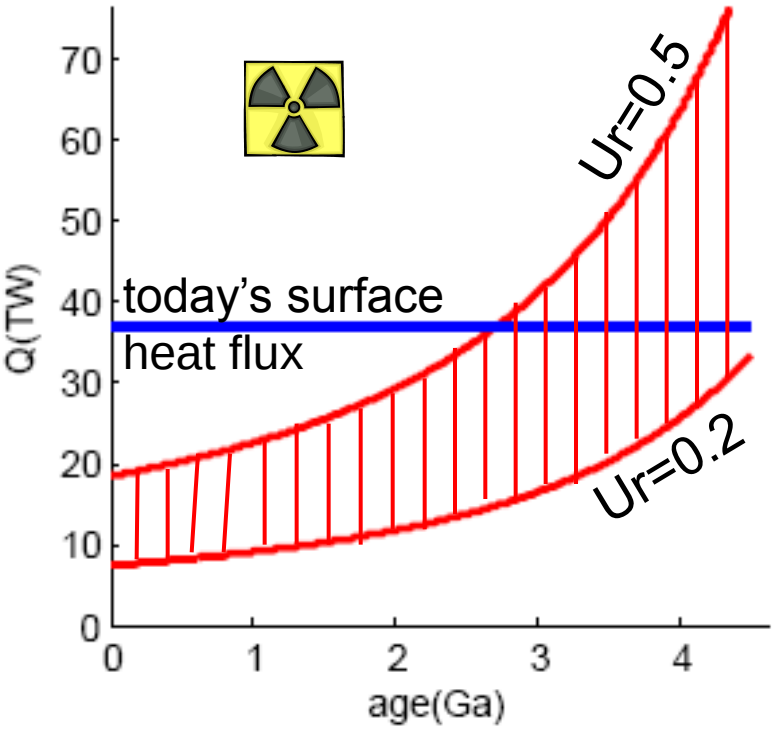


(Herzberg et al., 2010)

Consequences of more radiogenic heat

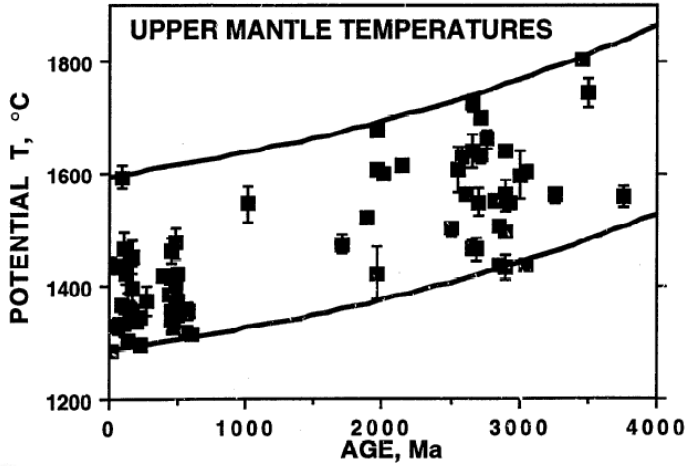
- Today's surface heat flux Q = 36 TS or 80 mW/m^2:
  - 20-50% ('Urey ratio', Ur) from H = radiogenic heat
  - rest = Earth cooling
- Cooling Archaean Earth?

  → more efficient mechanism than modern plate tectonics

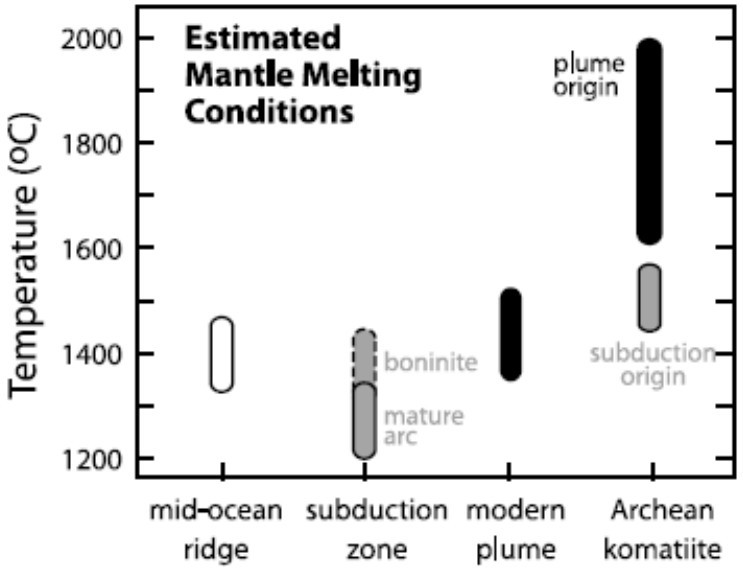


(Sleep, 2000; Turcotte and Schubert, 2002)

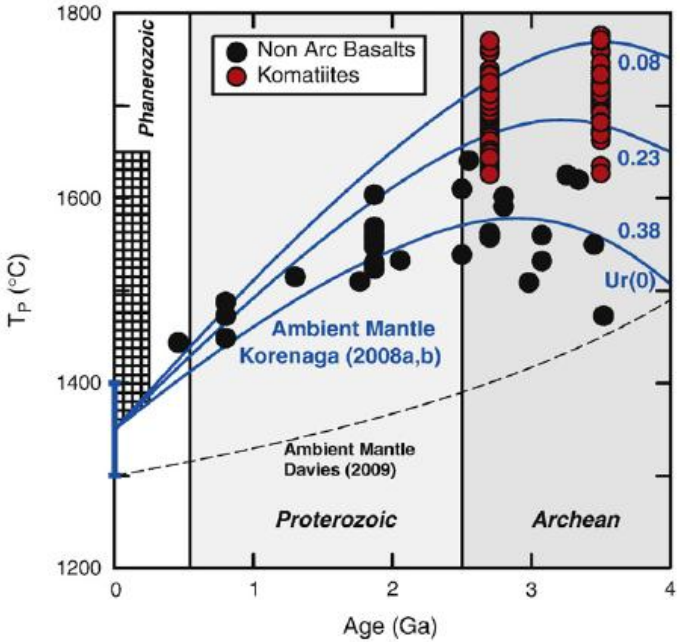
Archaean mantle was 100-300 K hotter



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



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



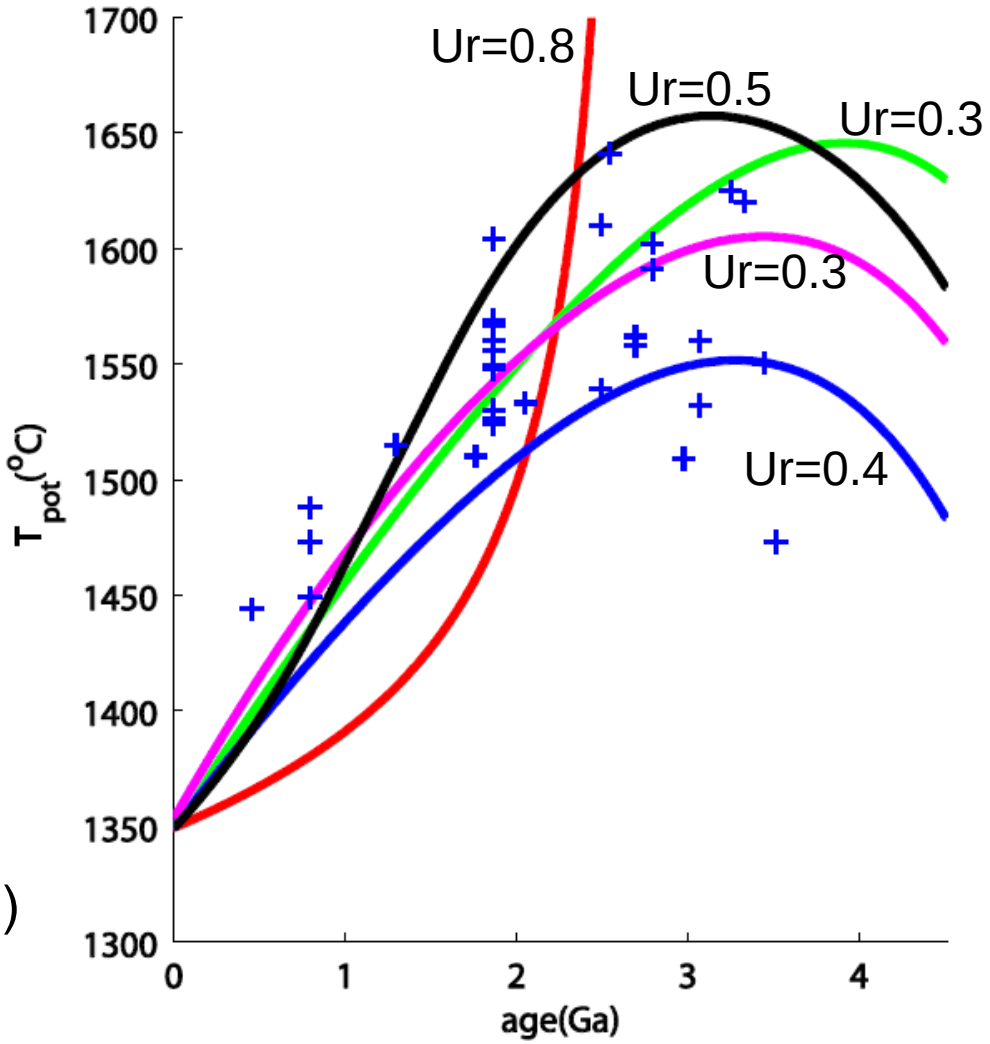
Peak temperature in Archaean? (Herzberg et al., 2010)

Thermal evolution of the Earth

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

Models for Q:

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



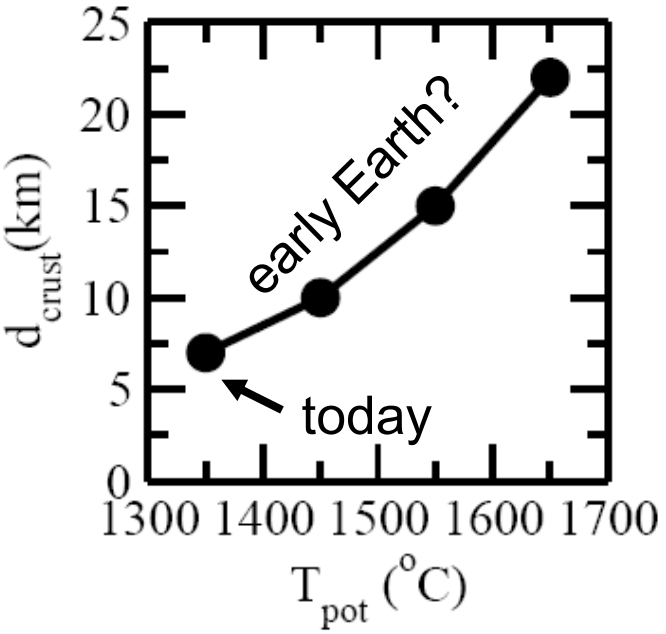
Parameterizations from (Korenaga, 2006; Labrosse & Jaupart, 2007; van Hunen and van den Berg, 2008; Davies, 2009). Data points from (Herzberg et al., 2010)

Consequences of a hotter mantle

1. BUOYANCY:

   More melting at mid-ocean ridges

   - thicker oceanic crust
   - thicker harzburgitic melt residue layer



2. STRENGTH:

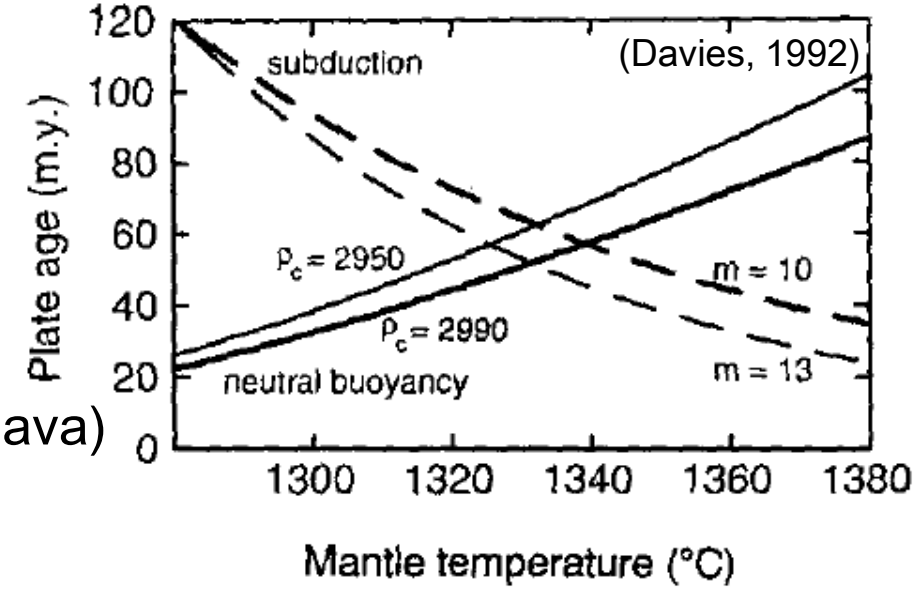
   Weaker plate and mantle material:

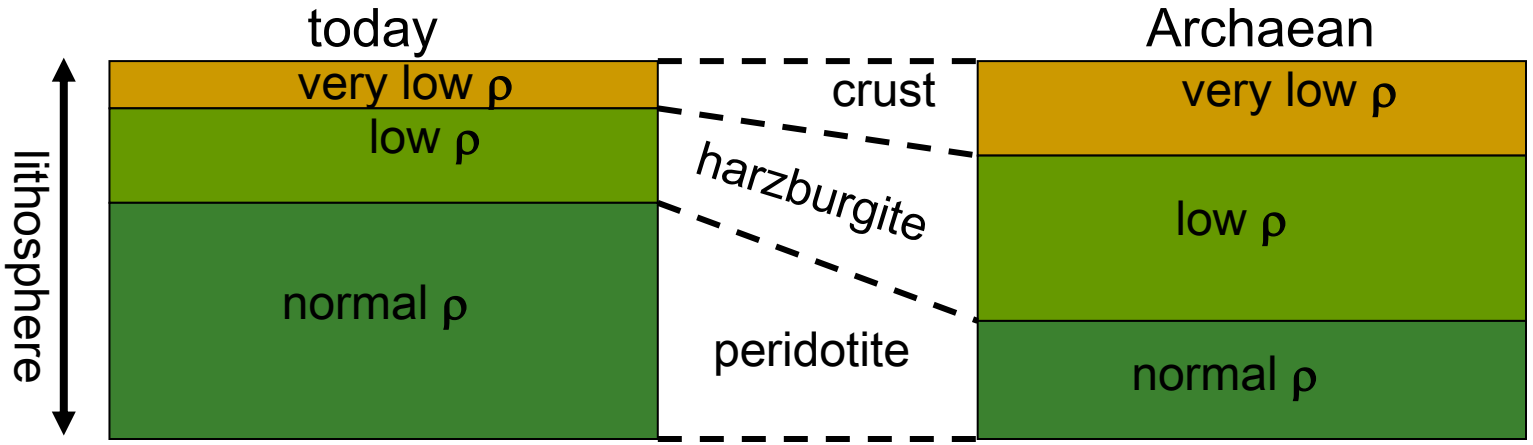
   - η = exp (T)
   - ~1 order of magnitude for every 100 K
   - Effect of dehydration strengthening?

(van Thienen & al., 2004)

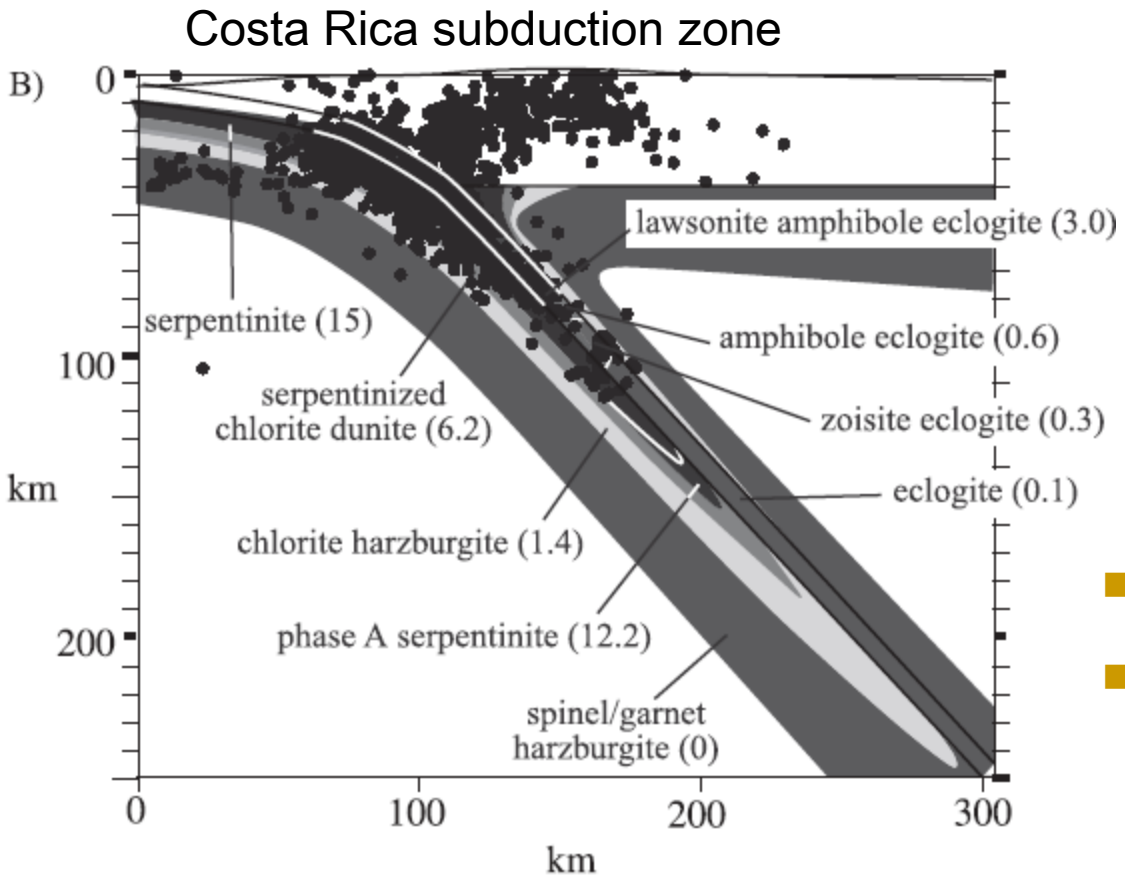
Consequences of more melting

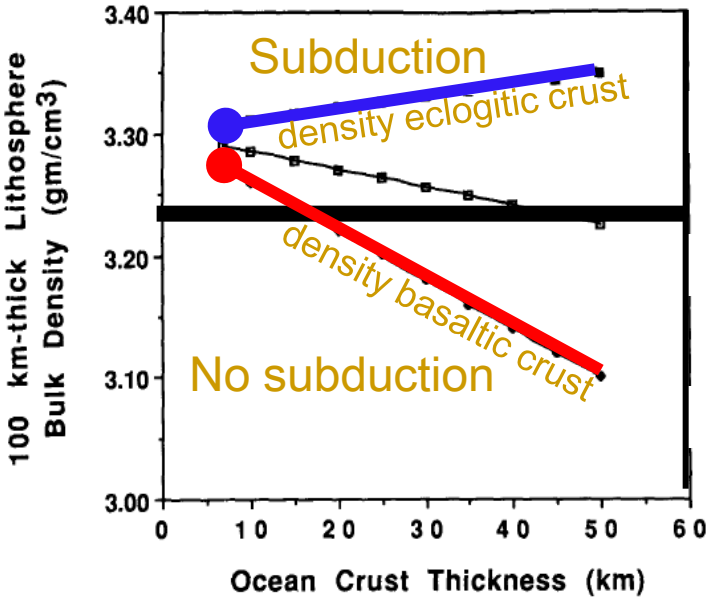
- more melting
- thick crust/harzburgite
- low average density ρ
- no slab pull?
- no subduction? (Ontong Java)
- no plate tectonics?





Effect of basalt-eclogite transition?



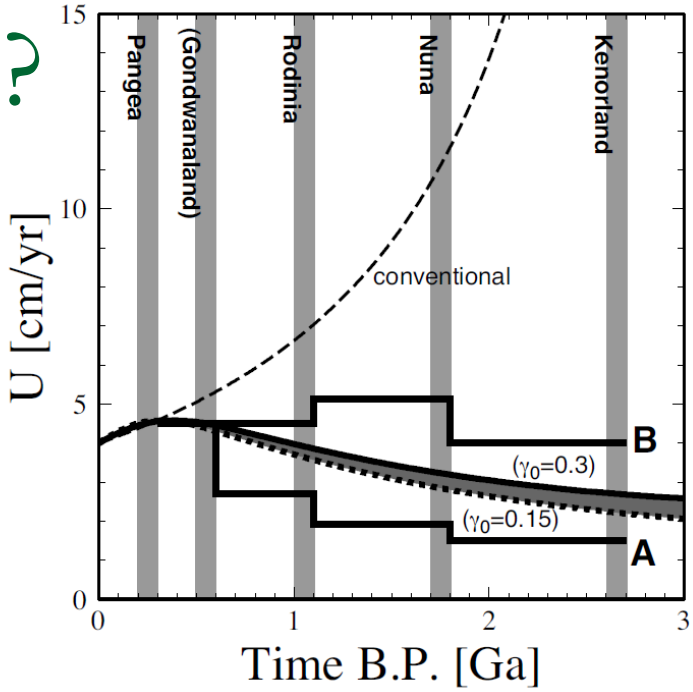


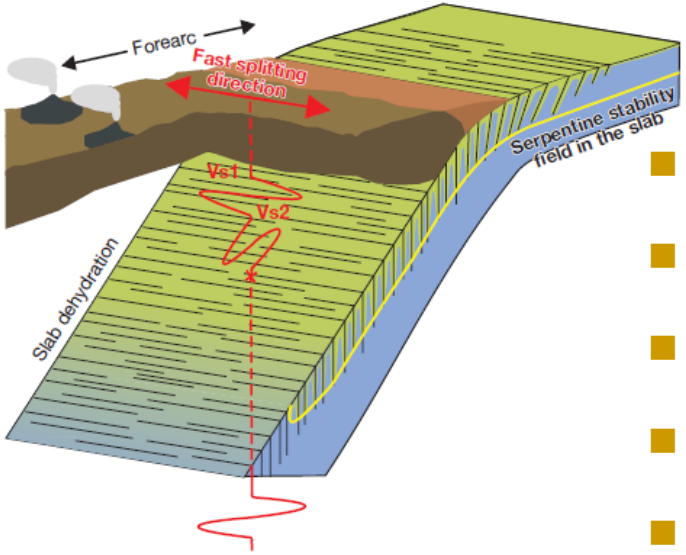
- Meta-stable basalt
- transition gradual

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

Strength Archaean plates?

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





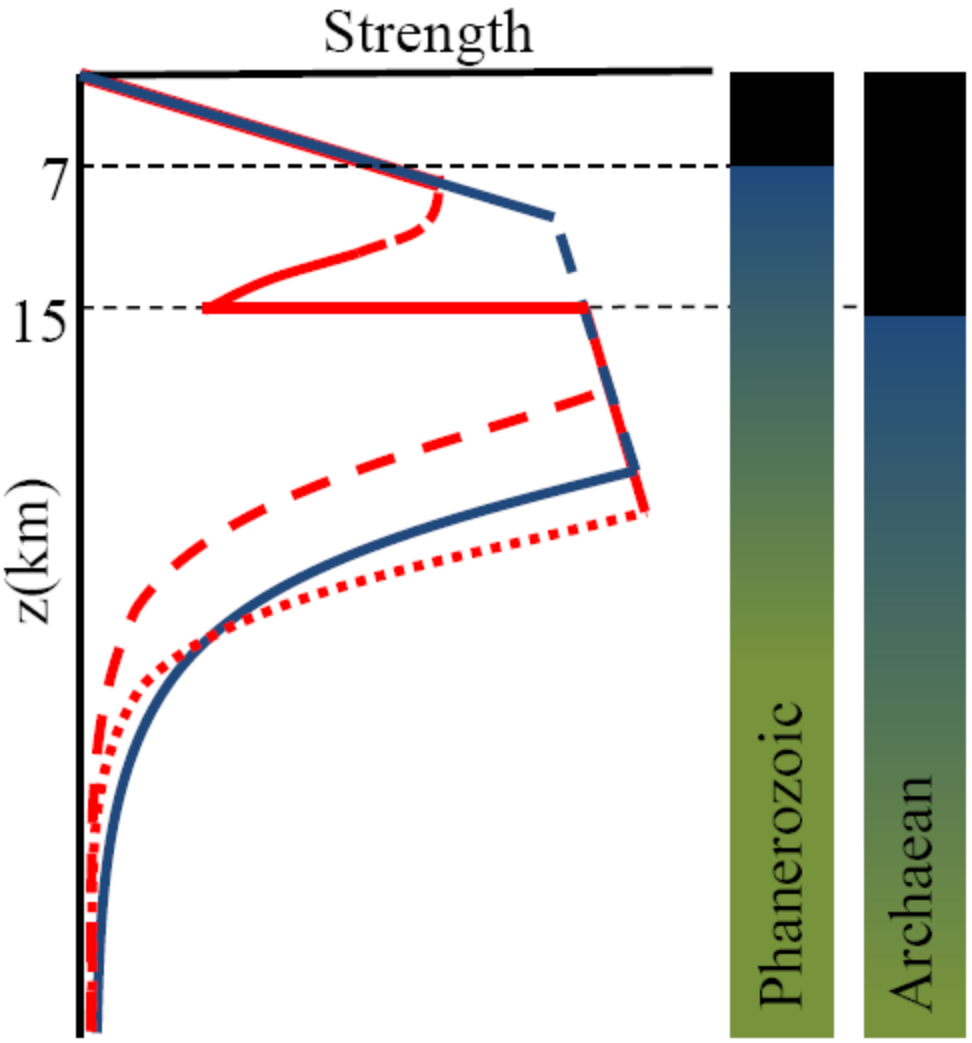
But:

- Before melting mantle isn't 'wet'
- Δ100 K → 1 order weakening
- $\eta_{crust} < \eta_{mantle}$
- plate strength in cold top part
- plates bending induces faulting + rehydration

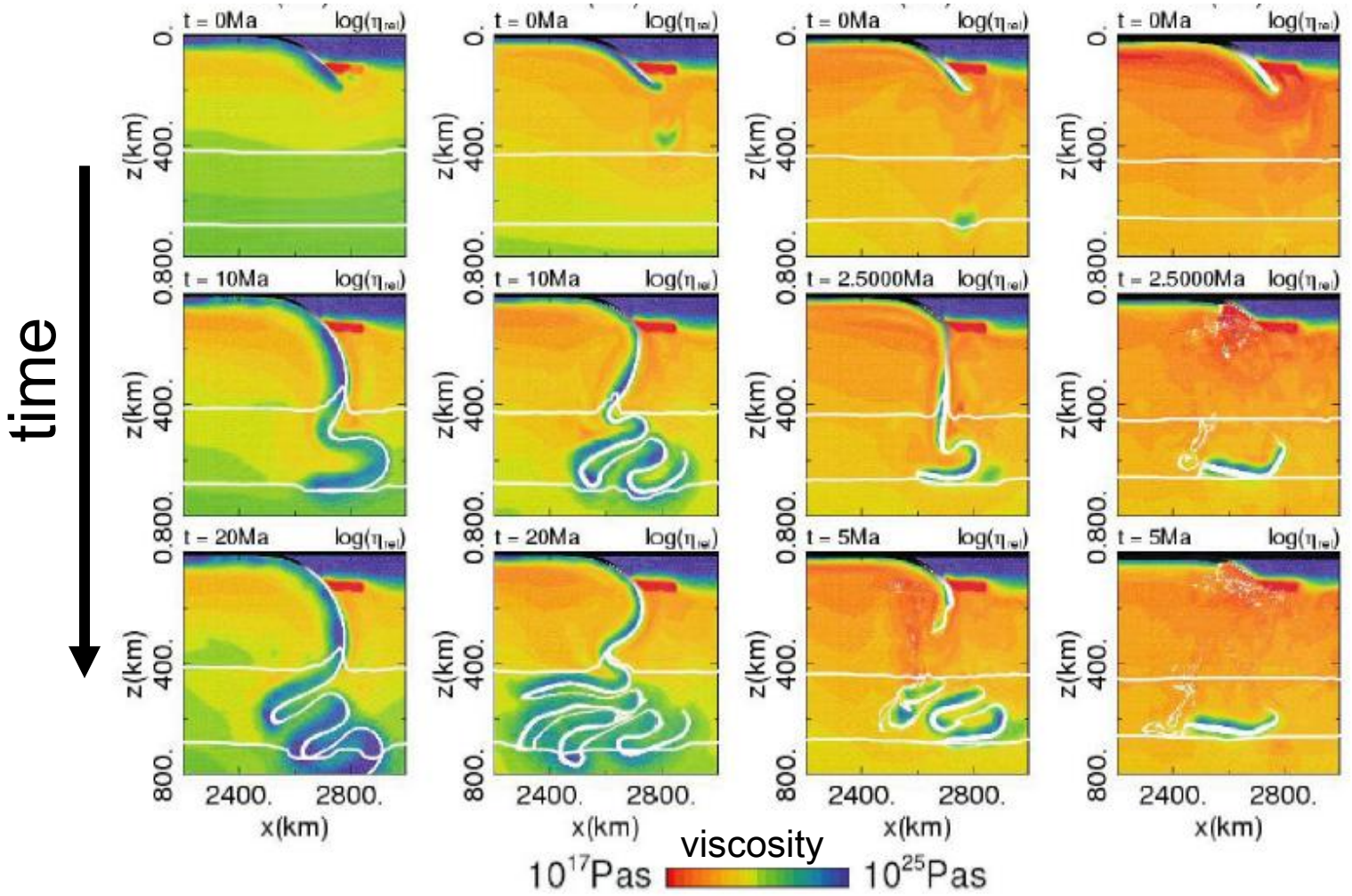
(Faccenda et al., 2008)

(Korenaga, 2006)

Strength Archaean plates?

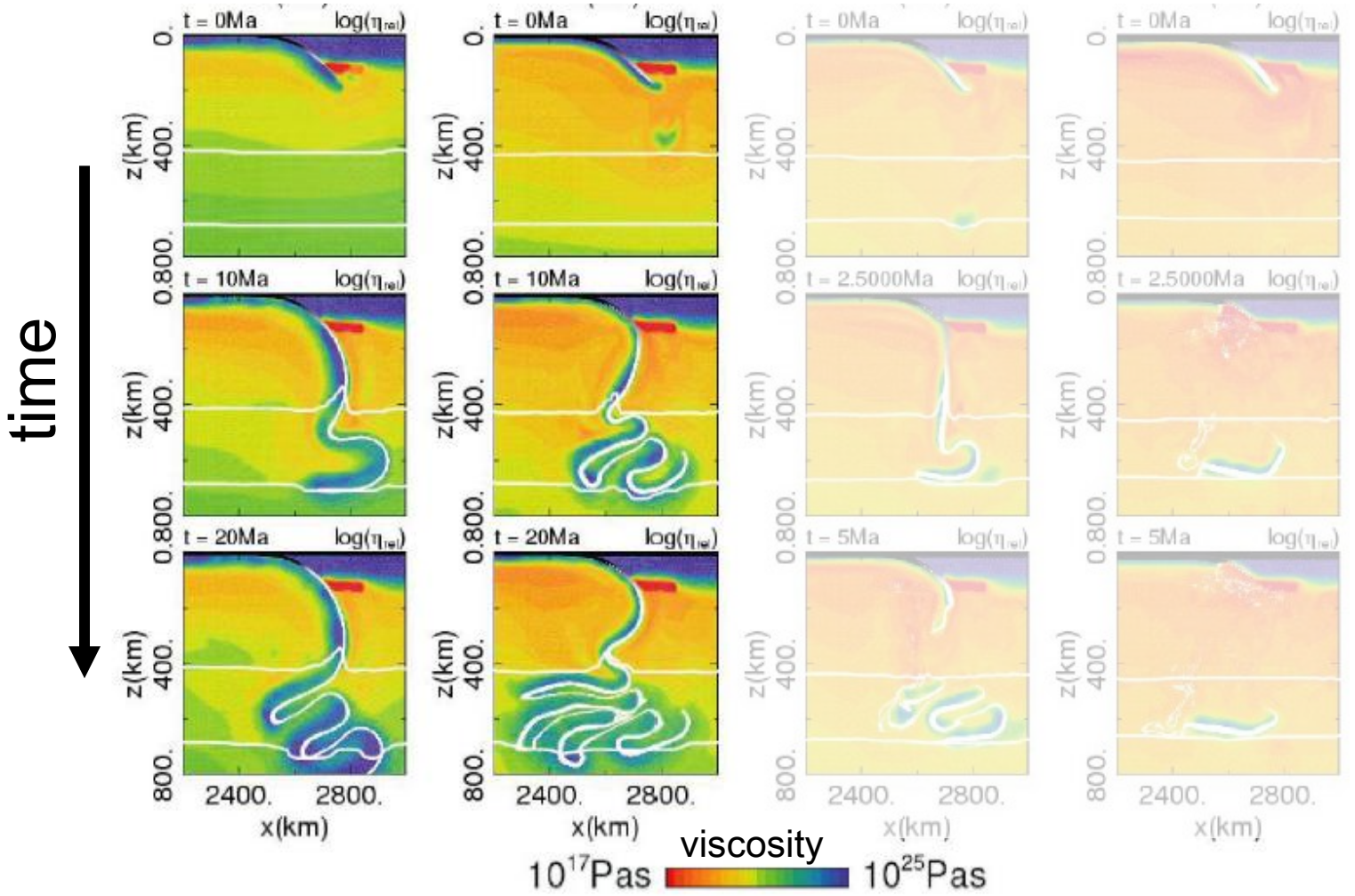


Weaker Archaean plates?



(van Hunen & van den Berg, 2008)

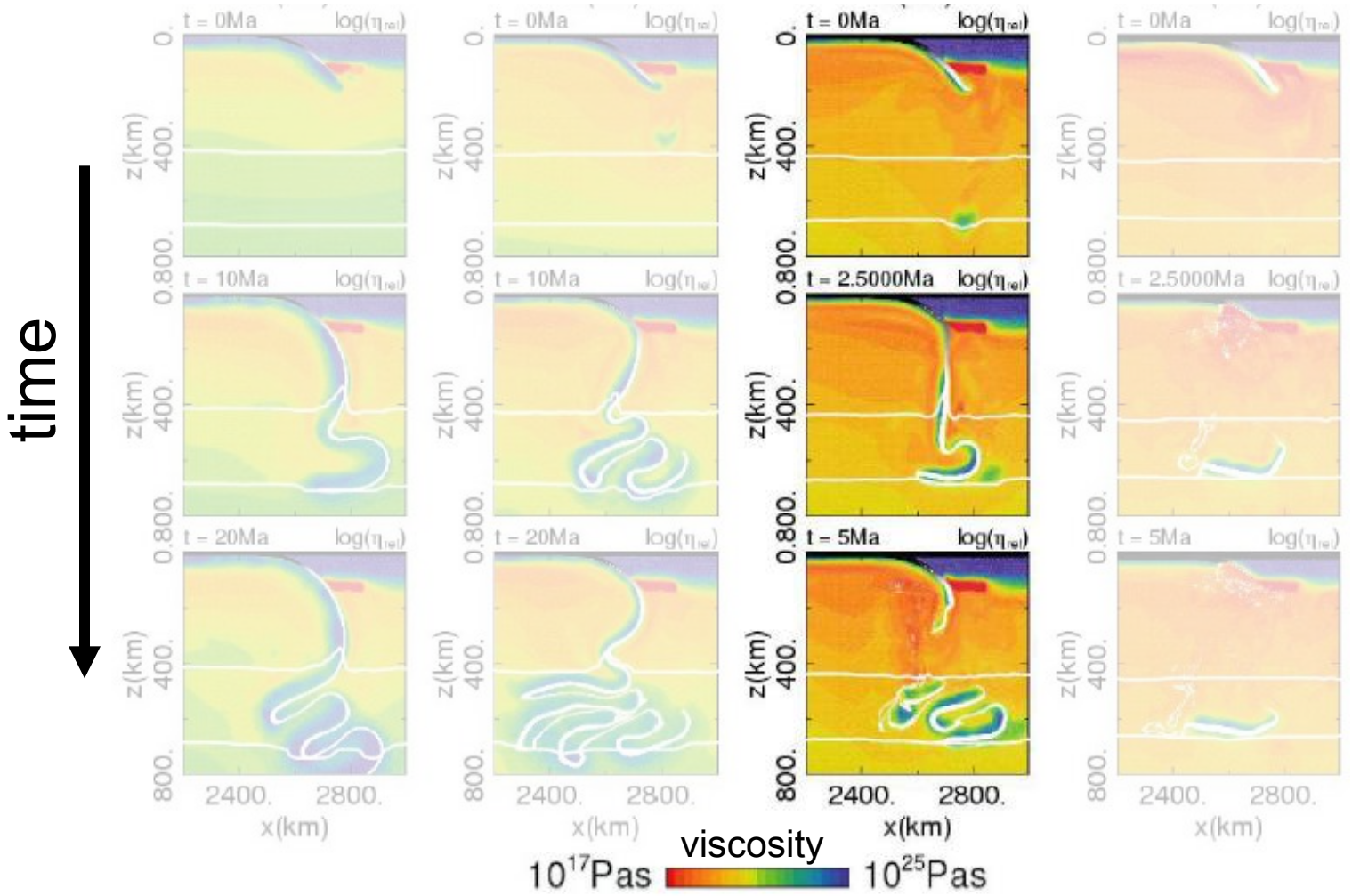
Weaker Archaean plates?



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

(van Hunen & van den Berg, 2008)

Weaker Archaean plates?



colors = viscosity

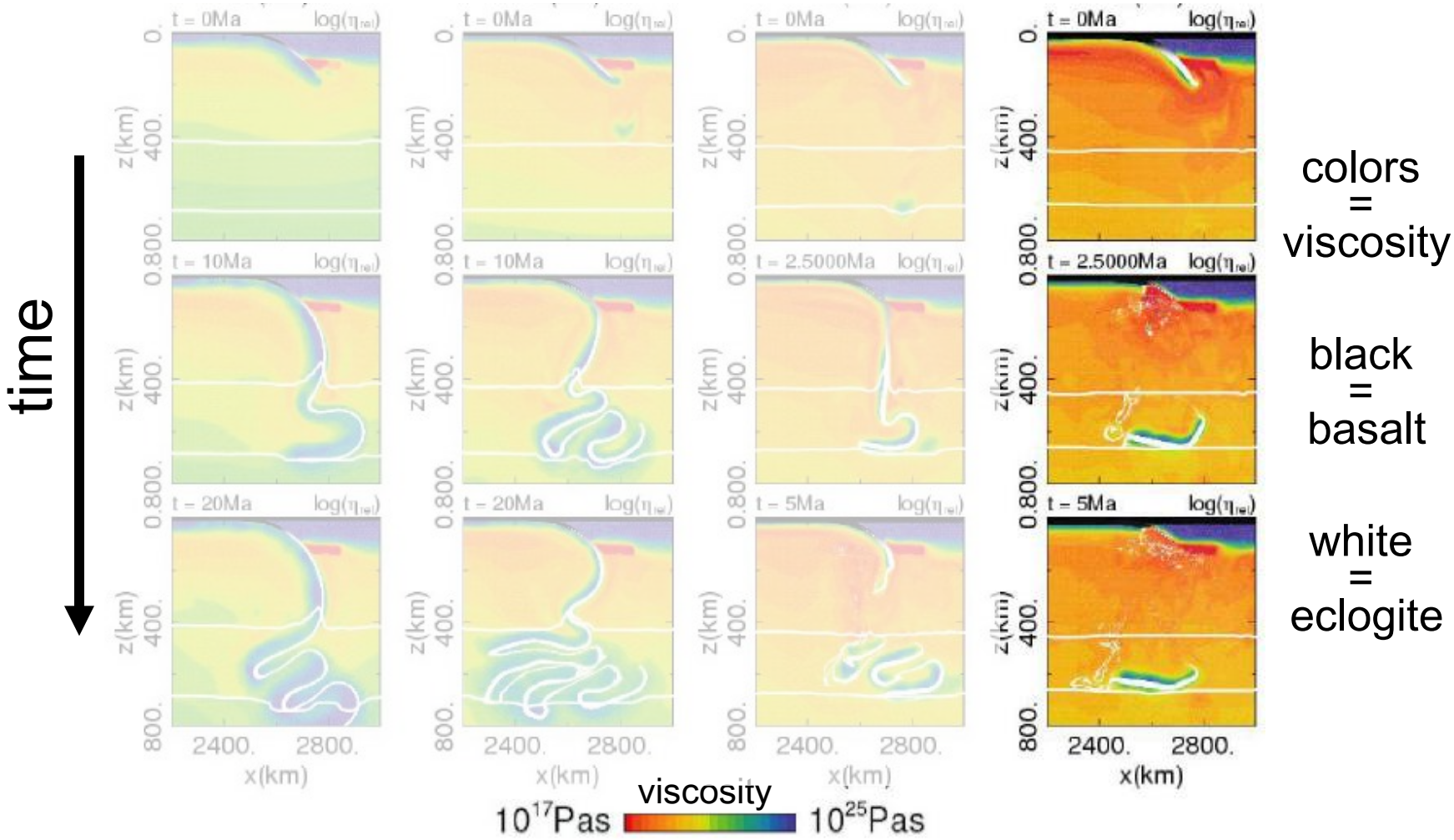
black = basalt

white = eclogite

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

(van Hunen & van den Berg, 2008)

Weaker Archaean plates?

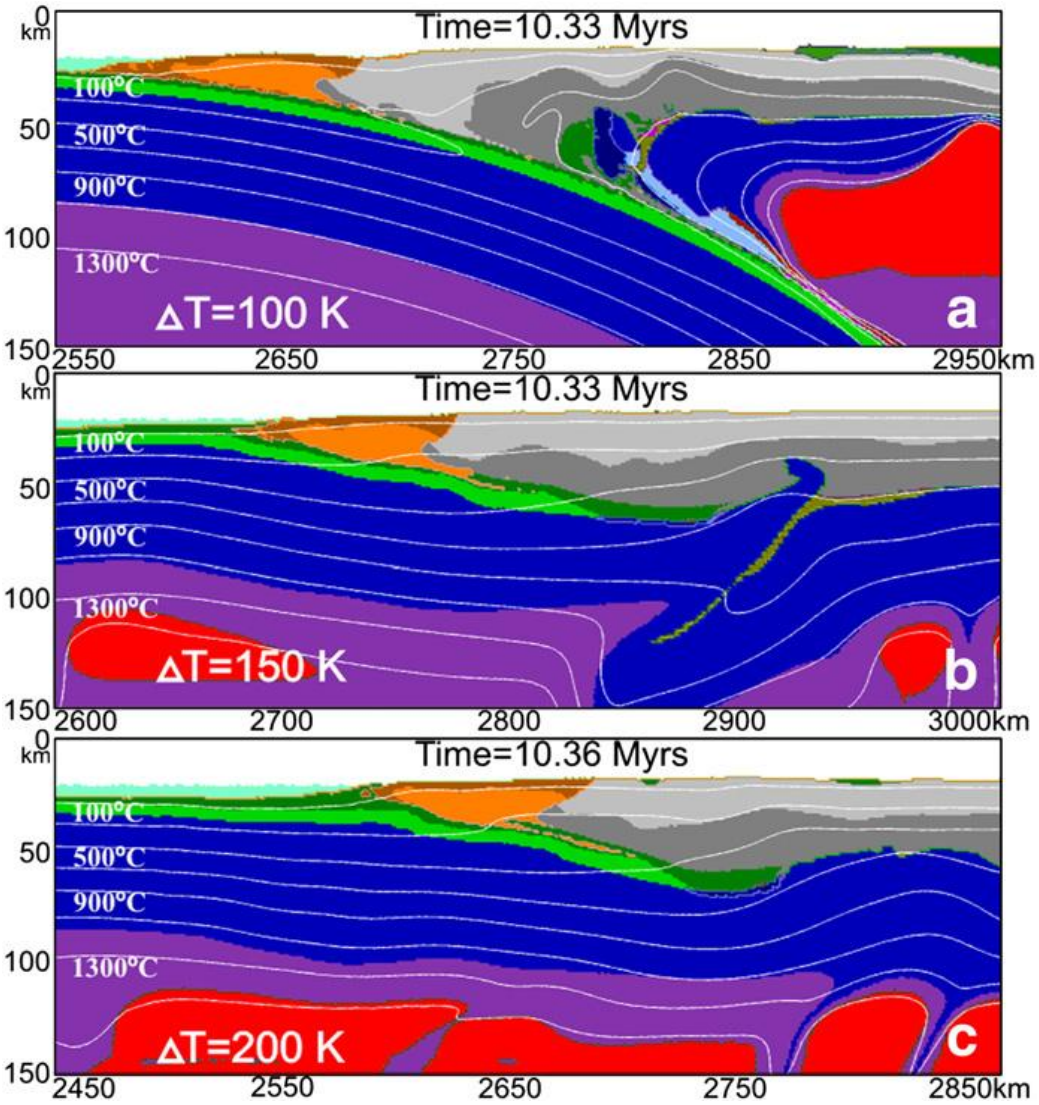


- … or subduction completely stops.

(van Hunen & van den Berg, 2008)

Other models

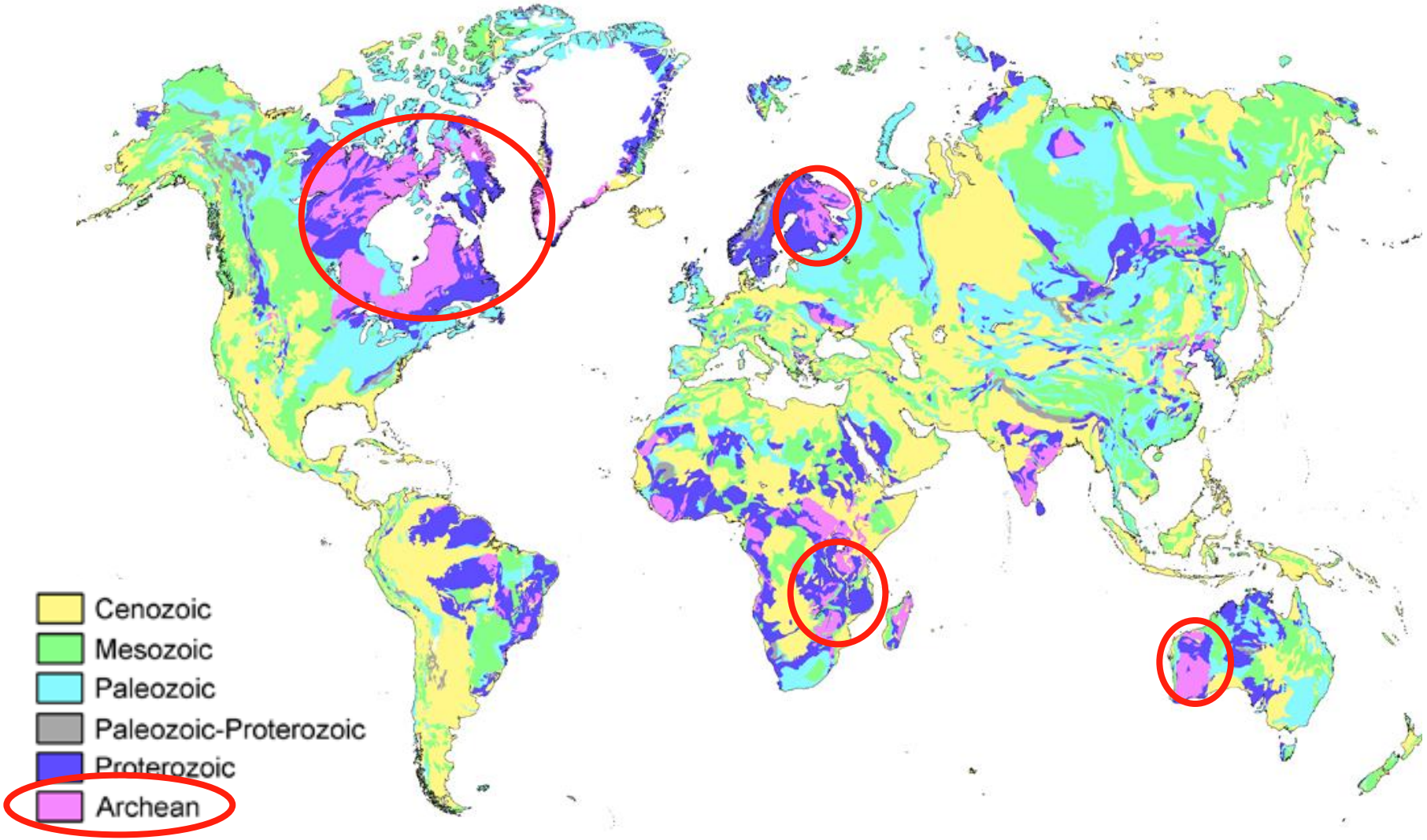
- modern subduction
- ‘pre-subduction’



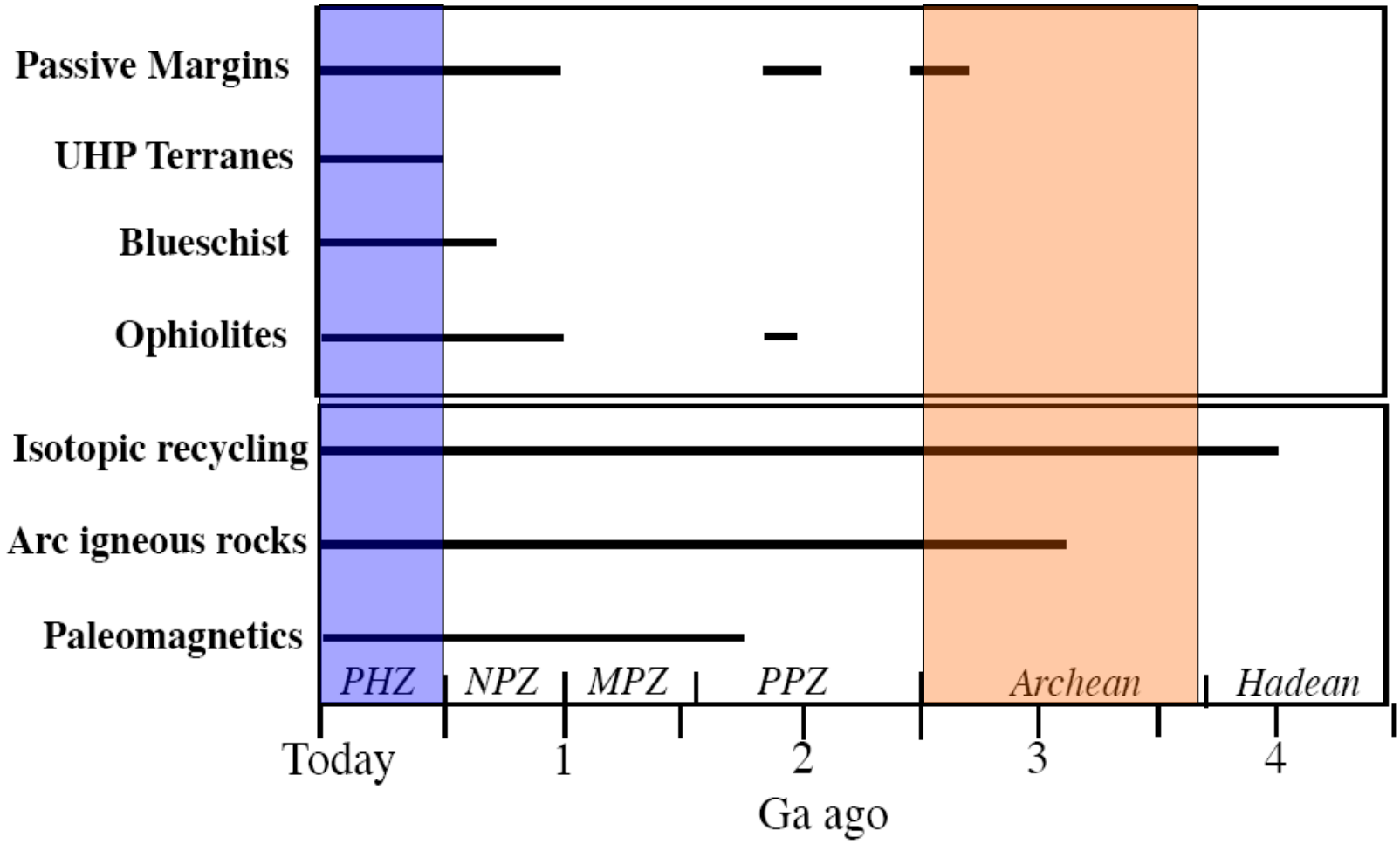
(Sizova et al., 2010)

Observations for early subduction

Archaean rocks: rare, remote, and reworked



Key characteristics of plate tectonics

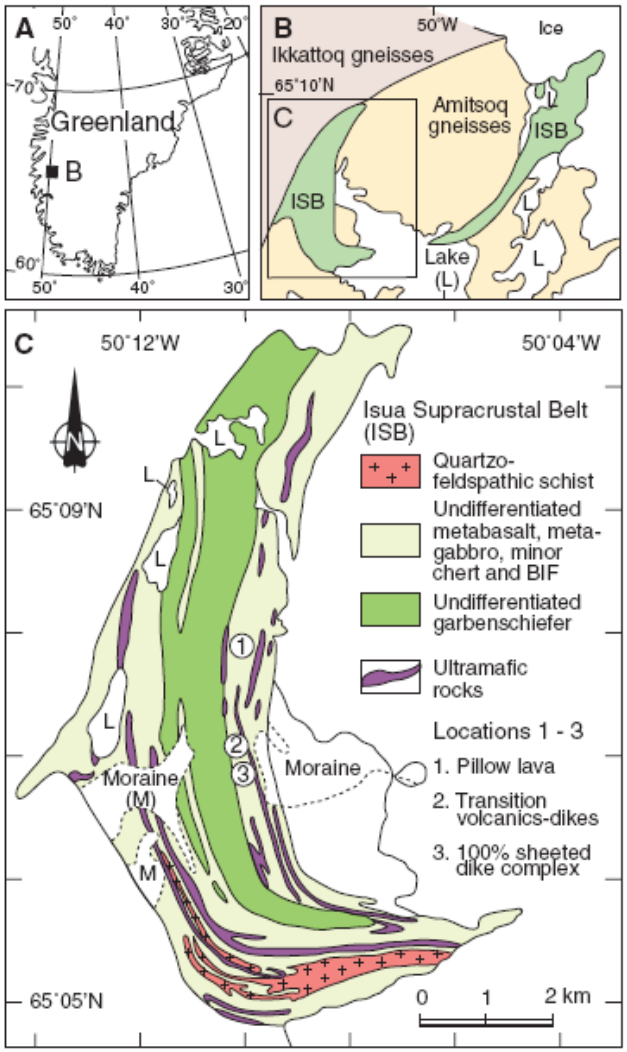


No subduction in Precambrian?

(Stern, 2008)

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

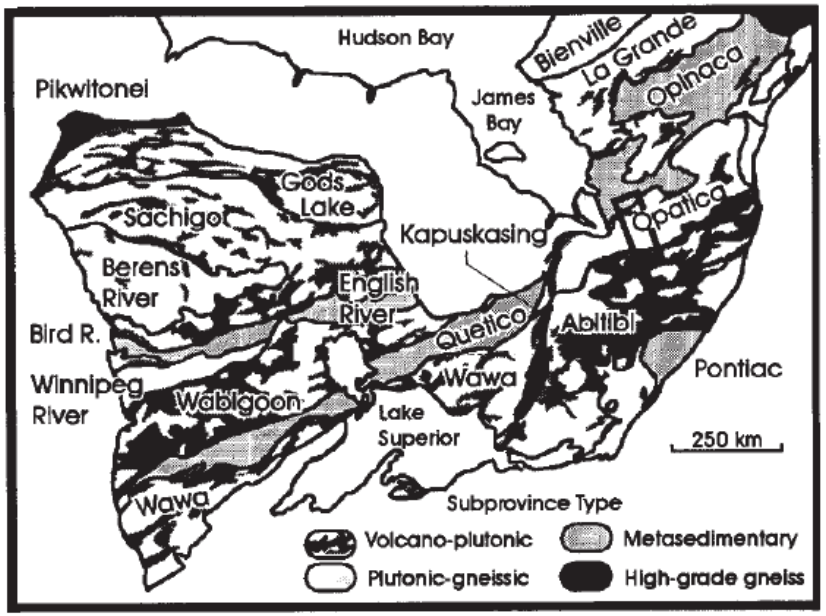


(Stern, 2005; Furnes et al., 2007)

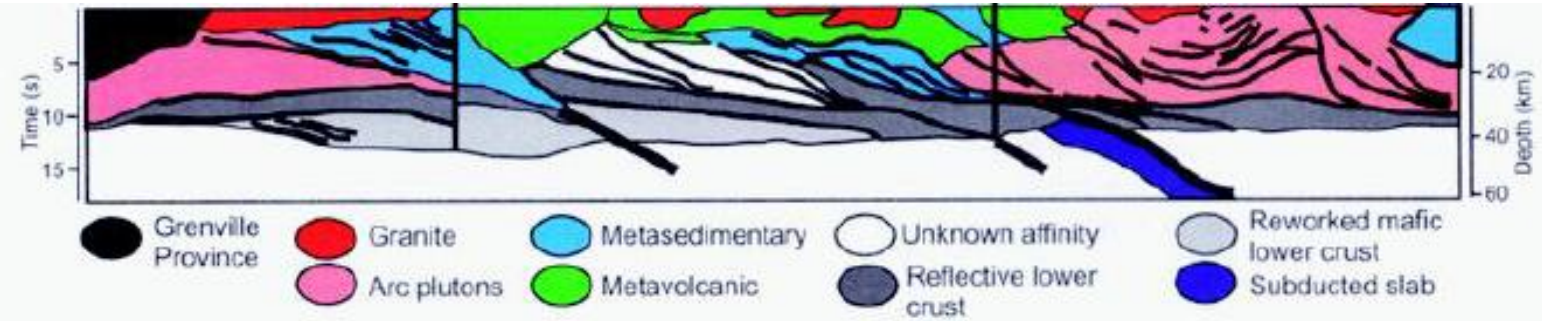
Structural observations

- Accreted terranes
- Low-angle reflectors

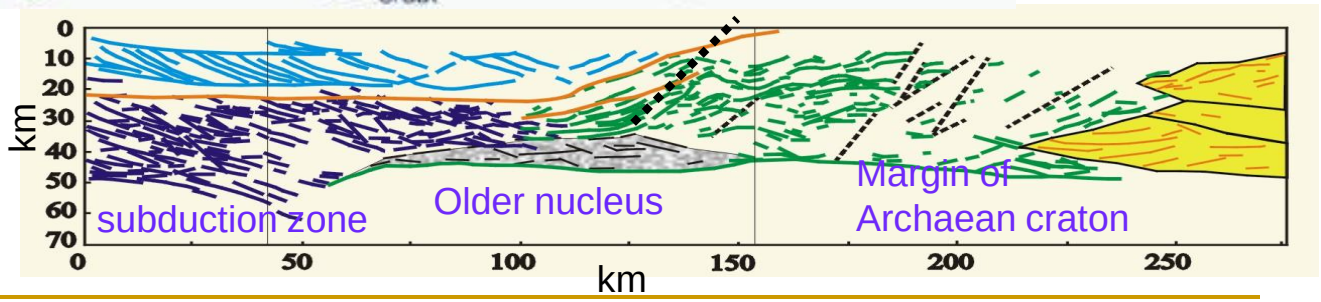
→ fossil subduction?



Superior Province



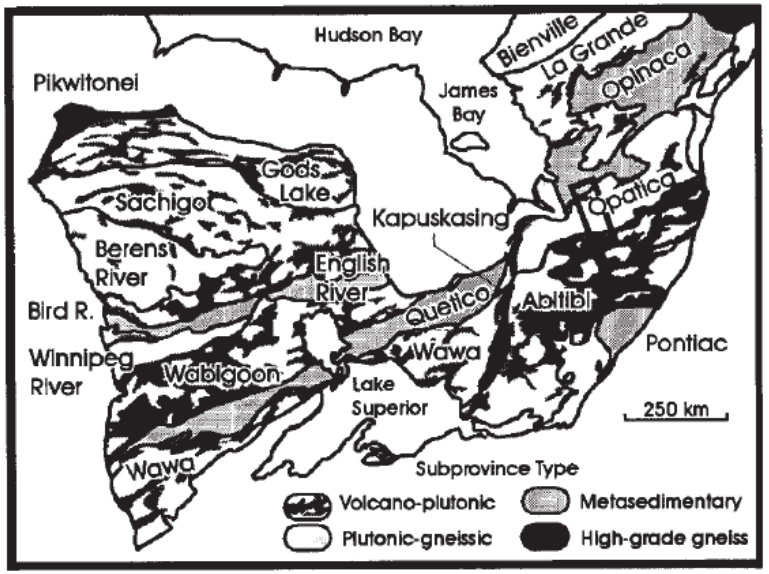
Fennoscandian Shield



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

Linear features?

Abitibi, Superior Province



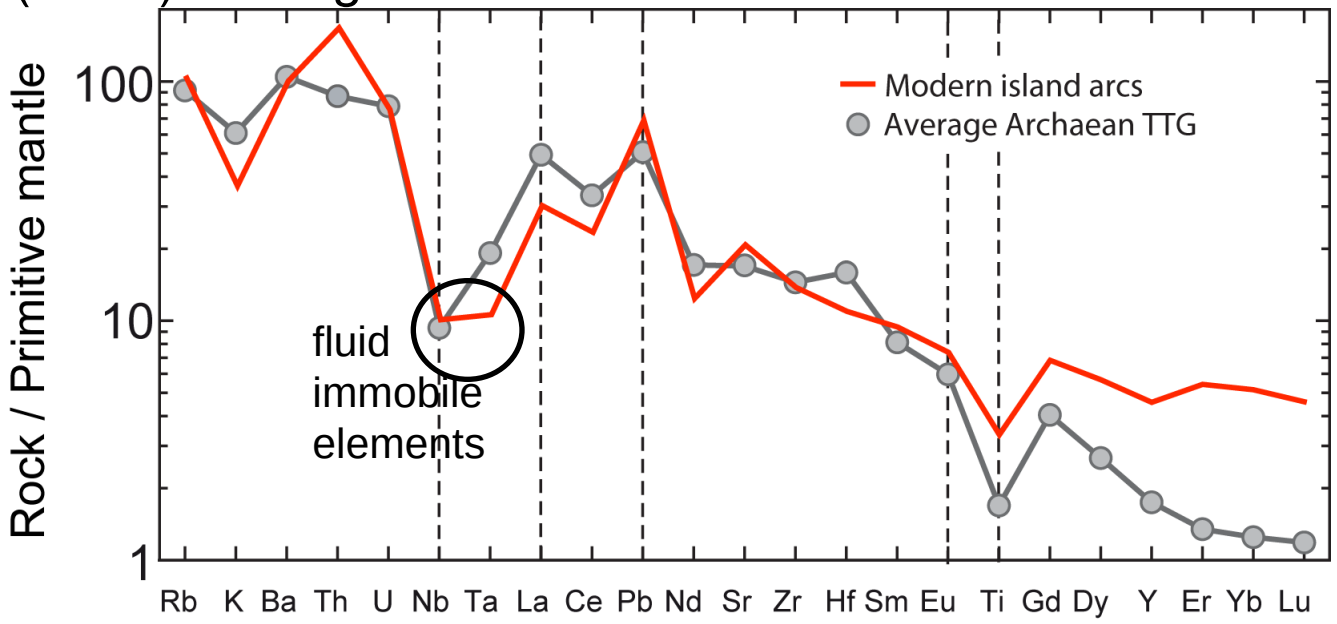
E-Pilbara, Australia

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

Geochemical 'arc' signature

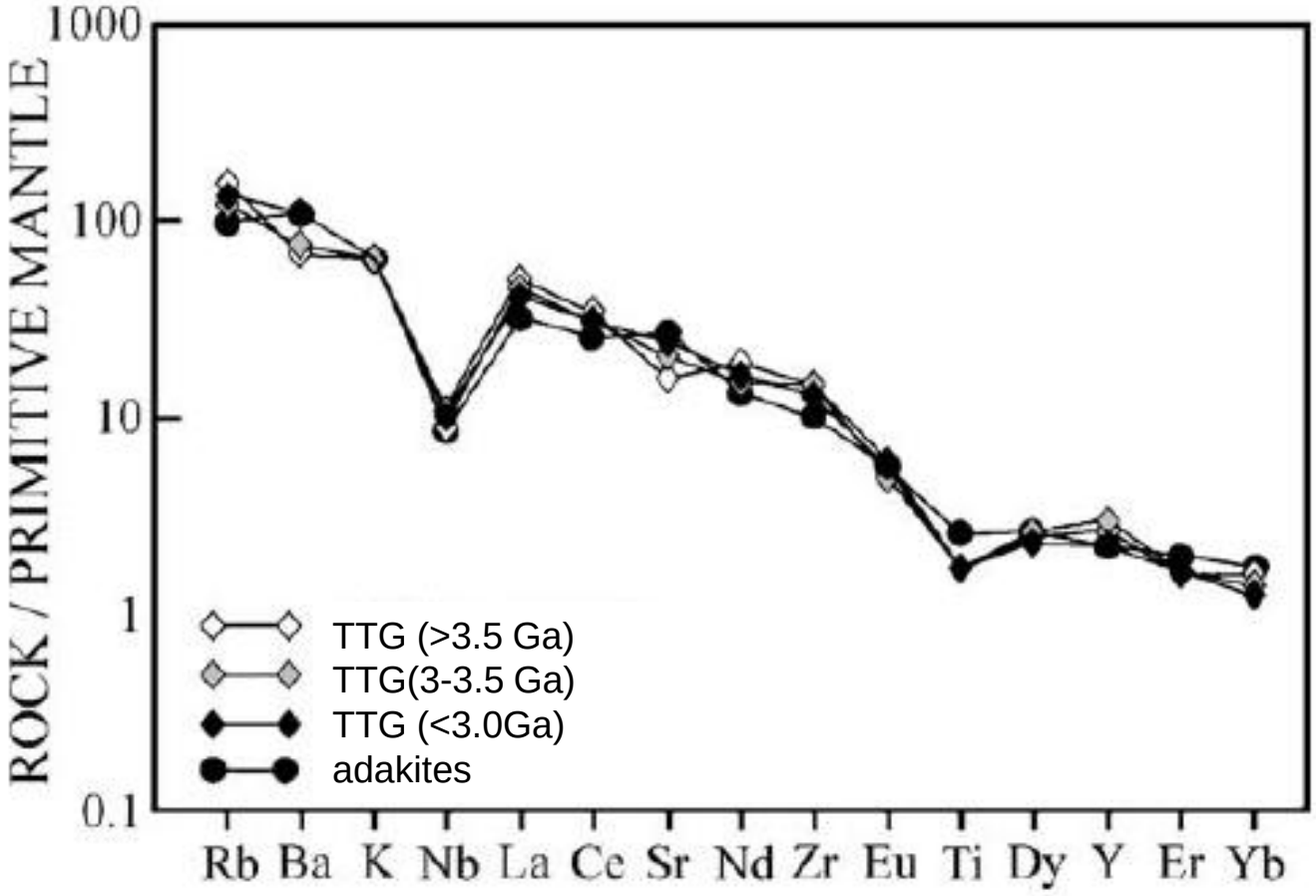
Bulk continental crust:

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



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

Geochemical 'arc' signature

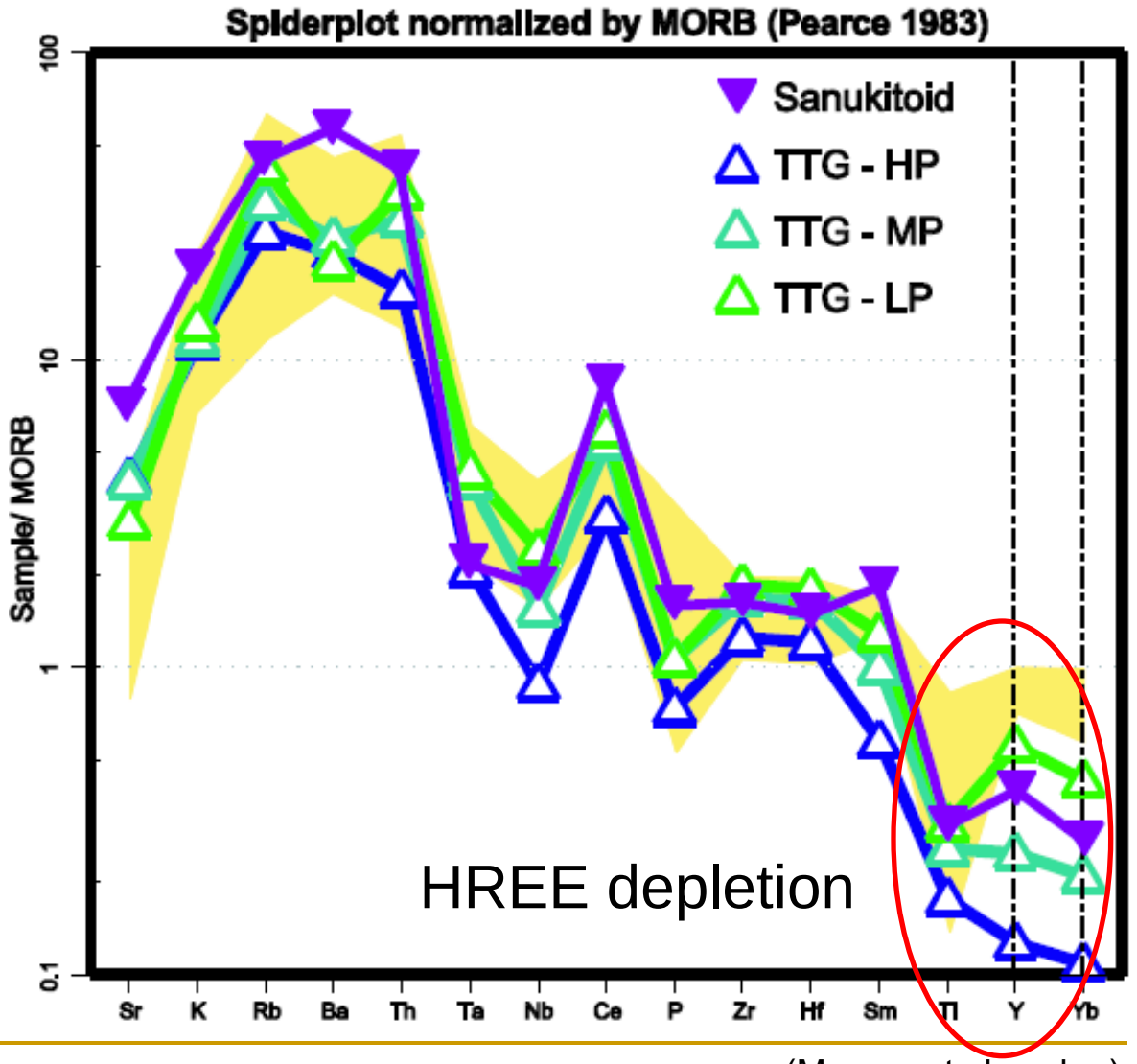


TTG are geochemically very similar to modern adakites
→ slab melting?

(Martin et al., 2005)

Different types of TTGs

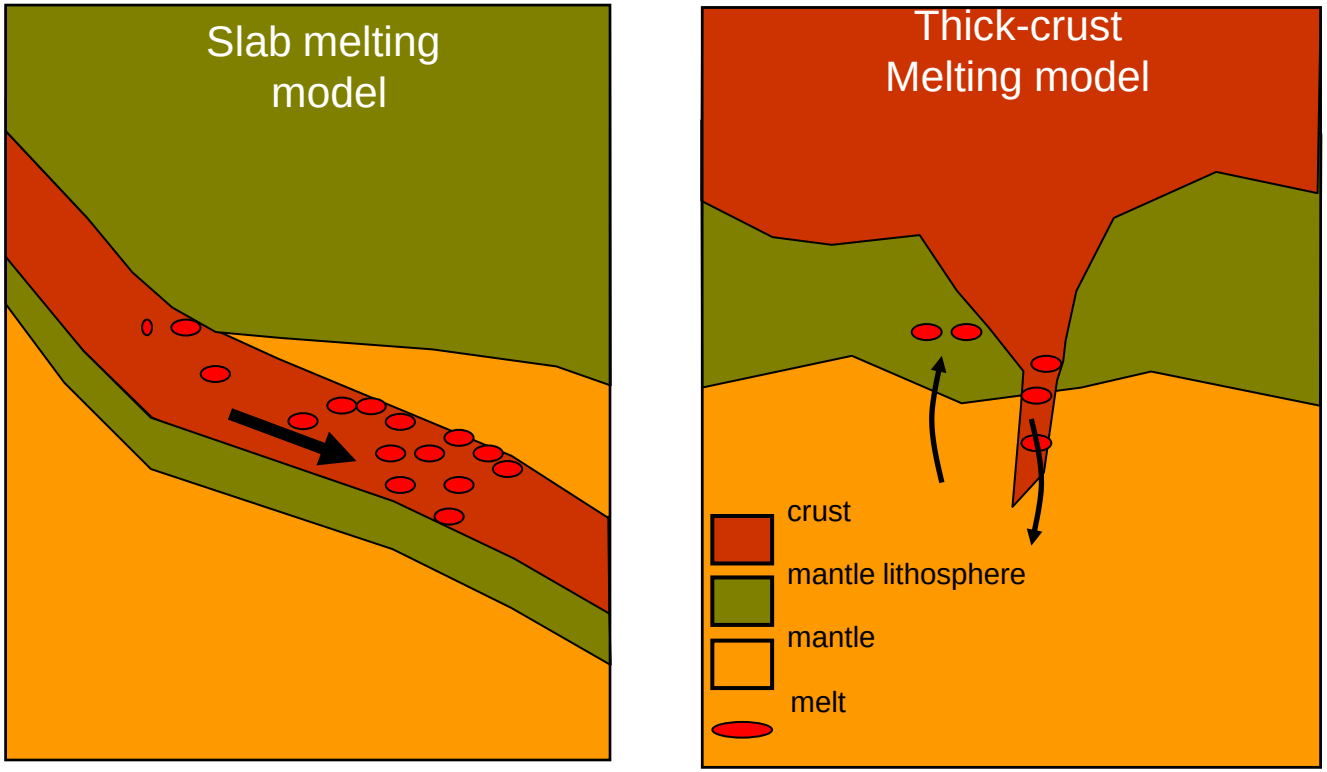
- HREE depletion indicates garnet in source.
- HP-TTG requires >18-20 kbar or >60 km.



(Moyren et al., subm)

Geochemical ‘arc’ signature

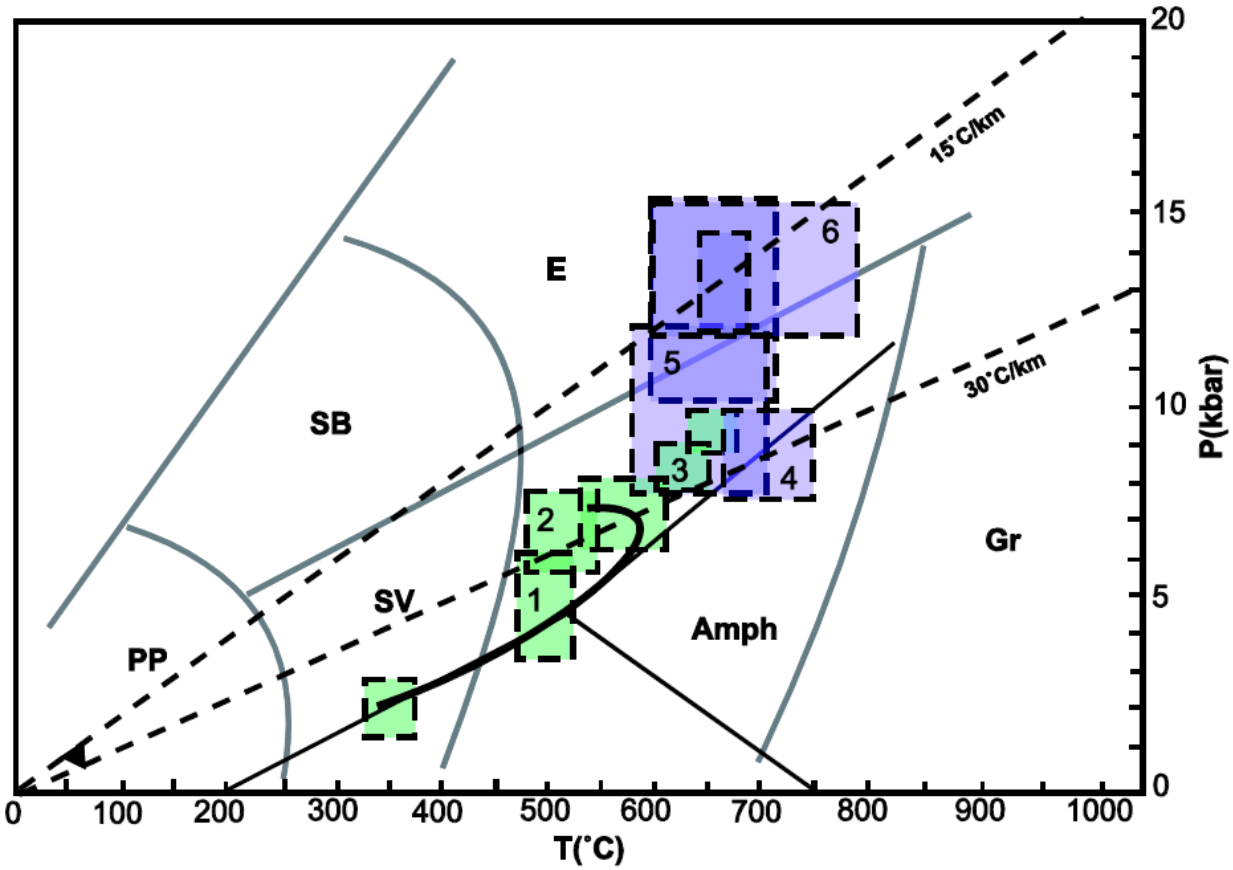
Various formation scenarios possible:



(Defant and Drummond, 1993; Foley et al., 2002, 2003; van Thienen et al., 2004; Bédard, 2006)

Subduction zone metamorphism

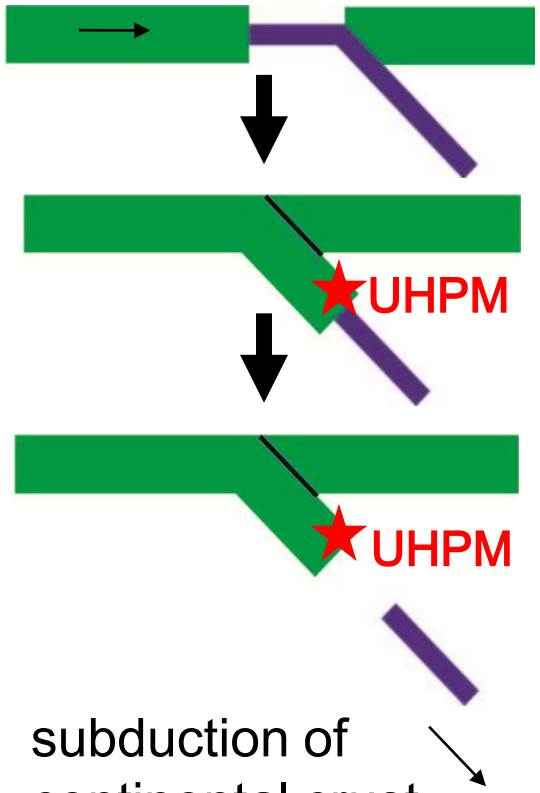
- low dT/dp – high dT/dp pairs typical for subduction
- Modern low dT/dp=5-8 K/km absent in Archaean
- But paired belts occur, shifted to higher geotherms.



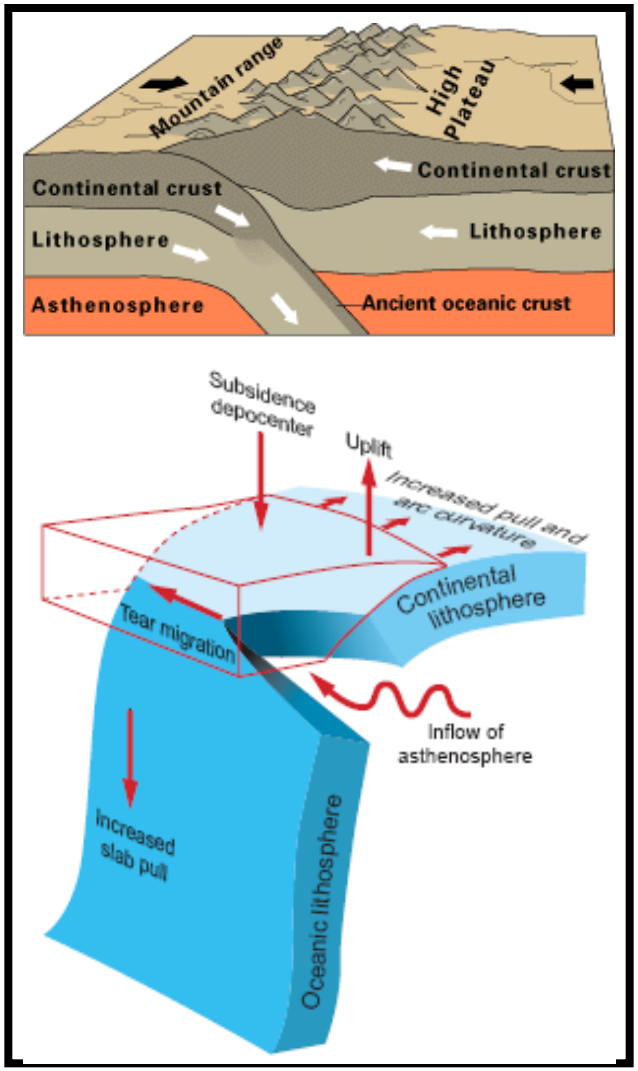
(plot courtesy of Gautier Nicoli; data from Stevens & Moyen, 2007; Lana et al., 2010; Saha et al., subm.)

Absence of UHPM by slab break-off?

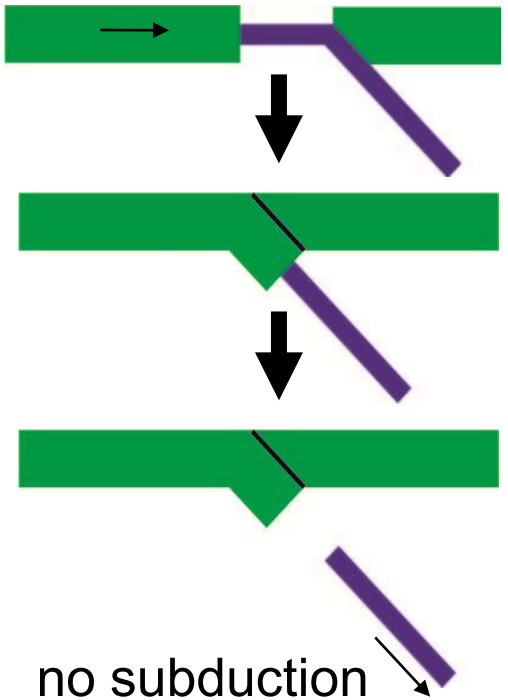
Phanerozoic



subduction of continental crust gives UHPM



Archaean



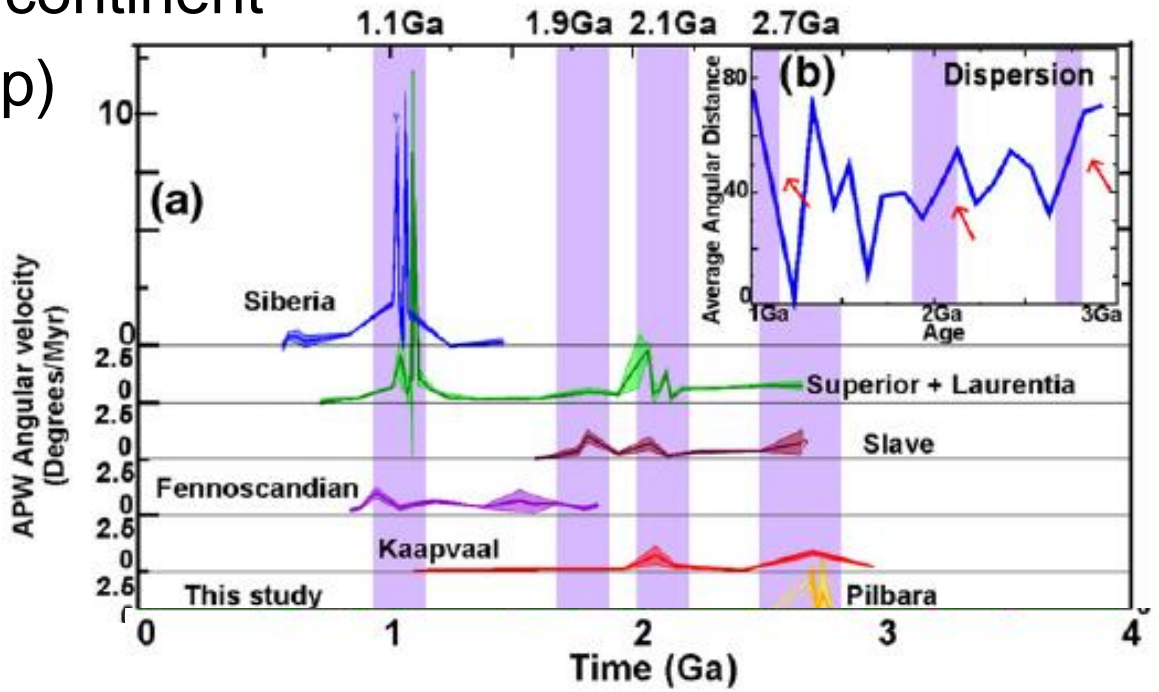
no subduction of continental crust: absence of UHPM

(USGS website; Wortel and Spakman, 2000; van Hunen and Allen, 2011)

Plate tectonics in Archaean?

Paleo-magnetism

- Paleo-latitudes of old continents varied over time
- Only during supercontinent (formation/breakup)
- Episodic early plate tectonics?



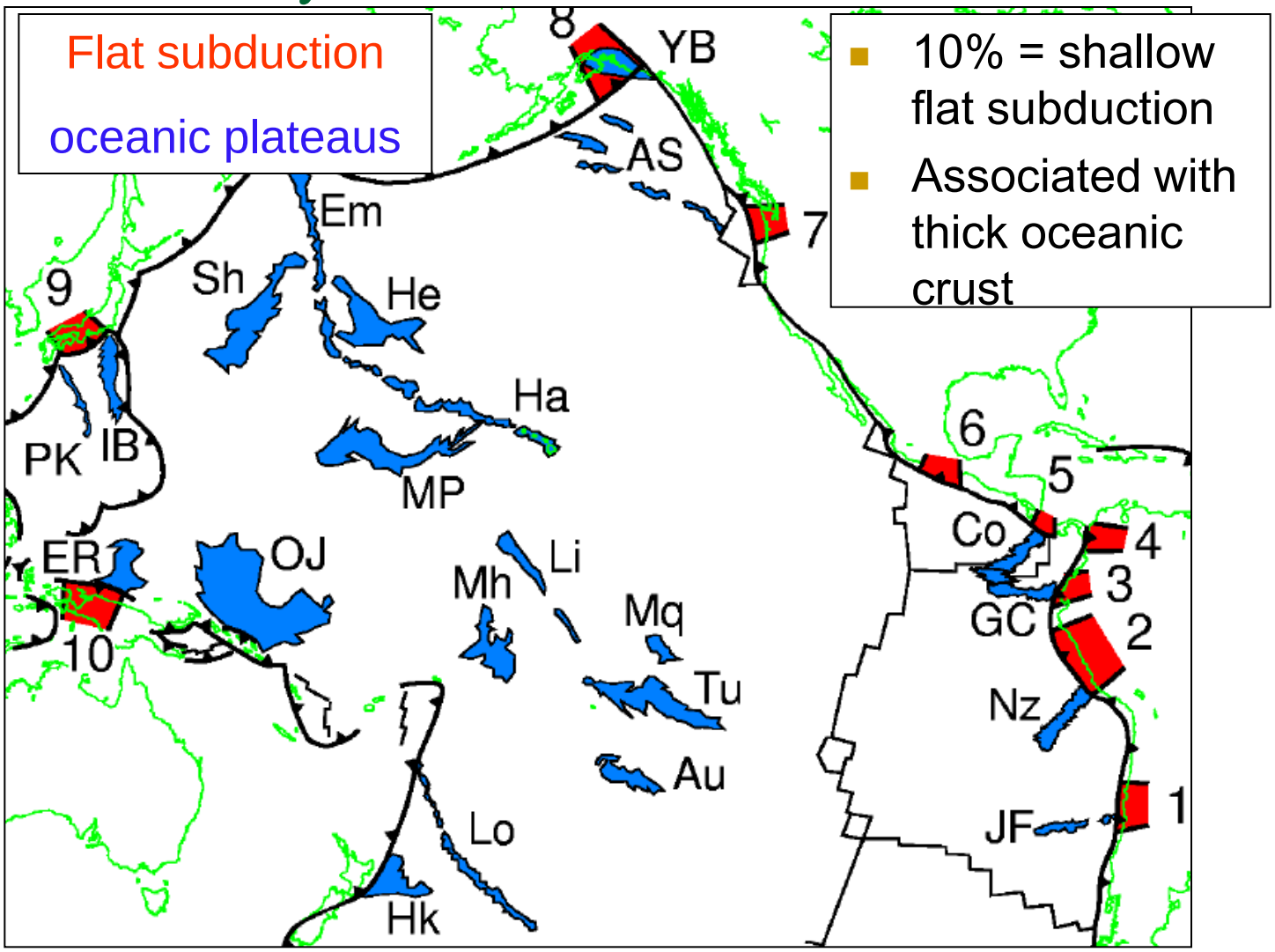
(O'Neill et al., 2007; Silver and Behn, 2008)

Changing subduction style:

Flat subduction?

Episodic subduction?

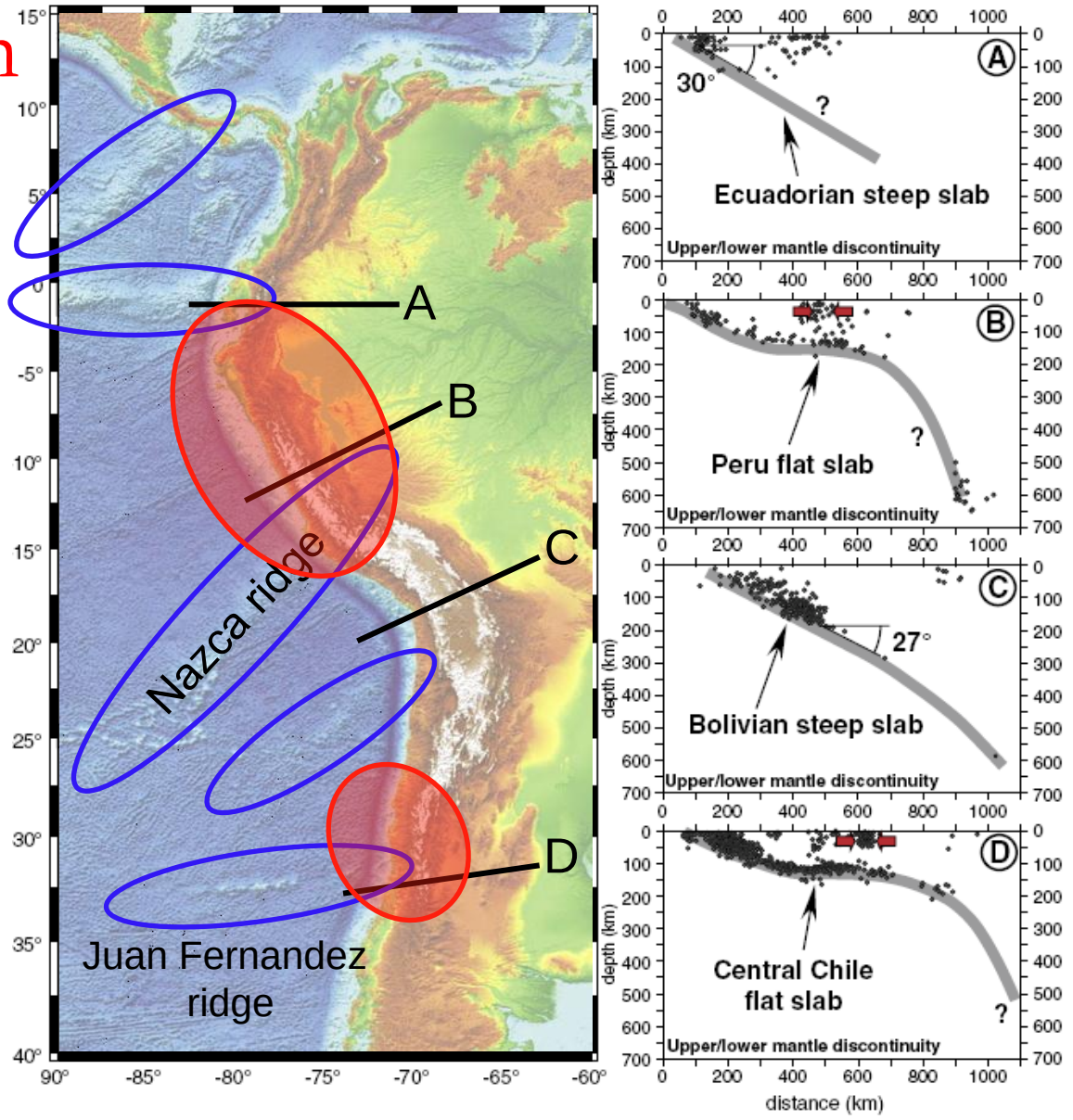
Present-day flat subduction



(Gutcher et al., 2000)

Flat subduction at S-America

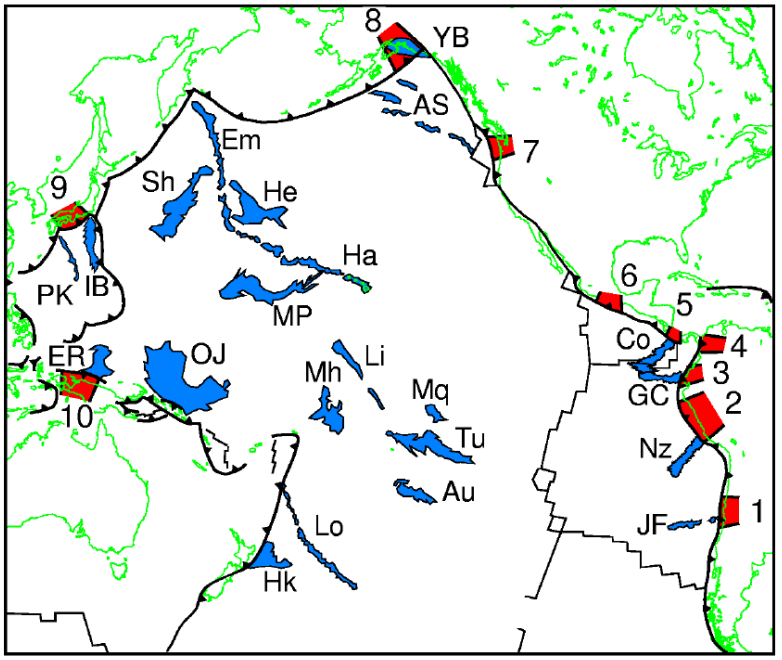
- Slab bends back to ~horizontal at 100-150 km depth
- Not along whole slab
- Correlation with aseismic ridges
- ~500-1000 km in size

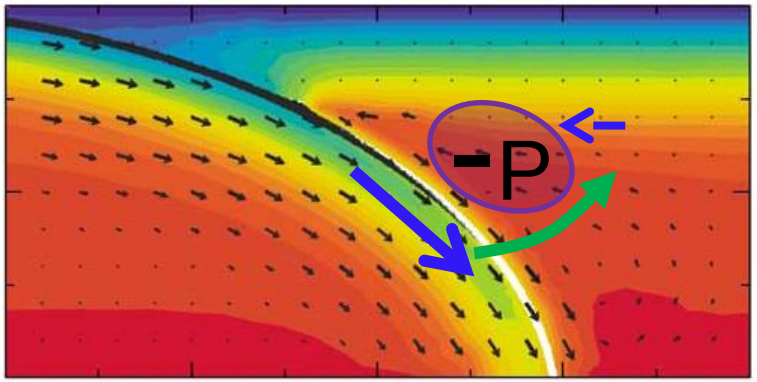


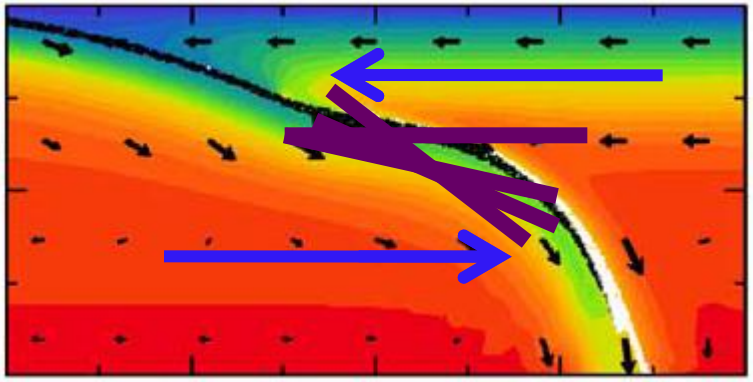
(Espurt et al., 2008; Martinod et al., 2010)

Archaean flat subduction?

- Dense slabs (slab pull) drives modern subduction
- 100% buoyant subduction
  = NO subduction
- Hot mantle too weak to support flat subduction



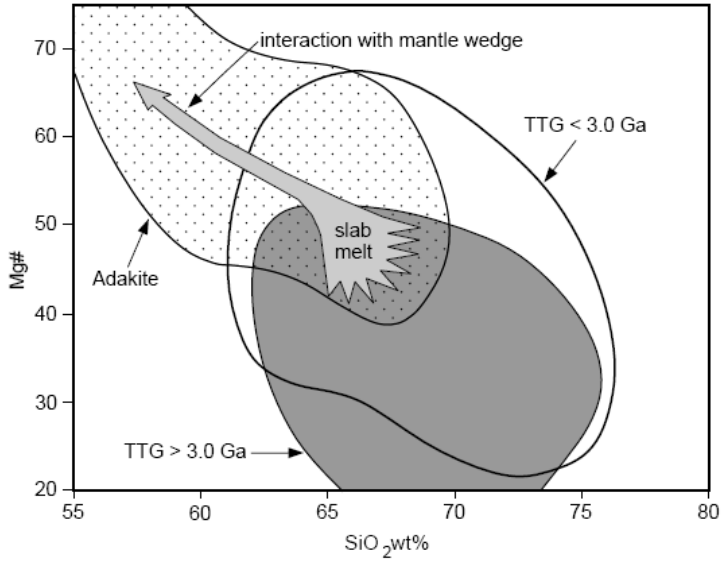


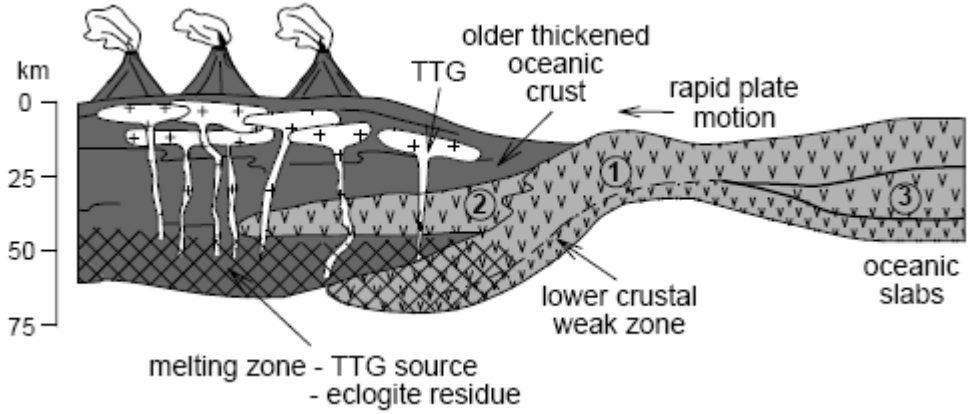


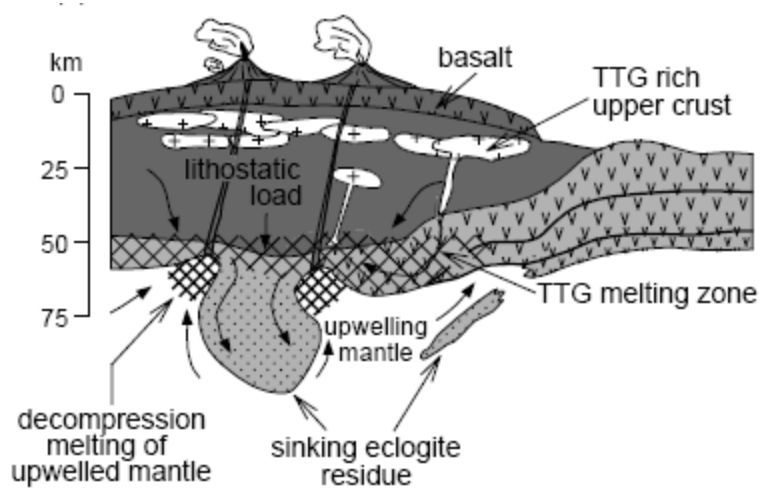
(Gutcher et al., 2000; van Hunen et al., 2004)

Flat subduction and TTGs

- TTG look like adakites
- Unlike most adakites, TTGs have lower Mg#: no/little wedge interaction ? → flat subduction?
- But Mg# variation can have different origins (e.g. different melting T)



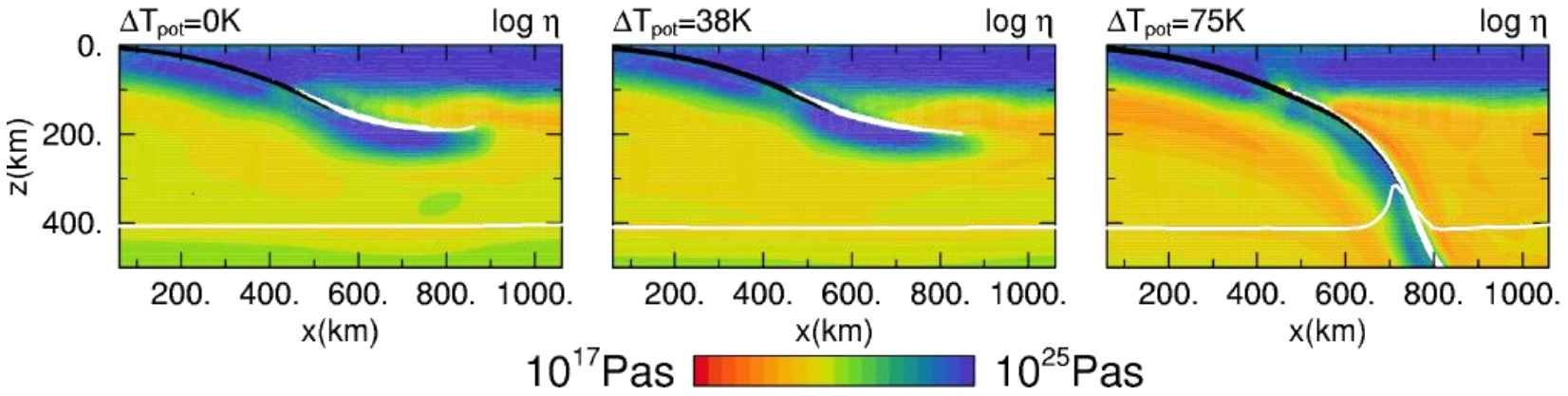




(Defant & Drummond, 1990; Smithies et al., 2003)

Archaean flat subduction?

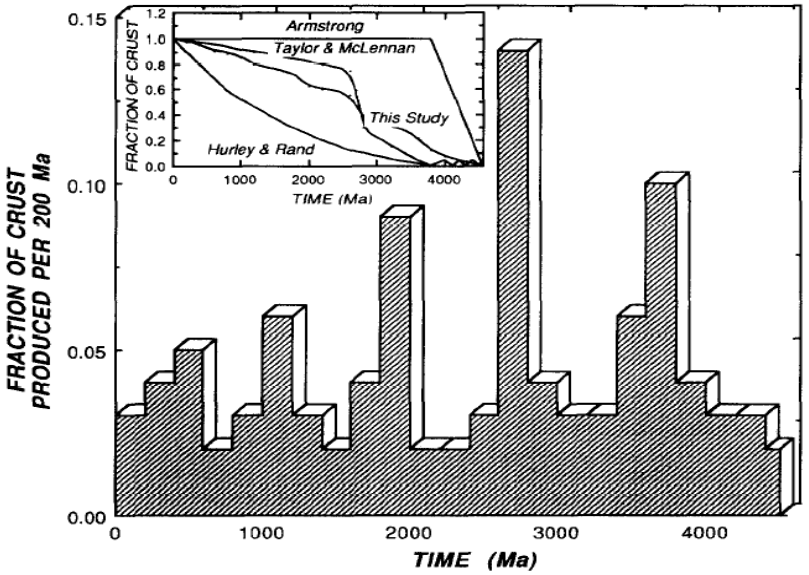
- Flat subduction difficult if $\Delta T_m > 50K$



- Flat subduction not required geochemically

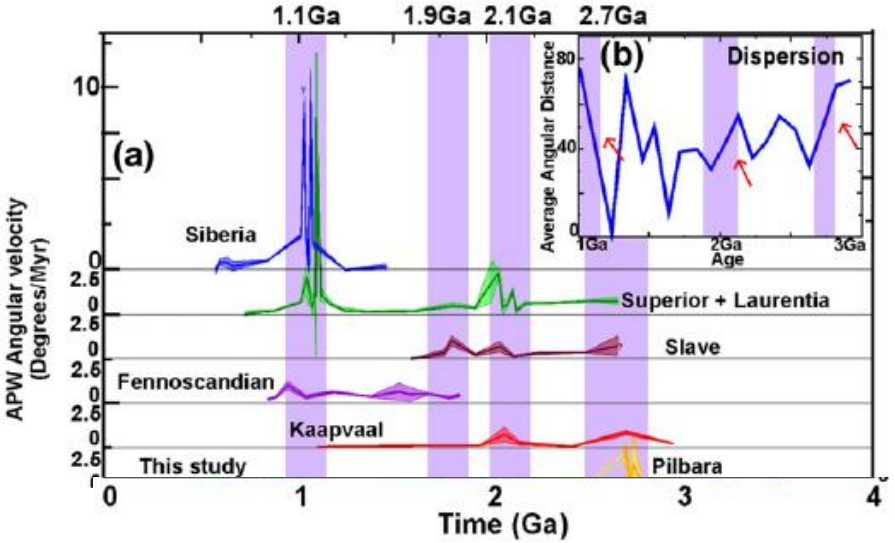
(van Hunen et al., 2004)

Long-term episodicity in subduction?



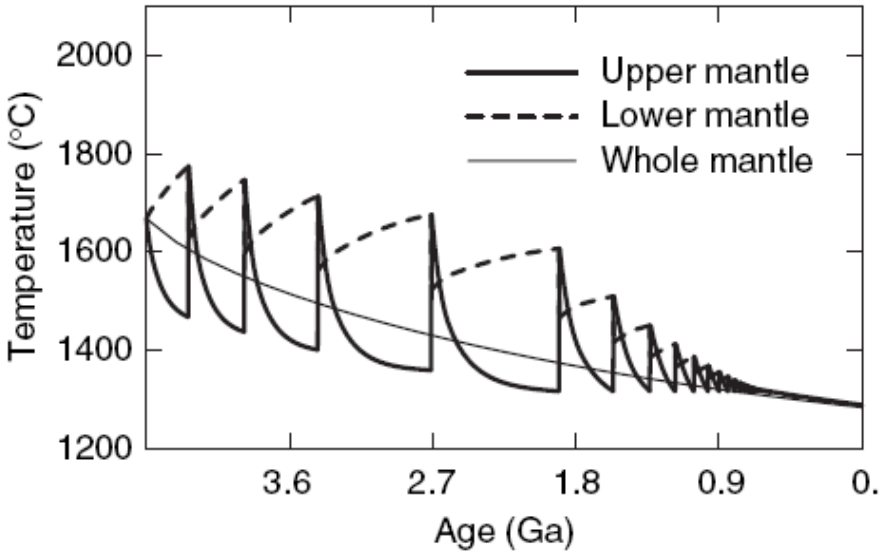
- Episodic crust formation

- Episodic continental drift?

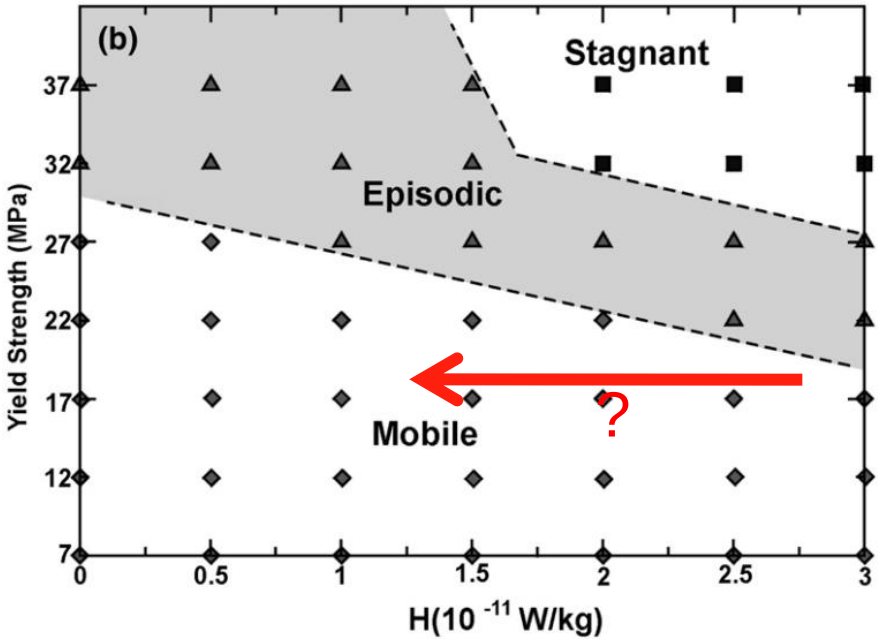


(McCulloch and Bennett, 1994; O'Neill et al., 2007)

Long-term episodicity in subduction?



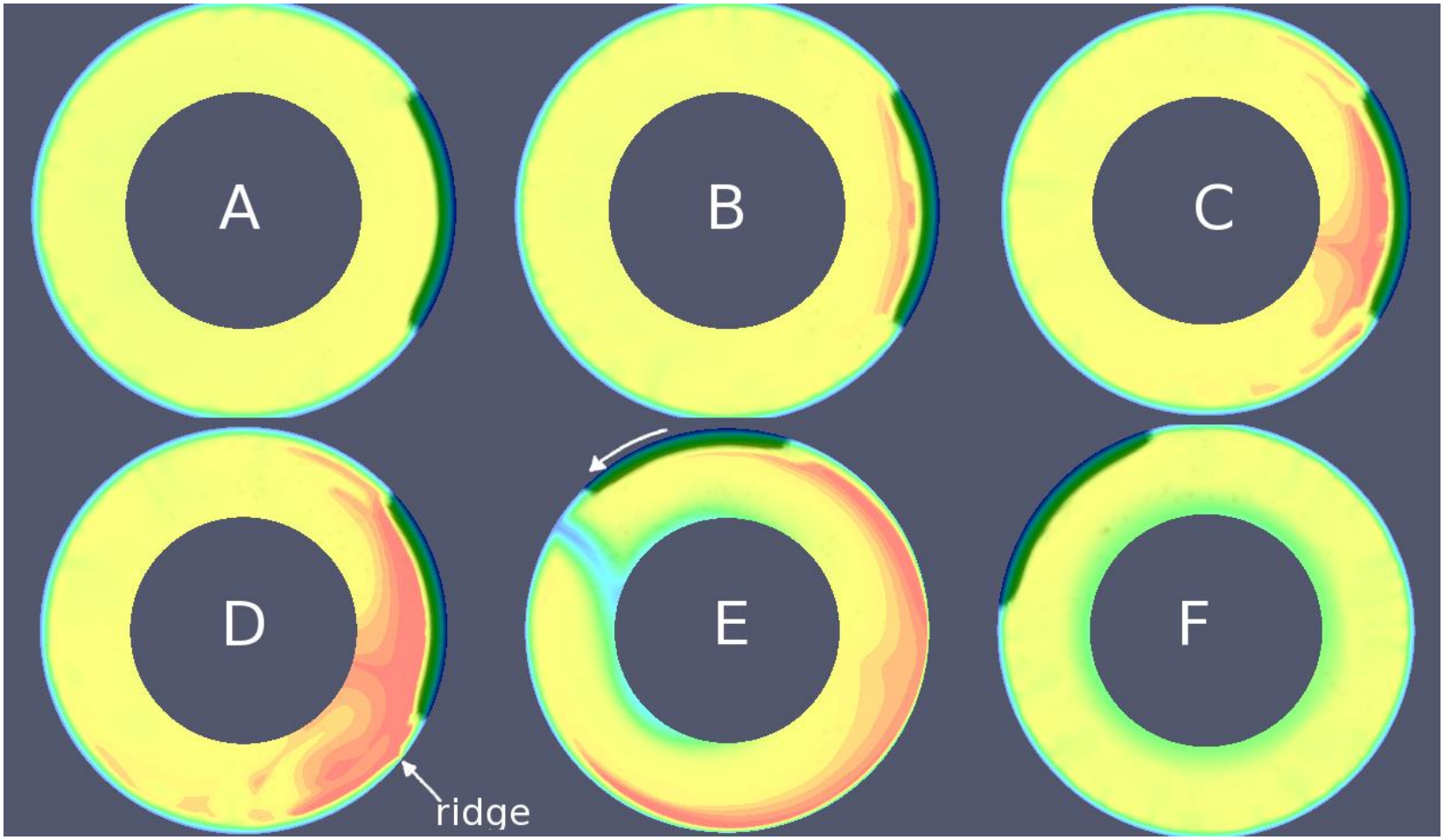
- Large-scale mantle overturns?



- Long-term 'stick-slip' behaviour?
- Break-up of supercontinents?

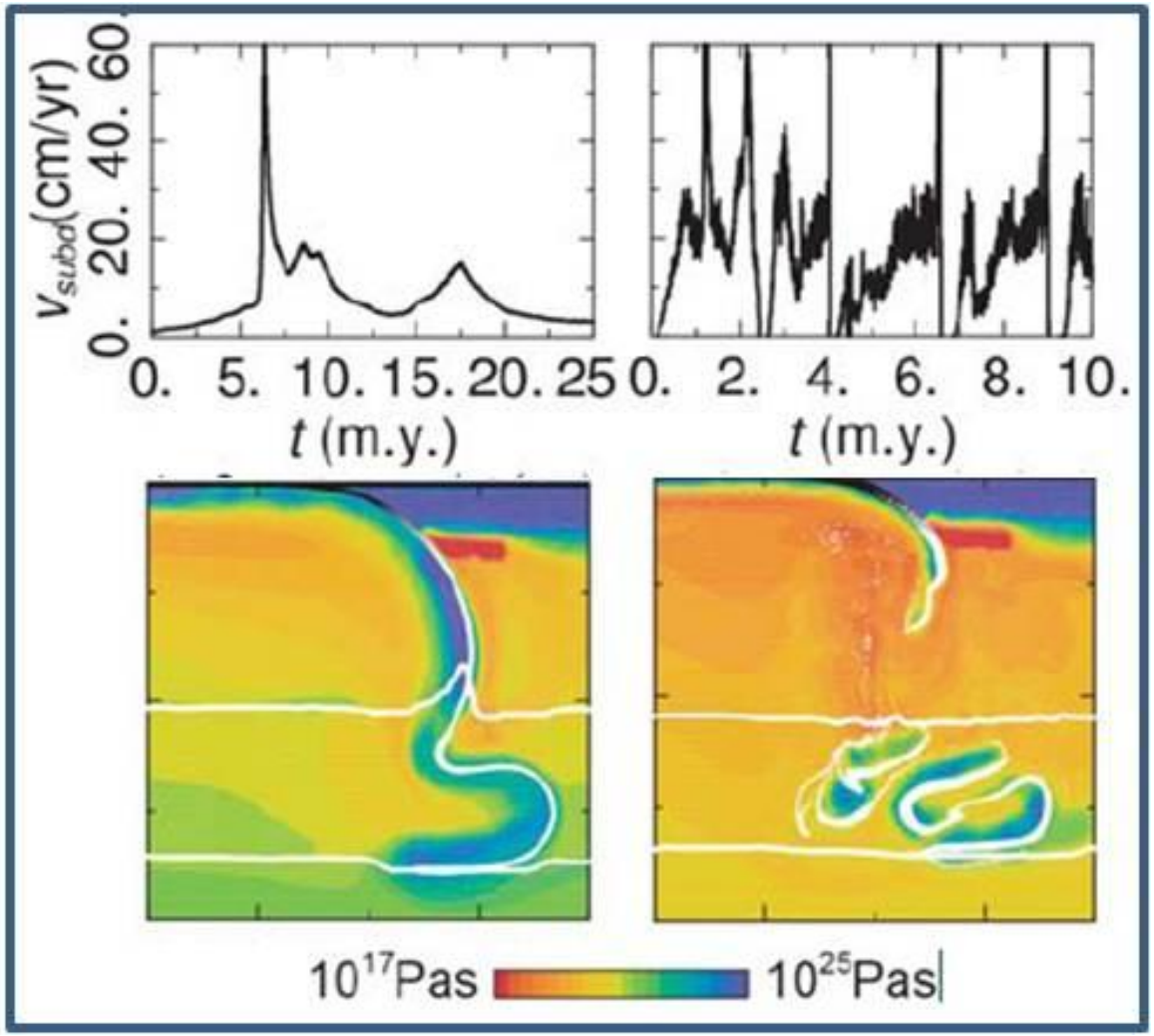
(Davies, 1995; O'Neill et al., 2007)

Episodic convection models



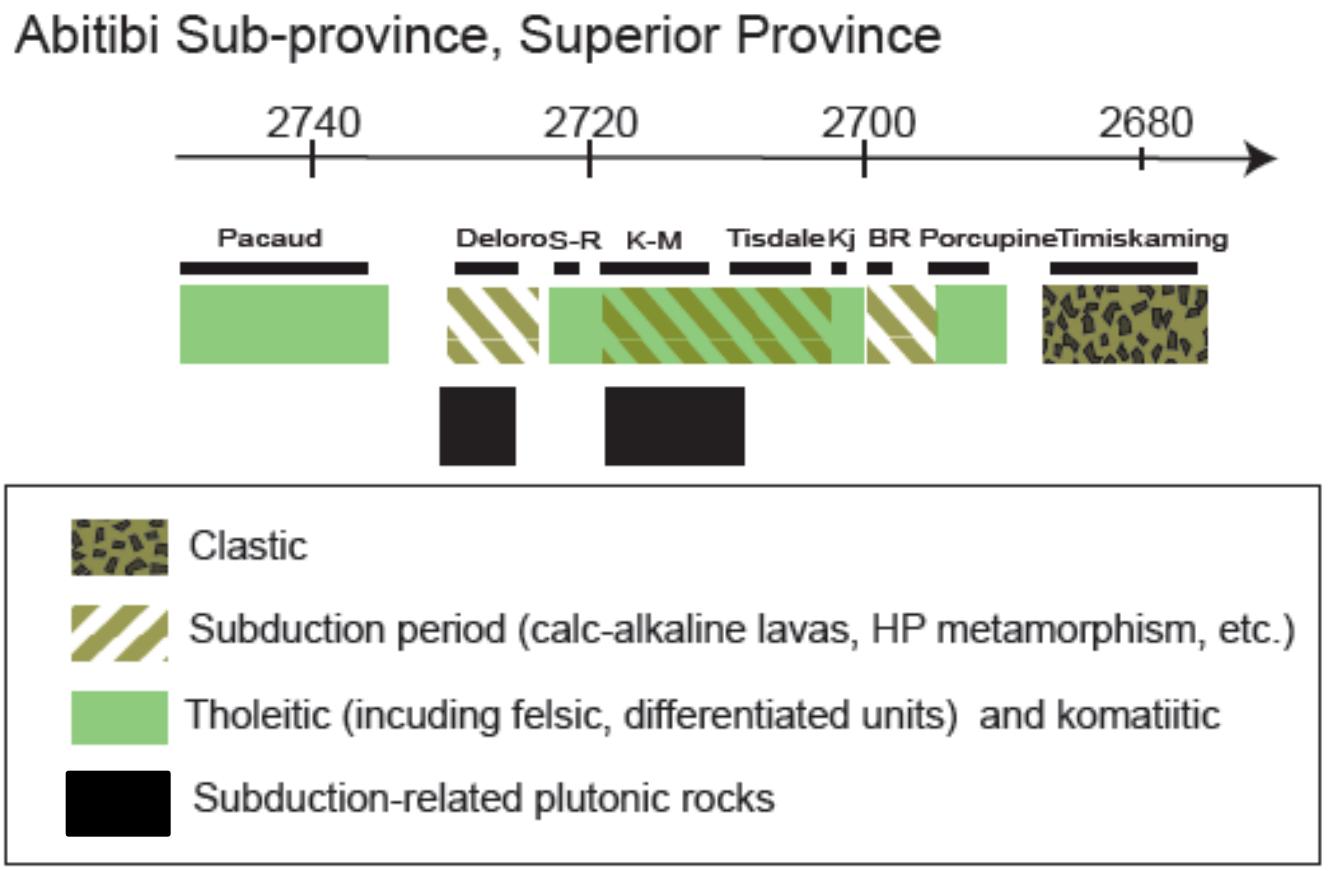
(Tobias Rolf, pers. comm.)

Short-term episodicity in subduction?



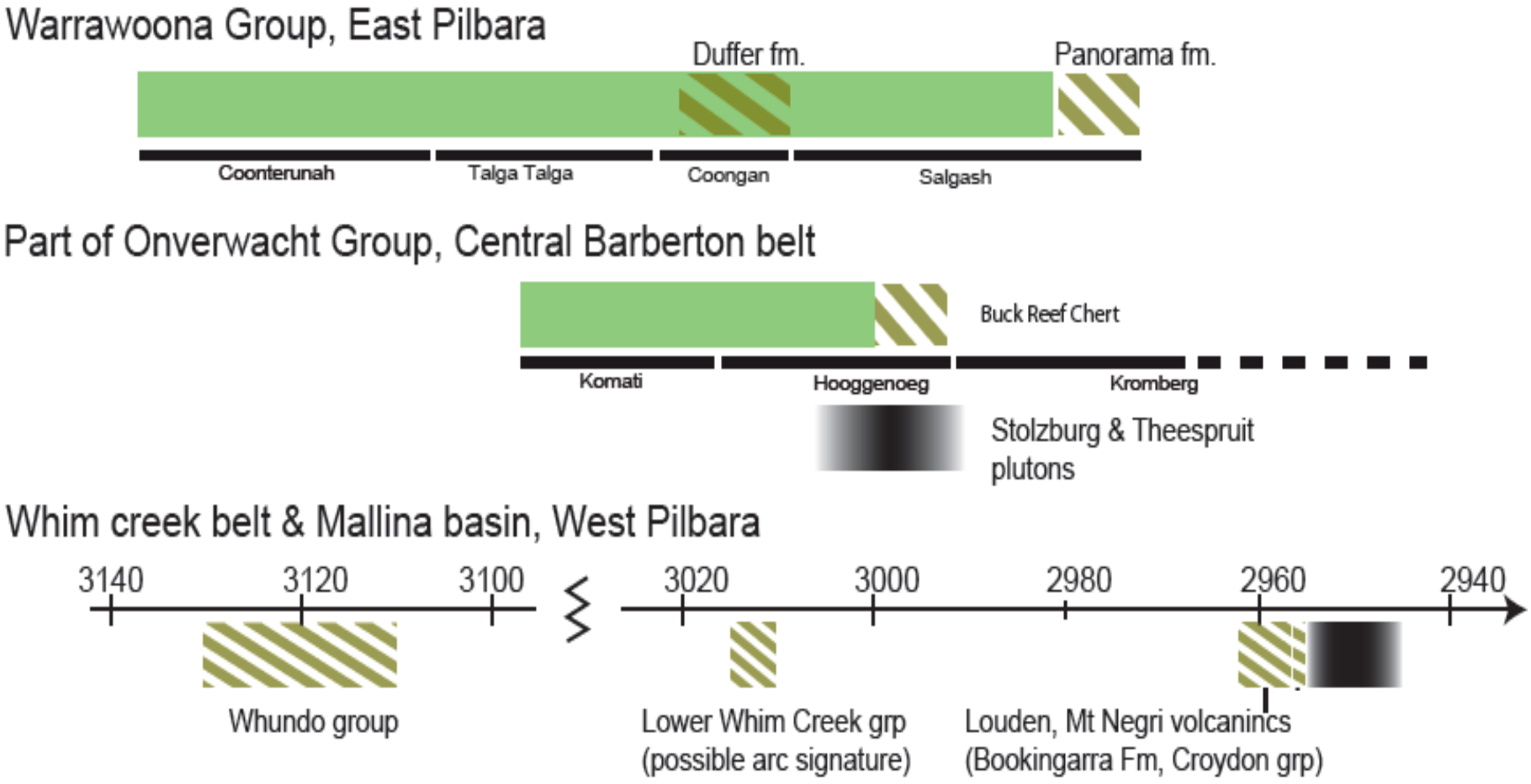
(van Hunen & van den Berg, 2008; Moyen and van Hunen, in prep.))

Episodic subduction in W-Abitibi?



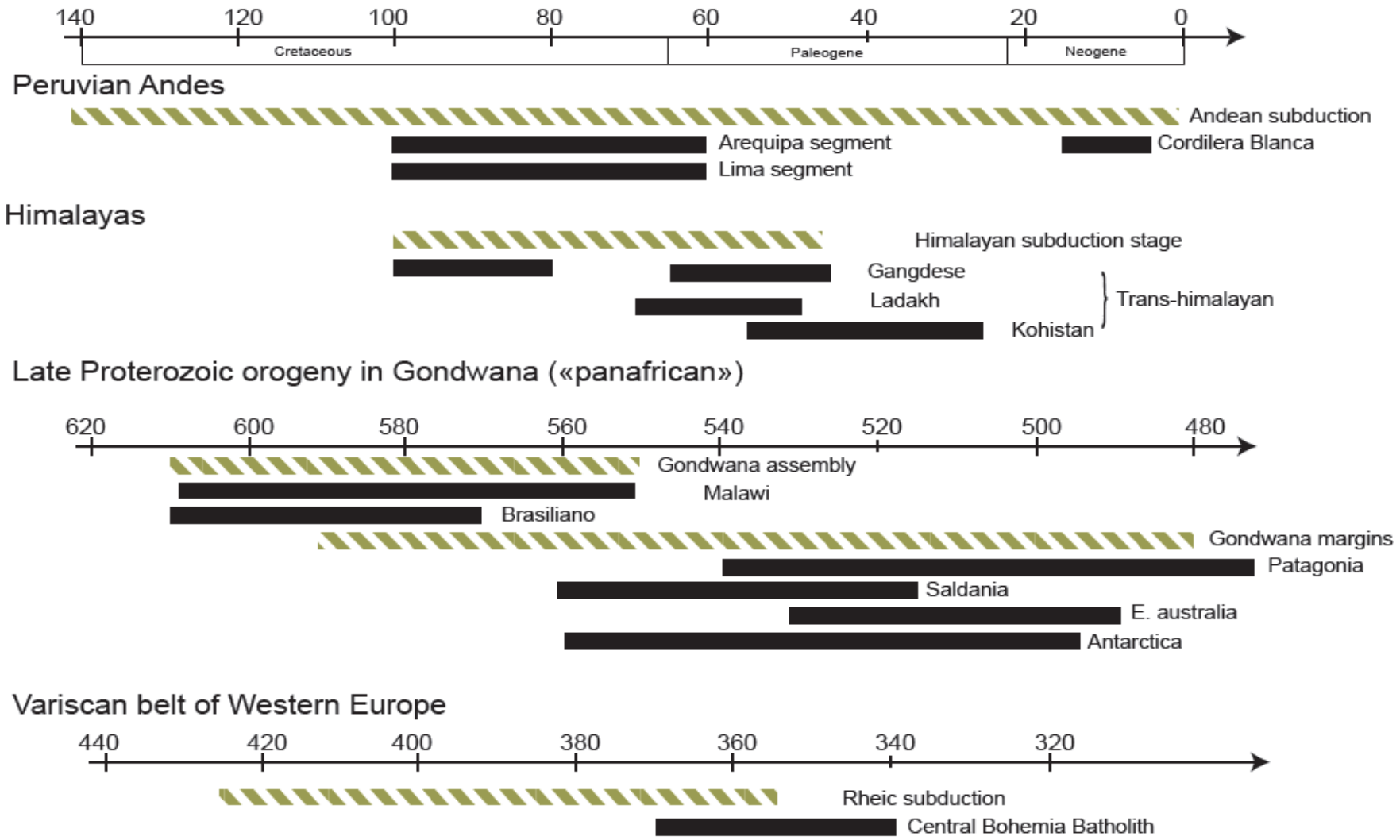
(Moyen and van Hunen, in prep.)

Other Archaean provinces?



(Moyen and van Hunen, in prep.)

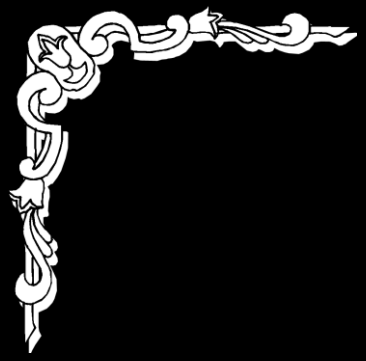
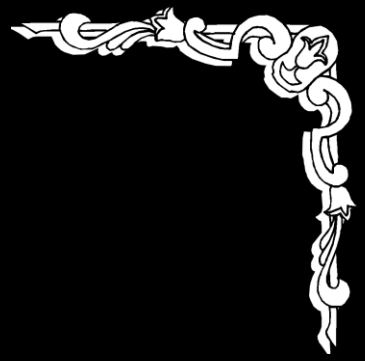
L.-Proterozoic/Phanerozoic subduction



Concluding remarks

Subduction evolution:

- Subduction viable for $\Delta T<200K$,
- perhaps not in hotter mantle
- Subduction recognized in L. Archaean rock record:
  - Ophiolites
  - Structural geology / seismic reflection studies
  - Geochemistry of TTG
  - Metamorphism
  - Paleomagnetism
- Potential changes in subduction style:
  - Episodic (long & short-term)
  - No Archaean flat subduction

The End