The dynamics of subduction throughout the Earth's history



Jeroen van Hunen

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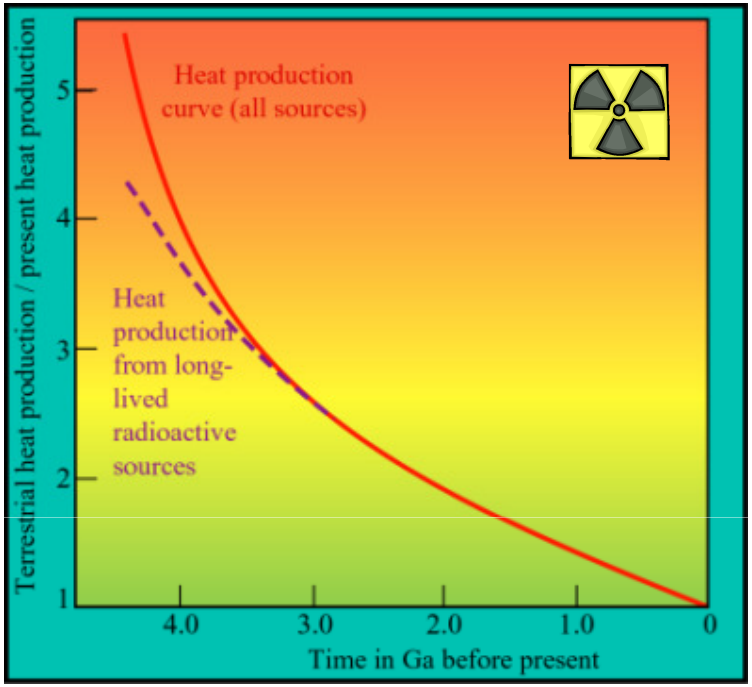
Thanks to: Jon Davidson (Durham)
Jean-Francois Moyen (St. Etienne)
Arie van den Berg (Utrecht)
Taras Gerya (ETH)

In this talk



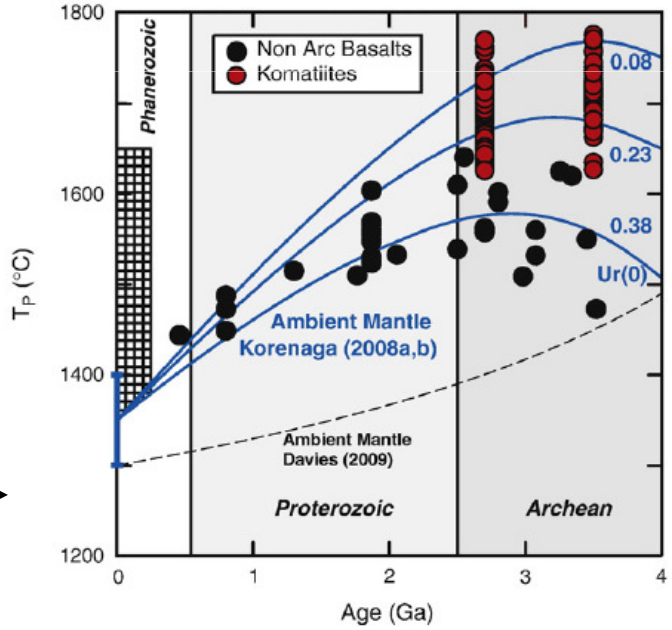
- Subduction and Earth evolution
- Since when did subduction operate?
  - Theories
  - Observables
- Did subduction style change over time?

How was Earth different in the past?



1) Produced 3x as much radiogenic heat

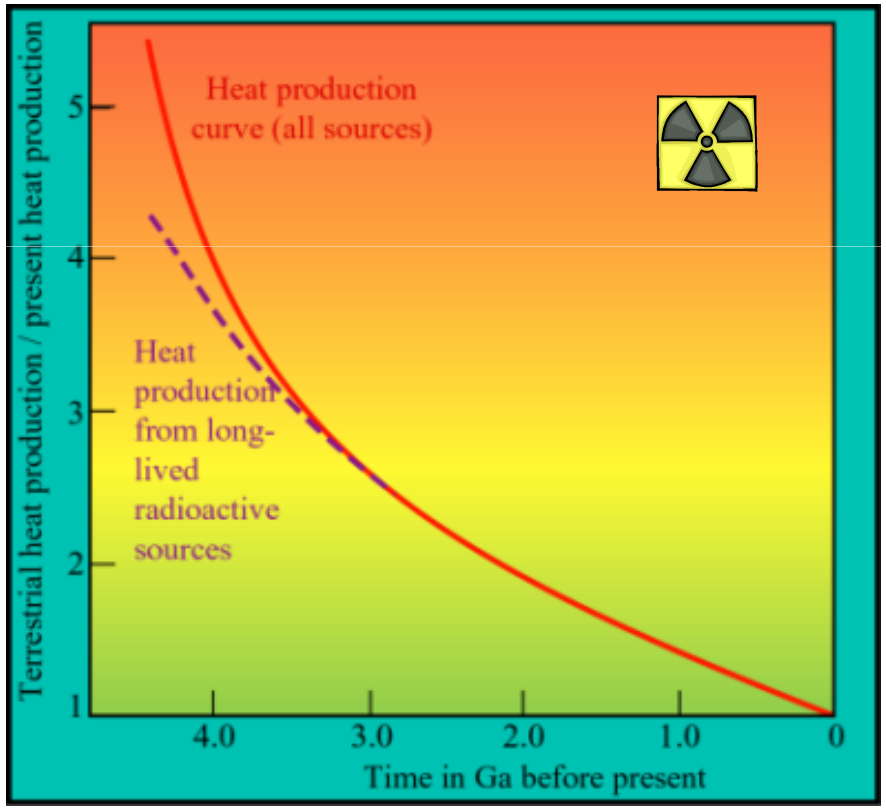
2) was 100-300 K hotter



(Herzberg et al., 2010)

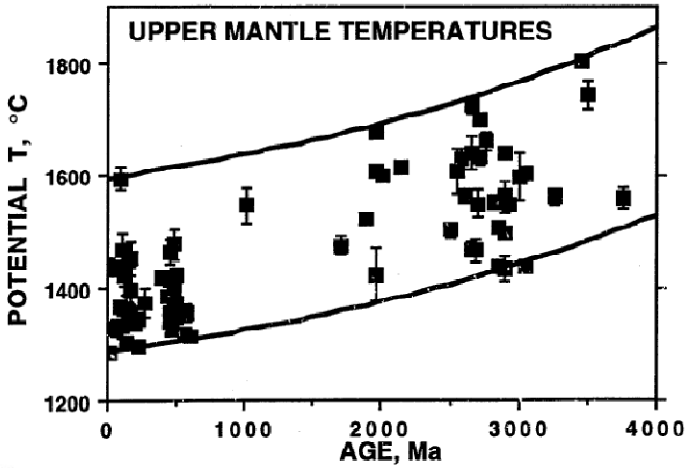
Consequences of more radiogenic heat

- Today's surface heat flux of 80 mW/m^2:
  - 50% = from radiogenic heat production
  - 50% = Earth cooling
- To have Earth cooling in Archaean, we need a cooling mechanism more efficient than plate tectonics (PT)

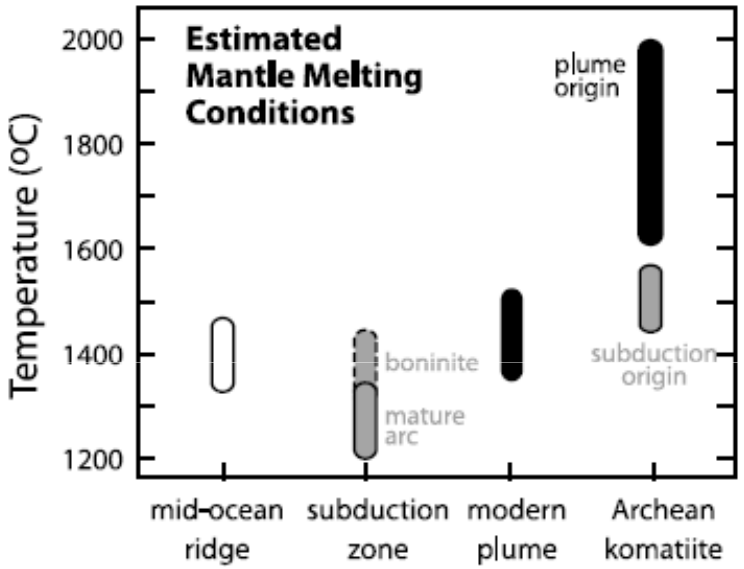


(Sleep, 2000; Turcotte and Schubert, 2002)

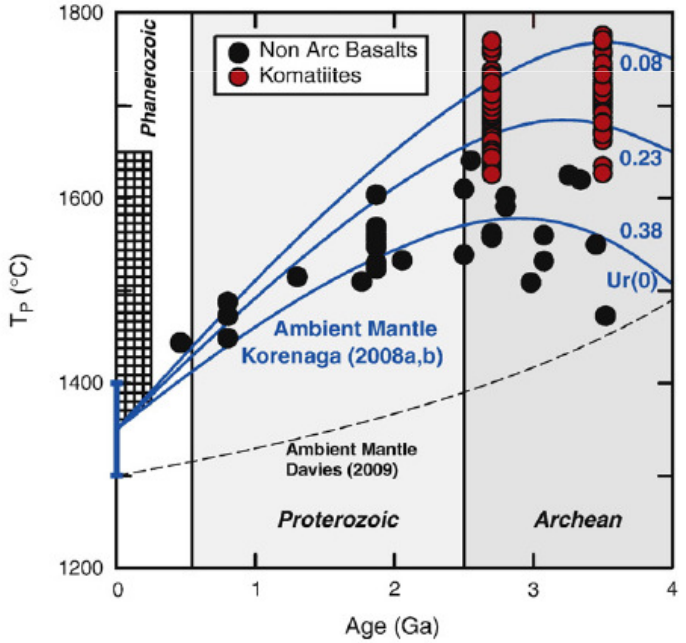
Archaean mantle was 100-300 K hotter



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



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

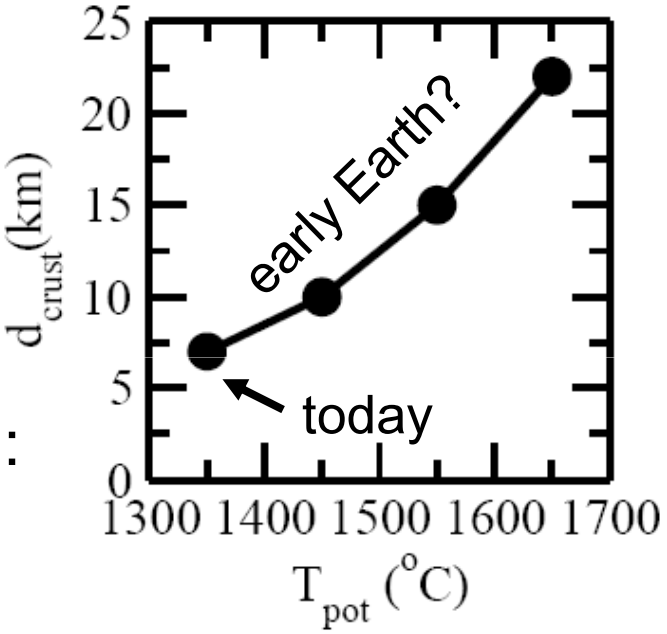


Peak temperature in Archaean? (Herzberg et al., 2010)

Consequences of a hotter mantle

1. More melting at mid-ocean ridges
   - thicker oceanic crust
   - thicker harzburgitic melt residue layer

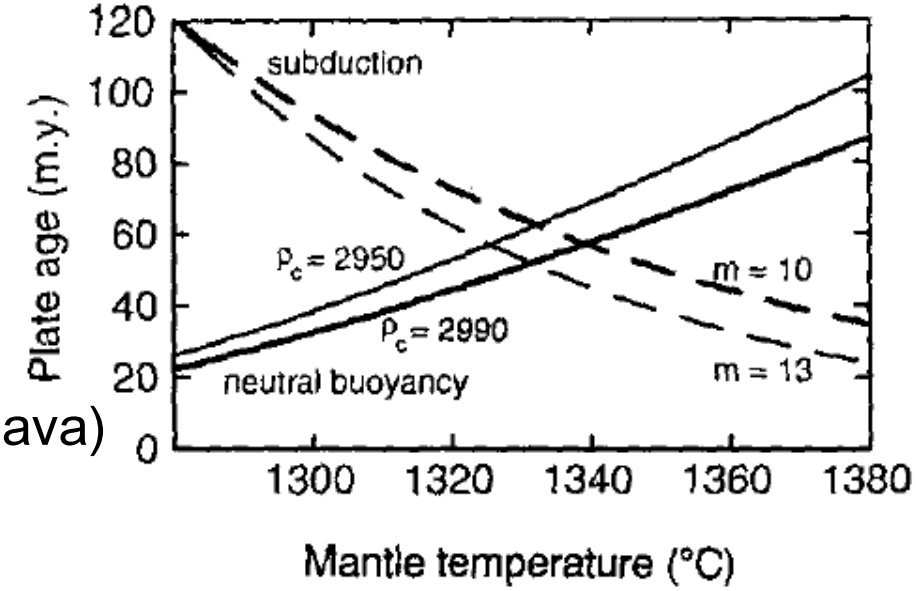
2. Weaker plate and mantle material:
   - $\eta = \exp(T)$
   - ~1 order of magnitude for every 100 K
   - Effect of dehydration strengthening?

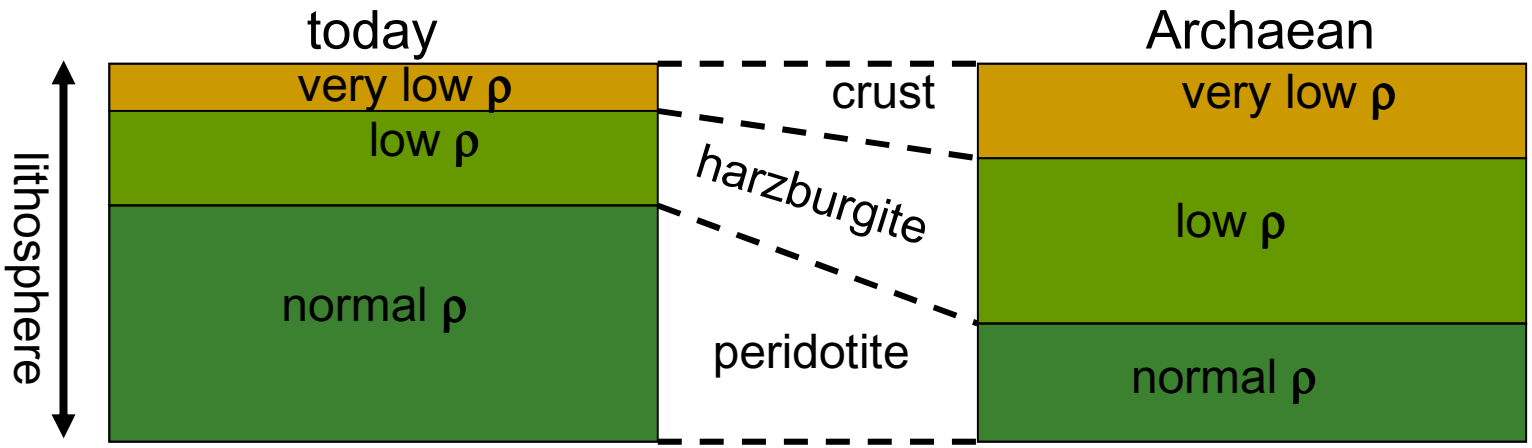


(van Thienen & al., 2004)

Consequences of more melting

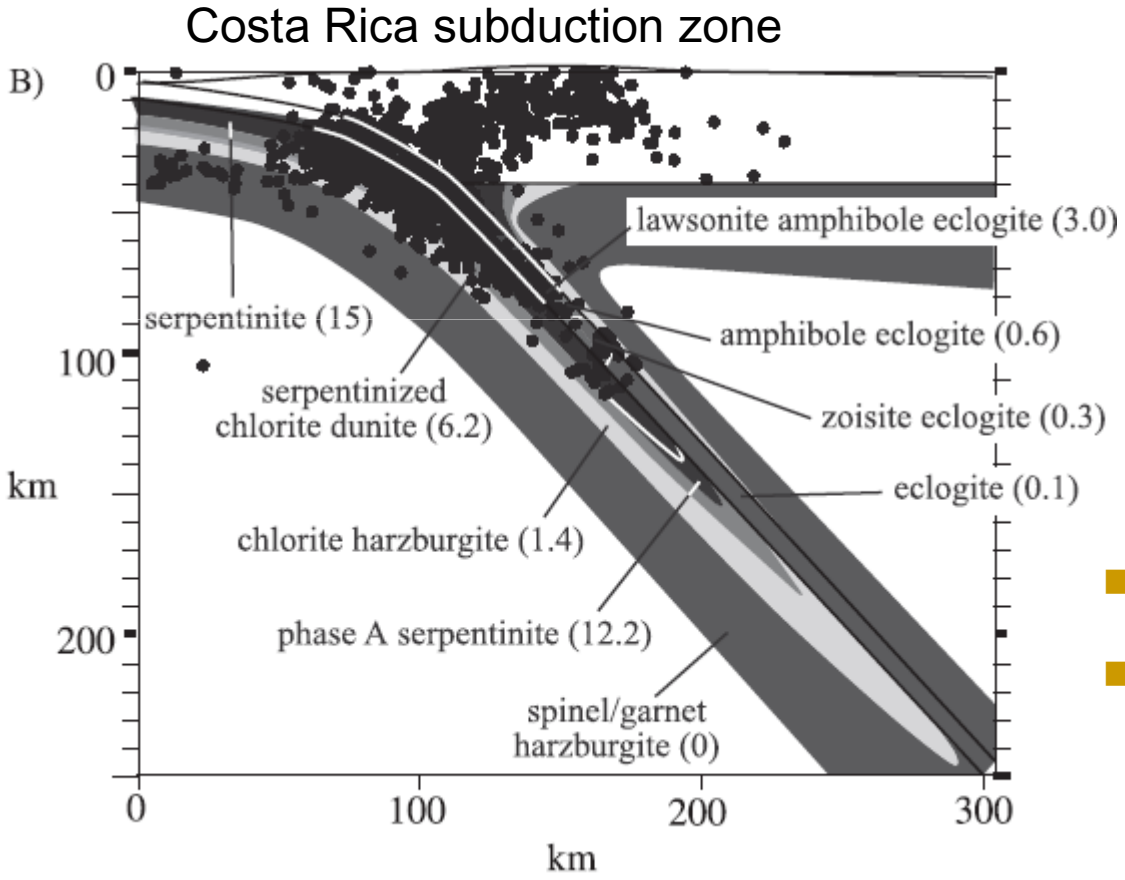
- more melting
- thick crust/harzburgite
- low average density ρ
- no slab pull?
- no subduction? (Ontong Java)
- no plate tectonics?

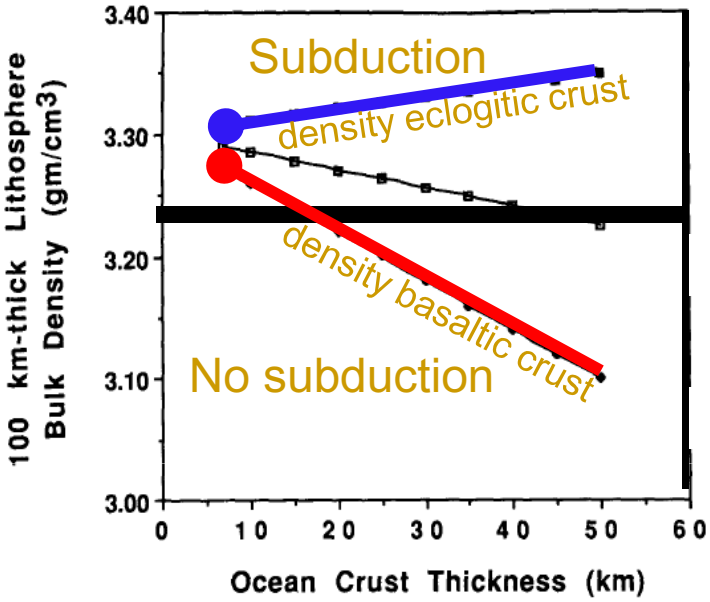




(Davies, 1992)

Effect of basalt-eclogite transition?



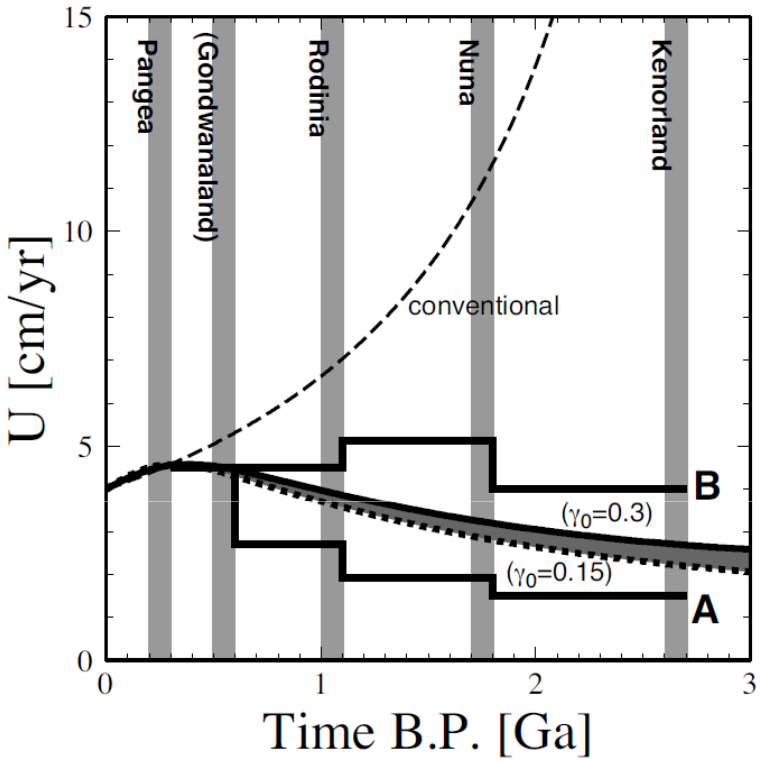


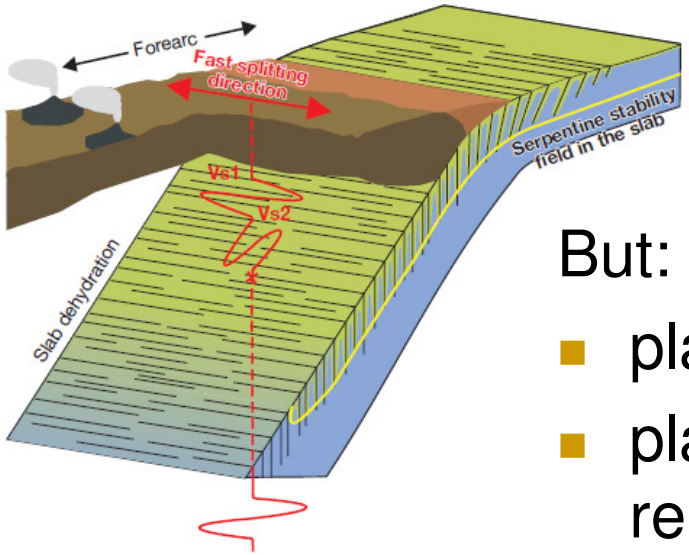
- Meta-stable basalt
- transition gradual

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

Stronger Archaean plates?

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





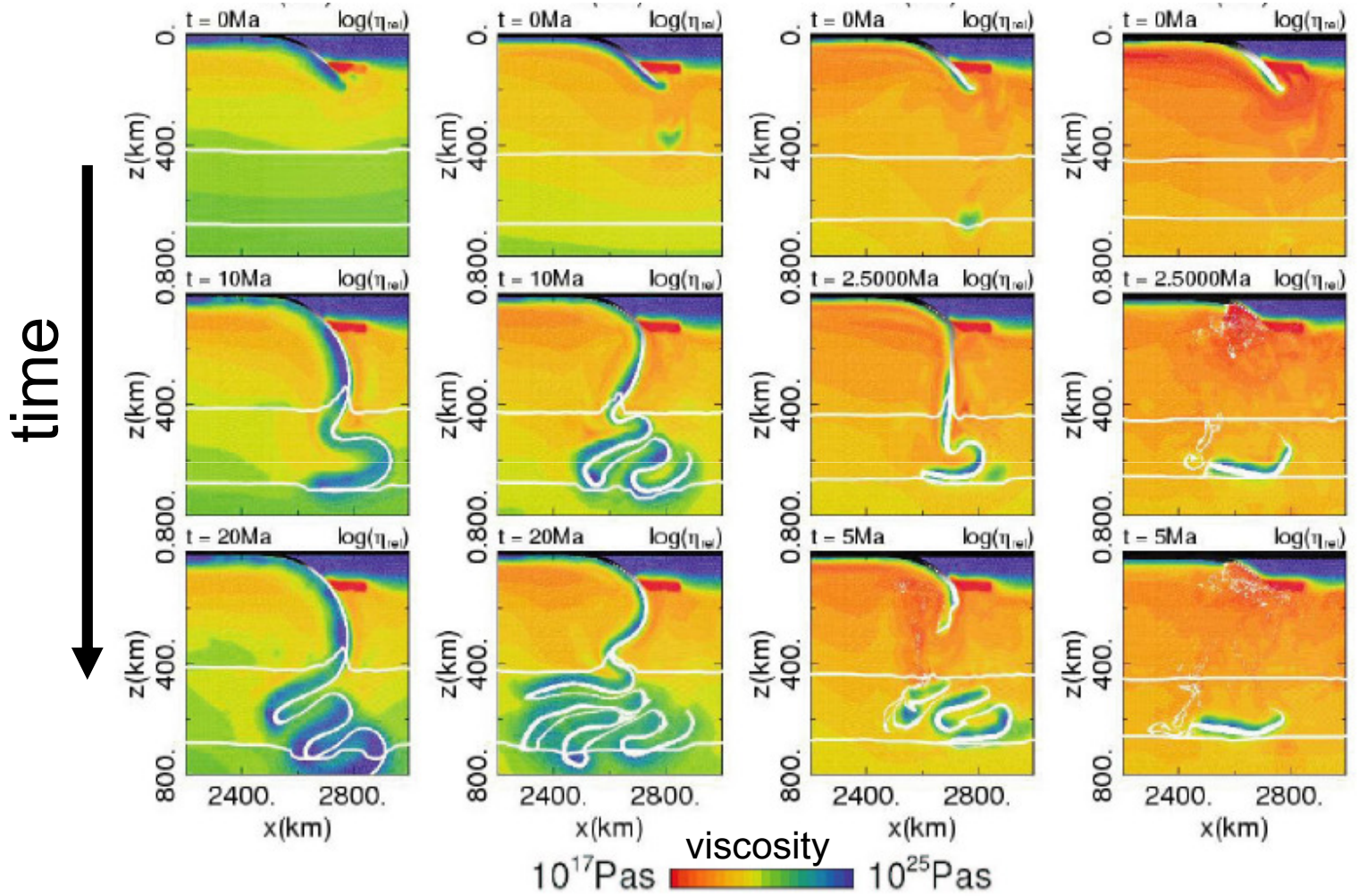
But:

- plate strength in cold top part
- plates bending induces faulting + rehydration

(Faccenda et al., 2008)

(Korenaga, 2006)

Weaker Archaean plates?



colors = viscosity

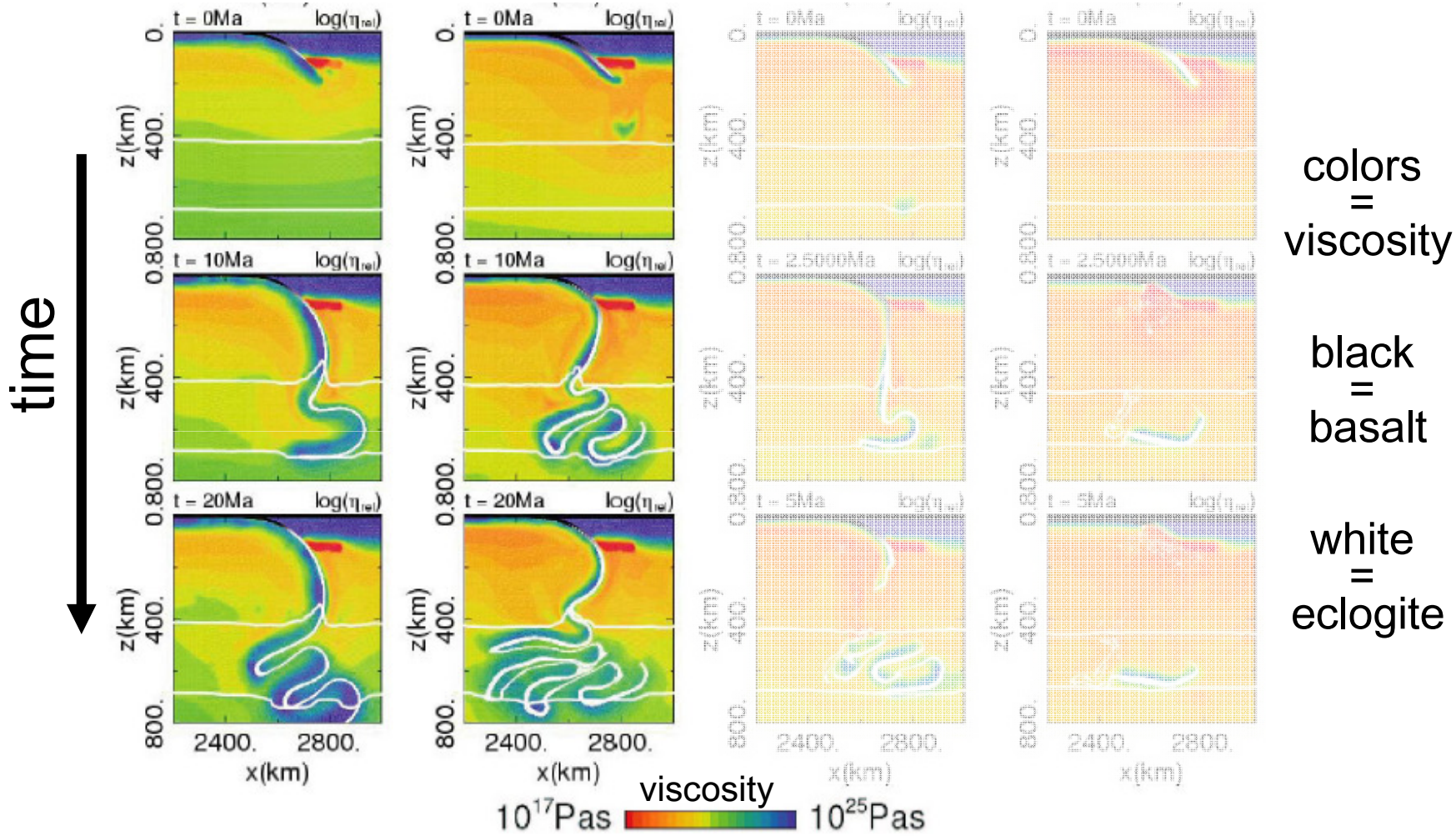
black = basalt

white = eclogite

ΔT_{mantle} = 0°C 100°C 200°C 300°C

(van Hunen & van den Berg, 2008)

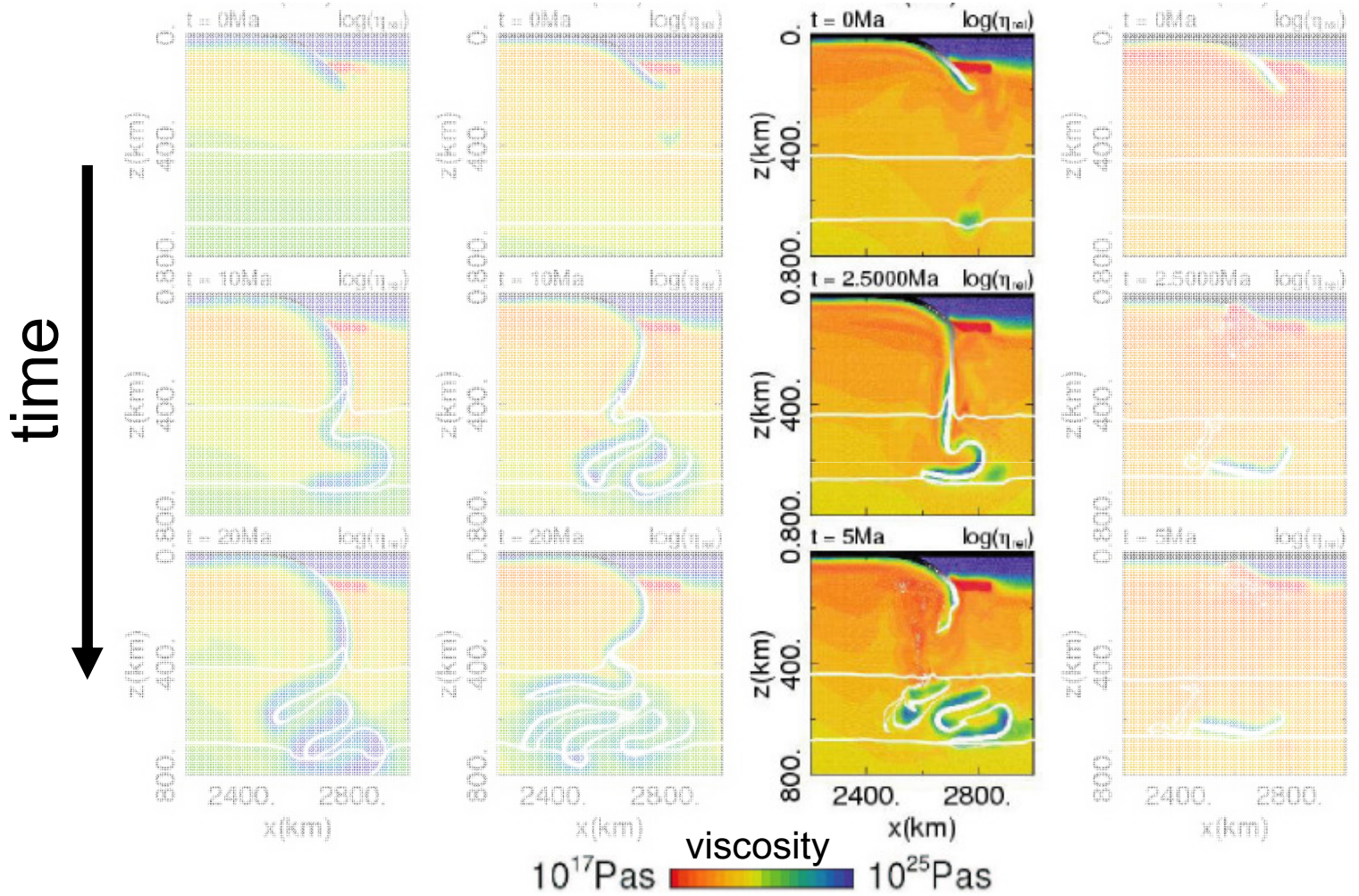
Weaker Archaean plates?



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

(van Hunen & van den Berg, 2008)

Weaker Archaean plates?



colors = viscosity

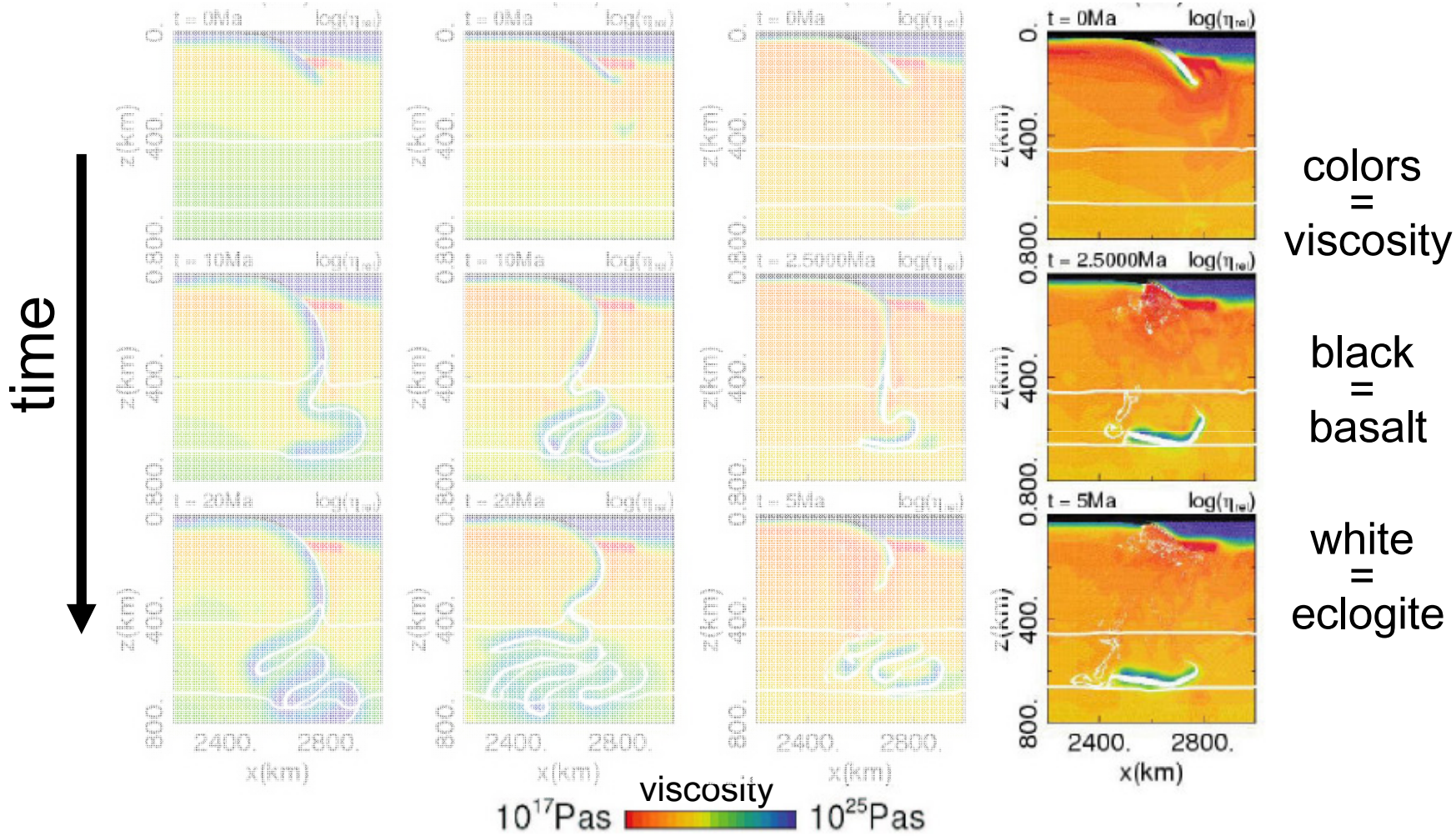
black = basalt

white = eclogite

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

(van Hunen & van den Berg, 2008)

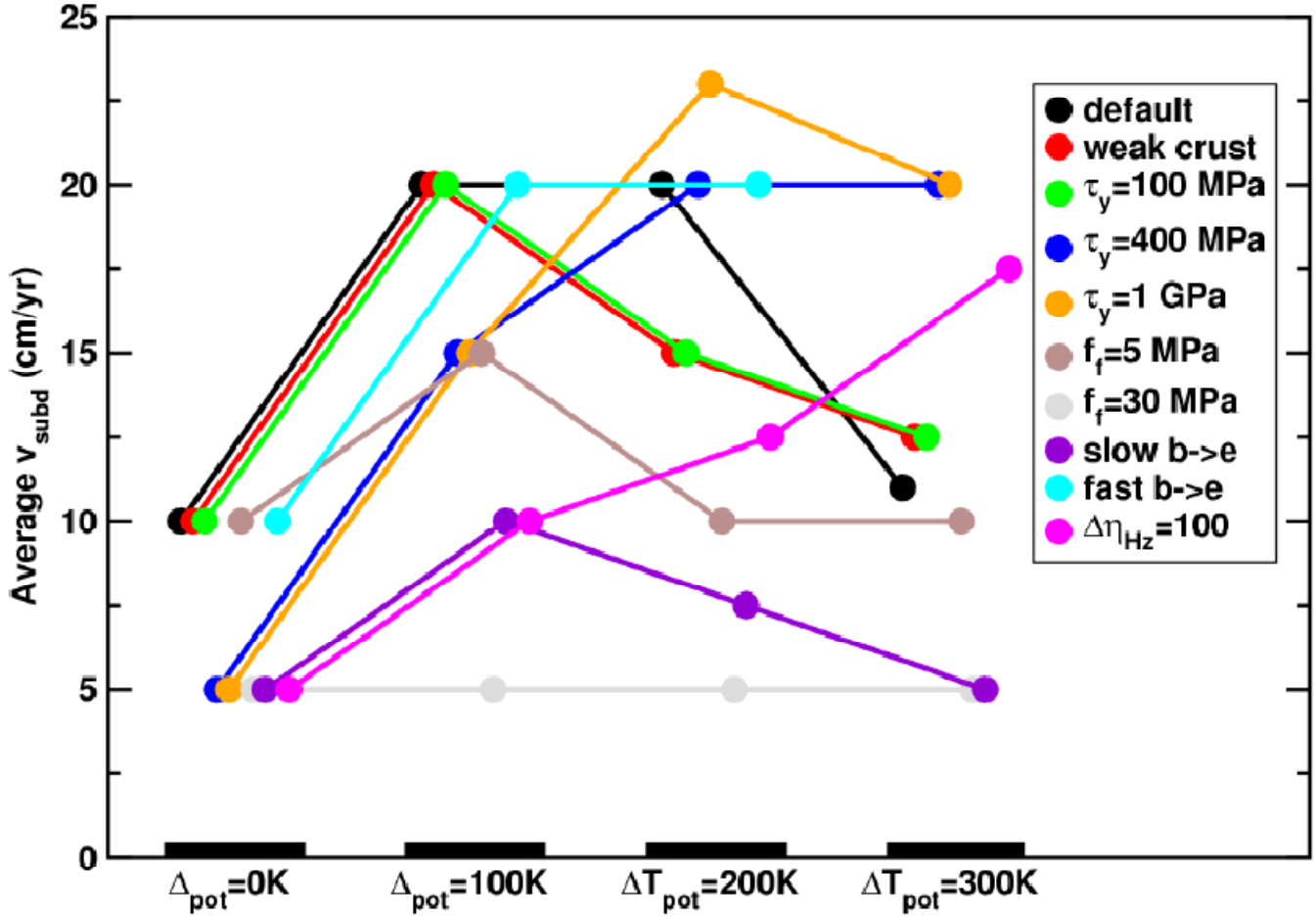
Weaker Archaean plates?



- … or subduction completely stops.

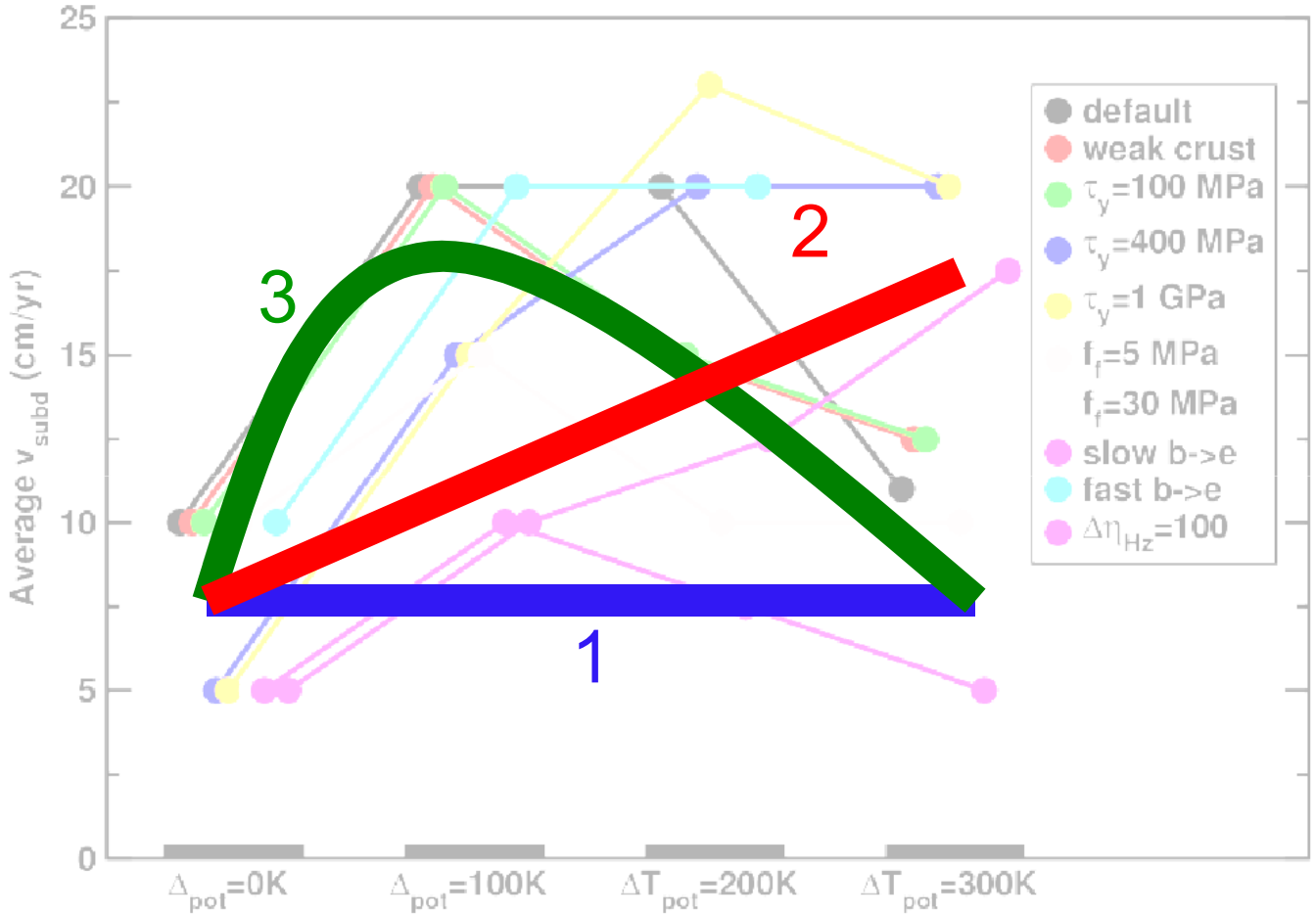
(van Hunen & van den Berg, 2008)

Summary of many model calculations



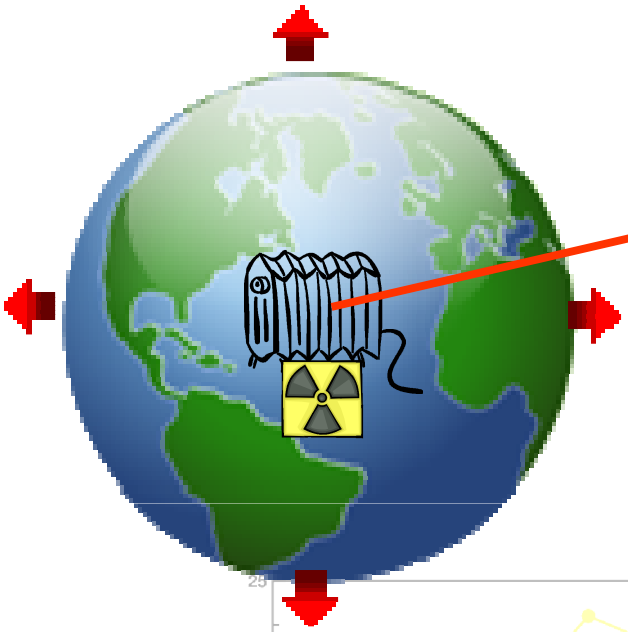
Are these subduction velocities enough to cool early Earth?

Possible parameterizations of v_{subd}



Are these subduction velocities enough to cool early Earth?

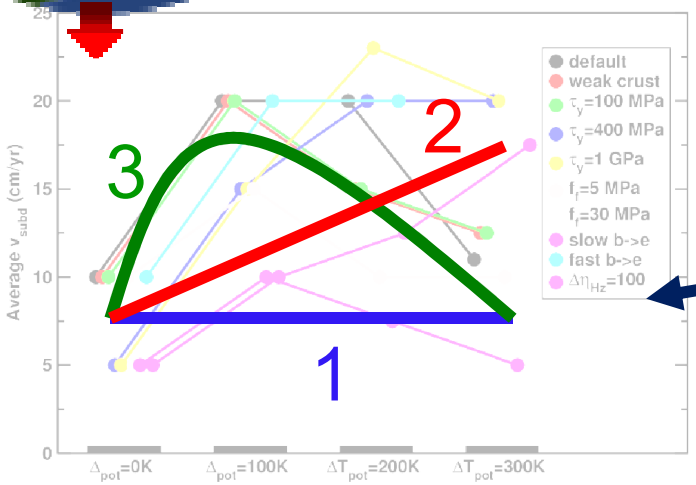
Thermal evolution the Earth



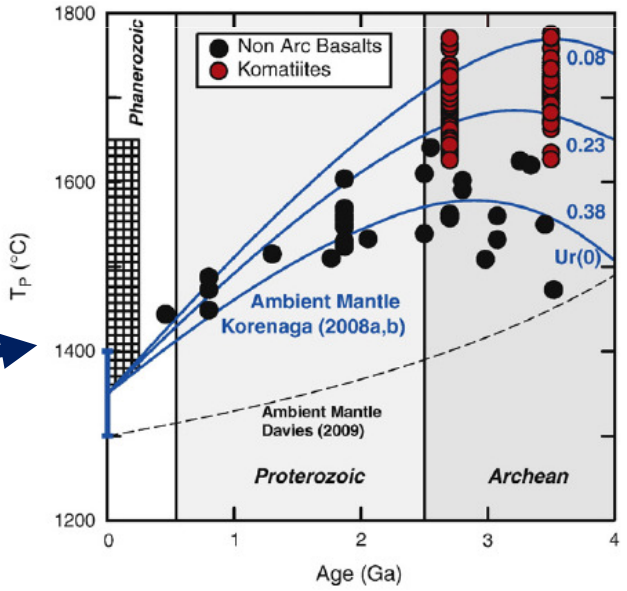
$$C_p \frac{dT}{dt} = H - Q$$

Heat production

Surface heat flow



?

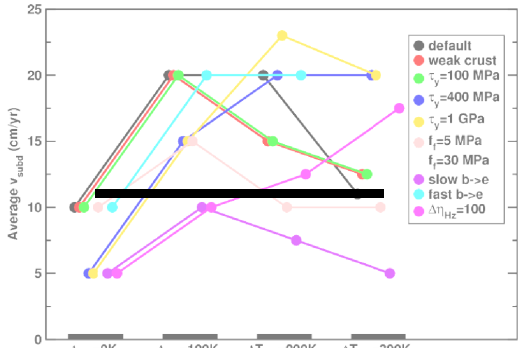


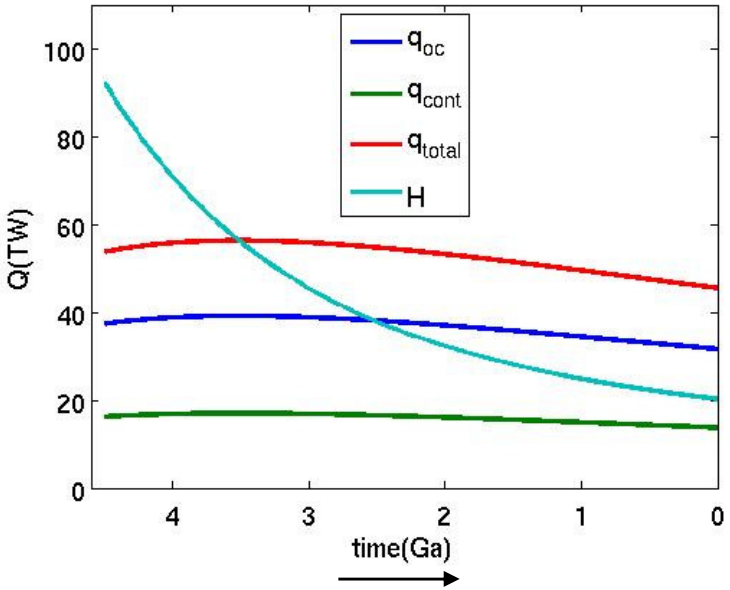
(Reymer and Schubert, 1984; Sleep, 2000; van Thienen et al., 2005)

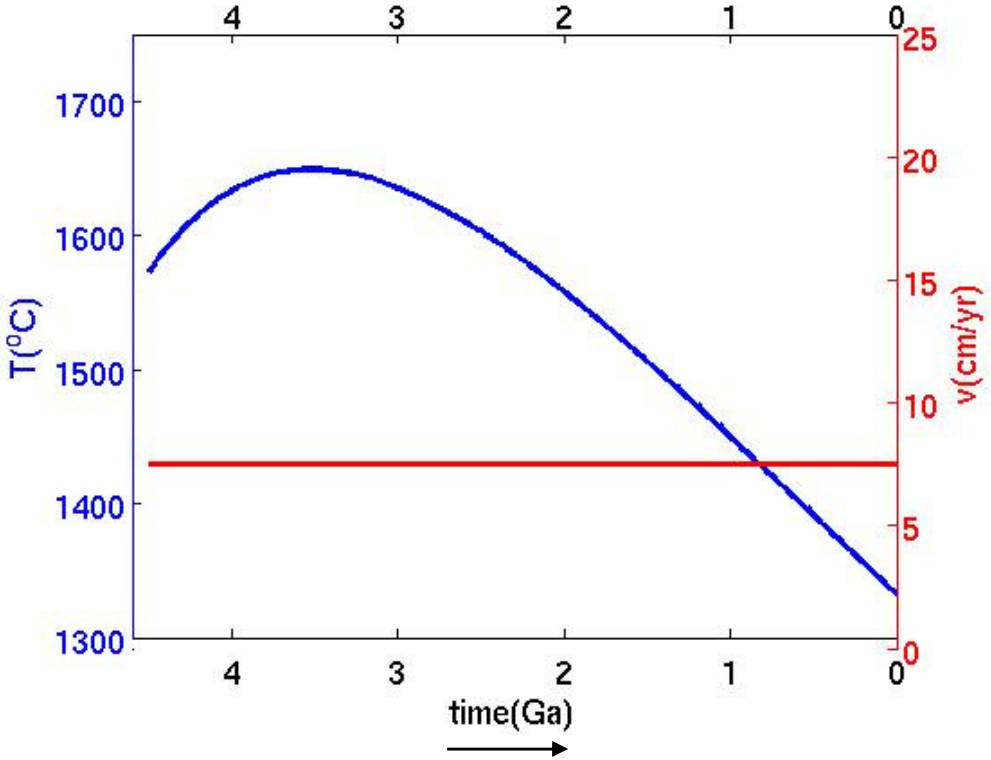
(Herzberg et al., 2010)

Model 1: subduction for all T_m

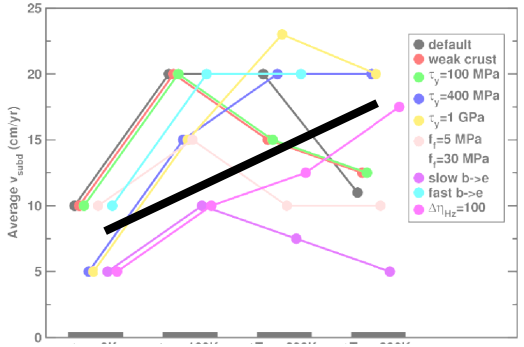
- Flat vsubd rate:
  cooling since early Archean
- Cooling curve similar to Korenaga,'06 and Labrosse & Jaupart,'07.

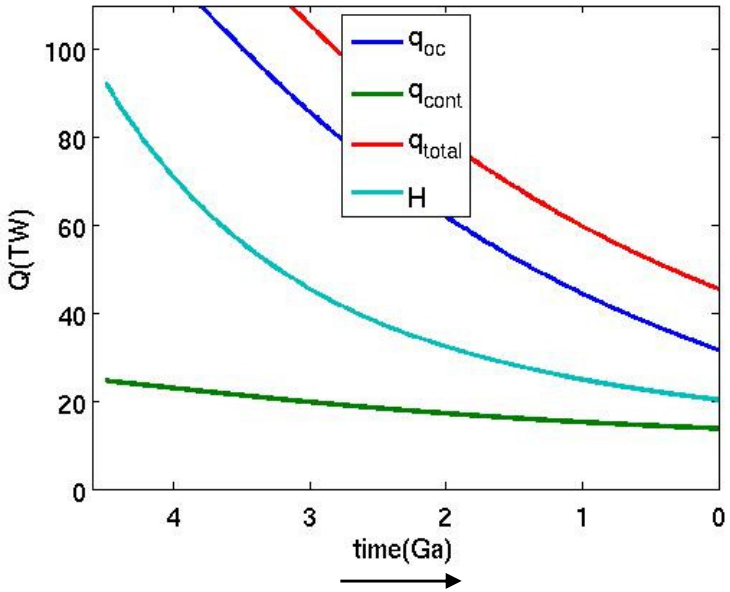




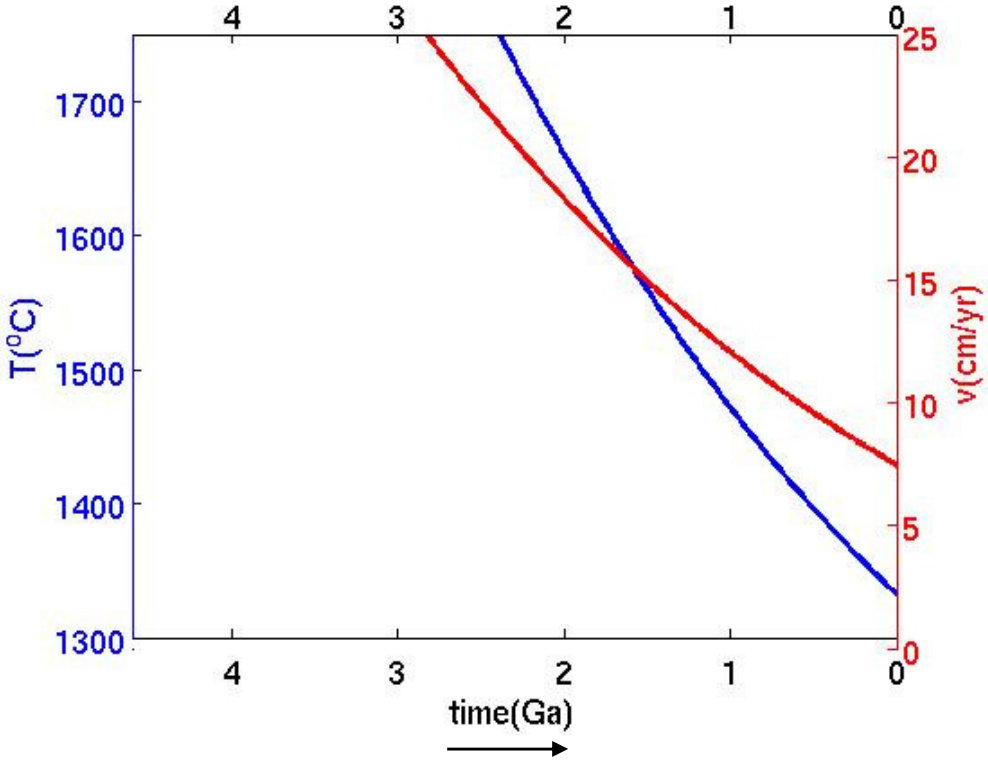


Model 2: Rapid plate tectonics → efficient cooling → 'thermal catastrophe'

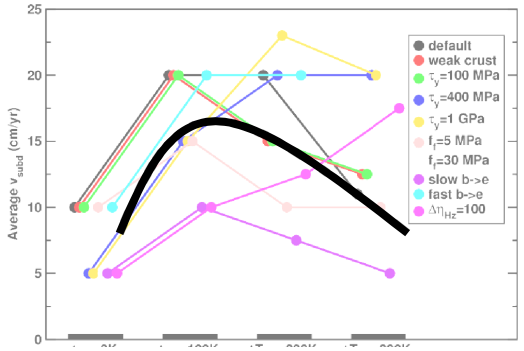




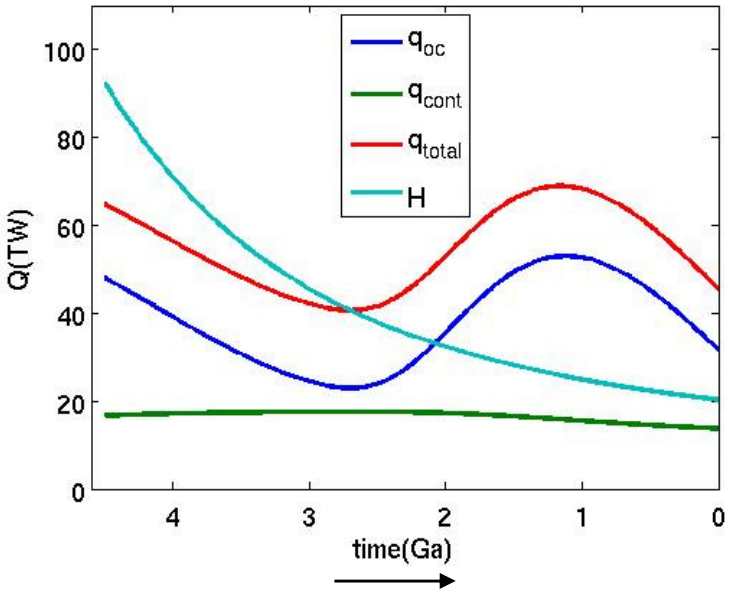
Increasing v_{subd} with T_{pot}:
'Thermal catastrophe'

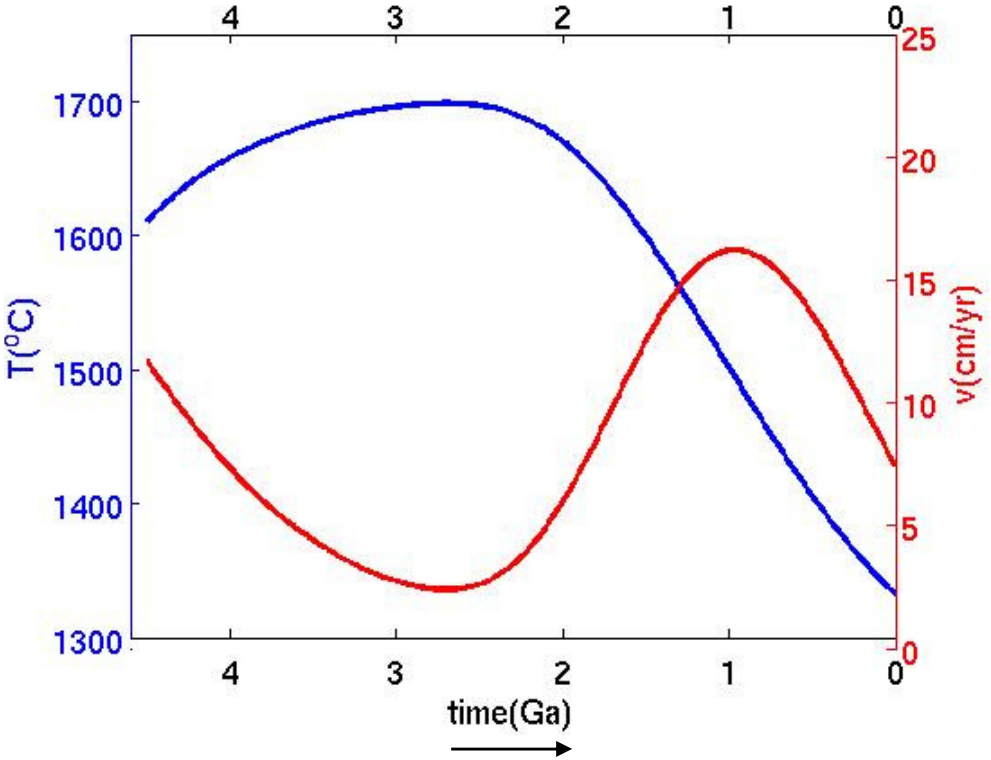


Model 3: Inefficient subduction → hotter Archaean mantle



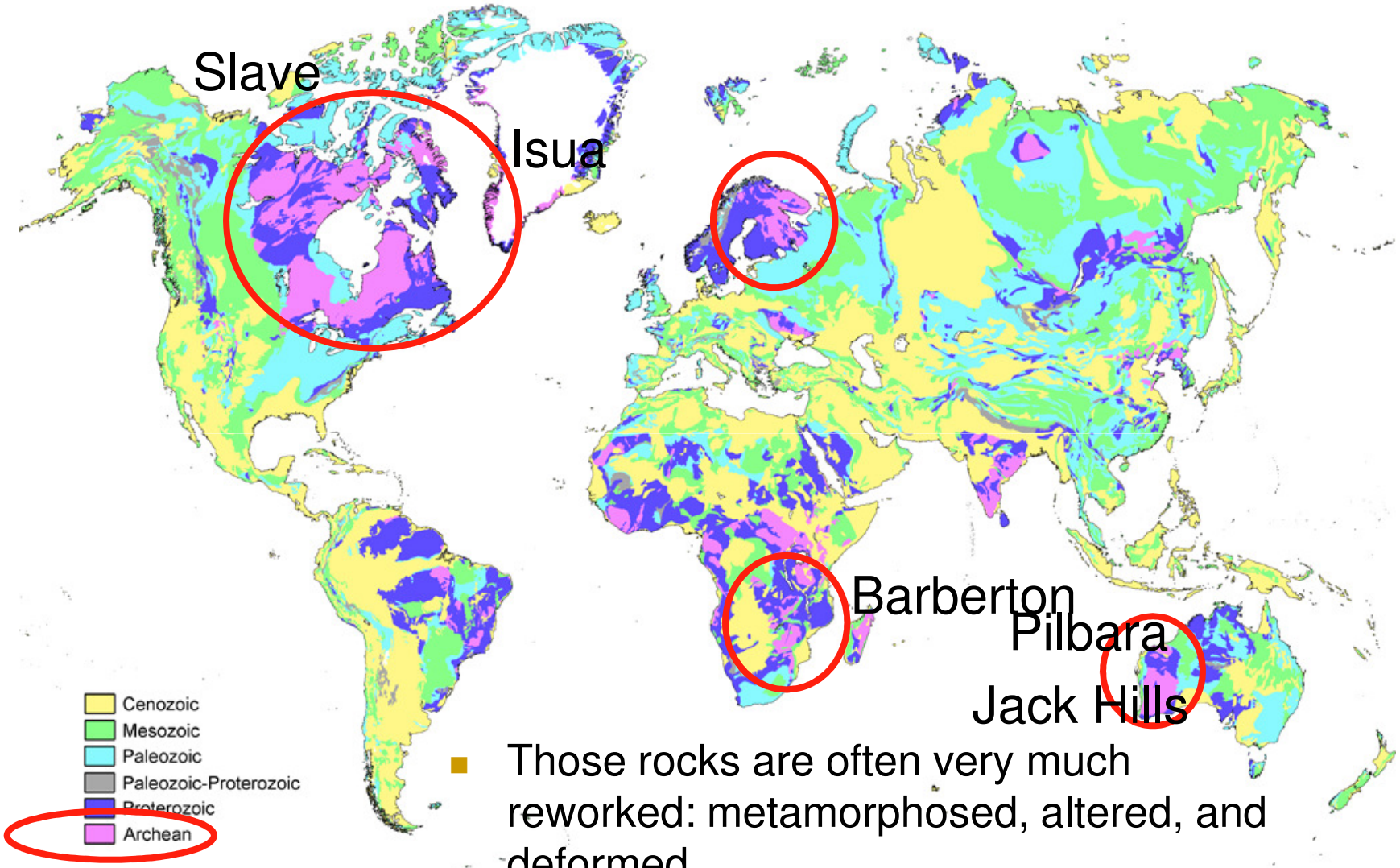
Peak in v_{subd}:
Recent rapid cooling since Proterozoic





Observations

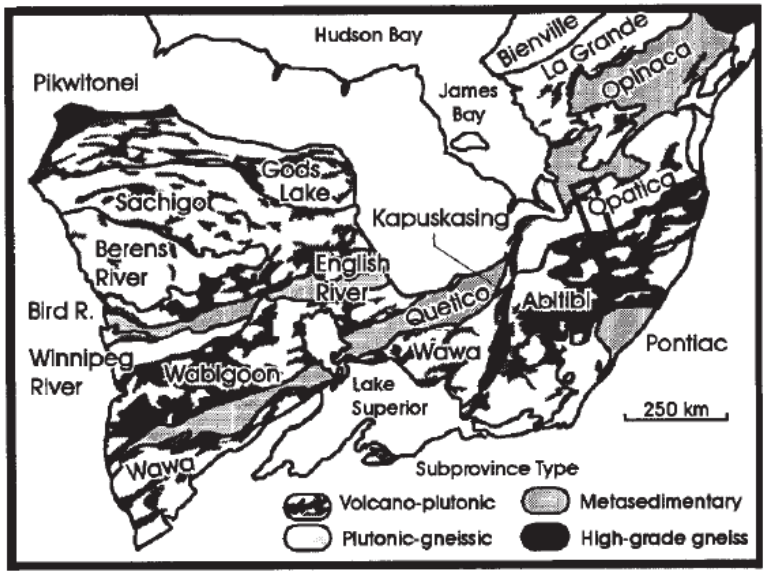
- Only very few old rocks are preserved.



- Those rocks are often very much reworked: metamorphosed, altered, and deformed

Linear features?

Abitibi, Superior Province



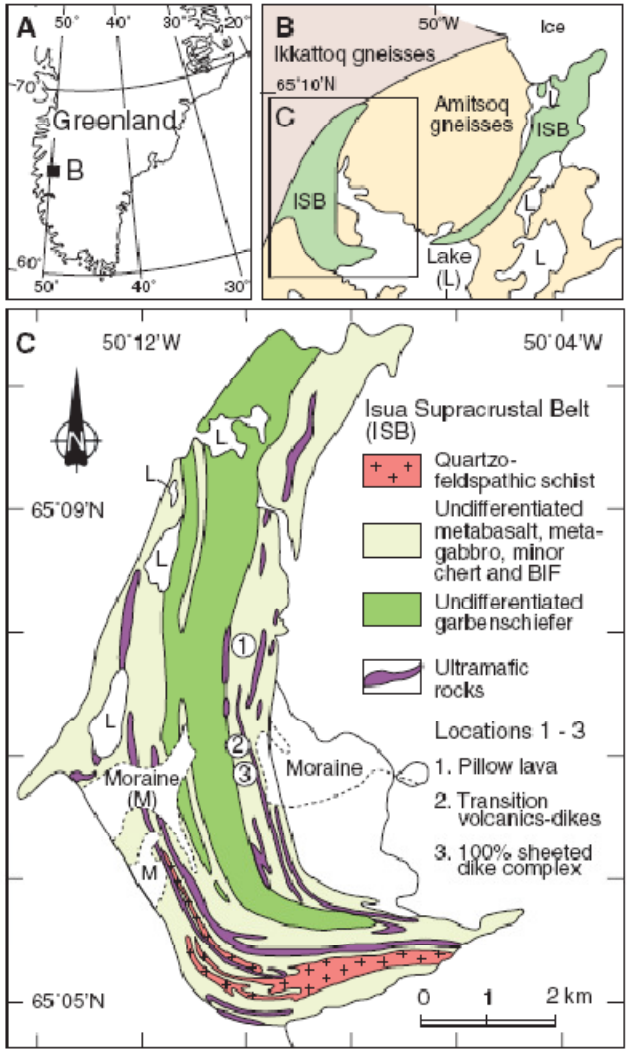
Pilbara, Australia



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

Oldest ophiolites

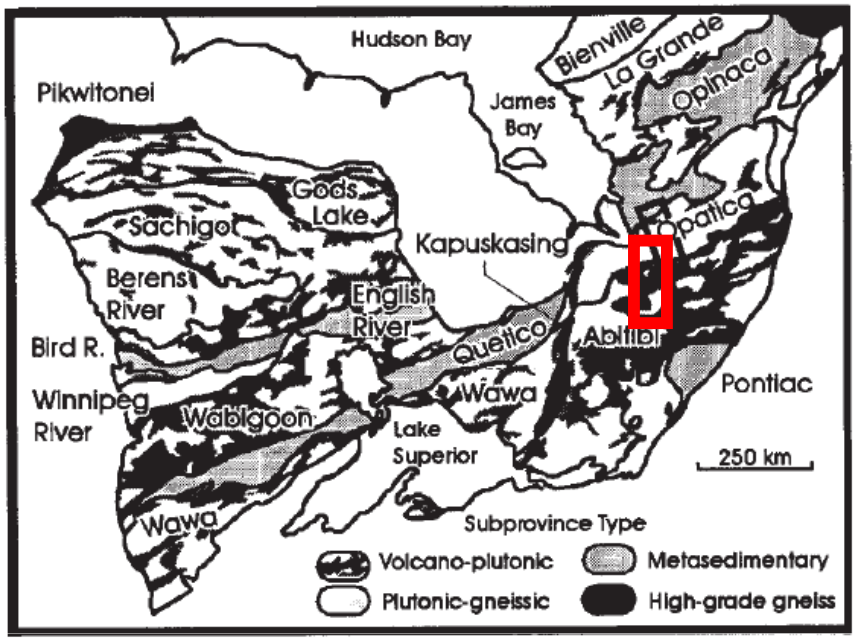
- Oldest ophiolite 3.7 Gyrs old?
- Oldest generally accepted ophiolites are ~2 Gyrs old (Jormua, Finland; Purtuniq, Canada)
- Ophiolites become wide-spread after 1.0 Gyrs ago

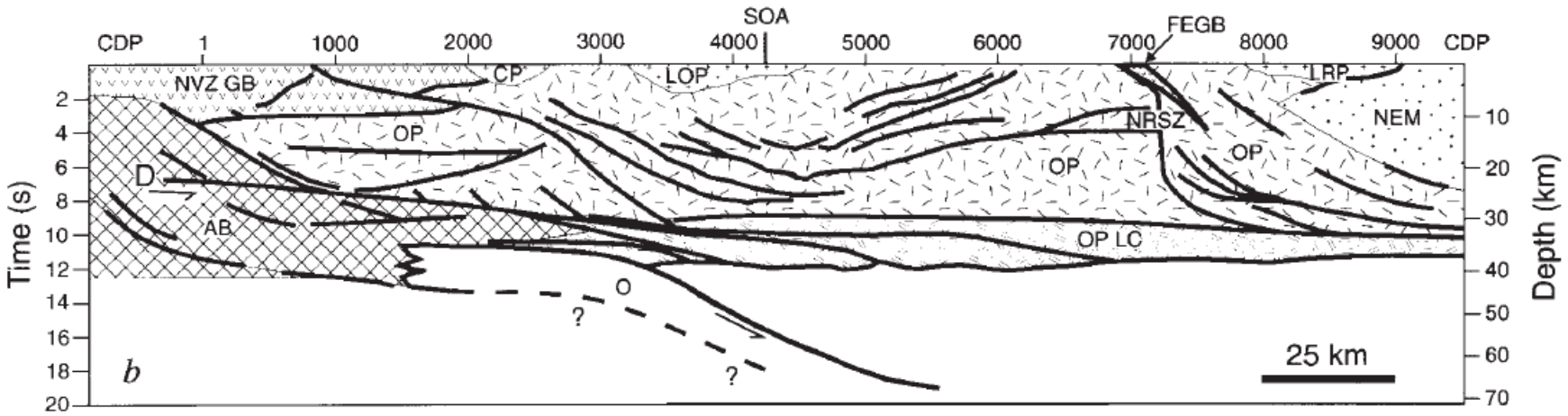


(Stern, 2005; Furnes et al., 2007)

Seismic observations

- Horizontal vs. vertical motion
- Sub-horizontal dipping reflectors suggest fossil subduction?



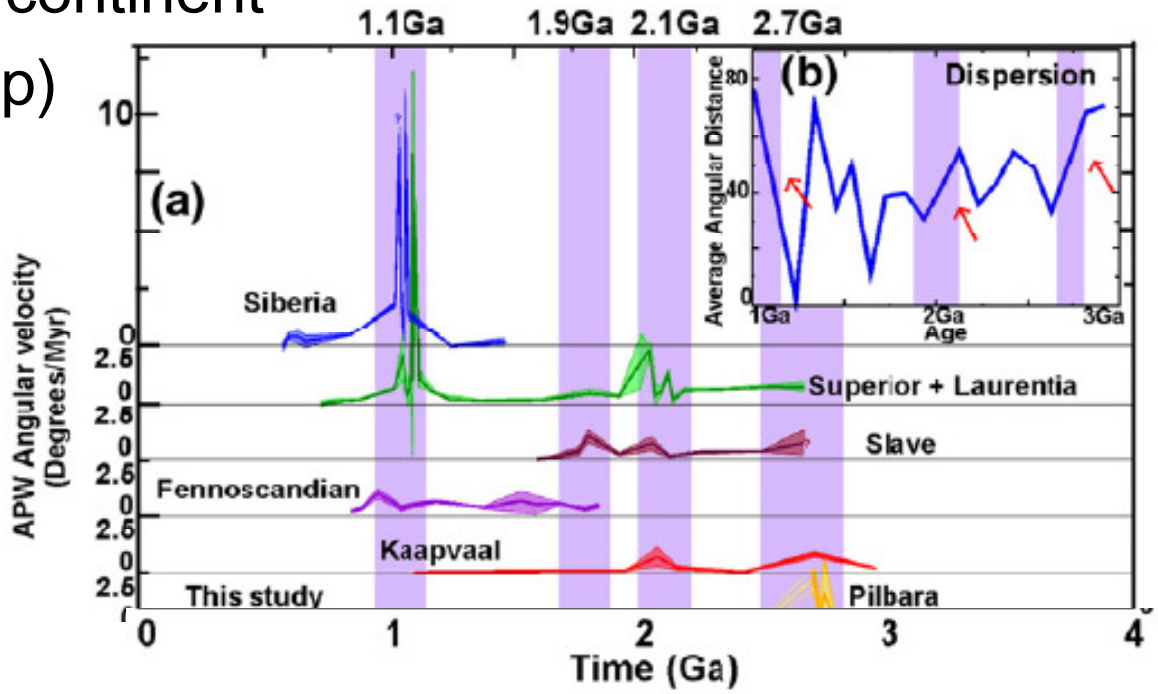


(Calvert et al., 1995)

Plate tectonics in Archaean?

Paleo-magnetism

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

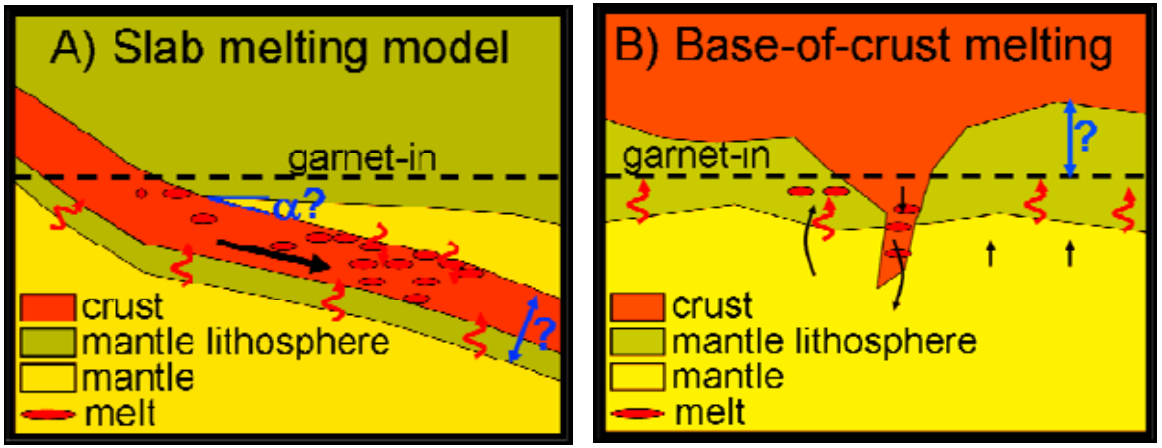


(O'Neill et al., 2007; Silver and Behn, 2008)

Subduction as site for crust formation

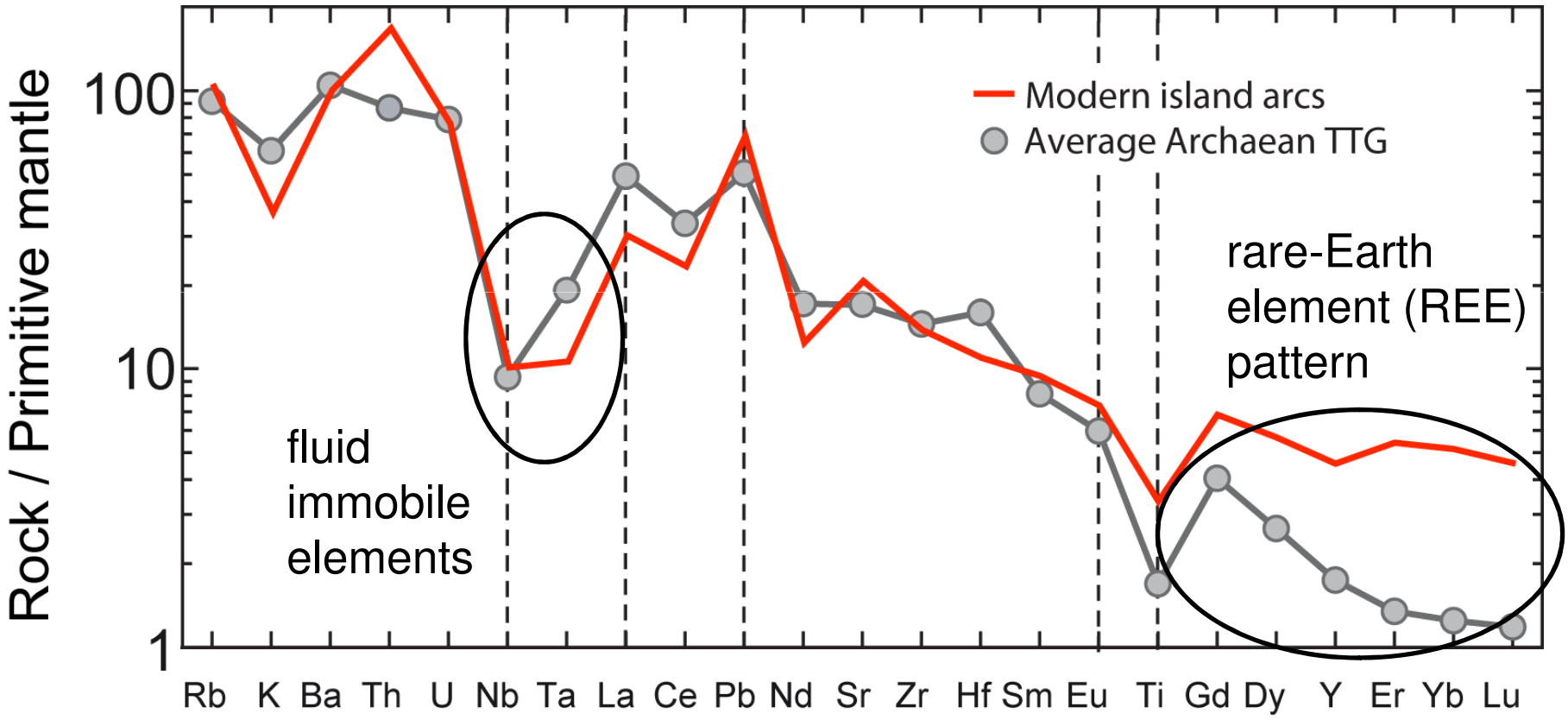
Bulk continental crust:

- Today: andesites
  - Formed in subduction zone
  - Mantle wedge hydration and -melting
- Archaean: tonalite-trondhjemite-granodiorite (TTGs)
  - (slab?) melting of mafic crust (Similarities with adakites?)
  - Interaction with a mantle wedge?
- Suggested formation scenarios:



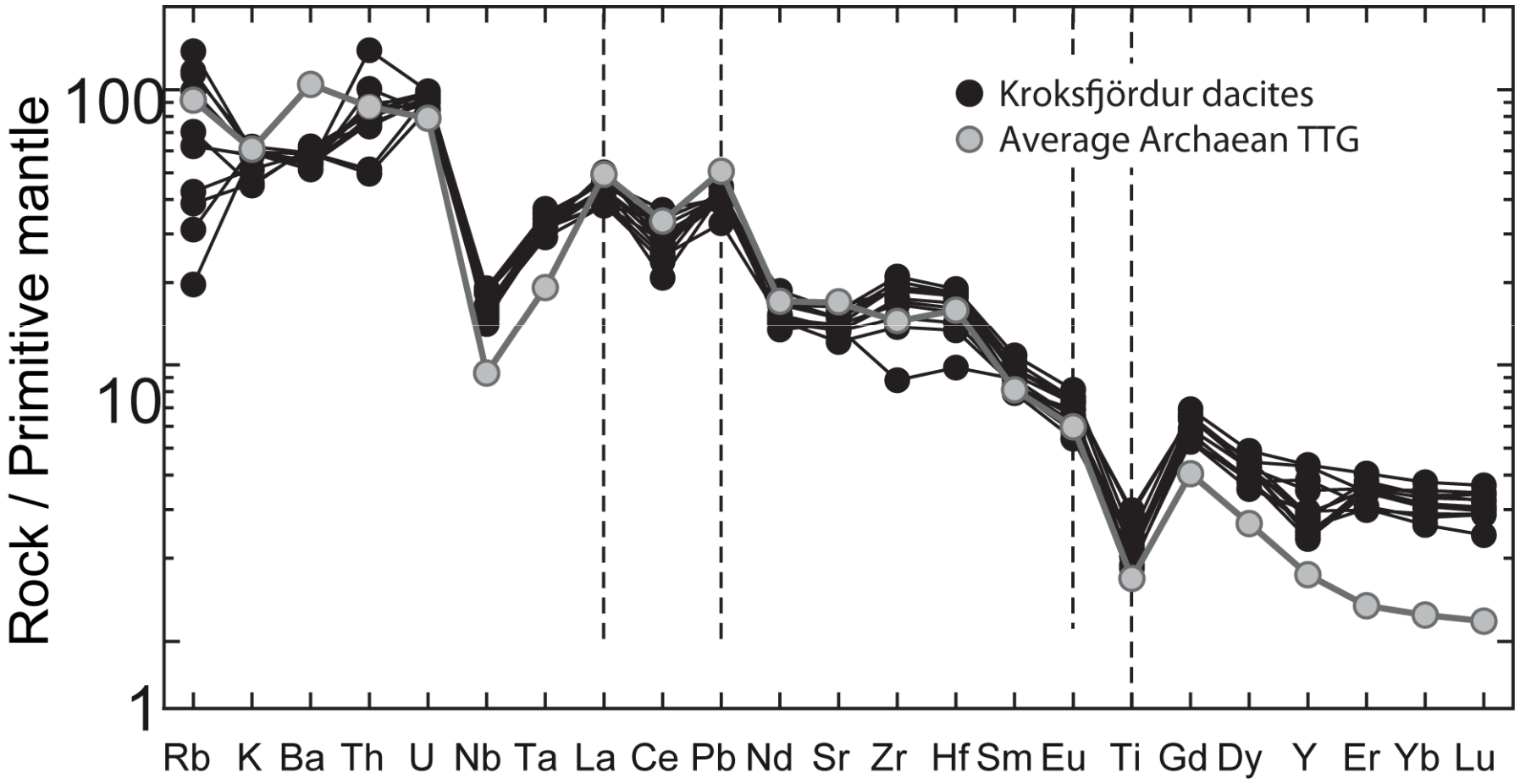
(Defant and Drummond, 1993; Foley et al., 2002, 2003; van Thienen et al., 2004; Bédard, 2006)

Arc signature in Archaean TTGs?



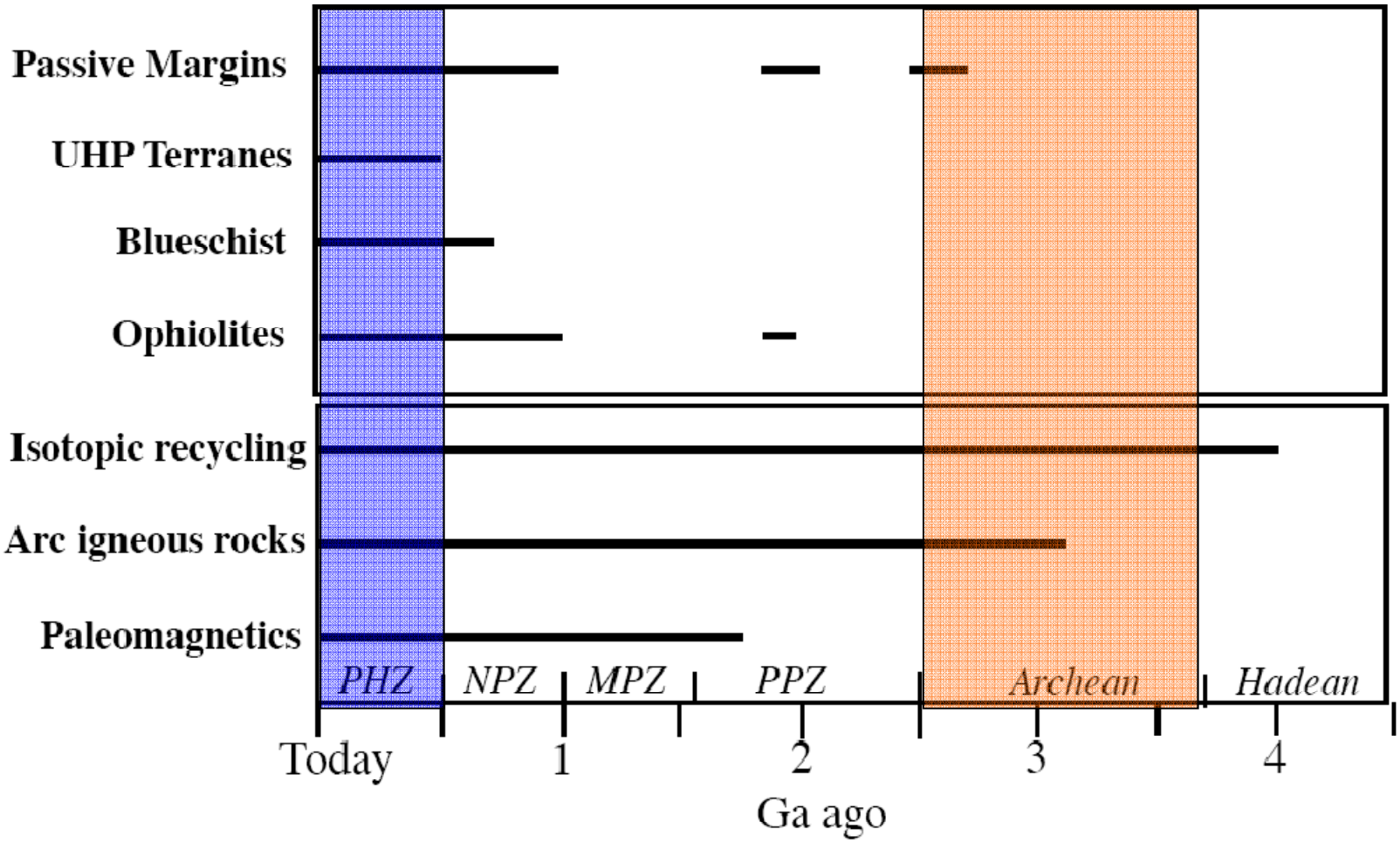
(JF Moyen, pers. comm.)

“Arc” signature in Icelandic dacites !?!



(Willbord et al., 2009; JF Moyen, pers. comm.)

Key characteristics of plate tectonics

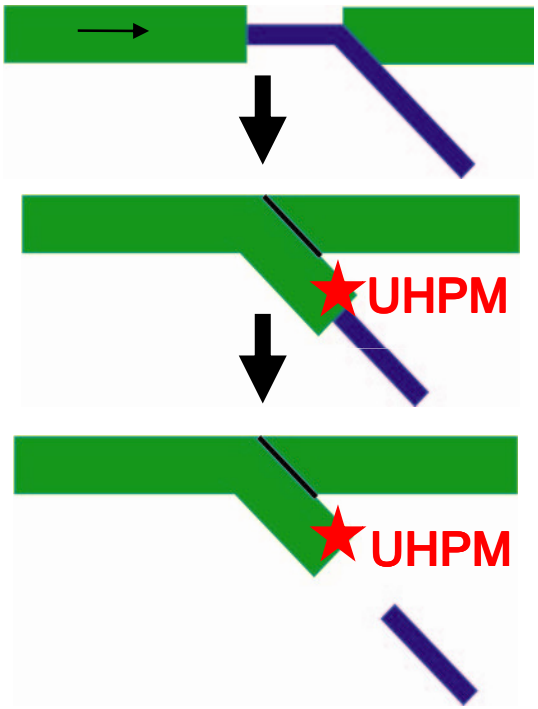


No subduction in Precambrian?

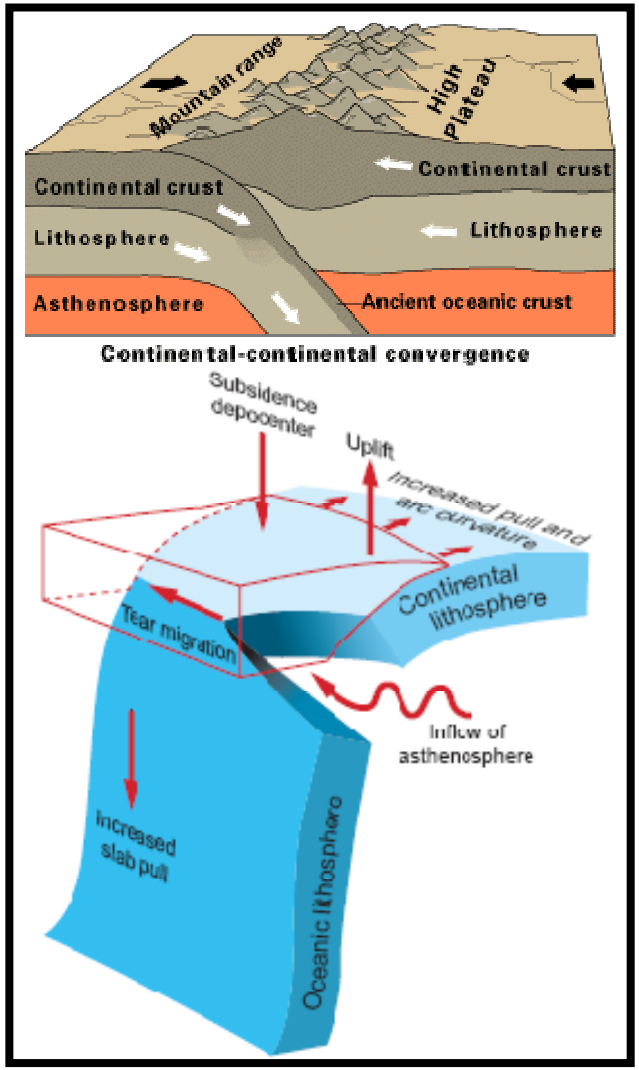
(Stern, 2008)

Absence of UHPM by slab break-off?

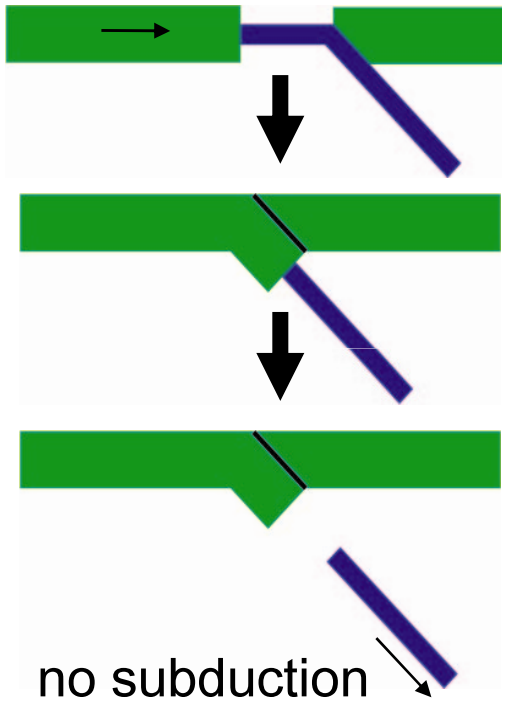
Phanerozoic



subduction of continental crust gives UHPM



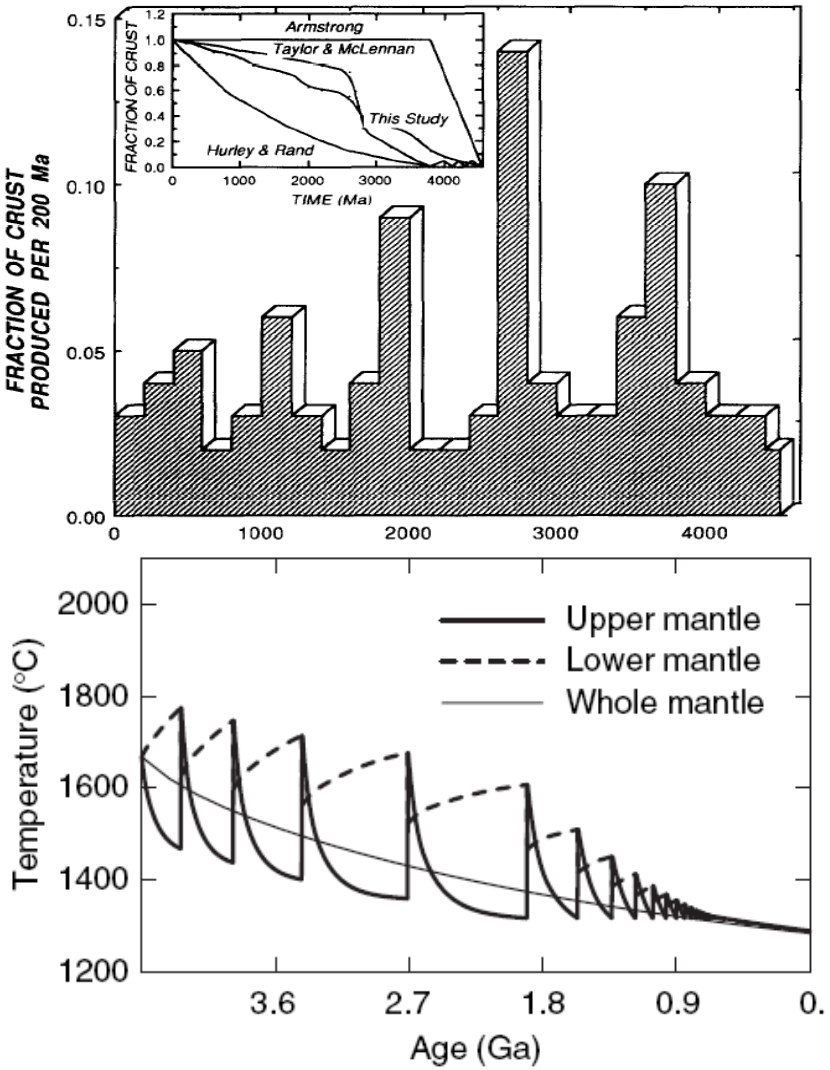
Archaean

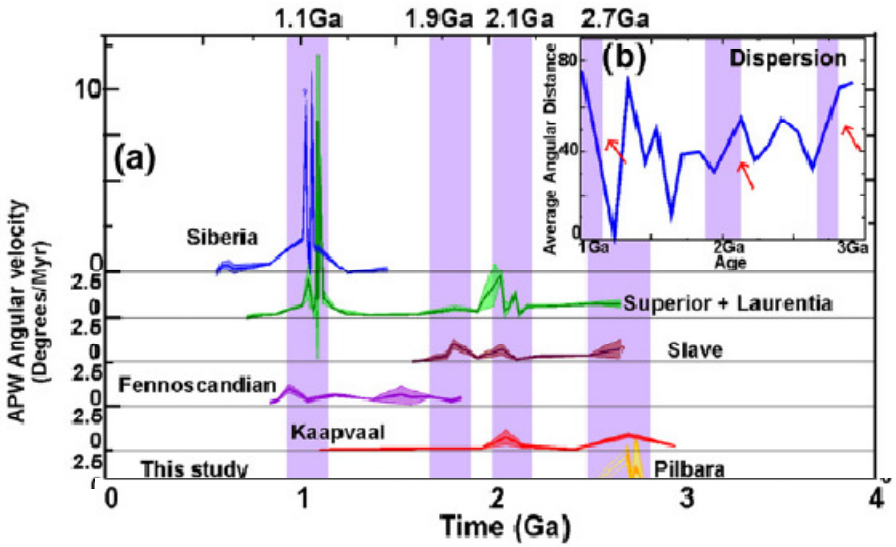


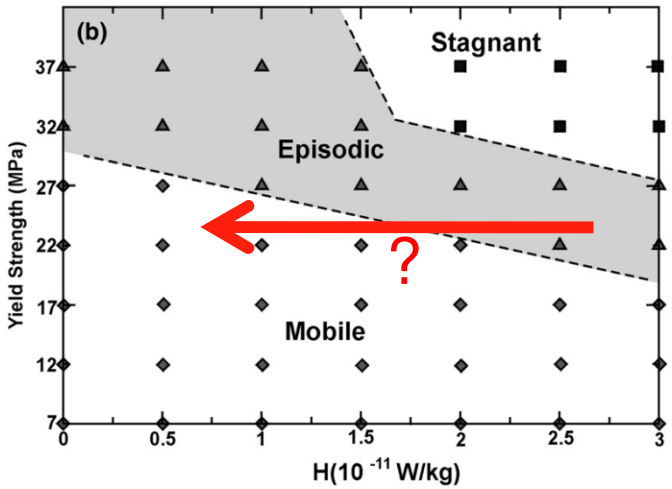
no subduction of continental crust: absence of UHPM

(USGS website; Wortel and Spakman, 2000; van Hunen and Allen, 2010, subm.)

Long-term episodicity in subduction?

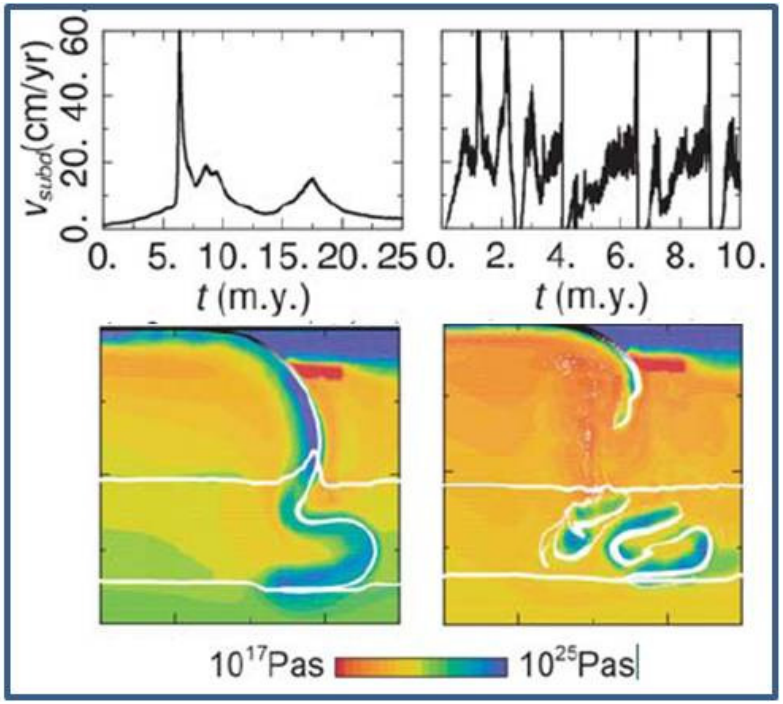




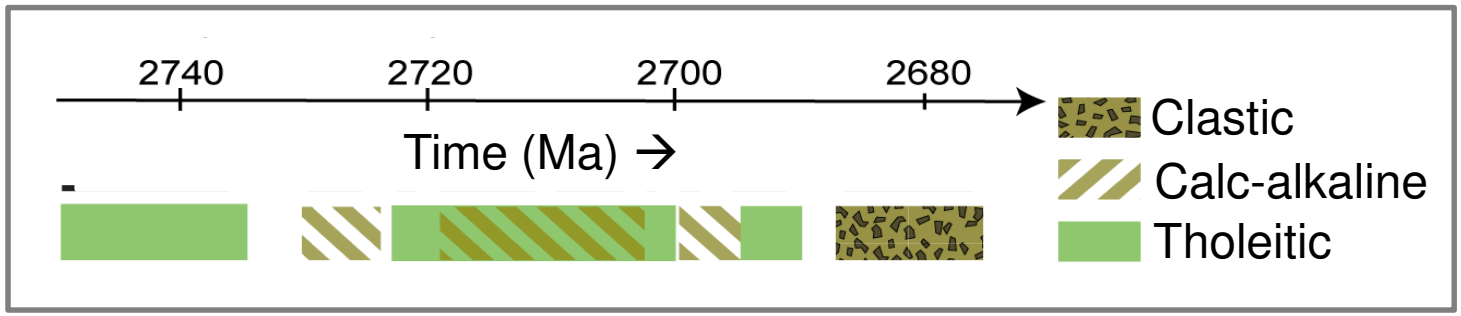


(McCulloch and Bennett, 1994; Davies, 1995; O'Neill et al., 2007)

Short-term episodicity in subduction?



Abitibi, Superior Province



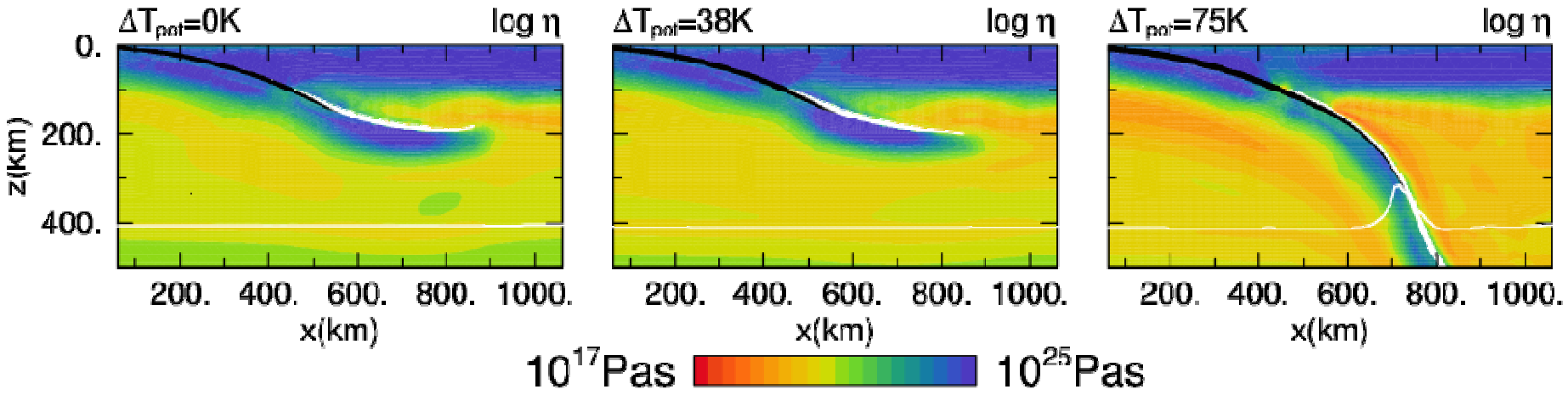
(van Hunen & van den Berg, 2008; Moyen and van Hunen, in prep.)

Did subduction style change over time?

Evolution flat → steep subduction (Abbott et al., 1994)?

→ No, because:

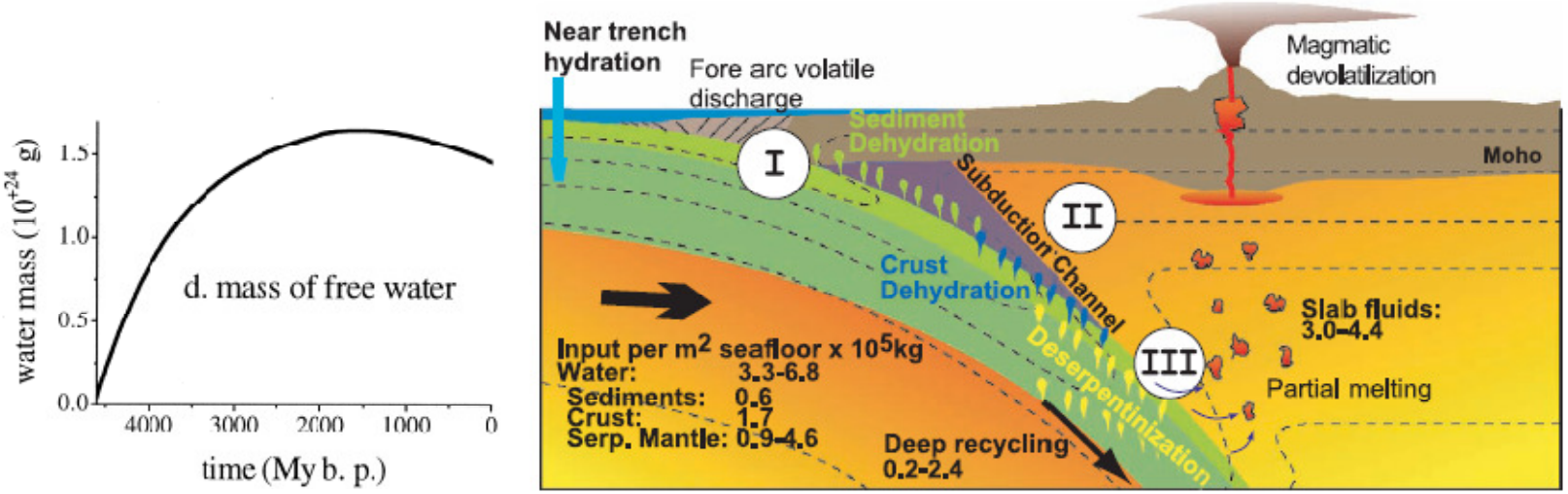
1. If too buoyant, slabs won't subduct at all
2. A hot, weak mantle is unable to support flat subduction



(Abbott et al., 1994; van Hunen et al., 2004)

‘Archaean water world’

- Today: regassing > degassing
- Early Earth:
  - More volcanism → more degassing
  - Hotter mantle → faster slab dehydration → less regassing?
  - Weaker rocks → no high mountain ranges?
  - Buoyant oceanic lithosphere → shallow ocean basins



(Wallmann, 2001; Rüpke et al., 2004; Rey & Coltice, 2009; Flament et al., 2008)

Concluding remarks

Subduction evolution:

- Changing dynamics due to changing mantle temperature:
  - Different crustal thickness, plate strength
  - Episodic subduction (long / short time scale)?



- Observational evidence:
  - Geology/Geophysics: Ophiolites, dipping reflectors, palaeomagnetism
  - Geochemistry: Continental crust, geochemical fingerprints
  - Petrology: Ultra-high pressure metamorphism, blueschists