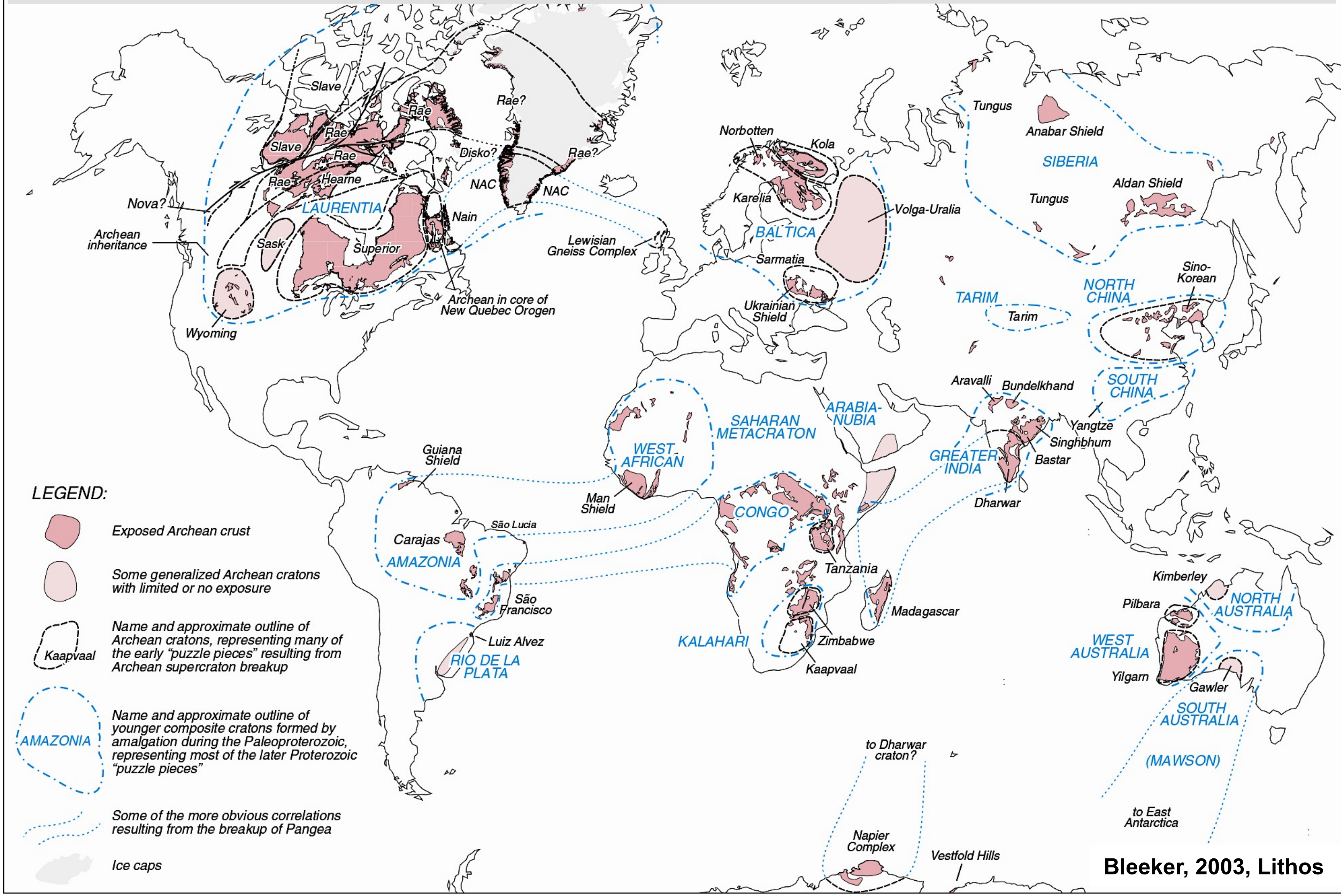
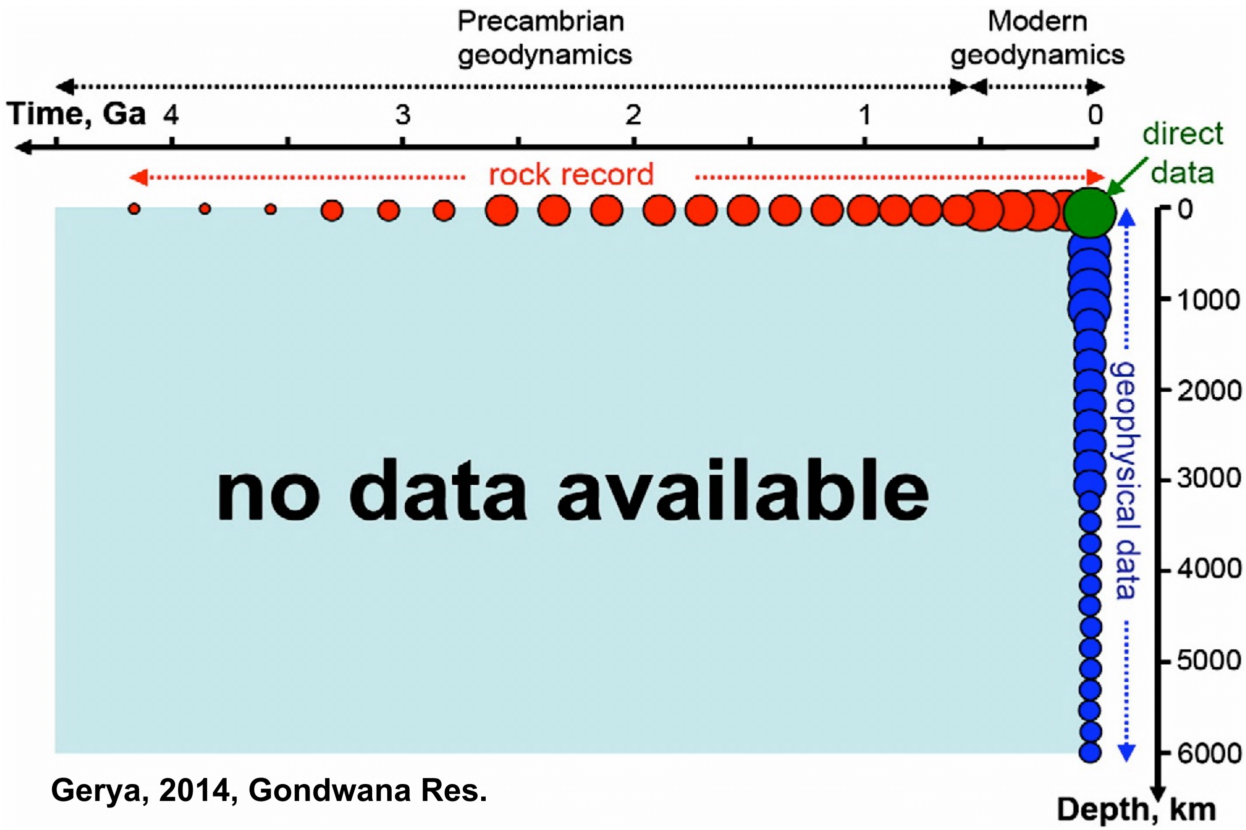
Early Earth

Michael Brown
University of Maryland



Bleeker, 2003, Lithos



Questions:

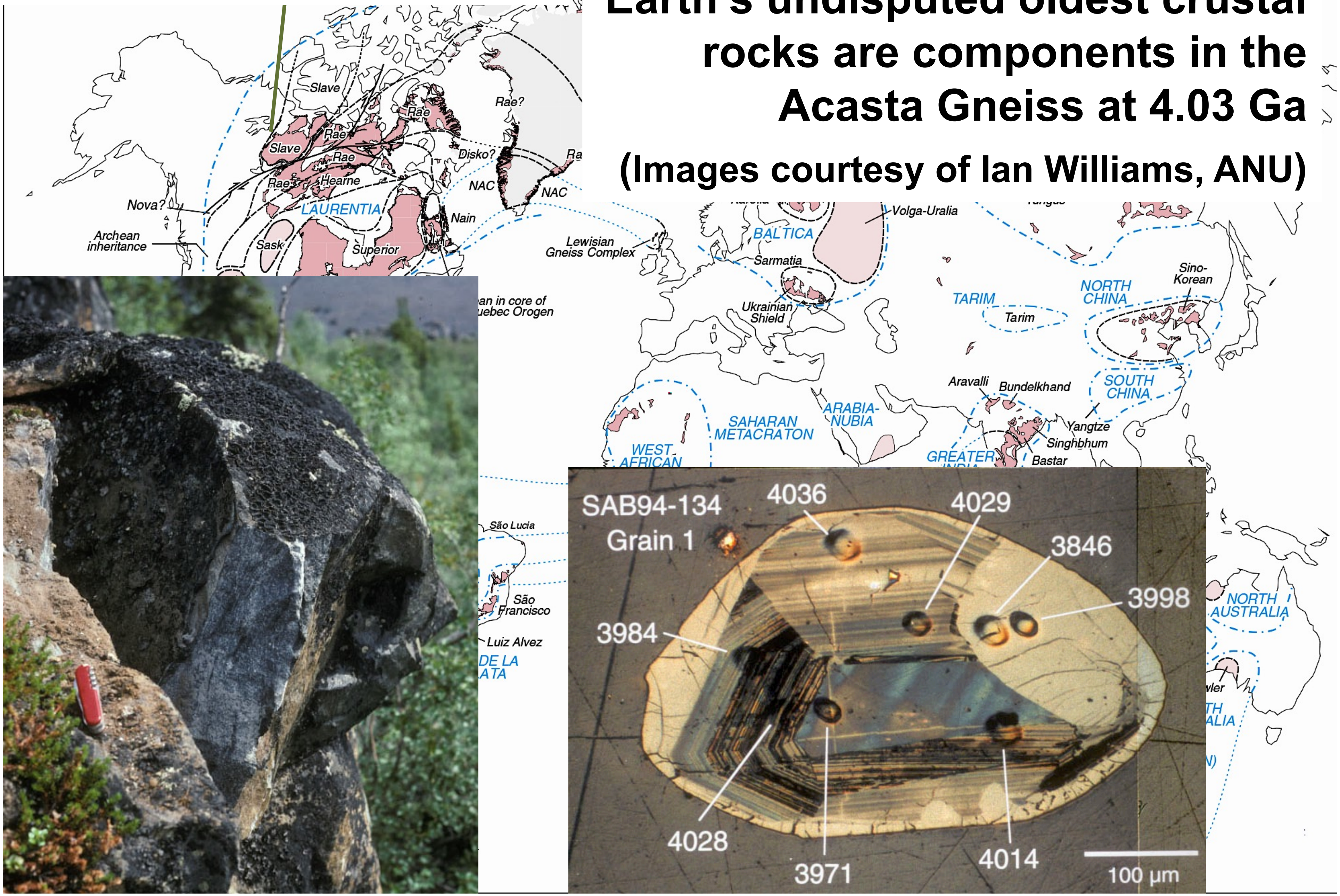
Was there only one style of “Precambrian geodynamics”? Or, was the geodynamic regime on a hotter early Earth different?

Did a subduction/mobile-lid plate tectonics regime only begin sometime during the (late) Archean? If so, what preceded it?

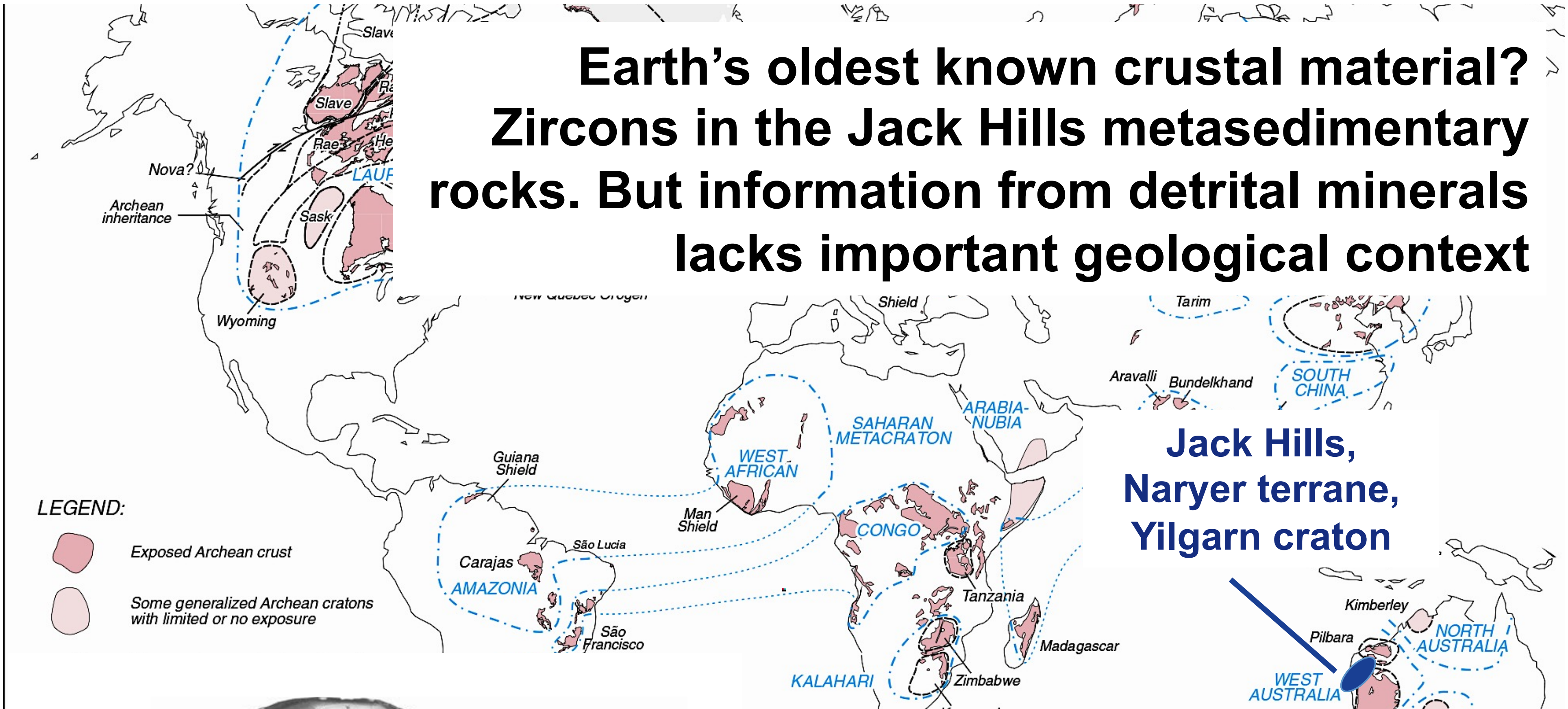
Acasta Gneiss complex on the west side of the Slave craton

Old rocks are rare!
Earth's undisputed oldest crustal rocks are components in the Acasta Gneiss at 4.03 Ga

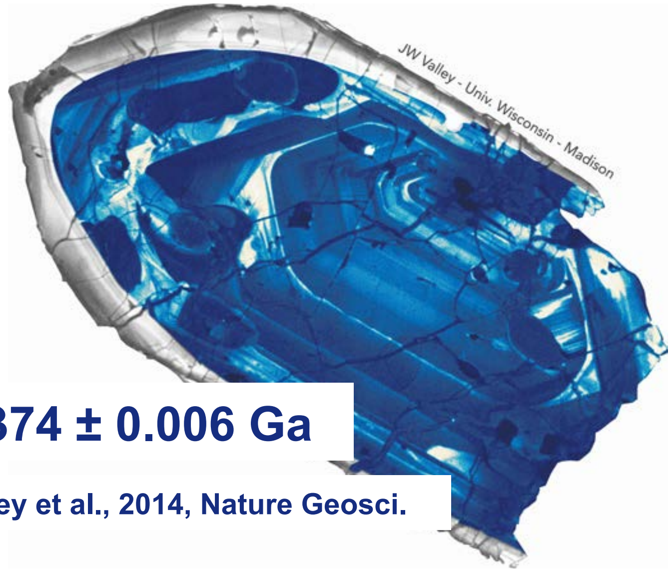
(Images courtesy of Ian Williams, ANU)



Earth's oldest known crustal material? Zircons in the Jack Hills metasedimentary rocks. But information from detrital minerals lacks important geological context



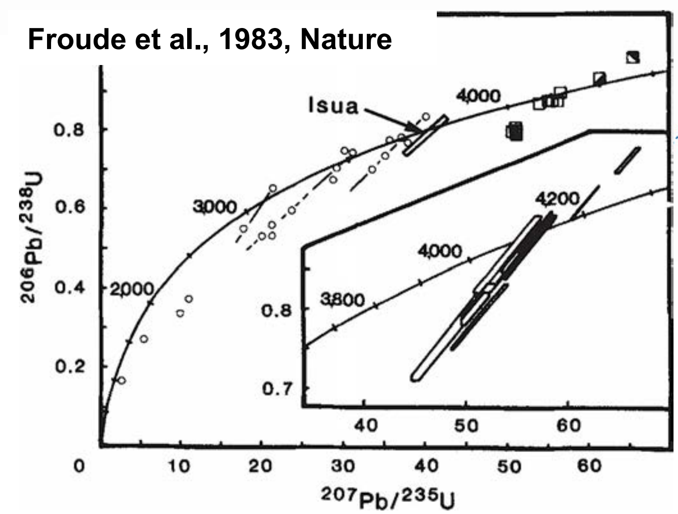
Jack Hills, Naryer terrane, Yilgarn craton



4.374 ± 0.006 Ga

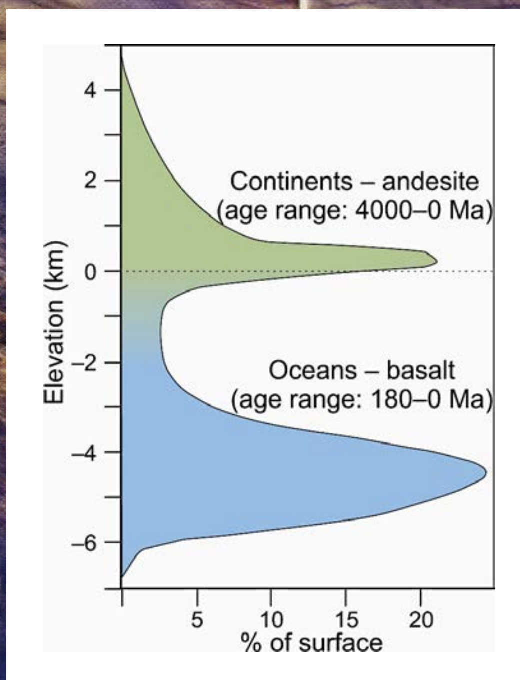
Valley et al., 2014, Nature Geosci.

Froude et al., 1983, Nature



"Water is essential for the formation of granite and granite, in turn, is essential for the formation of continents. Earth, the only inner planet with abundant water, is the only planet with granite and continents. The Moon and the other inner planets have little or no water and no granites or continents."

Campbell & Taylor, 1983, GRL



A Cool Early Earth?

The textbook view that the earth spent its first half a billion years drenched in magma could be wrong. The surface may have cooled quickly—with oceans, nascent continents and the opportunity for life to form much earlier

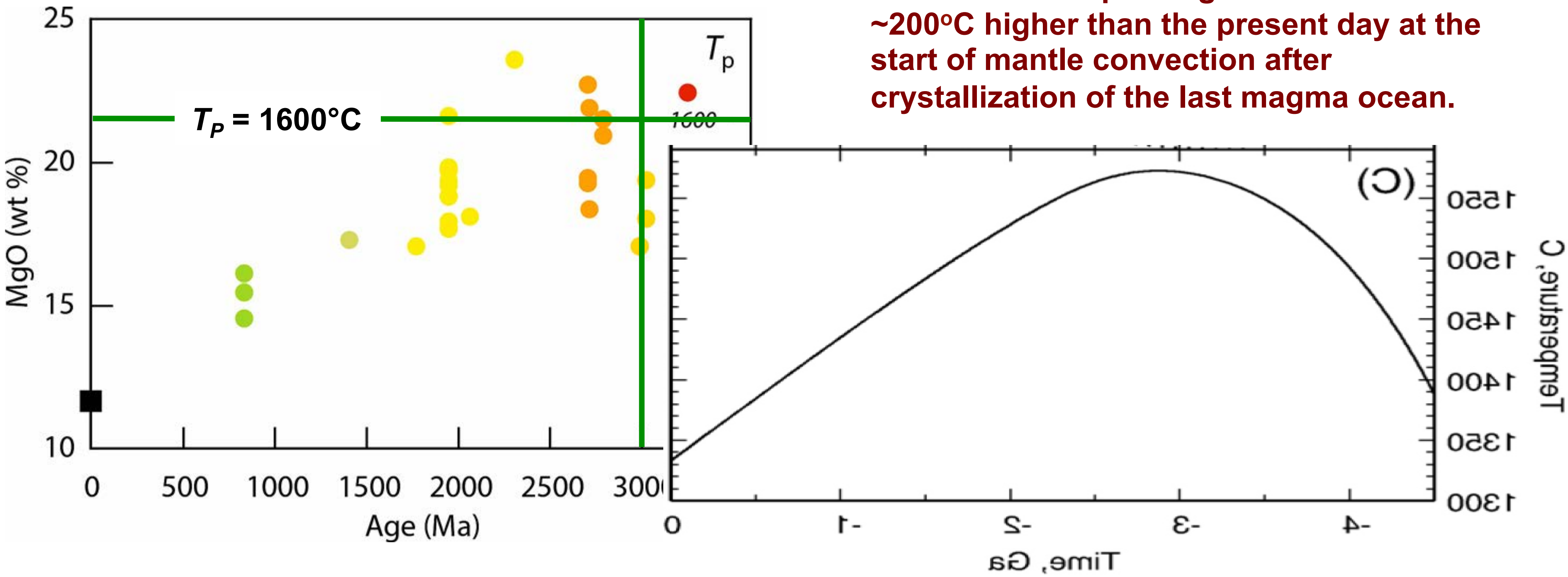
By John W. Valley

Evolution of mantle temperature

The decline in mantle T_P from the Mesoarchean to the present may have been as much as 250°C, but with a spread of values similar to the present day (~120°C).

Thermal history calculations by Labrosse & Jaupart (2007, EPSL) lead to a maximum temperature (ΔT ~250°C) at 3.0 Ga and cannot be extrapolated further back in time.

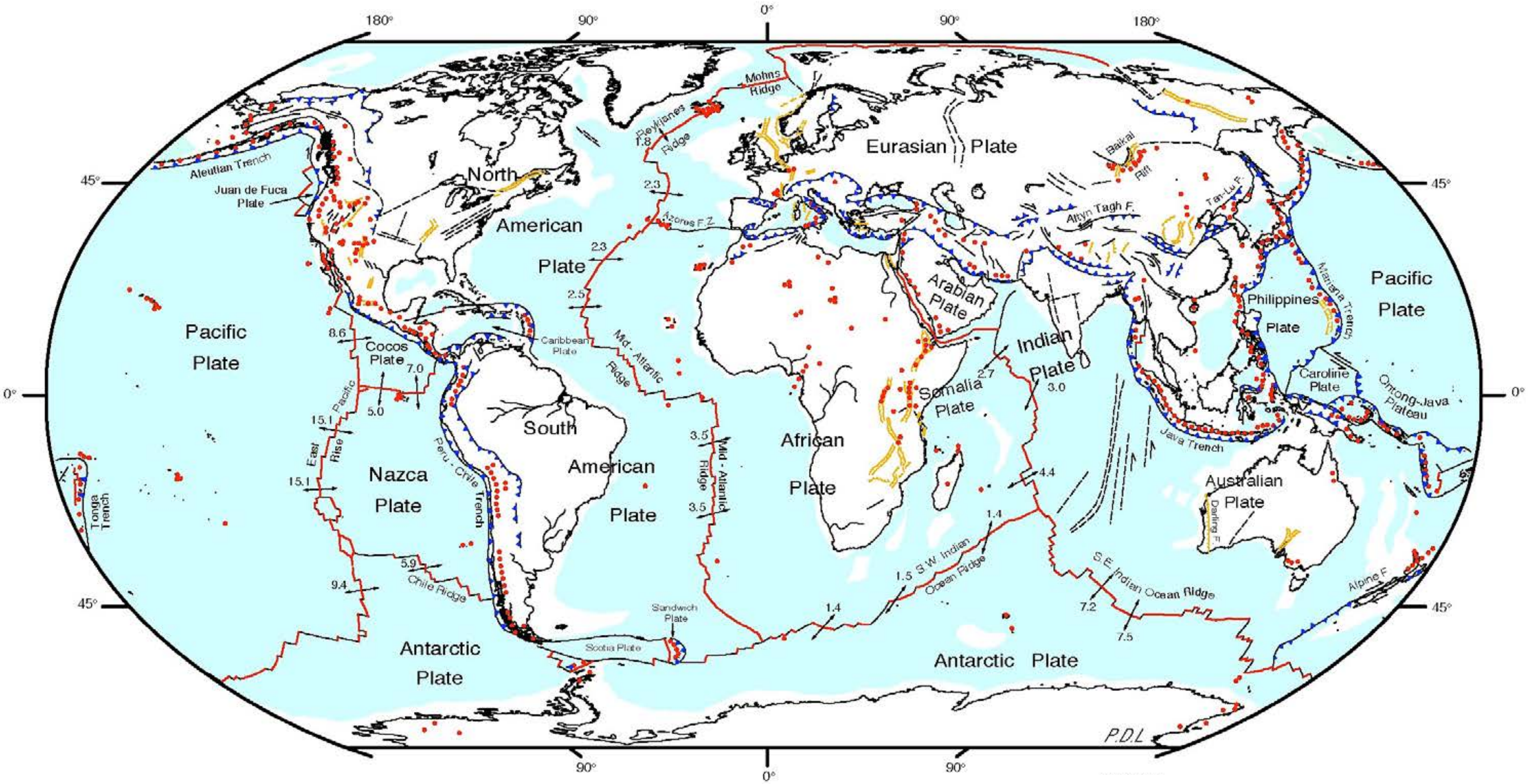
Labrosse & Jaupart argue that ΔT was ~200°C higher than the present day at the start of mantle convection after crystallization of the last magma ocean.



Petrological estimates of mantle potential temperature (T_P) for non-arc lavas (Herzberg et al., 2010, EPSL) with ages corrected (Johnson et al., 2014, Nature Geosci.). Herzberg et al. use the relation: T_P(°C) = 1463 + 12.74MgO − 2924/MgO, where MgO is the primary magma MgO content.

(see also Abbott et al., 1994, JGR)

Labrosse & Jaupart, 2007, EPSL



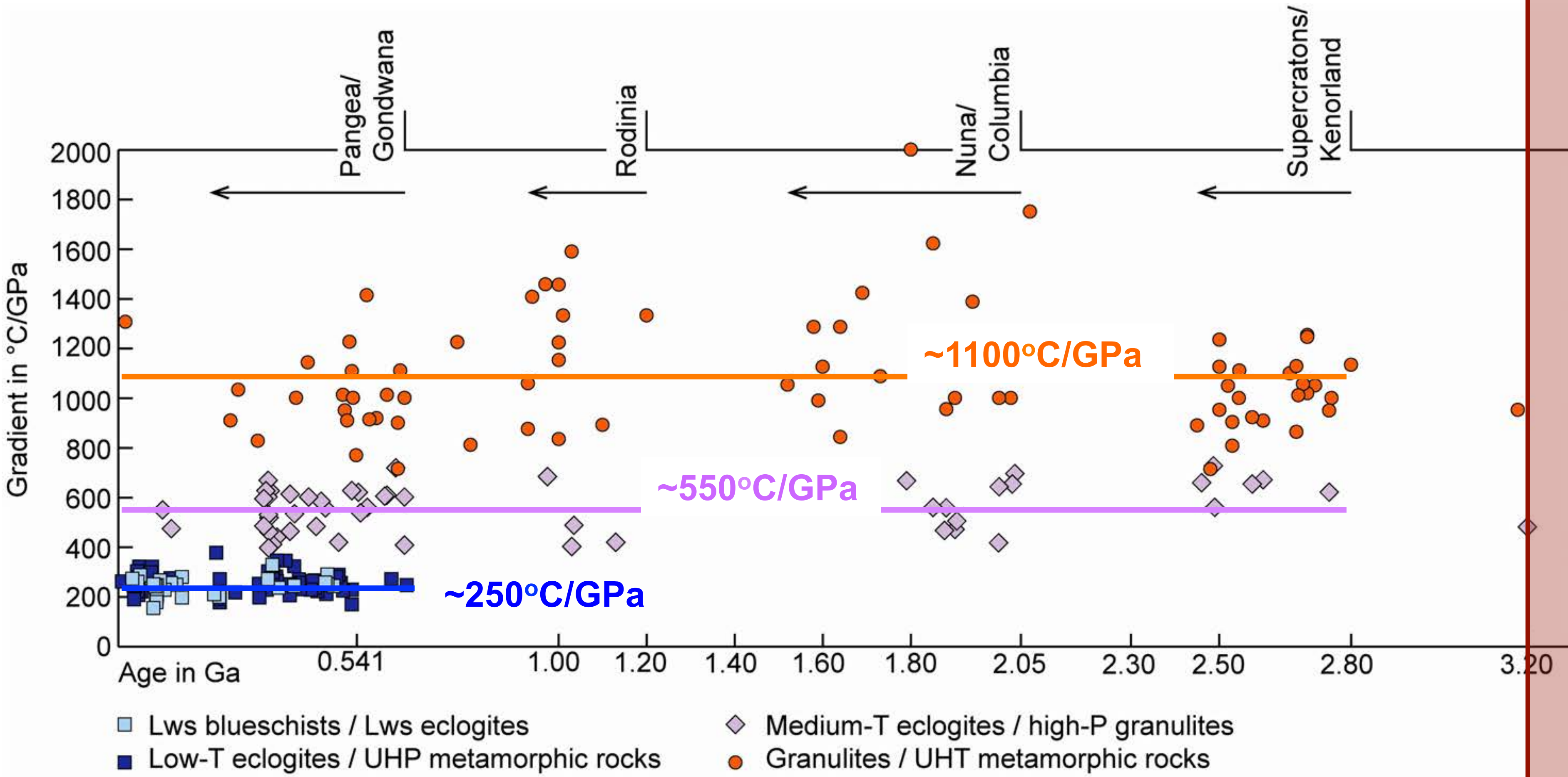
By construction the calculations of Labrosse & Jaupart are based on the present day tectonic regime. So, how far back in the geological record can the signals of subduction be recognized?

The geological record indicates the late Mesoarchean to early Paleoproterozoic was a 700 Myr long period of transition to subduction and global mobile-lid plate tectonics

- **Persistence of ^{142}Nd and ^{182}W anomalies and fractionated Sm/Nd and Lu/Hf domains, and the heterogenous distribution of HSEs in the mantle until the Neoarchean require sluggish mixing (Bennett et al., 2007; Debaille et al., 2013; Touboul et al., 2012, 2014; Maier et al., 2009; Puchtel et al., 2013, 2014).**

- **Change from diamonds with only peridotite mineral inclusions to those with eclogite and peridotite mineral inclusions, consistent with capture of eclogite and diamond-forming fluids in subcontinental lithospheric mantle via subduction and collision (Shirey & Richardson, 2011).**

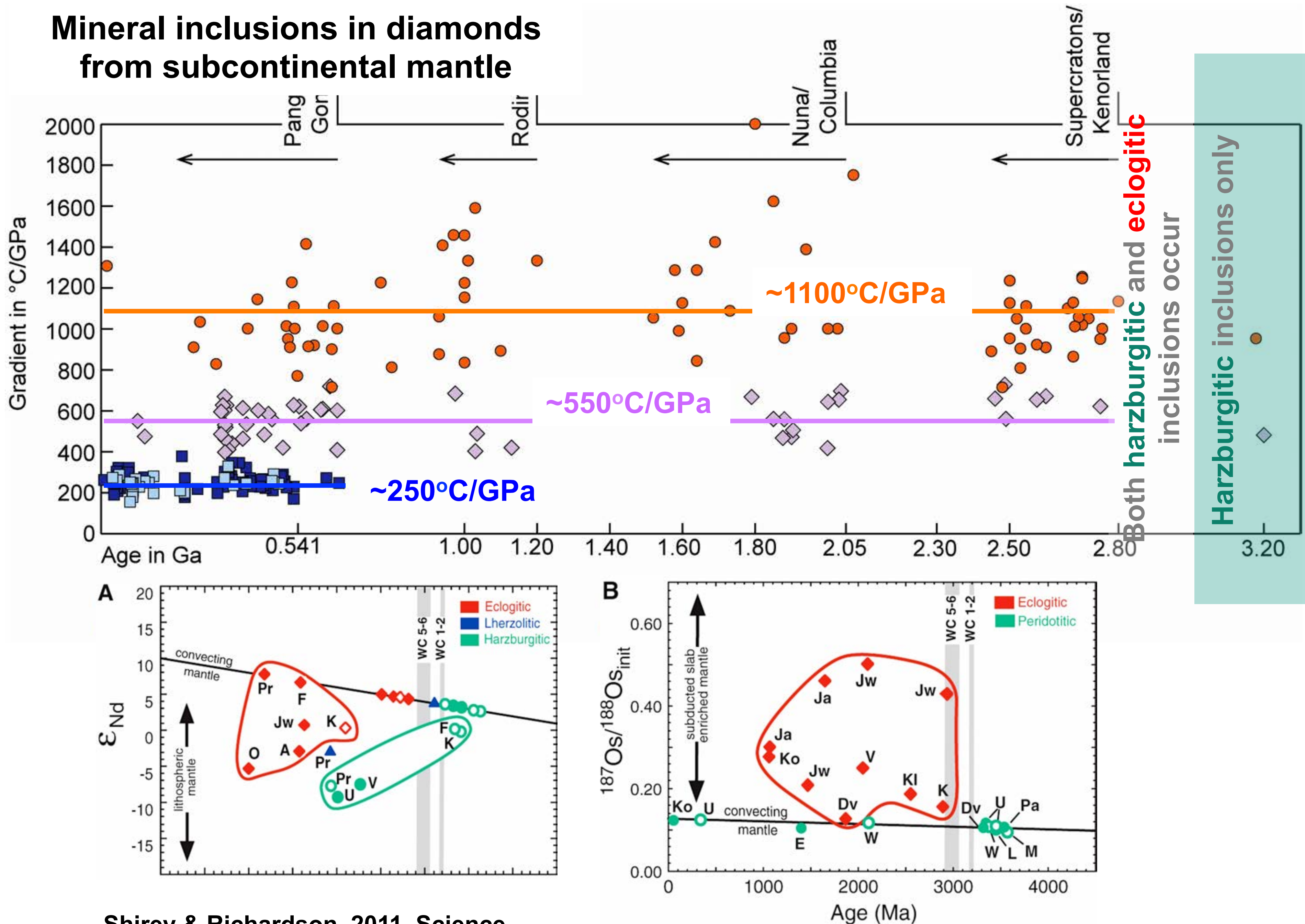
- **First appearance of eclogite–high-pressure granulite metamorphism and granulite–ultrahigh-temperature metamorphism records two contrasting thermal environments, interpreted to register the beginning of subduction (Brown, 2006, 2007, 2014).**



P–T **conditions retrieved from Eoarchean–Mesoarchean crust are low-to-moderate-*P*–moderate-to-high-*T*. Apparent thermal gradients for ("low grade") greenstone belts and ("high-grade") gneiss terrains are uniformly warm (850–1350ºC/GPa), with no evidence of paired metamorphism, consistent with higher crustal heat production, but not with subduction.**

Brown, 2007, Int. Geol. Rev.; Brown, 2014, Geosci. Frontiers

Mineral inclusions in diamonds from subcontinental mantle



Shirey & Richardson, 2011, Science

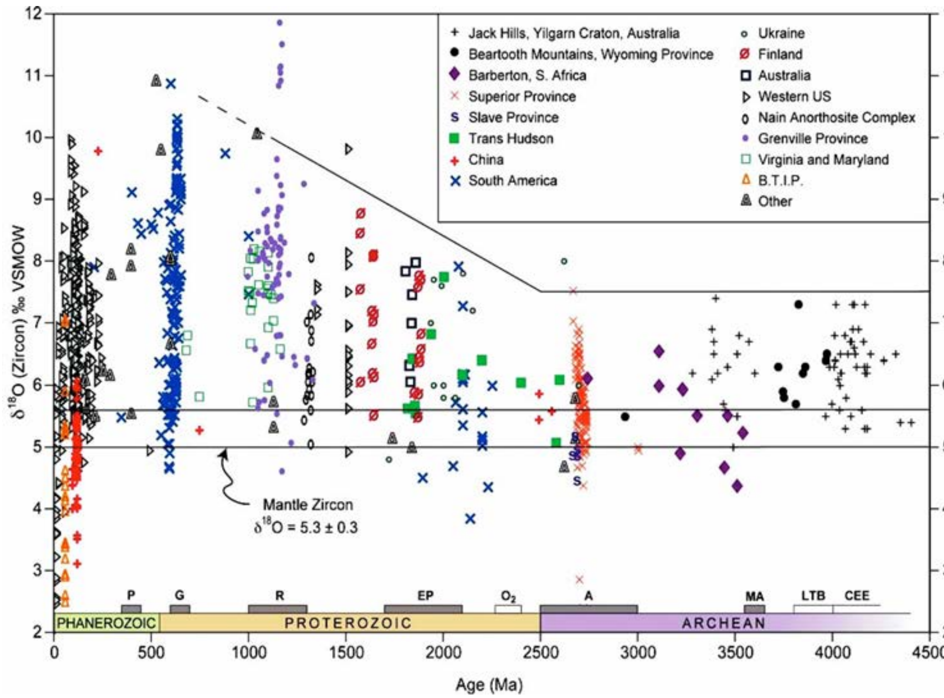
The geological record indicates the late Mesoarchean to early Paleoproterozoic was a 700 Myr long period of transition to subduction and global mobile-lid plate tectonics

- Persistence of ^{142}Nd and ^{182}W anomalies and fractionated Sm/Nd and Lu/Hf domains, and the heterogenous distribution of HSEs in the mantle until the Neoarchean require sluggish mixing (Bennett et al., 2007; Debaille et al., 2013; Touboul et al., 2012, 2014; Maier et al., 2009; Puchtel et al., 2013, 2014).

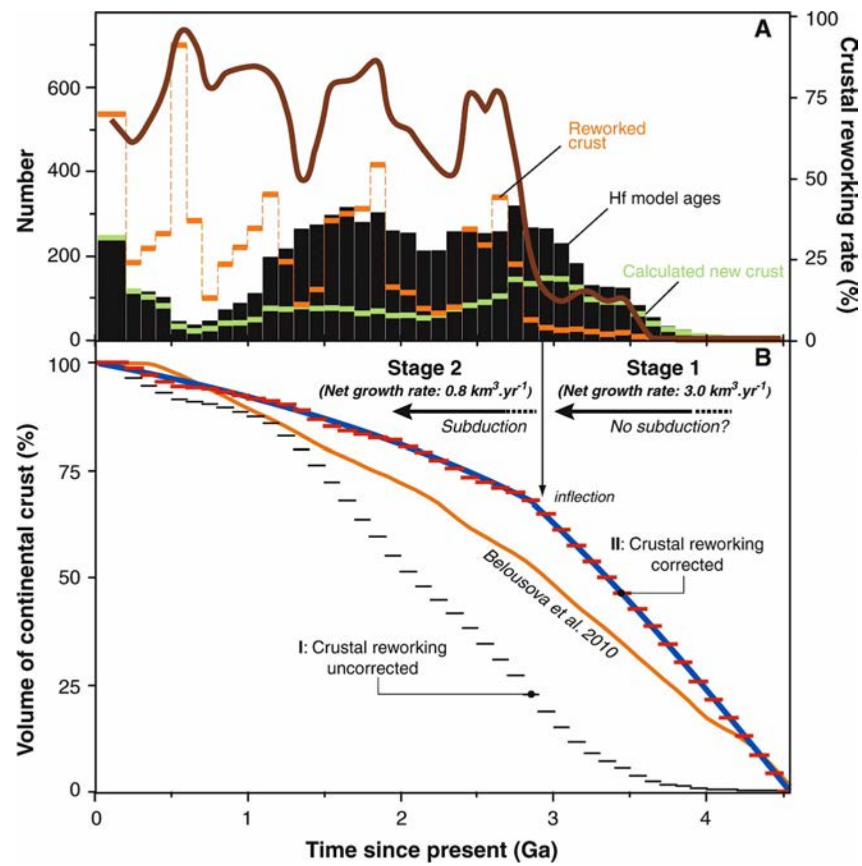
- Change from diamonds with only peridotite mineral inclusions to those with eclogite and peridotite mineral inclusions, consistent with capture of eclogite and diamond-forming fluids in subcontinental lithospheric mantle via subduction and collision (Shirey & Richardson, 2011).

- First appearance of eclogite–high-pressure granulite metamorphism and granulite–ultrahigh-temperature metamorphism records two contrasting thermal environments, interpreted to register the beginning of subduction (Brown, 2006, 2007, 2014).

- **Changes in style and chemistry of magmatic rocks (Valley et al., 2005; Pearce, 2008, 2014; Hiess et al., 2011; Keller & Schoene, 2012), rates of addition of juvenile crust vs crustal reworking (Dhuime et al., 2012), and sites of continental growth (Condie & Kröner, 2013).**



Valley et al., 2005, CMP



Dhuime et al., 2011, Science

The geological record indicates the late Mesoarchean to early Paleoproterozoic was a 700 Myr long period of transition to subduction and global mobile-lid plate tectonics

- Persistence of ^{142}Nd and ^{182}W anomalies and fractionated Sm/Nd and Lu/Hf domains, and the heterogenous distribution of HSEs in the mantle until the Neoarchean require sluggish mixing (Bennett et al., 2007; Debaille et al., 2013; Touboul et al., 2012, 2014; Maier et al., 2009; Puchtel et al., 2013, 2014).

- Change from diamonds with only peridotite mineral inclusions to those with eclogite and peridotite mineral inclusions, consistent with capture of eclogite and diamond-forming fluids in subcontinental lithospheric mantle via subduction and collision (Shirey & Richardson, 2011).

- First appearance of eclogite–high-pressure granulite metamorphism and granulite–ultrahigh-temperature metamorphism records two contrasting thermal environments, interpreted to register the beginning of subduction (Brown, 2006, 2007, 2014).

- Changes in style and chemistry of magmatic rocks (Valley et al., 2005; Pearce, 2008, 2014; Hiess et al., 2011; Keller & Schoene, 2012), rates of addition of juvenile crust vs crustal reworking (Dhuime et al., 2012), and sites of continental growth (Condie & Kröner, 2013).

- **Stabilization of cratonic lithosphere and the formation of supercratons (Bleeker, 2003; Herzberg & Rudnick, 2012); the beginning of the Proterozoic supercontinent cycle.**

- **End of the "flat Earth" (Rey & Coltice, 2008), emergence of continents (Viehmann et al., 2014) and development of significant topography, marked decrease in subaqueous continental flood basalts (Flament et al., 2011), changes in the style of orogeny (Gapais et al., 2009), and the rise in atmospheric oxygen (Campbell & Allen, 2008; Lyons et al., 2014).**

- **Appearance of passive margins (Bradley, 2008) and changes in style of sedimentation (Eriksson et al., 2013; Eriksson & Condie, 2014).**

Facts and speculations about the early Earth

1. Exposed Archean crust is different; tonalite–trondhjemite–granodiorite (TTG) crust dominates with subordinate high-Mg non-arc basalts, komatiites and sediments. Characteristic is the dome-and-keel architecture of many, but not all, cratons.

2. Ambient upper mantle was hotter. Higher mantle *T* would have led to higher vol. % melting, producing primary crust that was more MgO-rich and thicker (up to 45 km) than today. Mass balance considerations suggest that most of this crust is missing.

3. TTGs were derived by partial melting of amphibolite, most of which was Grt- (and Qtz-) bearing, and eclogite (i.e. mafic not ultramafic crust). Thus, either primary crust must be differentiated by partial melting or primary melts must be fractionated to generate suitable protolith compositions to source TTG magmas.

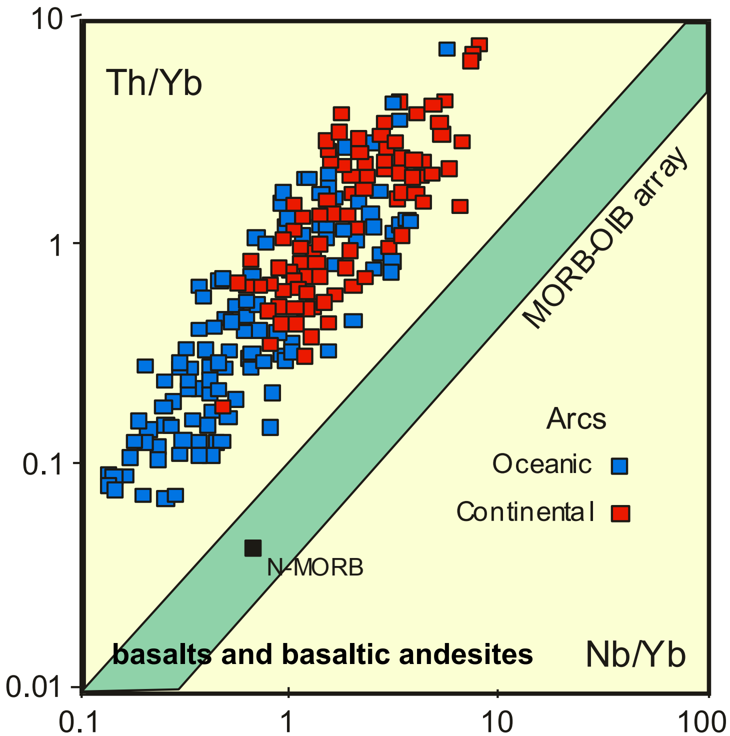
(2 & 3 – VanTongren et al. talk)

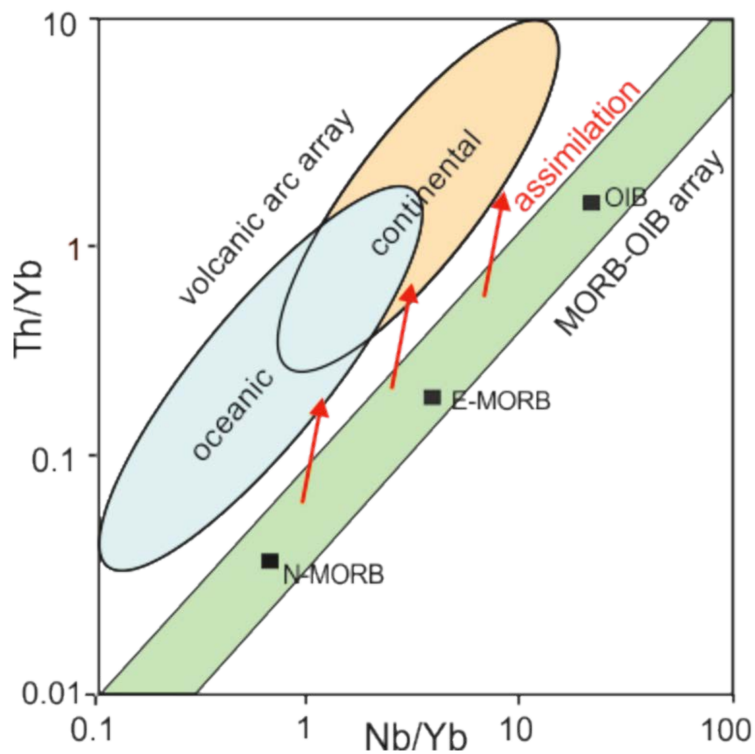
4. Geodynamic regimes posited for the Archean include:

- ❖ **Uniformitarian/selective-uniformitarian mobile-lid plate tectonics;**
- ❖ **stagnant-lid plate tectonics, without subduction;**
- ❖ **stagnant-lid plate tectonics with episodic subduction events; or,**
- ❖ **stagnant–deformable-lid plate tectonics evolving to episodic subduction.**

Geochemical fingerprinting of volcanic rocks

Very popular, but the results tend to be ambiguous

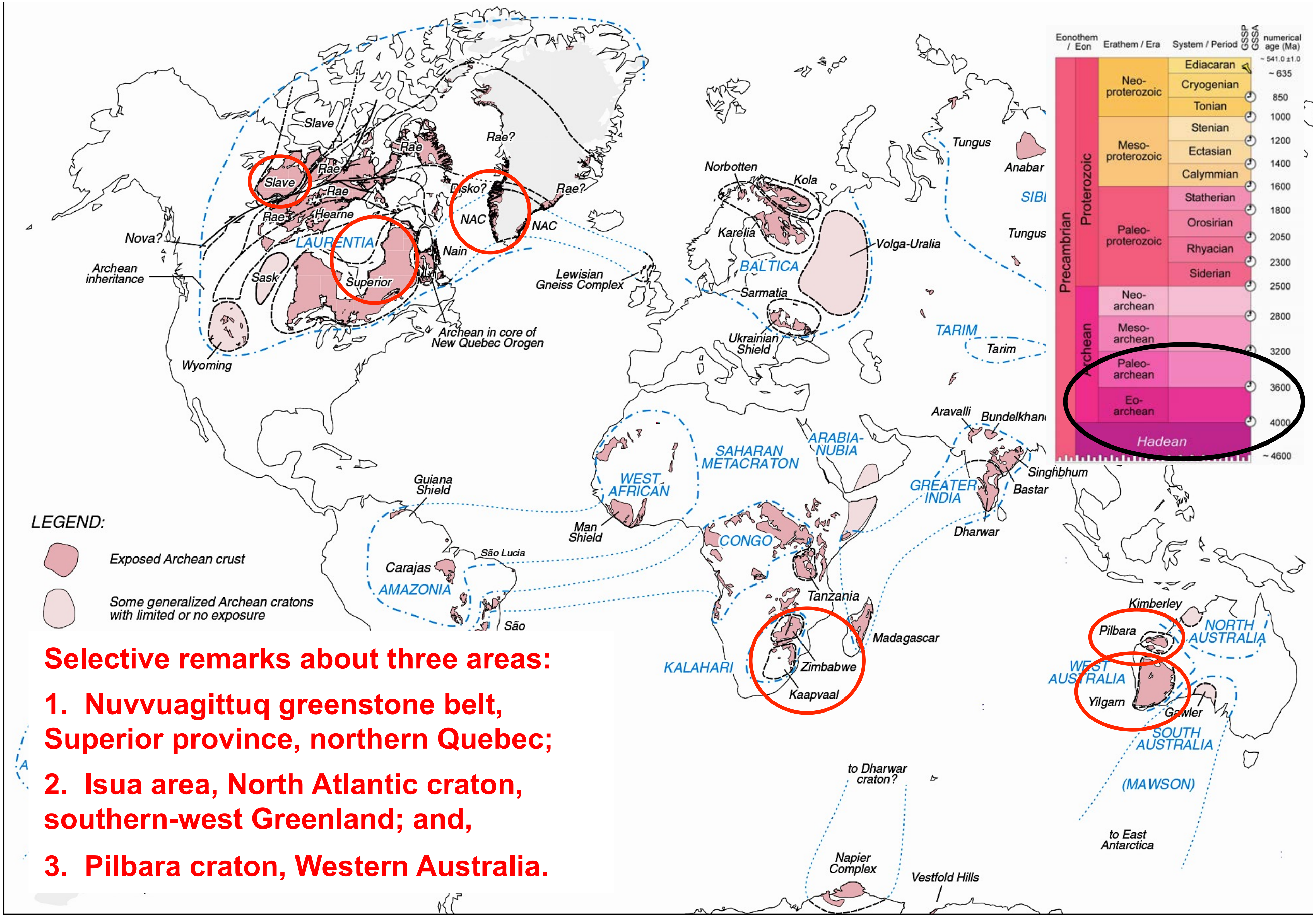




A particular concern in applying the Th/Yb vs Nb/Yb diagram (Pearce, 2008, Lithos) to fingerprint Archean volcanic rocks is the prospect of greater crustal assimilation resulting from higher magma temperatures (and element mobility at amphibolite facies or higher grade).

The earliest rock record

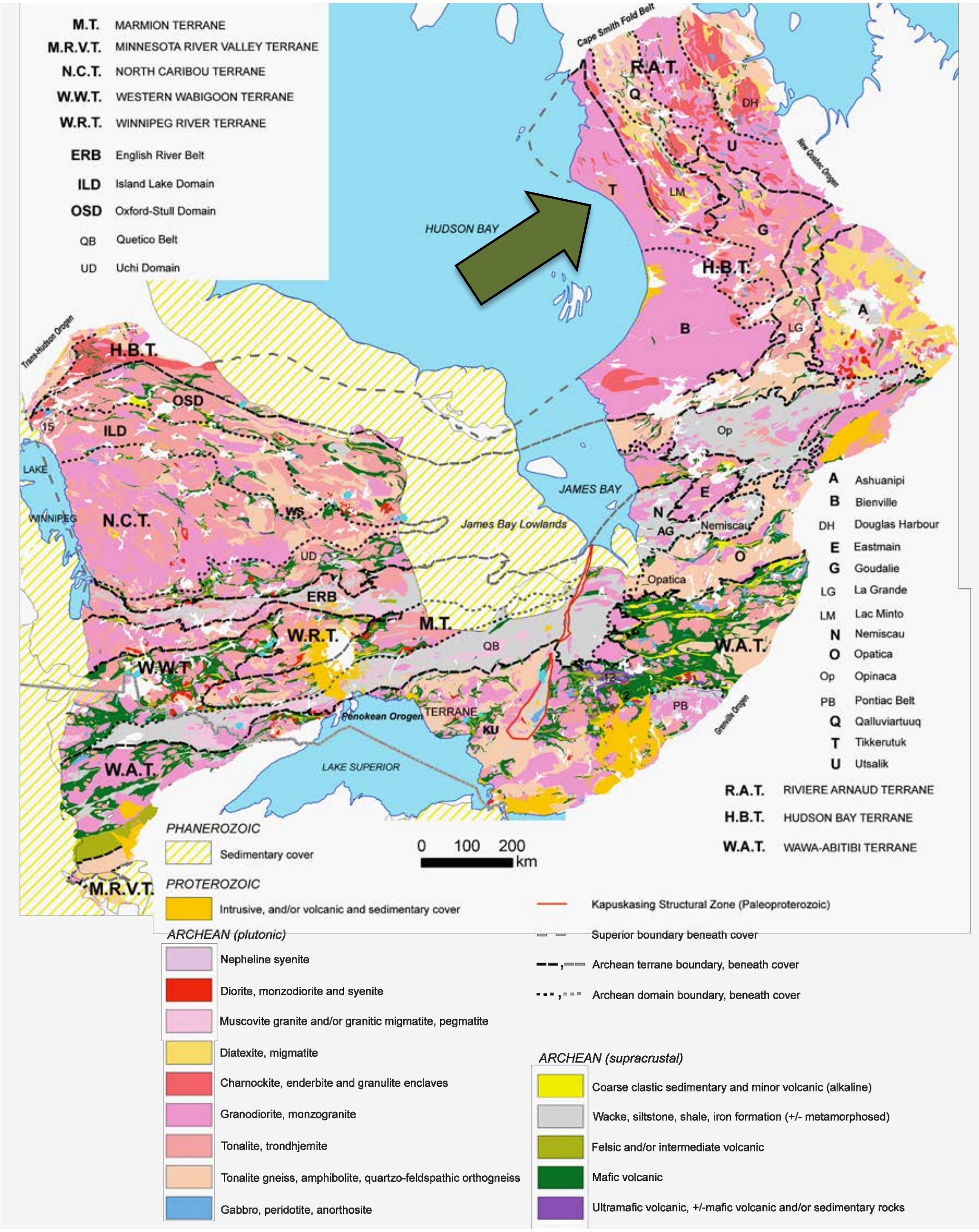
Where is the oldest real estate – something we can stand on?



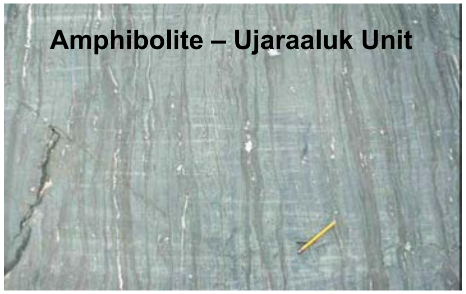
Selective remarks about three areas:

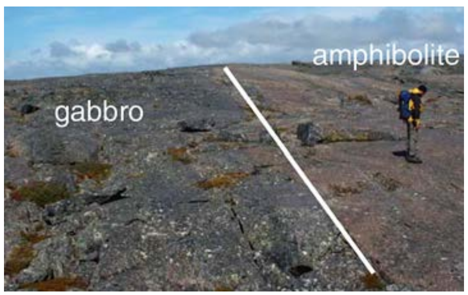
1. **Nuvvuagittuq greenstone belt, Superior province, northern Quebec;**
2. **Isua area, North Atlantic craton, southern-west Greenland; and,**
3. **Pilbara craton, Western Australia.**

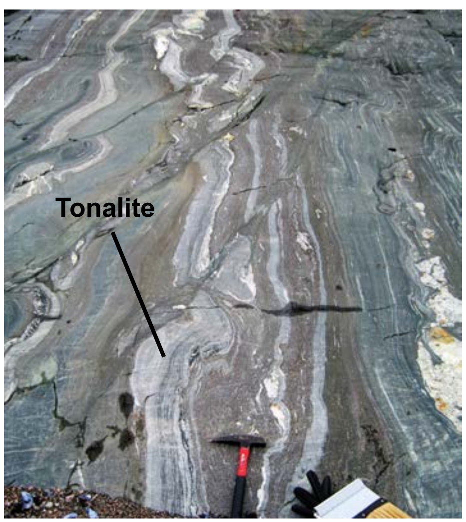
1. Nuvvuagittuq greenstone belt, Superior province, northern Quebec

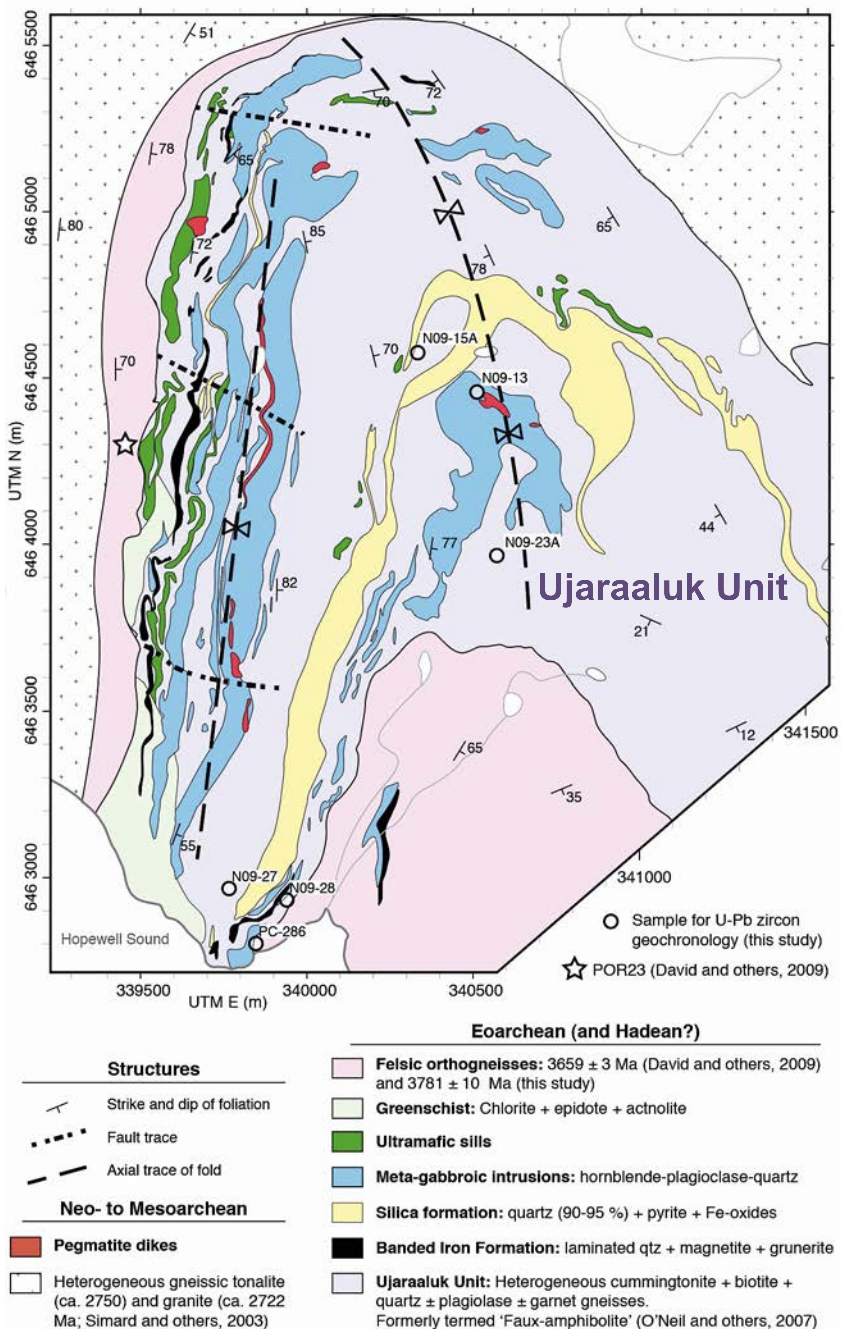


From: Percival et al. (2012, Chapter 6. Geology and Tectonic Evolution of the Superior Province, Canada. In: J. Percival, F. Cook and R. Clowes (Eds), Tectonic Styles in Canada The LITHOPROBE Perspective, Geological Association of Canada, SP 49, 321–378).









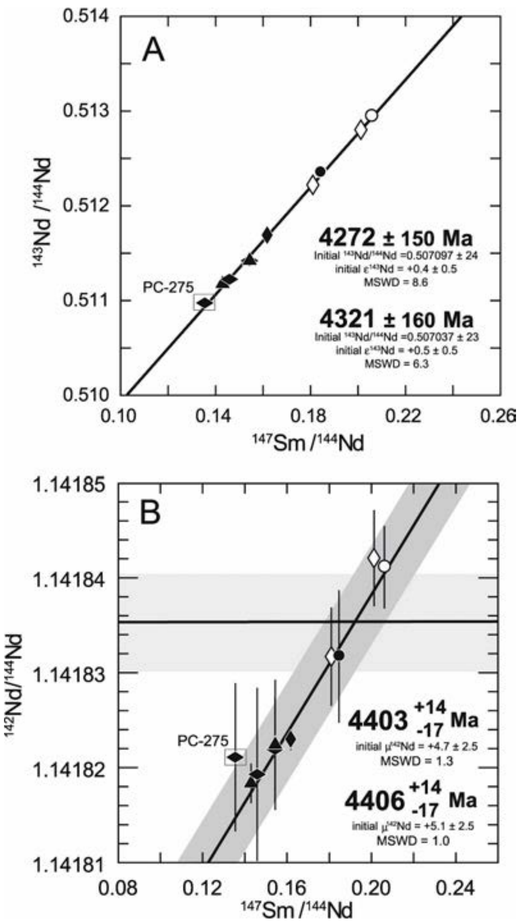
~9 km^2 of Hadean–Eoarchean real estate surrounded by Neoarchean tonalite gneiss

The late Eoarchean tonalites (felsic orthogneisses) are plausibly drived by ~30 vol.% partial melting of the Ujaraaluk Unit amphibolites (Adam et al., 2012, Geology)

At issue, the age and petrogenesis of the Ujaraaluk Unit volcanic rocks.

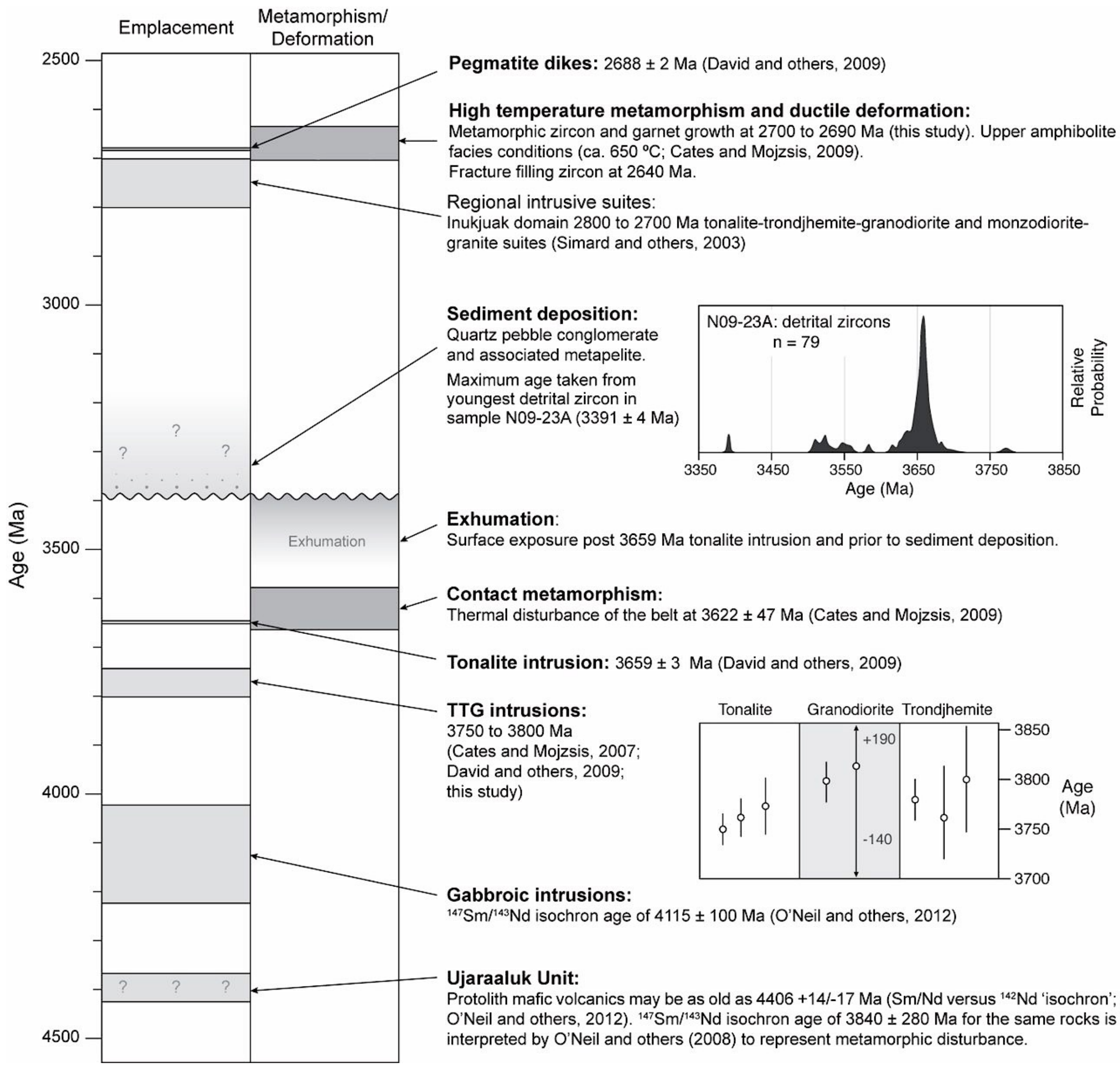
David et al., 2009, GSA Bull.; Darling et al., 2013, AJS

Least disturbed Ujaraaluk samples



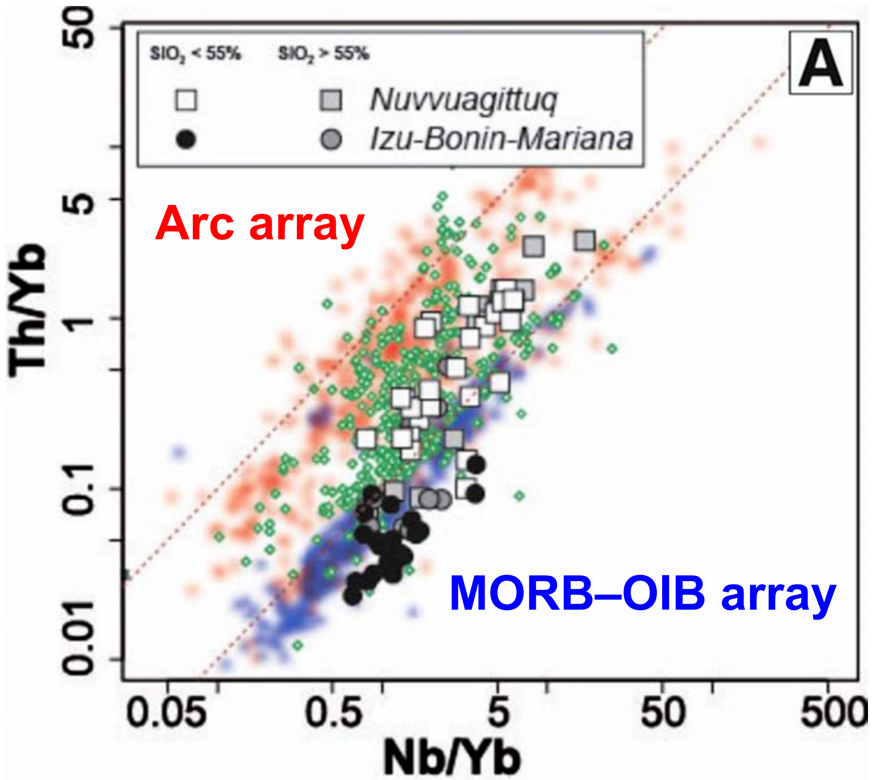
Isochron diagrams for the least disturbed Ujaraaluk samples and cogenetic ultramafic rocks. Gray bands show the 4.5 ppm external error on the terrestrial standard value and the best fit line.

O'Neil et al., 2012, Precambr. Res.



Darling et al., 2013, AJS

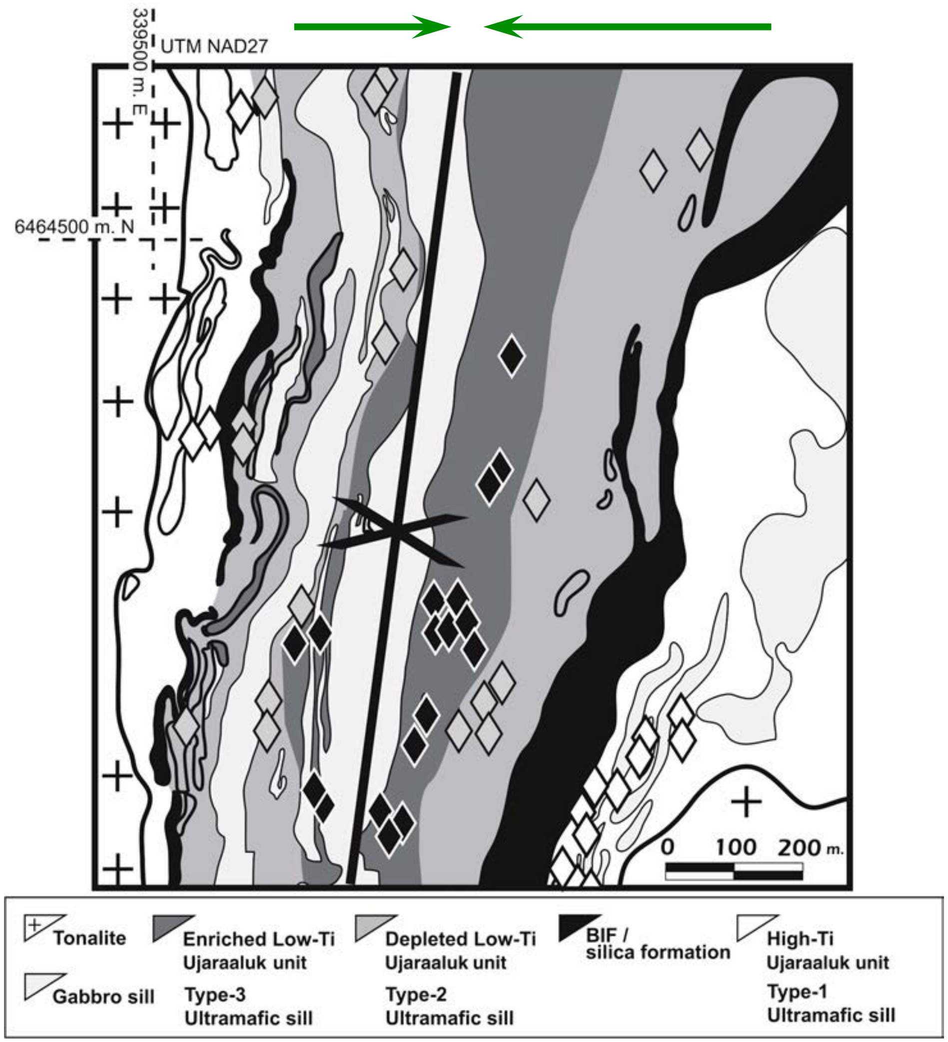
Geochemical fingerprinting

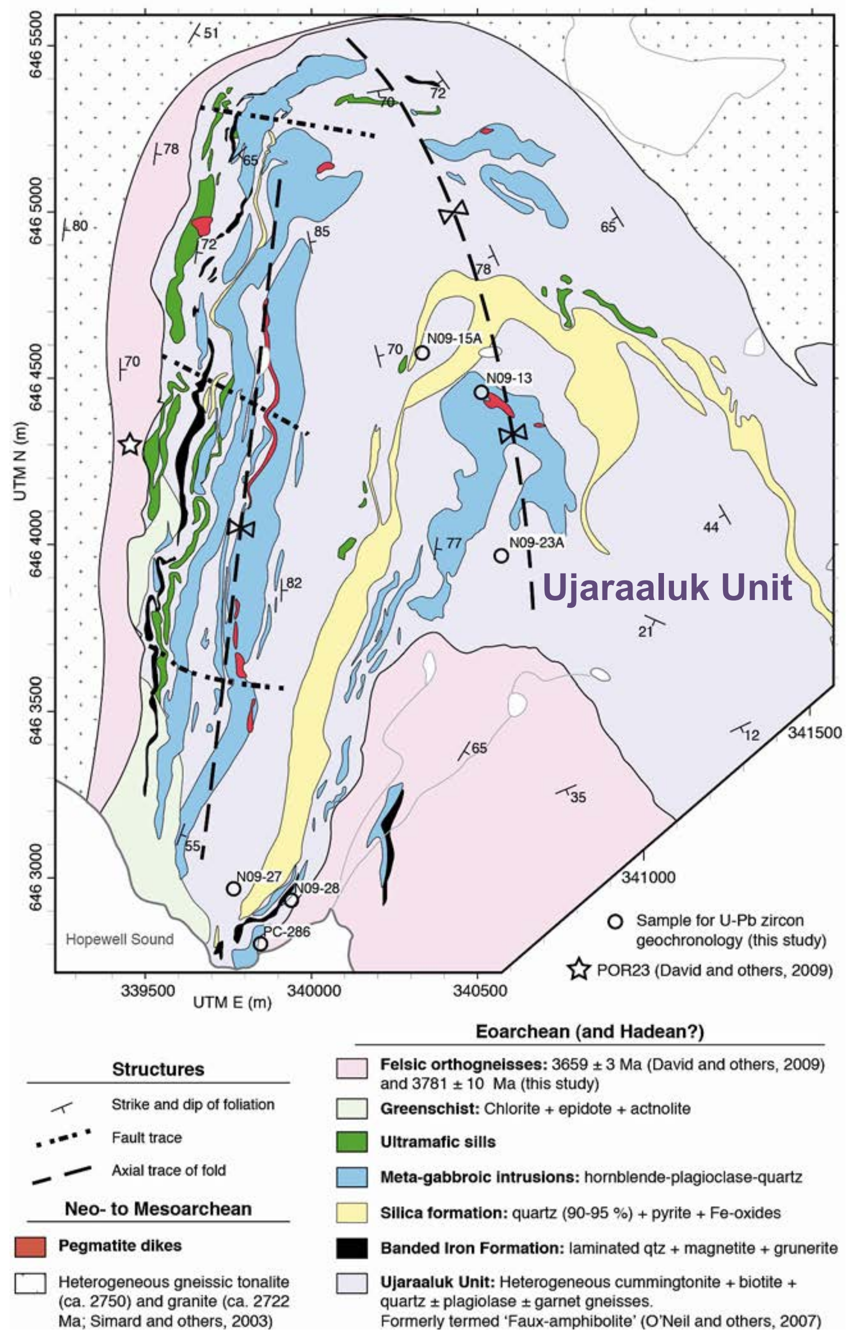


Comparison of modern arc basalts (red cloud) and mid-oceanic ridge basalts (MORB, blue cloud), Archean basalts (green), and rocks from proto Izu–Bonin–Mariana arc (circles) and Nuvvuagittuq supracrustal belt (squares).

Turner et al., 2014, Geology

Inferred stratigraphic younging



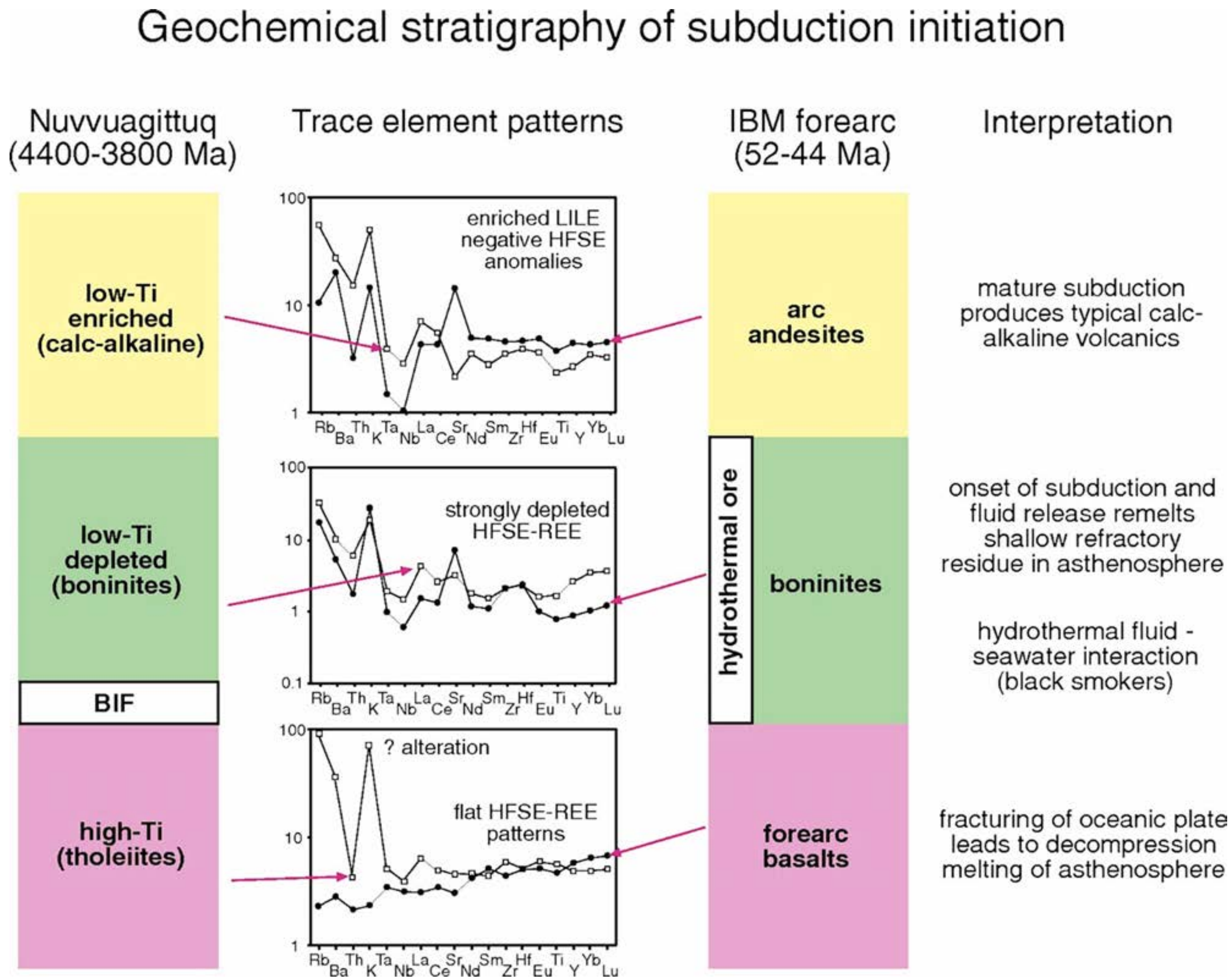


Symbols: open diamonds, high-Ti Ujaraaluk unit; grey diamonds, depleted low-Ti Ujaraaluk unit; black diamonds, enriched low-Ti Ujaraaluk unit.

O'Neil et al., 2011, JPet

The geochemical stratigraphy of the Ujaraaluk Unit closely matches that from the modern-day Izu–Bonin–Mariana forearc. This may suggest some form of subduction on early Earth, or perhaps a period of failed subduction initiation?

Turner et al., 2014, Geology

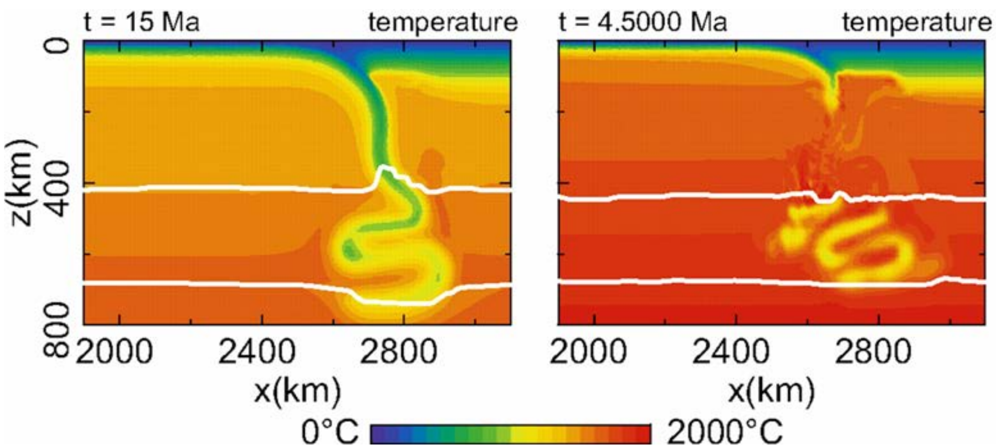


Two key issues (Pearce – Research focus, 2014, Geology):

(1) could hot Hadean lithosphere have had sufficient negative buoyancy to sink in the same way as the Pacific lithosphere in the IBM system to initiate subduction;

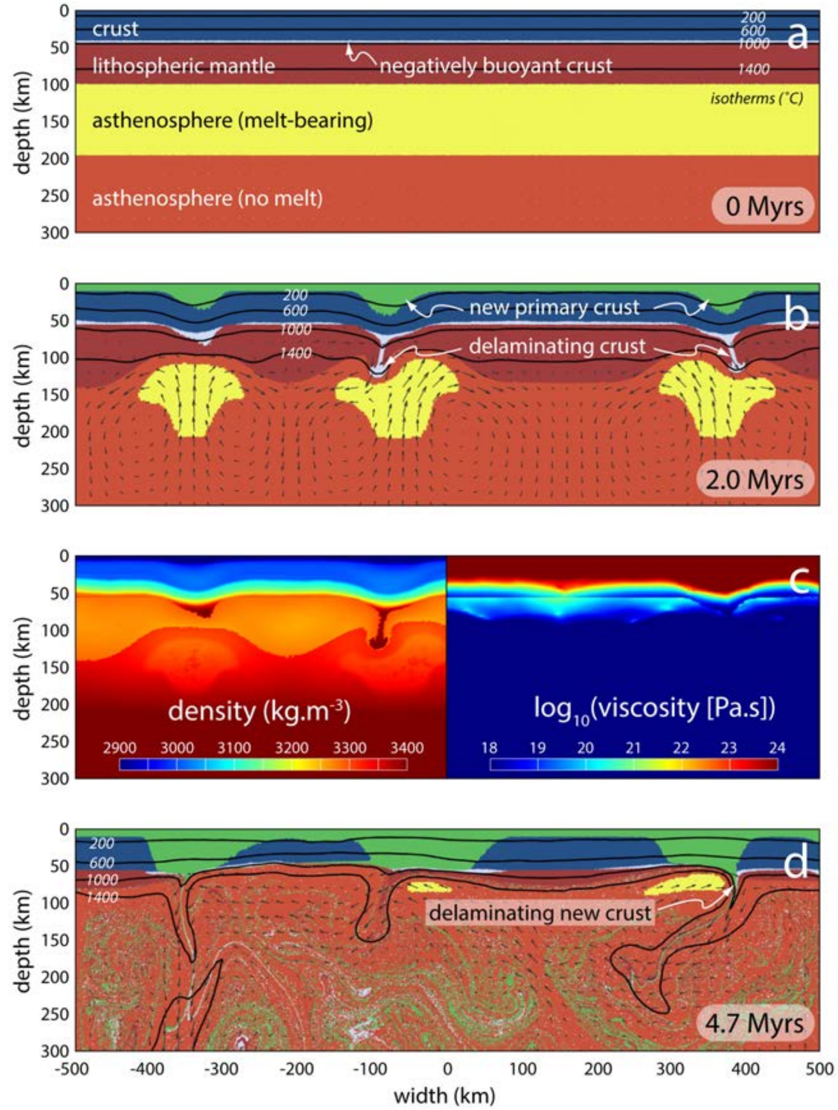
(2) is subduction initiation the only explanation or could Nb–Ta and Zr–Hf anomalies be expected in a stagnant-lid regime if the mantle was modified by melts derived from delaminated crust?

Short-term episodic subduction or stagnant-lid?

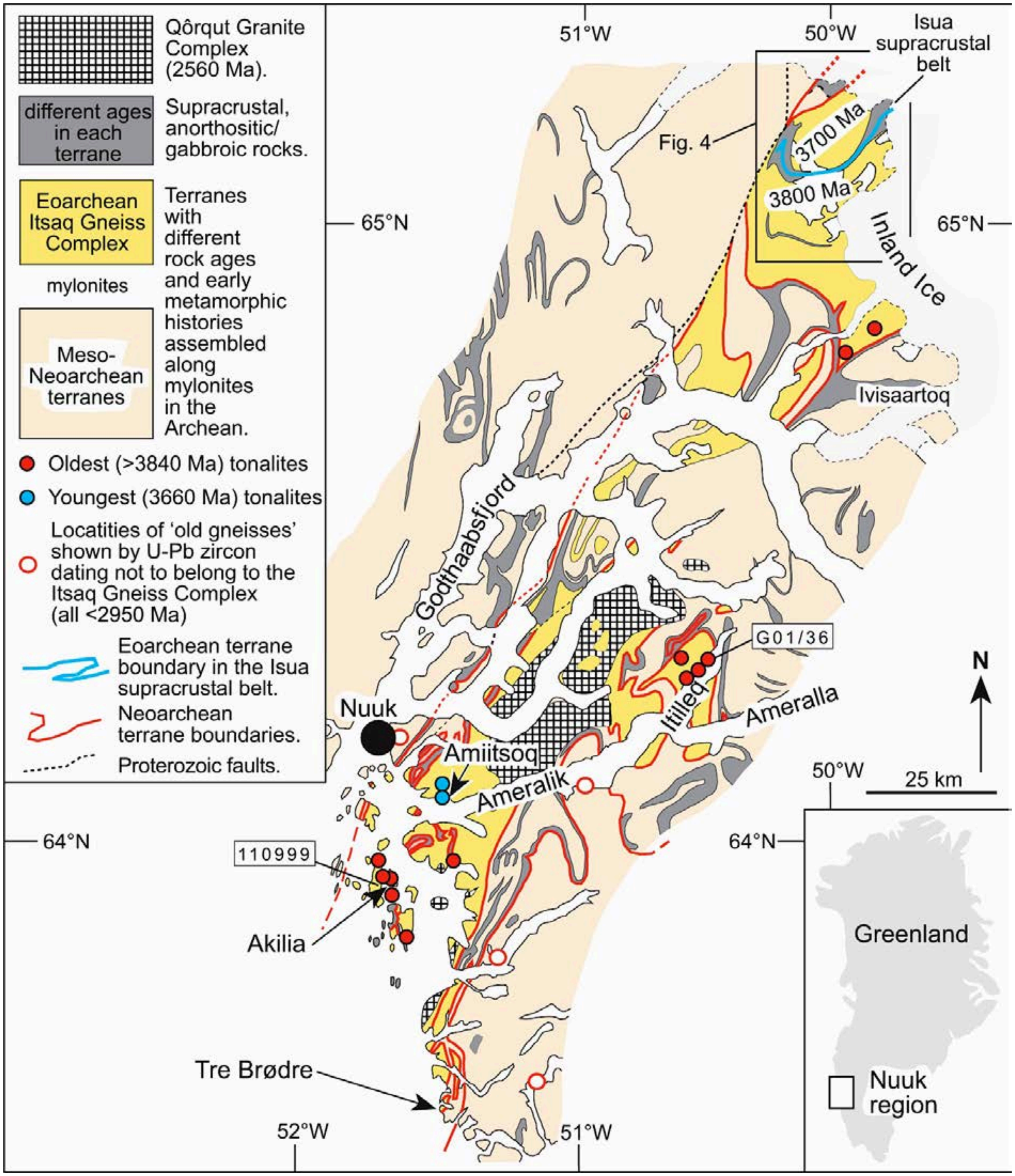


Moyen & van Hunen, 2012, Geology

T_P = 1600°C



Johnson et al., 2014, Nature Geosci.

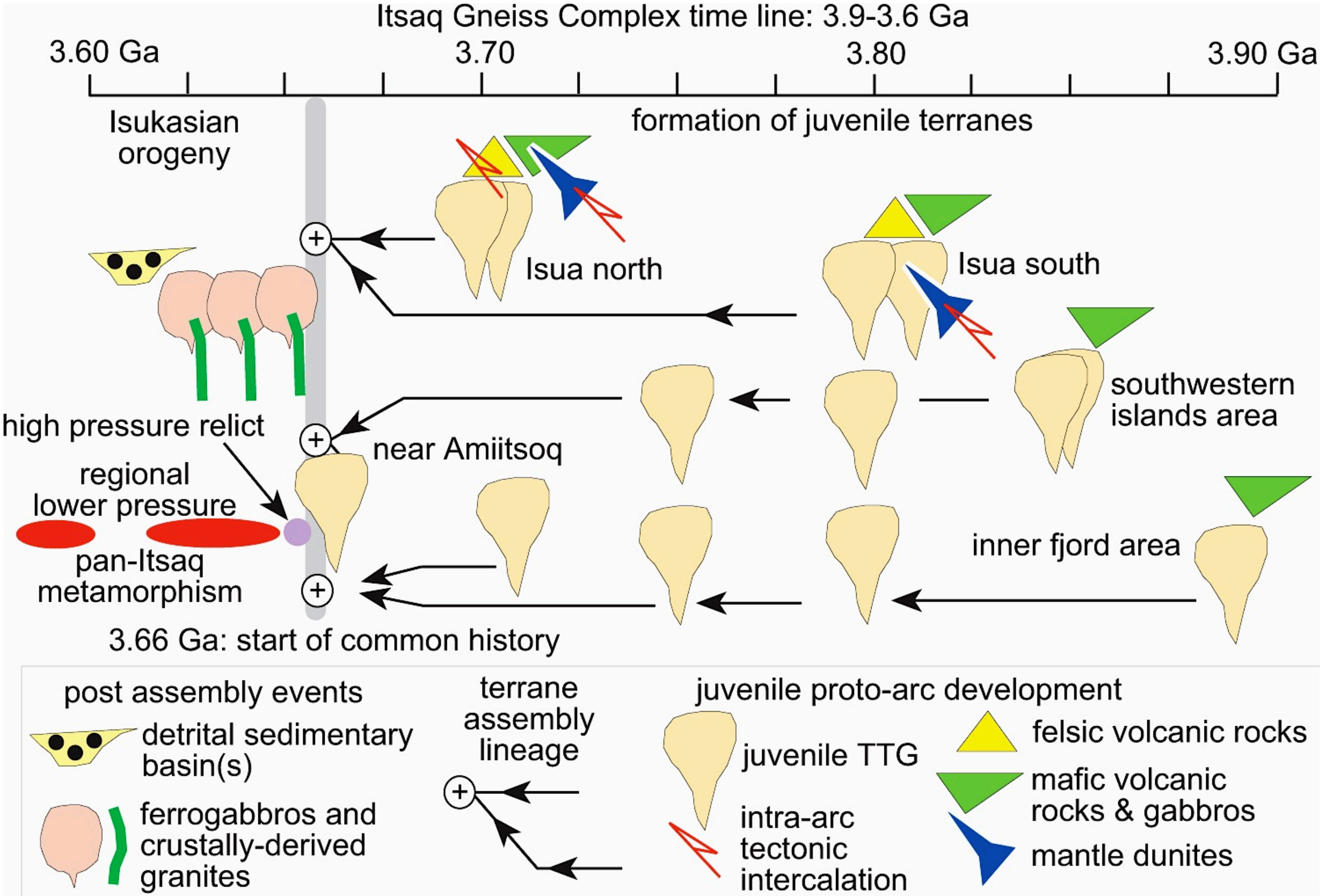


2. Isua area, North Atlantic craton, southern-west Greenland

At 10,000 km^2, the Itsaq Gneiss Complex represents the largest area of Eoarchean crust with relicts of >3850 Ga TTGs and supracrustal rocks on Earth!

Structural data from the north-western sector of Isua have been interpreted to support thrusting to the north-west of the >3.8 Ga unit over the ca. 3.7 Ga unit, followed by extension to the south-east (Hanmer & Greene, 2002, JSG) coeval with granulite facies metamorphism and lower crustal melting.

Nutman et al., 2013, AJS

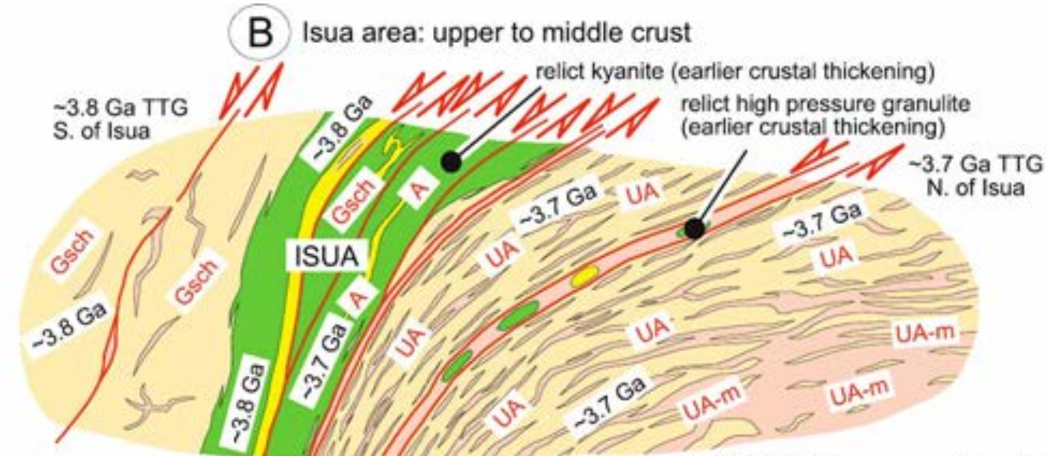


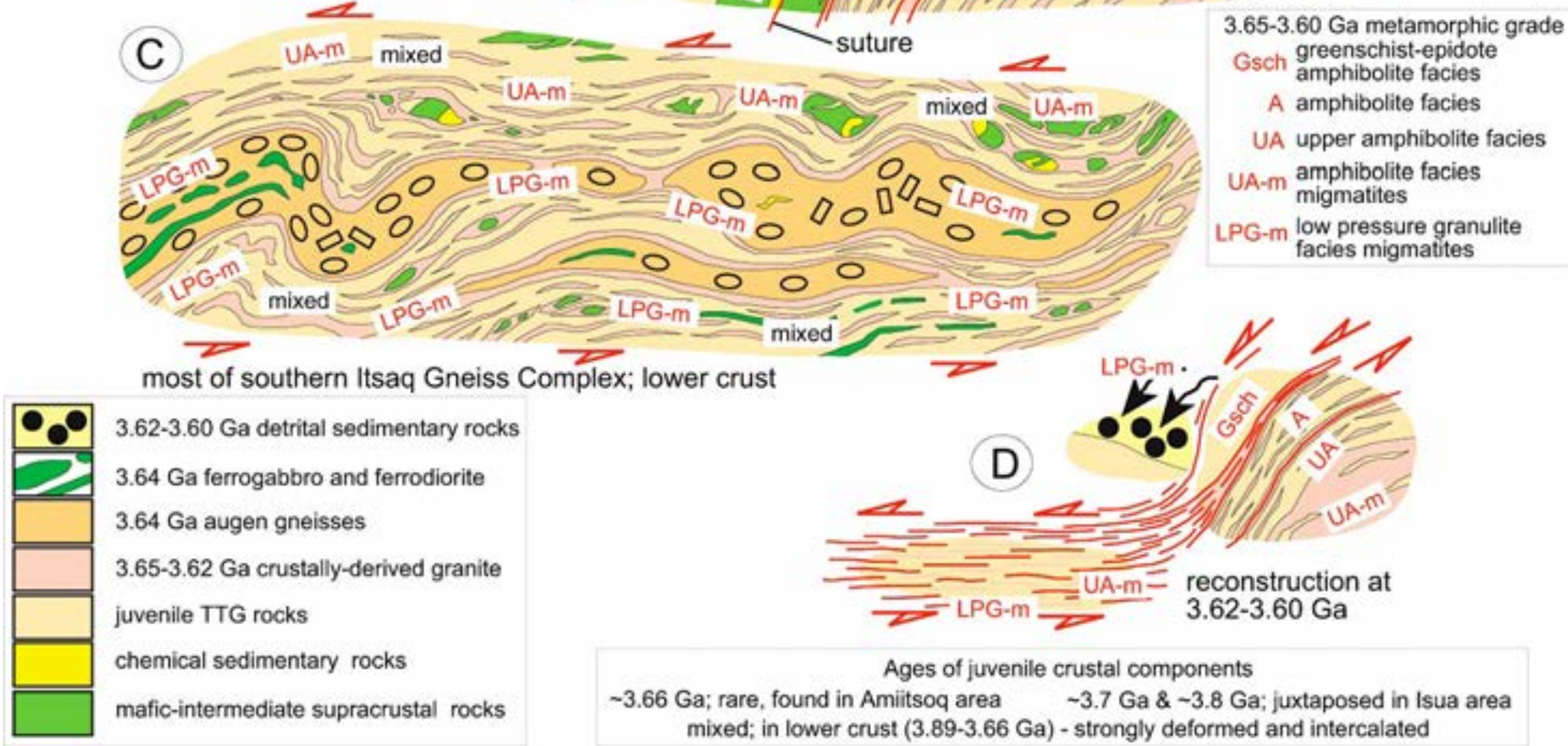
Timeline for the evolution of the Itsaq Gneiss Complex from 3900 to 3600 Ma. This is based on U-Pb zircon dating of more than 160 rocks integrated with geological mapping.

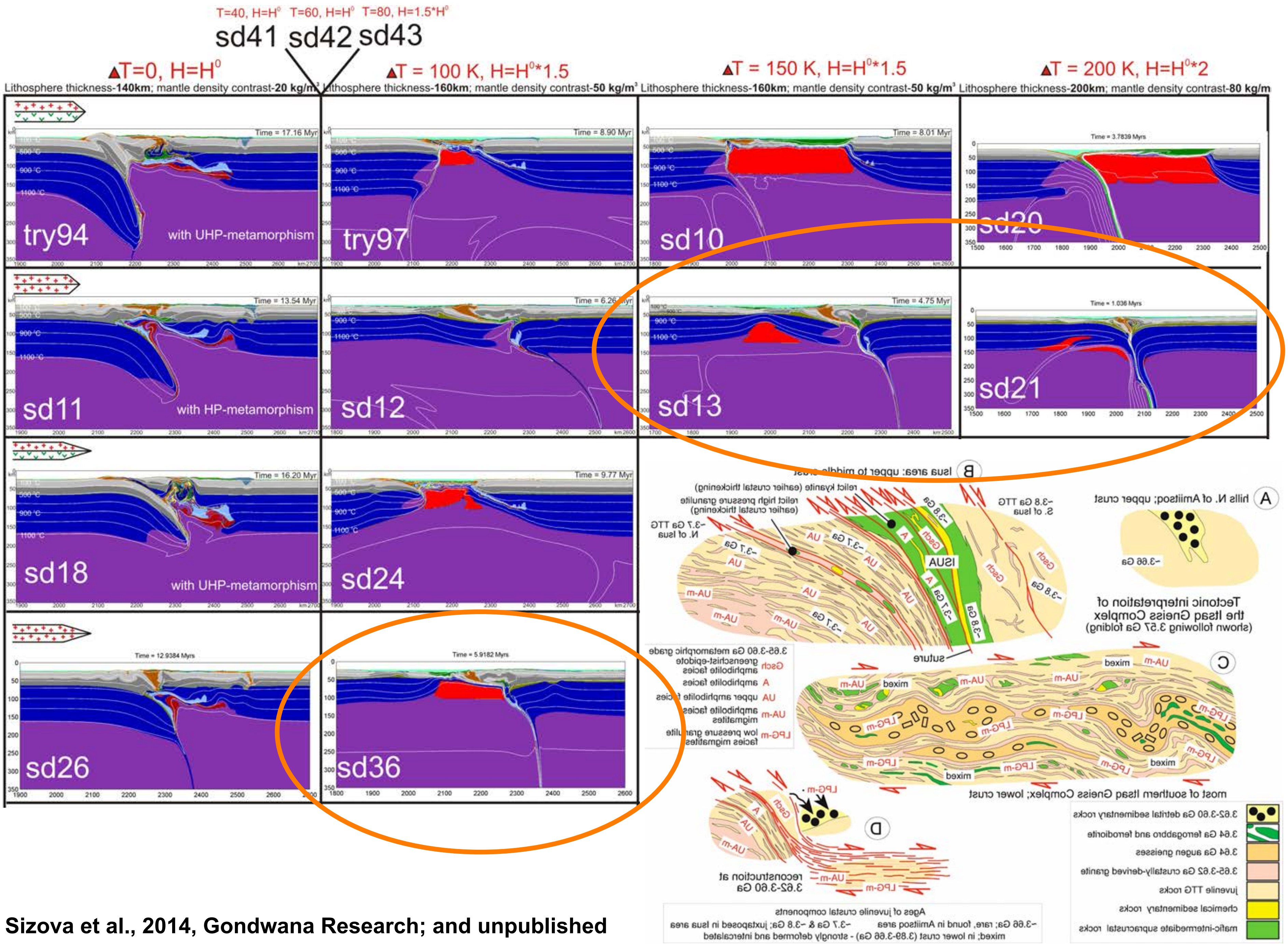
Nutman et al., 2013, AJS

Schematic cross-sections illustrating state of the Itsaq Gneiss Complex at the end of the Isukasian orogeny

Nutman et al., 2013, AJS

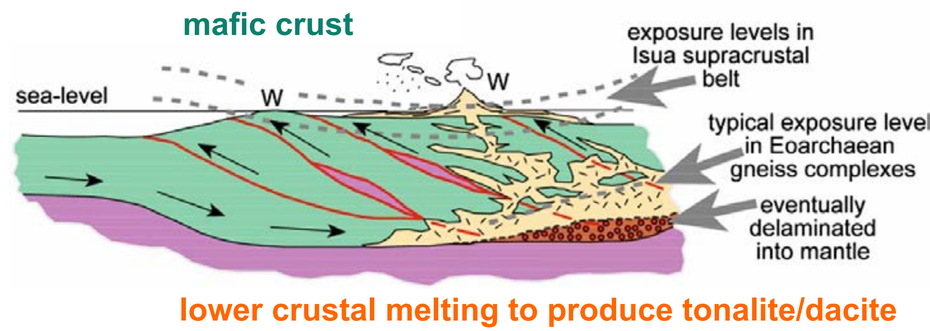


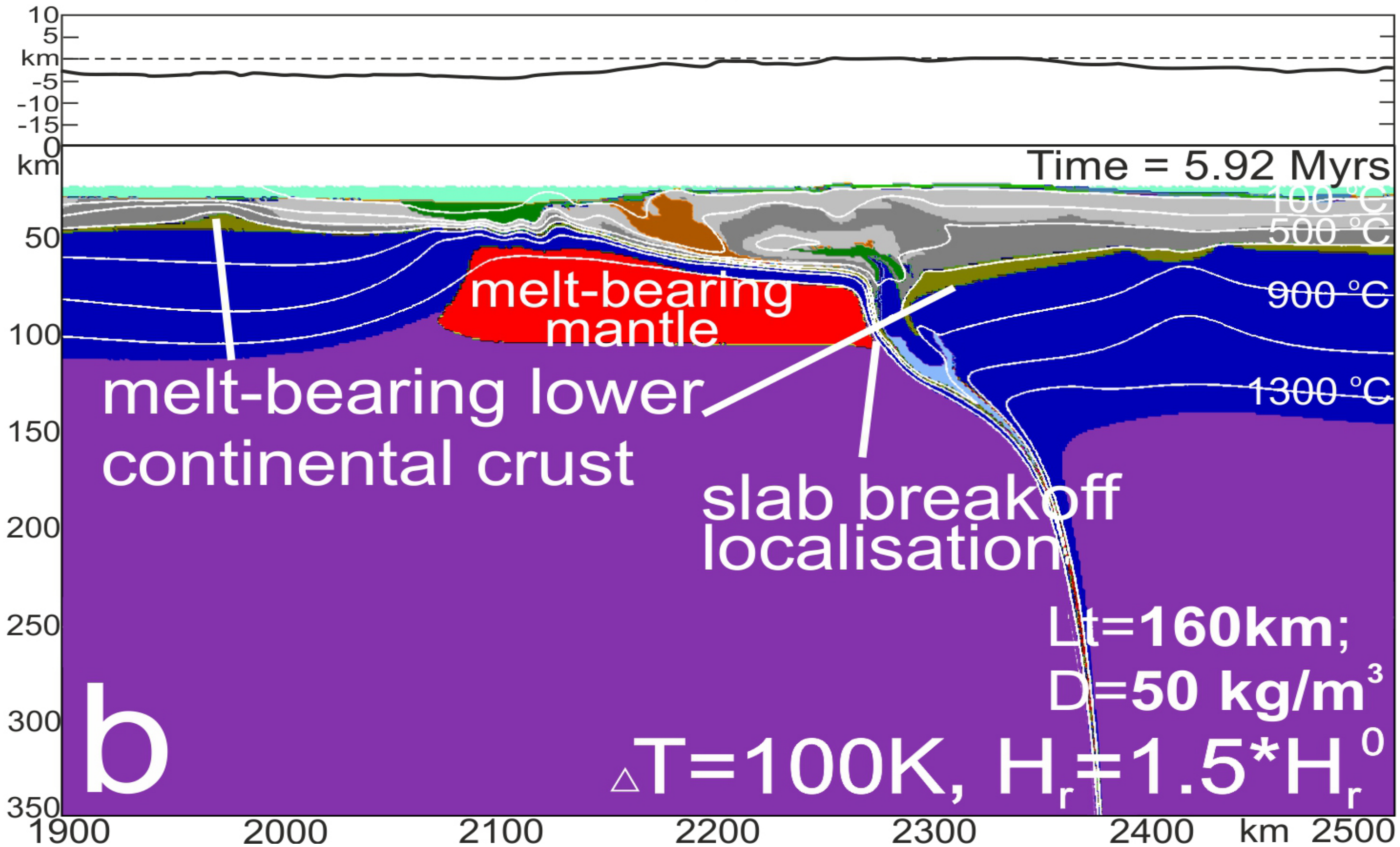




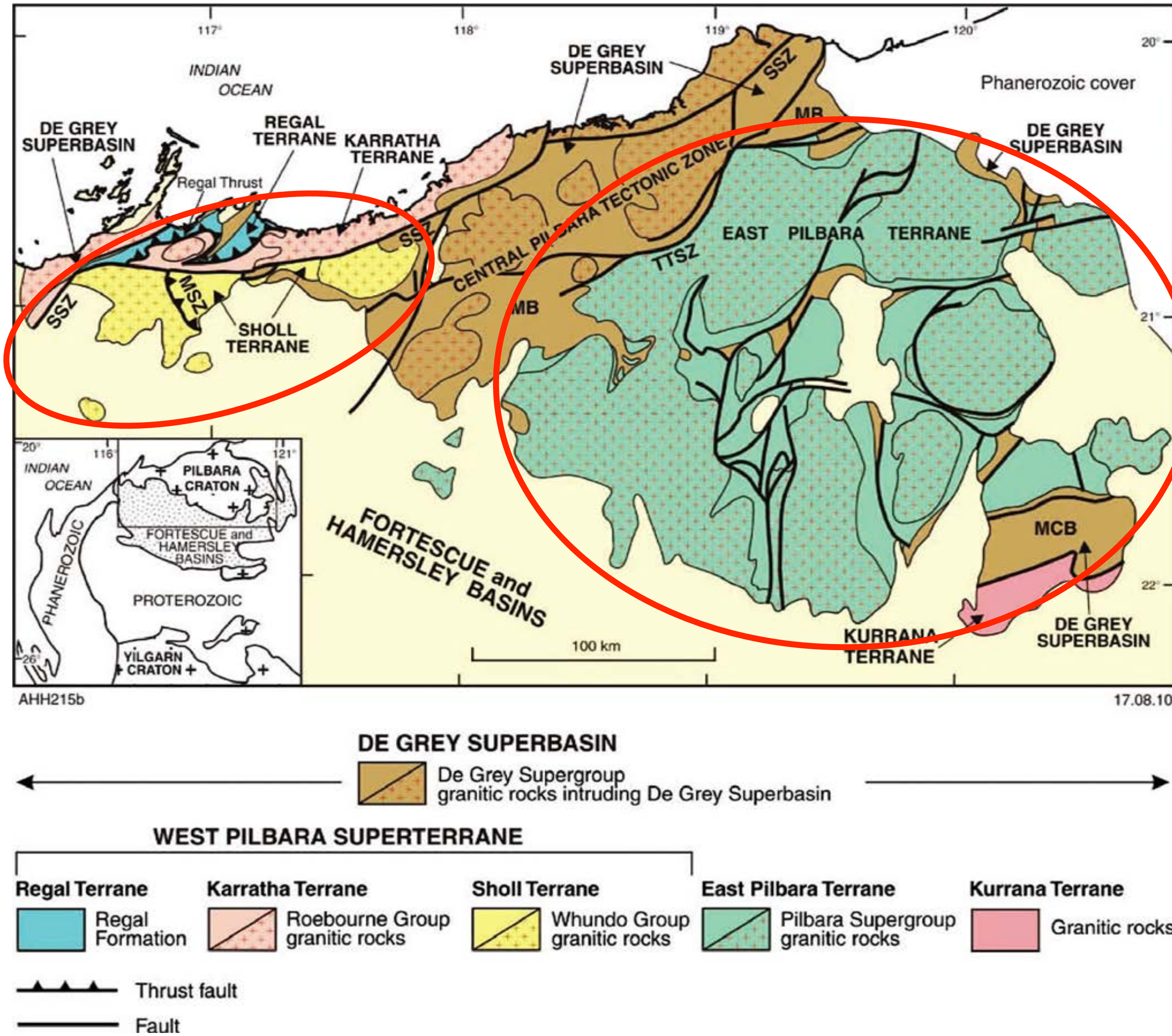
Sizova et al., 2014, Gondwana Research; and unpublished

Nutman et al., 2015, G.S. Lond. Sp.Publ.



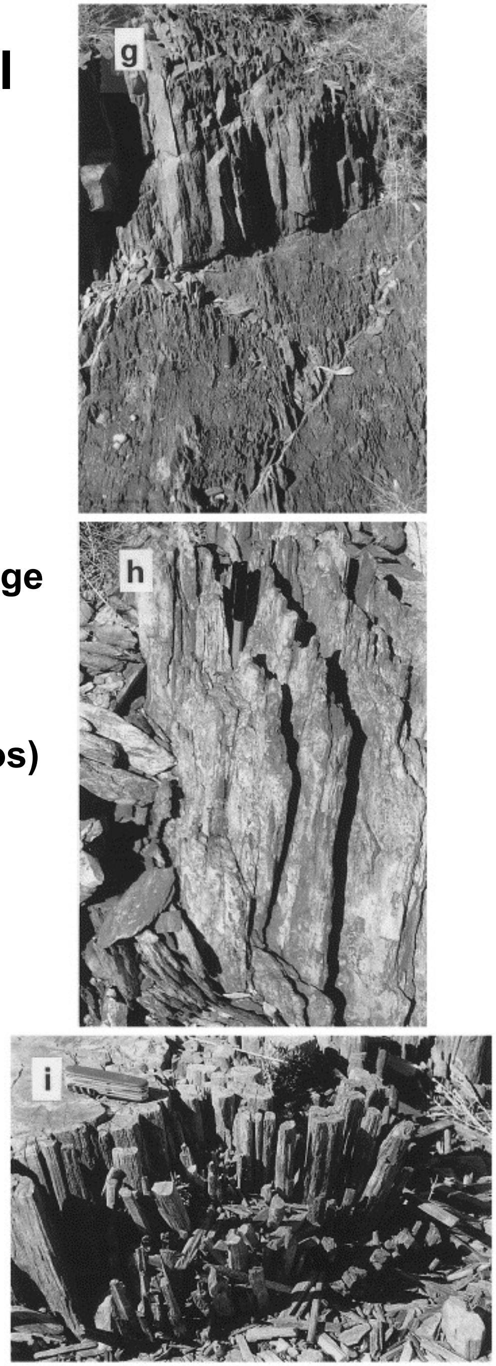


3. Pilbara craton, Western Australia



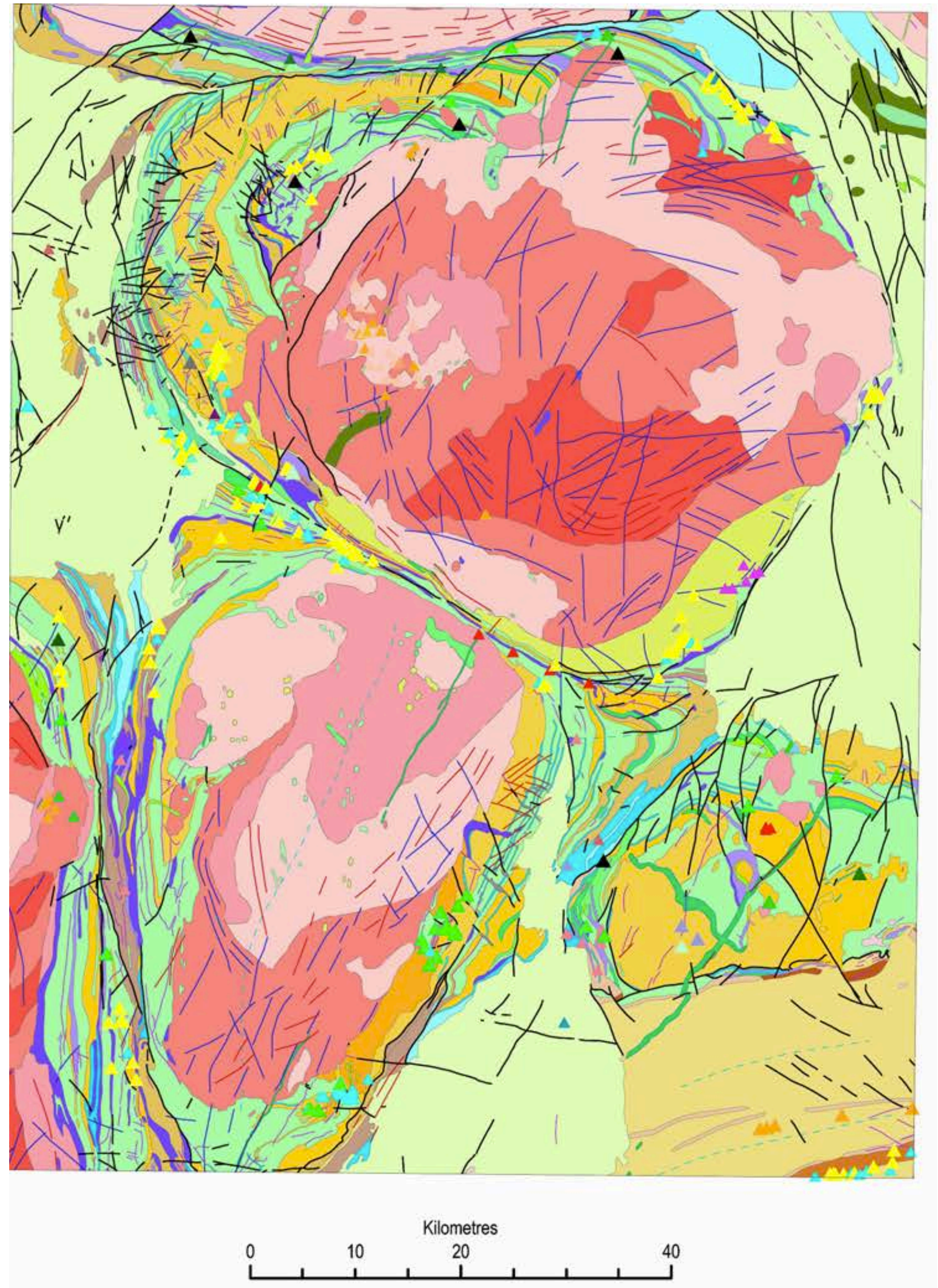
Hickman & Van Kranendonk, 2012, Episodes

Dome-and-keel architecture



The progressive change from L–S fabrics in greenstones close to the batholith contact (top and middle photos) to L-tectonites in the core of the syncline (bottom photo).

Collins et al., 1998, JSG

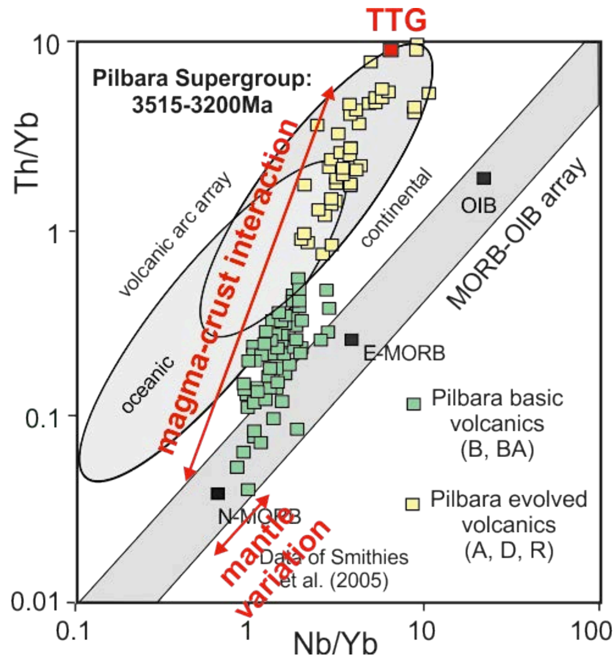


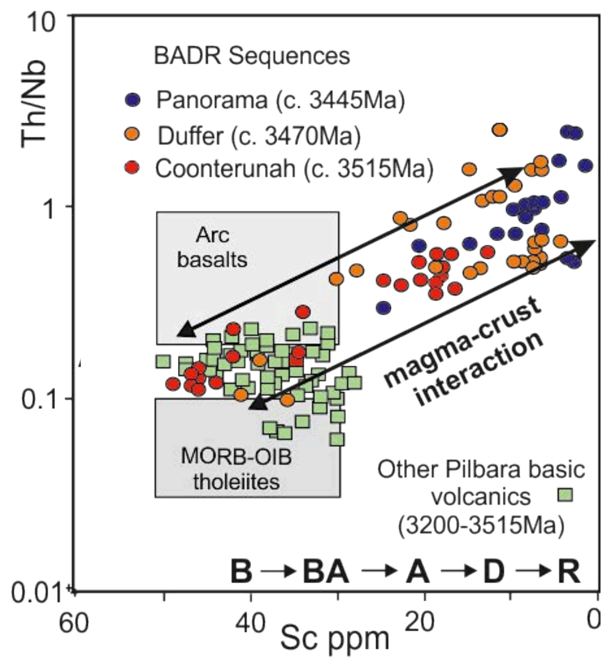
Geoscience Australia

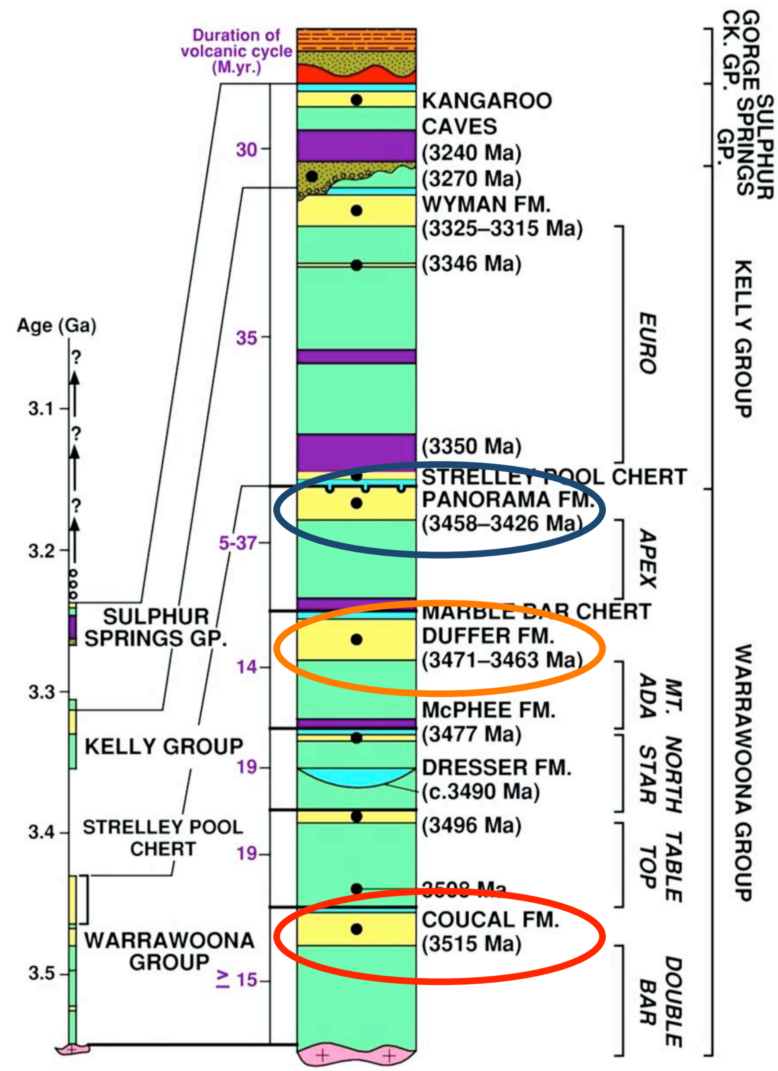
East Pilbara: petrogenesis of the volcanic sequences

East Pilbara basic volcanics and basalt–andesite–dacite–rhyolite sequences are best explained as the result of interaction between basic magmas and crustal melts.

Note the remarkably small mantle variation for >250 Ma of volcanic activity.

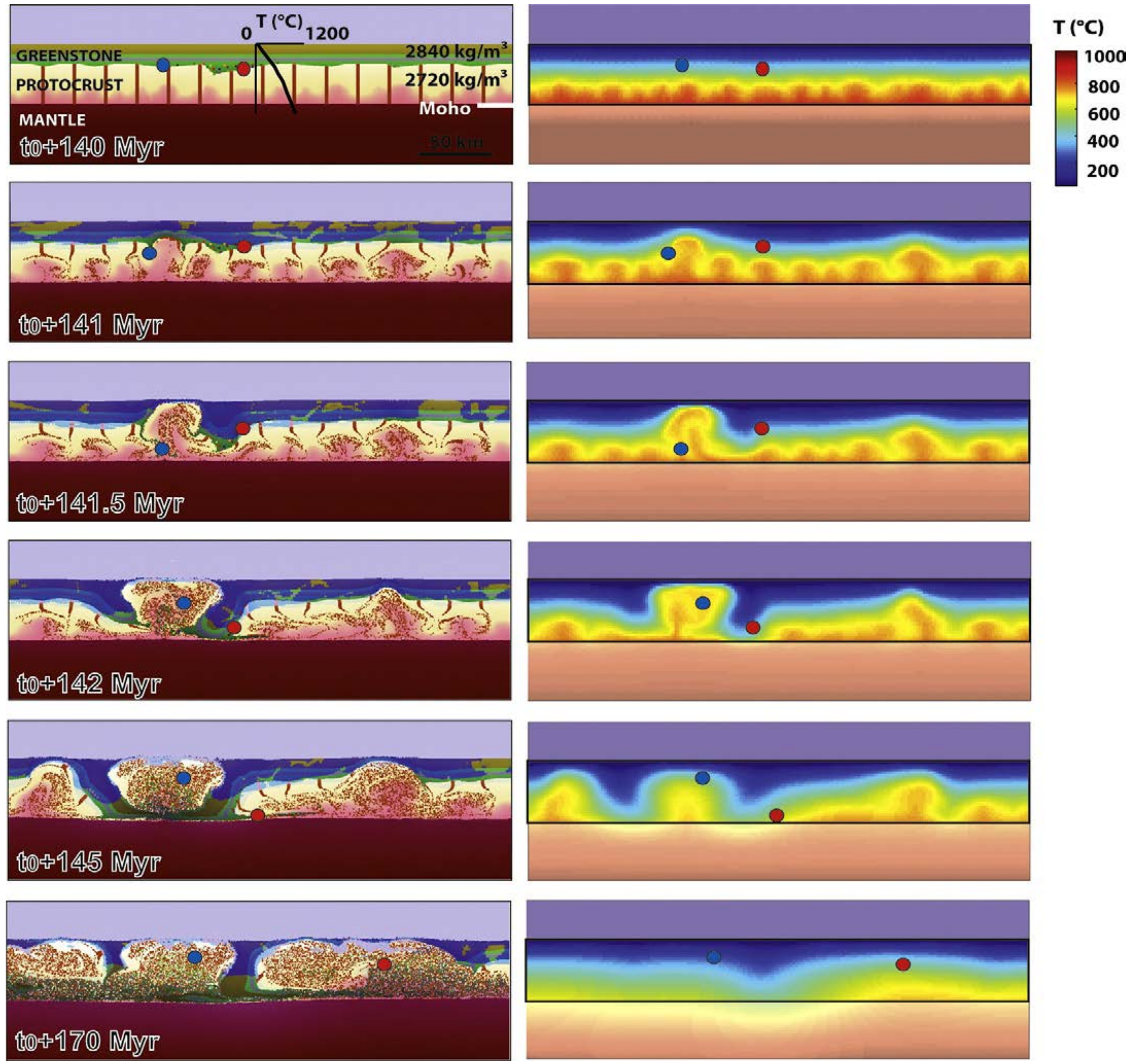






Yellow = dominantly felsic
Green = dominantly basic
Purple = dominantly komatiitic

J. Pearce, pers. comm. 10/2013

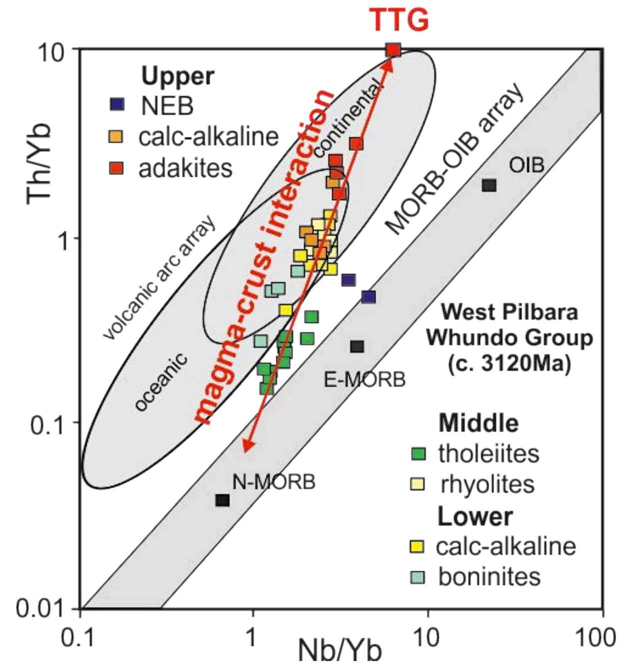


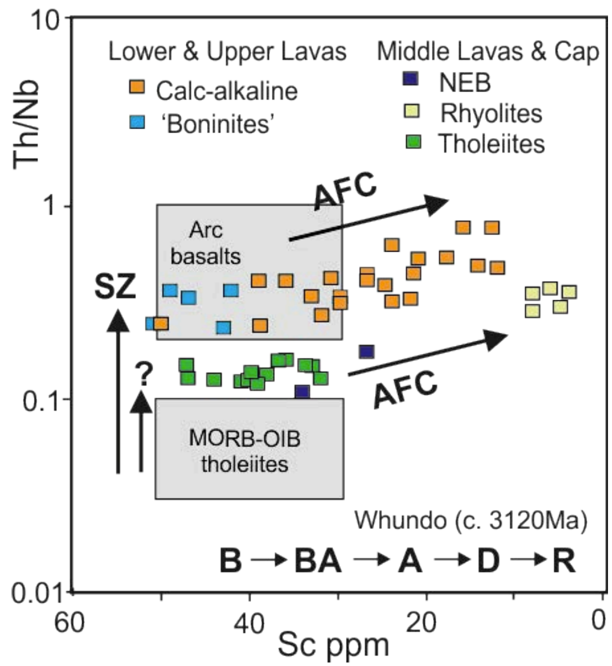
Francois et al.,
2014, EPSL

West Pilbara: petrogenesis of the volcanic sequences

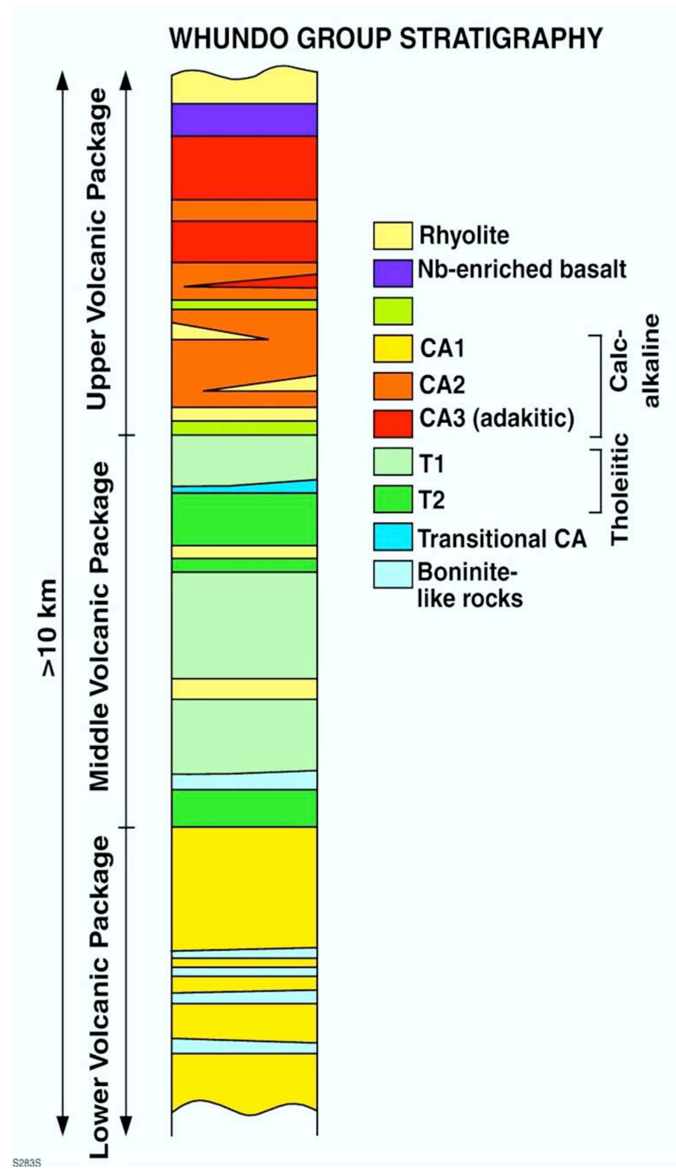
In the Th/Yb *vs* Nb/Yb diagram, a similar petrogenesis to the Pilbara Supergroup is possible – interaction between magma and crust with no subduction influence.

However, in the Th/Nb vs Sc diagram, the trend formed by the boninite and calc-alkaline lavas extrapolates back into the arc field, supporting a probable arc origin for these units (cf. Smithies et al., 2005, EPSL).





J. Pearce, pers. comm. 10/2013

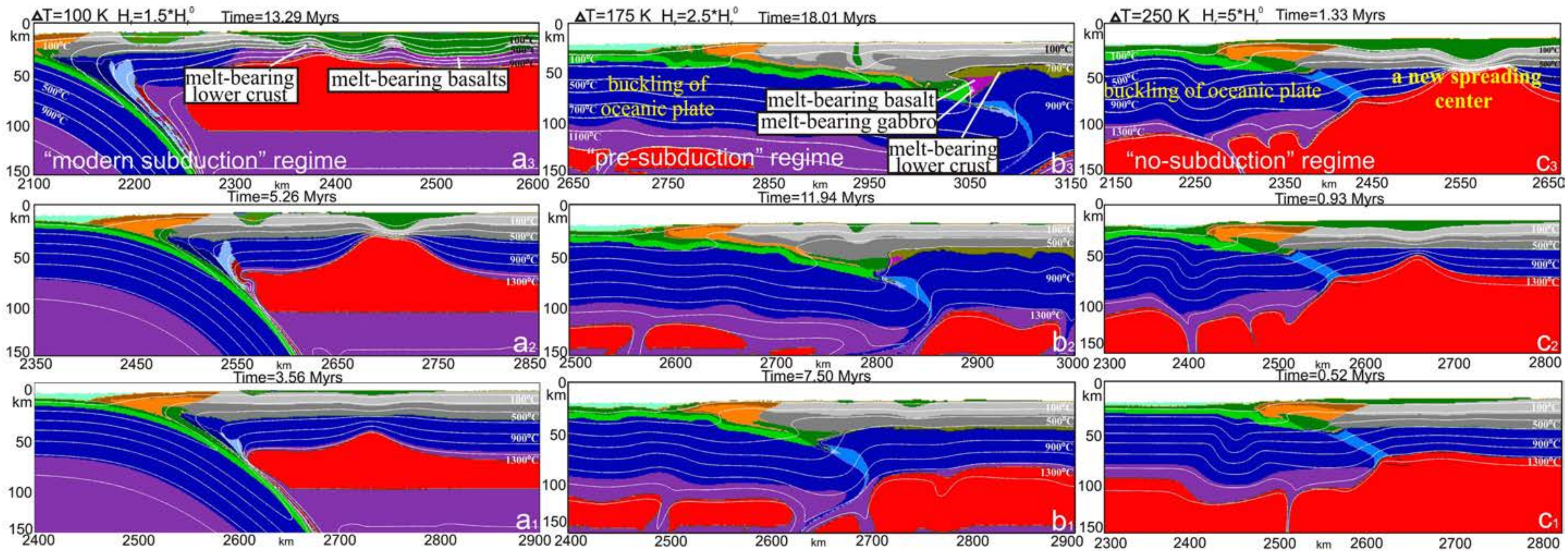


Key Point

There are two types of basalt–andesite–dacite–rhyolite (BADR) sequences in the Pilbara: one unrelated to subduction (‘plume’-related?) and another that was subduction-related.

The subduction events may be short-lived and mark the ends of long periods of ‘plume’-related activity.

The transition from stagnant lid to subduction



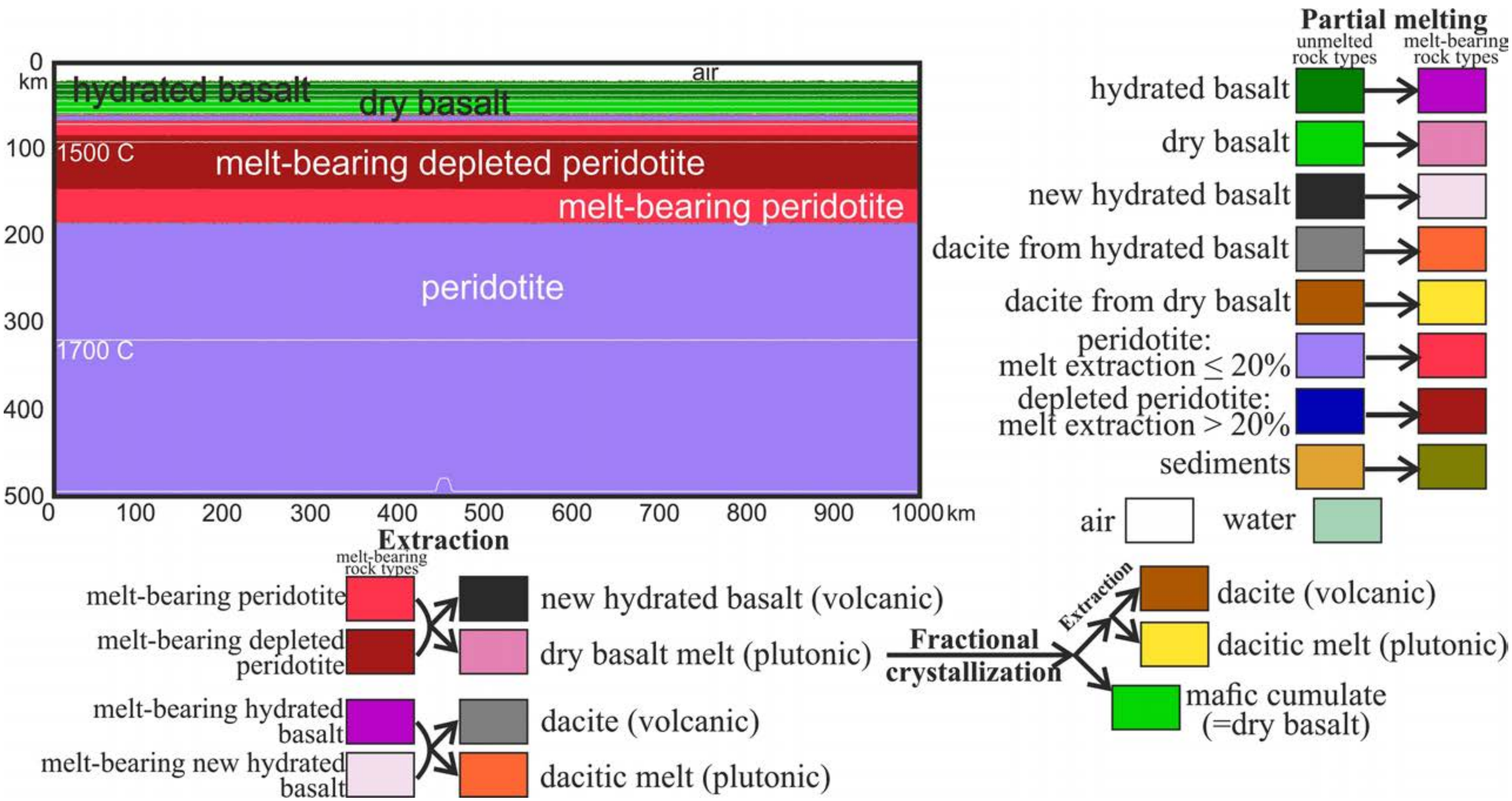
stagnant–deformable-lid regime

transitional (pre-subduction) regime

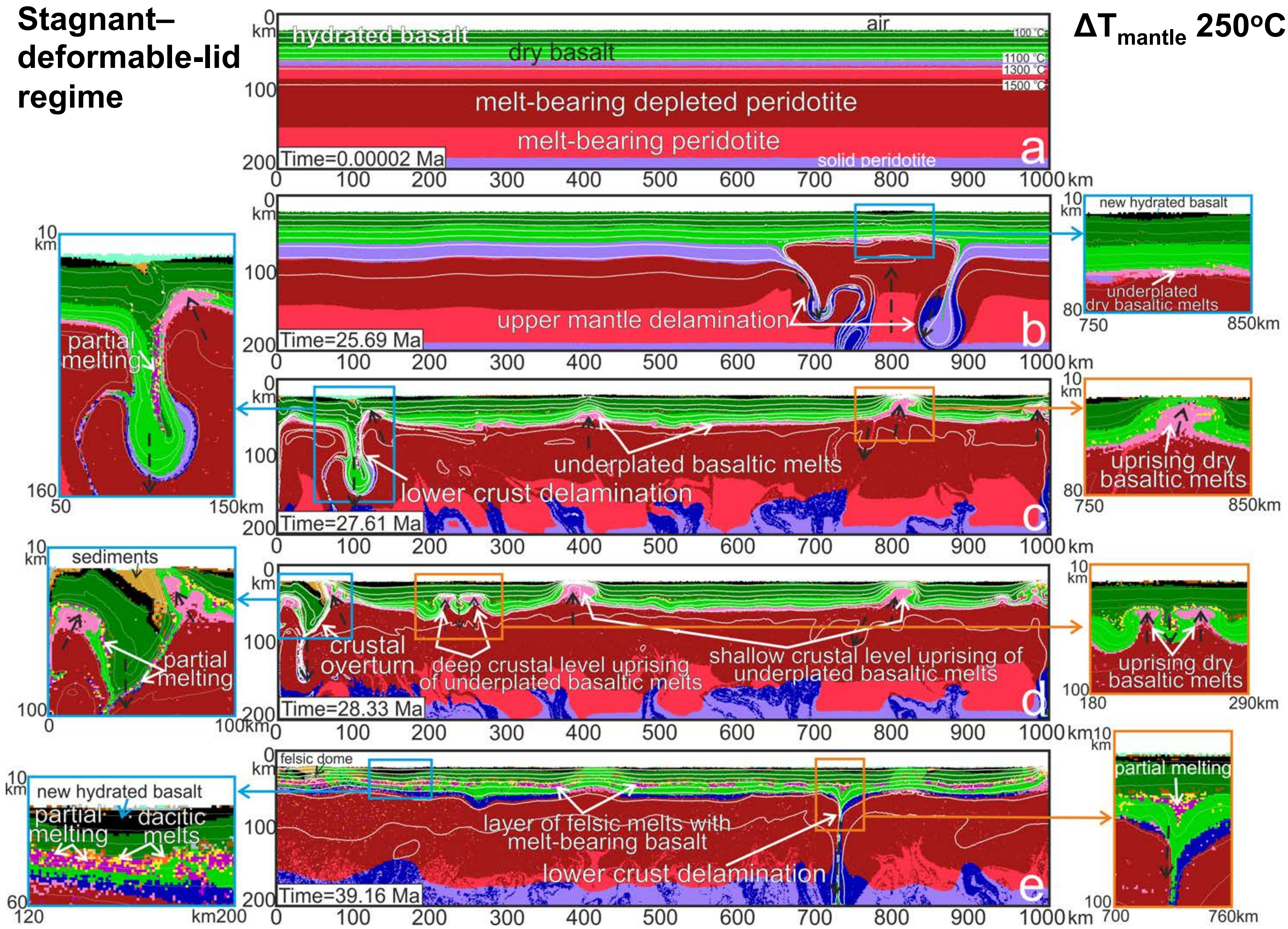
(modern) subduction regime

Sizova et al., 2010, Lithos

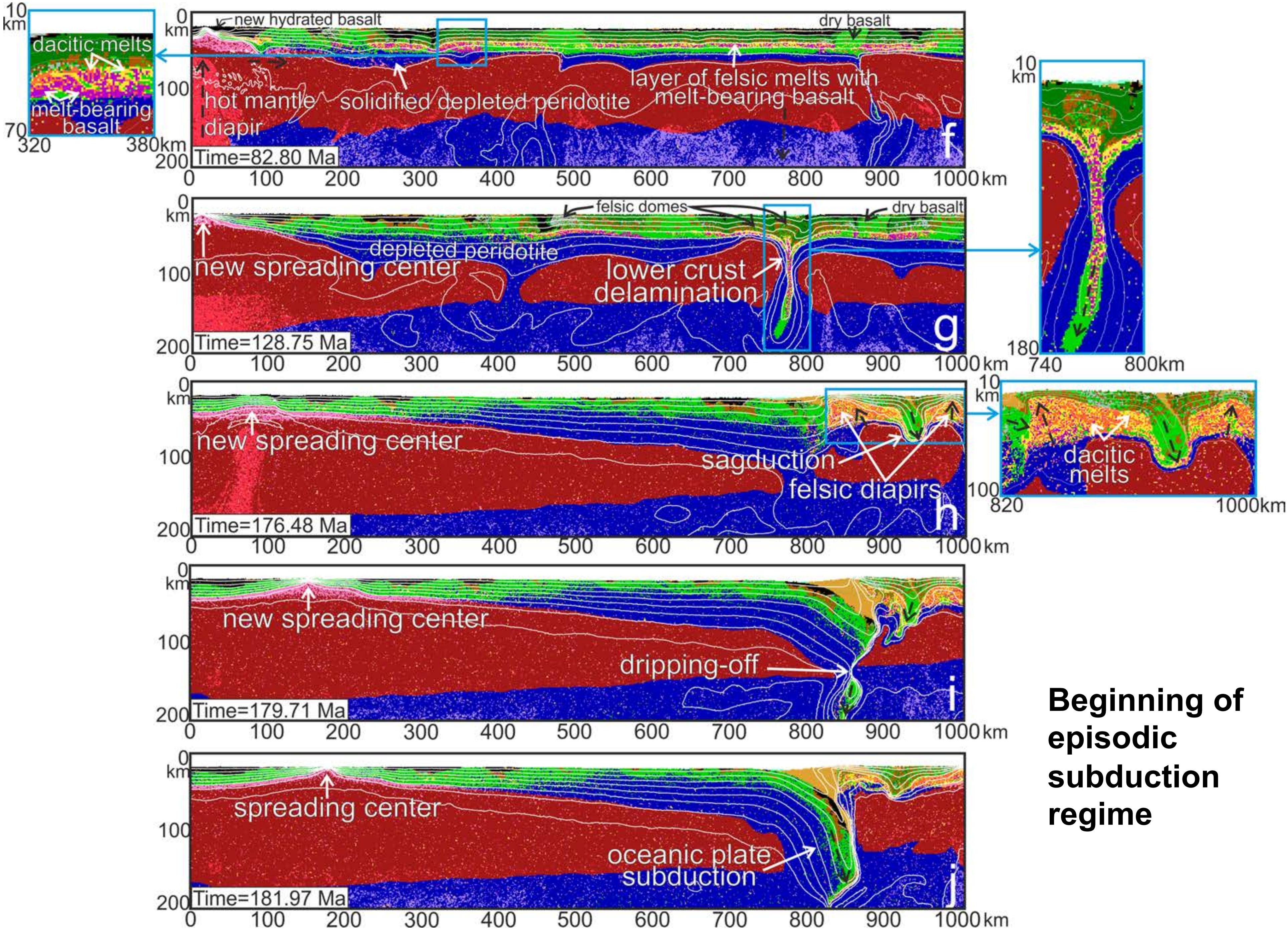
A new geodynamic model for the development and evolution of Archean lithosphere



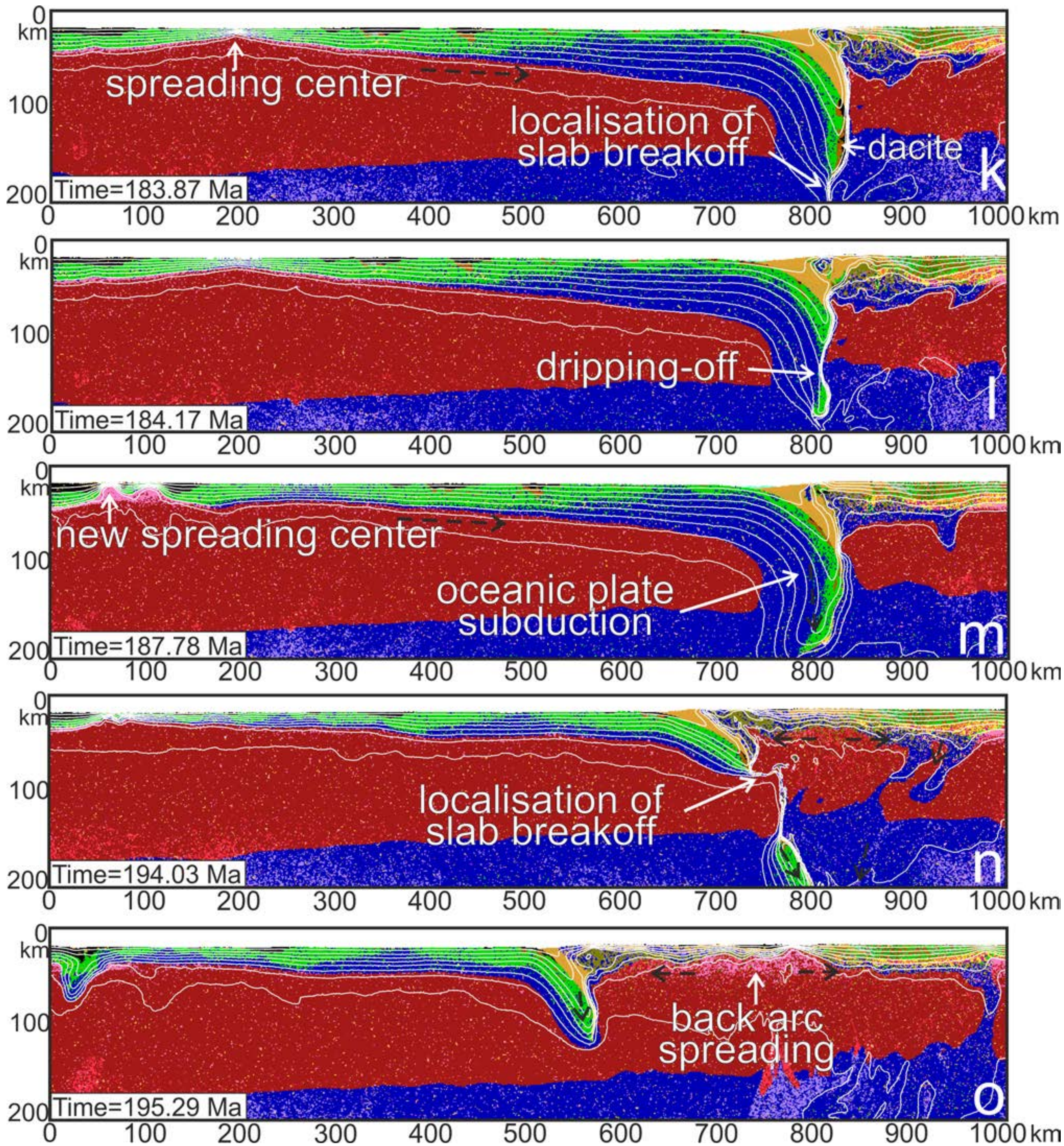
Sizova et al., in review, Precambr. Res.



Stagnant–deformable-lid regime
ΔT mantle 250°C
hydrated basalt
air
dry basalt
100 °C
1100 °C
1300 °C
1500 °C
melt-bearing depleted peridotite
melt-bearing peridotite
solid peridotite
Time=0.00002 Ma
a
Time=25.69 Ma
upper mantle delamination
b
new hydrated basalt
underplated dry basaltic melts
partial melting
Time=27.61 Ma
underplated basaltic melts
lower crust delamination
c
uprising dry basaltic melts
sediments
partial melting
crustal overturn
deep crustal level uprising of underplated basaltic melts
shallow crustal level uprising of underplated basaltic melts
Time=28.33 Ma
d
uprising dry basaltic melts
felsic dome
new hydrated basalt
partial melting
dacitic melts
layer of felsic melts with melt-bearing basalt
lower crust delamination
Time=39.16 Ma
e
partial melting

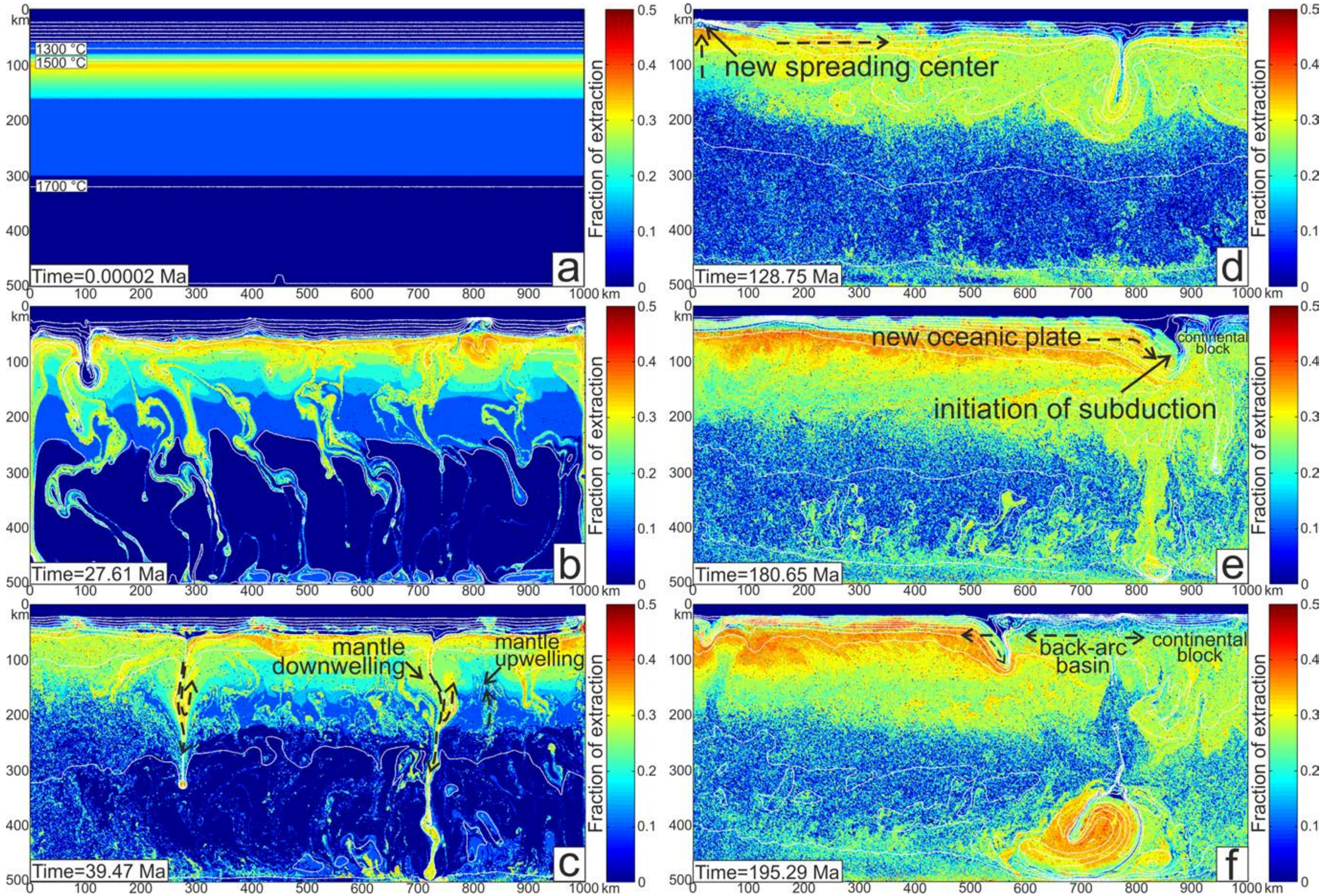


Beginning of episodic subduction regime



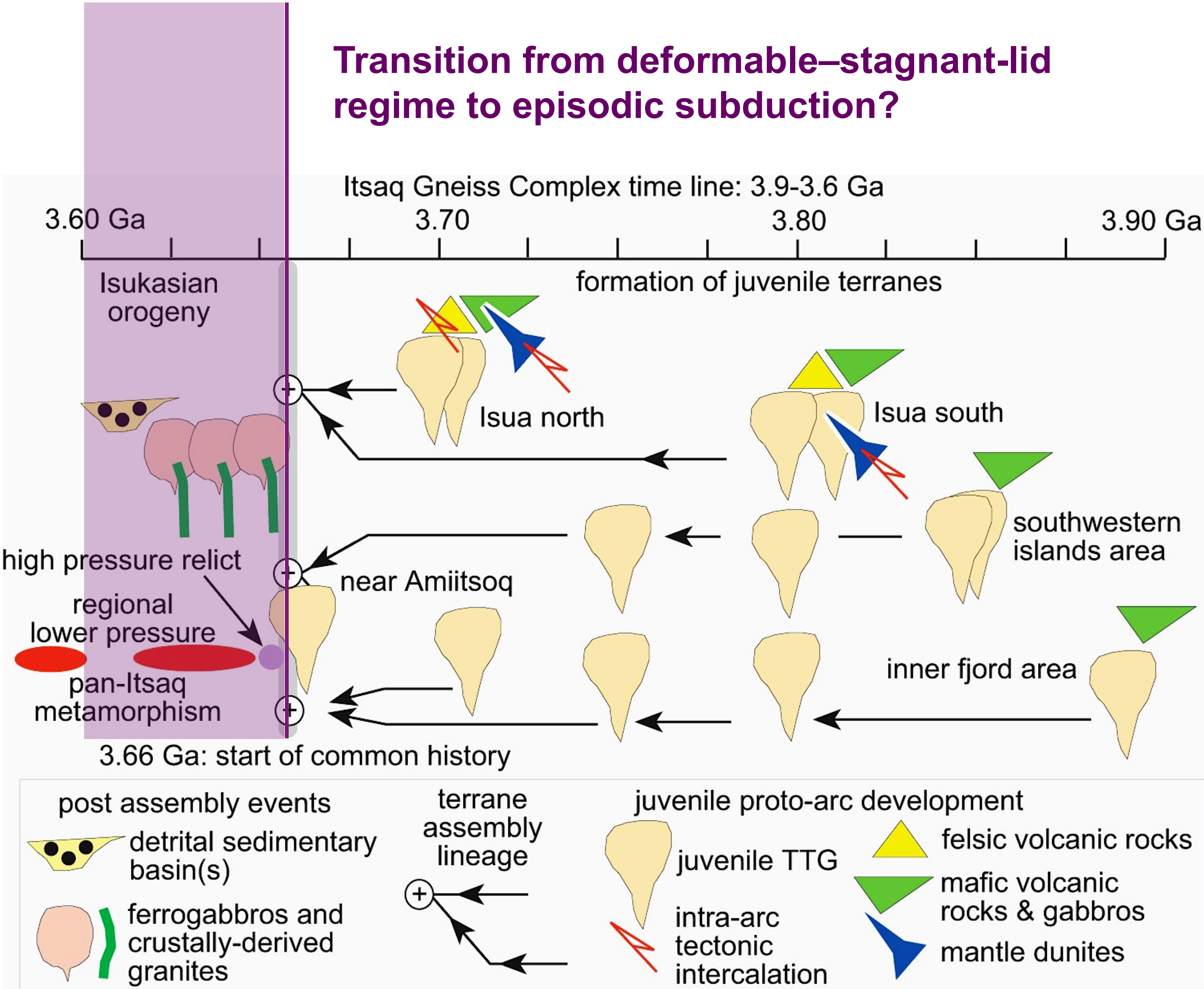
Change from generation of juvenile crust to significant crustal reworking in the episodic subduction regime

Formation of the sub-continental lithospheric mantle



Average melt depletion down to 200 km = 0.25–0.30

Transition from deformable–stagnant-lid regime to episodic subduction?



Transition from deformable–stagnant-lid regime to episodic subduction?