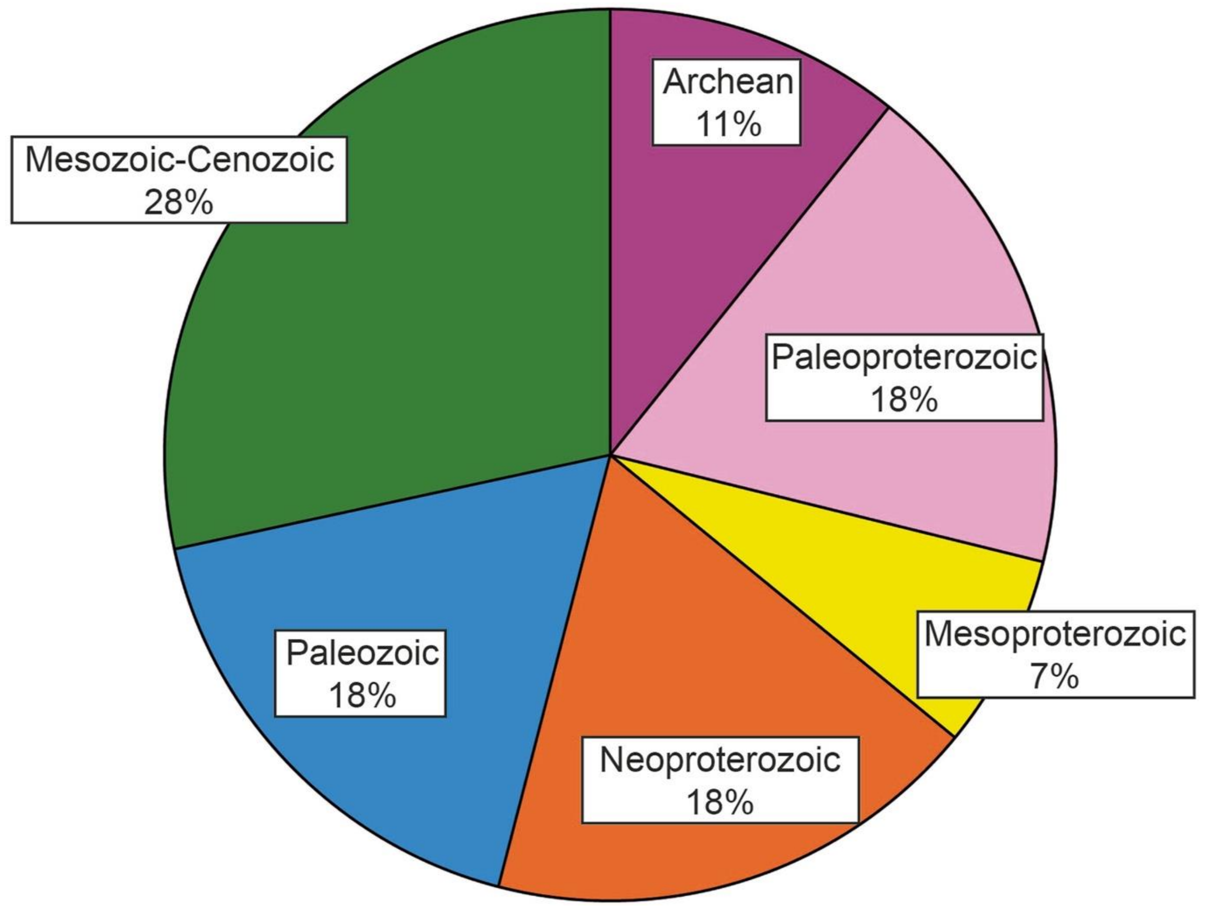
What can petrology tell us about Archean tectonics?

Michael Brown, University of Maryland

“Given the limited rock record available for the early Earth and the inherent preservation biases involved, it may simply not be possible to determine if early Earth had plate tectonics (Lenardic, 2018). Furthermore, Earth may have evolved into a plate tectonic regime sometime before sufficient evidence of its existence was retained in the global geological record. Thus, the geological record is only ever likely to provide a lower limit on the emergence of plate tectonics on Earth.”

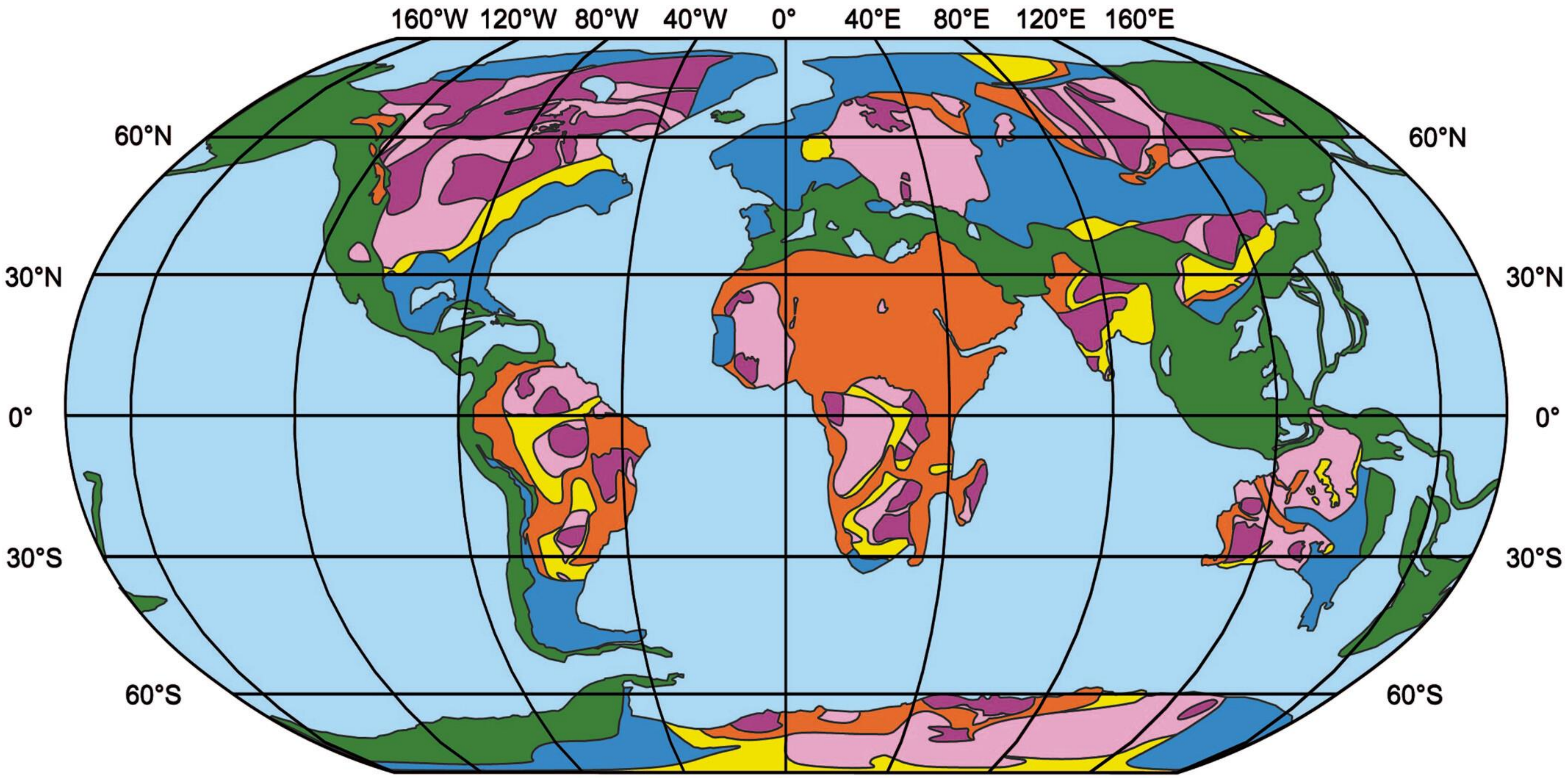
Brown and Johnson, 2019, Amer. Mineral.

The problem in a nutshell



- ❖ **Continental crust (CC) ~40% of Earth's surface; Archean cratonic nuclei ~11% of continental surface.**

- ❖ **Archean CC decreases to almost none by early Eoarchean.**



Age of continental crust (including margins; Mooney et al., 2025, JGR)

Given limited Archean crustal archive, how should we proceed?

In a theory-/model-driven approach, e.g., plate tectonics (PT) as default tectonic mode for the Archean, false positives may obscure novel interpretations, e.g., wrt ‘ophiolites’, ‘arcs’, etc.

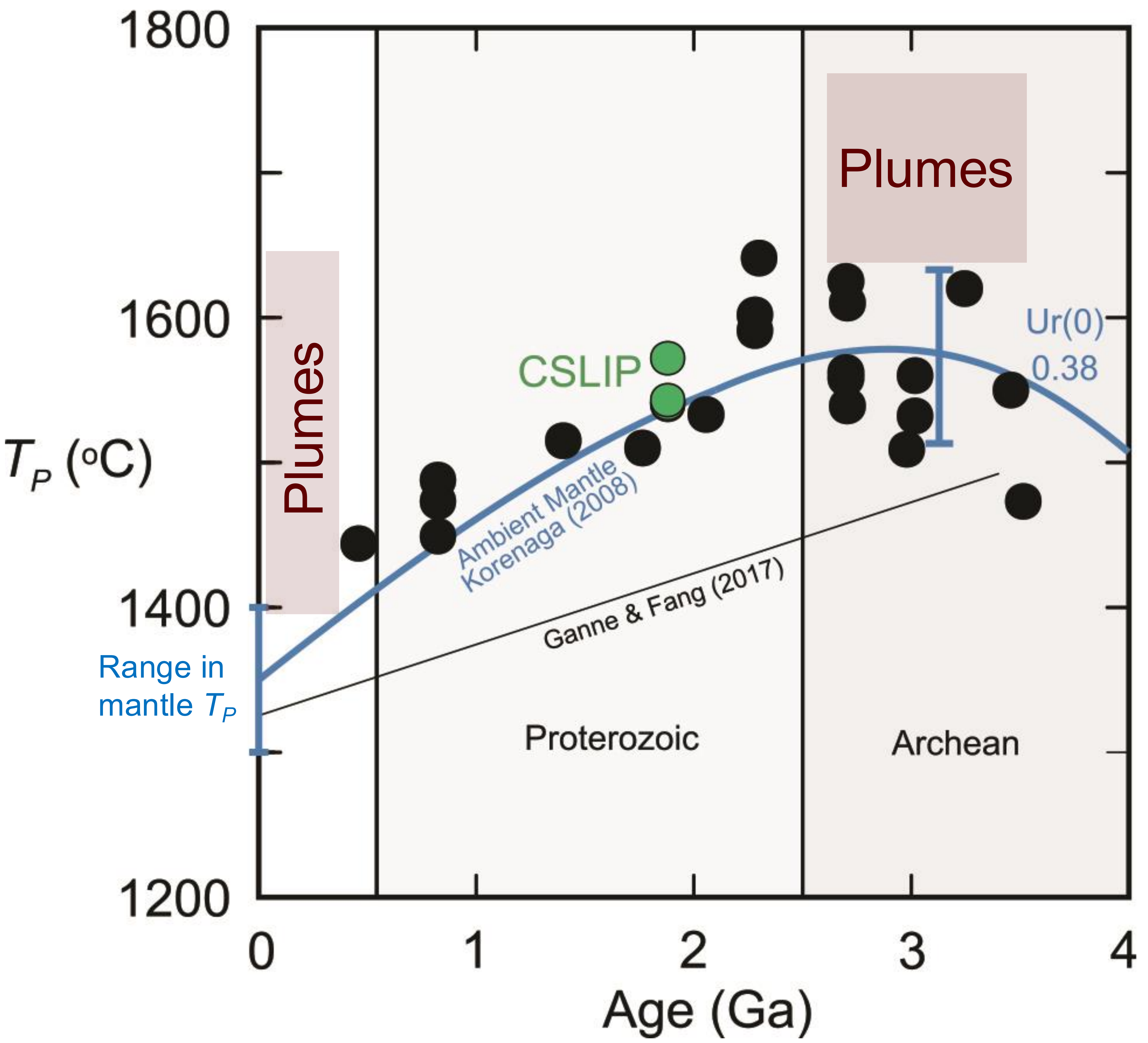
A data-driven approach tests hypotheses, e.g., wrt ‘ophiolites’, ‘arcs’, etc.; theory and models are used to explain results.

But data constrain models and models guide data collection and interpretation; thus, data and models are not independent, and in following a data-driven approach we must also be aware of possible bias.

More likely to achieve consensus if same protocols are followed to interpret data from Archean and post-Archean crust.

Caveats

- **Plate tectonics (PT) is an active tectonic mode (of global extent); it cools the mantle efficiently.**
- **PT requires subduction but subduction may occur in sluggish- and episodic-lid tectonic modes; evidence of subduction does not = PT.**
- **In the Archean, mantle T_P higher and plumes hotter; by how much is uncertain.**
- **Hotter mantle increases melting and affects tectonic mode.**
- **Evidence in Archean crust of magnetic field requires core convection to drive the geodynamo.**
- **If PT operated through the Archean, mantle T_P and plate velocities become unrealistically high, leading to rapid mantle cooling limiting core convection.**



Mantle T_P for primary magmas of non-arc basalts and mean T_P for Circum-Superior Large Igneous Province (CSLIP) basalts and low MgO komatiites (Herzberg et al., 2022, PR).

Urey ratio (Ur(0)) is internal heat generation divided by surface heat flux.

Topics

- **From an igneous perspective: Are purported ‘ophiolites’ and ‘arcs’ in Archean cratonic nuclei correctly recognized (**Brown et al., 2024, JGS**)?**

- **From a metamorphic perspective: Are eclogites key to understanding Archean tectonics (**Brown et al., 2024, JGS, 2026, Geology**)?**

- **A tectonic model based on petrology and discussion of some consequences (**Brown et al., 2024, JGS, 2026, Geology**).**

The igneous perspective

- Contemporary magmatism linked to PT occurs at: divergent and convergent plate boundaries; in collision zones (syn- and post-collision); and in pull-aparts along transform plate boundaries.

- Common to identify PT analogous to today operating in the past by recognizing plate boundary magmatism (‘ophiolites’ and ‘arcs’).

- Criteria used to fingerprint igneous rocks formed in contemporary settings may not apply at higher mantle T_P.

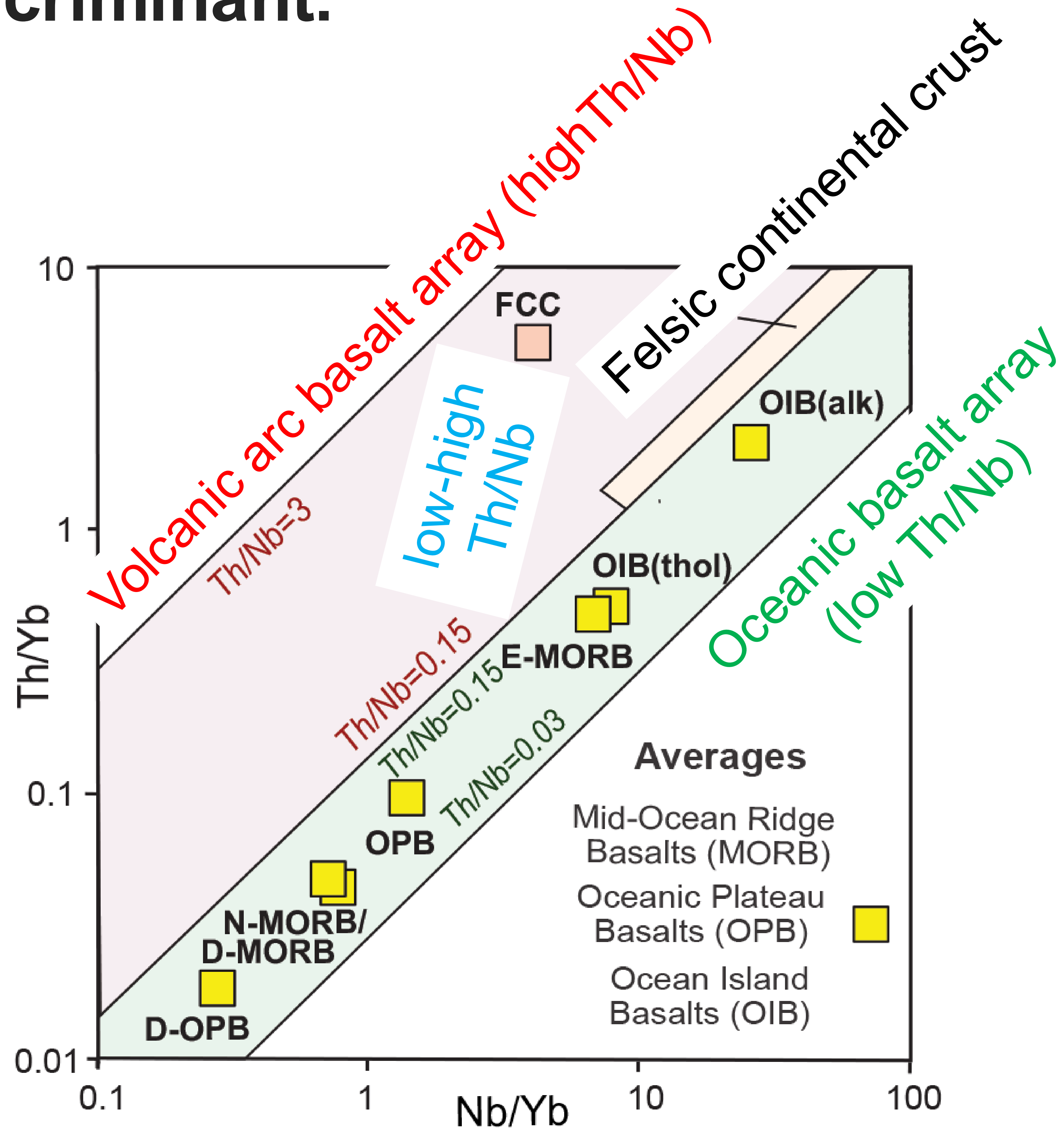
- Not just a question of recognizing products of potential plate boundary magmatism but showing they can be distinguished from magmas generated in non-PT settings likely dominated by mantle plumes.

Are purported ‘ophiolites’ and ‘arcs’ in Archean cratonic nuclei correctly recognized?

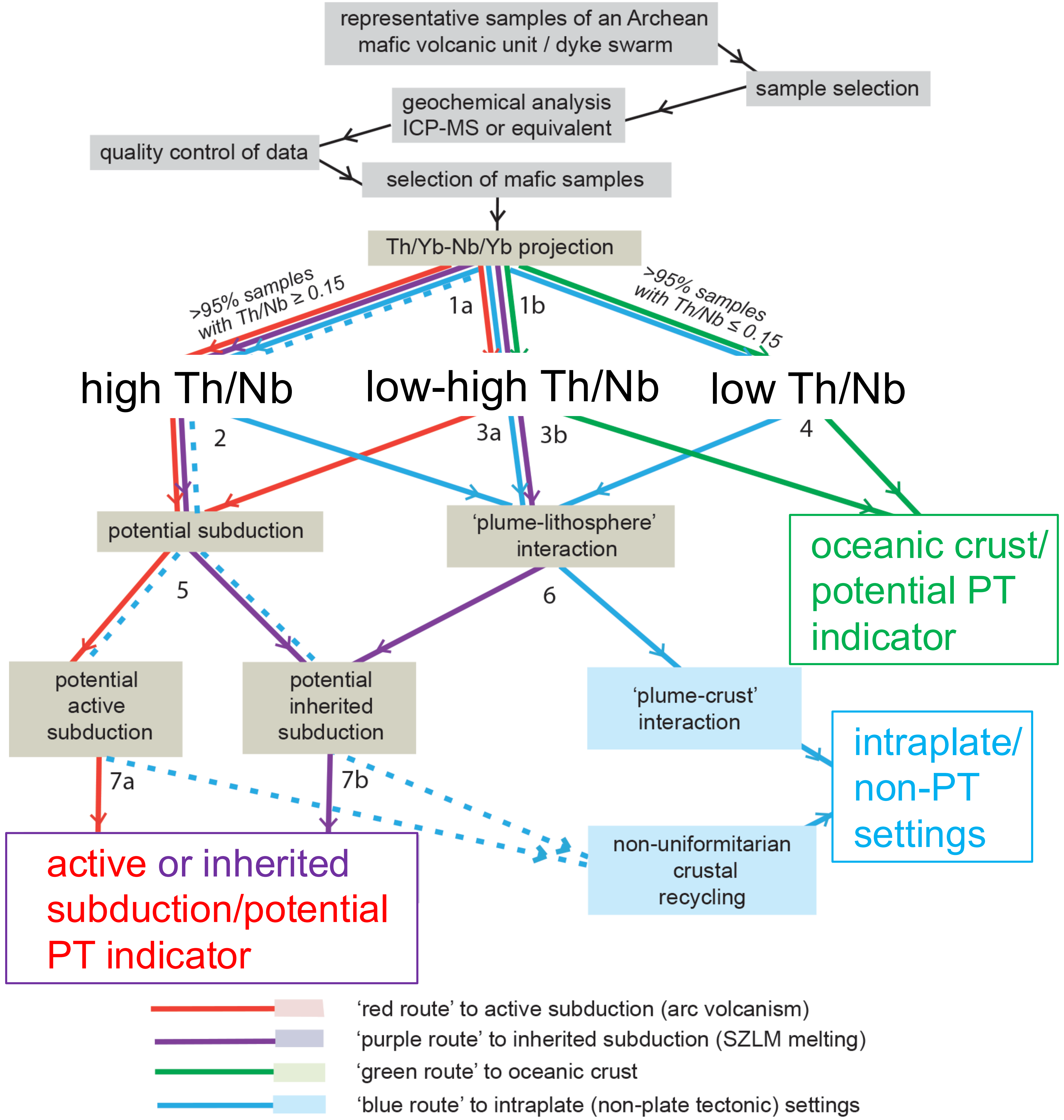
Methodology

2. To assign volcanics to process and tectonic setting, we start with the crustal proxy projection following a flow chart with 7 decision points that is robust at higher mantle T_P.

1. Test for 'ophiolites' and 'arcs' using geological relationships and Th/Nb, a robust discriminant.*



Th/Yb *v.* Nb/Yb crustal proxy projection, Th/Nb forms the diagonal.



representative samples of an Archean mafic volcanic unit / dyke swarm

sample selection

geochemical analysis ICP-MS or equivalent

quality control of data

selection of mafic samples

Th/Yb-Nb/Yb projection

high Th/Nb

low-high Th/Nb

low Th/Nb

potential subduction

'plume-lithosphere' interaction

oceanic crust/ potential PT indicator

potential active subduction

potential inherited subduction

'plume-crust' interaction

intraplate/ non-PT settings

non-uniformitarian crustal recycling

active or inherited subduction/potential PT indicator

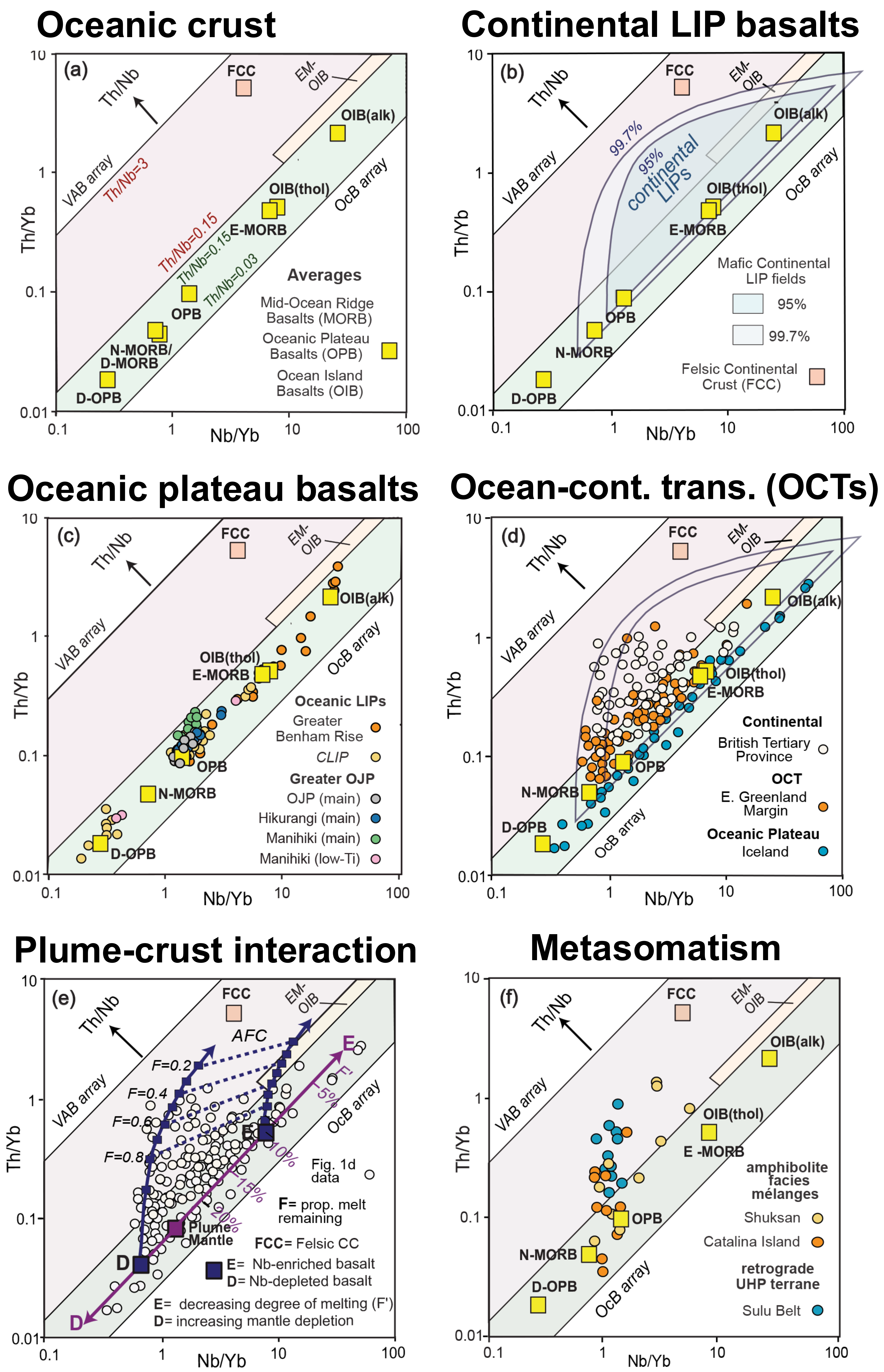
'red route' to active subduction (arc volcanism)

'purple route' to inherited subduction (SZLM melting)

'green route' to oceanic crust

'blue route' to intraplate (non-plate tectonic) settings

*Th/Nb is the most insensitive LILE/HFSE ratio to melting, source enrichment and depletion, and alteration.



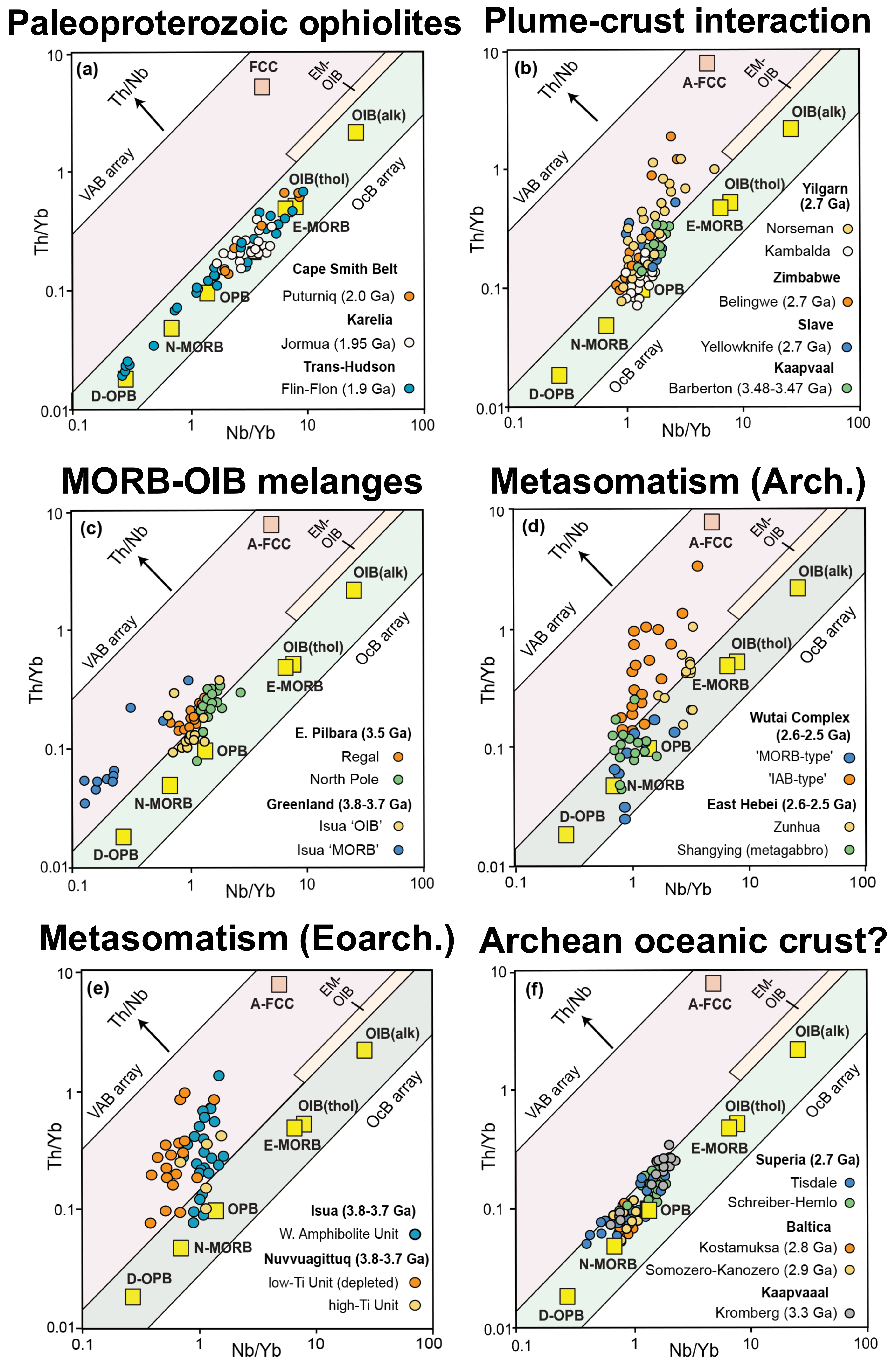
‘Ophiolites’

Left. Phanerozoic comparators.

Right. (a) Proterozoic comparators.

(b)–(e) Archean crust; most do not satisfy the first criterion of low and constant Th/Nb, mostly misinterpreted.

(f) Next slide.



Archean oceanic crust?

Only a small subset of purported ophiolites satisfies the first criterion of low and constant Th/Nb.

To be considered oceanic crust, must also have oceanic basement rather than highly attenuated continental crust.

Superia:

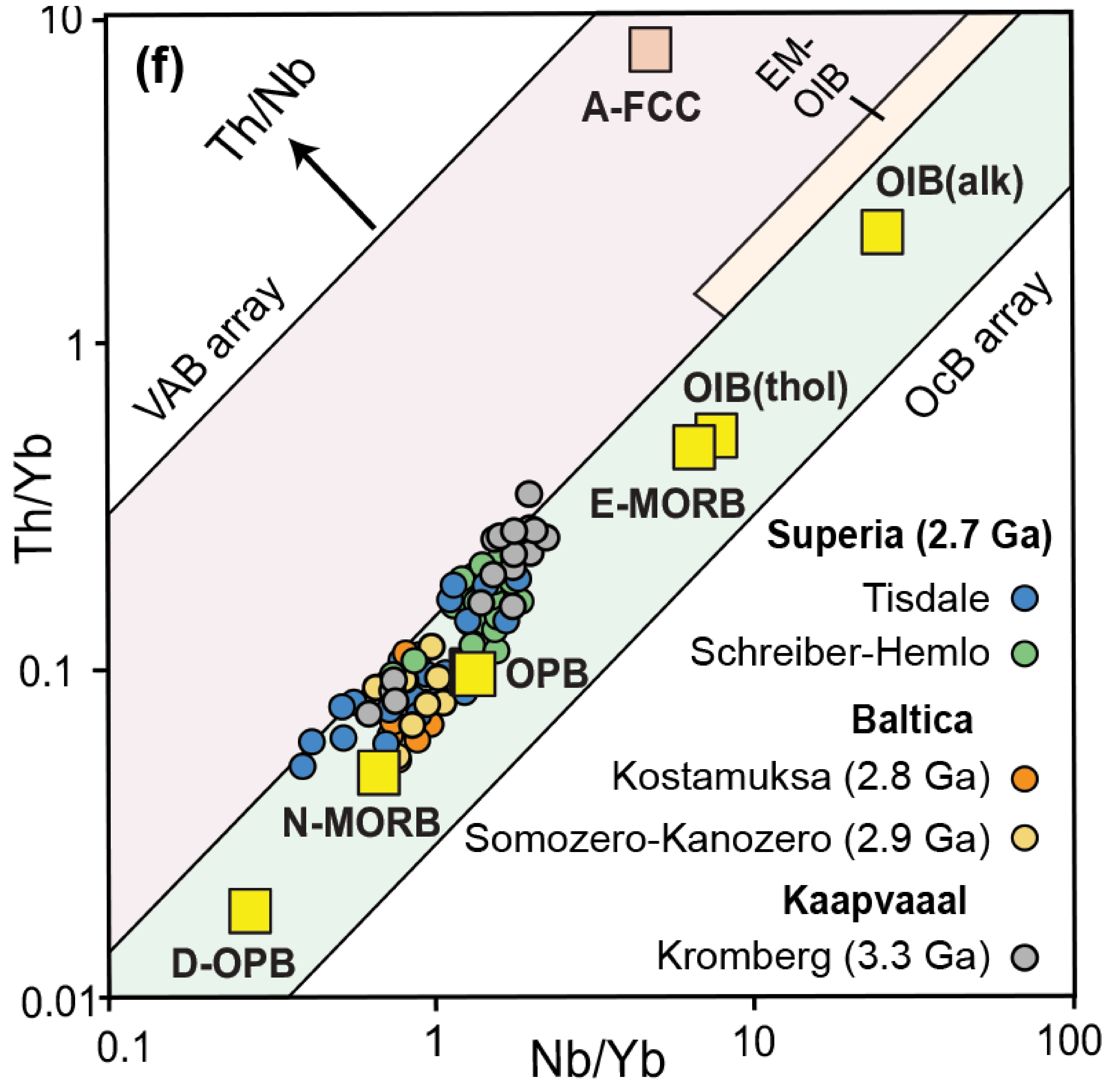
Interpreted as oceanic tracts between separating cratonic fragments; compositions plot like E. Greenland margin—continental intraplate setting more likely.

Baltica:

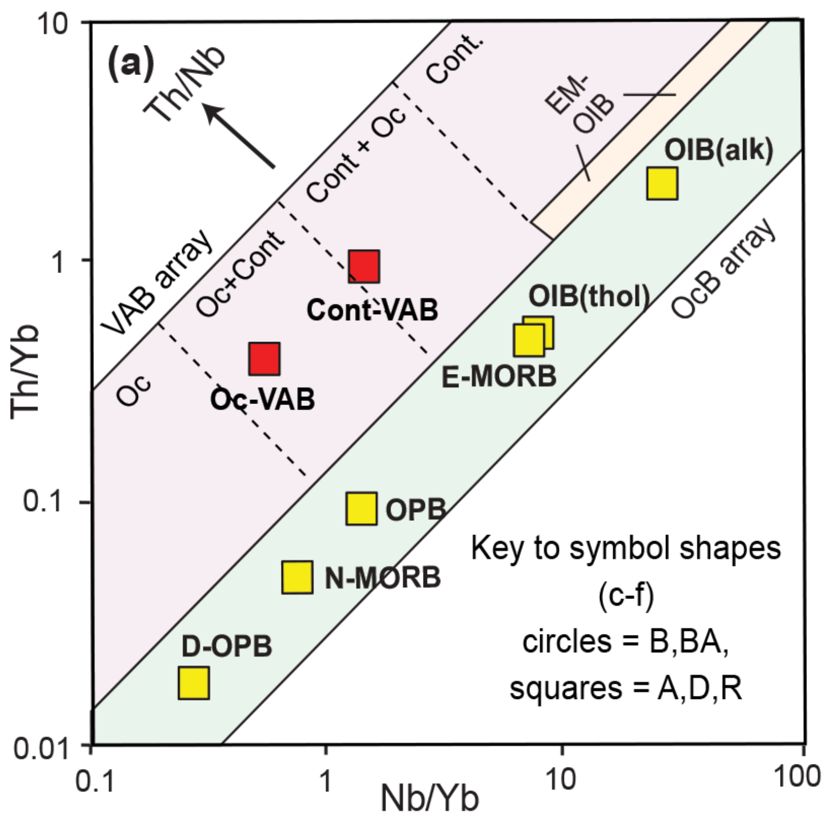
Interpreted as oceanic plateaus; compositions plot within the OcB array—most convincing examples.

Kaapvaal:

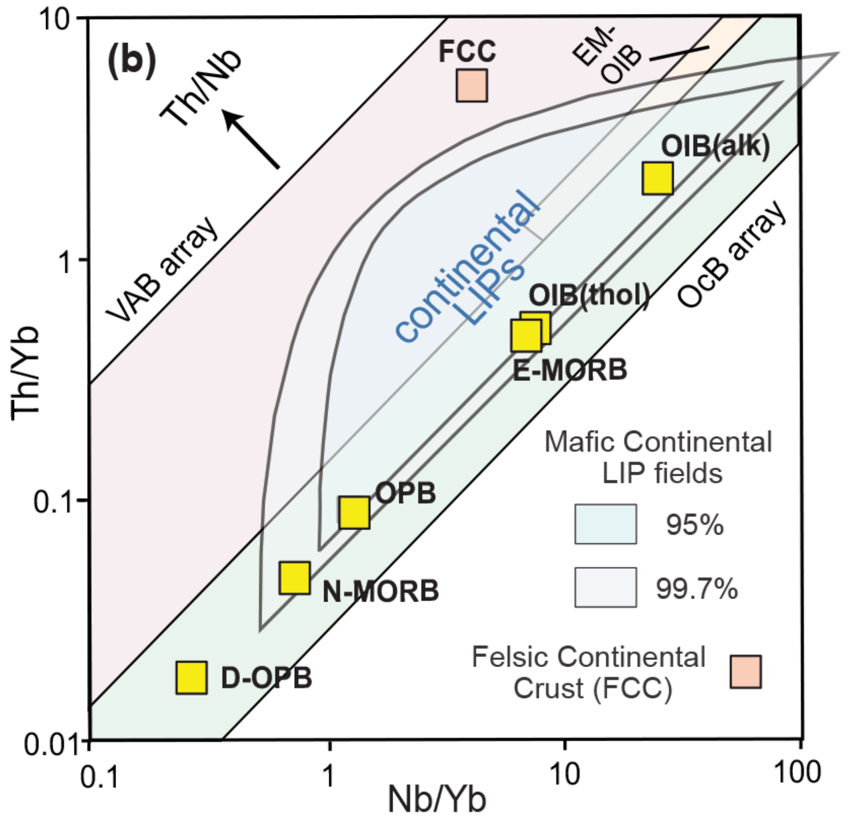
Kromberg mafic–ultramafic sequence interpreted as oceanic crust; Th/Nb higher than expected, attributed to primordial (higher Th/Nb) mantle source, but unlikely as older/younger volcanics have normal sources—continental intraplate setting more likely.



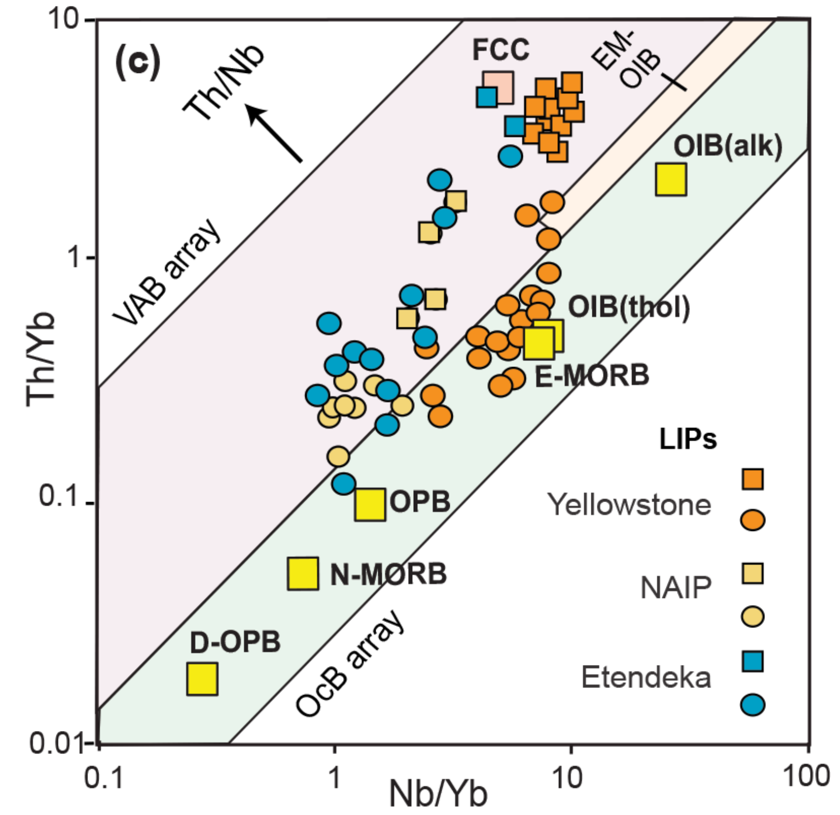
Volcanic arc basalts



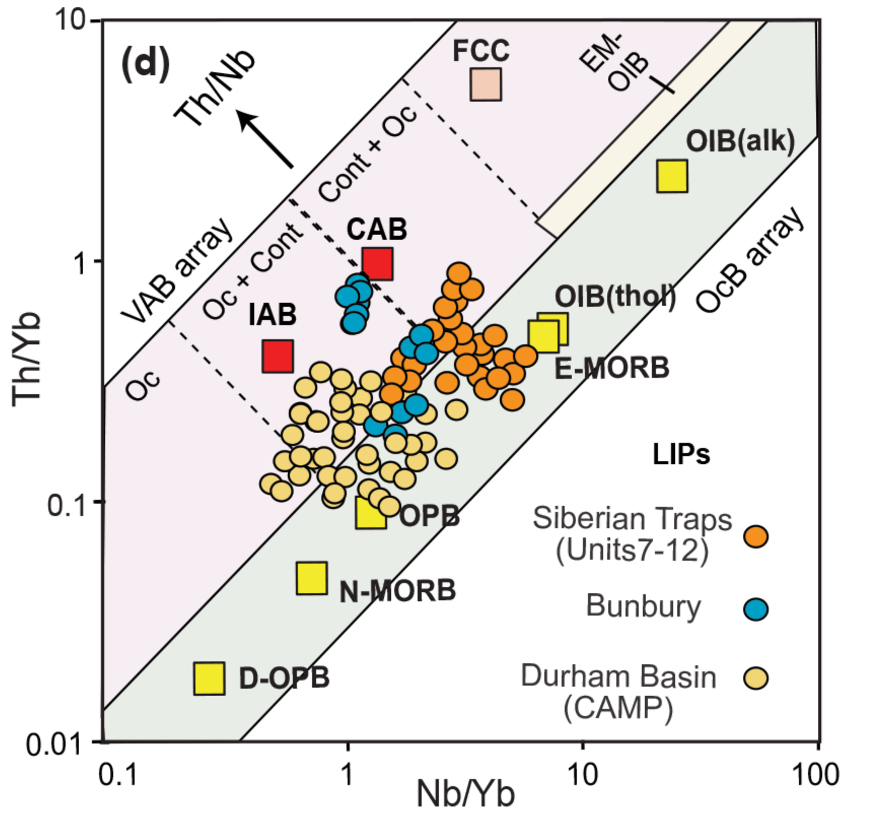
Continental LIP basalts



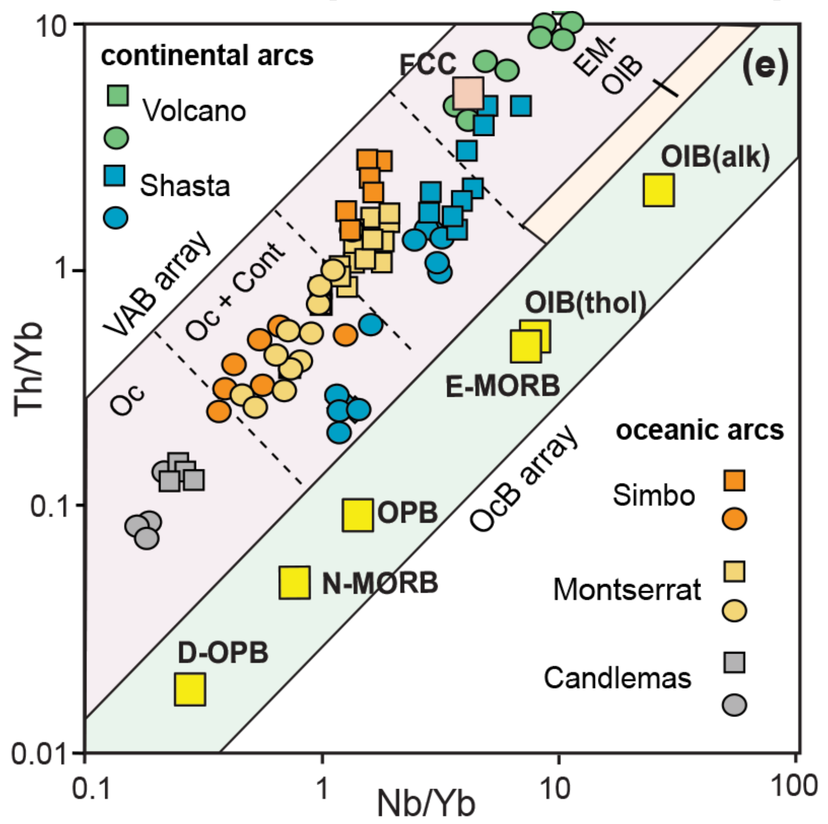
BADR (plume-crust int.)



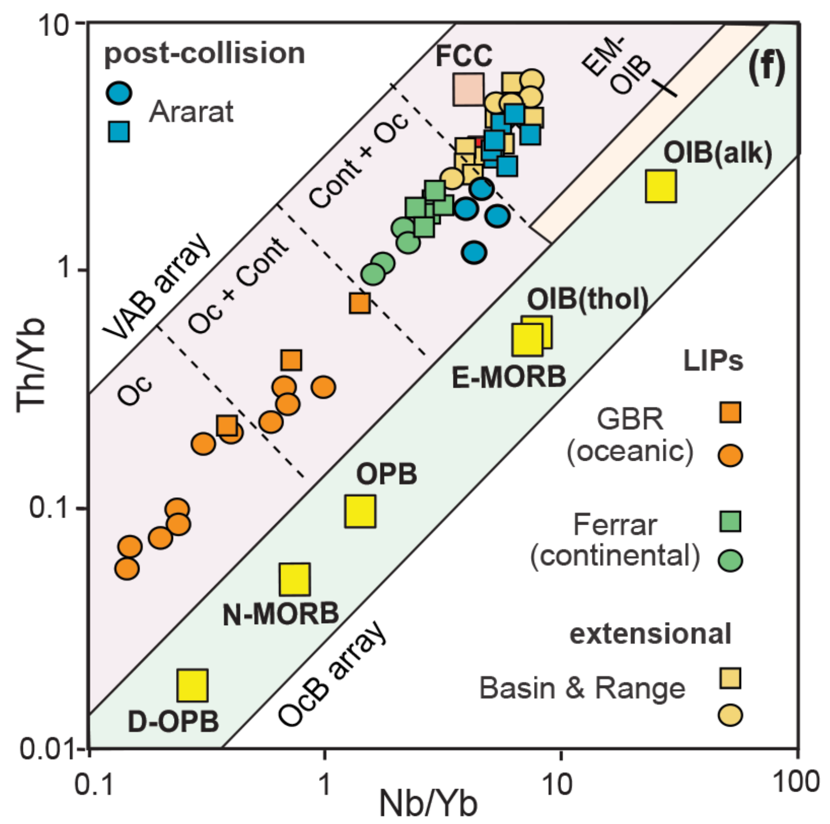
OcB-VAB (plume-SZLM int.)



BADR (active subd.)



BADR (subd. inheritance)



‘Arcs’

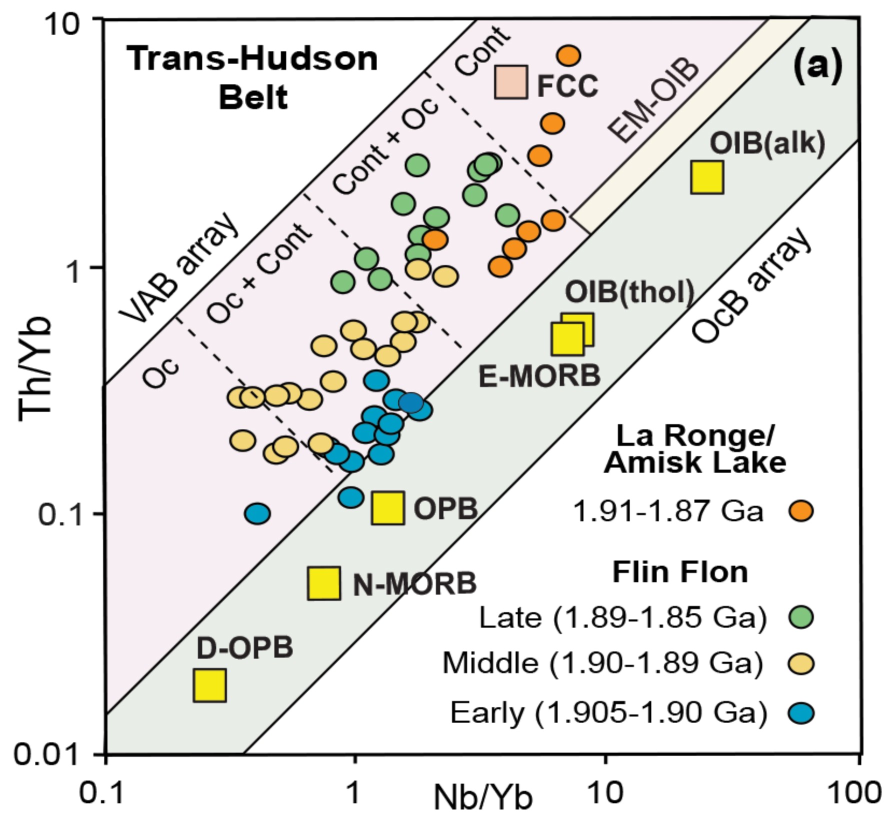
Left. Phanerozoic comparators.

Right. (a) Proterozoic comparators.

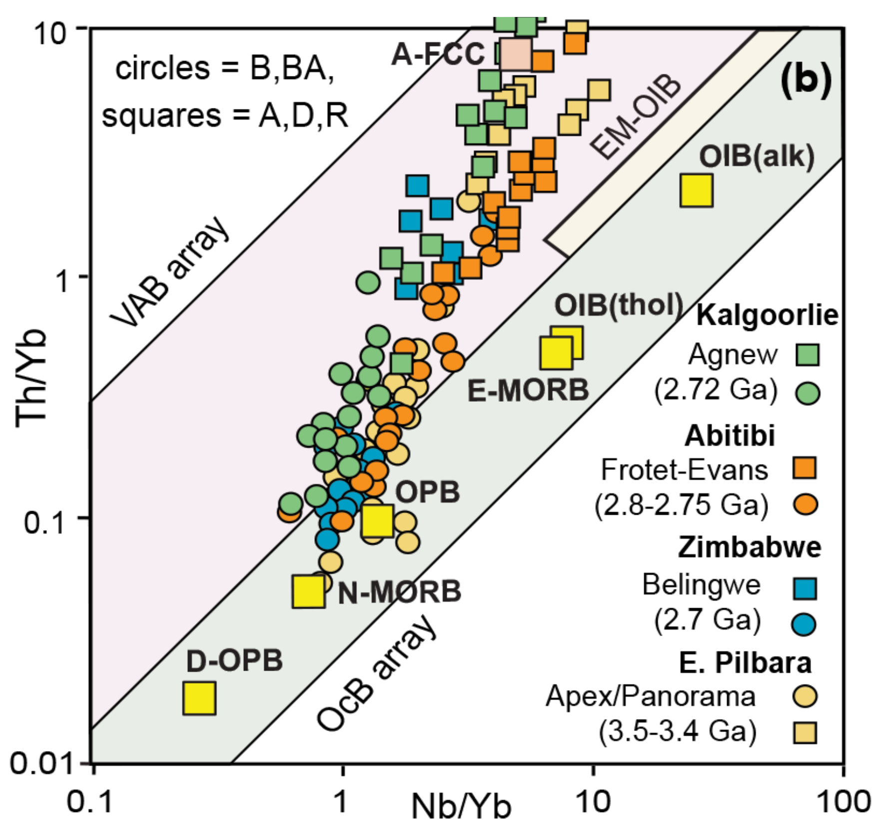
(b)–(d) Archean crust, recording multiple processes.

(e)–(f) Next 2 slides.

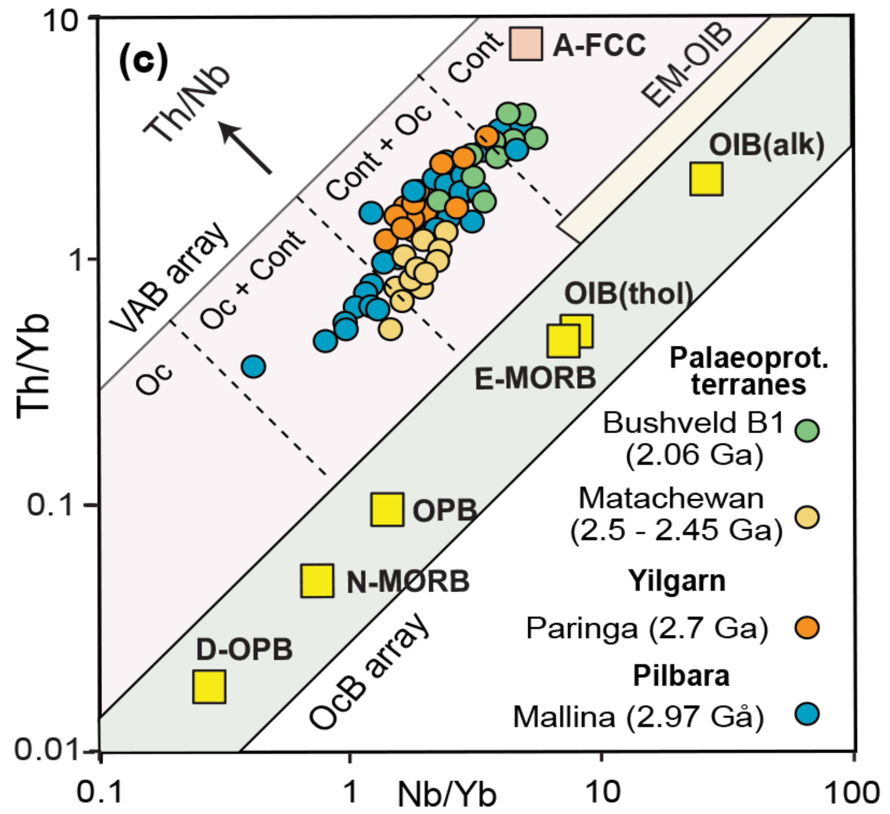
Paleoprot. active subd.



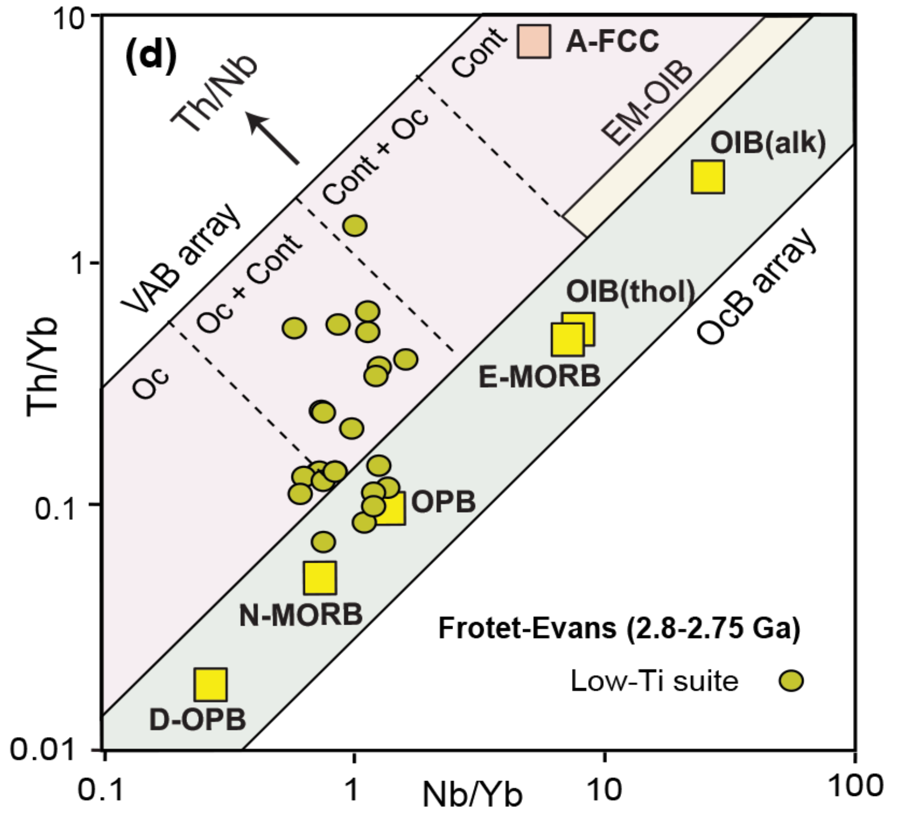
Plume-crust interaction



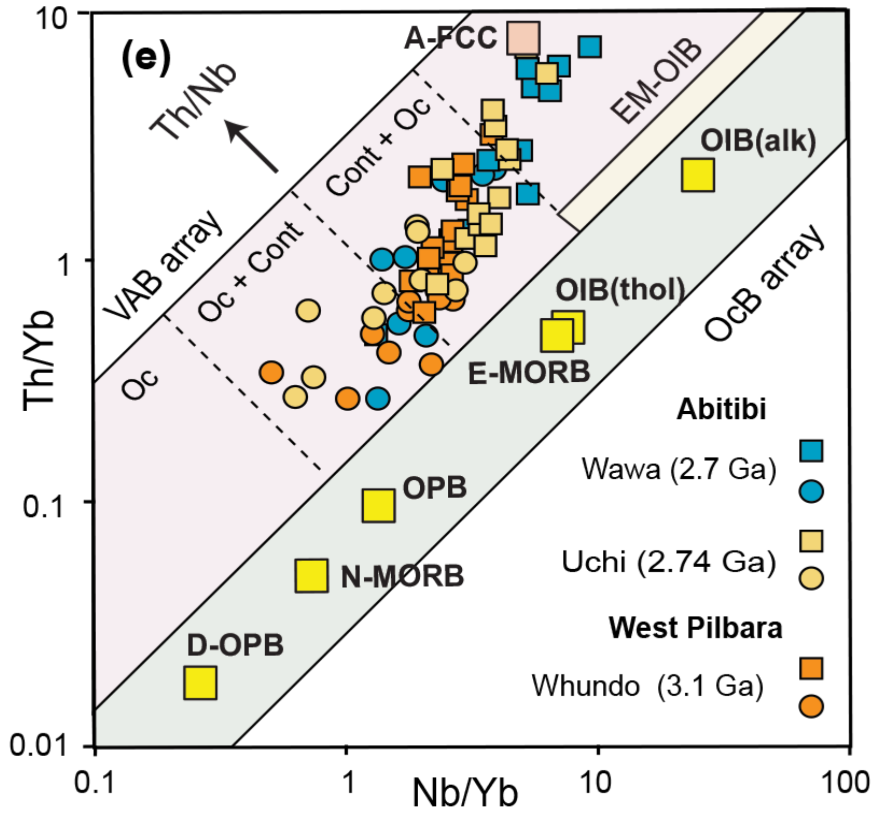
Subduction inheritance



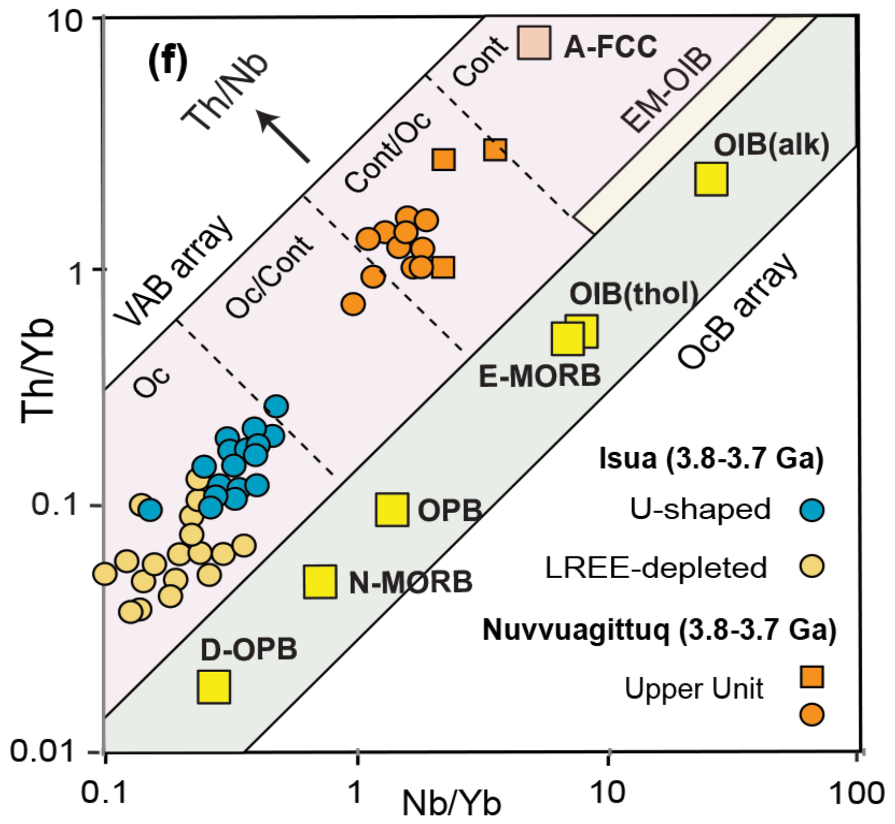
Plume-SZLM interaction



Active subduction



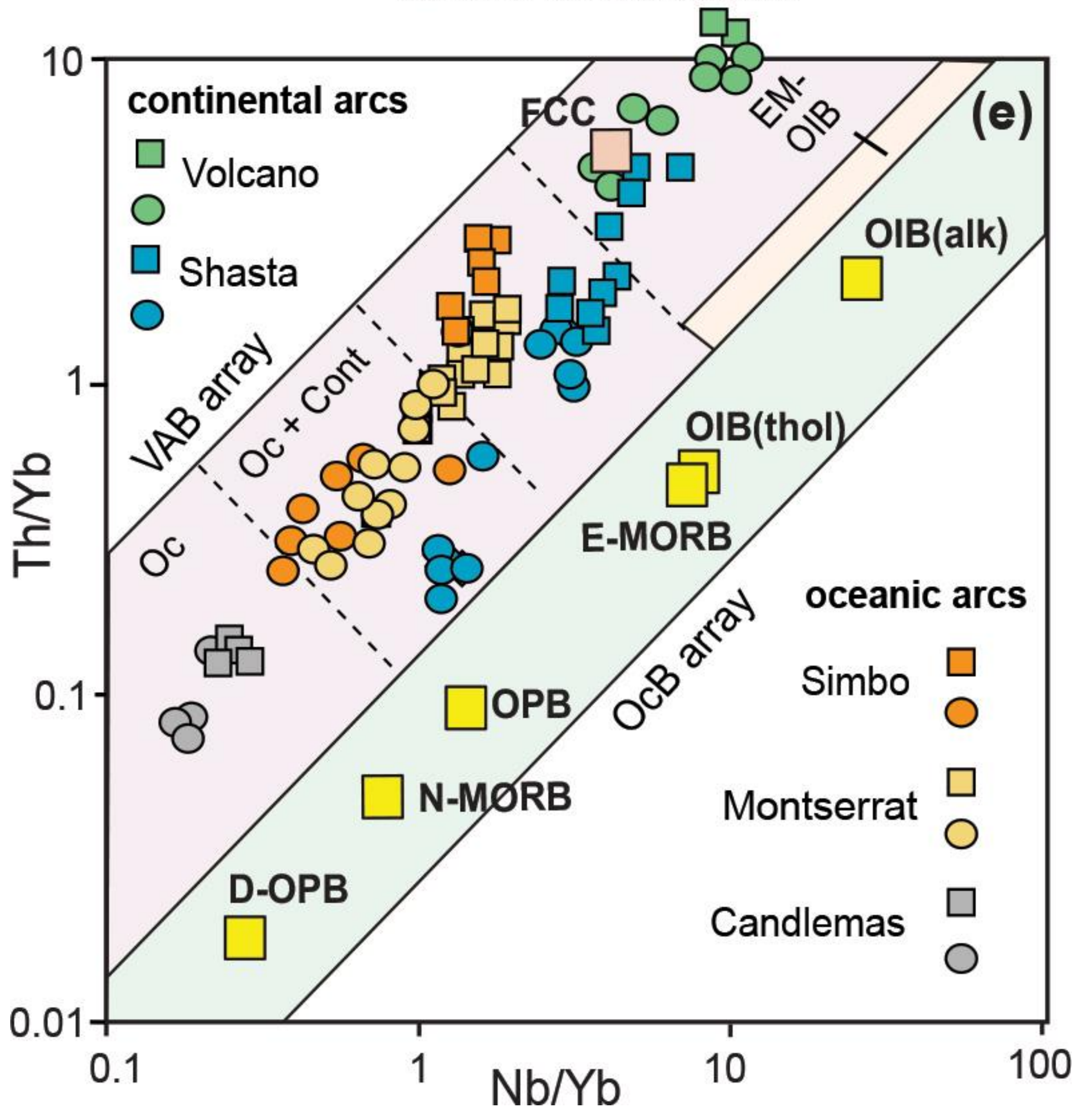
Active subduction?



Archean greenstone suites with likely active subduction signatures have been interpreted as ‘oceanic arcs’

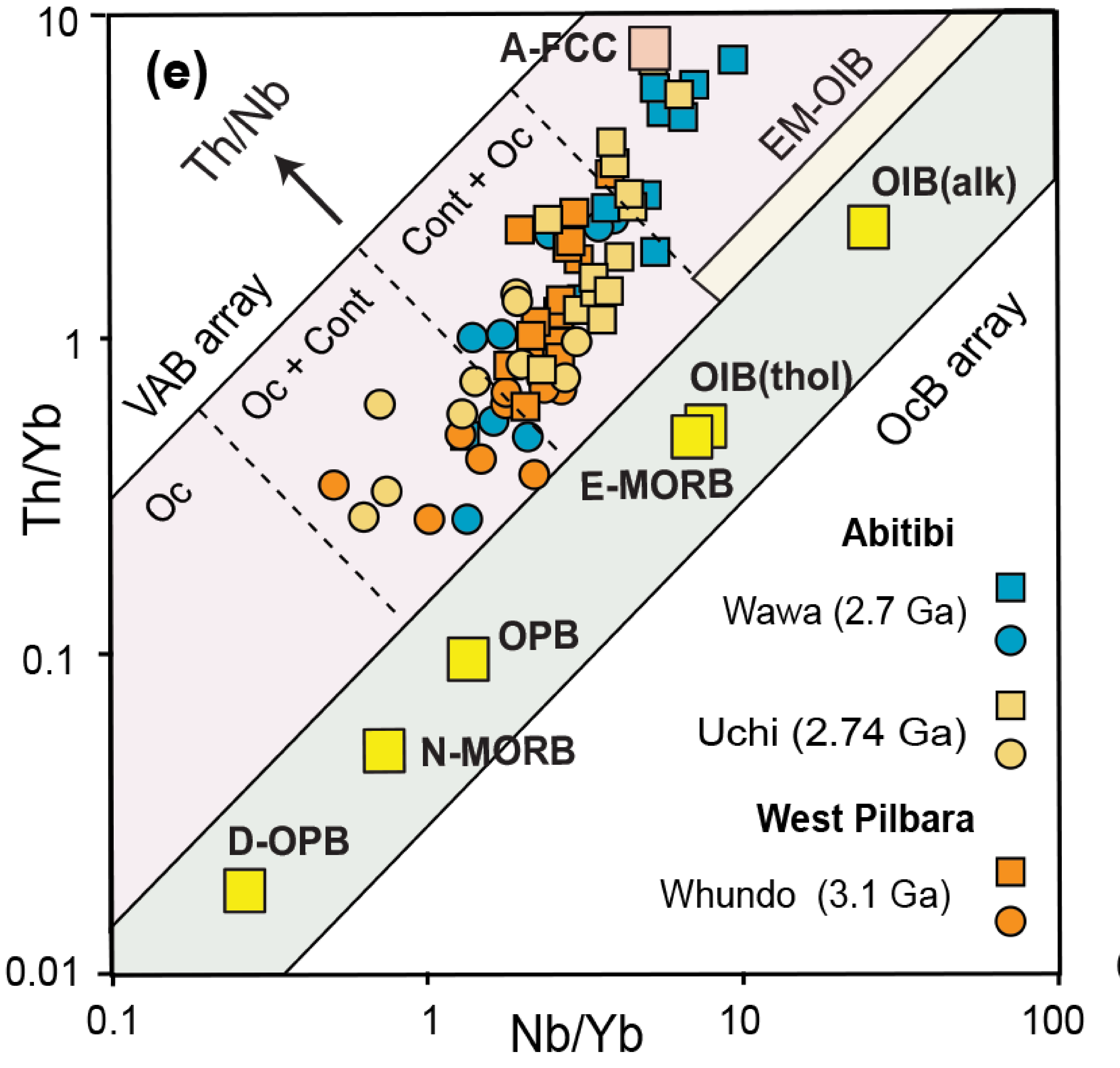
Comparison with Phanerozoic examples shows they resemble more closely continental arcs.

Phanerozoic: BADR Series related to active Subduction



Increase in Th/Nb and Nb/Yb from mafic to felsic and convergence on A-FCC is diagnostic, matching the continental hot-subduction Shasta comparator.

Archean: High Th/Nb most likely due to active Subduction Processes



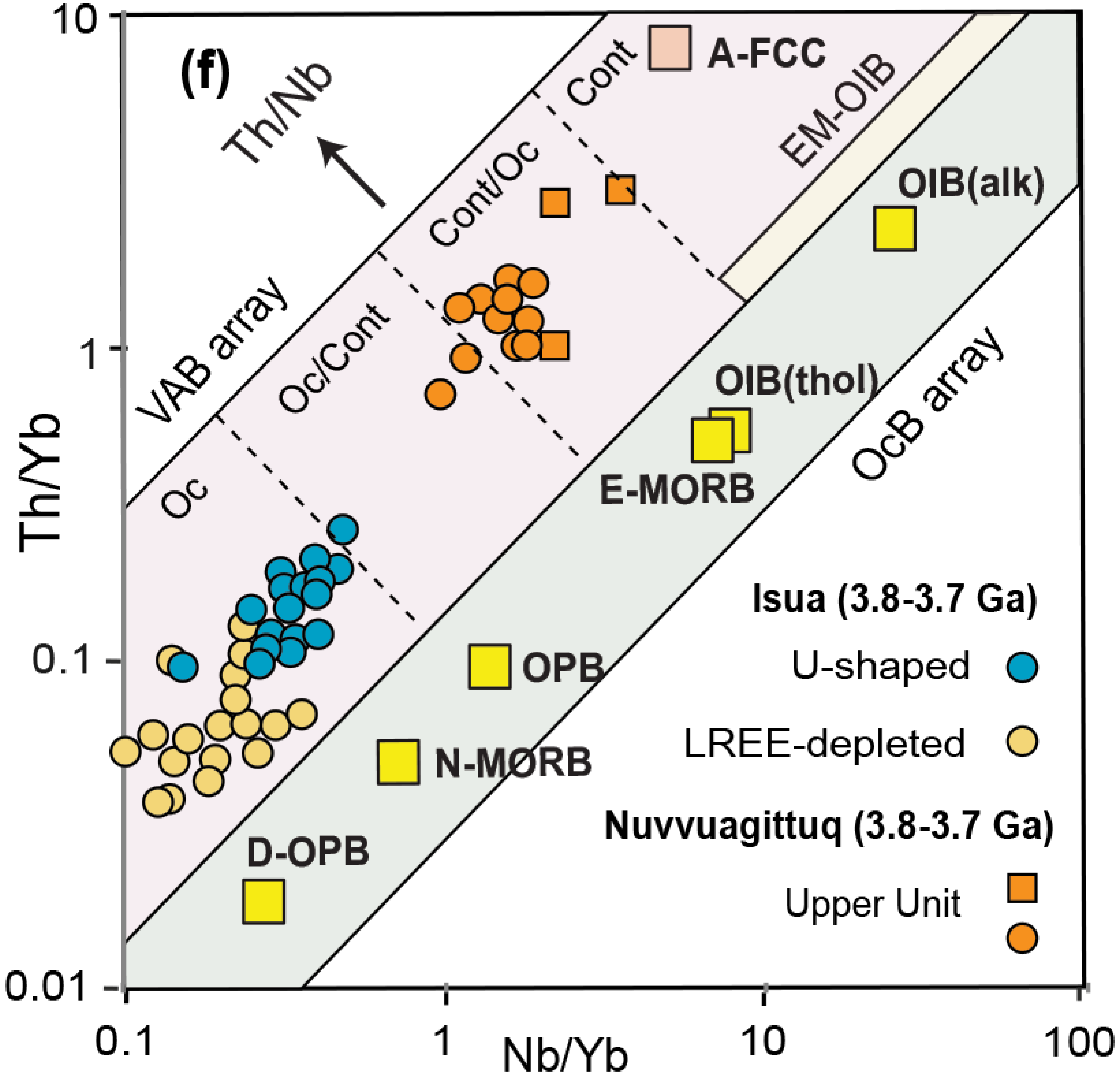
Low-Ti basalts and boninites at Isua plot at lower edge of the IAT segment of the VAB array; could have been boninites associated with subduction initiation.

Upper unit at Nuvvuagittuq has constant high Th/Nb indicative of potential subduction but is more like a 'continental' arc.

In both cases data insufficient to confirm as active or inherited subduction, or whether non-uniformitarian processes were involved*.

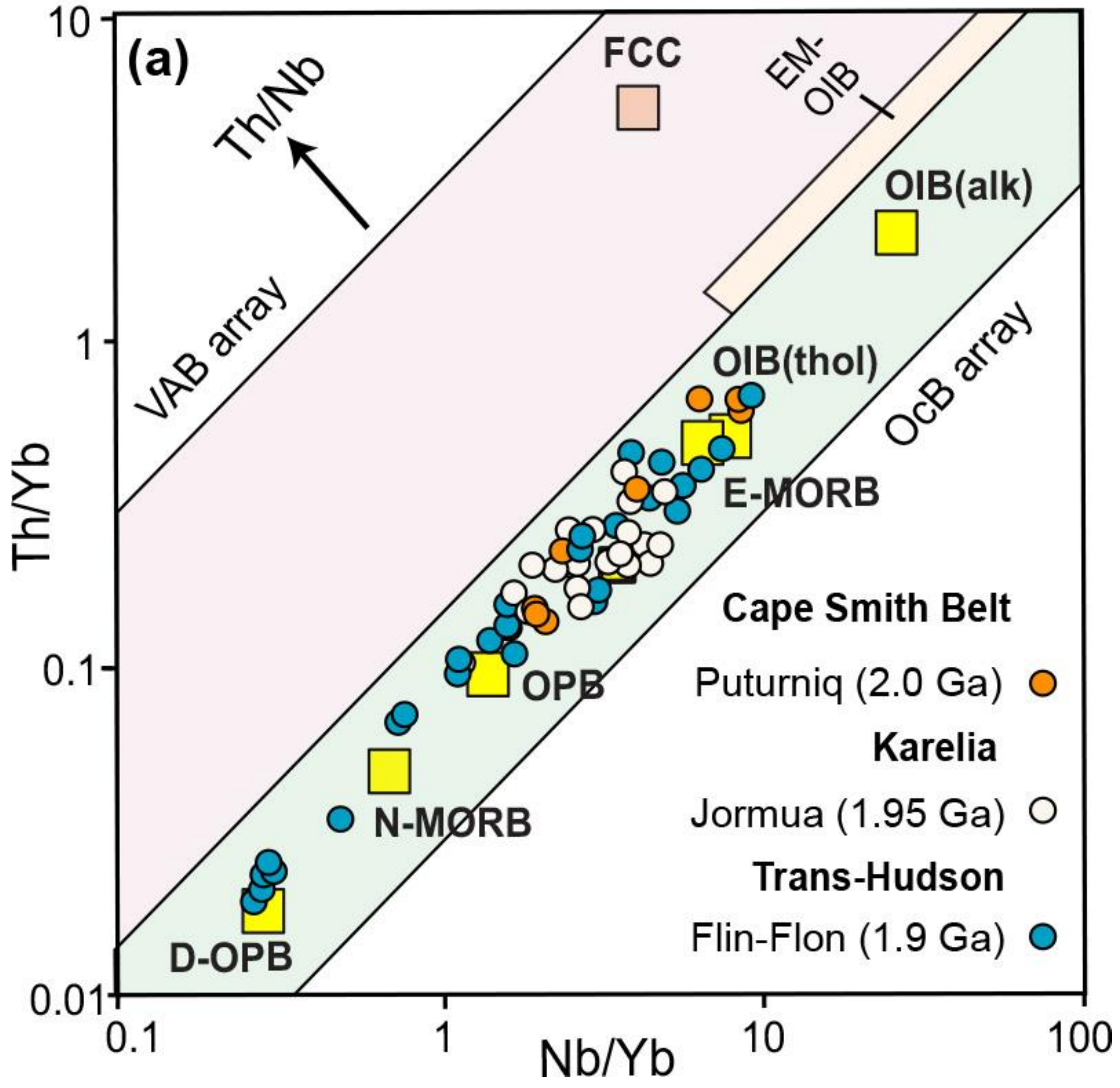
* Intense deformation, high-grade metamorphism, limited outcrop and unclear geological context make decisions through the flow chart hard to apply; unsurprising that interpretations are controversial.

Eoarchean: Active Subduction or Non-uniformitarian Processes



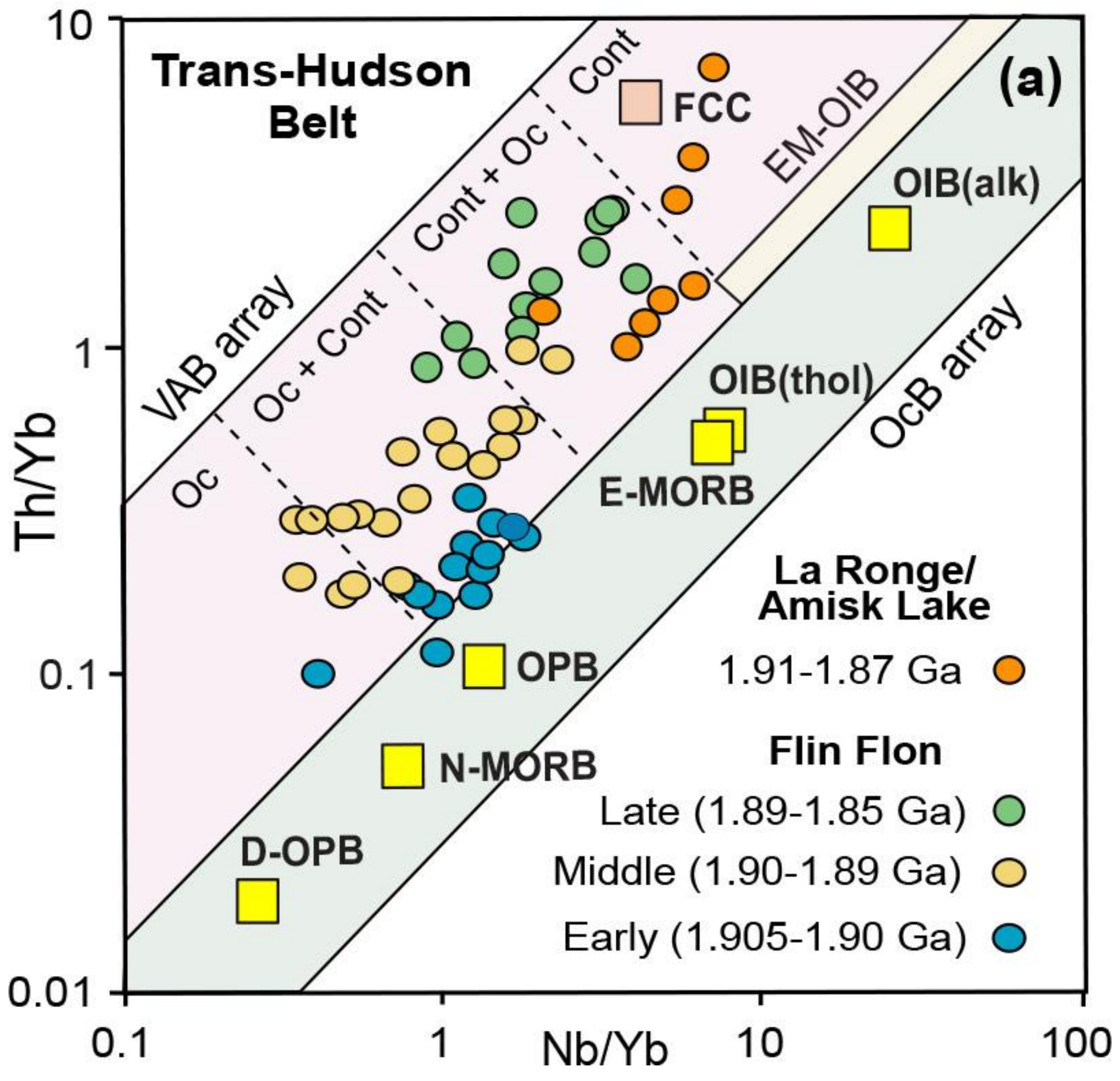
Outcome

Palaeoproterozoic Ophiolites
(oldest clear oceanic and OCT crust)



1. Prior to the Paleoproterozoic, based on geological relationships and Th–Nb systematics, no evidence of ‘ophiolite’ as part of a global plate system; data consistent with plumes ascending through attenuating lithosphere.

Palaeoproterozoic: High Th/Nb due to
active Subduction Processes



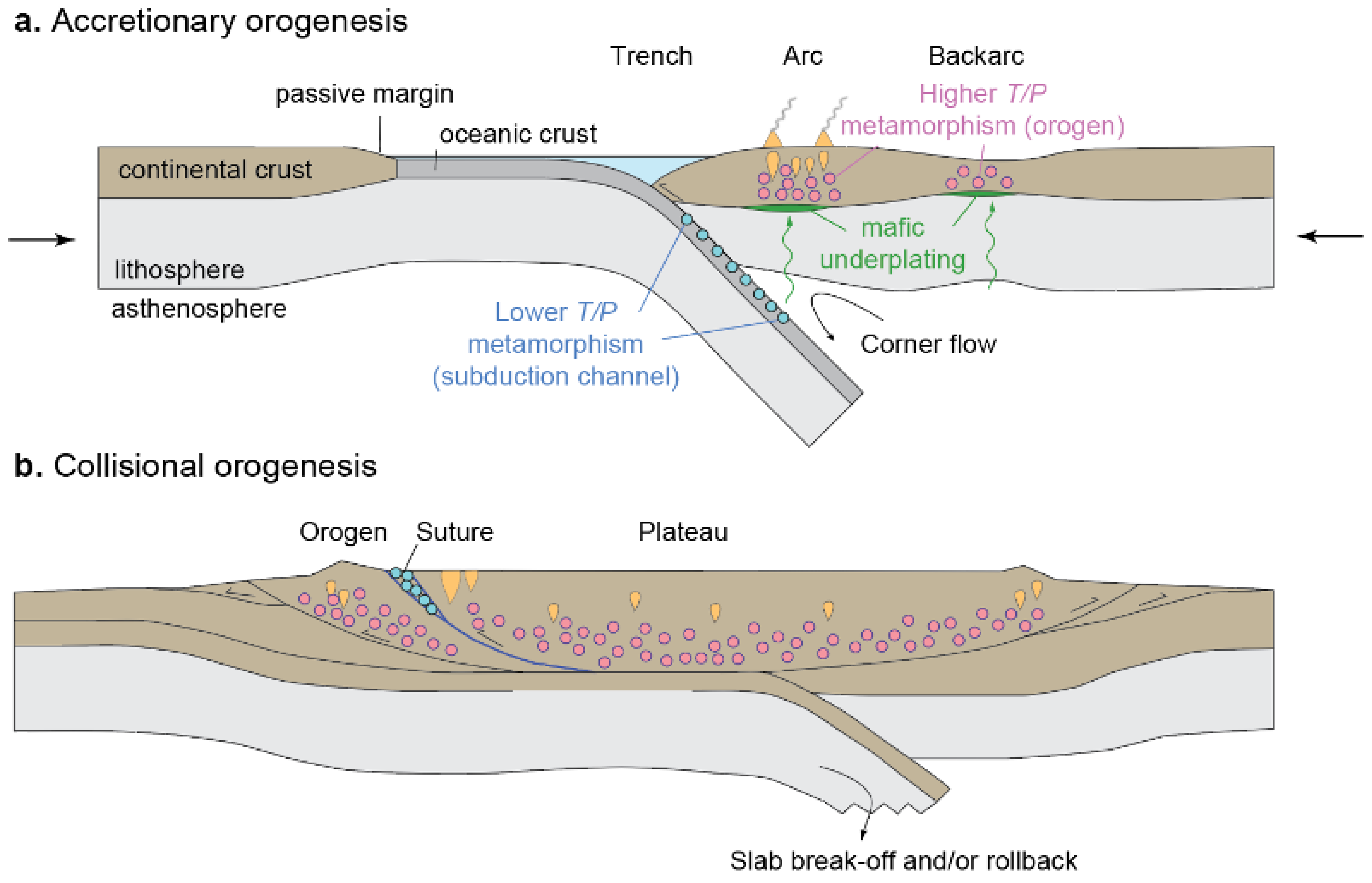
2. Prior to the Paleoproterozoic, rarity of arc-related suites, including their plutonic equivalents with good preservation potential, suggests limited convergence and only short-lived/episodic subduction.

The metamorphic perspective

- **Regional metamorphic rocks retain evidence of change in pressure (*P*) and temperature (*T*) with time, providing a record of heating/cooling during burial/exhumation.**

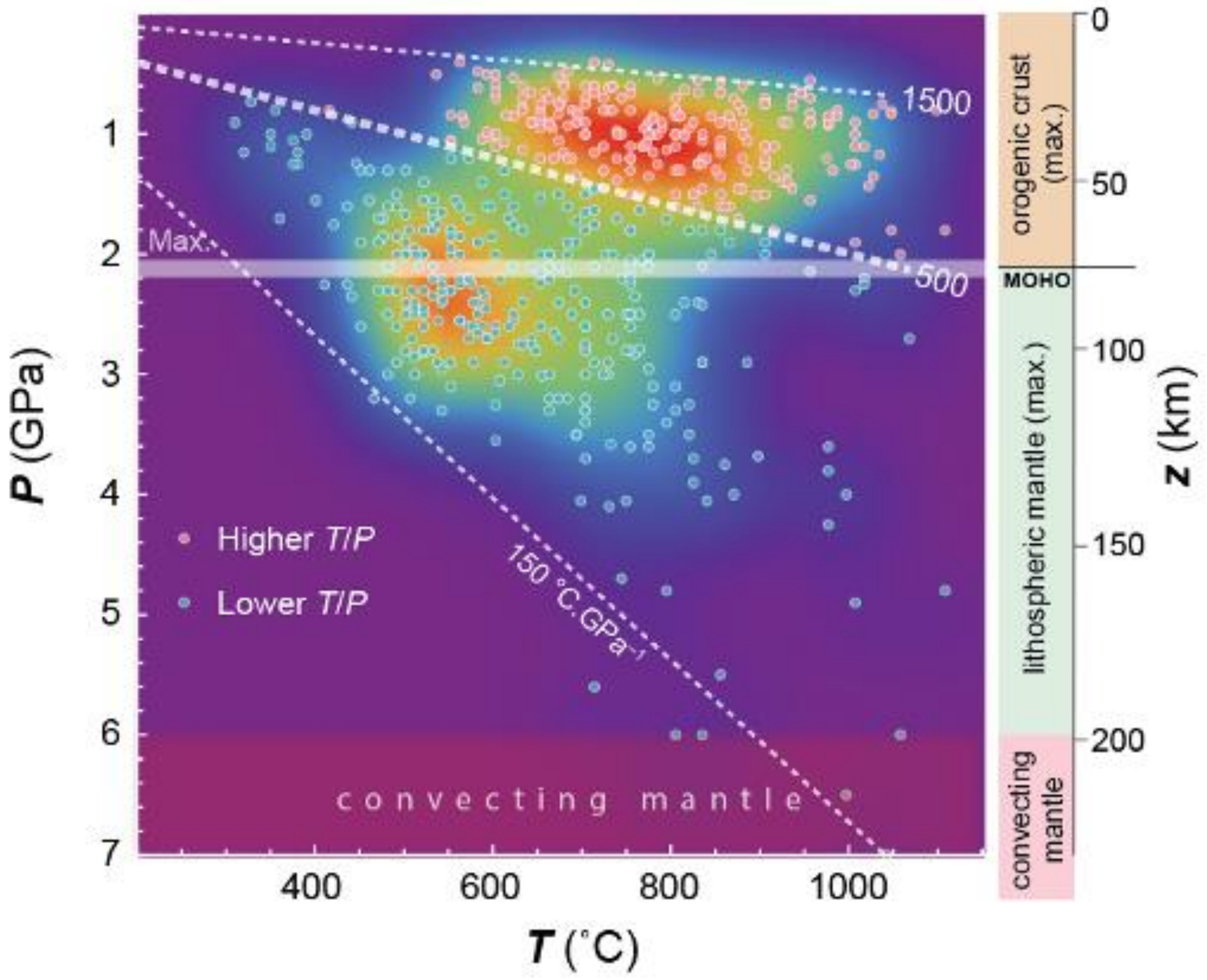
- **The thermobaric ratio, *T/P,* at the metamorphic peak is a proxy for the thermal gradient at which a sample equilibrated.**

- **> 900 metamorphic P-T-t data. For data <850 Ma, *T/P* varies with tectonic setting, subduction channel (T/P <500°C/GPa) vs orogen (T/P >500°C/GPa).**

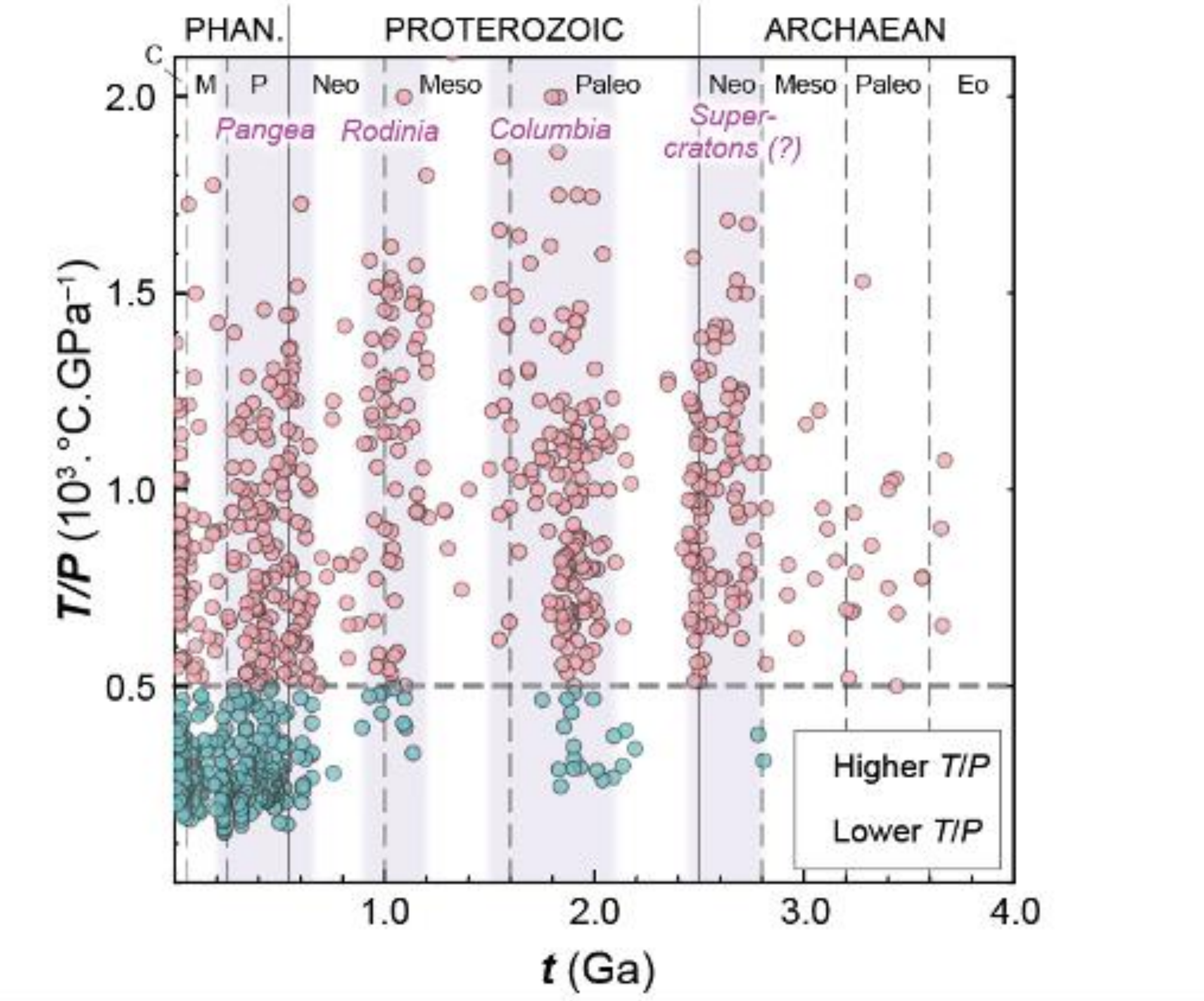


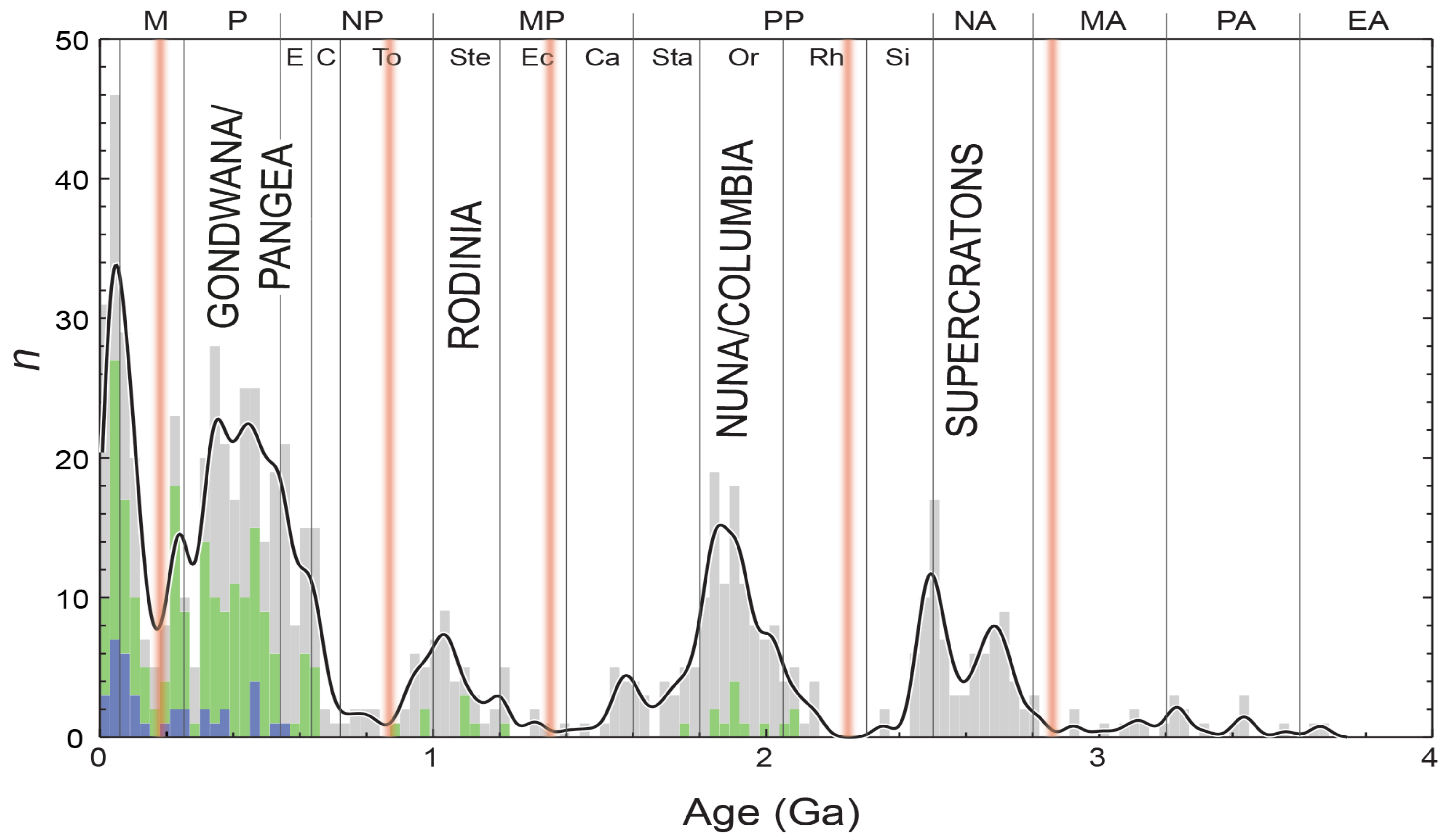
(A) Sketch of a continental arc with oceanic lithosphere (center) subducting beneath continental lithosphere (right). Lower *T/P* metamorphic rocks (blue dots; notably blueschists and eclogites) form within the subduction channel, whereas higher *T/P* metamorphic rocks (pink dots; notably amphibolites and granulites) form in the orogen above. (B) Sketch of a terminal collisional orogen, in which exhumed lower *T/P* metamorphic rocks occur in the suture (former subduction channel), and higher *T/P* metamorphic rocks in the orogen and plateau. (Modified from Weller et al., 2021, NREE).

(a) Age (*t*) ≤ 0.85 Ga



(b) All data

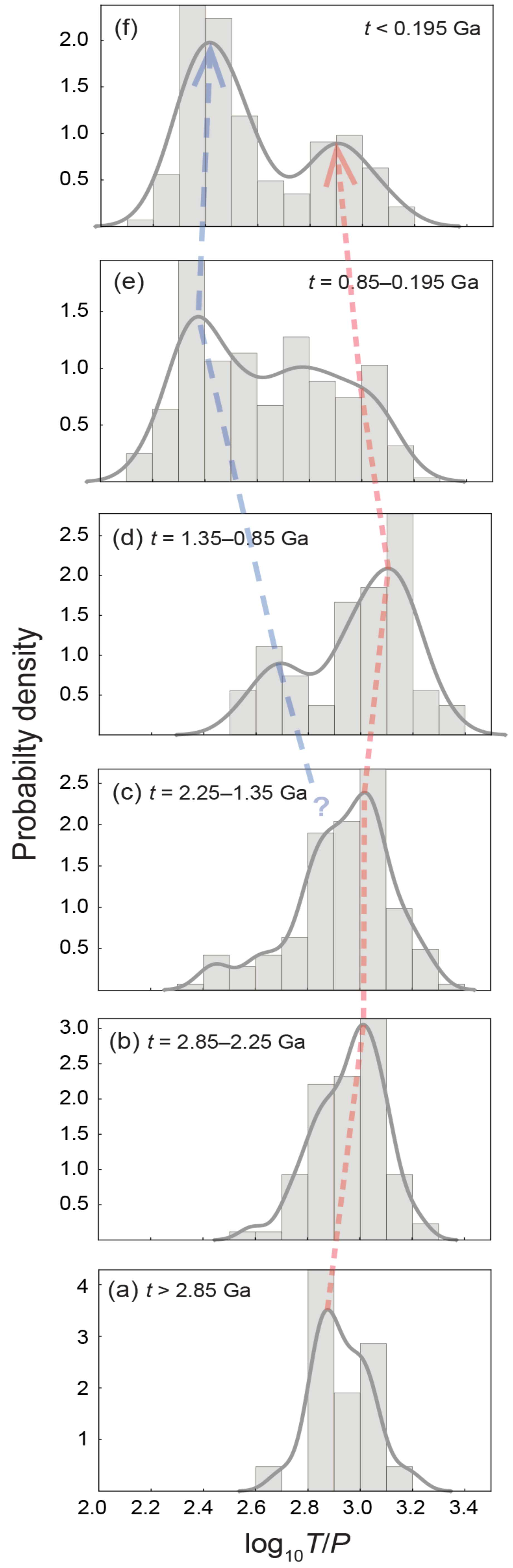




>850 Ma peaks in bimodality migrate to higher *T/P*, lower *T/P* strand is lost as distribution becomes unimodal, consistent with plumes.

What are the implications for Archean tectonics?

Are eclogites key to understanding Archean tectonics?



Modern PT

Bimodal, low *T/P* peak dominant

Proterozoic PT

Transitional, development of bimodality, high *T/P* peak dominant

Archean tectonics

Unimodal, high *T/P*

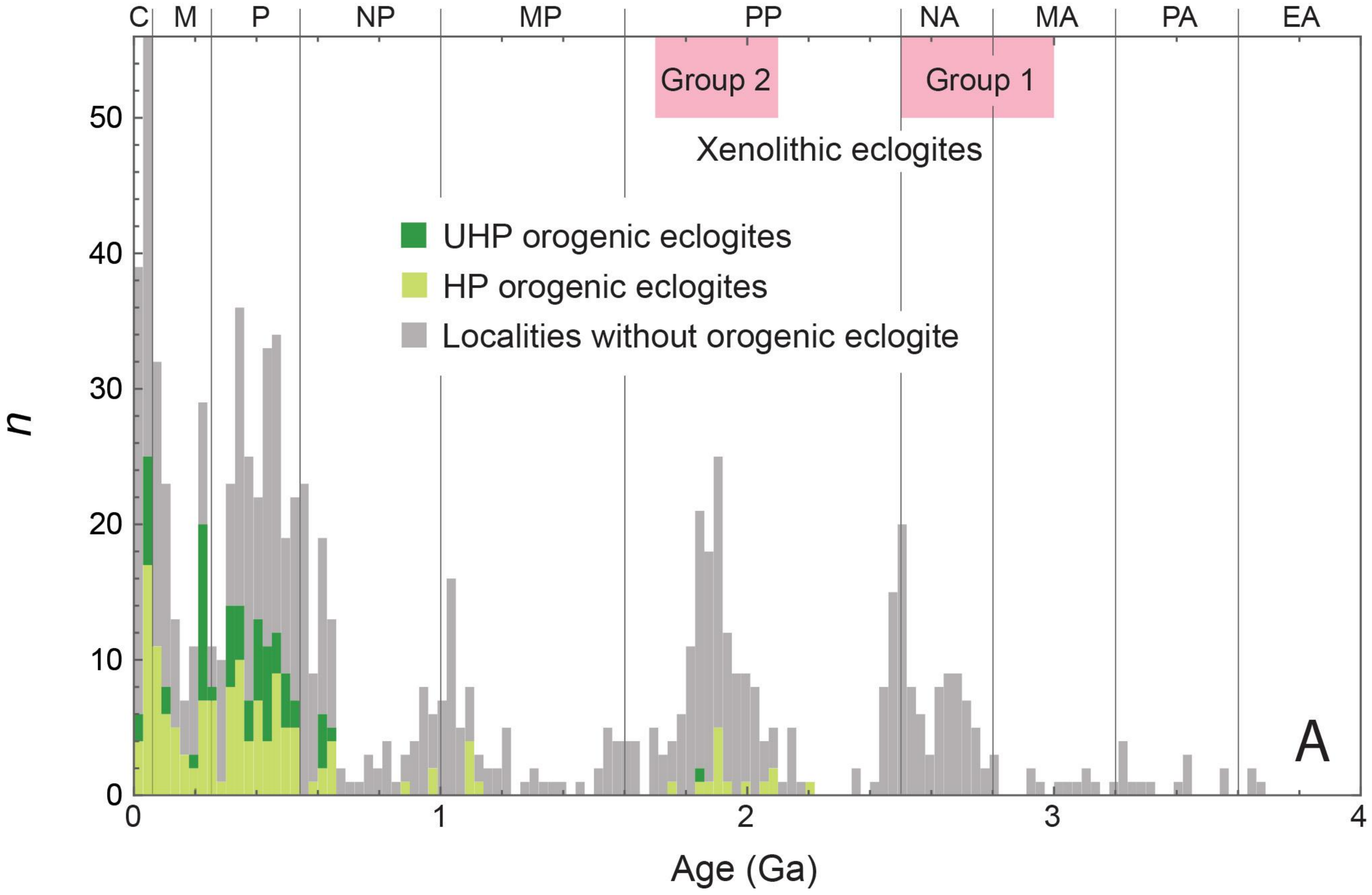
❖ **Landmark article in 1965* classified eclogites based on mode of occurrence:**

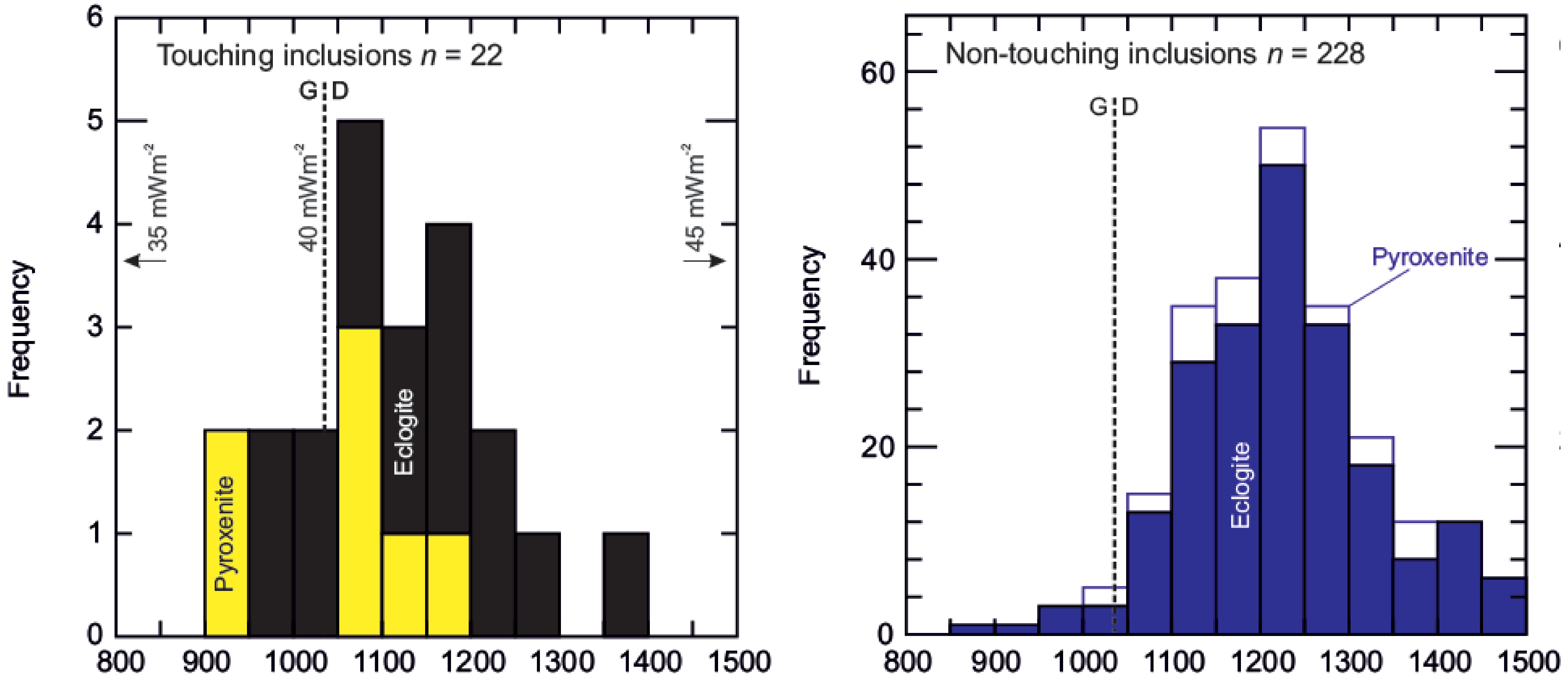
- **inclusions in kimberlites, basalts, or as layers in ultramafic rocks (Group A)—hereafter xenolithic eclogites;**
- **layers or lenses associated with migmatitic gneiss terrains (Group B) or alpine-type metamorphic rocks (Group C)—hereafter orogenic eclogites.**

❖ **In 1965 not much data; notwithstanding, has withstood the test of time.**

❖ **Simplicity compelling; fundamental to understanding the tectonic evolution of Earth!**

* Coleman, R. G., Lee, D. E., Beatty, L. B., and Brannock, W. W., 1965, Eclogites and eclogites: their differences and similarities, GSA Bulletin, 76, 483-508.





Xenolithic eclogites

- ❖ **All older than Mesoproterozoic.**
- ❖ **Oceanic crust from mantle roots of cratons entrained in younger carbonated magmas.***
- ❖ **Based on eclogitic Grt and Pxe inclusions in Dia (**Stachel et al., 2022, RIMG**),**
  - ○ **ambient *T* at time of entrainment (at 5 GPa) was ~950-1300ºC,**
  - ○ ***T* at time of entrapment (at 5 GPa) was ~1050-1450ºC, consistent with cool Paleoproterozoic/Archean geotherms.**
- ❖ **Formation of cratonic mantle roots remains contentious; xenolithic eclogites suggest late subduction-driven thickening.**

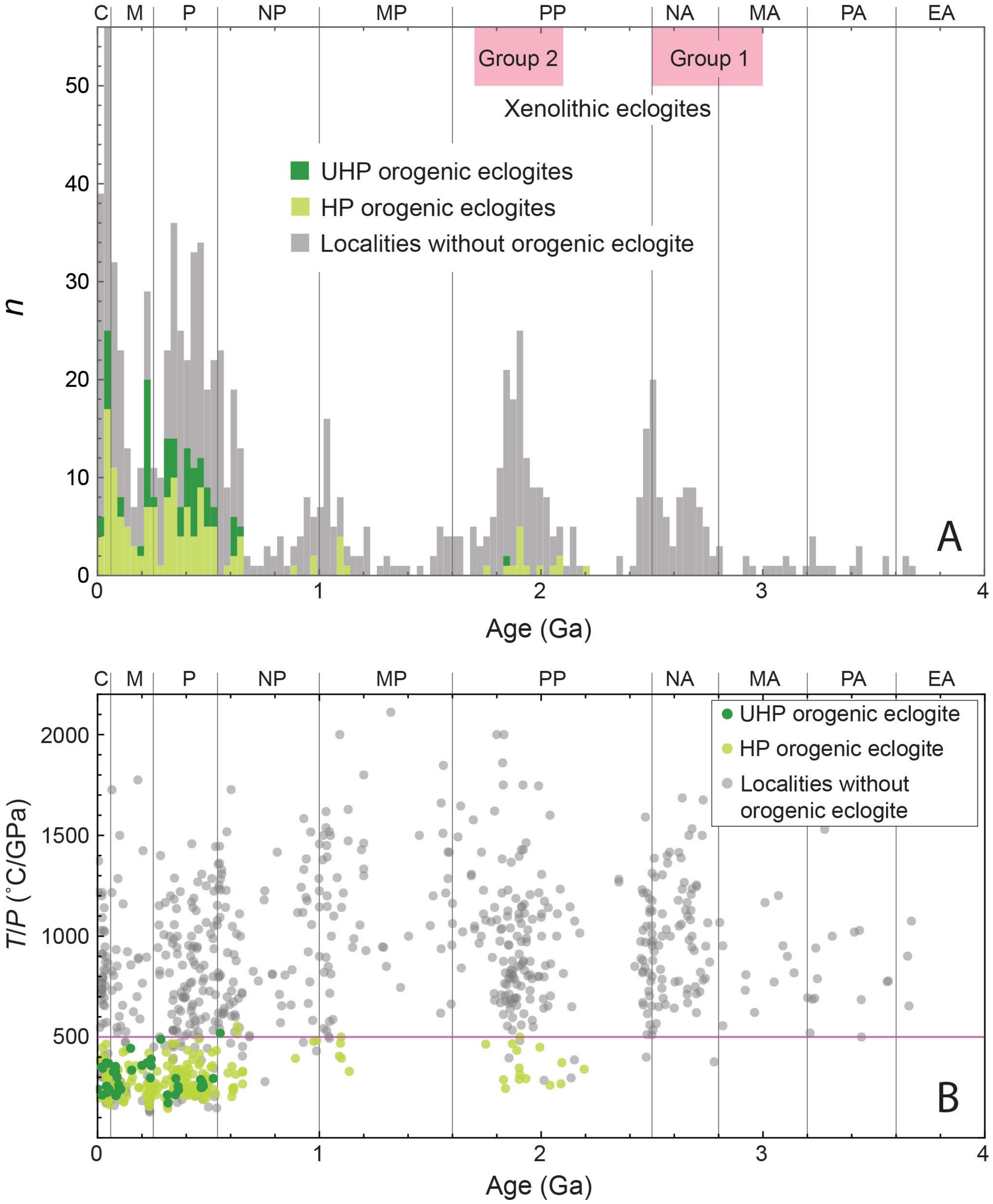
*Group 1: Congo-Kasai, Kaapvaal, North Atlantic, Siberia and Zimbabwe cratons; Group 2, Sask and Slave cratons, margin of the Siberian craton (Aulbach and Smart, 2023, AREPS).

Orogenic eclogites

- **Orogenic eclogites (210 of 898 localities) mostly record *T/P* <500°C/GPa, consistent with subduction**

- **All reliably dated orogenic eclogites post-Archean.**

- **Is sample population representative? Geological record biased towards the recent past, could the absence of orogenic eclogites in the Archean be due to preservation and survivorship bias?**

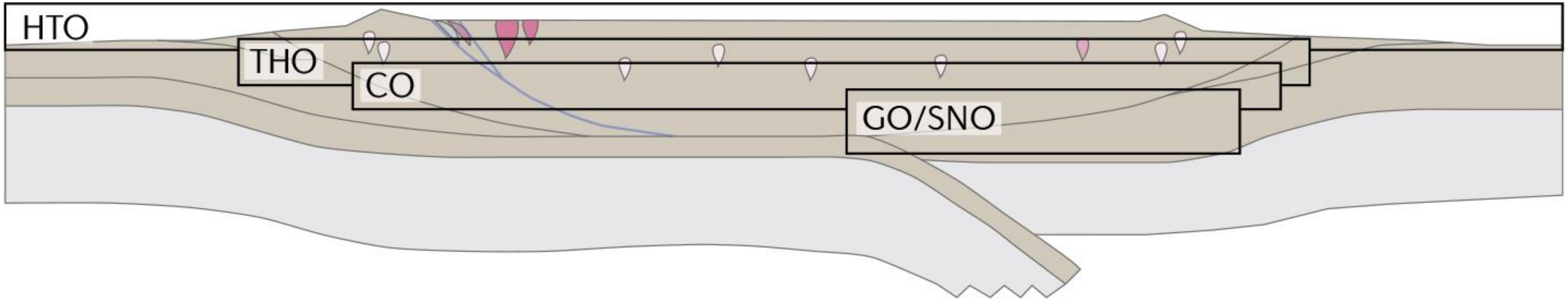


If preserved, can orogenic eclogites survive erosion?

❖ **Orogenic eclogites generally preserved in collisional sutures, likely survive deep erosion that exposes mid-levels of young and old orogenic belts alike.**

❖ **Depth of erosion in cratons variable; if orogenic eclogites were formed and preserved in the Archean, unlikely all would be lost to erosion.**

e.g., Paleozoic CO is more deeply exposed than the Paleoproterozoic THO



CO = Caledonian orogen; GO/SNO = Grenville/Sveconorwegian orogen; HTO = Himalaya-Tibet orogen; and THO = Trans-Hudson orogen (Weller et al., 2021, NREE)

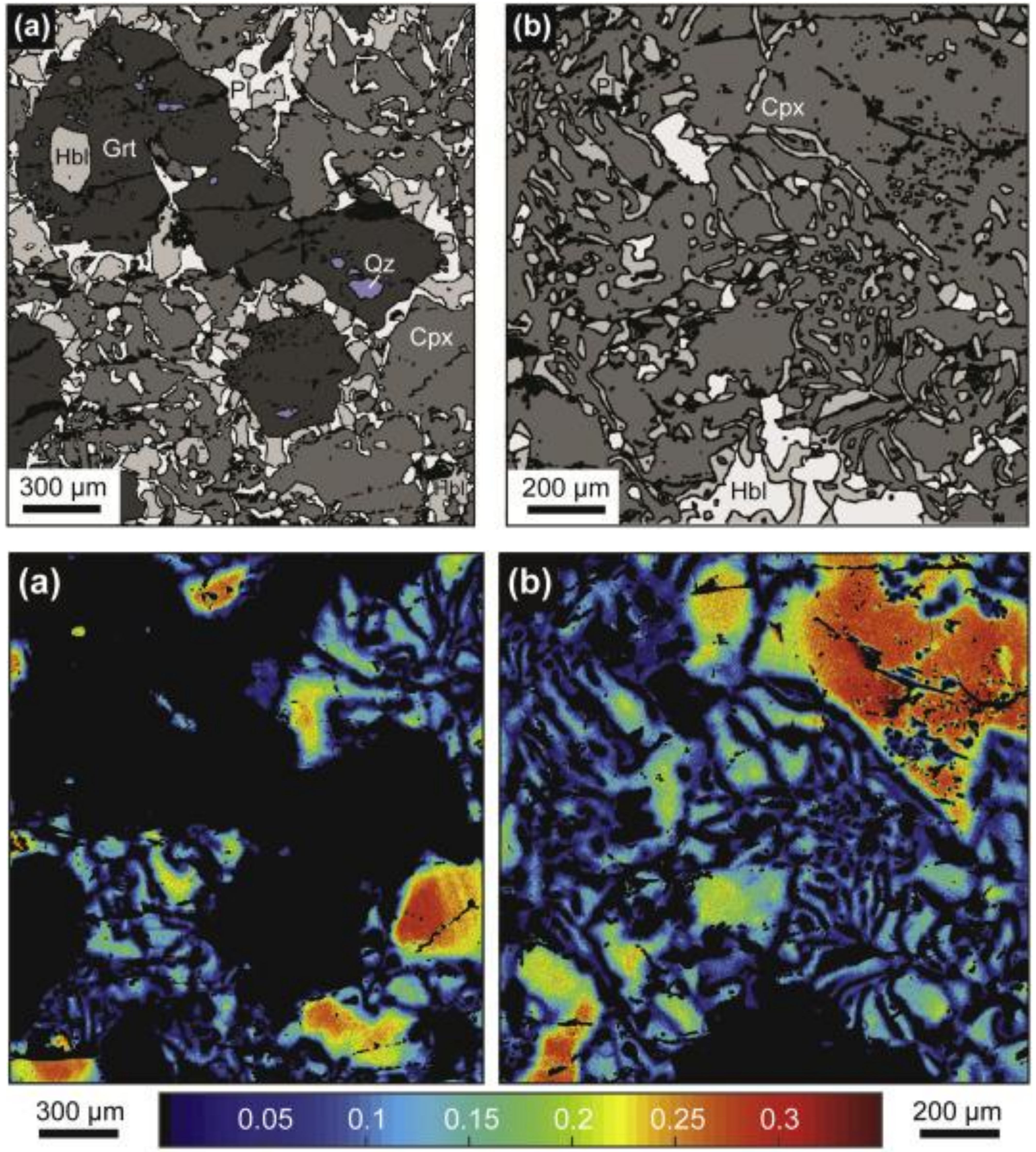
Can orogenic eclogites survive overprinting during exhumation?

- **Proposed that Archean eclogites do not survive exhumation because they are overprinted beyond recognition by (higher *T*) lower *P* mineral assemblages or by partial melting (**e.g., Wang et al., 2021, EPSL; Liu et al., 2023, JGR**).**

- **Regardless of age and exhumation *P-T* path, overprinted (or partially melted) eclogite is generally recognizable—Grt commonly less affected than Om, and Om commonly replaced by distinctive symplectite of Di+NaPl.**

- **Rocks with similar symplectites in association with Grt not observed in Archean cratonic nuclei.**

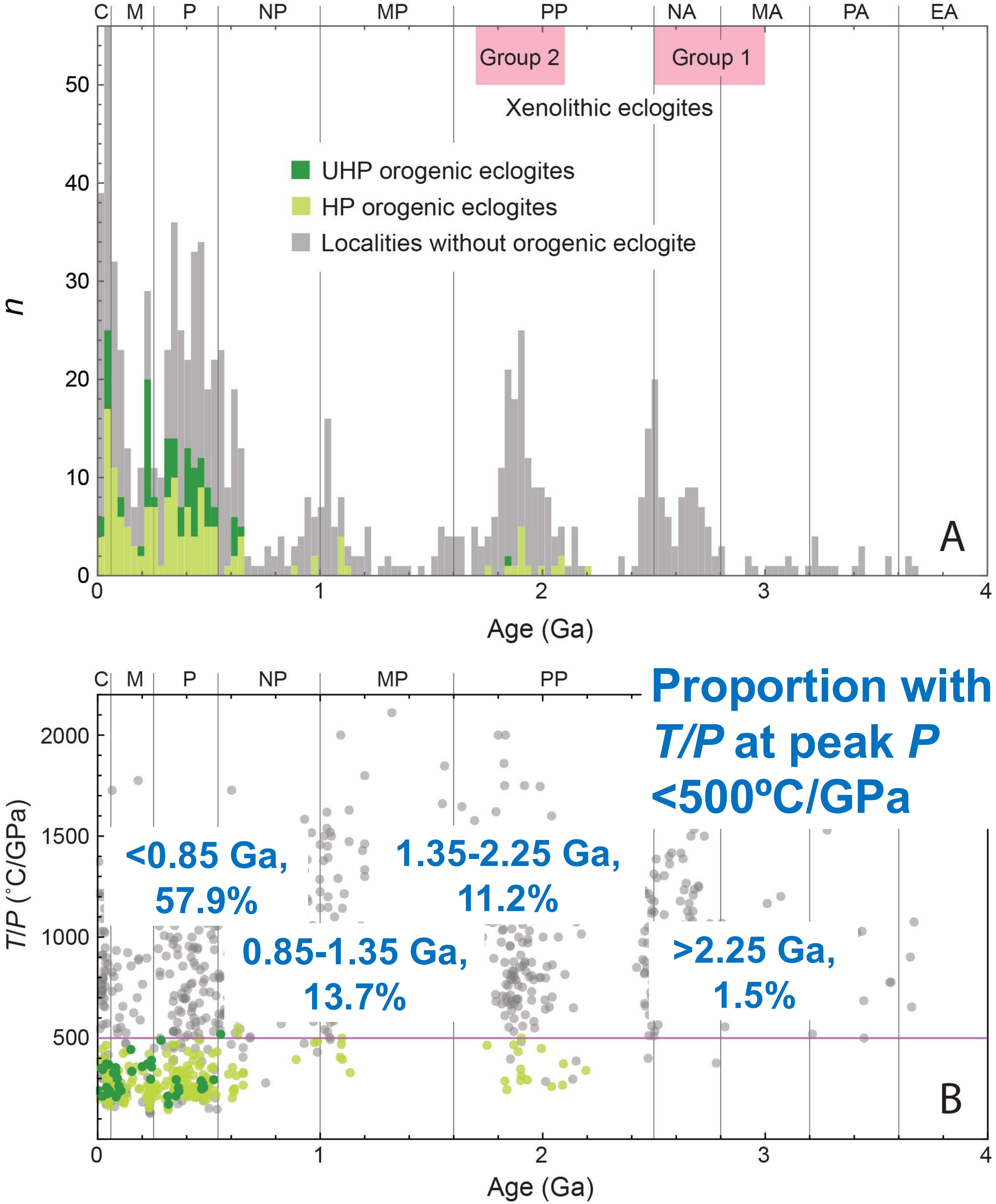
Paleoproterozoic (*c.* 1.9 Ga) orogenic eclogite (Gridino complex, Belomorian; Yu et al., 2019, Lithos**)**



Maps of J_O in clinopyroxene, where J_O = (Na)M2

Metamorphism and subduction

- **Two step increase in the proportion with *T/P* <500ºC/GPa, first in the early Paleoproterozoic and second after the Tonian.**
- **Steps represent a change to colder thermal gradients (stable subduction) and then to deeper slab breakoff.**
- **Inconsistent with the exponential decay expected from a standard survivorship model (**Gregor, 1970, Nature**).**
- **Lack of orogenic eclogites and metamorphic rocks with *T/P* <500ºC/GPa in the Archean consistent with absence of long-lived subduction.**

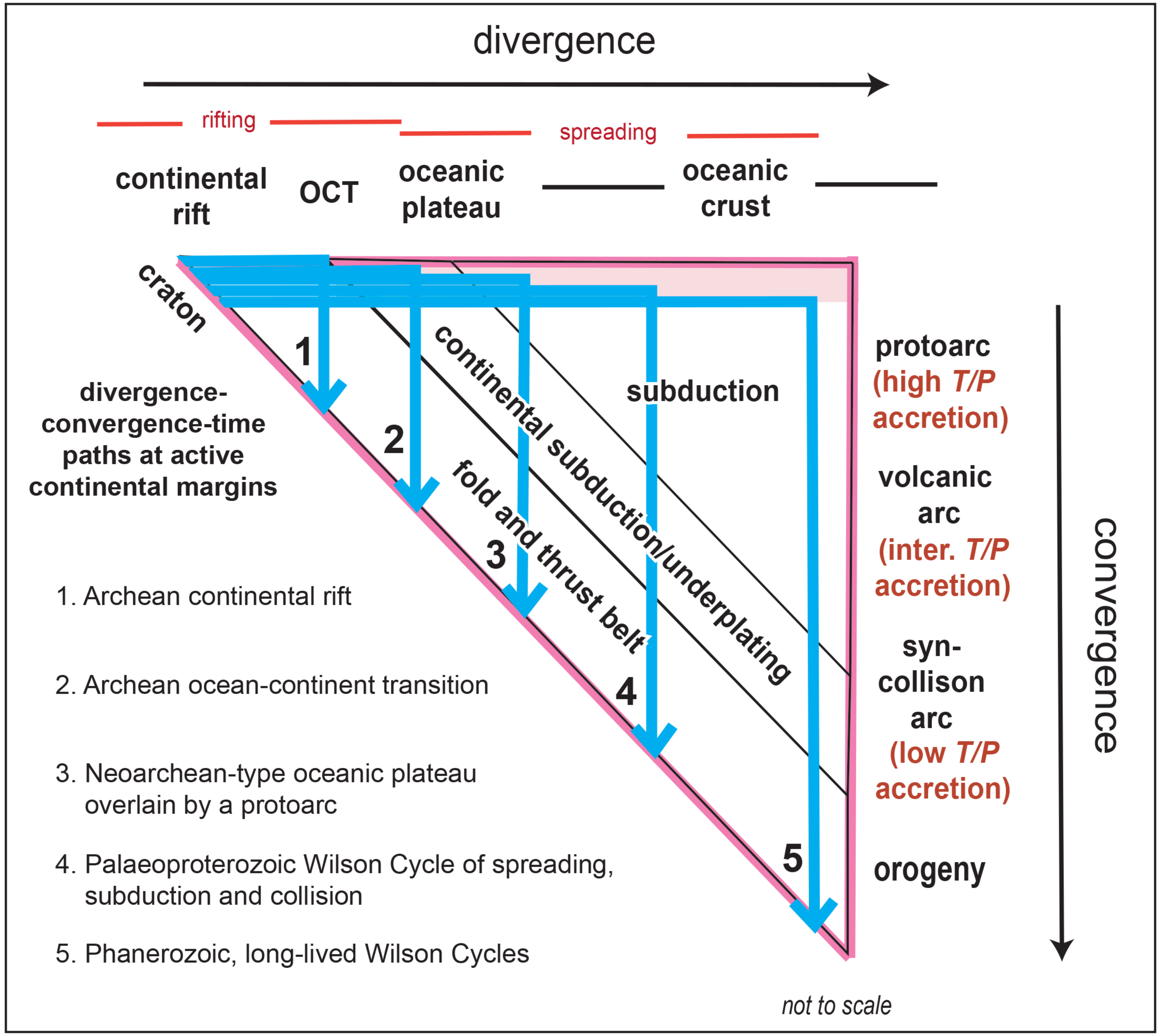


A tectonic model and some consequences

- **Model based on divergence vs convergence**
- **Extent of divergence determines the amount of convergence**
- **Leads to different outcomes as Earth cools**

Early Archean (>3.2 Ga)

- **Limited divergence (1 and 2) leads to formation of rifts and OCTs**
- **Subsequent convergence produces fold-and-thrust belts or accretion via underplating before terminal thickening**
- **Does not produce plate tectonic indicators (ophiolites, arc-rocks, orogenic eclogites)**



1. Archean continental rift
2. Archean ocean-continent transition
3. Neoarchean-type oceanic plateau overlain by a protoarc
4. Palaeoproterozoic Wilson Cycle of spreading, subduction and collision
5. Phanerozoic, long-lived Wilson Cycles

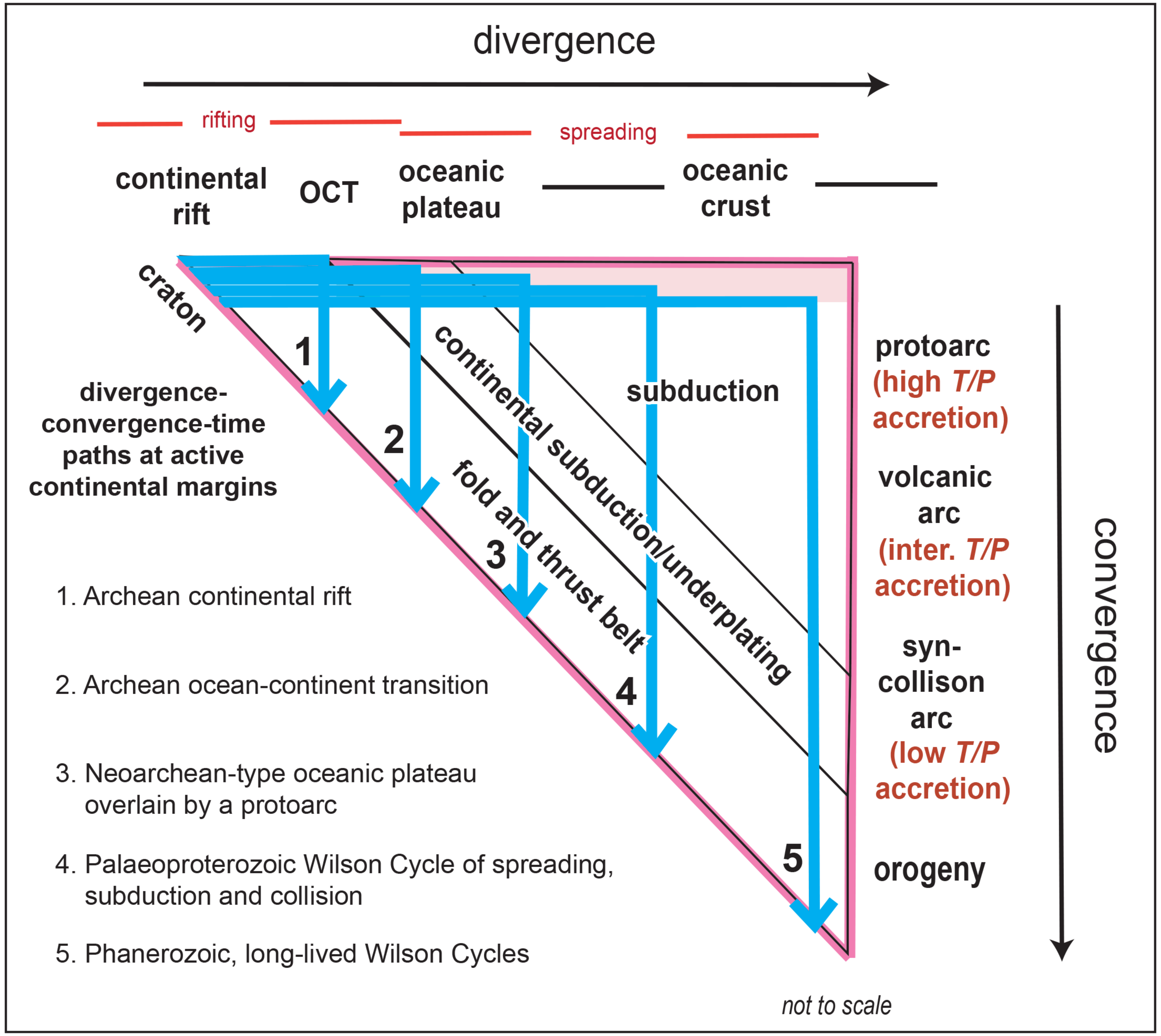
Brown et al., 2024, JGS

Mesoarchean–Neoarchean (3.2–2.5 Ga)

- **Intermediate cycles (3) mostly generate oceanic plateau-like basins without continental basement**
- **Some arc-like rocks generated by local short-lived ‘hot’ subduction driven by mantle traction**
- **Convergence generally insufficient to drag the colliding margin to eclogite-facies depths, producing amphibolites instead**

Proterozoic–Phanerozoic (<2.5 Ga)

- **Longer cycles (4 and 5) produce large ocean basins that close via long-lived subduction driven by slab pull**
- **Produces ophiolites, arcs and HP eclogites (4) or at lower *T/P* blueschists and UHP rocks (5)**



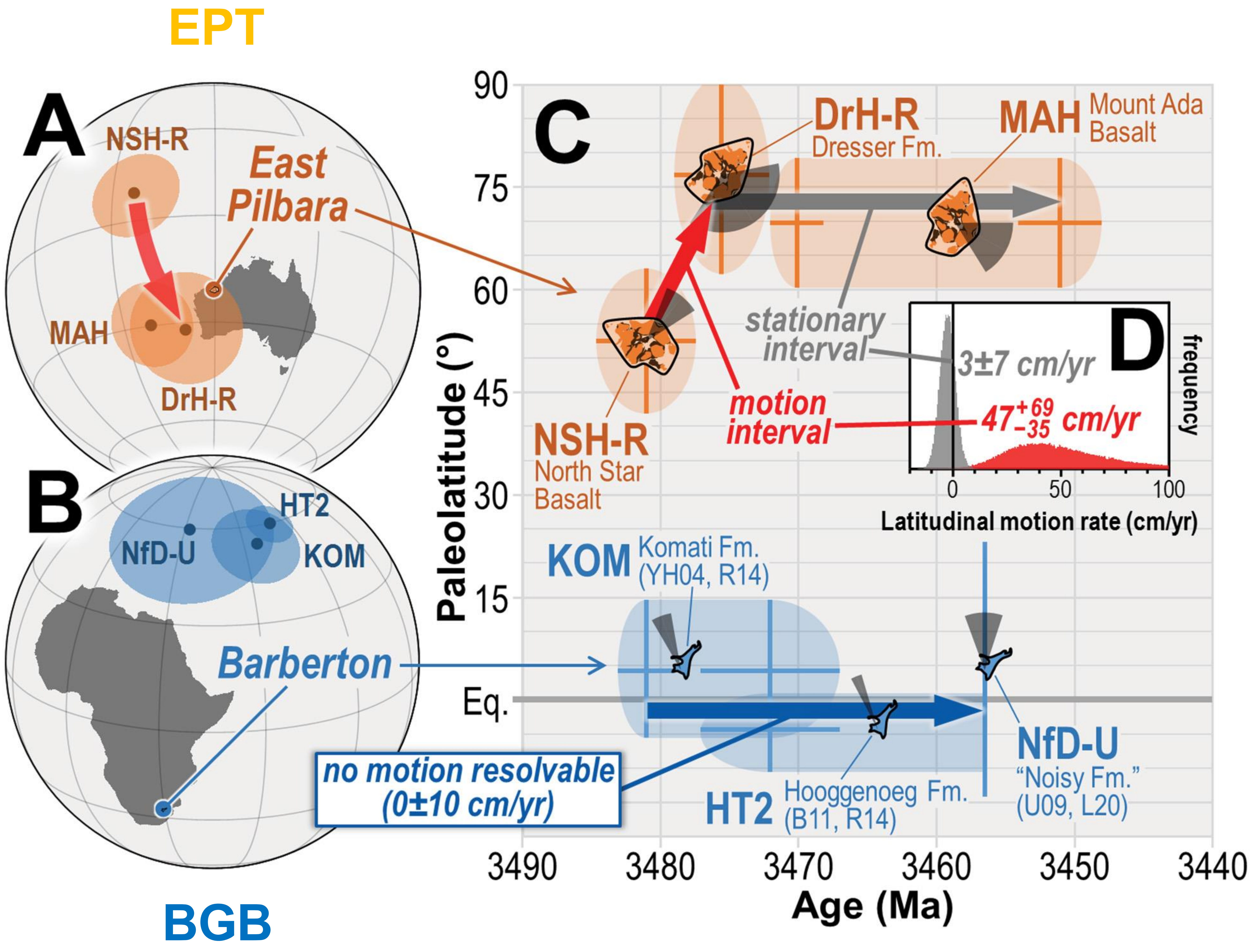
1. Archean continental rift
2. Archean ocean-continent transition
3. Neoarchean-type oceanic plateau overlain by a protoarc
4. Palaeoproterozoic Wilson Cycle of spreading, subduction and collision
5. Phanerozoic, long-lived Wilson Cycles

Brown et al., 2024, JGS

What about evidence of lithospheric mobility in the Archean?

- Paleomag. data from some cratonic nuclei require periods of mobility at rates of cm/yr, cf. the Phanerozoic
- For the EPT, paleomag. data suggest local mobility up to 10s cm/yr for <10 myr slowing to a prolonged period of stasis within <10 myr
- In the Paleoarchean, paleomag. data for the EPT and the BGB demonstrate differential motion, implying an active tectonic boundary between them

Refs: Brenner et al., 2020, SciAdv; Brenner et al., 2022, PNAS; 2026, Science; Kasbohm et al., 2023, PR



Brenner et al., 2026,Science

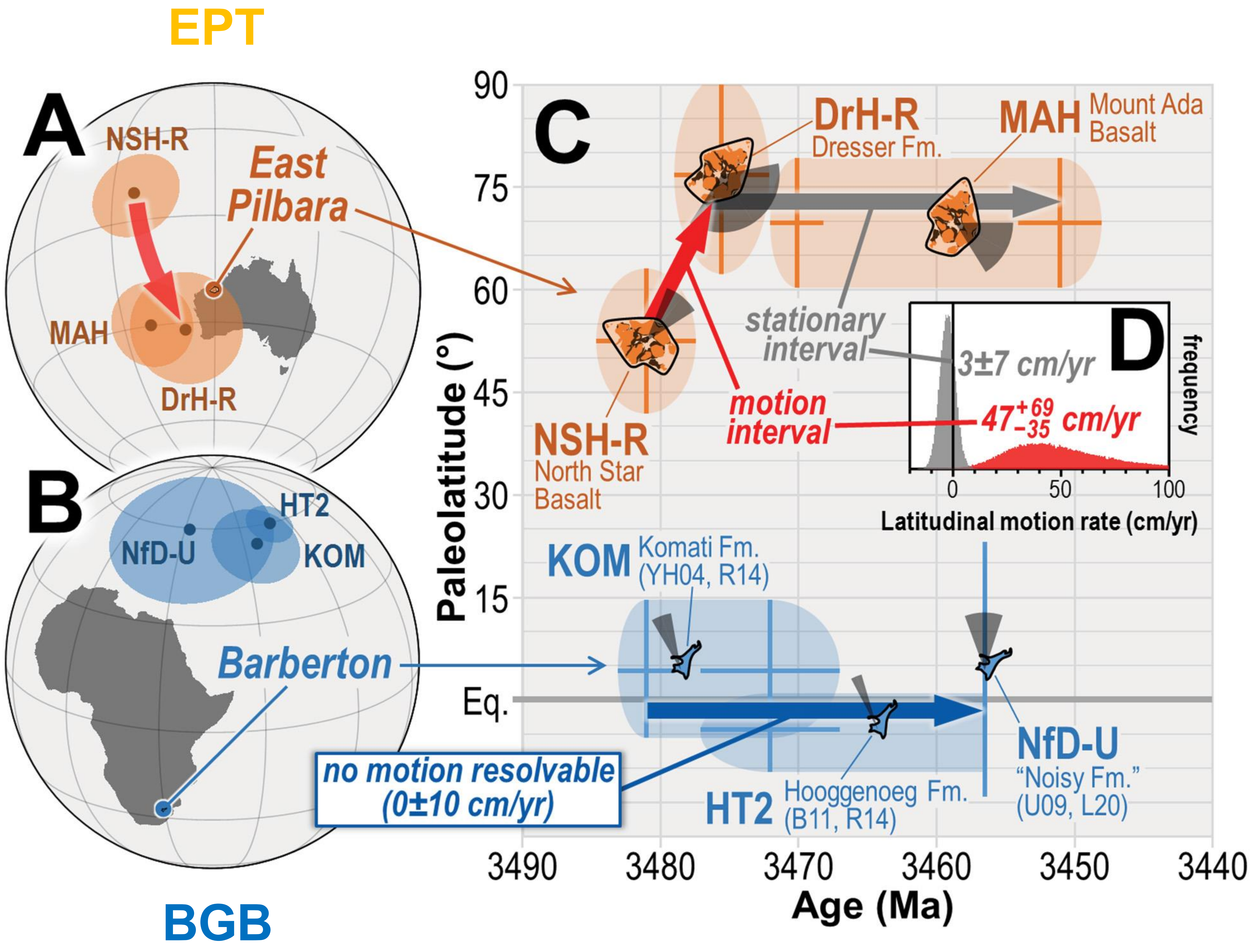
Reconciliation

Compatibility between plume-generated crust and episodic mobility requires:

- **tectonic units larger than cratonic nuclei with active tectonic boundaries off craton,**

and

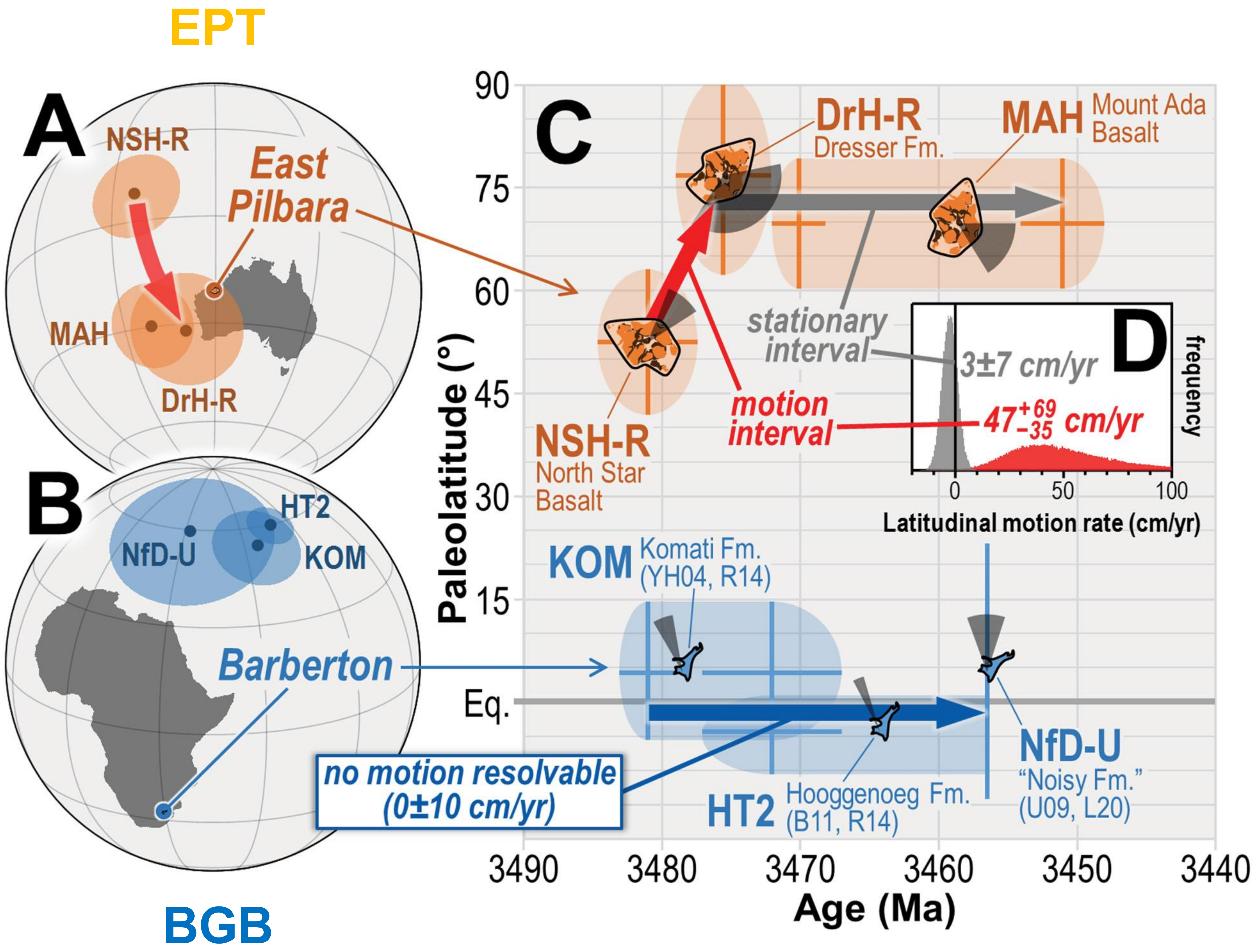
- **a mechanism for mobility.**



Brenner et al., 2026,Science

Which tectonic mode can generate this mobility?

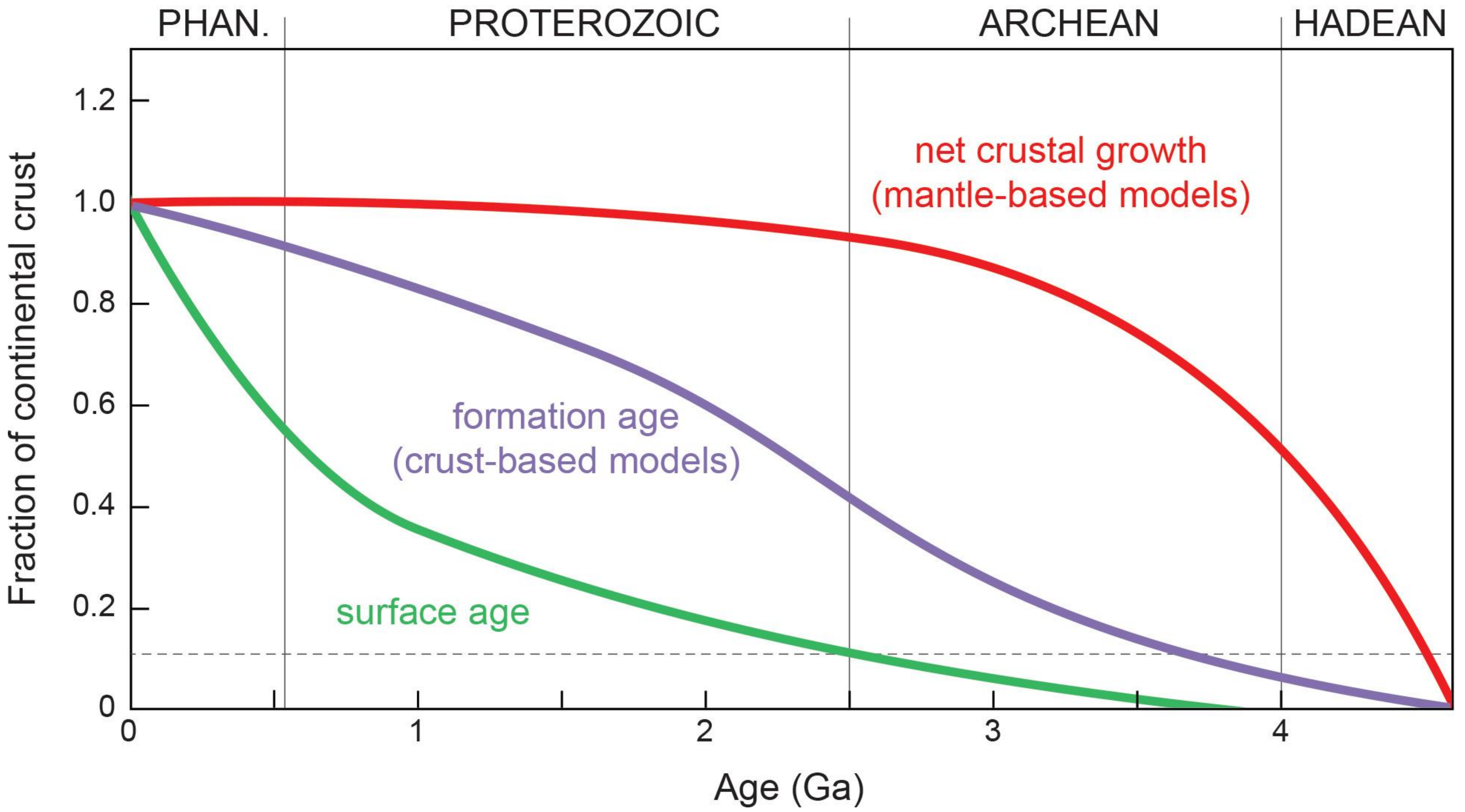
- **Stagnant or sluggish lid** insufficient mobility
- **Mobile lid** could drive differential motions like those inferred by Brenner et al., but slow-downs would be less abrupt
- **Episodic modes** more likely as periodic slab necking and detachment (‘overturns’) could result in accelerating horizontal motion followed by abrupt stop and quiescence until subduction restarts



Brenner et al., 2026,Science

Where is evidence of Archean tectonics archived?

- **Popular to refer to the ‘continental archive’**
- **But much Archean crust has been recycled or reworked**
- **What remains is an imperfect record of Archean ‘continental’ tectonics with limited evidence of subduction**
- **By contrast, evidence of Neoarchean off-craton (global) tectonics is archived by fragments of oceanic lithosphere sequestered in mantle roots of cratons**
- **To understand Archean tectonics and formation of cratons, we must combine evidence from both crust and underlying mantle (**Brown et al., 2026, Geology**)**

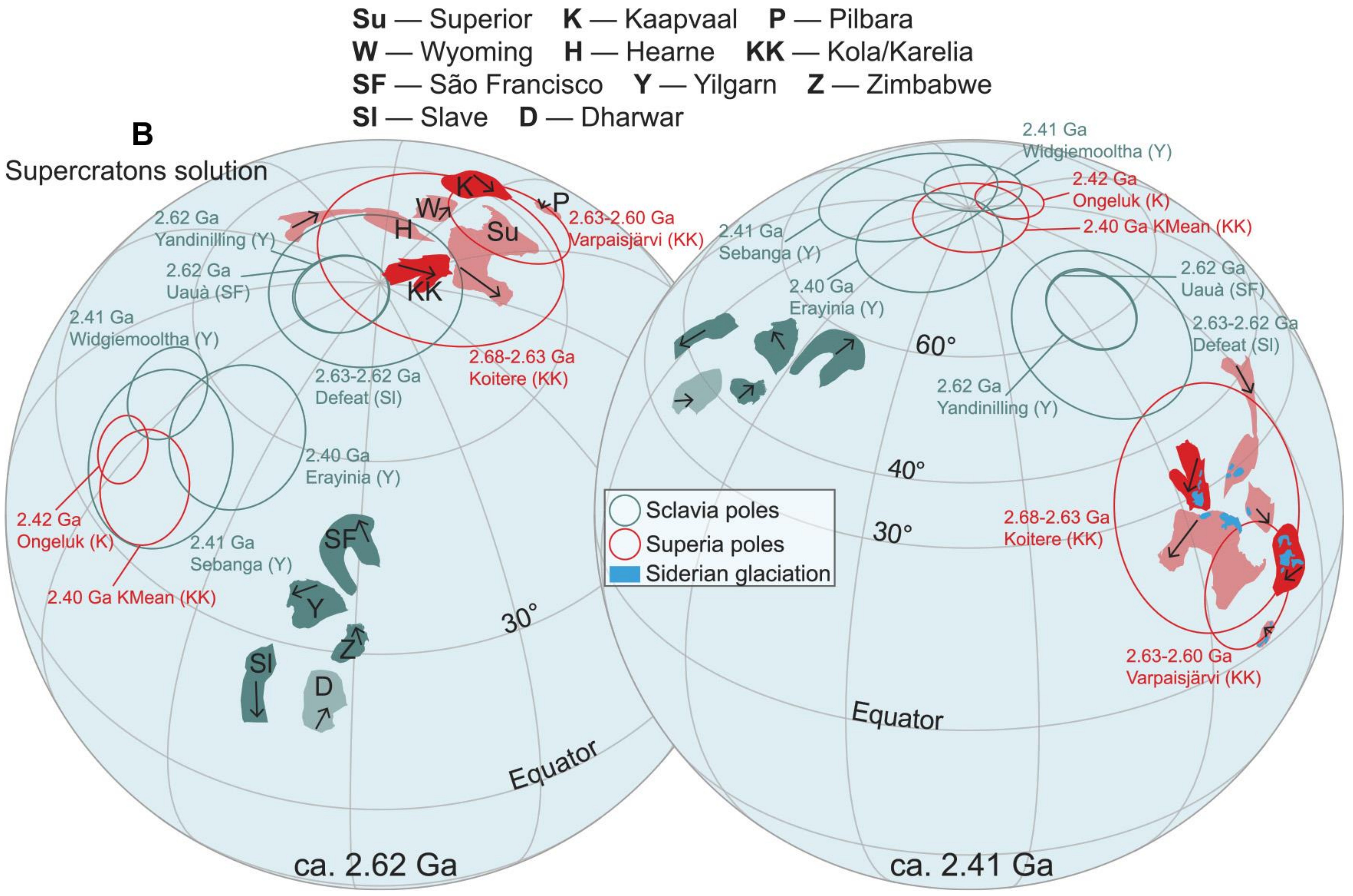


Schematic relationship among net crustal growth (mantle-based models), crust formation ages (crust-based models), and surface age. Difference between models due to crustal recycling, whereas difference between crust-based models and surface age due to crustal reworking. Line at 0.11 fraction of continental crust is area of the Archean cratonic nuclei relative to present continental area (Mooney et al., 2025, JGR). Modified from Korenaga (2018, ProcRS).

A wider view

- **Cratonic nuclei not isolated**
- **Formed part of larger entities* that extended and contracted in response to mantle plume activity, consistent with the plume-driven divergence–convergence model and off-craton subduction.**

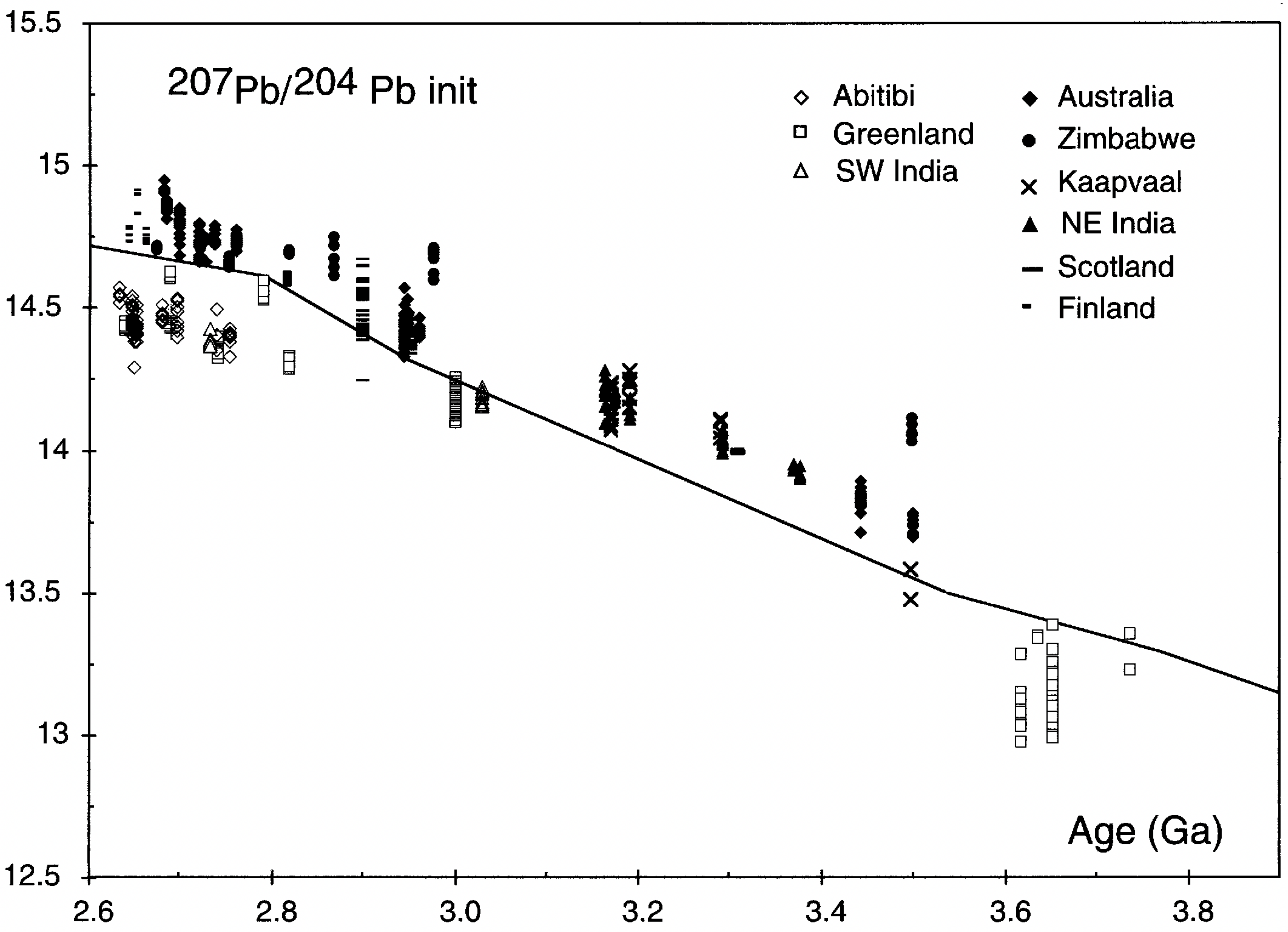
* The supercratons of Bleeker (2003, Lithos).



Liu et al., 2021, Geology

Archean isotope domains . . .

- Luais and Hawkesworth (2002, GSSP) noted that cratons show two trends of initial $^{207}Pb/^{204}Pb$ evolution
- Samples from Abitibi, Greenland and SW India have lower initial $^{207}Pb/^{204}Pb$ ratios through time than those from Australia (Pilbara), southern Africa and NE India

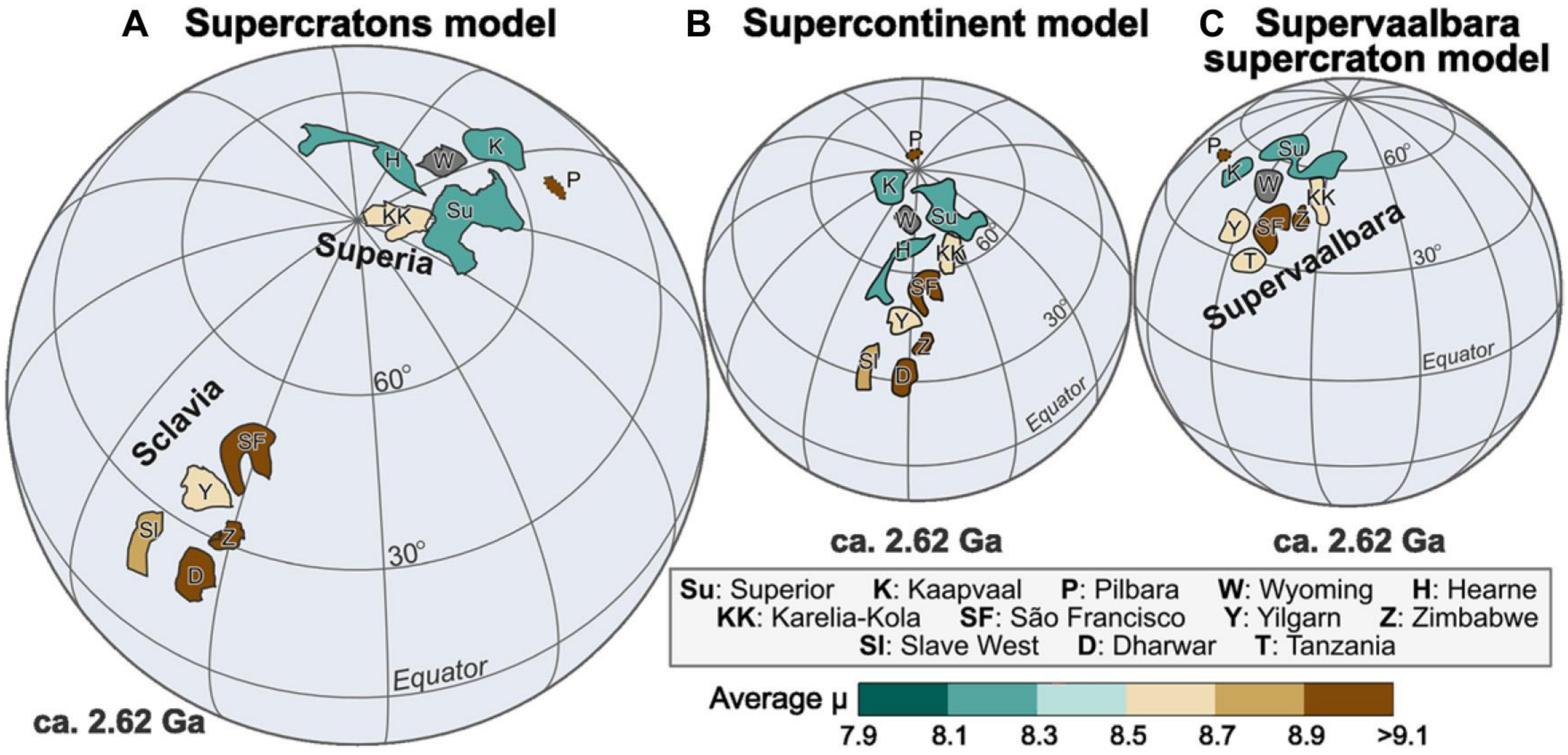


. . . and supercratons

- Armistead et al. (2025, Geology) noted spatial patterns in model age and source μ ($^{238}U/^{204}Pb$) showing isotopic domains align with proposed Archean supercratons

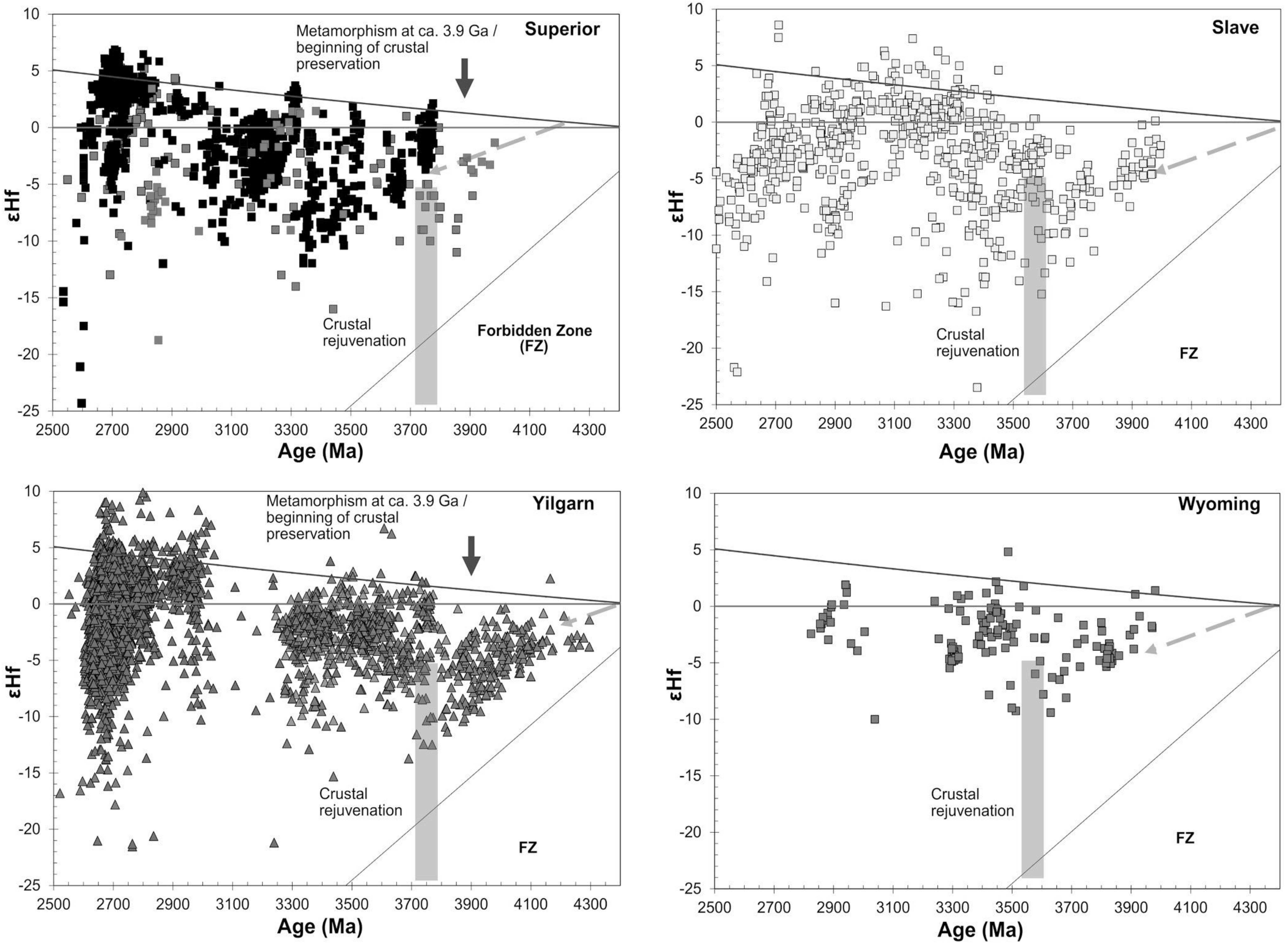
- Low μ values characterize cratons within the Superia supercraton (e.g., Superior, Kaapvaal and Hearne)

- Moderate to high μ values are typical of cratons forming the Sclavia supercraton (e.g., Slave, Yilgarn, Dharwar and Zimbabwe)



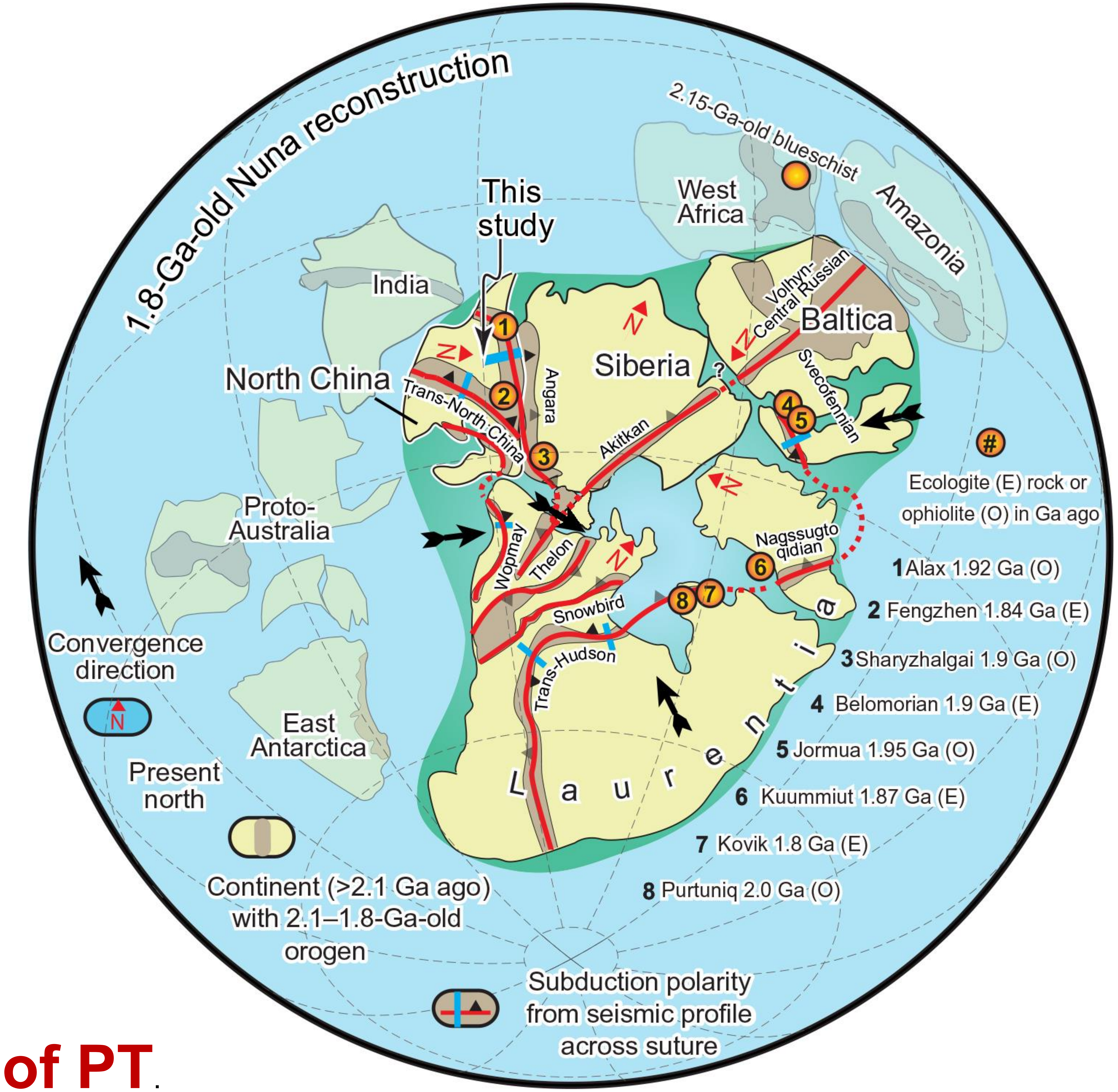
Two first order tectonic thresholds

- ❖ **First tectonic threshold crossed during the late Eoarchean–early Paleoarchean (3.8–3.5 Ga), as evidenced by a change in crust production**
- ❖ **Likely related to an exogenic to endogenic transition, the onset of plume-driven ‘continental’ tectonics and, in oceanic domains, episodic subduction**



Strong et al., 2026, EPSL

- **Progressive cooling of the mantle since the Mesoarchean allowed stable subduction to propagate leading to . .**
- **. . a second tectonic threshold crossed during the Neoarchean to early Paleoproterozoic.**
- **Crossing this threshold allowed the emergence of (global) PT driven by slab pull**
- **Led to collision/suturing, forming the larger composite cratons we recognize today**



Wan et al., 2020, SciAdv

Nuna (Columbia) may provide a minimum age for the emergence of PT.

Conclusions

1. Necessary to use both the continental crust and lithospheric mantle archives to constrain Archean tectonic mode.

2. PT indicators (ophiolites, arcs, orogenic eclogites) rare in Archean cratonic nuclei; petrological evidence consistent with plume tectonics, limited convergence and rare short-lived subduction.

3. Xenolithic and orogenic eclogites record complementary information about Archean off-craton subduction and post-Archean subduction-driven collision, respectively.

4. By looking outside cratonic nuclei to consider their global tectonic context, maybe a consensus about Archean tectonics is in reach?