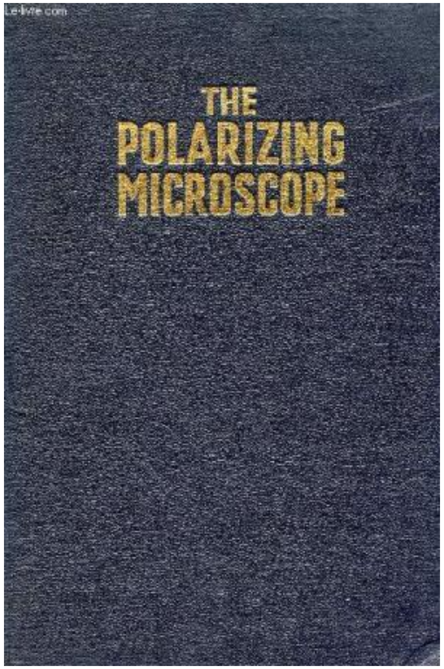
THE HALLIMOND LECTURE

Hallimond (1890–1968) joined the Mineralogical Society of Great Britain & Ireland in 1912, the same year he began his career with the British Geological Survey; he served on Council for many years.

"The annual lecture is a tribute to Hallimond's valuable contribution to the science of mineralogy, particularly in the fields of ore mineralogy and instrument design. His book, Manual of the Polarising Microscope, first published in 1948, is regarded as one of the foundation stones of modern ore-microscopy."

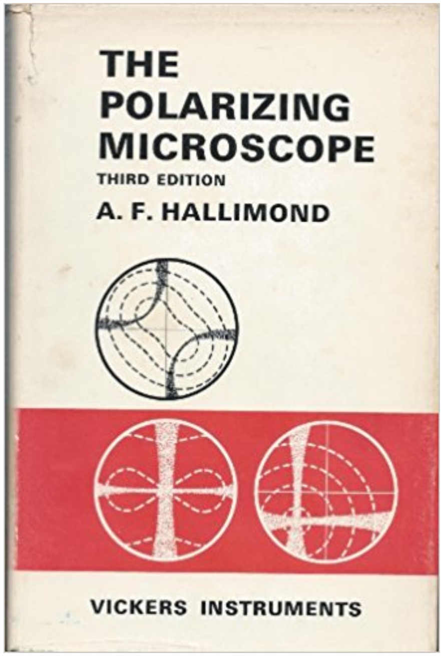


THE POLARIZING MICROSCOPE

A. F. HALLIMOND

Published by Cooke, Troughton & Simms Ltd. (1953; 23 editions)

US$ 131.33



THE POLARIZING MICROSCOPE

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Published by Vickers Ltd.; 3rd Revised edition (February 1970; 9 editions)

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- ✧ **<u>Post-doctoral Fellows</u>: Nathalie Marchildon, Renato Moraes, Tim Johnson, Julia Baldwin, Fawna Korhonen, Satoshi Saito, Longlong Gou, Bin Xia, Zuolin Tian**

- ✧ **<u>Collaborators</u>: too numerous to list by name**


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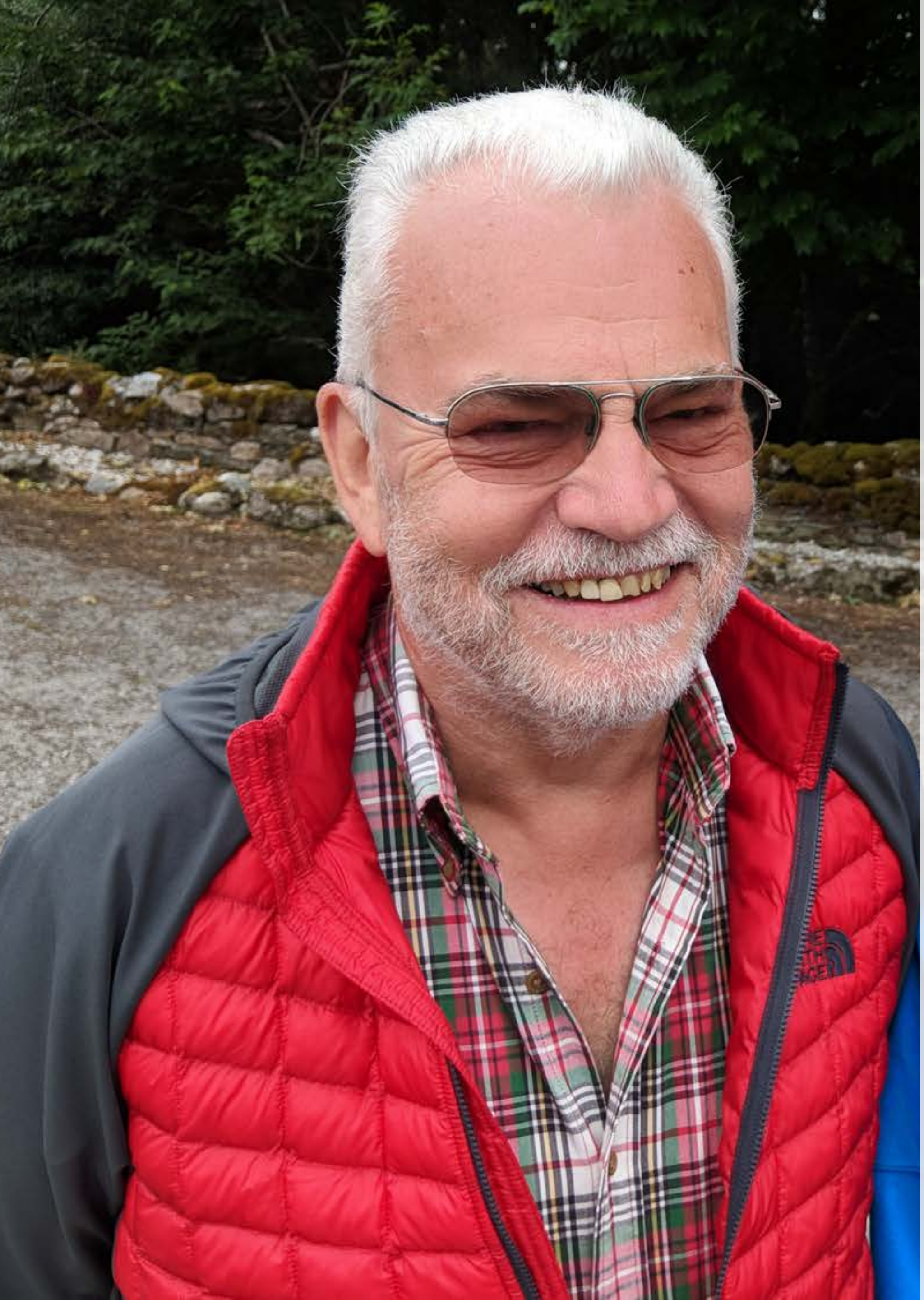

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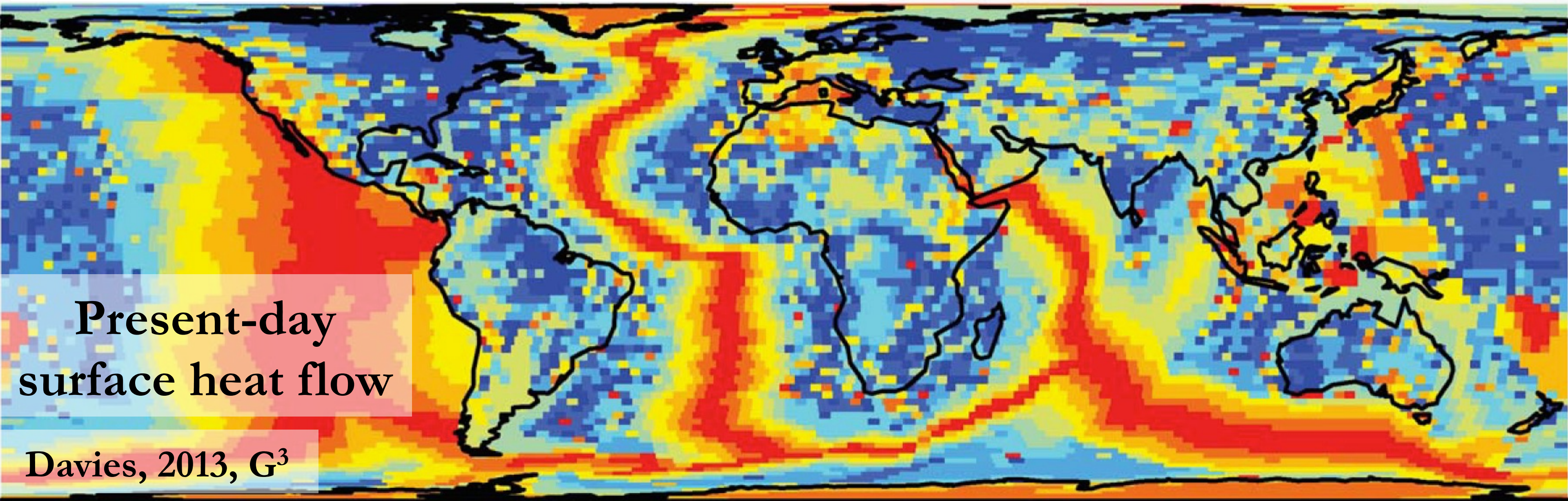
The 51st Hallimond Lecture

Time's arrow, time's cycle: Granulite metamorphism and geodynamics

Michael Brown

University of Maryland, USA

1020 °C @ 0.7 GPa

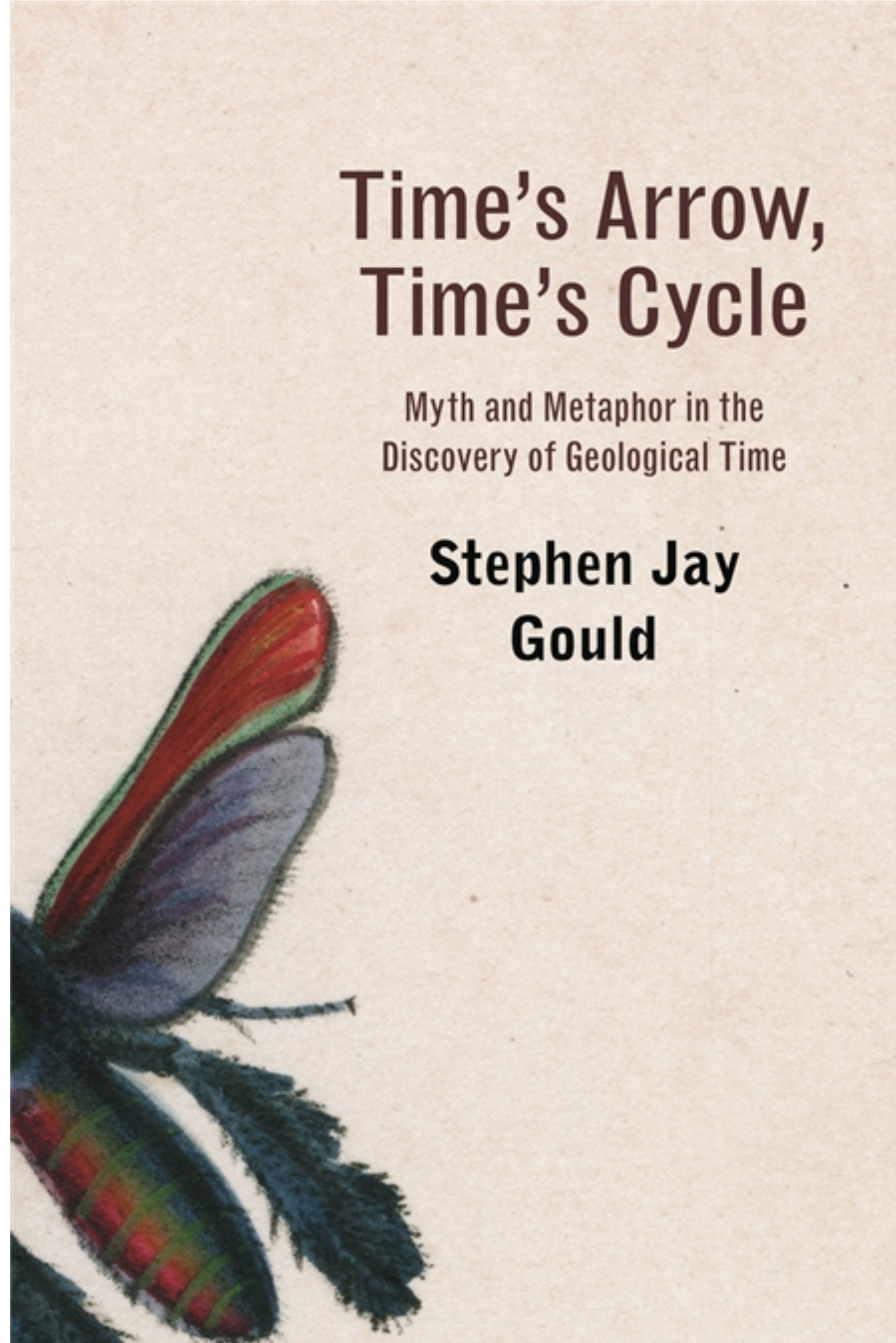


In 1987* Stephen Jay Gould introduced us to a powerful pair of lasting metaphors—time's arrow and time's cycle—by which we have tried to understand the concept of deep time.

"Time's arrow is the intelligibility of distinct and irreversible events, while time's cycle is the intelligibility of timeless order and lawlike structure" (p. 15–16).

The arrow and the circle *"do not blend, but dwell together in tension and fruitful interaction"* (p. 200).

***Time's Arrow, Time's Cycle:** Myth and Metaphor in the Discovery of Geological Time**, Stephen Jay Gould, Harvard University Press, 1987.**



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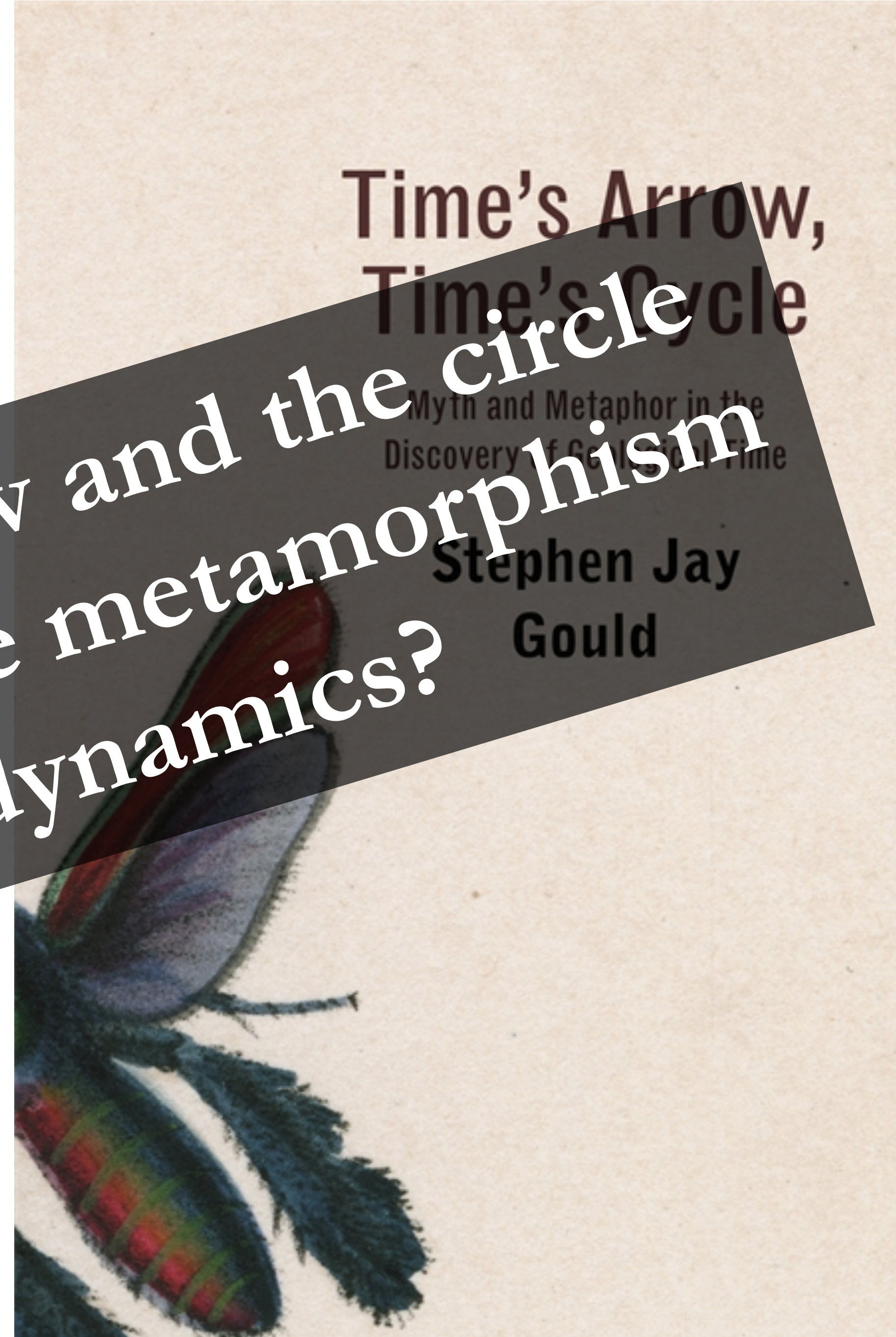
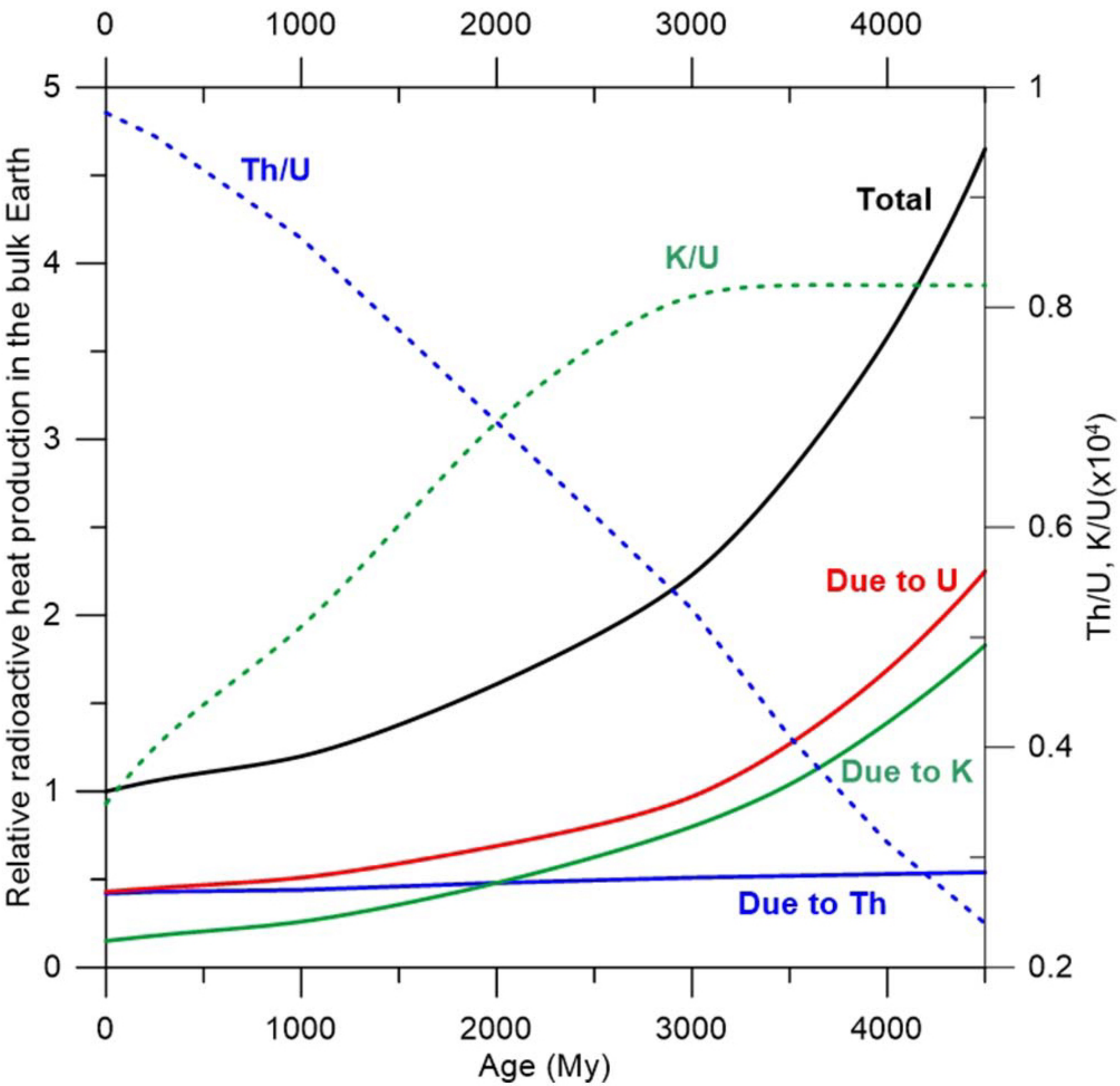
The arrow and the circle *"do not blend, but dwell together in tension and fruitful interaction"* (p. 200).

How do the arrow and the circle relate to granulite metamorphism and geodynamics?

***Time's Arrow, Time's Cycle:** Myth and Metaphor in the Discovery of Geological Time**, Stephen Jay Gould, Harvard University Press, 1987.**

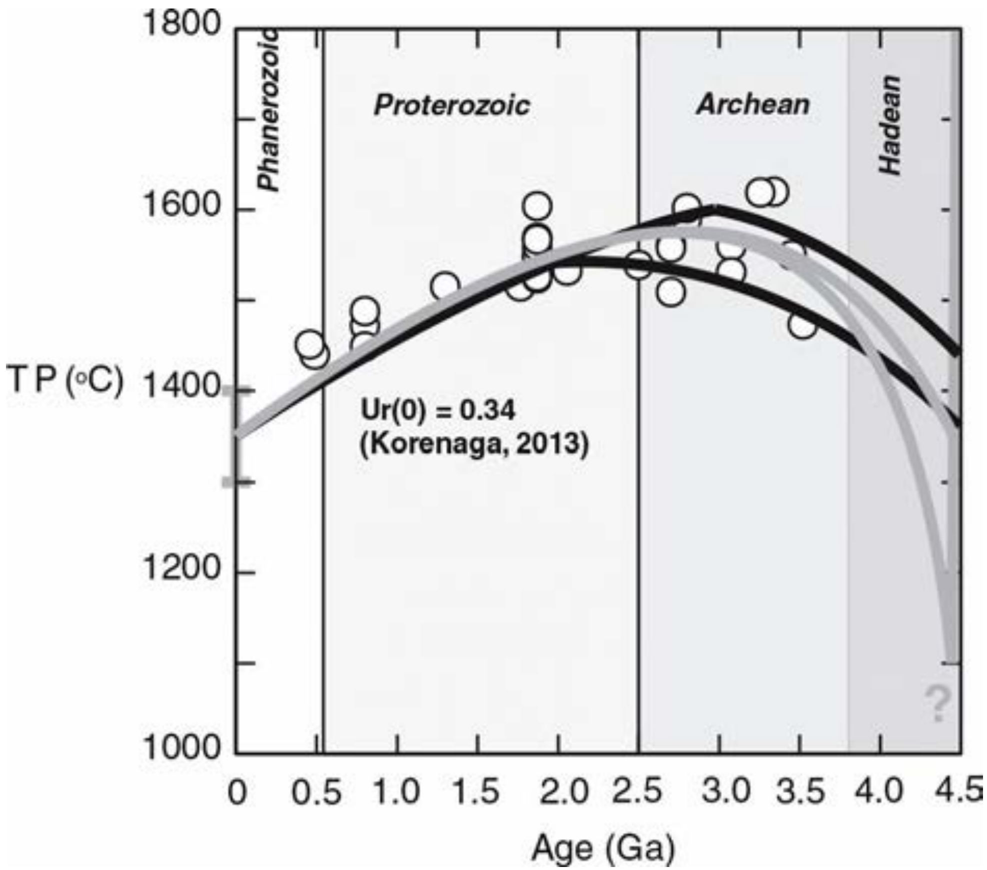


Time's arrow: thermal evolution of Earth



Relative radioactive heat production in the bulk Earth normalized by present-day values (Artemieva et al., 2017, ESR)

T_P of ambient mantle derived from petrology

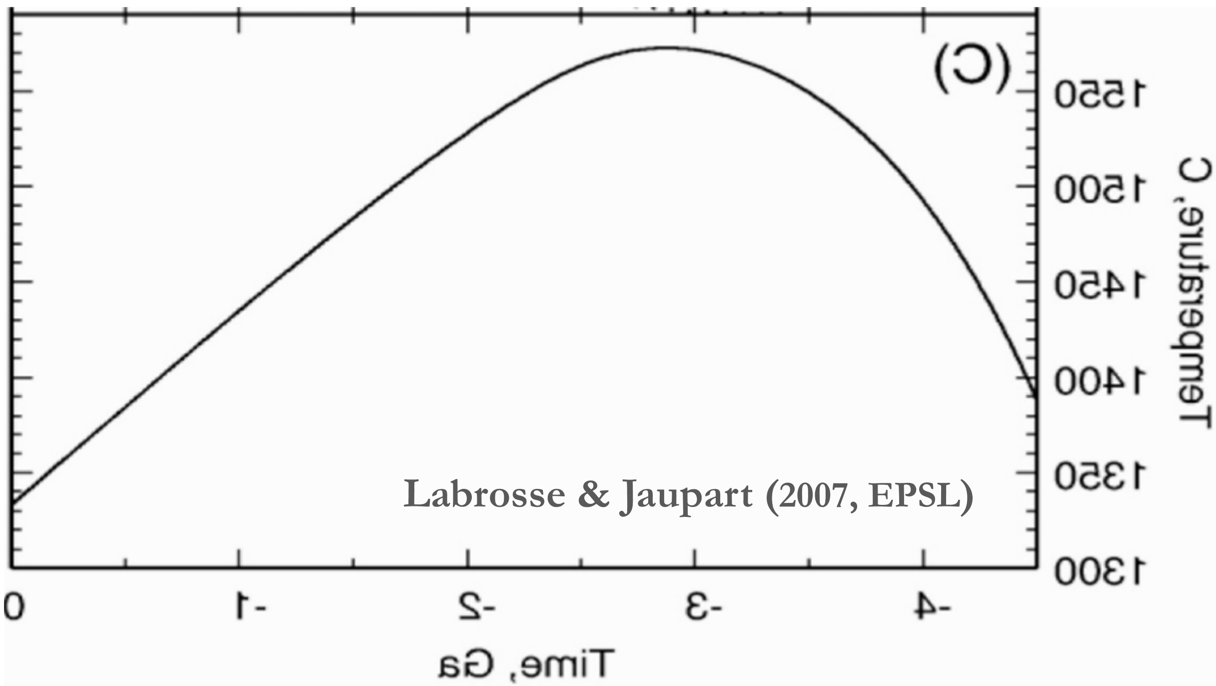


The secular evolution of mantle T_P before *c*. 3.0 Ga is ambiguous, but since *c*. 3.0 Ga mantle T_P has declined by 200–300 °C due to secular cooling.

Circles are mantle *Tp* derived by petrological modeling of basalts. Black lines are solutions for models with a switch in heat-flow scaling from plate tectonics to stagnant lid convection at 2 Ga and 3 Ga, respectively (from Korenaga, 2013, Ann Rev); Ur(0), present-day Urey ratio (mantle heat production divided by heat loss). Grey lines demonstrate the switchover from magma ocean cooling and crystallization to mantle heating by radioactive decay in the Hadean.

(Herzberg, 2016, J Pet)

Calculated time variation of mantle temperature



- ✧ Based on the balance between heat production and a parameterized heat loss scheme.
- ✧ Calculations allow a maximum ΔT_P (difference relative to present-day mantle T_P) of ~250 °C higher at 3.0 Ga and cannot be extrapolated back further.
- ✧ Although uncertain, ΔT at the start of mantle convection—after crystallization of the last magma ocean—may have been ~200°C higher. Either cooling changed to warming as heat production overwhelmed heat loss or the mantle evolved at nearly constant T.
- ✧ Since 3.0 Ga, secular cooling has dominated over heat production.

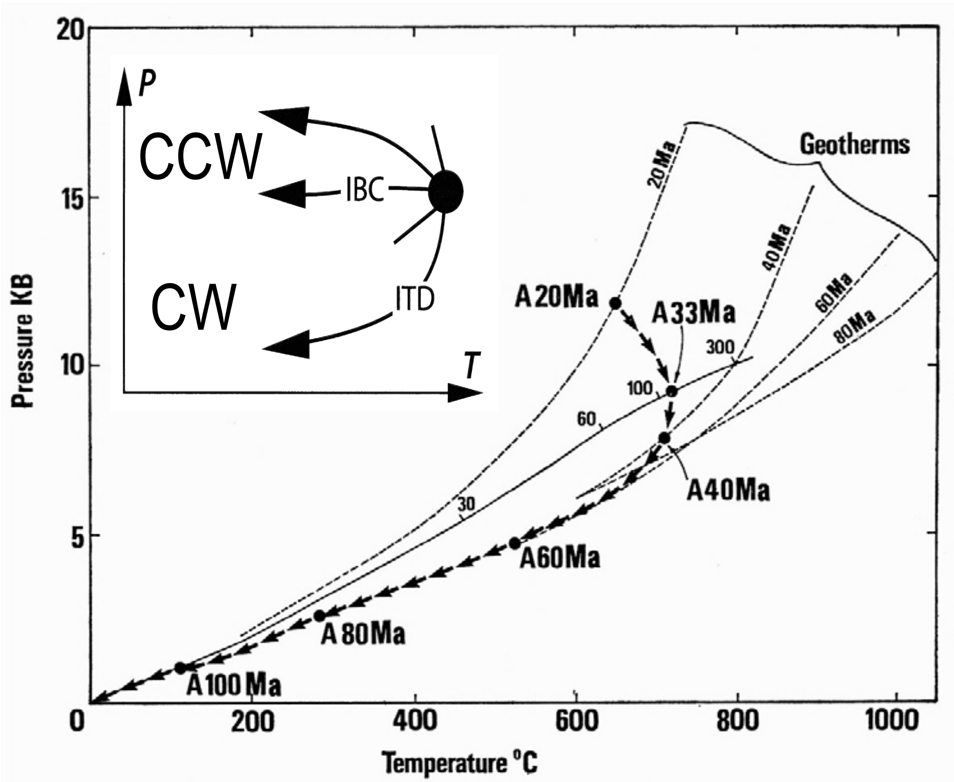
The metamorphic record and time's cycle

- For the metamorphic record, we compile 'peak' T, P, apparent thermal gradient (T/P), and age from Cenozoic to Eoarchean crust, although before the Neoarchean data are sparse.
- Variations in T/P of granulite facies metamorphism and the uneven distribution of ages of metamorphism allow us to define multiple geodynamic cycles.

Metamorphism is a dynamic process

Burial and exhumation of rocks leads to evolution of pressure (*P*) and temperature (*T*) with time (*t*), resulting in changes in modes and compositions of phases. Mode, composition and 'age' become fixed at some point along the evolutionary (*P–T–t*) path, but not necessarily at the same point!

- P_{max} and T_{max} generally do not coincide
- along CW *P–T–t* paths, P_{max} occurs before T_{max}
- along CCW *P–T–t* paths, T_{max} occurs before P_{max}
- derived *P–T* is commonly inferred to record 'peak' conditions, but may record P_{max} or T_{max}
- historically ages were inferred to record the timing of 'peak' *P–T*, but may record a time along the late prograde or retrograde path
- during the past decade our ability to link age with *P–T* has improved significantly

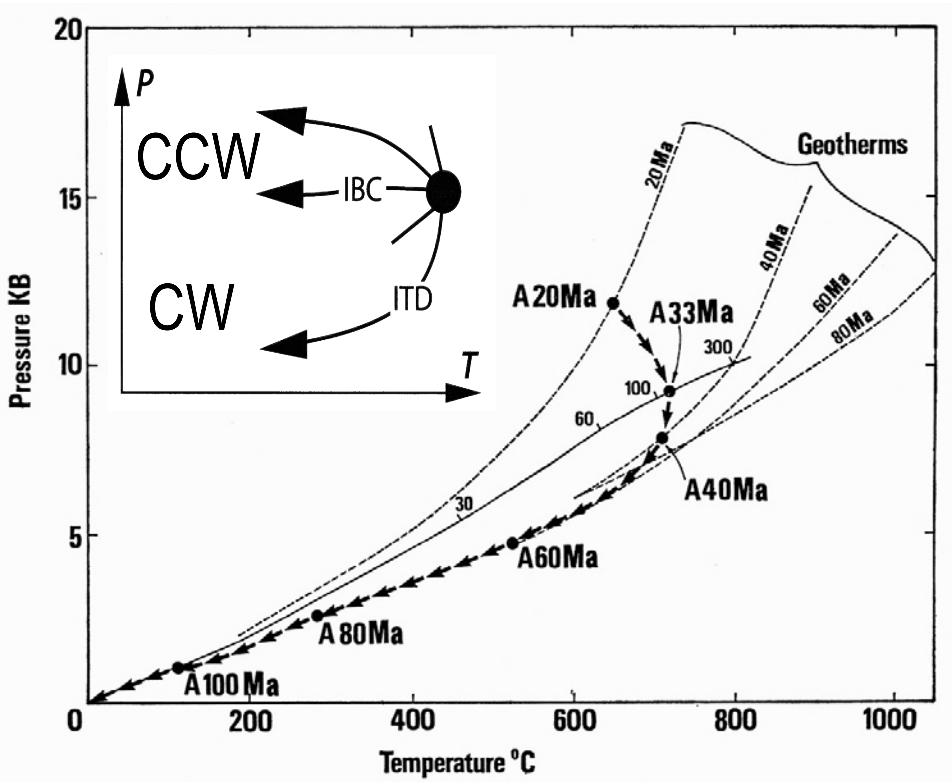


England & Richardson, 1977, JGS

What have we done?

✧ We[1] have reviewed P–T and age data from the literature and compiled our best estimate of 'peak' P–T and t for 564 localities ranging in age from Eoarchean to Cenozoic.

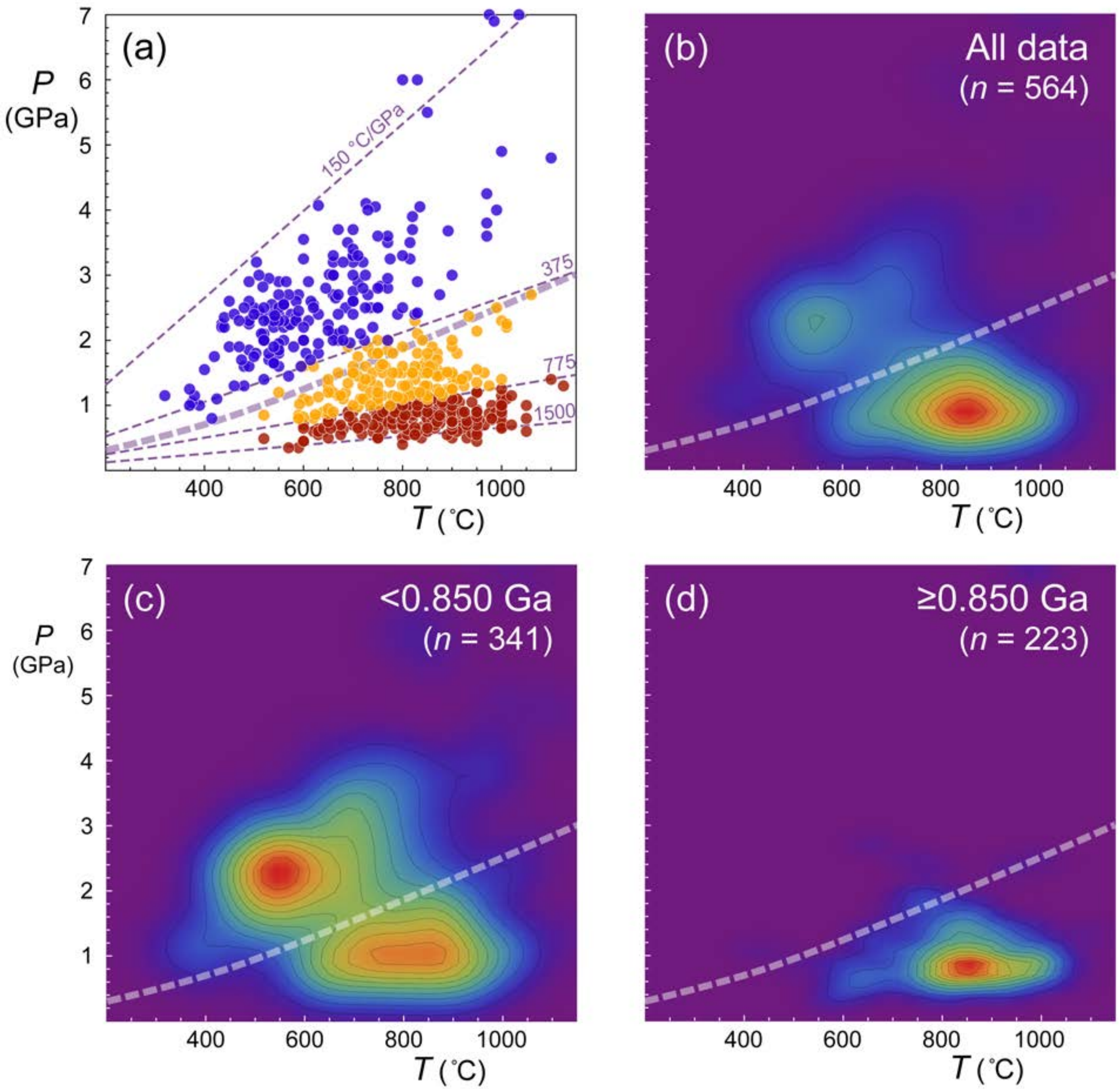
✧ Each datum records an apparent thermal gradient crossed during a dynamic evolution from lower to higher or higher to lower gradients.



England & Richardson, 1977, JGS

[1]Brown & Johnson, 2018, American Mineralogist, 103, 181–196. Dataset updated 02-28-2018.

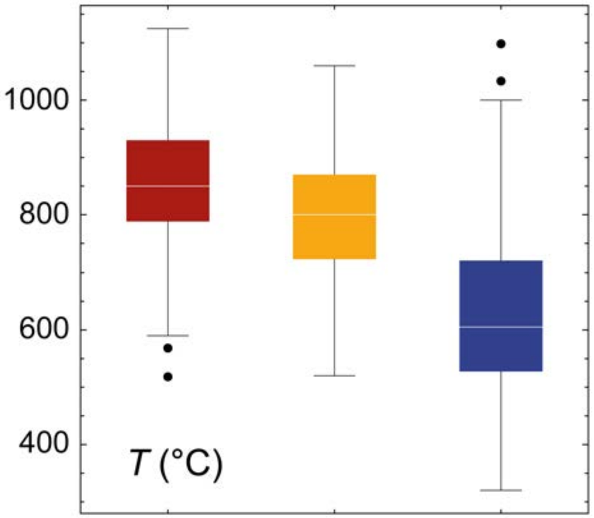
The metamorphic rock record

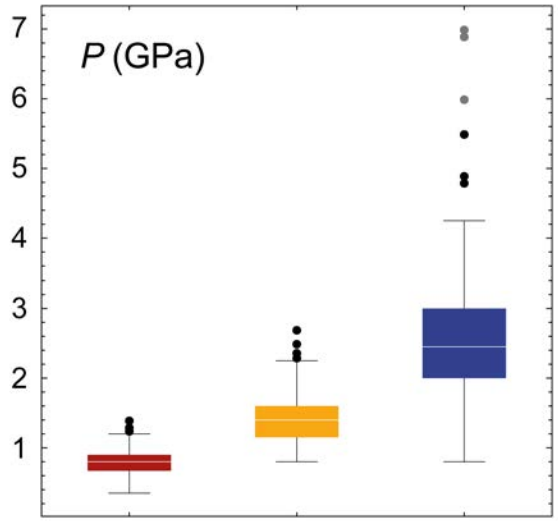


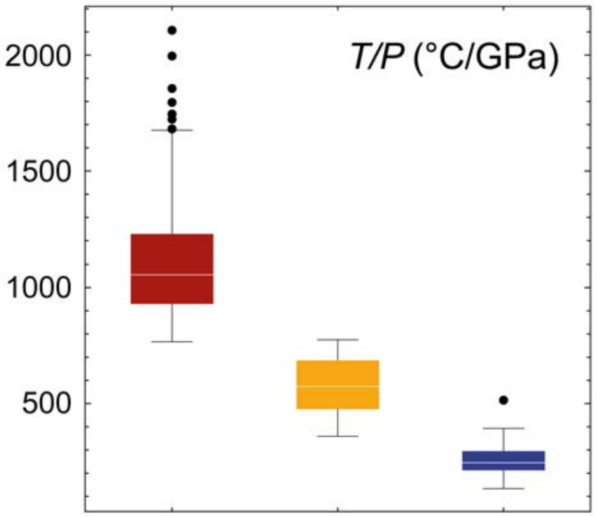
✧ Conditions of 'peak' metamorphism for 564 localities with 'robust' *P*, *T* and *t* grouped by type (a), with the 'normal' geotherm from Stüwe (2007; thick dashed line) and representative thermal gradients (thin dashed lines).

✧ The three types of metamorphism shown in (a) are high dT/dP in red (n = 223), intermediate dT/dP in orange (n = 152) and low dT/dP in blue (n = 189).

The three types of metamorphism are distinct





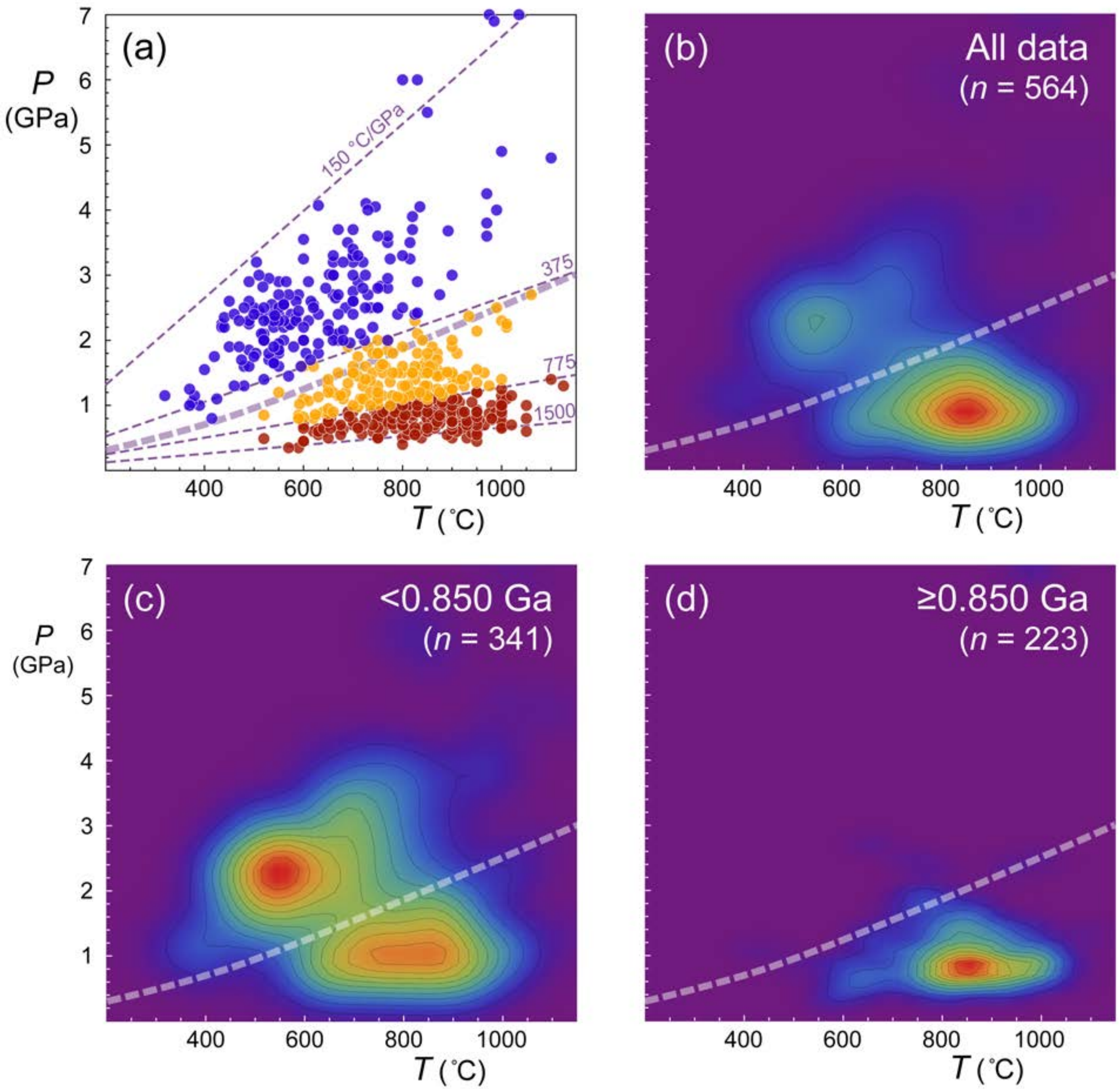


Mean $T = 848 \pm 112$ (1σ)
Mean $T = 793 \pm 107$ (1σ)
Mean $T = 631 \pm 145$ (1σ)

Mean $P = 0.80 \pm 0.18$ (1σ)
Mean $P = 1.44 \pm 0.36$ (1σ)
Mean $P = 2.64 \pm 1.0$ (1σ)

Mean $T/P = 1107 \pm 246$ (1σ)
Mean $T/P = 577 \pm 116$ (1σ)
Mean $T/P = 254 \pm 60$ (1σ)

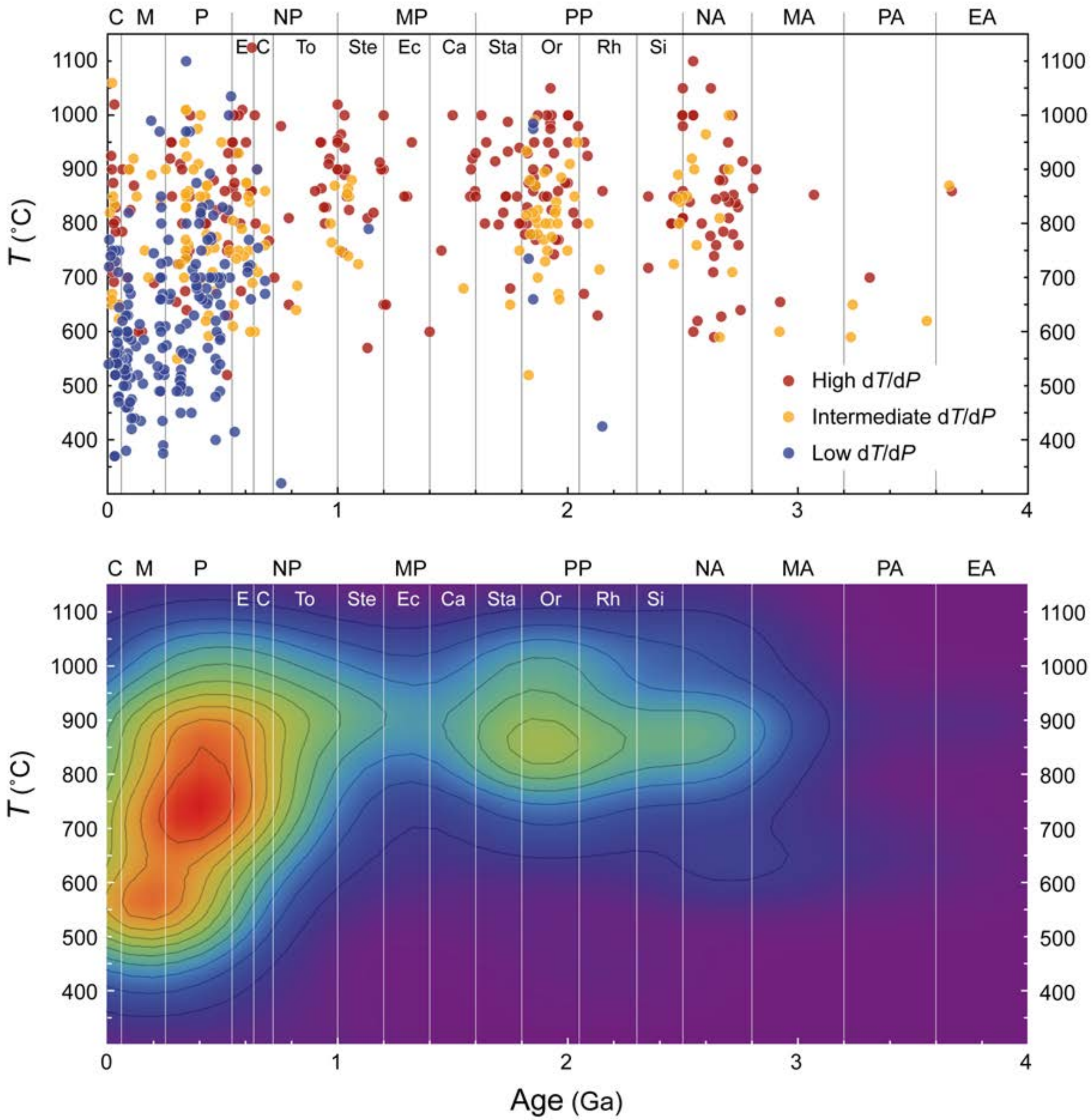
The metamorphic rock record



✧ All data (b), data <850 Ma in age (c) and data ≥850 Ma in age (d), contoured for density.

NB. The 'normal' geotherm only applies to the contemporary tectonic regime!

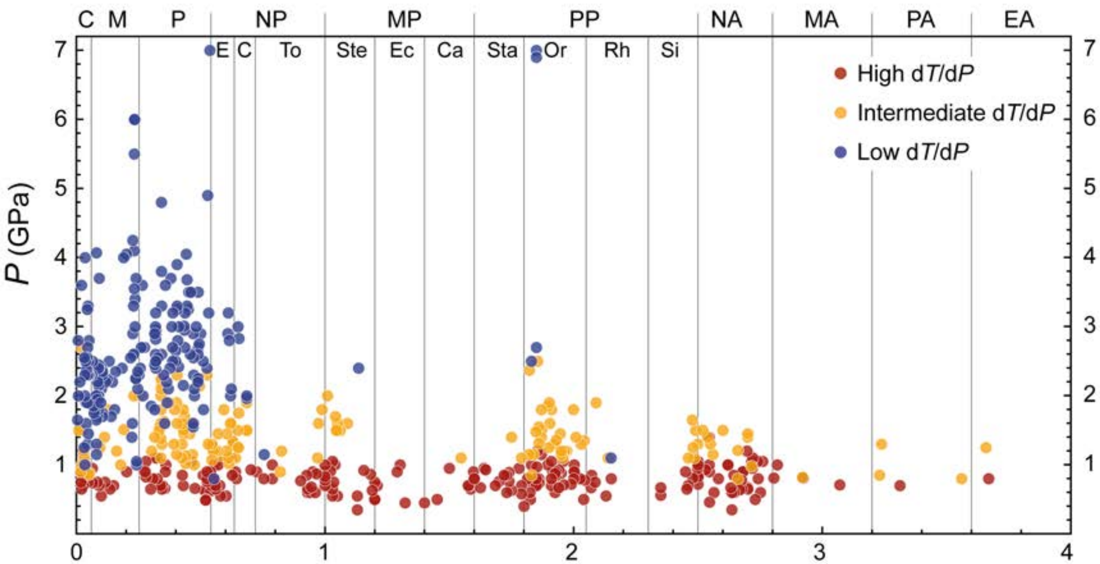
Secular change in temperature



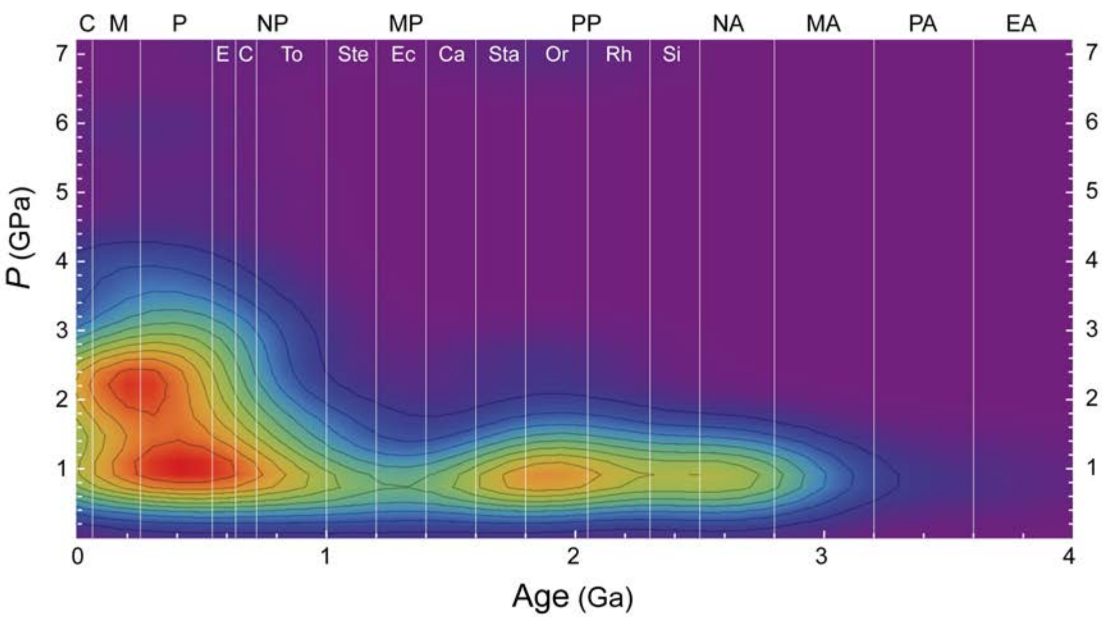
Metamorphic temperature for 564 localities grouped by type plotted against age (high dT/dP in red, intermediate dT/dP in orange and low dT/dP in blue).

All data contoured for density.

Secular change in pressure

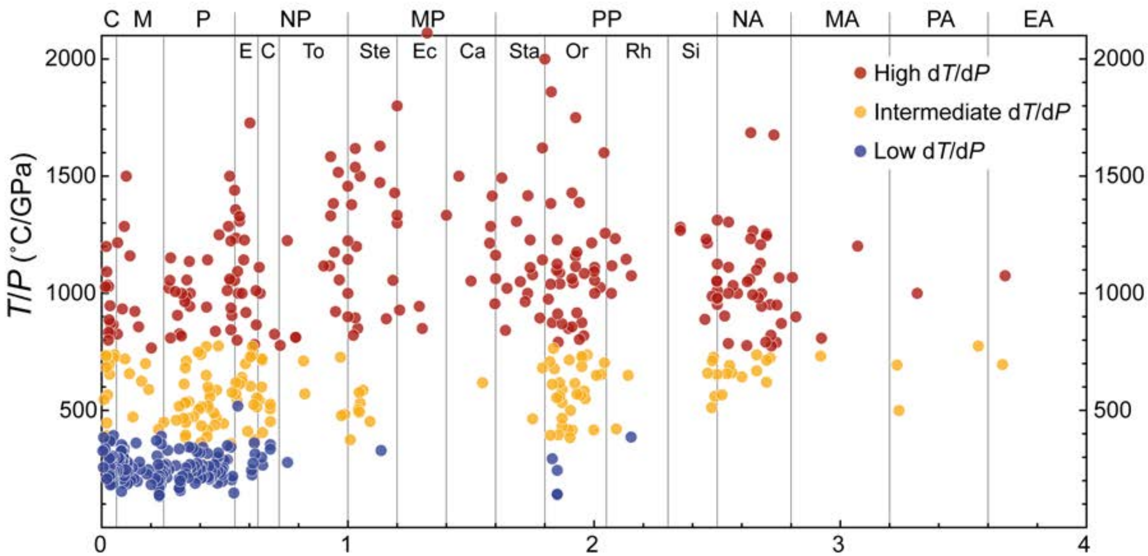


Metamorphic pressure for 564 localities grouped by type plotted against age (high dT/dP in red, intermediate dT/dP in orange and low dT/dP in blue).

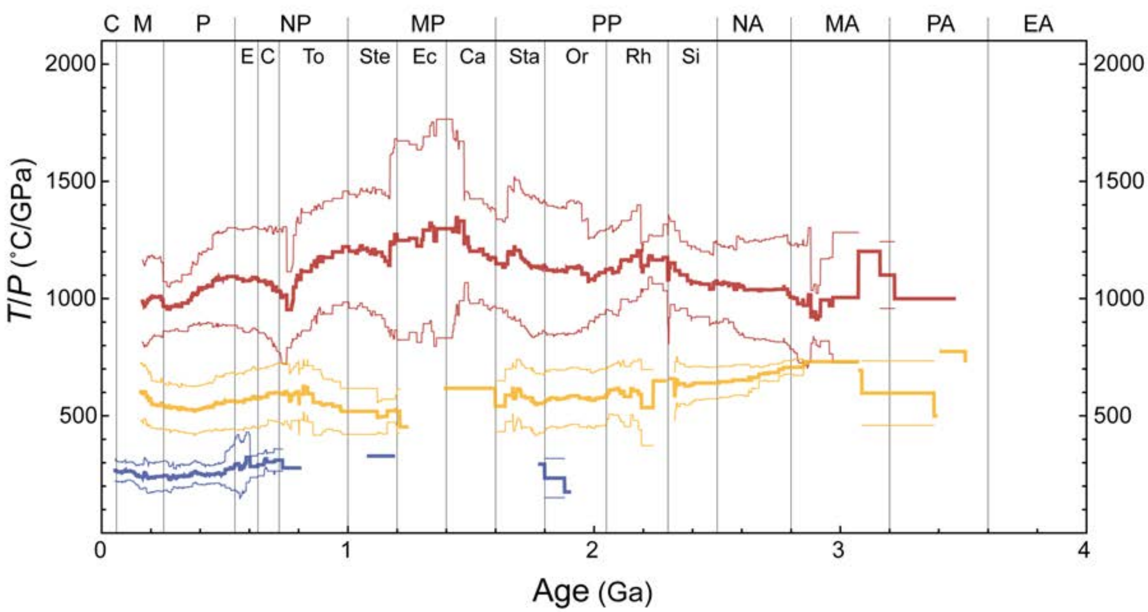


All data contoured for density.

Secular change in T/P

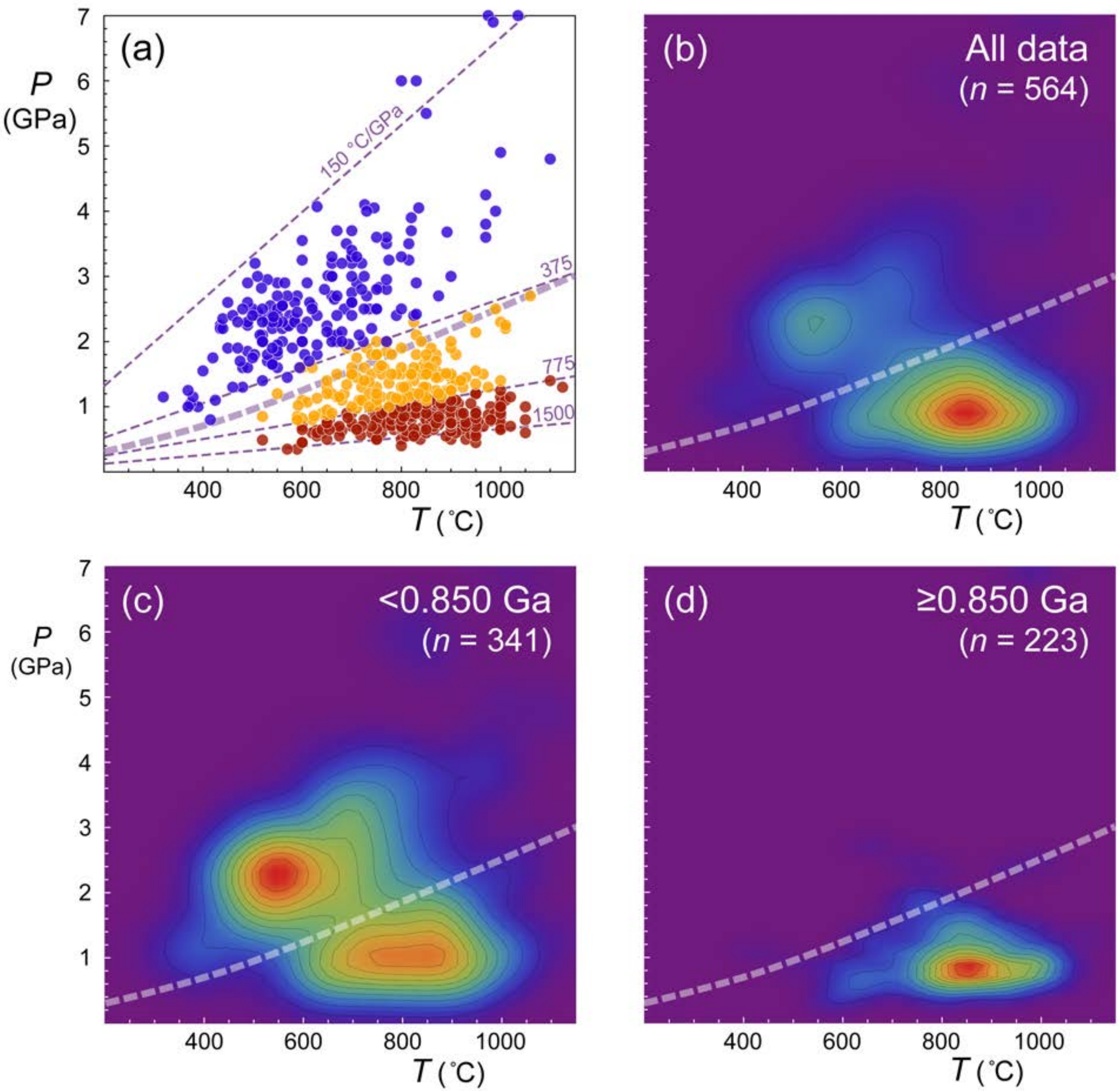


Apparent thermal gradient (T/P) for 564 localities grouped by type of metamorphism plotted against age (high dT/dP in red, intermediate dT/dP in orange and low dT/dP in blue).



Moving means with 1 σ uncertainty (calculated every 1 Myr within a moving 300 Myr window, except for low dT/dP metamorphism calculated every 1 Myr within a moving 100 Myr window).

Why is T/P a more useful parameter than T or P?

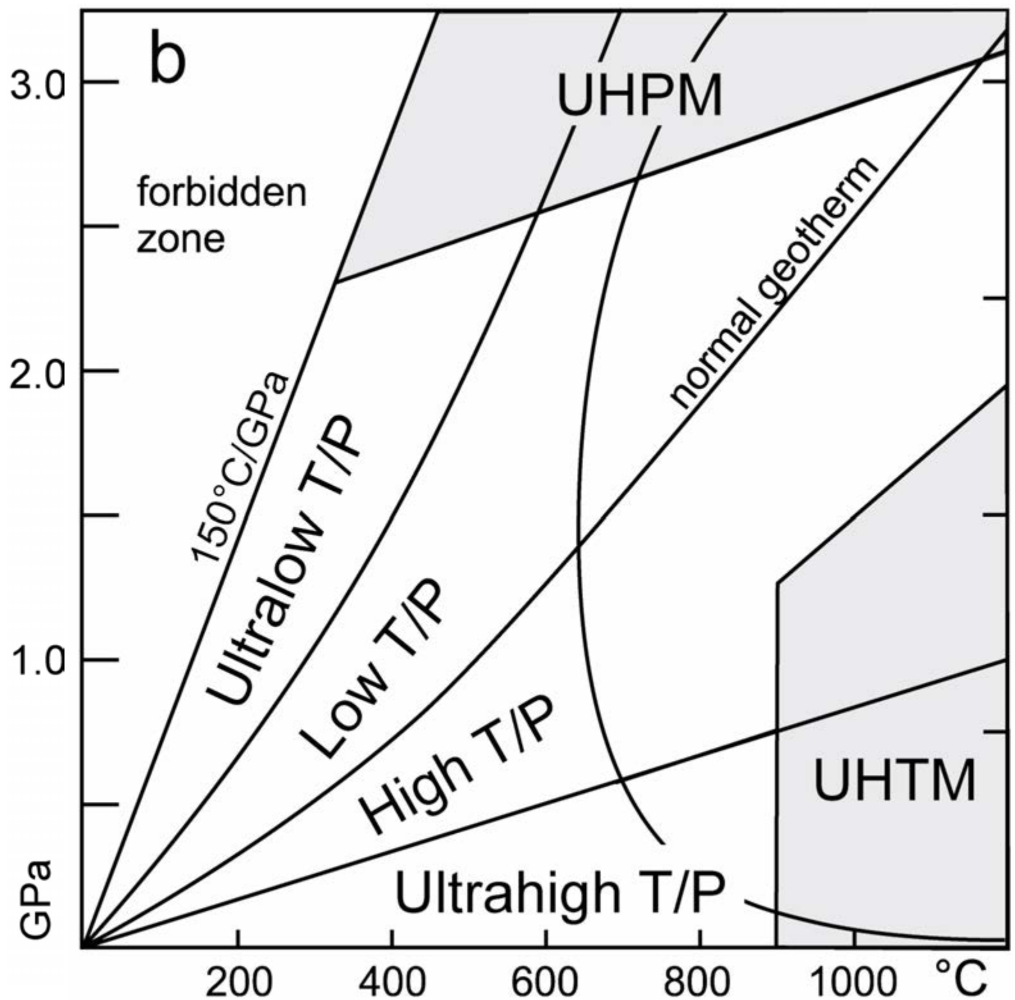


On contemporary Earth, each type of metamorphism is associated with a particular plate tectonic setting.

- low dT/dP metamorphism (blueschists/LT eclogites, and UHP (Coe/Dia) eclogites) – **subduction (accretionary orogens and sutures in collisional orogens)**
- intermediate dT/dP metamorphism (HP granulites and MT/HT eclogites) – **mountain belts (collisional orogens)**
- high dT/dP metamorphism (migmatites, granulites and UHT granulites) – **orogenic hinterlands** (**plateaus** (high HPE/low erosion rate; CW P–T paths)/**backarcs** (thermal decay; CCW P–T paths))

Care should be exercised in extrapolating these relationships back in time.

UHPM and UHTM



<u>Notwithstanding</u>

1. the benefit to petrology of highlighting UHPM and UHTM during the past 35 years,

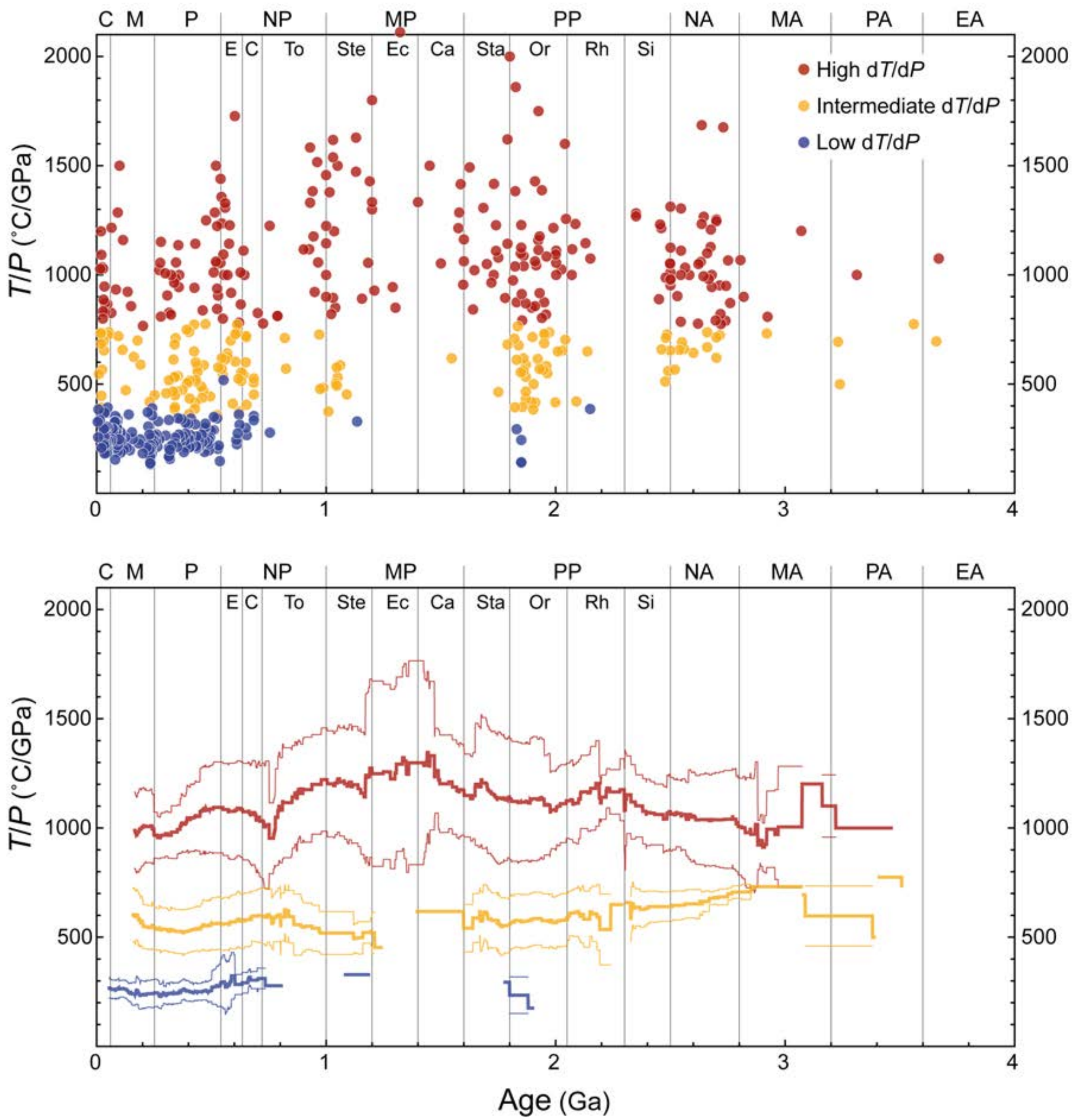
2. the simplicity of a first-order phase transition that makes the presence of one phase, whatever its grain size or abundance, an immediate indicator of minimum pressure attained, and

3. the importance of producing Opx + Sill at the expense of Bt in pelites.

<u>We may ask</u>

1. are those pressures just greater than Qz → Coe significant compared with those just below, and

2. is < or > 900 °C a useful discriminant?

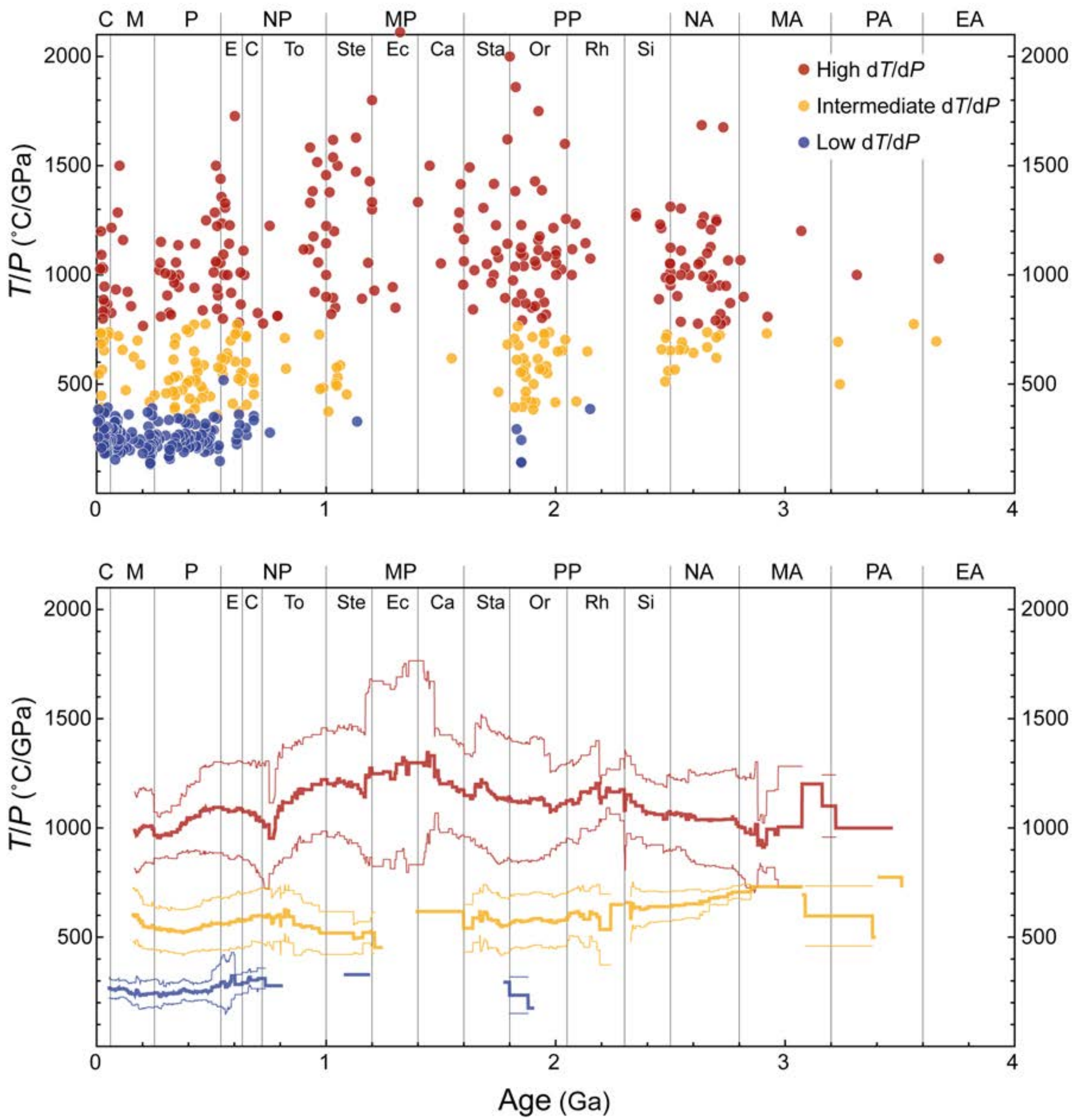


Is using T/P more useful using than T or P?

✧ Ends the arbitrary separation of UHPM and UHTM from the rest of regional metamorphism.

✧ Eliminates the mindless chase for the highest P or T ("the principle of maximum astonishment" R. Powell).

An illustration



Napier Complex, Antarctica

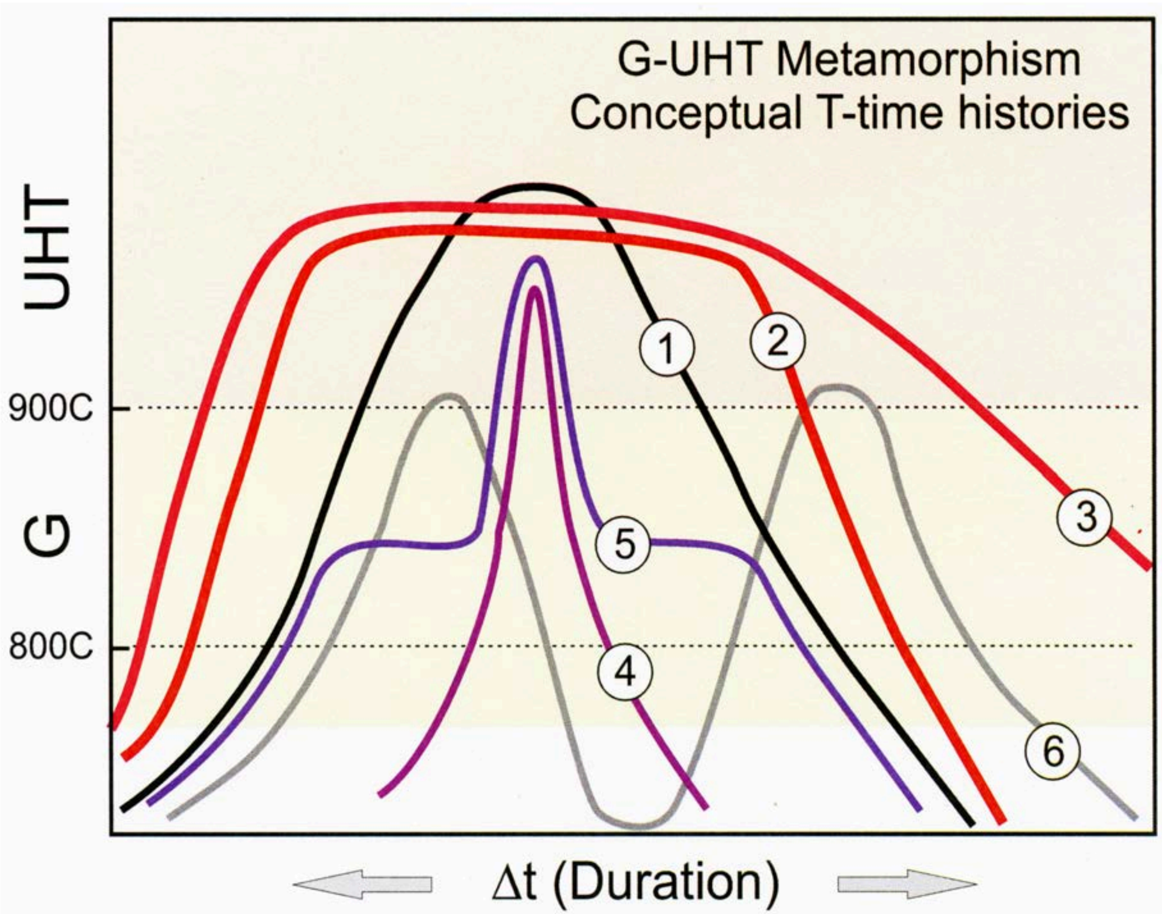
T >1100 °C, maybe as much as 1150 °C, at P of 1.1 GPa, with a CW path, yields dT/dP of >1000 °C/GPa (e.g. Mitchell & Harley, 2017, Lithos)

Eastern Ghats belt, India

T ≥1000 °C at P of 0.7 GPa and T ~900 °C at P of 0.8 GPa, with a CCW path, yield dT/dP of >1400/1125 °C/GPa (e.g. Korhonen et al., 2015, EPSL)

Both record high dT/dP metamorphism, but it's not about which is more extreme—each is extreme, but they are different in terms of tectonic setting and questions posed!

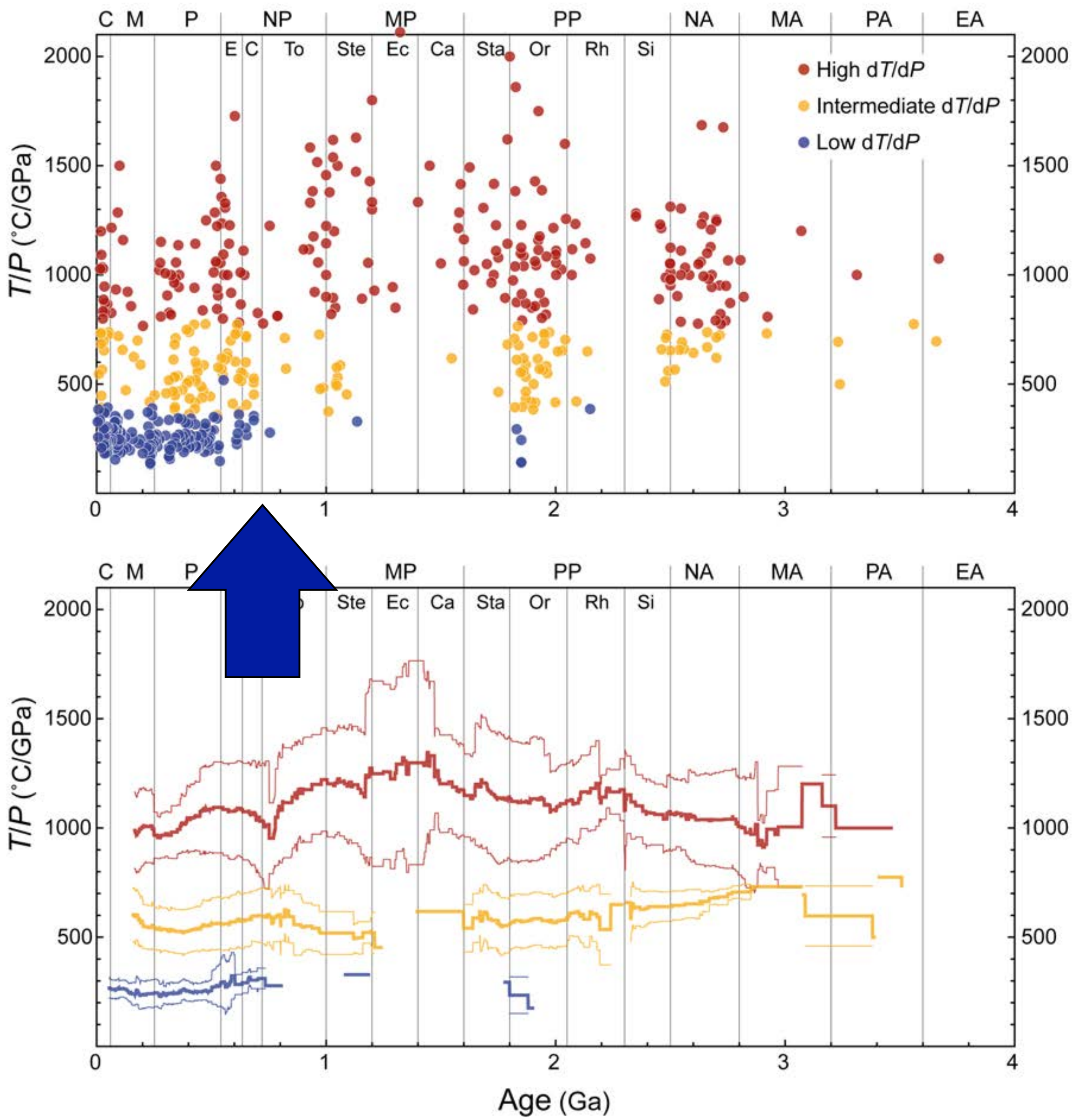
What about Δt_{900} and Δt_{800}?



Introduced by Harley (2016, JMPS) to characterize the thermal history of high dT/dP (granulite and UHT) metamorphism, where the duration of metamorphism may be defined as either Δt_{900} or Δt_{800} (which Harley termed Δt_{UHT} or $\Delta t_{granulite}$) or with respect to any temperature of interest.

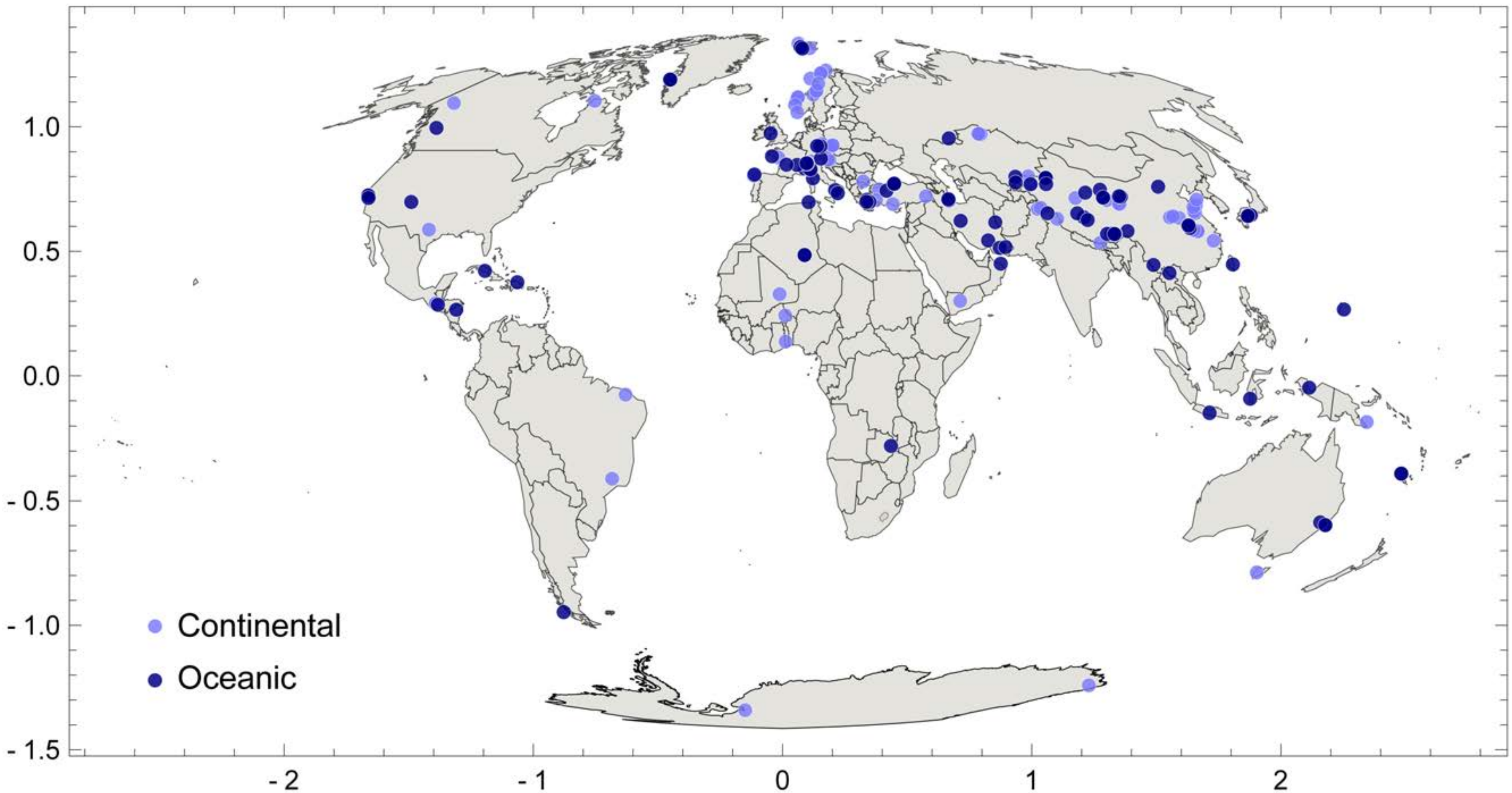
The length of time rocks reside above a particular temperature (Δt) remains a useful parameter

Key changes in the metamorphic record



Dramatic change during the Neoproterozoic: The widespread appearance of low dT/dP metamorphism (blueschists and low T eclogites (Coe/Dia-bearing)).

Distribution of low dT/dP metamorphic rocks

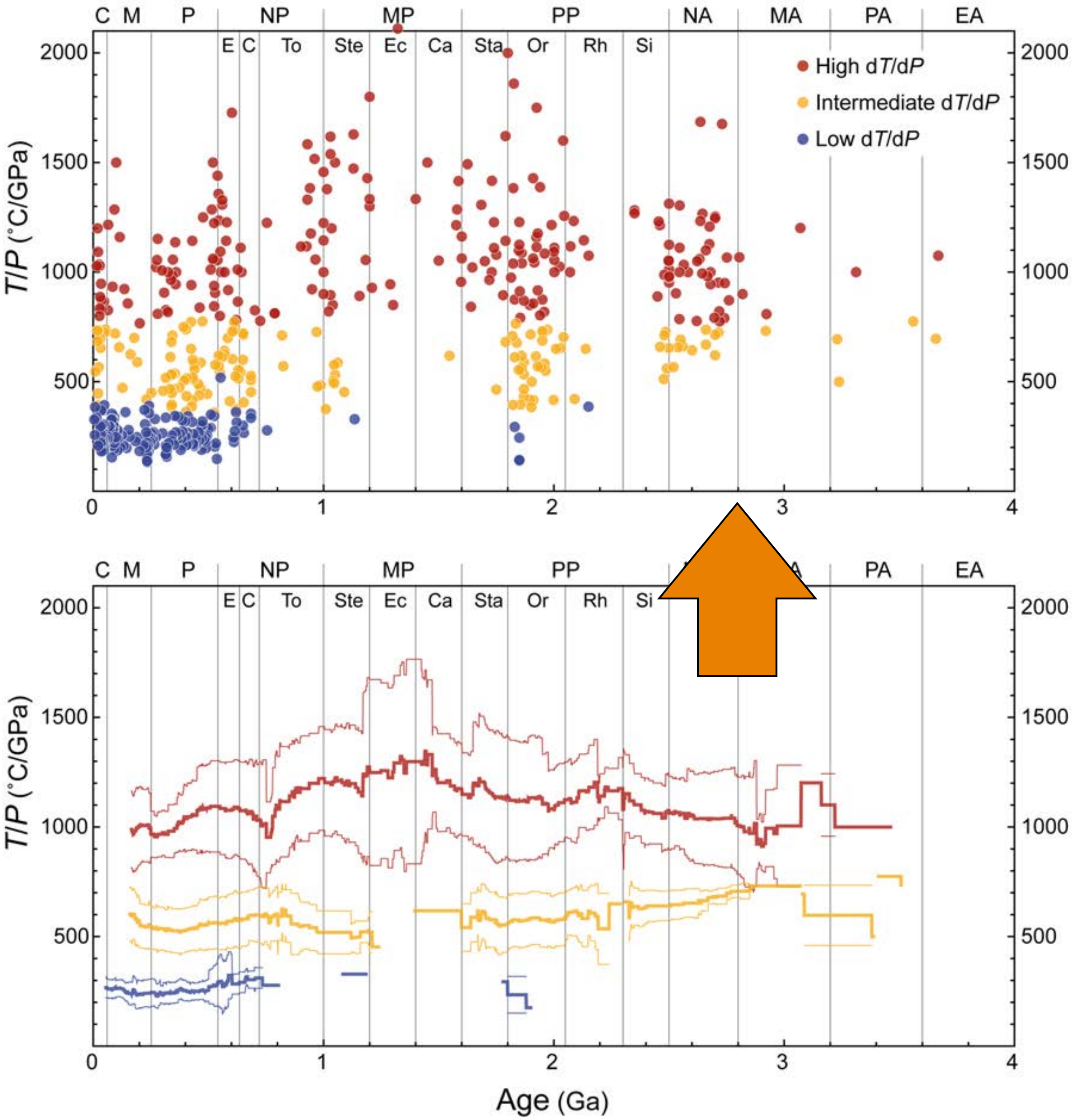


✧ **Low dT/dP metamorphism occurs mostly in sutures associated with late Neoproterozoic and Phanerozoic collisional orogens.**

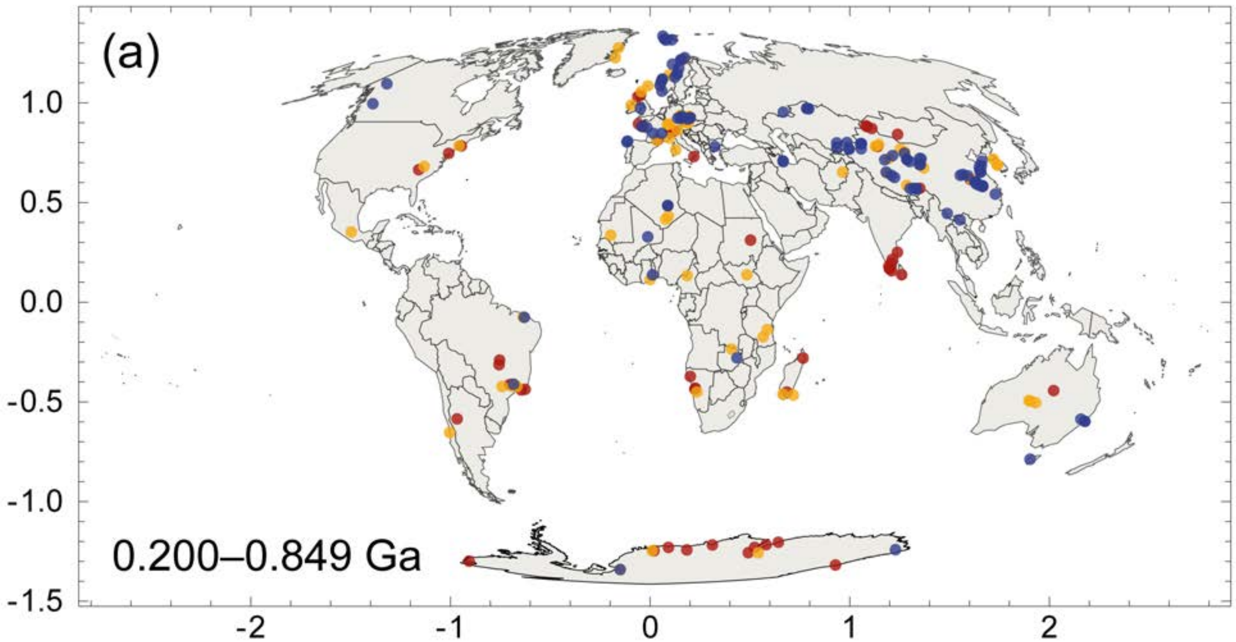
✧ **Records a change to deeper slab breakoff and colder collisional orogenesis, and a widespread change in tectonic style to terrane tectonics.**

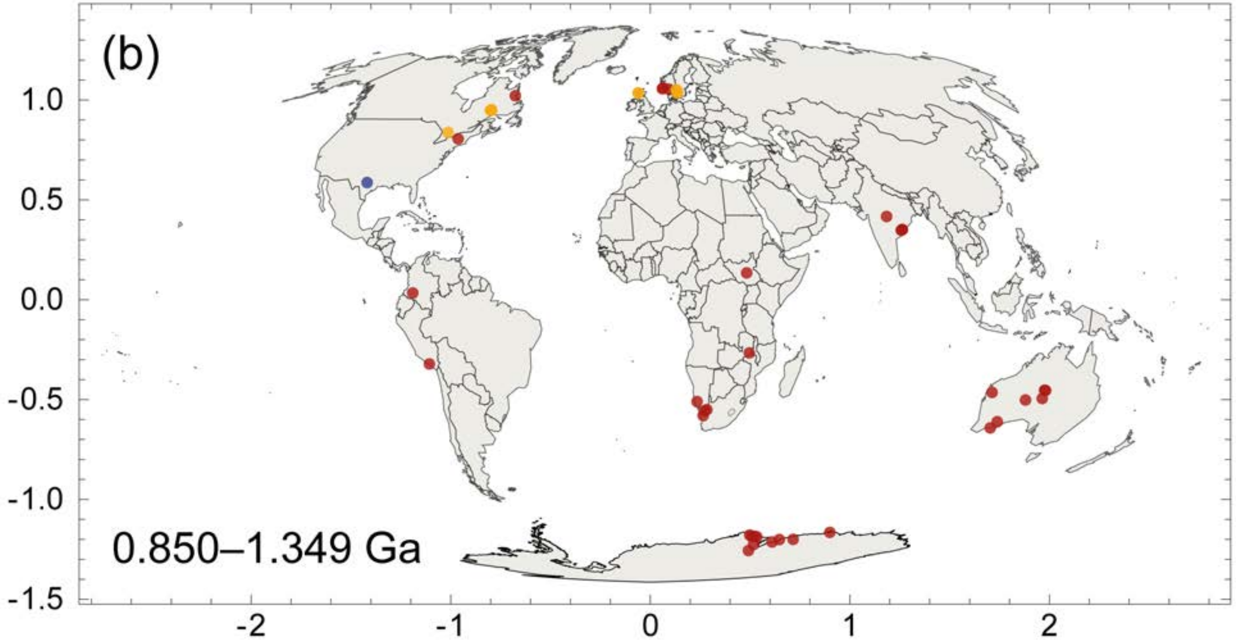
✧ **Implies a different style of collisional orogenesis prior to the Neoproterozoic.**

Key changes in the metamorphic record

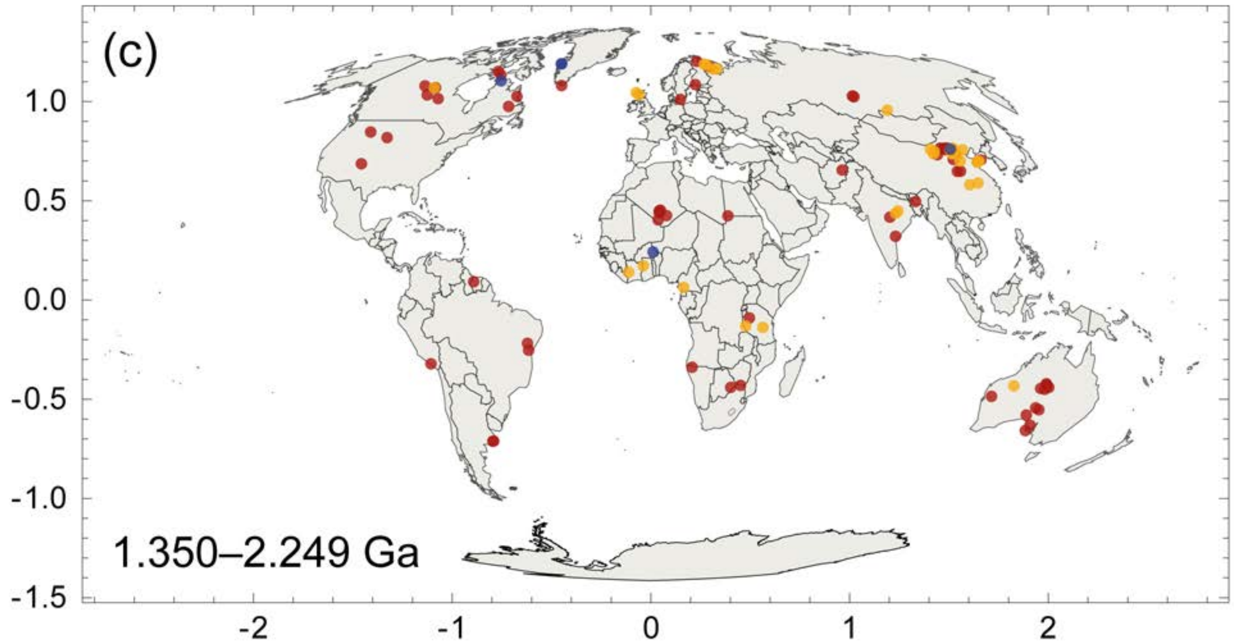


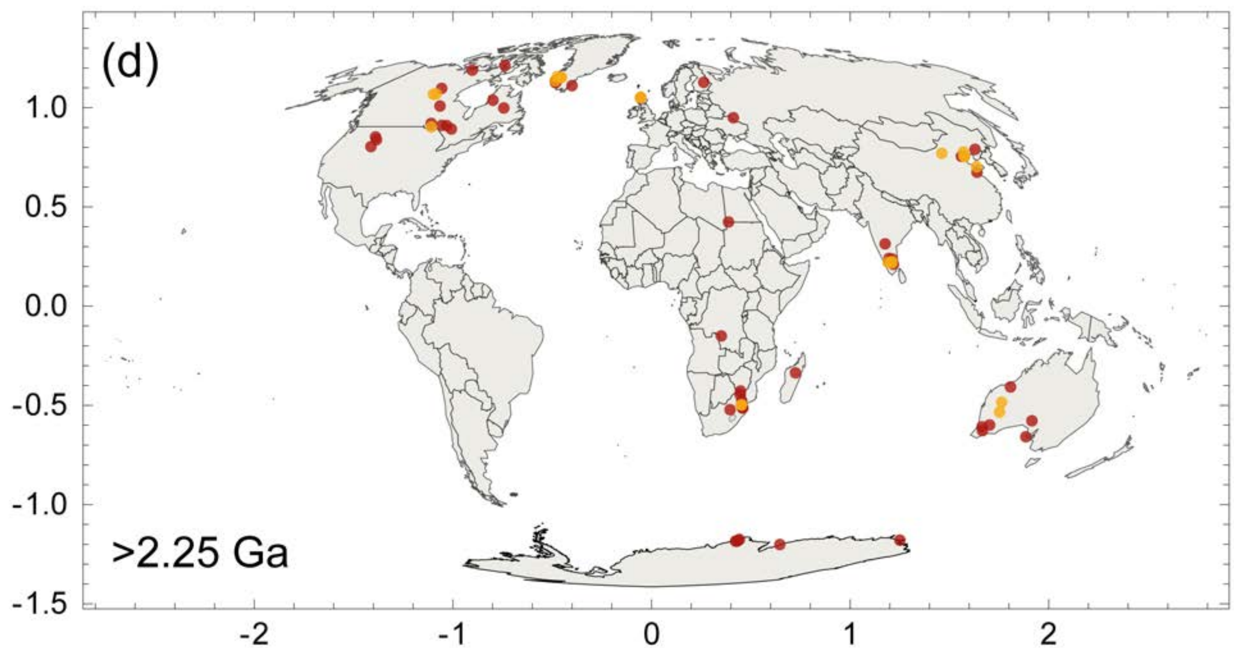
Significant change at the beginning of the Neoarchean: the global appearance of paired metamorphism and cyclicity.





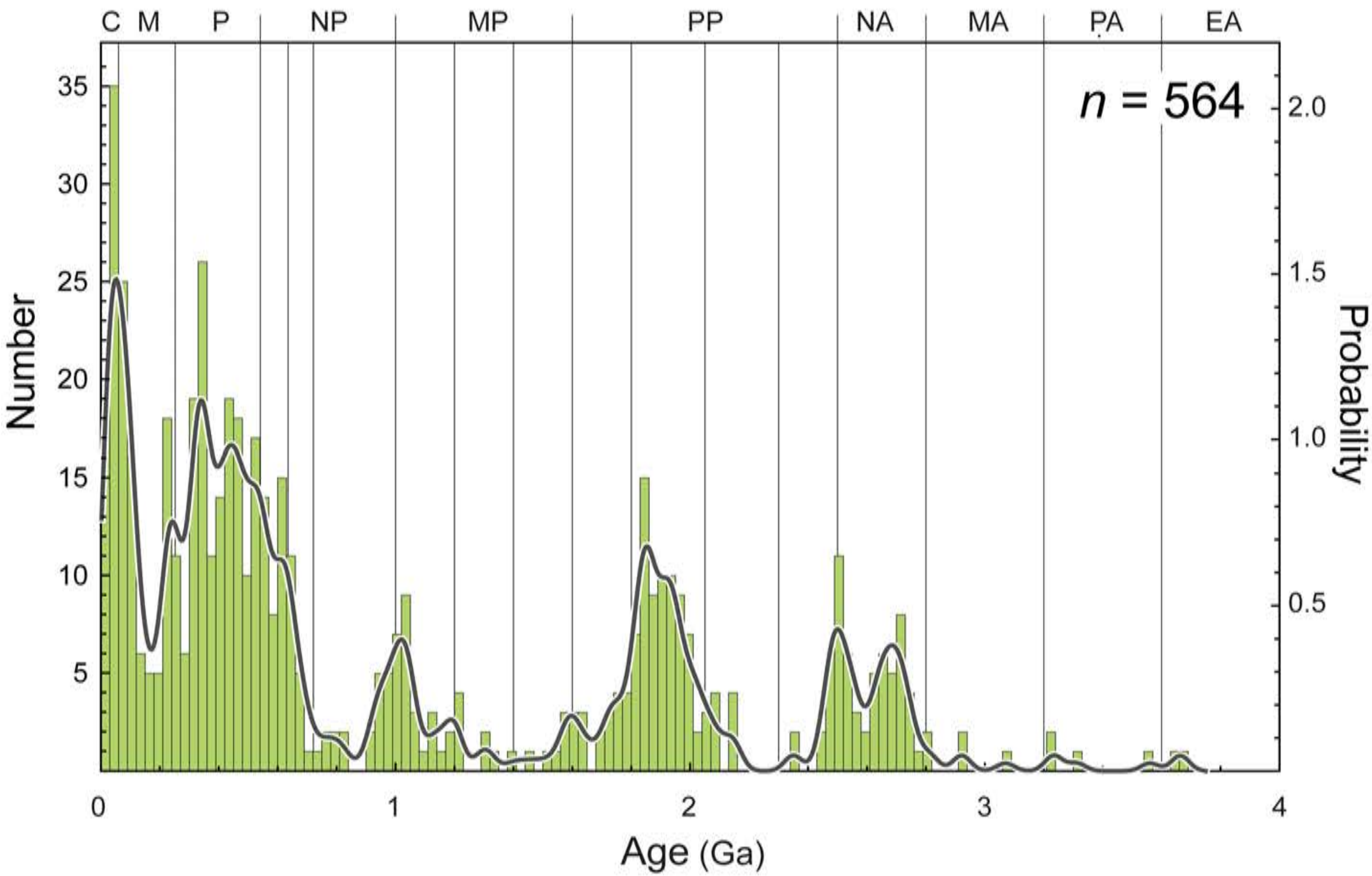
Distribution of low, intermediate and high dT/dP metamorphic rocks



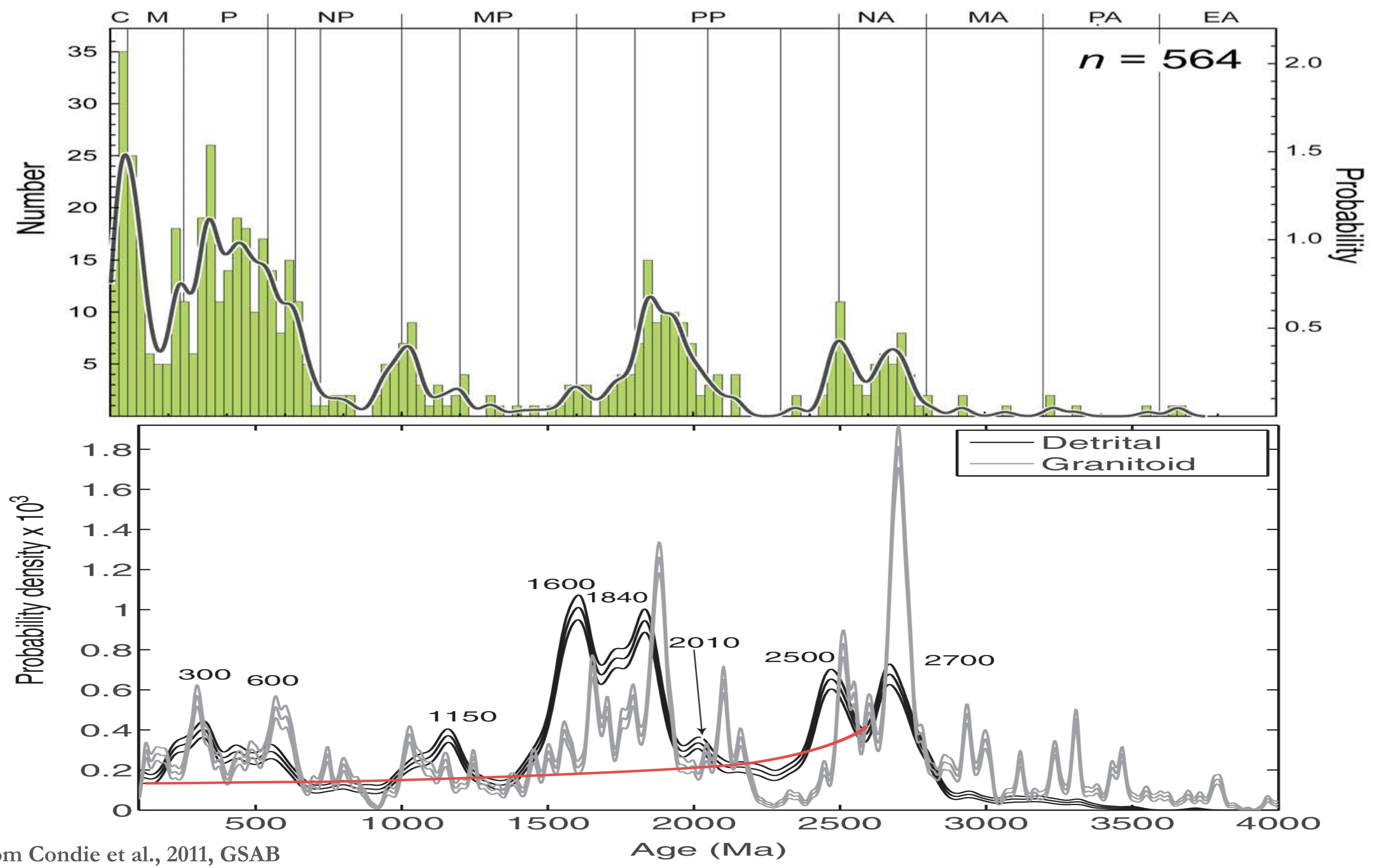


Distribution of low, intermediate and high dT/dP metamorphic rocks

<u>Time's cycle</u>: Cyclicity is suggested by the distribution of ages of metamorphism,

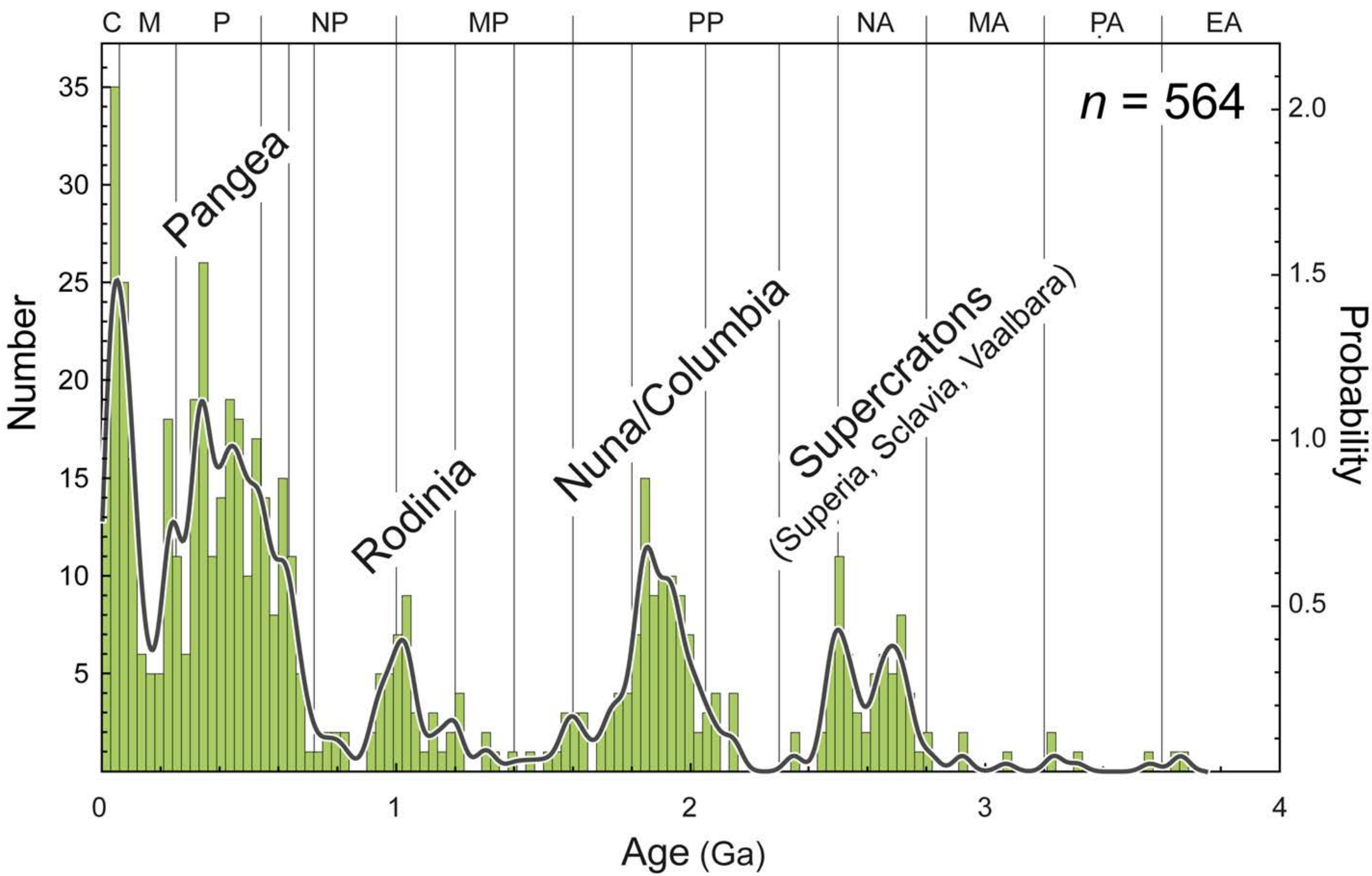


which is similar to the distribution of ages of magmatic crustal rocks.



From Condie et al., 2011, GSAB

These distributions are commonly related to the supercontinent cycle



Main features of the transition from the Neoarchean to the Paleoproterozoic Era

Observations

1. Appearance of paired metamorphism (essentially HP granulites and medium/high temperature eclogites *vs* common granulites) recording two contrasting tectono-thermal environments
2. Appearance of large volume of granitoids and voluminous detrital zircons
3. Evidence of cyclicity in metamorphic and magmatic rock records

Inferences

1. Transition to some form of (global? continuous?) subduction
2. Development of 'continental' margin arcs
3. Break-up of supercratons and formation of the supercontinent Columbia

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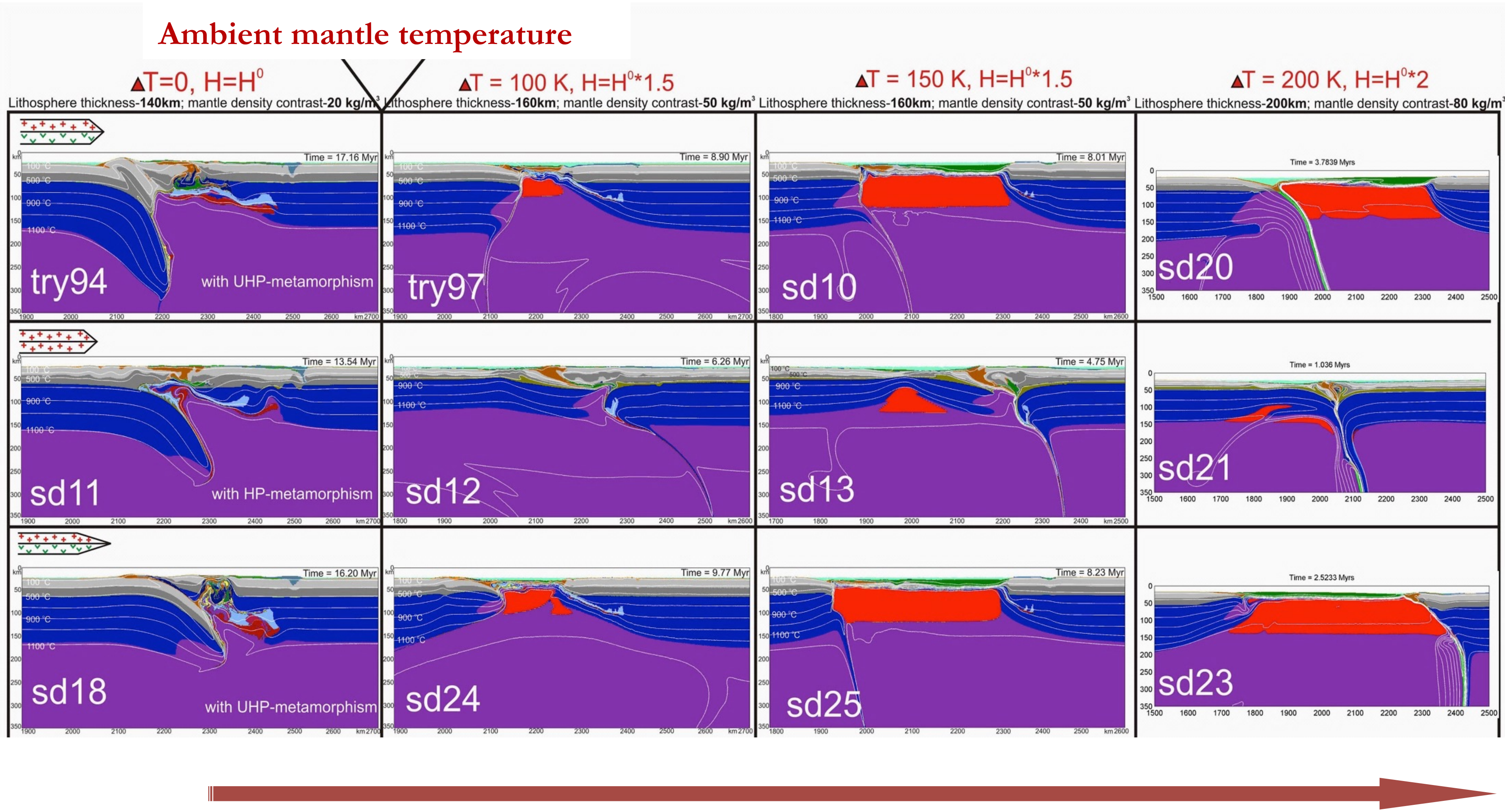
Interpretation: transition to a (global?) network of mobile belts dividing the lithosphere into plates; cyclicity reflects preservation related to collisional orogenesis and, in the conventional interpretation, the so-called 'supercontinent cycle'.

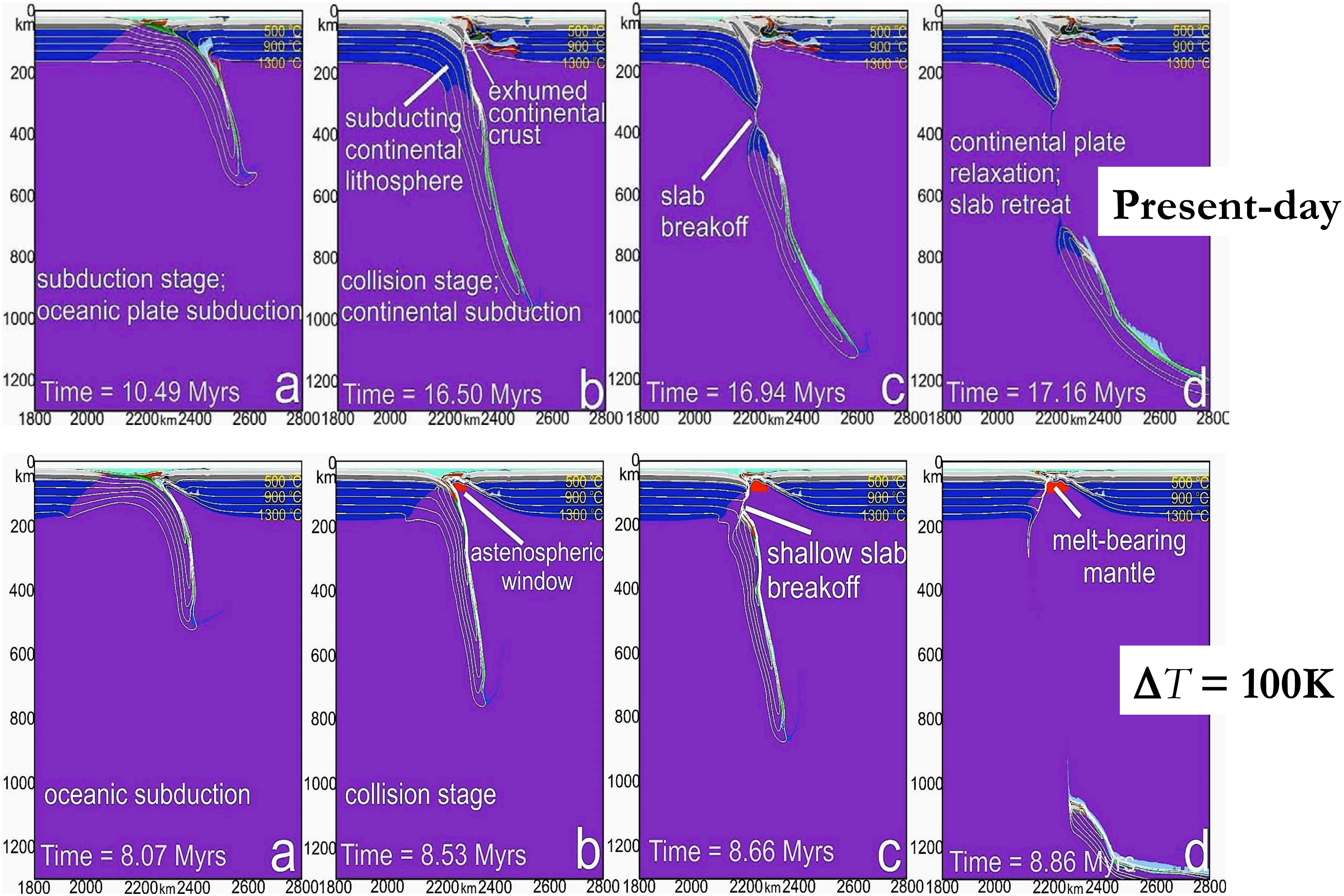
Implications for granulites: Insight from numerical models



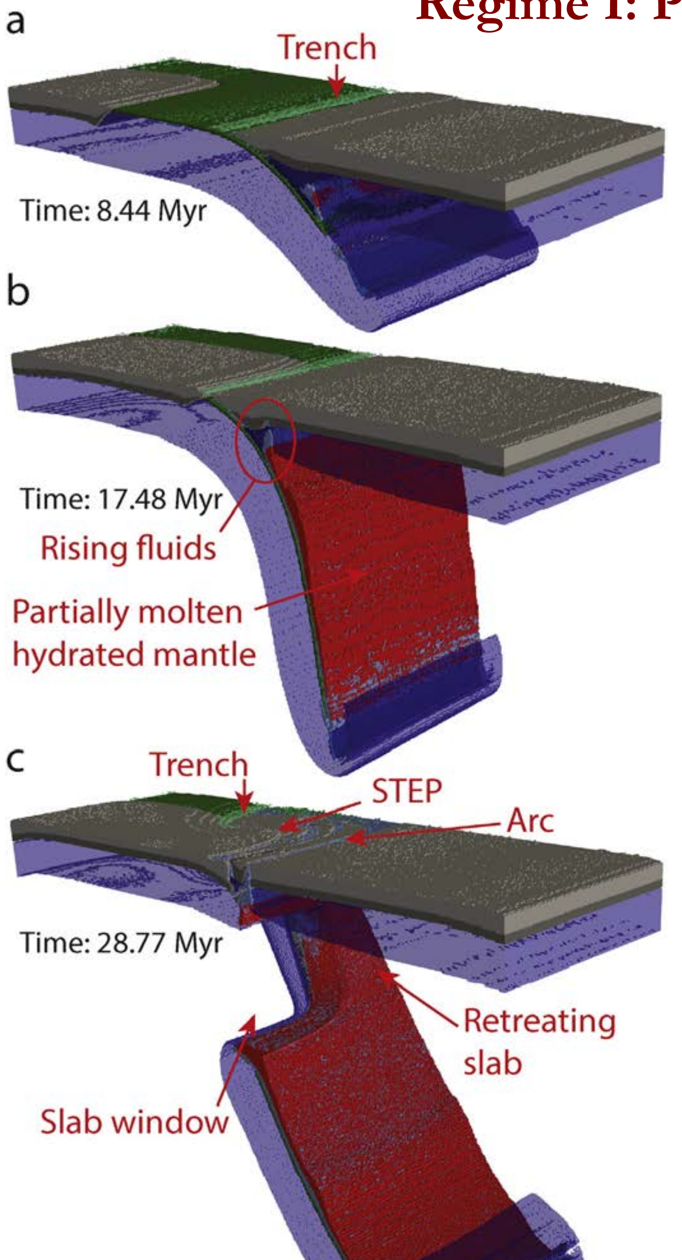
Conditions appropriate to the Proterozoic

Sizova et al. (2014, GR)

At higher mantle T_P, slab breakoff occurs at shallow depth

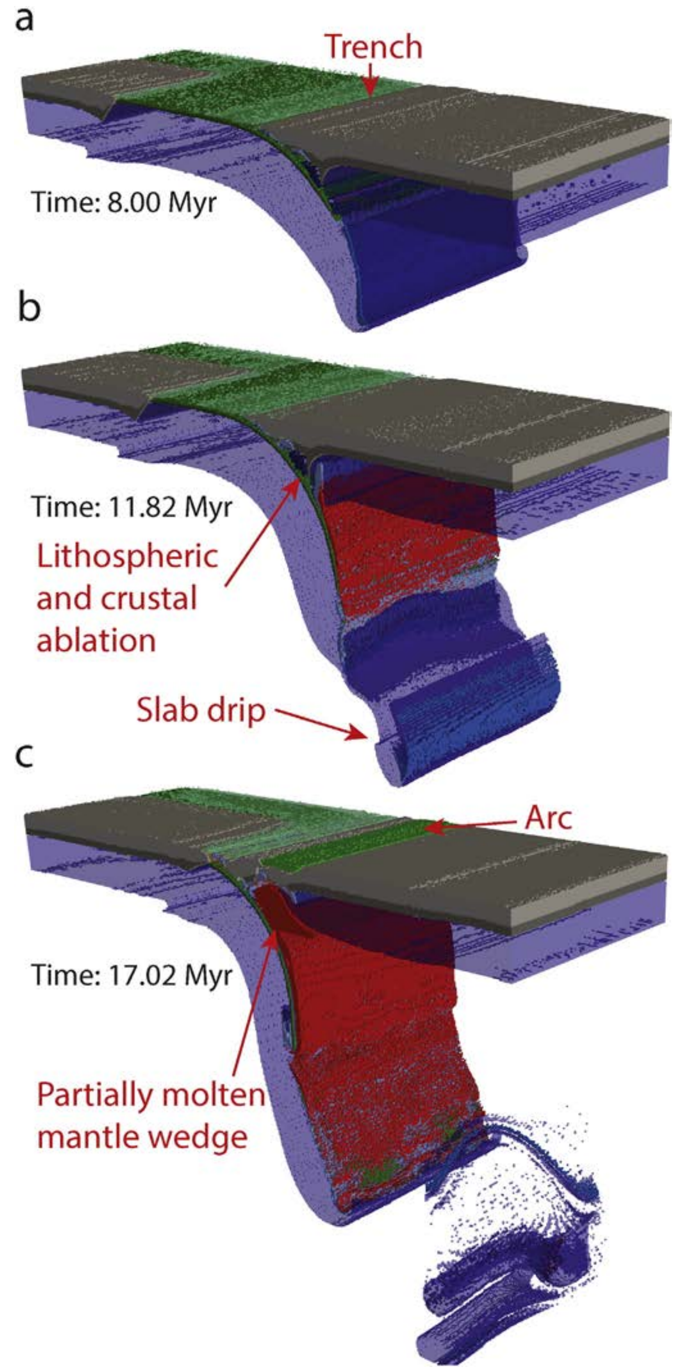


Regime I: Present day subduction ($\Delta T_P \leq 50°C$)

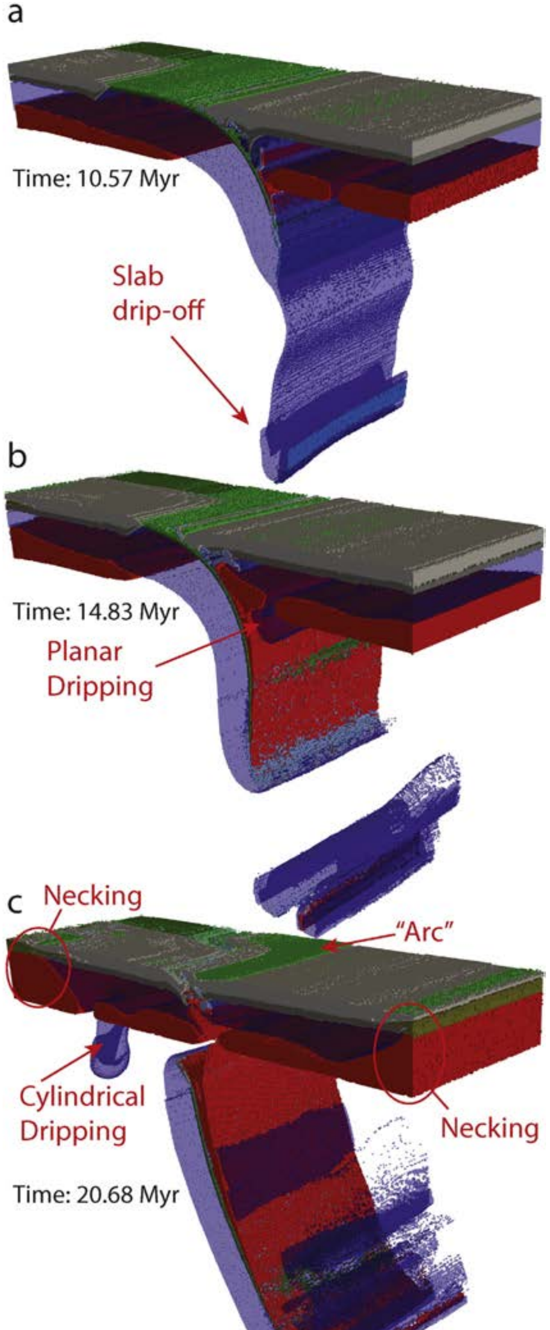


Regime II: Dripping subduction ($\Delta T_P = 50–150°C$)

Operates similarly to present day subduction, but with clear indications of plate weakening, e.g. buckling of the subducting plate, start of delamination of lower crust in the overriding plate, increasingly earlier drip off from the slab tip, necking of the slab and larger volumes of partially molten asthenosphere. Drip-off from the subducting slab occurs repeatedly.

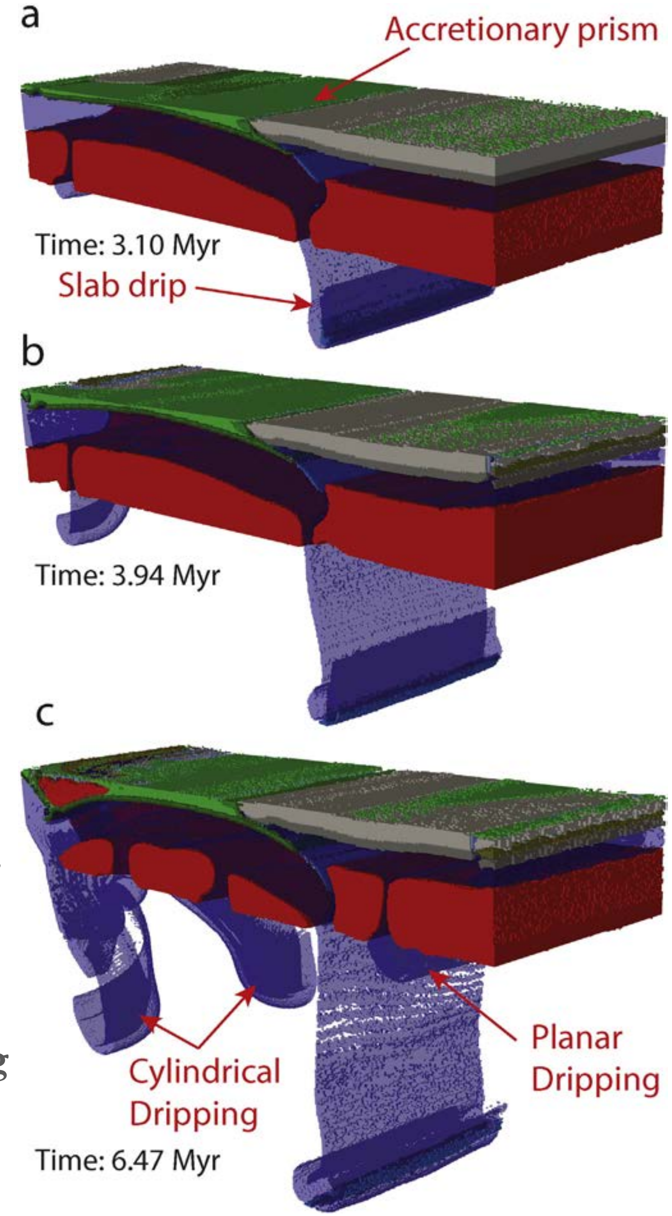


Fischer and Gerya (2016, GR)



Regime III: Transitional mode (ΔT_P = 150–200°C)

Shows features of both subduction and plume-lid tectonics. In this mode, the slab tip starts to weaken and neck off very rapidly after subduction initiation, although not fast enough to terminate the formation of a slab.



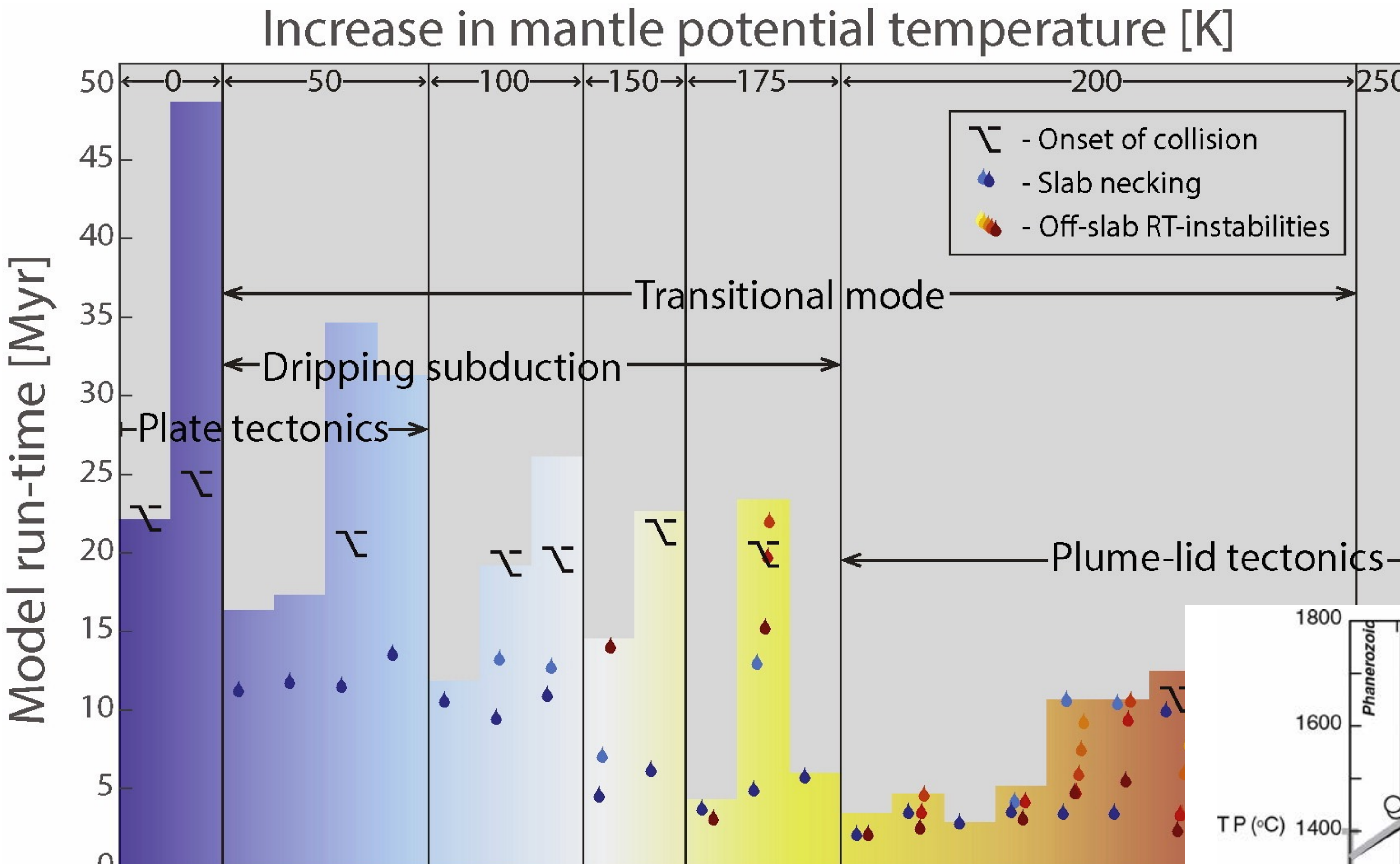
Regime IV: Plume-lid tectonics ($\Delta T_P \geq$ 200°C)

Subduction is no longer observed. Instead a new tectonic style emerges which is strongly dominated by upwelling/ downwelling, intensely convecting mantle which interacts with the internally deforming (non-subducting) lithospheric lid.

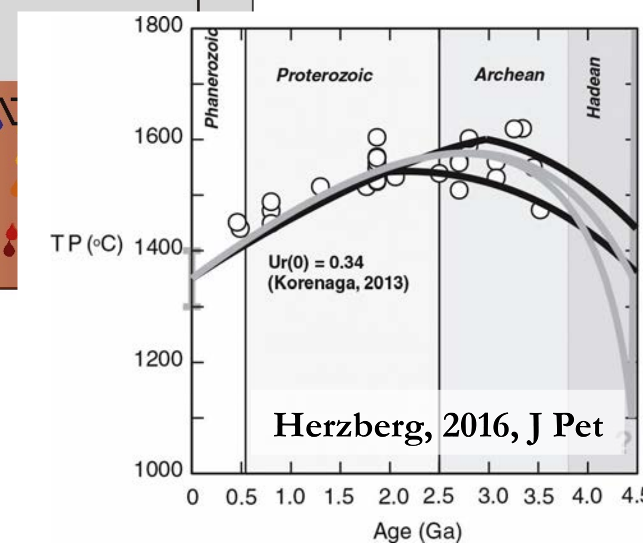
Intense volcanism is no longer constrained to volcanic arcs but forms extensive belts of mantle-derived mafic (basaltic) crust. Oceanic and continental crust grow to similar thickness hindering subduction.

Fischer and Gerya (2016, GR)

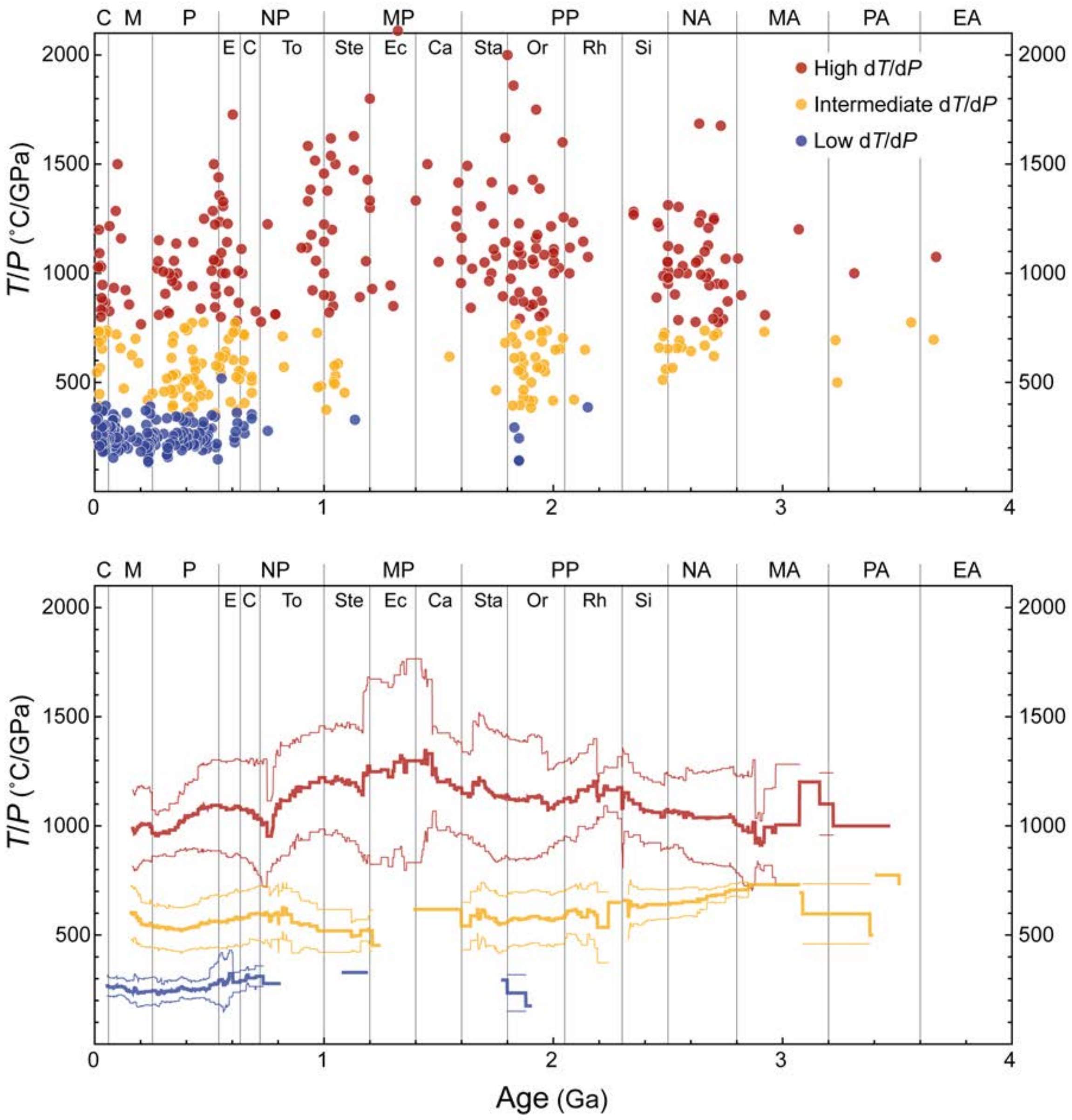
An interpretation that (dripping) subduction was widespread by the Neoarchean is consistent with the metamorphic and magmatic records



Summary of regimes and events for 25 experiments; height of bar shows run-time. Black symbol at *c*. 20–25 Myr indicates continental collision. Blue drips signify necking or dripping from the slab tip, whereas yellow/red drips signify dripping away from the slab.



Tectonic settings for granulite metamorphism during the Precambrian



Intermediate dT/dP metamorphism (HP granulites and associated MT/HT eclogites) records plate convergence and 'hot' collisional orogenesis

High dT/dP metamorphism(common granulites) records overriding plate extension

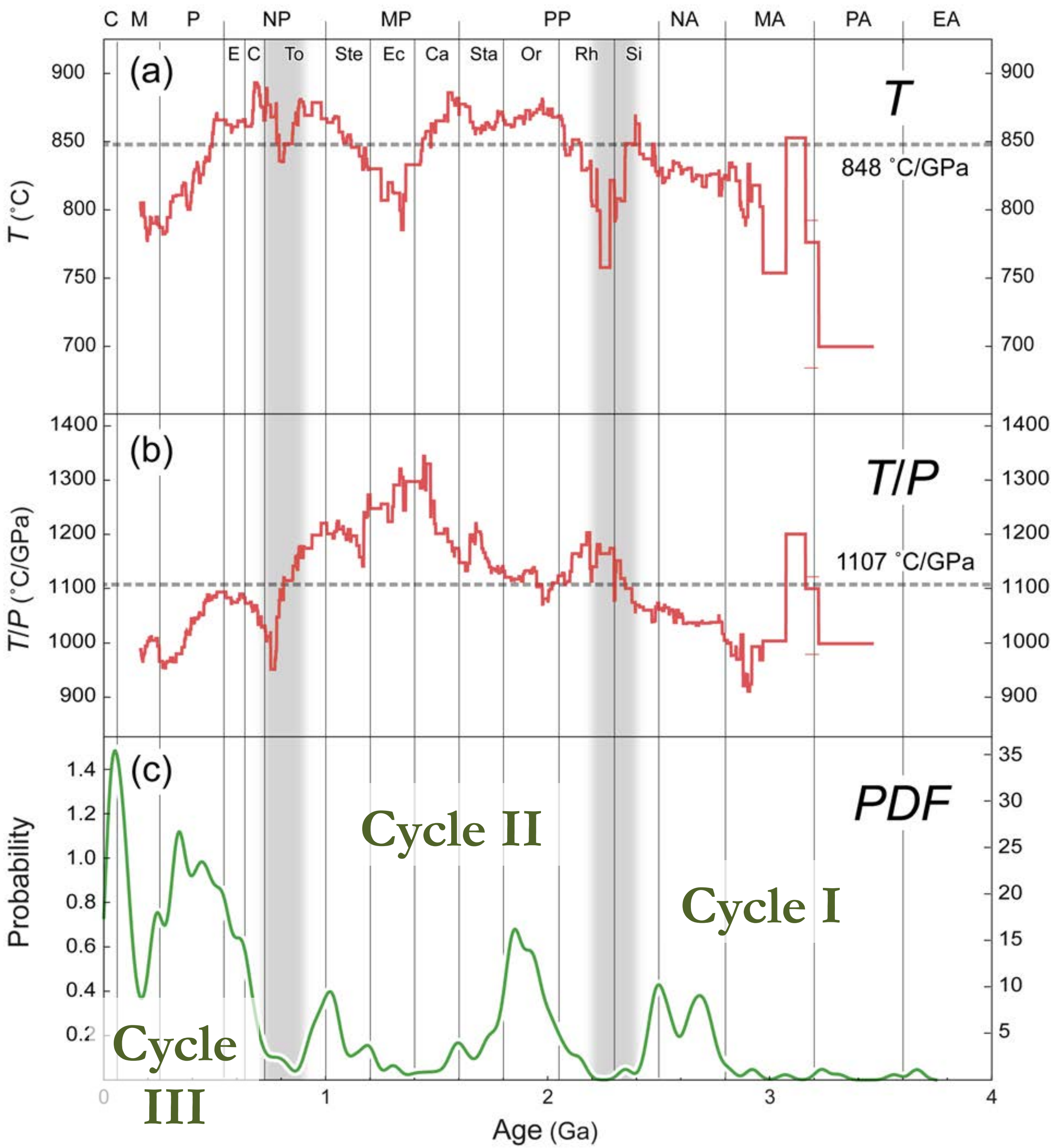
Different styles of Proterozoic metamorphic belt: examples

1. Some Proterozoic orogens record high dT/dP metamorphism with heating before thickening (CCW *P–T–t* paths), followed by close-to-isobaric cooling; these orogens are similar to truncated hot collision in the numerical models of Sizova et al. (2014), with renewed convergence immediately following extension, e.g.,
   - ✧ the late Mesoproterozoic–early Neoproterozoic Eastern Ghats Province (EGP)–Rayner Province (RP) of India and East Antarctica.

2. Other Proterozoic orogens are characterized by high dT/dP metamorphism with CW looping *P–T–t* paths and extensive granite magmatism sourced from supracrustal and plutonic rocks (syn-orogenic) and SCLM (post-orogenic); these orogens are similar to two-sided hot collision in the numerical models of Sizova et al. (2014), e.g.,
   - ✧ the Paleoproterozoic Svecofennides of southern Finland, and
   - ✧ the late Mesoproterozoic Namaqua orogen in Namibia.

3. Finally, there are Proterozoic orogens where the collision style was similar to large Phanerozoic orogens, but without generation of extreme low dT/dP conditions (UHPM), perhaps identifying locations where contemporary mantle was cooler, e.g.,
   - ✧ the Paleoproterozoic Trans–Hudson orogen of North America, and
   - ✧ the Mesoproterozoic Grenville orogen of North America.

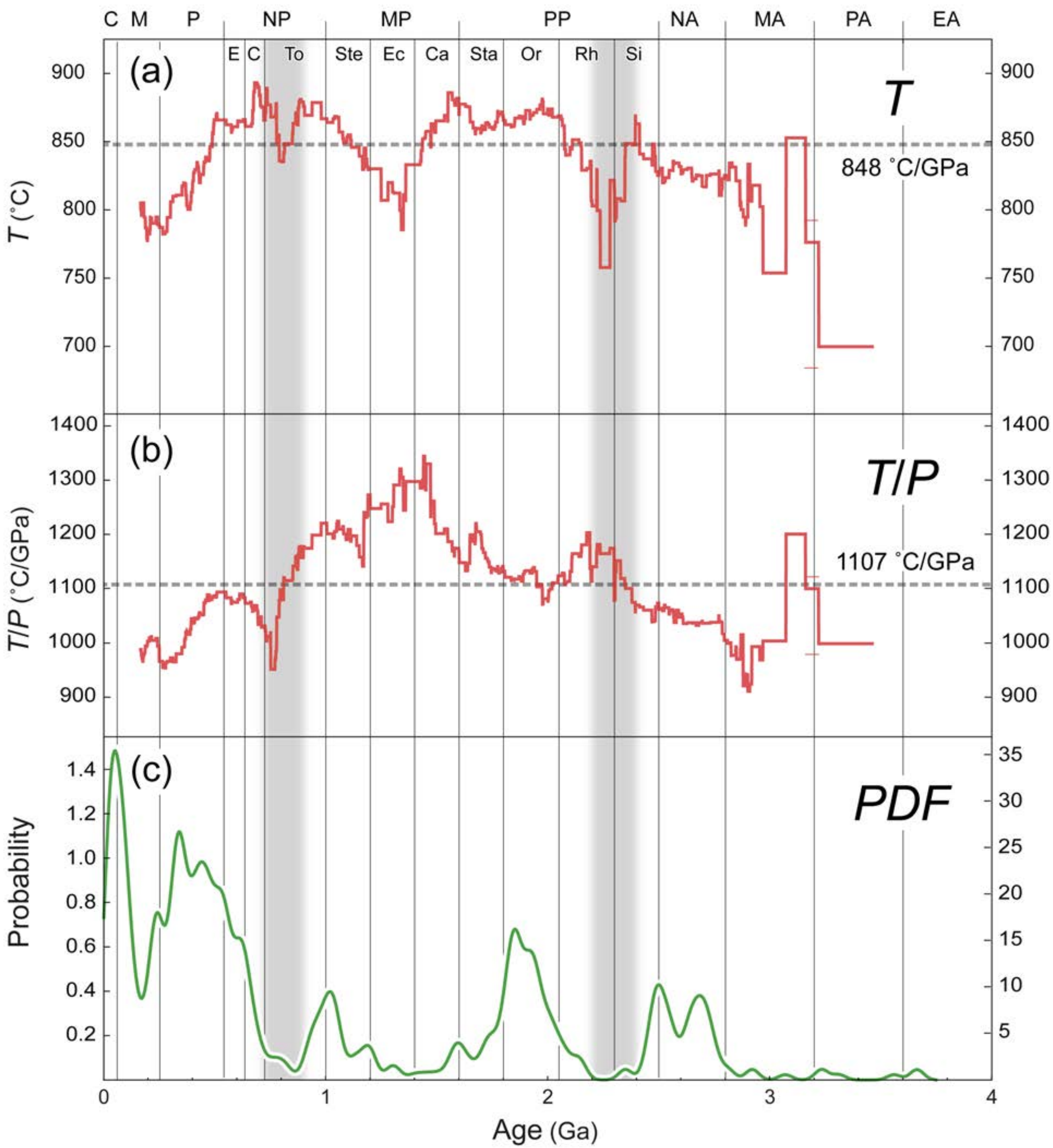
Back to time's cycle



Using the moving and arithmetic means of T and T/P, and the probability density function (PDF) of age for all 564 localities, it is clear that since *c.* 3.0 Ga cyclic variations in the heat budget of the crust have been superimposed on secular cooling identifying 3 (or 4) geodynamic cycles.

Cf. Brown & Johnson (2018, Amer. Mineral.)

Cycle I

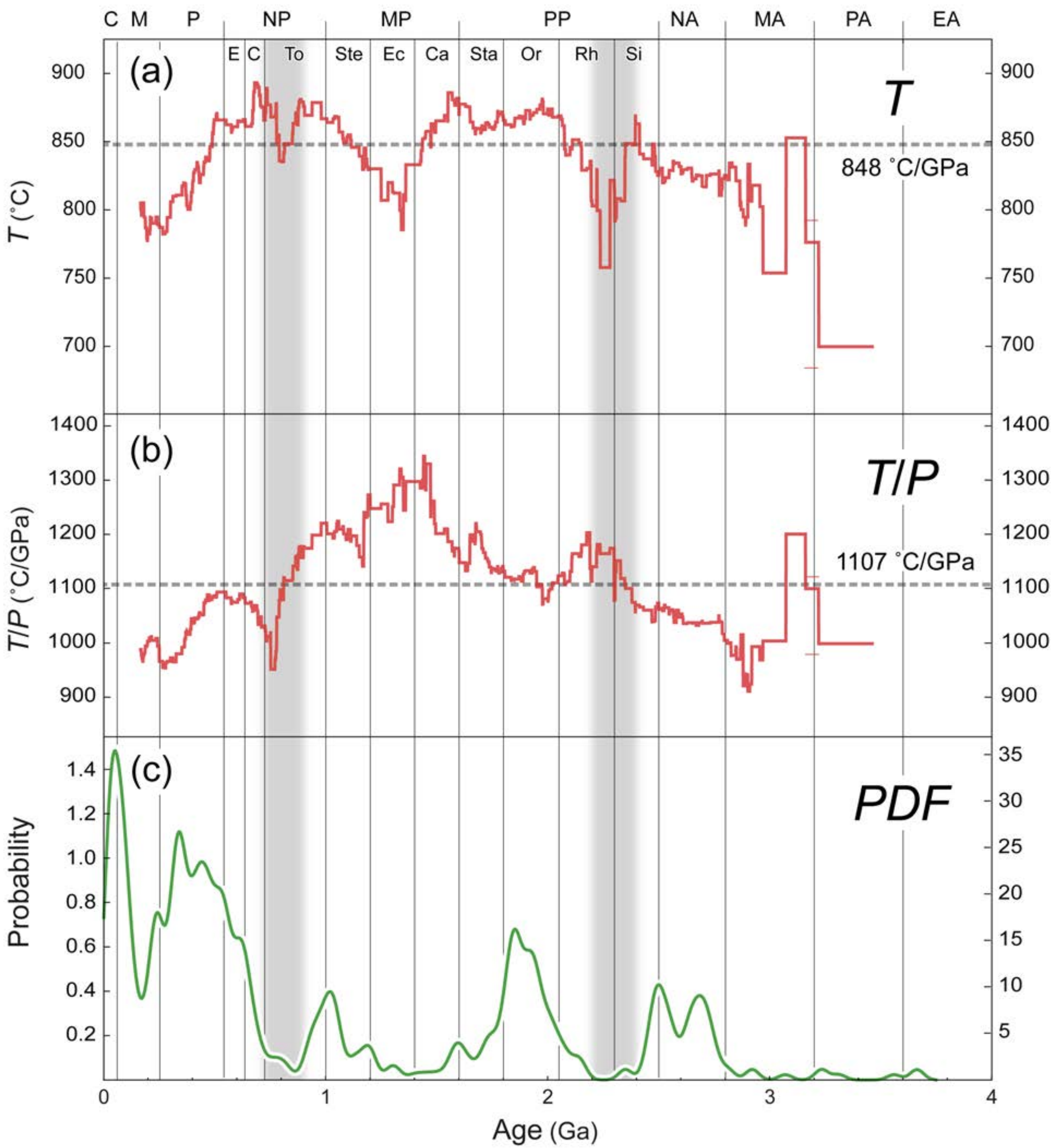


✧ Began with the widespread appearance of paired metamorphism in the Neoarchean.

✧ Was coeval with amalgamation of dispersed blocks of protocontinental lithosphere into supercratons.

✧ Was terminated by the progressive fragmentation of the supercratons into cratons in the early Paleoproterozoic.

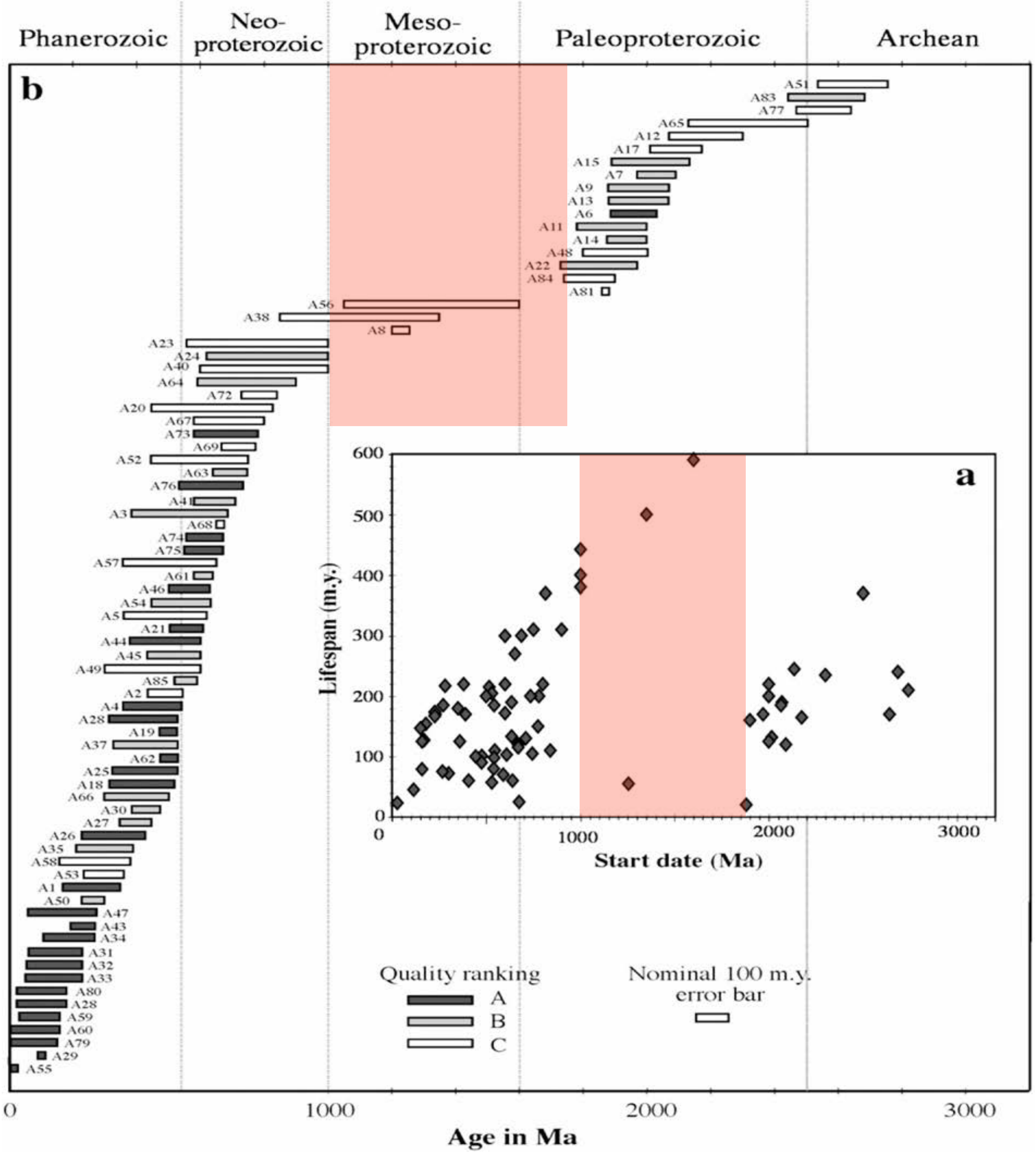
Cycle II



- Began with the progressive amalgamation of the cratons into the supercontinent Columbia in the Paleoproterozoic.
- Extended until the breakup of the supercontinent Rodinia in the Neoproterozoic.
- Represents a period of relative tectonic stability (the "boring billion").
- The boring billion may have been a time of limited subduction.

During most of the Proterozoic the moving means for both T and T/P exceeded the arithmetic means, reflecting insulation of the mantle beneath the quasi-integrated lithosphere of Columbia and, after a limited reorganization, Rodinia.

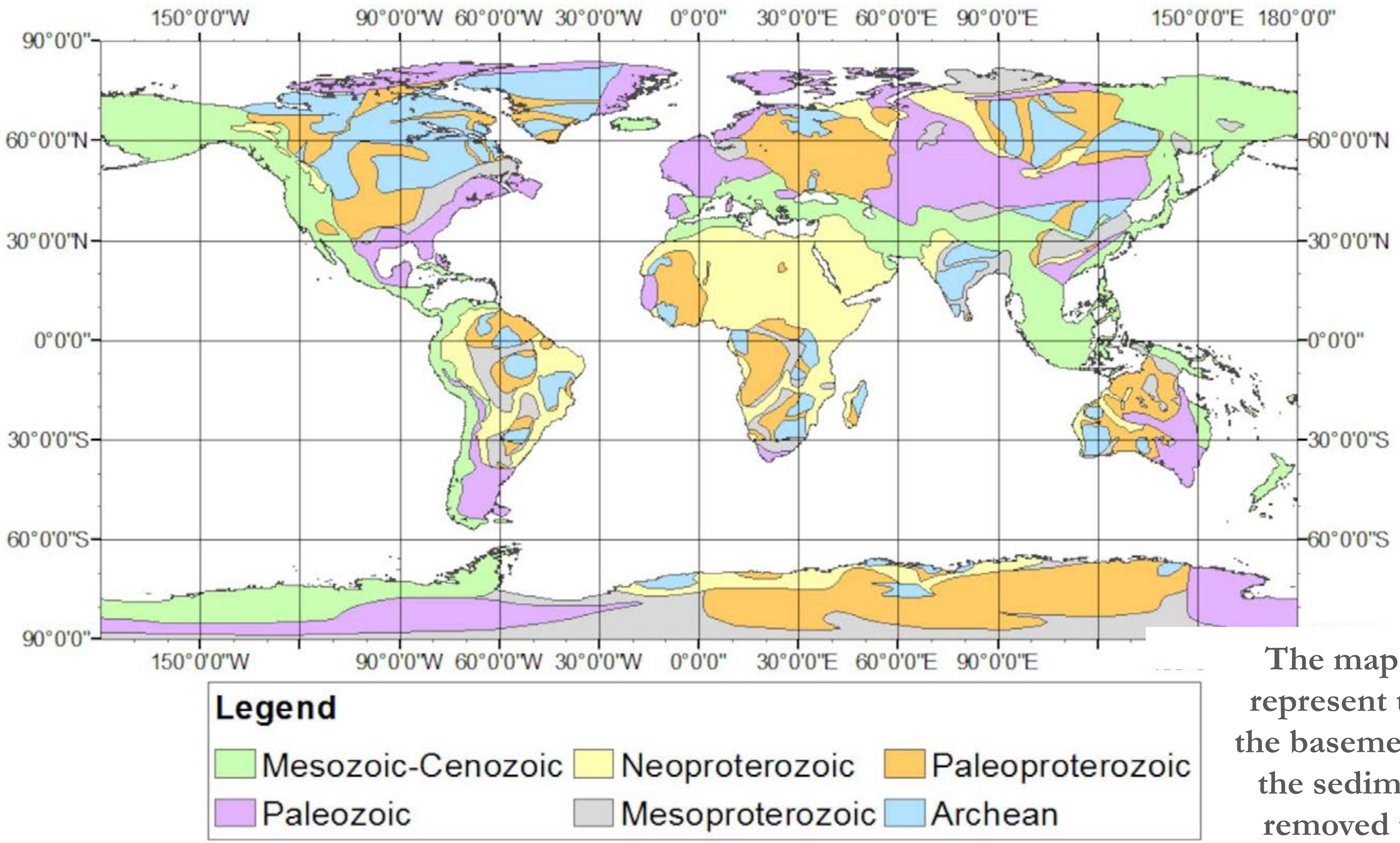
Tectonic stability evidenced by absence of passive margins



Lifespans of ancient passive margins (a) against start date, shows two cycles of declining lifespan, and (b) as bar extending from the start to end date.

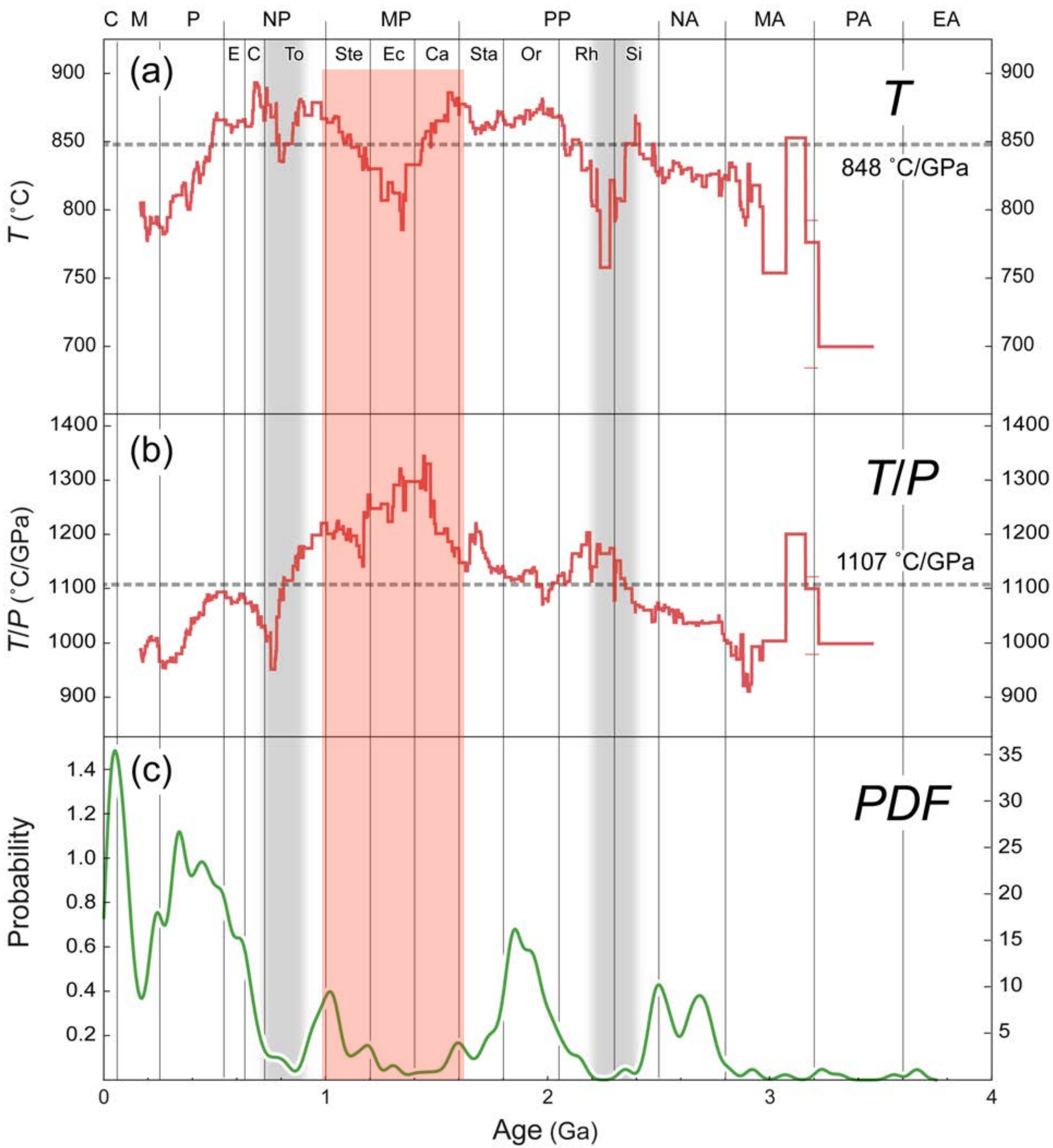
Bradley (2008, ESR)

Limited subduction globally during cycle II is suggested by the low volume of Mesoproterozoic crust



The map claims to represent the age of the basement (i.e. all the sediments were removed to display the inferred age).

W. Mooney
(Pers. Comm., 2017)



Volume* of crust normalized by length of Eon/Era

Ar Eon - $5x10^5$ km^3 Myr^{-1}

PP Era - $2x10^6$ km^3 Myr^{-1}

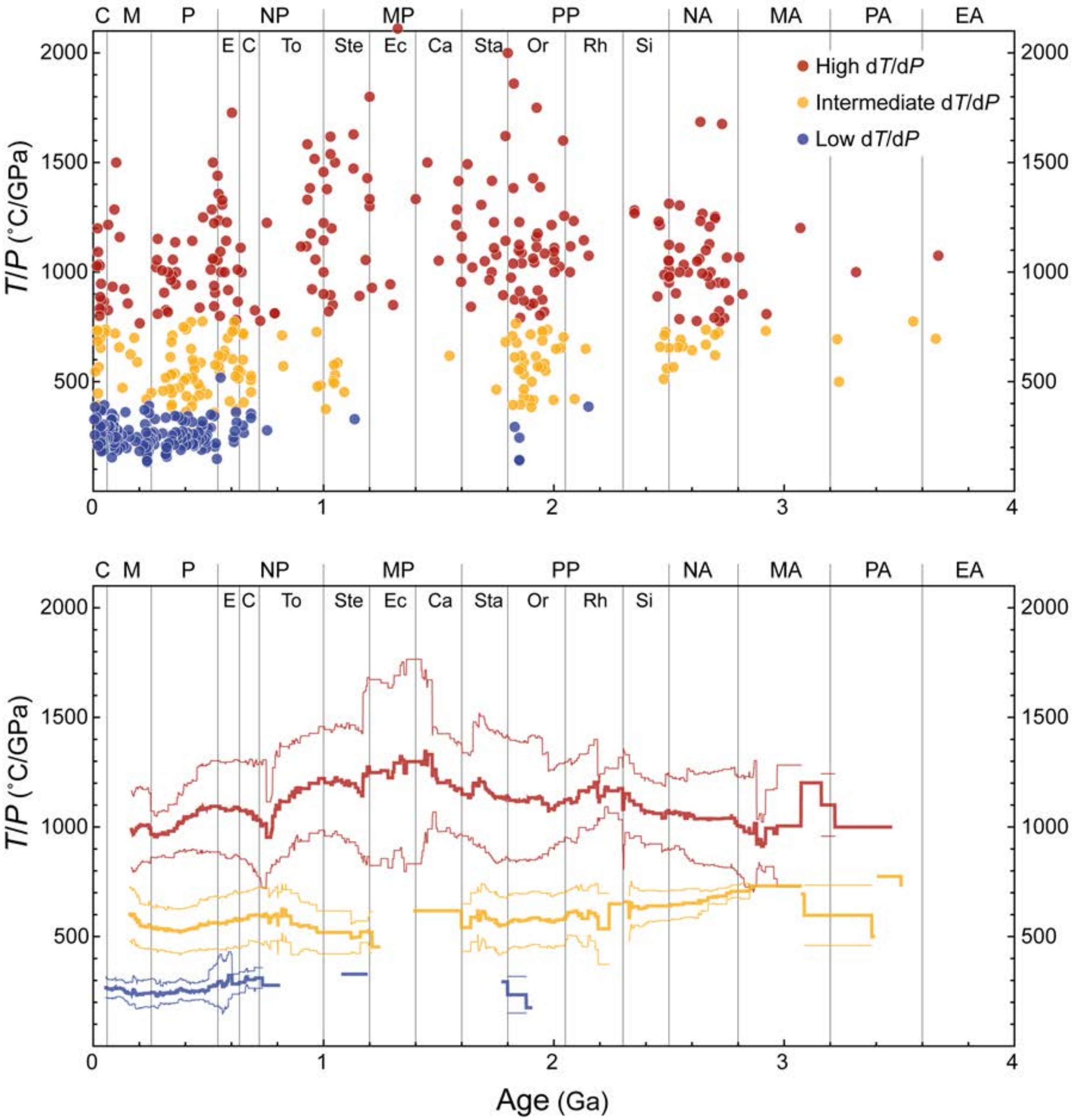
MP Era - $1x10^6$ km^3 Myr^{-1}

NP Era - $2x10^6$ km^3 Myr^{-1}

Ph Eon - $5x10^6$ km^3 Myr^{-1}

*Volumes from W. Mooney (Pers. Comm., 2017)

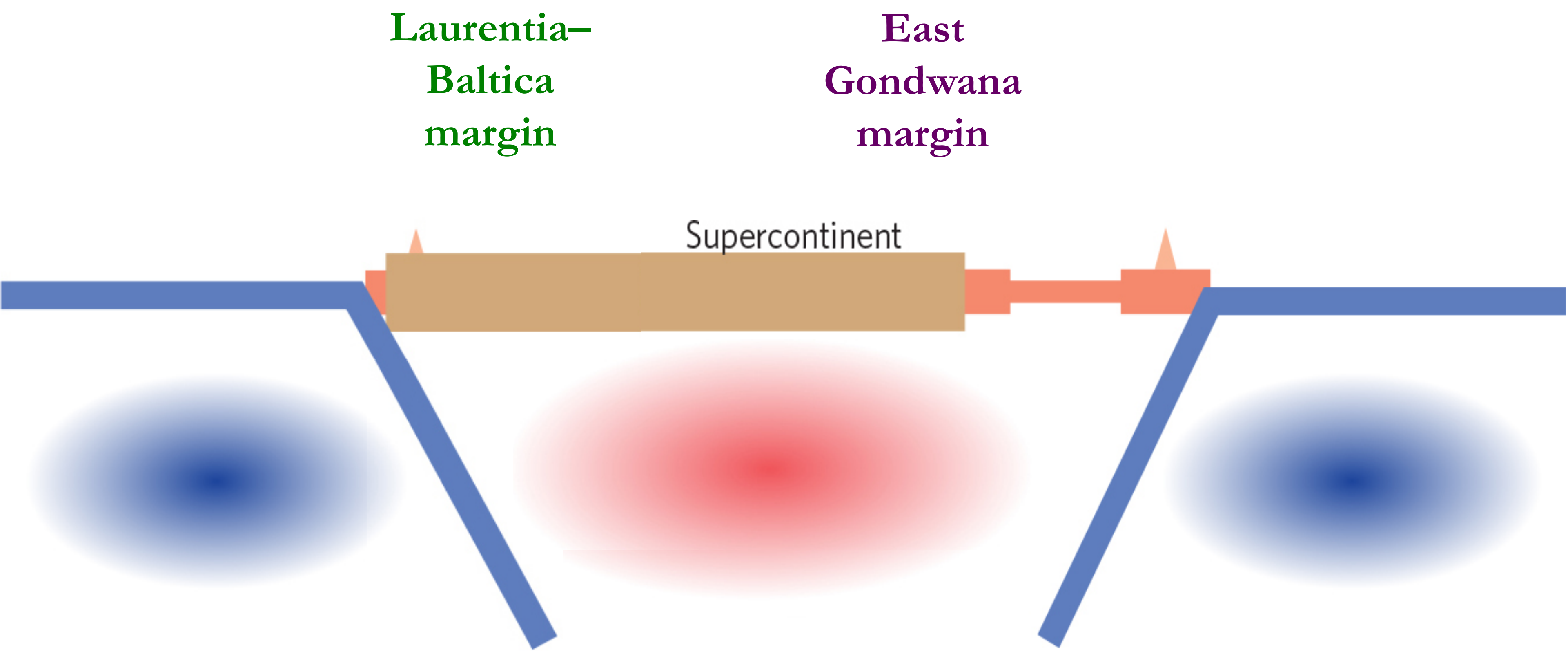
Why quasi-integrated lithosphere?



✧ Columbia was amalgamated over a period of >600 myr.

✧ Supercontinents are intrinsically unstable due to the insulating effect on the underlying ambient mantle.

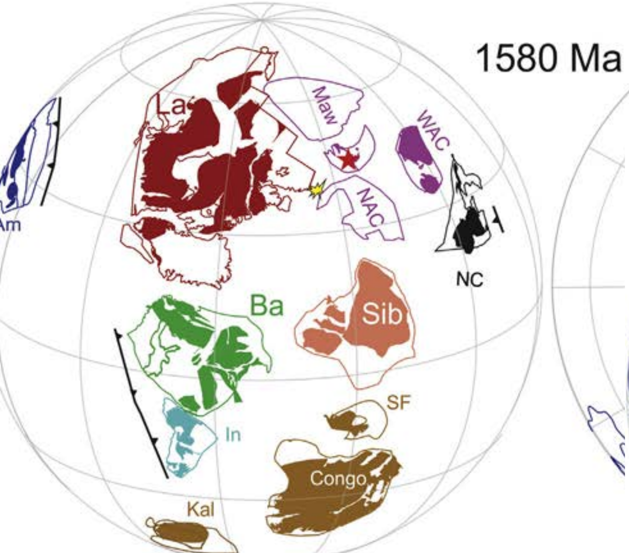
✧ In the case of Columbia, the East Gondwana cratons probably split away and returned during the late Mesoproterozoic.



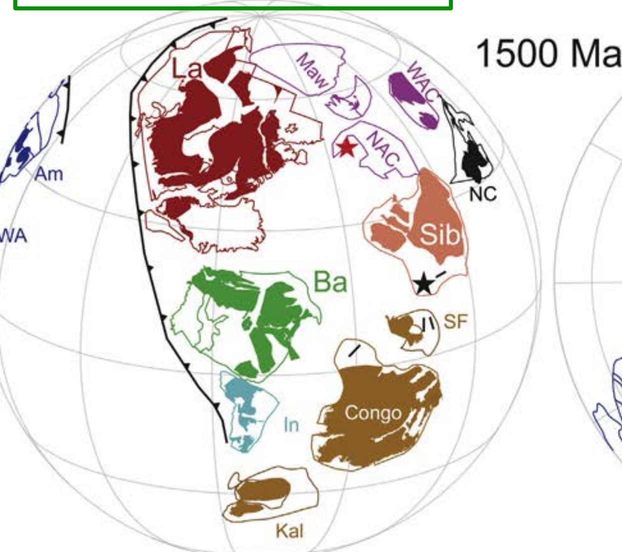
- ✧ While in place, supercontinent may have an insulating effect on the ambient mantle (blue), creating a warm mantle anomaly (red).
- ✧ This anomaly may destabilize the supercontinent and cause it to attempt to break apart. With attempted break-up, hot mantle stored beneath the supercontinent delivers a pulse of high heat flux and melt. If breakup is successful, such anomalies may take up to 100 Ma to dissipate, leading to the formation of locally thicker oceanic crust.

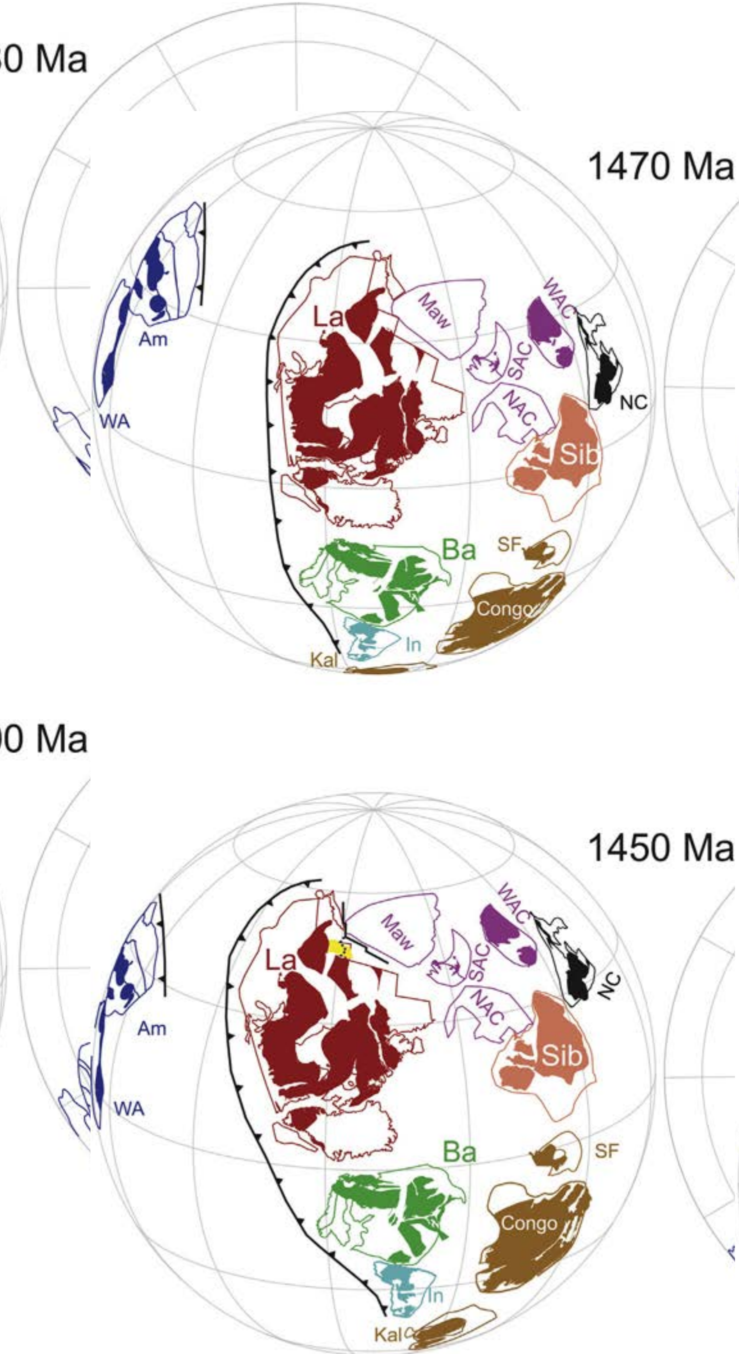
Modified after Lenardic (2017, NG)

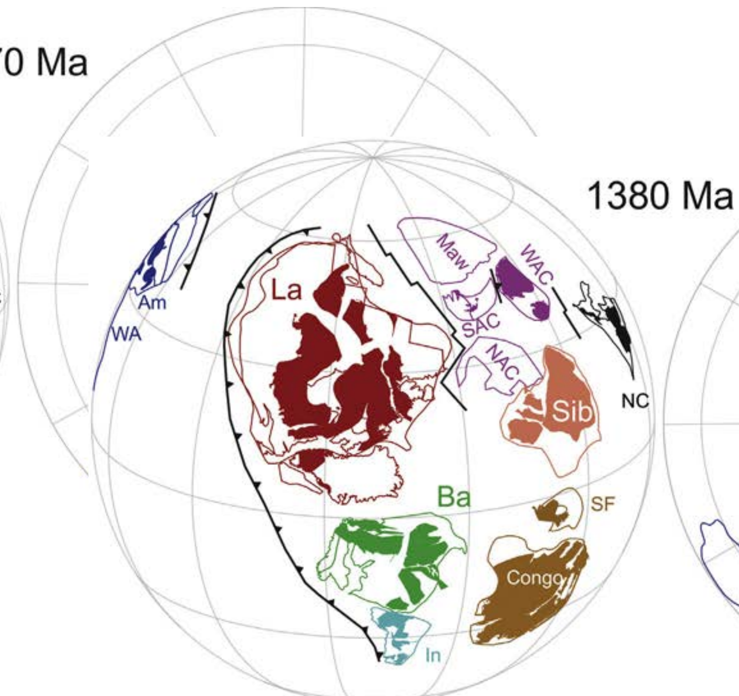
Columbia



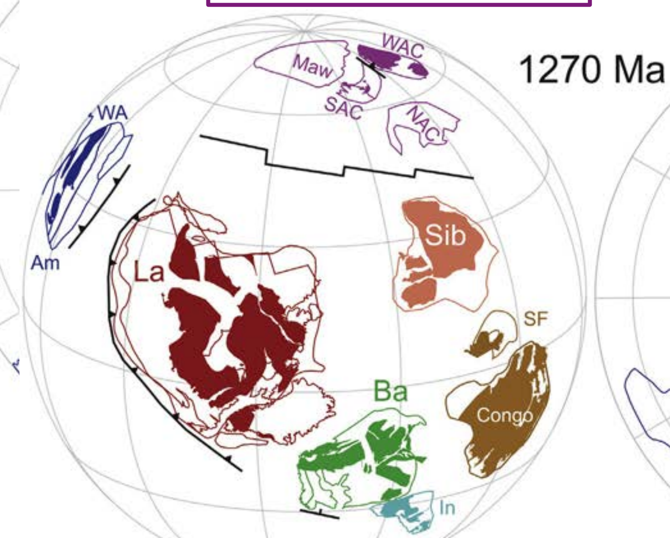
Laurentia, Baltica, Siberia





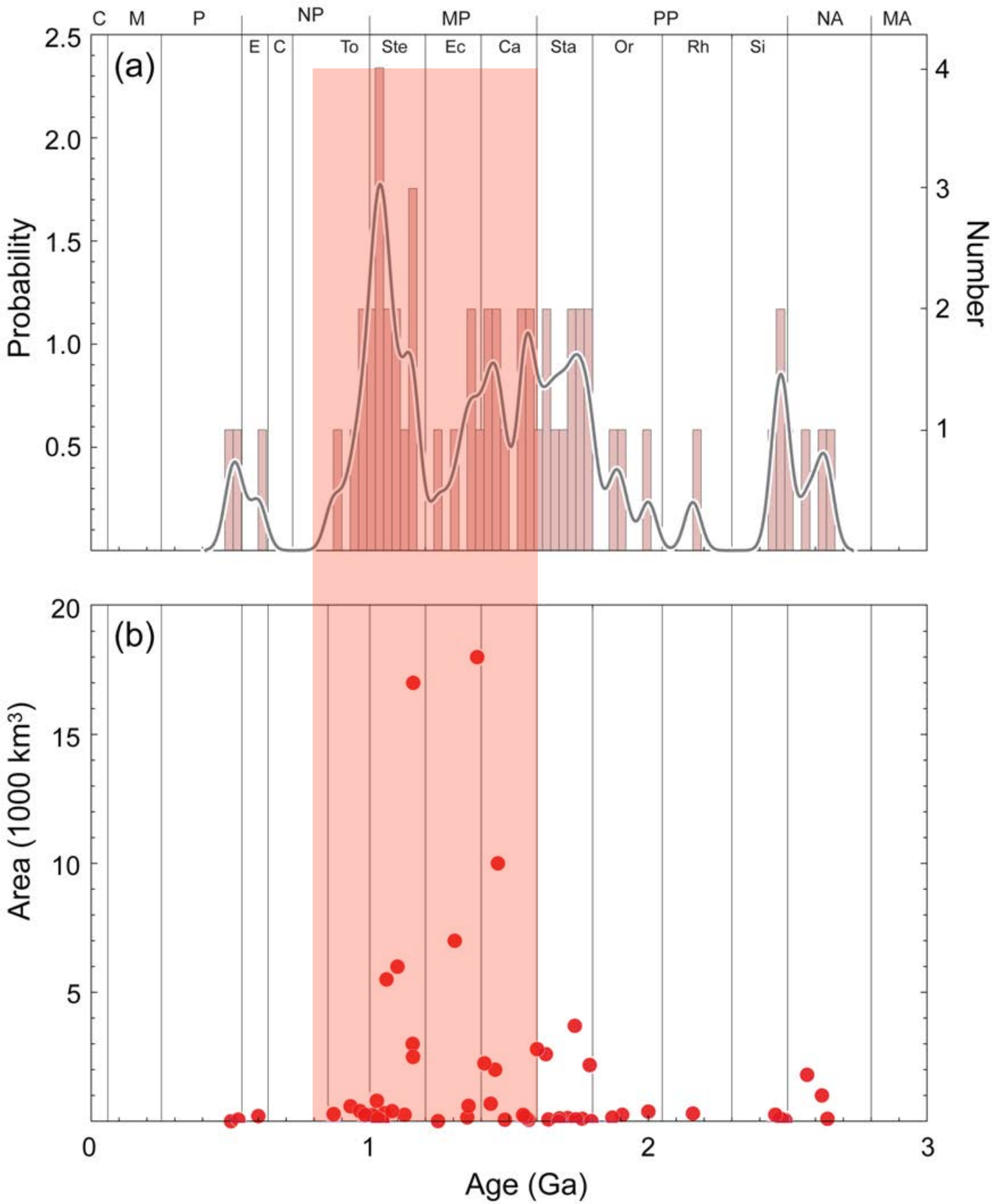


East Gondwana



Pisarevsky et al., 2014, PR
(Meert, 2014, GF)

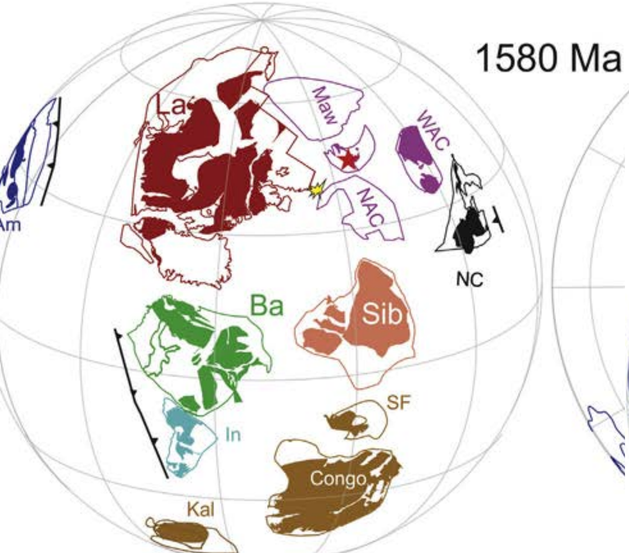
Hotter mantle during the Proterozoic is supported by the temporality of massif-type anorthosites



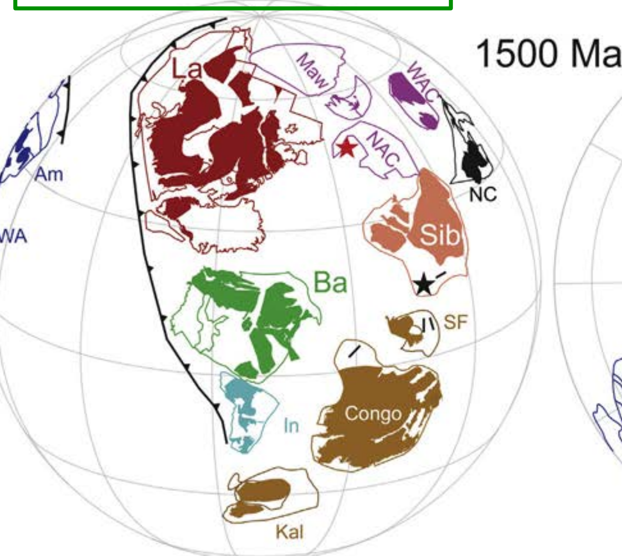
Massif type anorthosites are the most volumetrically abundant of terrestrial varieties and are almost entirely restricted in age to the Proterozoic Eon, although most of the volume (taking area as a proxy for volume) was emplaced during the Mesoproterozoic.

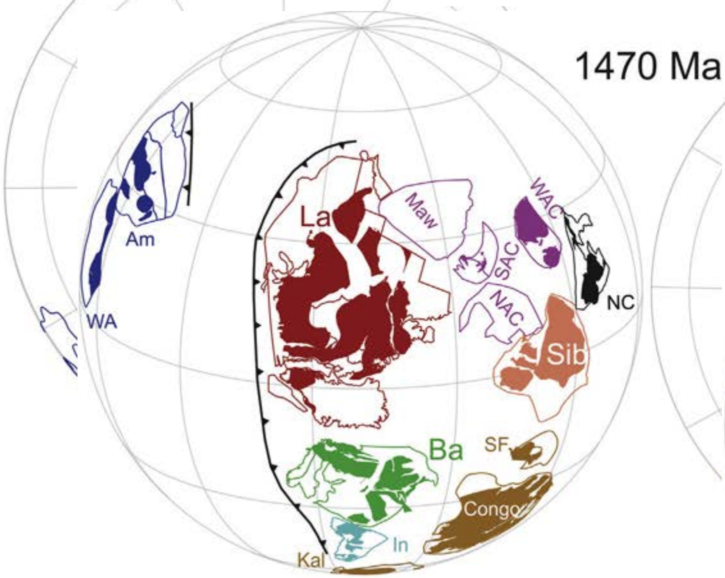
Ashwal (2010, Can. Min.)

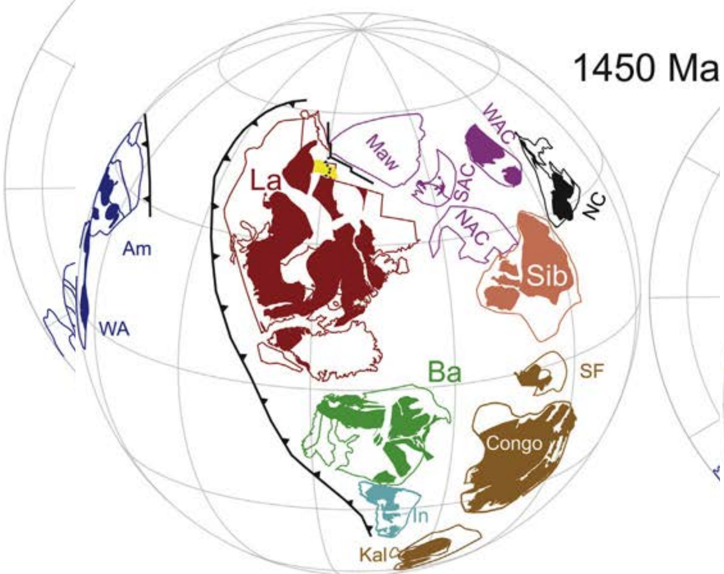
Anorthosites and Columbia

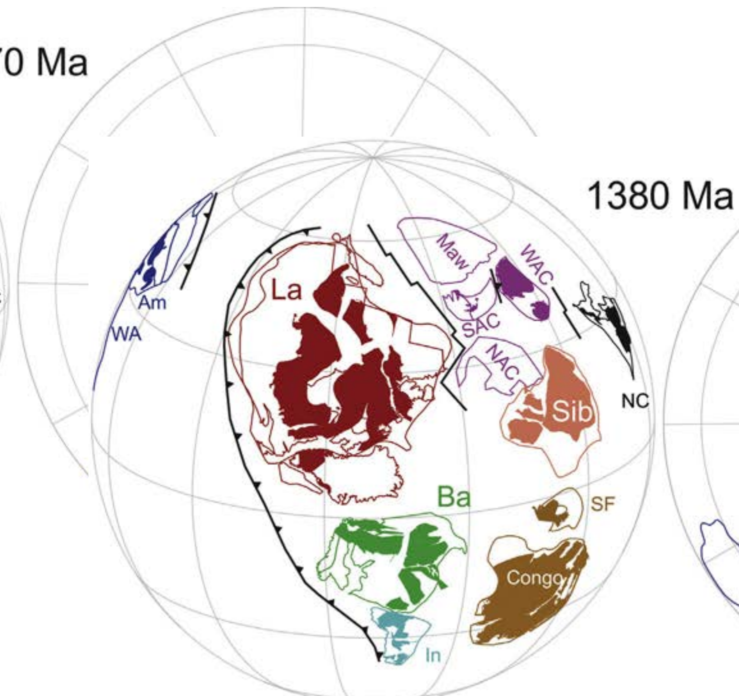


Laurentia, Baltica, Siberia

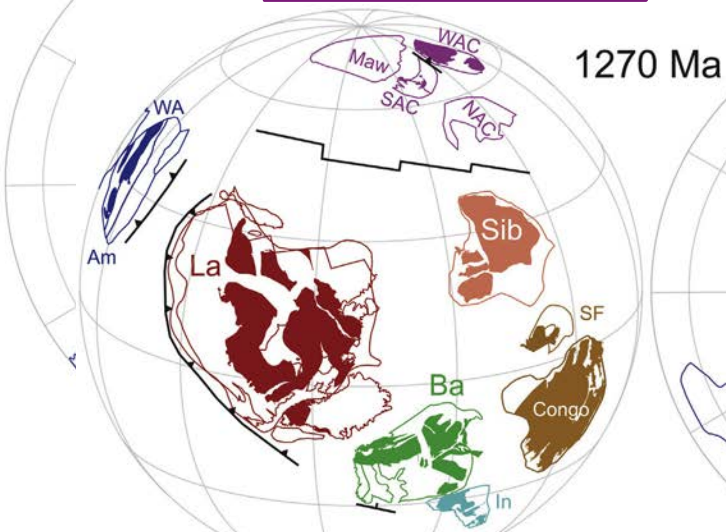




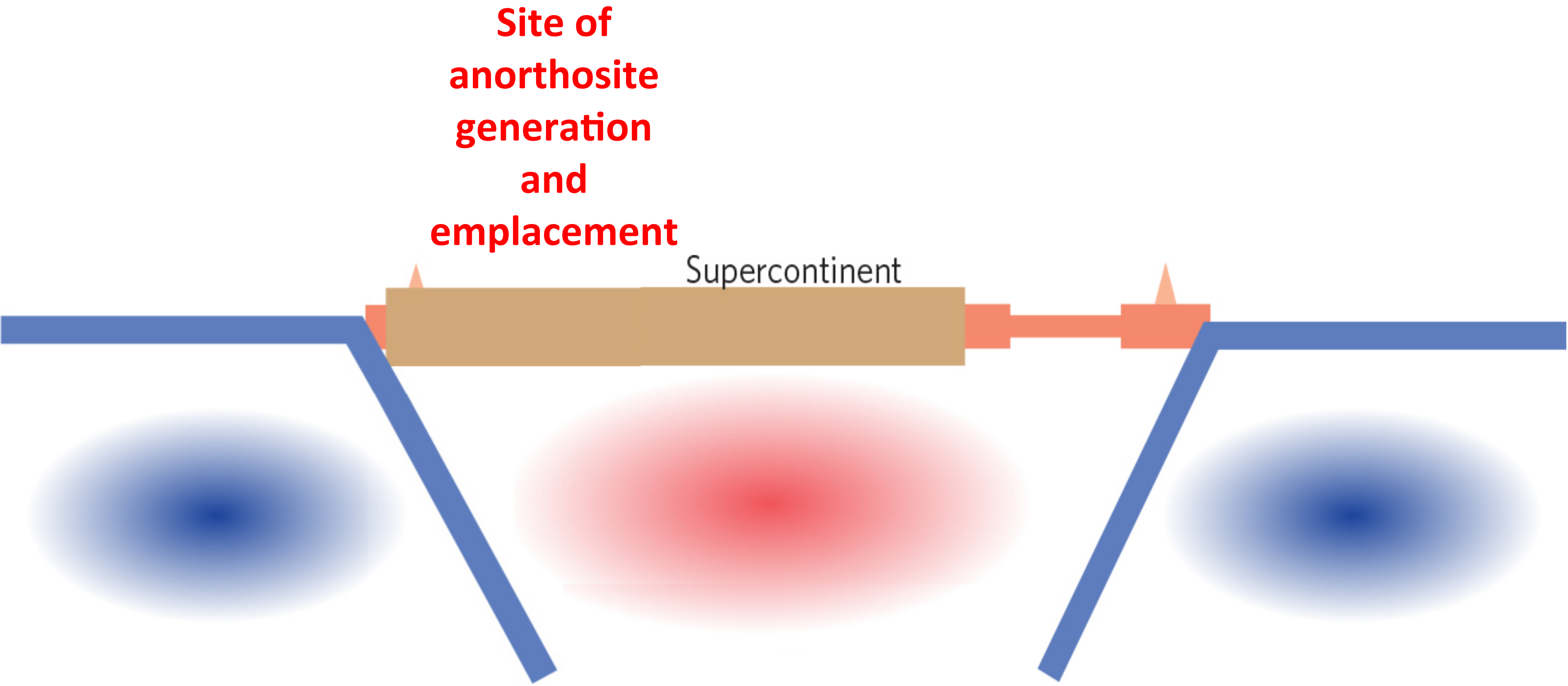




East Gondwana



Pisarevsky et al., 2014, PR
(Meert, 2014, GF)



- While in place, supercontinent may have an insulating effect on the ambient mantle (blue), creating a warm mantle anomaly (red).
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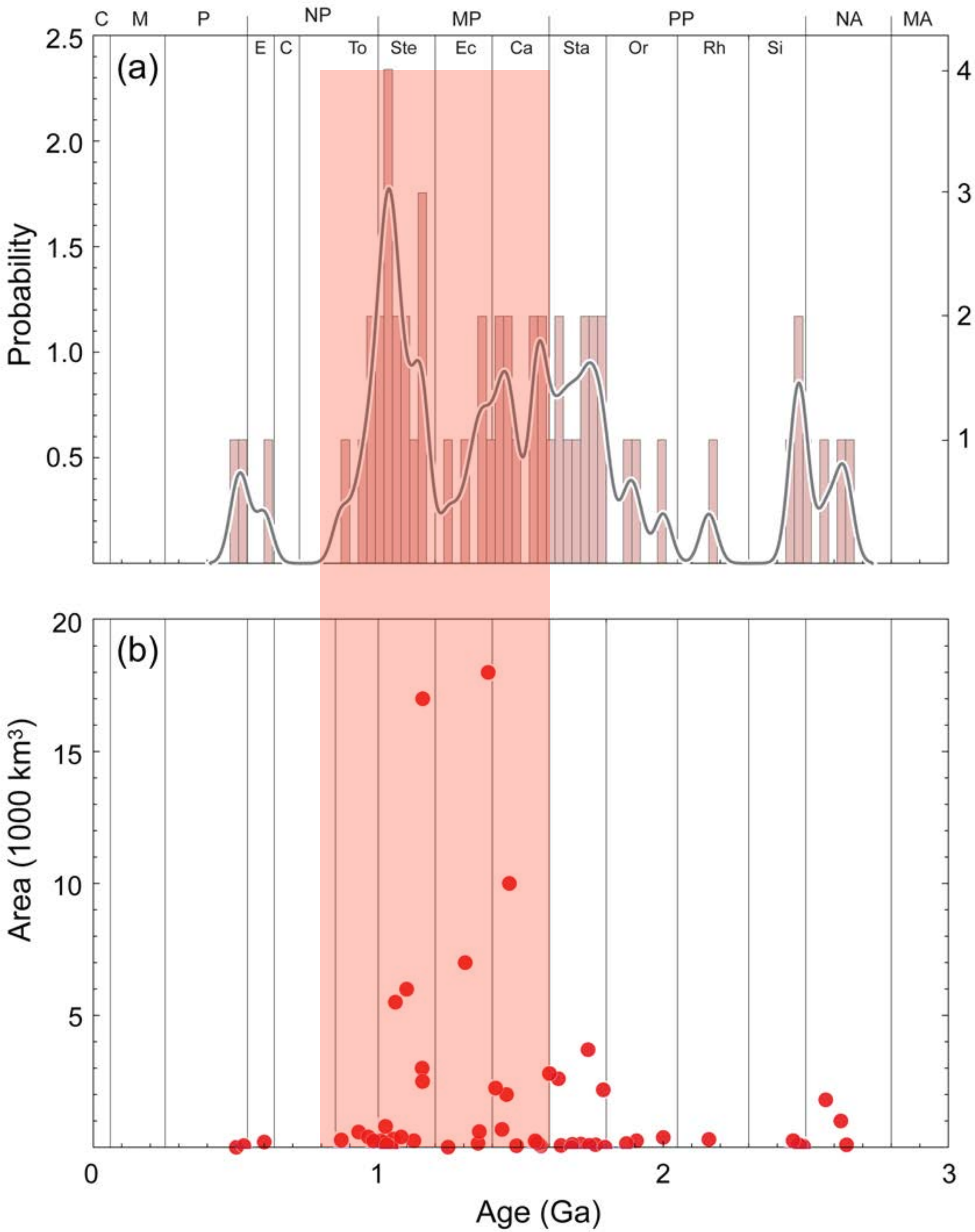
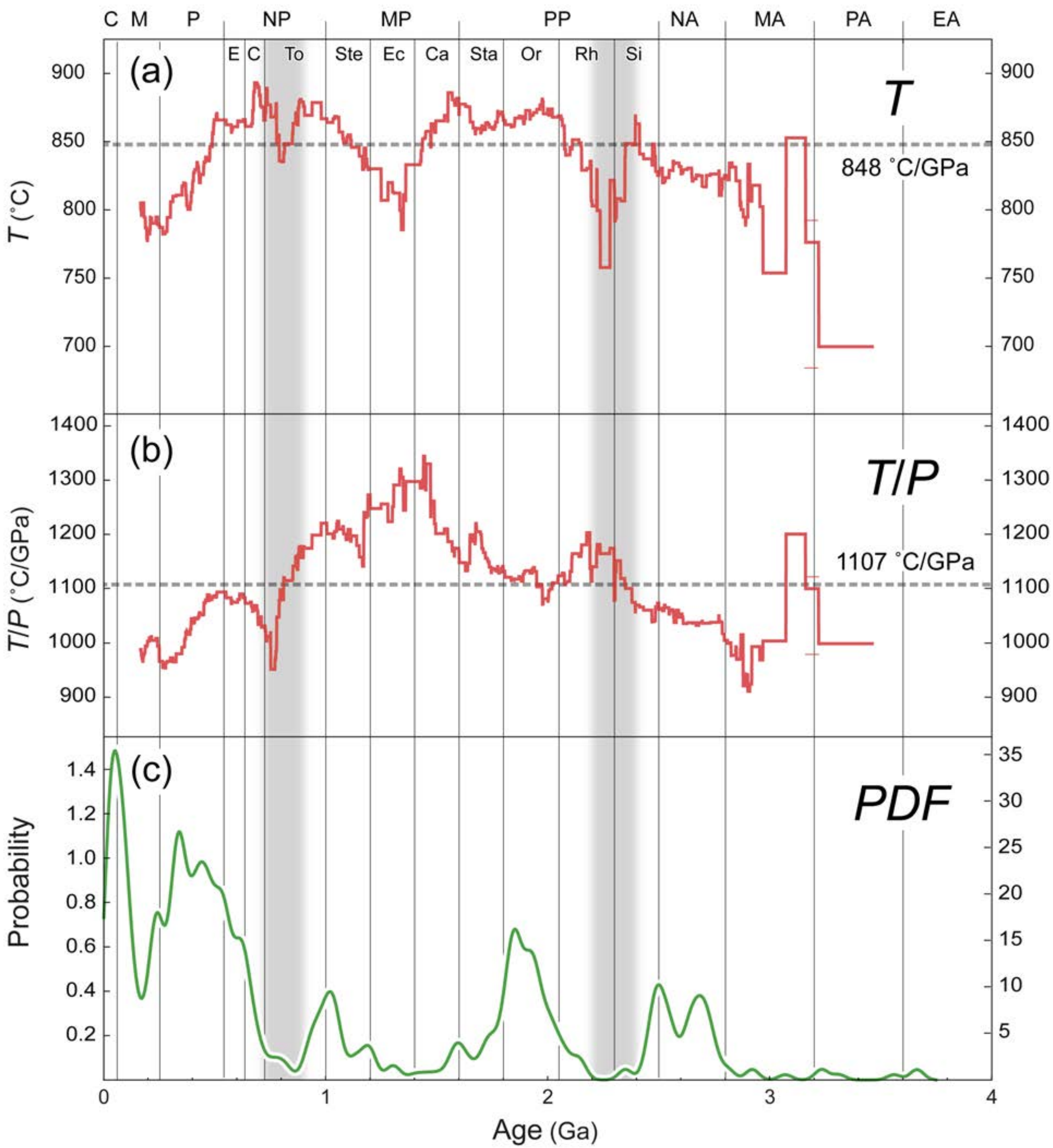


The Goldilocks period

- ✧ Anorthosite petrogenesis most readily explained in a convergent plate setting.
- ✧ Onset in Paleoproterozoic may reflect increased lithosphere strength and crustal thickness, which allowed Moho-depth ponding and slow crystallization of basaltic magma (comagmatic, cumulate high-Al Opx megacrysts; magmatism in individual massifs commonly lasted up to 100 m.y.).
- ✧ Many anorthosites are spatially and temporally related to the convergent margin along the Laurentia–Baltica side of the Columbia–Rodinia supercontinent—an example of a 'Goldilocks period' in the Earth history when the combination of amalgamated continental lithosphere, mantle temperature and location of the active margin produced conditions that were were 'just right'.
- ✧ The disappearance of anorthosite massifs in the Neoproterozoic likely relates to the breakup of Rodinia.

Cycle III



- Begins with the steep decline in thermal gradients of high dT/dP metamorphism to their lowest value, although *T* remains relatively high, and the appearance of low dT/dP metamorphism in the rock record.

- Extends to another steep decline in thermal gradient of high dT/dP metamorphism associated with the breakup of Pangea and the start of a possible fourth cycle at *c.* 0.175 Ga.

Thermal gradients for high dT/dP metamorphism show a rise to a second peak at the end of the Variscides during the formation of Pangea, again reflecting insulation of the mantle.

The Phanerozoic–Neoproterozoic vs the Precambrian

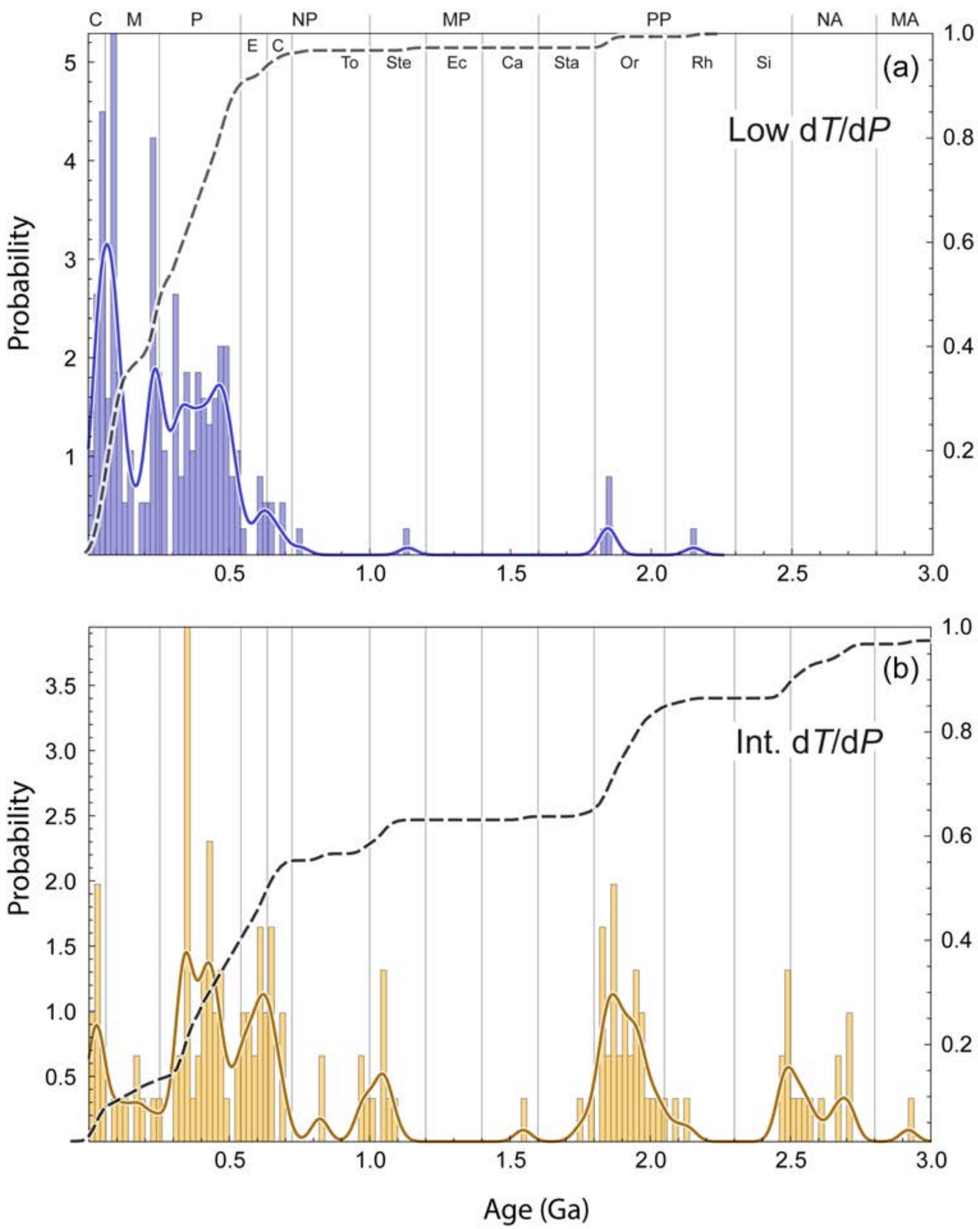


Plate tectonics is a kinematic theory of global lithosphere behavior that can be demonstrated to have operated at least back to the breakup of Pangea and probably continuously back to the beginning of the Cryogenian.

This is the modern plate tectonics regime characterized by low dT/dP metamorphism (Brown, 2006, Geology).

Subduction became a dominant process in the late Mesoarchean, so it is likely that the Proterozoic was dominated by a mobile-lid tectonic regime, but was this global and was it continuous?

This is the Proterozoic mobile-lid tectonic regime in which hot collision is typical, but not universal (Brown, 2006, Geology).

Conclusions

- The limited occurrence of high and intermediate dT/dP metamorphism before the late Mesoarchean suggests that suitable tectonic environments to generate these types of metamorphism were not widely available.
- The widespread appearance of high dT/dP metamorphism in the Neoarchean and low dT/dP metamorphism in the late Neoproterozoic identify changes in global geodynamic regime.
- The change in the late Mesoarchean identifies the beginning of widespread subduction and generation of a network of plate boundaries in a mobile-lid tectonic regime as the balance between heat production and heat loss changed in favor of secular cooling – time's arrow. Whether this was a globally linked system or remained continuous to the present day are unanswered questions.
- During the Precambrian, intermediate (high-P granulites and associated eclogites) and high dT/dP metamorphism (common granulites) identify belts of plate convergence/collisional orogenesis and overriding plate extension.
- The Proterozoic is characterized by stability and higher than average gradients of high dT/dP metamorphism, from the formation of Columbia to the breakup of Rodinia. This period is the middle of 3 geodynamic cycles – time's cycle.