An attack on our knowledge-gaps about:

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

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Exit seminar
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Mt. Sumbing, Central Java, Indonesia, 2016

introduction

Phanerozoic

Cenozoic

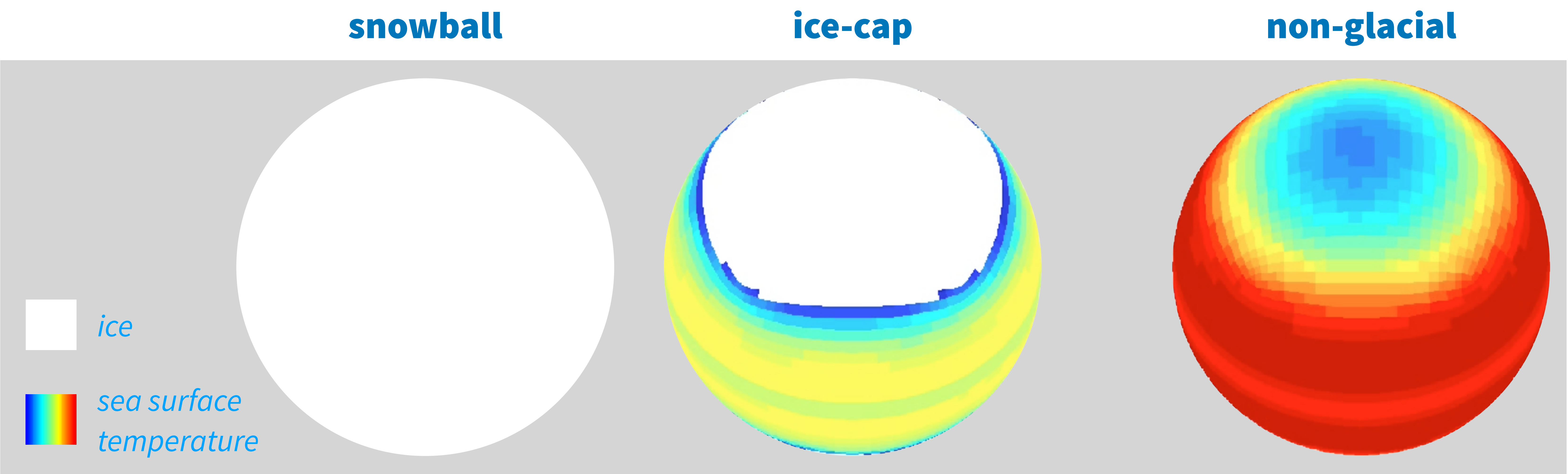
Neoproterozoic

conclusions

acknowledgements

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

EARTH'S STABLE CLIMATE STATES



aqua-planet GCM results, Ferreira et al. (2011)

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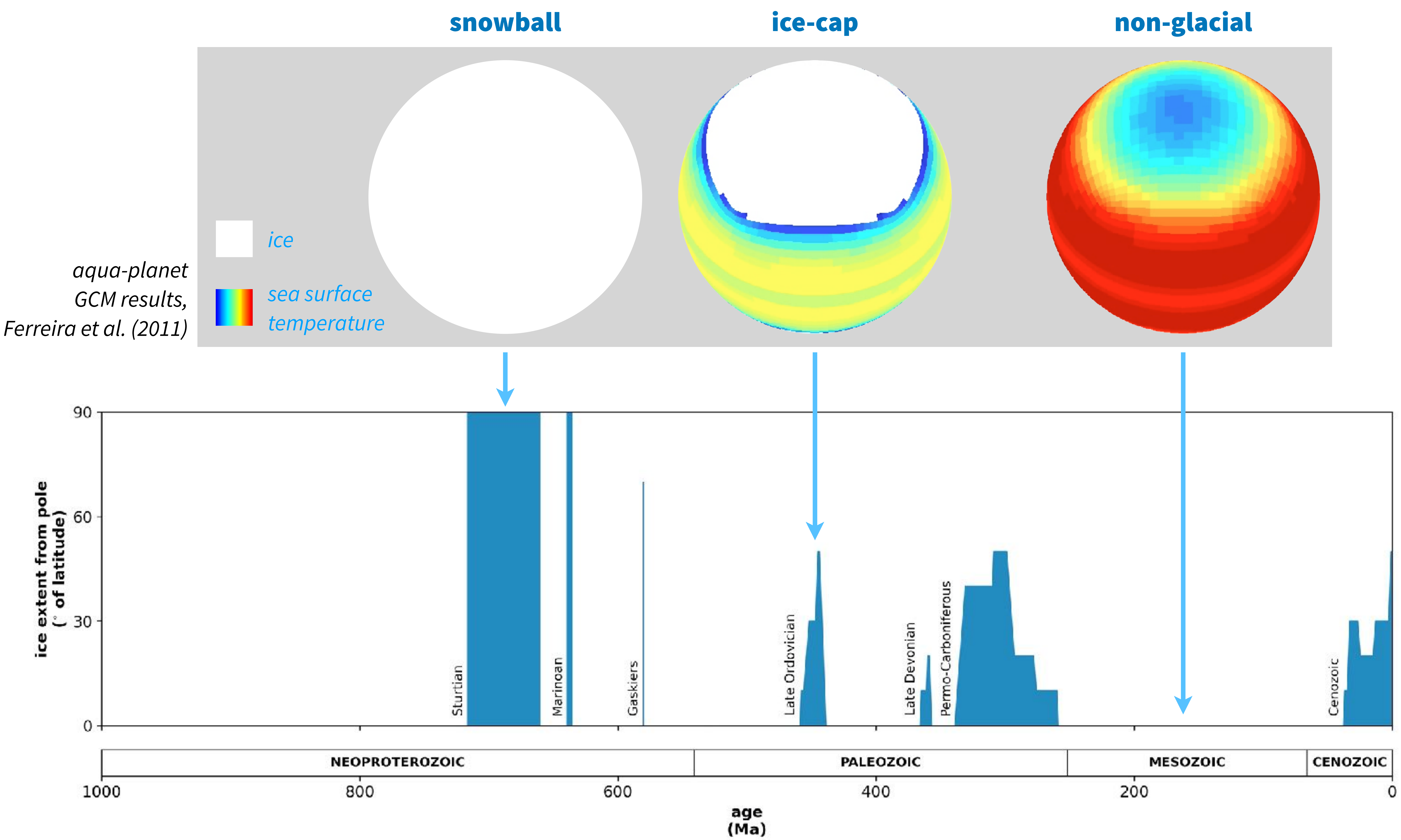

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

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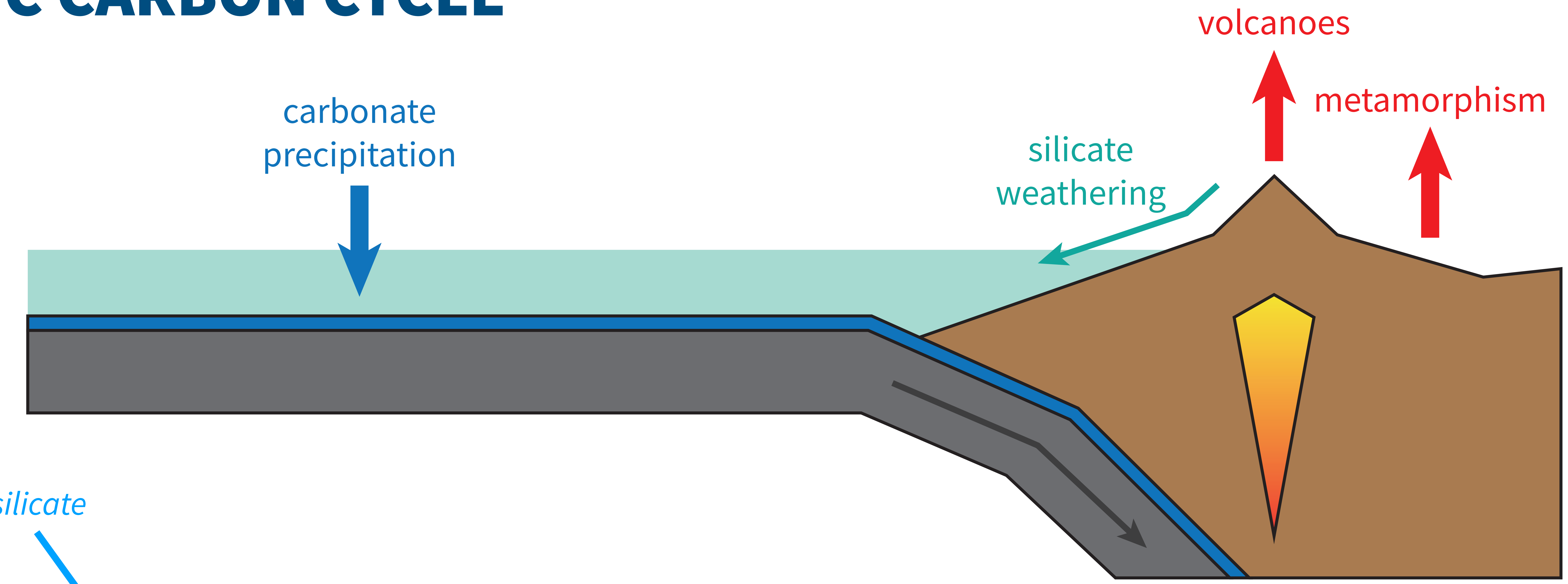
GEOLOGIC CARBON CYCLE



Ca/Mg silicate

silicate weathering:

$$(\mathrm{Ca/Mg})\mathrm{SiO_3} + 2\,\mathrm{CO_2} + \mathrm{H_2O} \longrightarrow (\mathrm{Ca/Mg})^{2+} + 2\,\mathrm{HCO_3^-} + \mathrm{SiO_2}$$

carbonate precipitation:

$$(\mathrm{Ca/Mg})^{2+} + 2\,\mathrm{HCO_3^-} \longrightarrow (\mathrm{Ca/Mg})\mathrm{CO_3} + \mathrm{CO_2} + \mathrm{H_2O}$$

Ca/Mg carbonate

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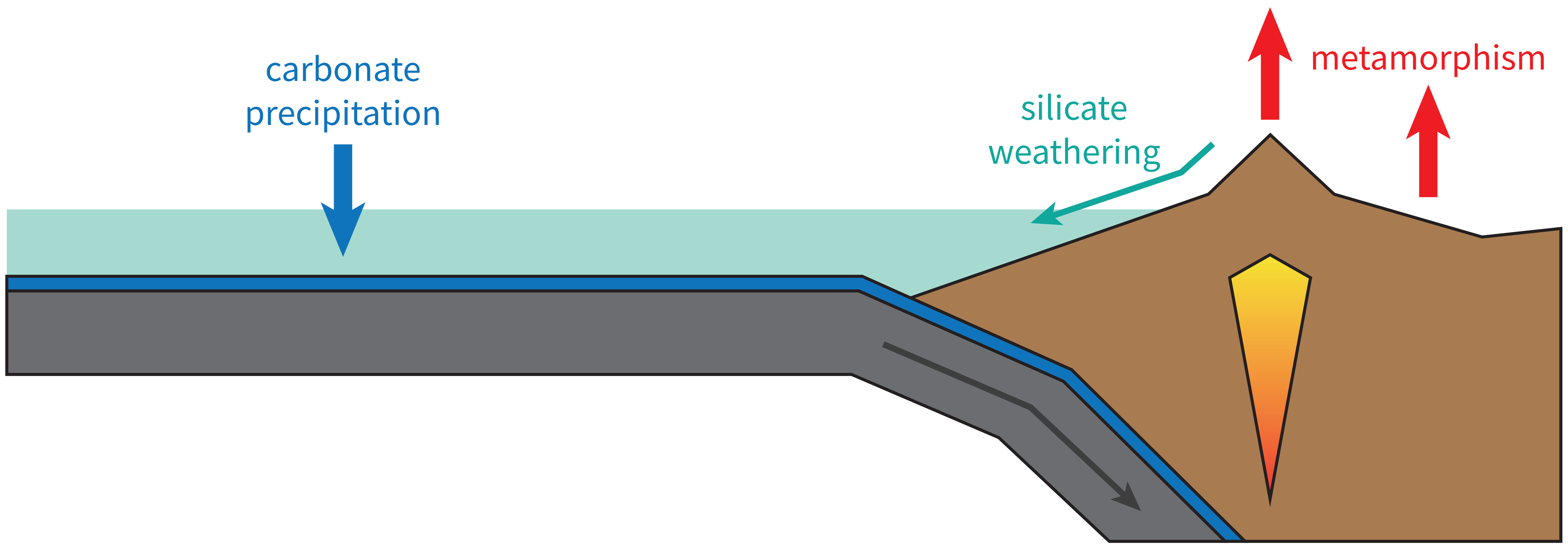

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net reaction:

$$(\mathrm{Ca/Mg})\mathrm{SiO_3} + \mathrm{CO_2} \longrightarrow (\mathrm{Ca/Mg})\mathrm{CO_3} + \mathrm{SiO_2}$$

one mole of CO_2 removed for every mole of Ca+Mg liberated

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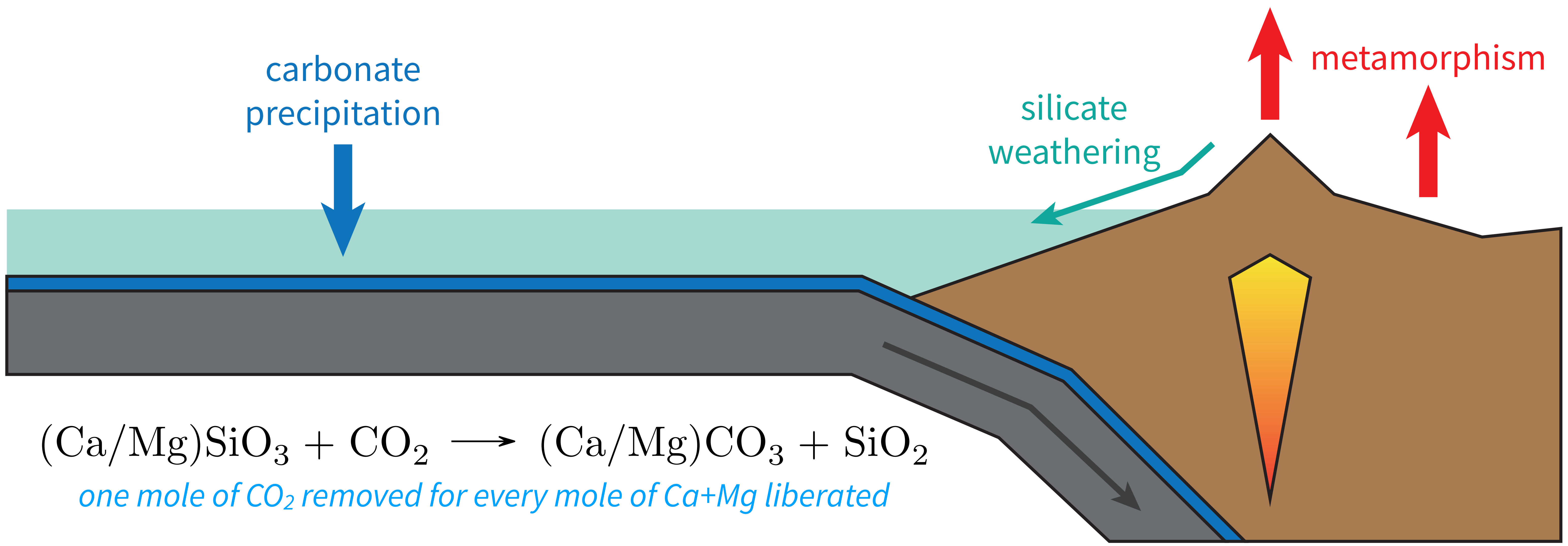

$$(Ca/Mg)SiO_3 + CO_2 \longrightarrow (Ca/Mg)CO_3 + SiO_2$$

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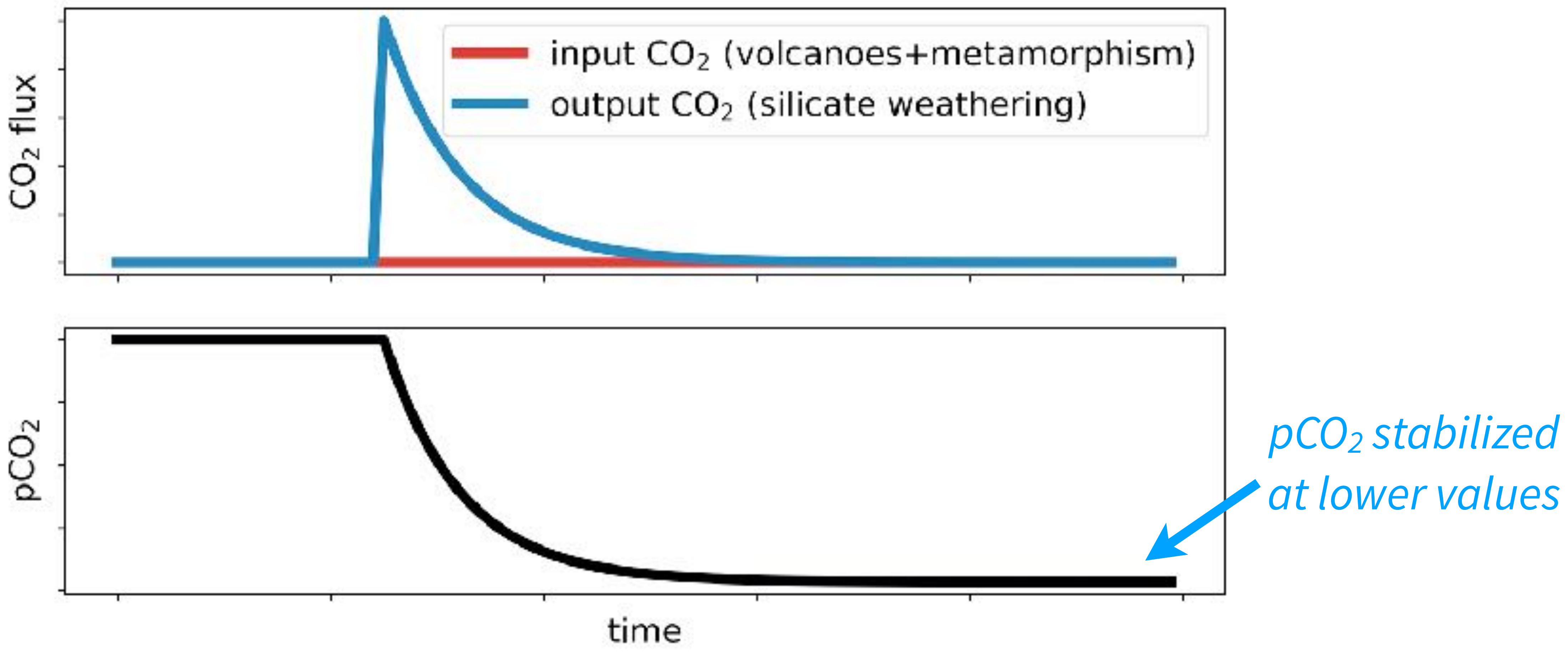
silicate weathering feedback:

- ↑ silicate weathering flux in one place *(output > input)*
- ↓ pCO$_2$ *(amount of CO_2 in the atmosphere)*
- ↓ temperature and precipitation
- ↓ silicate weathering flux elsewhere *(output = input)*
- — ***pCO$_2$ stabilized at lower values***



Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

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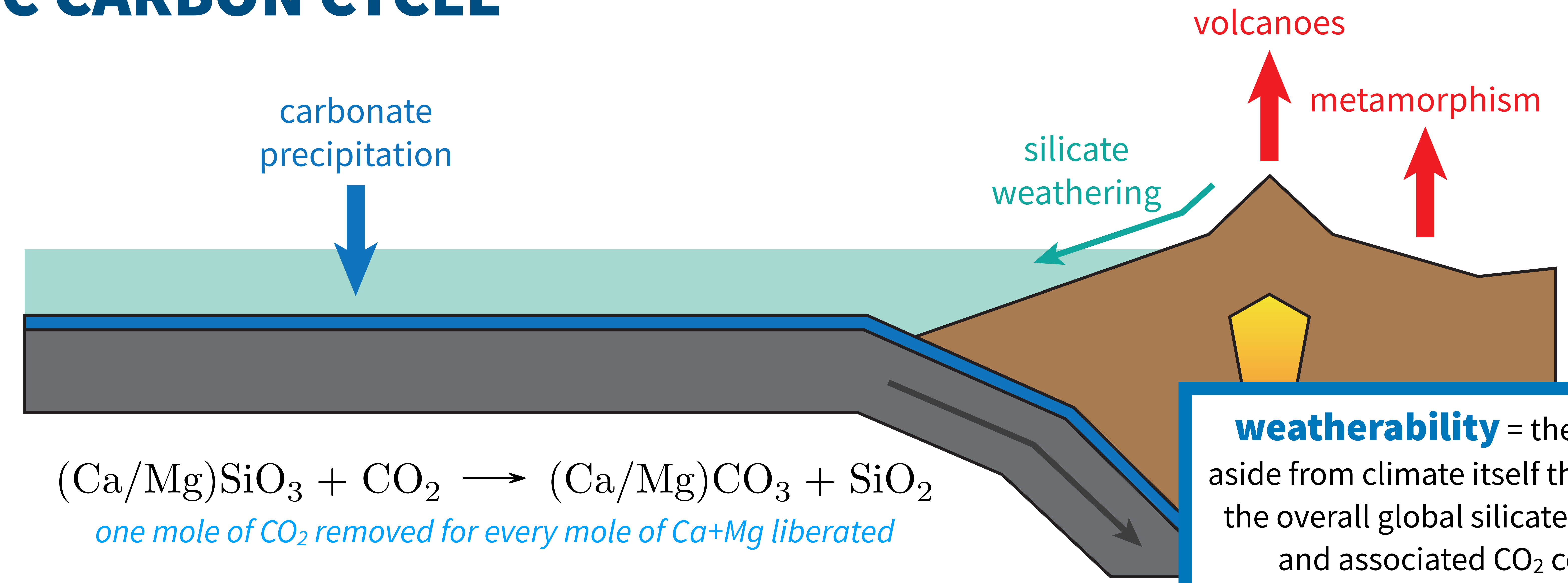

Kump & Arthur (1997)

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weatherability = the sum of factors aside from climate itself that contributes to the overall global silicate weathering flux and associated CO_2 consumption

silicate weathering feedback:

↑ **weatherability**

↑ silicate weathering flux in one place *(output > input)*

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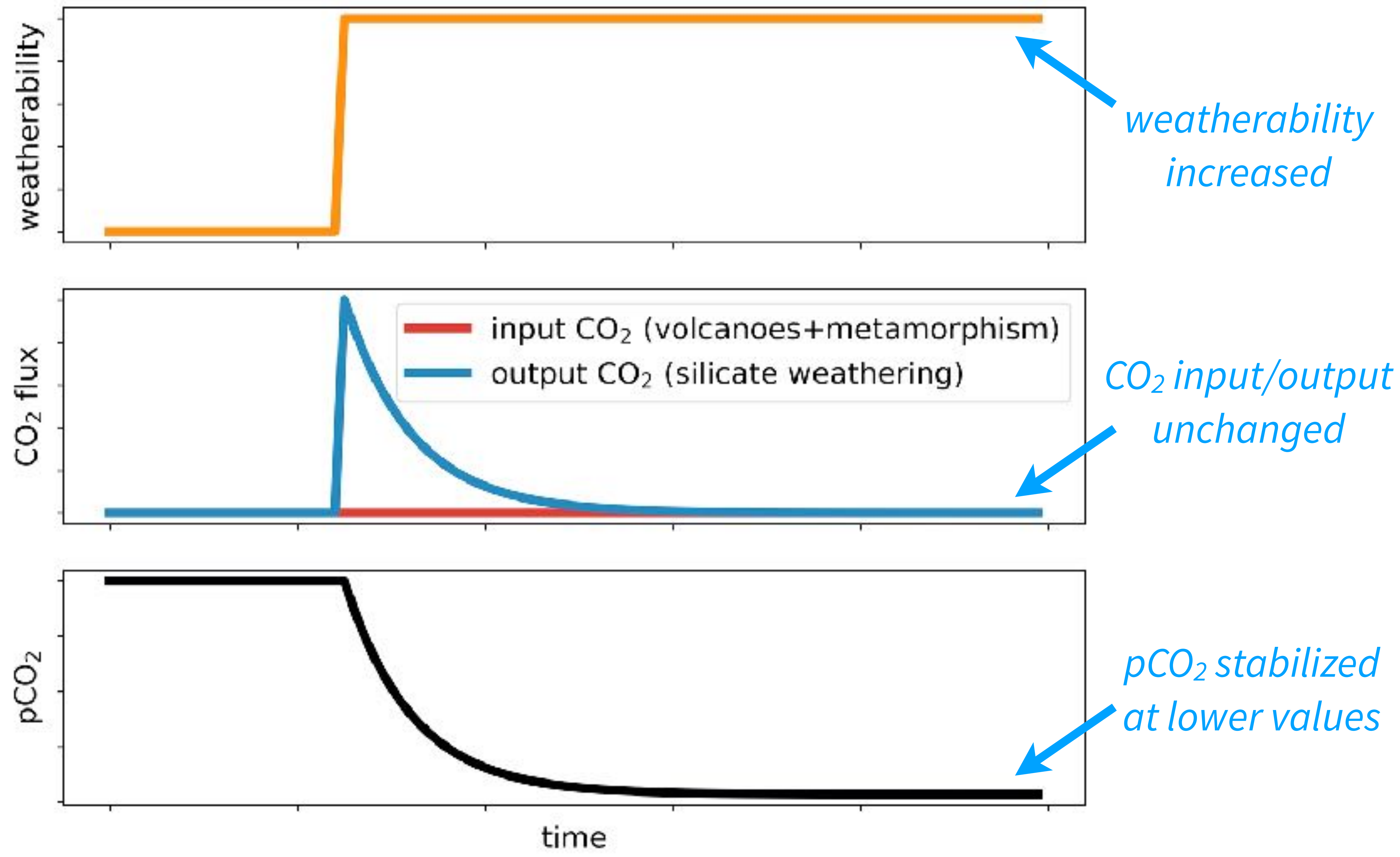


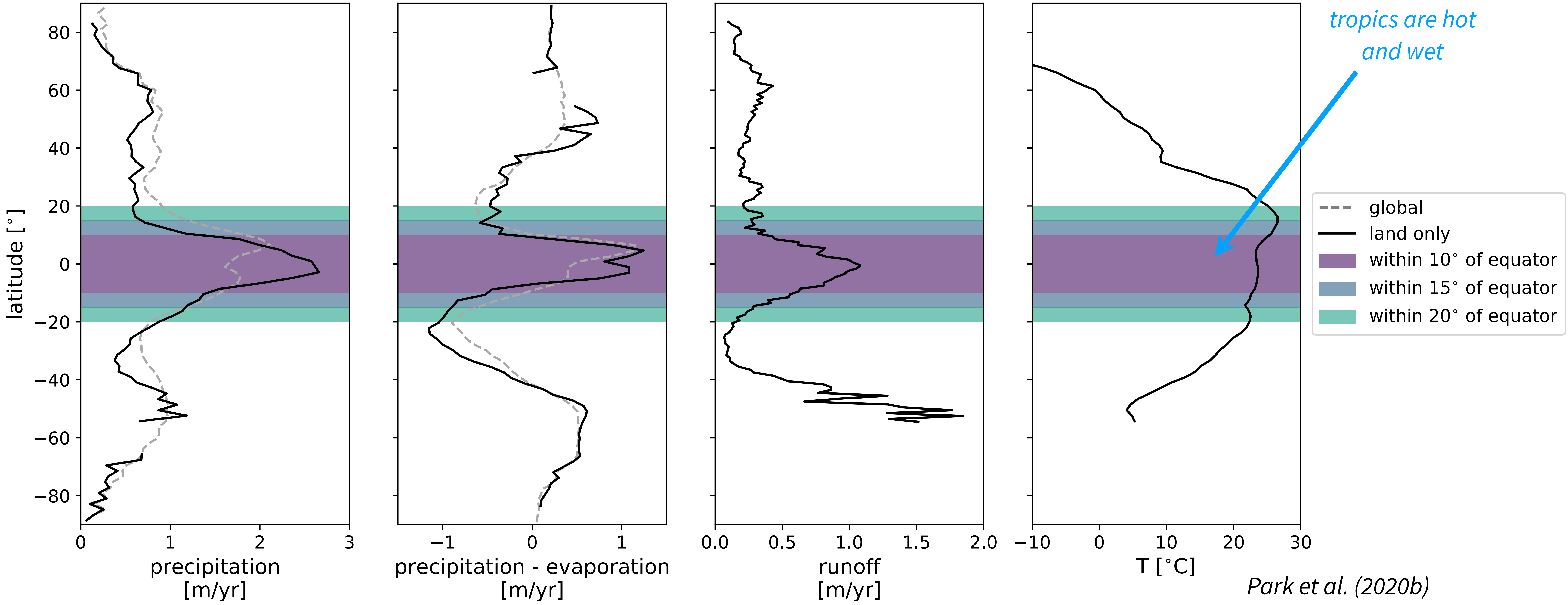
Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

WEATHERABILITY

What affects planetary weatherability?

1. location of rocks

- the tropics have the highest temperatures and runoff



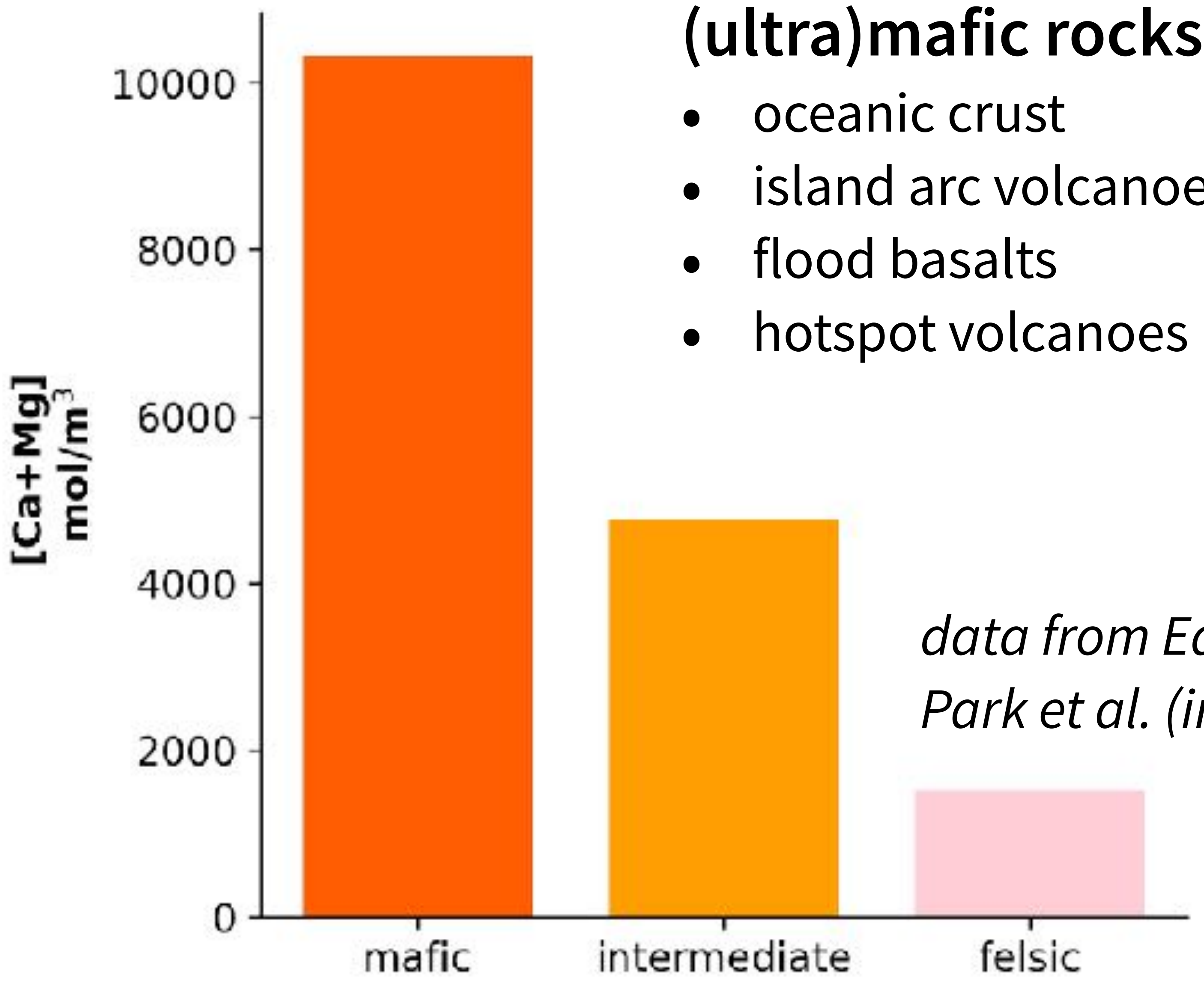
Park et al. (2020b)

WEATHERABILITY

What affects planetary weatherability?

2. Ca+Mg concentration

- (ultra)mafic rocks from the mantle have the most Ca+Mg



(ultra)mafic rocks:

- oceanic crust
- island arc volcanoes
- flood basalts
- hotspot volcanoes

data from EarthChem, Park et al. (in press)

$$(\mathrm{Ca/Mg})\mathrm{SiO_3} + \mathrm{CO_2} \longrightarrow (\mathrm{Ca/Mg})\mathrm{CO_3} + \mathrm{SiO_2}$$

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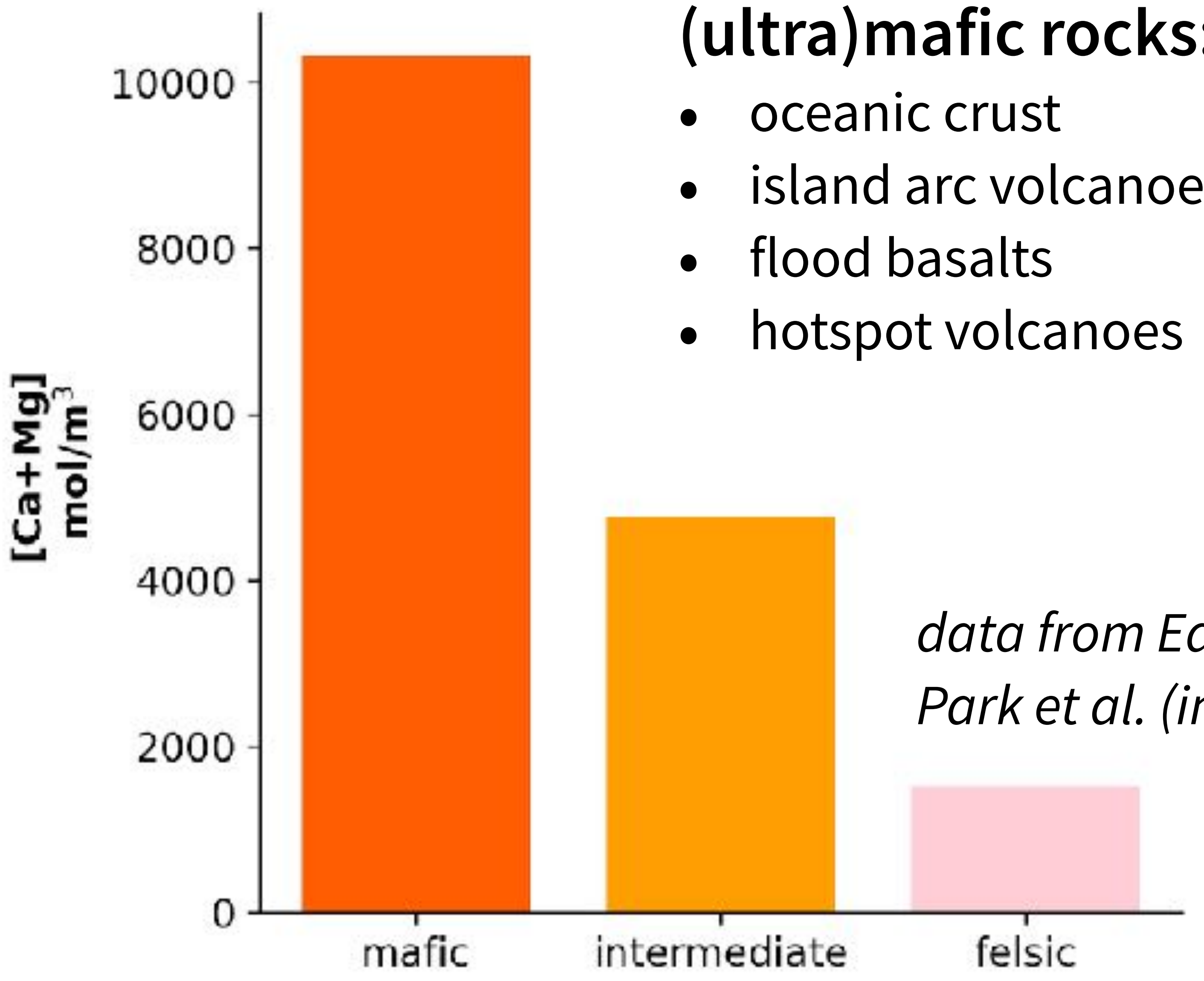

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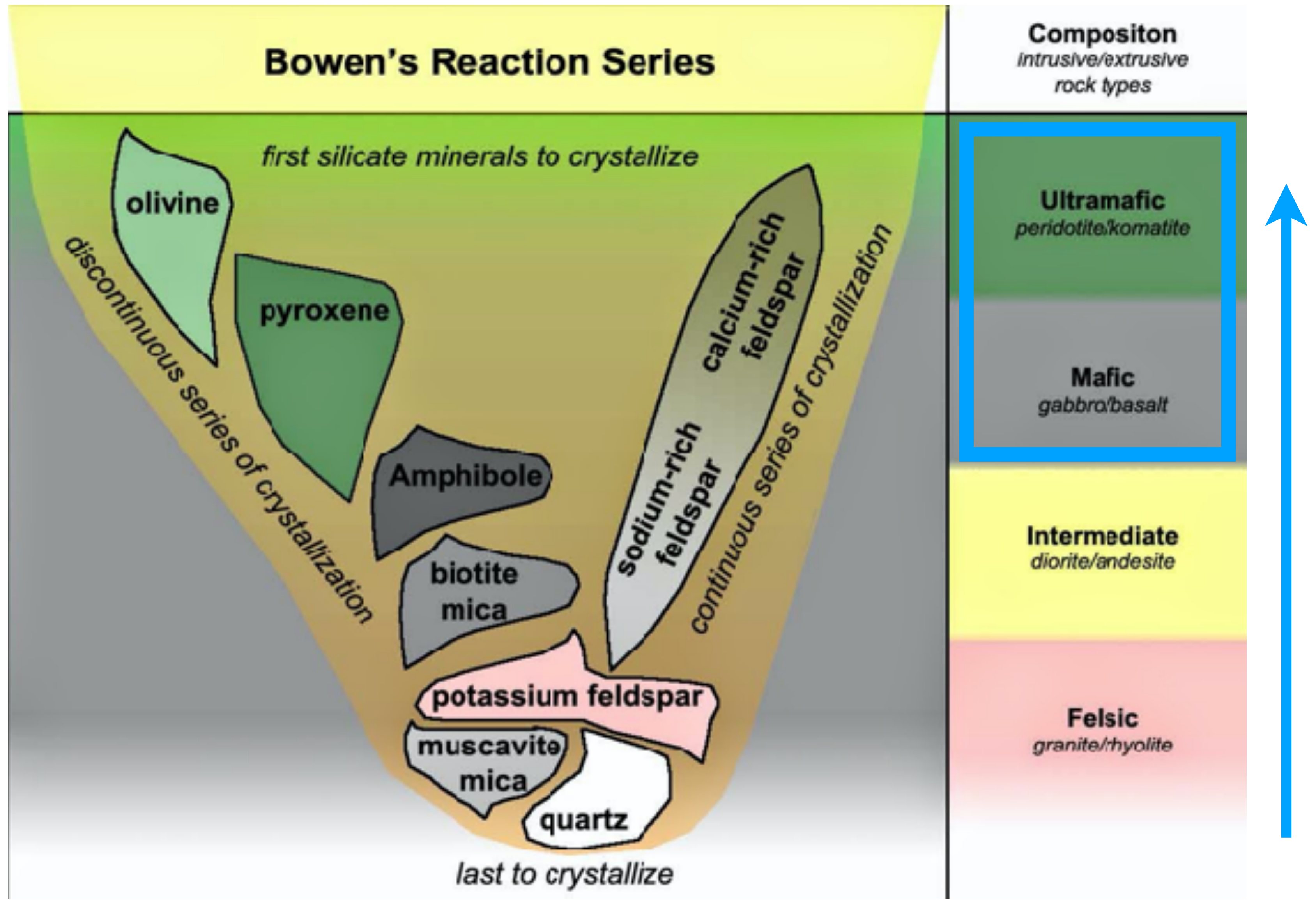
3. reactivity

- (ultra)mafic rocks from the mantle are the most reactive



less stable/ more reactive

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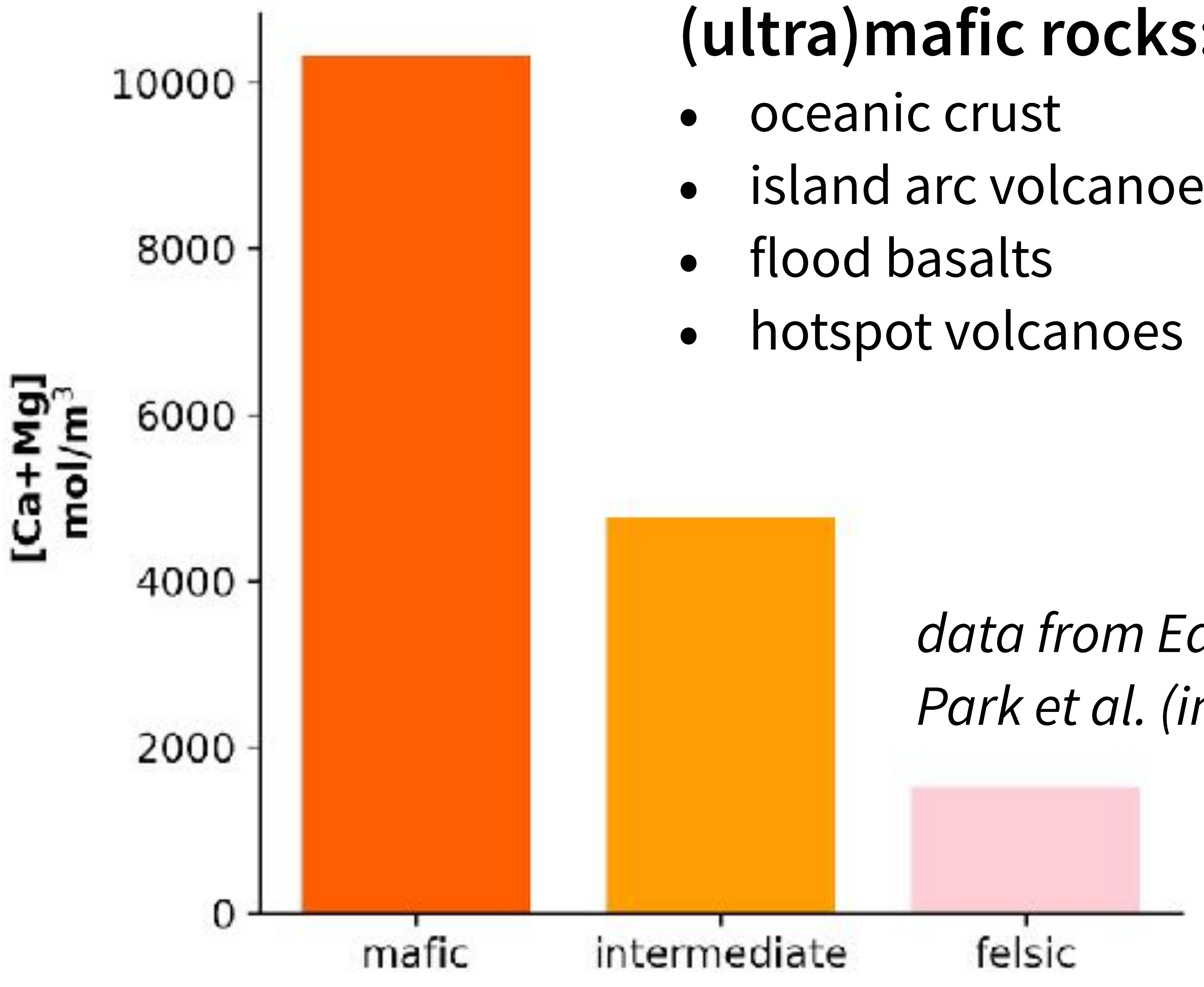
2+3. lithology

- (ultra)mafic rocks



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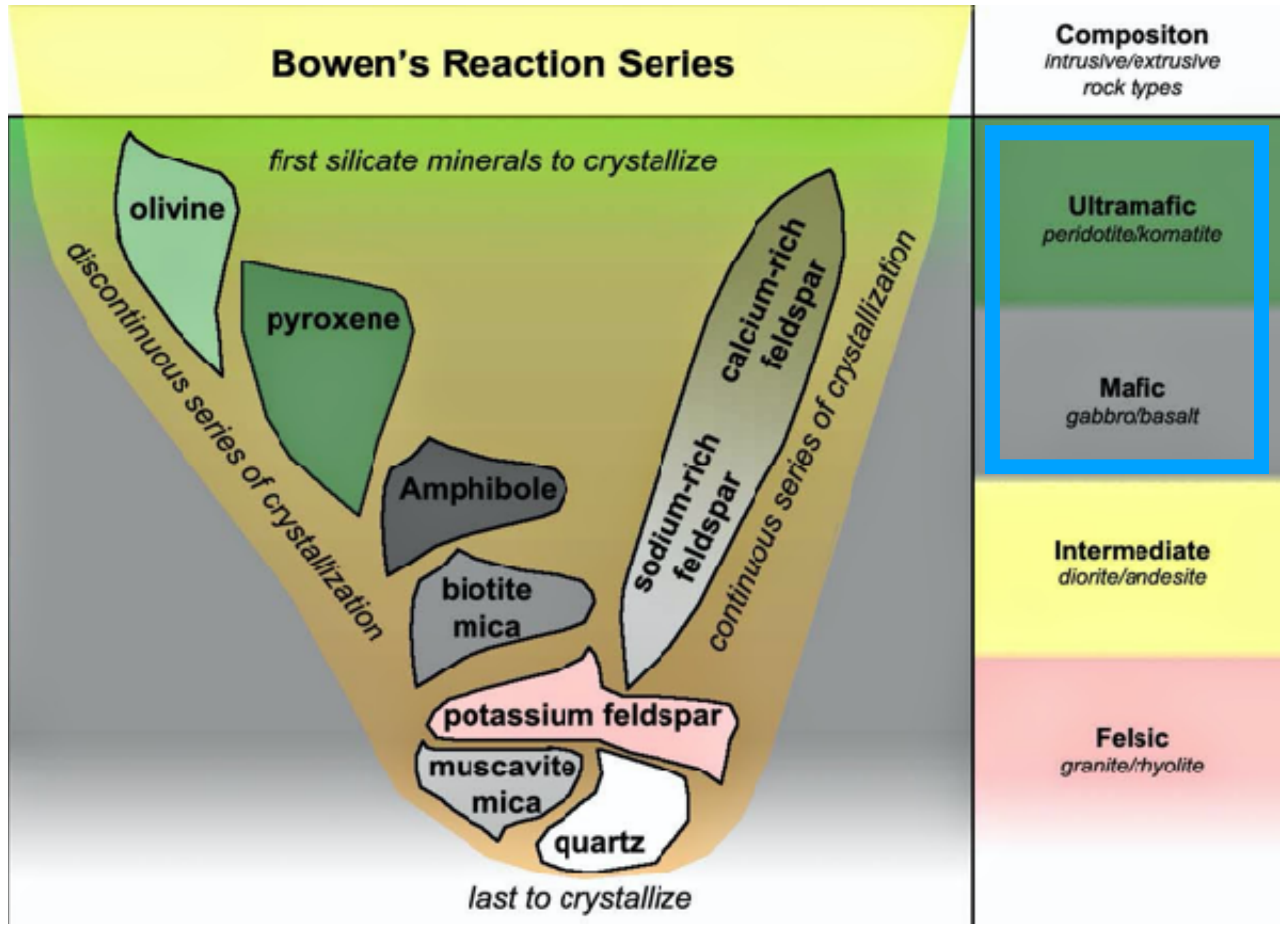

less stable/ more reactive

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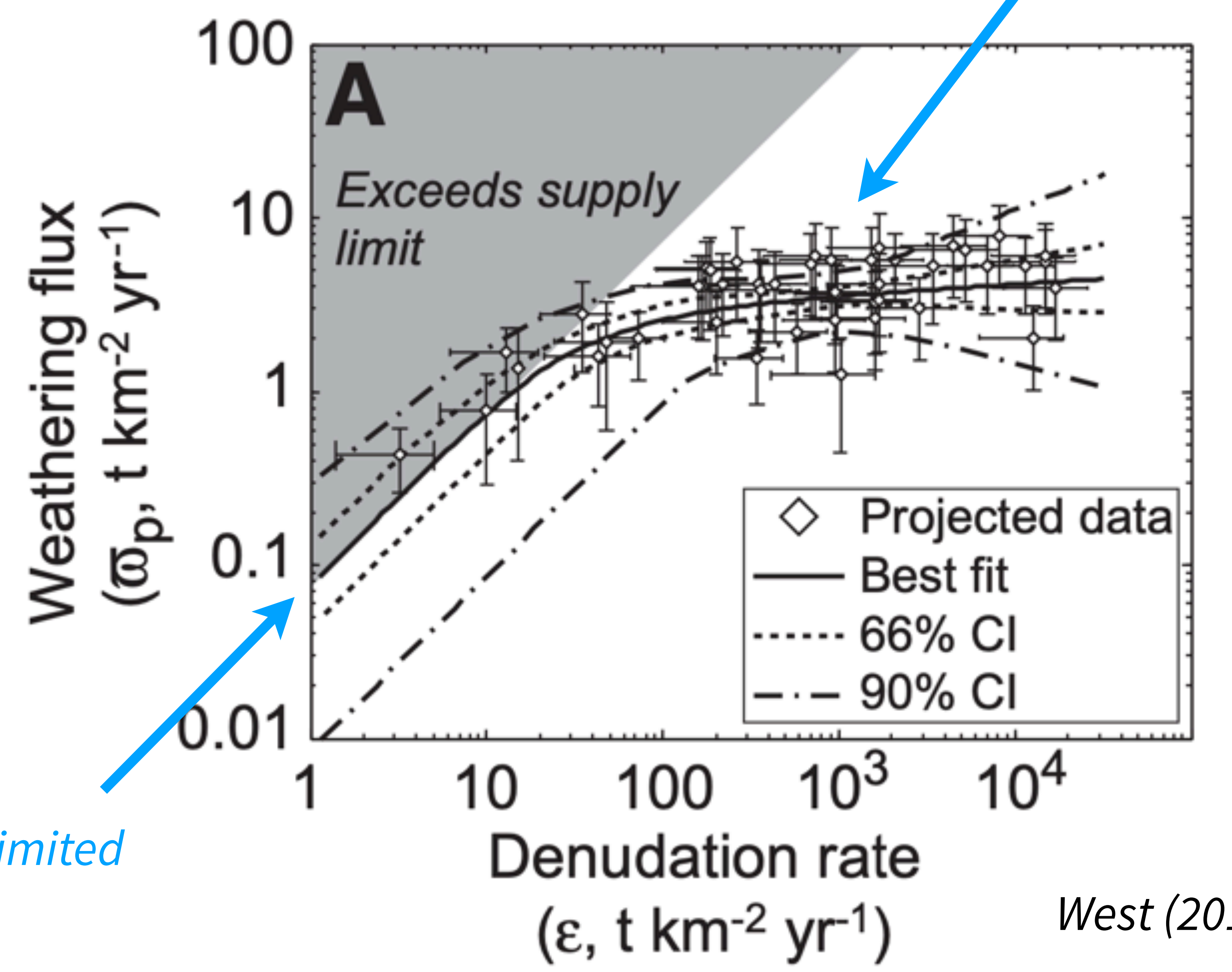
WEATHERABILITY

What affects planetary weatherability?

4. uplift rate + topography

- convergent regions have the highest uplift rates and steepest topography

transport-limited



supply-limited

West (2012)

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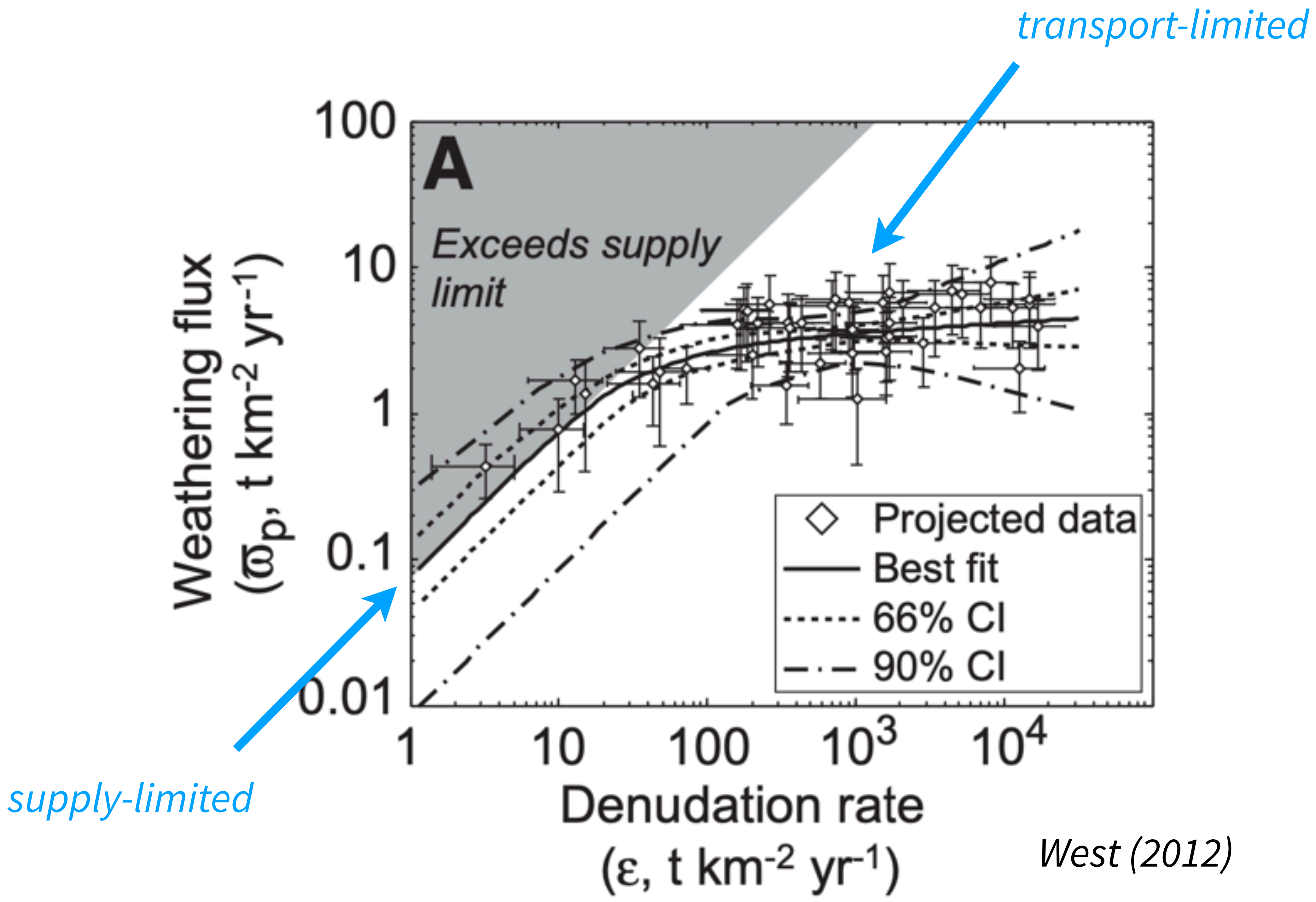

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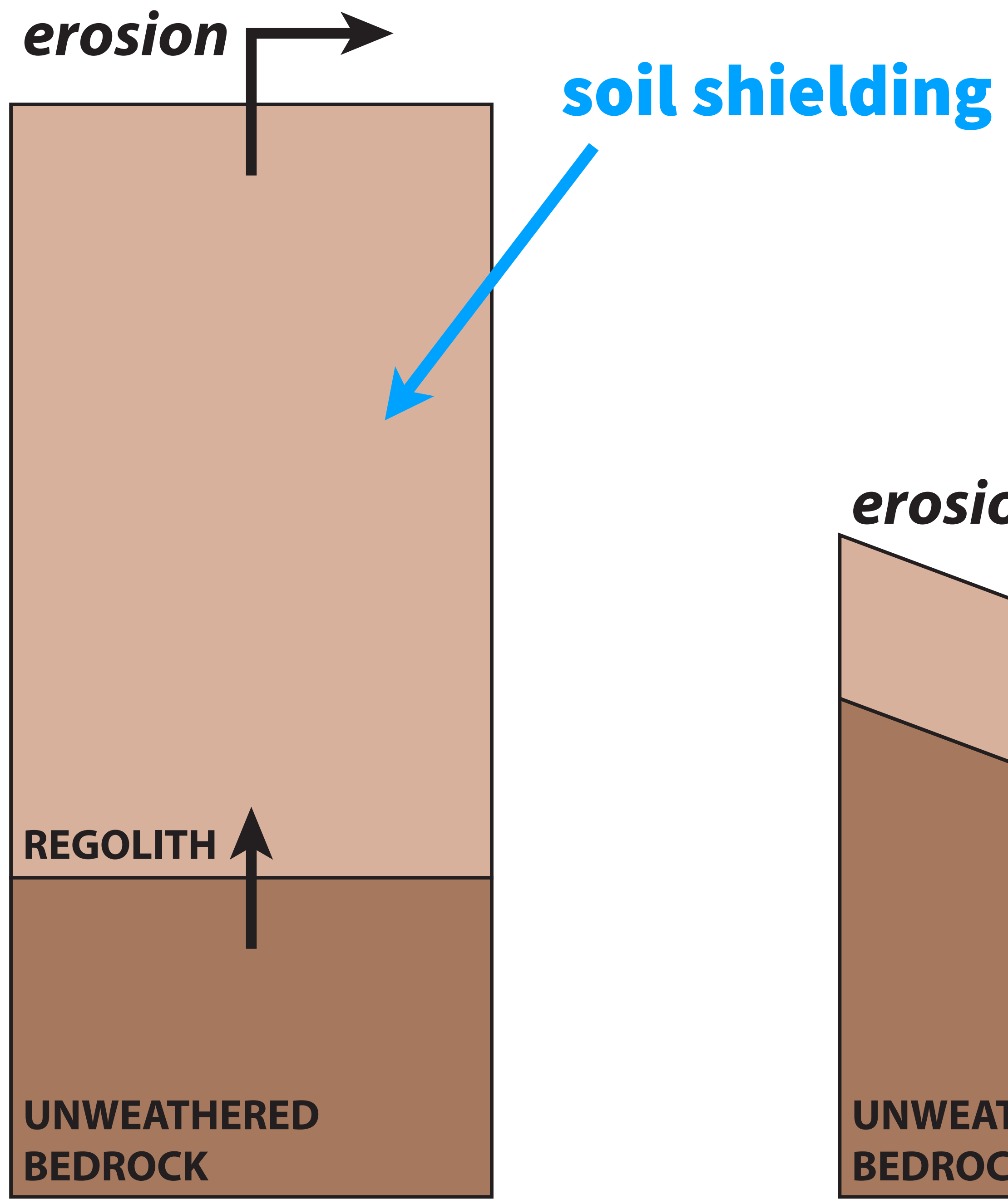
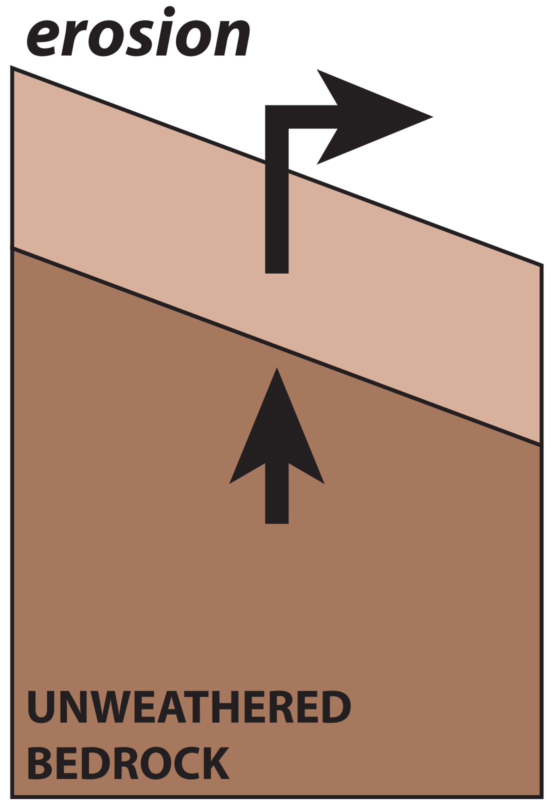


slow uplift
gentle topography
slow erosion



fast uplift
steep topography
fast erosion

WEATHERABILITY

What geologic environment brings together these 4 factors?

large igneous province eruption in the tropics

island arc exhumation in the tropics

1. location of rocks

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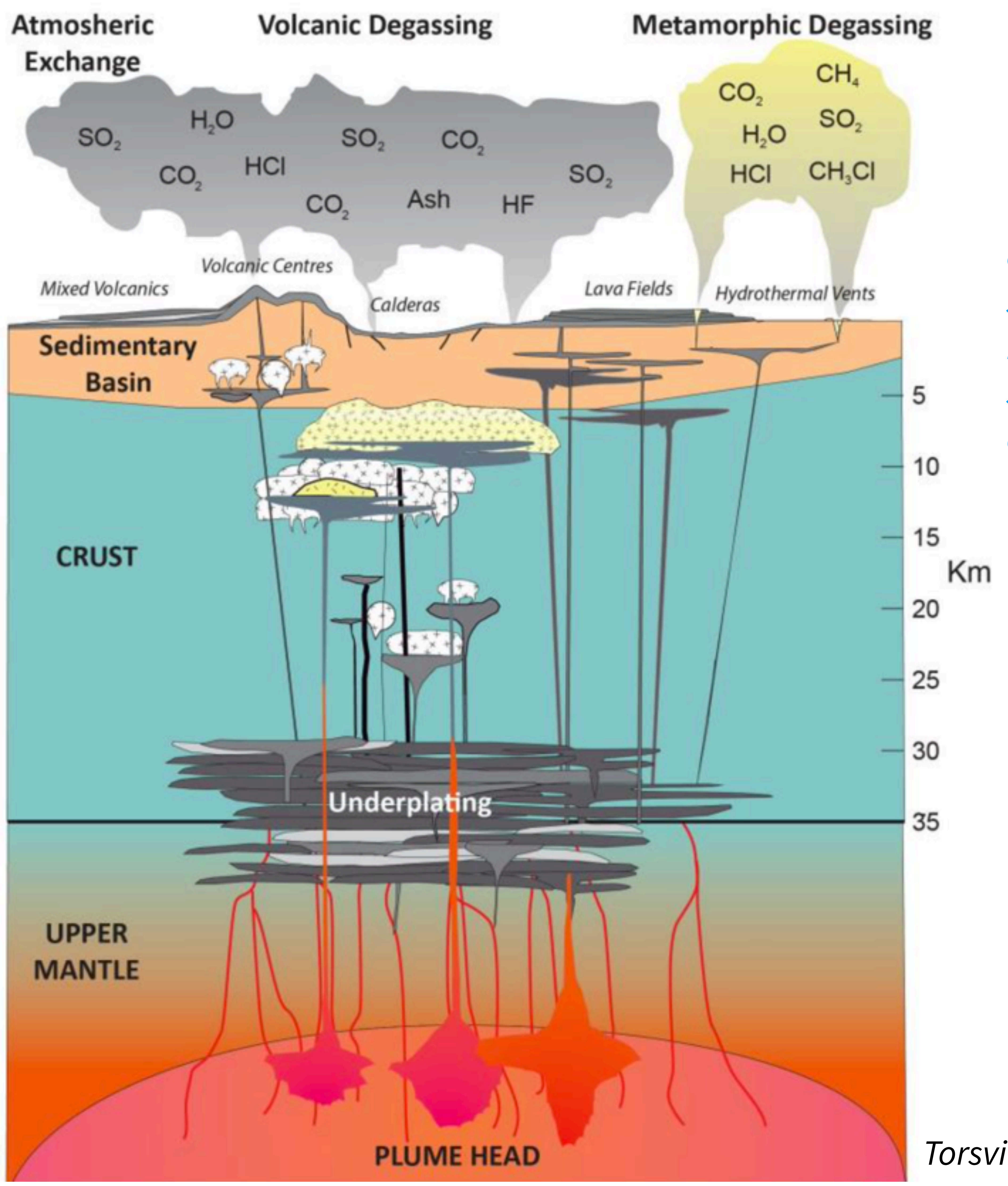

large igneous provinces

erupted onto stable continental interiors or subsiding basins during rifting

Torsvik et al. (in press)

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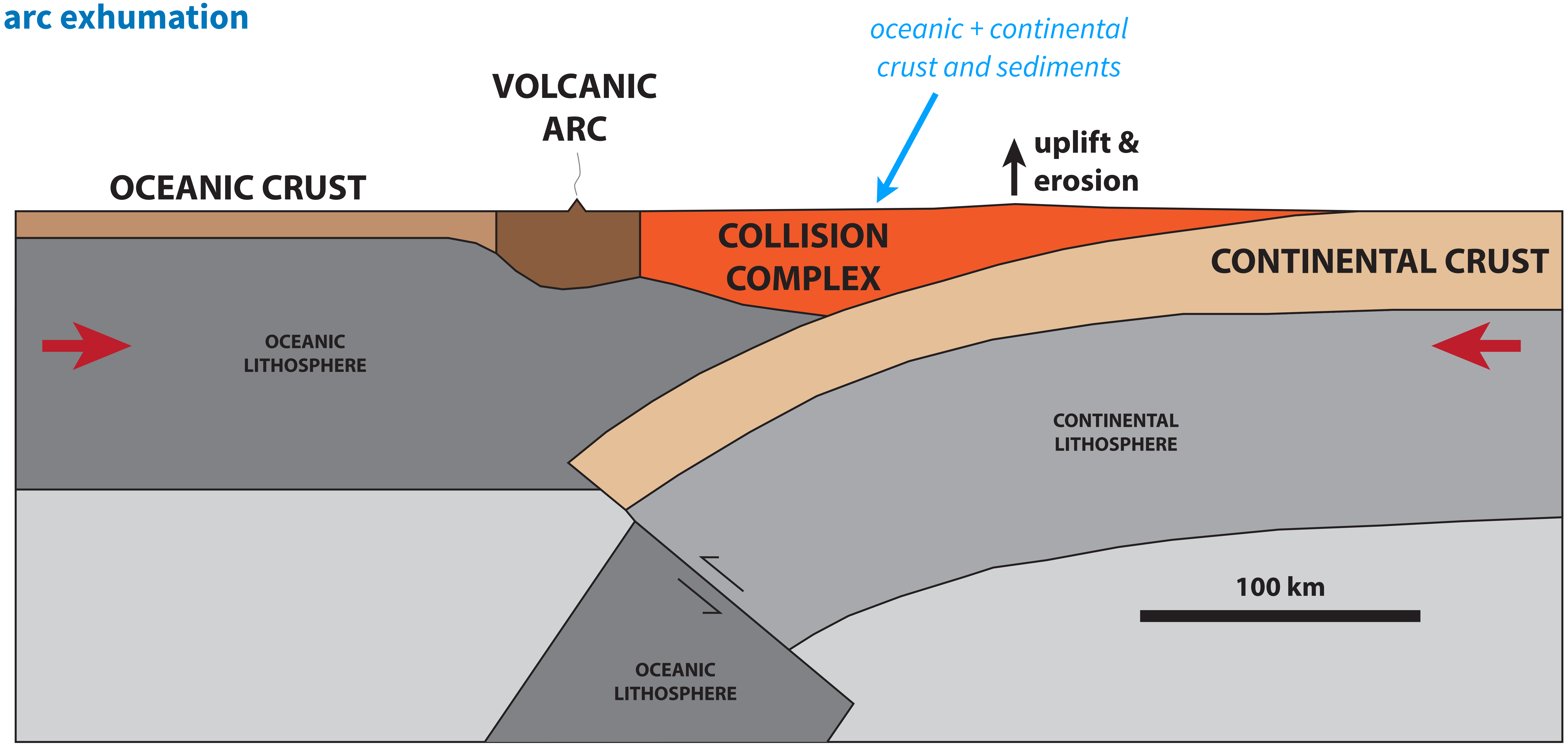
arc exhumation



Banda Arc, simplified from Charlton (1991)

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WEATHERABILITY

hypothesis:

tropical island arc exhumation is important for setting Earth's long-term climate state

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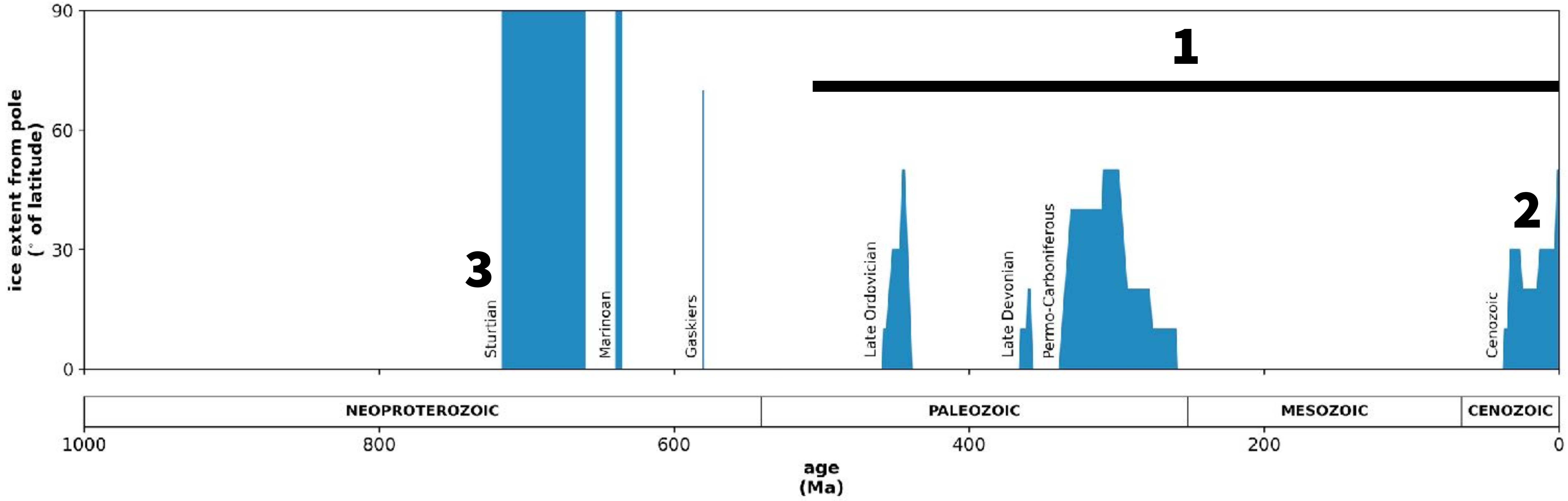
OUTLINE

hypothesis:

tropical island arc exhumation is important for setting Earth's long-term climate state

1. If we look at the past ~520 million years as a whole, do tropical arc-continent collisions coincide with times of glacial climate?
2. Arc-continent collision is happening in the tropics today in the Southeast Asian islands: is this event responsible for cooling over the past ~15 million years?
3. Is tropical island arc exhumation also responsible for a "snowball" glaciation ~717 million years ago?



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PHANEROZOIC ARC-CONTINENT COLLISIONS

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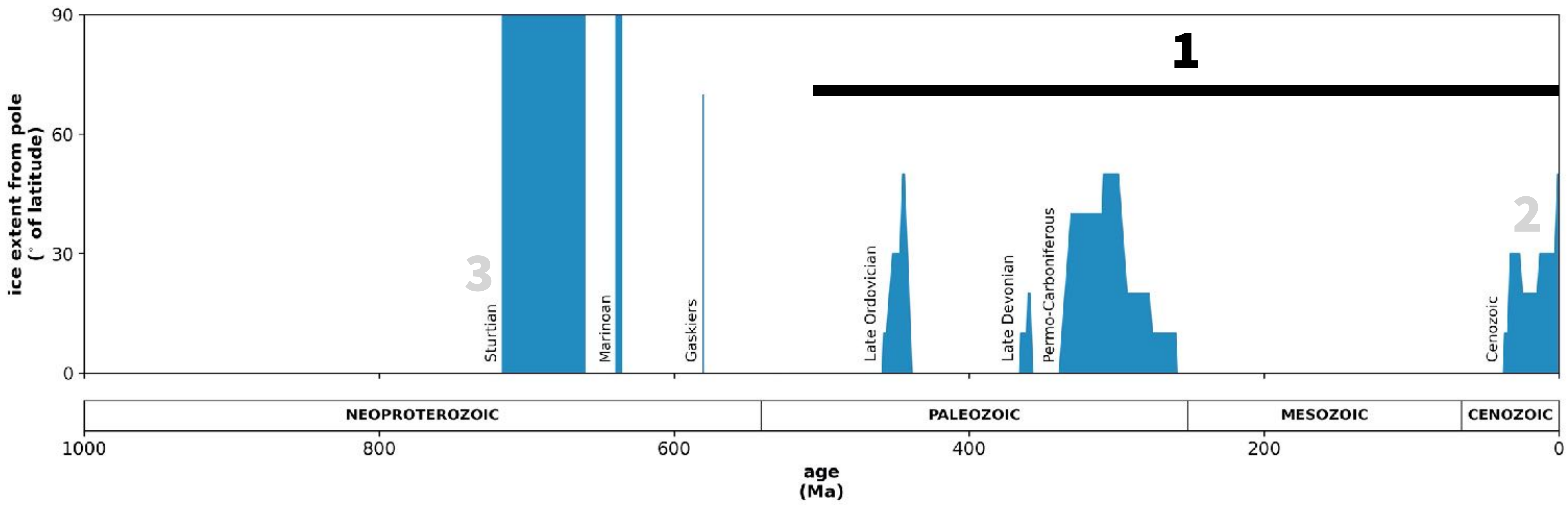
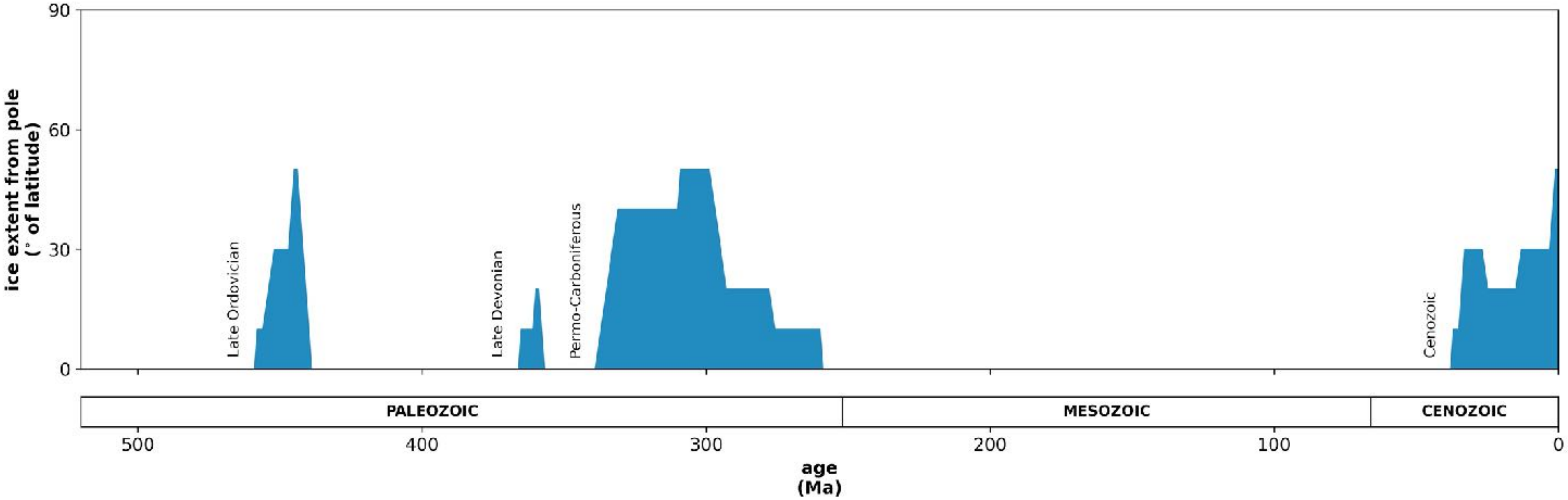


PHANEROZOIC ARC-CONTINENT COLLISIONS

1. If we look at the past ~520 million years as a whole, do tropical arc-continent collisions coincide with times of glacial climate?

   1. location of preserved remnants of arc-continent collisions
   2. age of exhumation of mafic lithologies
   3. paleogeographic model
   4. a record of Earth's climate state

Macdonald, Swanson-Hysell, Park, Lisiecki, Jagoutz (2019)



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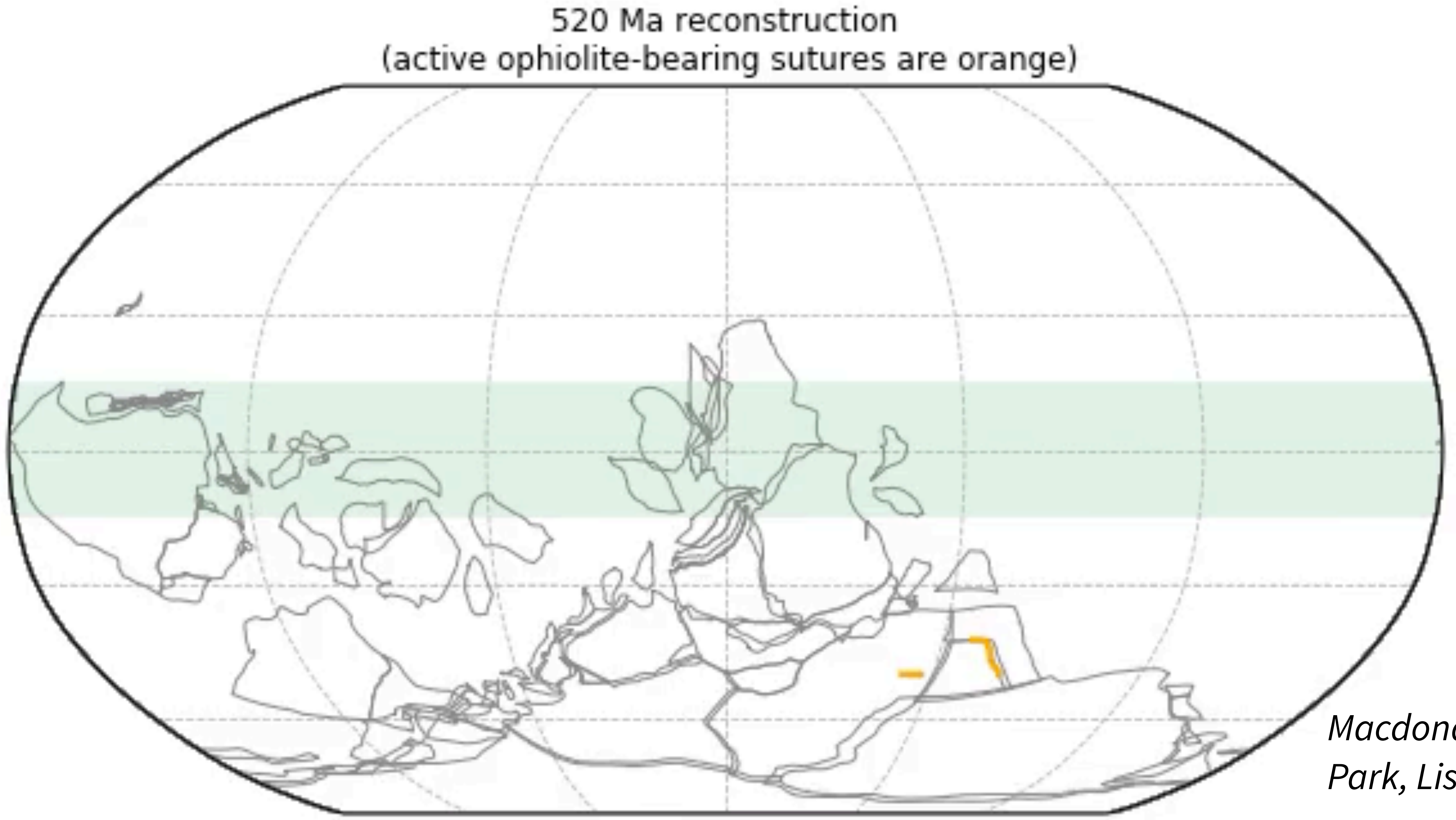

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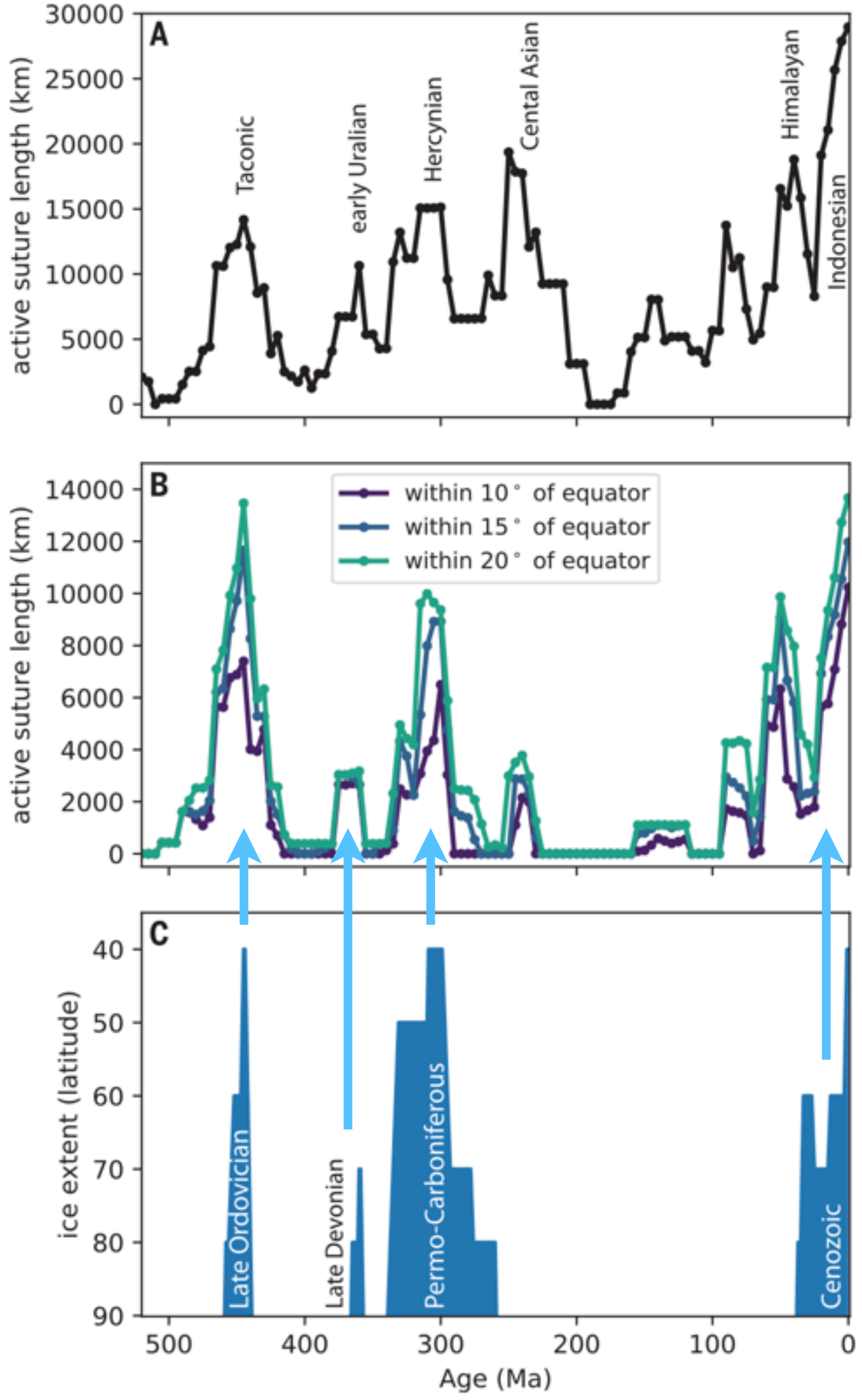

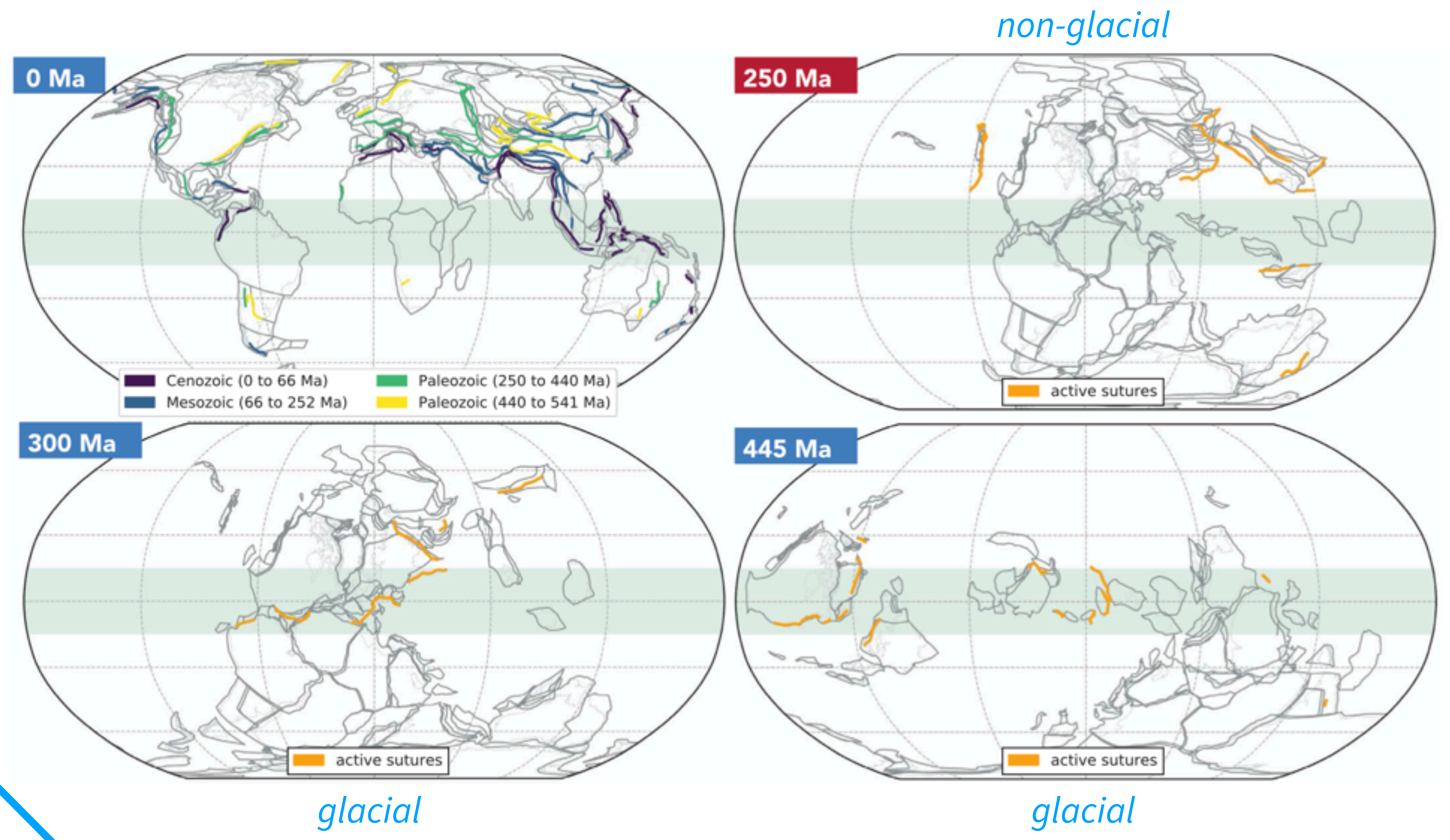

well correlated

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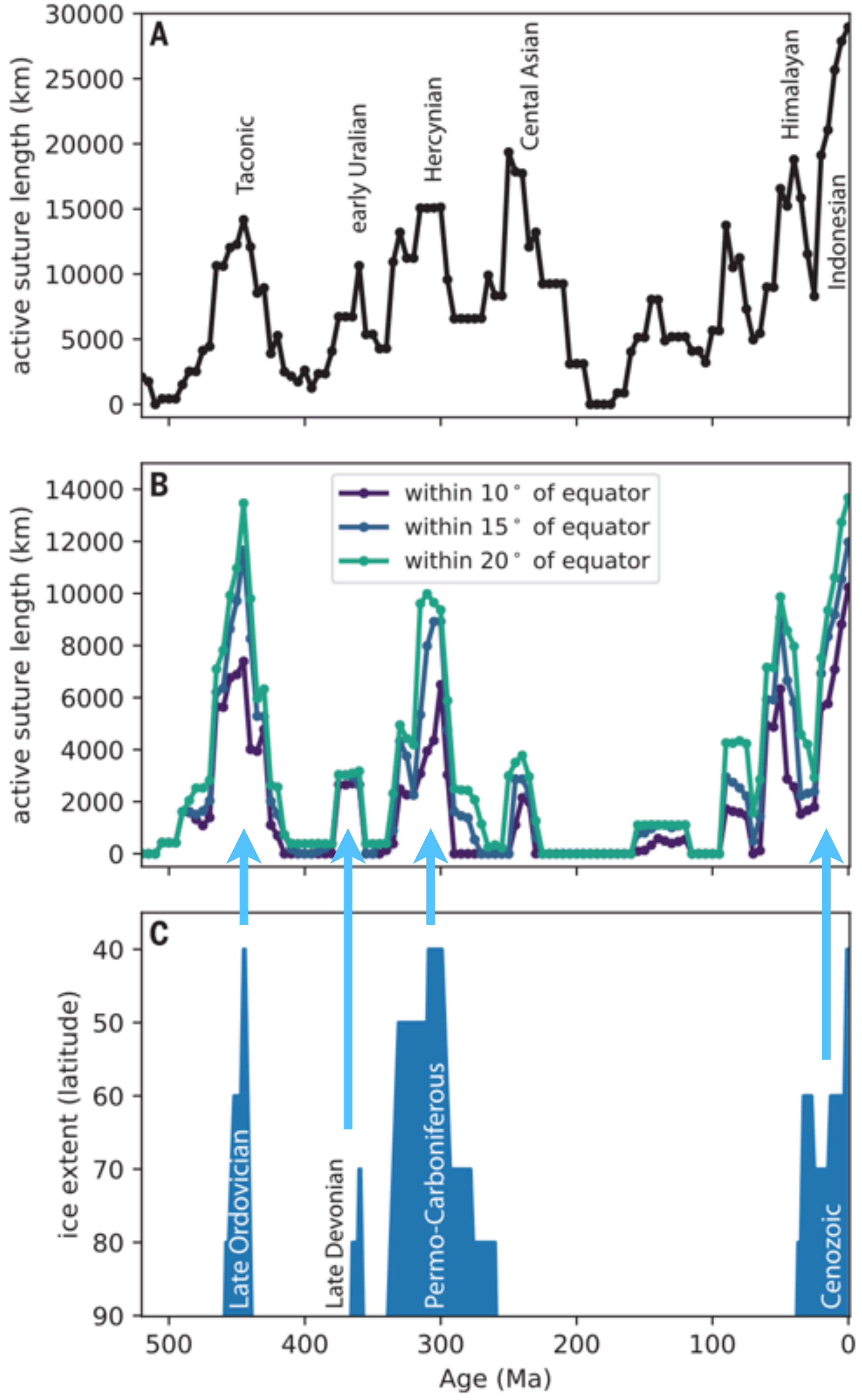
PHANEROZOIC ARC-CONTINENT COLLISIONS



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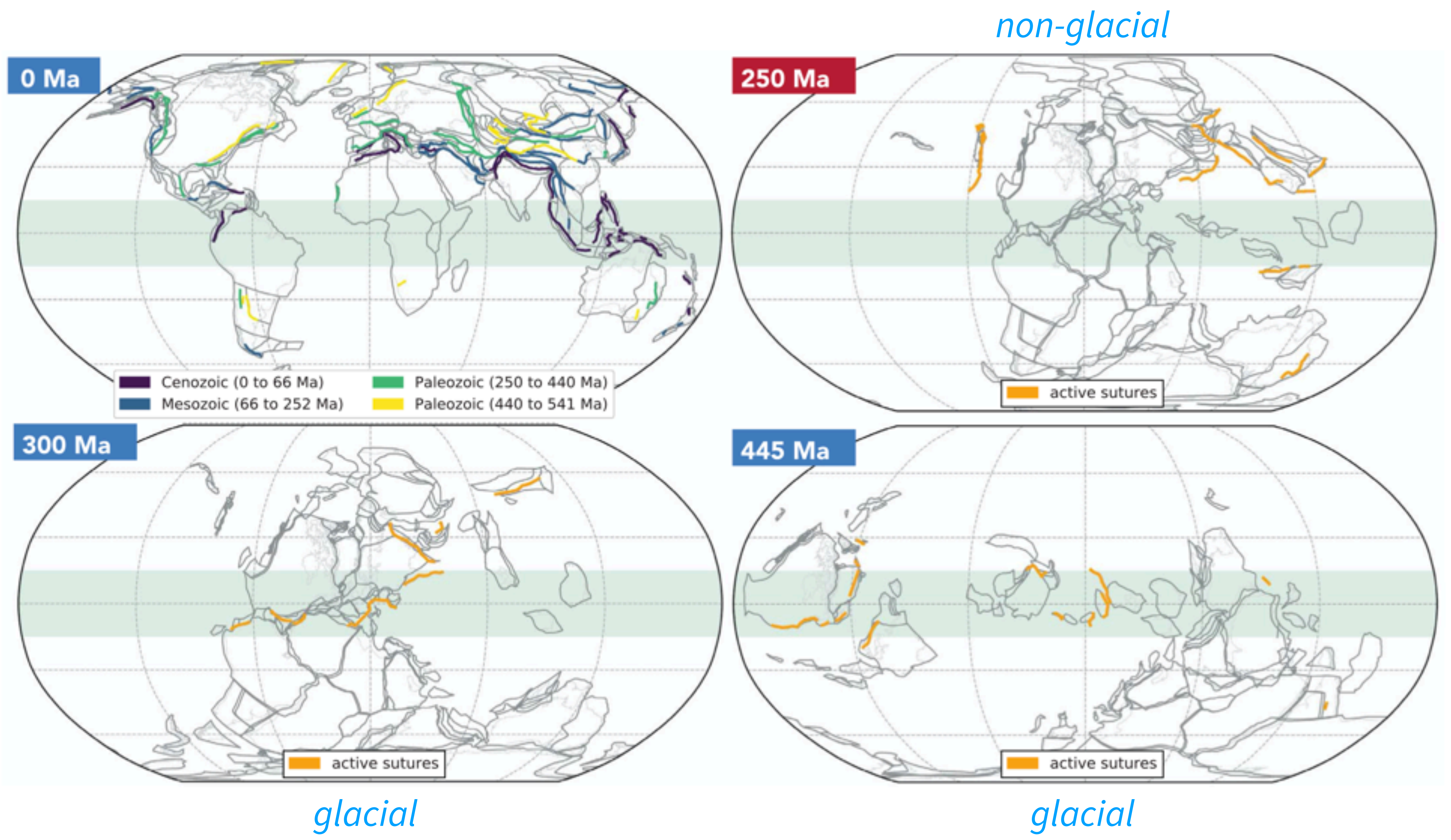

null hypothesis:
"glacial intervals do not correlate with the length of active sutures in the tropics"

reject at 99.998% confidence level

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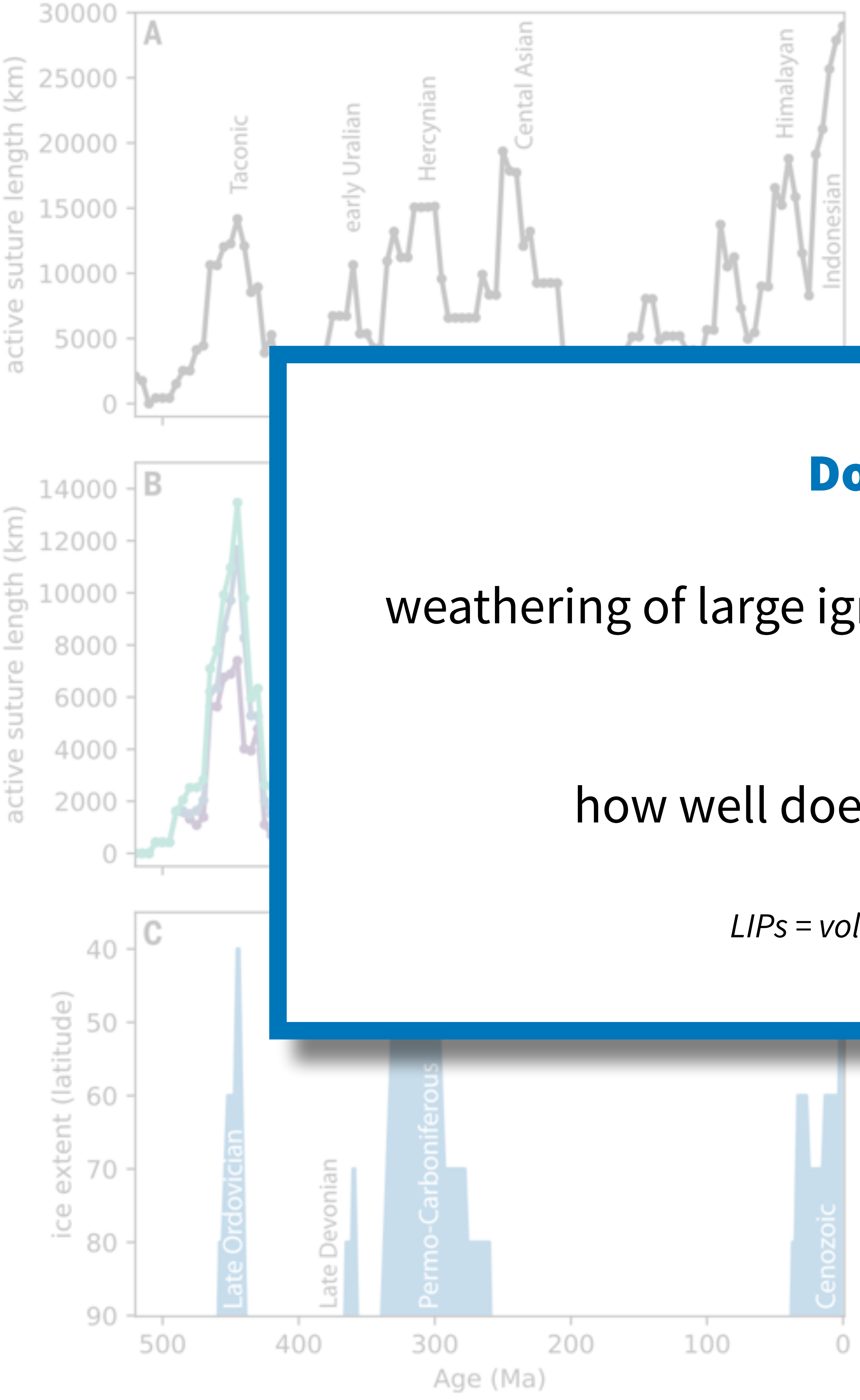

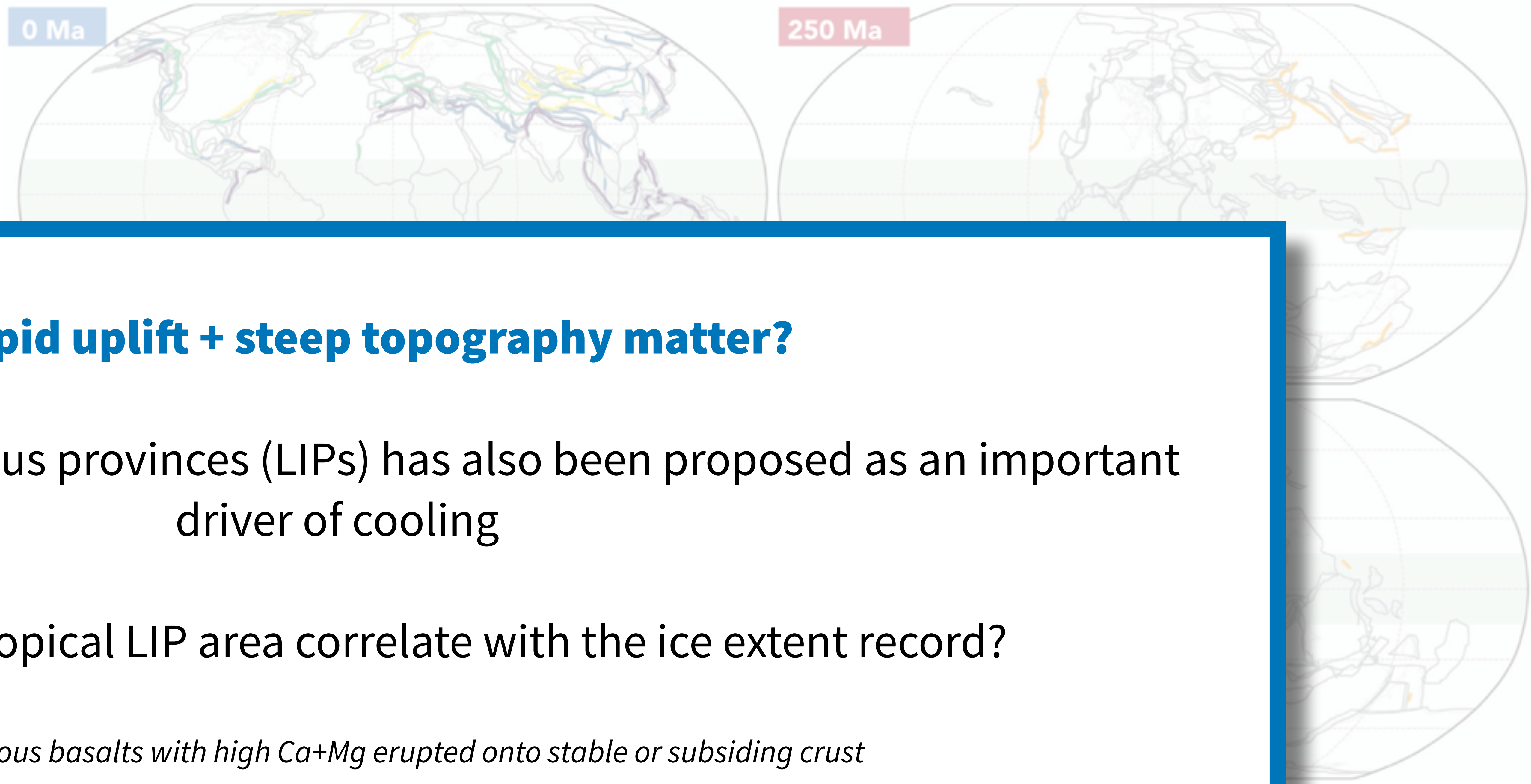

Do rapid uplift + steep topography matter?

weathering of large igneous provinces (LIPs) has also been proposed as an important driver of cooling

how well does tropical LIP area correlate with the ice extent record?

LIPs = voluminous basalts with high Ca+Mg erupted onto stable or subsiding crust

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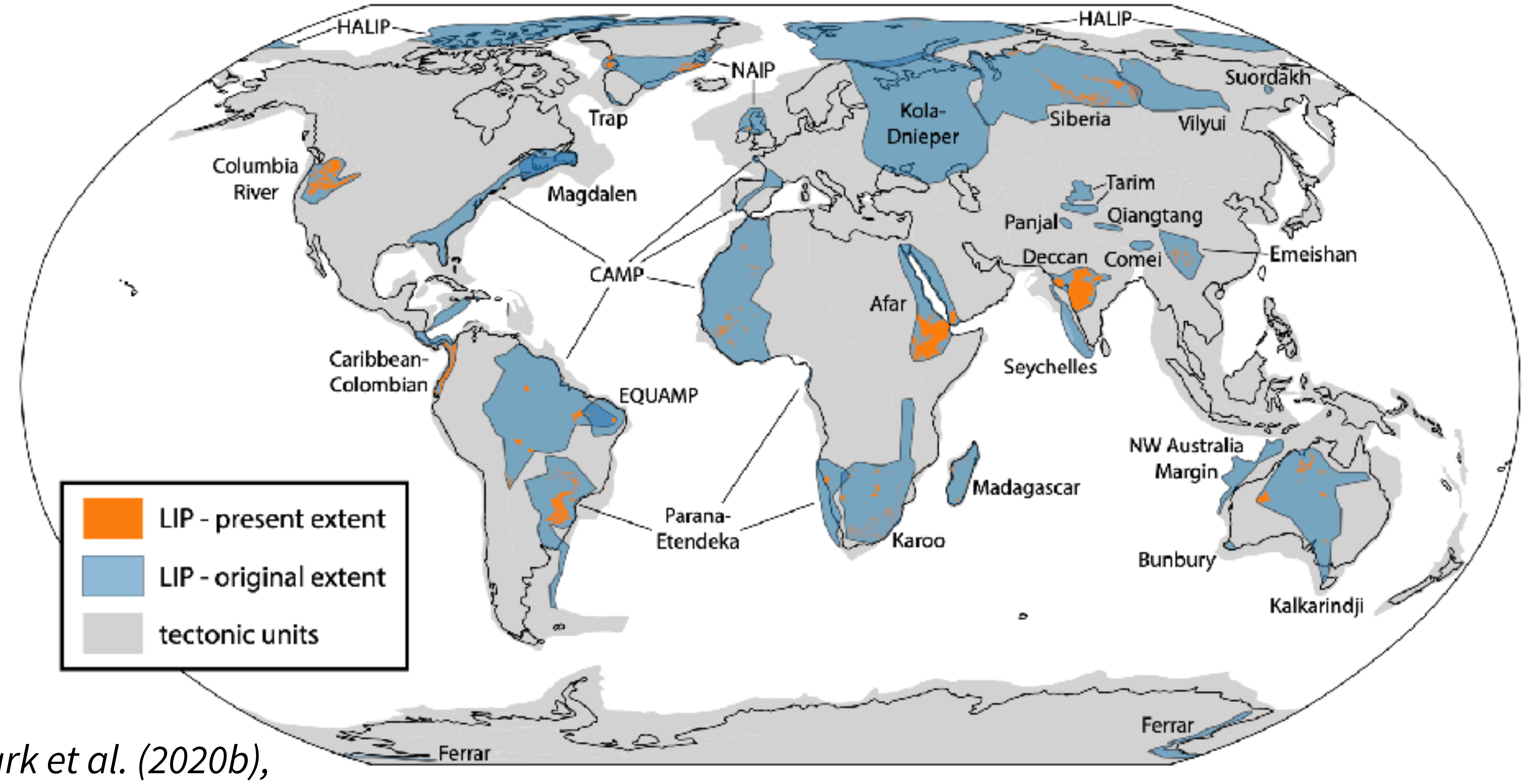
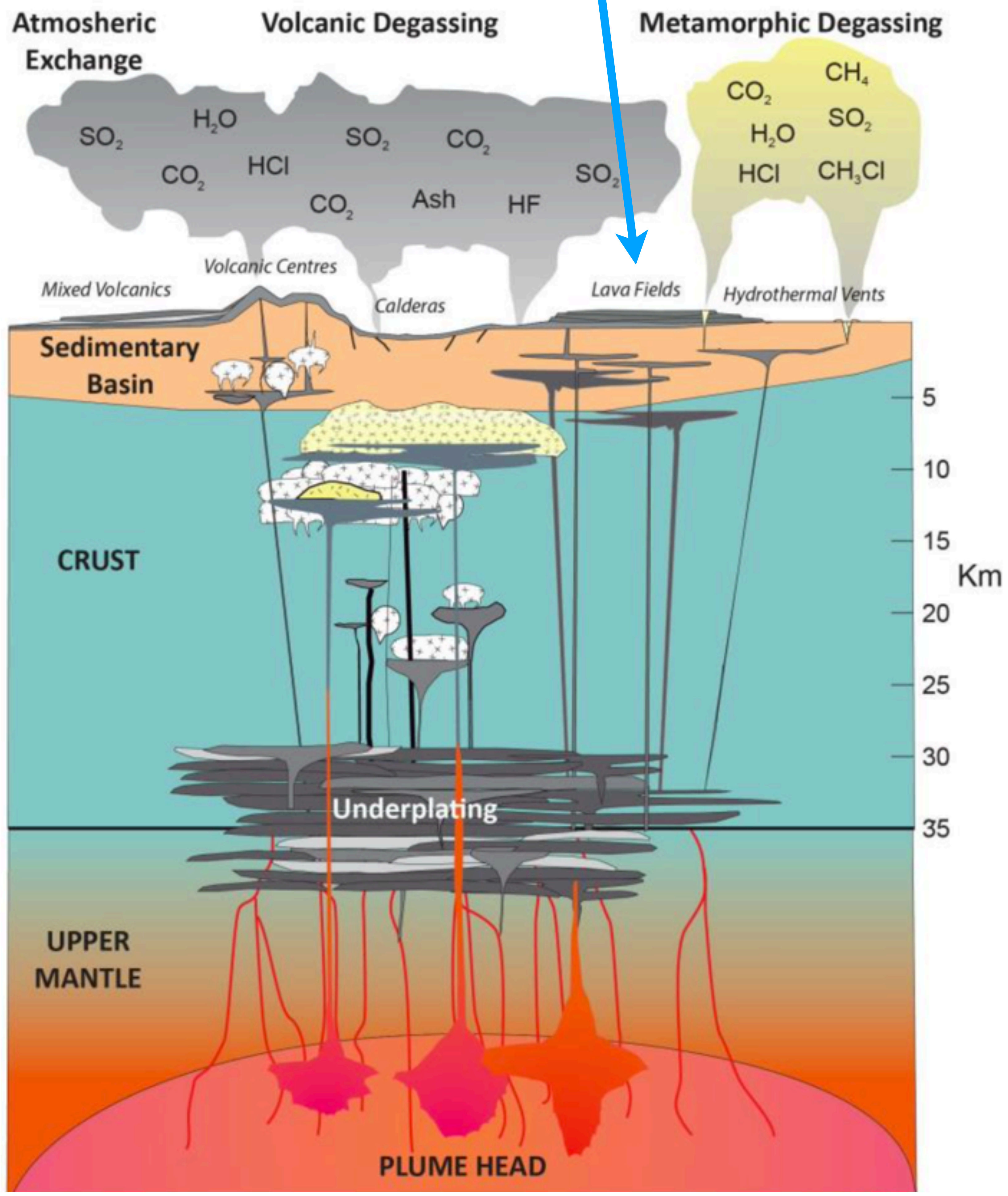
PHANEROZOIC LARGE IGNEOUS PROVINCES



Park et al. (2020b),
modified from Ernst and Youbi (2017)

LIPs remain at the surface after eruption



Torsvik et al. (in press)

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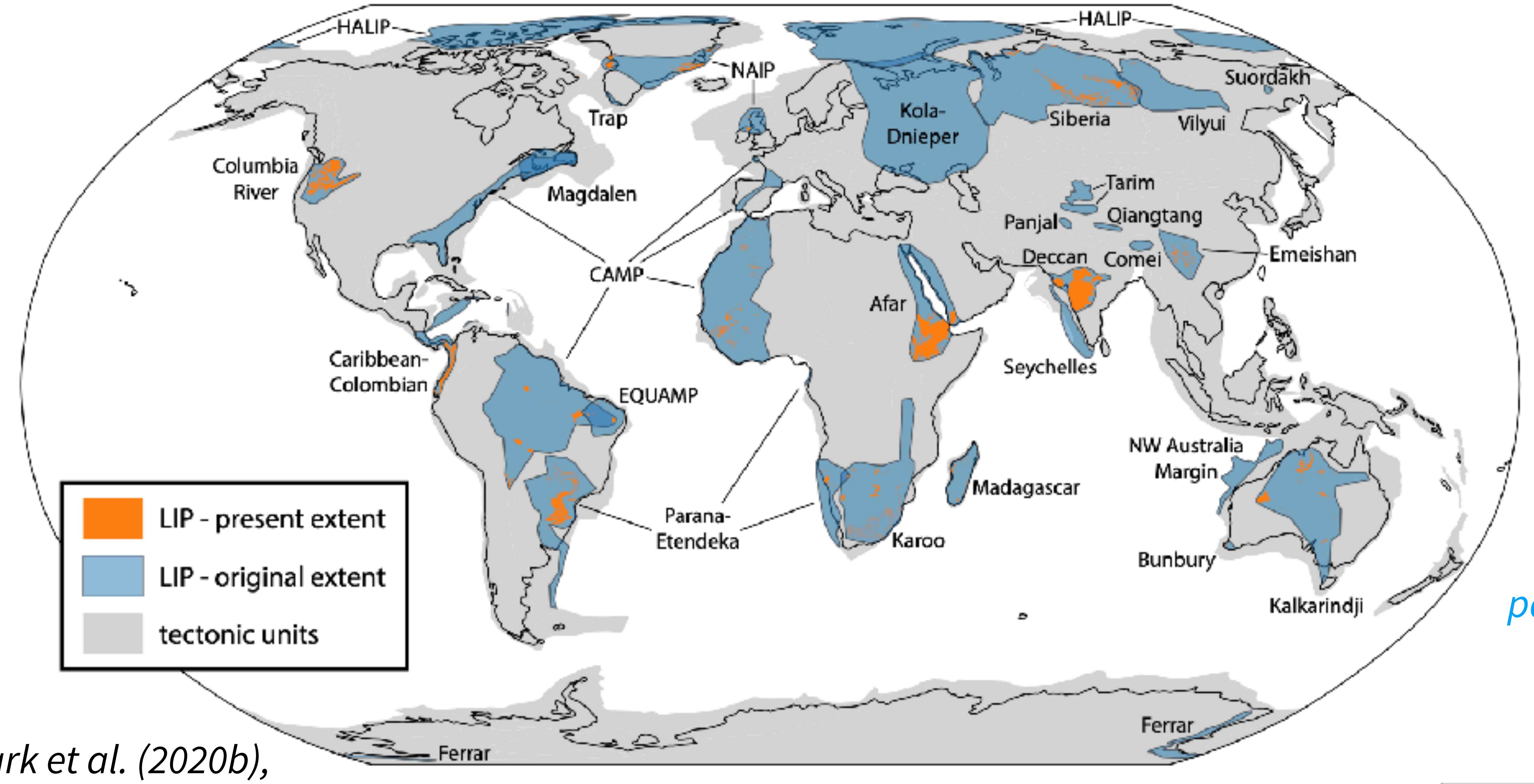

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parameterization
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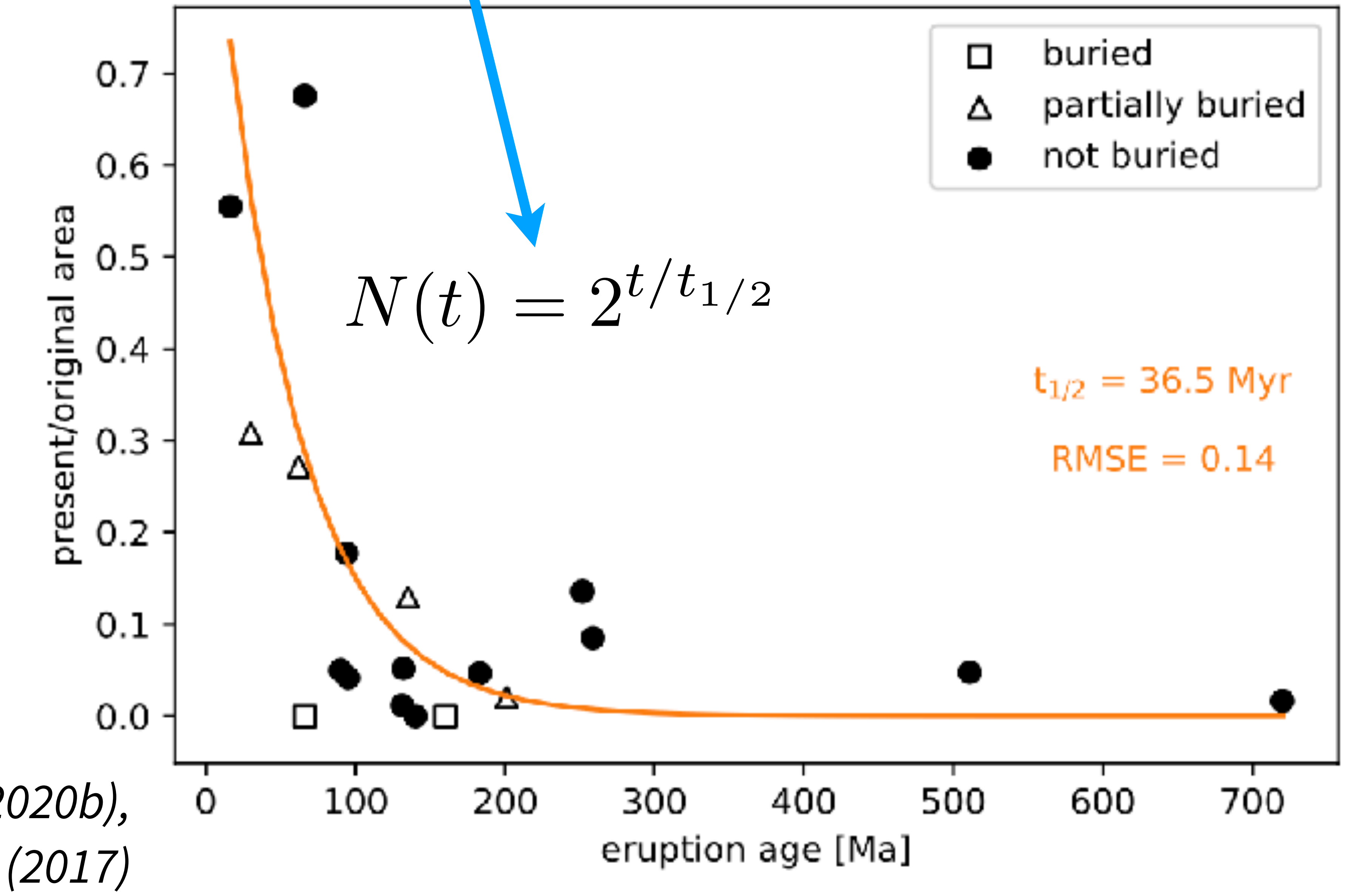

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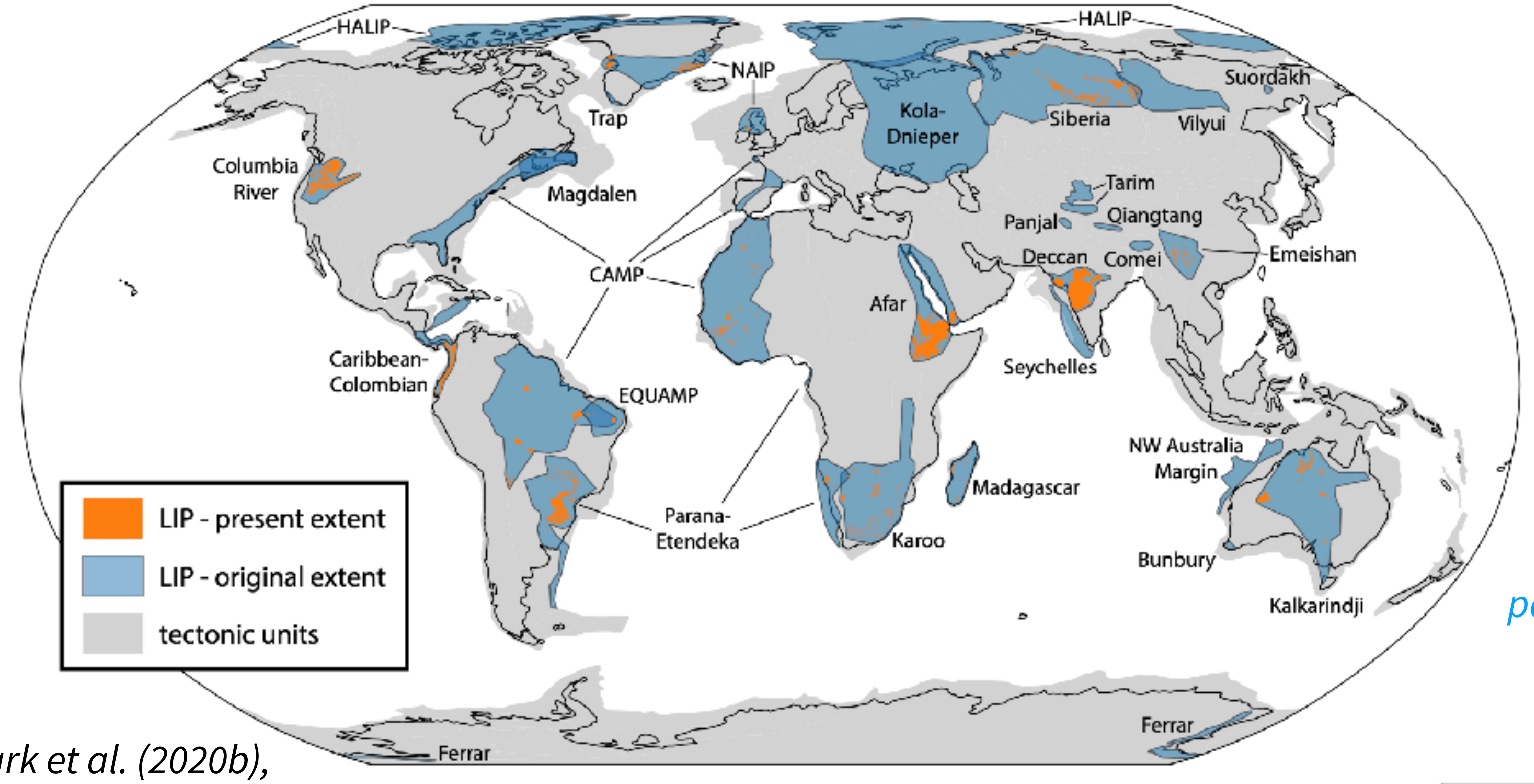
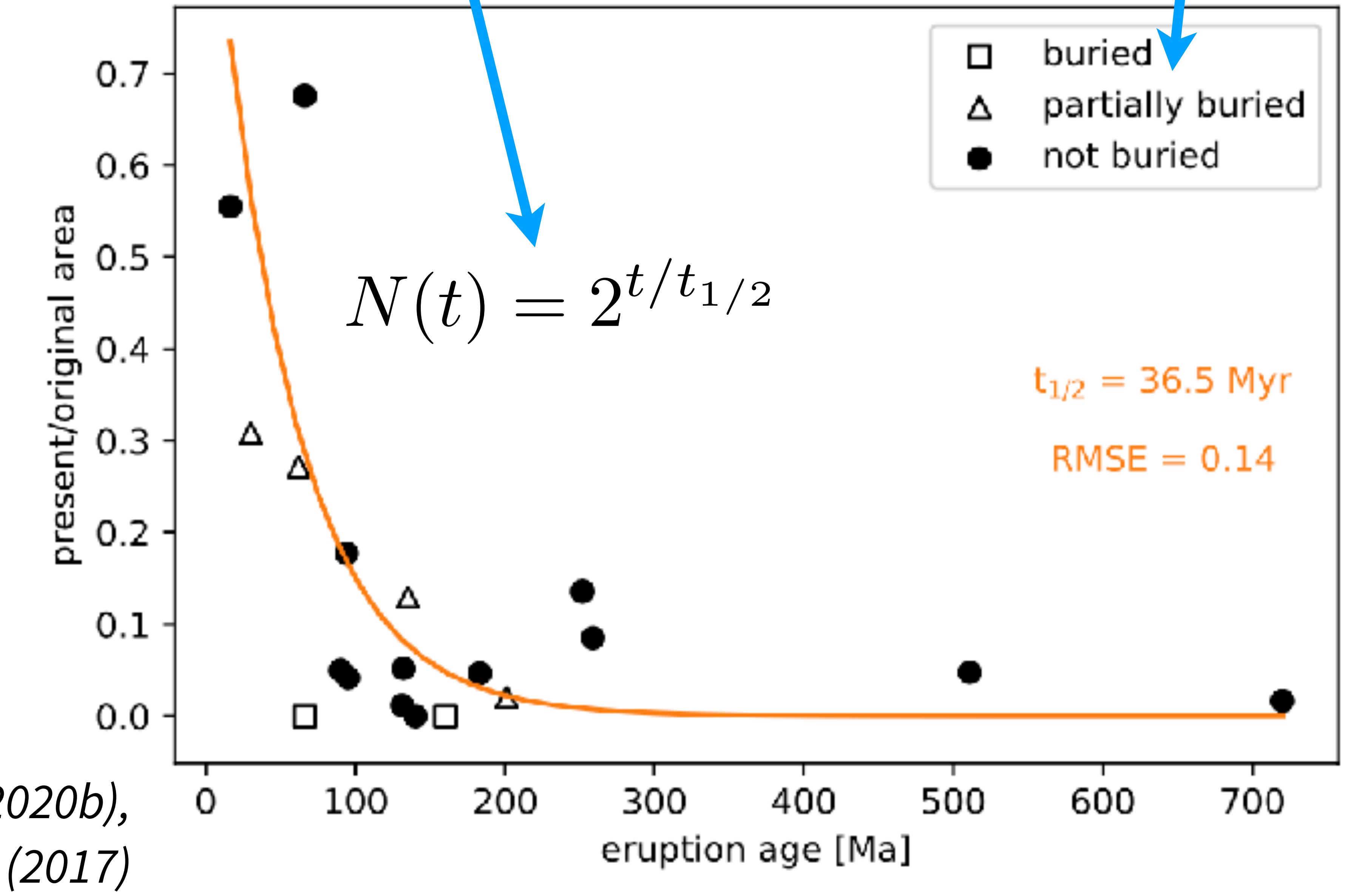


Park et al. (2020b), modified from Ernst and Youbi (2017)

"bury" LIPs associated with rifting

instantly remove 50% of area

parameterization of LIP erosion



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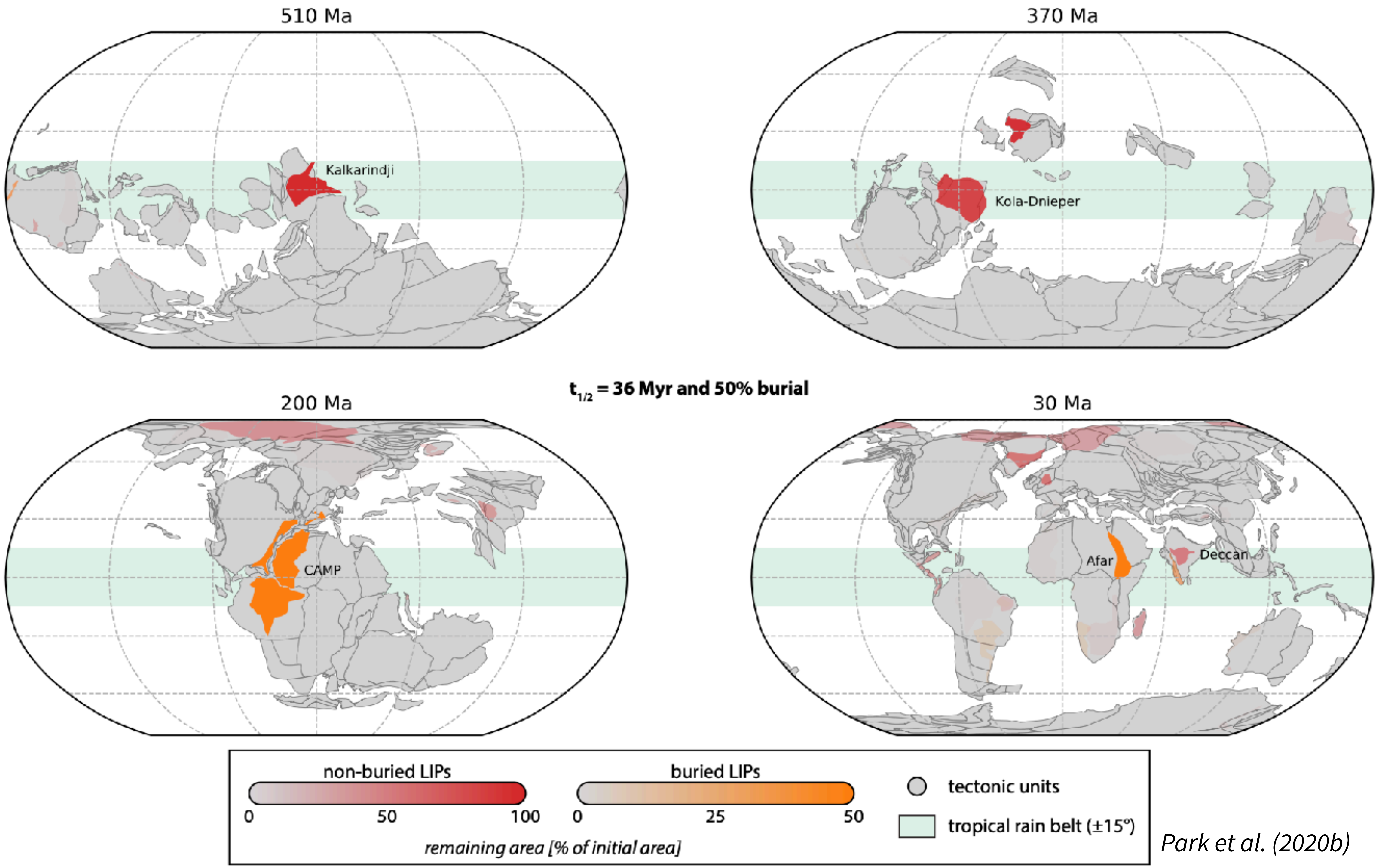

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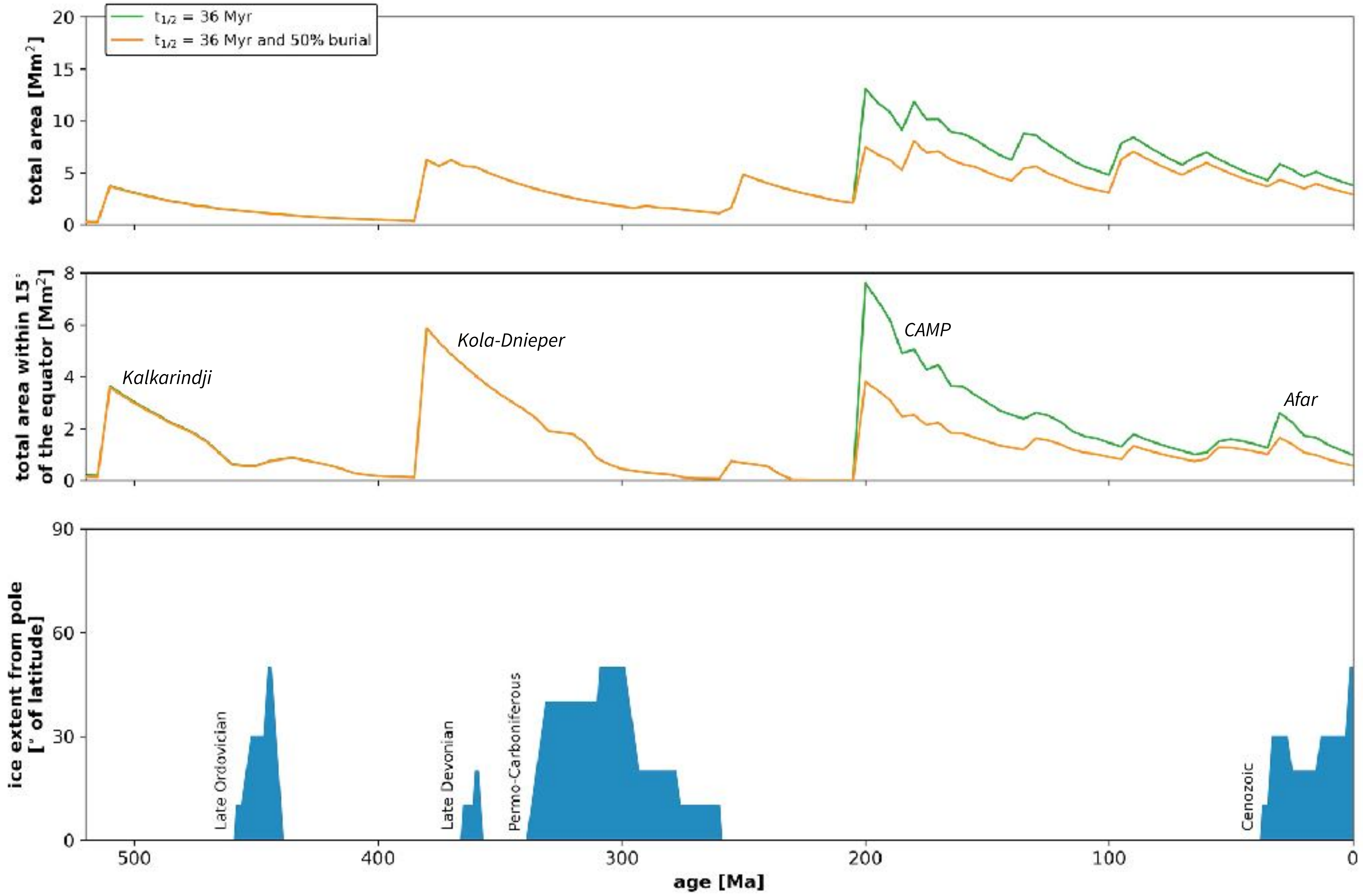

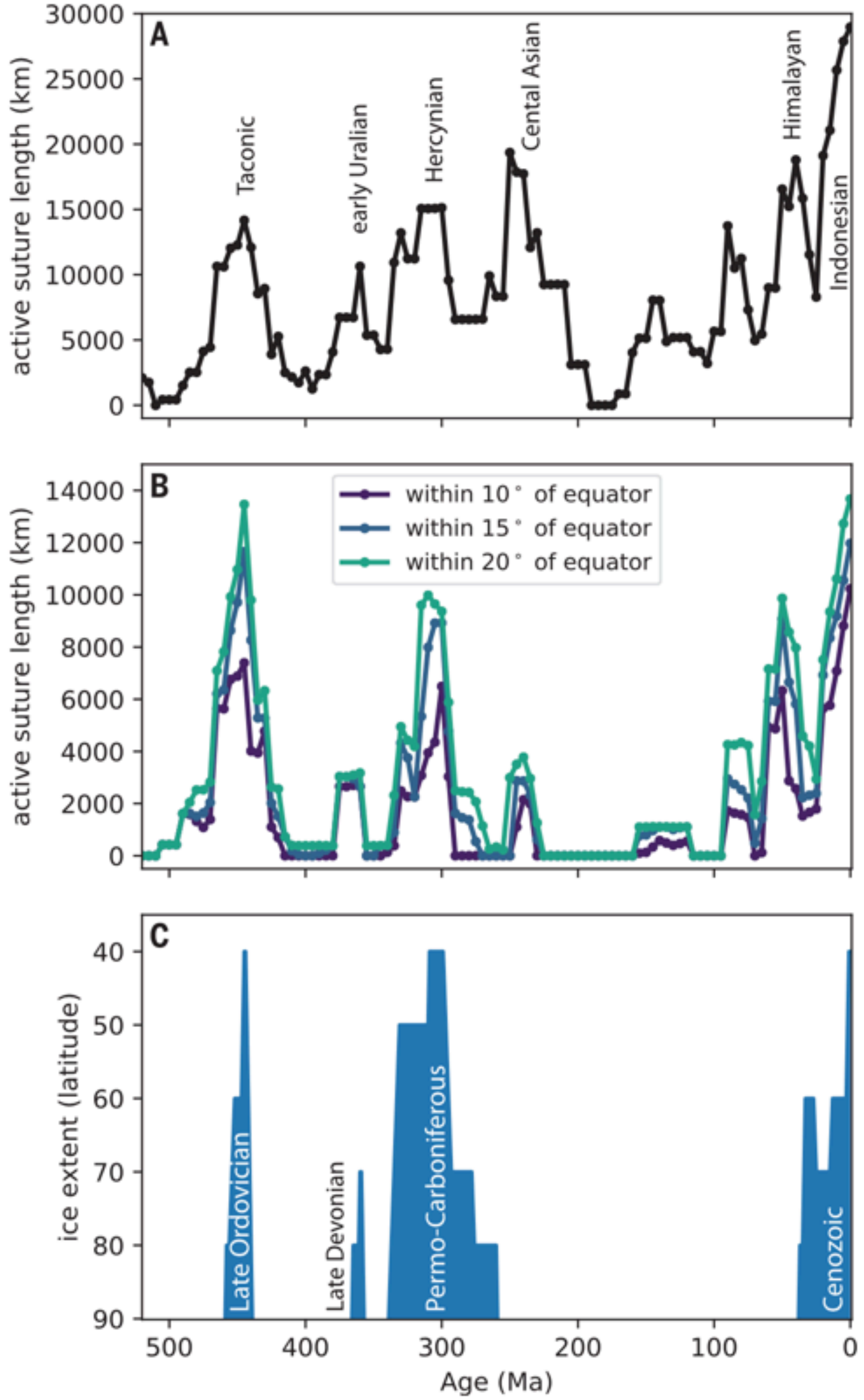

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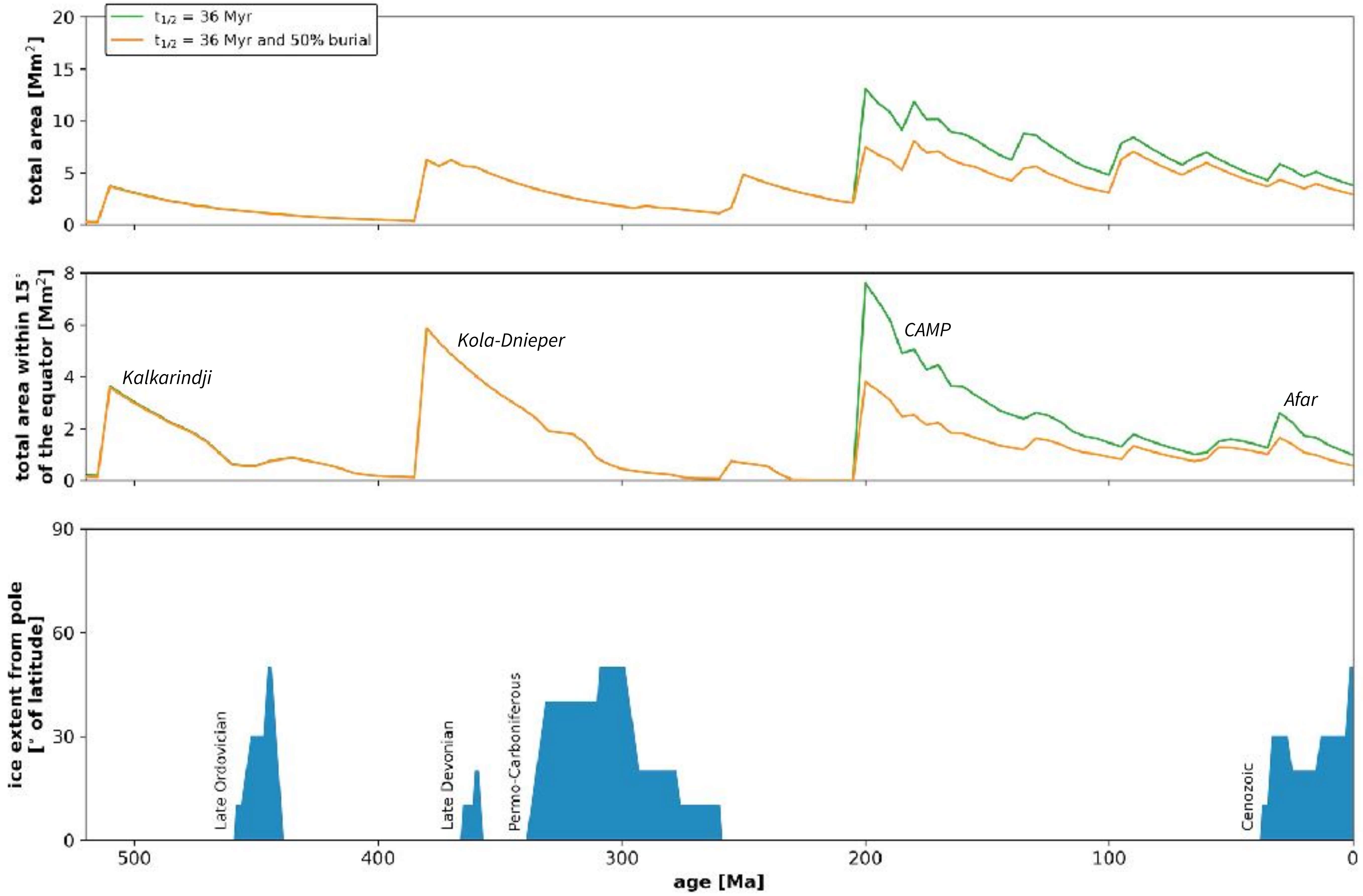


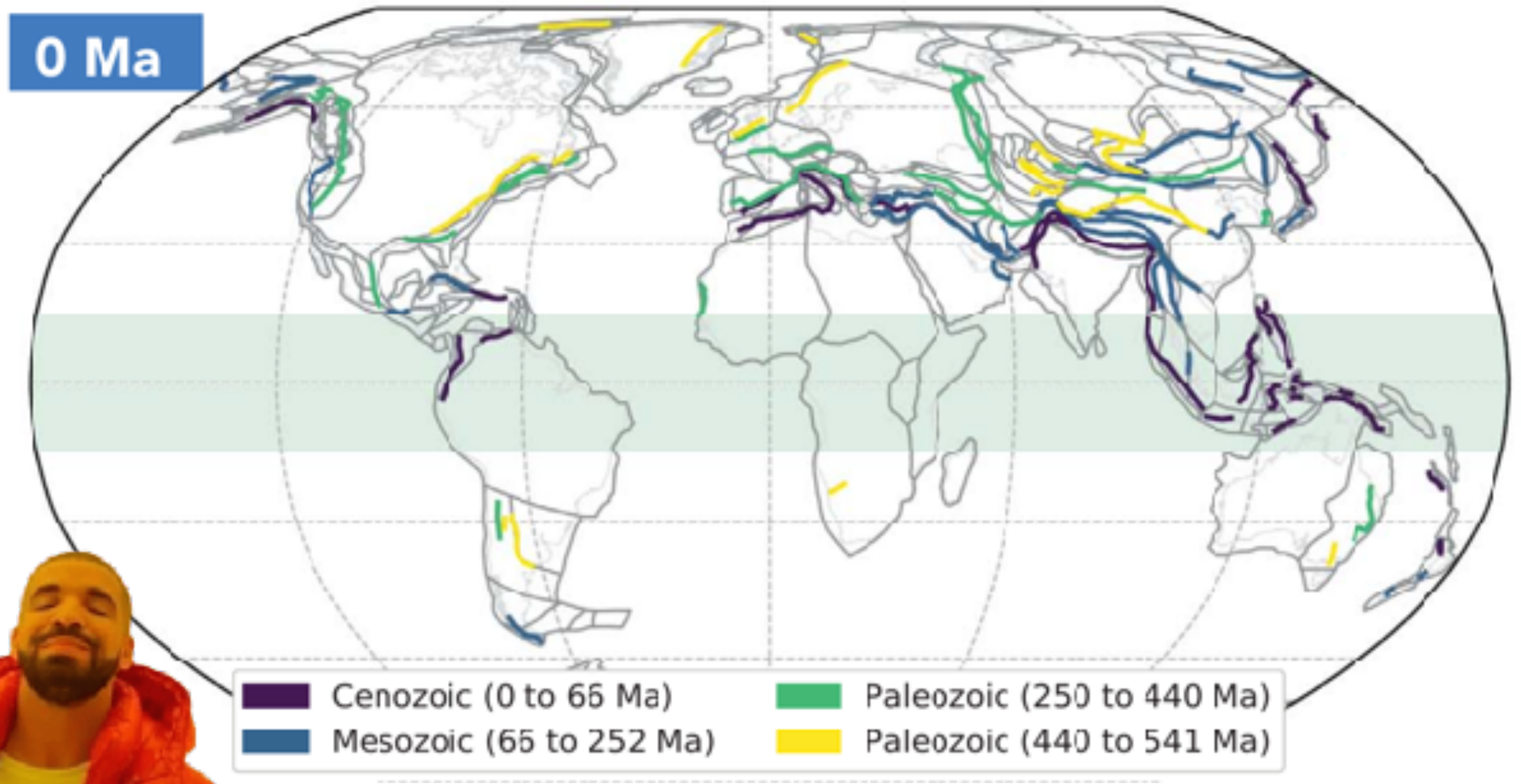
null hypothesis:

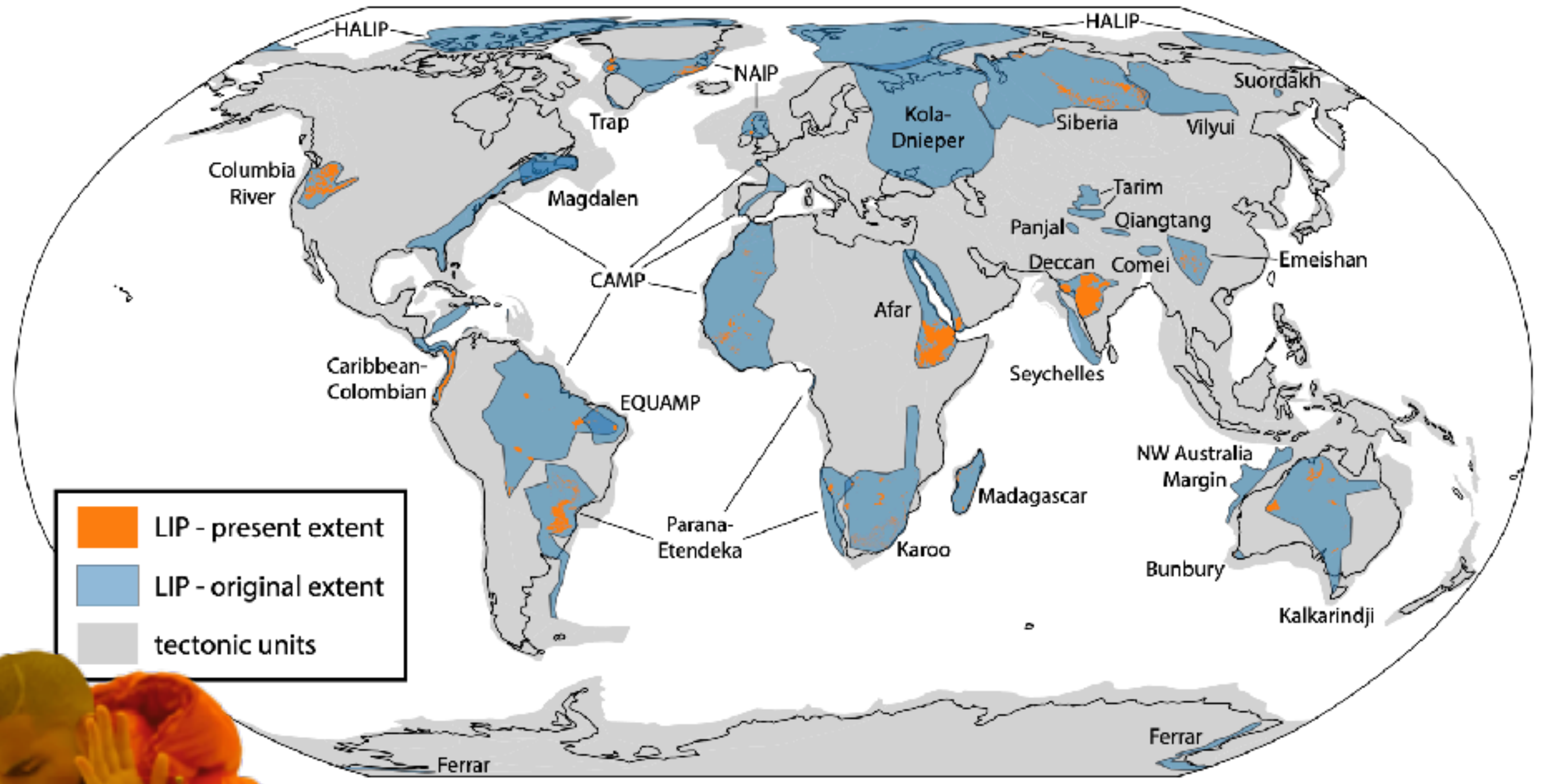
"glacial intervals do not correlate with the area of LIPs in the tropics"

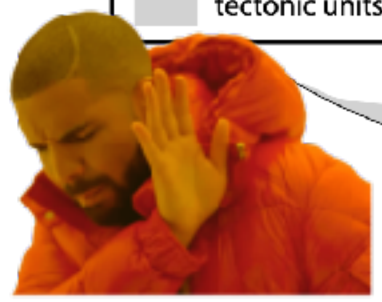
cannot reject

SUMMARY

If we look at the past ~520 million years as a whole, do tropical arc-continent collisions coincide with changes in Earth's climate state?







tropical arc-continent collisions

***correlates well* with ice extent**

- (ultra)mafic lithologies
- high runoff & temperature
- **rapid uplift & steep topography**
  - rapid supply of fresh minerals to weather
  - rapid erosional removal of shielding regolith

tropical large igneous provinces

***correlates poorly* with ice extent**

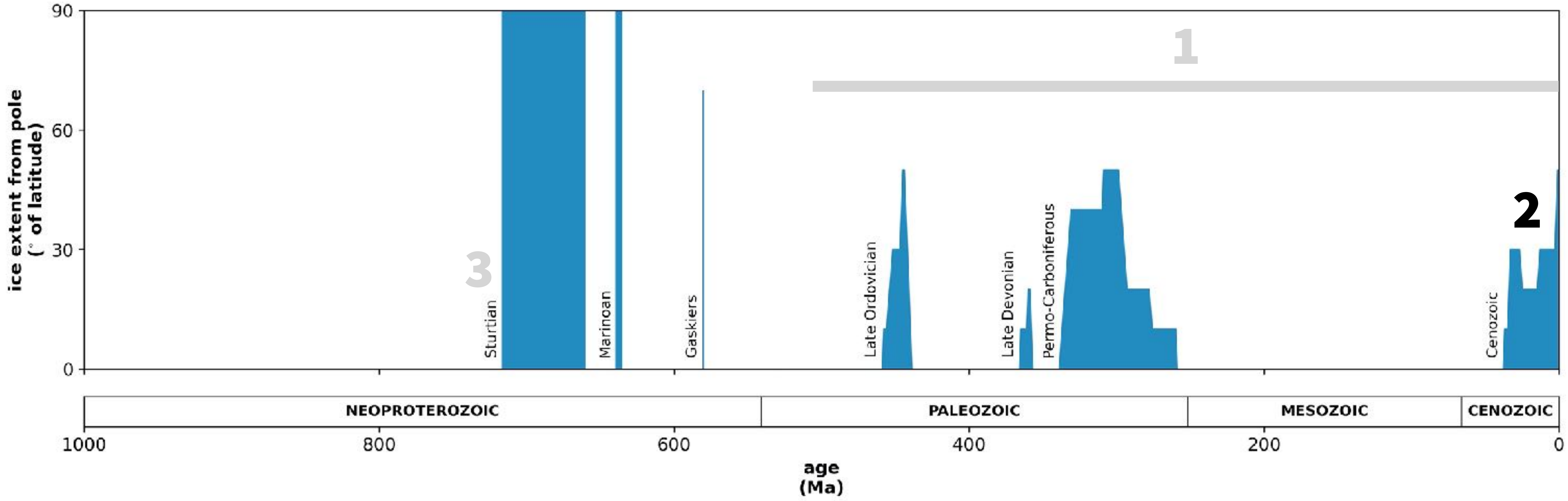
- mafic lithologies
- high runoff & temperature
- **no uplift & gentle topography**
  - slow supply of fresh minerals to weather
  - slow erosional removal of shielding regolith

SOUTHEAST ASIAN ISLANDS AND NEOGENE COOLING

hypothesis:

tropical island arc exhumation is important for setting Earth's long-term climate state

1. If we look at the past ~520 million years as a whole, do tropical arc-continent collisions coincide with times of glacial climate?
2. **Arc-continent collision is happening in the tropics today in the Southeast Asian islands: is this event responsible for cooling over the past ~15 million years?**
3. Is tropical island arc exhumation also responsible for a "snowball" glaciation ~717 million years ago?

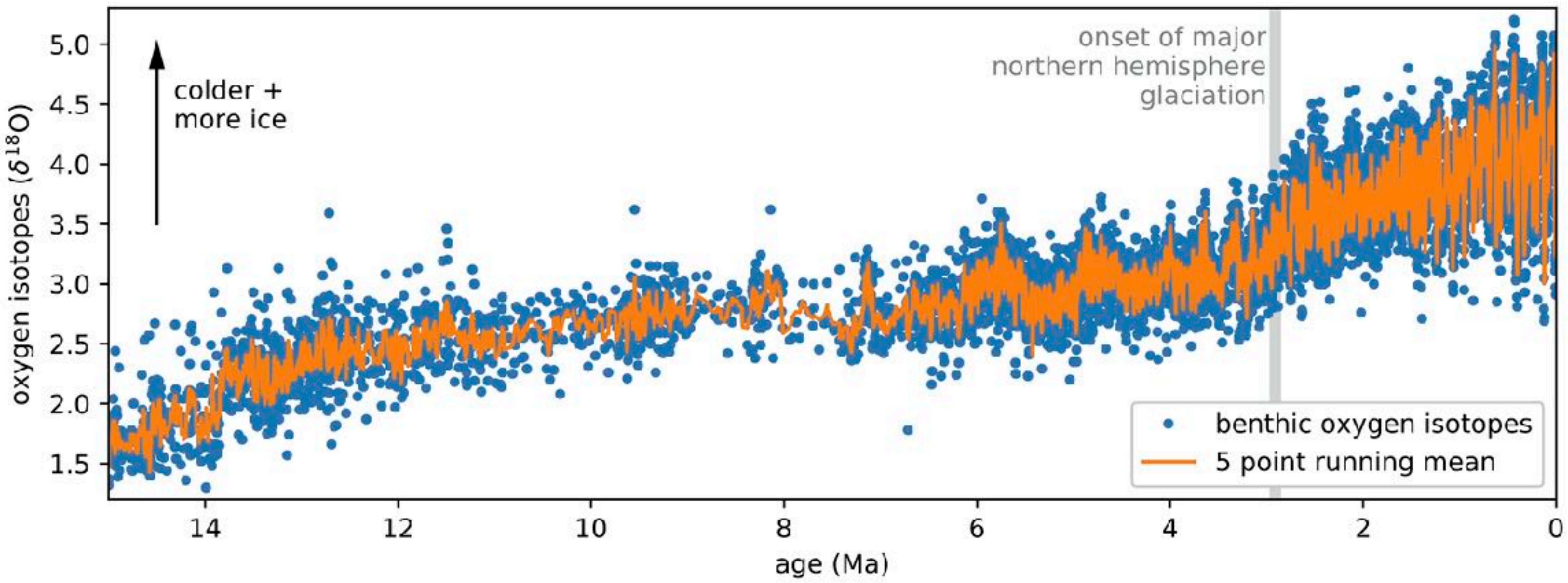


Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

NEOGENE COOLING

Park et al. (in press), data from Zachos et al. (2008)

major Antarctic glaciers already established



Miocene		Pliocene	Pleistocene
NEOGENE			QUATERNARY

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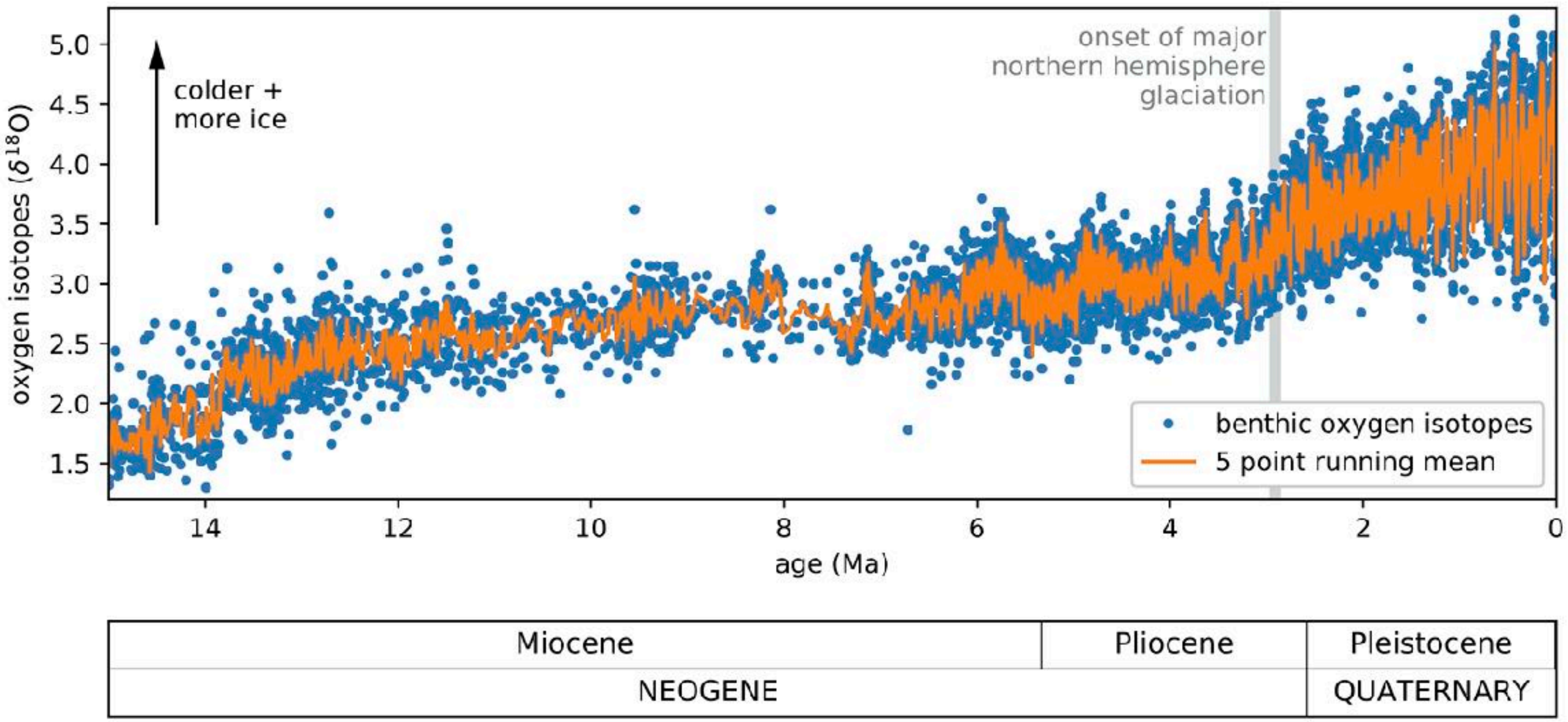
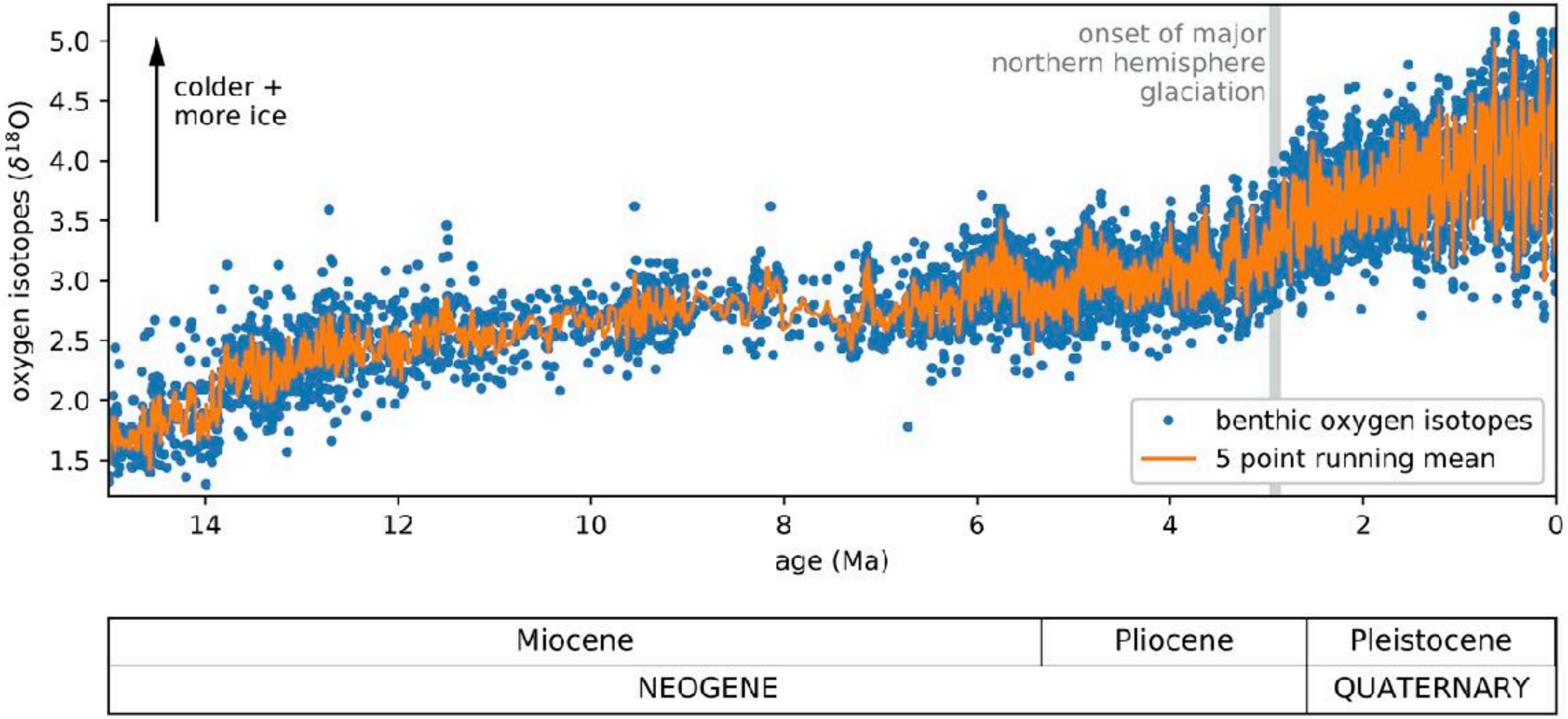


previous hypotheses for Neogene cooling:

- changes in ocean/atmosphere circulation
  - e.g. Haug and Tiedemann (1998), Shevenell (2004), Molnar and Cronin (2015)
- decrease in volcanic outgassing
  - e.g. Berner et al. (1983)
- increase in organic carbon burial
  - e.g. Galy et al. (2007)
- uplift in the Himalayas
  - e.g. Raymo and Ruddiman (1992)

NEOGENE COOLING

Park et al. (in press), data from Zachos et al. (2008)



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- uplift in the Himalayas
  - e.g. Raymo and Ruddiman (1992)

the hypothesis we test:

Enhanced silicate weathering in the Southeast Asian islands was the primary driver for Neogene cooling.

SOUTHEAST ASIAN ISLANDS

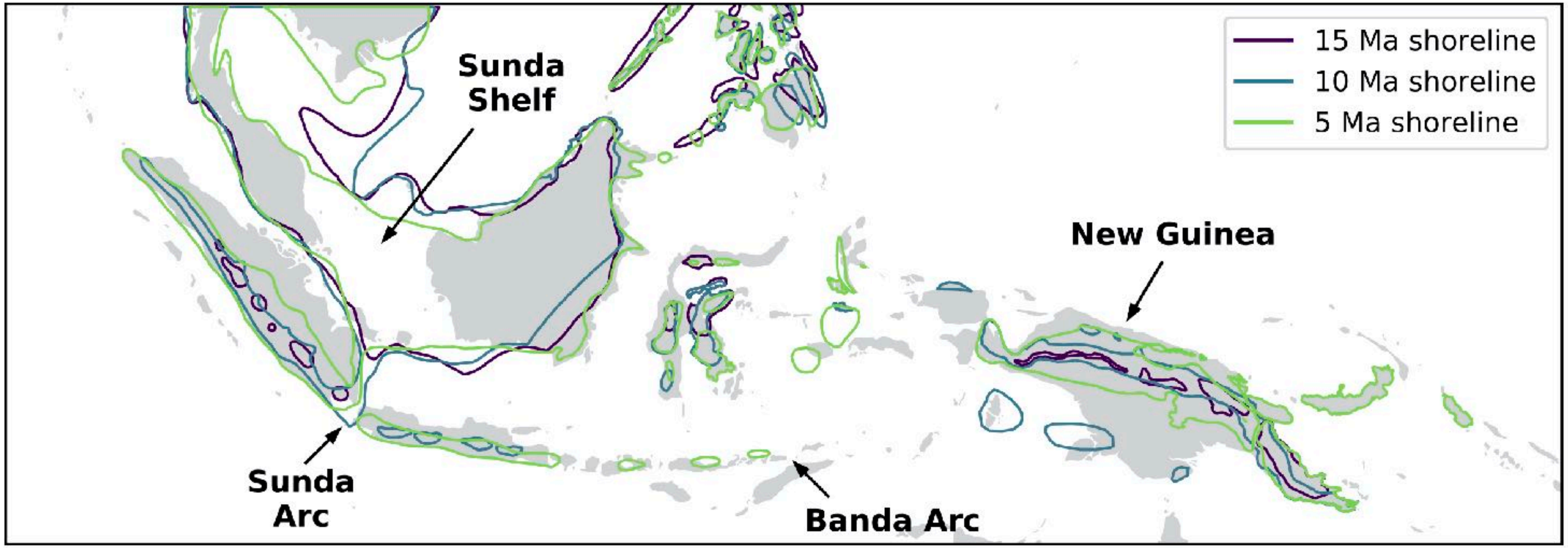
Hall (2017)

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

SOUTHEAST ASIAN ISLANDS

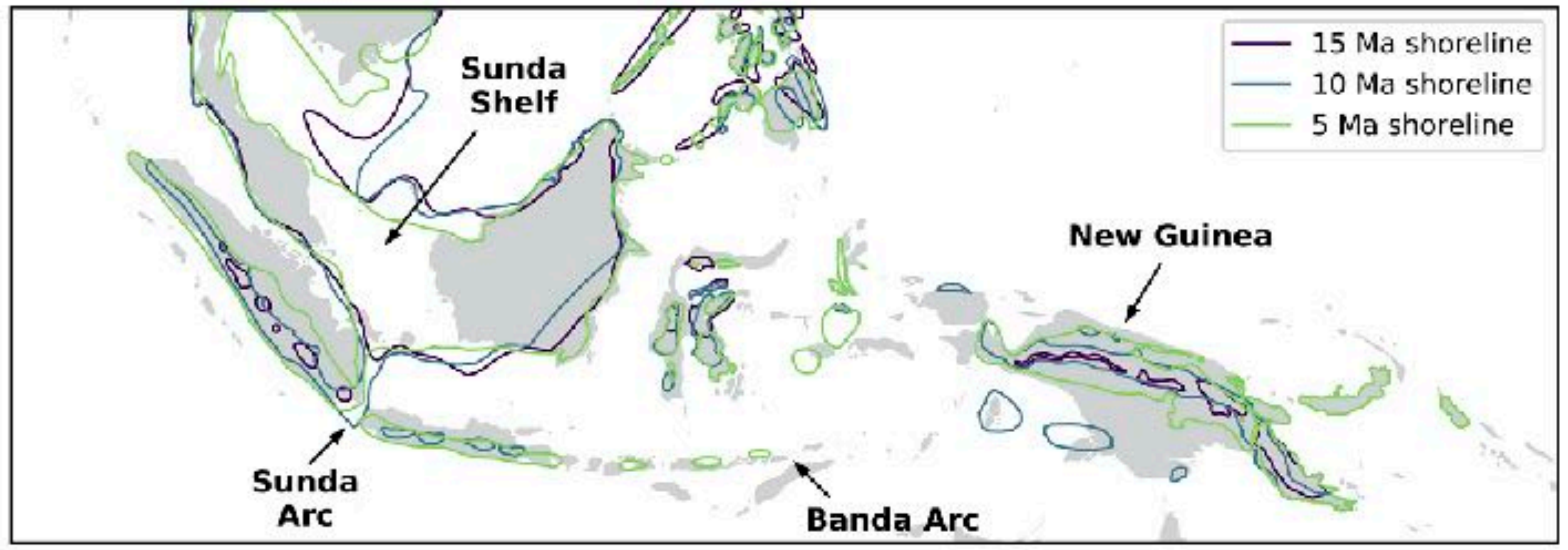
paleoshoreline compilation

based on geologic maps, stratigraphic data, and other paleoshoreline compilations



Park et al. (in press)

SOUTHEAST ASIAN ISLANDS



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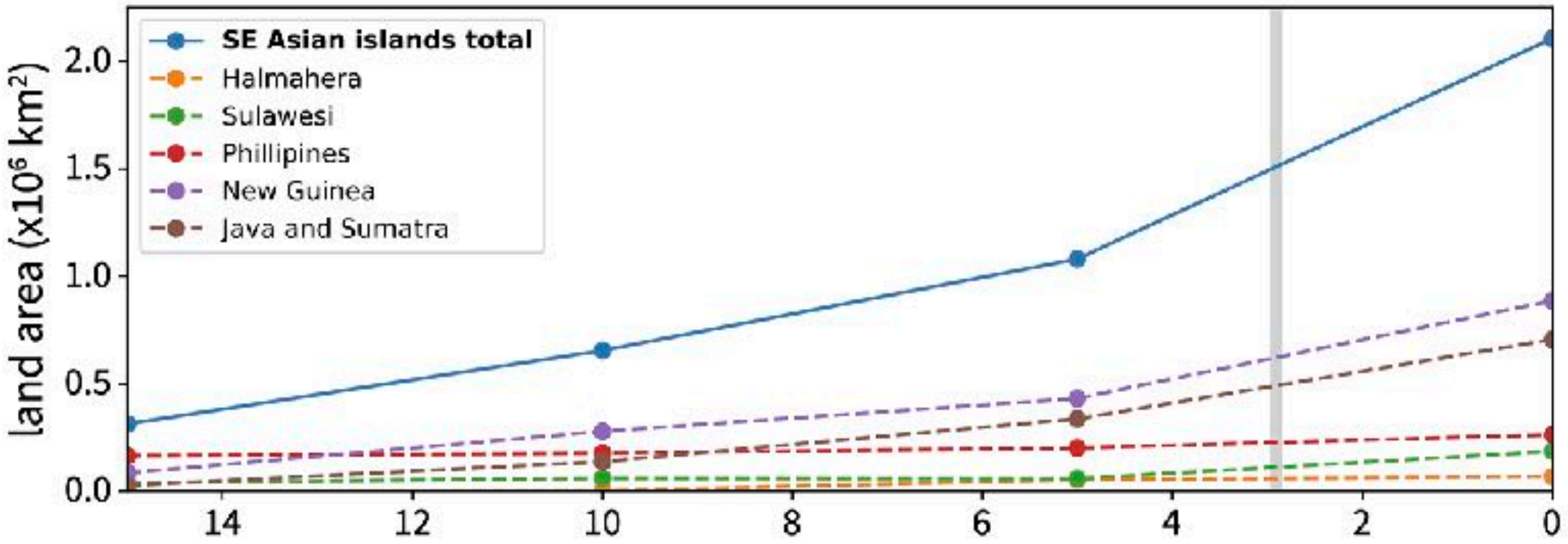
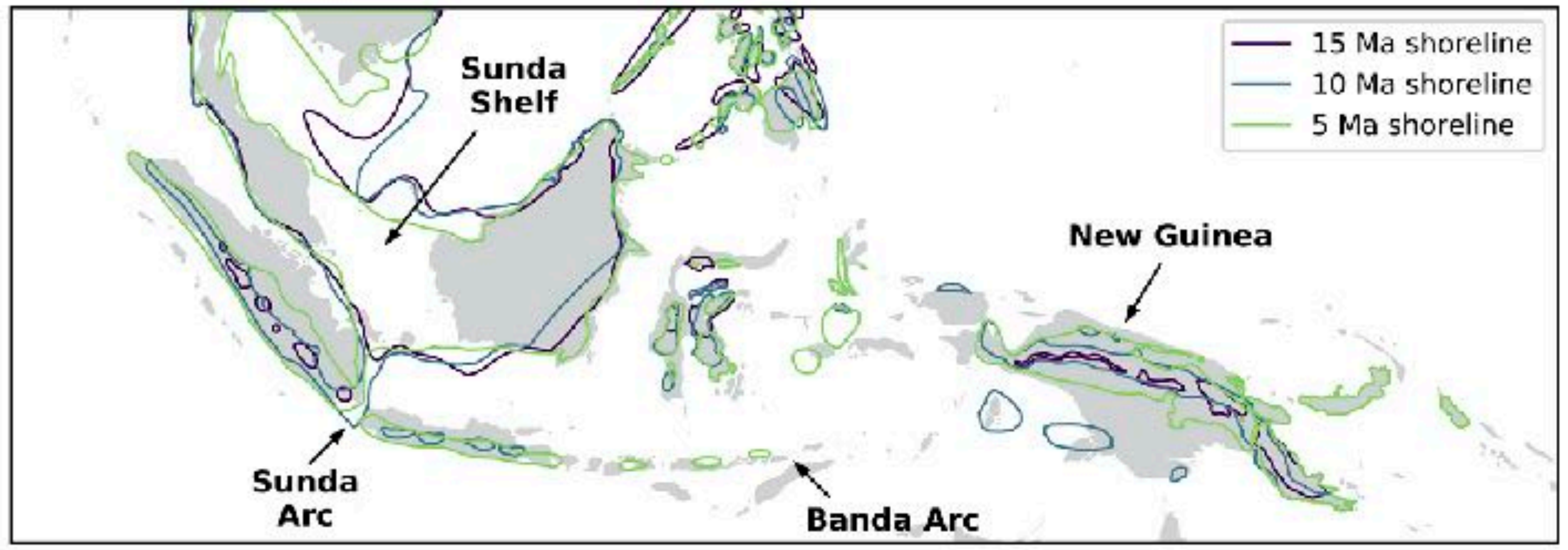


SOUTHEAST ASIAN ISLANDS



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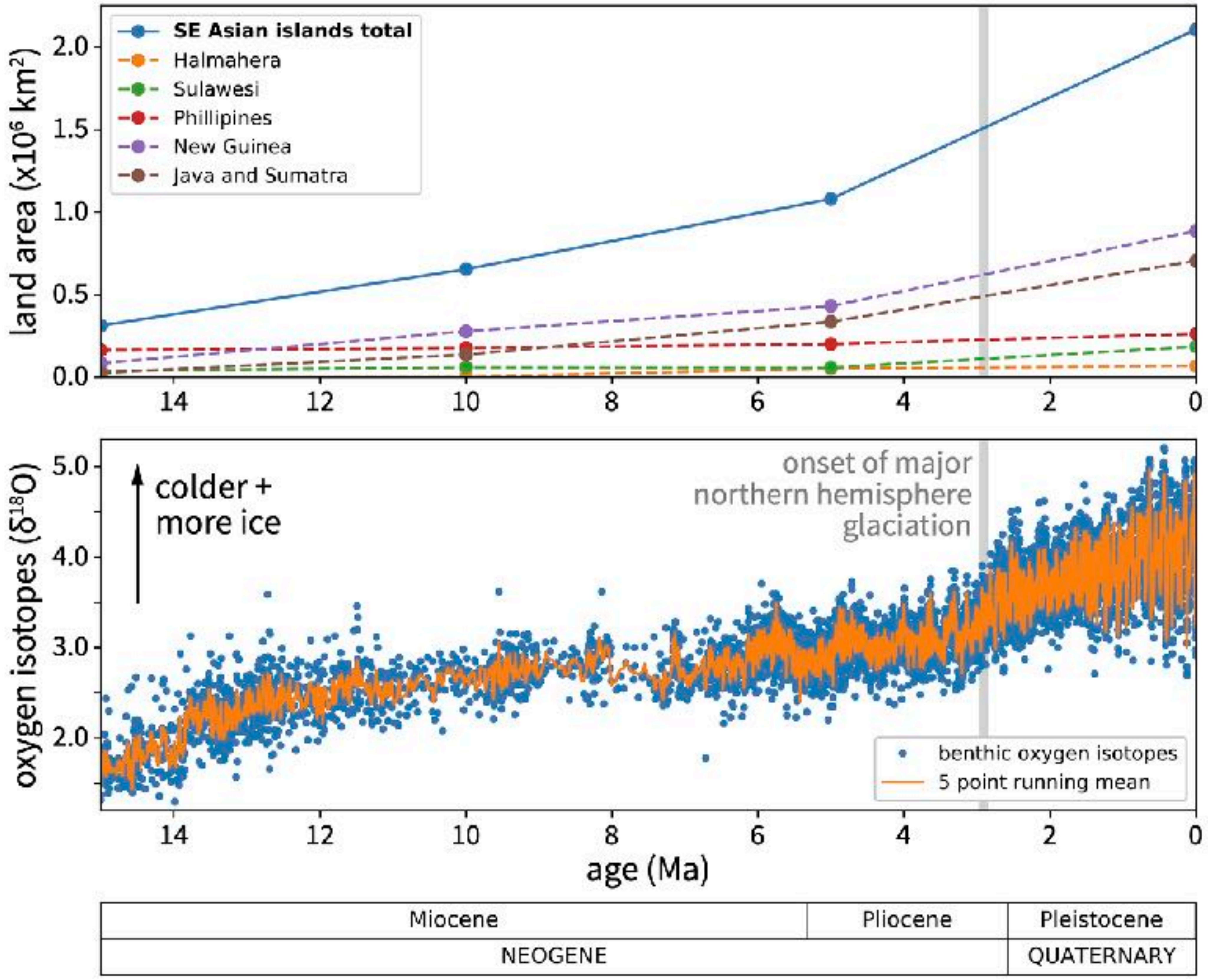


first-order correlation

Was the decrease in pCO_2 associated with emergence of the Southeast Asian islands enough to explain Neogene cooling?

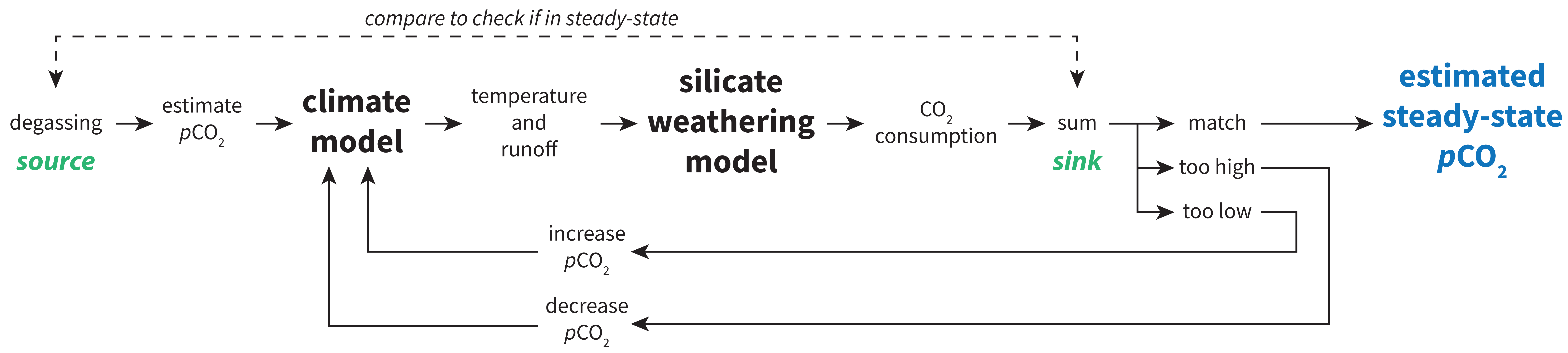
Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

GEOCLIM

GEOCLIM estimates changes in steady-state pCO_2 associated with coupled changes in silicate weathering and climatology

adapted from Goddéris & Donnadieu (2017)

(finds the pCO_2 at which the sink equals the source)



climate model:
GFDL CM2.0 at pCO_2 = 286, 572, 1144 ppm
equilibrium climate sensitivity = 2.9°C

GEOCLIM

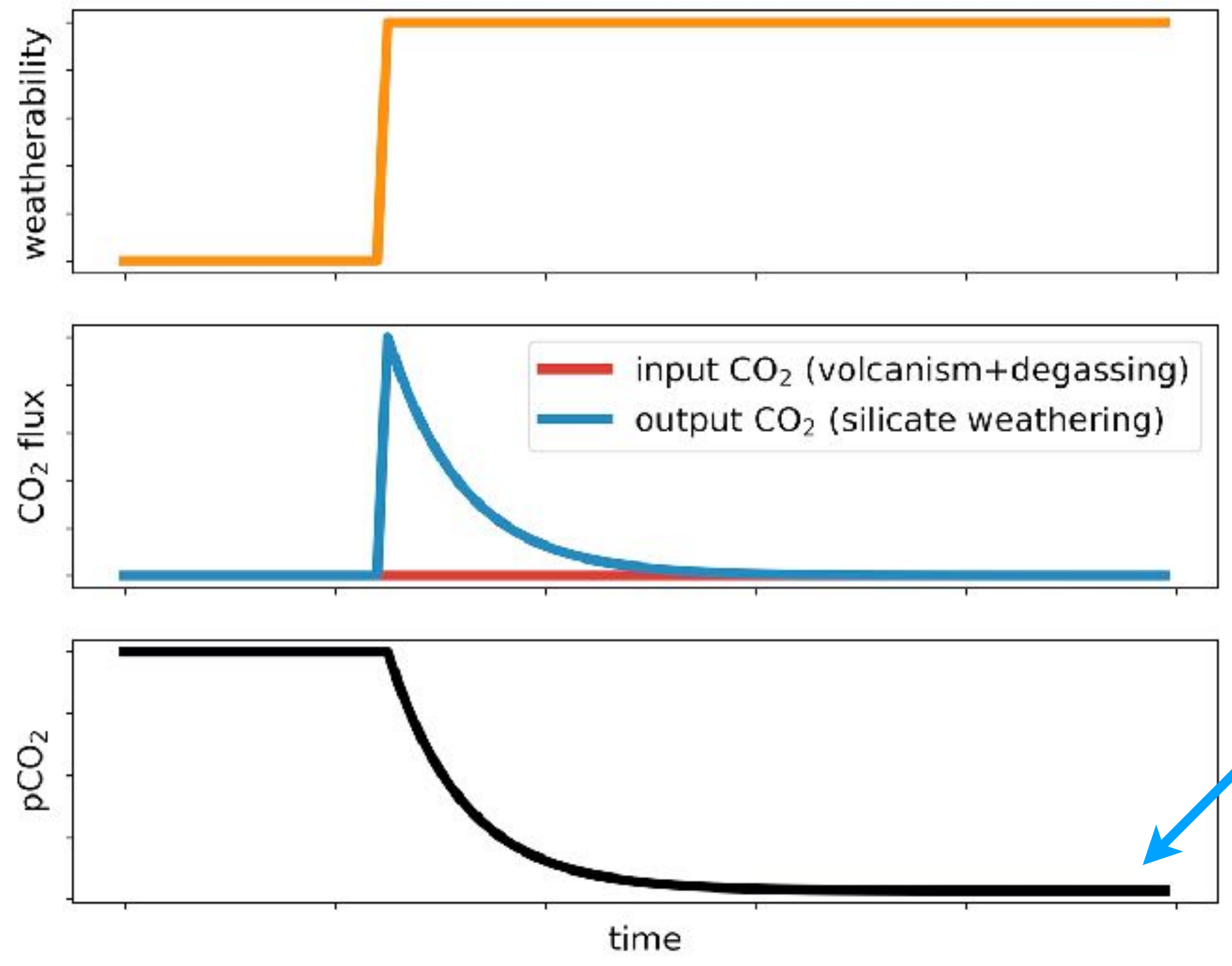
GEOCLIM estimates changes in steady-state *p*CO_2 associated with coupled changes in silicate weathering and climatology

adapted from Goddéris & Donnadieu (2017)

(finds the *p*CO_2 at which the sink equals the source)

degassing → estimate *p*CO_2 →

source



finds the steady-state pCO₂ for a given weatherability

estimated steady-state *p*CO_2

climate model:

GFDL CM2.0 at pCO_2 = 286, 572, 1

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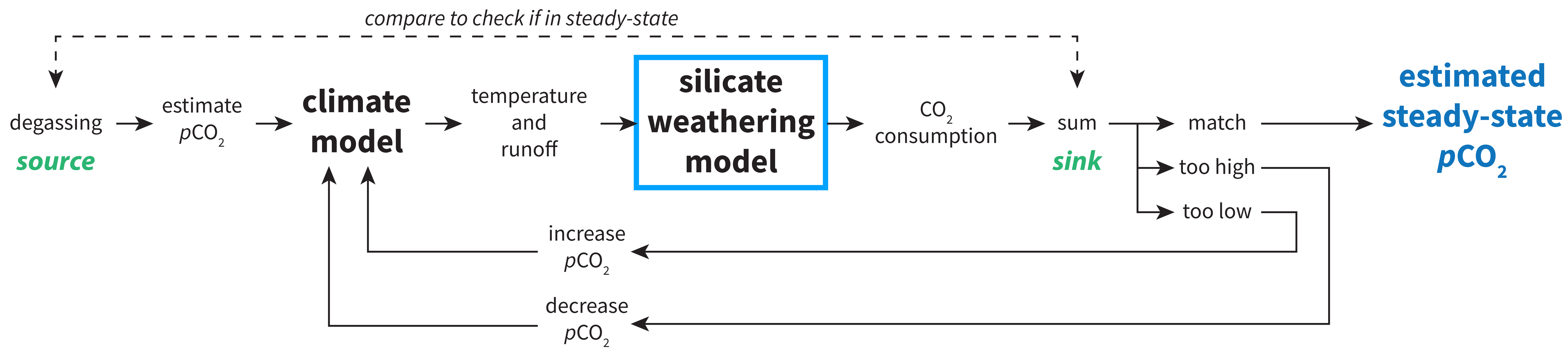

climate model:
GFDL CM2.0 at pCO_2 = 286, 572, 1144 ppm
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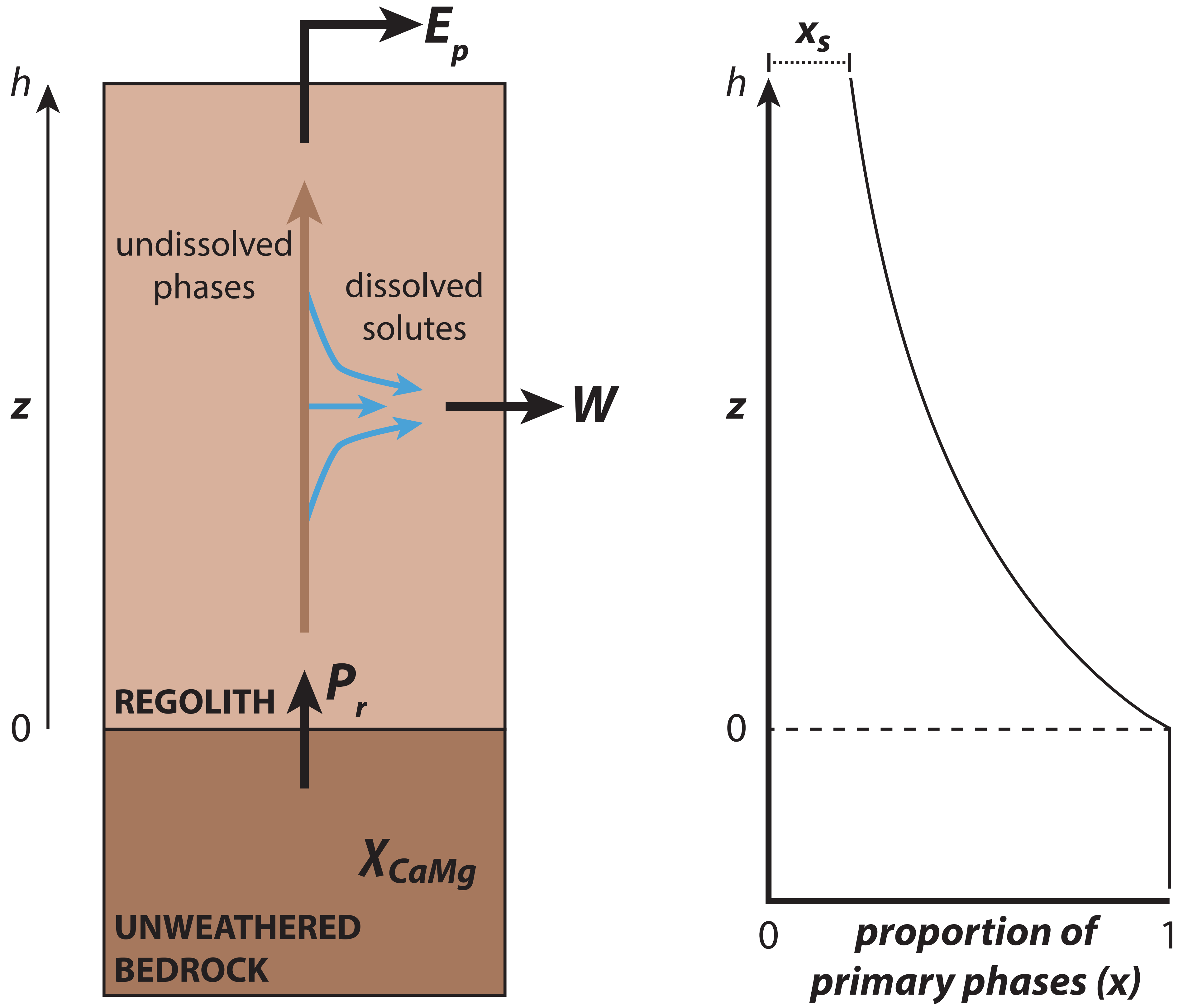
GEOCLIM

DynSoil

a regolith production + weathering model



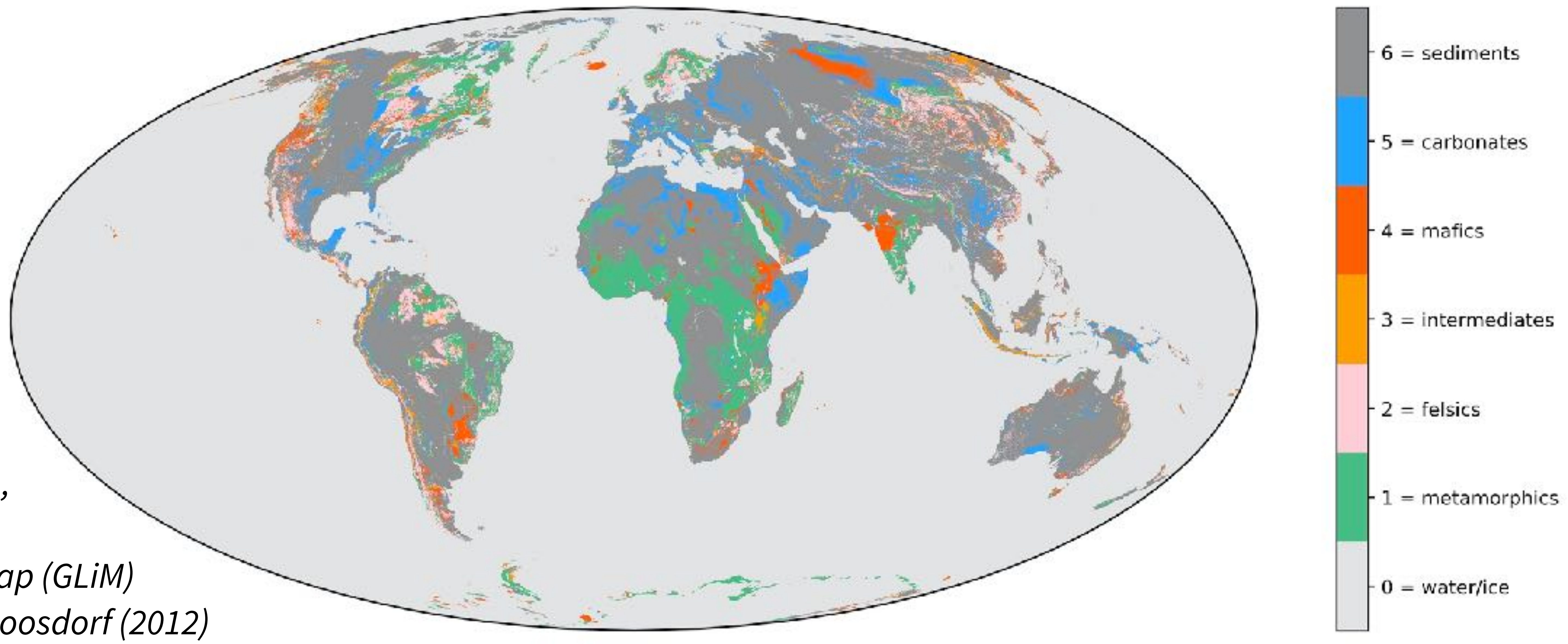
Maffre et al. (2018), formulation based on Gabet & Mudd (2009) and West (2012)

weathering was modeled to be a function of:

temperature
runoff
topography

we introduce a dependence on lithology

GEOCLIM



*Park et al. (in press),
simplified from the
Global Lithologic Map (GLiM)
of Hartmann and Moosdorf (2012)*

lithology	Ca+Mg (mol/m³)
felsic	1,521
intermediate	4,759
mafic	10,317
carbonate	ignored
metamorphics	???
sediments	???

mean of data compiled in EarthChem

dependent on protolith composition and degree of previous chemical depletion

CALIBRATION

poorly constrained lithologies		poorly constrained model parameters (from West, 2012)			
metamorphic$_{Ca+Mg}$	**sediment$_{Ca+Mg}$**	**k_d**	**k_w**	**σ**	**k_{rp}**
6 values	6 values	10 values	10 values	6 values	6 values

permute to get 93,600 unique combinations of these 6 parameters

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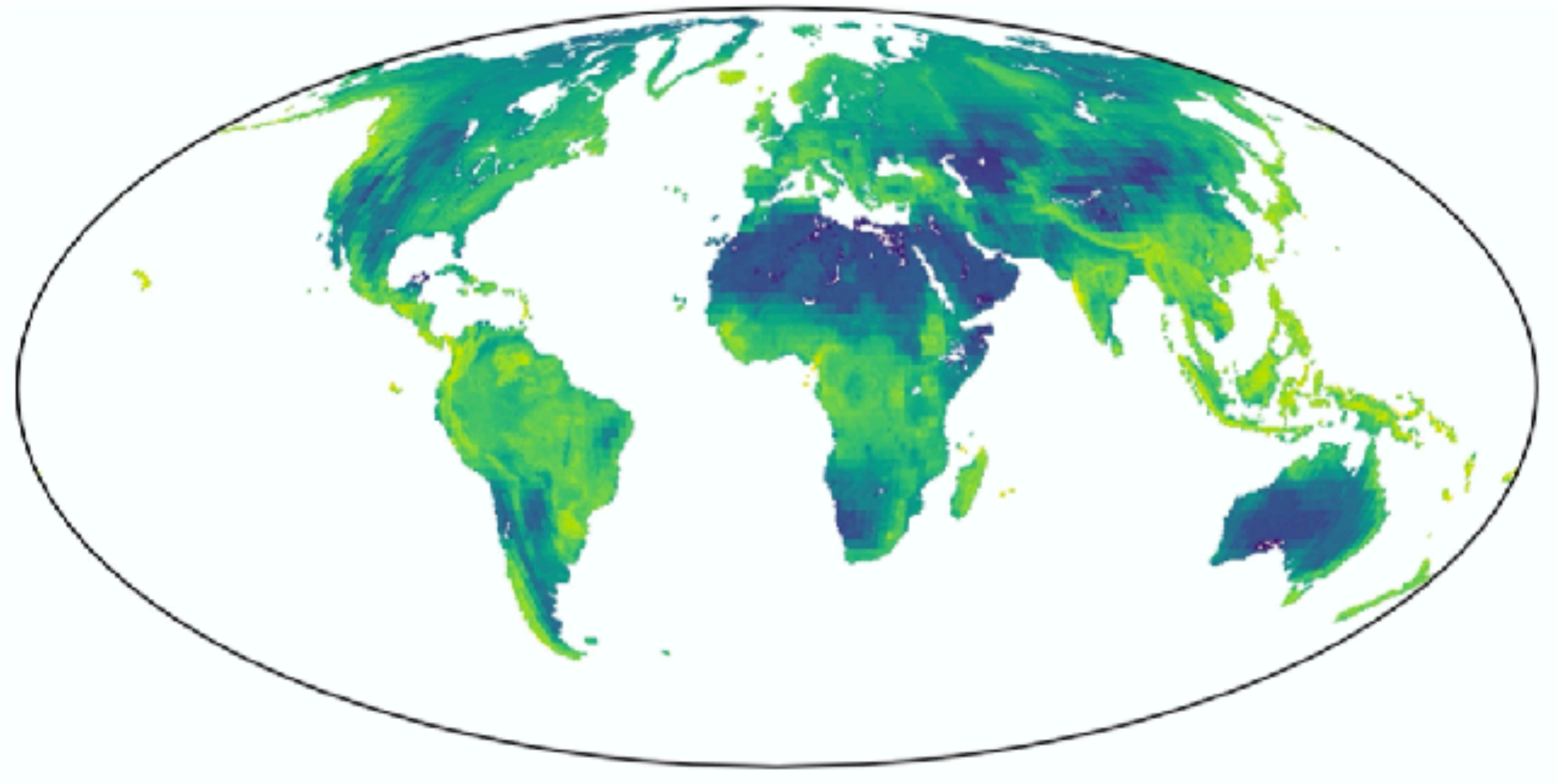
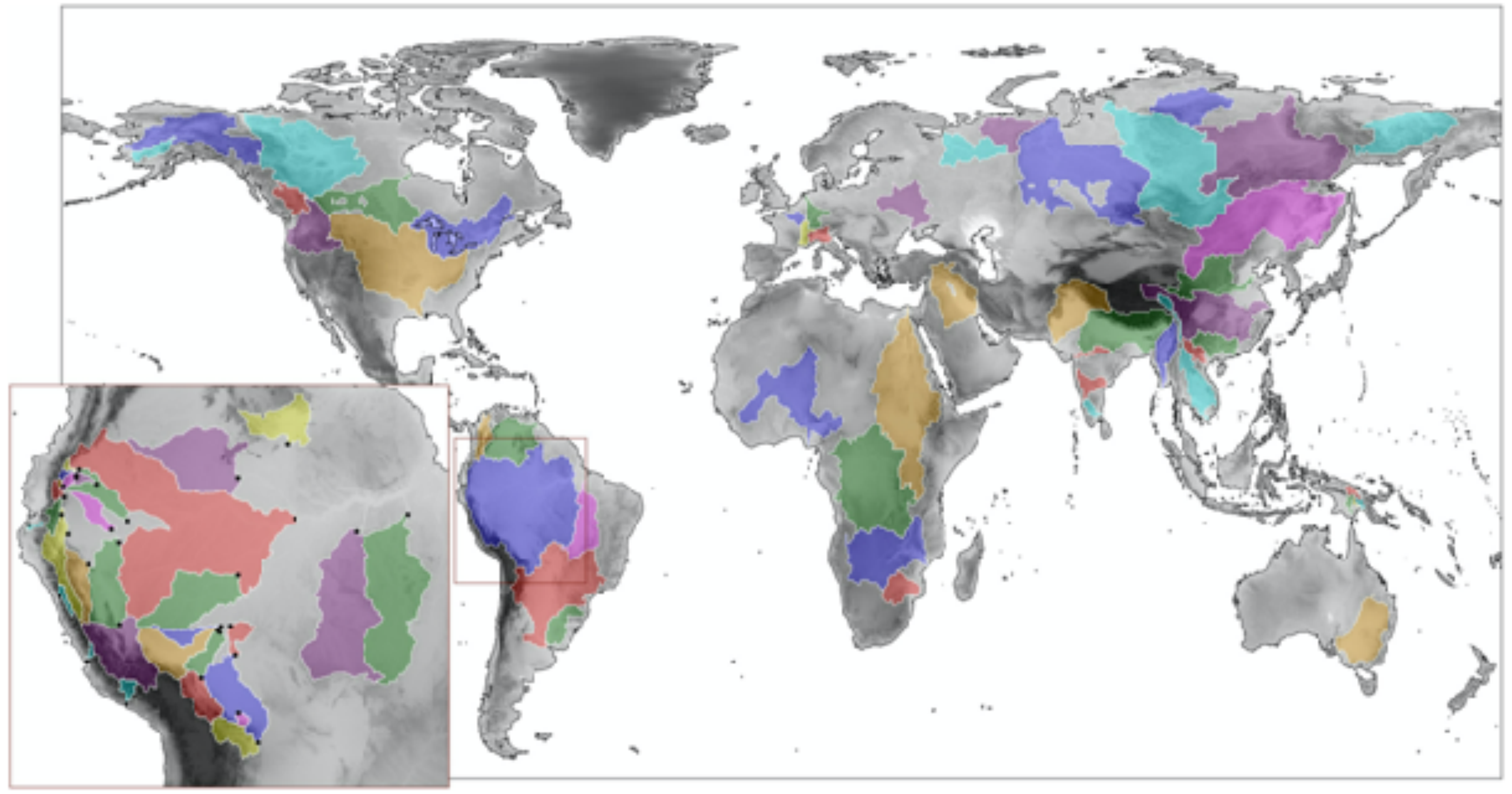
CO_2 consumption map for one of the 93,600 parameter combinations



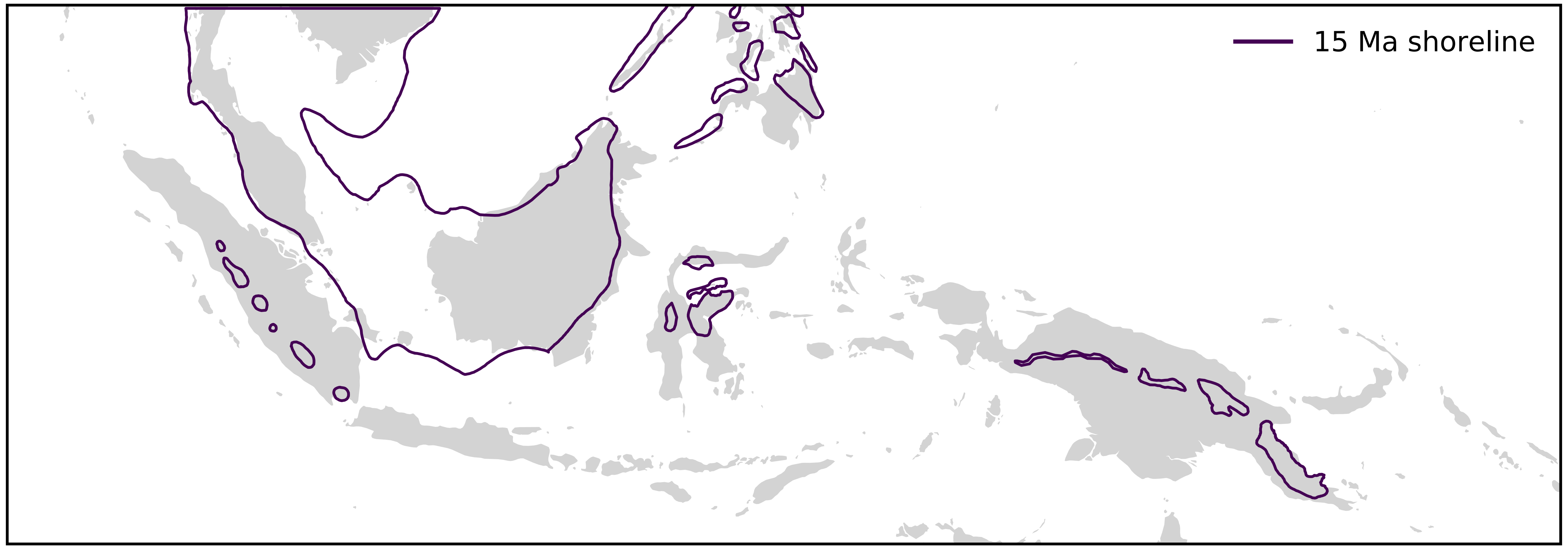
compare modeled vs. measured CO_2 consumption over watersheds



Maffre et al. (2018)

5,381 "good" parameter combinations that result in chemical weathering maps that closely resemble that observed in the present day

TECTONIC BOUNDARY CONDITIONS

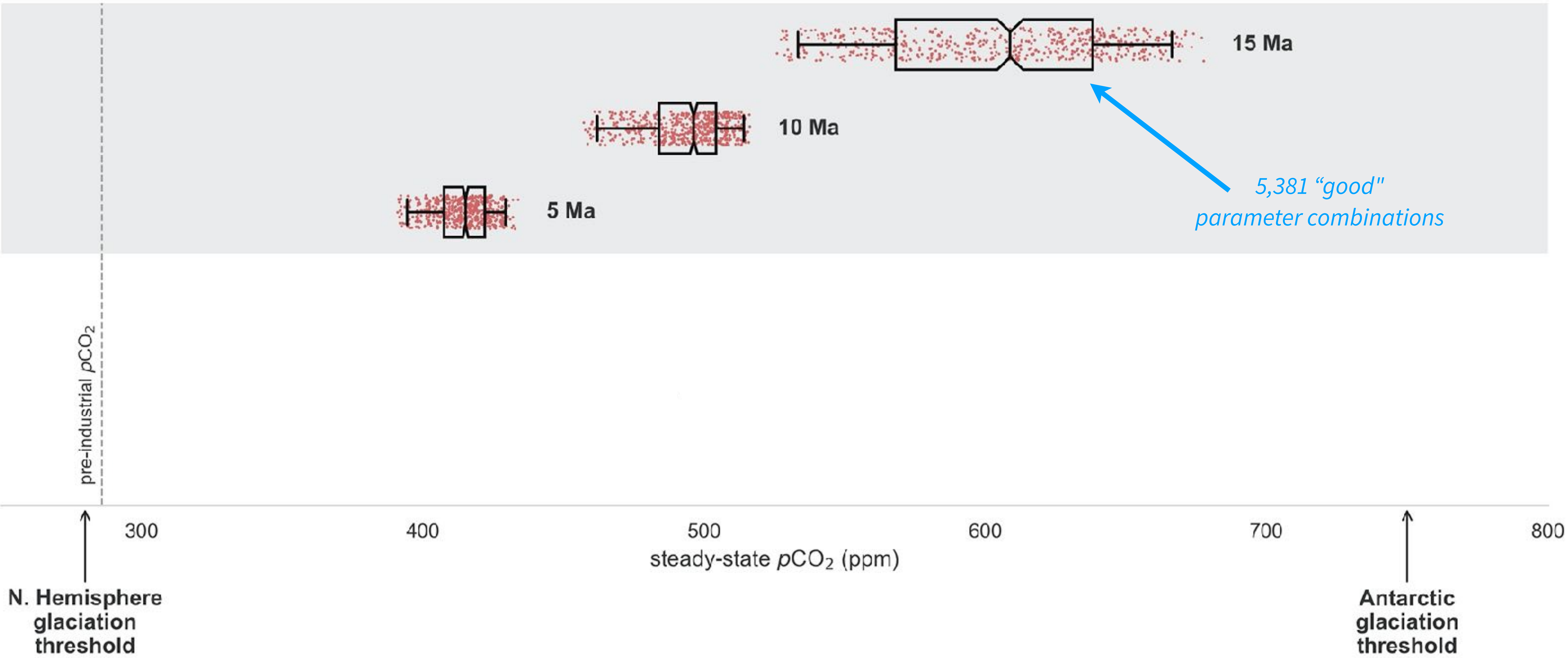


paleogeography elsewhere on Earth is not changed

for each of the 5,381 "good" parameter combinations, run the full GEOCLIM model and get an estimate for steady-state $p\mathrm{CO_2}$

RESULTS

Park et al. (in press)



Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

RESULTS

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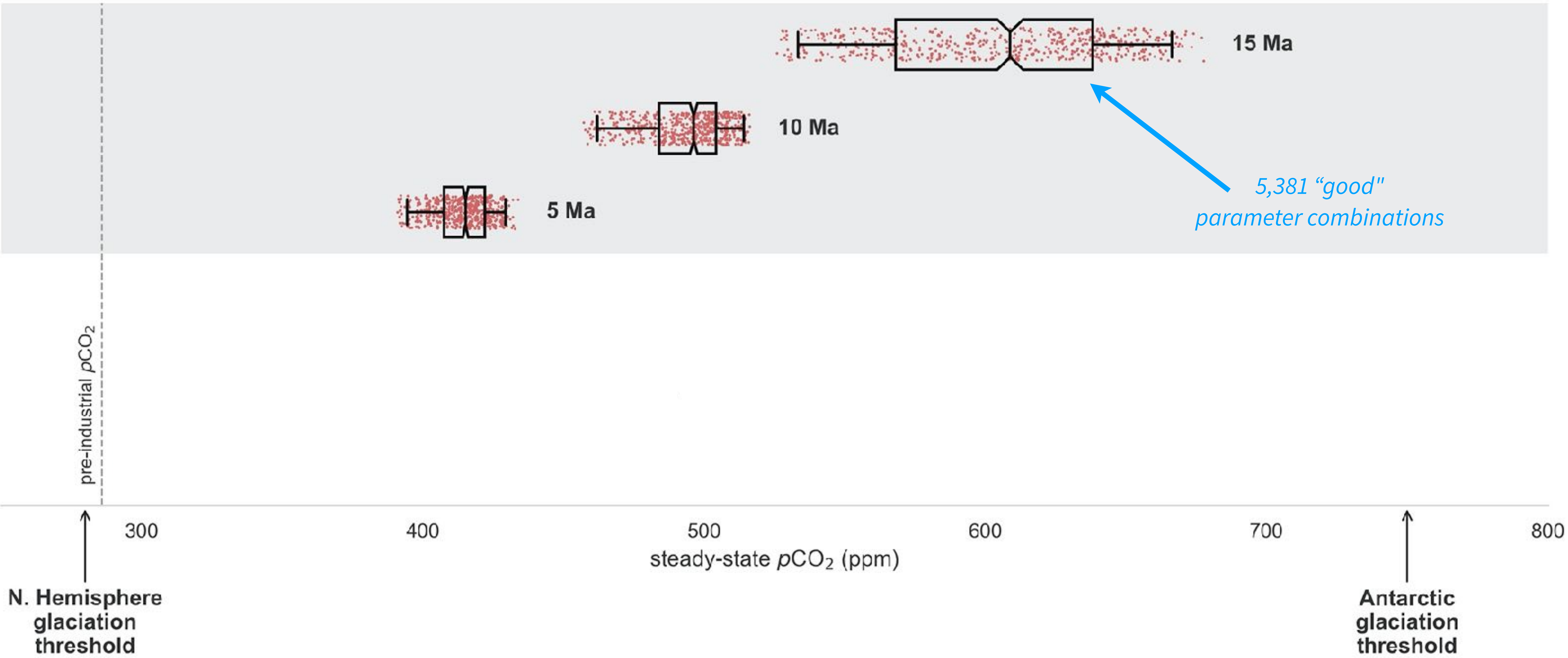


glaciation thresholds suggest ***p*CO₂ decline over the past ~33.6 million years** of ~750 ppm to 280 ppm = **~470 ppm**

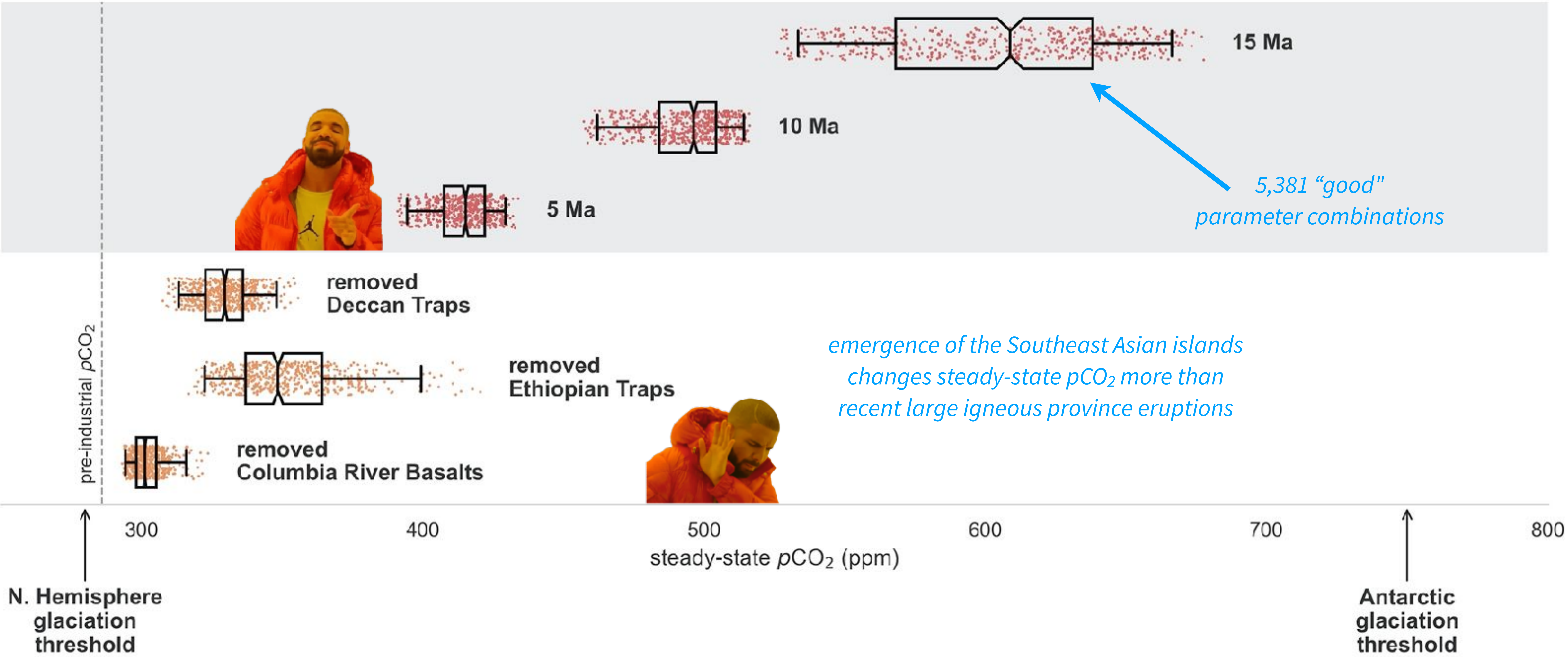
GEOCLIM suggests **Southeast Asian island emergence caused pCO_2 decline** of ~700-550 ppm to 280 ppm = **~420-270 ppm**

majority of the pCO_2 decline over the past ~33.6 million years can be attributed to paleogeographic changes in the Southeast Asian islands

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

RESULTS

Park et al. (in press)



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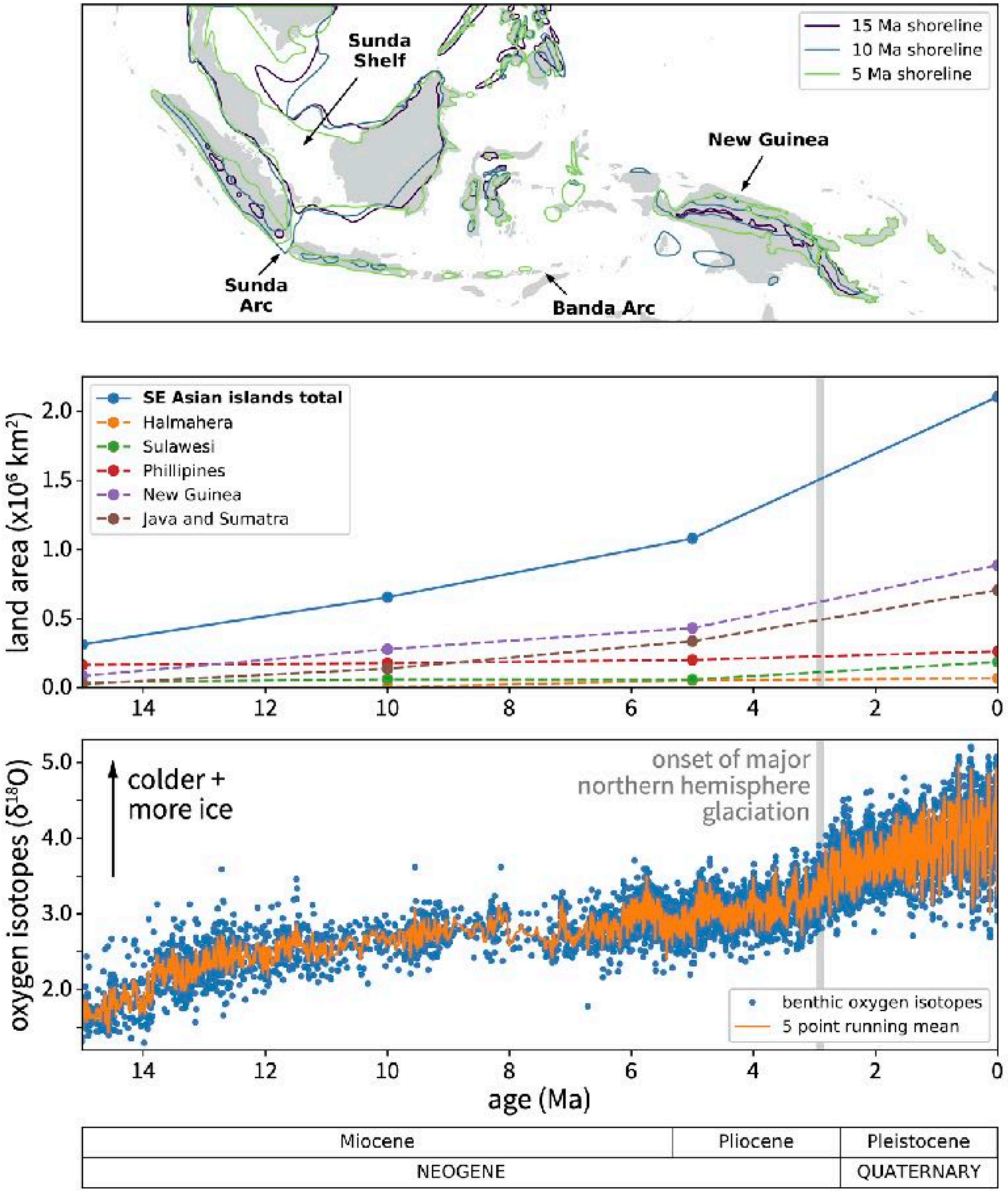
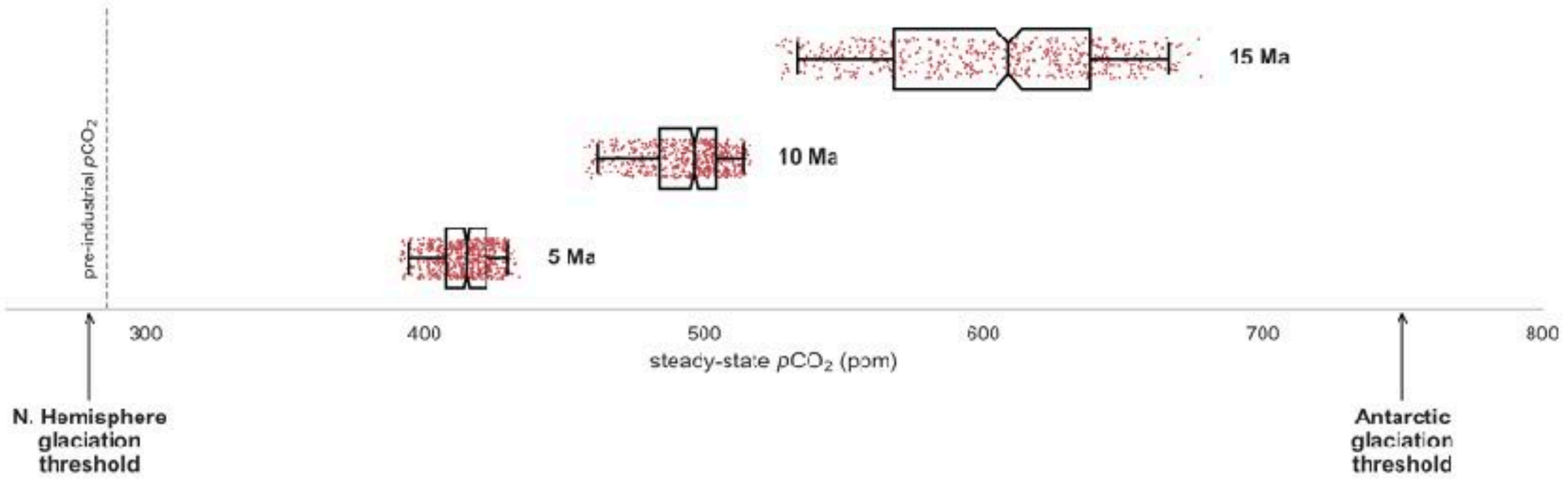
SUMMARY





changes in paleogeography and volcanic outgassing elsewhere on Earth (e.g. Himalayan uplift) would have affected geologic carbon sources and sinks…

but:

history of Southeast Asian island emergence coincides with Neogene cooling

associated pCO_2 change explains the majority of this cooling

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

introduction

Phanerozoic

Cenozoic

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Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

LEAD-UP TO THE STURTIAN SNOWBALL EARTH

hypothesis:

tropical island arc exhumation is important for setting Earth's long-term climate state

1. If we look at the past ~520 million years as a whole, do tropical arc-continent collisions coincide with times of glacial climate?
2. Arc-continent collision is happening in the tropics today in the Southeast Asian islands: is this event responsible for cooling over the past ~15 million years?
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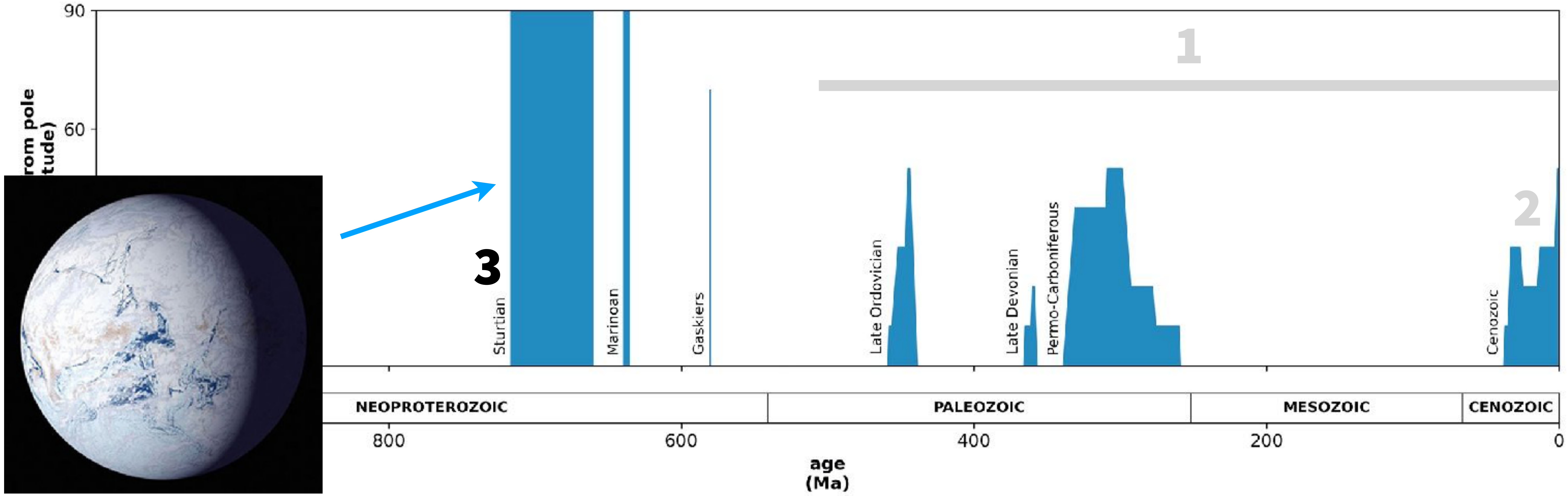

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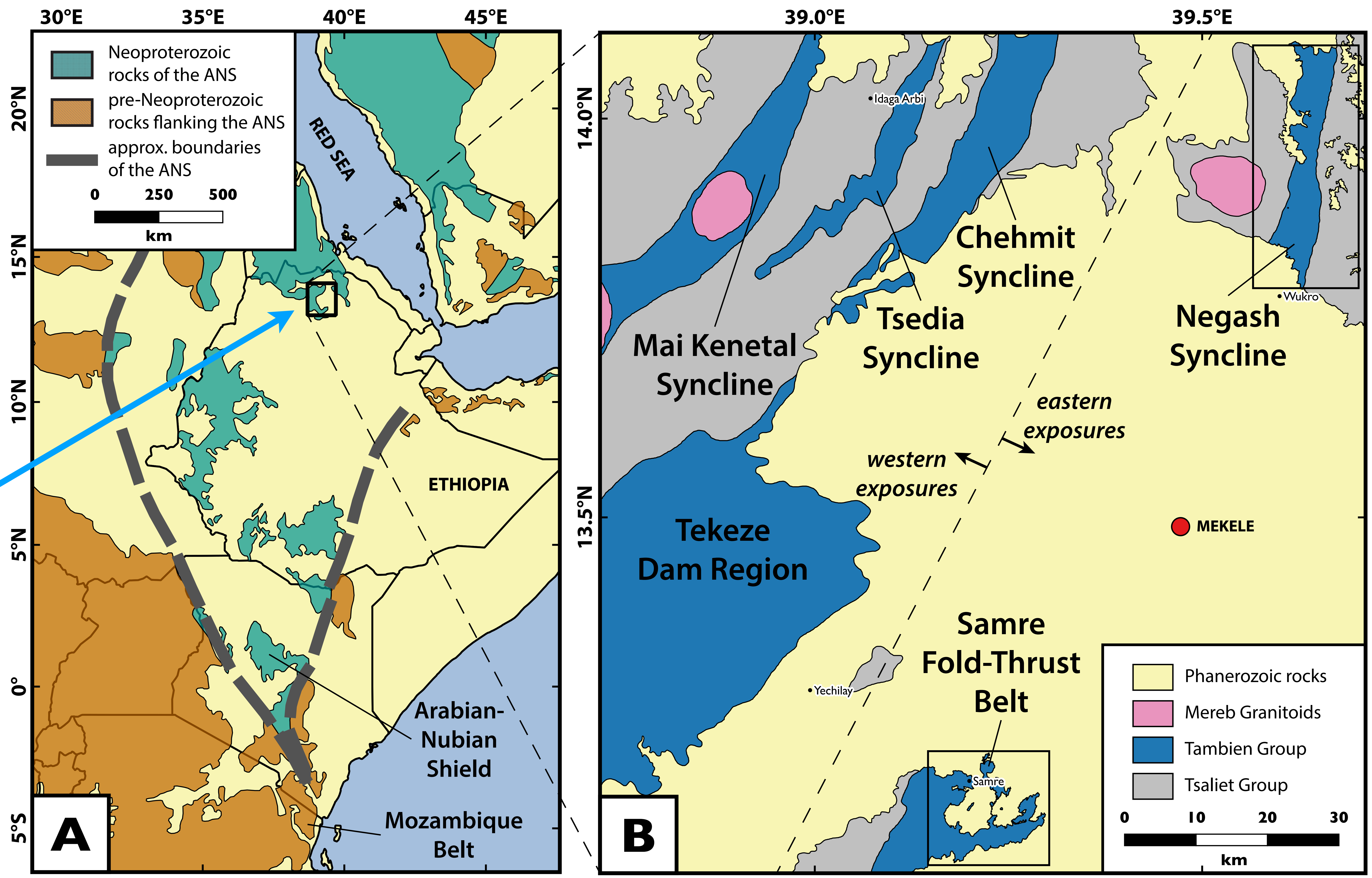
Arabian-Nubian Shield

a series of juvenile arc terranes that came together during the Neoproterozoic

Park et al. (2020a)



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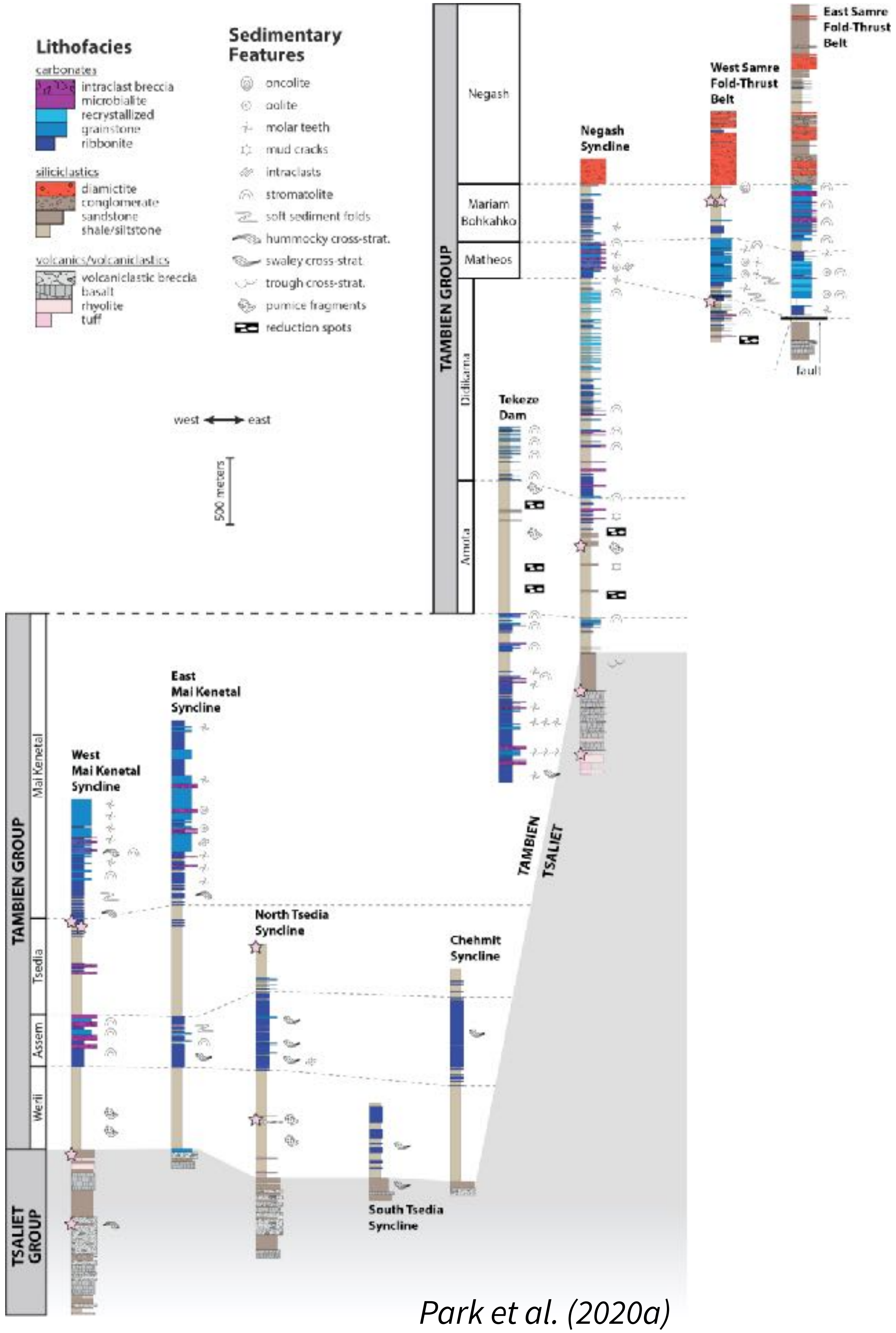

Park et al. (2020a)

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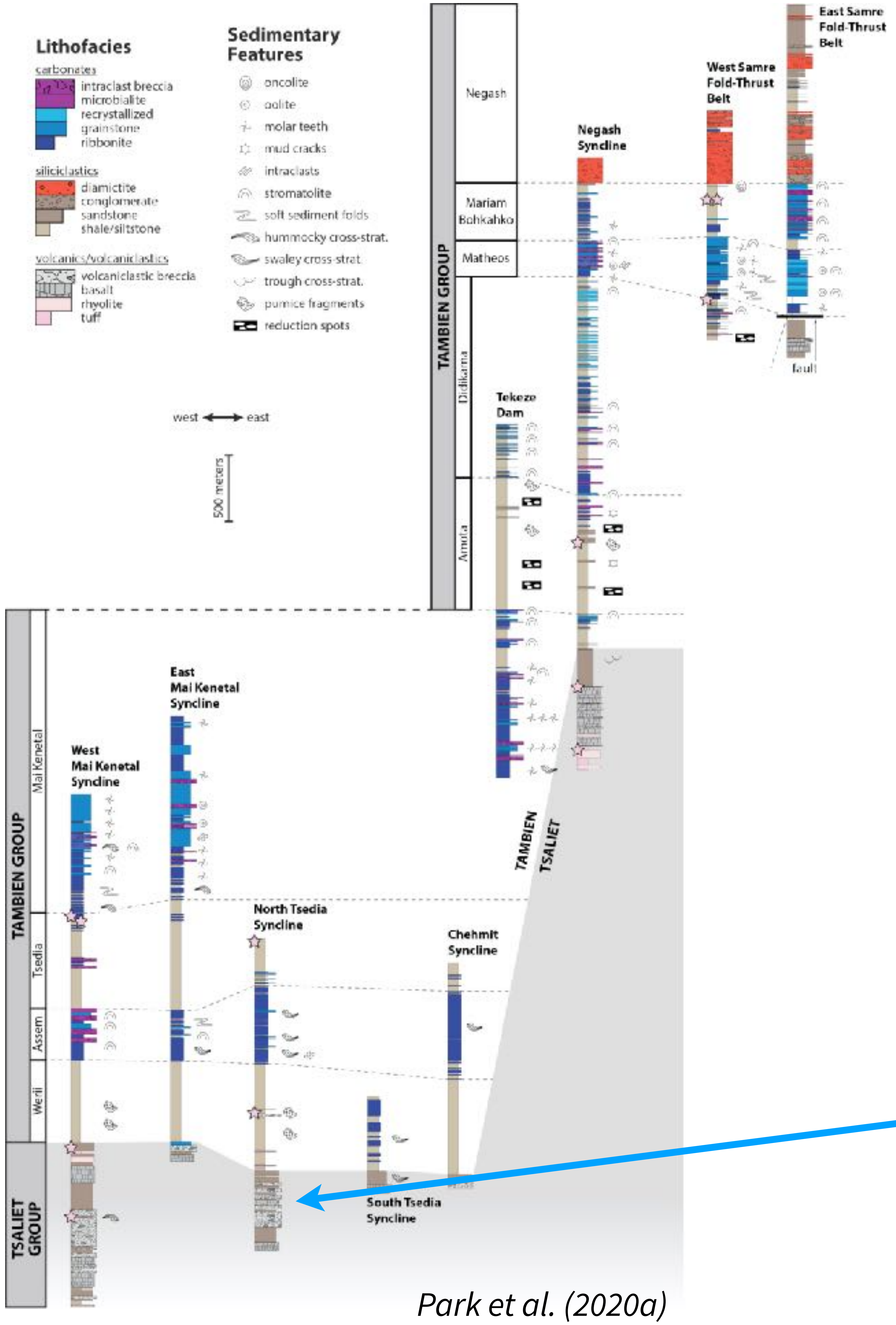

Park et al. (2020a)

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- Neoproterozoic
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Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

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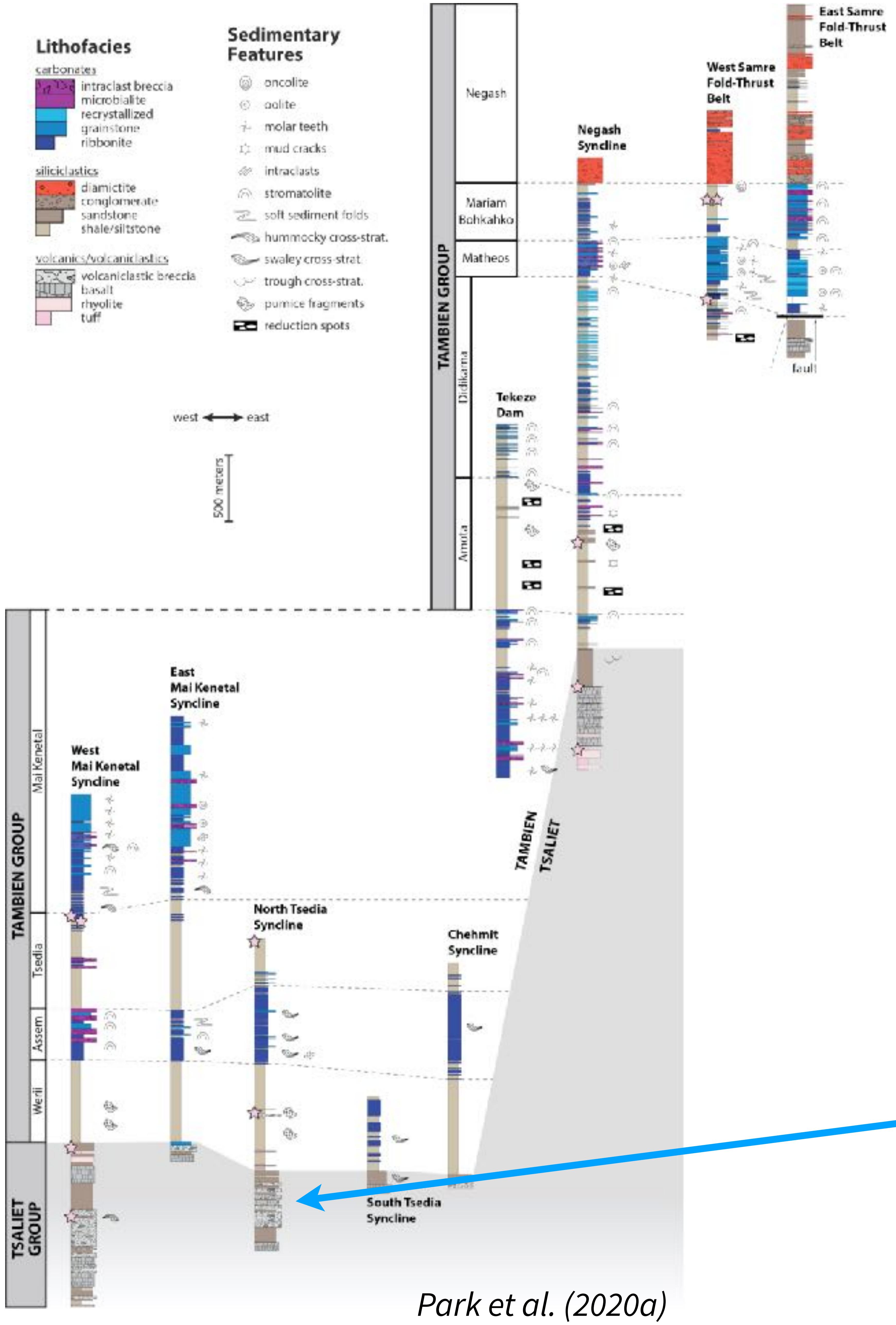

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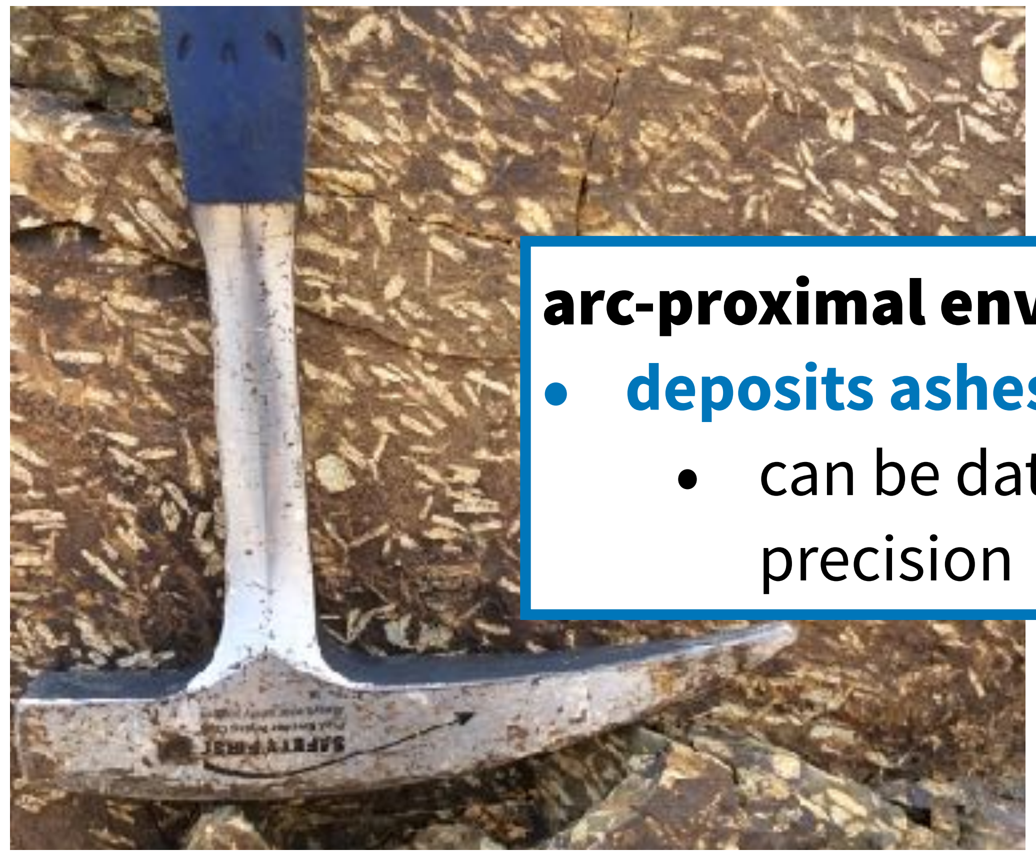

arc-proximal environment
- **deposits ashes**
  - can be dated to very high precision

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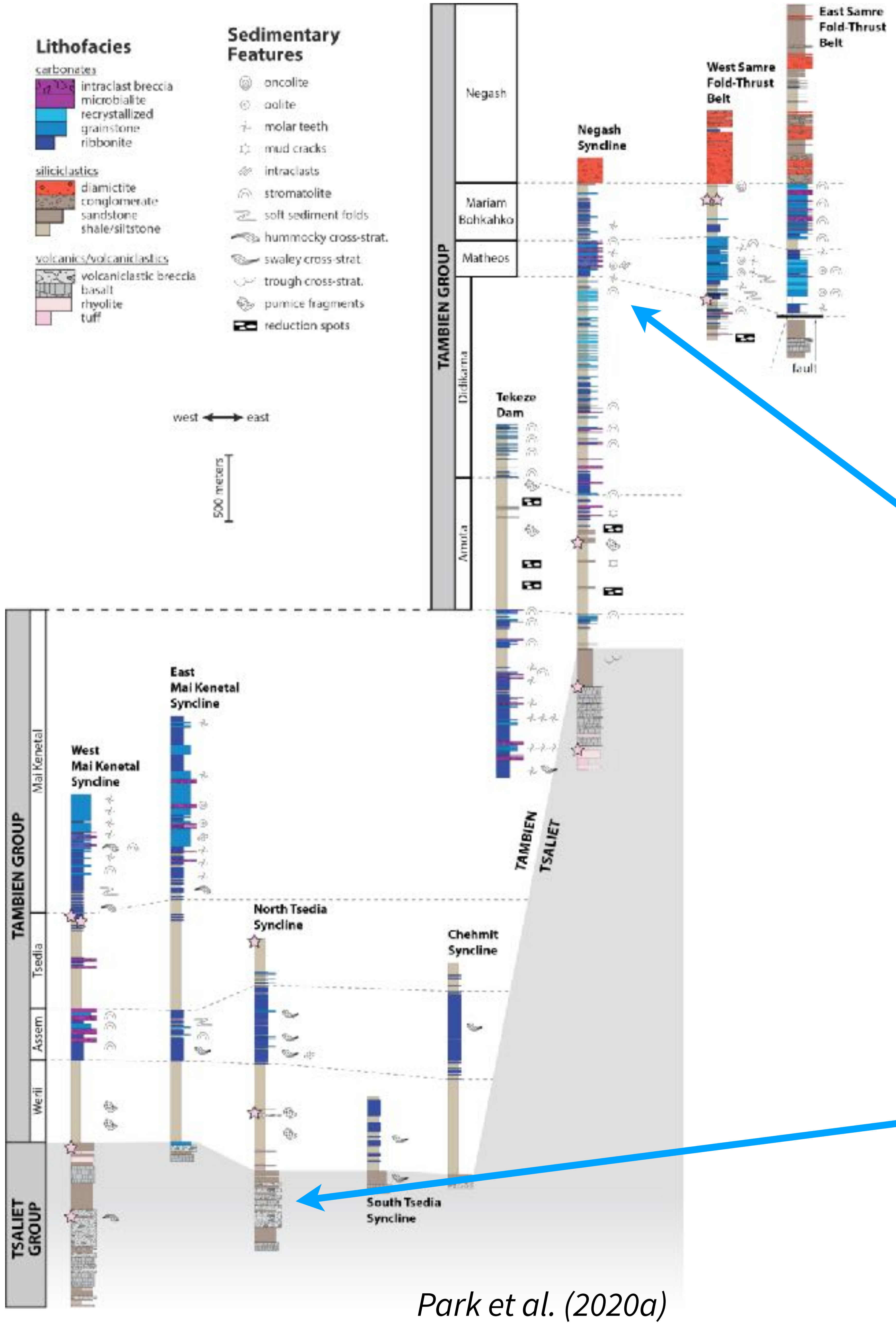

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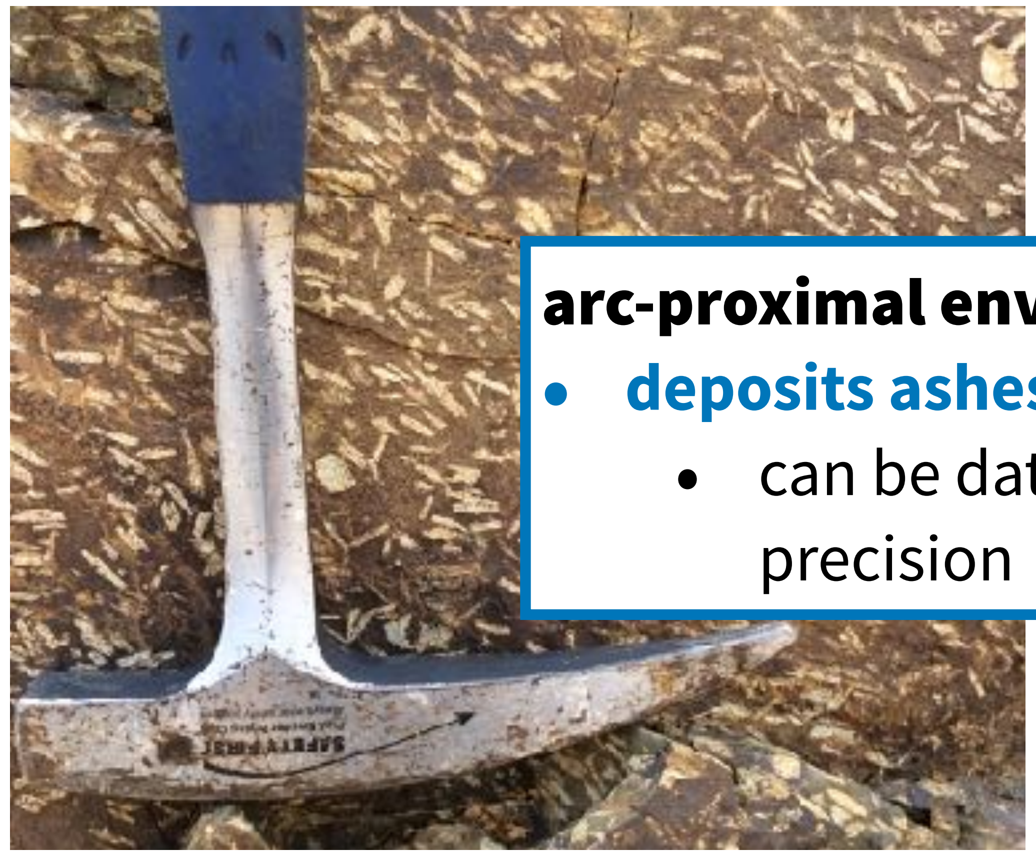

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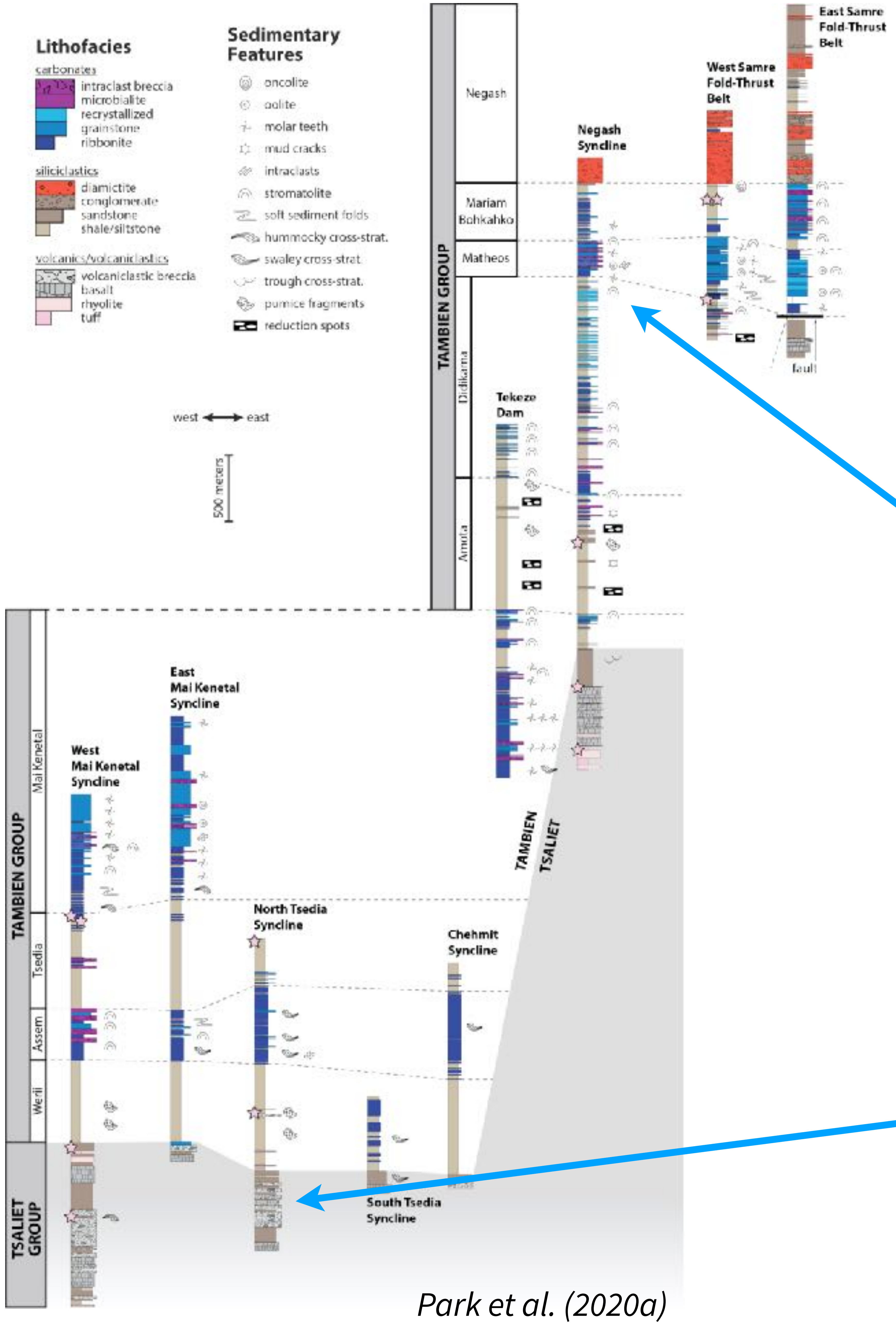

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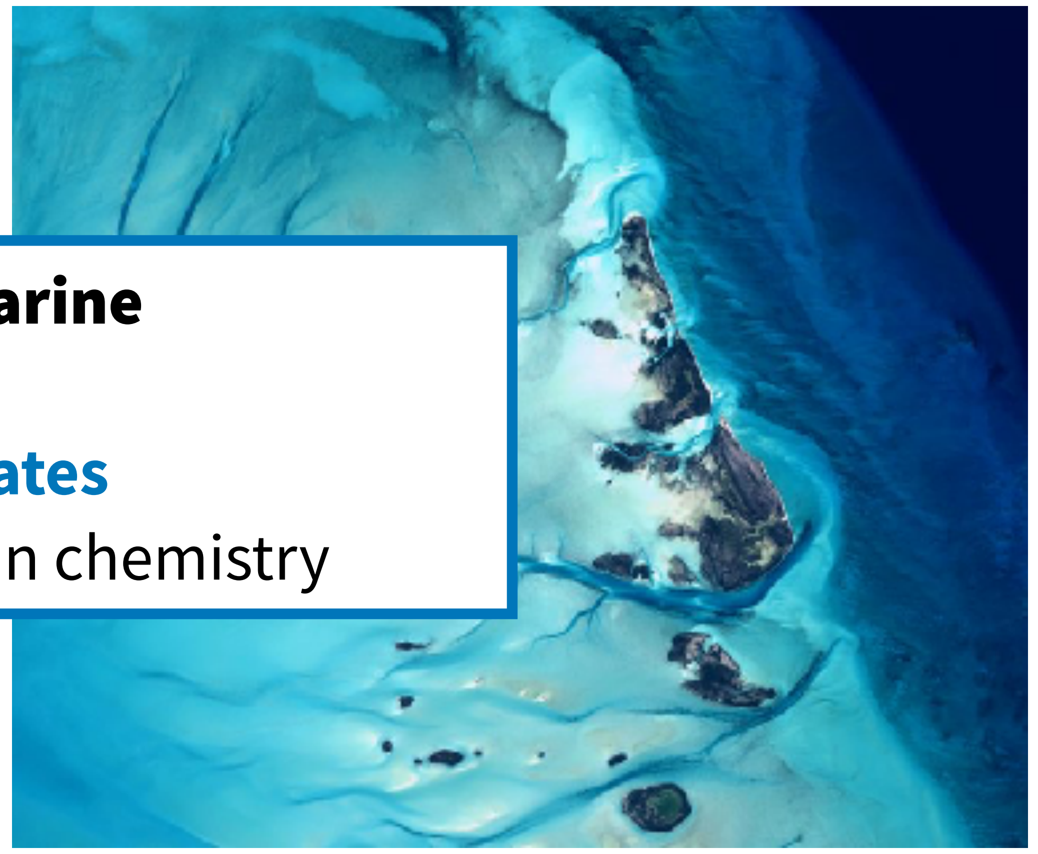
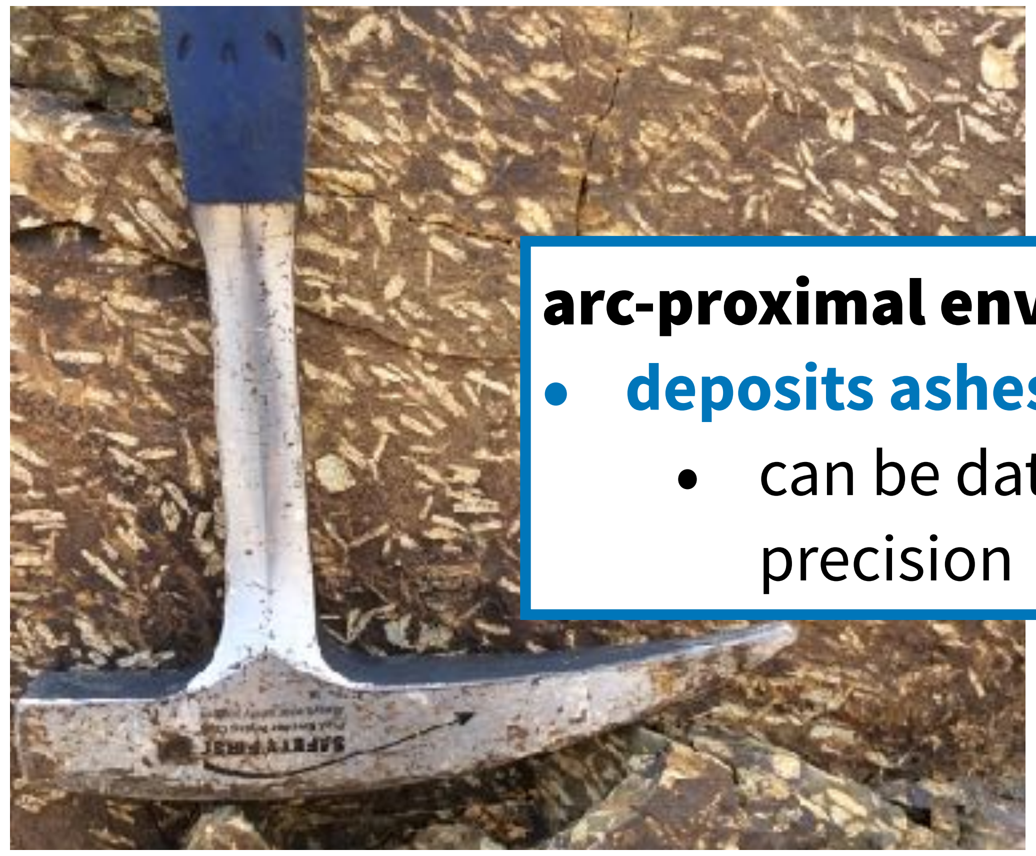


warm & shallow marine environment

- **deposits carbonates**
  - records ocean chemistry



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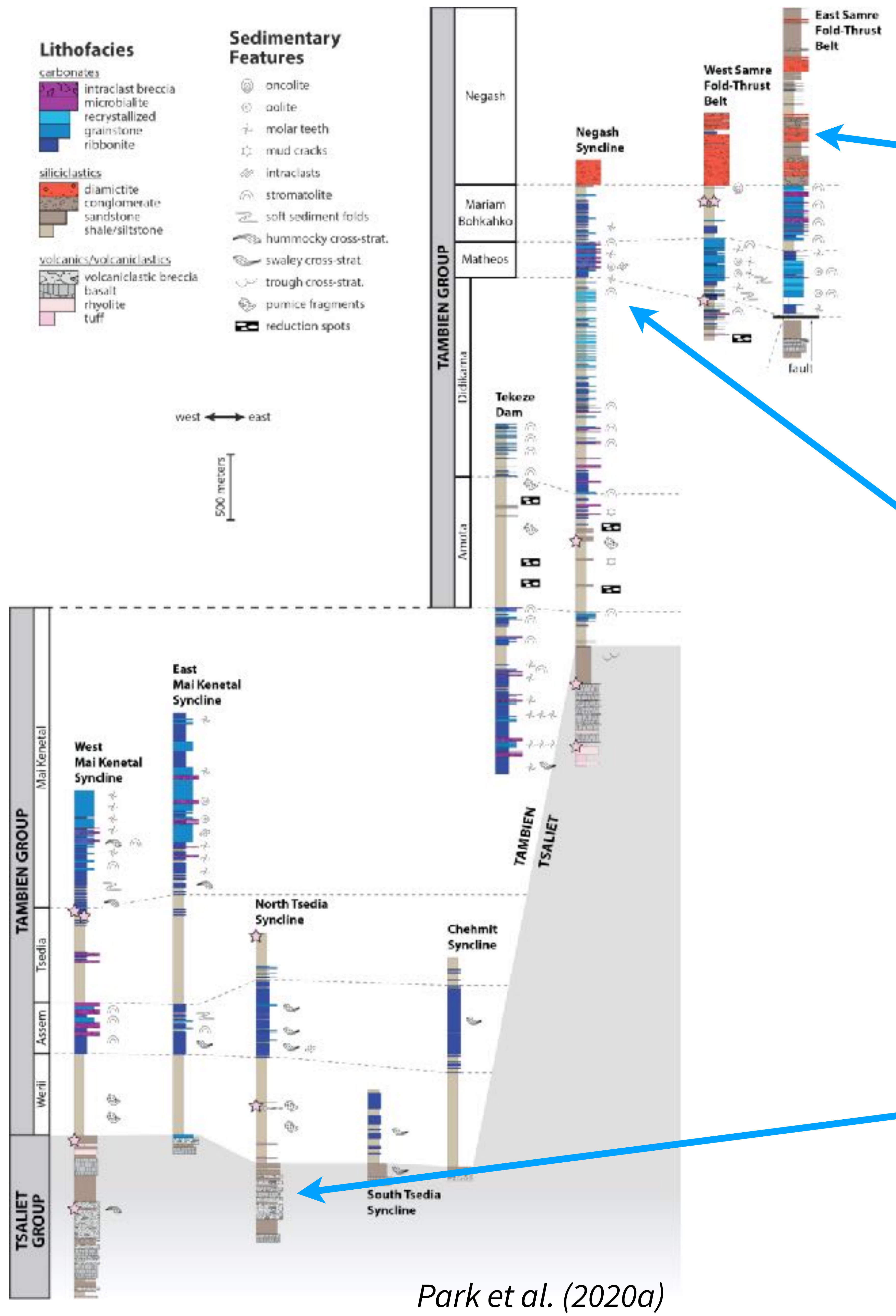

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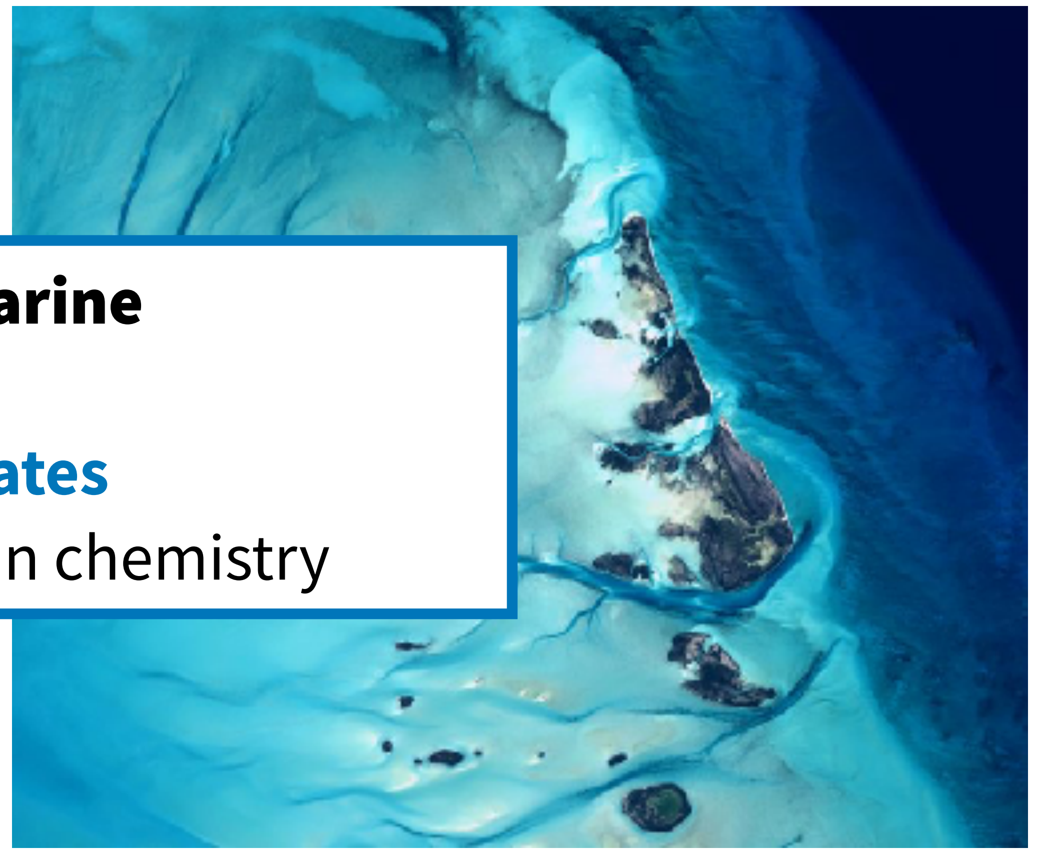

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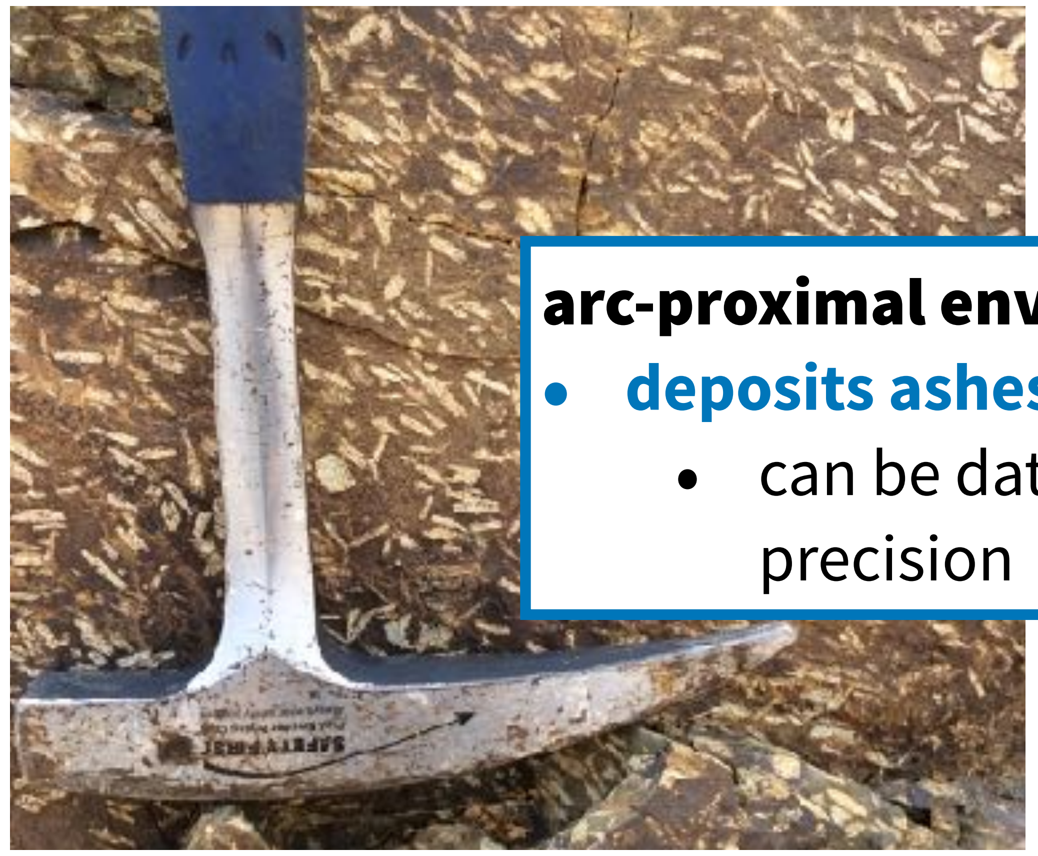

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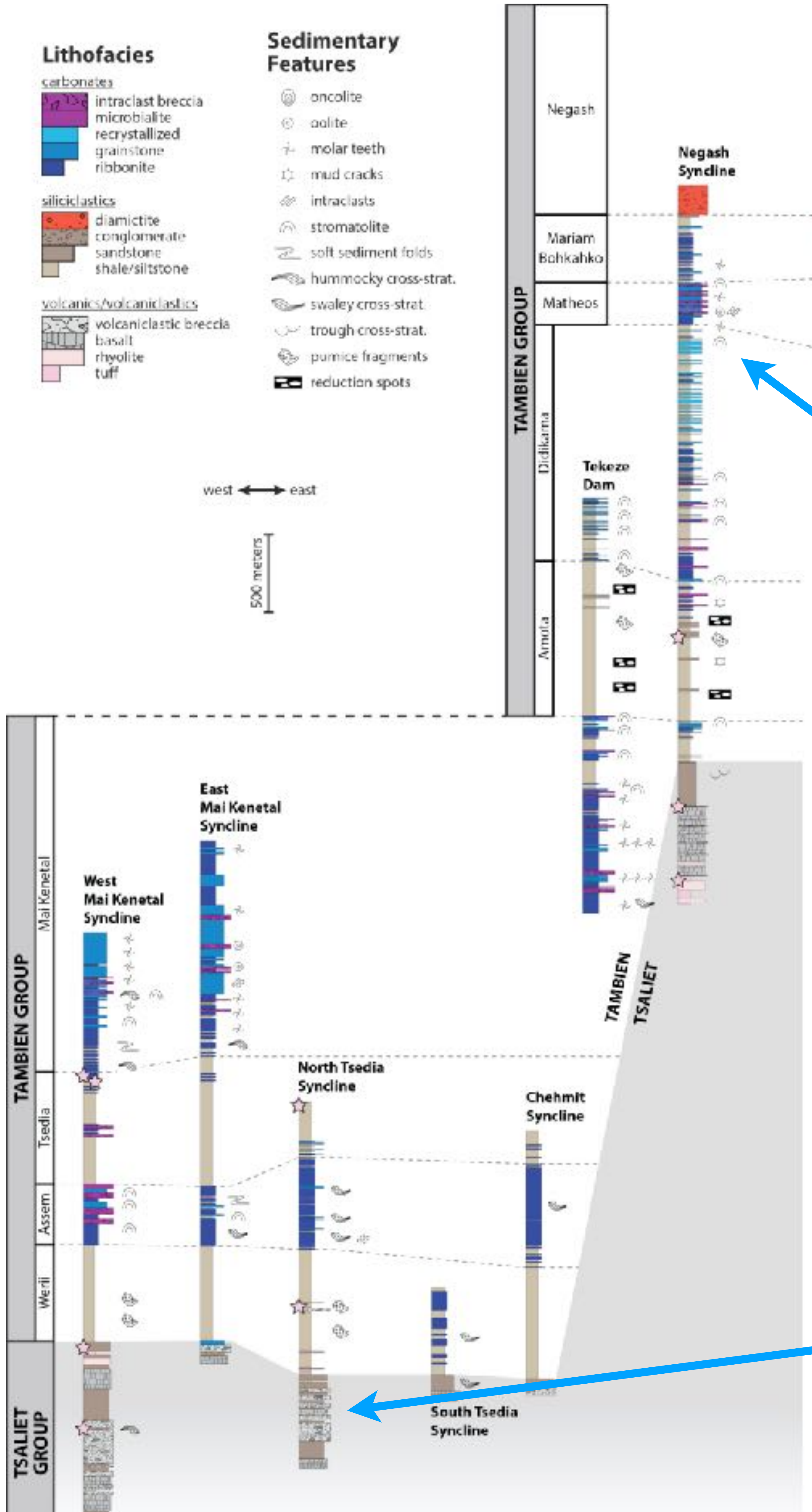

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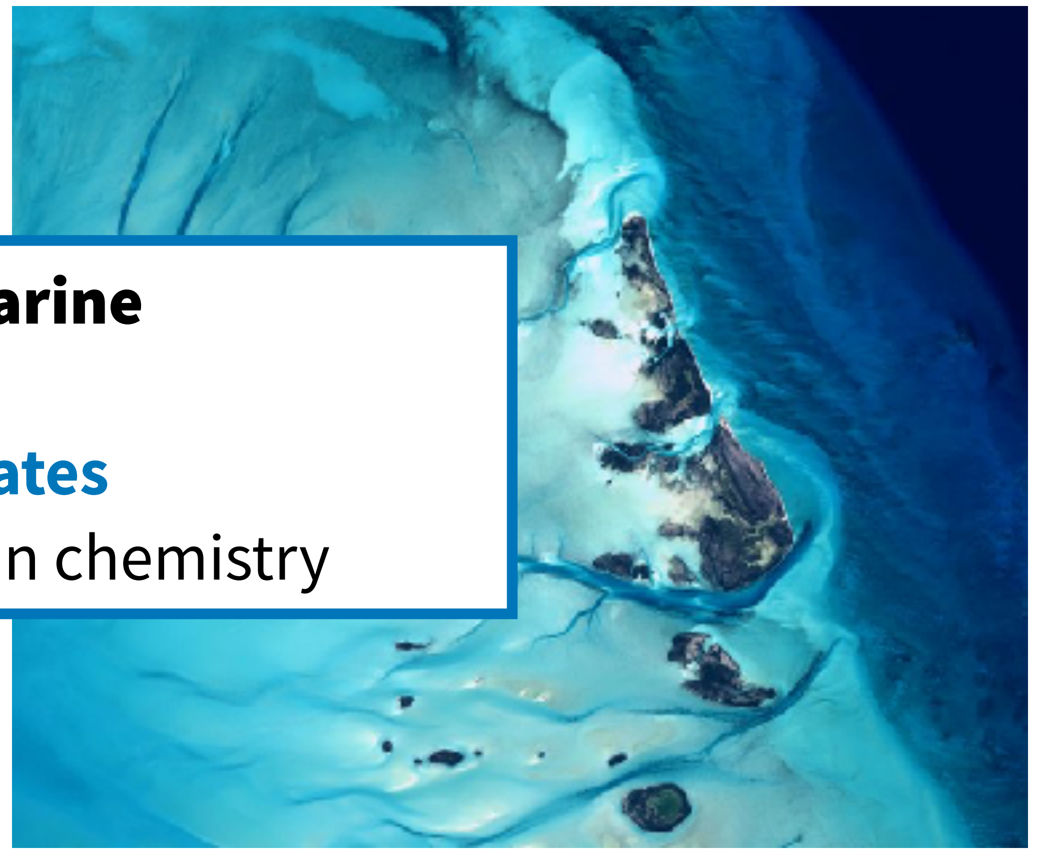

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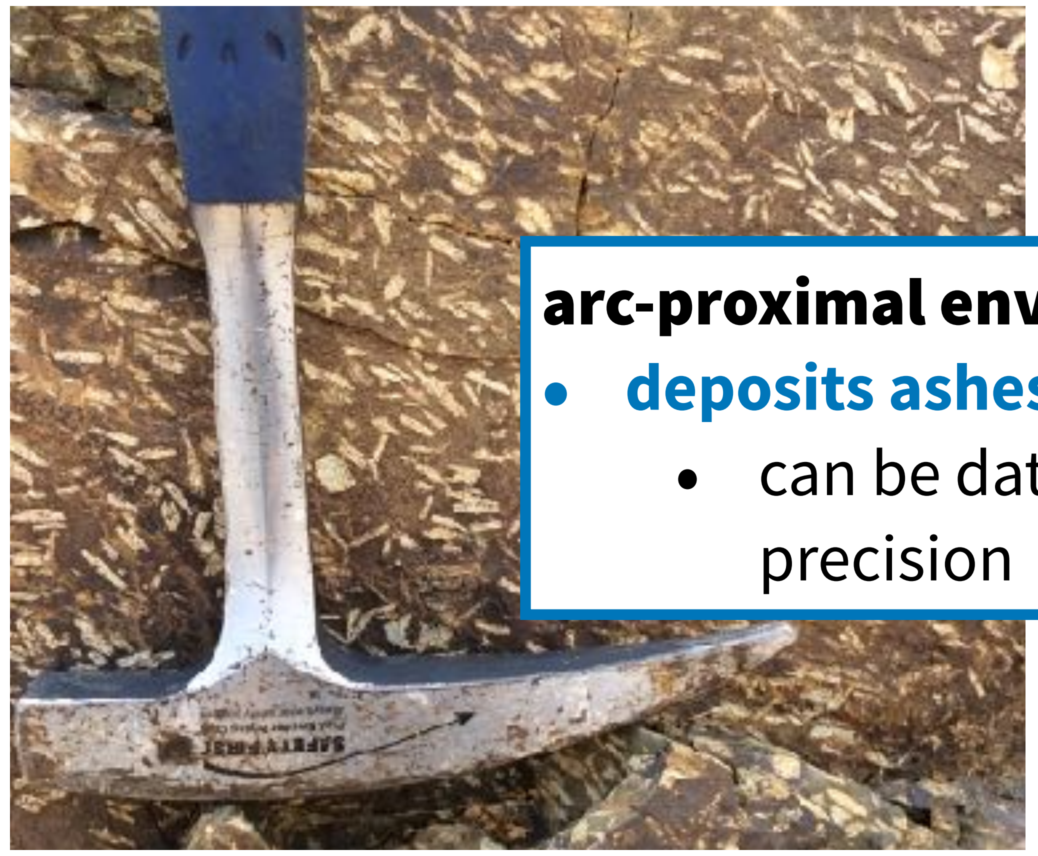

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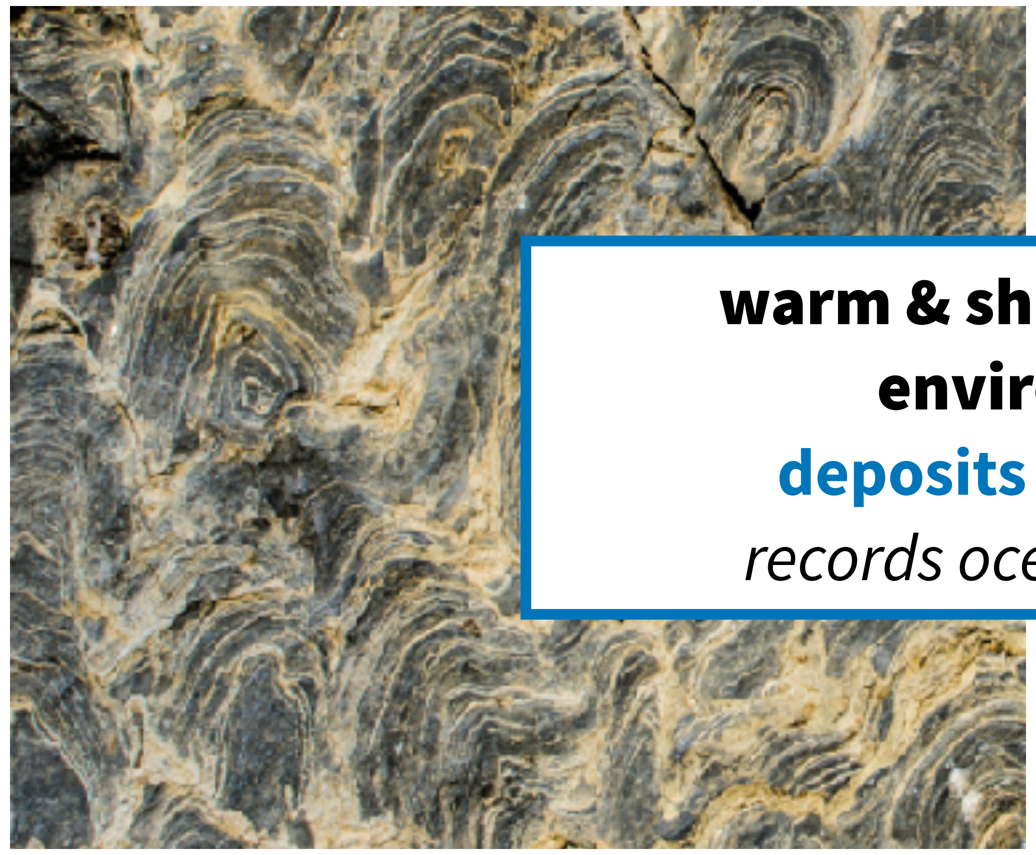
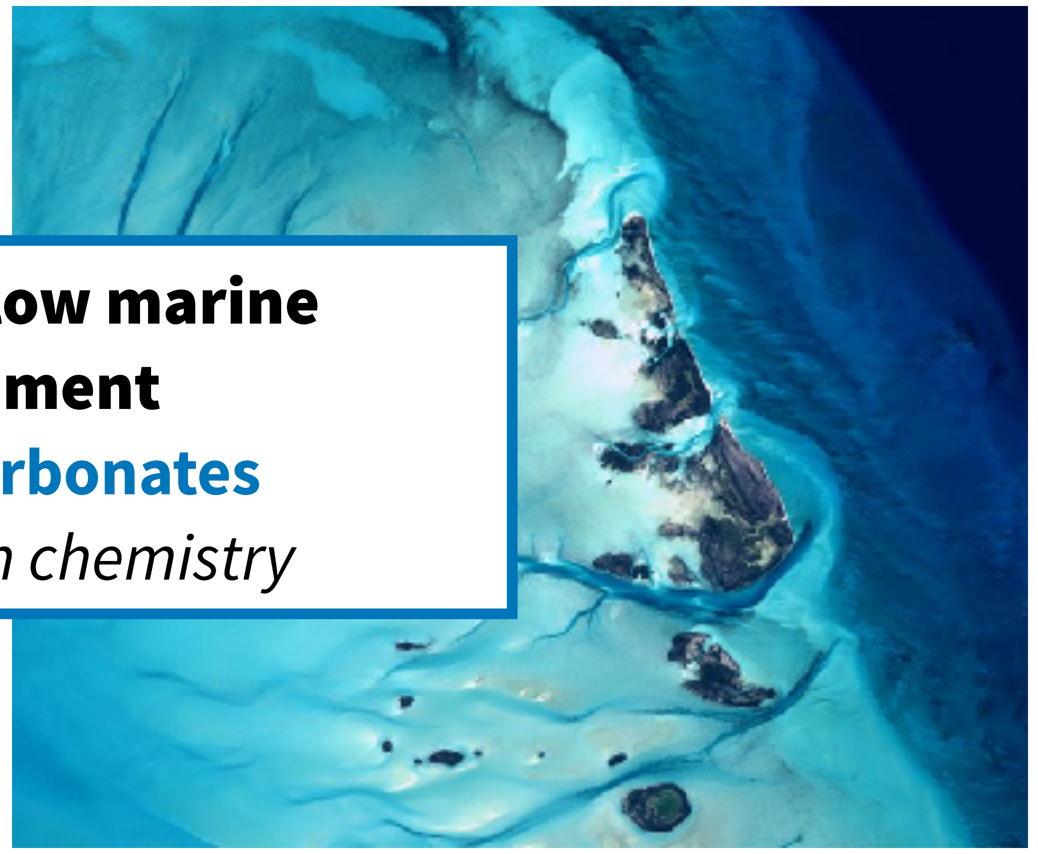
TAMBIEN GROUP


snowball glaciation

The Tambien Group is the only sedimentary sequence identified so far that leads into the Sturtian glaciation and hosts both carbonates and ashes

allows us to produce a precisely time-calibrated record of ocean chemistry leading up to snowball glaciation

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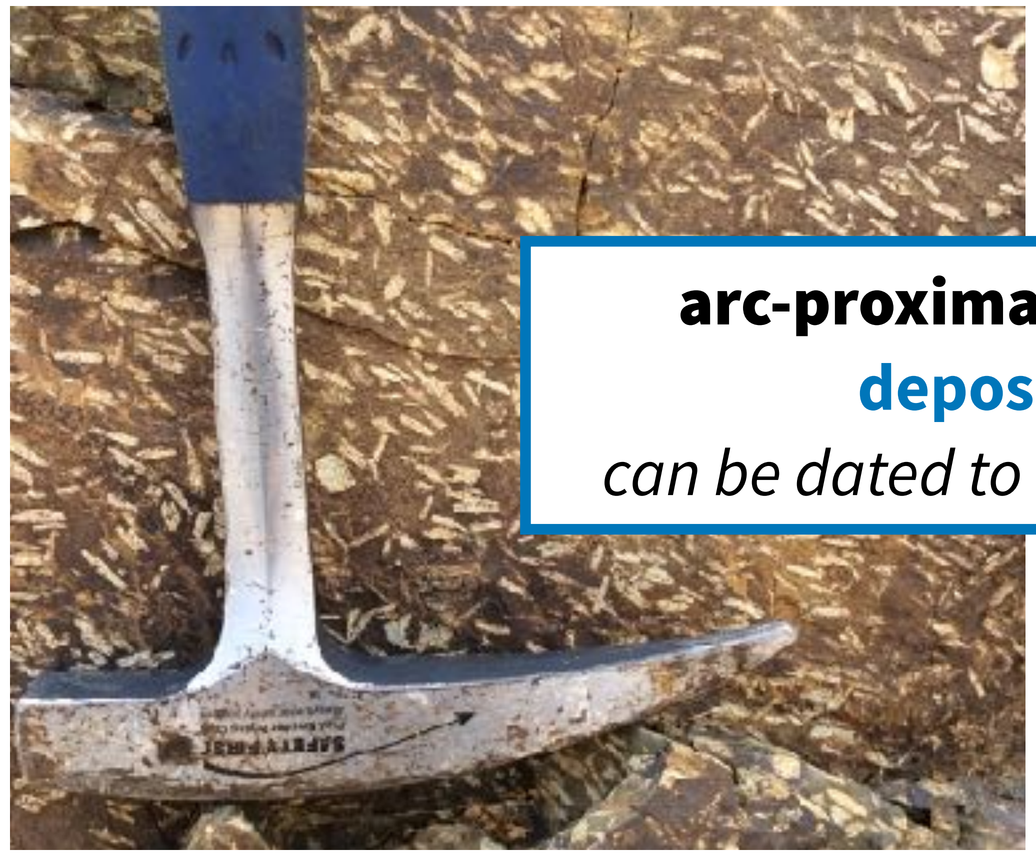


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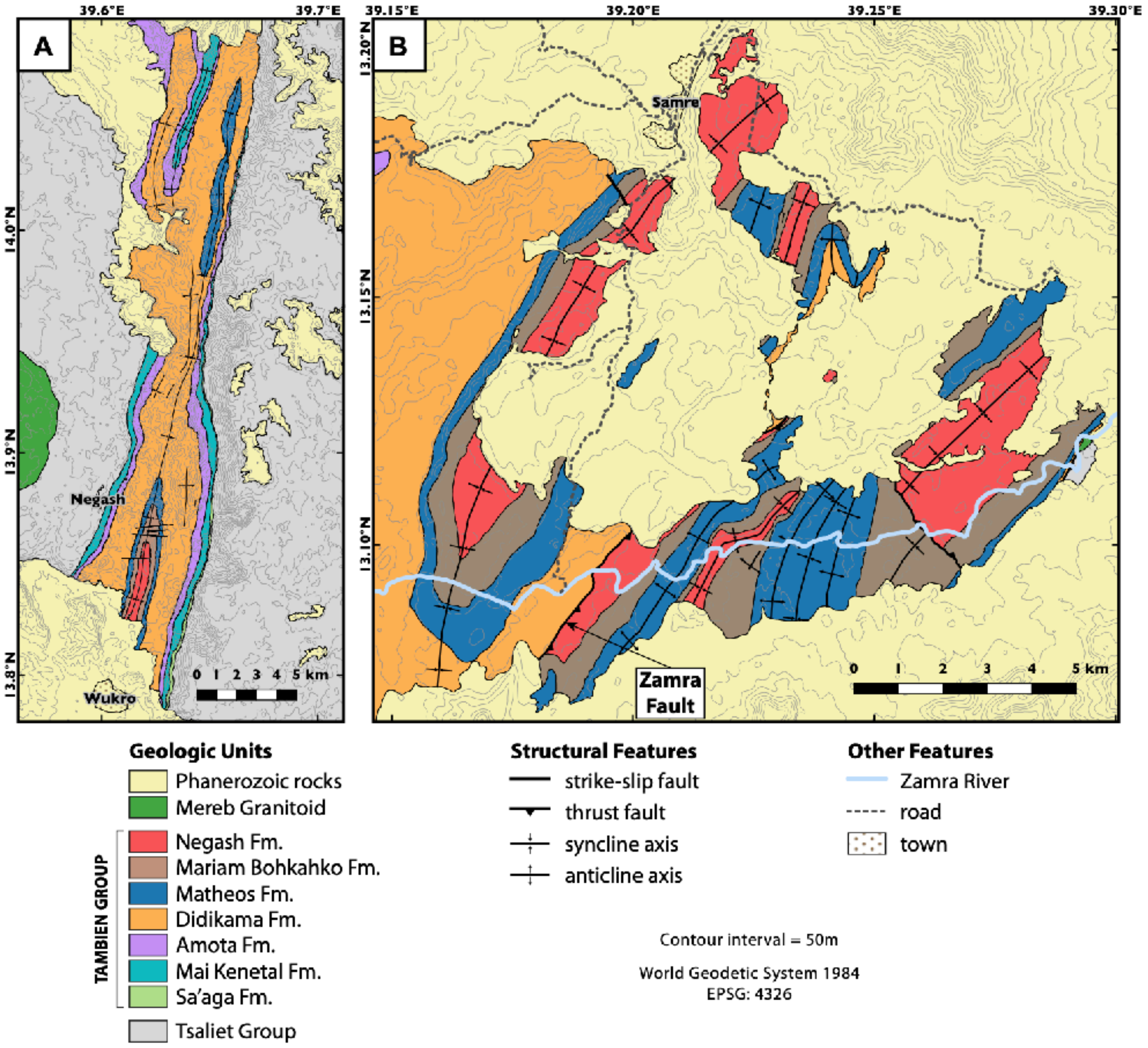
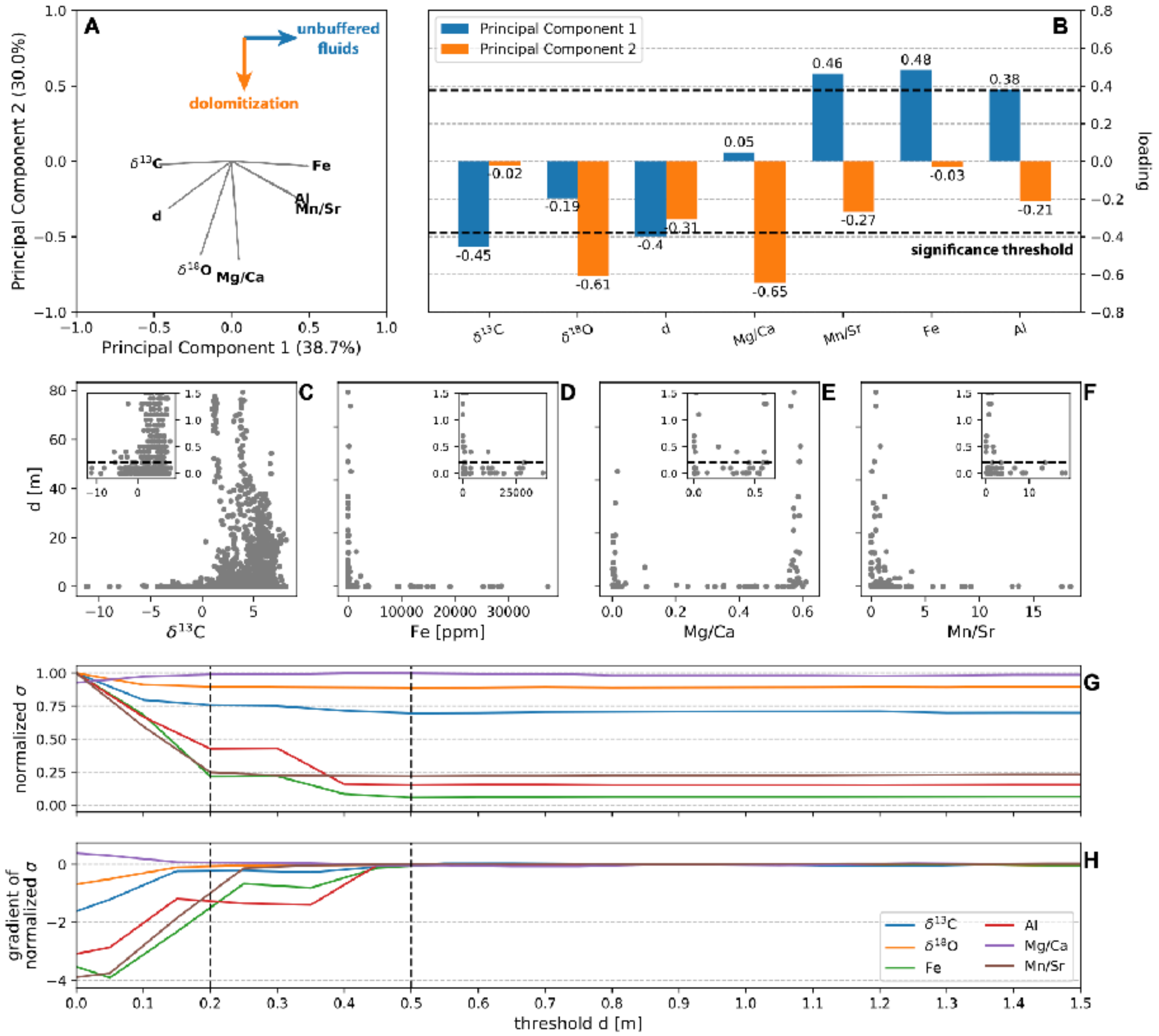


geologic maps

TAMBIEN GROUP

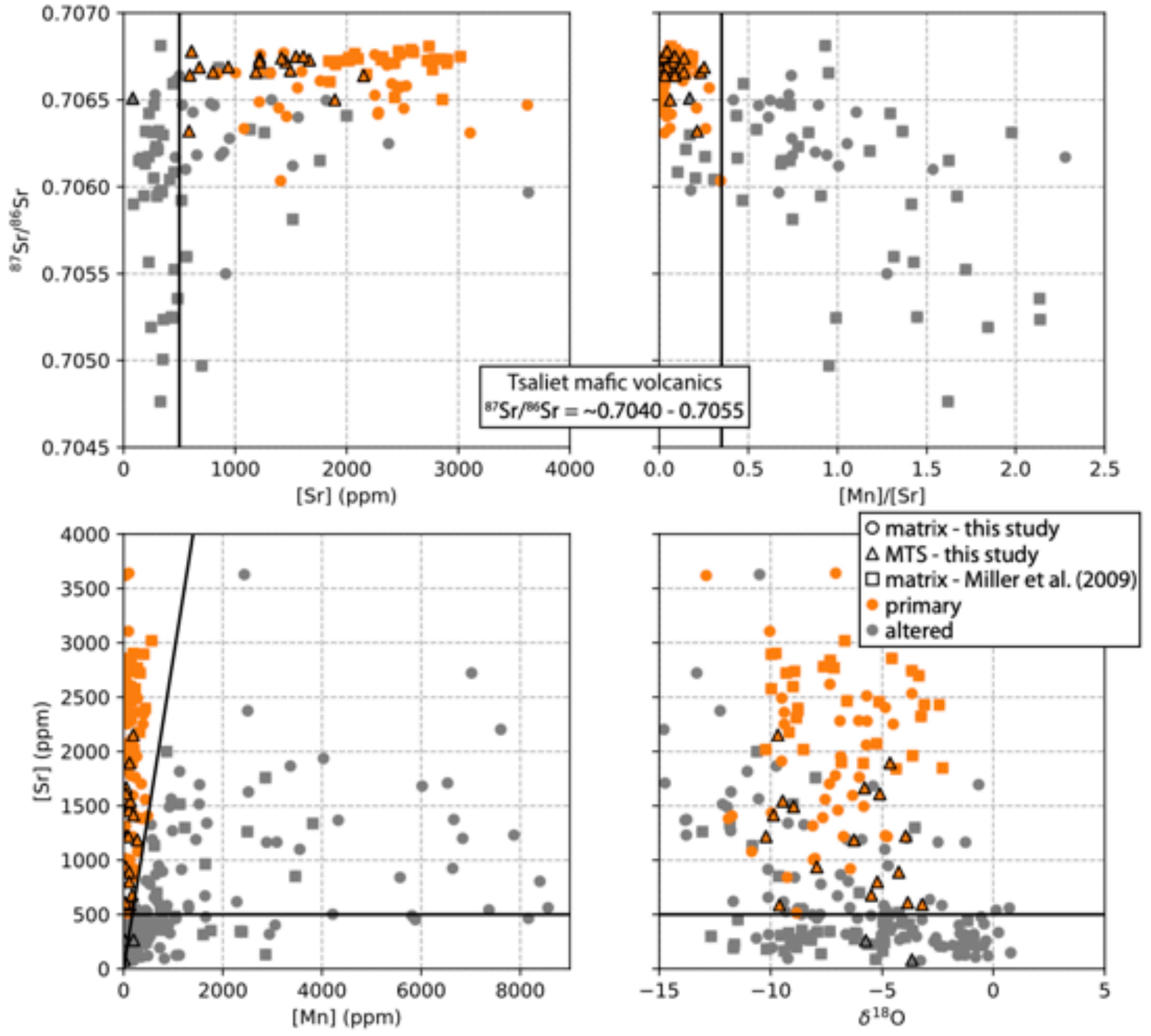
Park et al. (2020a)



principal components analysis
carbon isotopes - δ¹³C

identifying alteration in carbonate samples

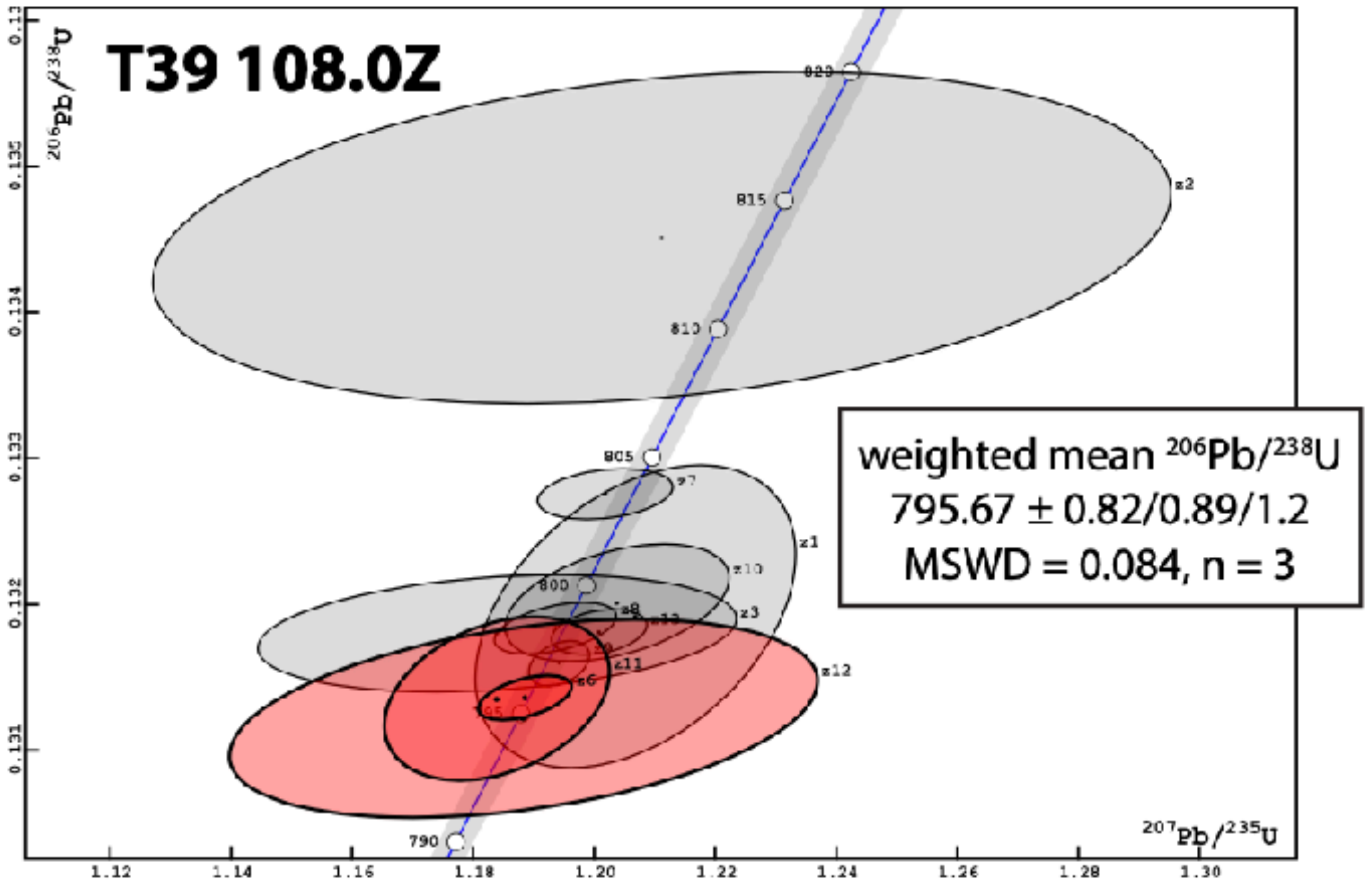
Park et al. (2020a)

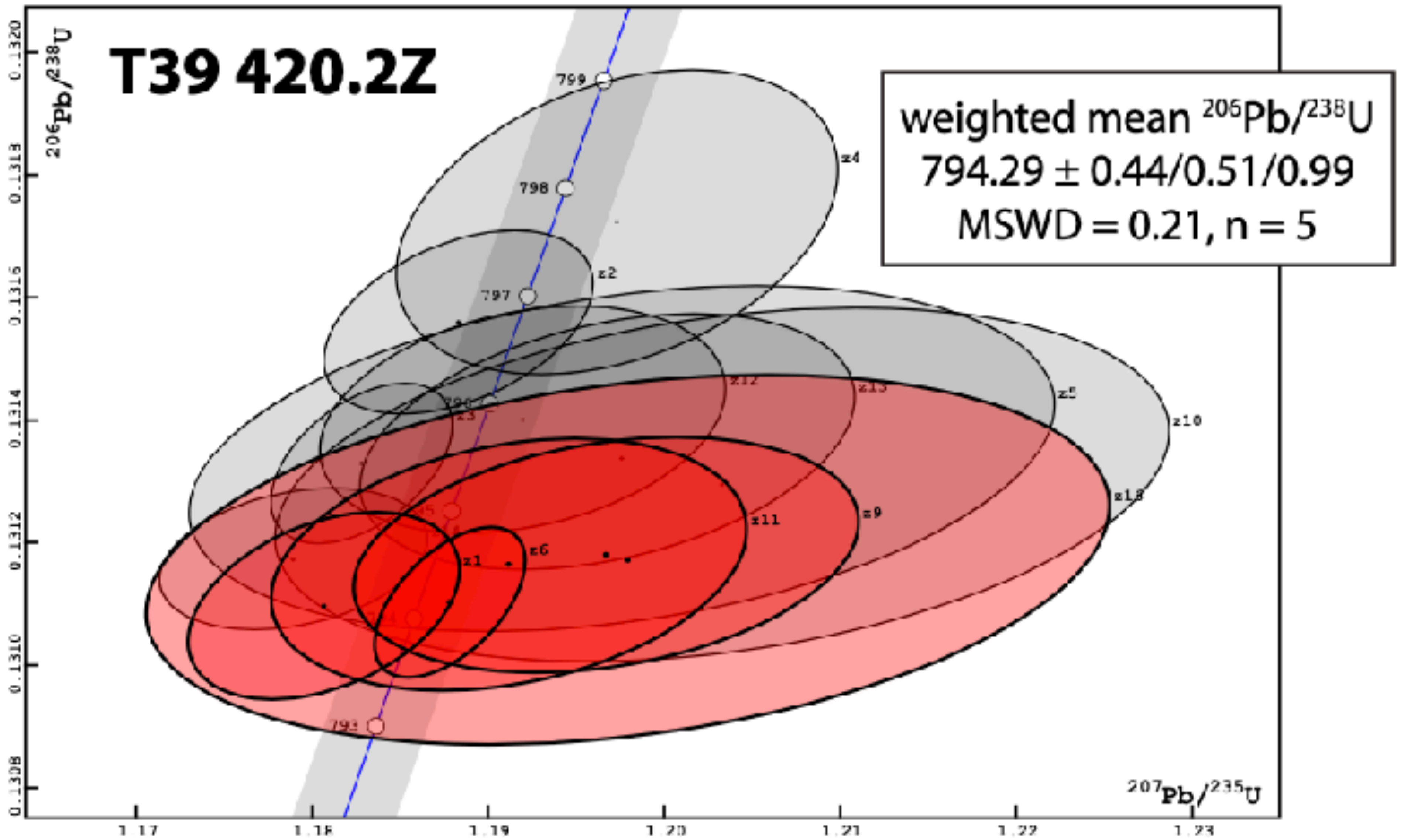


thresholds
strontium isotopes - ⁸⁷Sr/⁸⁶Sr

TAMBIEN GROUP

Park et al. (2020a)



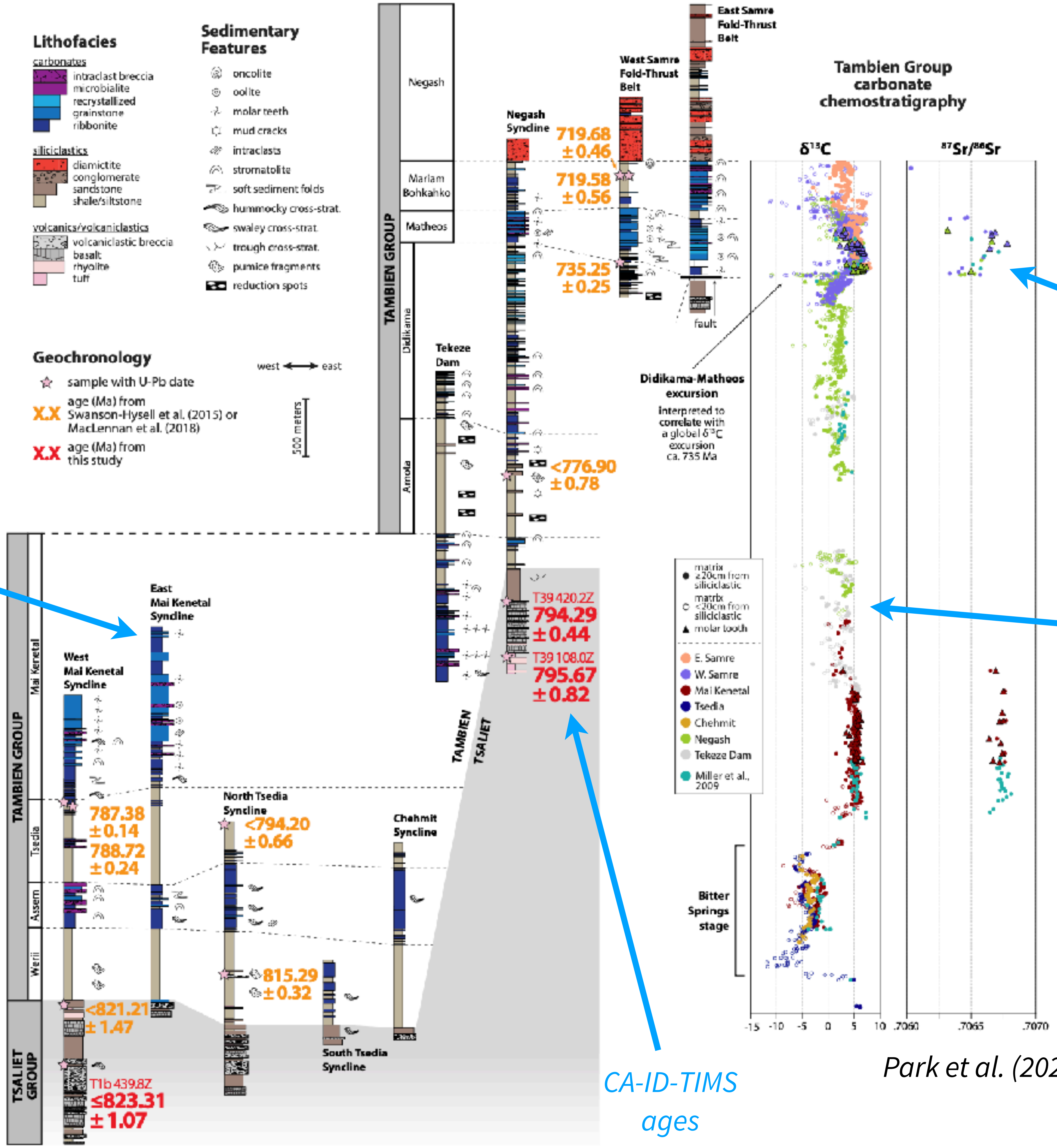


generating precise ages from ashes

U-Pb
chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) on zircon

TAMBIEN GROUP

put it all together...



stratigraphic sections

CA-ID-TIMS ages

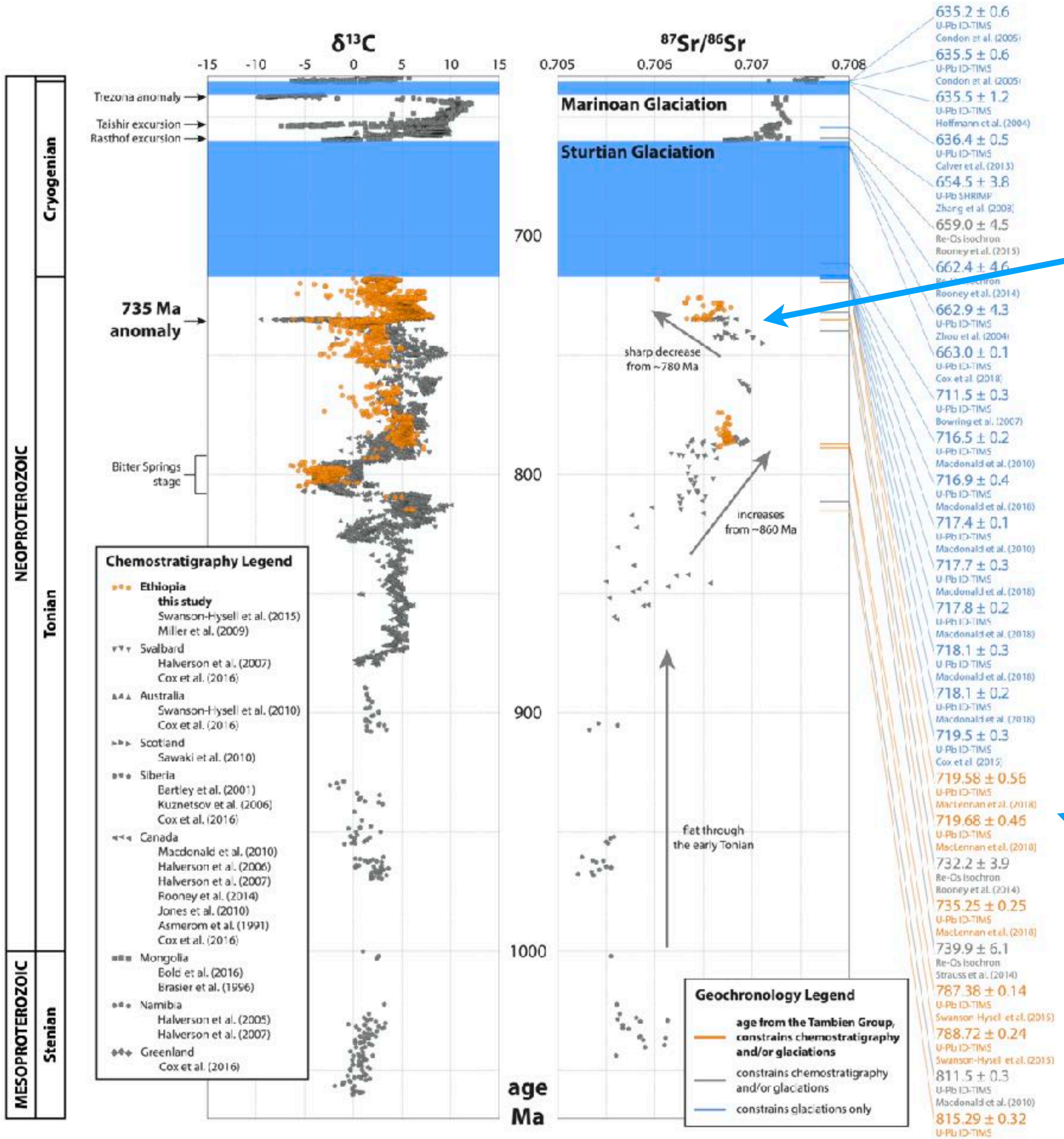
marine strontium isotope record

marine carbon isotope record

Park et al. (2020a)

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

CHEMOSTRATIGRAPHY



Park et al. (2020a)

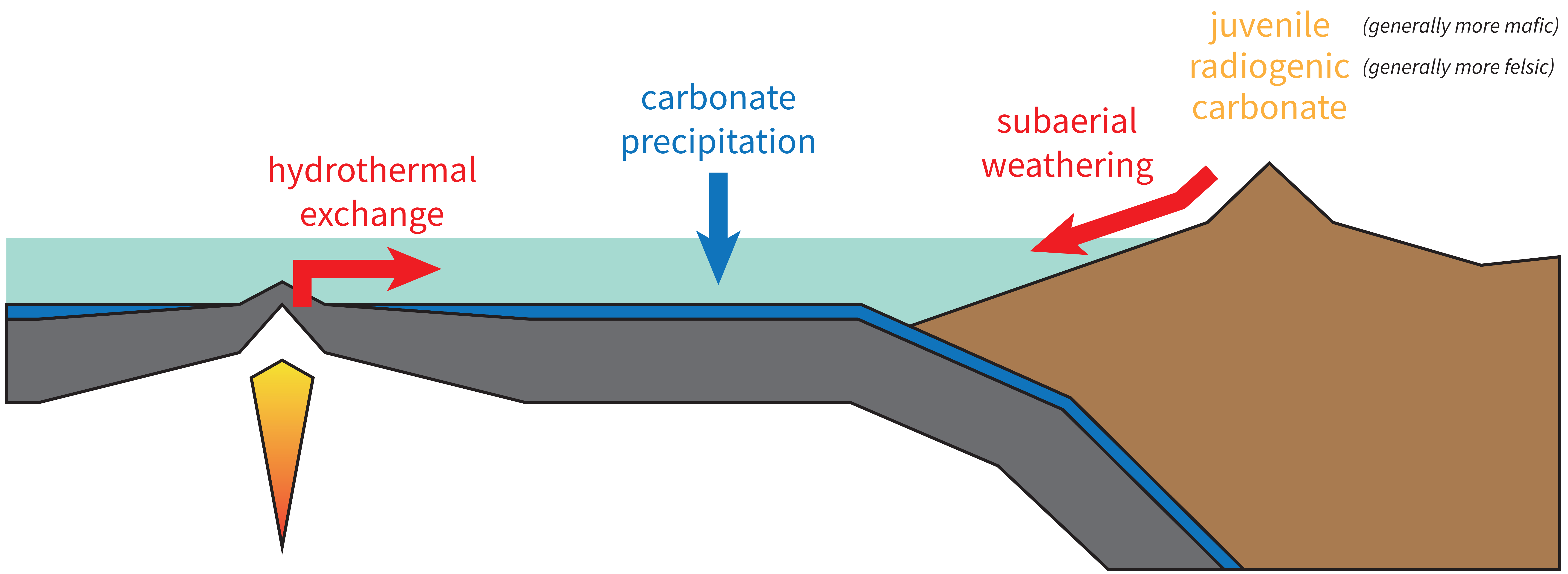
ocean chemistry record derived from carbonates

most precisely time-calibrated marine isotope record leading into the Sturtian Glaciation to date

age constraints derived from ashes

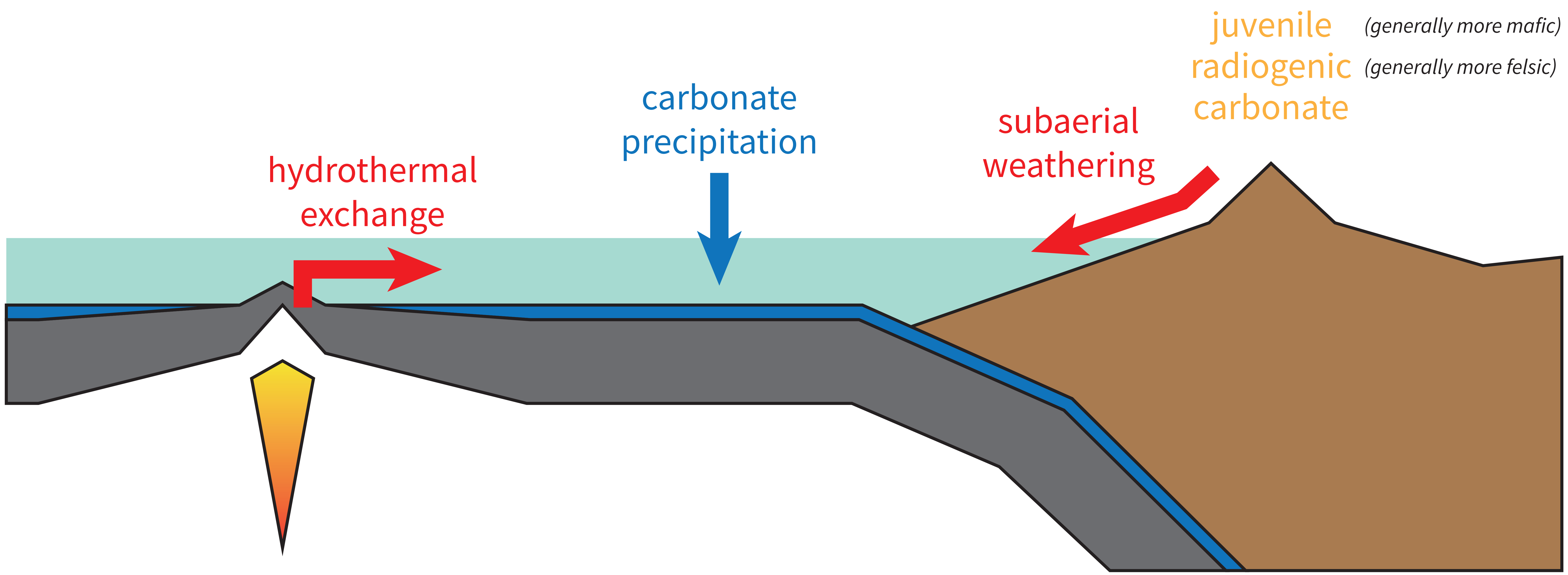
Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM



Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM



juvenile rocks (generally more mafic)	*low* $^{87}Sr/^{86}Sr$
radiogenic rocks (generally more felsic)	*high* $^{87}Sr/^{86}Sr$
carbonate rocks	*variable* $^{87}Sr/^{86}Sr$
hydrothermal exchange	*low* $^{87}Sr/^{86}Sr$

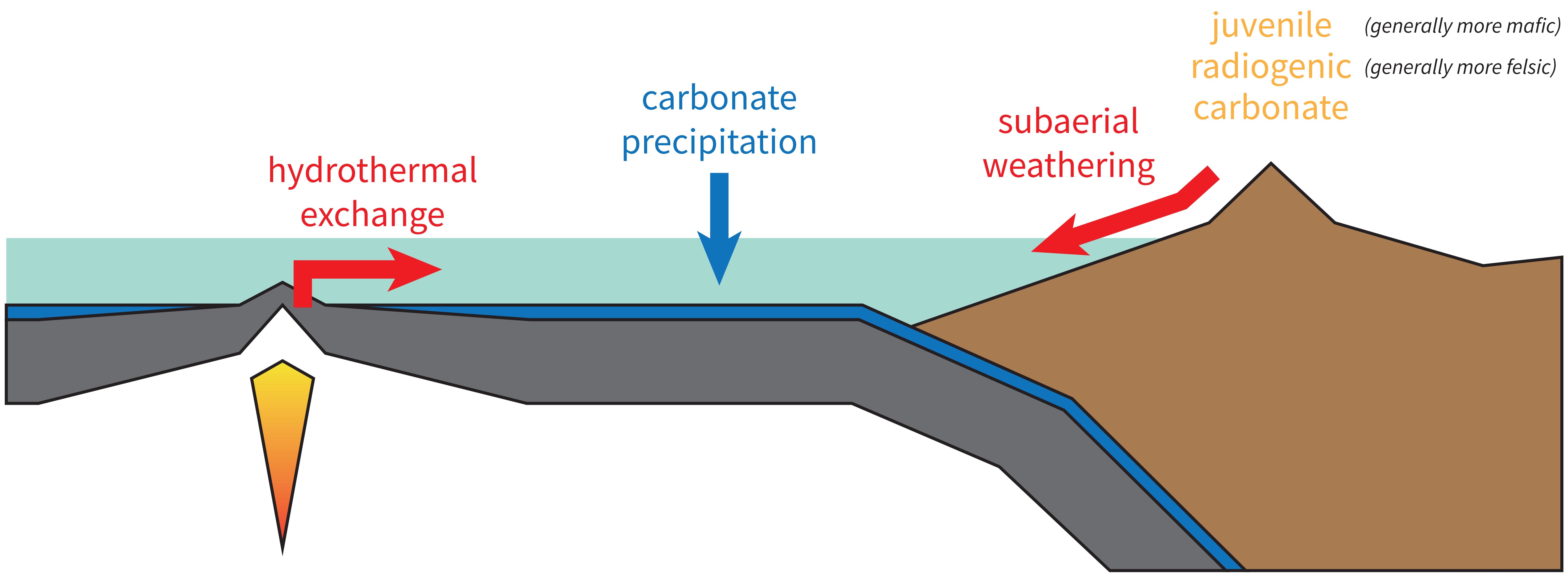
→ **MIX** →

$^{87}Sr/^{86}Sr$ of oceans is set by the relative proportion of globally averaged fluxes coming from each of these four sources

introduction
Phanerozoic
Cenozoic
Neoproterozoic
conclusions
acknowledgements

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM



juvenile rocks (generally more mafic) — *low* $^{87}Sr/^{86}Sr$

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Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

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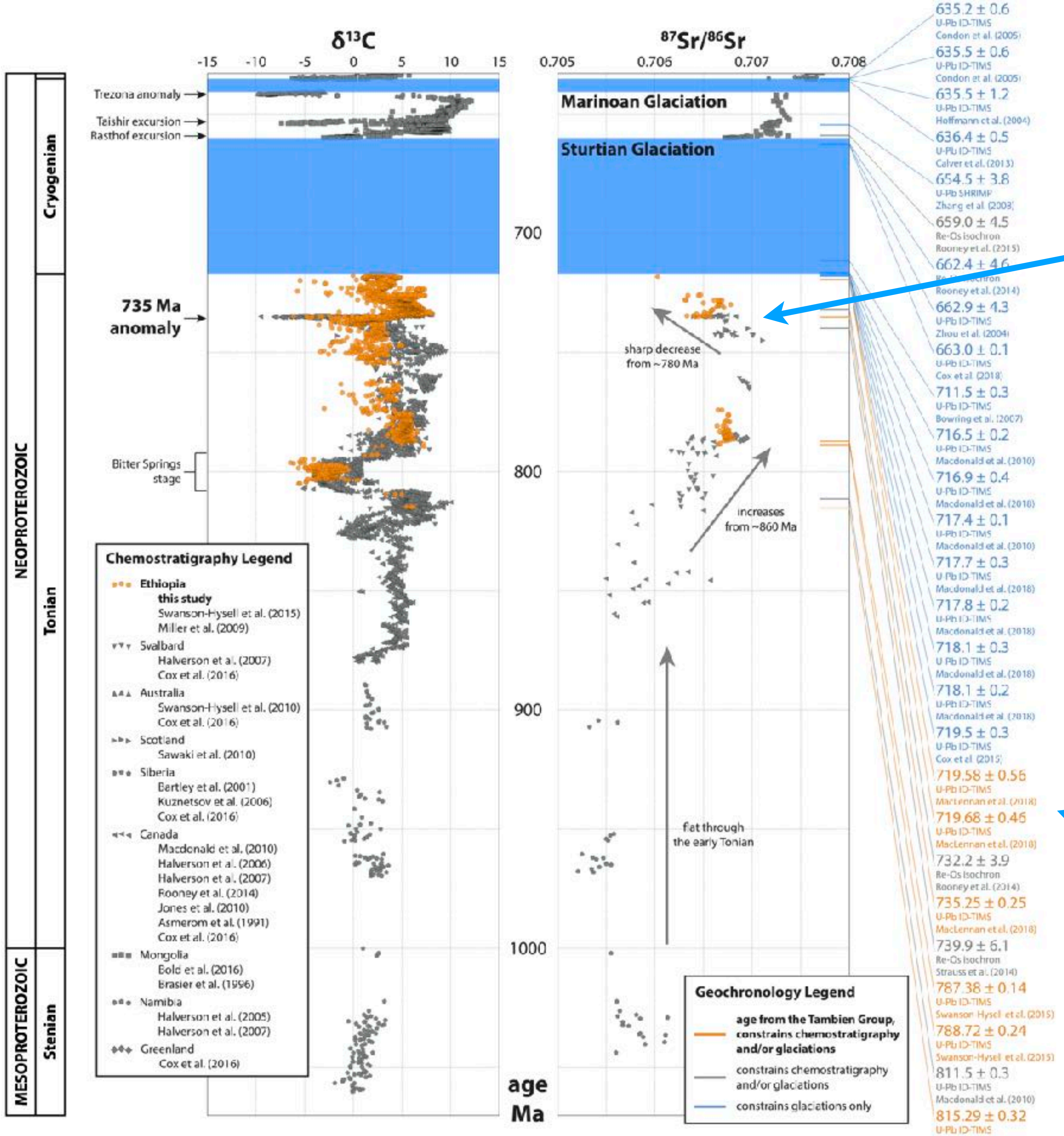

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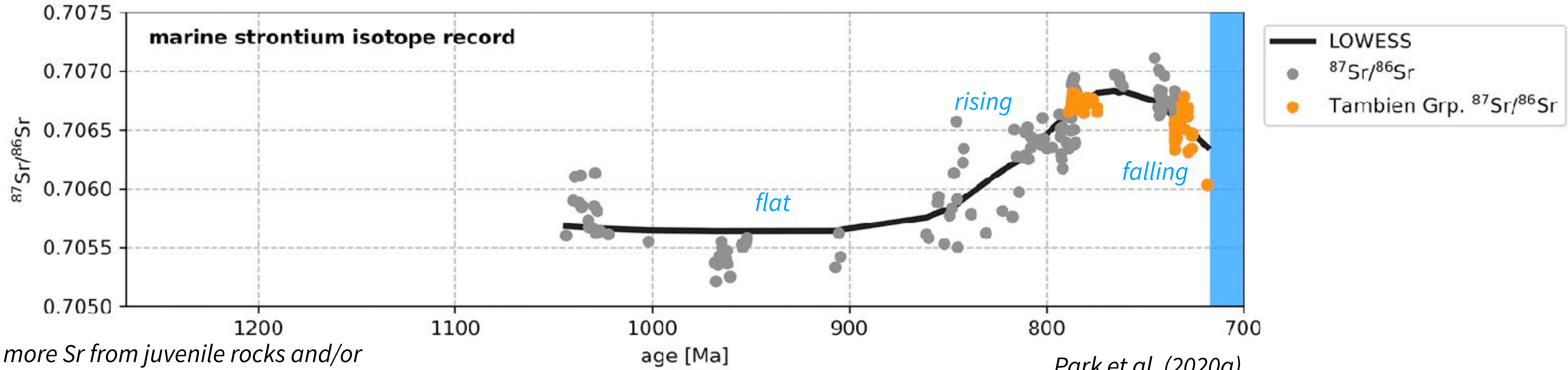
STRONTIUM

more Sr from radiogenic rocks



more Sr from juvenile rocks and/or hydrothermal exchange

Park et al. (2020a)

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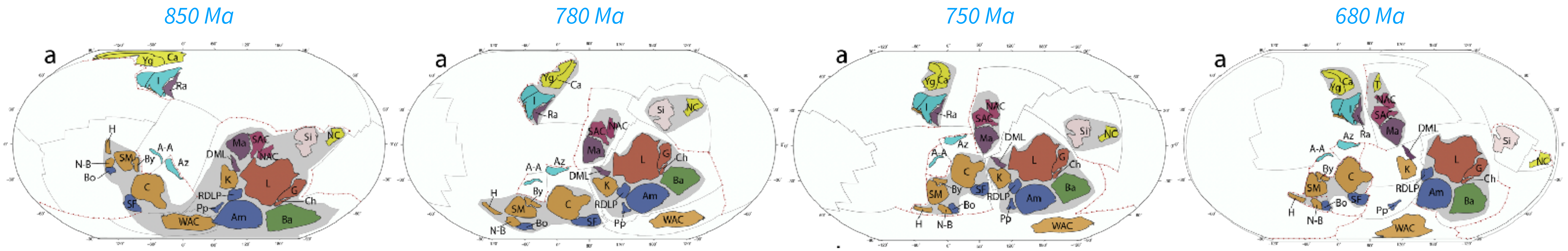
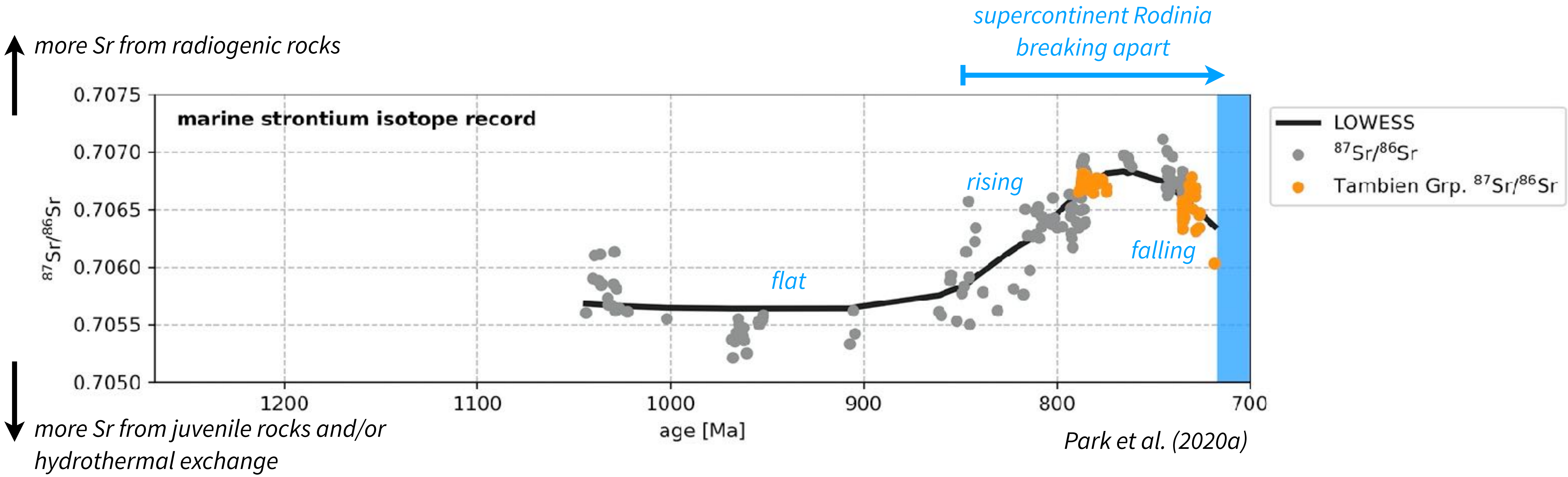
STRONTIUM

Merdith et al. (2017)



supercontinent breakup leads to increased hydrothermal exchange flux

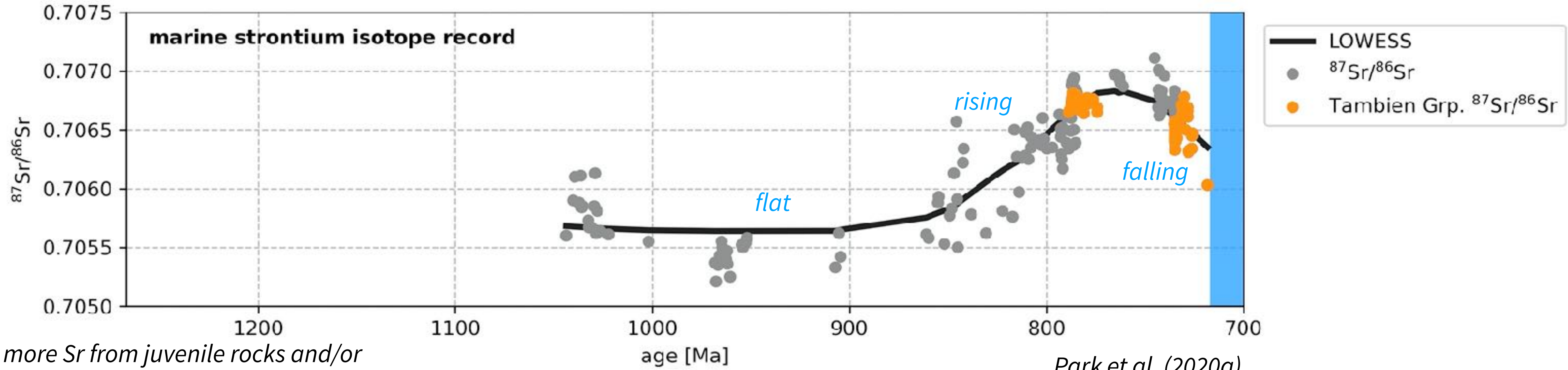


Park et al. (2020a)

STRONTIUM

falling $^{87}Sr/^{86}Sr$ starting ~780 Ma most likely driven by increased weathering of juvenile rocks

more Sr from radiogenic rocks



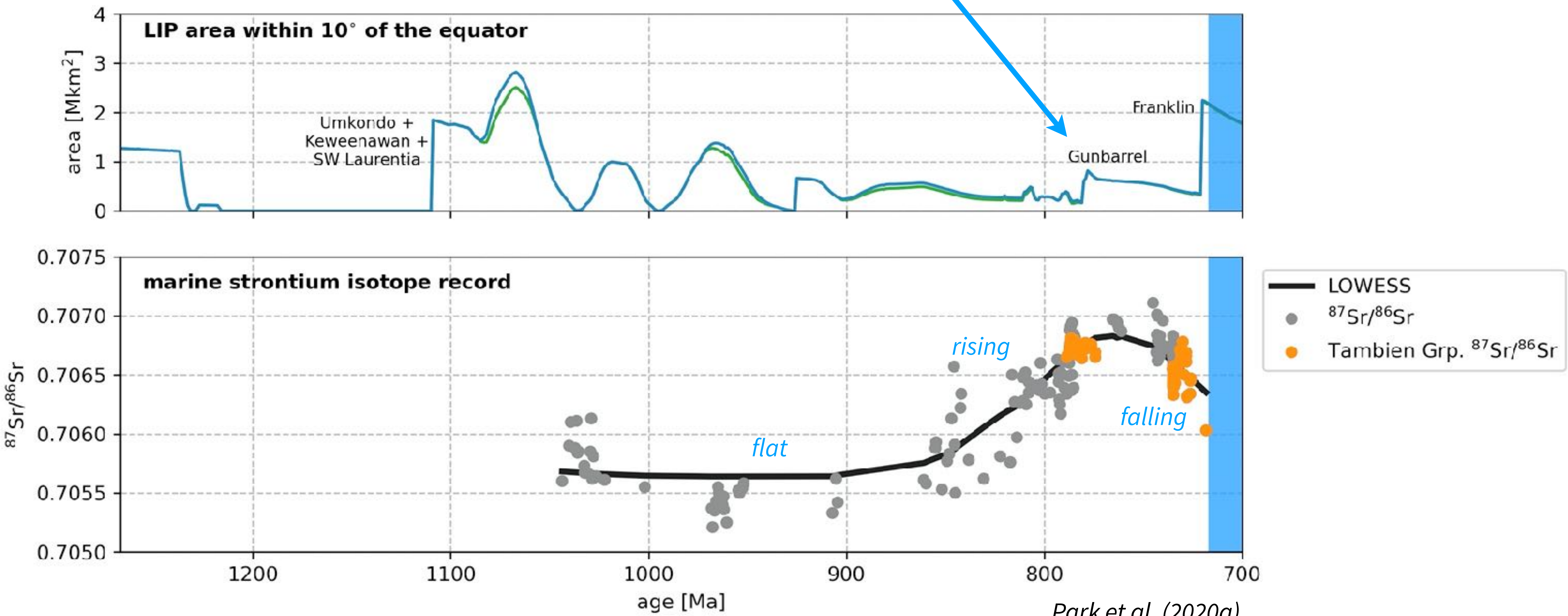
more Sr from juvenile rocks and/or hydrothermal exchange

Park et al. (2020a)

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM

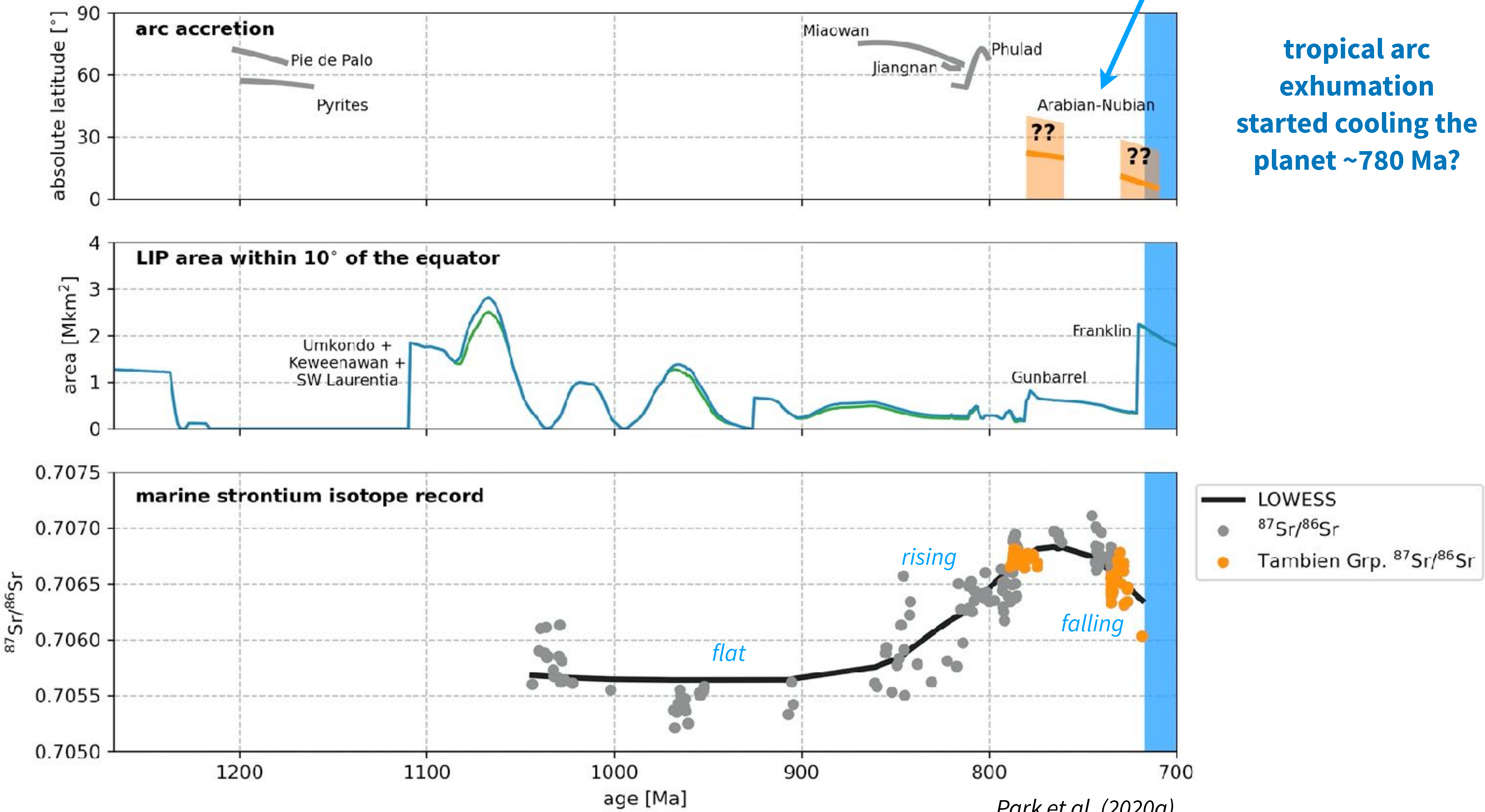
Gunbarrel coincides with $^{87}Sr/^{86}Sr$ fall ~780 Ma, but larger tropical LIP area peaks do not cause $^{87}Sr/^{86}Sr$ to fall



Park et al. (2020a)

STRONTIUM

the only low-latitude arc accretion events coincide with $^{87}Sr/^{86}Sr$ fall ~780 Ma



Park et al. (2020a)

tropical arc exhumation started cooling the planet ~780 Ma?

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM

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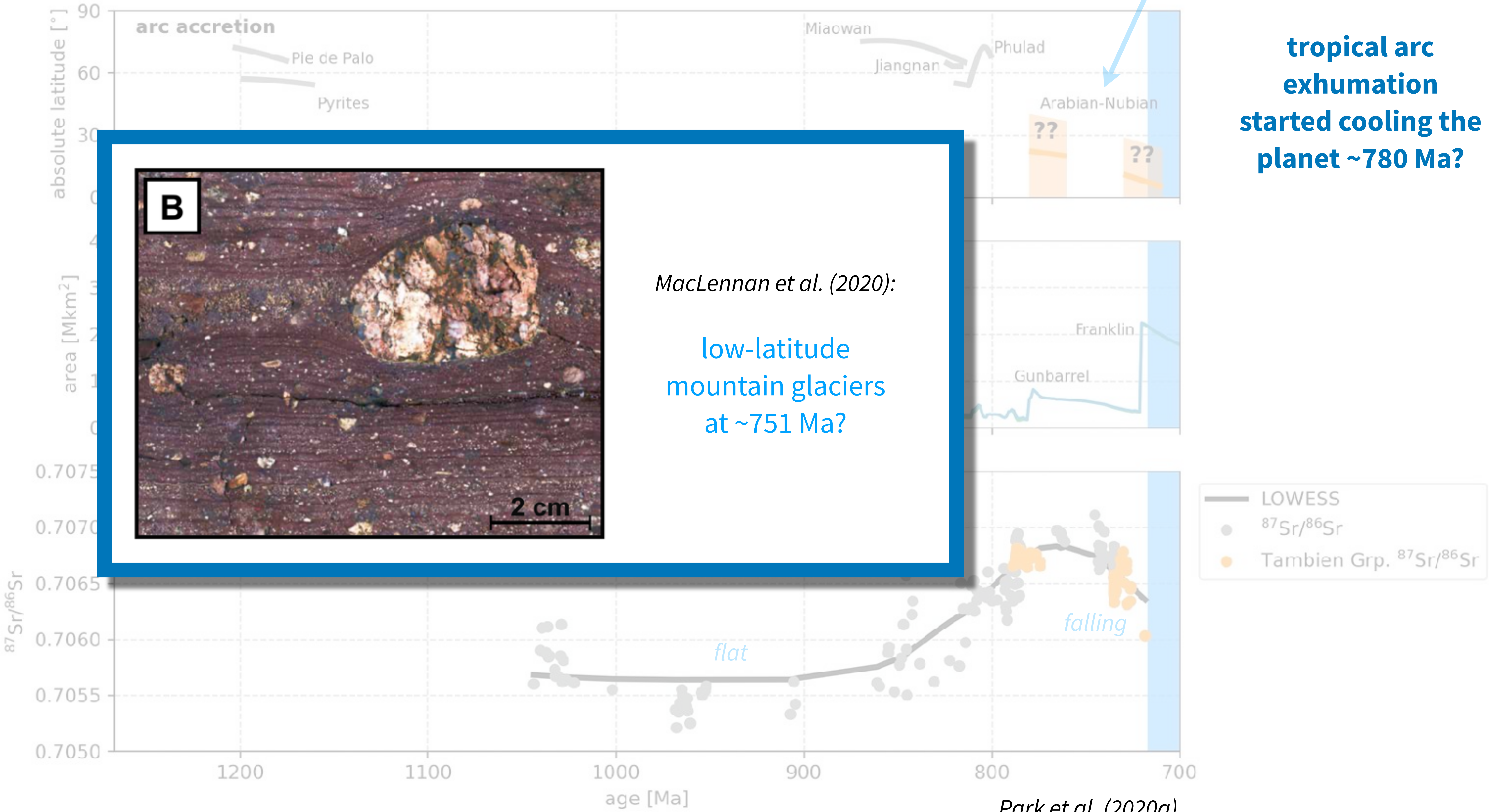


MacLennan et al. (2020):

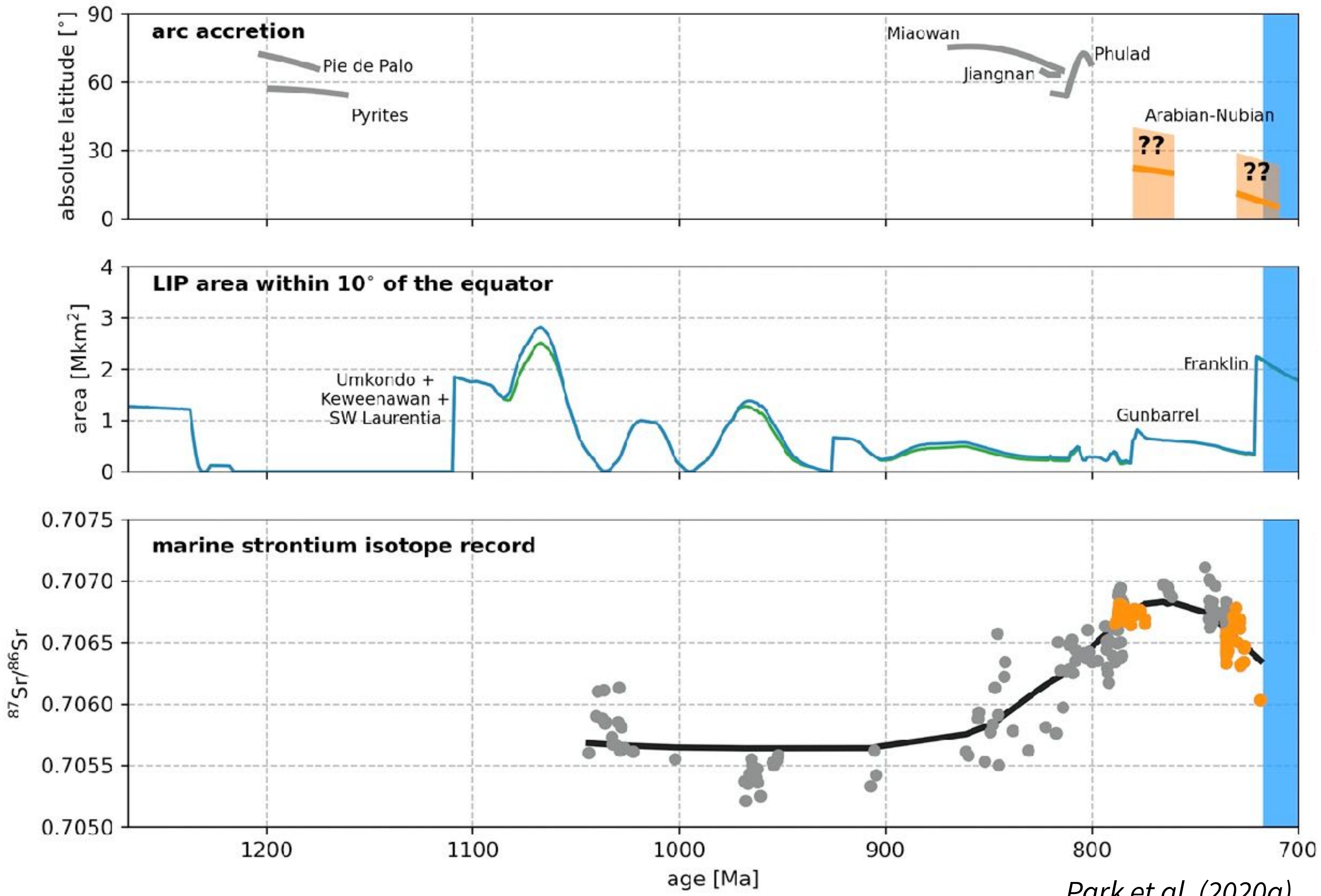
low-latitude mountain glaciers at ~751 Ma?

Park et al. (2020a)

tropical arc exhumation started cooling the planet ~780 Ma?

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

STRONTIUM

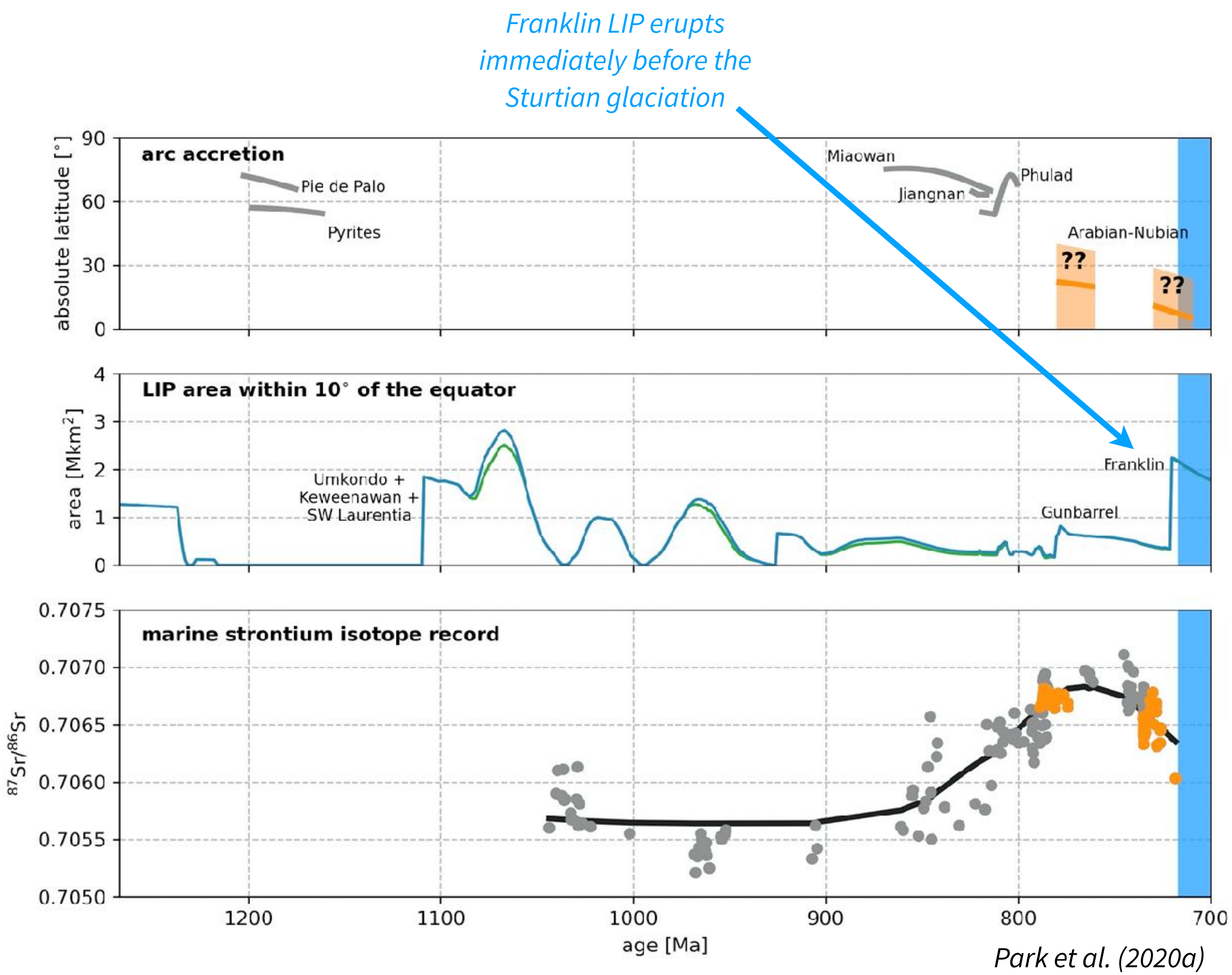


Park et al. (2020a)

but there are serious limitations…

- paleolatitude is poorly constrained
- arc-accretion database is not well developed

FRANKLIN LARGE IGNEOUS PROVINCE



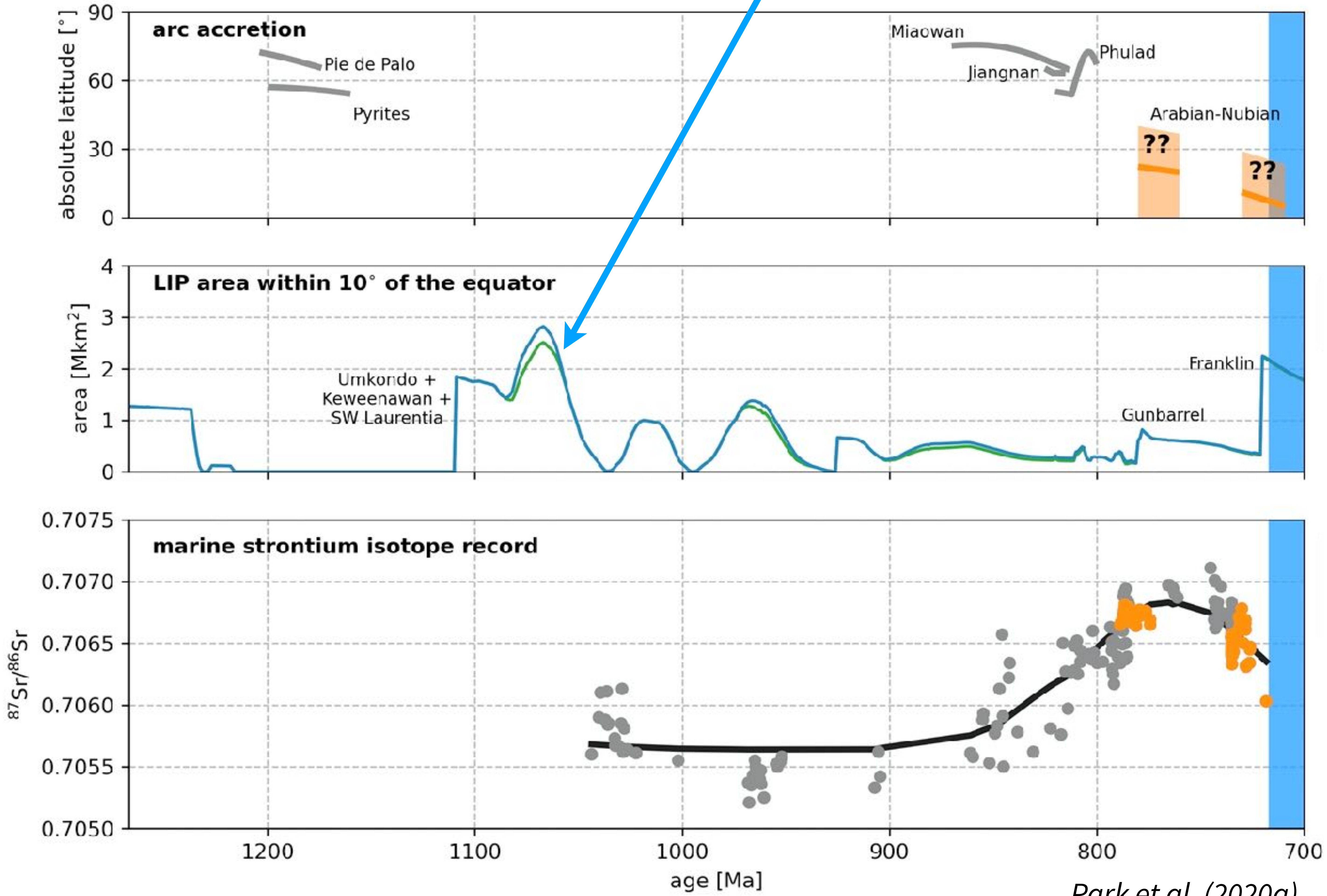
Park et al. (2020a)

Goddéris et al. (2003)

'Fire and Ice' hypothesis: enhanced weatherability due to the eruption of the Franklin LIP in the tropics initiated the Sturtian Snowball Earth

FRANKLIN LARGE IGNEOUS PROVINCE

large area of LIPs in the tropics, but no snowball glaciation



Park et al. (2020a)

Goddéris et al. (2003)

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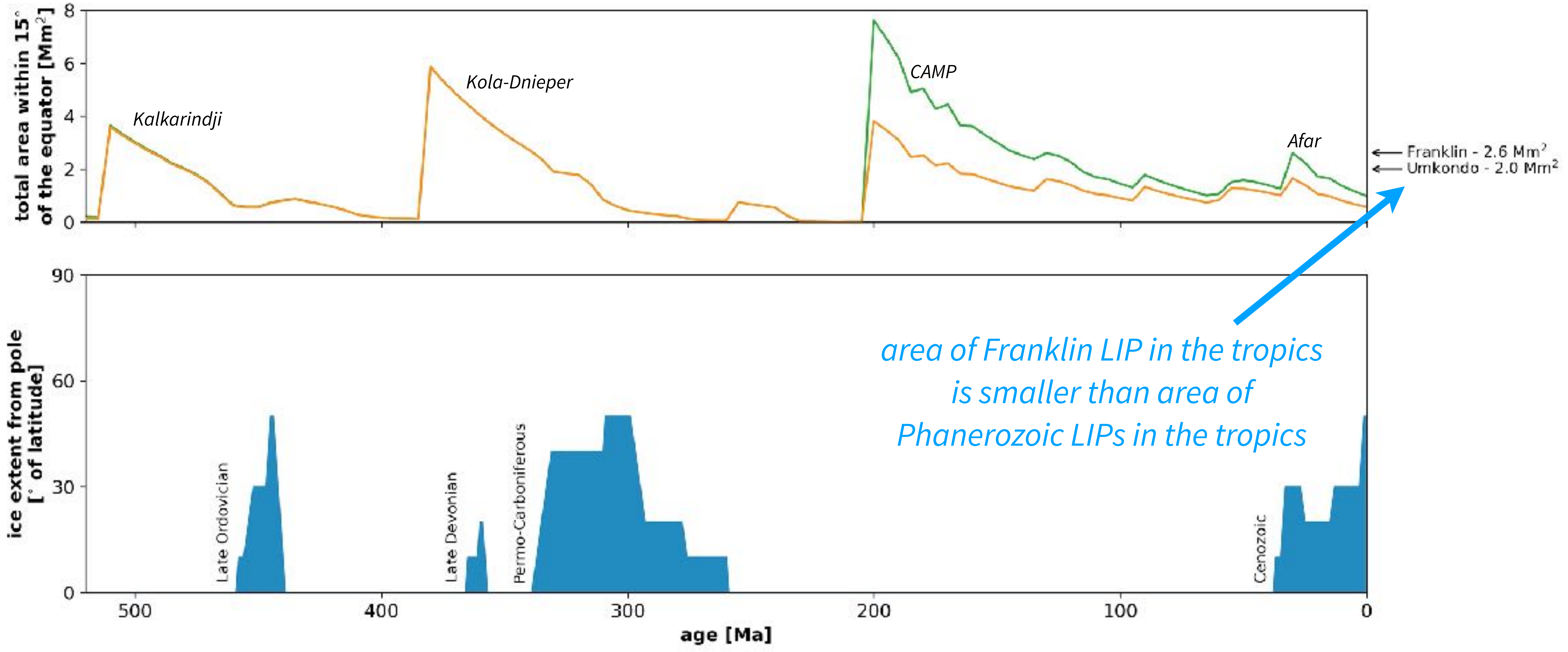
Goddéris et al. (2003)

'Fire and Ice' hypothesis: enhanced … on of the … ed the

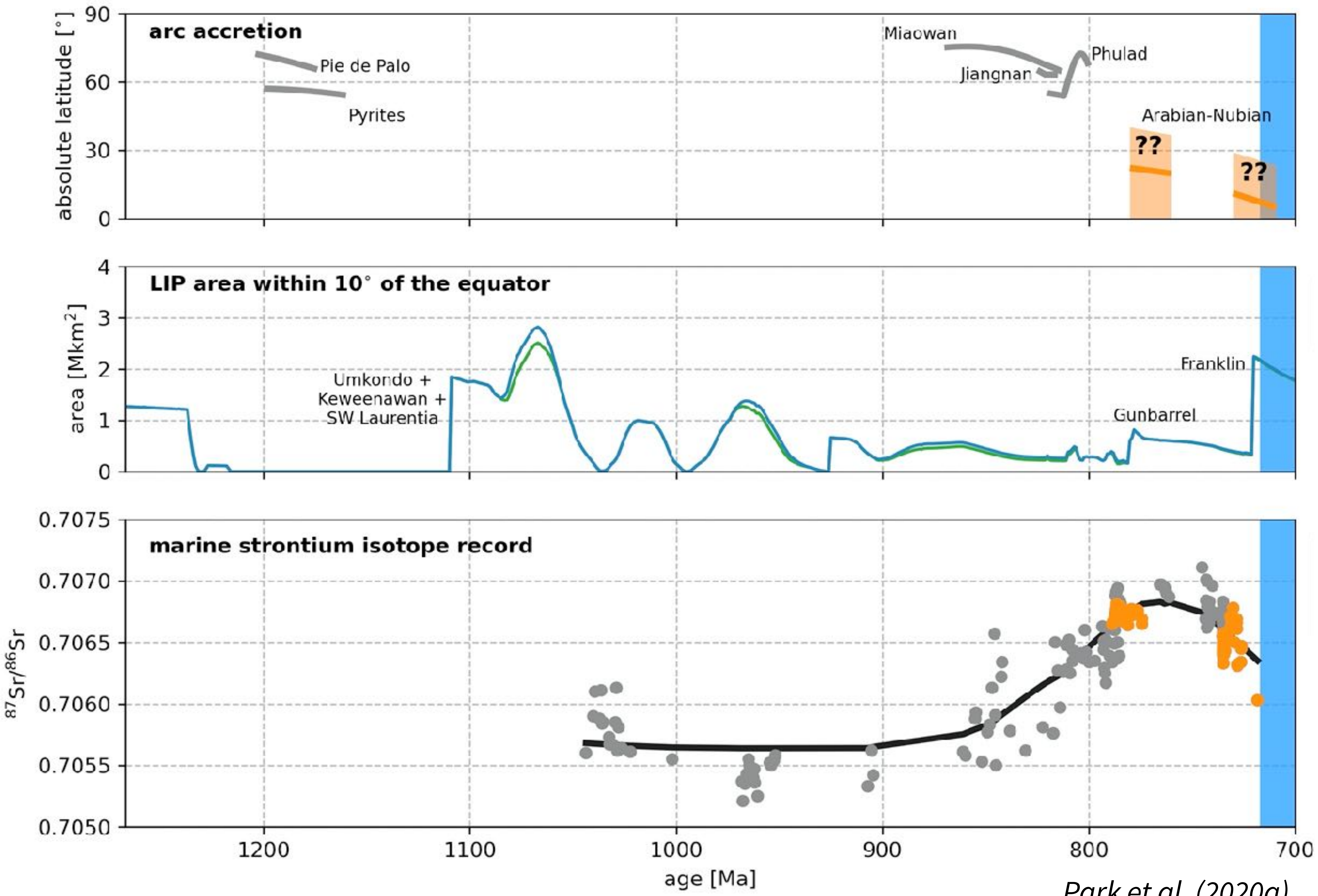
Park et al. (2020b)



area of Franklin LIP in the tropics is smaller than area of Phanerozoic LIPs in the tropics

Park et al. (2020a)

FRANKLIN LARGE IGNEOUS PROVINCE



Park et al. (2020a)

Goddéris et al. (2003)

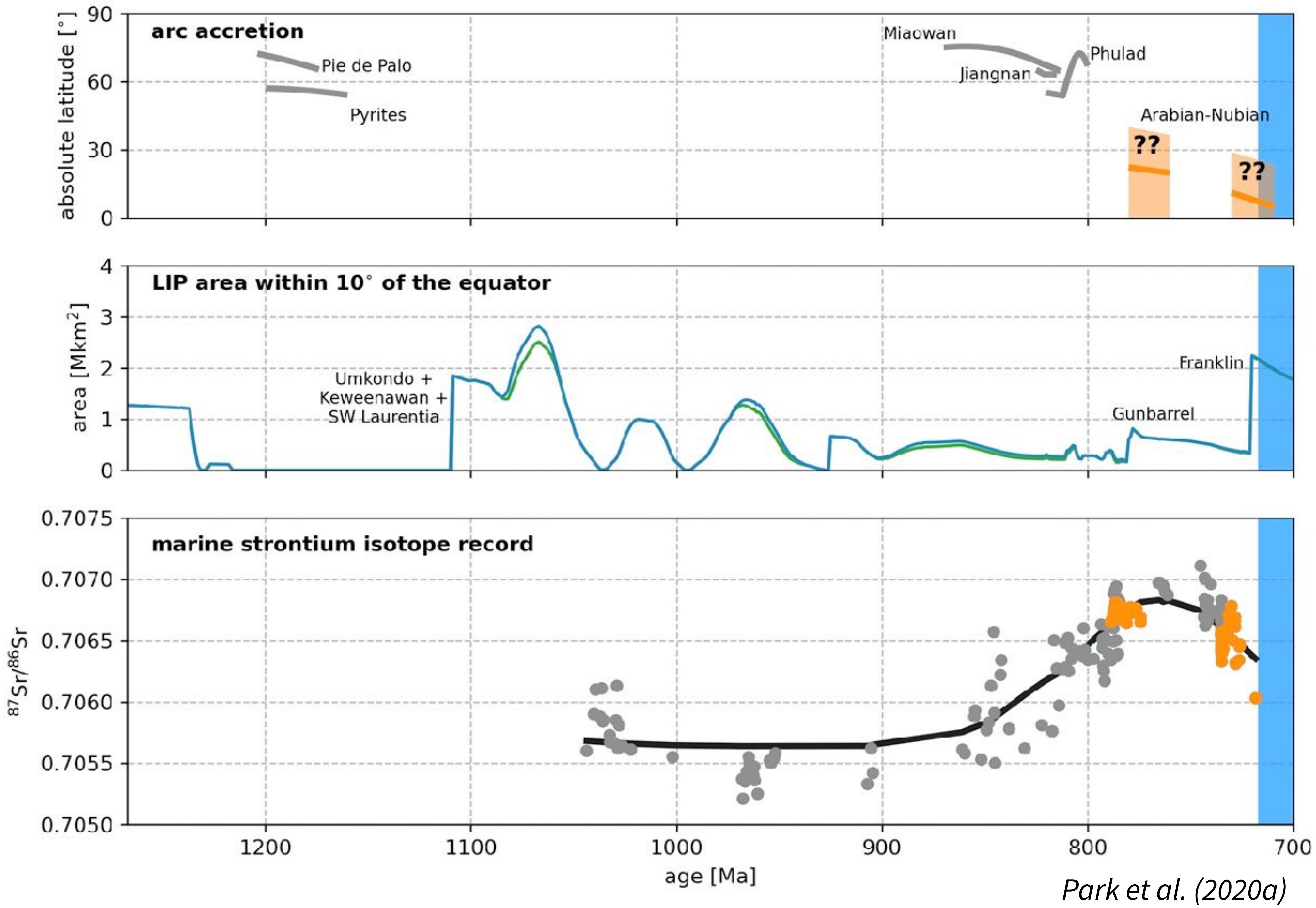
'Fire and Ice' hypothesis: enhanced weatherability due to the eruption of the Franklin LIP in the tropics initiated the Sturtian Snowball Earth

Franklin LIP eruption injects sulfate aerosols into the stratosphere, increasing albedo and cooling the planet?

Macdonald & Wordsworth (2017)

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

SUMMARY



Park et al. (2020a)

1. low-latitude arc-accretion in the Arabian-Nubian Shield starts cooling the Earth ~780 Ma

↓

2. Franklin LIP increases planetary albedo and further increases weatherability

↓

3. Earth plunges into a snowball glaciation

tropical arc-accretion was required to "set the stage" for the Sturtian Snowball Earth

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

CONCLUSIONS

Island arc exhumation in the tropics is important for setting Earth's climate state over the past 1 billion years.

1. Arc-continent collisions in the tropics correlate well with glacial intervals over the past 520 million years.

2. Arc-continent collision in the Southeast Asian islands can explain the majority of cooling over the past 15 million years.

3. Arabian-Nubian Shield arc accretion may have set the stage for the Sturtian Snowball Earth 717 million years ago.

Other potentially important mechanisms:

- volcanic degassing
- sulphide oxidation coupled to carbonate weathering
- organic carbon burial/weathering
- changes in weatherability due to other processes

But the evidence so far suggests that island arc exhumation in the tropics is one of the most important of these for setting Earth's climate state.

ACKNOWLEDGEMENTS

Faculty collaborators:

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- Daniel Stolper
- Shihong Zhang

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- Hairuo Fu
- Mulubrhan Gebreslassie
- Scott MacLennan
- Pierre Maffre
- Tadele Tesema
- Marissa Tremblay
- Hanbiao Xian

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- Blake Hodgin
- Taylor Kilian
- Sarah Slotznick
- Yiming Zhang

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- Isabel Fendley
- Jinsol Kim
- Tanis Leonhardi
- Nate Lindsey
- Alex Robson
- Allison Sharrar

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- Margie Winn

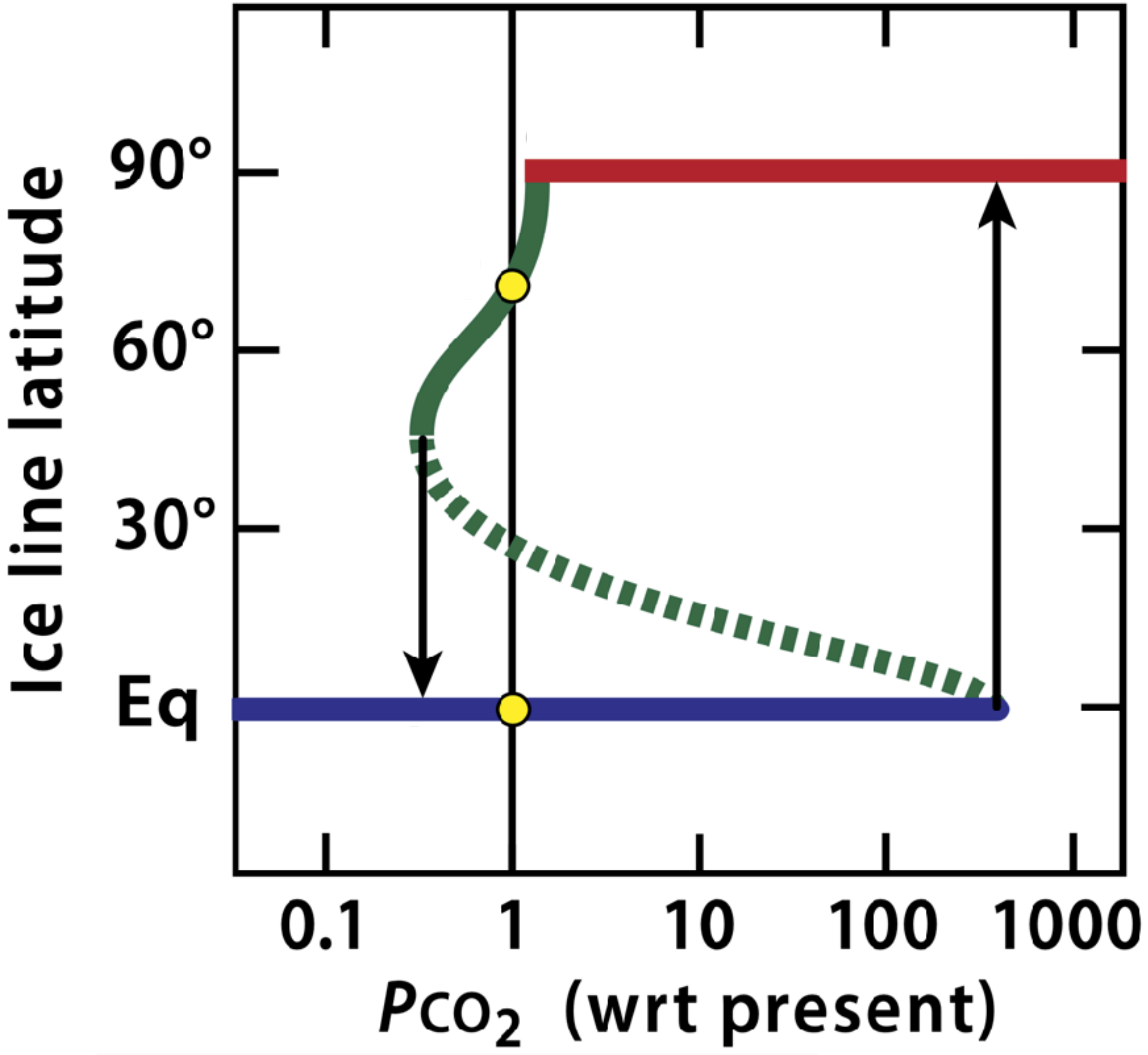
All the other undergrad. students, grad. students, post-docs, staff, and faculty at UC Berkeley EPS!

Friends, frands, Yudith

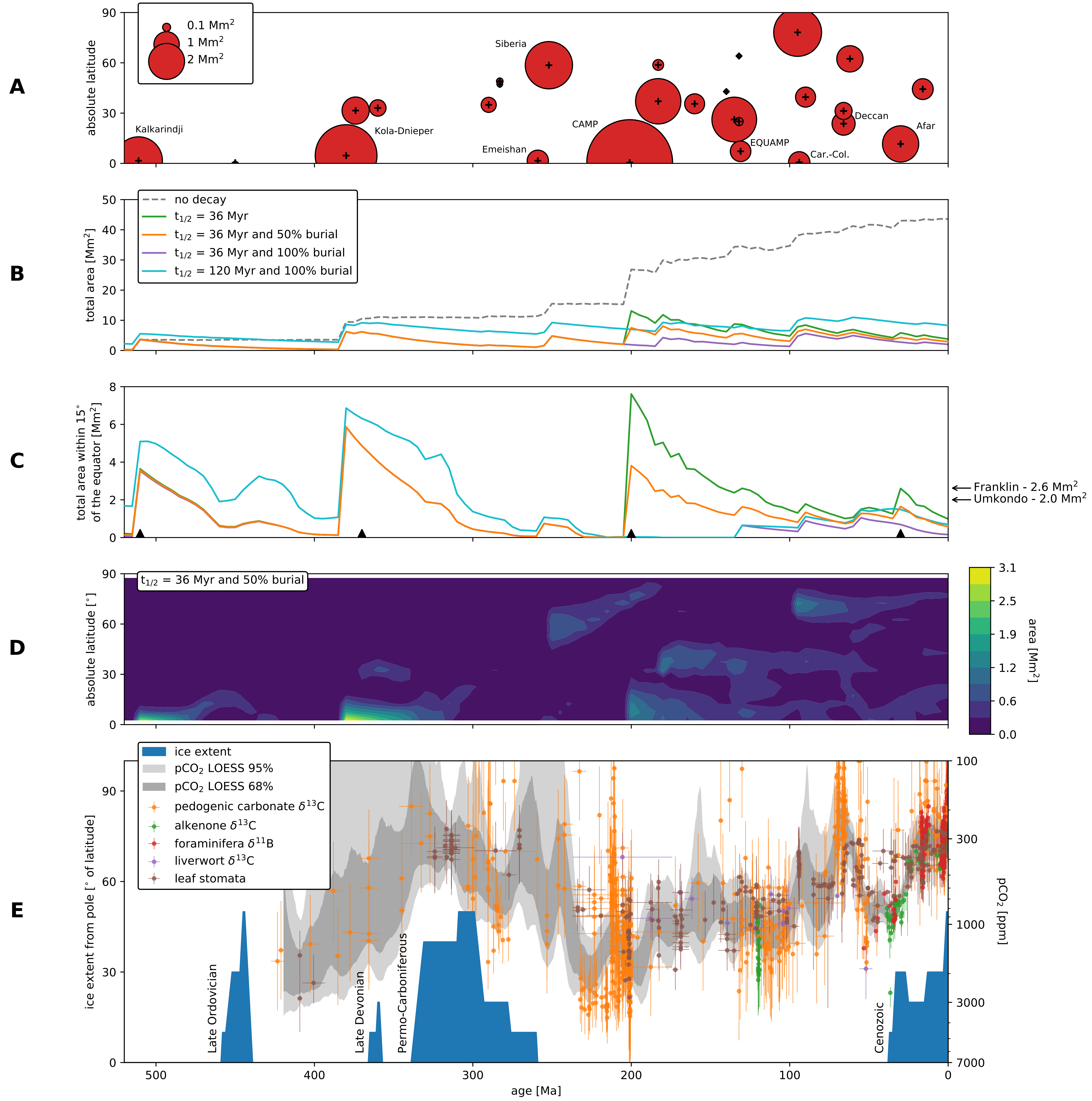
My family

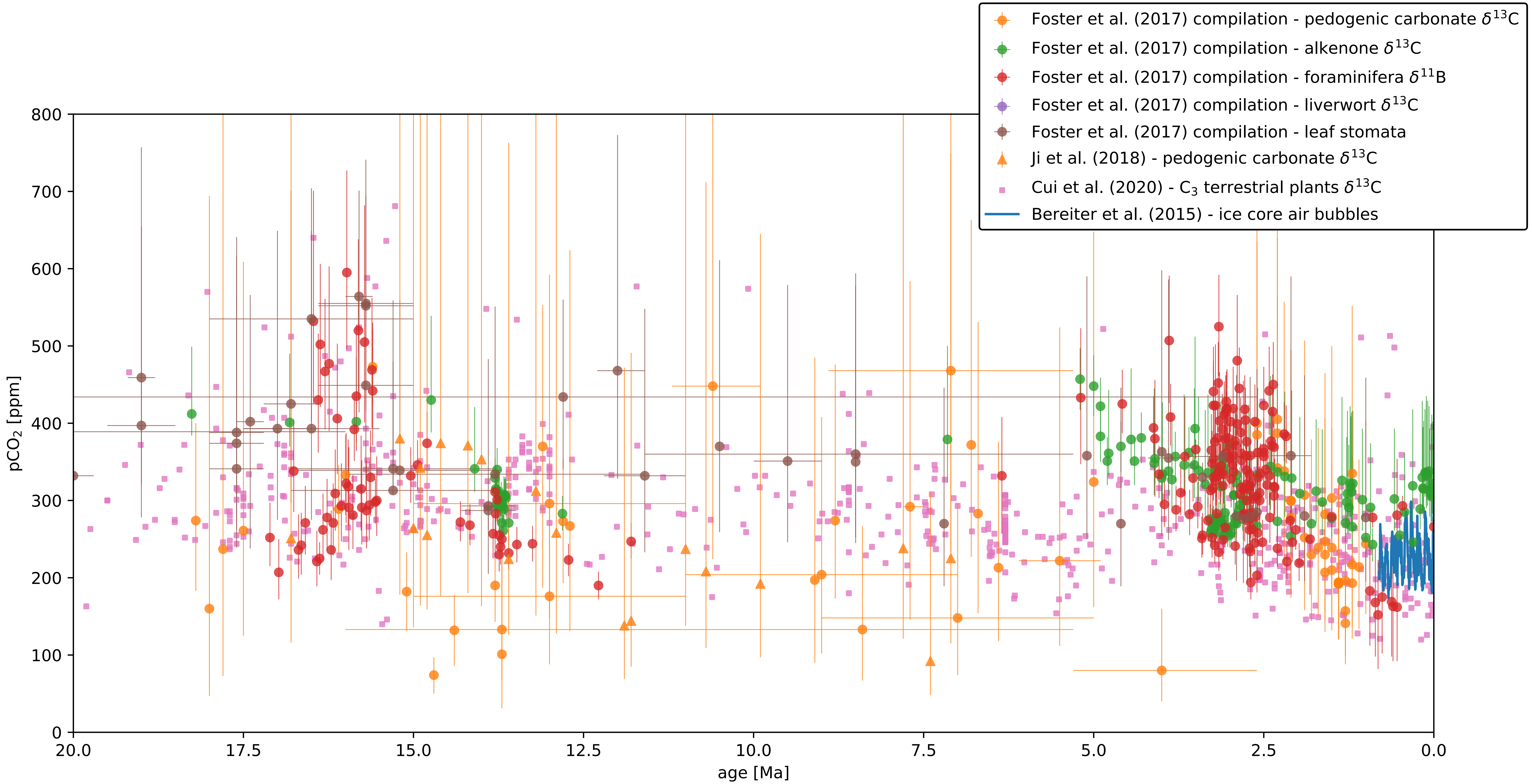
Nick Swanson-Hysell

EXTRA SLIDES

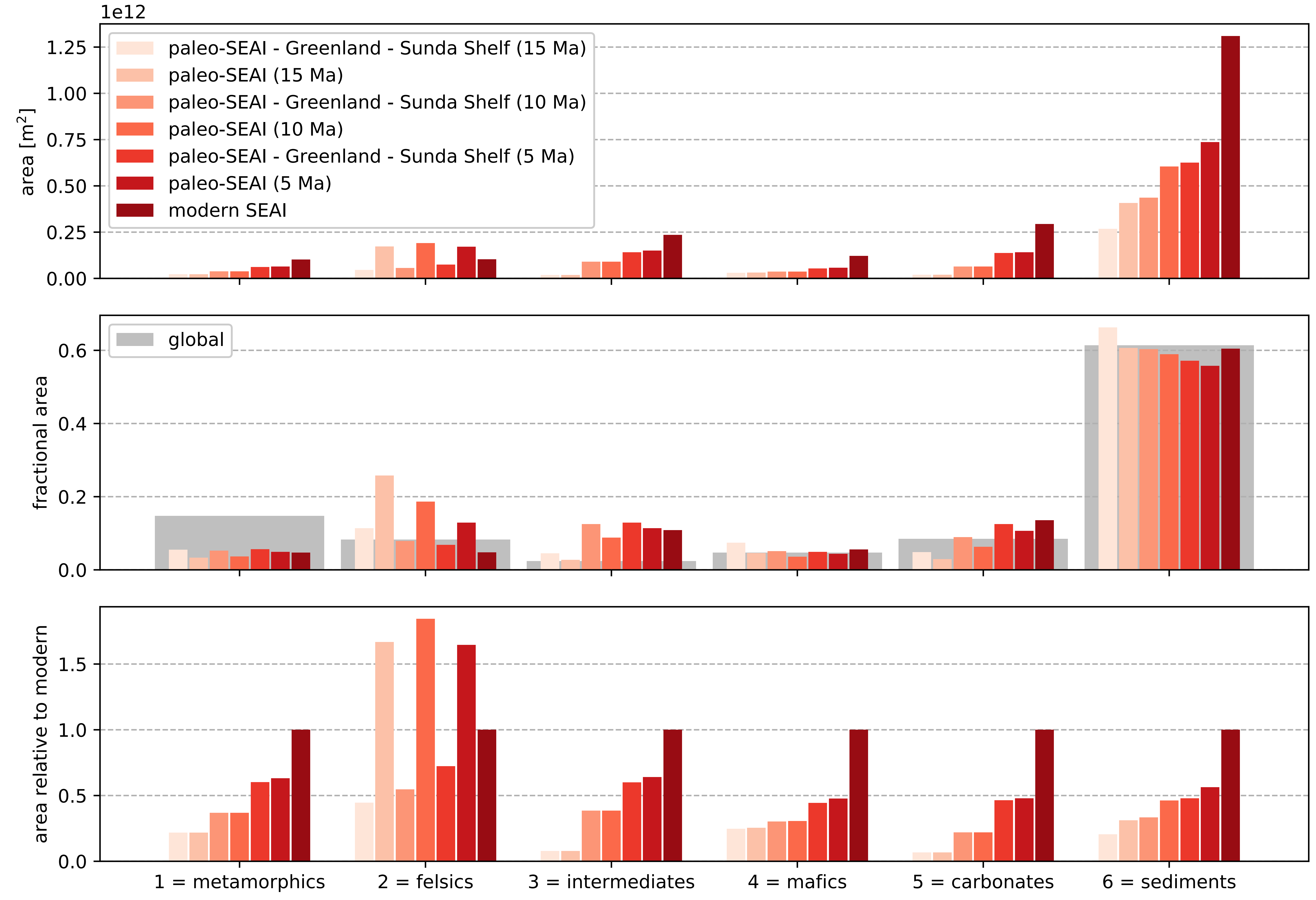


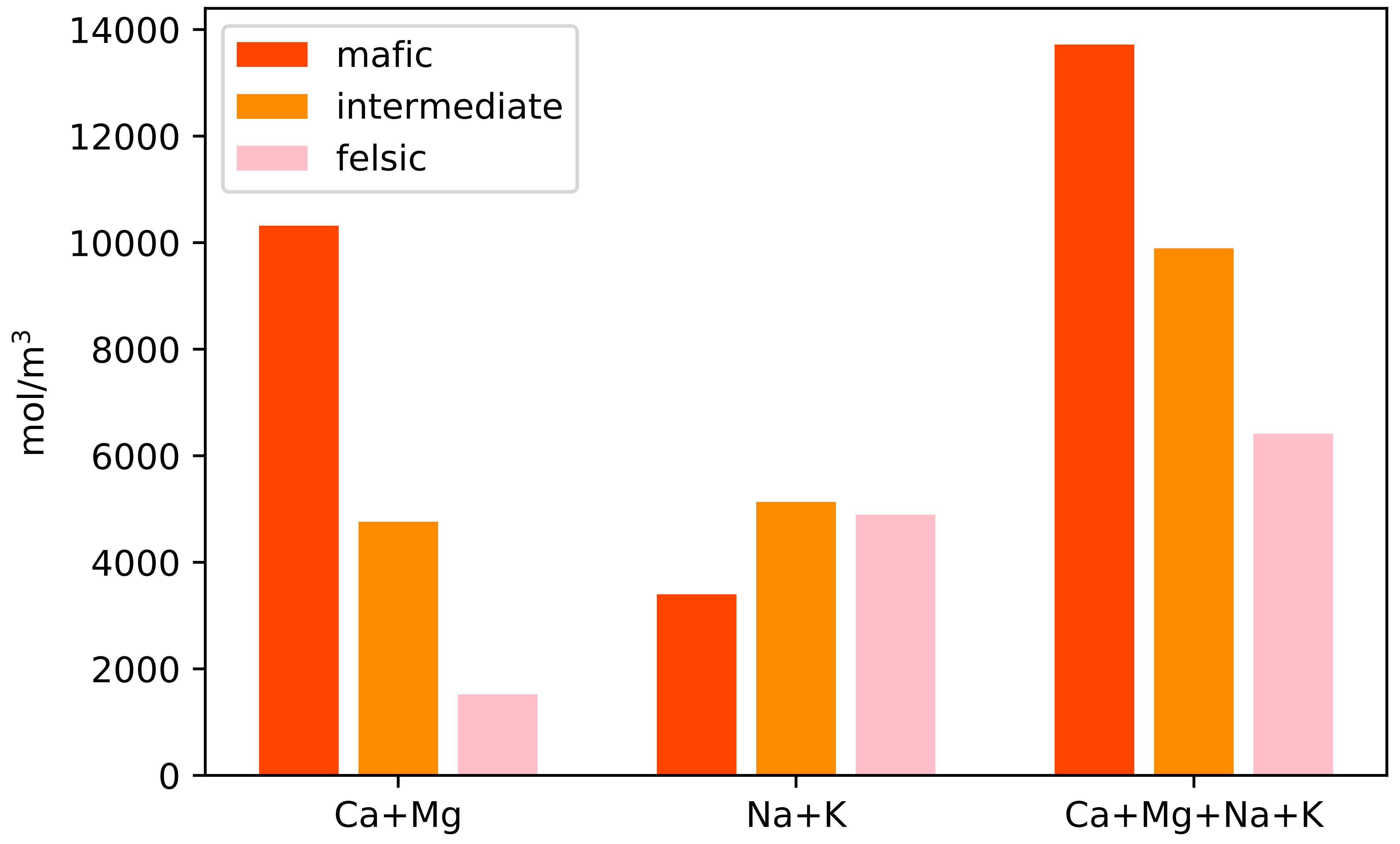
Ice line latitude
90°
60°
30°
Eq
0.1
1
10
100
1000
P_{CO_2} (wrt present)

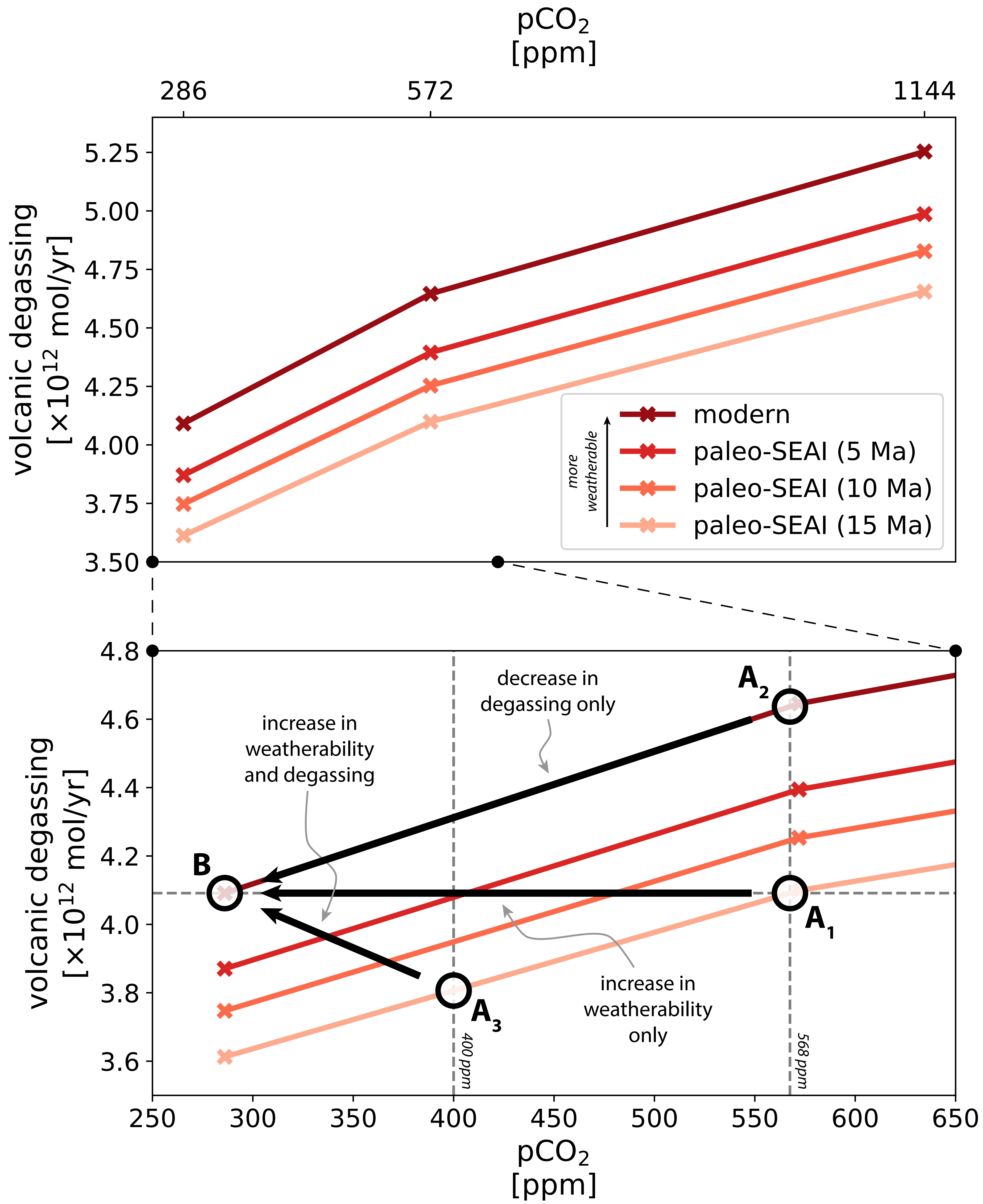

A
B
C
D
E
absolute latitude
0.1 Mm2
1 Mm2
2 Mm2
Kalkarindji
Kola-Dnieper
Siberia
Emeishan
CAMP
EQUAMP
Deccan
Car.-Col.
Afar
no decay
t1/2 = 36 Myr
t1/2 = 36 Myr and 50% burial
t1/2 = 36 Myr and 100% burial
t1/2 = 120 Myr and 100% burial
total area [Mm2]
total area within 15° of the equator [Mm2]
Franklin - 2.6 Mm2
Umkondo - 2.0 Mm2
t1/2 = 36 Myr and 50% burial
absolute latitude [°]
area [Mm2]
ice extent
pCO2 LOESS 95%
pCO2 LOESS 68%
pedogenic carbonate δ13C
alkenone δ13C
foraminifera δ11B
liverwort δ13C
leaf stomata
ice extent from pole [° of latitude]
pCO2 [ppm]
Late Ordovician
Late Devonian
Permo-Carboniferous
Cenozoic
age [Ma]



Foster et al. (2017) compilation - pedogenic carbonate δ^{13}C
Foster et al. (2017) compilation - alkenone δ^{13}C
Foster et al. (2017) compilation - foraminifera δ^{11}B
Foster et al. (2017) compilation - liverwort δ^{13}C
Foster et al. (2017) compilation - leaf stomata
Ji et al. (2018) - pedogenic carbonate δ^{13}C
Cui et al. (2020) - C_3 terrestrial plants δ^{13}C
Bereiter et al. (2015) - ice core air bubbles
800
700
600
500
400
300
200
100
0
pCO_2 [ppm]
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
0.0
age [Ma]


1e12
paleo-SEAI - Greenland - Sunda Shelf (15 Ma)
paleo-SEAI (15 Ma)
paleo-SEAI - Greenland - Sunda Shelf (10 Ma)
paleo-SEAI (10 Ma)
paleo-SEAI - Greenland - Sunda Shelf (5 Ma)
paleo-SEAI (5 Ma)
modern SEAI
area [m^2]
global
fractional area
area relative to modern
1 = metamorphics
2 = felsics
3 = intermediates
4 = mafics
5 = carbonates
6 = sediments


mafic
intermediate
felsic
mol/m^3
Ca+Mg
Na+K
Ca+Mg+Na+K



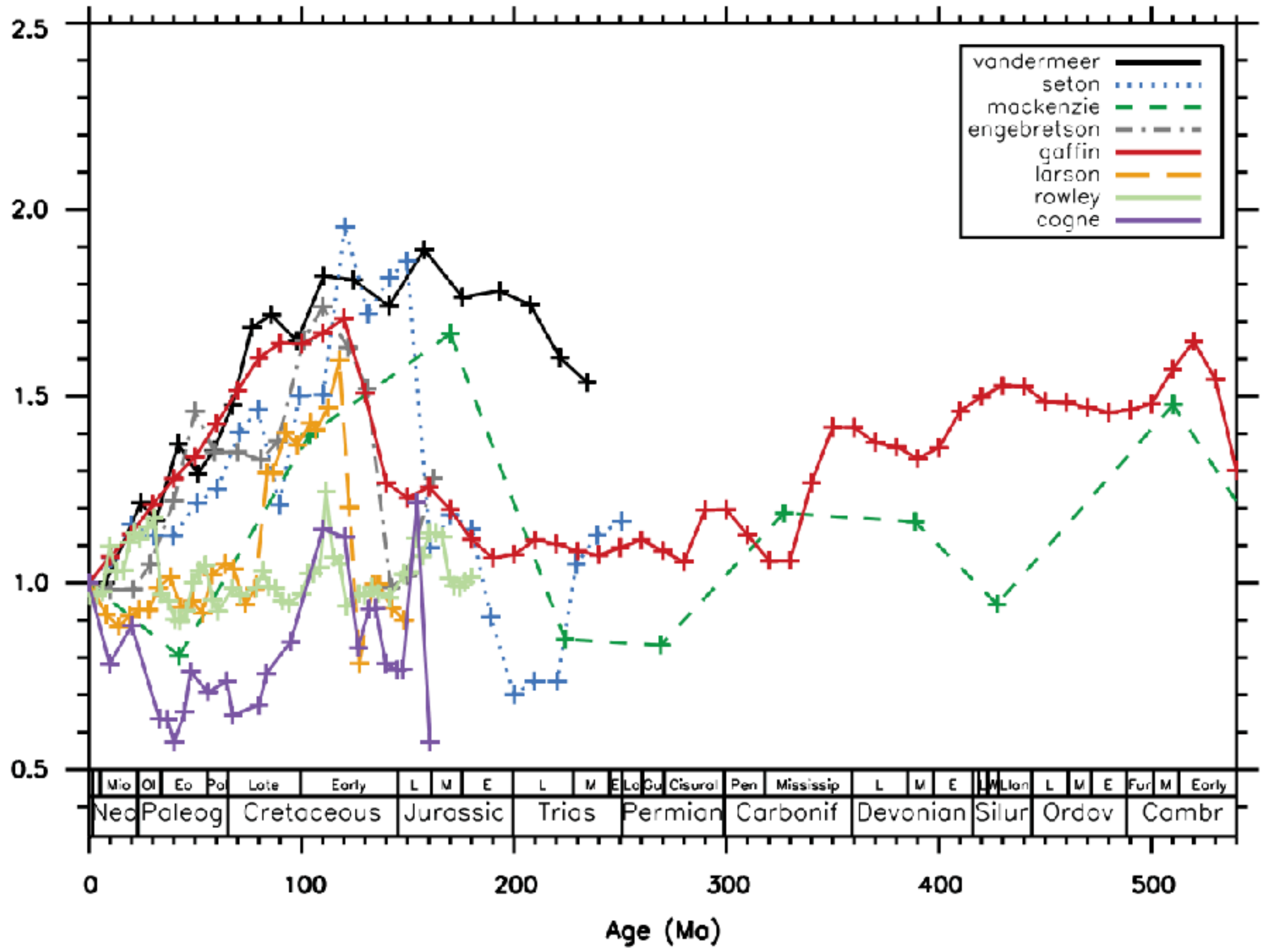
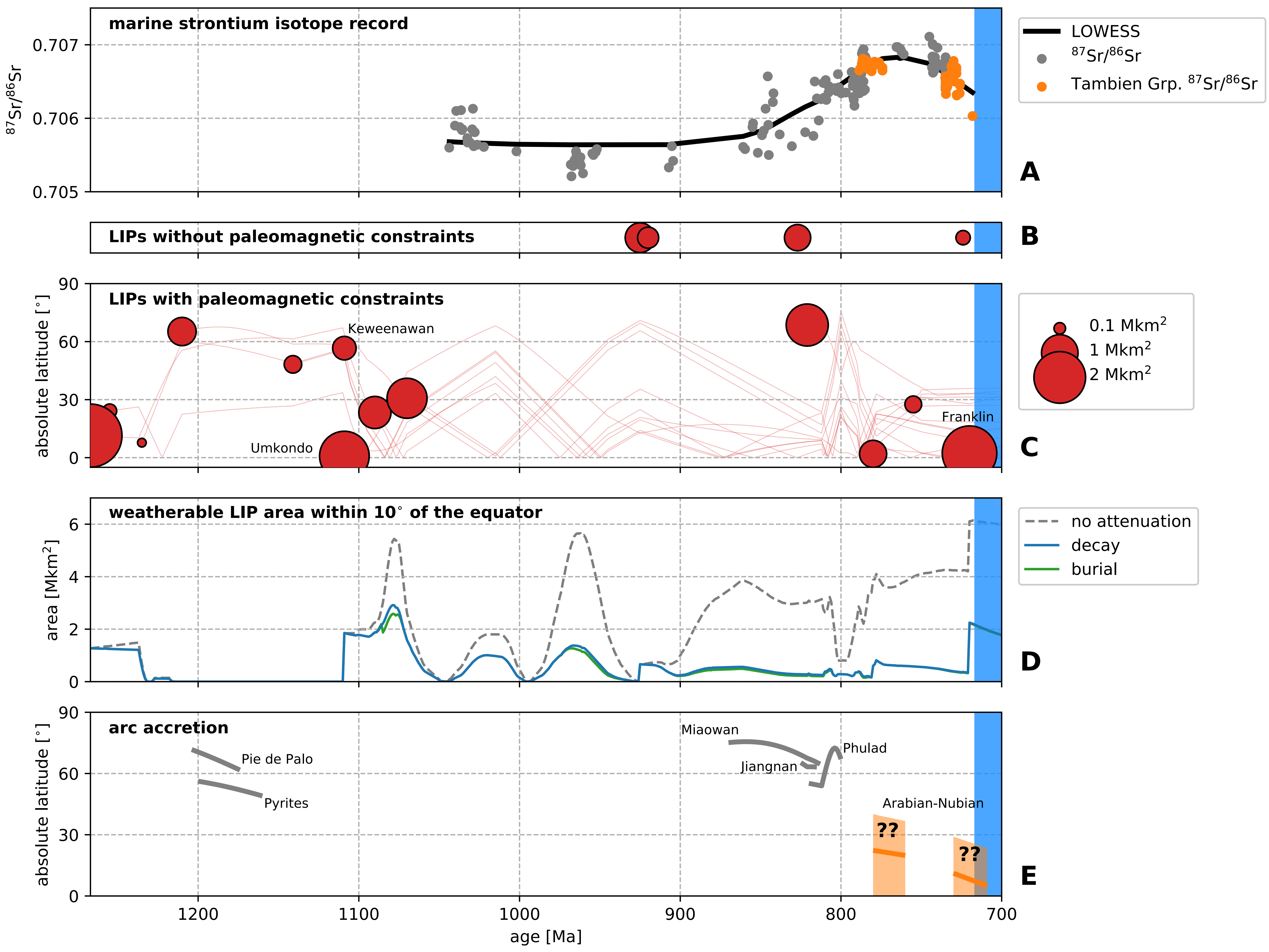
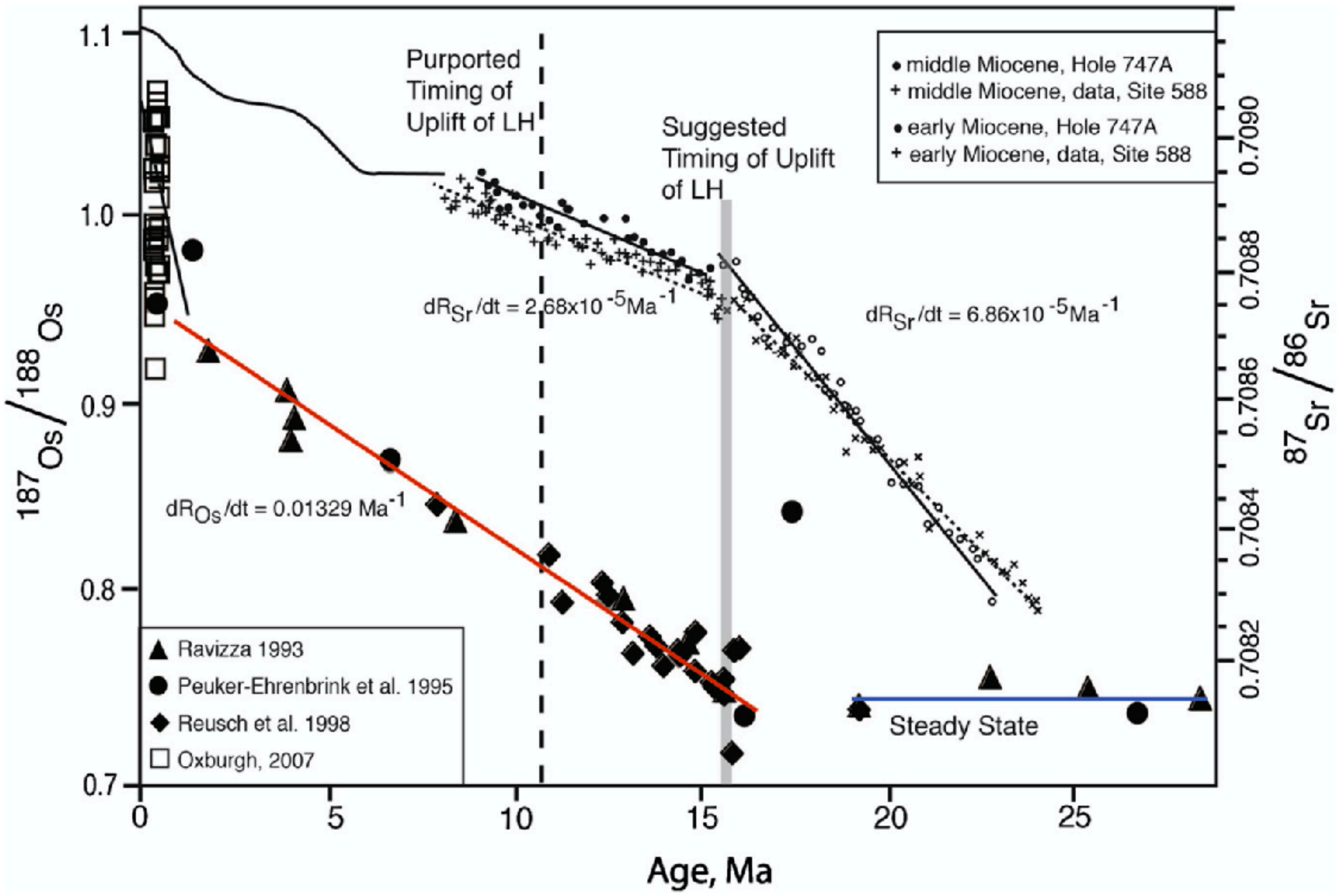


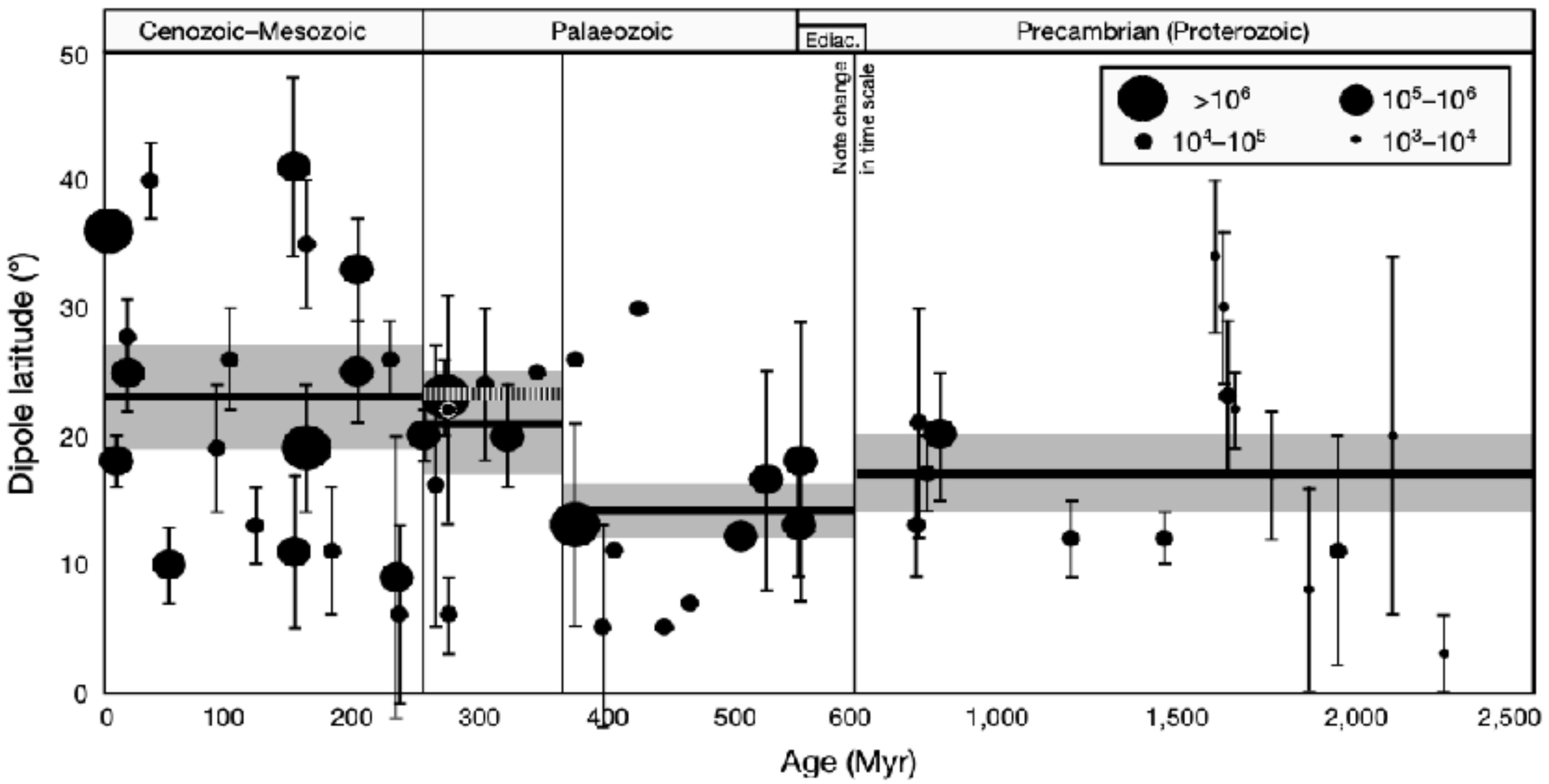
Figure 4. (Colour online) Indices for the evolution of the solid Earth degassing rate (normalized to the indices for the evolution of the solid Earth degassing rate (normalized to their present-day values)). See Table 2 for references.



marine strontium isotope record
LIPs without paleomagnetic constraints
LIPs with paleomagnetic constraints
Keweenawan
Umkondo
Franklin
weatherable LIP area within 10° of the equator
arc accretion
Pie de Palo
Pyrites
Miaowan
Jiangnan
Phulad
Arabian-Nubian
??
??
LOWESS
87Sr/86Sr
Tambien Grp. 87Sr/86Sr
0.1 Mkm2
1 Mkm2
2 Mkm2
no attenuation
decay
burial
A
B
C
D
E
87Sr/86Sr
absolute latitude [°]
area [Mkm2]
absolute latitude [°]
age [Ma]

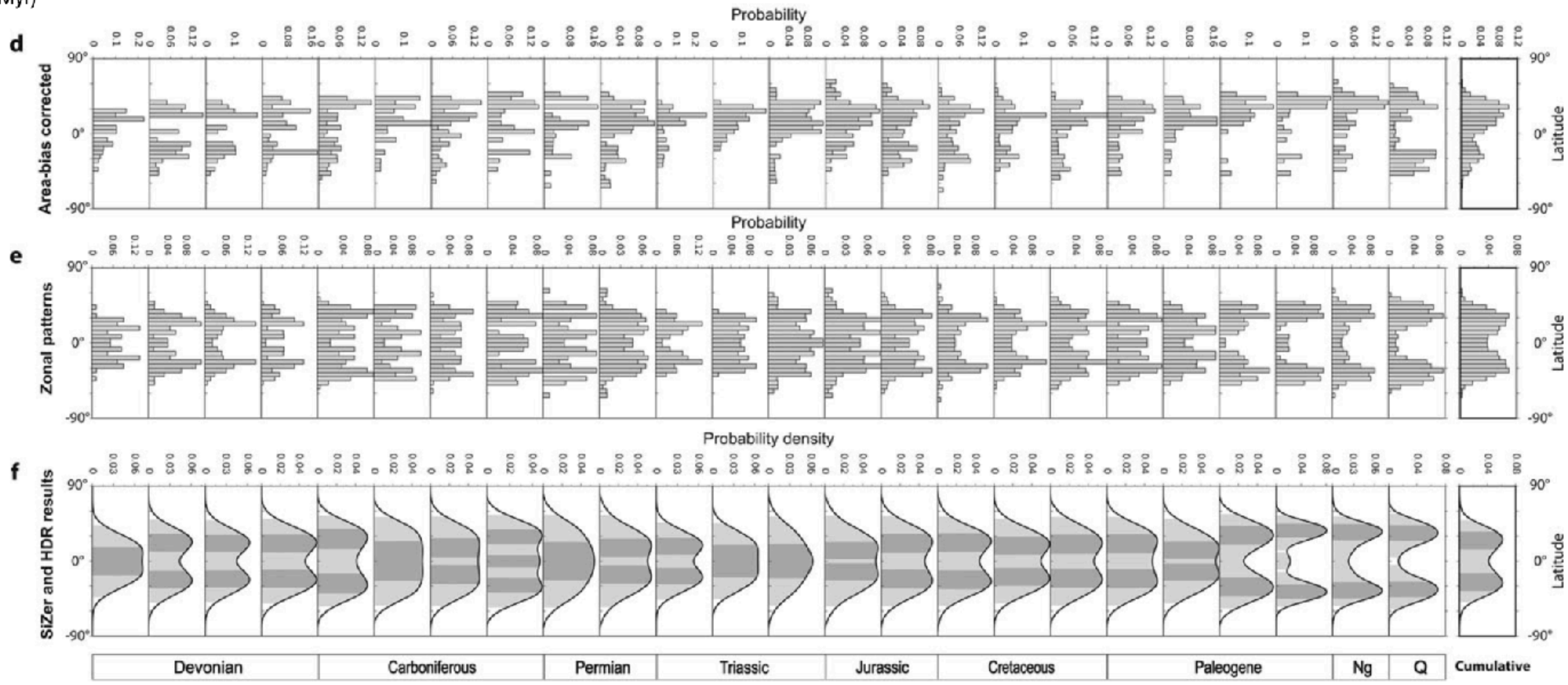
Myrow et al. (2015)





thick, basin-wide evaporite deposits only

includes dispersed evaporate occurrences



DELETED SLIDES

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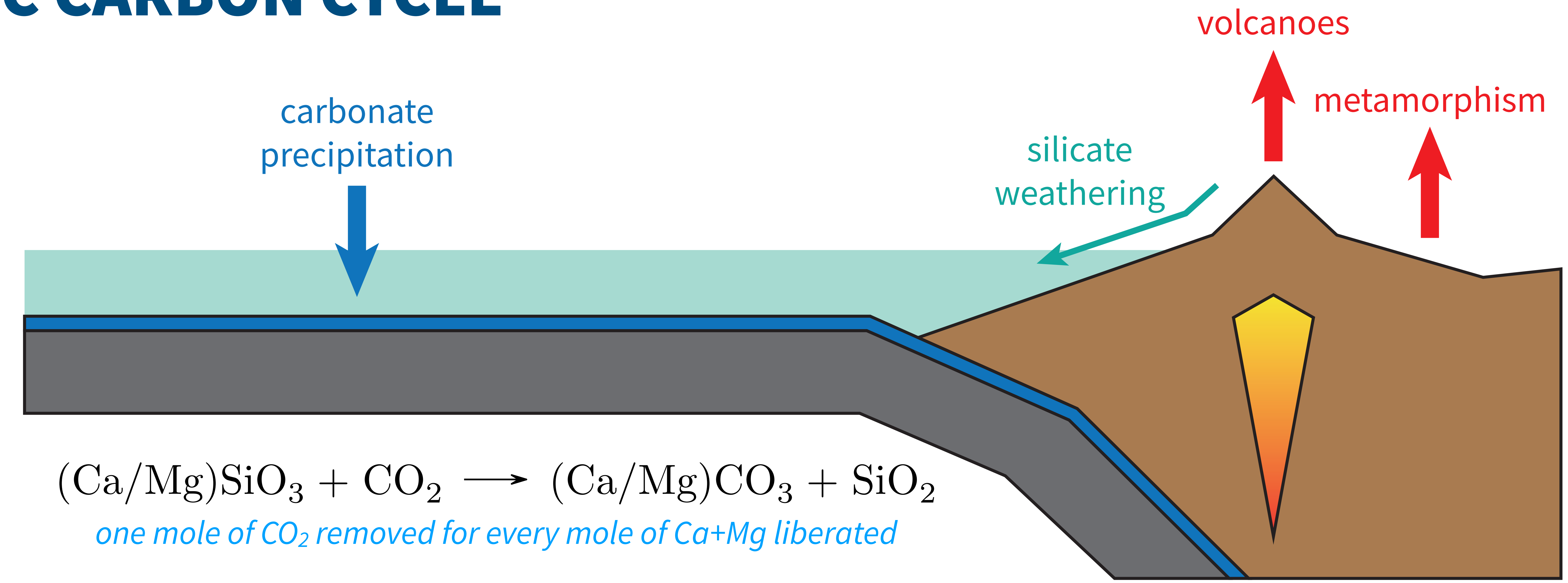
GEOLOGIC CARBON CYCLE



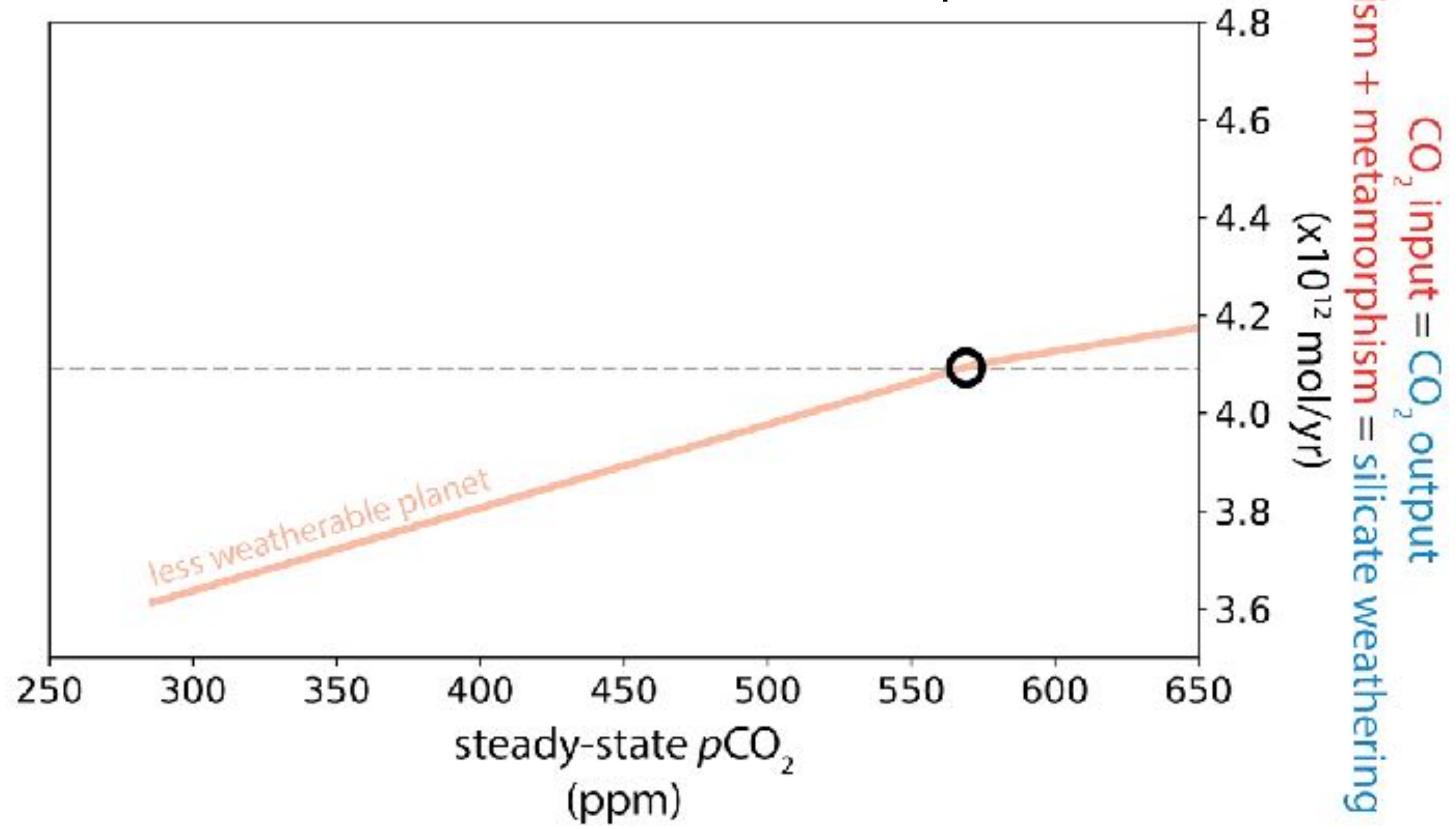
$$(Ca/Mg)SiO_3 + CO_2 \longrightarrow (Ca/Mg)CO_3 + SiO_2$$

one mole of CO_2 removed for every mole of Ca+Mg liberated

silicate weathering feedback:

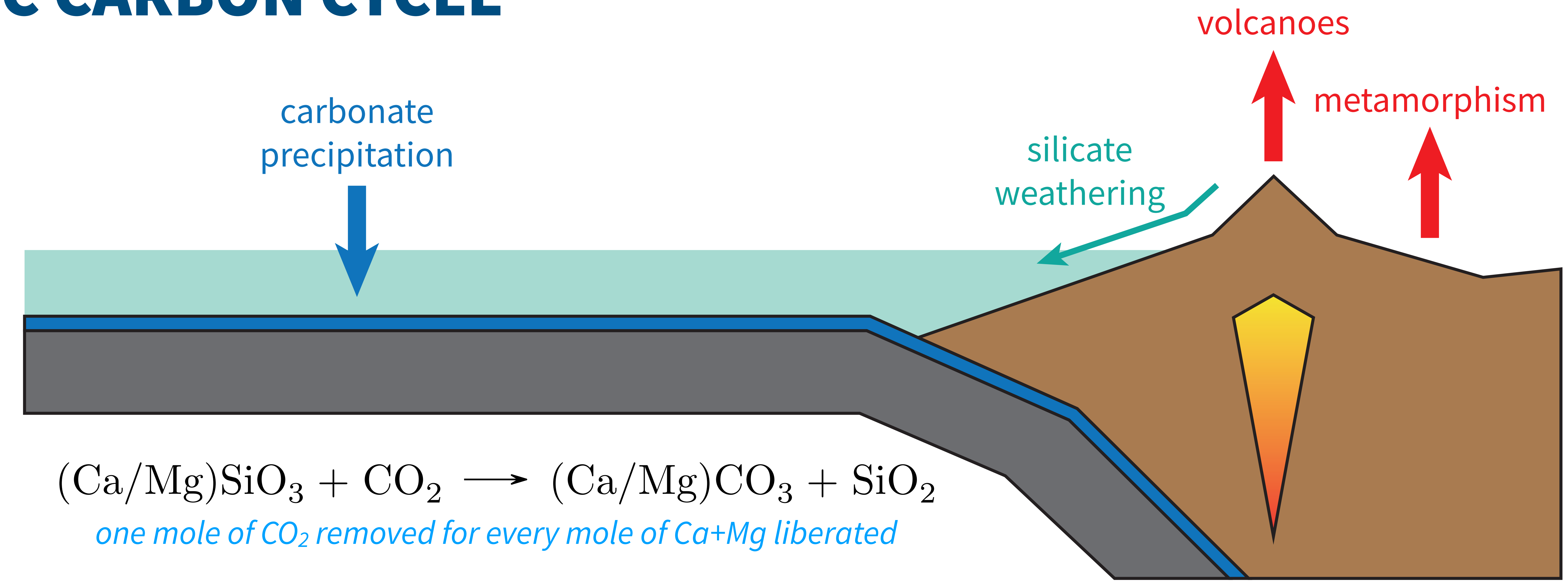
- ↑ **weatherability**
- ↑ silicate weathering flux in one place *(output > inp*
- ↓ pCO$_2$ *(amount of CO_2 in the atmosphere)*
- ↓ temperature and precipitation
- ↓ silicate weathering flux elsewhere *(output = input,*
- **pCO$_2$ stabilized at lower values**

weatherability = the sum of factors aside from climate itself that contributes to the overall global silicate weathering flux and associated CO_2 consumption



Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

GEOLOGIC CARBON CYCLE



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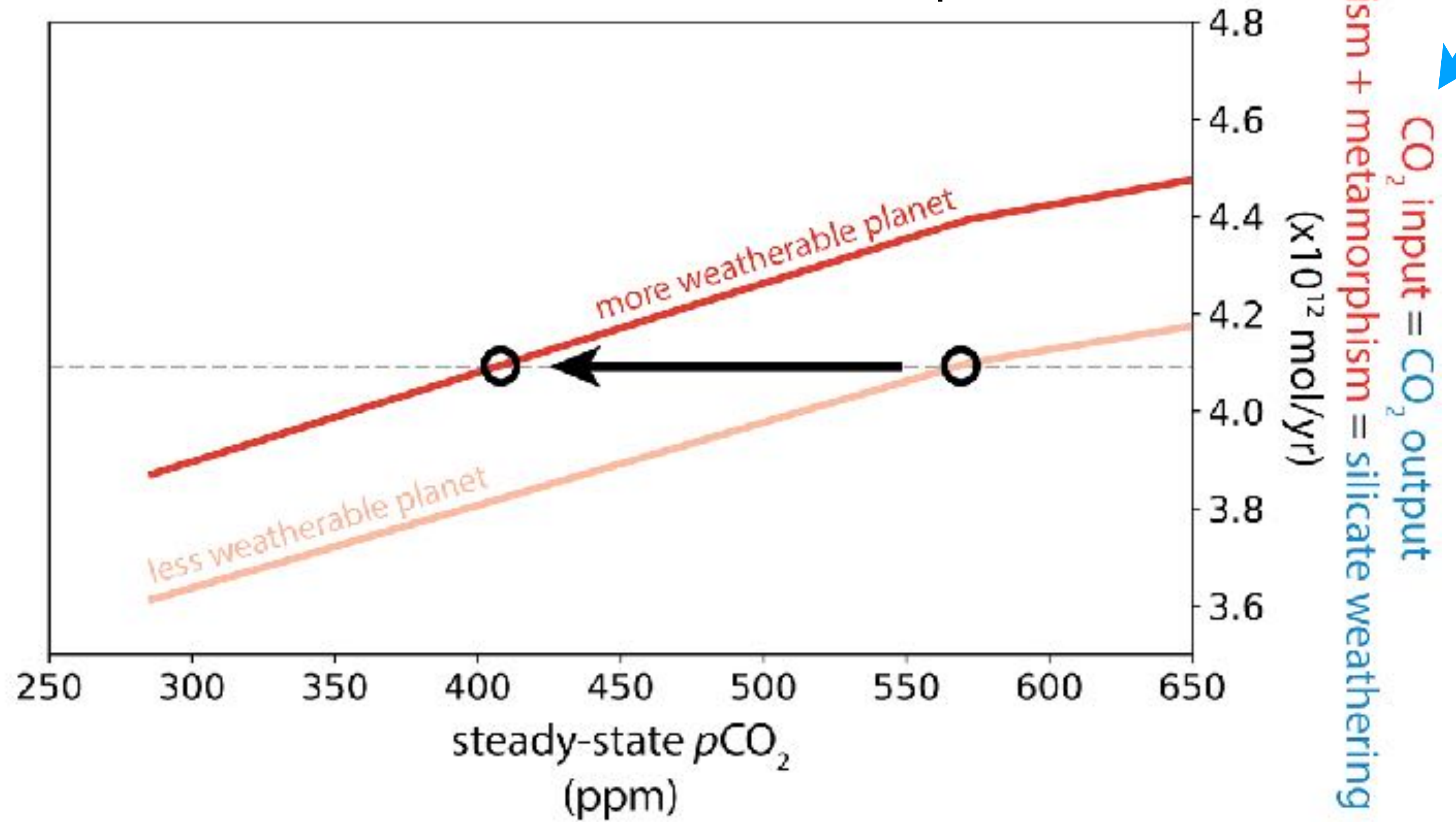
- ↓ silicate weathering flux elsewhere *(output = input)*
- — ***p*CO_2 stabilized at lower values**

weatherability = the sum of factors aside from climate itself that contributes to the overall global silicate weathering flux and associated CO_2 consumption

carbon input and output fluxes do not permanently change



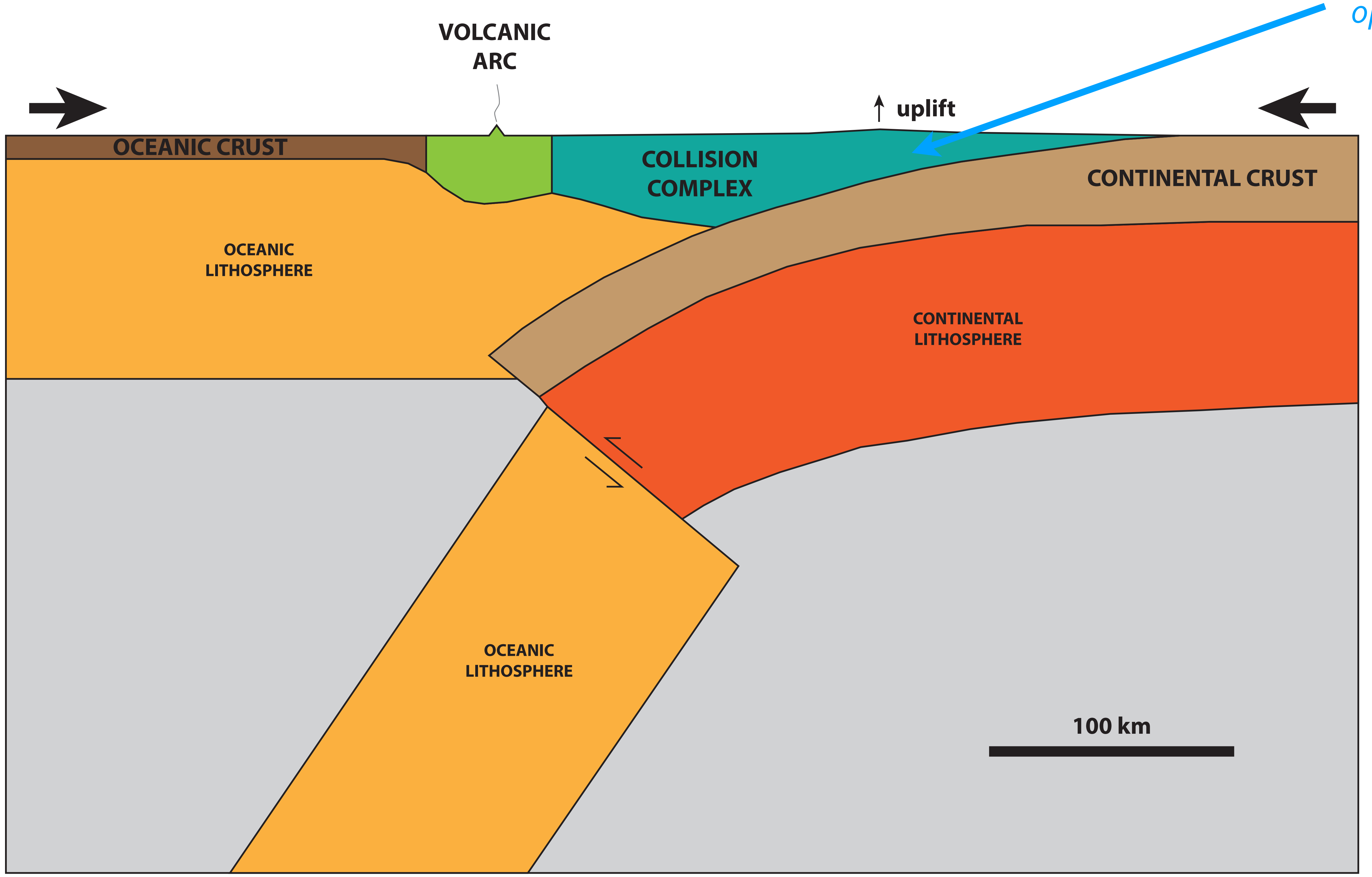
Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

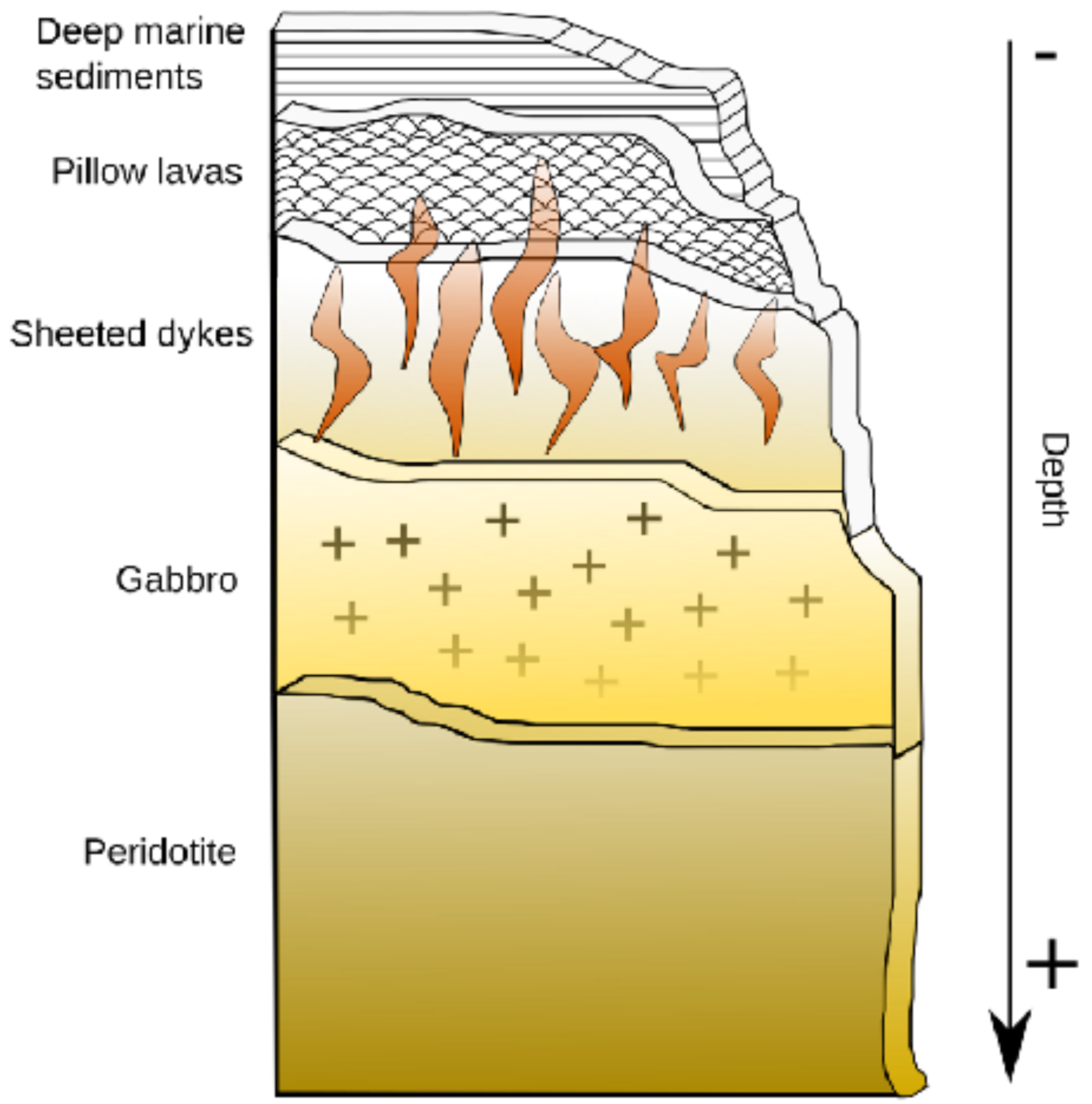
PHANEROZOIC ARC-CONTINENT COLLISIONS

1. location of preserved remnants of arc-continent collisions

(often) includes ophiolites



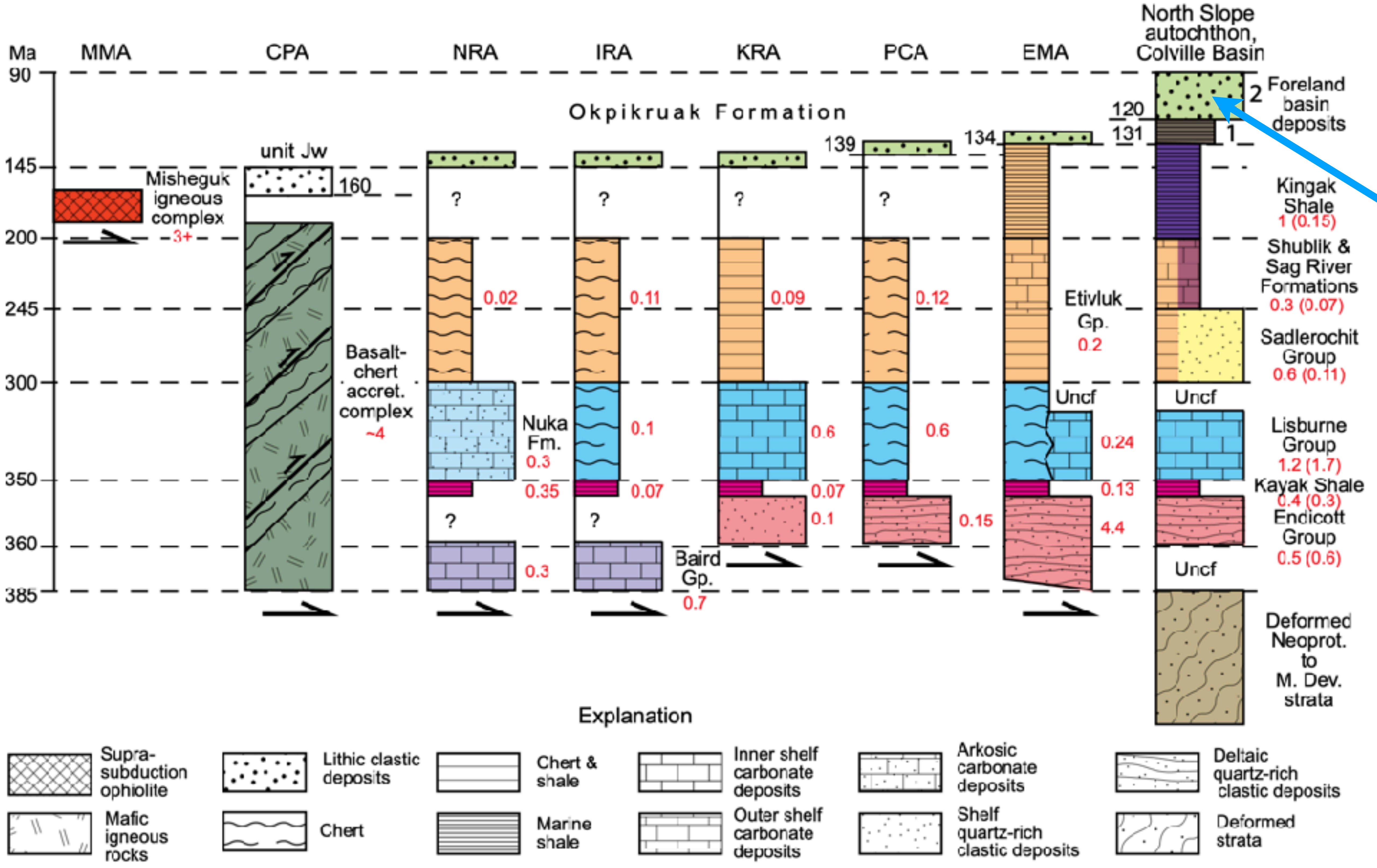
Banda Arc, simplified from Charlton (1991)



PHANEROZOIC ARC-CONTINENT COLLISIONS

2. age of exhumation of (ultra)mafic lithologies

- collision complex includes lower Ca+Mg continental crust and overlying sediment
- constrain age of exhumation of mafic lithologies using **dates on ophiolitic detritus in syn-orogenic sedimentary basins**



ophiolitic detritus

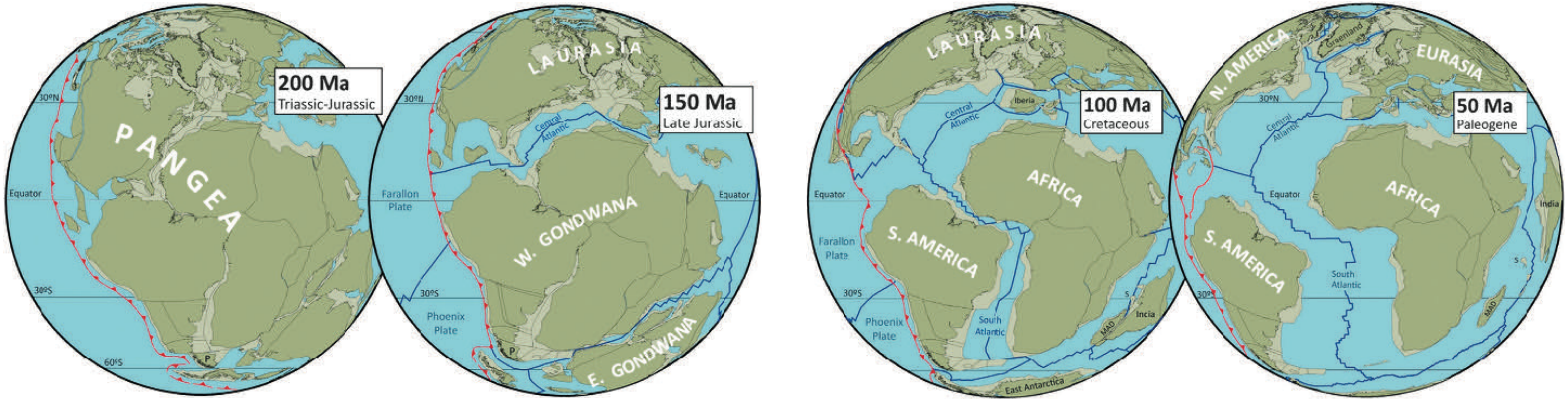
North Slope stratigraphy, Moore et al. (2015)

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

PHANEROZOIC ARC-CONTINENT COLLISIONS

3. paleogeographic model

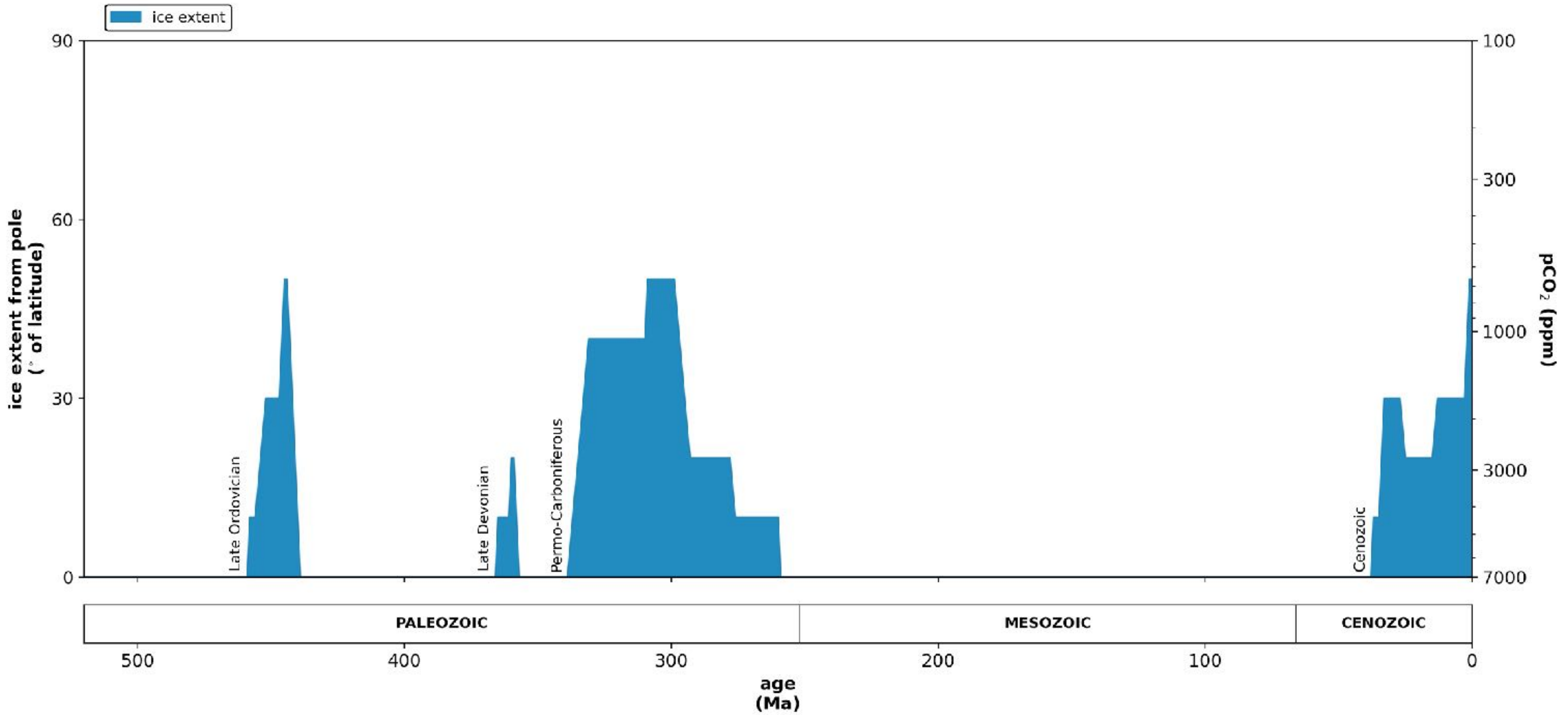
- mostly **Torsvik and Cocks (2012)**
- update Laurentia in the Ordovician (Swanson-Hysell and Macdonald, 2017)
- update Asia in the Paleozoic (Domeier, 2018)



Torsvik and Cocks (2012)

PHANEROZOIC ARC-CONTINENT COLLISIONS

4. a record of Earth's climate state



Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

introduction

Phanerozoic

Cenozoic

Neoproterozoic

conclusions

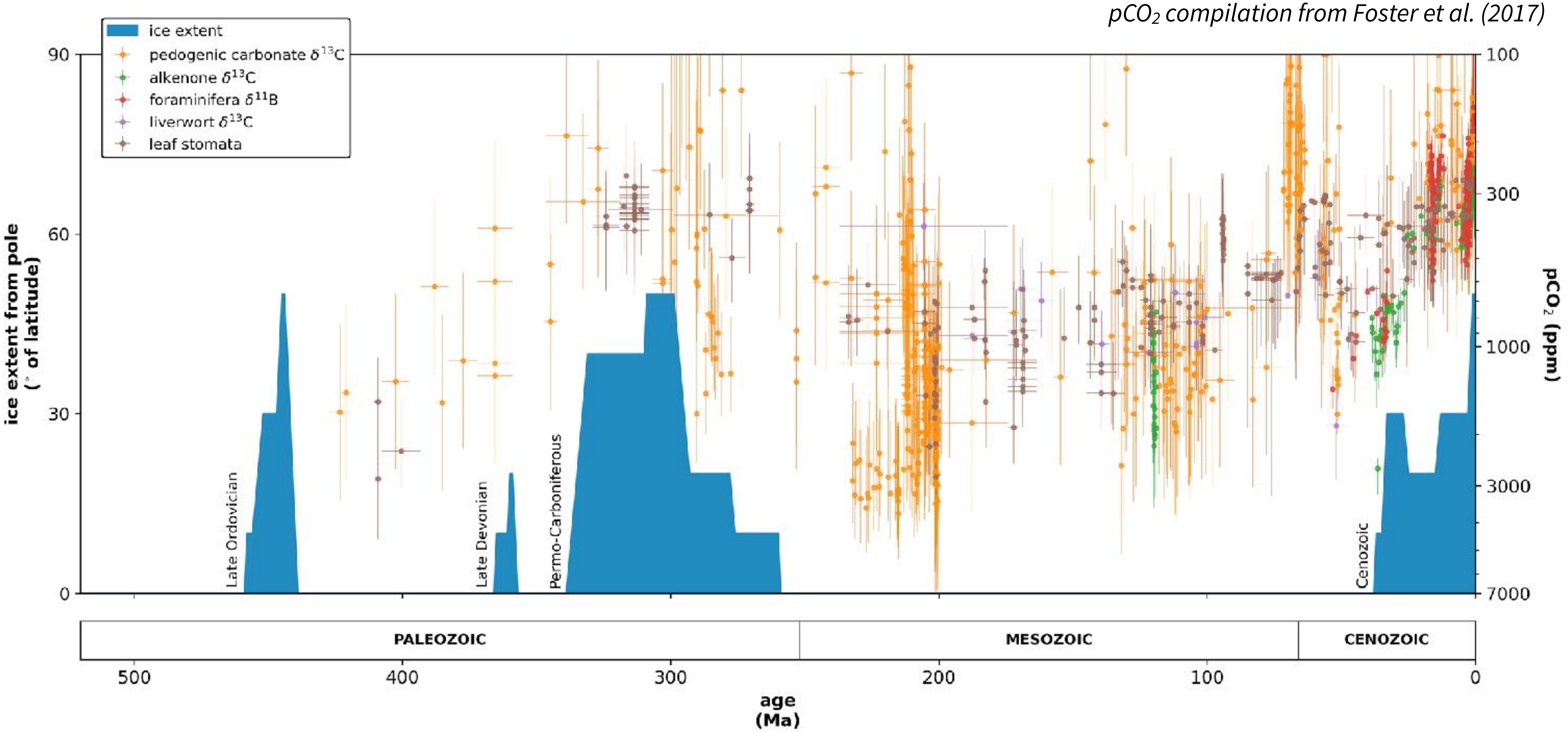
acknowledgements

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

PHANEROZOIC ARC-CONTINENT COLLISIONS

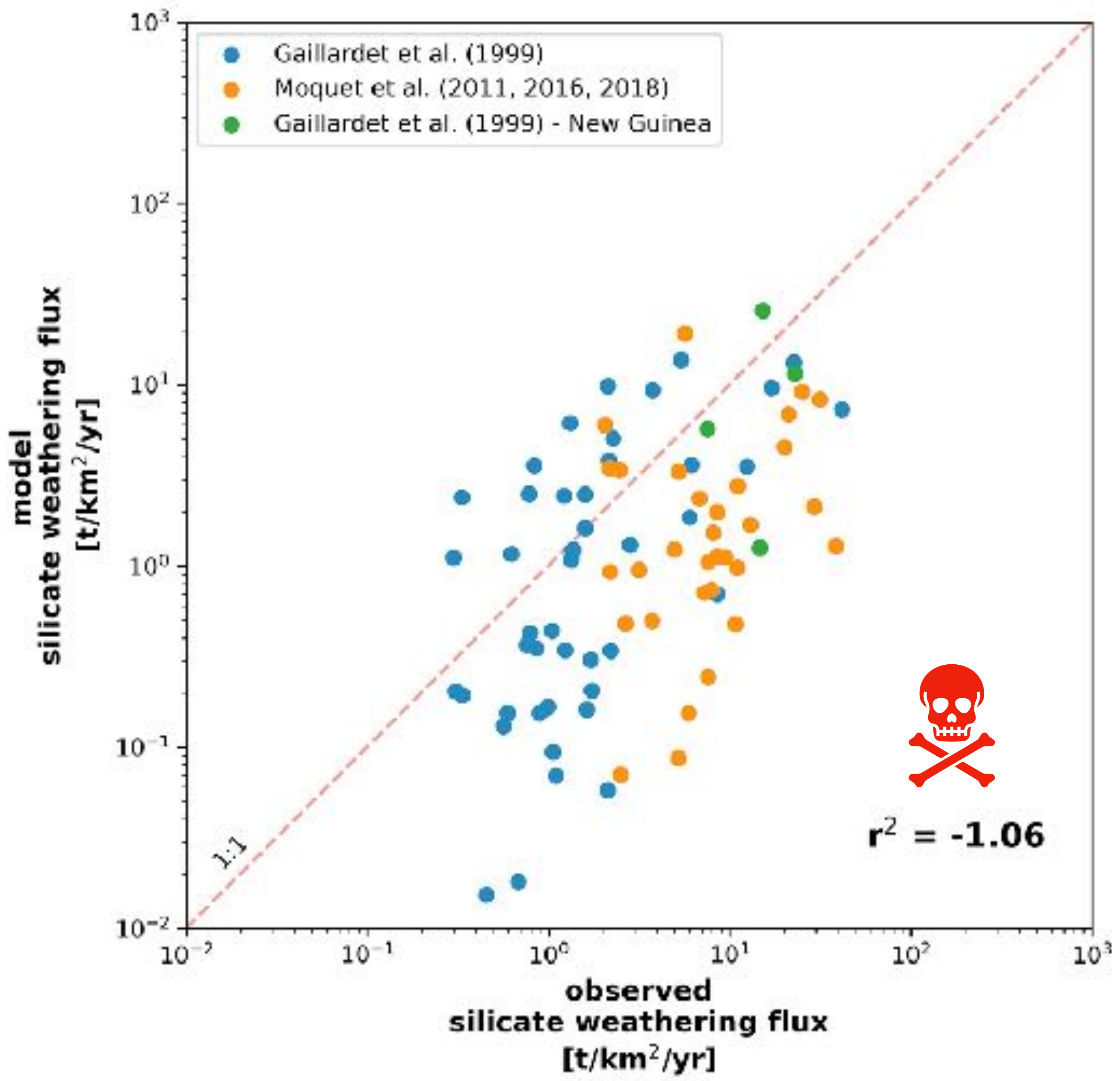
4. a record of Earth's climate state

pCO_2 compilation from Foster et al. (2017)

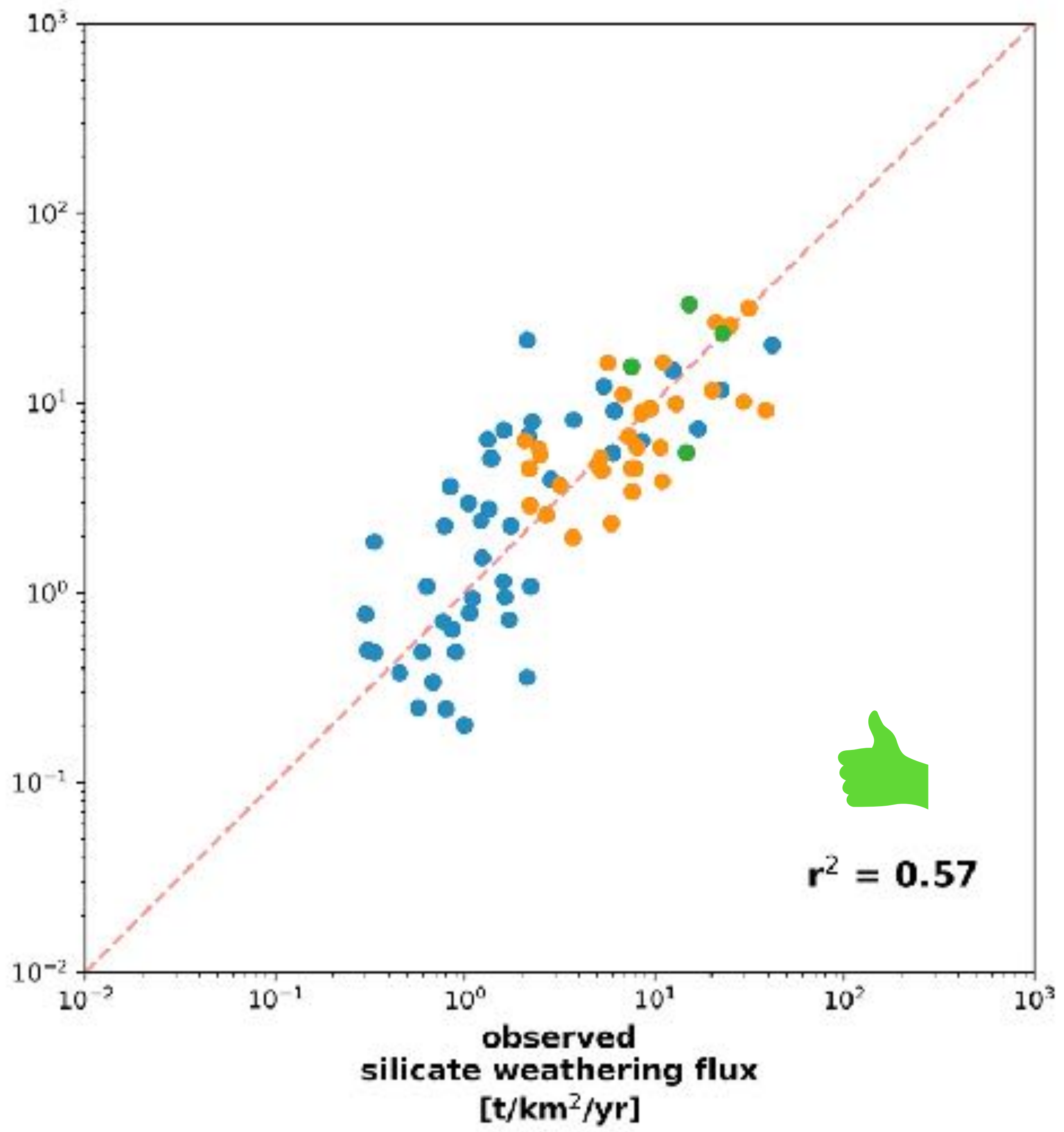


CALIBRATION

metamorphic$_{Ca+Mg}$	3500 mol/m^3
sediment$_{Ca+Mg}$	500 mol/m^3
k_d	0.0001
k_w	0.005
σ	0.3
k_{rp}	0.0012



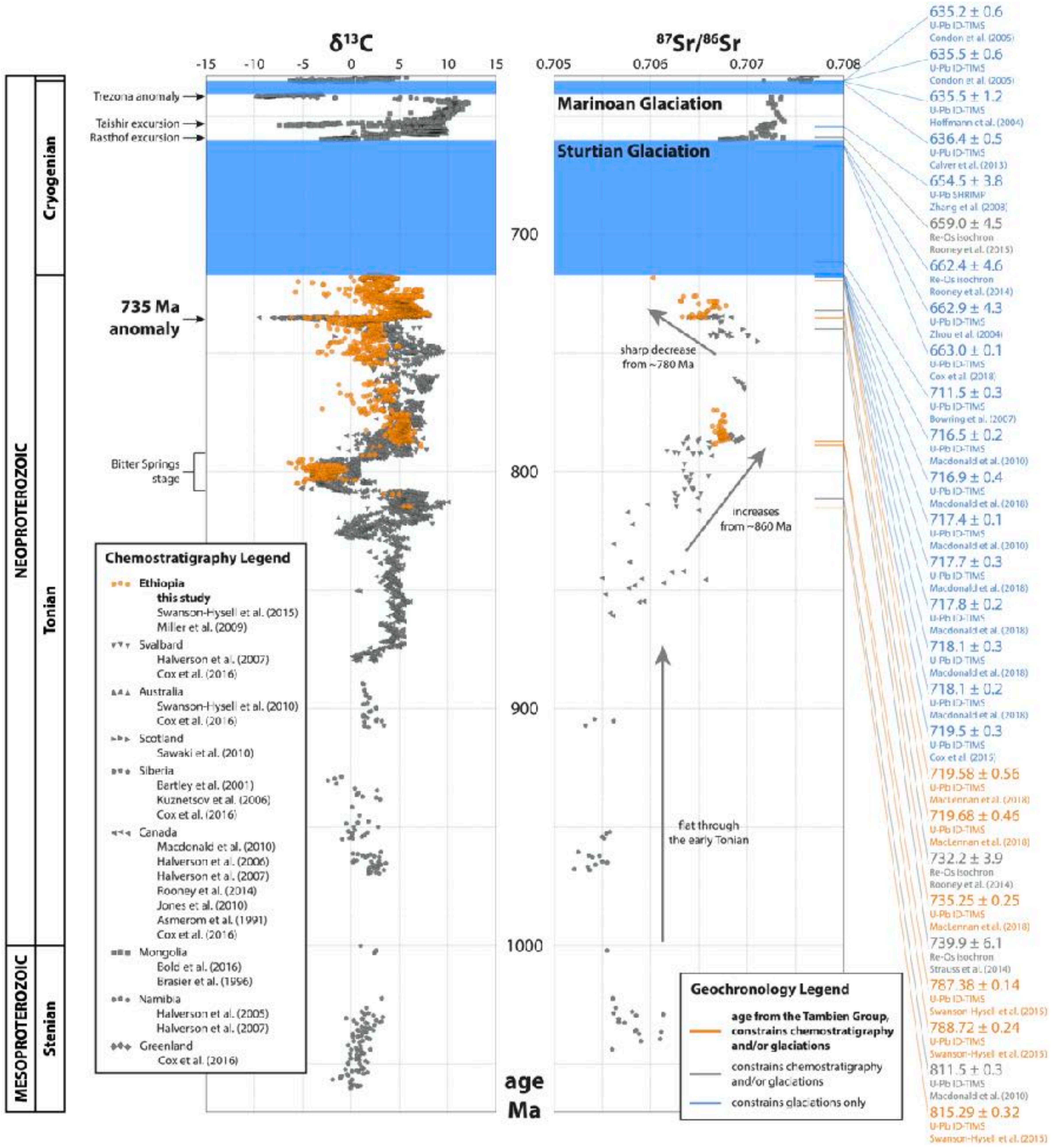
metamorphic$_{Ca+Mg}$	2500 mol/m^3
sediment$_{Ca+Mg}$	2000 mol/m^3
k_d	0.0005
k_w	1
σ	-0.4
k_{rp}	0.001



5,381 "good" parameter combinations that result in chemical weathering maps that closely resemble that observed in the present day

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

CHEMOSTRATIGRAPHY



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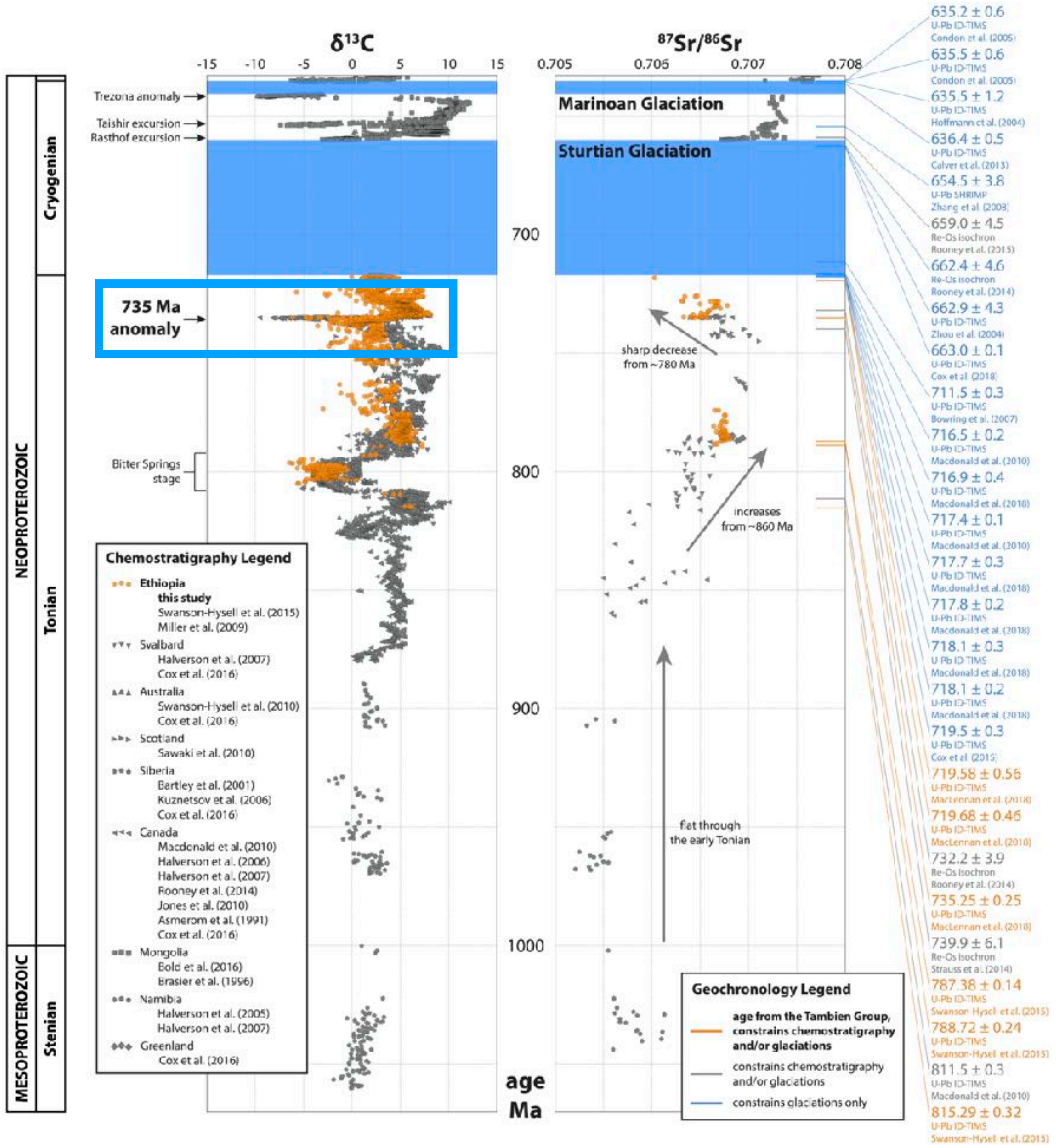
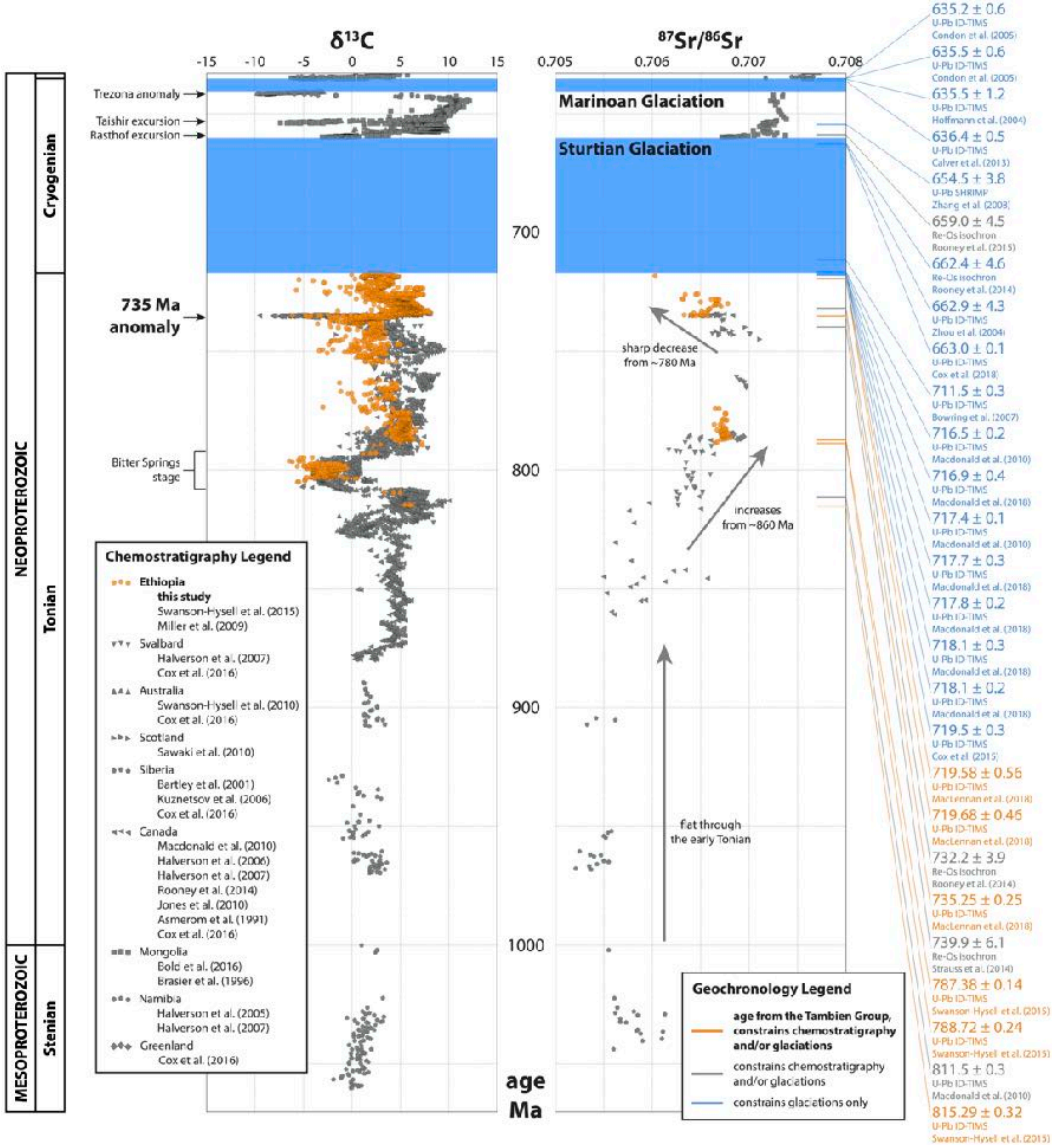
Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

CHEMOSTRATIGRAPHY



CHEMOSTRATIGRAPHY

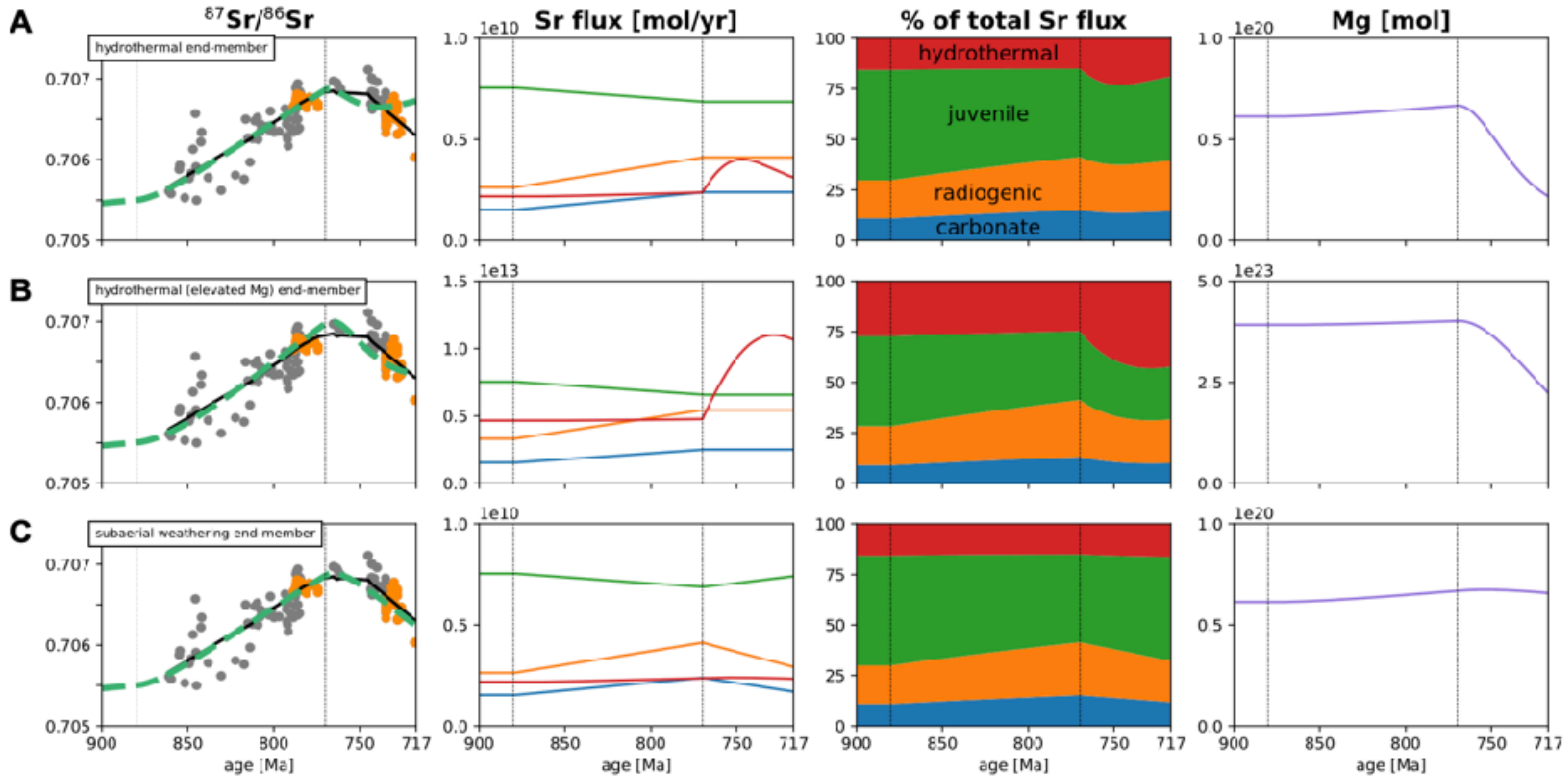


most precisely time-calibrated marine isotope record leading into the Sturtian Glaciation to date

Planetary cooling, tectonics, and weathering from 1 billion years ago to the present

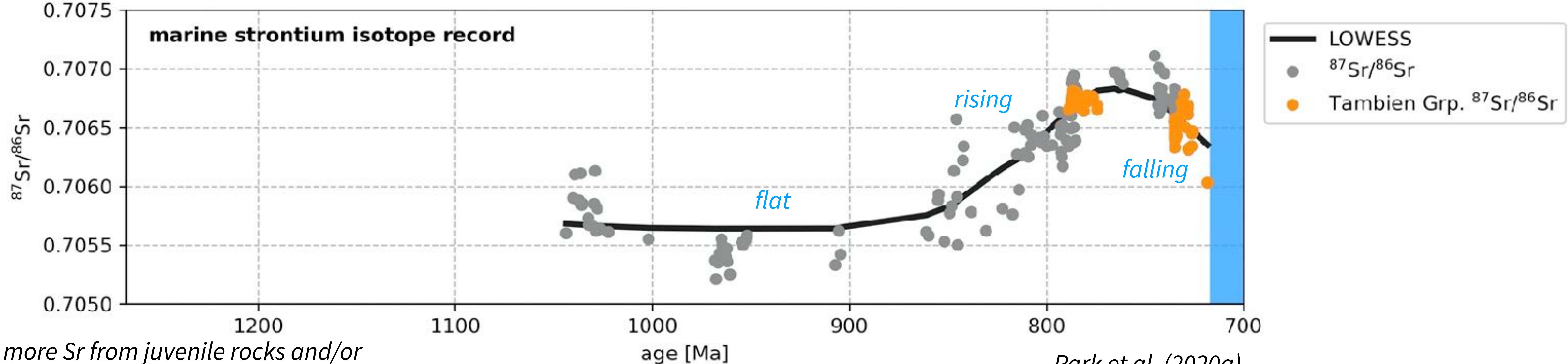
STRONTIUM

box model indicates that driving the falling $^{87}Sr/^{86}Sr$ using an increase in the hydrothermal exchange flux requires unrealistic Ca and Mg fluxes and reservoirs



Park et al. (2020a), formulation from Maloof et al. (2010)

more Sr from radiogenic rocks



more Sr from juvenile rocks and/or hydrothermal exchange

Park et al. (2020a)

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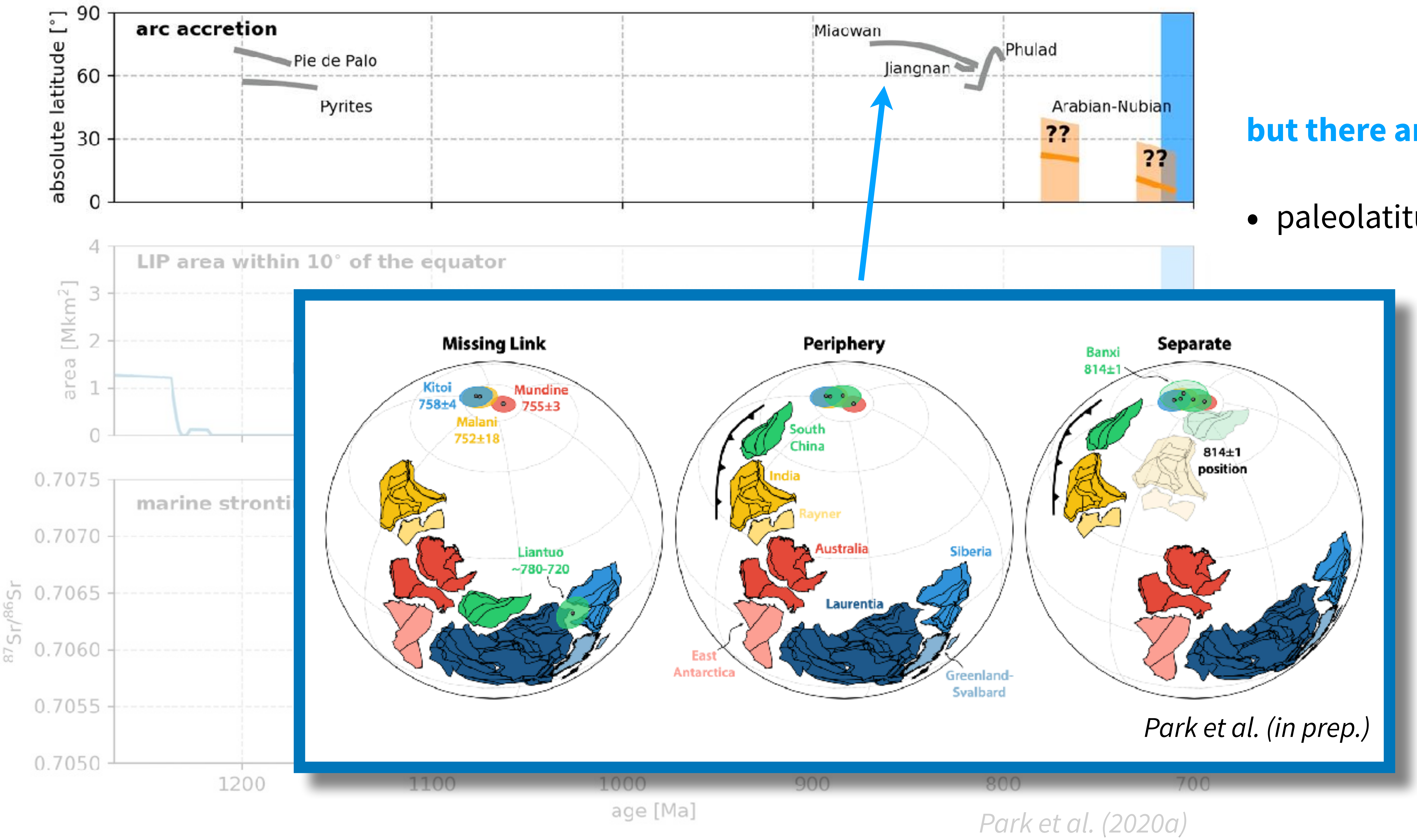
STRONTIUM



but there are serious limitations…

- paleolatitude is poorly constrained

where was South China?