

Geochemistry in the Age of Open Data

New insights into the formation and evolution of
Earth's continental crust.

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Motivation

1. Understanding how the Earth system operates
 - There is still a lot we don't know about our own planet

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Plate Tectonics

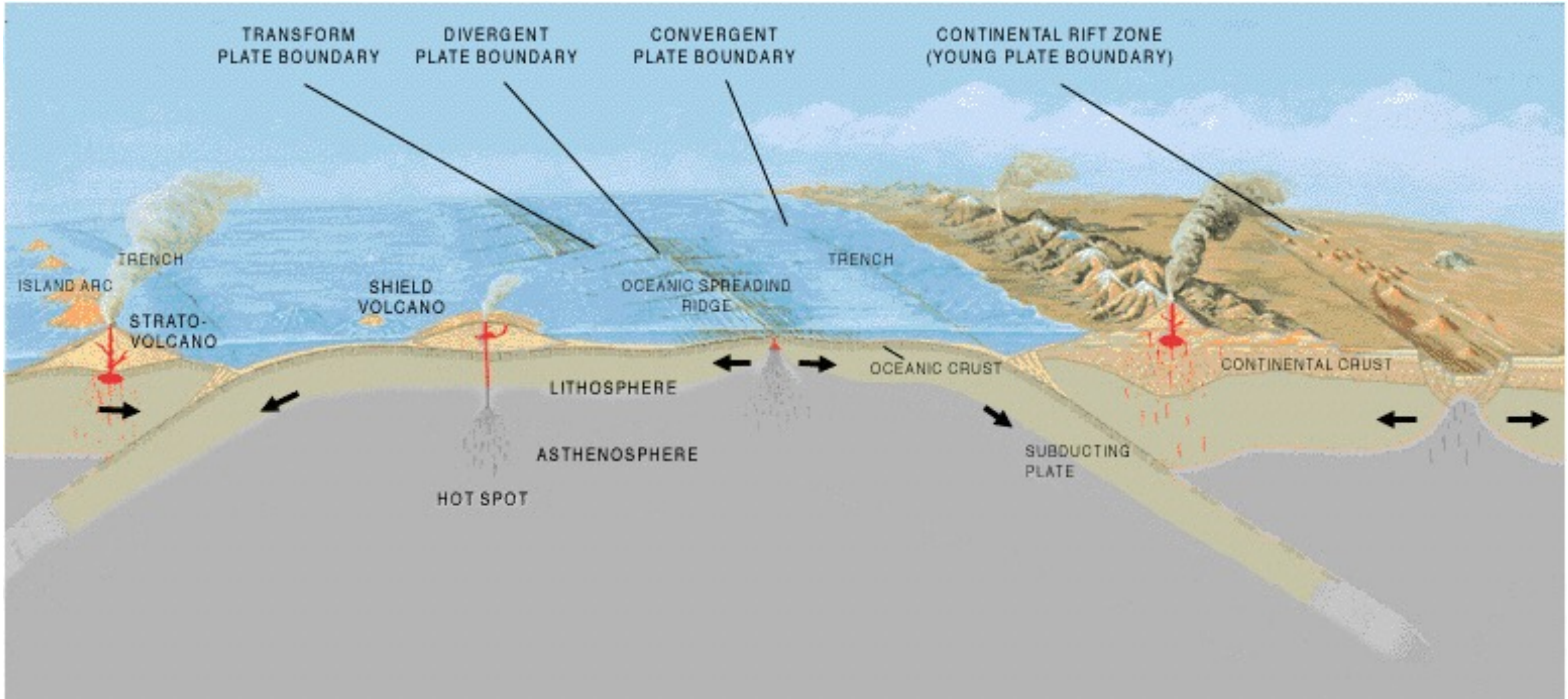


Plate Tectonics

Sites of magmatism

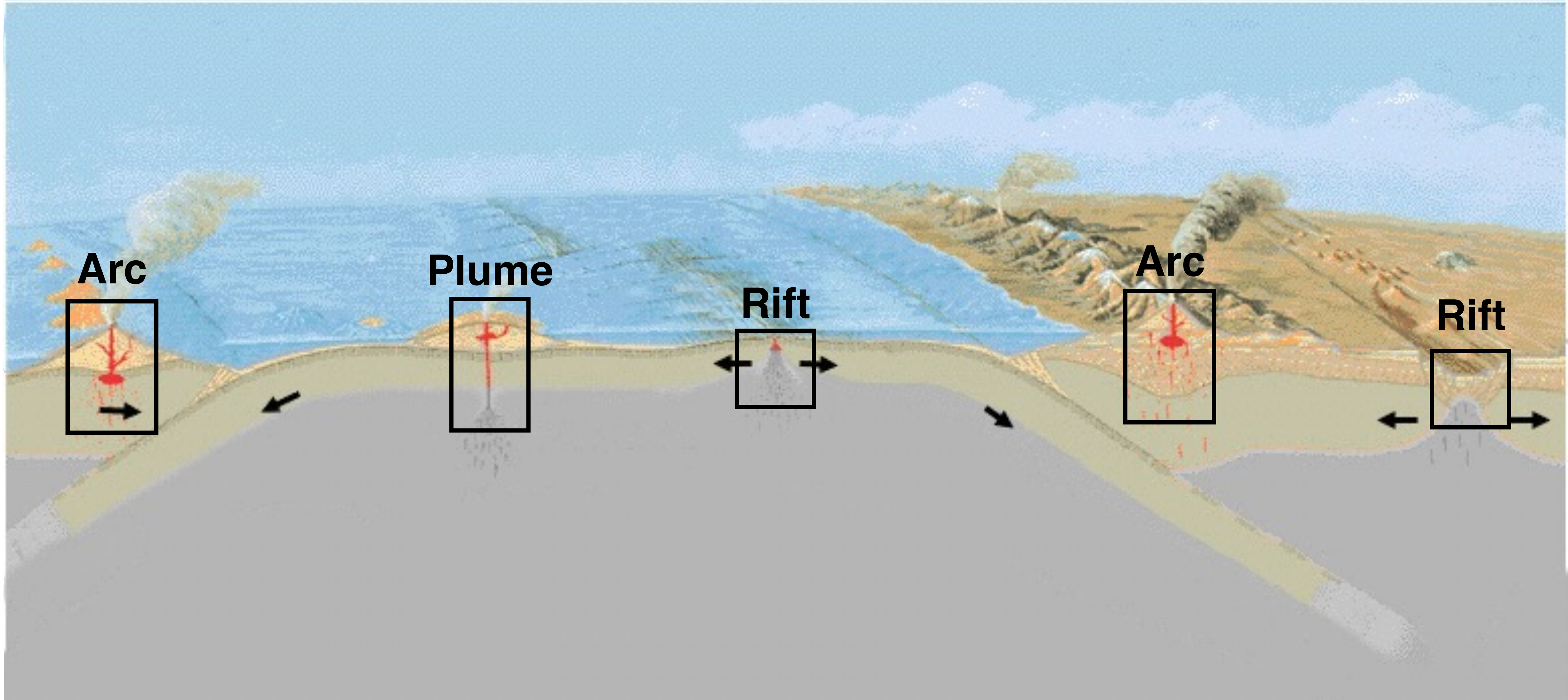
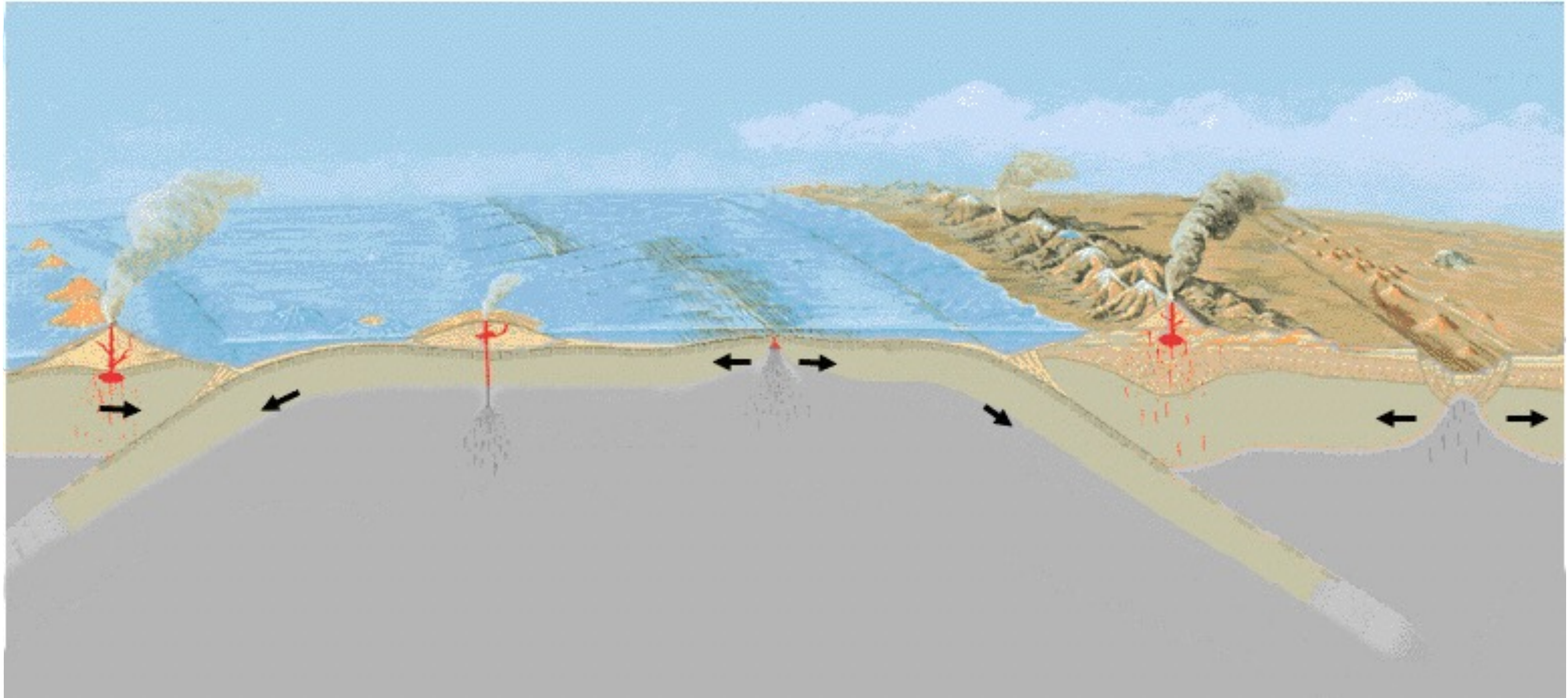


Plate Tectonics

Sites of magmatism



USGS

$T \uparrow$

Plate Tectonics

Sites of magmatism

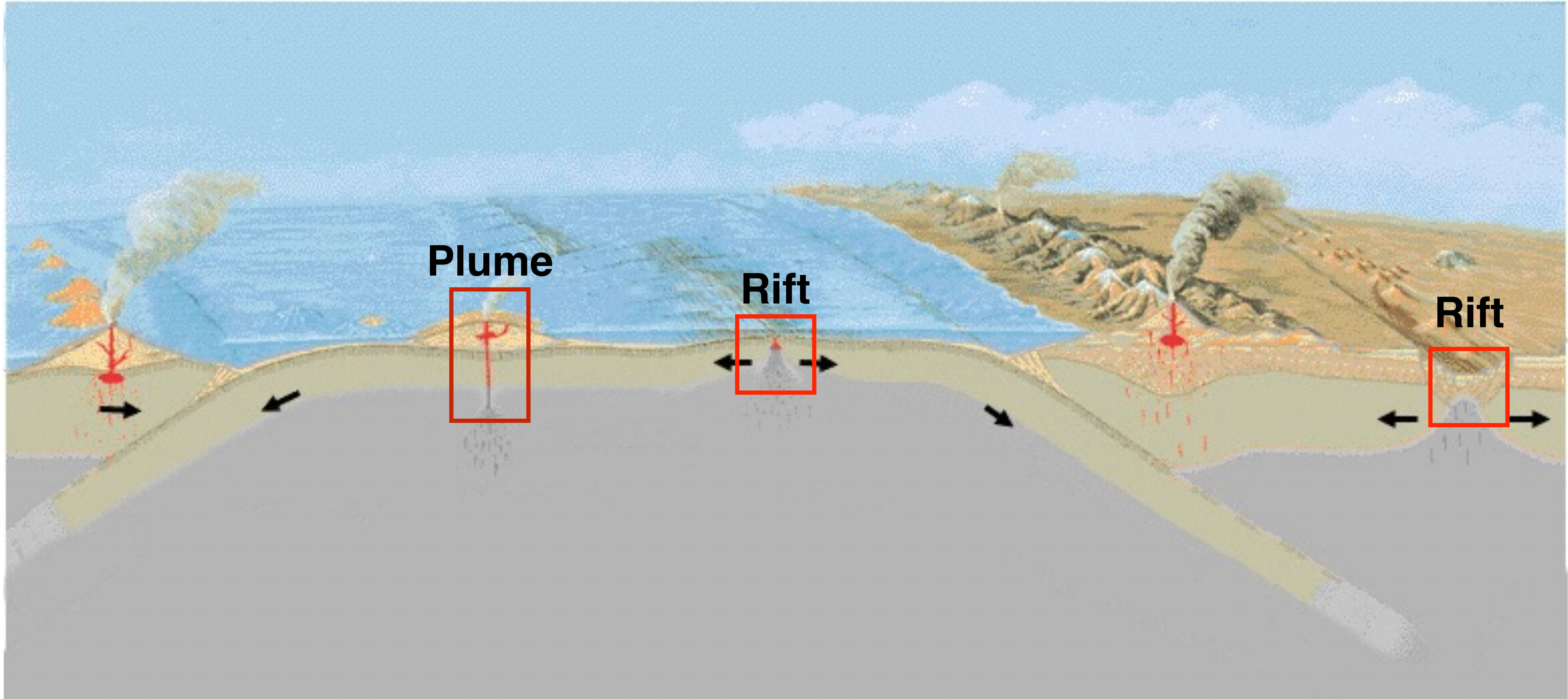
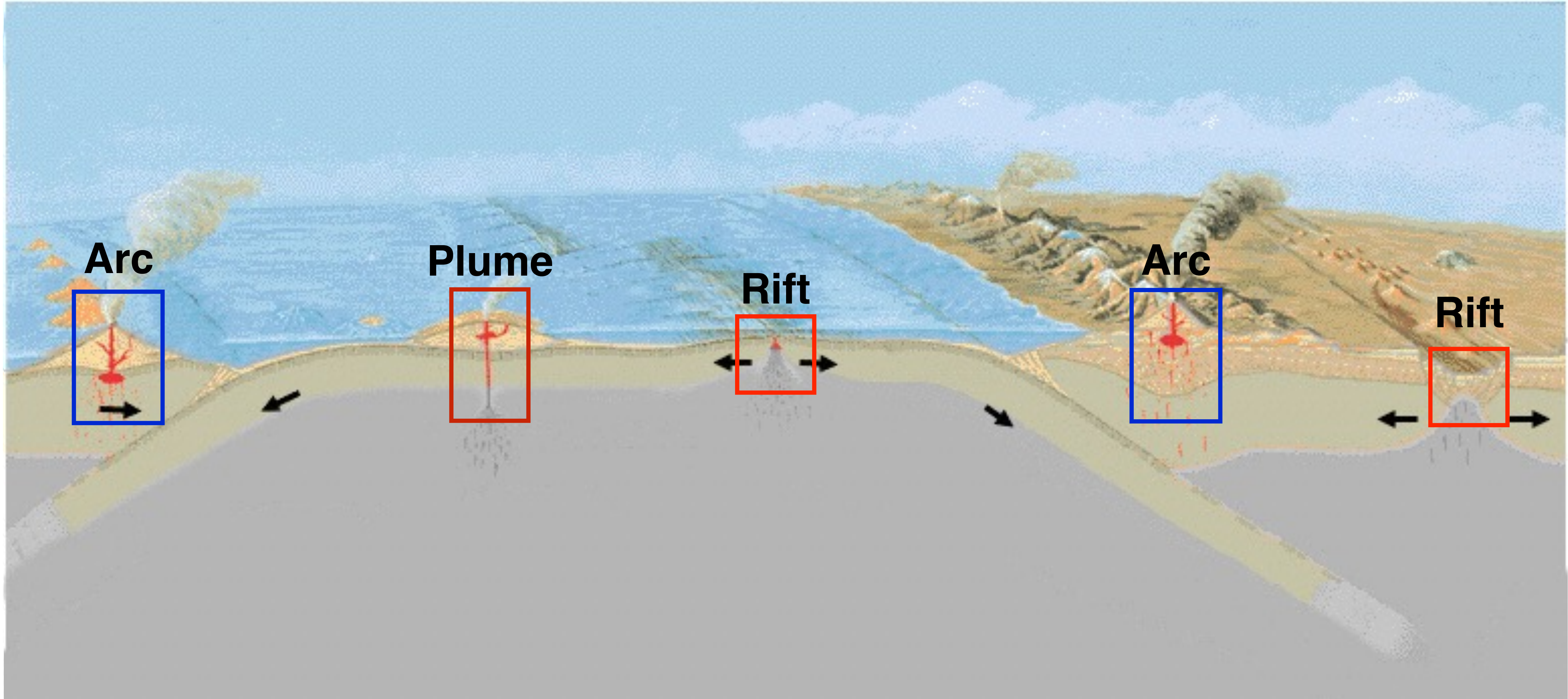


Plate Tectonics

Sites of magmatism



USGS

$T \uparrow, P \downarrow, H_2O \uparrow$

Plate Tectonics

Two types of crust

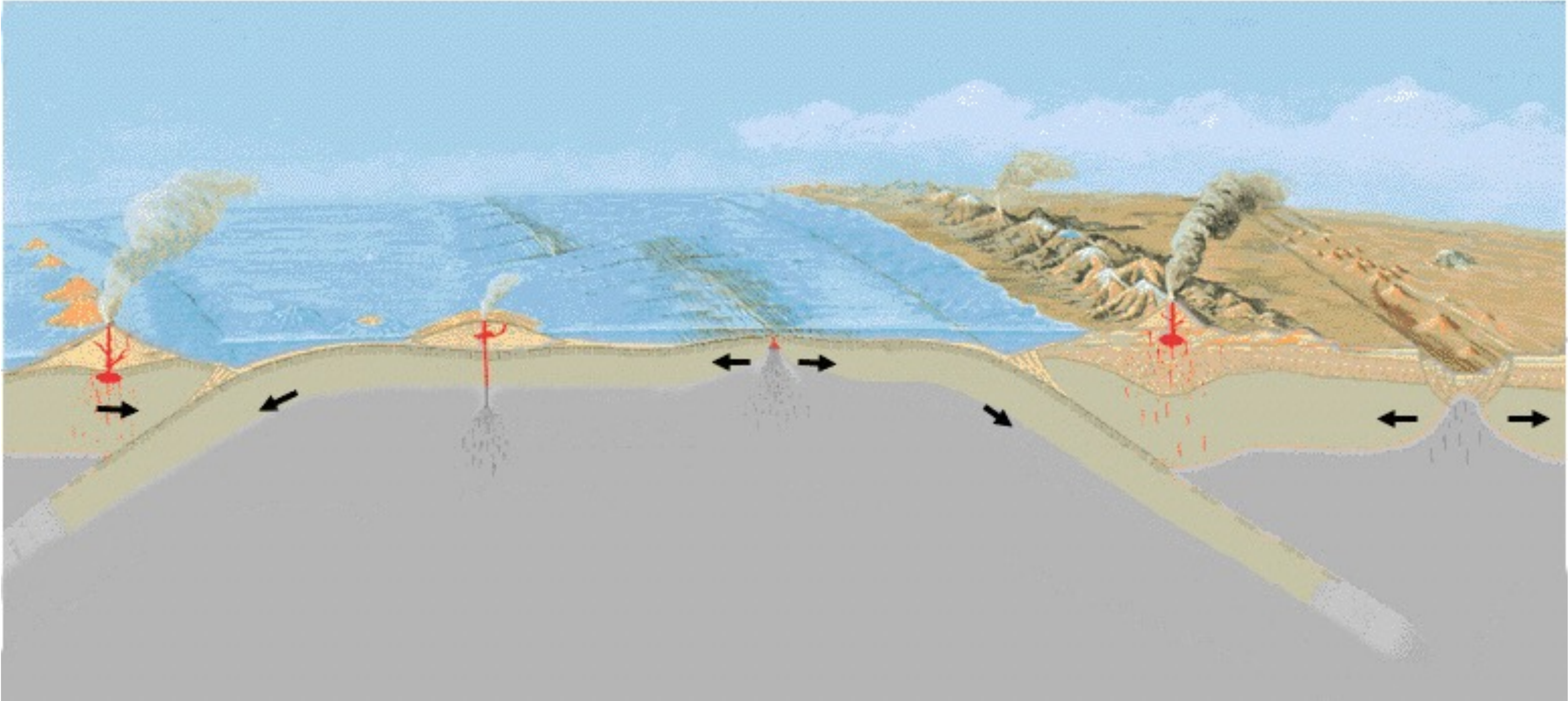
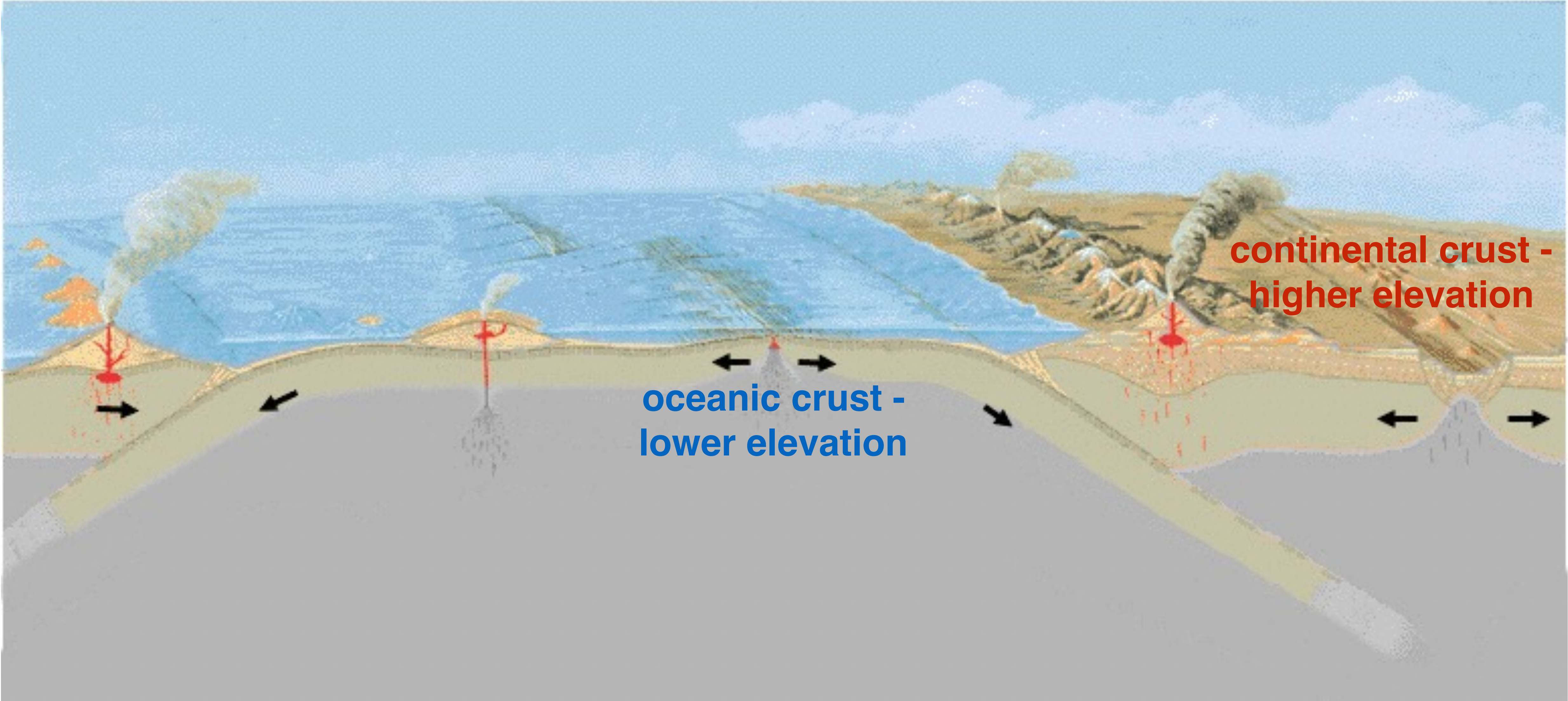


Plate Tectonics

Two types of crust



Mineralogy & Composition

high [SiO₂],
low density



Quartz
SiO₂



Orthoclase
KAlSi₃O₈



Plagioclase
(Na,Ca)(Si,Al)AlSi₂O₈



Pyroxene
(Fe,Mg,Ca)₂Si₂O₆

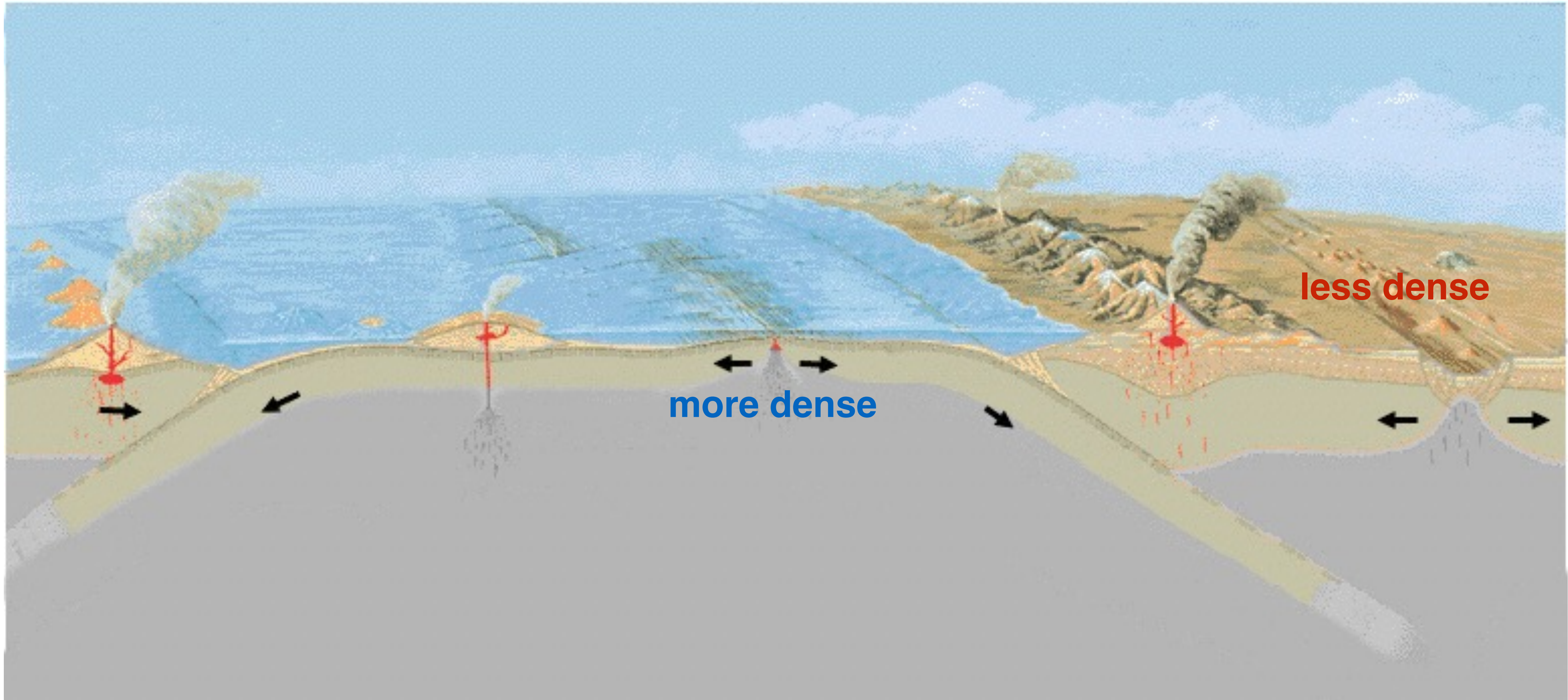
low [SiO₂],
high density



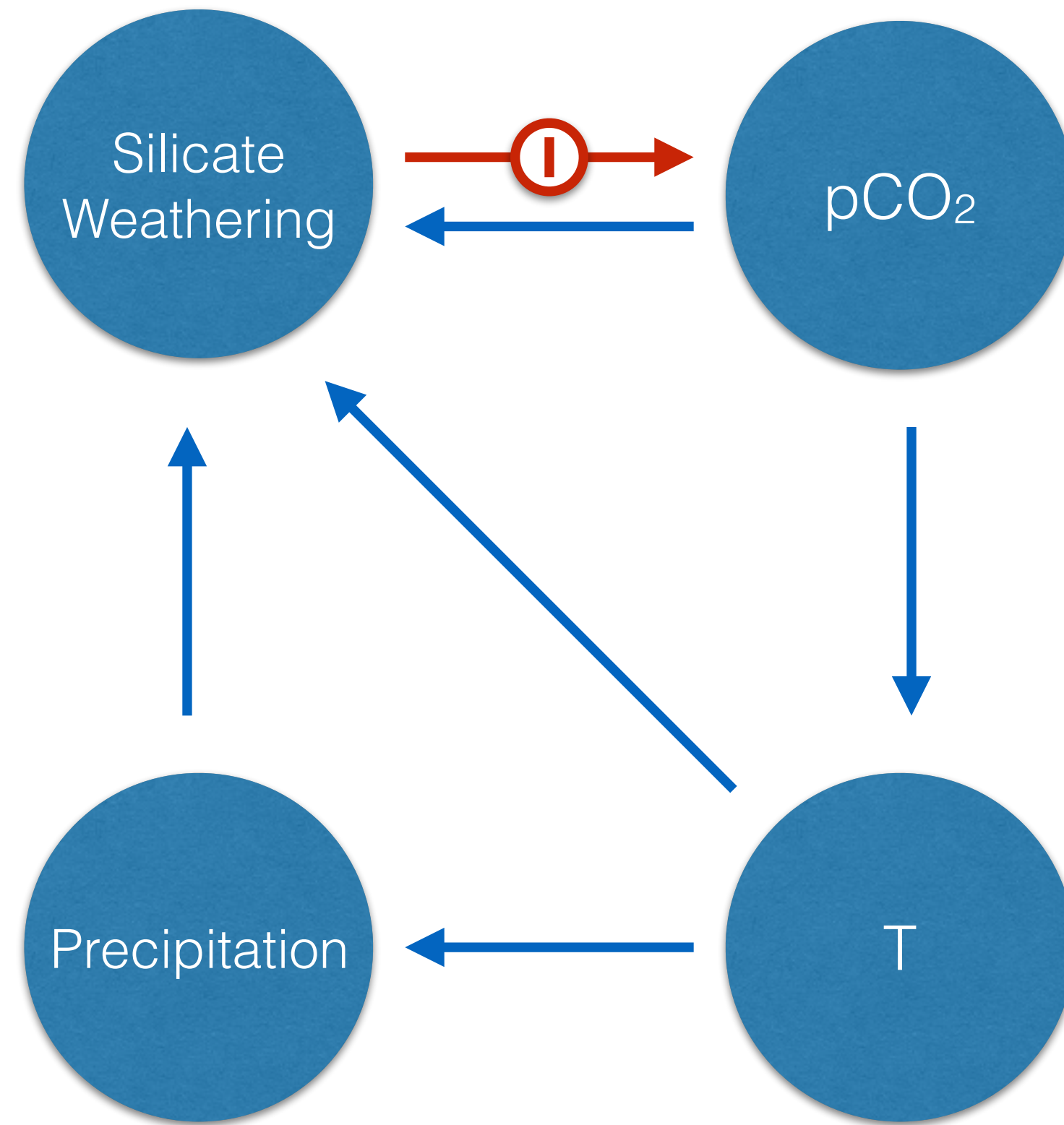
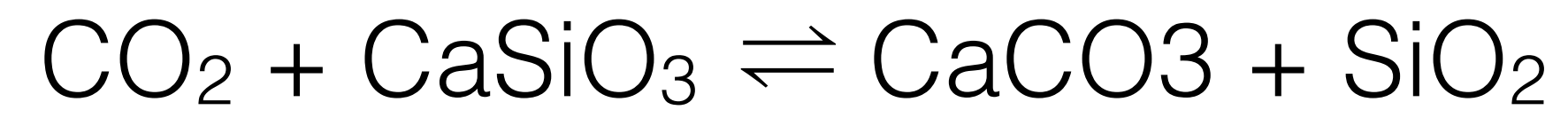
Olivine
(Fe,Mg)₂SiO₄

Bimodal Topography

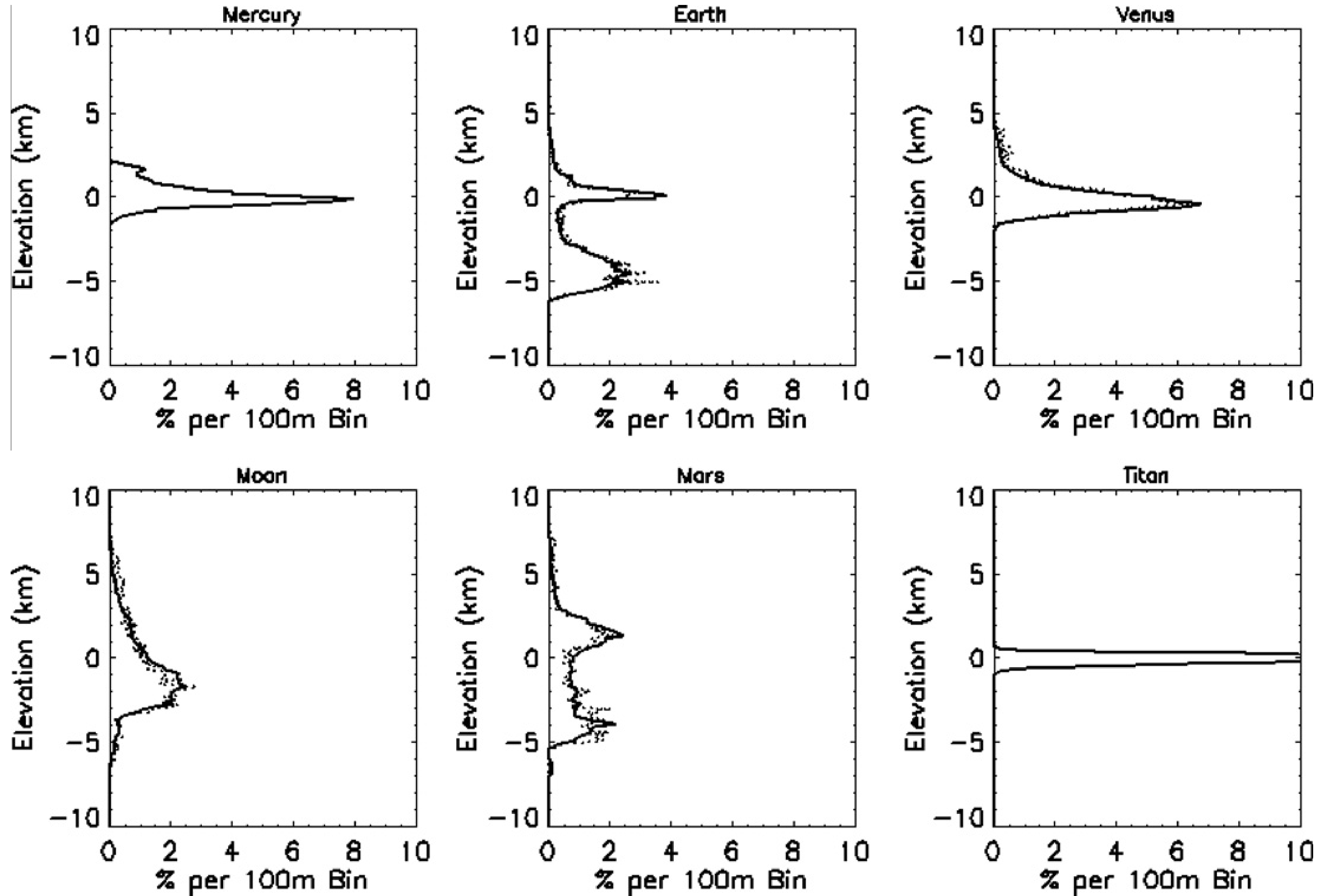
Required for efficient silicate weathering



Silicate Weathering Feedback

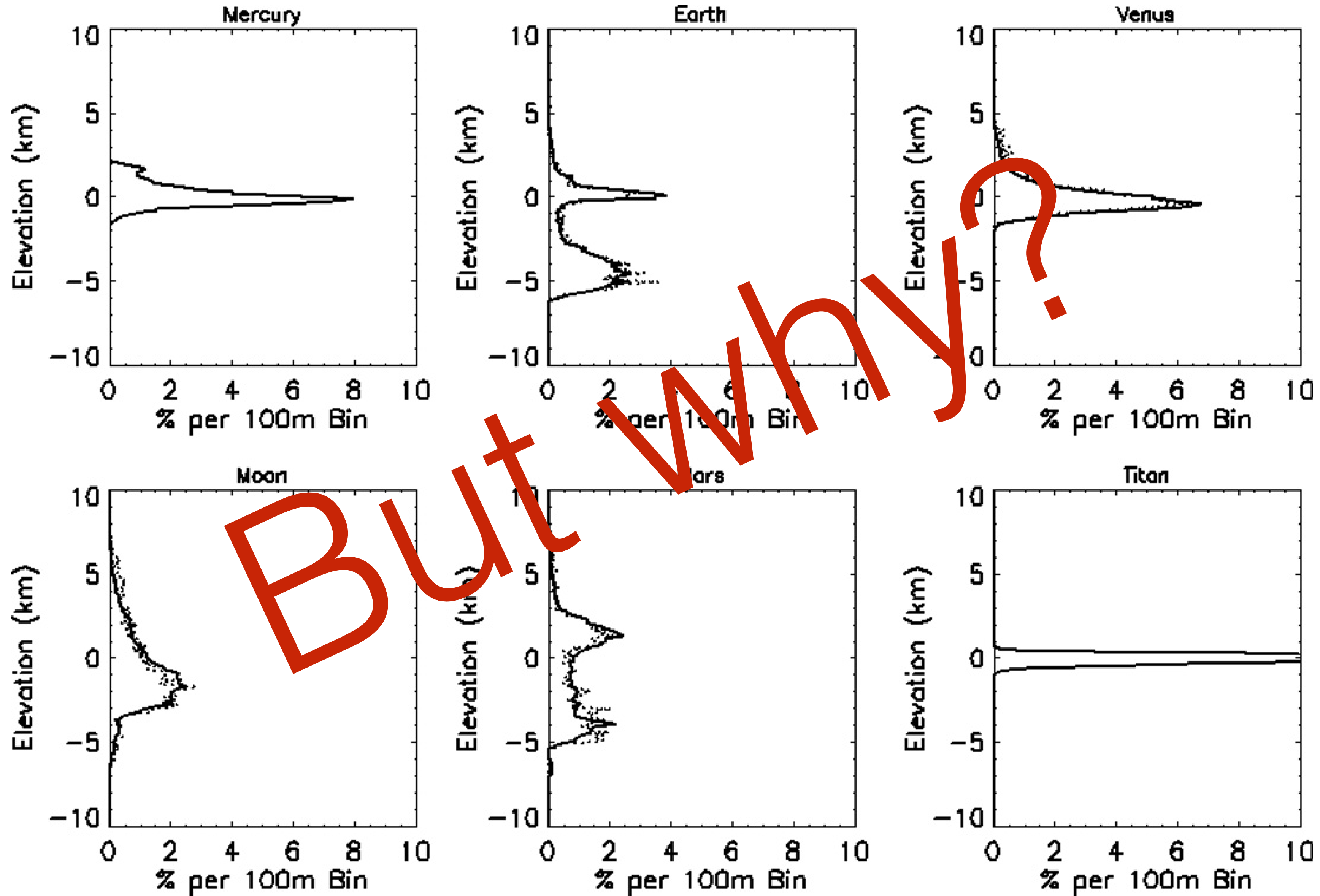


Bimodal Topography



Lorenz et al.
(2011) *Icarus*

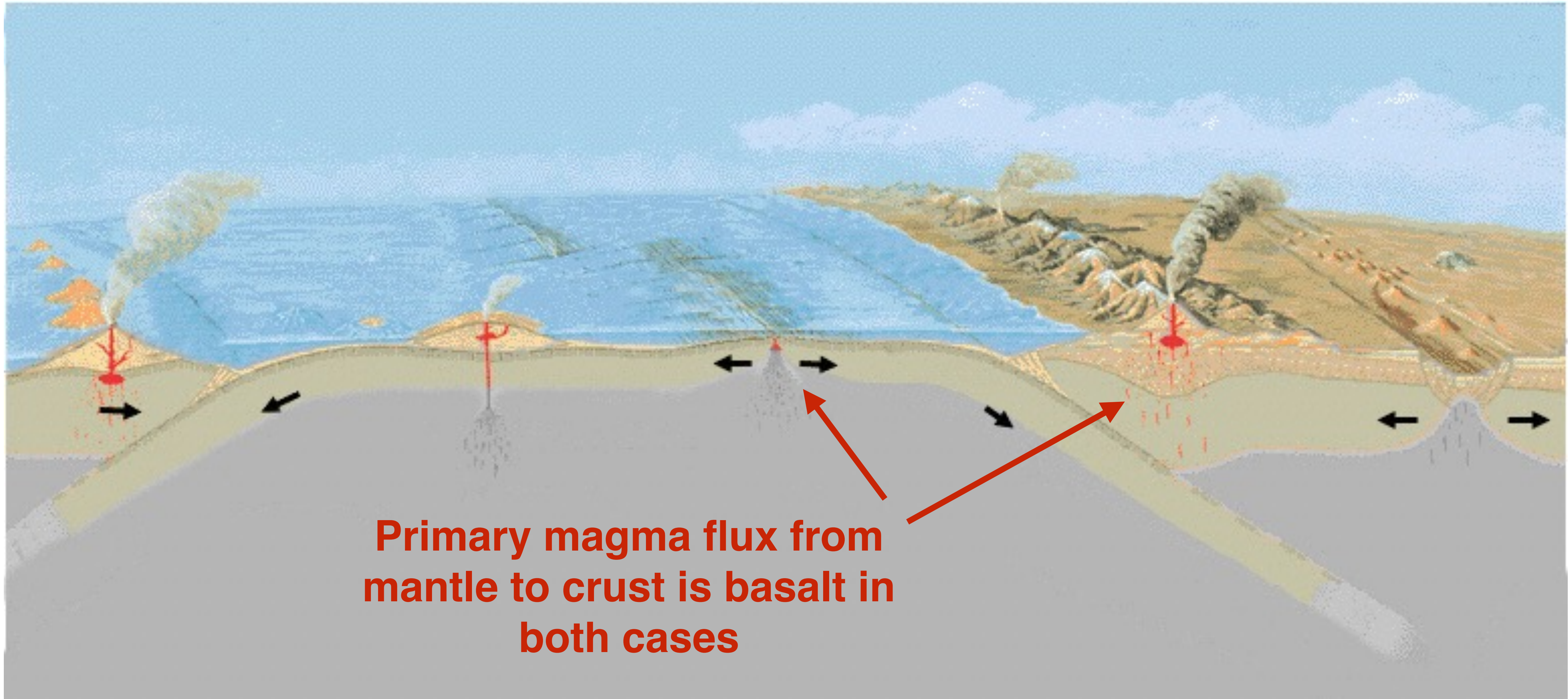
Bimodal Topography



Lorenz et al.
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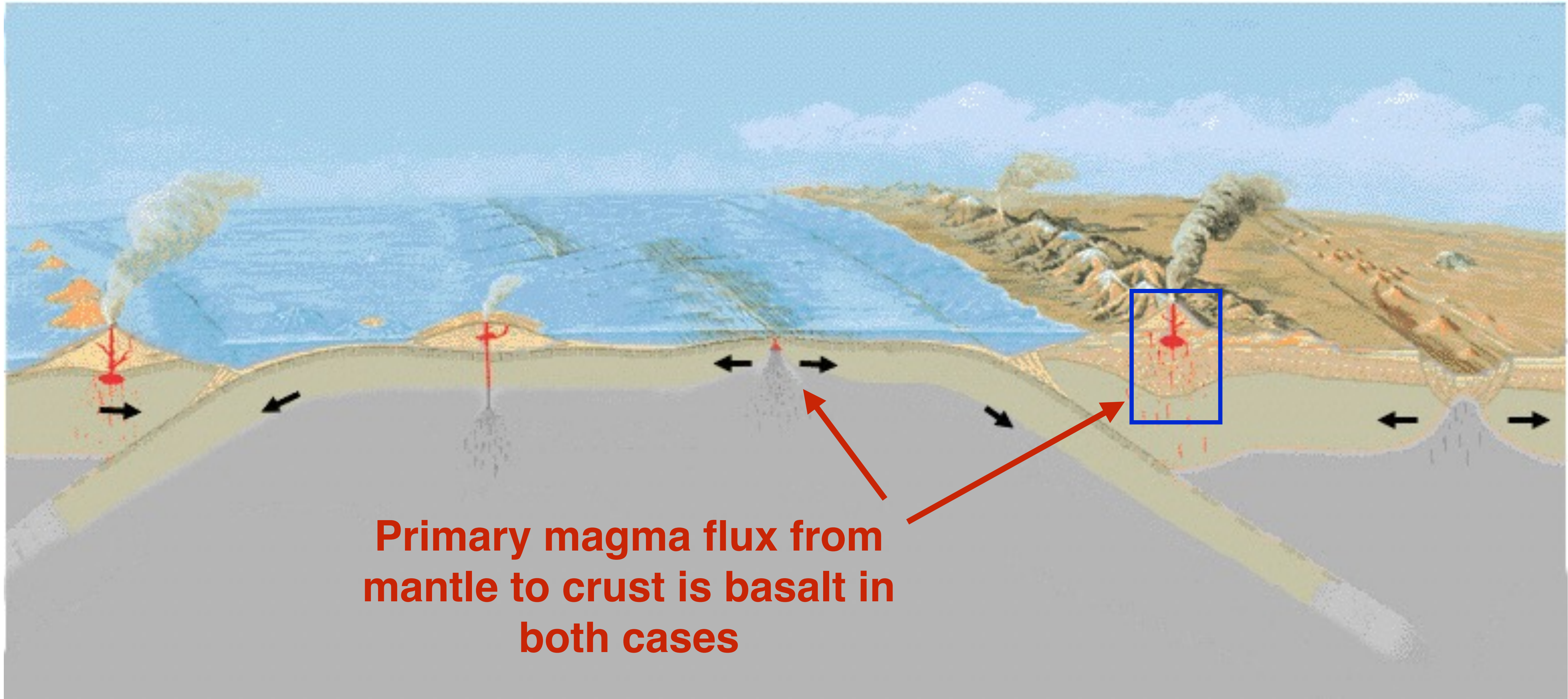
Production & Evolution of Continental Crust

Why is continental crust less dense than oceanic crust?



Production & Evolution of Continental Crust

Why is continental crust less dense than oceanic crust?

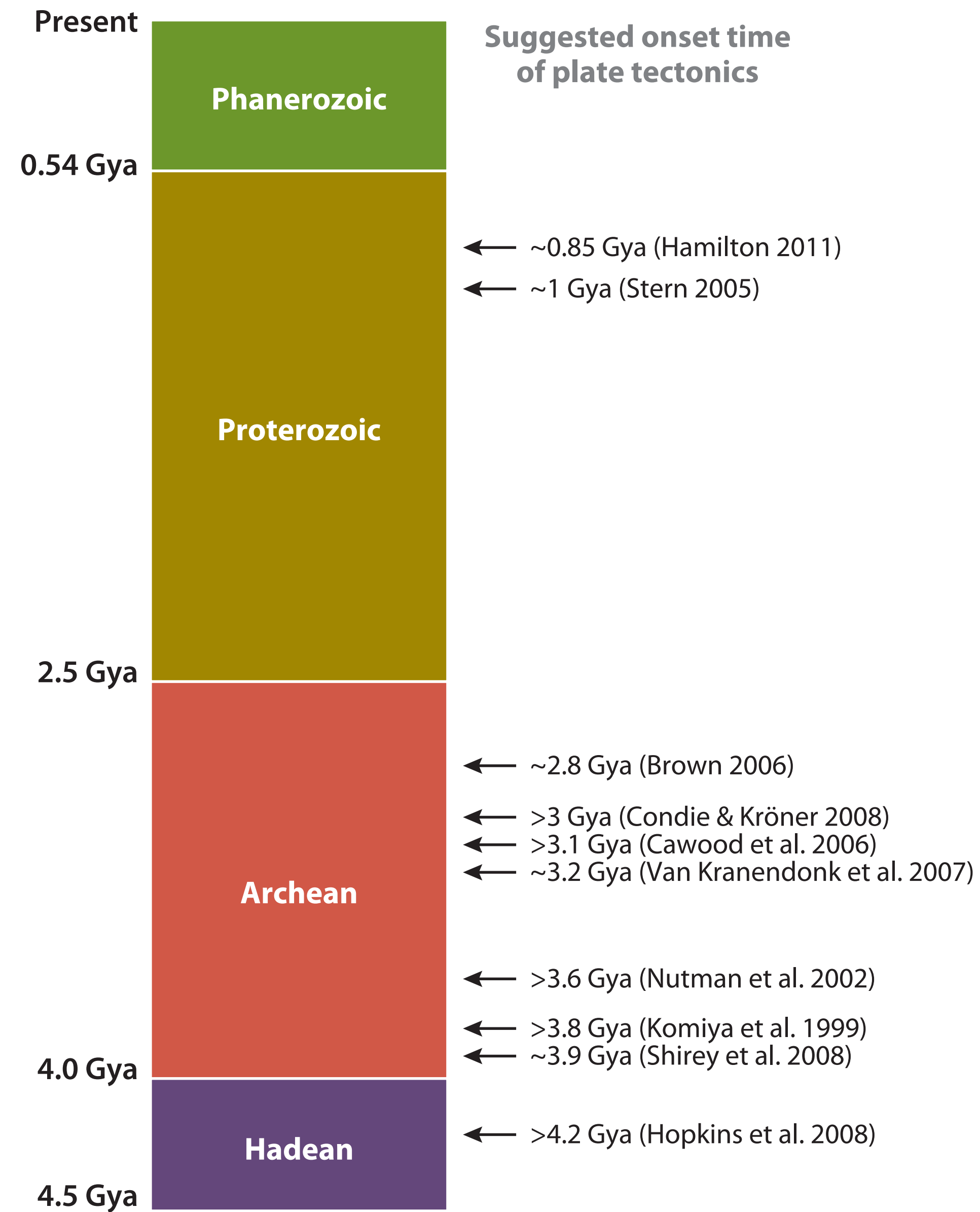


Production & Evolution of Continental Crust

Fundamental question:

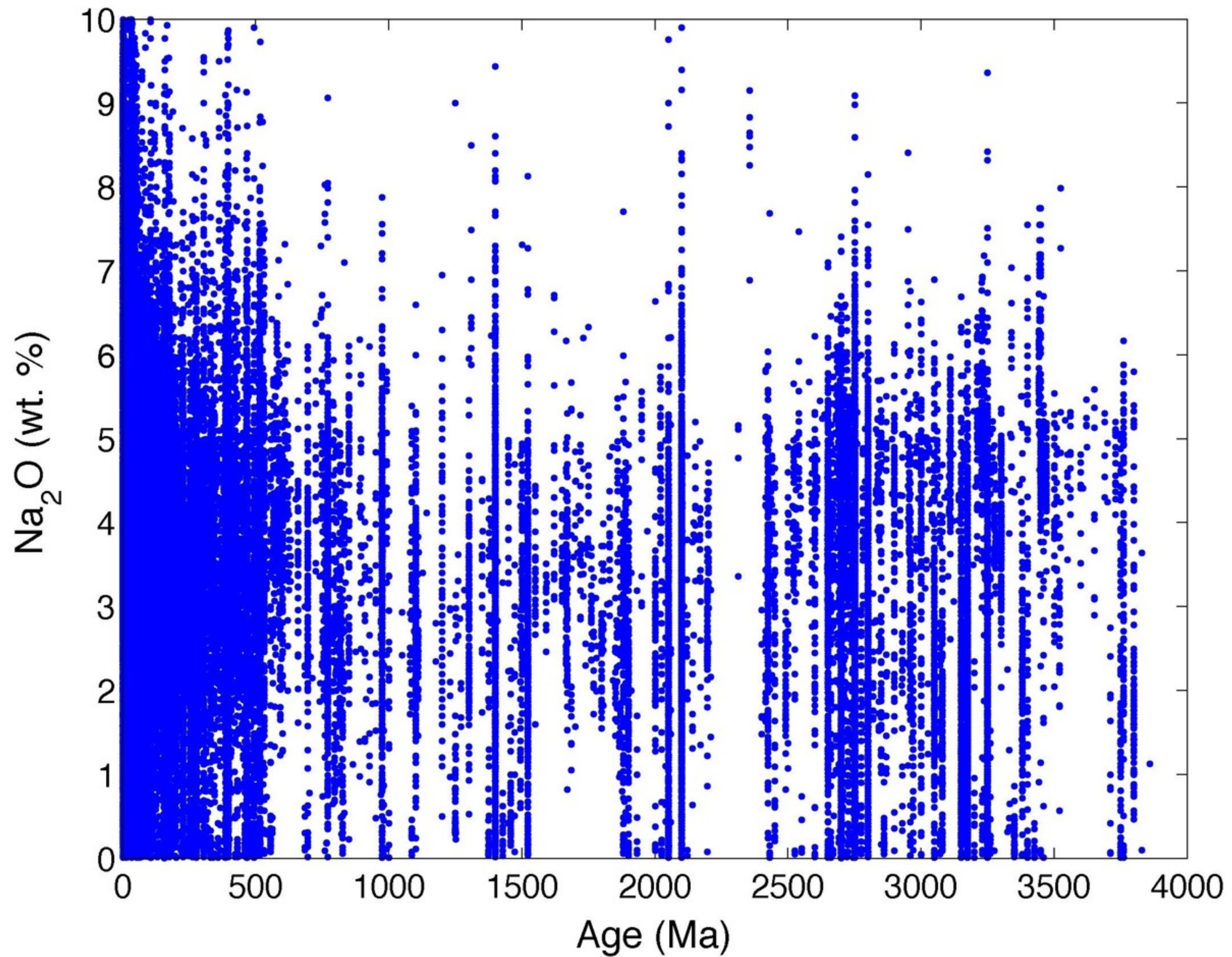
- How long has plate tectonics been operating on Earth?

Proposed initiations of plate tectonics

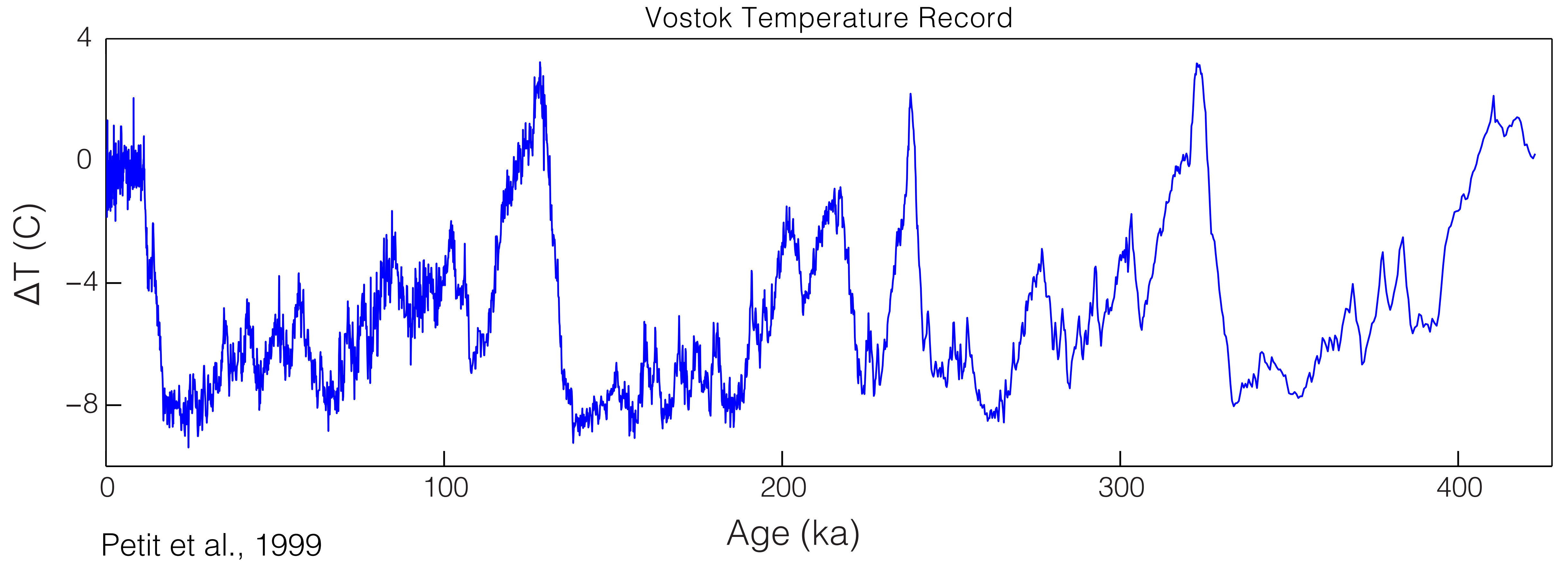


Korenaga, 2013

Earth's crust is chemically heterogeneous

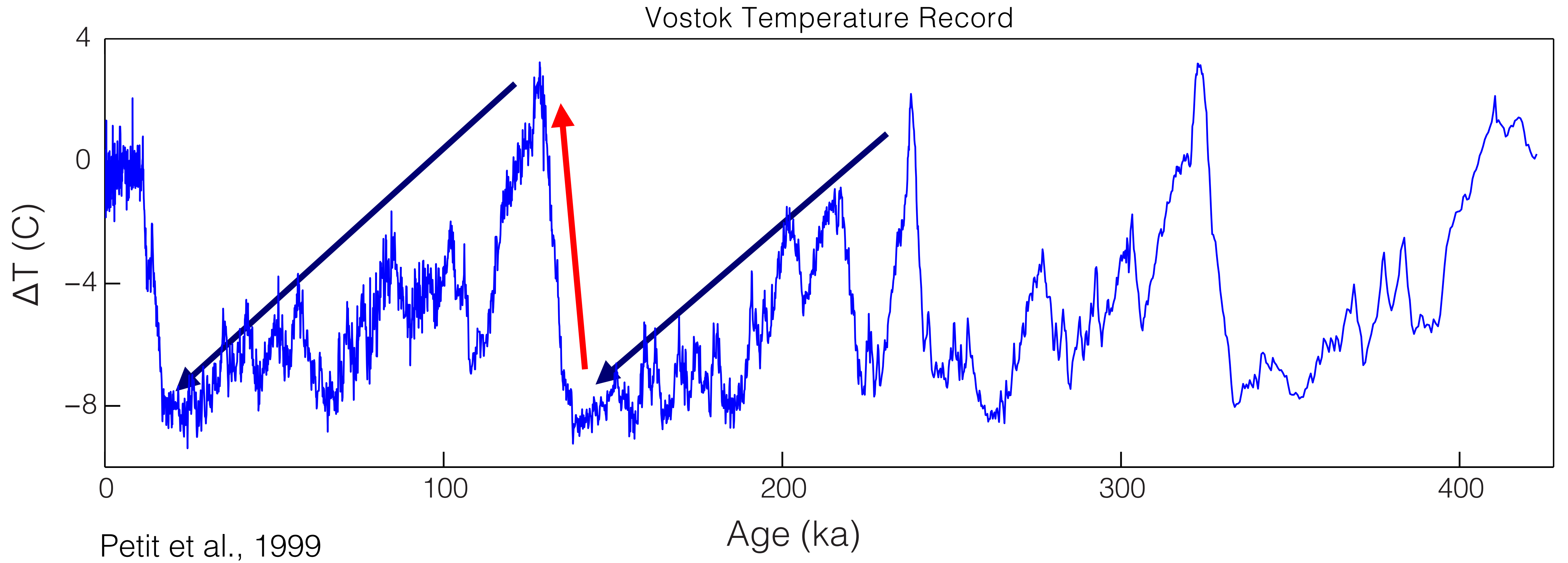


Average Temporal Trends

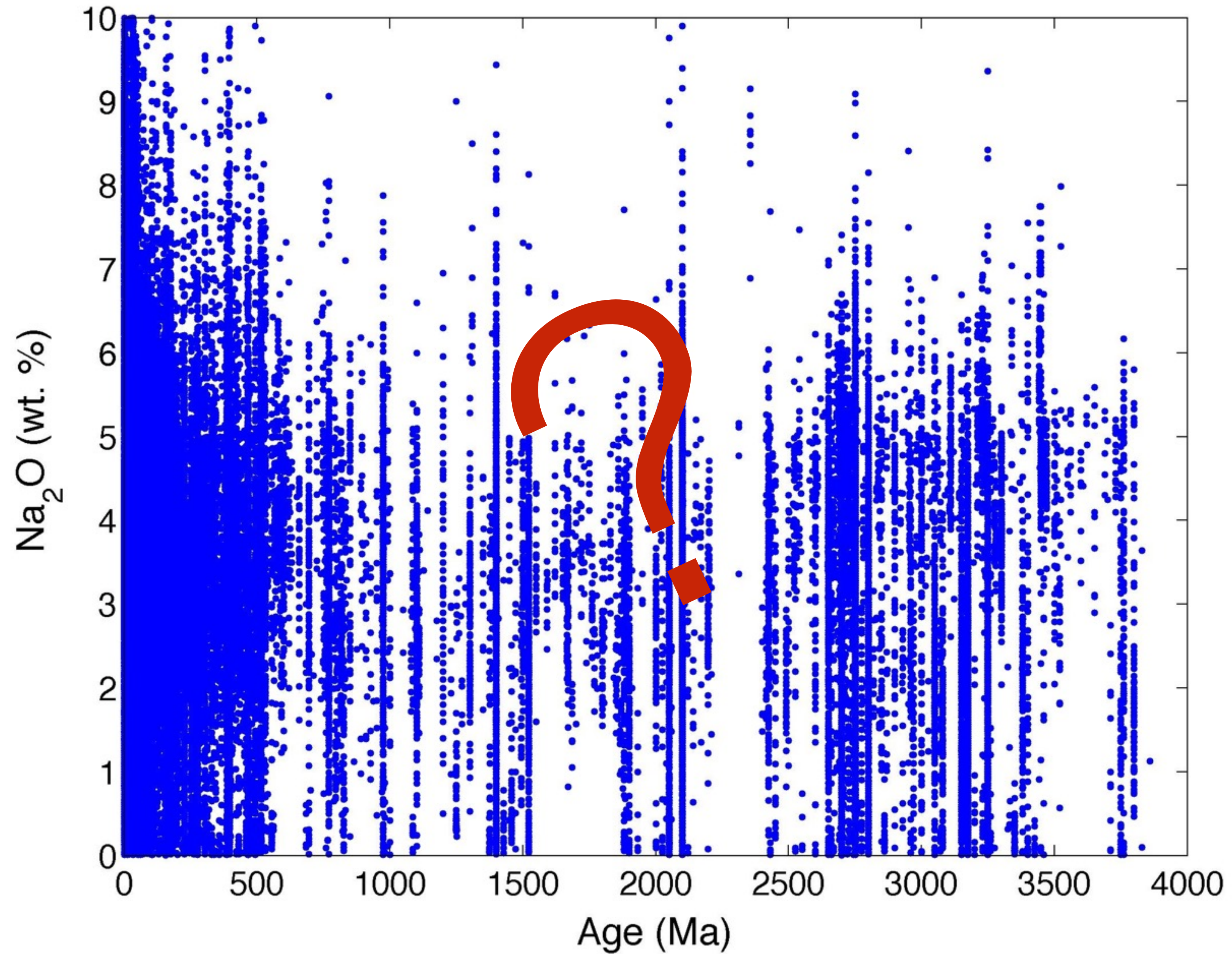


Average Temporal Trends

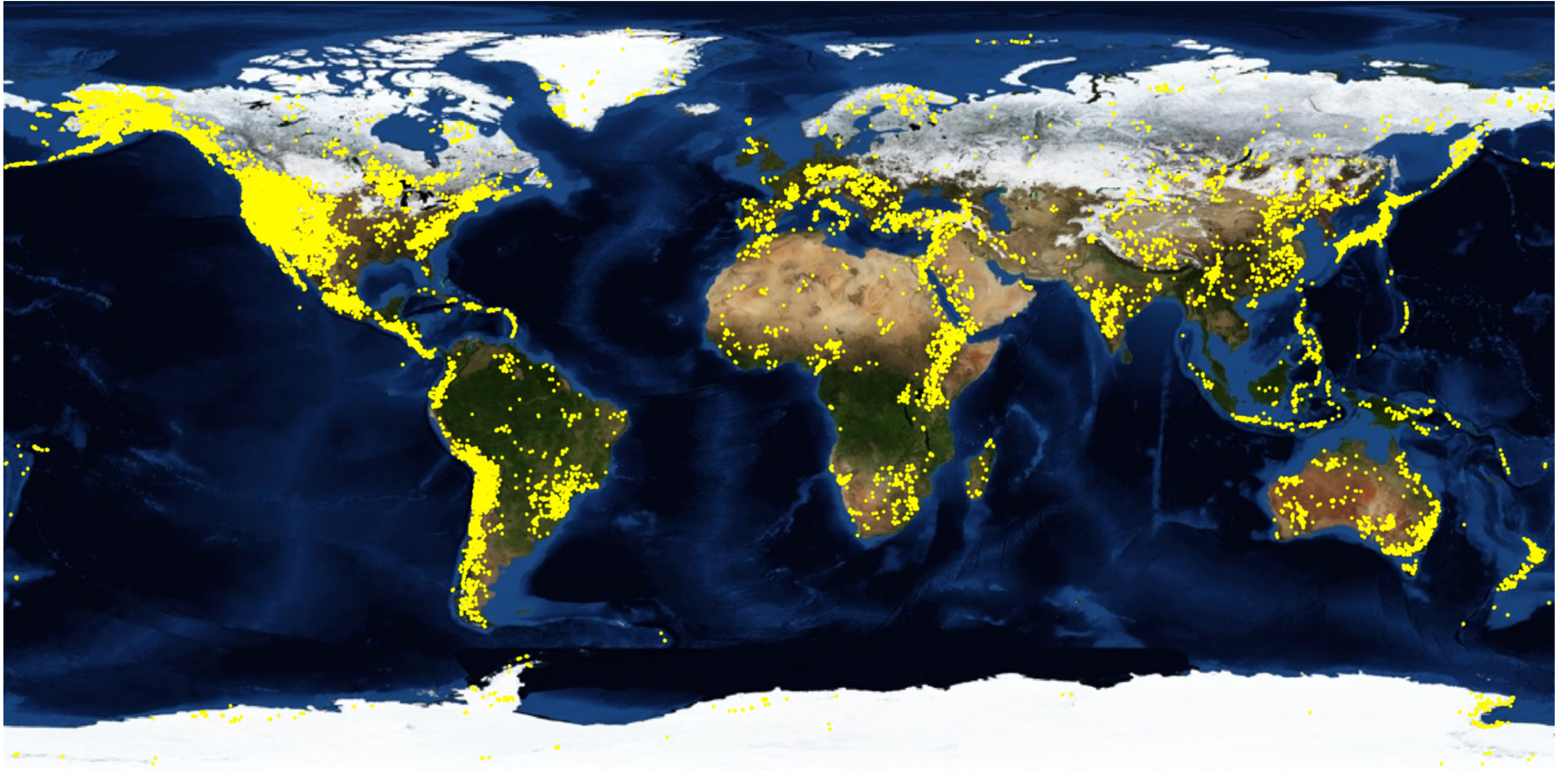
Change over time can resolve process



Average Temporal Trends

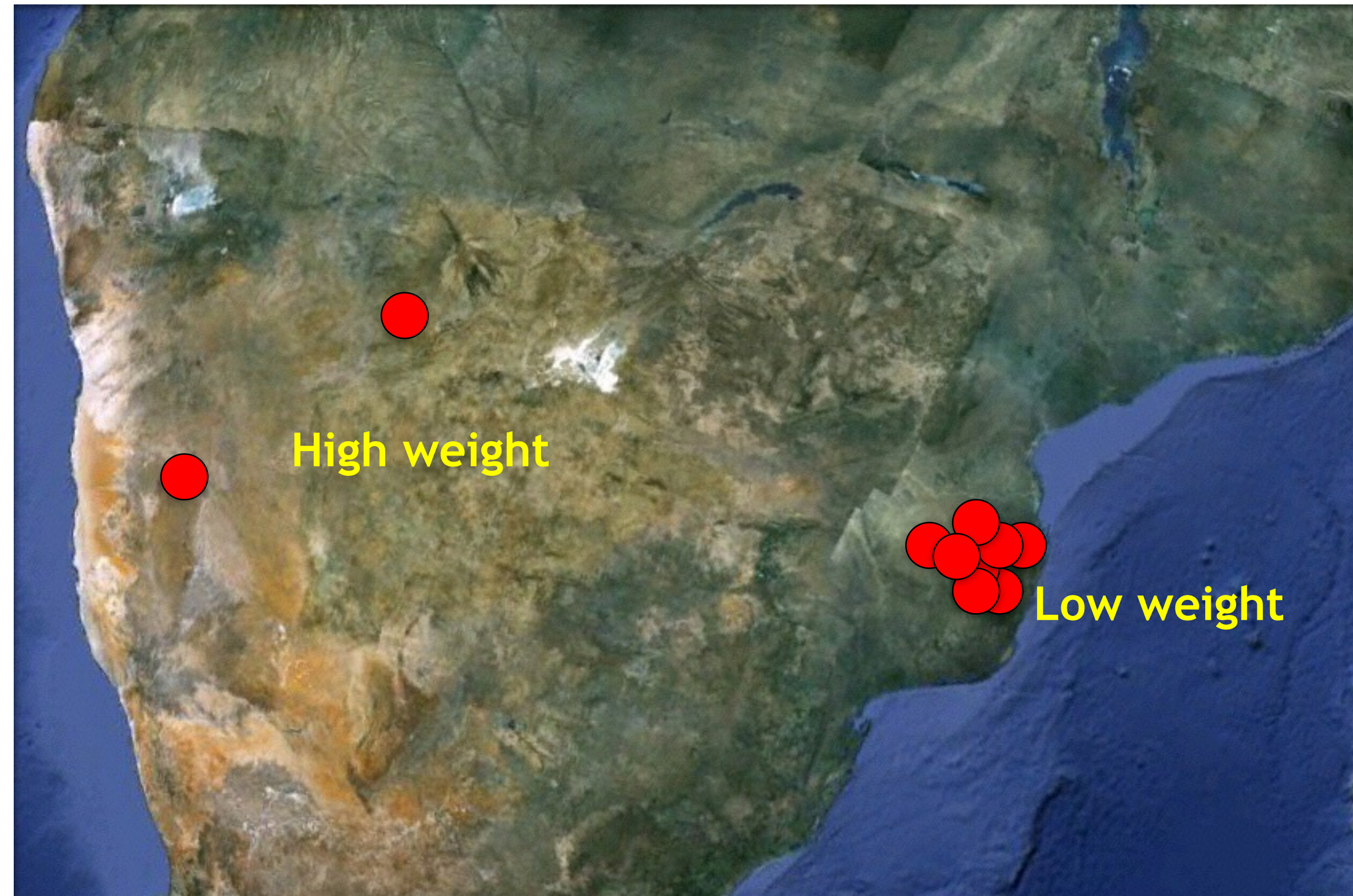


Sample Locations



~66,000 samples via EarthChem, ~2500 via K. Condie, ~1500 via J-F. Moyon

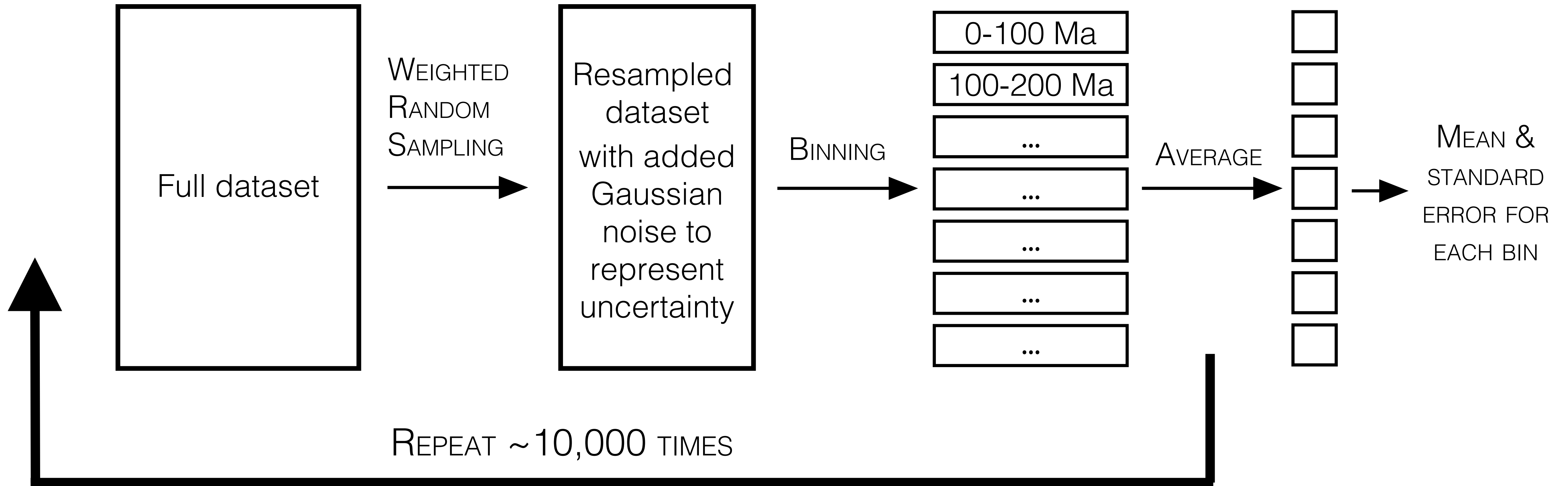
Weighted Bootstrap Resampling Monte Carlo Analysis



$$W_i \propto \frac{1}{\sum_{j=1}^n \left(\frac{1}{\left(\frac{z_i - z_j}{a} \right)^2 + 1} + \frac{1}{\left(\frac{t_i - t_j}{b} \right)^2 + 1} \right)}$$

Minimizing sampling bias by sample weighting

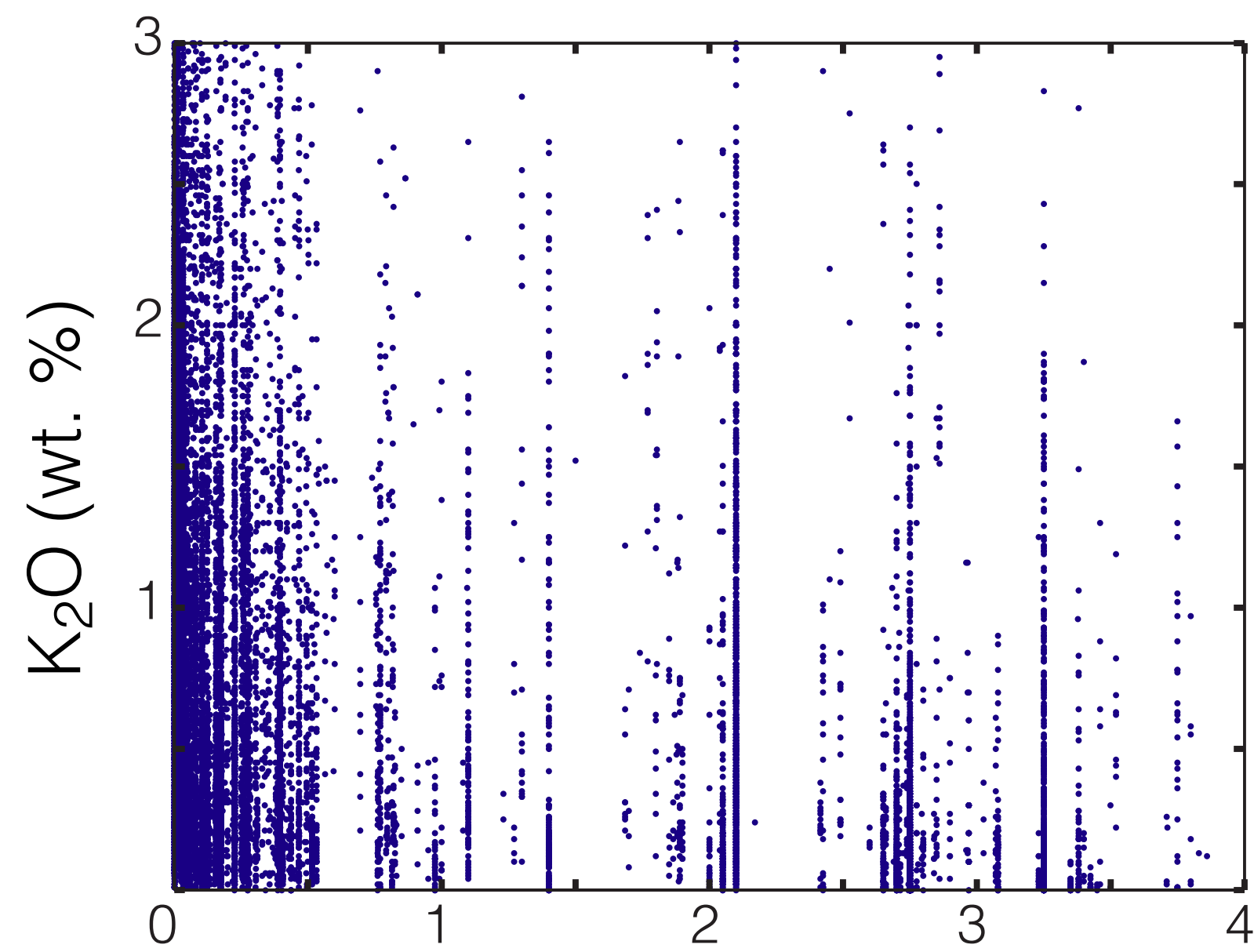
Weighted Bootstrap Resampling



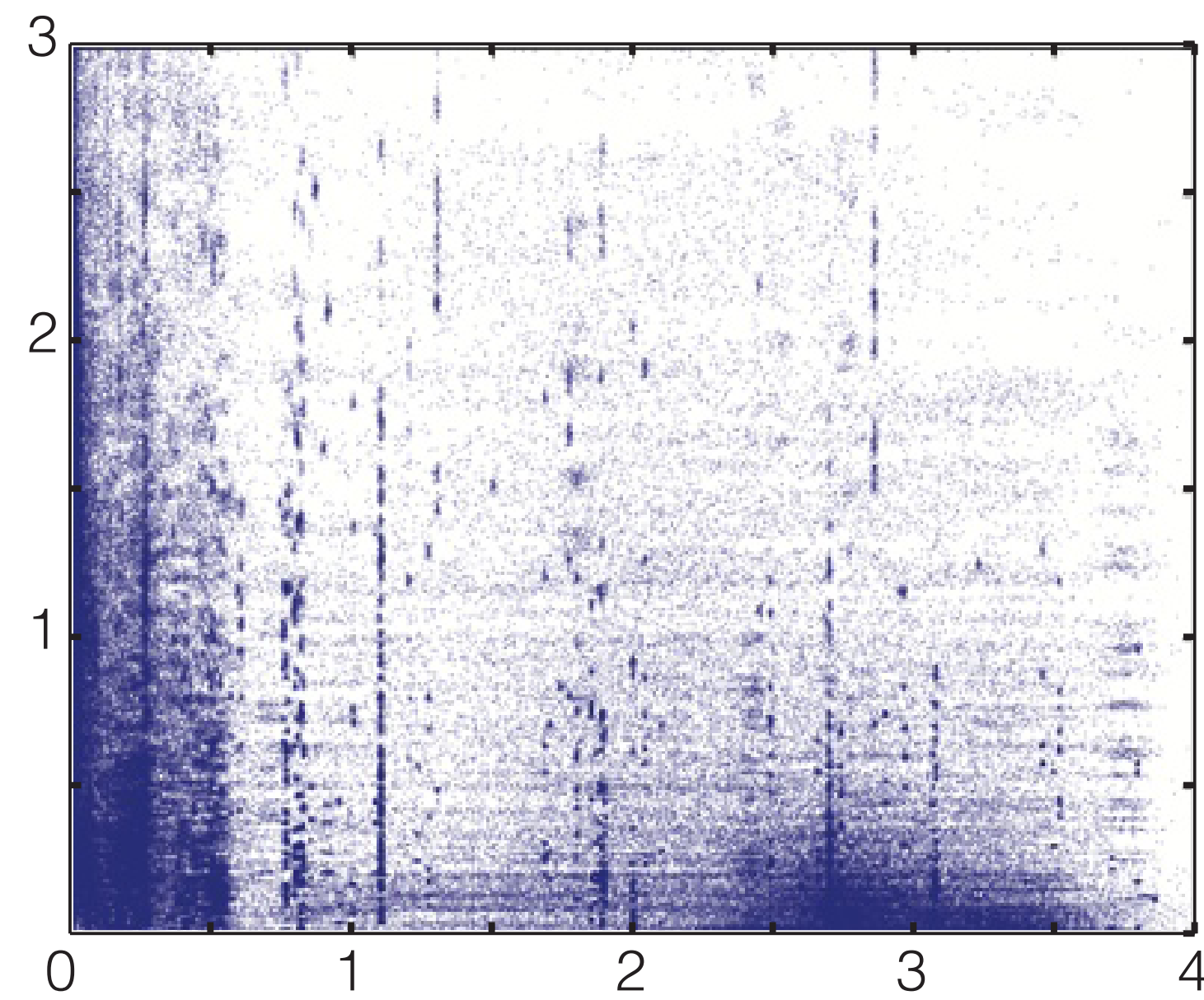
Weighted Bootstrap Resampling Monte Carlo Analysis

Example: basaltic K_2O content

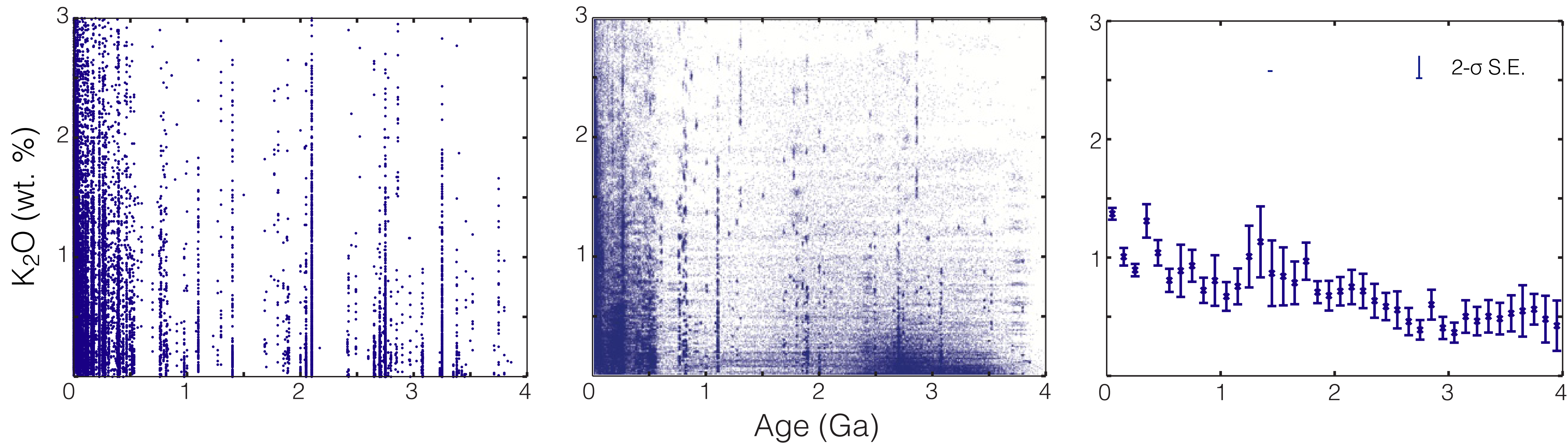
Raw data



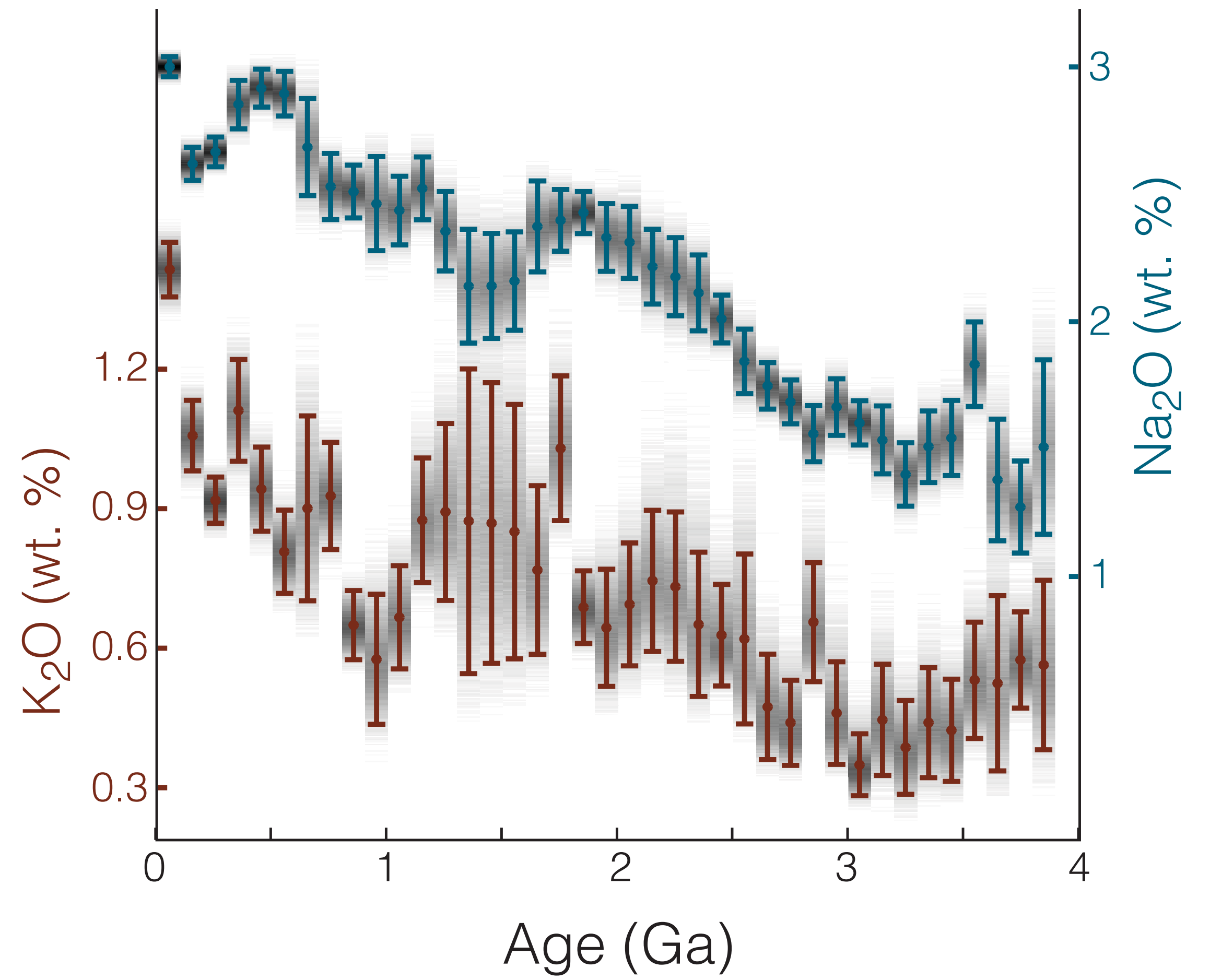
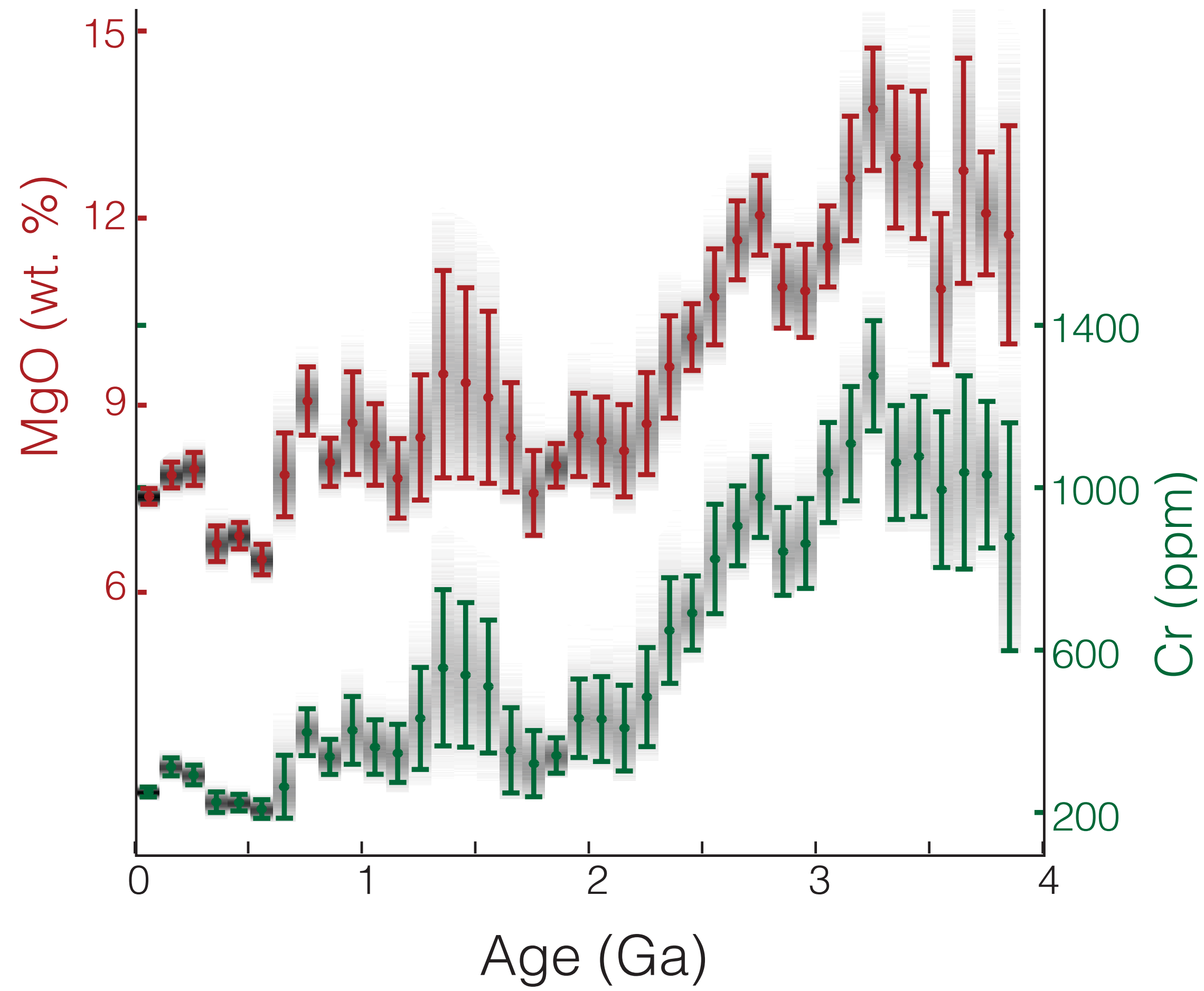
Resampled data



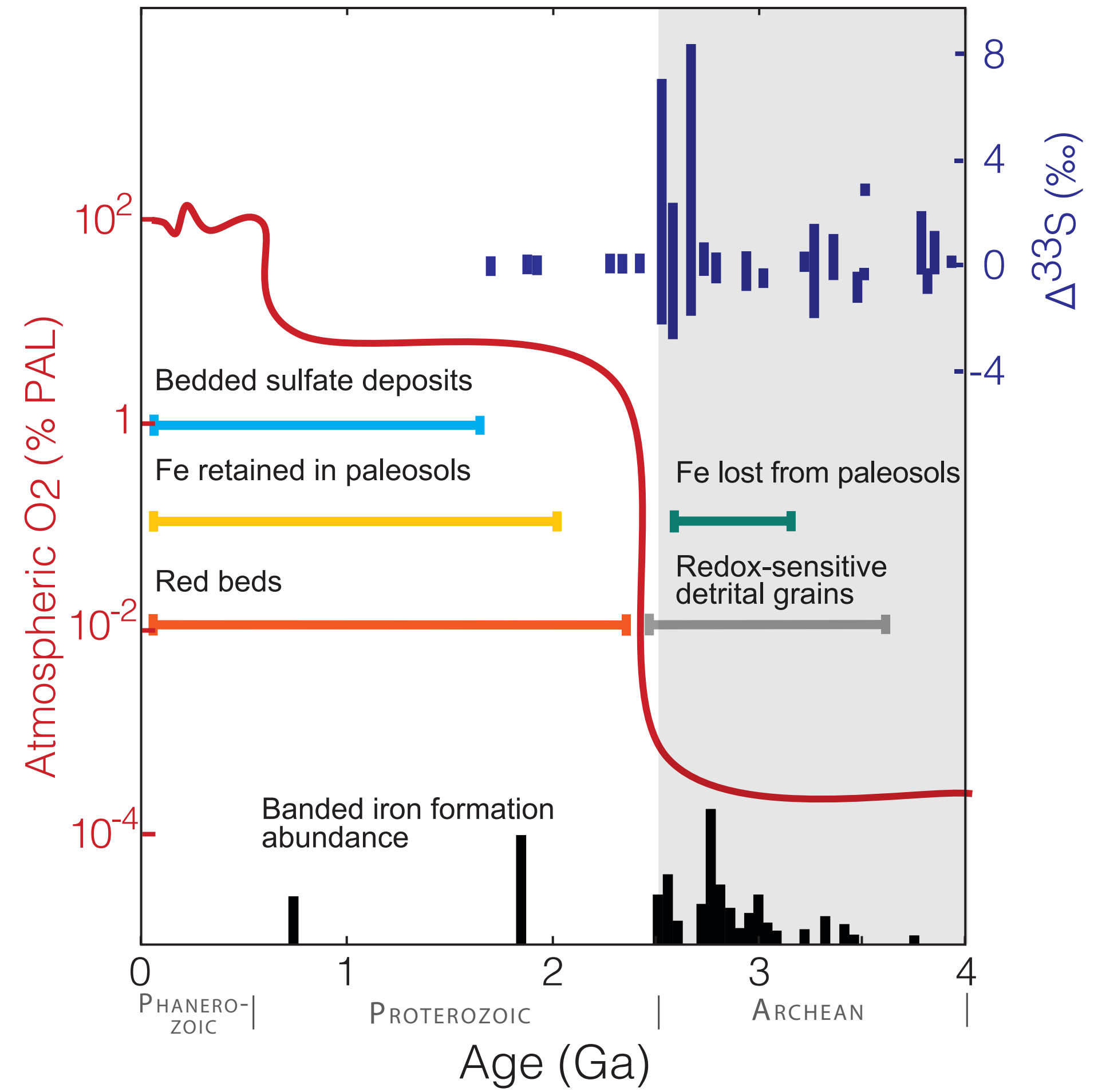
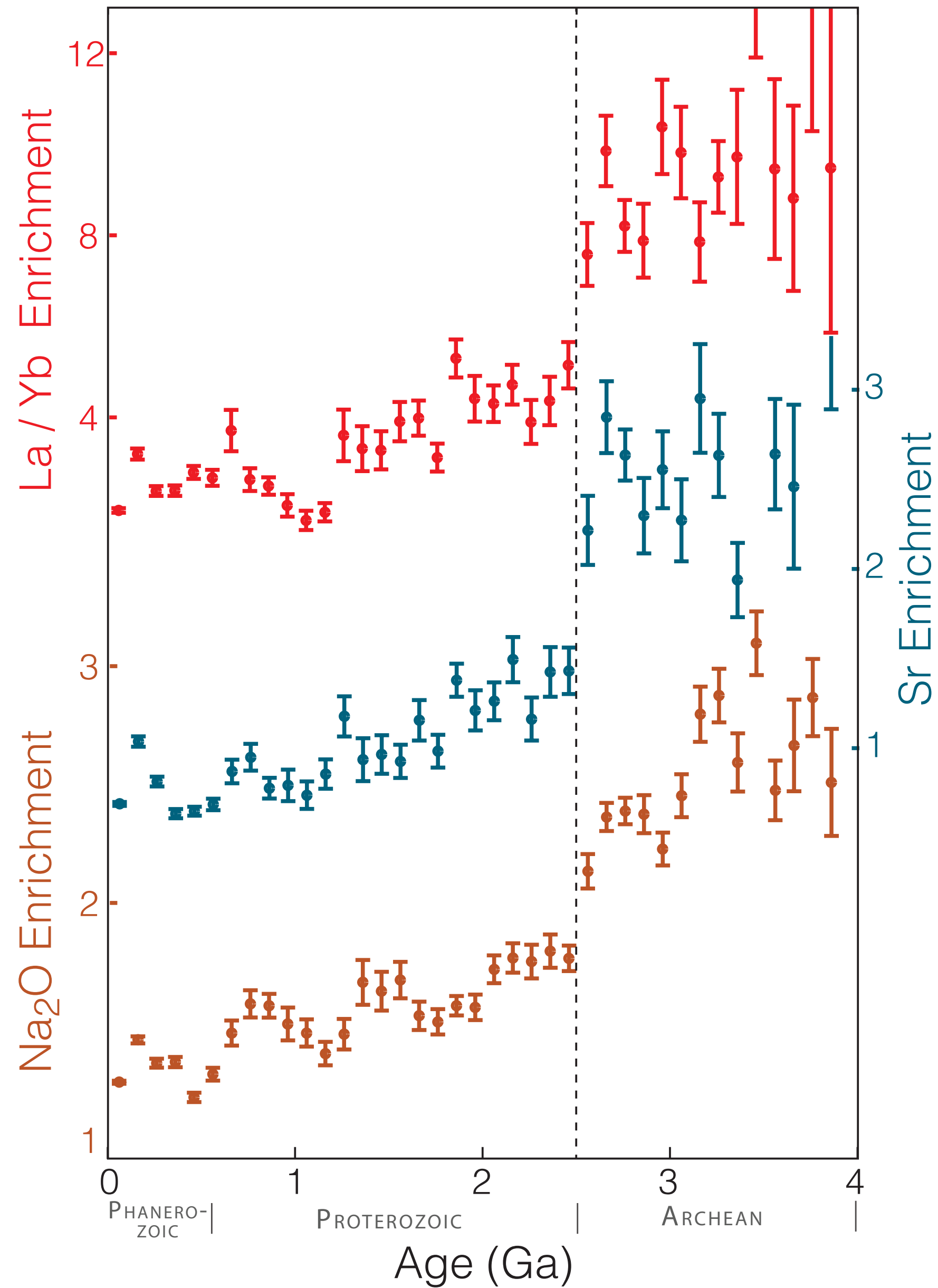
Estimated mean



Temporal trends in basalt geochemistry (43-51% SiO₂)



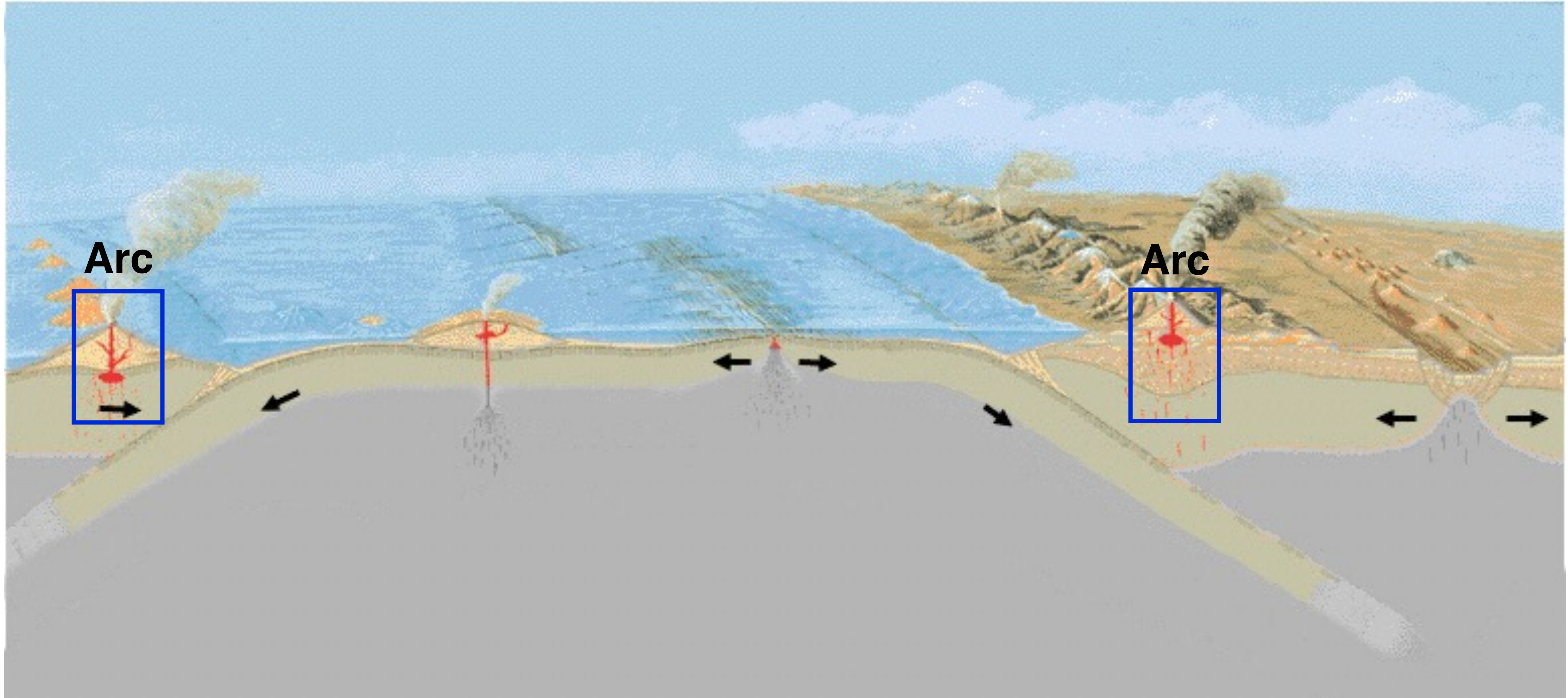
Temporal correlation with Great Oxidation Event



Fundamental question:

- How long has plate tectonics been operating on Earth?

Flux melting



USGS

$H_2O \uparrow$

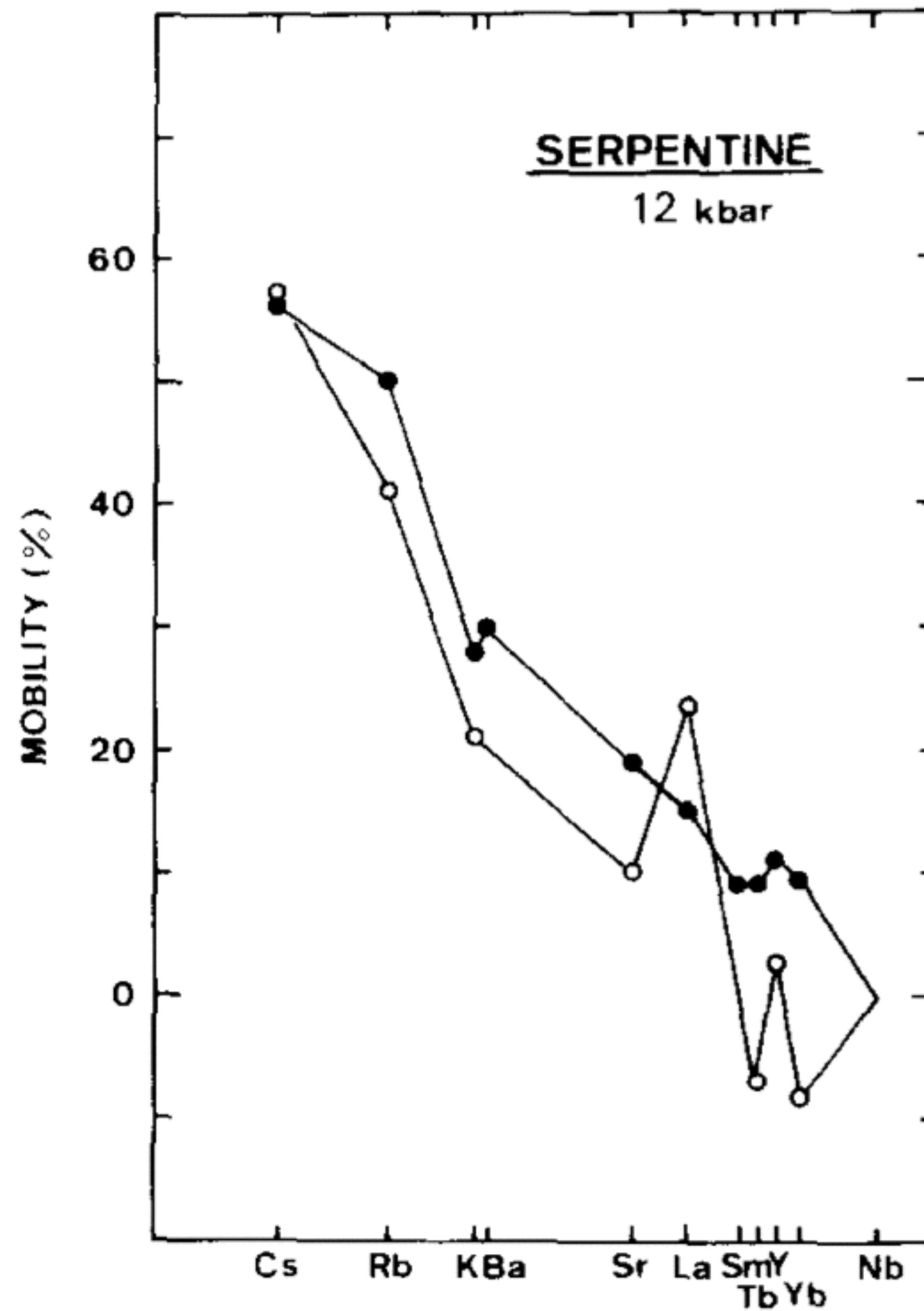
Fluid solubility

1																18	
1 H ⁺ hydrogen											2	13	14	15	16	17	2 He helium
3 Li ⁺ lithium	4 Be ²⁺ beryllium											5 B boron	6 C carbon	7 N ³⁻ nitride	8 O ²⁻ oxide	9 F ⁻ fluoride	10 Ne neon
11 Na ⁺ sodium	12 Mg ²⁺ magnesium											13 Al ³⁺ aluminum	14 Si silicon	15 P ³⁻ phosphide	16 S ²⁻ sulfide	17 Cl ⁻ chloride	18 Ar argon
19 K ⁺ potassium	20 Ca ²⁺ calcium	21 Sc ³⁺ scandium	22 Ti ⁴⁺ titanium	23 V ³⁺ vanadium(III) V ⁵⁺ vanadium(V)	24 Cr ³⁺ chromium(III) Cr ²⁺ chromium(II)	25 Mn ²⁺ manganese(II) Mn ⁴⁺ manganese(IV)	26 Fe ³⁺ iron(III) Fe ²⁺ iron(II)	27 Co ²⁺ cobalt(II) Co ³⁺ cobalt(III)	28 Ni ²⁺ nickel(II) Ni ³⁺ nickel(III)	29 Cu ²⁺ copper(II) Cu ⁺ copper(I)	30 Zn ²⁺ zinc	31 Ga ³⁺ gallium	32 Ge ⁴⁺ germanium	33 As ³⁻ arsenide	34 Se ²⁻ selenide	35 Br ⁻ bromide	36 Kr krypton
37 Rb ⁺ rubidium	38 Sr ²⁺ strontium	39 Y ³⁺ yttrium	40 Zr ⁴⁺ zirconium	41 Nb ⁵⁺ niobium(V) Nb ³⁺ niobium(III)	42 Mo ⁶⁺ molybdenum	43 Tc ⁷⁺ technetium	44 Ru ³⁺ ruthenium(III) Ru ⁴⁺ ruthenium(IV)	45 Rh ³⁺ rhodium	46 Pd ²⁺ palladium(II) Pd ⁴⁺ palladium(IV)	47 Ag ⁺ silver	48 Cd ²⁺ cadmium	49 In ³⁺ indium	50 Sn ⁴⁺ tin(IV) Sn ²⁺ tin(II)	51 Sb ³⁺ antimony(III) Sb ⁵⁺ antimony(V)	52 Te ²⁻ telluride	53 I ⁻ iodide	54 Xe xenon
55 Cs ⁺ cesium	56 Ba ²⁺ barium	57 La ³⁺ lanthanum	72 Hf ⁴⁺ hafnium	73 Ta ⁵⁺ tantalum	74 W ⁶⁺ tungsten	75 Re ⁷⁺ rhenium	76 Os ⁴⁺ osmium	77 Ir ⁴⁺ iridium	78 Pt ⁴⁺ platinum(IV) Pt ²⁺ platinum(II)	79 Au ³⁺ gold(III) Au ⁺ gold(I)	80 Hg ²⁺ mercury(II) Hg ₂ ²⁺ mercury(I)	81 Tl ⁺ thallium(I) Tl ³⁺ thallium(III)	82 Pb ²⁺ lead(II) Pb ⁴⁺ lead(IV)	83 Bi ³⁺ bismuth(III) Bi ⁵⁺ bismuth(V)	84 Po ²⁺ polonium(II) Po ⁴⁺ polonium(IV)	85 At ⁻ astatide	86 Rn radon
87 Fr ⁺ francium	88 Ra ²⁺ radium	89 Ac ³⁺ actinium															
			58 Ce ⁴⁺ cerium(IV) Ce ³⁺ cerium(III)	59 Pr ³⁺ praseodymium	60 Nd ³⁺ neodymium	61 Pm ³⁺ promethium	62 Sm ³⁺ samarium	63 Eu ³⁺ europium(III) Eu ²⁺ europium(II)	64 Gd ³⁺ gadolinium	65 Tb ³⁺ terbium	66 Dy ³⁺ dysprosium	67 Ho ³⁺ holmium	68 Er ³⁺ erbium	69 Tm ³⁺ thulium	70 Yb ³⁺ ytterbium	71 Lu ³⁺ lutetium	
			90 Th ⁴⁺ thorium	91 Pa ⁵⁺ protactinium(V) Pa ⁴⁺ protactinium(IV)	92 U ⁶⁺ uranium(VI) U ⁴⁺ uranium(IV)	93 Np ⁵⁺ neptunium	94 Pu ⁴⁺ plutonium(IV) Pu ⁶⁺ plutonium(VI)	95 Am ³⁺ americium(III) Am ⁴⁺ americium(IV)	96 Cm ³⁺ curium	97 Bk ³⁺ berkelium(III) Bk ⁴⁺ berkelium(IV)	98 Cf ³⁺ californium	99 Es ³⁺ einsteinium	100 Fm ³⁺ fermium	101 Md ²⁺ mendelevium(II) Md ³⁺ mendelevium(III)	102 No ²⁺ nobelium(II) No ³⁺ nobelium(III)	103 Lr ³⁺ lawrencium	

Fluid solubility

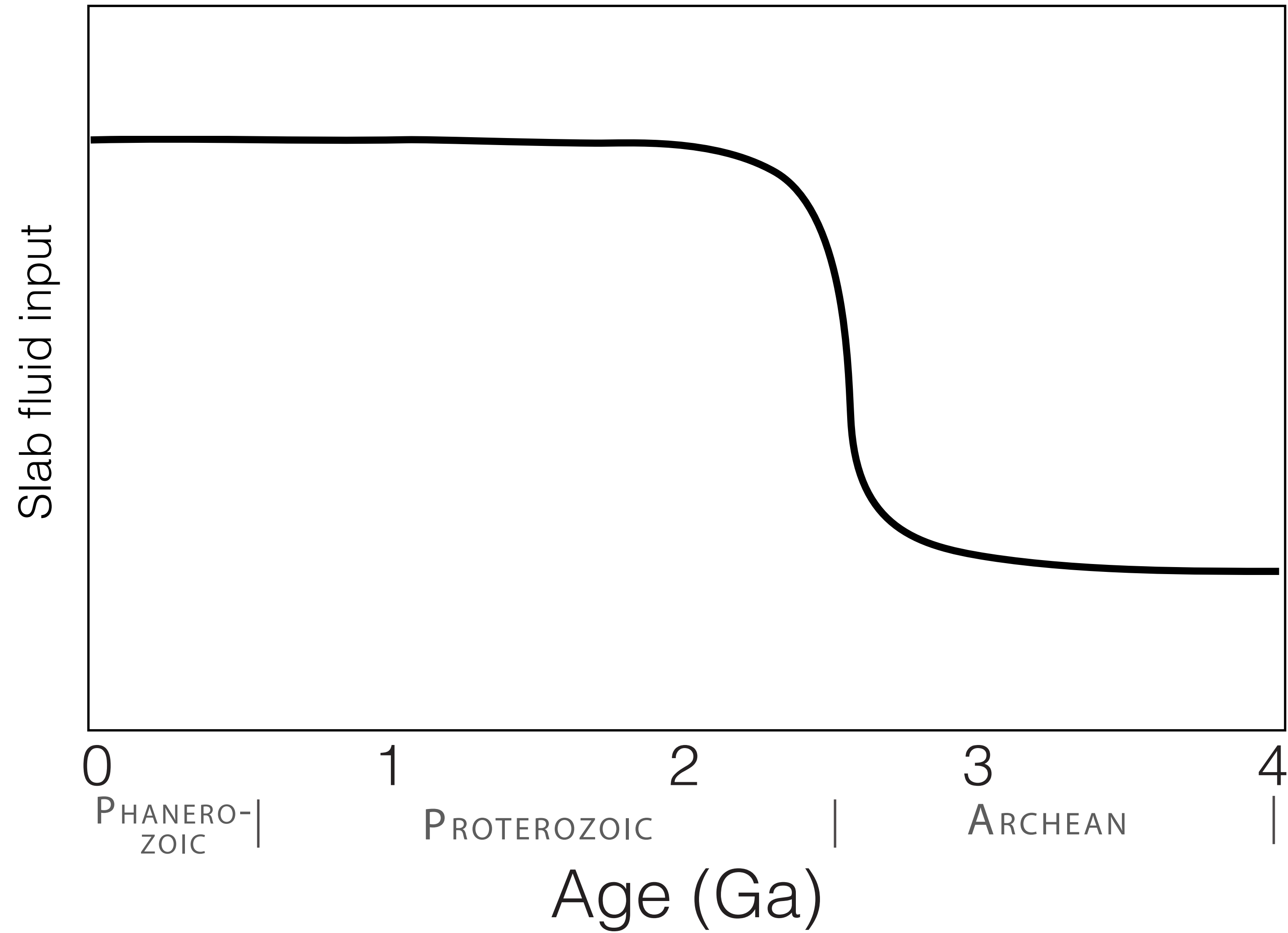
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Element mobility in slab fluids

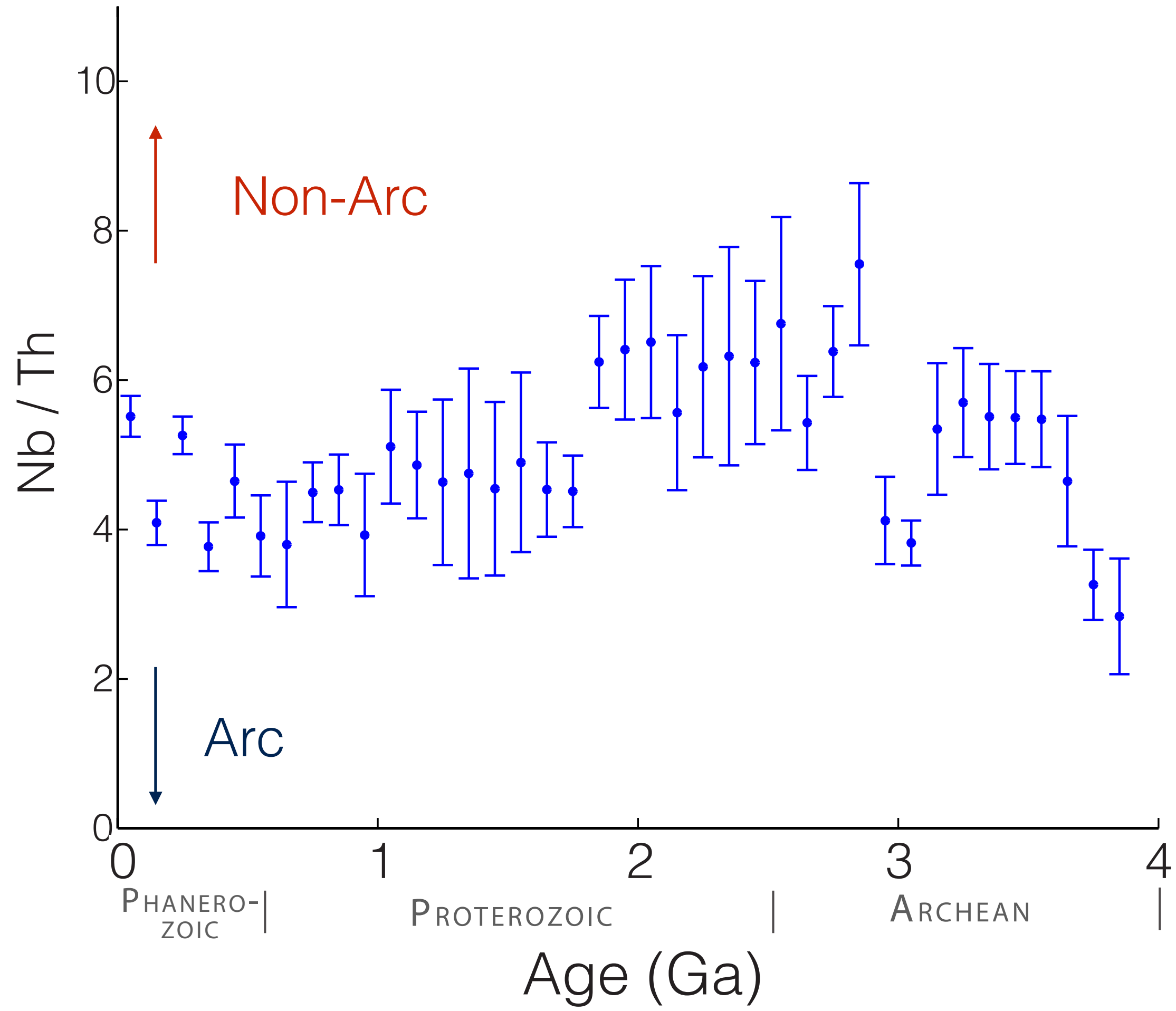


Tatsumi, 1986

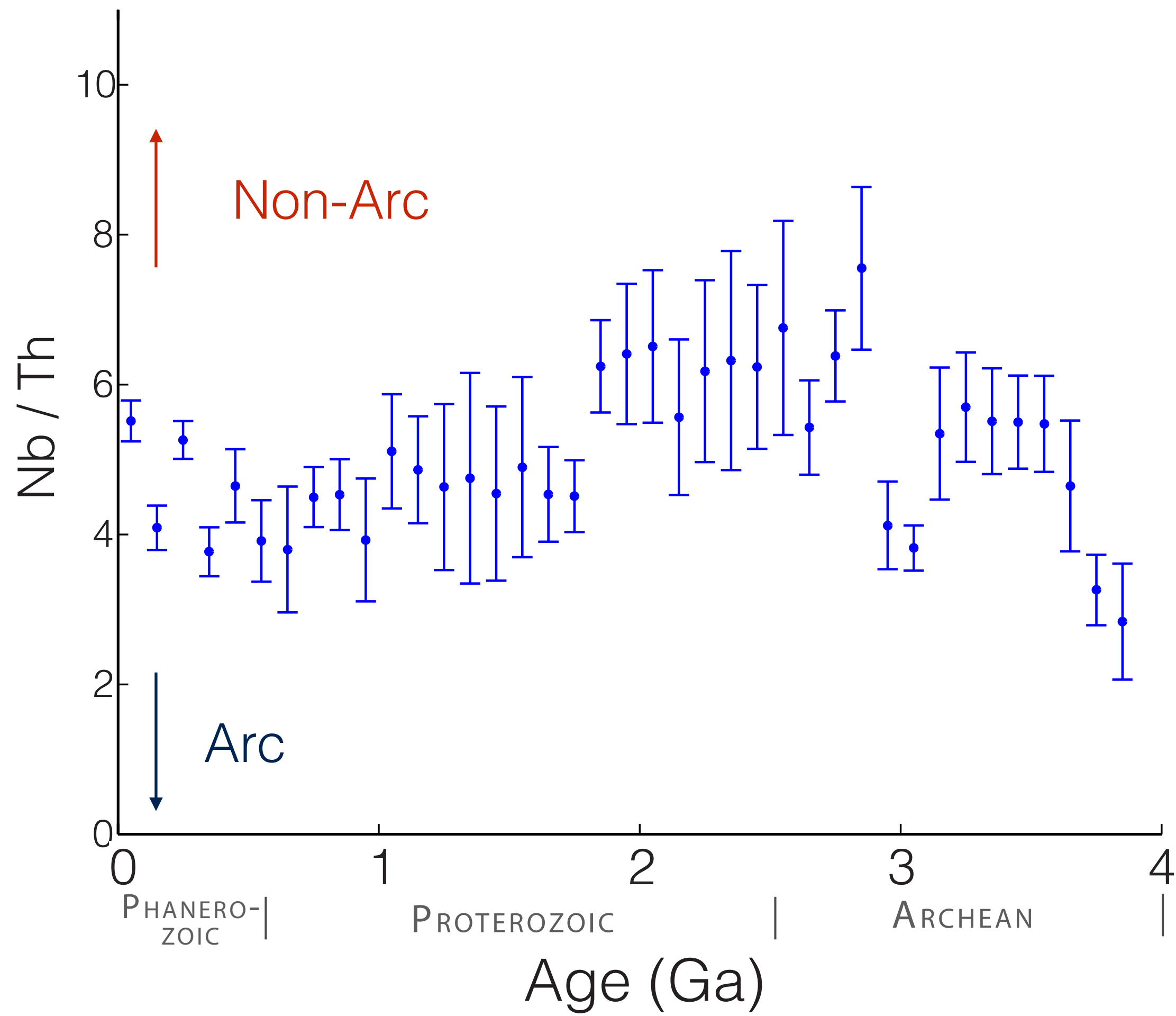
Expectation for subduction initiation at 2.5 Ga



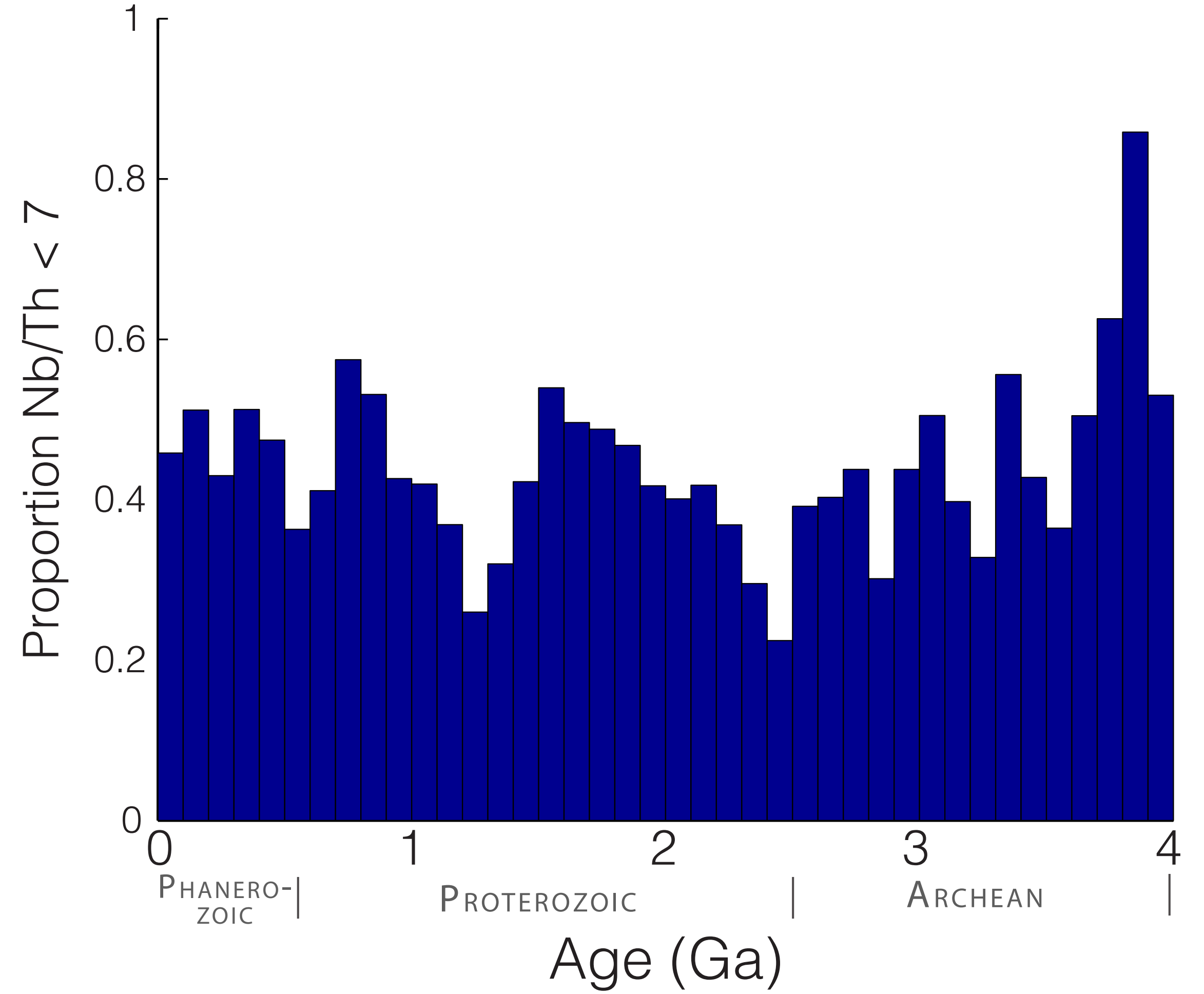
Average basalt Nb/Th



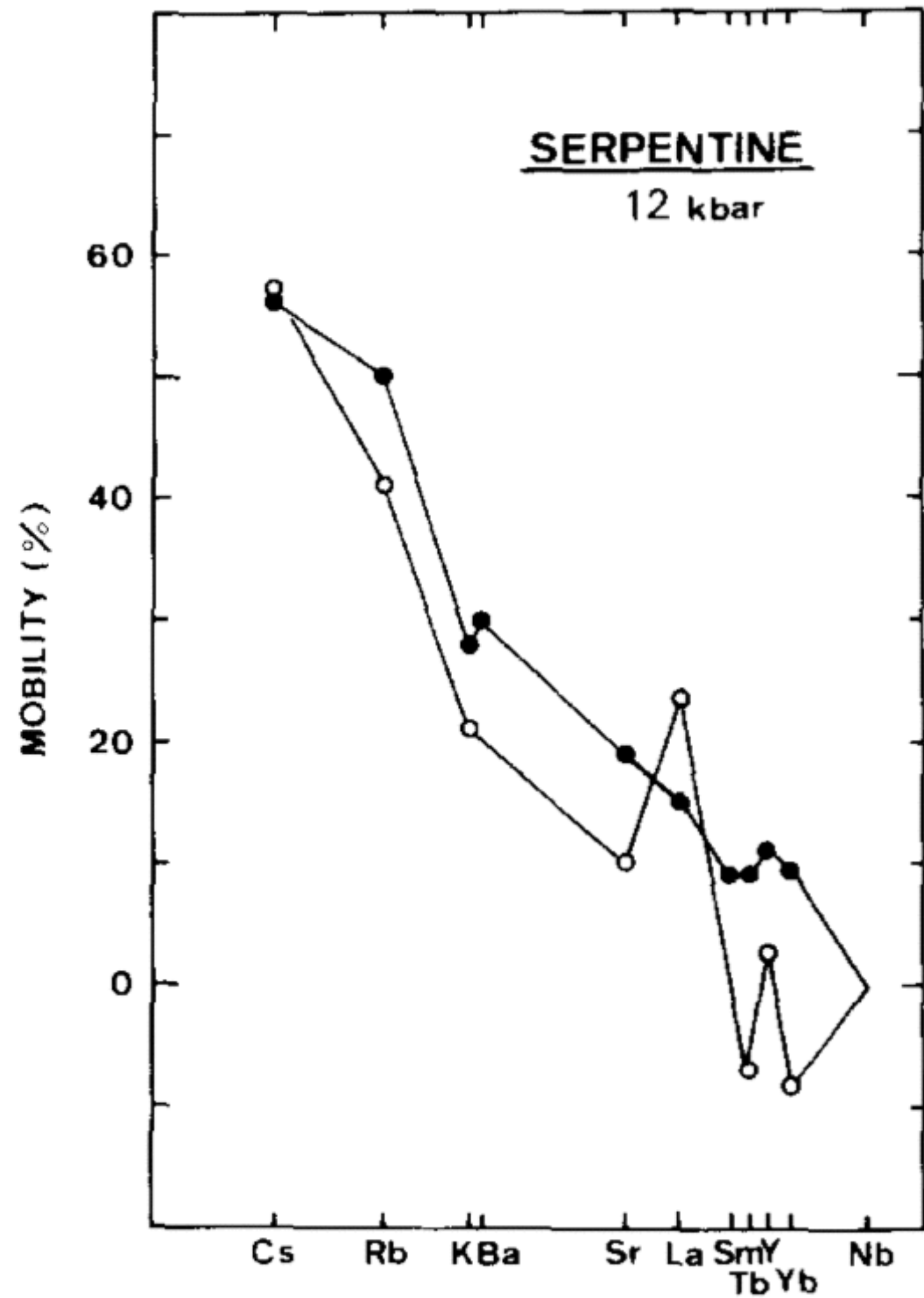
Average basalt Nb/Th



Proportion of samples with Arc-like Nb/Th

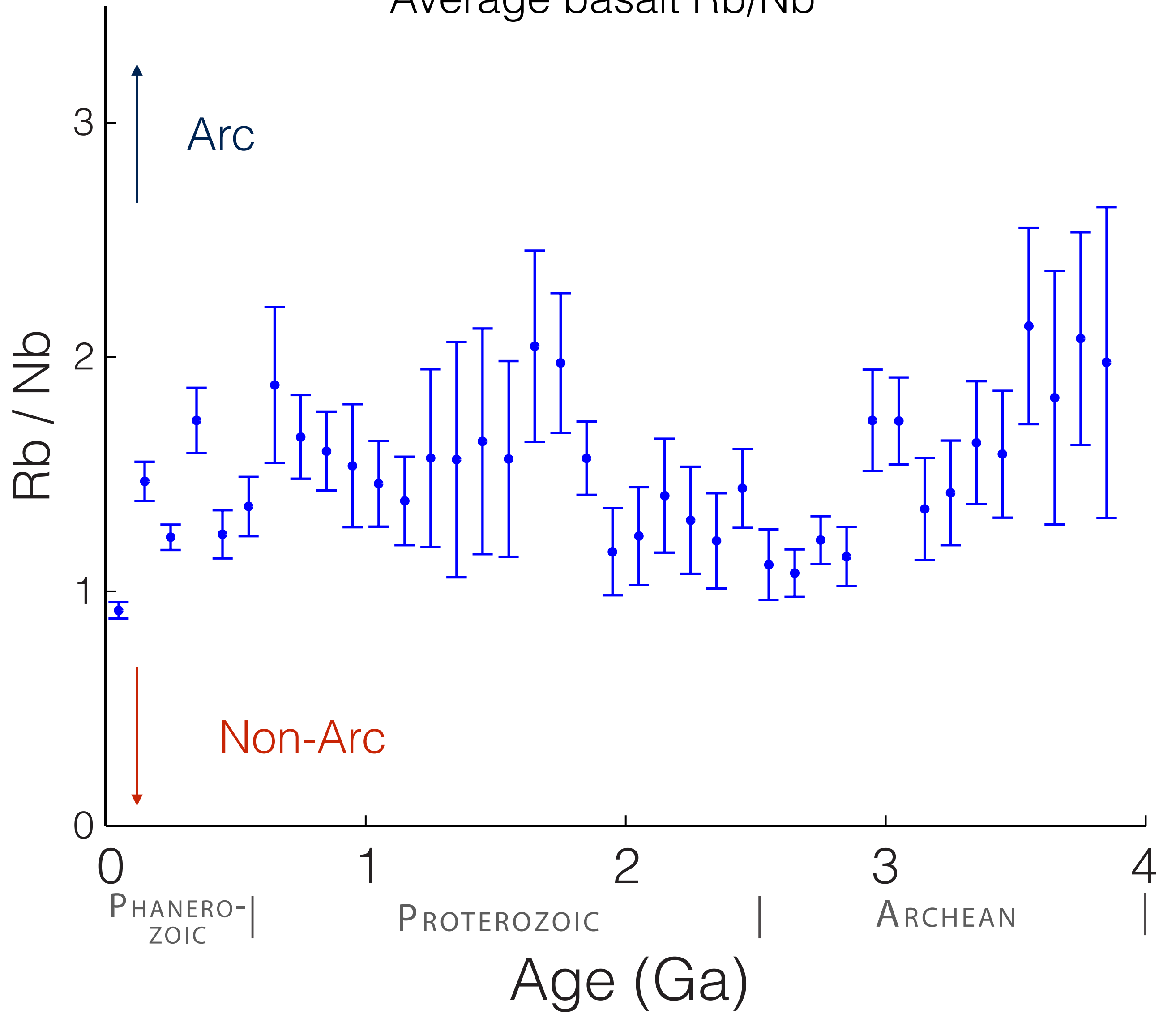


Mobility in slab fluids



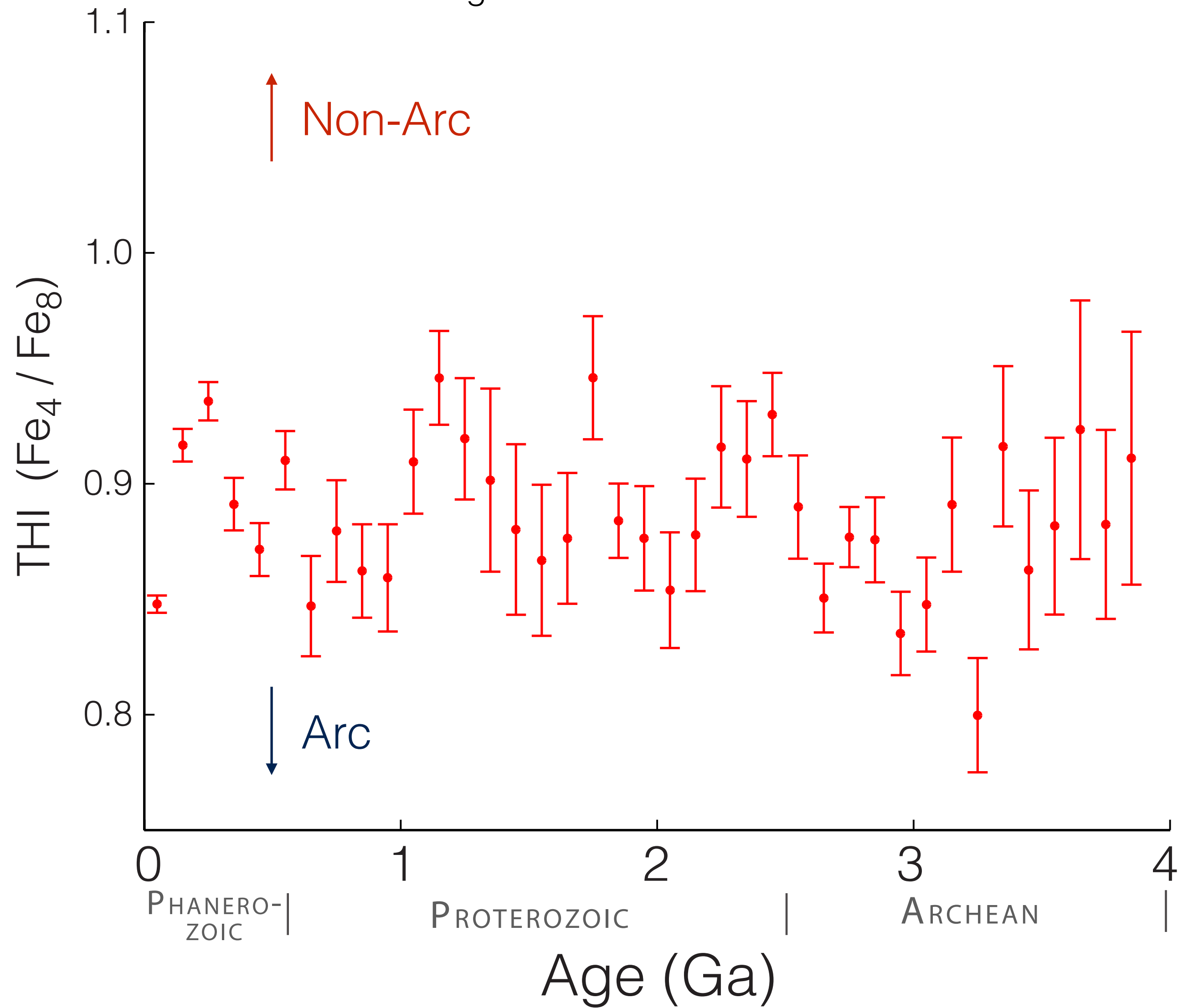
Tatsumi, 1986

Average basalt Rb/Nb



Tholeiitic vs. Calc-Alkaline Differentiation

Average for all continental crust



Conclusions

Fundamental question:

- How long has plate tectonics been operating on Earth?

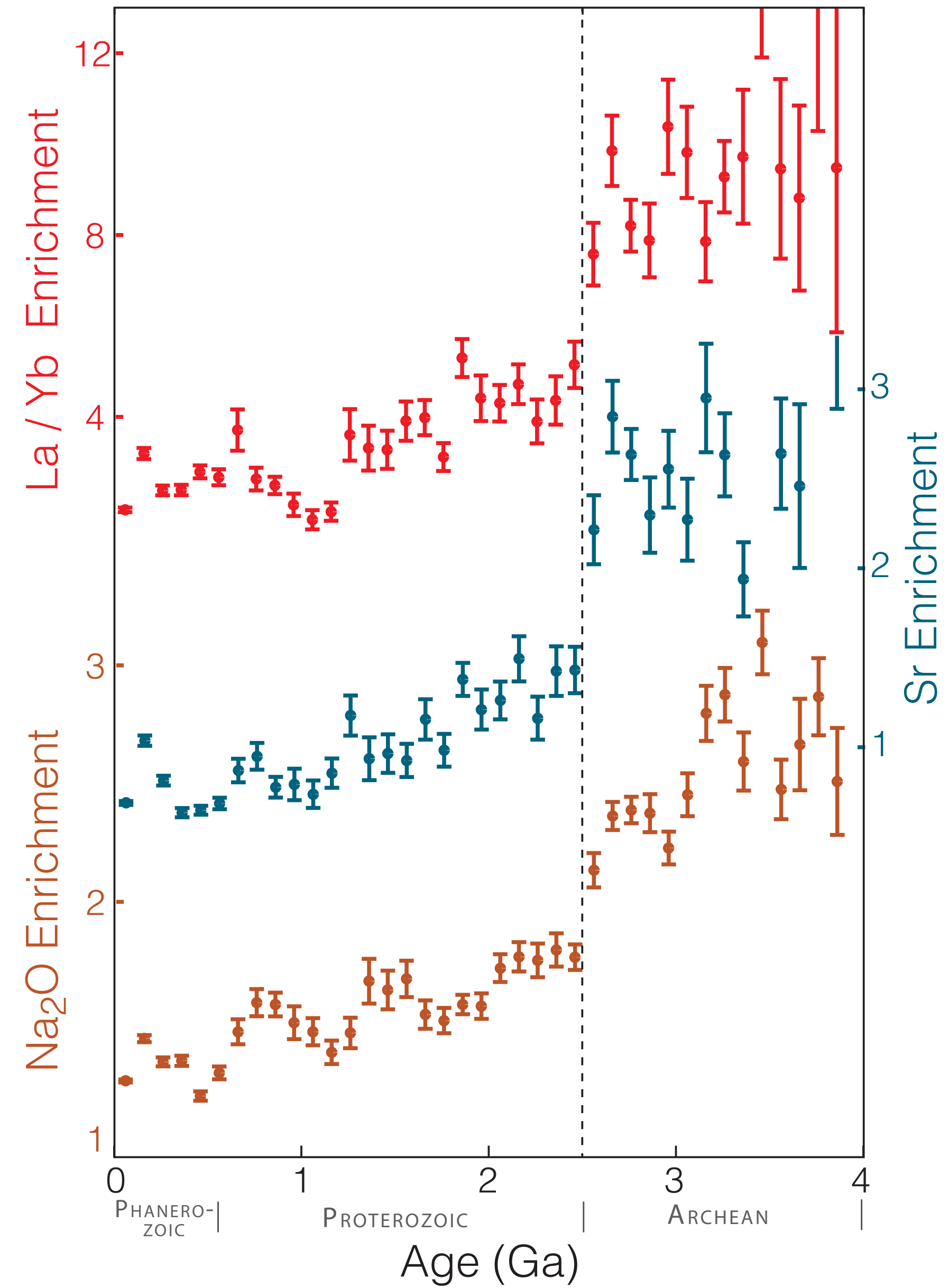
Conclusions

Fundamental question:

- How long has plate tectonics been operating on Earth?

Throughout the entire preserved rock record

Crustal differentiation?



Results from:

- Keller & Schoene (2012) “Statistical geochemistry reveals disruption in secular lithospheric evolution about 2.5 Gyr ago” *Nature* **485**, 490-493
- Keller et al. (2015) “Volcanic–plutonic parity and the differentiation of the continental crust ” *Nature* **523**, 301-307
- Keller & Schoene (*in preparation*) “Geochemical evolution of basalts preserved in the continental crust throughout Earth history”

Acknowledgements

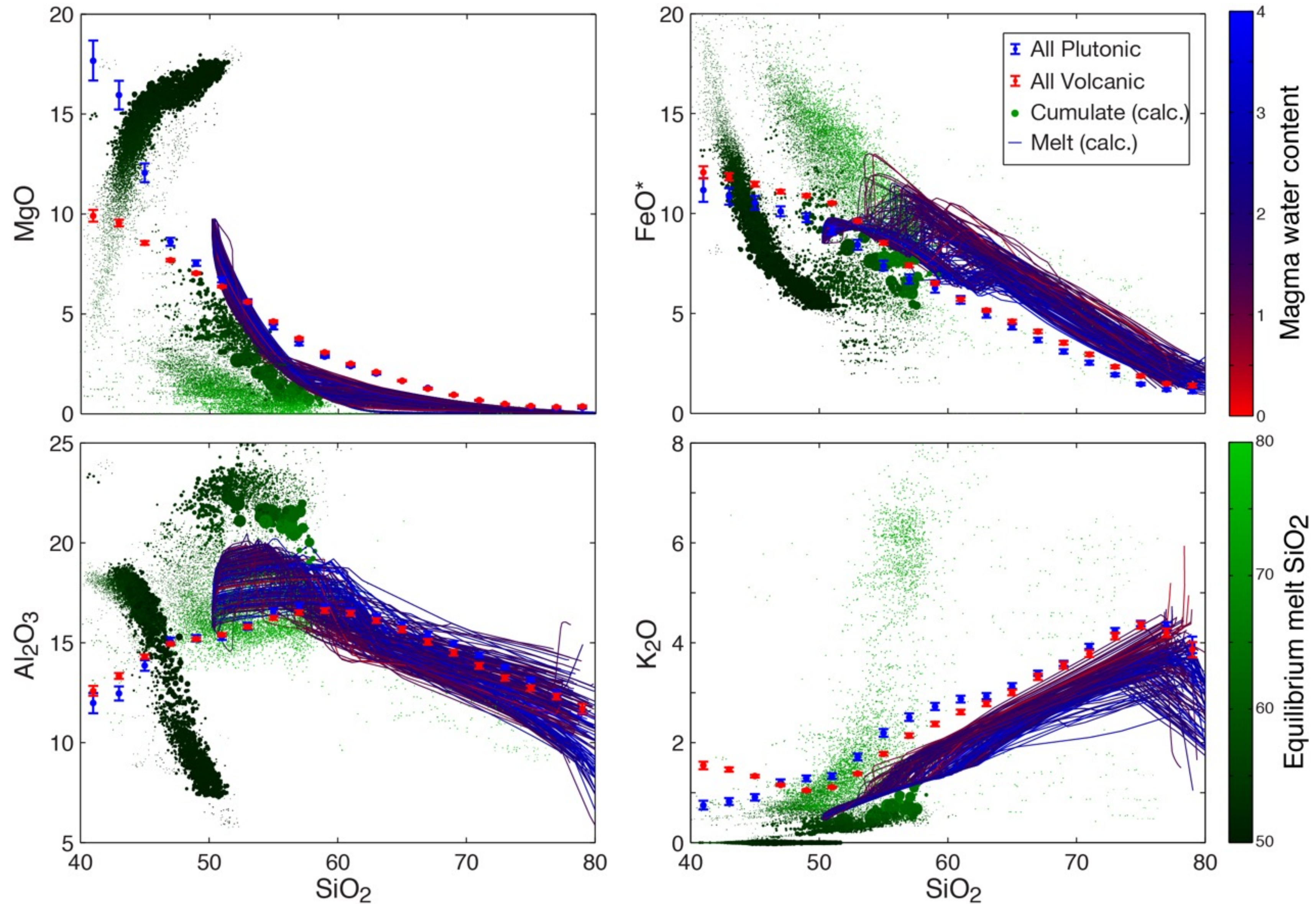


Blair Schoene
Kyle Samperton
Jon Husson

Melanie Barboni
Frederik Simons
Blake Dyer

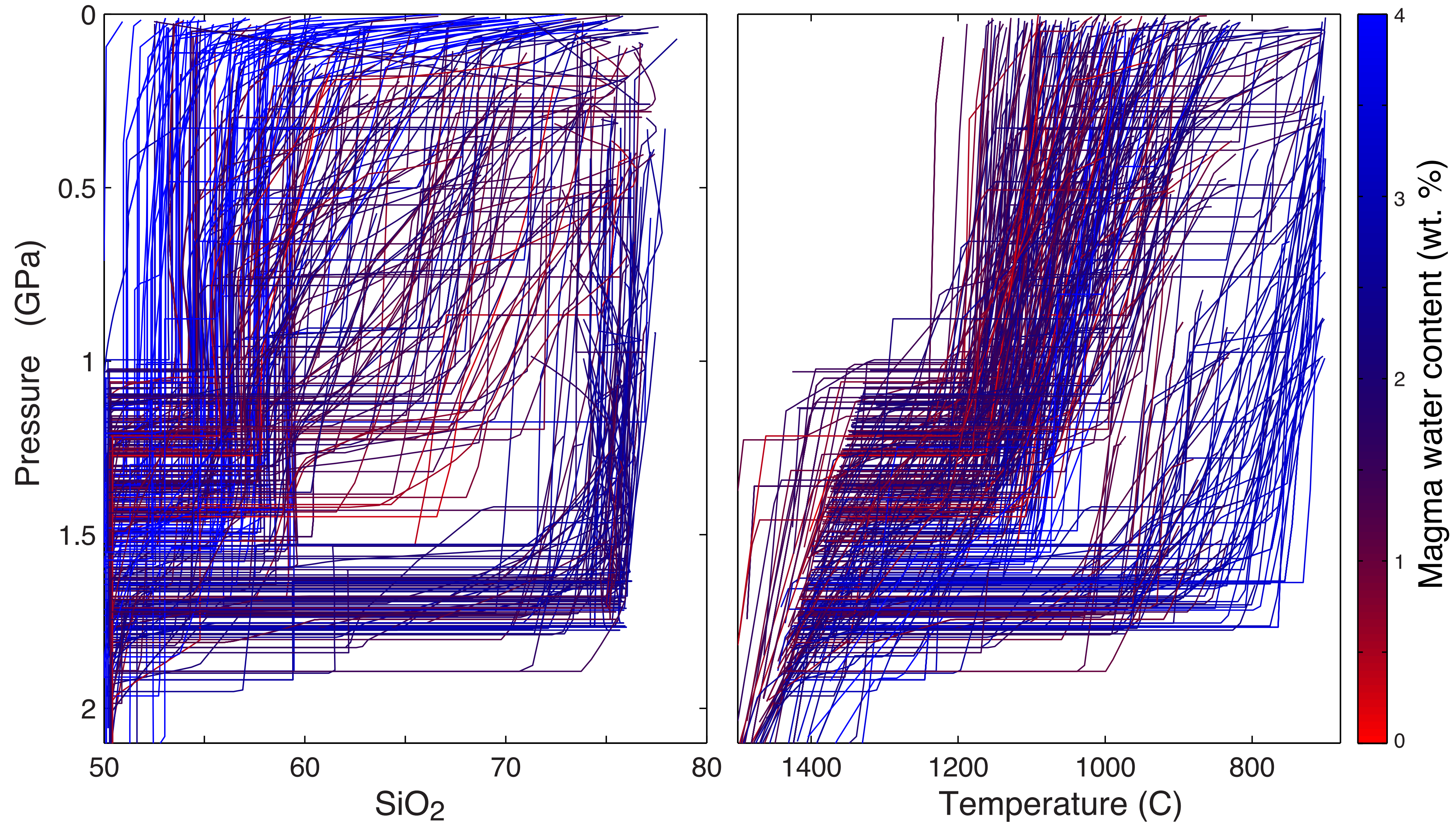
Simulation results

High-silica melts can leave a low-silica cumulate



Simulation results

Differentiation at the base of the crust may help



Temporal correlation with Great Oxidation Event

