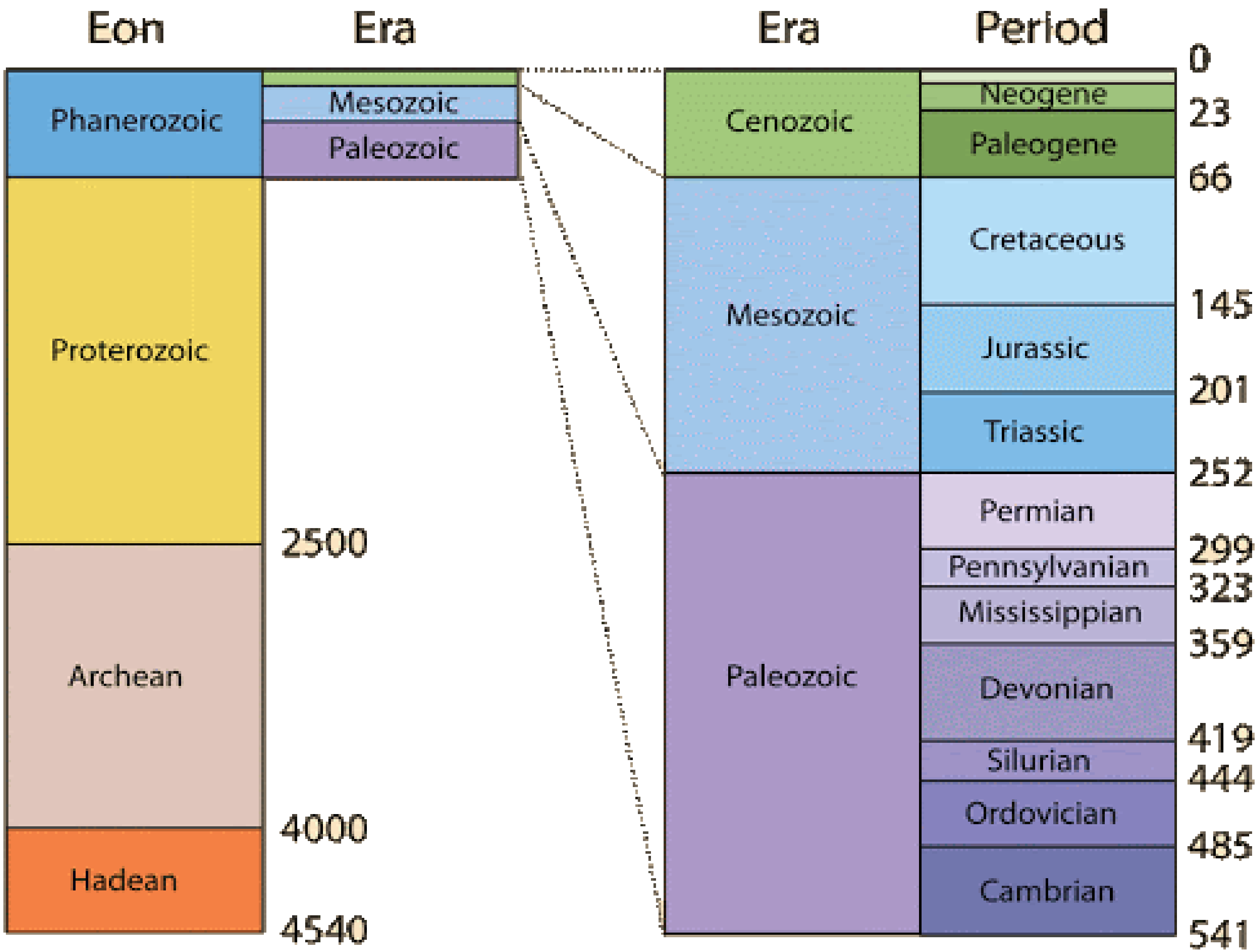
Introduction to early Earth Geoscience

What do we know?
What do we not know?
How do we know?

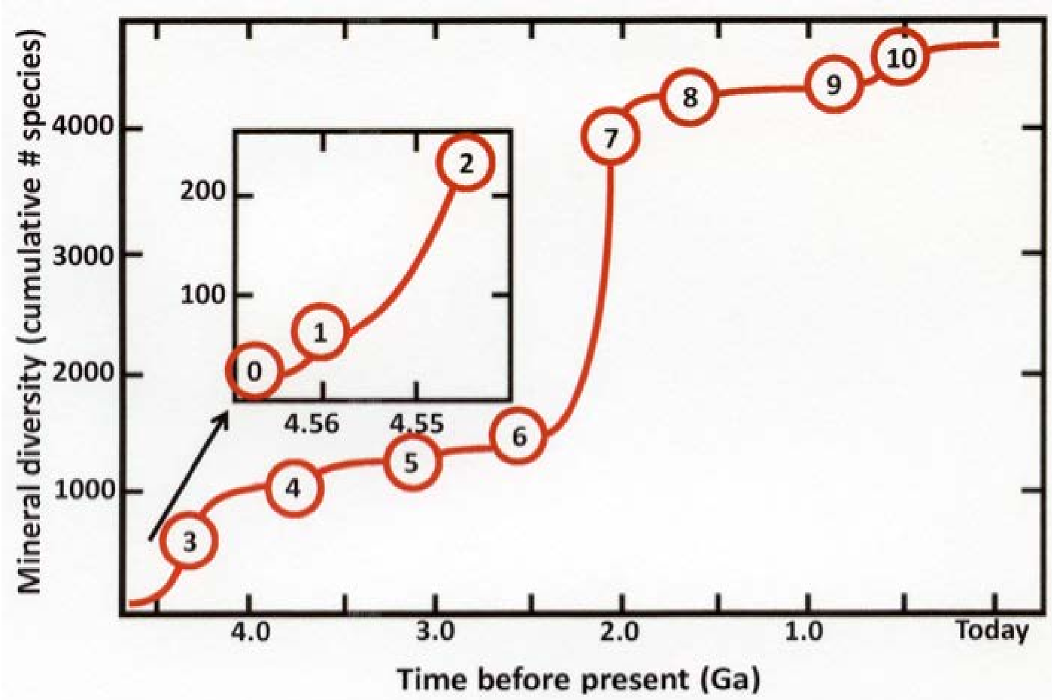
Bettina Scheu, Earth & Environmental Sciences LMU

Geologic time



Geologic time and the geologic column

Minerals – Evolution of Diversity



Stage	Age (Ga)	~Cumulative no. species
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetesimal alteration	>4.56 to 4.55 Ga	250
3. Igneous rock evolution	4.55 to 4.0 Ga	350 to 500*
4. Granite and pegmatite formation	4.0 to 3.5 Ga	1000
5. Plate tectonics	>>3.0 Ga	1500
6. Anoxic biological world	3.9 to 2.5 Ga	1500
7. Great Oxidation Event	2.5 to 1.9 Ga	>4000
8. Intermediate ocean	1.9 to 1.0 Ga	>4000
9. Snowball Earth events	1.0 to 0.542 Ga	>4000
10. Phanerozoic era of biomineralization	0.542 Ga to present	4300+

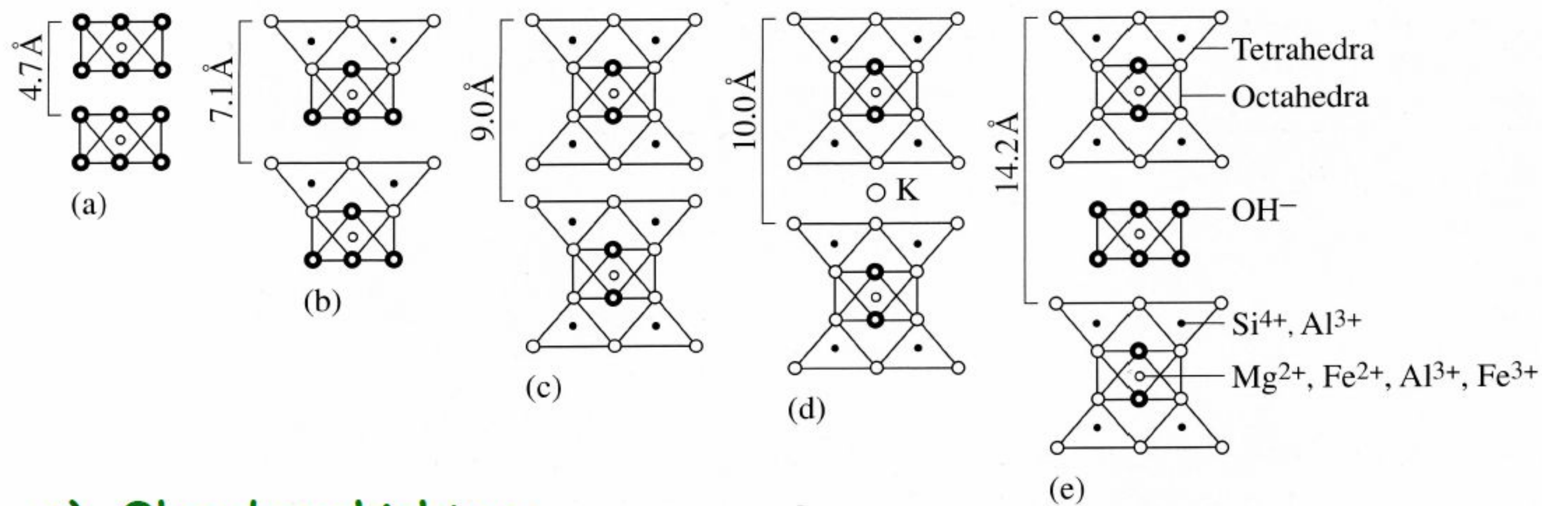
Note: Note that the timings of some of these stages overlap, and several stages continue to the present (after Hazen et al. 2008).

* Depending on the volatile content of the planet or moon.

Source: Hazen at al. (2008)

Schichtsilikate (sheet silica)

Einteilung: Oktaeder-/Tetraederschichten



a) Okaederschichten:
Brucitschicht $Mg(OH)_2$ bzw. Gibbsitschicht $Al(OH)_3$

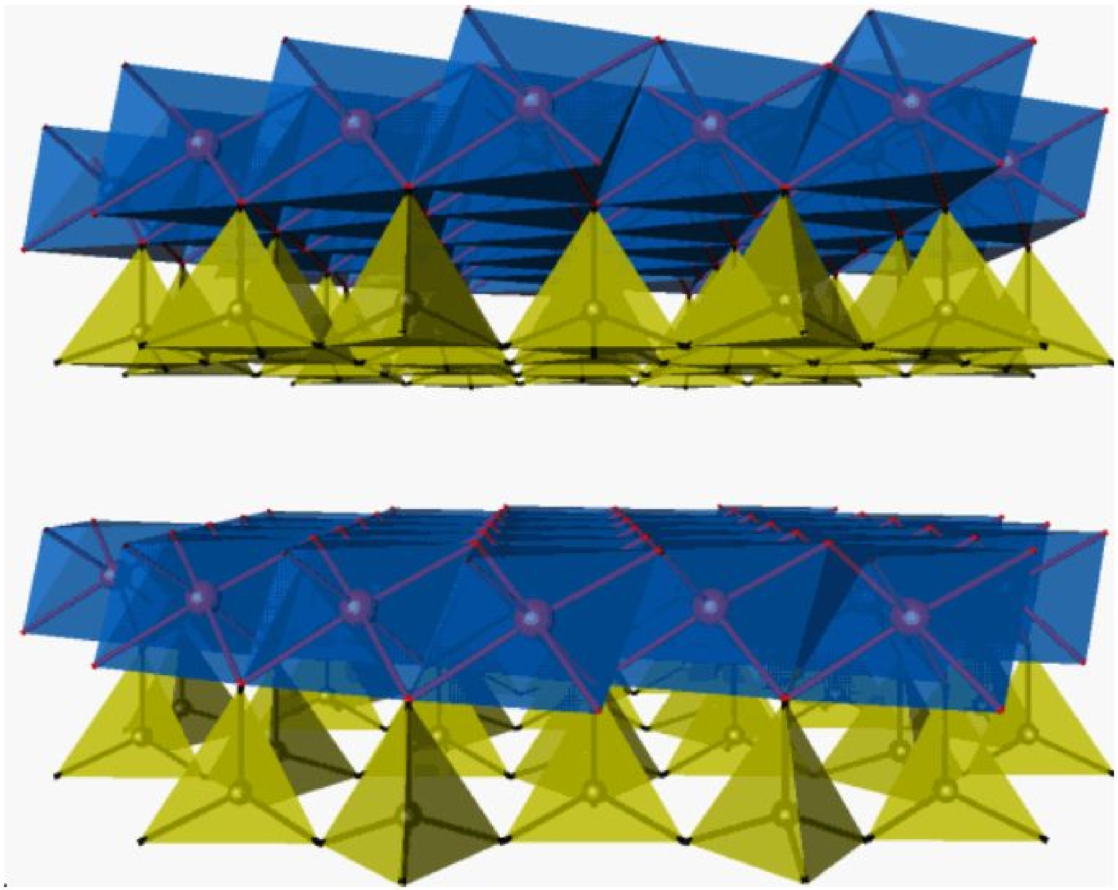
b) Zweischichtsilikat, z.B. Serpentin $Mg_3[Si_2O_5(OH)_4]$

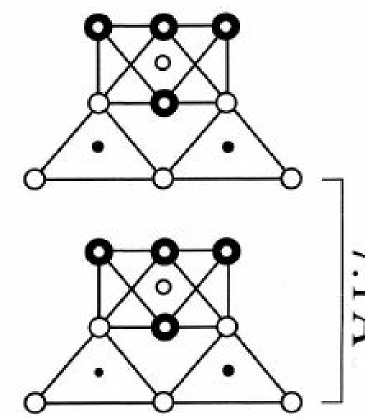
c) Dreischichtsilikat, z.B. Talk $Mg_3[Si_4O_{10}(OH)_2]$

d) Glimmer (große Kationen zwischen den Schichten)

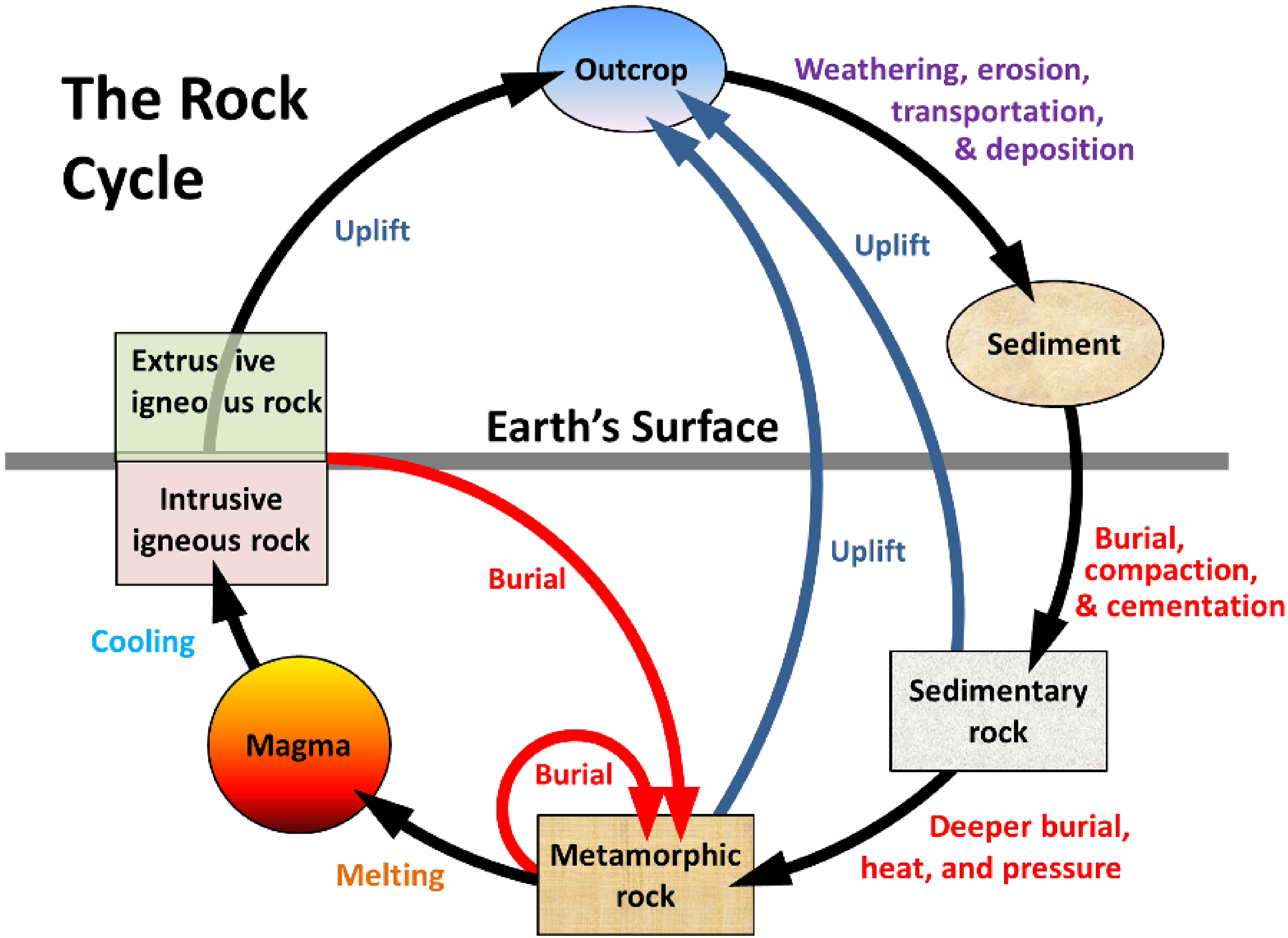
e) Chlorit (Vierschichtsilikat aus Talk-ähnlicher Schicht (TOT) und Brucit-ähnlicher Zwischenschicht)

Serpentin $Mg_3[Si_2O_5(OH)_4]$





2-Schicht-Silikat



The Rock Cycle
Outcrop
Weathering, erosion, transportation, & deposition
Uplift
Uplift
Sediment
Extrusive igneous rock
Earth's Surface
Intrusive igneous rock
Burial
Uplift
Burial, compaction, & cementation
Cooling
Sedimentary rock
Magma
Burial
Deeper burial, heat, and pressure
Metamorphic rock
Melting

Chemical classification of igneous rocks (TAS-Diagram)

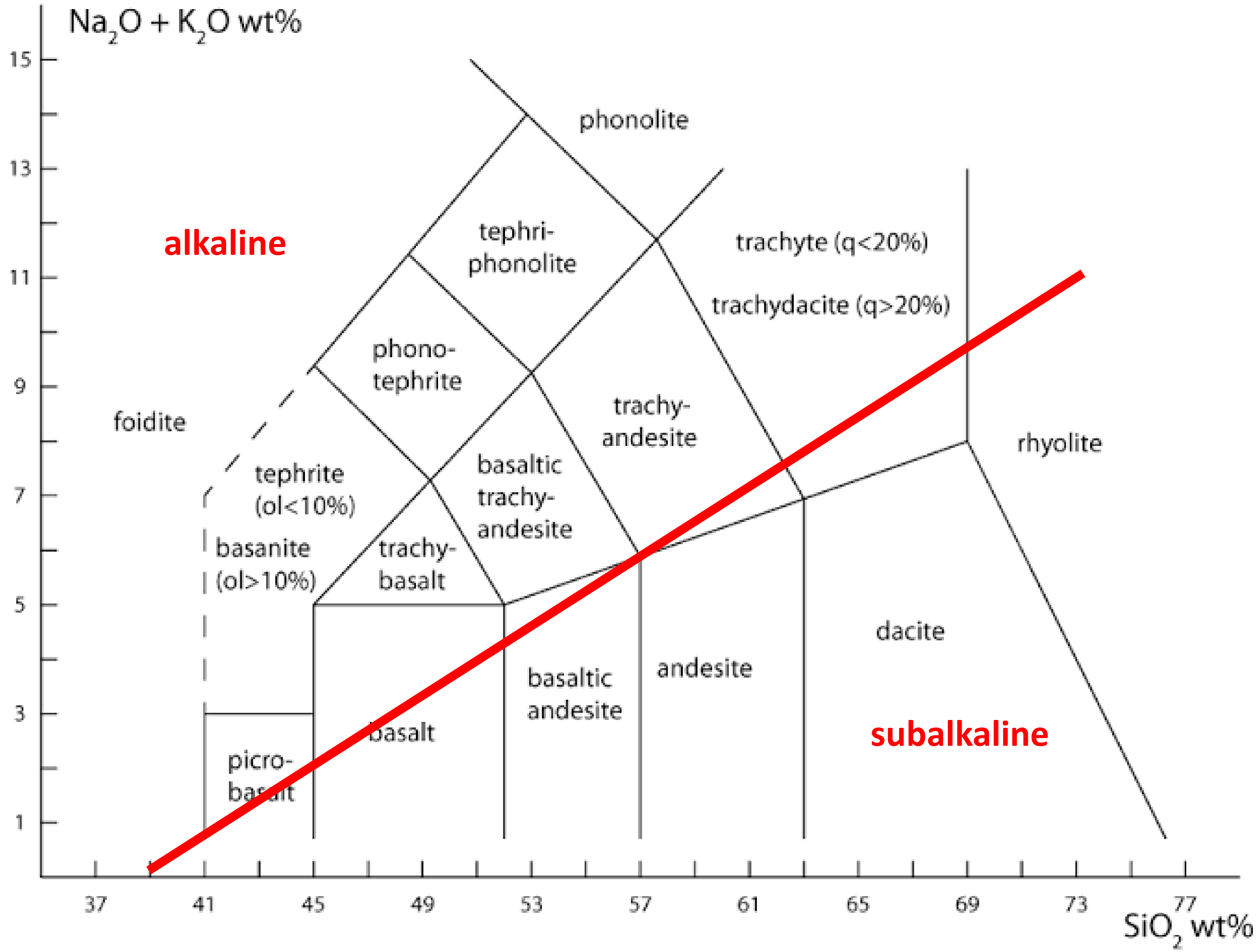


Table 7.1. Goldschmidt's Classification of the Elements

Siderophile	Chalcophile	Lithophile	Atmophile
Fe*, Co*, Ni*	(Cu), Ag	Li, Na, K, Rb, Cs	(H), N, (O)
Ru, Rh, Pd	Zn, Cd, Hg	Be, Mg, Ca, Sr, Ba	He, Ne, Ar, Kr, Xe
Os, Ir, Pt	Ga, In, Tl	B, Al, Sc, Y, REE	
Au, Re†, Mo†	(Ge), (Sn), Pb	Si, Ti, Zr, Hf, Th	
Ge*, Sn*, W‡	(As), (Sb), Bi	P, V, Nb, Ta	
C‡, Cu*, Ga*	S, Se, Te	O, Cr, U	
Ge*, As†, Sb†	(Fe), Mo, (Os)	H, F, Cl, Br, I	
	(Ru), (Rh), (Pd)	(Fe), Mn, (Zn), (Ga)	

*Chalcophile and lithophile in the earth's crust
†Chalcophile in the earth's crust
‡Lithophile in the earth's crust

- *Atmophile* elements are generally extremely volatile
- *Lithophile* elements are those showing an affinity for silicate phases
- *Siderophile* elements have an affinity for a metallic liquid phase.
- *Chalcophile* elements have an affinity for a sulfide liquid phase.

Isotope Geochemistry

Two principal applications of radiogenic isotope geochemistry:

1) *Geochronology*
uses the constancy of the rate of radioactive decay

→ Dating method

2) T*racer studies*
Uses the differences in the ratio of the radiogenic daughter isotope to other isotopes of an element. (as e.g. in biology)

→Origin of volatiles, minerals & rocks

Archean-eon craton were found in the area of the Nuvvuagittuq greenstone belt in northern Quebec.

- Different ages determined: ca. 3.7 billion years and ca. 4.3 billion years.
- Dispute so far unsolved…
- Evidence for fossils of microorganisms discovered in these rocks, which would be the oldest trace of life yet discovered on Earth.

Age determination of Nuvvuagittuq Greenstone Belt

- U-Pb dating on zircons → minimum of 3.7 billion years old.

  Done 2007 on zircons found within granitic intrusions that cut portions of the belt, and therefore, are younger than the features it cuts.
  -> This measurement is widely accepted.
  -> It alone does not provide a maximum age.

- Sm-Nd dating and Nd isotope fractionation in 2012→ age of 4.3 billion years

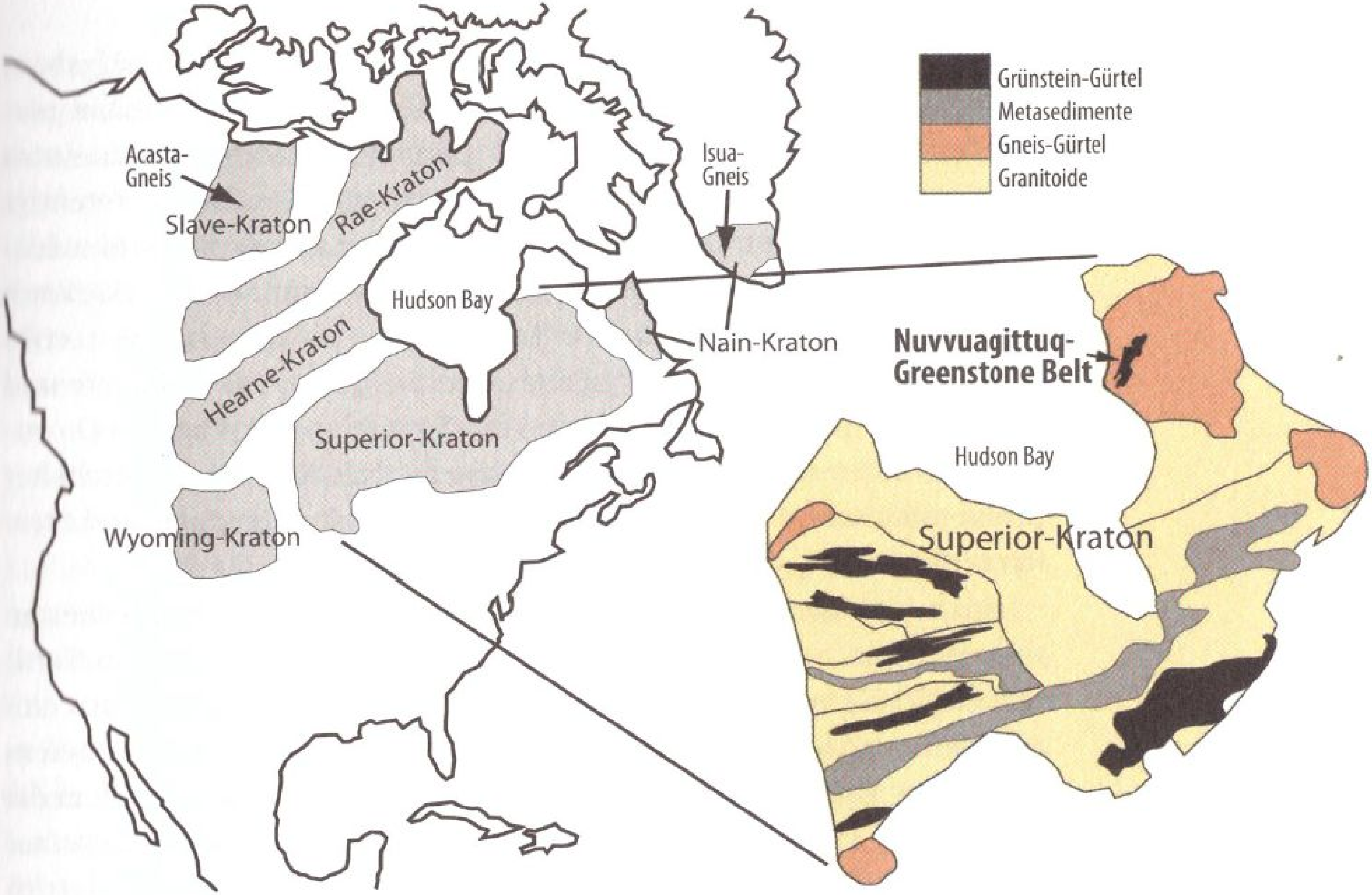
  -> dating of intruding gabbros and measuring neodymium isotope fractionation in less-deformed members of a sub-unit.
  ->The age of 4.3 billion years would make the NGB the oldest known rocks on Earth.

- Detrital zircons from quartz–biotite schists → max age of 3780 Ma.

  → This study states that the age of 4.3 billion years reflects isotope ratios inherited from Hadean crust that was melted to form the parent rocks of the NGB.

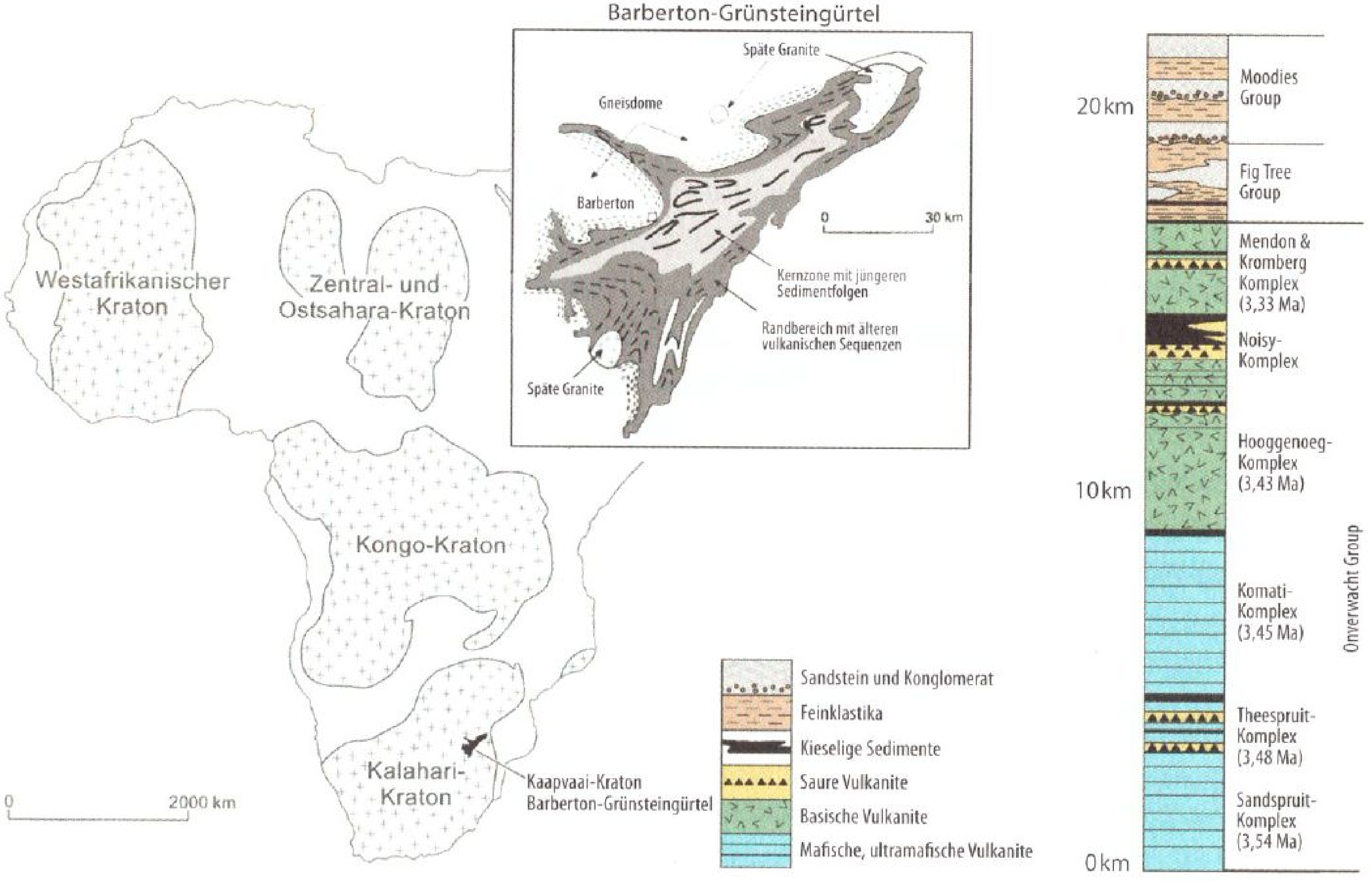
Die ältesten bislang datierten Gesteine stammen alle aus Nordamerika (verändert nach Eisbacher 1996 aus Walter 2014): Der Nuvvuagittuq Greenstone Belt, aus der Superior Provinz (möglicherweise ~ 4.3 Mia. Jahre) und der Acasta-Gneis (~ 4 Mia. Jahre), beide aus Kanada, sowie der Amitsoq-Gneis mit dem Isua-Grünsteingürtel (~ 3.9 Mia. Jahre) aus Südgrönland.

Abb. 4-4



Source: Oschmann, Evolution der Erde (2018)

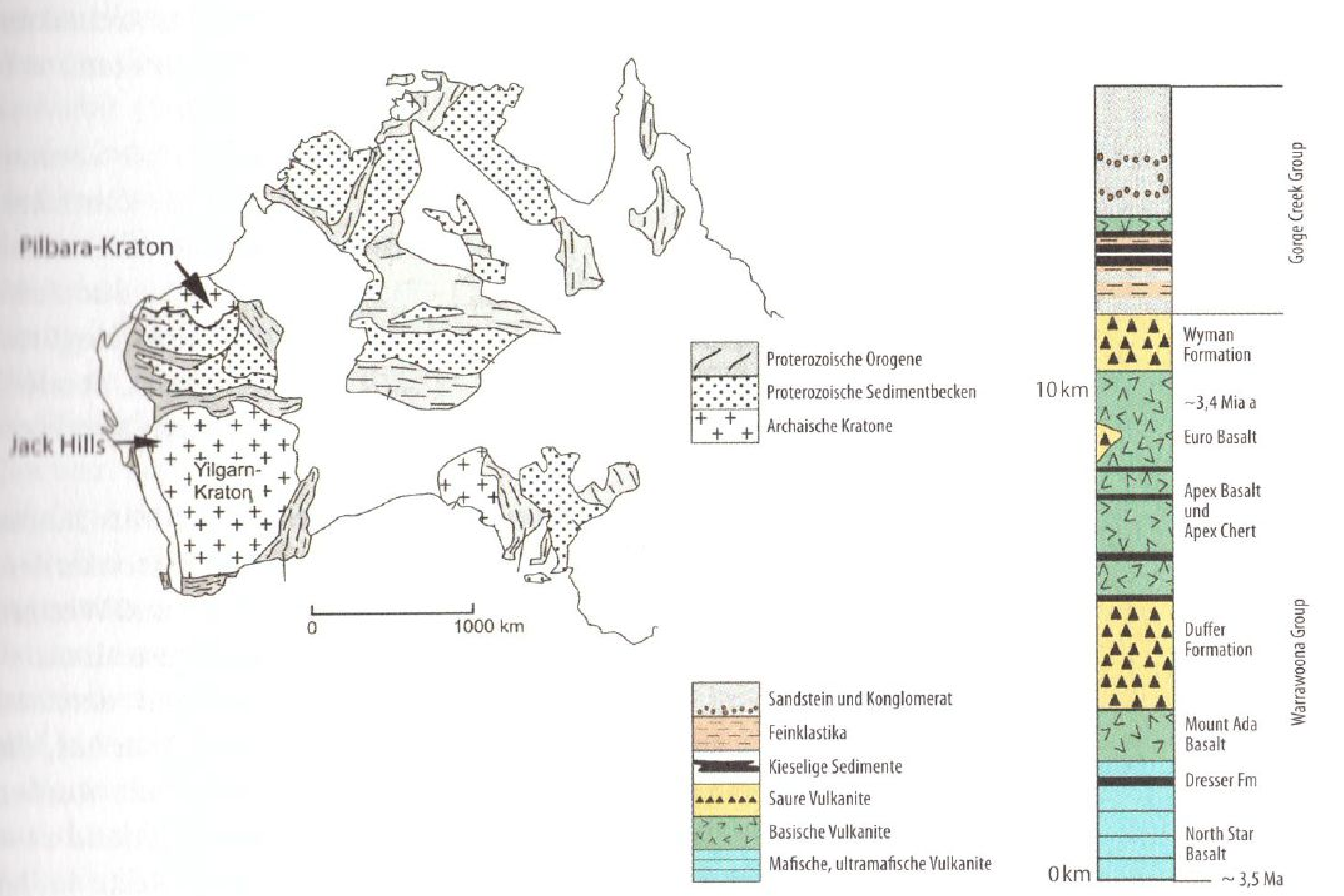
Abb. 4-5 Afrika wird aus mehreren archaischen Kratonen aufgebaut. (modifiziert nach Walter 2014, Stanley 2001 und Furnes et al. 2013).



Source: Oschmann, Evolution der Erde (2018)

Die Kratone in Australien (modifiziert nach Walter 2014 und Stanley 2001).

Abb. 4-6



Source: Oschmann, Evolution der Erde (2018)

Neoproterozoikum

sehr hohe Raten der oxischen Photosynthese durch Eucaryota und Metabionta $CO_2 + H_2O \xrightarrow{\text{Licht}} CH_2O + O_2$

Sehr wenig CH_4, wenig CO_2, viel O_2

Resultat: neoproterozoische Eiszeit

Spätes Paläoproterozoikum und Mesoproterozoikum

Anstieg der Solarstrahlung und der CO_2-Konzentration durch Karbonatbildung. Resulat: keine Eiszeit

Frühes Paläoproterozoikum

Maximum der Krustenbildung, intensive Verwitterung, oxische Photosynthese: $CO_2 + H_2O \xrightarrow{\text{Licht}} CH_2O + O_2$

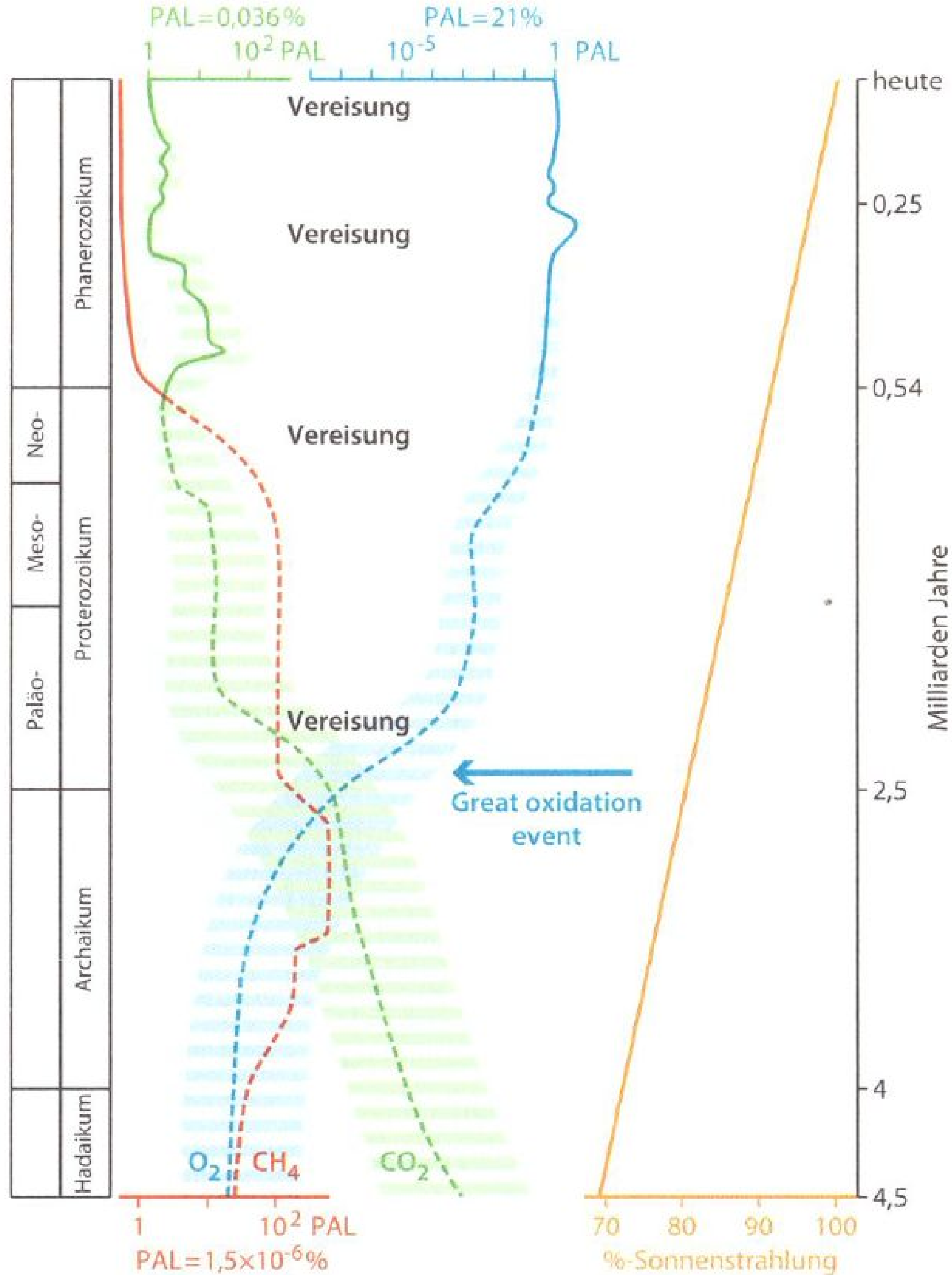
Wenig CH_4, wenig CO_2 führen zur huronischen Eiszeit

Archaikum

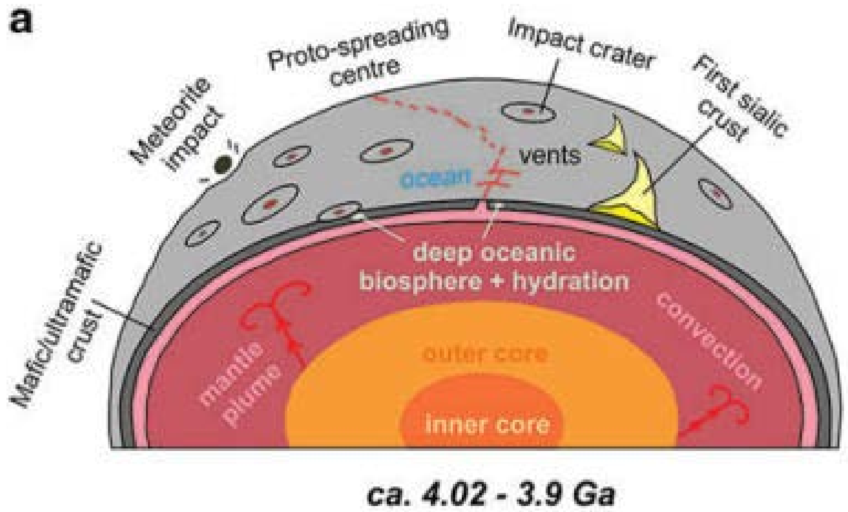
anoxische Photosynthese: $CO_2 + 2H_2S \xrightarrow{\text{Licht}} CH_2O + H_2O + 2S$

Methanogenesis: $CH_2O \longrightarrow CO_2 + CH_4$

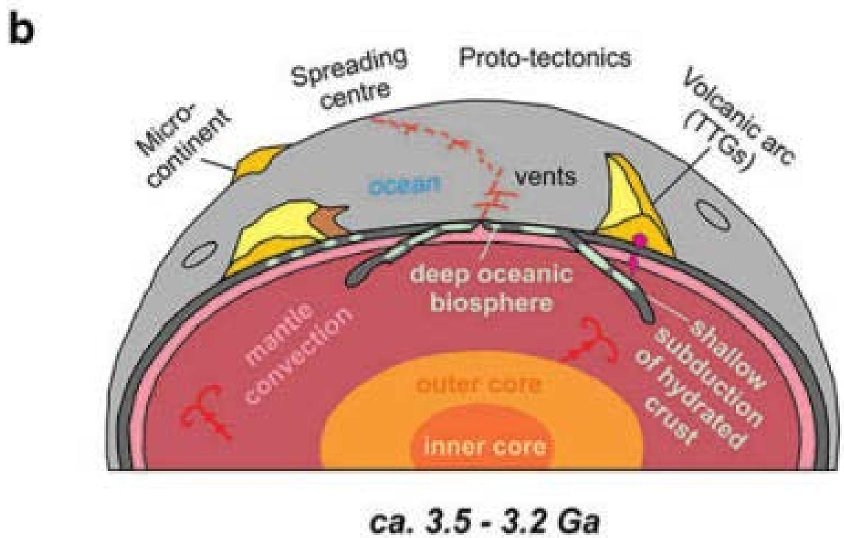
Methan als sehr effektives Treibhausgas verhindert eine Eiszeit.

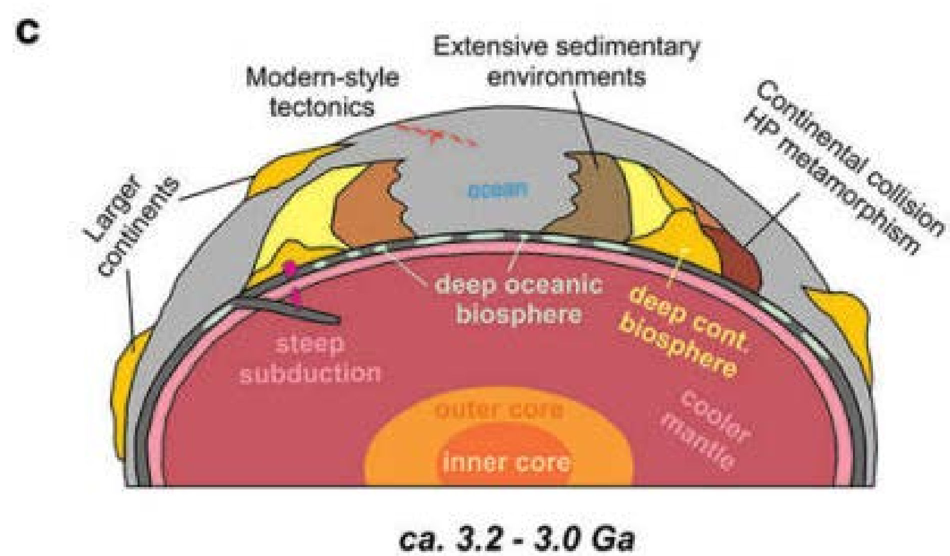


Source: Oschmann, Evolution der Erde (2018)

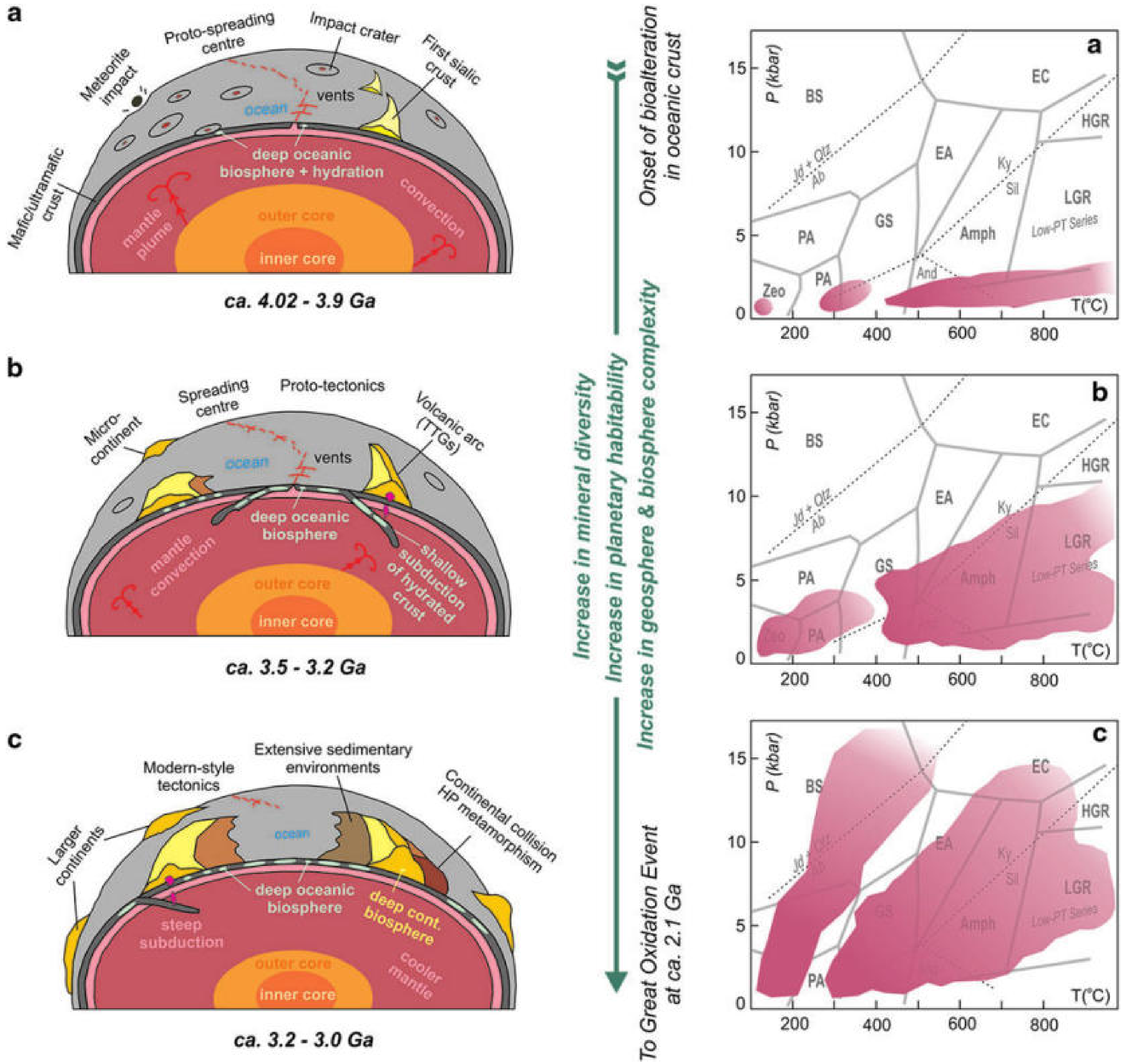


Coevolution of the geosphere and biosphere before the Great Oxidation Event from the onset of possible subsurface bioalteration at around 4.0 billion years ago until modern-style tectonic environments operating on Earth's surface at ca. 3.0 billion years ago.



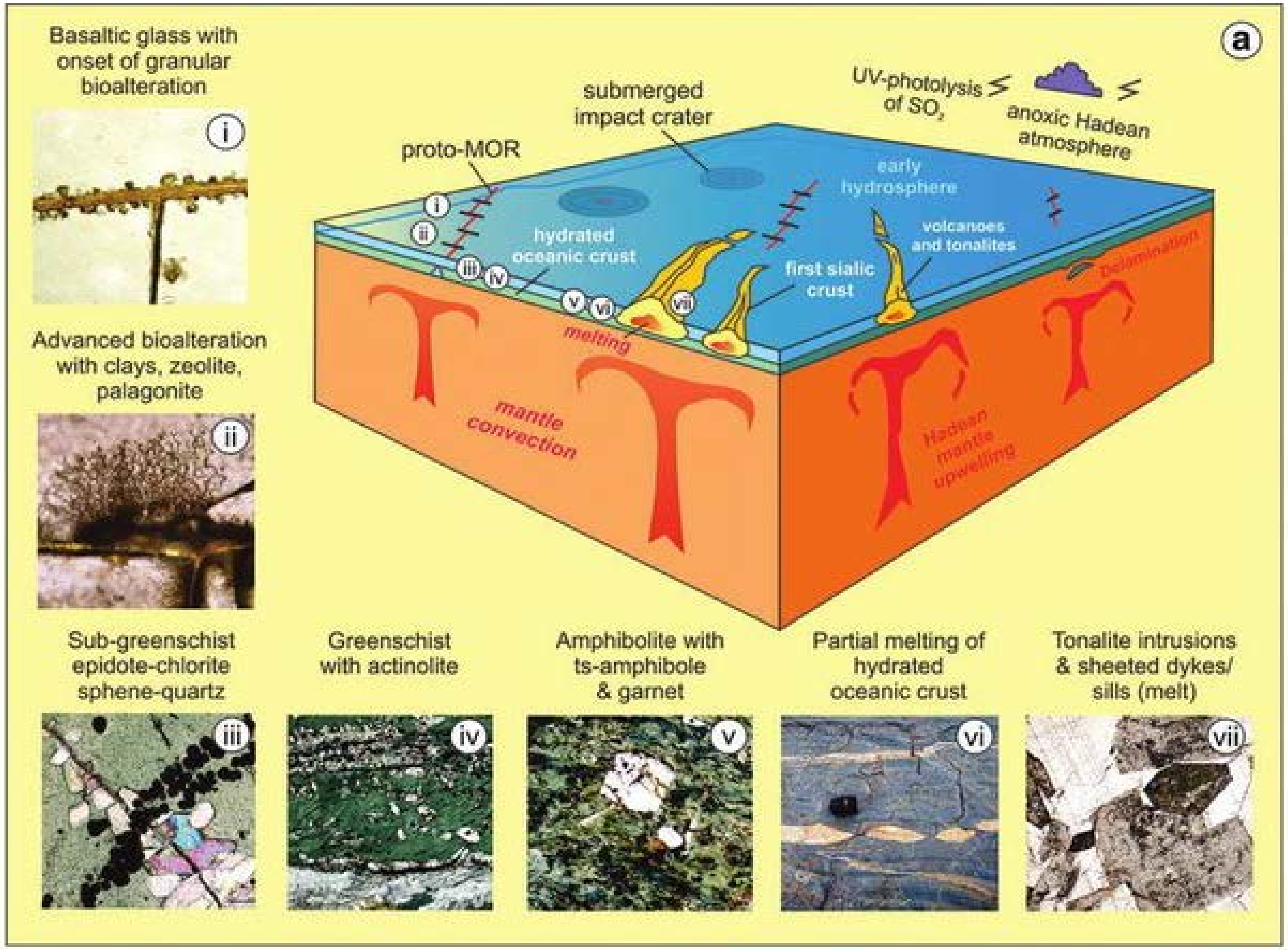


Source: Grosch & Hazen (2015) Astrobiology



Source: Grosch & Hazen (2015) Astrobiology

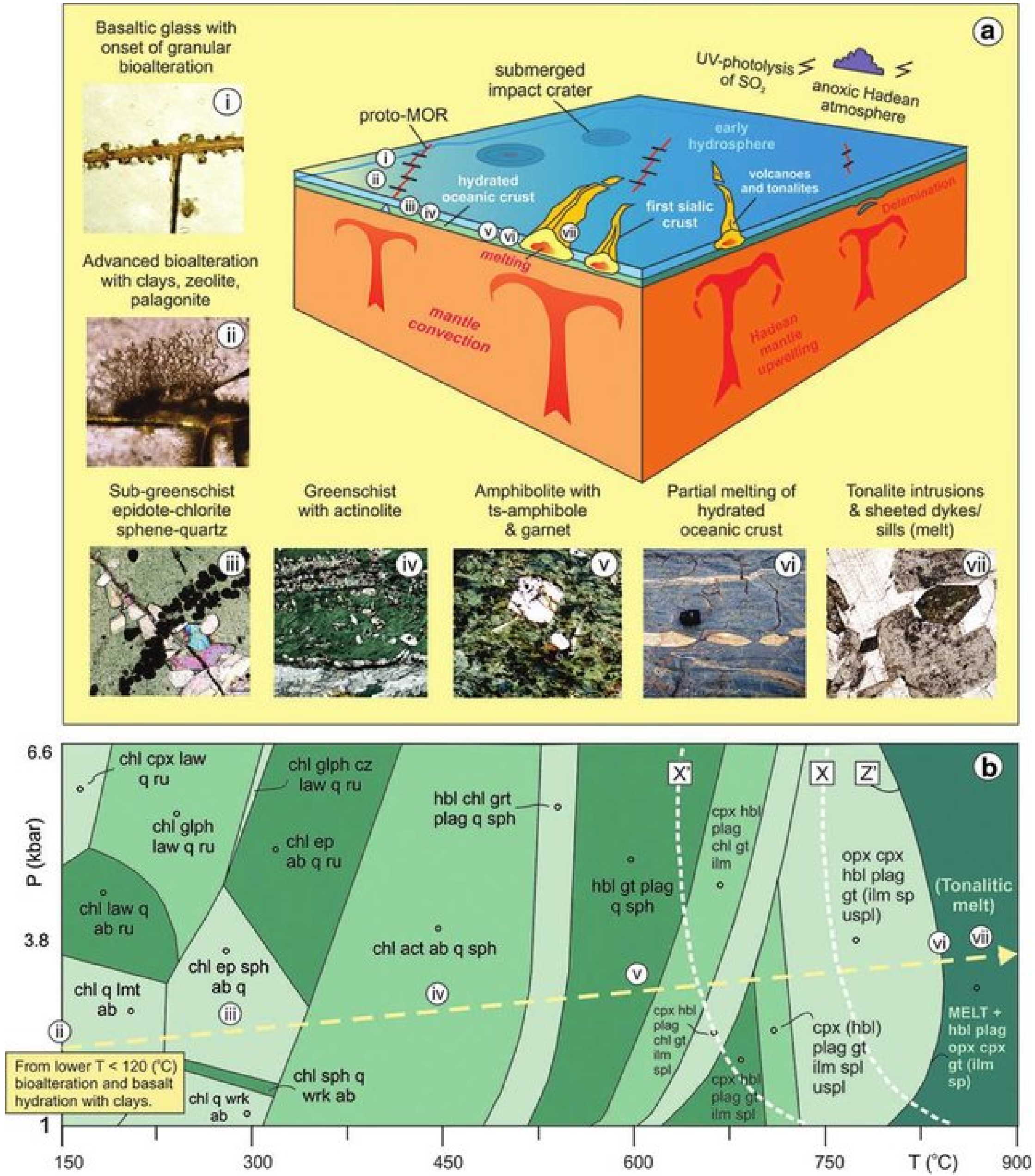
Surface environments on the Hadean-early Archean Earth and the role subsurface microbes may have played in shaping Earth's mineral evolution



Source: Grosch & Hazen (2015) Astrobiology

i-vii: representative Archean petrographic images of the mineral assemblages expected at different locations on early Earth, with subsurface fluid-rock-microbe interactions forming a range of hydrated minerals

Surface environments on the Hadean-early Archean Earth and the role subsurface microbes may have played in shaping Earth's mineral evolution



Source: Grosch & Hazen (2015) Astrobiology

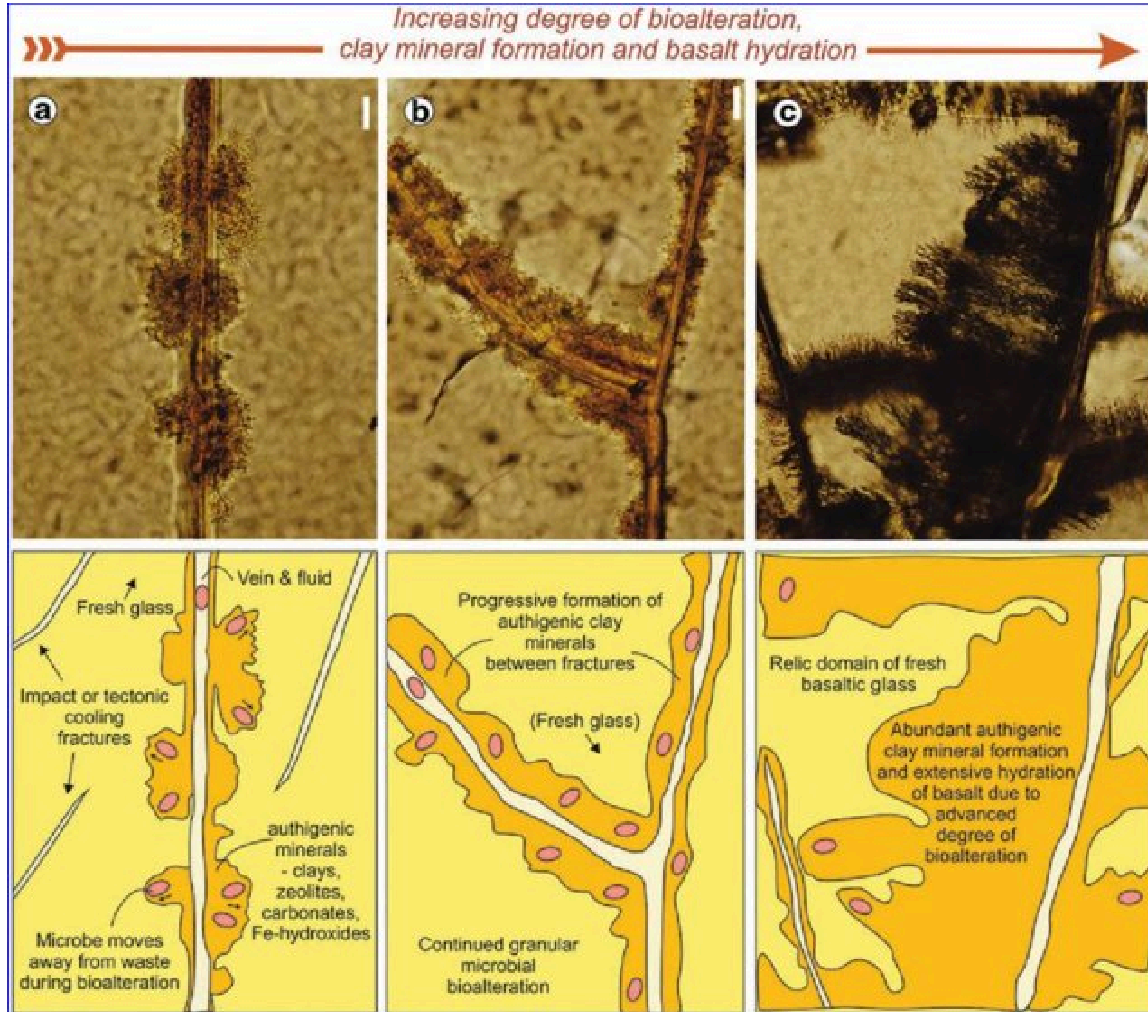
Progressive stages of alteration of subseafloor volcanic glass from the in situ oceanic crust:

(a) clusters of granular alteration textures in which individual granules are a few microns across;
(b) more extensive granular and mossy alteration textures along a fracture network;
(c) extensive tubular alteration extending more than 100 microns into fresh glass.

All samples contain smectite and iron oxides in the alteration textures.

Cartoons represent the bioalteration model of Thorseth et al. (1992, 1995) with increasing degrees and extent of microbe-fluid-rock interaction.

Some important chemical reactions (with corresponding available energy) that would have provided energy for microbial lithoautotrophs (from Edwards et al., 2005; Cockell, 2011) living in the Hadean-early Archean subseafloor environment



$HCO_3^- + H^+ + 4H_2 \rightarrow CH_4 + 3H_2O$ (Methanogenesis) - 130 kJmol^{-1}

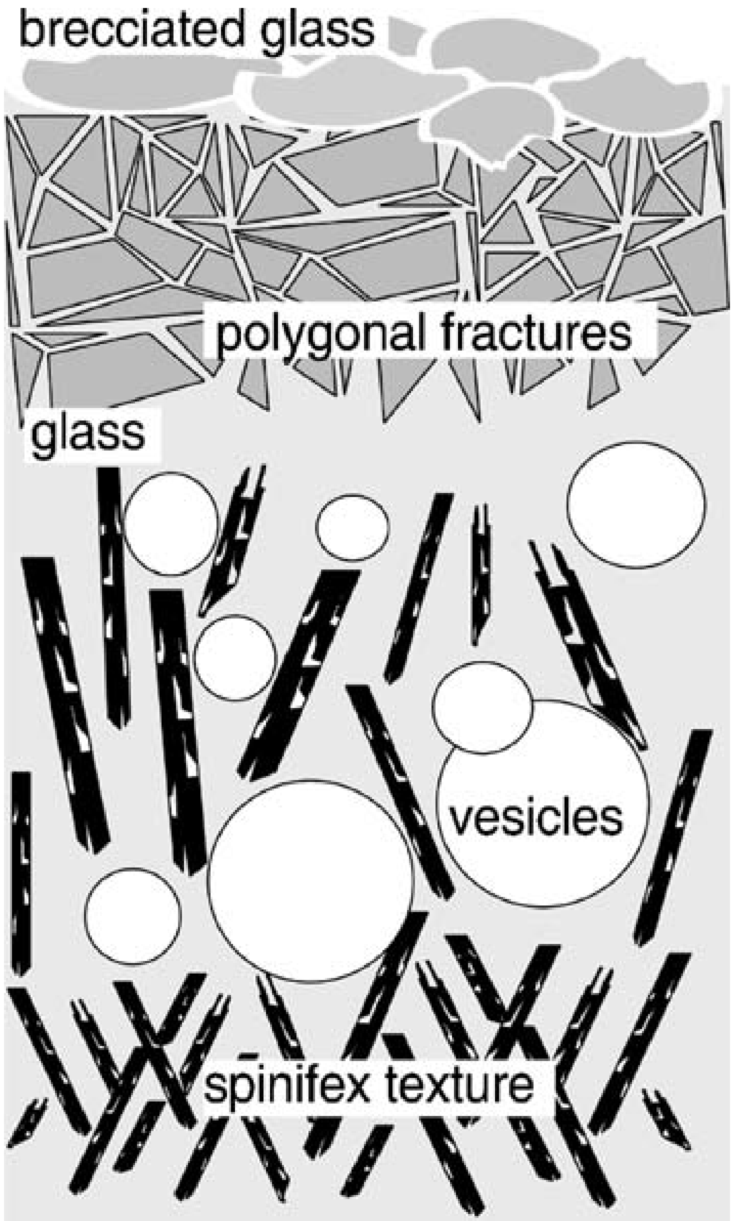
$SO_4^{2-} + H^+ + 4H_2 \rightarrow HS^- + 4H_2O$ (Sulphate reduction) - 170 kJmol^{-1}

$10Fe^{2+} + 2NO_3^- + 12H^+ \rightarrow 10\,Fe^{3+} + N_2 + 6H_2O$ (Anaerobic iron oxidation) - 100 kJmol^{-1}

$4FeCO_3 + 7H_2O \rightarrow CH_2O + 4Fe(OH)_3 + 3\,CO_2$ (Phototrophic iron oxidation)

Source: Grosch & Hazen (2015) Astrobiology

Melt – Glass – Minerals / Rocks in Lava Flows & Complexes

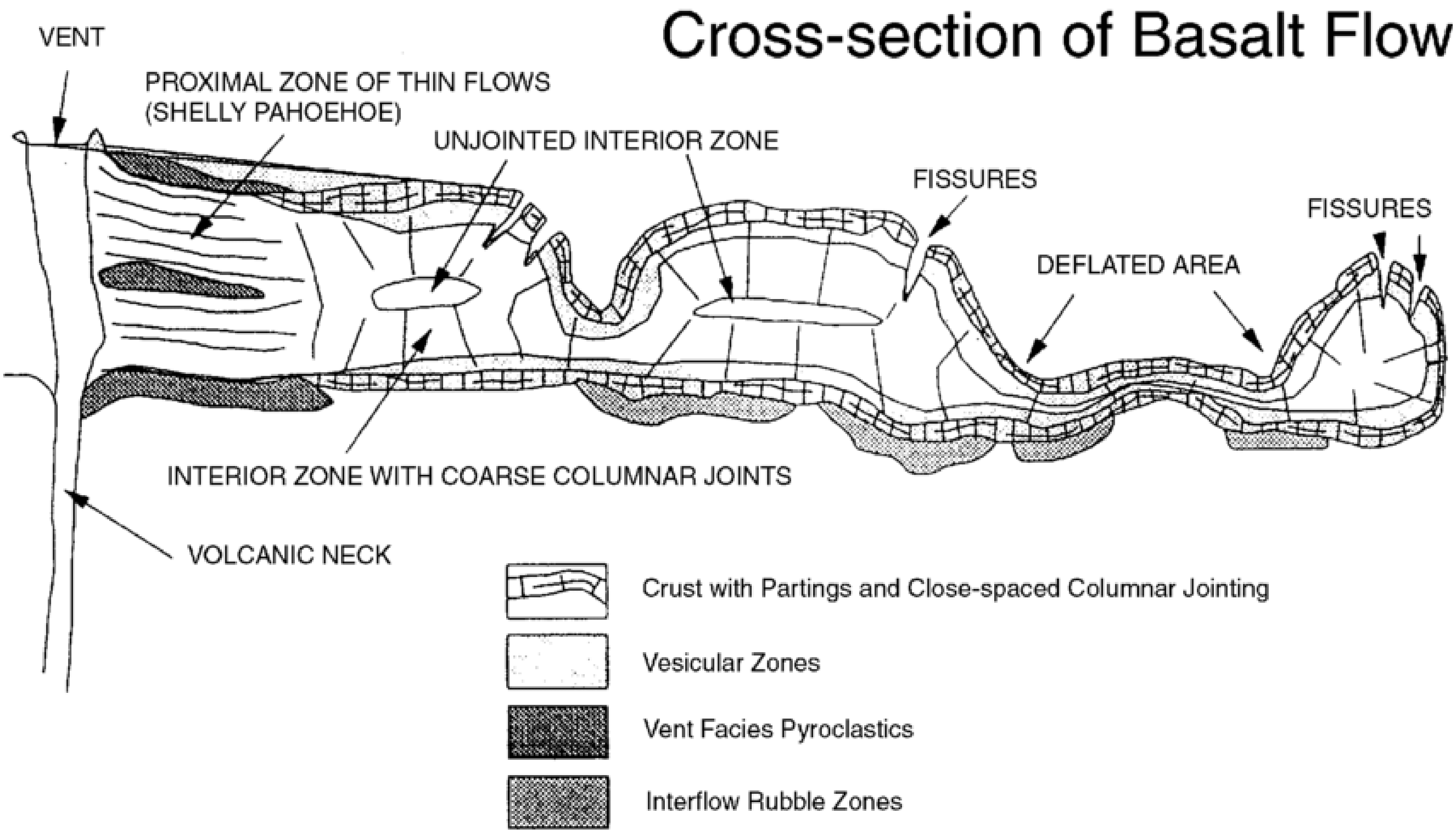


(Meunier et al., 2010)

Schematics of the upper part of a **komatiite** lava flow (simplified from Arndt et al. 2008).

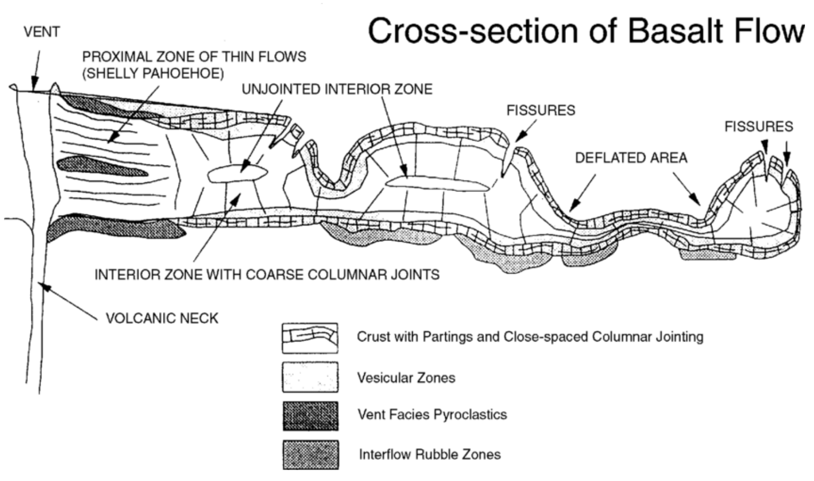
From top to bottom, the section shows four levels exhibiting different structures:
brecciated pillow lava; massive glassy zone fragmented by polygonal fractures; vesicle-rich level; glass-skeletal olivine (spinifex texture) level. The glassy zones are represented using different grey colors

Melt – Glass – Minerals / Rocks in Lava Flows & Complexes



(Hughes et al. 1999)

Melt – Glass – Minerals / Rocks in Lava Flows & Complexes



(Hughes et al. 1999)

Annual Review of Earth and Planetary Sciences

Earth's Continental Lithosphere Through Time

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Annual Review of Earth and Planetary Sciences

Plate Tectonics and the Archean Earth

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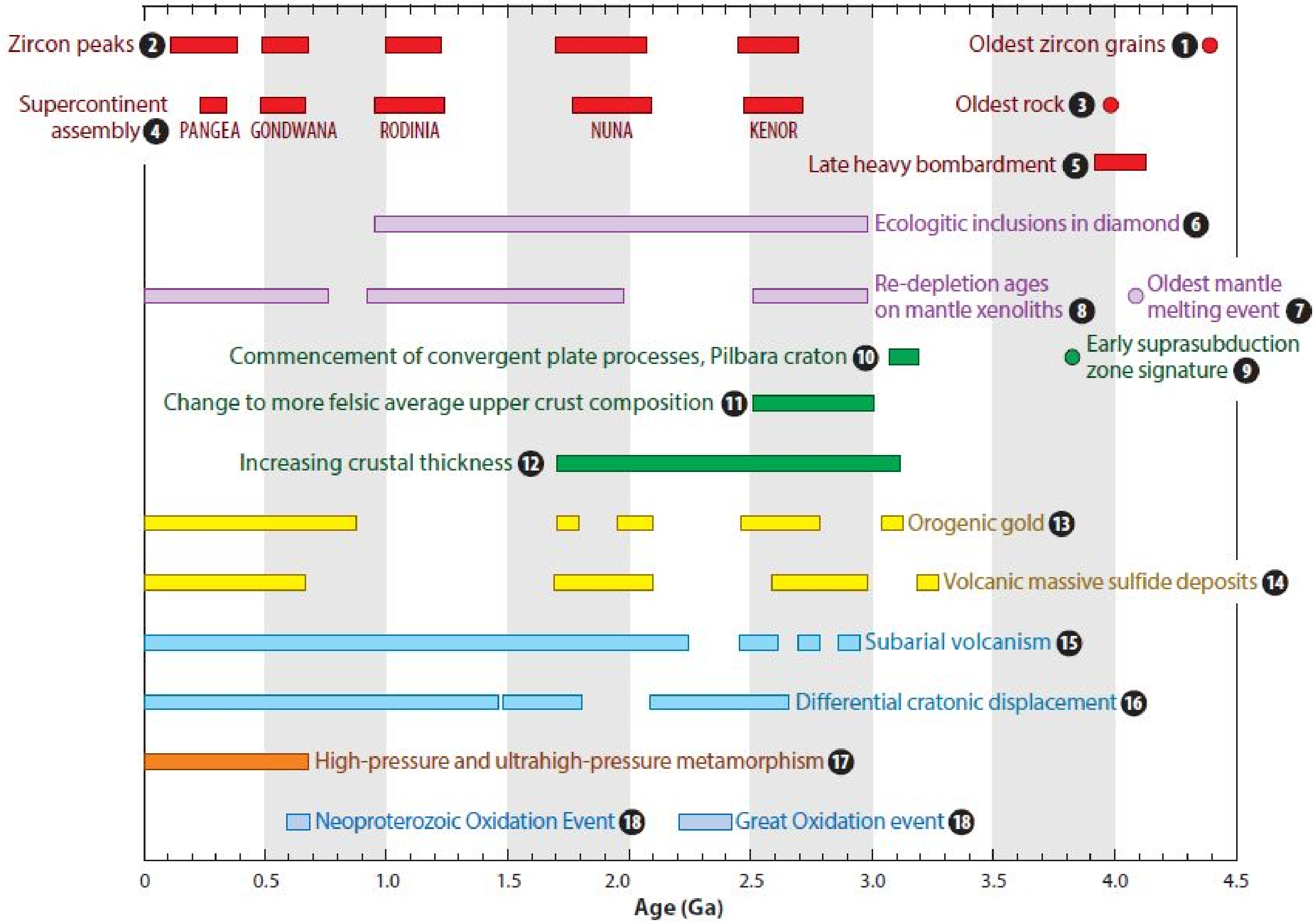
Ages and age ranges of major events cycles preserved in Earth history (with sources)



1. Wilde et al. 2001
2. Voice et al. 2011 and references therein
3. Bowring & Williams 1999
4. Adapted from Campbell & Allen 2008
5. Marchi et al. 2014
6. Shirey & Richardson 2011
7. Malitch & Merkle 2004
8. Figure 5 and references
9. Jenner et al. 2009, O'Neil et al. 2011, and Turner et al. 2014
10. Smithies et al. 2007 and Van Kranendonk et al. 2007
11. Keller & Schoene 2012 and Tang et al. 2016
12. Dhuime et al. 2015
13. Goldfarb et al. 2001
14. Mosier et al. 2009
15. Kump & Barley 2007, Shields 2007, Cawood et al. 2013, and Flament et al. 2013
16. Cawood et al. 2006, Evans & Pisarevsky 2008
17. Brown 2006, 2007, 2014
18. Campbell & Squire 2010, Farquhar et al. 2013 and references therein

Source: Hawkesworth et al. Ann Rev EPS (2017)

Ages and age ranges of major events cycles preserved in Earth history (with sources)

Figure 2

Ages (*circles*) and age ranges (*bars*) of major events and cycles preserved in Earth history. Sources of the data are indicated in the figure key: (1) The oldest terrestrial fragments, zircons from the Jack Hills; (2) the age range of principal peaks in U-Pb crystallization ages; (3) the oldest rocks, Slave craton; (4) the approximate age range of supercontinent assembly; (5) the late heavy bombardment; (6) the age range of eclogitic inclusions in diamonds; (7) the oldest Os model ages from detrital osmiridium grains, Witwatersrand Basin; (8) Re-depletion age ranges for peridotite xenoliths (see also **Figure 5**); (9) the ~3.8 Ga Nuvvuagittuq greenstone belt, Superior craton, and 3.85 Ga metabasalts from Isua, Greenland, are similar to modern subduction-related islands; (10) the pre-3.2 Ga rock units from Pilbara craton are associated with vertical tectonics, and rocks younger than 3.1 Ga are inferred to have formed by plate subduction processes; (11) the shift from predominantly mafic crustal compositions prior to 3.0 Ga to increasingly felsic compositions by 2.5 Ga; (12) the secular increase in time-integrated Rb/Sr ratios between 3.1 Ga and 1.7 Ga, indicative of a doubling in average continental crustal thickness from ca. 20 km to ca. 40 km; (13) the main pulses of orogenic gold deposition; (14) the main pulses of volcanic-hosted massive sulfide deposits; (15) subaerial large igneous province magmatism increases from 3.0 to 2.5 Ga, corresponding with the increase in $^{87}Sr/^{86}Sr$ ratios of seawater consistent with the emergence and weathering of continental crust; (16) the significant difference between the relative paleopositions of the Kaapvaal and Superior cratons at 2.68 Ga and 2.07 Ga and Baltica and Australia between 1.77 Ga and 1.5 Ga; (17) the high-pressure and ultrahigh-pressure metamorphism, which are limited to rock units dated at <0.7 Ga; and (18) the increases in atmospheric oxygen values during the Great Oxidation Event and the Neoproterozoic Oxidation Event.

Source: Hawkesworth et al. Ann Rev EPS (2017)

Plate Tectonics and the Archean Earth

- Higher mantle temperature in the Archean precluded or limited stable subduction,
  → requires a transition to present day plate tectonics from another tectonic mode.
- Plate tectonics can be demonstrated on Earth since the early Paleoproterozoic (since c. 2.2 Ga), but before the Proterozoic Earth's tectonic mode remains ambiguous.
- The Mesoarchean to early Paleoproterozoic (3.2–2.3 Ga) represents a period of transition from an early tectonic mode (stagnant or sluggish lid) to plate tectonics.
- The development of a global network of narrow boundaries separating multiple plates could have been kick-started by plume-induced subduction.

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Survivorship Bias and the Geological Record in the Archean

- Rocks older than Paleoarchean in age (>3.6 Ga) are rare.
- Age distribution of detrital zircon grains and magmatic rocks shows a marked decline in the amount of preserved crust older than Neoarchean (>2.8 Ga).

→ To what extent is preserved crust older than Neoarchean is representative, in terms of either relative volume of rock types or the processes it records?

a) Is this crust the surviving remnants of a much larger volume that was destroyed?

b) was there only ever a small volume produced?

??? How significant is the scarcity of Eoarchean crustal rocks and the almost complete absence of a Hadean rock record?

THE ARCHEAN ROCK RECORD

Lithological differences between pre- and post-Archean geology

- Archean continental crust is compositionally distinct from younger andesitic continental crust
- Archean upper crust may have been more mafic than post-Archean emergent crust
- Exposed Archean crust mostly comprises higher-grade gray gneiss terrains and lower-grade granite–greenstone belts.
  → probably lower and upper levels of the ancient continental crust, respectively (Johnson et al. 2016), but they have also been interpreted as analogs of modern active continental arc margins and associated backarcs.
- Gray gneiss terrains are volumetrically dominated by sodic granitoids of the **tonalite–trondhjemite–granodiorite (TTG) series**. TTGs are compositionally similar to, but subtly different from, modern adakites that mostly form by partial melting of subducting hydrated oceanic crust.

  -> Were TTGs also products of slab melting, or are other tectonic settings likely?

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Lithological differences between pre- and post-Archean geology

tonalite–trondhjemite–granodiorite (TTG) series

- Results of partial melting and fractional crystallization
- Typical for all Archean cratons (thick continental crust)
- high Na/K ratios

THE TONALITE–TRONDHJEMITE–GRANODIORITE SUITE OF ROCKS

Archean rocks are generally found in cratons, which form the stable interiors of continents. Archean cratons are dominantly composed of gneisses derived from a variety of initial rock types, but mostly of igneous origin, many of which have been tectonically transposed during strong deformation, obscuring their original relationships. Within these gneisses, an important group of igneous rocks is the tonalite–trondhjemite–granodiorite (TTG) suite, which is largely confined to the Archean. TTGs are silica-rich (SiO_2 > 64 wt%, but commonly ~70 wt% or greater) rocks with high Al_2O_3 (15.0–16.0 wt%) and Na_2O (3.0–7.0 wt%) contents, low K_2O/Na_2O (<0.5) ratios, and low total ferromagnesian oxide (Fe_2O_3 total + MgO + MnO + TiO_2 ≤ 5 wt%) contents. TTGs generally have fractionated rare earth element (REE) patterns and low heavy REE contents.

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Lithological differences between pre- and post-Archean geology

- In addition to felsic domes, granite–greenstone belts comprise sequences of mainly (metamorphosed) basalt, with subordinate ultramafic to felsic volcanic rocks and various sedimentary rocks.
- A significant feature is the common occurrence of komatiites, high-Mg (MgO > 18 wt%) lavas that are rare in the post-Archean rock record.

  → unusually high mantle temperatures required to form komatiites

    → commonly explained by invoking more vigorous plume activity promoted by higher temperatures at the core–mantle boundary.

- Majority of Archean lavas were erupted subaqueously, suggesting not large landmasses had emerged before the late Archean–early Proterozoic.
- However clear evidence for continental settings in Archean preserved, including signs of active explosive effusive volcanisms, geysers, hot springs and pools.

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Petrogenesis of Archean Crust compared to present-day Crust

- **Modern arc basalts** have characteristic compositions reflecting partial melting, on average at∼100 km depth below the active magmatic arc, of depleted mantle that was hydrated and enriched in incompatible elements through interaction with fluids derived from subducted materials.

→ **Relative to MORB, arc basalts**:
1) are enriched in large ion lithophile elements (LILE);
2) show fractionated rare earth element (REE) patterns, with preferential incorporation of light REE (LREE) over heavy REE (HREE);
3) are depleted in high field strength elements, leading to pronounced negative anomalies in Nb, Ta, Zr, Hf, and Ti.

!! Although these characteristics are taken as a reliable proxy for subduction in many studies, they also occur in basalts derived from subduction-modified lithospheric mantle.

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Key Features of Archean Geology

Petrogenesis of Archean Crust compared to present-day Crust

- **fundamental questions:**

  1? do modern arc basalts really provide the key to the genesis of Archean basalts with similar compositional characteristics?

  2? are there plausible mechanisms by which hydrated crust can be recycled into the mantle other than by subduction?

-> Numerical modeling suggests that subduction and dripping of the lowermost crust and crustal overturns may represent plausible alternatives

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Key Features of Archean Geology

Petrogenesis of Archean Crust compared to present-day Crust

- The so-called arc signature is also found in most TTGs, which show extreme REE fractionation, with high chondrite-normalized La/Yb ratios (LaN/YbN > 15) and preferential enrichment of Sr over Y (SrN/YN > or 20) Not withstanding that some TTGs may have formed through fractional crystallization the pronounced HREE and Y depletion in most TTGs (~80%) is interpreted to record partial melting of hydrated basaltic rocks (amphibolite) at depth within the stability field of garnet. Although garnet may indicate pressures >1.5 GPa based on experimental studies of amphibolite, its stability is highly sensitive to bulk rock Mg# [atomic Mg/(Mg + Fe2+)] and garnet may be stable at pressures as low as 0.7 GPa.
- This lower pressure is within the range of thickness for primary crust generated during the Archean, and melting this crust may not require subduction.

Source: Brown et al. Ann Rev EPS (2020)

THE ARCHEAN ROCK RECORD

Key Features of Archean Geology

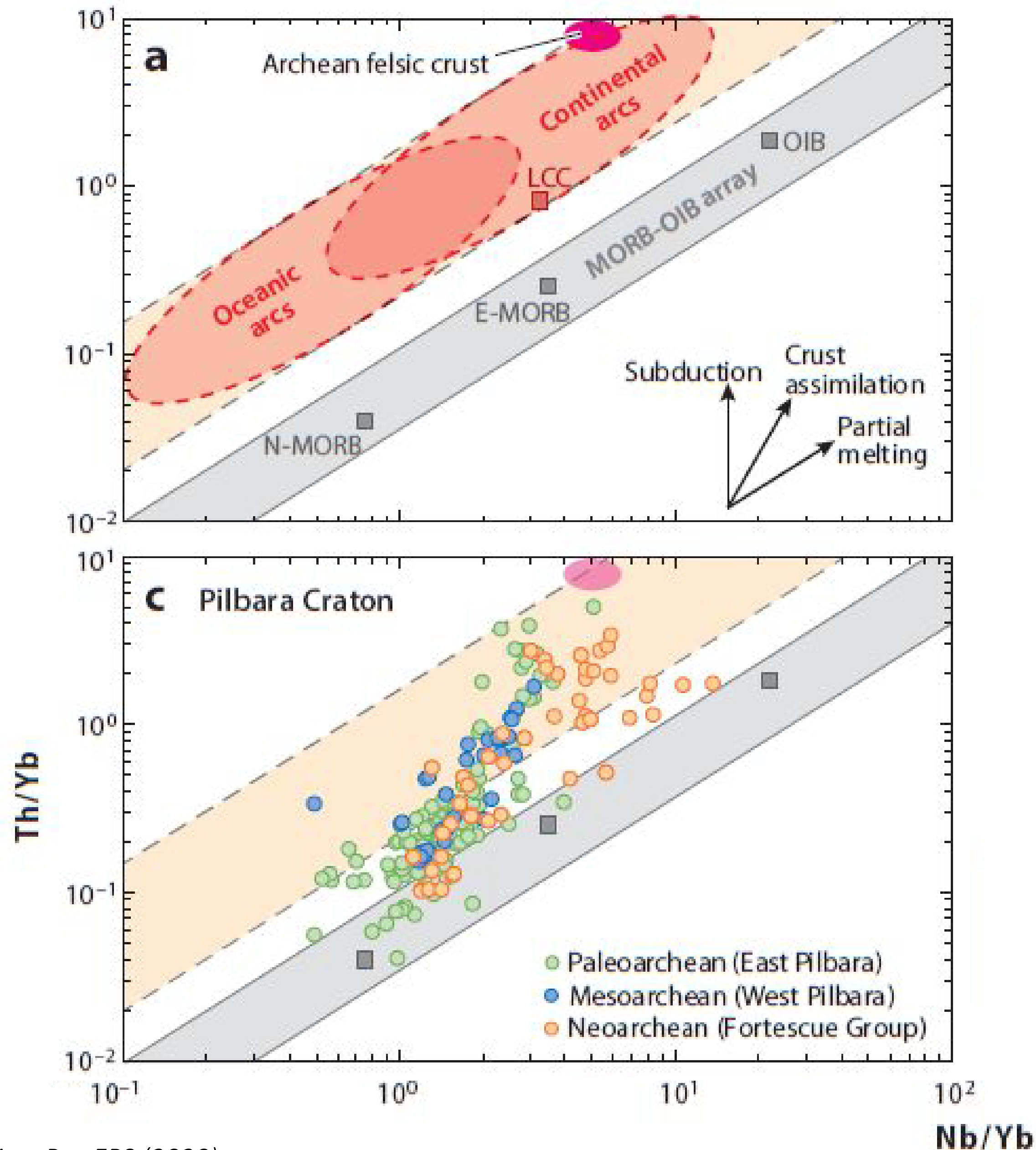
Petrogenesis of Archean Crust compared to present-day Crust

- Around 20% of TTGs record a high-pressure signature, considered to record extraction from an eclogite residue at pressure >2.0 GPa, corresponding to the extreme depths (>60 km) experienced by younger crustal rocks only during deep subduction.

→ such high-pressure TTGs have recently been interpreted to represent fractionated sanukitoid (high-Mg diorite) melts derived by partial melting of chemically enriched hydrated lithospheric mantle.

Source: Brown et al. Ann Rev EPS (2020)

How to interpret isotope signatures



Source: Brown et al. Ann Rev EPS (2020)

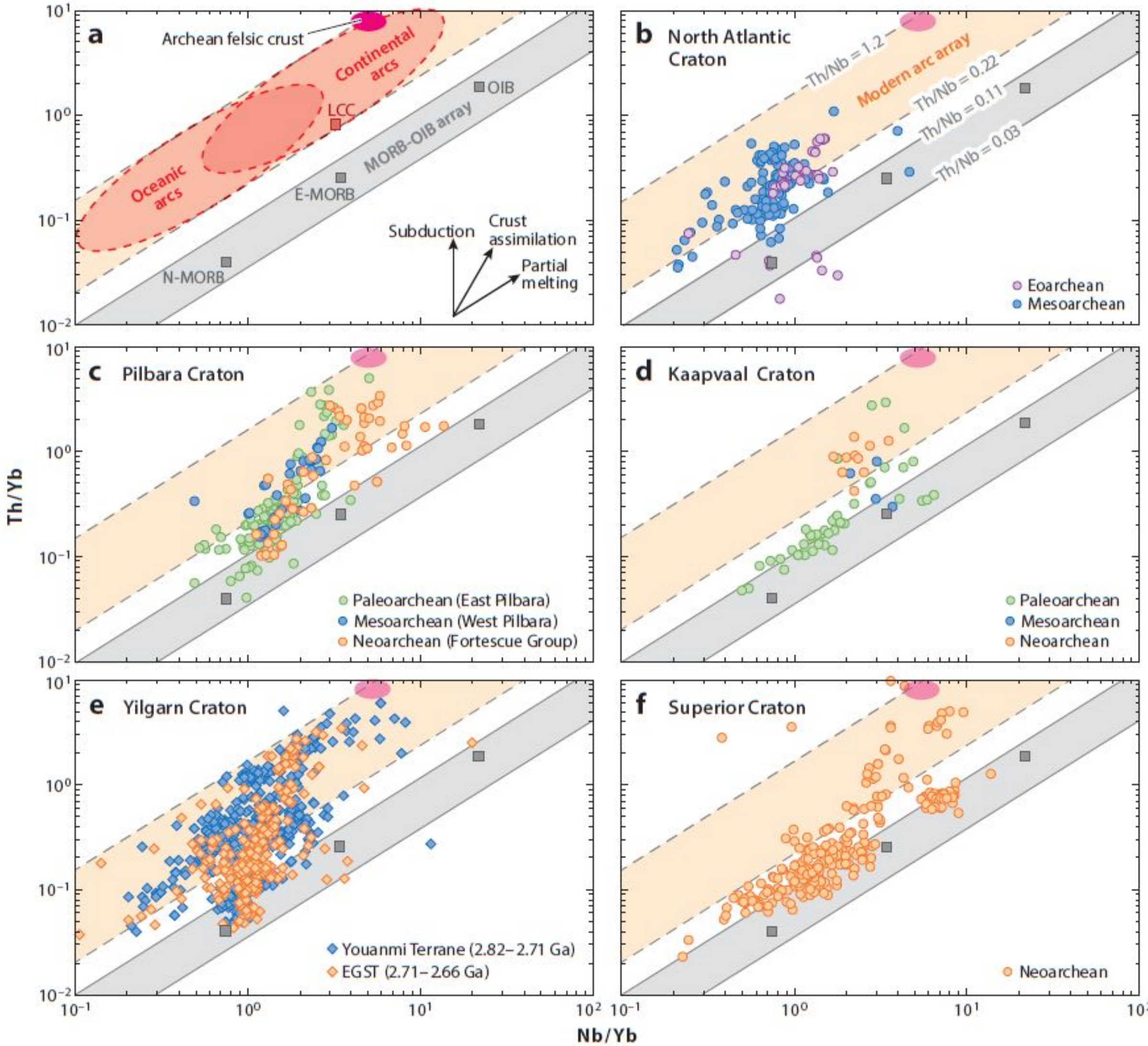


Figure 4

(*a*) The Th/Yb–Nb/Yb plot of Pearce (2008) showing main fields as well as composition vectors expected during subduction enrichment of a mantle source, crustal assimilation, and partial melting. Panel *a* adapted from Smithies et al. (2018). Copyright 2018, with permission from Elsevier; data for ocean floor basalt compositions (N-MORB, E-MORB, and OIB) from Sun & McDonough (1989); for the average composition of Archean felsic crust from Moyen (2011); and for modern LCC from Rudnick & Gao (2014). (*b*)–(*f*) Plots of Th/Yb versus Nb/Yb for basalts from the North Atlantic Craton (southwest Greenland), the Pilbara Craton, the Kaapvaal Craton (Barberton Granite–Greenstone Belt), and the Superior Craton (Abitibi Greenstone Belt) colored by age, and for the Yilgarn Craton colored by terrane. Data for panels *b*–*f* from GeoRoc (**http://georoc.mpch-mainz.gwdg.de/georoc/**) and GSWA (2019), filtered by MgO (<18 wt%) and SiO_2 (>45 and <57 wt%) content. Abbreviations: EGST, Eastern Goldfields Superterrane; E-MORB, enriched mid-ocean ridge basalt; LCC, lower continental crust; MORB, mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean island basalt.

Source: Brown et al. Ann Rev EPS (2020)

Present-day plate boundaries

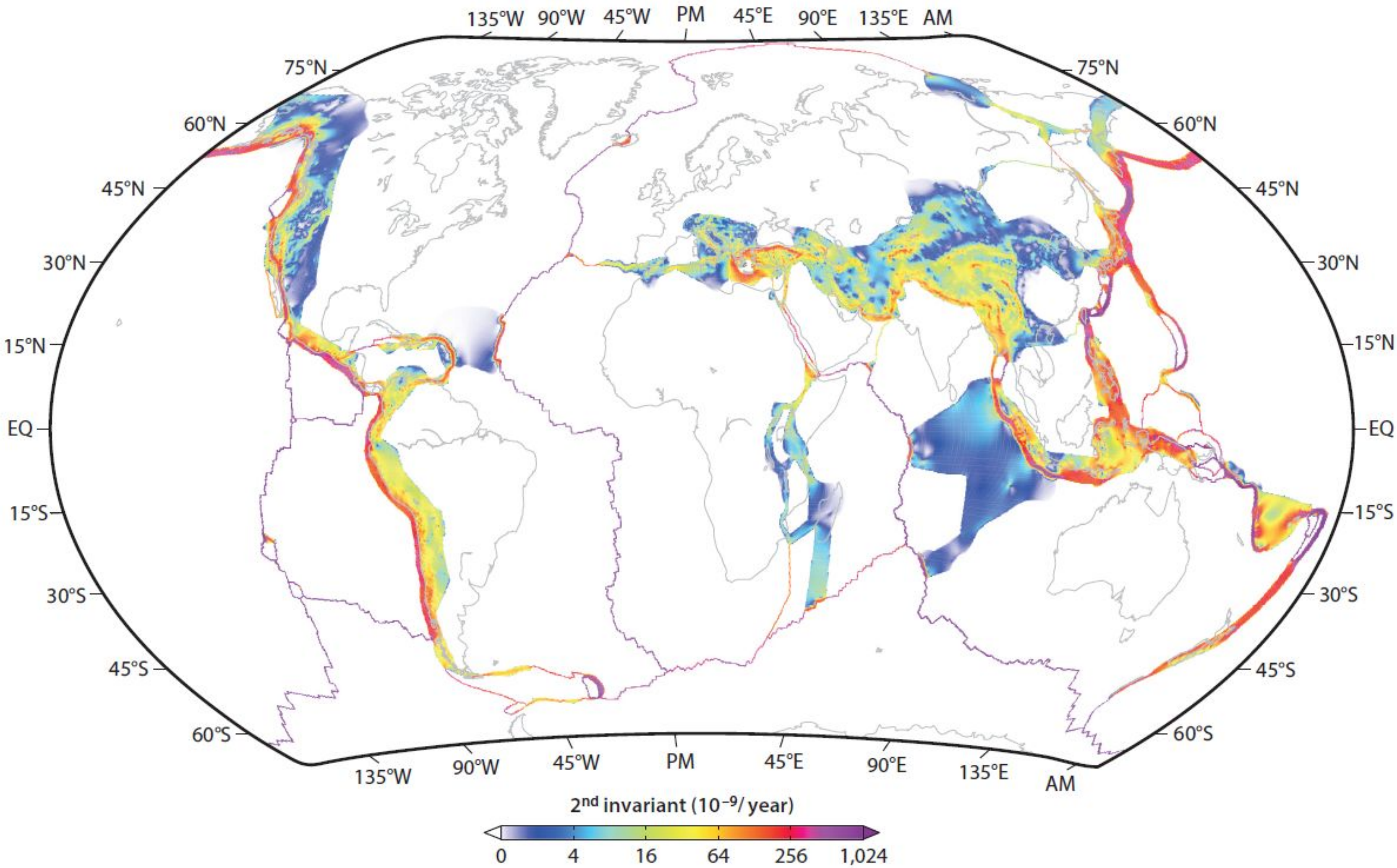


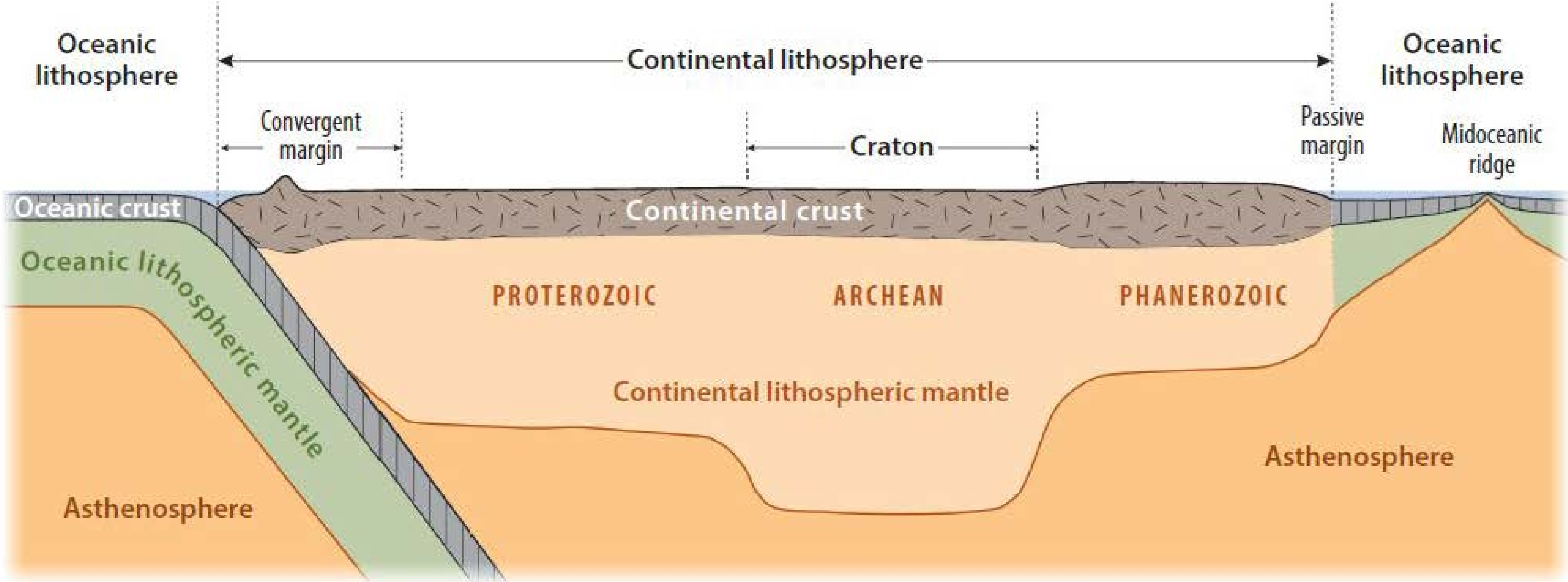
Figure 1

Map of present-day plate boundary deformation zones. White areas were assumed to be rigid plates, and the rigid body rotation of these plates was imposed as a boundary condition when solving for plate boundary strain rates from geodetic velocities. Figure adapted from Kreemer et al. (2014).

Source: Brown et al. Ann Rev EPS (2020)

Schematics of continental and oceanic lithosphere

note the thick stable nature of Archean cratons



Crystallization age
Age of crystallization of a mineral or rock from a melt

Model age
Age at which new crust is generated from the mantle

Depleted mantle
Mantle depleted through extraction of one or more basaltic melts

Crust generation
Formation of new crust; extracted from the mantle

Crust recycling (and destruction)
Return of crust to the mantle

Crust reworking
Intracrustal remobilization, involving erosion and sedimentation, and/or (re)melting of preexisting crustal rocks

Growth of crust
The volume of new crust less the amount lost by recycling

Supercontinents
Assembly of large volumes of continental crust, i.e., redistribution of continental crust on Earth's surface

Source: Hawkesworth et al. Ann Rev EPS (2017)

Vertical Tectonics: stagnant lid

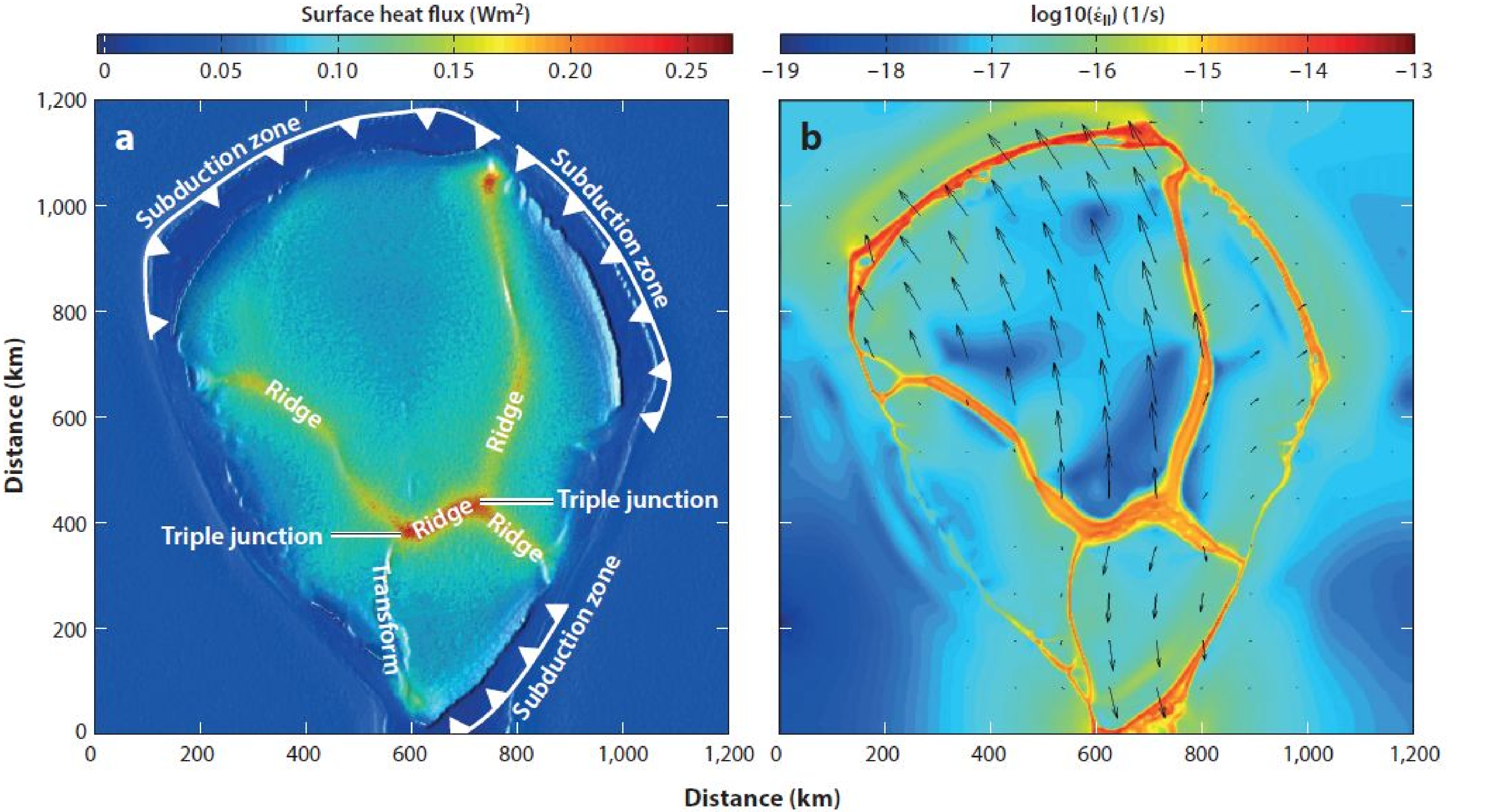


Figure 5

Development of an embryonic mosaic of plates separated by spreading centers (ridges), triple junctions, and transform faults at the latest stage of plume-induced subduction. (*a*) Surface heat fluxes projected onto the modeled surface topography, showing a pattern of spreading centers (*white lines with triangles* show dip directions of retreating subducting slabs). (*b*) Spatial distribution of the second strain rate invariant at a depth of 20 km (*arrows* show horizontal velocities of individual, young, nonsubducting plates moving toward retreating subducting slabs). Figure adapted from Gerya et al. (2015). Copyright 2015, with permission from Springer Nature.

Source: Brown et al. Ann Rev EPS (2020)

Vertical Tectonics: stagnant lid and lithosperic drips

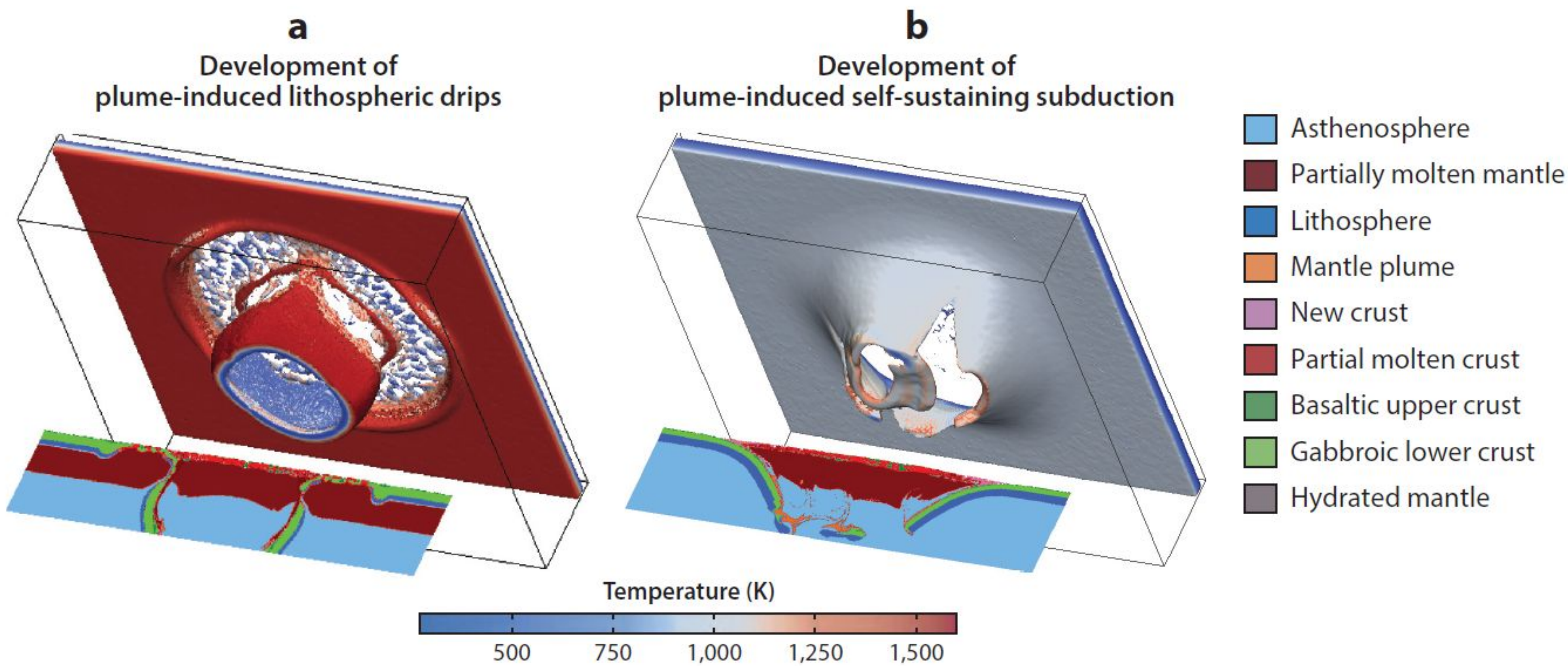


Figure 6

Plume–lithosphere interaction for hotter mantle temperature (ΔT_P of +200°C) and thicker oceanic crust. (*a*) Development of plume-induced lithospheric drips for 20-Myr oceanic plate with 30-km-thick crust. (*b*) Development of plume-induced self-sustaining subduction for 80-Myr oceanic plate with 20-km-thick crust. Figure adapted from Gerya et al. (2015). Copyright 2015, with permission from Springer Nature.

Source: Brown et al. Ann Rev EPS (2020)

Vertical Tectonics: stagnant lid

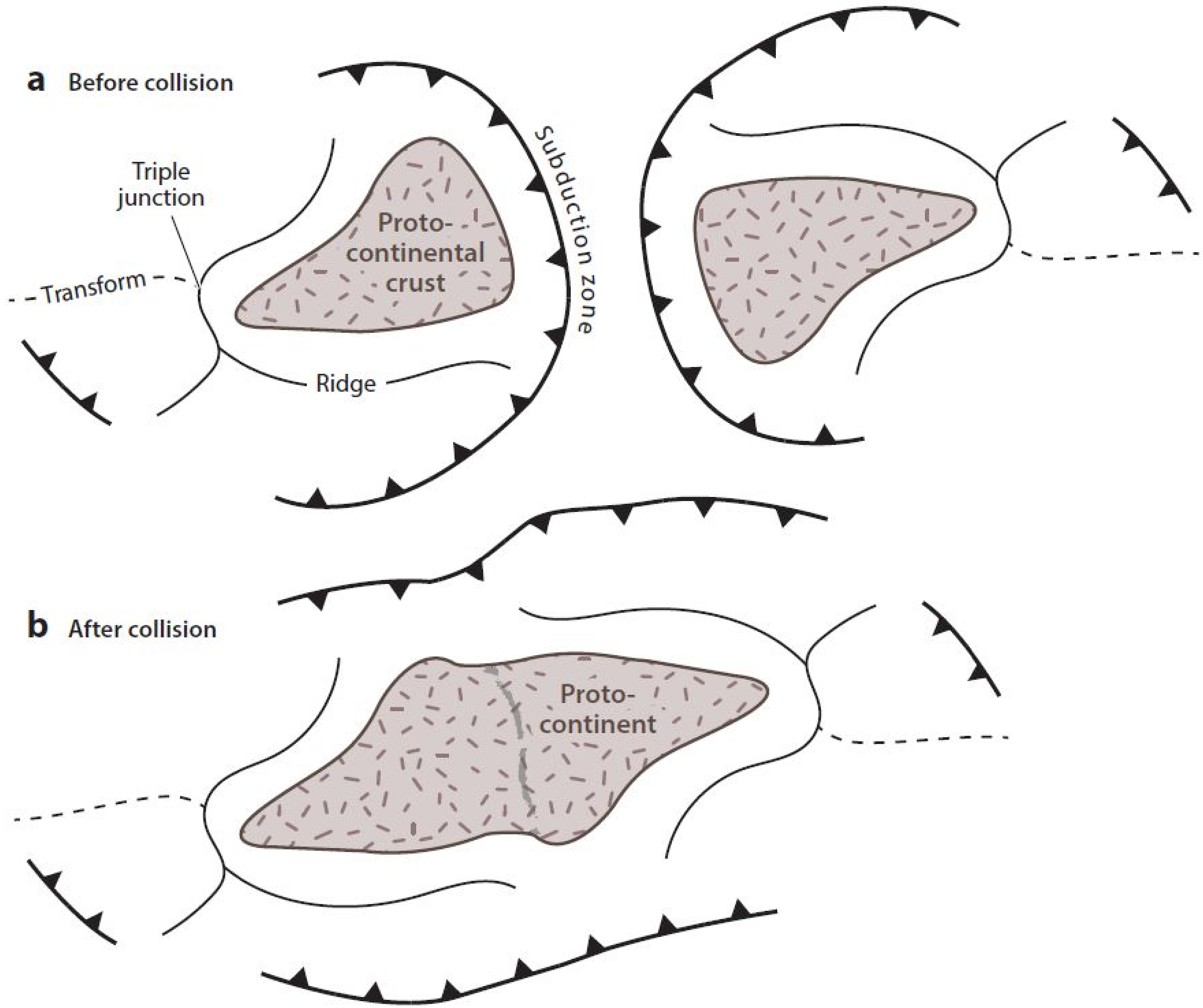
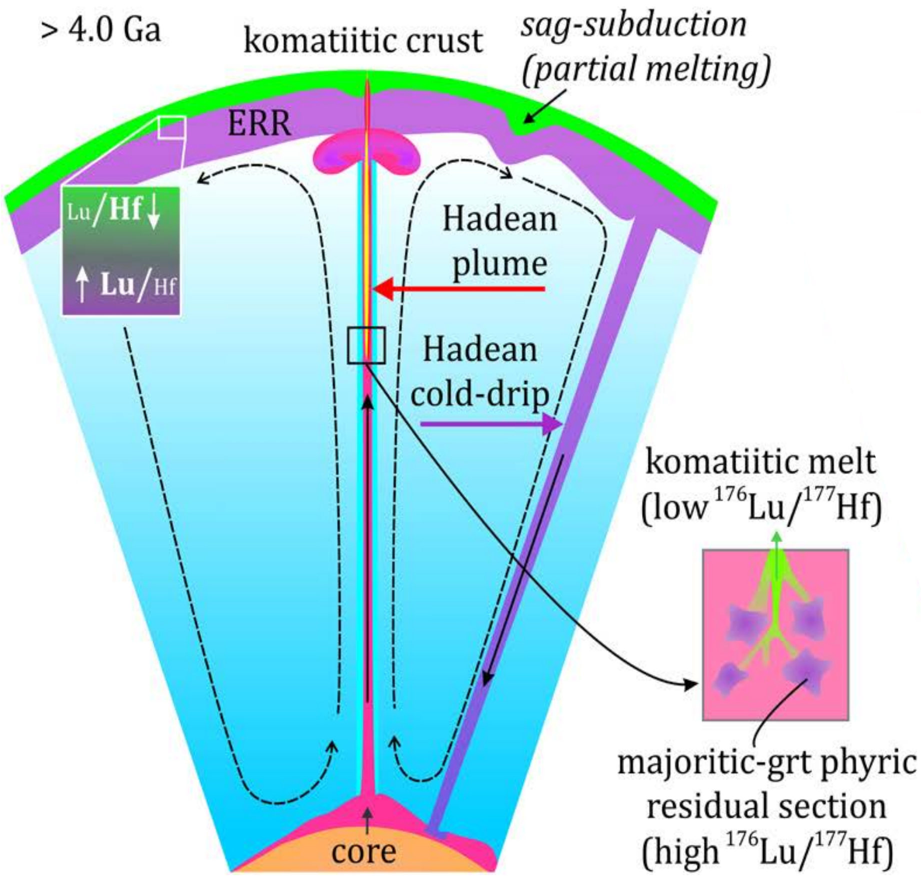


Figure 7

Sketches showing approaching plume-induced subduction cells (*a*) before elimination of the intervening oceanic lithosphere and collision and (*b*) after collision and formation of a proto-continent.

Source: Brown et al. Ann Rev EPS (2020)

Isotopes in early Archean rocks record a plume-driven convection cycle in Hadean

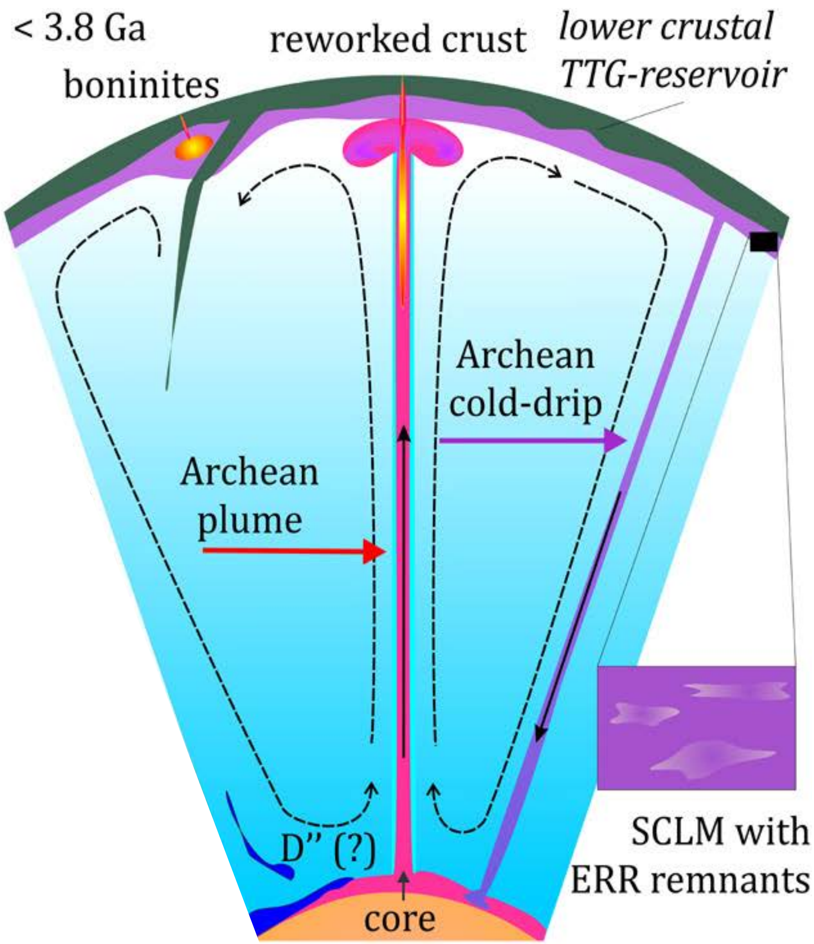


ERR: Early Refractory Reservoir

- Rising mantle plumes melt deep in the hot Hadean Earth.
- The hottest parts of the plume melt deepest, in the presence of majoritic garnet, to produce high-temperature komatiites, leaving a high Lu/Hf ERR residual component in the rising plume.
- The komatiitic melts, together with basaltic melts produced by melting cooler parts of the plume, erupt at the surface to form a thickened komatiitic–basaltic crust, which subsequently melted during burial and produced the preserved Hadean zircons.
- The residual mantle, after plume melting, had a Lu/Hf that was complementary to this Hadean crust.
- This hot residual material continued to rise in the plume and it collected under the Hadean crust where, together with congealed asthenospheric mantle, it formed to the lithosphere under the Hadean crust.
- The ERR was the dominant component of the plume contribution to this lithosphere.

Source: Nebel et al. (2014)

Isotopes in early Archean rocks record a plume-driven convection cycle in Hadean



- Cooling of the lithosphere gave rise to cold drips, which were the dominant form of downward convection in the Hadean mantle.
- These cold drips, which emanate from the base of the lithosphere, include a significant fraction of the ERR.
- The balance of the ERR remained in the Hadean lithosphere, where it was later sampled by melting in Archean subduction zones
- Subsequent convective erosion erased the ERR and incorporated it into the convective mantle over a period of approximately a billion years.

ERR: Early Refractory Reservoir
SCLM: sub-continental lithospheric mantle

Source: Nebel et al. (2014)

Tectonic processes and its control on evolution of lithosphere on early Earth

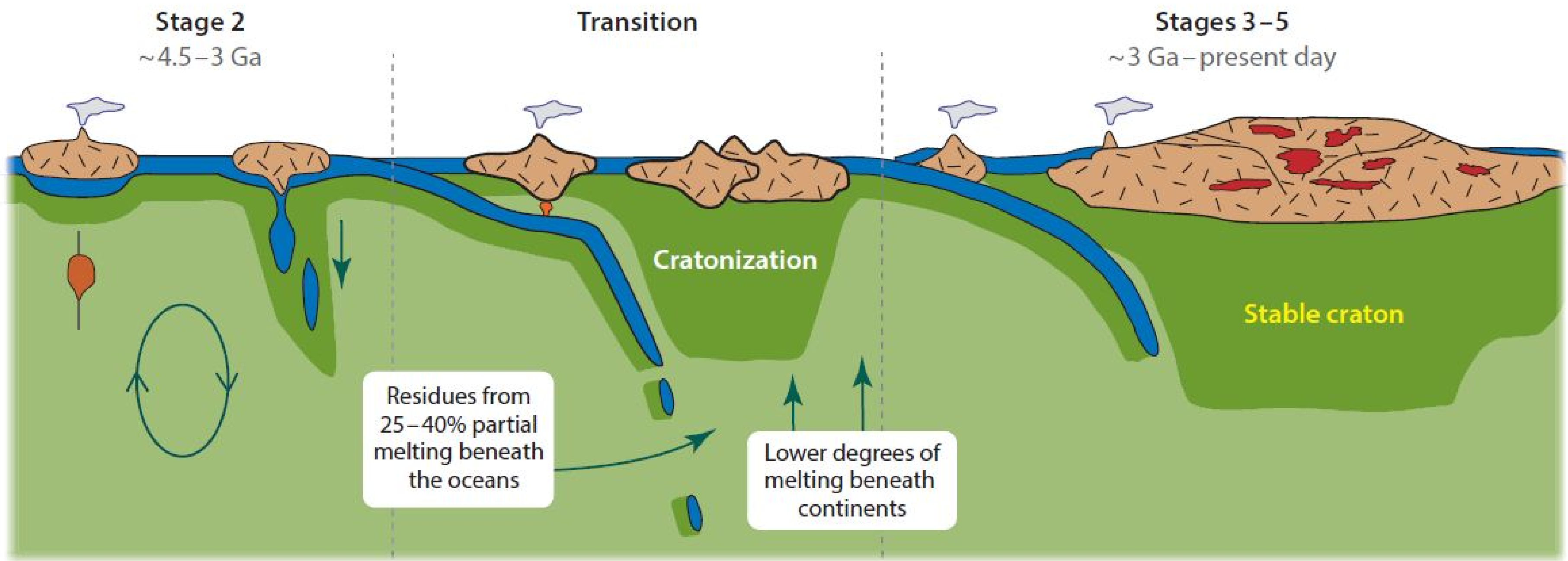


Figure 9

Schematic depiction of changing tectonic processes controlling the evolution of the lithosphere from an early Earth dominated by nonplate processes (stage 2) to one in which plate tectonics is the main mechanism for the generation and recycling of lithosphere (stages 3–5). These changes are a response to the secular cooling of the mantle and the consequent increase in lithospheric strength and rigidity. The mantle xenolith record suggests that they represent residues (from relatively shallow partial melting of hot mantle beneath the oceans), which subsequently accreted beneath continents. In contrast, the mafic crust that is the source of Archean tonalite-trondhjemite-granodiorites has relatively low Lu/Hf and Sm/Nd ratios, implying lower degrees of partial melting.

Source: Hawkesworth et al. Ann Rev EPS (2017)

Tectonic processes on early Earth

- Vertical tectonics:
  stagnant lid separated by a thermal boundary layer from a vigorously convecting Hadean mantle.
  → only single zircon grains remain (predominantly from Australia's Narryer Gneiss Terrane but also other cratons)
- Transitional tectonics:
  Archaean passive stagnant-lid tectonics, with a continuous crustal cover on top of a convecting mantle
- Active plate tectonics:
  Plate tectonics with subduction zones at convergent plate margins shape the Earth surface throughout the Phanerozoic, Proterozoic and possibly part of the Late Archaean
  -> early active plate tectonics: hot subduction
  -> later active plate tectonics: cold subduction

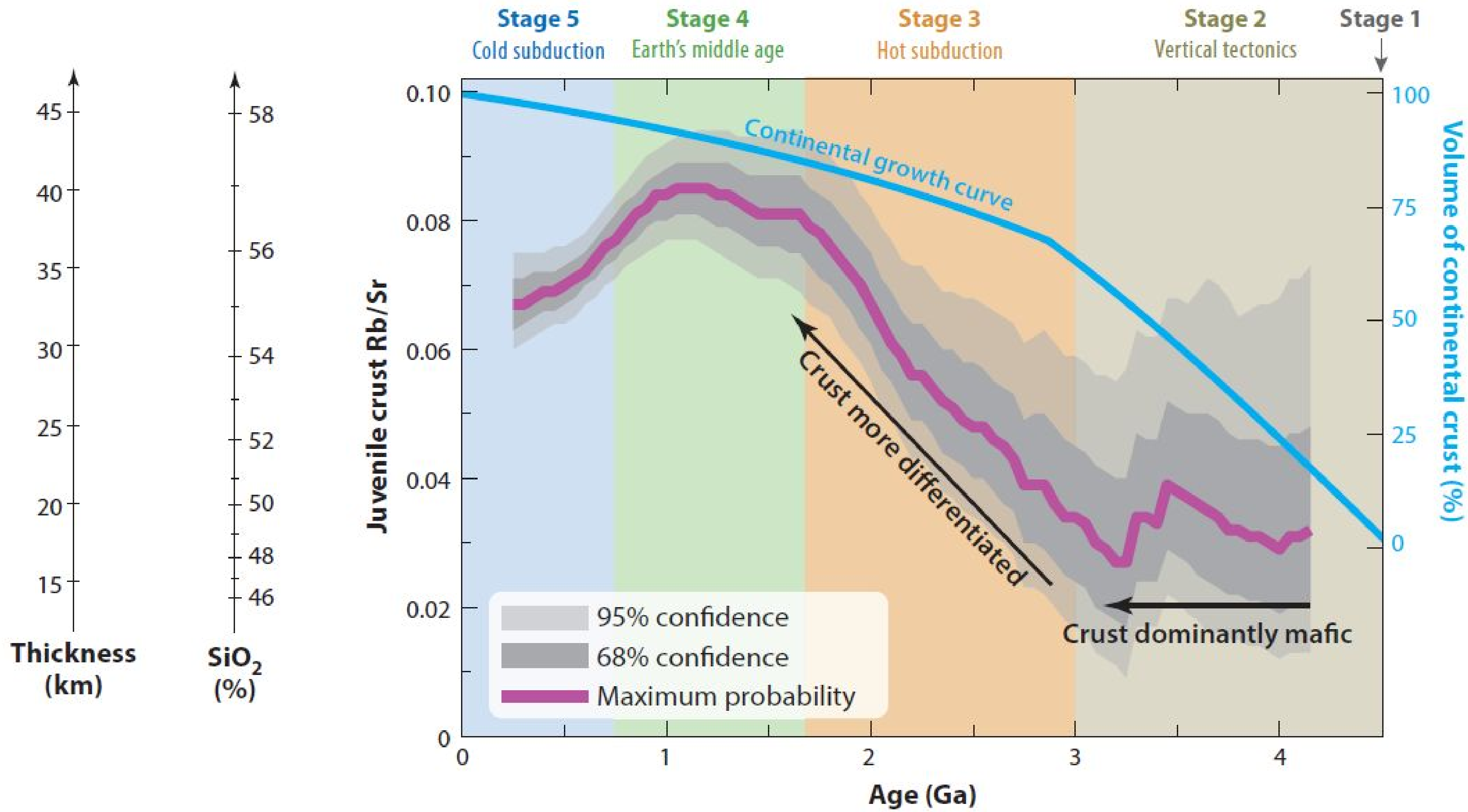
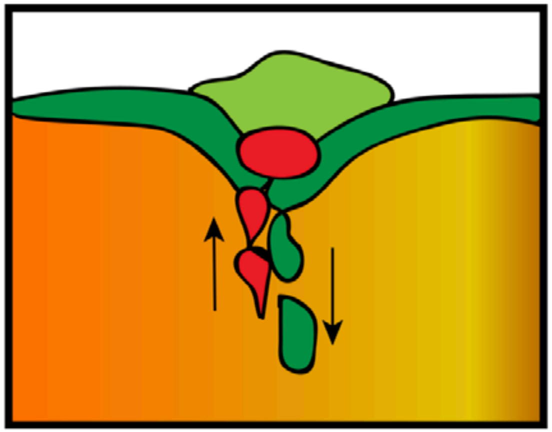


Figure 7

The estimated Rb/Sr ratios of juvenile continental crust plotted against the age of crust formation for ~13,000 whole-rock analyses (Dhuime et al. 2015). Rb/Sr increases with both whole-rock silica content and crustal thickness at the site of magma generation. The calculated volumes of continental crust from Dhuime et al. (2012) are presented for comparison. Stages of Earth evolution: Stage 1 is the early accretion of Earth, which may have persisted for 5–10 Myr (Elkins-Tanton 2008); stage 2 is dominated by vertical tectonics; stage 3 is dominated by hot subduction; stage 4 is Earth's middle age; and stage 5 is characterized by cold subduction.

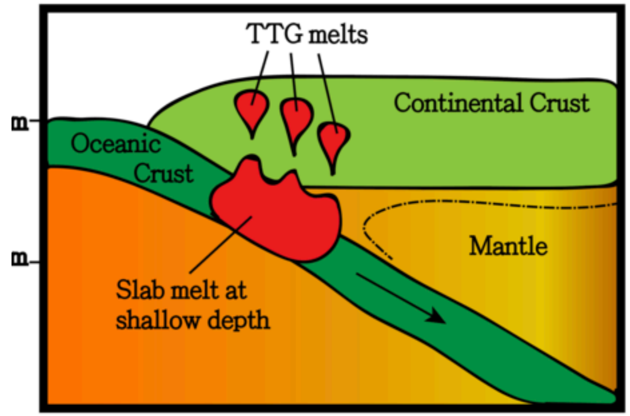
Source: Hawkesworth et al. Ann Rev EPS (2017)

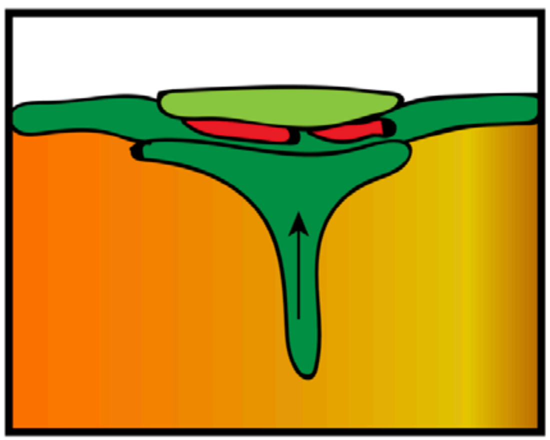
Tectonic processes for the formation of Archean TTGs



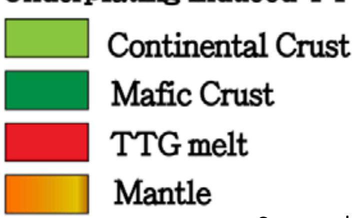
Delamination induced TTG generation

Hypothesized Archean Hot Subduction





Underplating induced TTG generation



<u>Hypothesized Neo-Archean hot subduction:</u>

The subducting slab is young and hot, thus when it is heated, it partially melts to generate TTG magmas, which rise and intrude into the continental crust.

<u>Delamination:</u>

heavier mafic crust delaminates into the lighter mantle.

P, T increases induce partial melting of the delaminated block to generate TTG magma, which rises and intrudes to the crust.

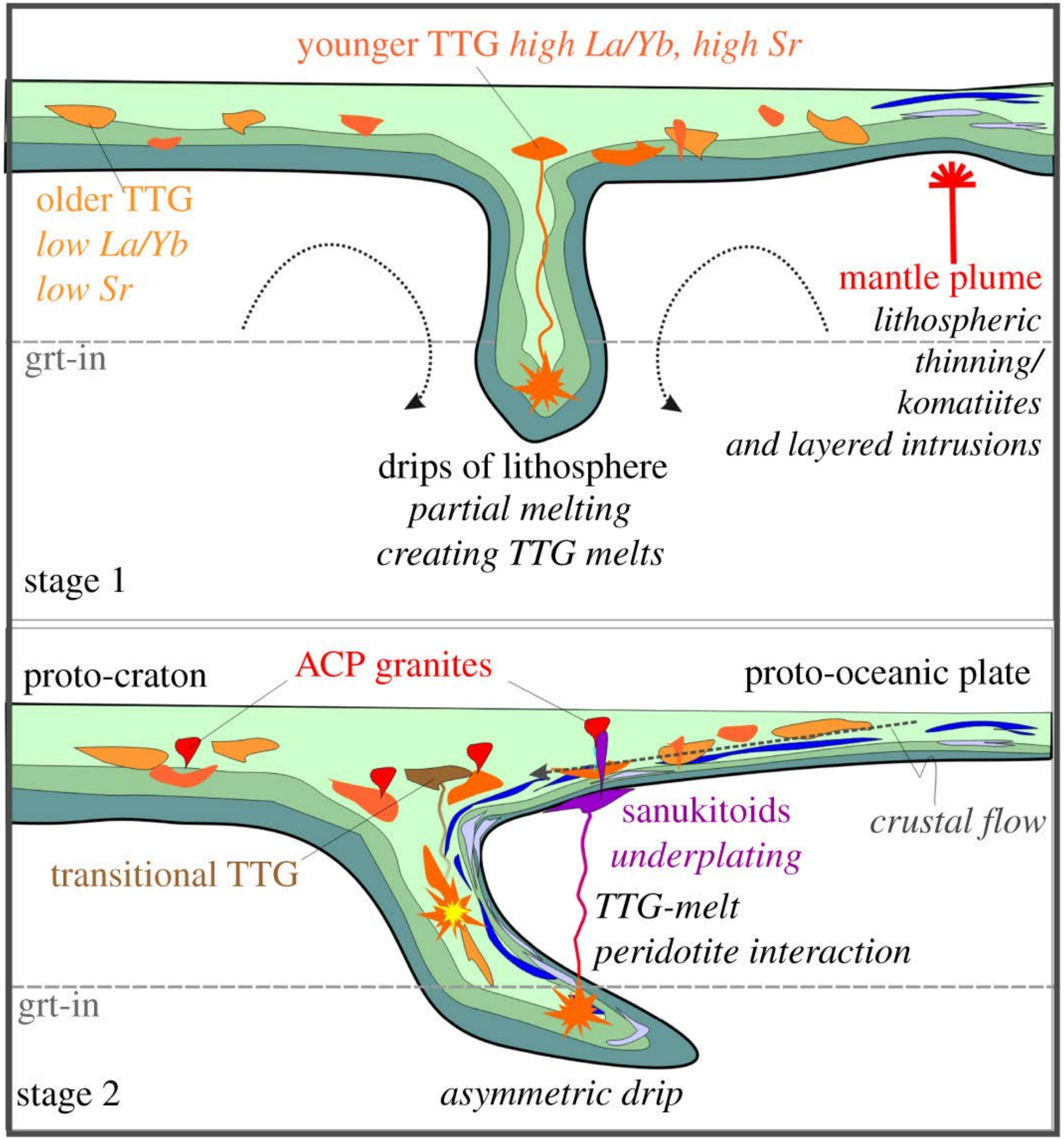
<u>Underplating:</u>

Mantle plume rises to the base of the mafic crust and thickens the crust. The partial melting of the mafic crust due to the plume heating generates TTG magma intrusions.

Source: https://commons.wikimedia.org/w/index.php?curid=74383755

Modified from Moyen & Martin (2012)

Tectonic processes for the formation of TTGs



<u>ACP granites:</u>

Archaean **c**rustal rogeny granites, formed by remelting of earlier, silicic crust.

Plutonic rocks with a markedly elevated K content compared to TTG.

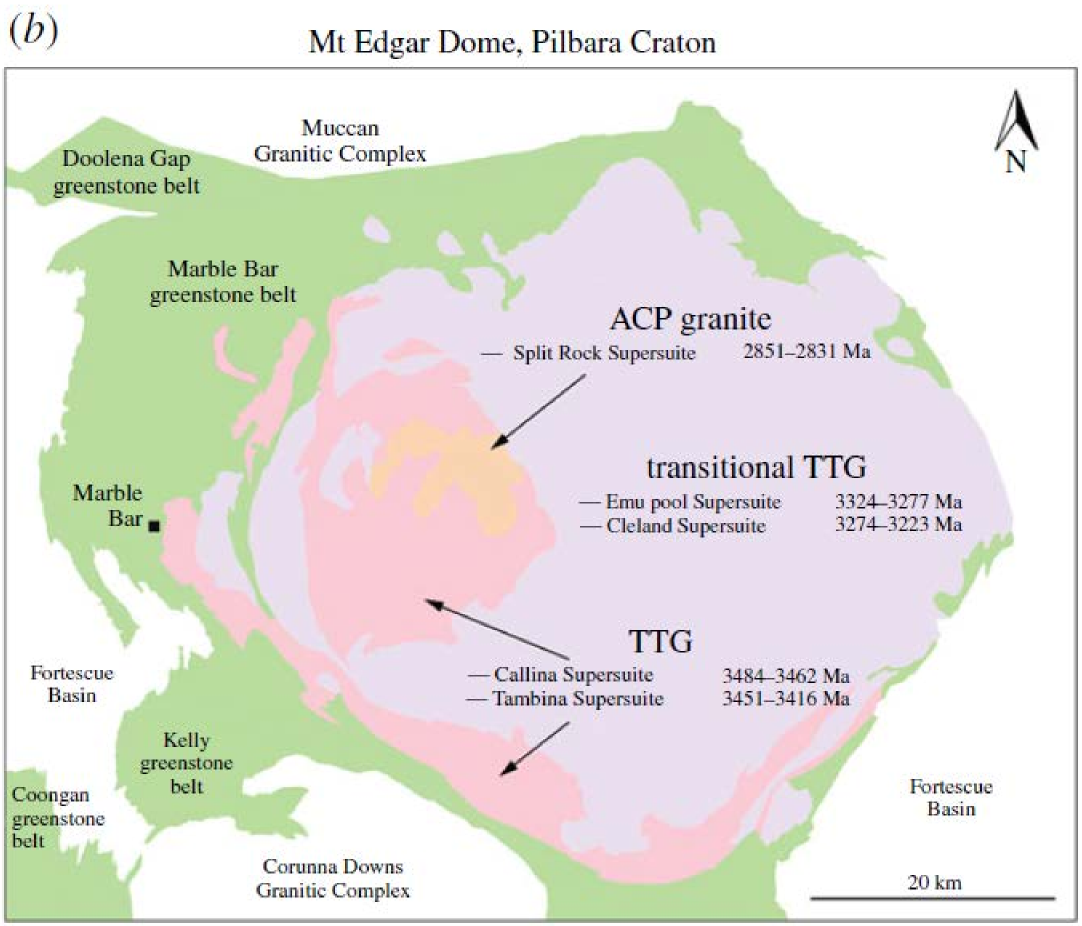
<u>Sanukitoids:</u>

potassic diorites with elevated Mg, Cr and Ni;

Proposed to have formed by interactions of TTG melt with peridotite.

Source: Nebel et al. (2018)

Example of an exposed TTG complex



Source: Nebel et al. (2018)

Concept of melt generation in a broad temporal context on early Earth

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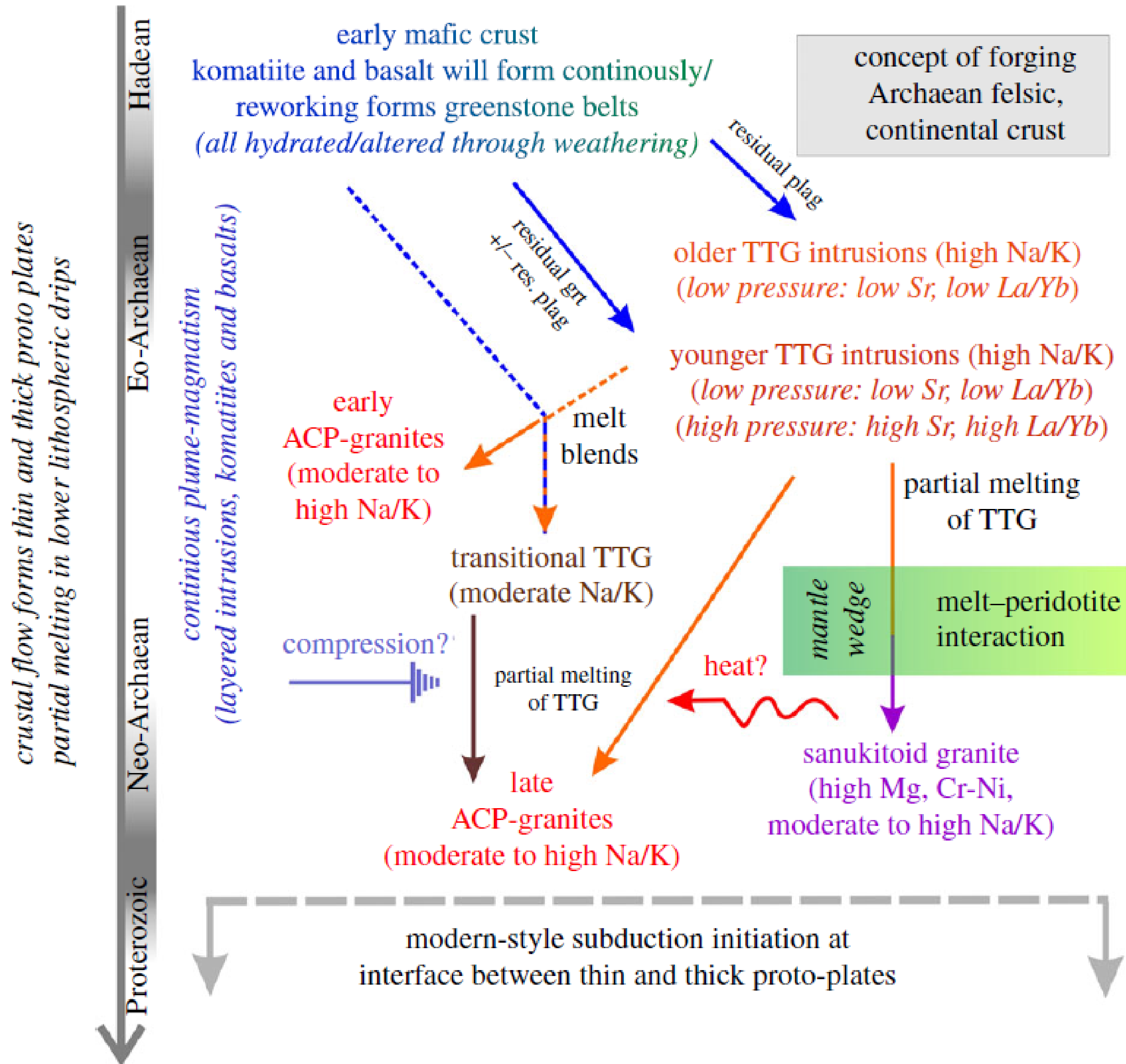


Source: Nebel et al. (2018)

Concept of melt generation in a broad temporal context on early Earth

term	definition in this contribution
TTG	tonalite–trondhjemite–granodiorite; a plutonic rock series that is characterized by high Na_2O/K_2O; towards the Mid- to Late Archaean elevated Sr/Y and heavy rare-earth element depletion through retention in residual garnet and/or amphibole during partial melting become increasingly common proposed to be derived from melting of (hydrous) mafic successions trondhjemites versus tonalites may be a function of pressure of melting
transitional TTG	similar to TTG, but with a spectrum of K content intermediate between TTG and ACP granites within Archaean Domes typically offset from TTG melts by 100–300 Ma, in the North Kaapvaal craton of South Africa often dispersed within TTG gneisses
sanukitoids	potassic diorites with elevated Mg, Cr and Ni; Proposed to have formed by interactions of TTG melt with peridotite. The sanukitoids s.s. are the root of a series of more differentiated rocks (sanukitoid suite)
ACP granites or high-K granites	Archaean crustal progeny granites, formed by remelting of earlier, silicic crust. Plutonic rocks with a markedly elevated K content compared to TTG. Plausible petrogenetic models to create elevated K contents granitic melts towards the Mid- to Late Archaean argue for a re-melting of earlier TTG succession. For this, petrologic phase equilibria require either excess heat in TTG-bearing crust, or elevated pressure–temperature through subsidence
stagnant lid	the entire lithosphere of the planet that covers the mantle as a lid without active tectonics. Sporadic subduction is possible; the lid is characterized by felsic intrusions into a stationary lithosphere
(down- or lithospheric) drips	drip of the lowermost lithosphere into the underlying mantle, initiated by converging convection cells. These drips have a limited lifespan of several hundreds of millions of years and occur randomly between rather small convection cells

Source: Nebel et al. (2018)

Plate Tectonics and the Archean Earth

Summary Points

1. Before the Mesoarchean–Neoarchean, a stagnant lid or sluggish lid or lid and plate tectonics mode, with a deformable (squishy) lithosphere and either intermittent (unstable) subduction or subduction on a locally confined scale, may have been dominant. A hotter mantle prohibited widespread stable subduction and plate tectonics, and magmatism was largely due to upwelling mantle and plume–lithosphere interactions.
2. During a Mesoarchean–Neoarchean transition, as secular cooling overwhelmed heat production, plate tectonics emerged, possibly in part via plume-initiated retreating subduction cells that generated proto-continents.
3. The rise of proto-continents and enhanced erosion to provide sediments at their edges may have enabled initiation of subduction under the proto-continents by spreading of continental margins over oceanic lithosphere. This process could have stabilized subduction and promoted the spread of plate tectonics globally, as recorded by the widespread appearance of high and intermediate T/P metamorphism in the Neoarchean.
The formation and breakup of the supercratons, and the formation of the first supercontinent Columbia, demonstrate that plate tectonics was fully developed by the early Paleoproterozoic.

Source: Brown et al. Ann Rev EPS (2020)

Plate Tectonics and the Archean Earth

Future Issues

1. Geochemical criteria need to be identified to distinguish impact-induced from plume-induced melt products, so that we may determine the contribution of each process to the formation of the Hadean and Eoarchean tonalite-trondhjemite-granodiorite crust.
2. To evaluate hypotheses regarding the tectonics of early Earth, it is necessary to increase the number of metamorphic pressure, temperature, and age data from exposures of ancient (older than 2.8 Ga) continental crust worldwide. Retrieval of such data should be a priority of metamorphic studies.
3. To understand secular change in tectonics on Earth requires a better knowledge of the thermal evolution of Earth and mantle potential temperature and further research to resolve the contentious issue of the amount and temporal evolution of water in the mantle.
4. To understand the evolution of life on Earth, it is necessary to assess linkages between secular change in tectonic mode and the evolution of Earth's atmosphere, oceans, and landscape, since these control nutrient supply and environment.

Source: Brown et al. Ann Rev EPS (2020)

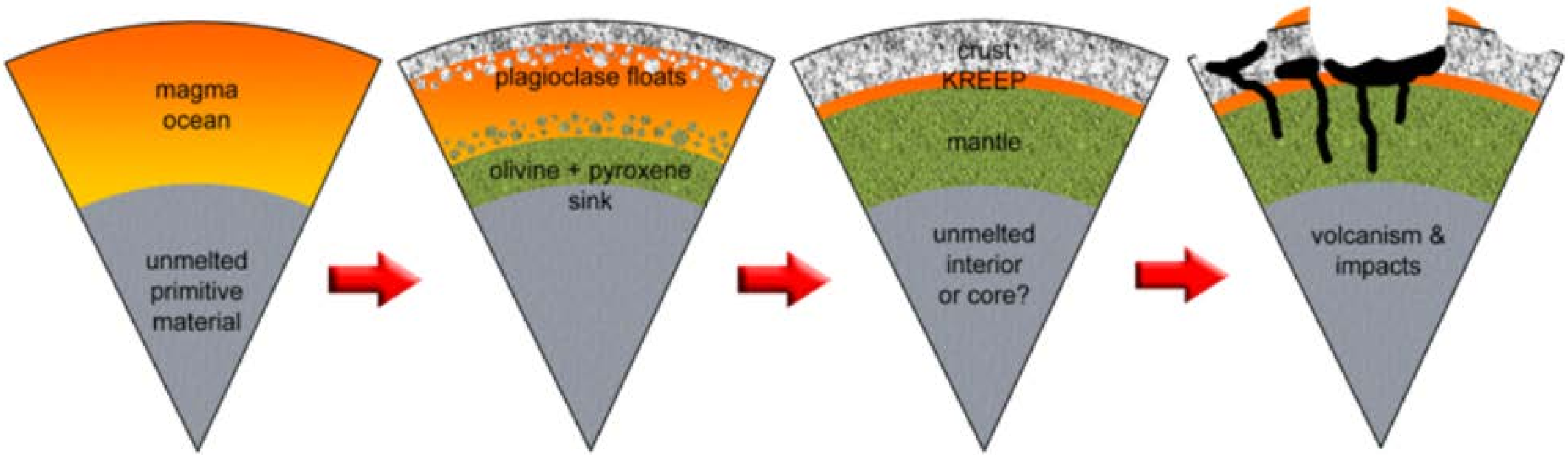
WATER IN THE EARTH

An additional complication is the critical control of water on the viscosity of the mantle. Unfortunately, how water has been distributed between the interior and surface of Earth through time is uncertain. Some have argued that present-day Earth's mantle may be highly outgassed, containing only a small fraction of its original water content. Others have suggested that Earth in the Hadean had abundant surface water and a dry mantle, implying that regassing of the mantle has dominated Earth evolution. However, recent research has demonstrated that a deep hydrous mantle reservoir has been present in Earth's interior since at least the Paleoarchean. This is another unsolved and highly contentious issue that is fundamental to the question of whether plate tectonics could have operated on the Archean Earth, but one that is beyond our scope here.

Source: Brown et al. Ann Rev EPS (2020)

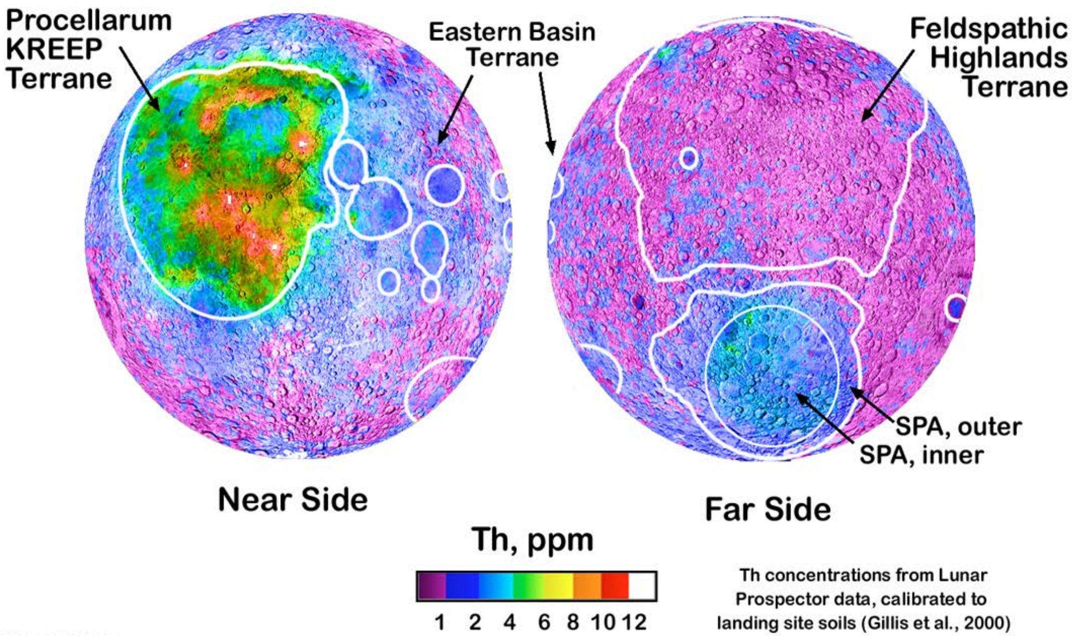
Lunar petrological evolution

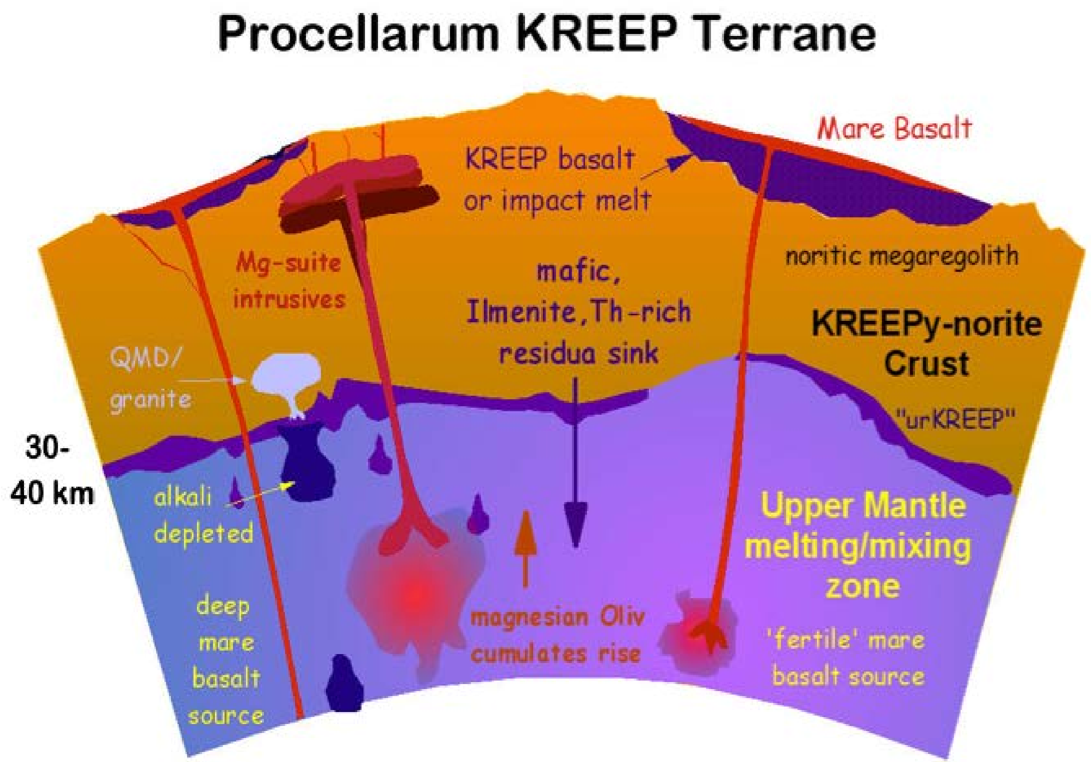
- Differentiation via igneous processes
- Basaltic volcanism via mantle density overturn
- Incompatible elements in KREEP layer
- Redistribution by impact processes



Lunar KREEP Basalts

Thorium map of the Moon outlining the area of the Procellarum KREEP Terrane on left, on the Moon's Earth-facing side.

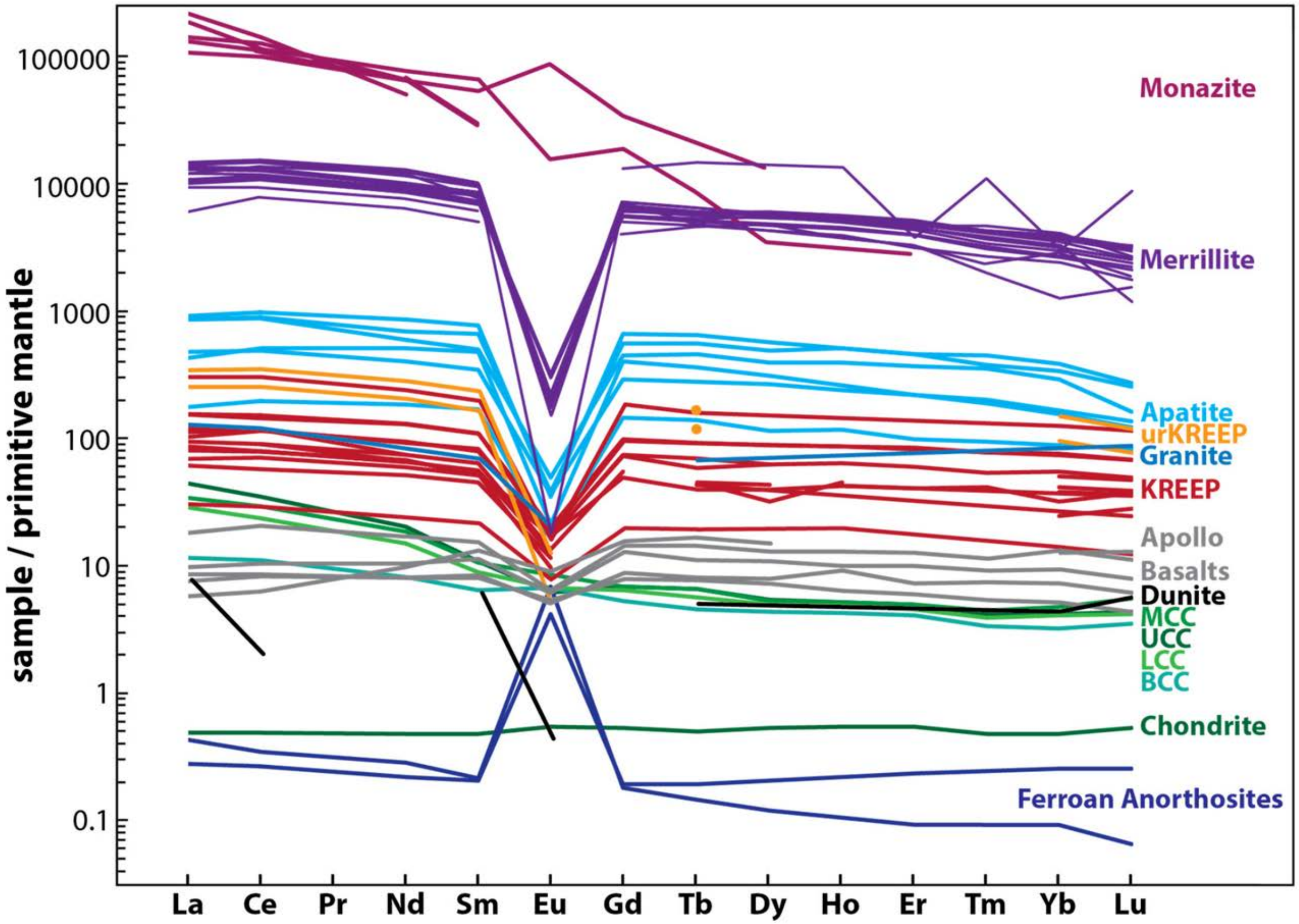




Schematic cross section illustrating some of the magmatic and volcanic processes that may have occurred in the Procellarum KREEP Terrane.

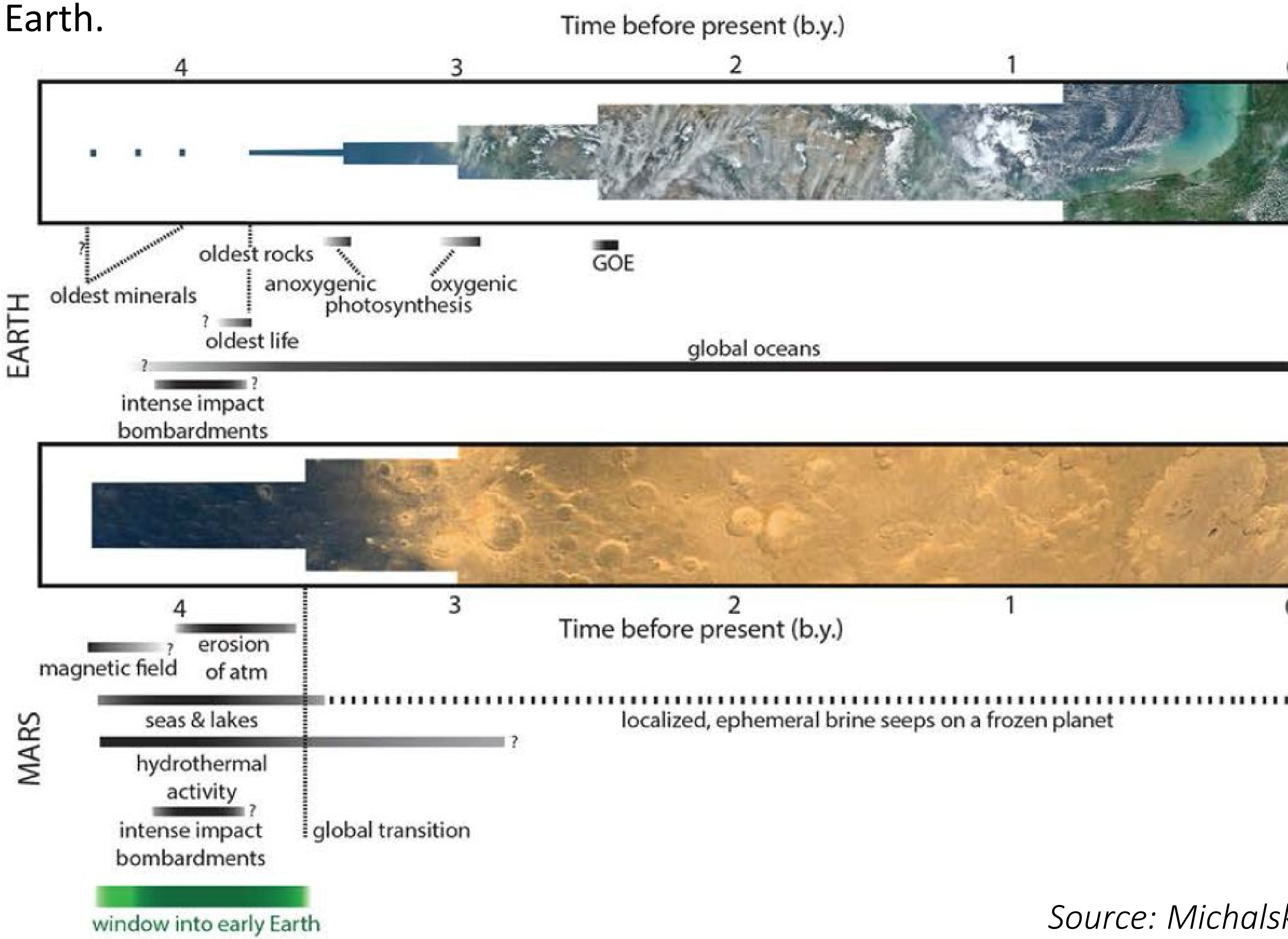
(Jolliff et al., 2000)

REE in terrestrial and lunar basalts



A comparison of key events in the histories of the Earth and Mars.

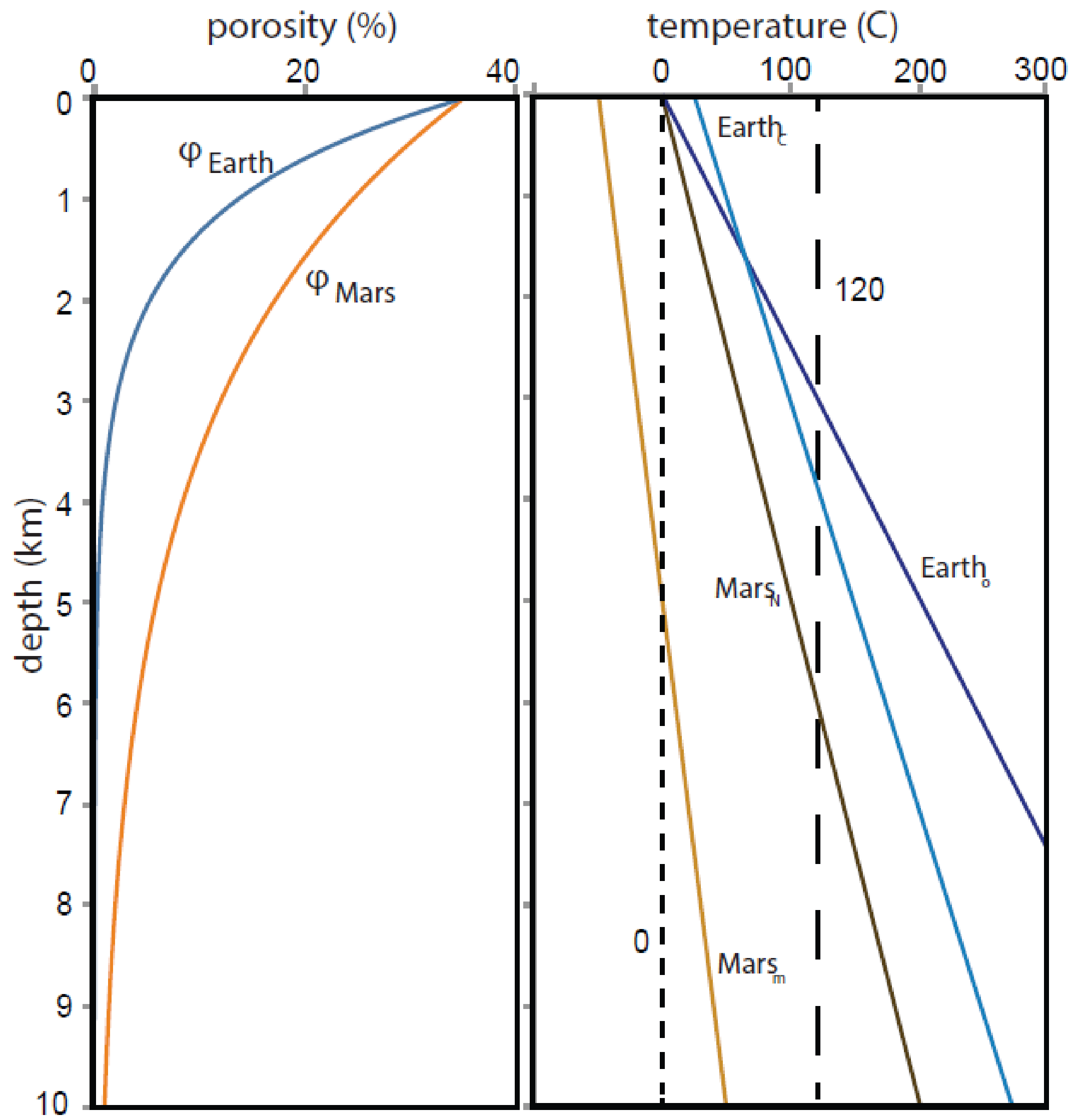
The area of each time line is an approximation of the amount of crust preserved from over different epochs. The generally unmetamorphosed and well-preserved geologic record of early Mars is an invaluable window into the geology and prebiotic chemistry of the early Earth.



Source: Michalski et al.

A comparison of the average porosity of thermal gradients of the crusts of Earth and Mars.

For similar rock types and surface porosities, the martian crust contains significantly more porosity to greater depth than that of the Earth (left). Estimated thermal gradients for Noachian (ϕN) and modern (ϕm) Mars are lower than that of the modern continental (ϕc) or oceanic (ϕo) crust of Earth (right). A hypothetical 120ºC limit is encountered at 3-4 km depth on Earth, where the porosity is 1-2%. The same temperature limit would not be encountered until ~6 km depth on Noachian Mars or much deeper on modern Mars.



Source: Michalski et al.

BREAK

Hydrothermal Alteration & Fluid-Rock Interaction

Metamorphism: isochemical change of rocks in response to P-, T- changes and/or directed stress

Metasomatism: change of chemistry of the rocks, usually as result of fluid rock interaction

→ Hydrothermal alteration is causing metasomatic changes.

Hydrothermal Fluids: usually hot water with dissolved ions and volatiles

Hydrothermal alteration does critically depend on:

- chemical composition of rock (mineral assemblage, glass, ..)
- physical properties of the rock
    - connected pore space (accessible to fluids)
    - permeability
    - internal surface area
- amount of hydrothermal fluid, and flow speed
- composition of the hydrothermal fluid, thus its pH-value, ionic strength, oxigen fugacity, ...
- temperature
- pressure
- exposure time

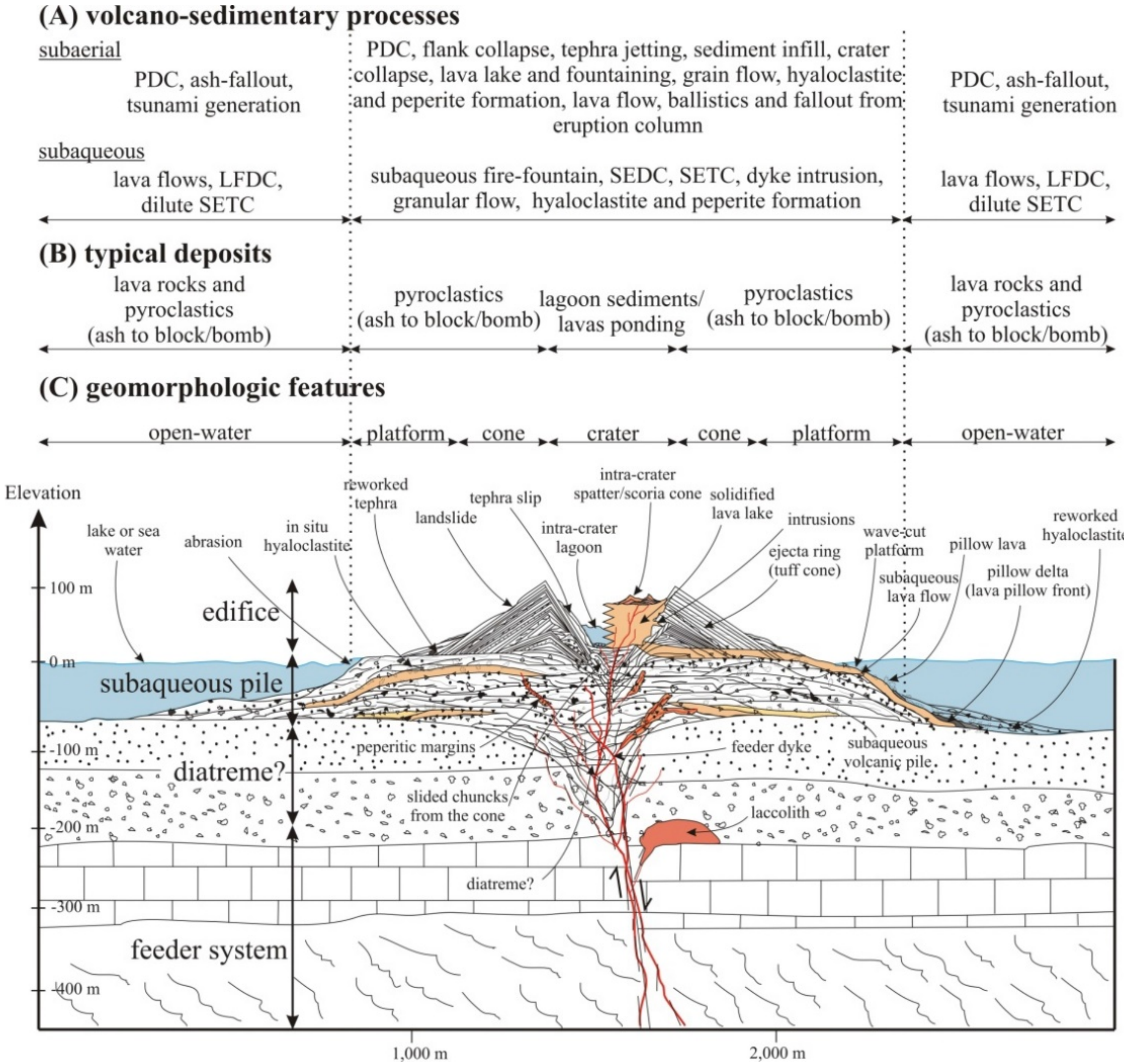
Hydrothermal Alteration & Fluid-Rock Interaction

Next we will explore a few types and settings:

- Palagonitization
- Serpentinitization

- Submarine hydrothermal vents
- Terrestrial hydrothermal systems, hot pools & geysirs

Tuff Cone



(A) volcano-sedimentary processes
subaerial
PDC, ash-fallout, tsunami generation
PDC, flank collapse, tephra jetting, sediment infill, crater collapse, lava lake and fountaining, grain flow, hyaloclastite and peperite formation, lava flow, ballistics and fallout from eruption column
PDC, ash-fallout, tsunami generation
subaqueous
lava flows, LFDC, dilute SETC
subaqueous fire-fountain, SEDC, SETC, dyke intrusion, granular flow, hyaloclastite and peperite formation
lava flows, LFDC, dilute SETC
(B) typical deposits
lava rocks and pyroclastics (ash to block/bomb)
pyroclastics (ash to block/bomb)
lagoon sediments/ lavas ponding
pyroclastics (ash to block/bomb)
lava rocks and pyroclastics (ash to block/bomb)
(C) geomorphologic features
open-water
platform
cone
crater
cone
platform
open-water
Elevation
100 m
0 m
-100 m
-200 m
-300 m
400 m
edifice
subaqueous pile
diatreme?
feeder system
lake or sea water
abrasion
in situ hyaloclastite
reworked tephra
landslide
tephra slip
intra-crater lagoon
intra-crater spatter/scoria cone
solidified lava lake
intrusions
ejecta ring (tuff cone)
wave-cut platform
subaqueous lava flow
pillow lava
pillow delta (lava pillow front)
reworked hyaloclastite
peperitic margins
feeder dyke
subaqueous volcanic pile
slided chuncks from the cone
laccolith
diatreme?
1,000 m
2,000 m

Fluid-Rock Interaction: Palagonitization

Palagonite = alteration product of basaltic glass in interaction with water.

→ quite fast interaction between water and basaltic melt / hot pyroclasts:
- + effusive submarine volcanism: pillow lavas,
- + explosive subglacial or shallow submarine eruptions, forming tuff cones (light colored, often brownish palagonite tuff cones)

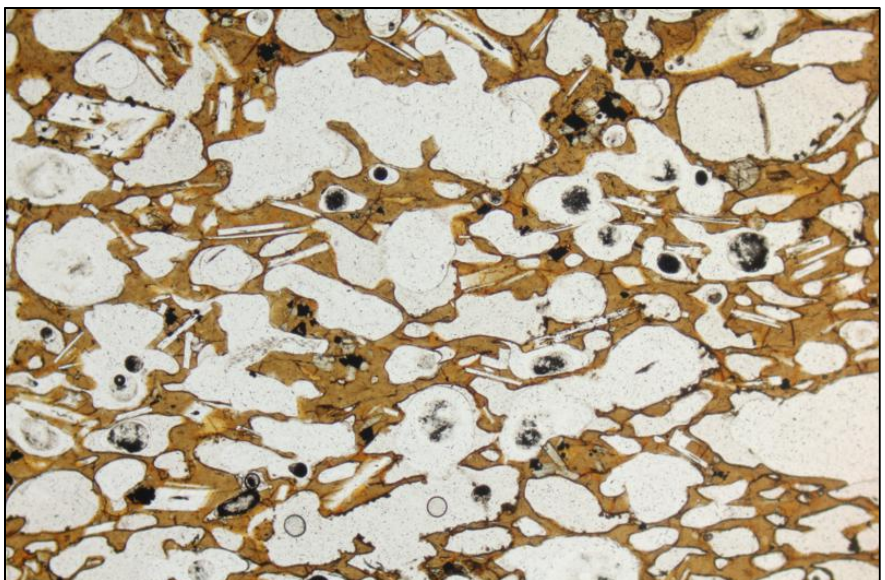
→ slower weathering of lava into palagonite:
- + thin, yellow-orange rind on the surface of the rock.

Palagonitization = process of conversion of mafic glass to palagonite.

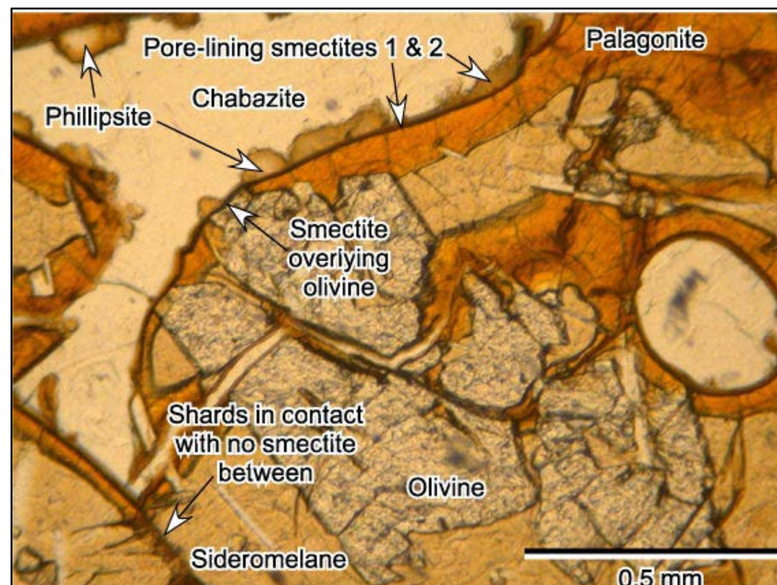
Fluid-Rock Interaction: Palagonitization

Palagonite = alteration product of basaltic glass in interaction with water.

Palagonite amorphous → **AGS I** mix palagonite & crystalline phases → **AGS II** mainly crystalline → **Smectite**



Glass fragment, plagiolcase crystals and vesicles in a Hyaloclastite.



Fractured hyaloclastite shards coated with brown pore-lining smectite

Fluid-Rock Interaction: Palagonitization

→rinds of variable thickness on every mafic glass surface exposed to aquatic fluids.

→formed by dissolution of glass with contemporaneous precipitation of insoluble material at the glass–fluid interface.

→The process of palagonitization is accompanied by extensive mobilization of all elements involved in the alteration process, resulting in the depletion or enrichment of certain elements.

→Extent, direction & rate of element mobility and the palagonitization process itself depend on a number of different, complex interacting properties:

(1) temperature,
(2) time,
(3) structure of the primary material,
(4) reactive surface area of the primary material,
(5) structure of the precipitating secondary phases
(6) growth rates of the secondary phases,
(7) fluid properties such as fluid flow rates, pH, Eh, ionic strength, and oxygen fugacity.

Fluid-Rock Interaction: Palagonitization

- Process of glass palagonitization is a two-stage process:
  1) glass dissolution
  2) palagonite precipitation

  → these 2 processes have different controlling mechanisms, as well as complex feedback mechanisms.

- Exact reaction mechanisms of palagonitization so far remain controversial

→ 4 general theories for the reaction kinetics of glass dissolution:

1. "Precipitate–layer hypotheses", according to which the primary phase is protected by a precipitate layer. Alteration is thus controlled by diffusion through this precipitate layer.
2. "Surface-reaction hypotheses", according to which the alteration rate is controlled by reactions occurring at the primary phase–fluid interface.
3. "Leached-layer hypotheses", in which diffusion through a cation-depleted layer controls the release of other cations deeper in the primary material. At more advanced stages, a steady state is developed between dissolution and development of the leached layer.
4. "Hydrated-layer hypotheses", according to which a hydrated layer develops before dissolution of the primary phase. Alteration is thus controlled by diffusion of fluids into the primary phase.

Fluid-Rock Interaction: Palagonitization

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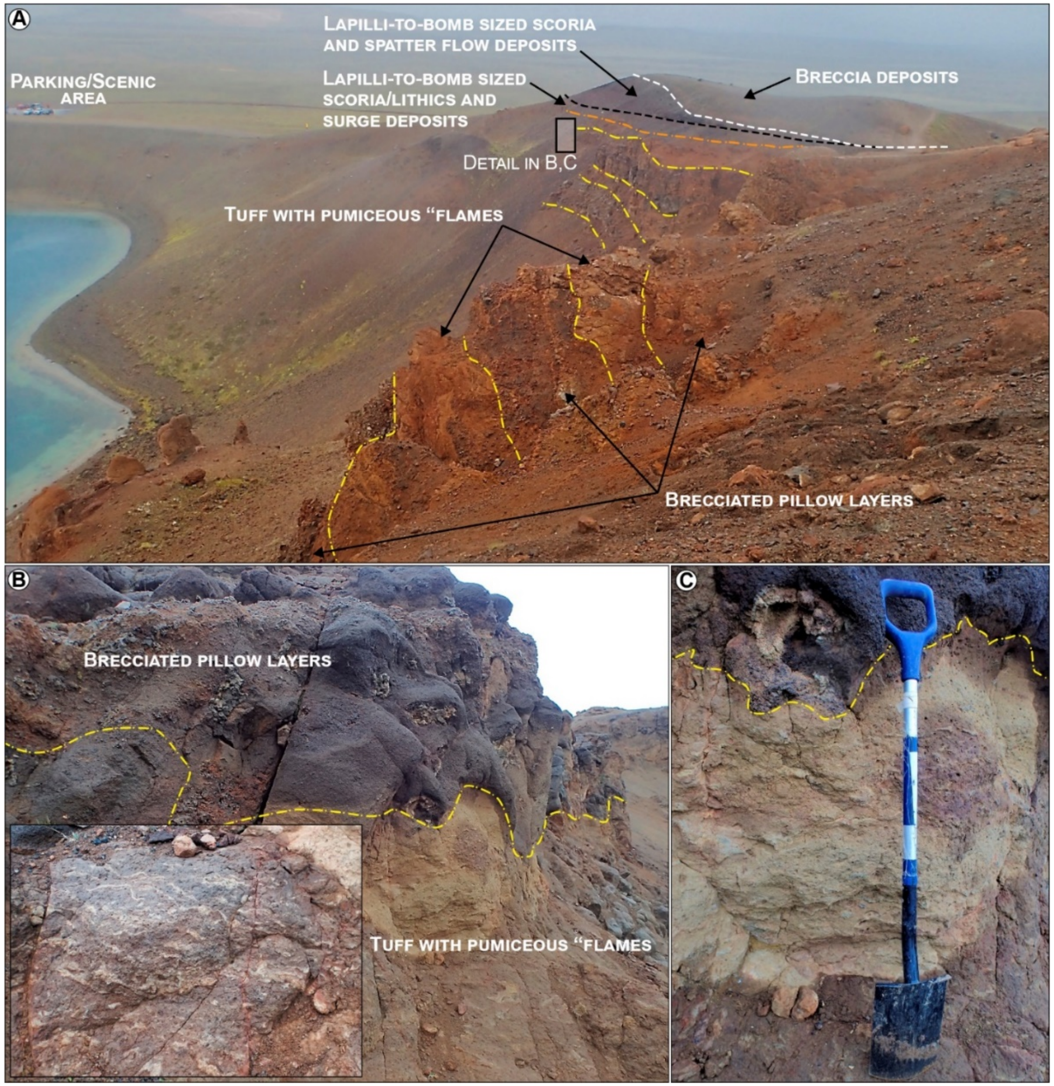
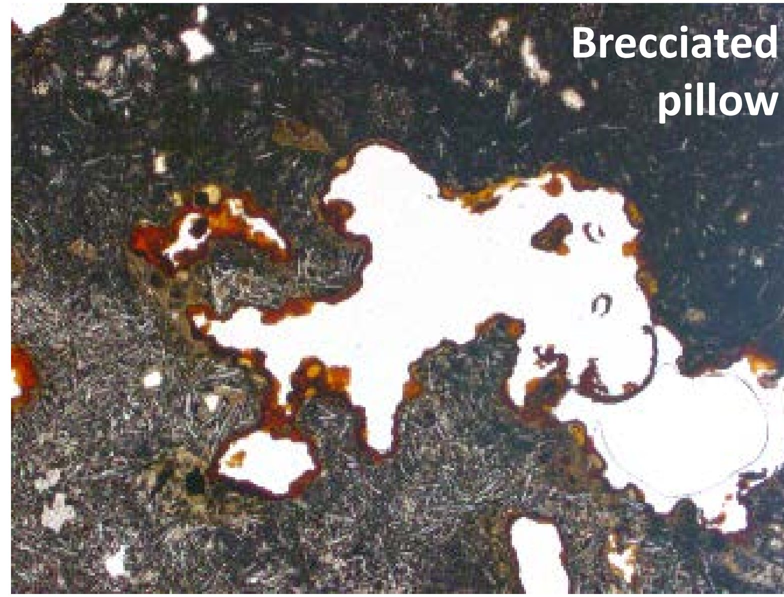
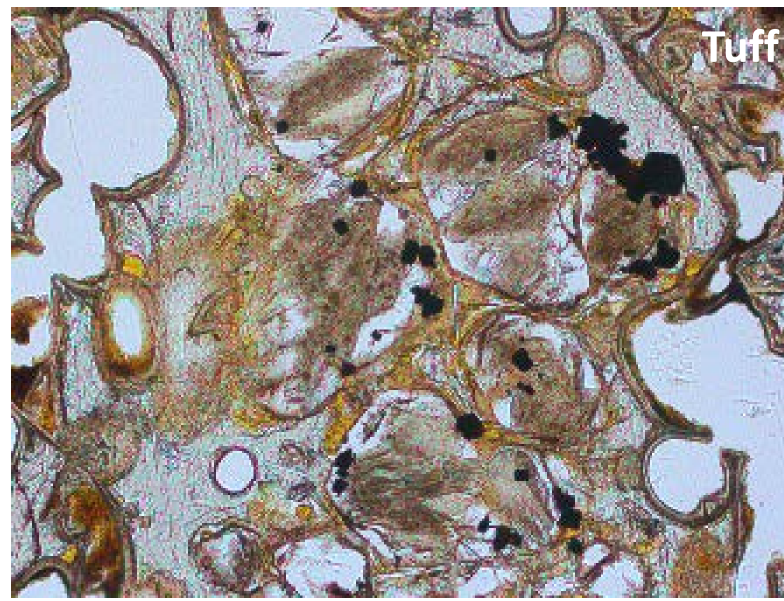
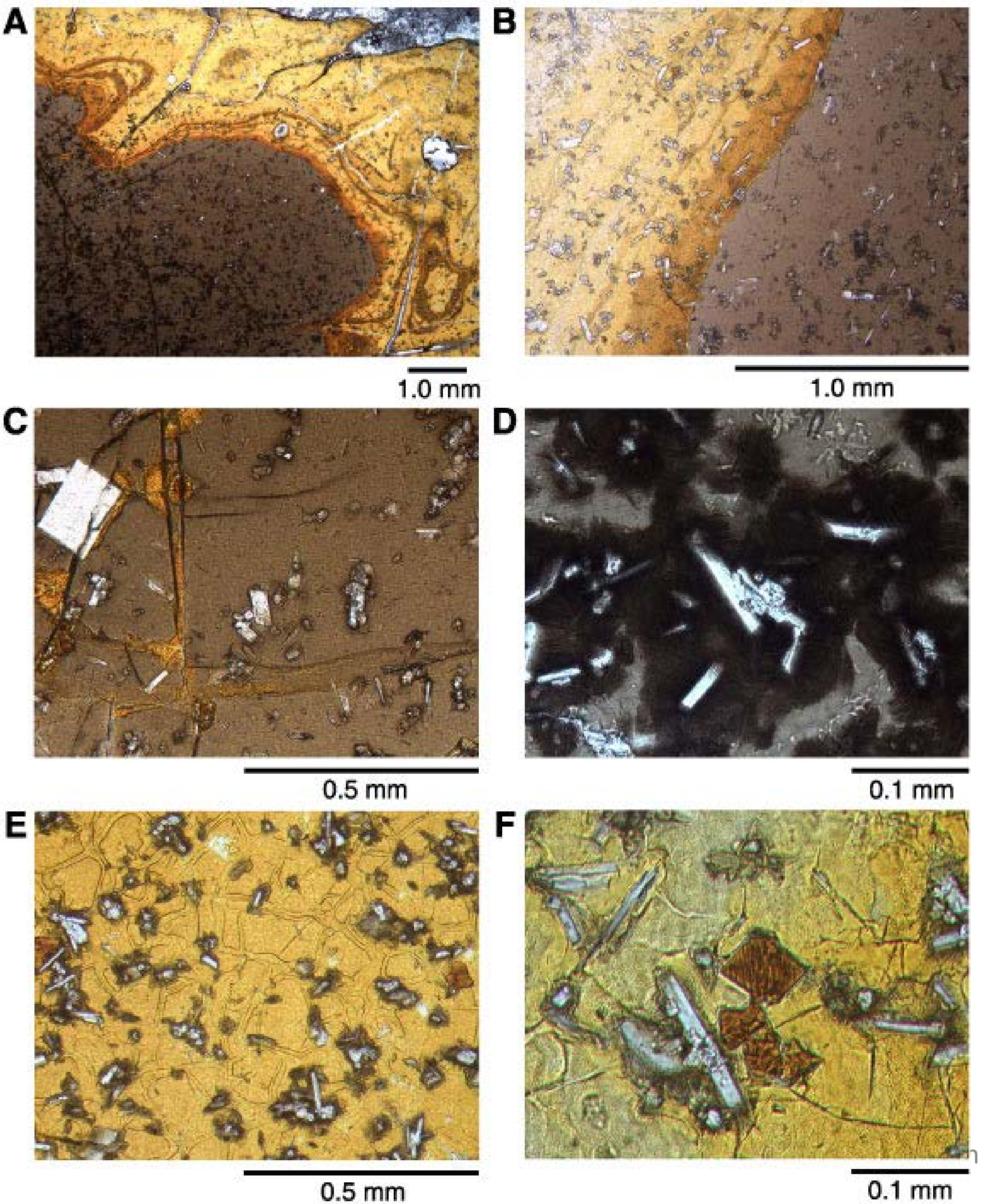






Fluid-Rock Interaction: Palagonitization



Features of a hyaloclastite:

A. A palagonitic rim (yellow) embayed along cracks into fresh basalt glass .

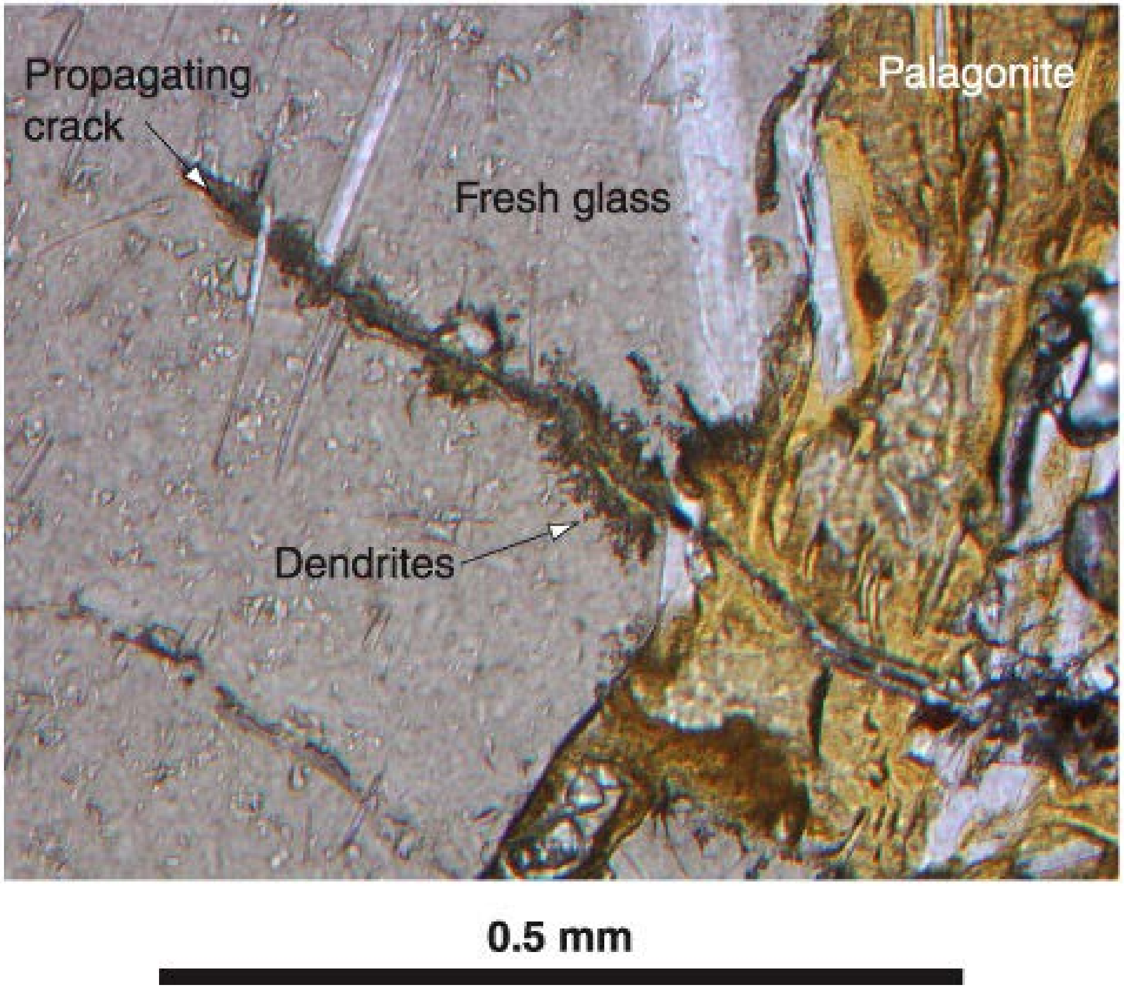
B. Layered palagonite rim (left) next to fresh glass. Note the sharp boundary. **C.** Detail of fresh quenched glass at the edge of a breccia shard showing small plagioclase euhedra and tiny acicular plag crystals, some of them intergrown with cpx. A fracture lined with palagonite cuts vertically through the section. **D.** Individual tabular crystals of plag and plag-cpx intergrowths coated with dark-brown spherulitic material near the edge of a glass shard.

E. Palagonite replacing glass with acicular needles of plag and stellate plag-cpx intergrowths. Most crystals are coated with a thin rim of brown spherulitic material. Note the fracture pattern in the altered glass.

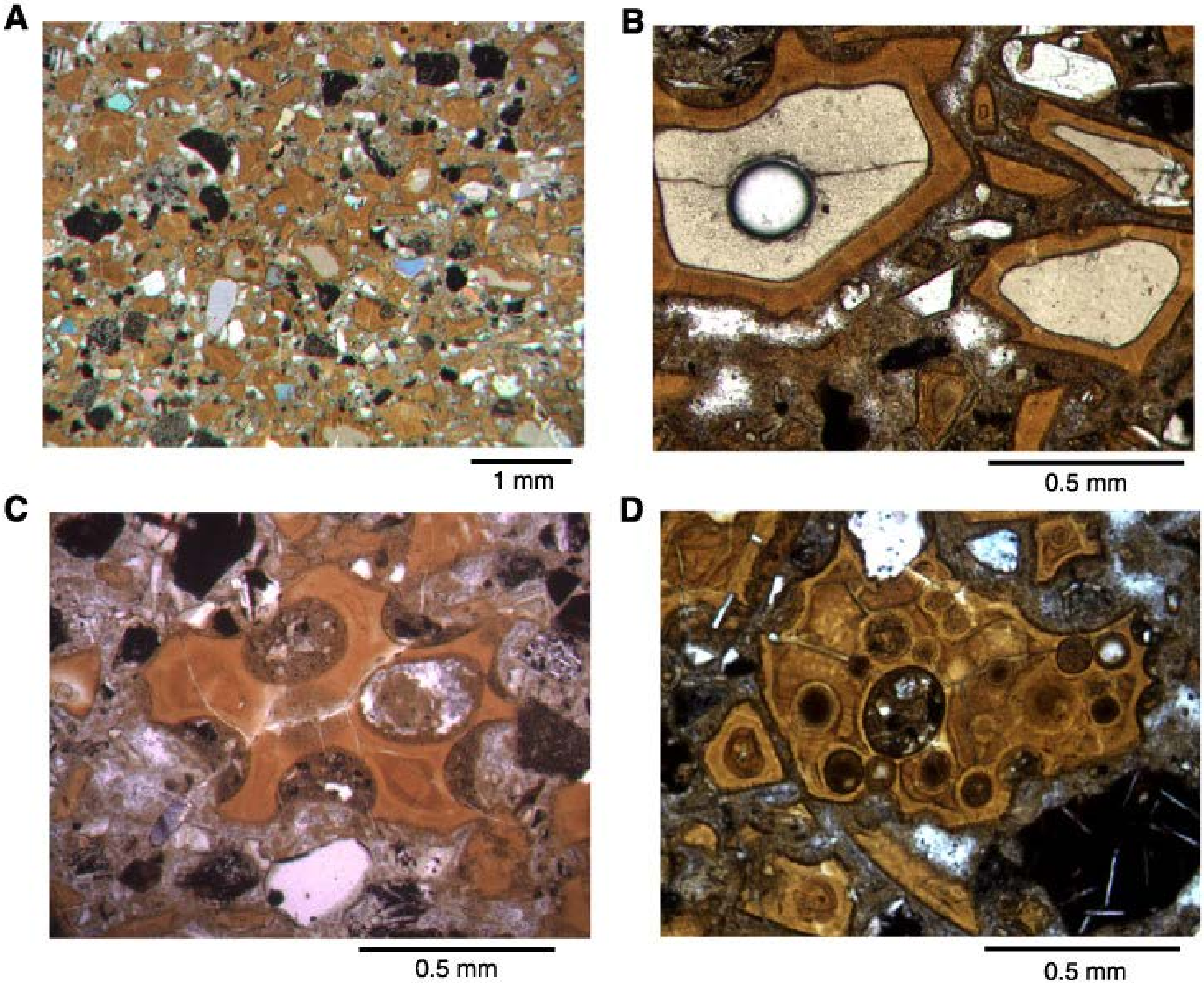
F. Detail of a palagonitized glass shard showing crystal intergrowths and an altered skeletal olivine replaced by orange secondary minerals.

Fluid-Rock Interaction: Palagonitization

Basaltic glass altered to yellowish brown-orange palagonite.
Note the early stages of palagonitization surrounded by dendrites along the crack, aligned perpendicularly to the palagonitization front.



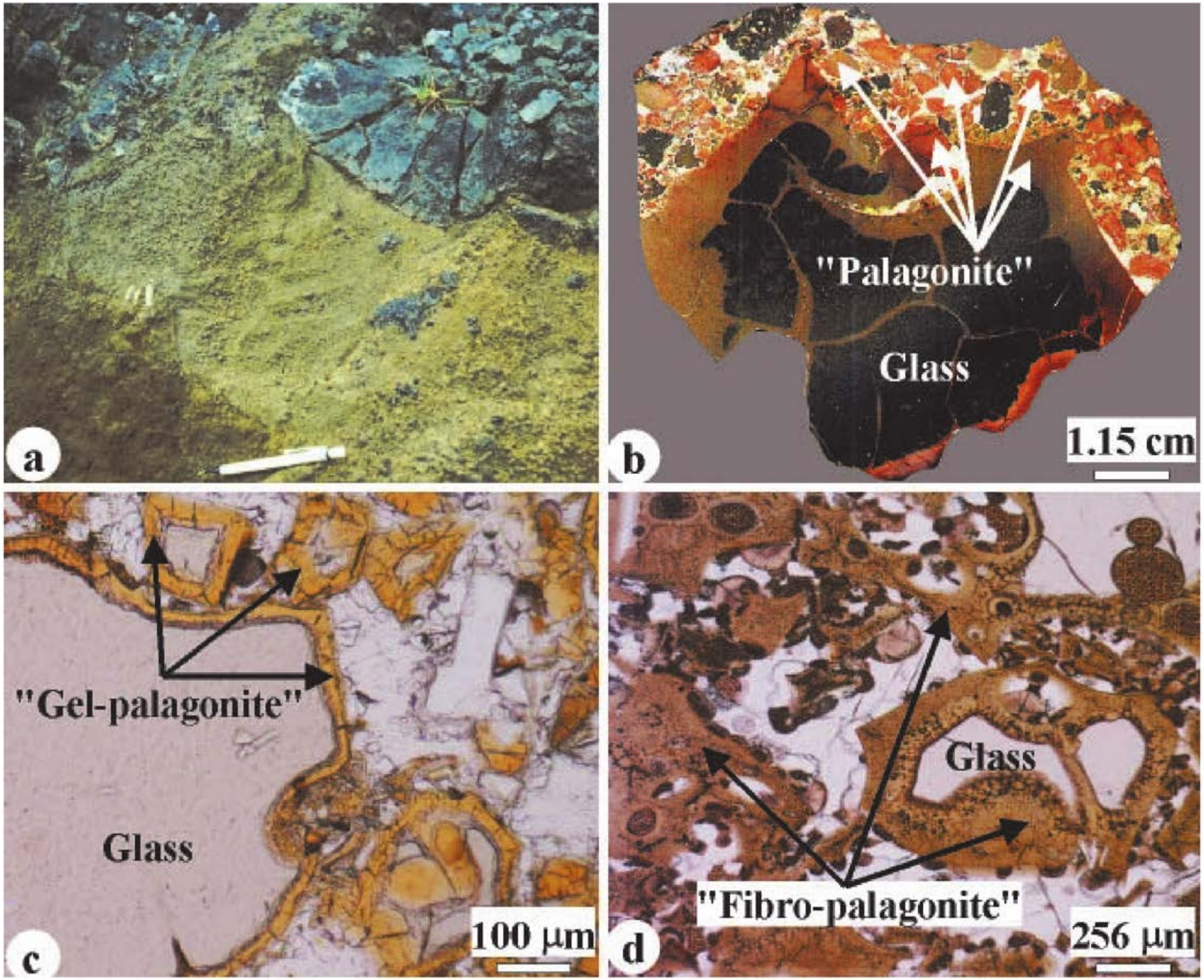
Fluid-Rock Interaction: Palagonitization



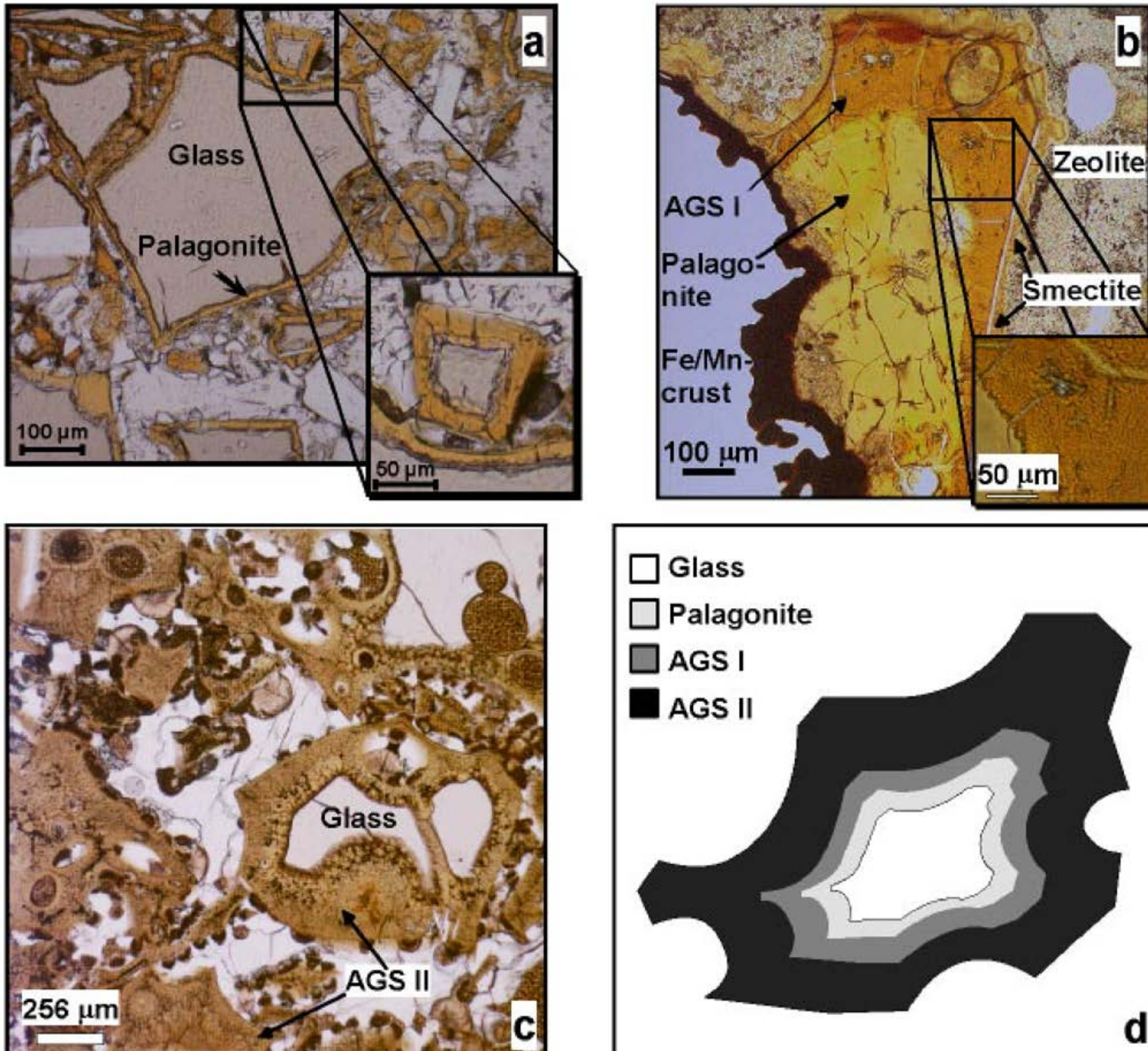
Thin sections of palagonitic basaltic glass shards in a palagonitized crystal vitric tuff (plane-polarized light).

A. Palagonitized crystal vitric tuff texture.
B. Glass fragments with palagonitic rims.
C. Completely palagonitized vesicular glass shard with matrix material in vesicles.
D. Palagonitized glass shard containing spherulites and filled vesicles. Individual vesicles are rimmed with palagonite

Fluid-Rock Interaction: Palagonitization

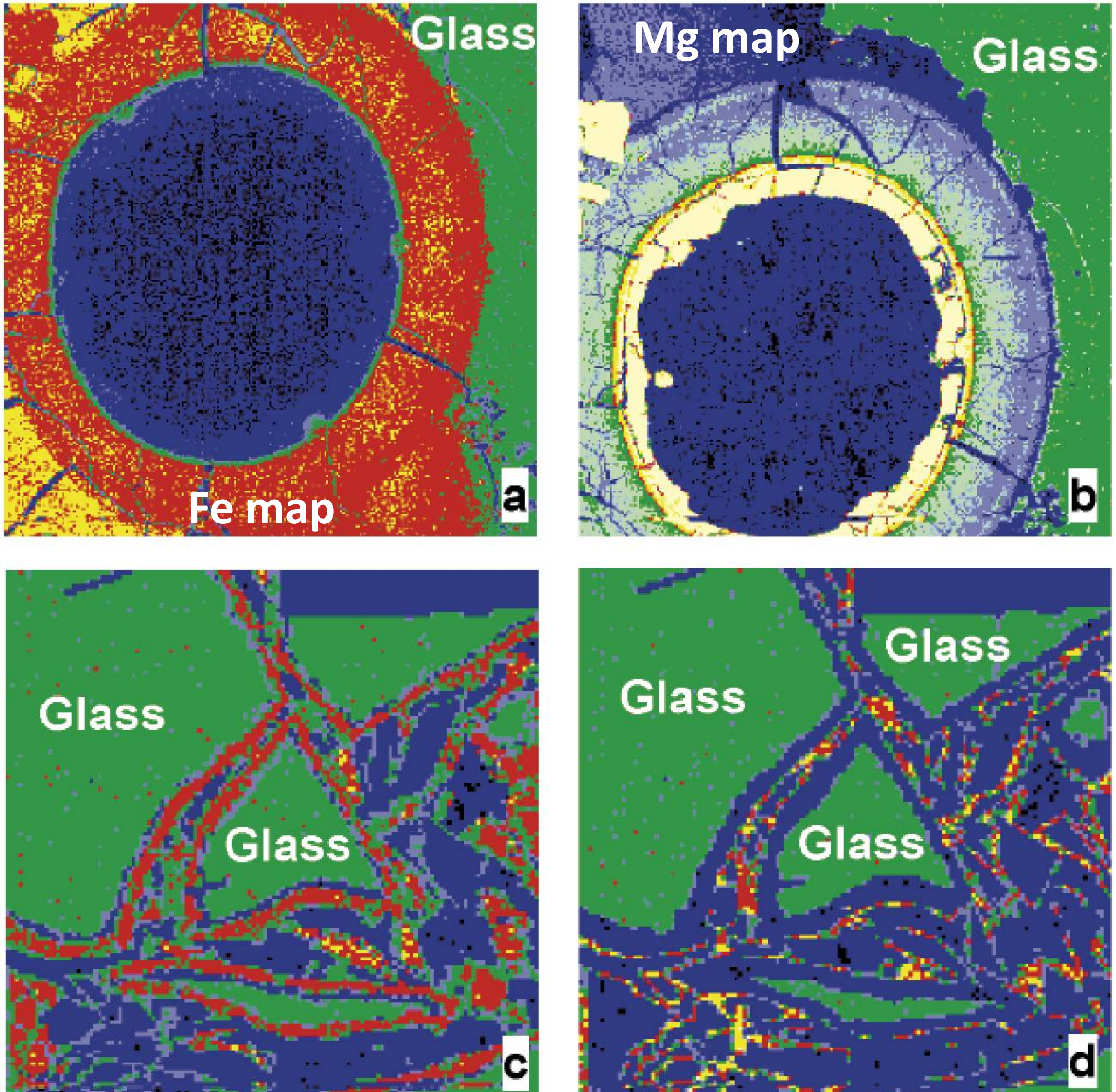


Fluid-Rock Interaction: Palagonitization

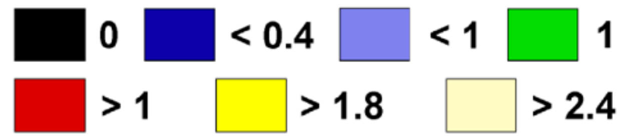


Stroncik and Schmincke, 2001

Fluid-Rock Interaction: Palagonitization



EMP element maps and different aging step materials showing the distribution of Fe and Mg

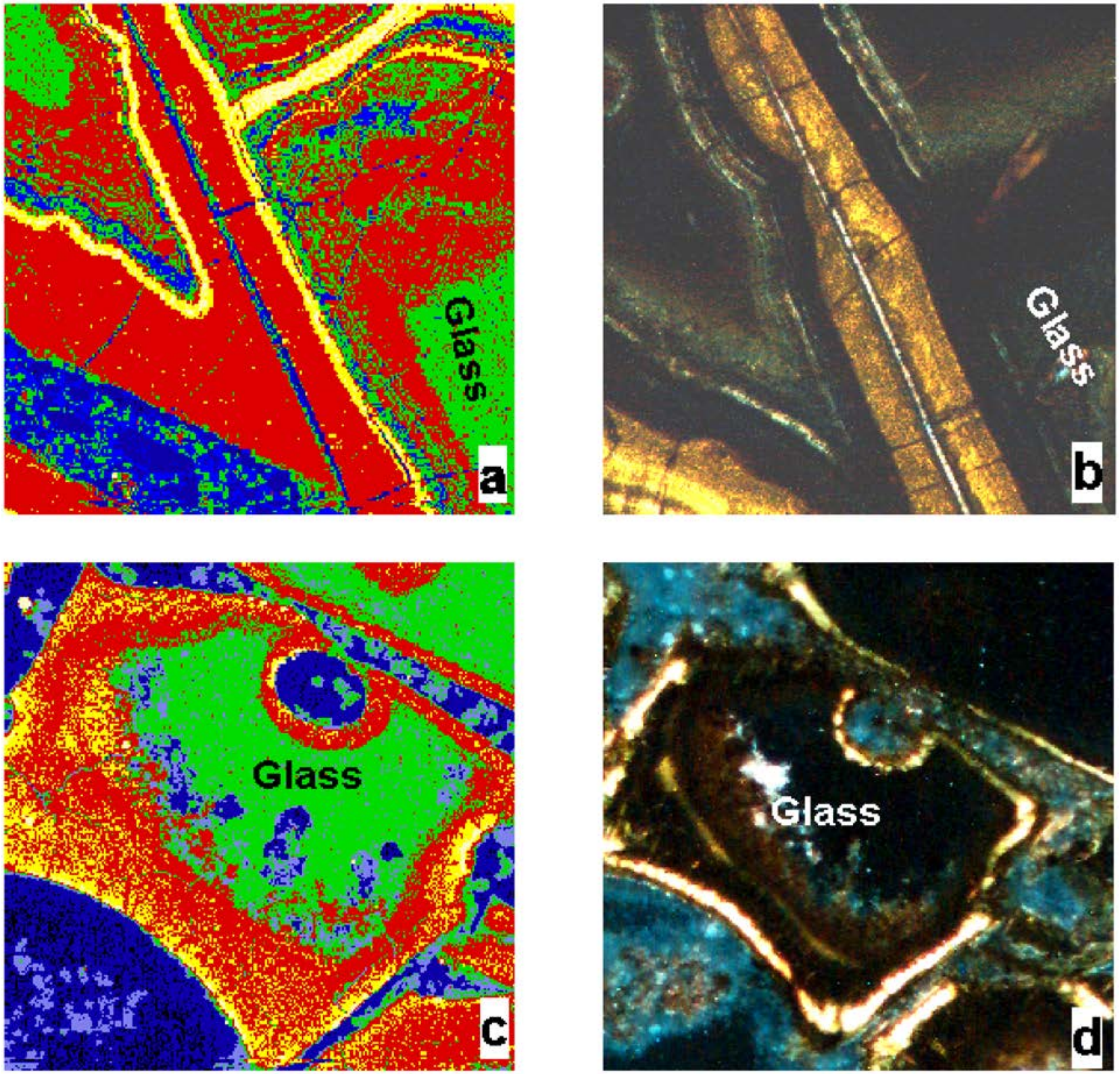


> 1 enrichment
<1 depletion

of a specific element relative to the glass

Stroncik and Schmincke, 2001

Fluid-Rock Interaction: Palagonitization



EMP element maps and different aging step materials showing the distribution of Fe

0 | < 0.4 | < 1 | 1
> 1 | > 1.8 | > 2.4

> 1 enrichment
<1 depletion

of a specific element relative to the glass

→ *The variation of anysotropy is and index for crystallinity of the sample*