THE STORY OF EARTH: How the Geosphere and Biosphere Co-Evolved

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Robert M. Hazen—11 July 2013

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Mineral Evolution Collaborators

Johns Hopkins Univ.
- Dimitri Sverjensky
- John Ferry
- Namhey Lee
- David Azzolini

Univ. of Arizona
- Robert Downs
- Hexiong Yang
- Joaquin Ruiz
- Joshua Golden
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- Dominic Papineau

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Geol. Survey Canada
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Mineral Evolution: Outline

1. What is mineral evolution?
2. Ten stages of mineral evolution.
3. Implications of mineral evolution.
4. Recent discoveries in mineral evolution.

What Is Mineral Evolution?

A change over time in:

- The diversity of mineral species
- The relative abundances of minerals
- The compositional ranges of minerals
- The grain sizes and shapes of minerals

Hazen et al. (2008) *Amer. Mineral*. 93, 1693; Hazen et al. (2009) *Amer. Mineral*. 94, 1293; Hazen et al. (2010) *Elements* 6, #1, 9-46; Hazen et al. (2011) *Amer. Mineral*. 96, 953.

What Is Mineral Evolution?

Focus exclusively on near-surface (<3 km depth) phases.

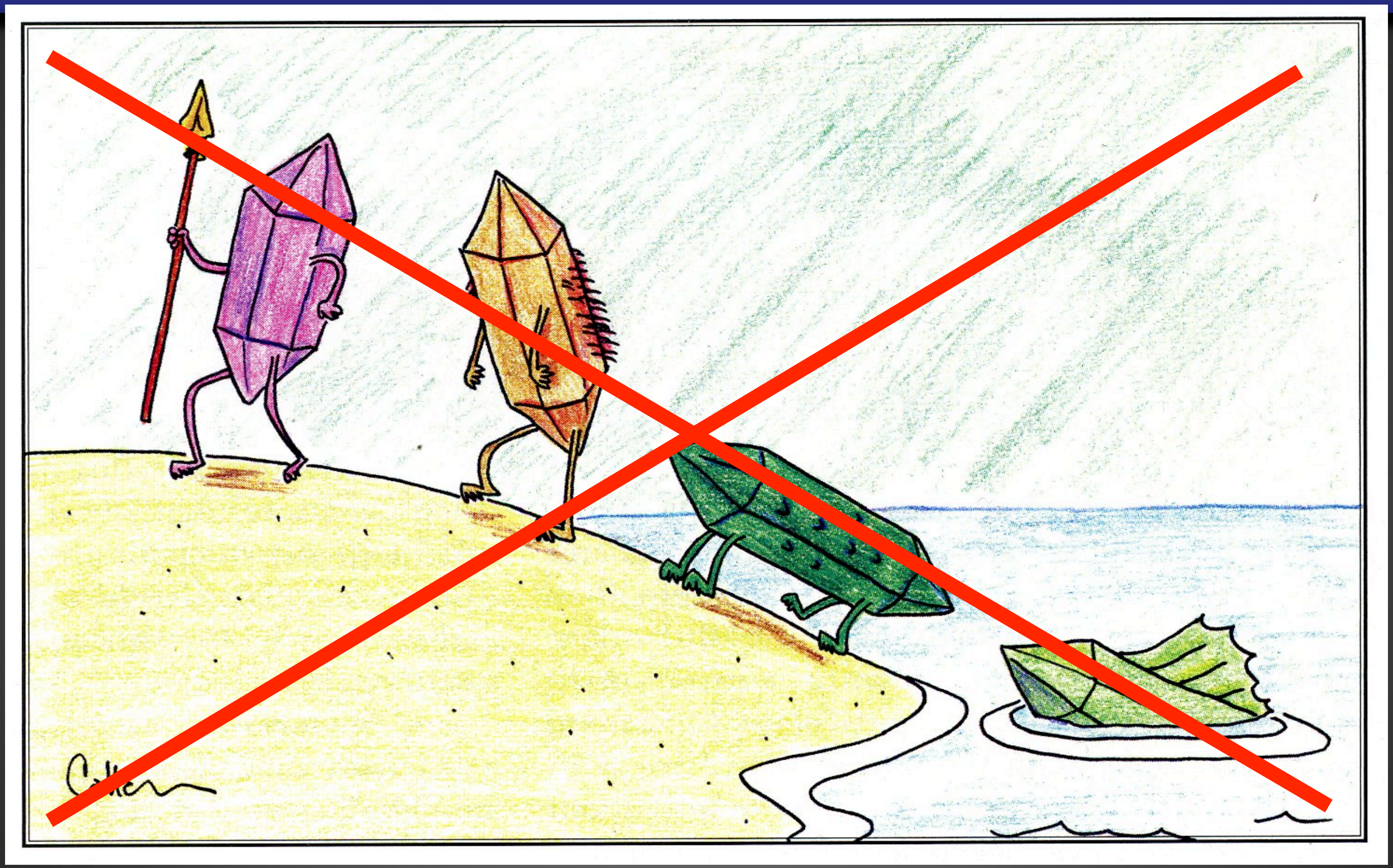
- **Accessible to study on Earth**
- **Most likely to be observed on other planets and moons**
- **Direct interaction with biology**

Hazen et al. (2008) *Amer. Mineral*. 93, 1693; Hazen et al. (2009) *Amer. Mineral*. 94, 1293; Hazen et al. (2010) *Elements* 6, #1, 9-46; Hazen et al. (2011) *Amer. Mineral*. 96, 953.

Why Mineral Evolution?

- Reframe mineralogy in a dynamic historical context
- Classify terrestrial planets and moons & identify mineralogical targets
- Explore general principles related to complex evolving systems
- Pose new mineralogical questions

A Comment on "Evolution"

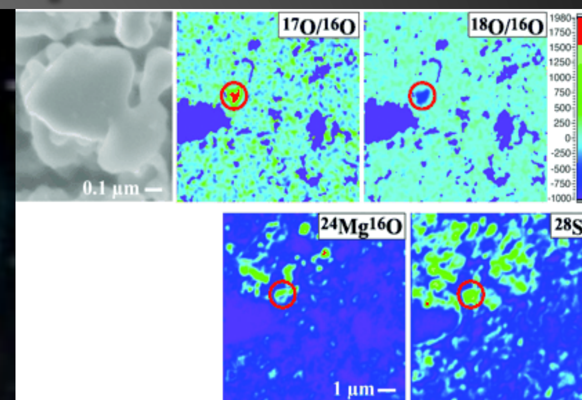


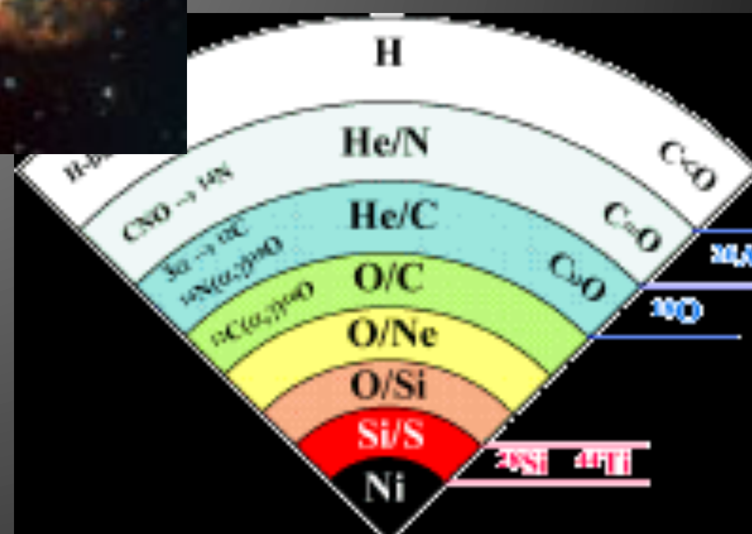
- **But <u>NOT</u> Darwinian evolution!**

"Ur"-Mineralogy

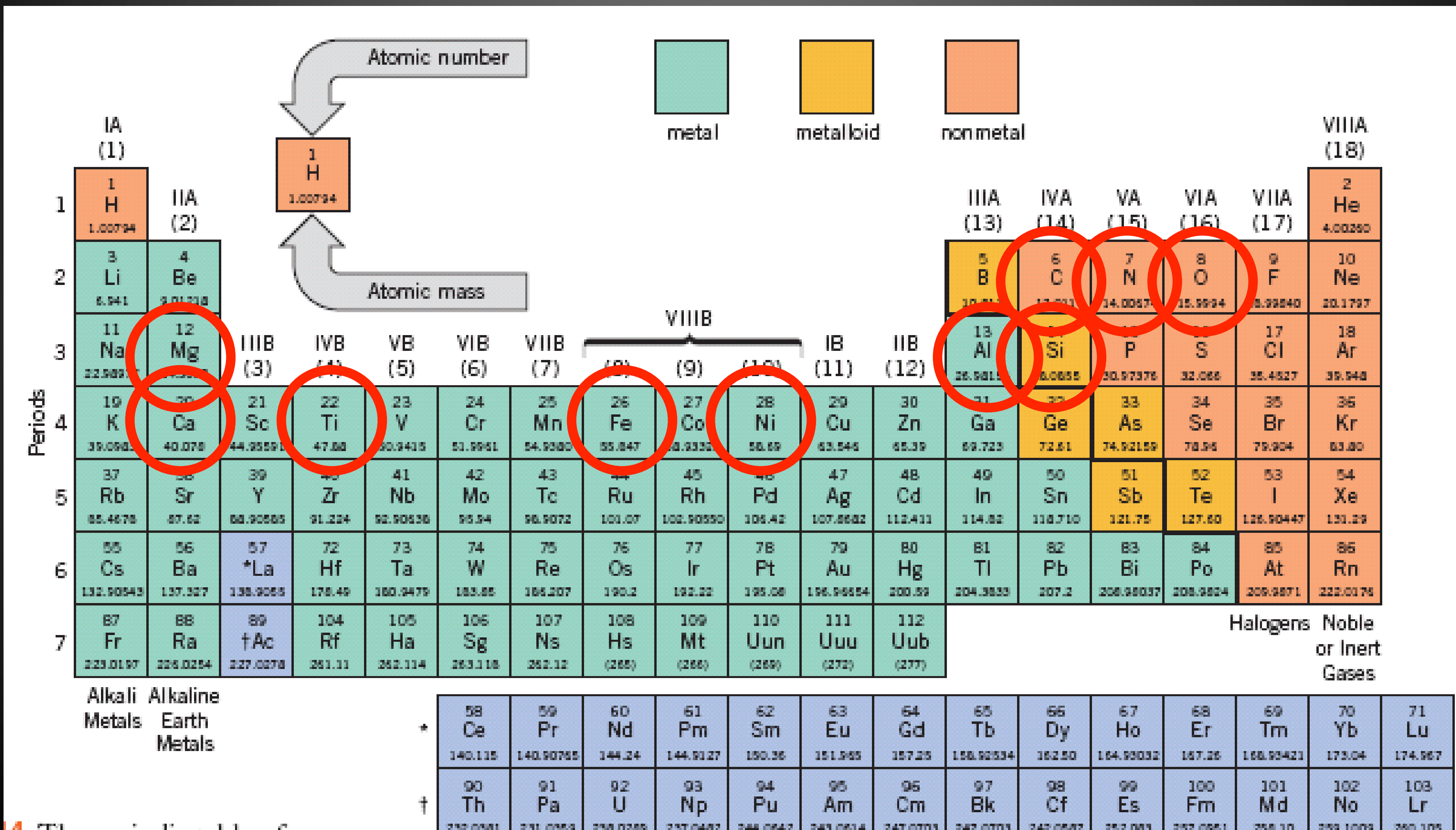
Pre-solar grains contain about a dozen micro- and nano-mineral phases:

- Diamond/Lonsdaleite
- Graphite (C)
- Moissanite (SiC)
- Osbornite (TiN)
- Nierite (Si_3N_4)
- Rutile (TiO_2)
- Corundum (Al_2O_3)
- Spinel ($MgAl_2O_4$)
- Hibbonite ($CaAl_{12}O_{19}$)
- Forsterite (Mg_2SiO_4)
- Nano-particles of TiC, ZrC, MoC, FeC, Fe-Ni metal within graphite.
- GEMS (silicate glass with embedded metal and sulfide).





Ur-Minerals


Atomic number
Atomic mass
metal
metalloid
nonmetal
Periods
Alkali Metals
Alkaline Earth Metals
Halogens
Noble or Inert Gases
The periodic table of

Mineral Evolution:

How did we get from a dozen minerals (with 10 elements) to >4800 on Earth today?

What does the distribution of minerals through time tell us about key events in Earth history?

What Drives Mineral Evolution?

Deterministic and stochastic processes that occur on any terrestrial body:

1. The progressive separation and concentration of chemical elements from their original uniform distribution.

Hazen & Ferry (2010) *Elements* 6, #1, 9-12.

What Drives Mineral Evolution?

Deterministic and stochastic processes that occur on any terrestrial body:

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What Drives Mineral Evolution?

Deterministic and stochastic processes that occur on any terrestrial body:

1. **The progressive separation and concentration of chemical elements from their original uniform distribution.**

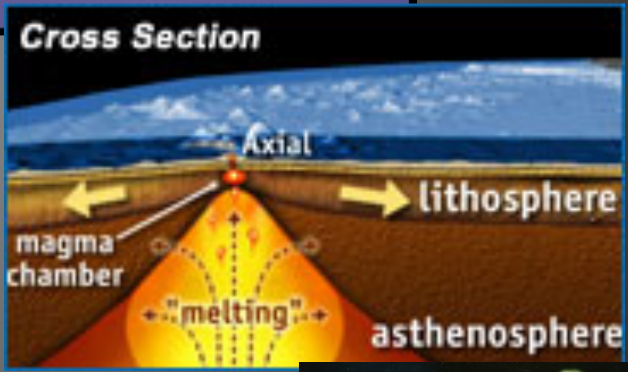
2. **An increase in the range of intensive variables (T, P, activities of volatiles).**

3. **The generation of far-from-equilibrium conditions by living systems.**

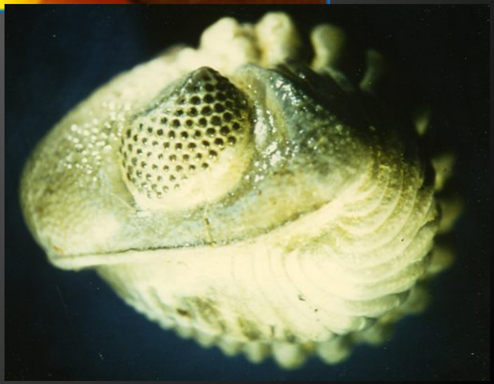
Hazen & Ferry (2010) *Elements* 6, #1, 9-12.

Three Eras of Earth's Mineral Evolution

1. The Era of Planetary Accretion



2. The Era of Crust and Mantle Reworking



3. The Era of Bio-Mediated Mineralogy

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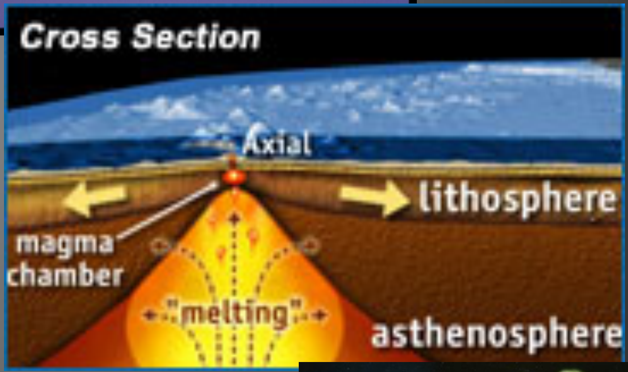

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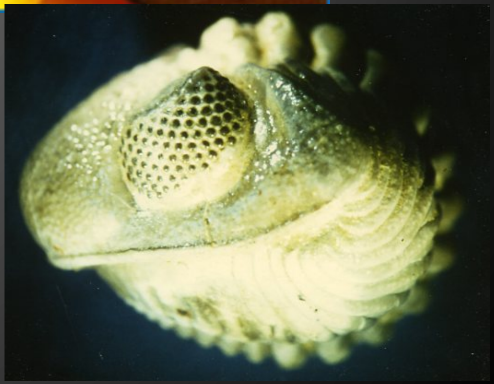
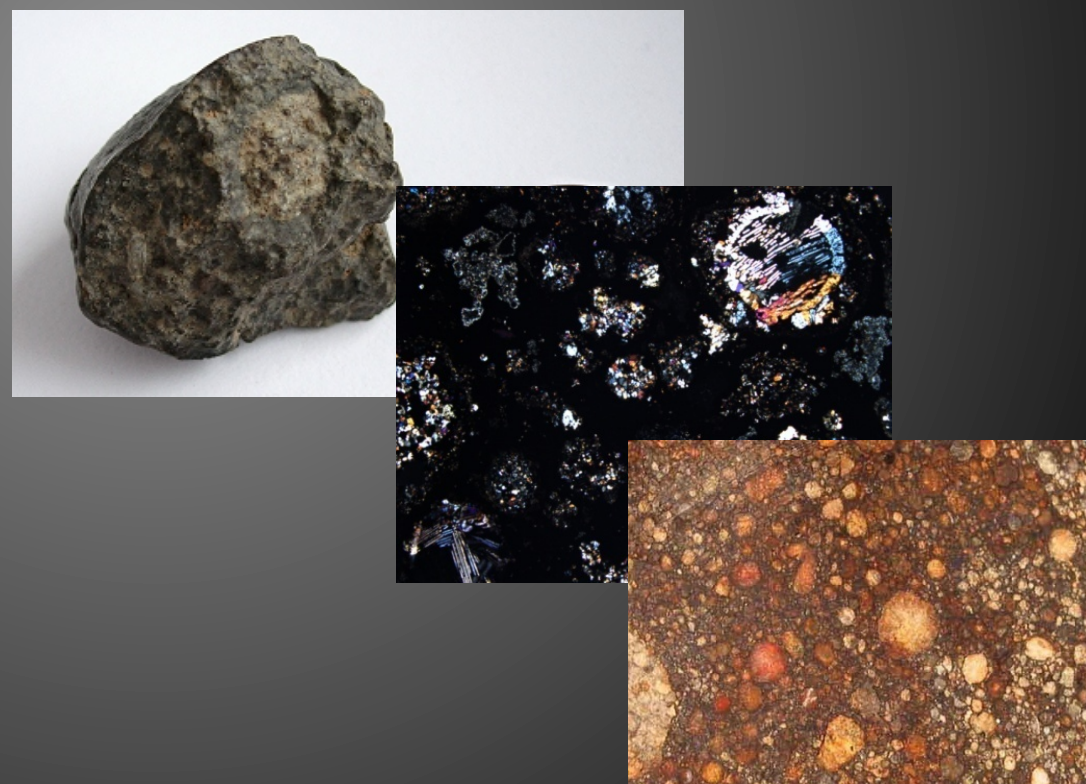


Stage 1: Primary Chondrite Minerals

Minerals formed ~4.56 Ga in the Solar nebula as a consequence of condensation, melt solidification, or recrystallization

~60 mineral species

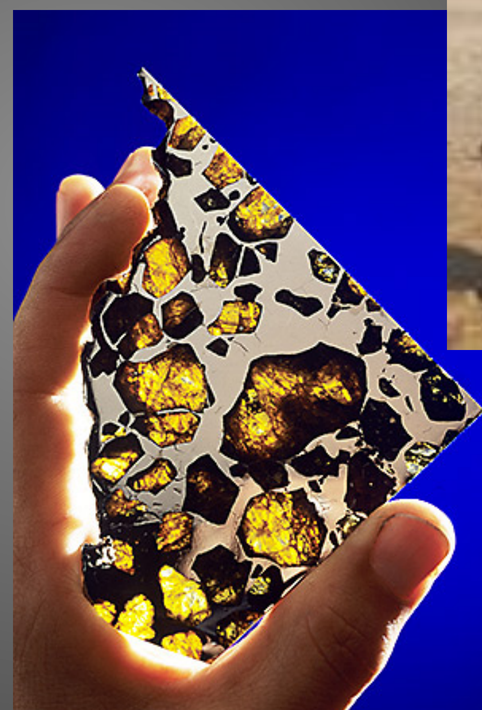
- CAIs
- Chondrules
- Silicate matrix
- Opaque phases

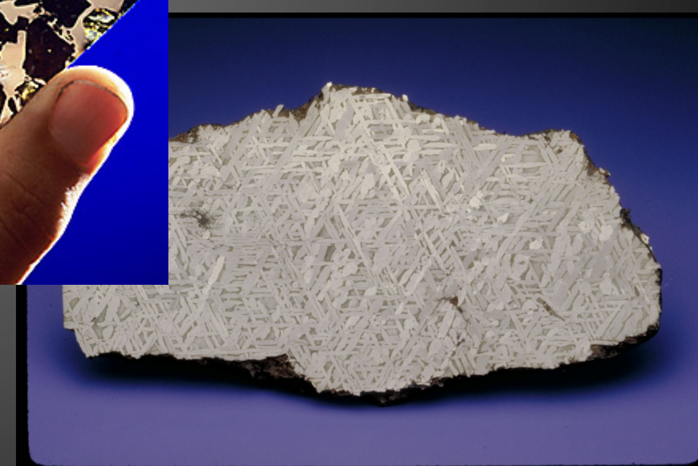


Stage 2: Aqueous alteration, metamorphism and differentiation of planetesimals

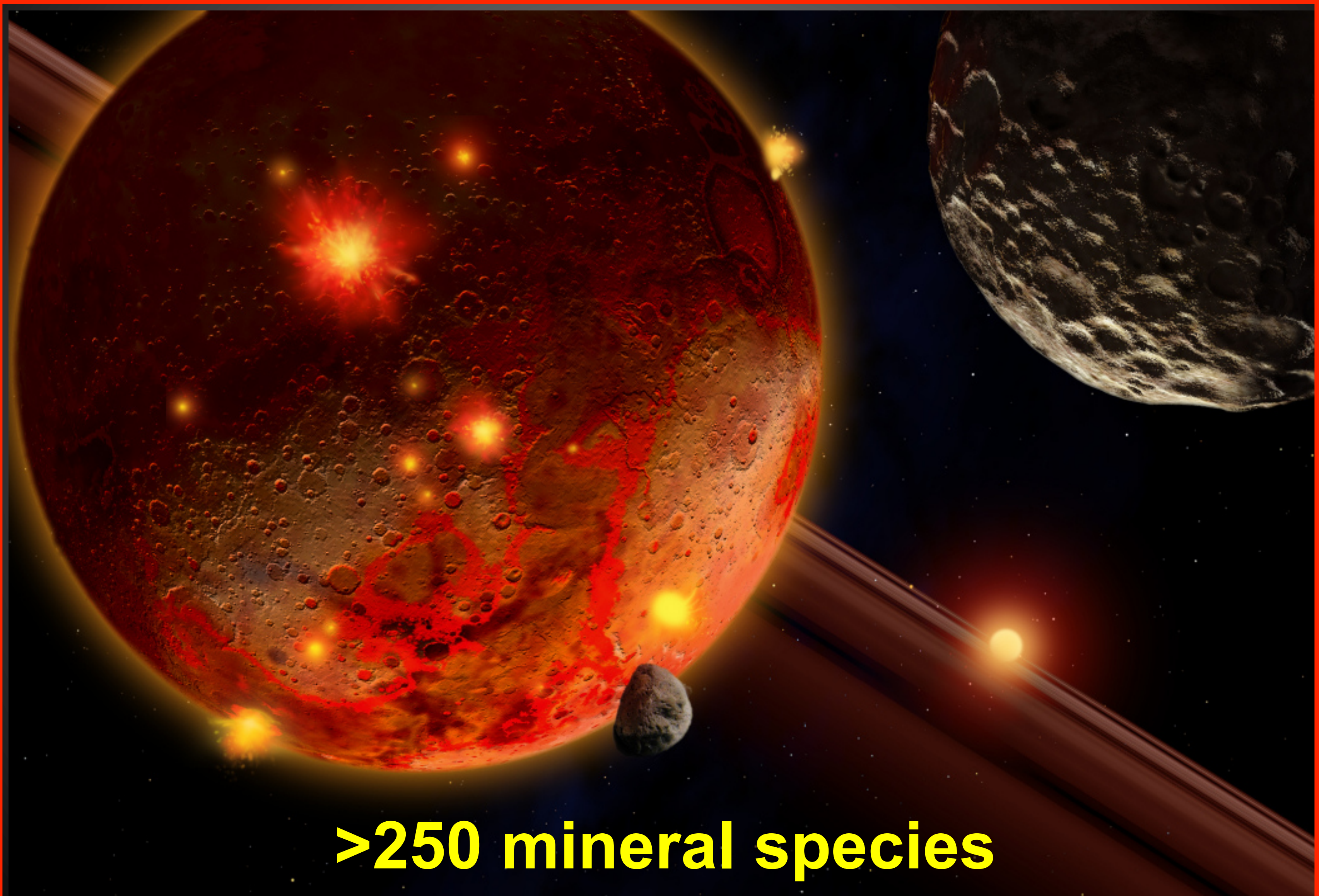
~250 mineral known species: 4.56-4.55 Ga

- First albite & K-spar
- First significant SiO_2
- Feldspathoids
- Hydrous biopyriboles
- Clay minerals
- Zircon
- Shock phases





Stage 2: Planetary Accretion

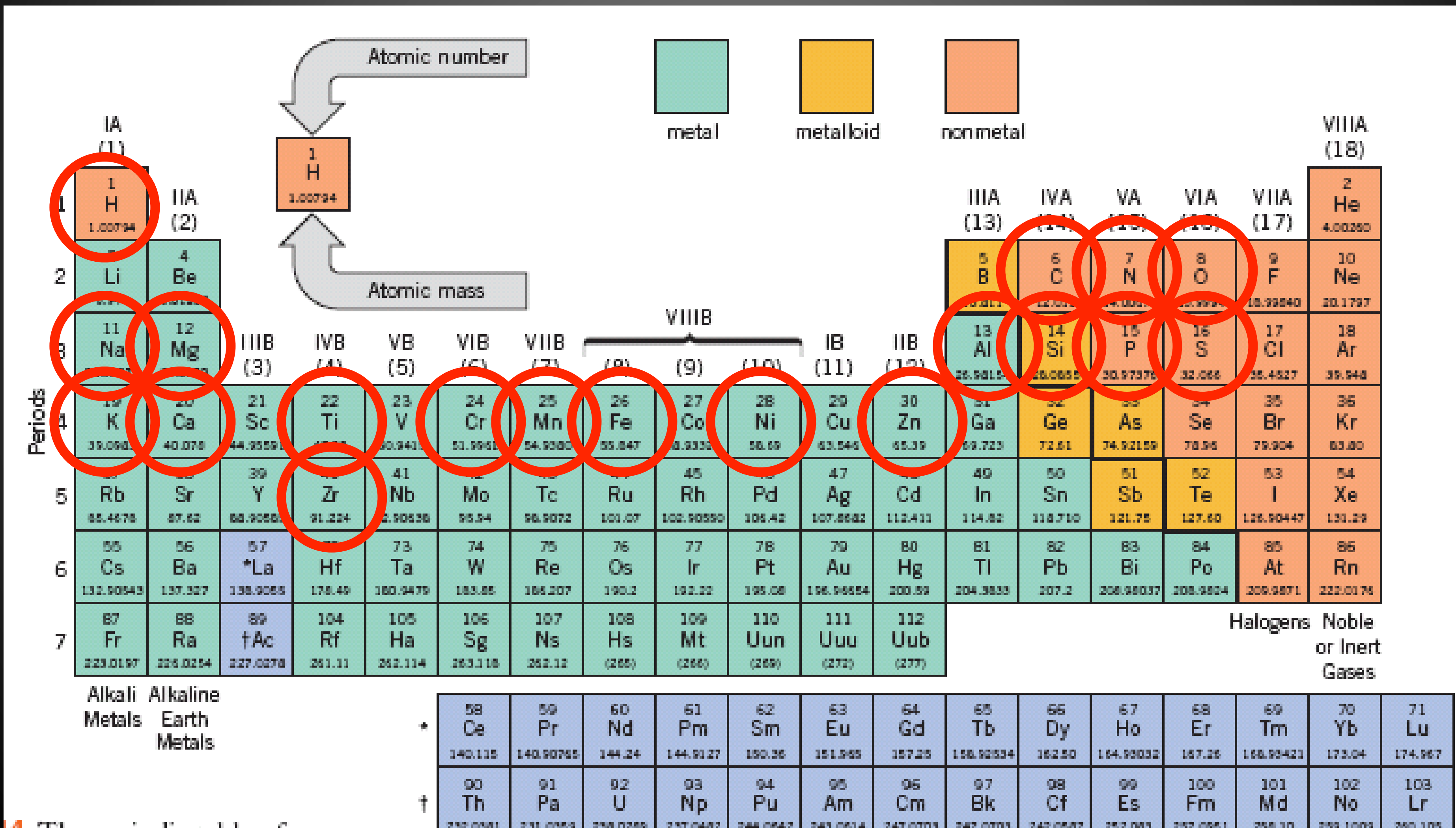


Stages 1 and 2: Planetary Accretion

In these early stages all of Earth's near-surface compositional complexity was present, but it was not manifest in a diversity of unusual mineral species.

>250 mineral species

Stages 1 & 2 Minerals



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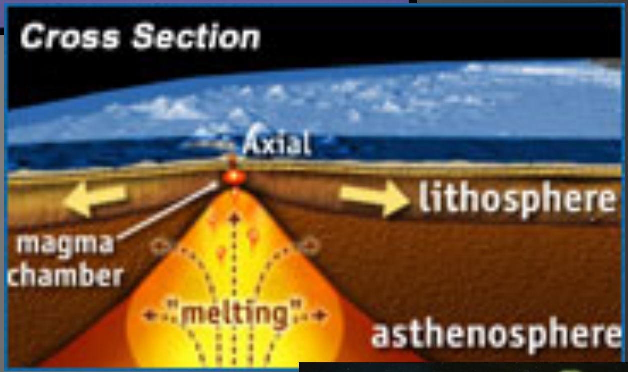
2. The Era of Crust and Mantle Reworking



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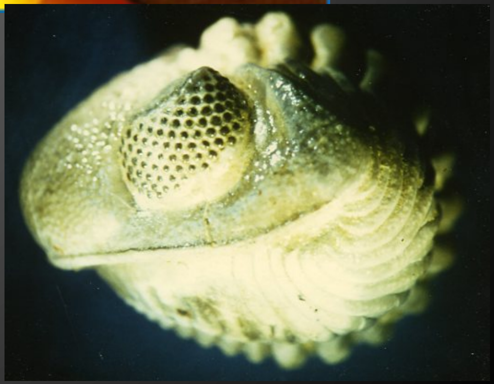
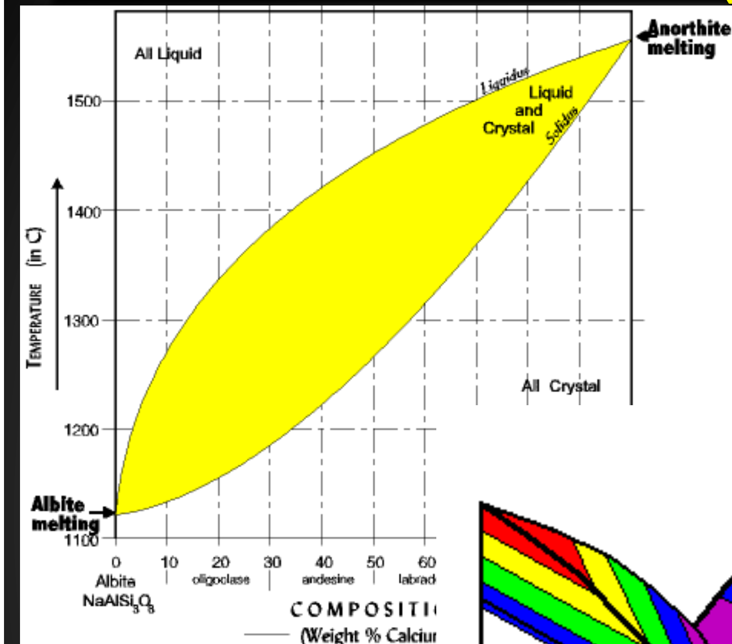
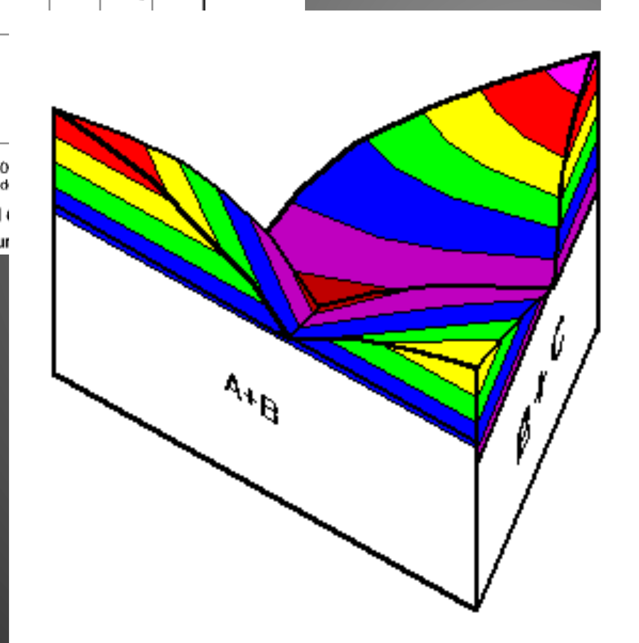
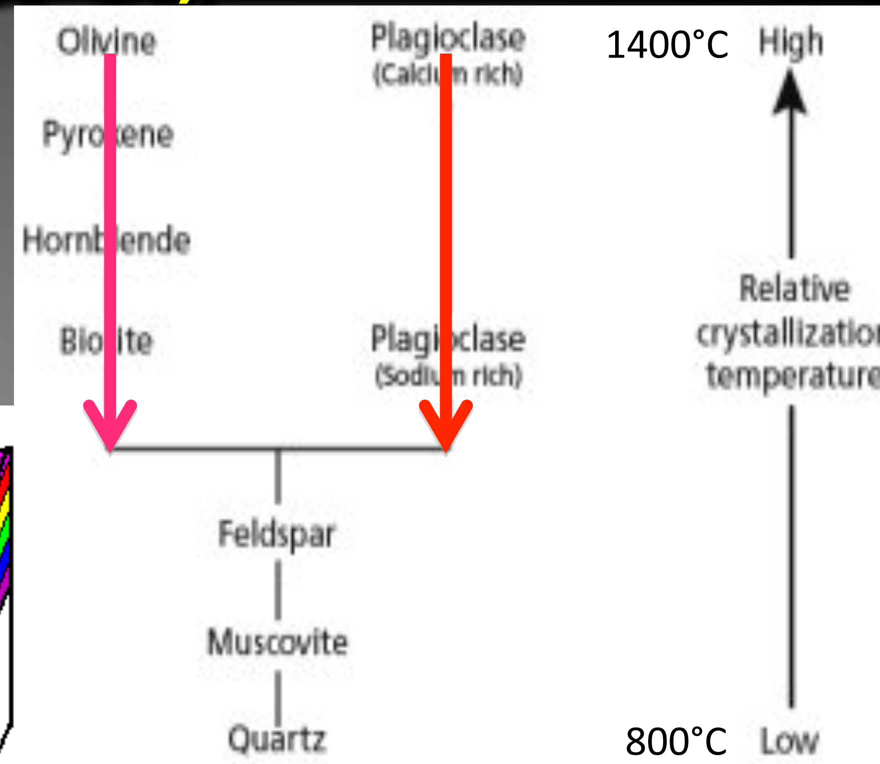


Stage 3: Initiation of Igneous Rock Evolution (4.55-4.0 Ga)



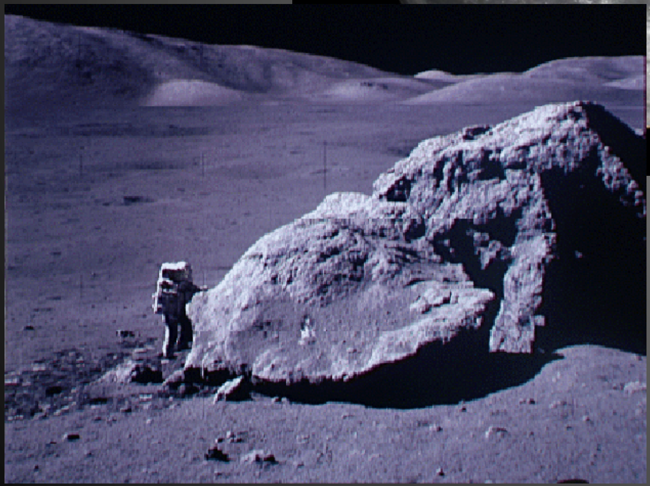


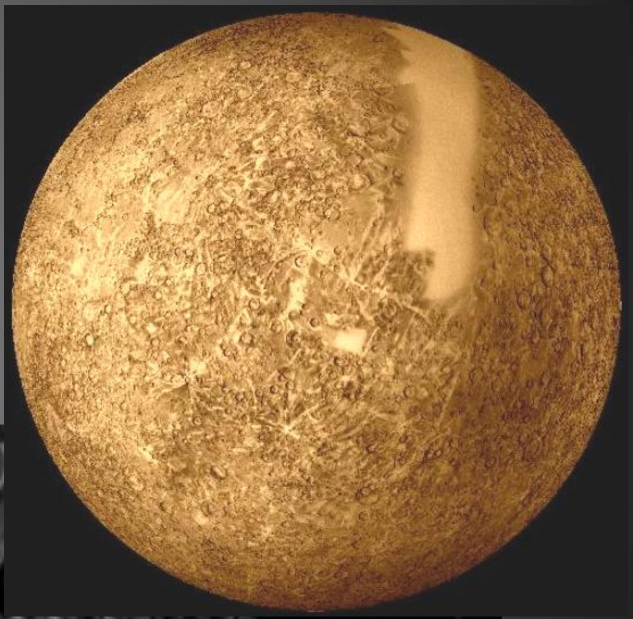


Partial melting, fractional crystallization and magma immiscibility

Stage 3: Initiation of Igneous Rock Evolution Volatile-poor Body

~350 mineral species?





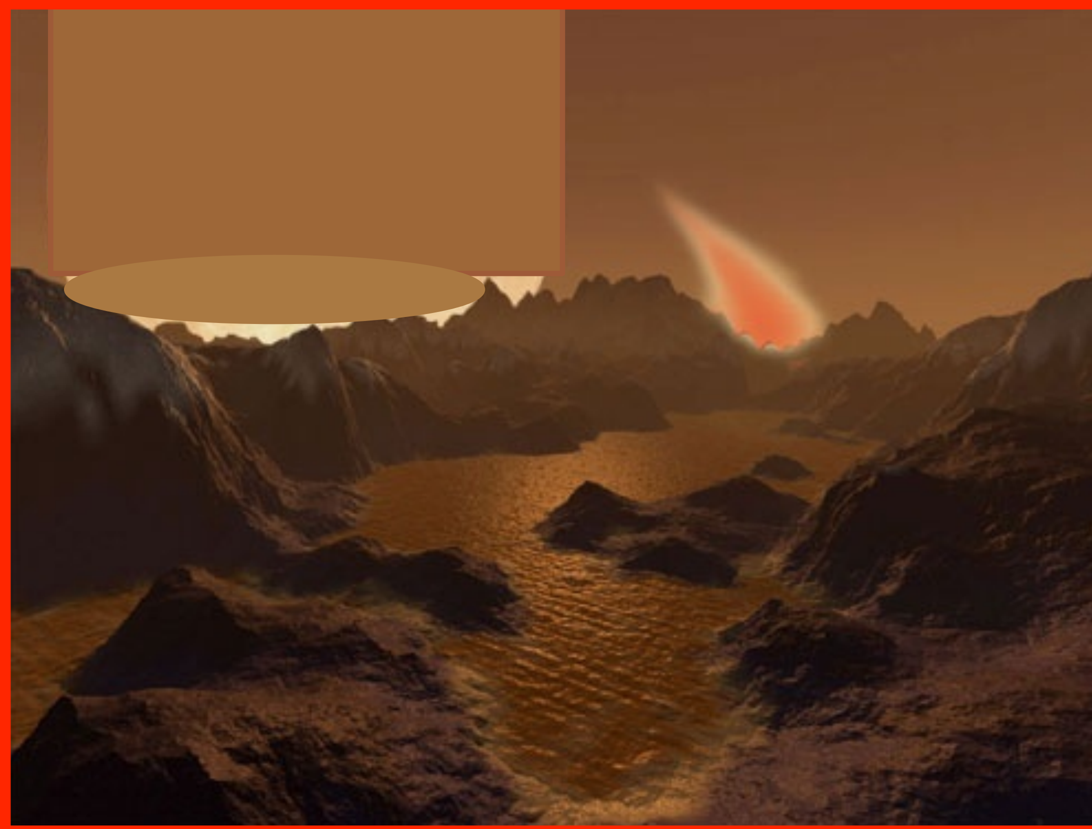
Is this the end point of the Moon and Mercury?

Stage 3: Initiation of Igneous Rock Evolution on a Volatile-rich Body (4.55-4.0 Ga)

Volcanism, outgasing and surface hydration.

Stage 3: Initiation of Igneous Rock Evolution
Volatile-rich Body

>500 mineral species (hydroxides, clays)



Volcanism, outgasing, surface hydration, evaporites, ices.

The Formation of the Moon

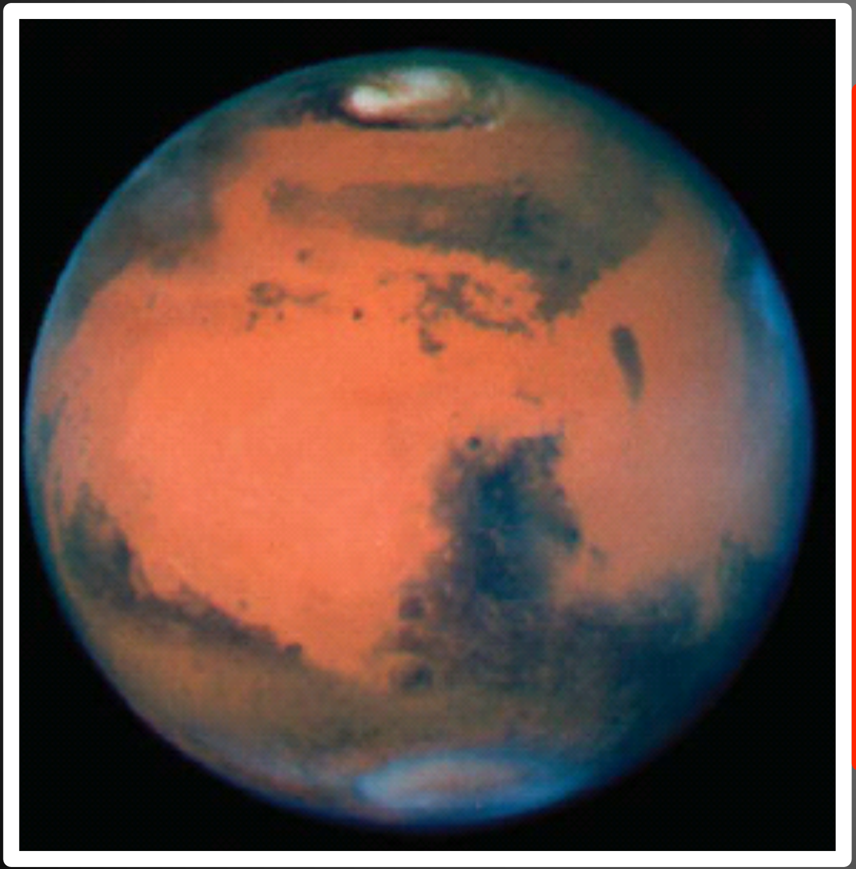
Stage 3: Initiation of Igneous Rock Evolution
Volatile-rich Body

>500 mineral species (hydroxides, clays)

Volcanism, outgasing, surface hydration, evaporites, ices.

Stage 3: Initiation of Igneous Rock Evolution
Volatile-rich Body

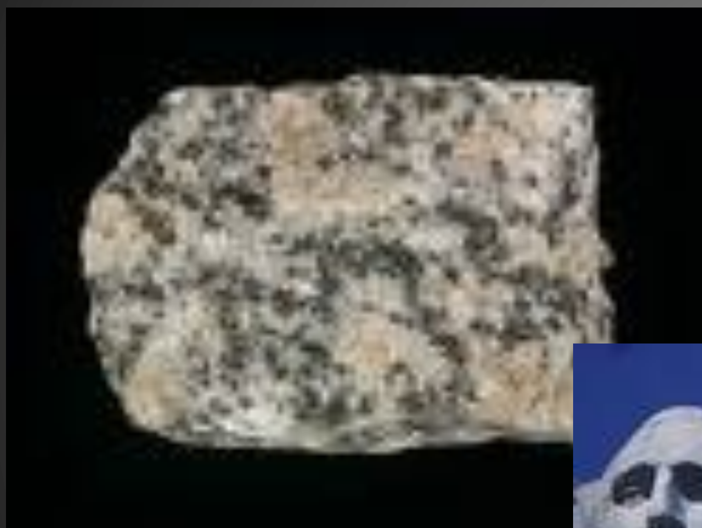
Is this the end point for Mars?



Volcanism, outgasing, surface hydration, evaporites, ices.

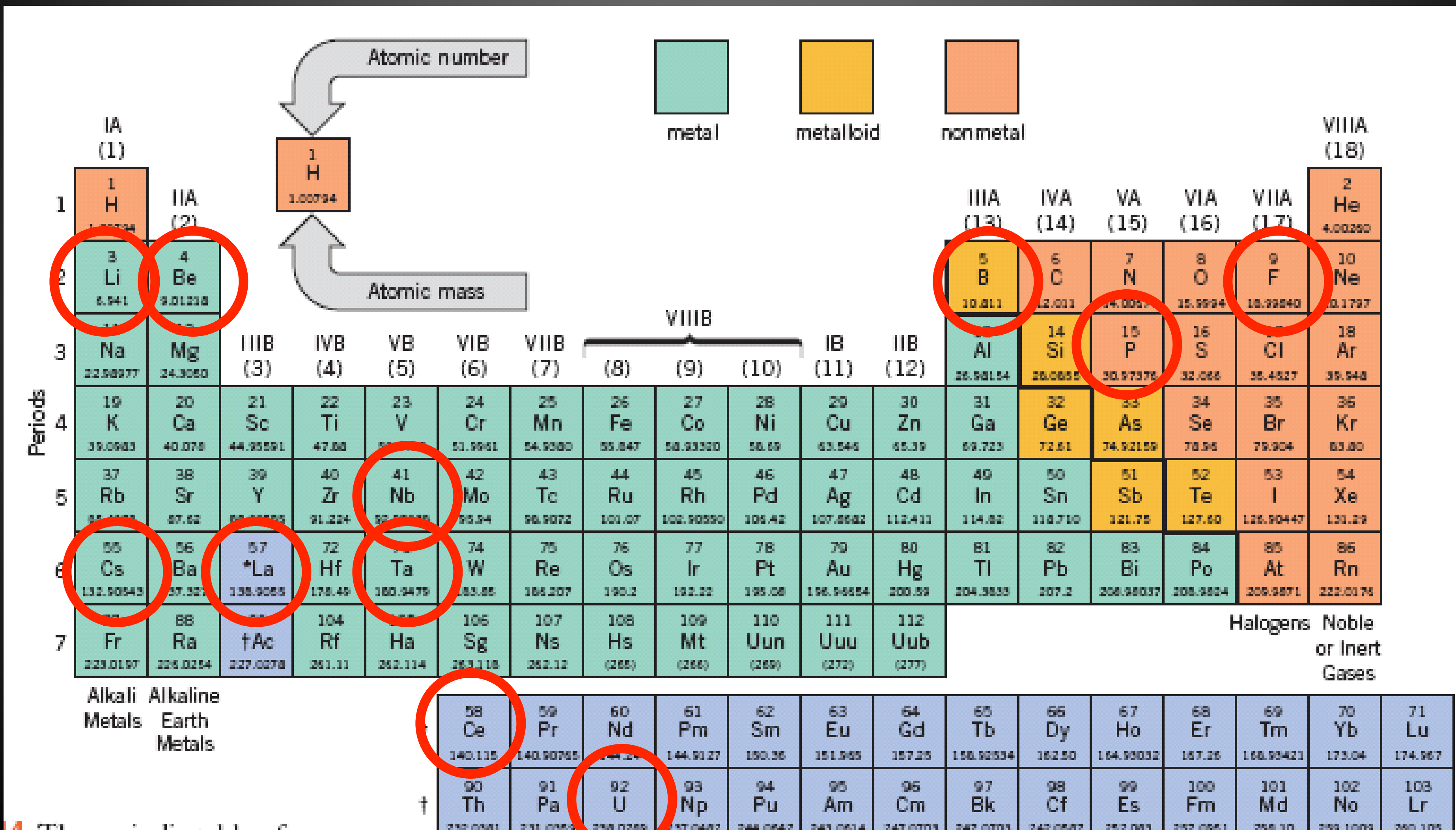
Stage 4: Granitoid Formation (>3.5 Ga)

>1000 mineral species (pegmatites)



Partial melting of basalt and/or sediments.

Stage 4 Minerals



Stage 4: Granitoid Formation (>3.5 Ga)

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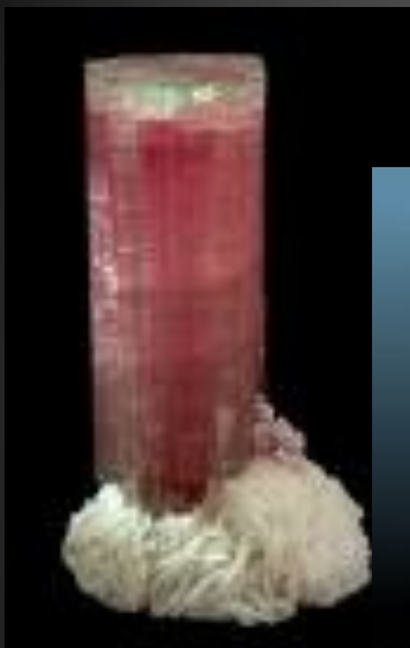


Tourmaline

Spodumene

Beryl

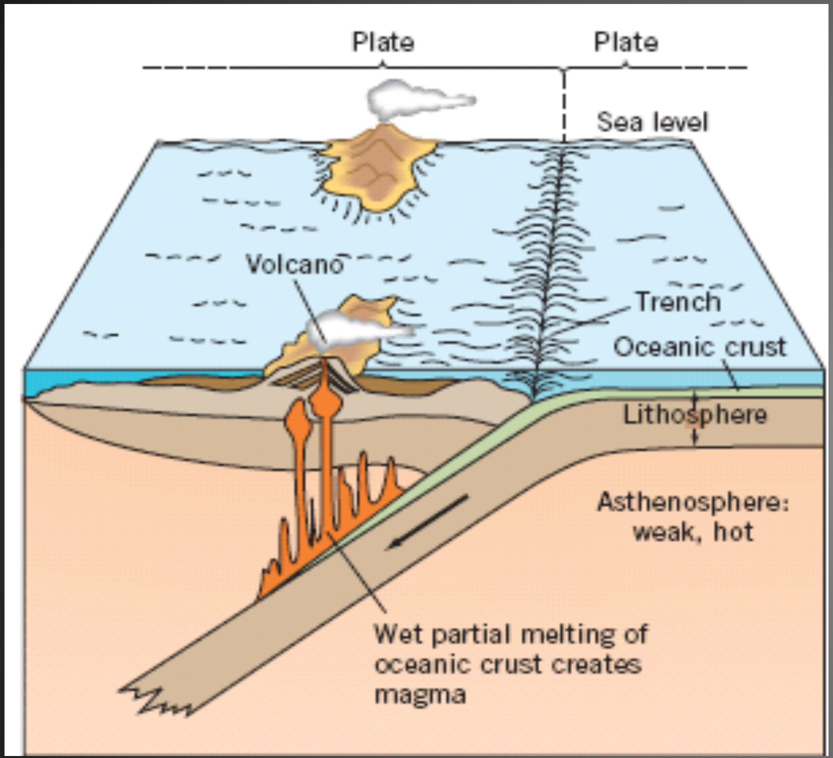
Tantalite

Pollucite

Complex pegmatites require multiple cycles of "eutectic" melting and fluid concentration.

Must they be younger than 3.5 Ga?

Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)

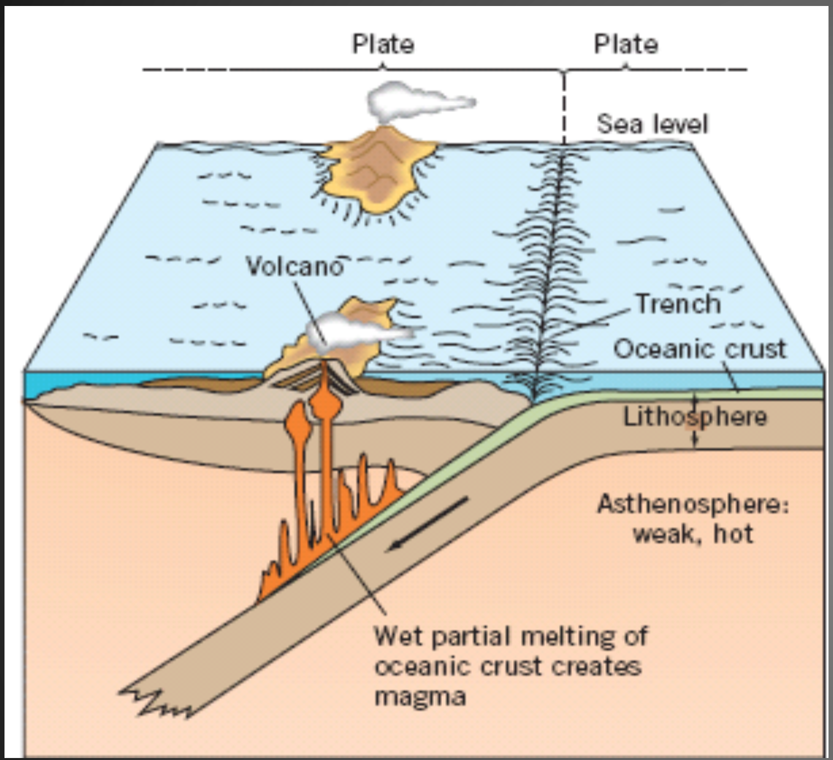


~10^8 km^3 of reworking

Mayon Volcano, Philippines

New modes of volcanism

Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)



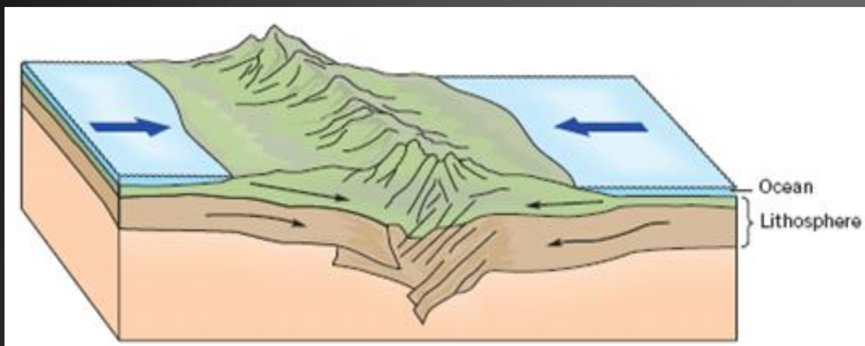
Rio Tinto. Spain

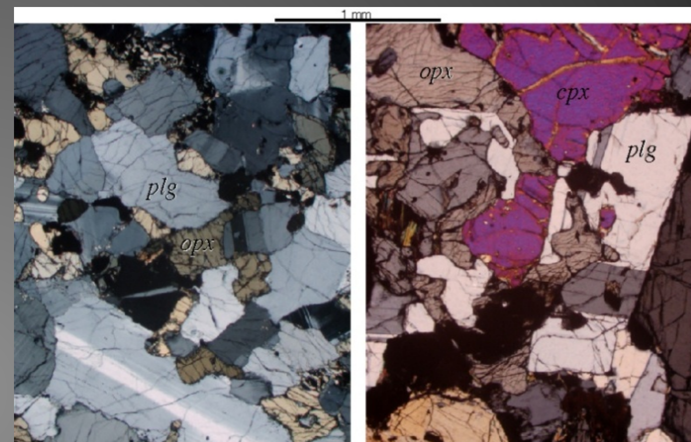
New modes of volcanism

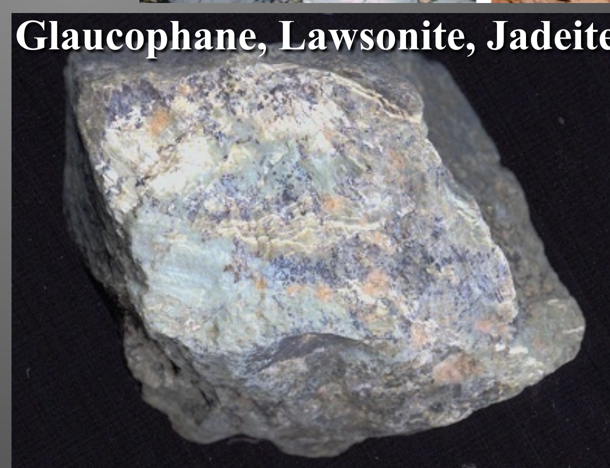
Massive base metal deposits (sulfides, sulfosalts)

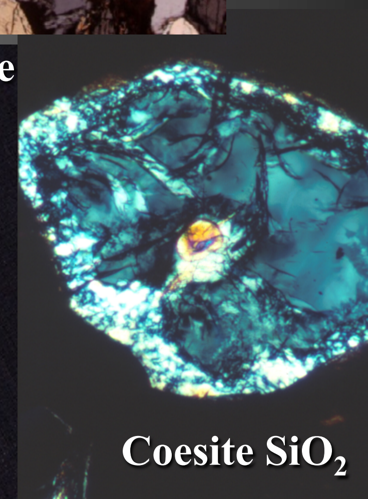
Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)

1,500 mineral species



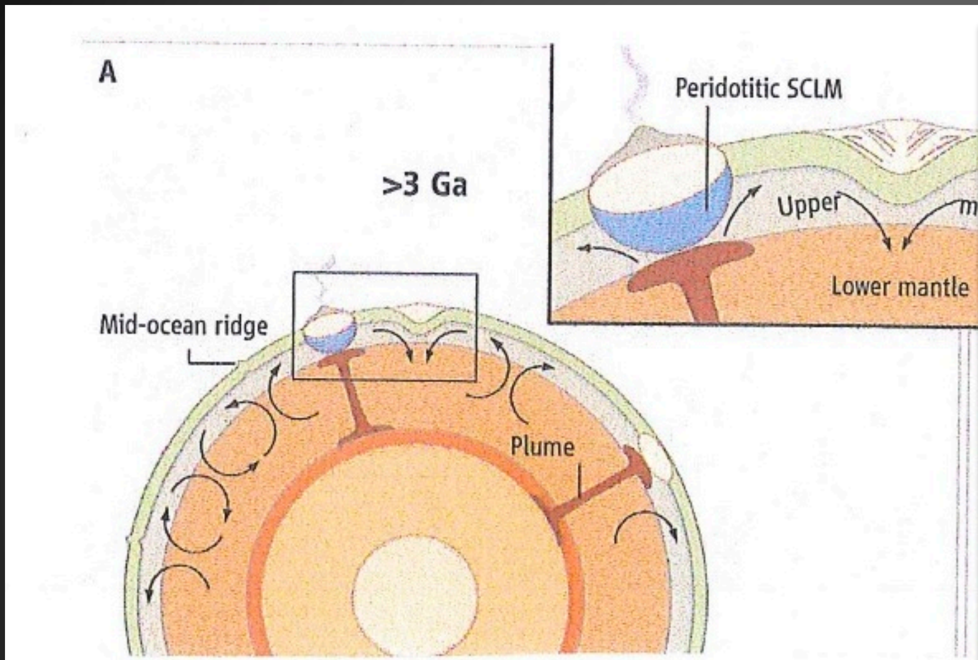






High-pressure metamorphic suites (blueschists; granulites; UHP phases)

Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)

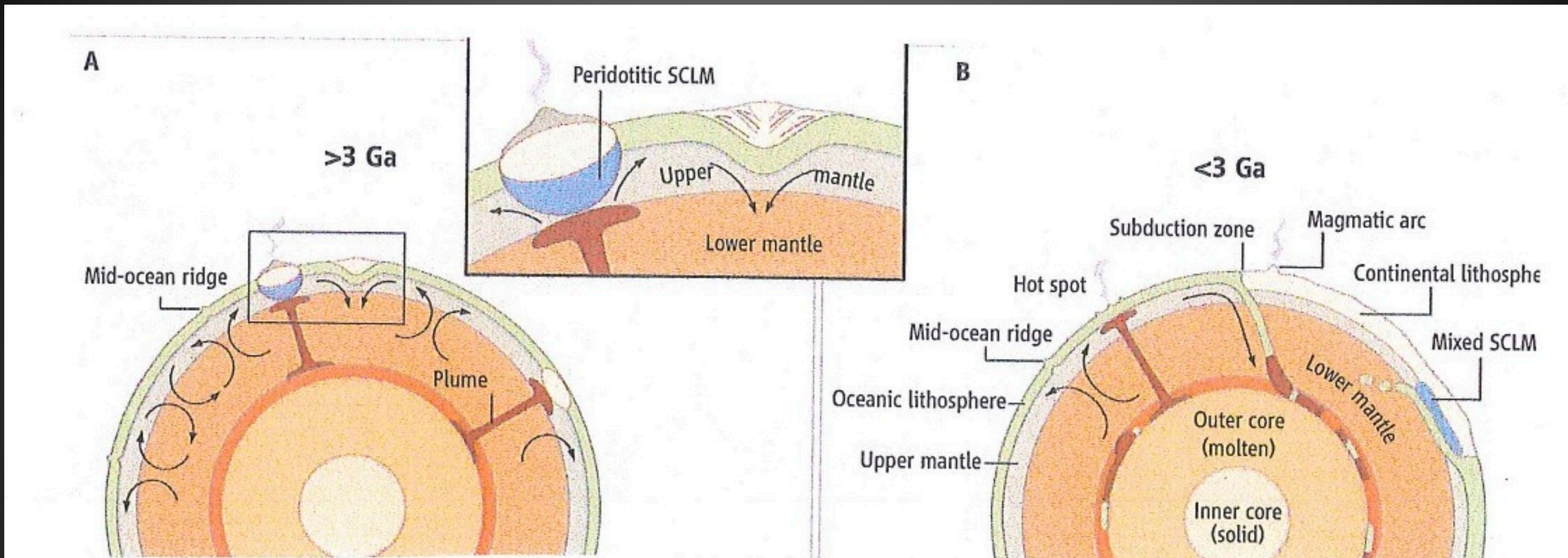


Van Kranendonk (2011)

> 3 Ga

When did subduction begin?

Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)



Van Kranendonk (2011)

> 3 Ga **< 3 Ga**

When did subduction begin?

Stages 3-5: Era of crust-mantle processing (igneous evolution; plate tectonics)

New geologic processes, especially fluid-rock interactions associated with igneous activity and plate tectonics, led to a greater diversity of geochemical environments and thus new mineral species.

~1500 mineral species

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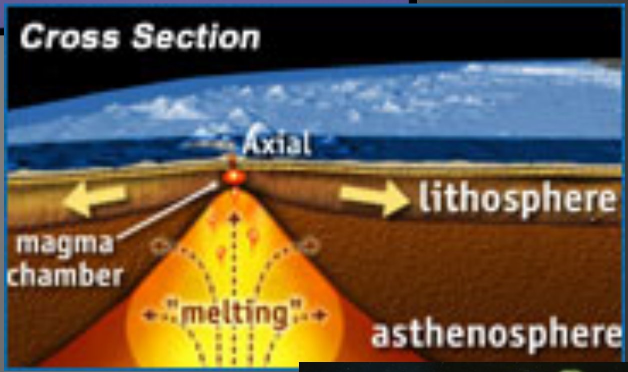
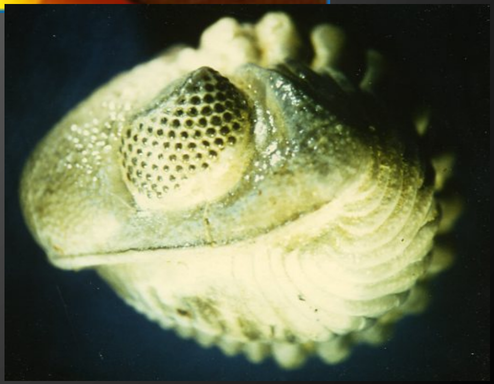
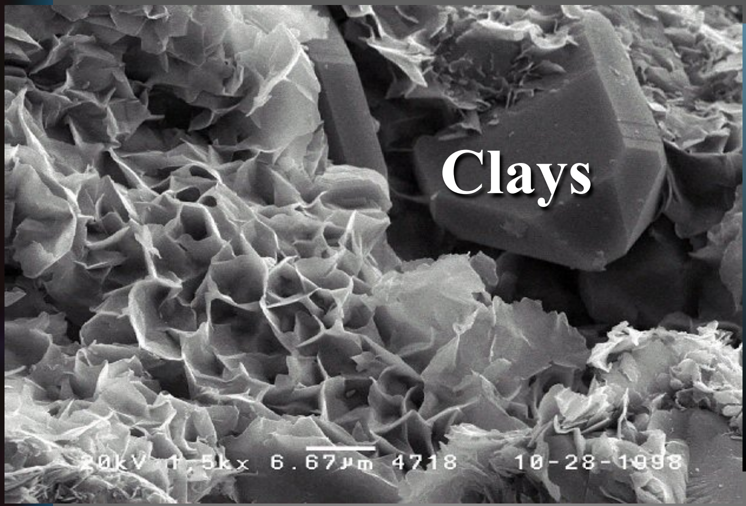
2. The Era of Crust and Mantle Reworking



3. The Era of Bio-Mediated Mineralogy



The origin of life may require some minimal degree of mineral evolution.



Conversely, does further mineral evolution depend on life?

Hence the co-evolution of the geo- and biospheres.

Stage 6: Anoxic Archean biosphere (3.9-2.5 Ga)

~1,500 mineral species (BIFs, carbonates,

Photo credit: D. Papineau

Photo credit: F. Corsetti, USC

Stage 6: Anoxic Archean biosphere (3.9-2.5 Ga)

~1,500 mineral species (BIFs, carbonates, sulfates, evaporites, skarns)

Death Valley evaporites (courtesy Smith College)

Diopside

Grossular

Idocrase

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 Ga)

>4500 mineral species, including perhaps >2,800 new oxides/hydroxides

Rise of oxidative photosynthesis.

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>4500 mineral species, including perhaps >2,800 new oxides/hydroxides

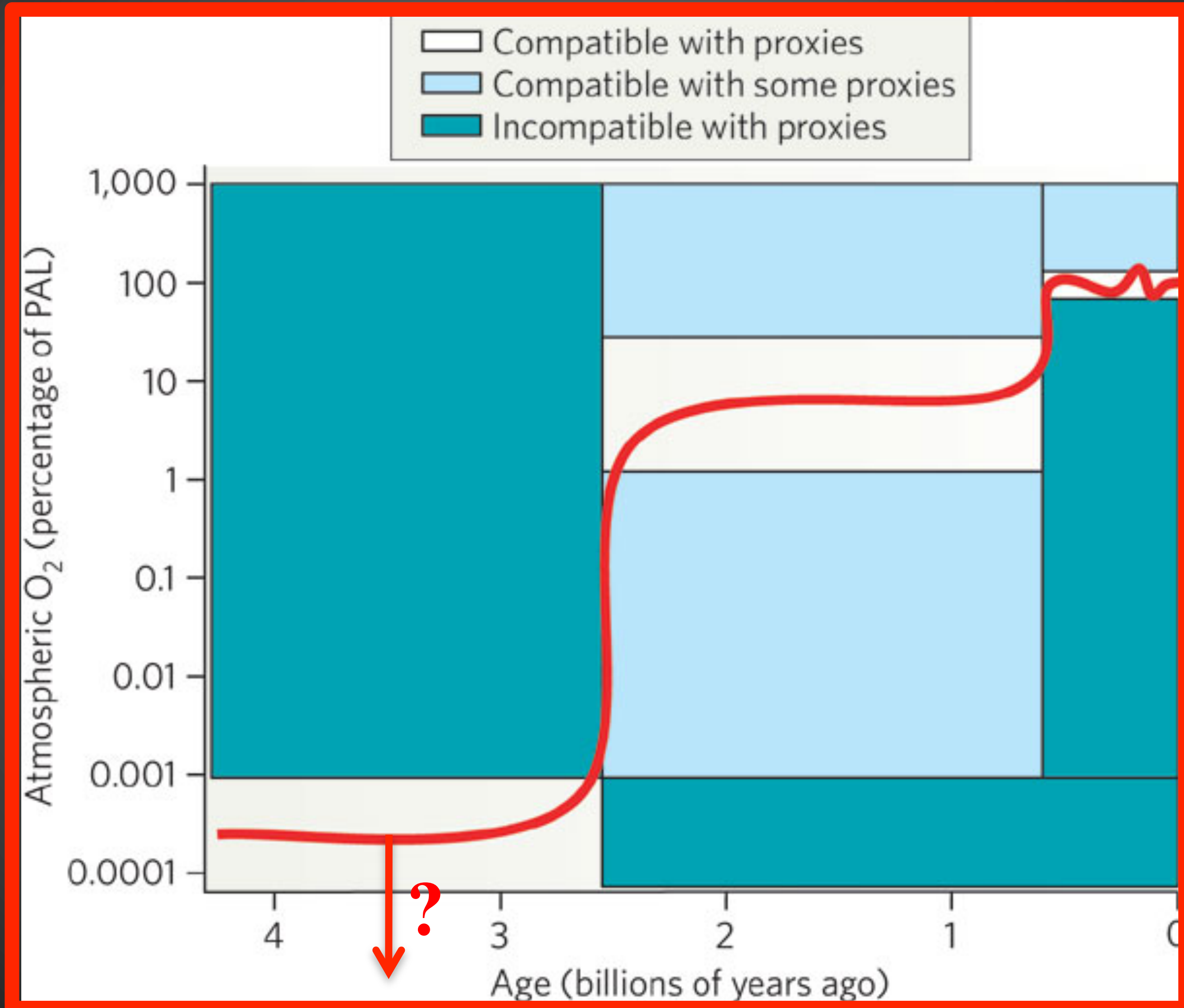
Rise of oxidative photosynthesis.

Hypothesis

Approximately 2/3rds of all known mineral species cannot form in an anoxic environment, and thus are the indirect consequence of biological activity.

Many lines of evidence point to an Archean atmosphere that was essentially lacking in oxygen.

What was the oxygen level in the Archean Eon?



Kump (2008) *Nature* 451, 277-278.

What was the oxygen level in the Archean Eon (> 2.5 billion years)?

Published estimates of log O_2 Pressure

Ohmoto (numerous refs)	> -2
Farquhar et al. (2000)	< -5
Frimmel (2005)	< -5
Kump (2008)	< -5
C-W-K-H Model (1968+)	~ -13
Sverjensky et al. (2008, 2010)	~ -70

Key constraints on Archean surface oxygen levels.

Detrital uraninite and pyrite

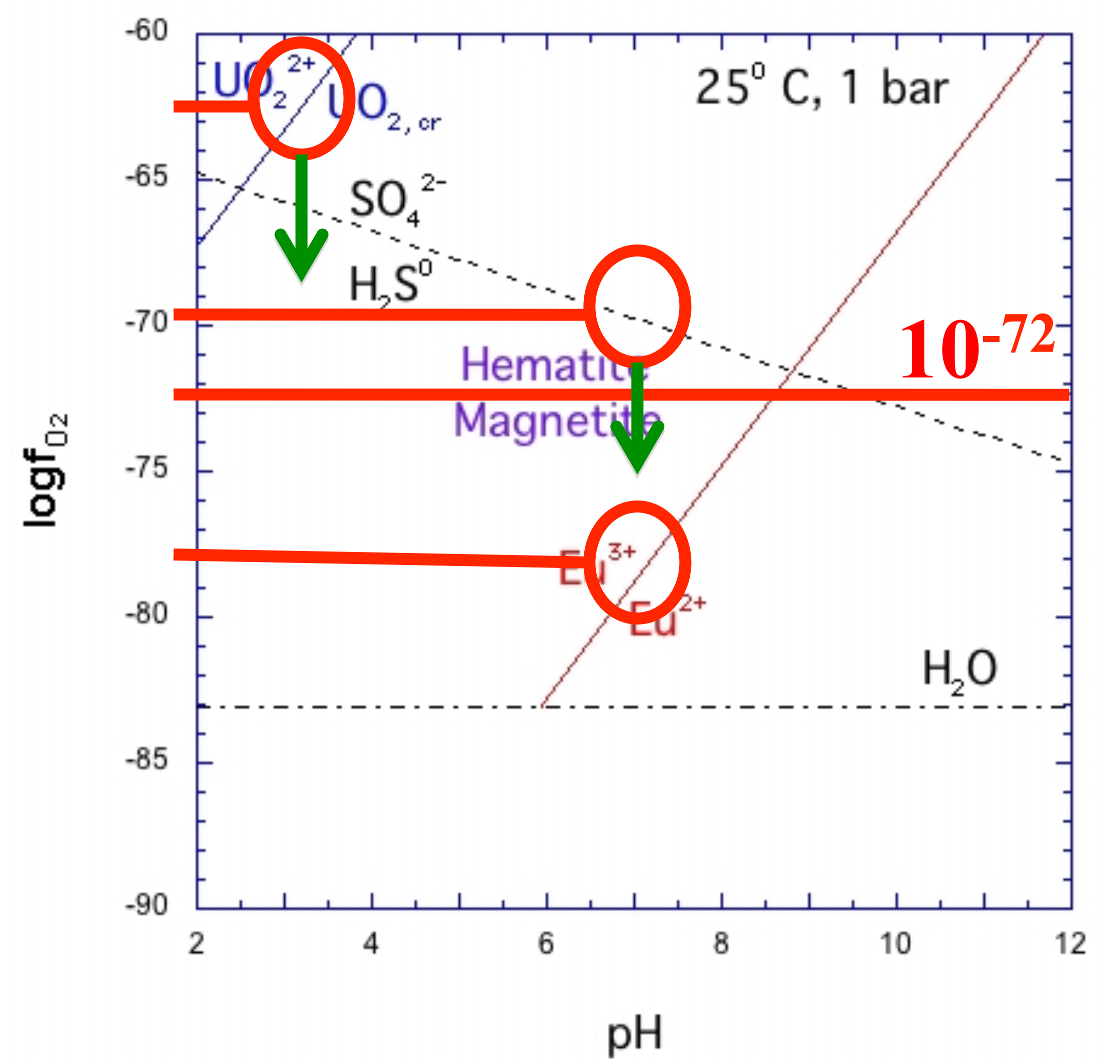
Paleosols lacking iron oxides

[Surface waters with aqueous Fe^{2+}]

[Surface waters with low SO_4^{2-}]

Eu^{2+} anomalies

What was the oxygen level in the Archean Eon?



Key constraints on Archean surface oxygen levels.

Detrital uraninite, pyrite and siderite

Paleosols lacking iron oxides

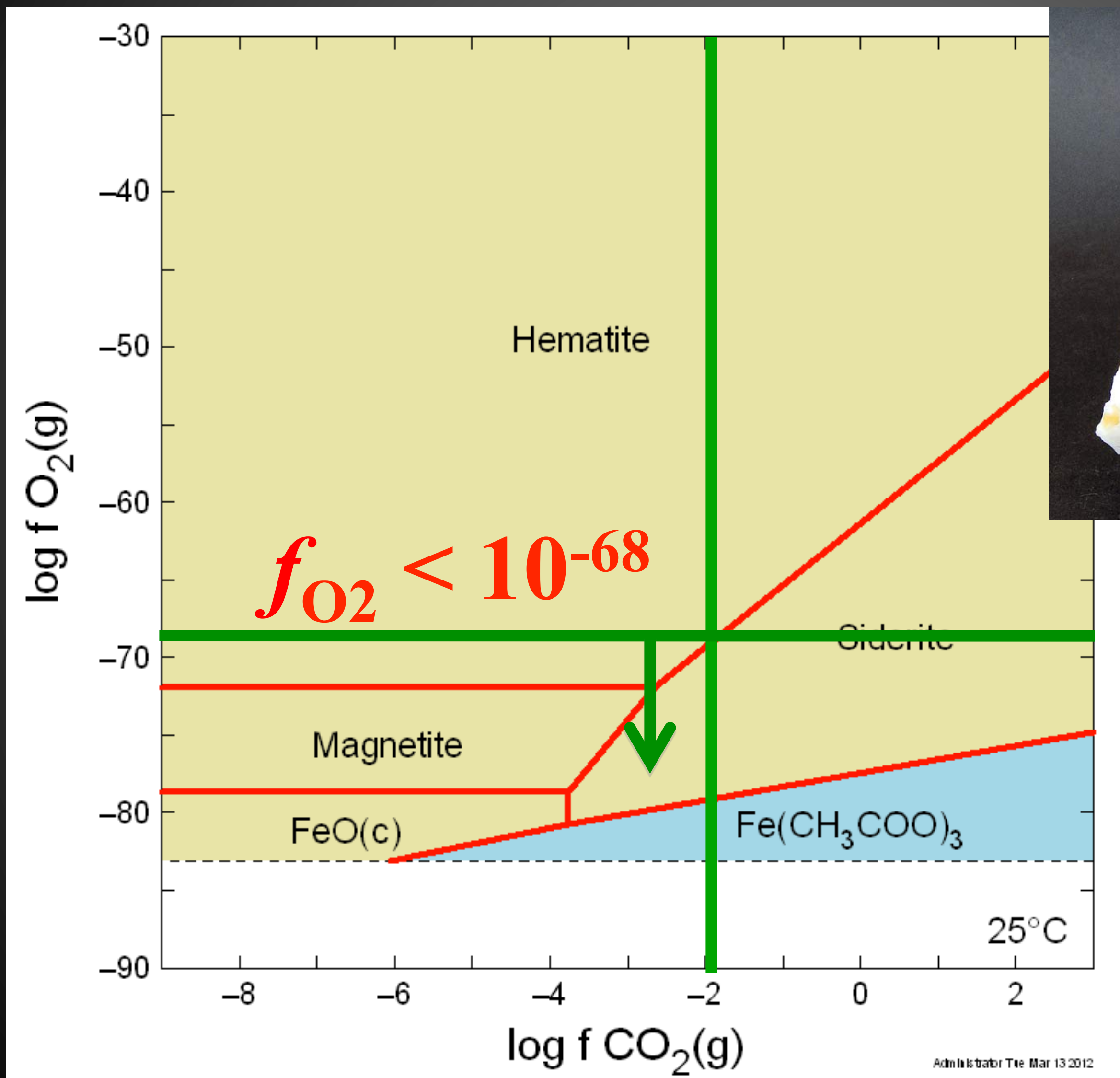
[Surface waters with aqueous Fe^{2+}]

[Surface waters with low SO_4^{2-}]

Eu^{2+} anomalies

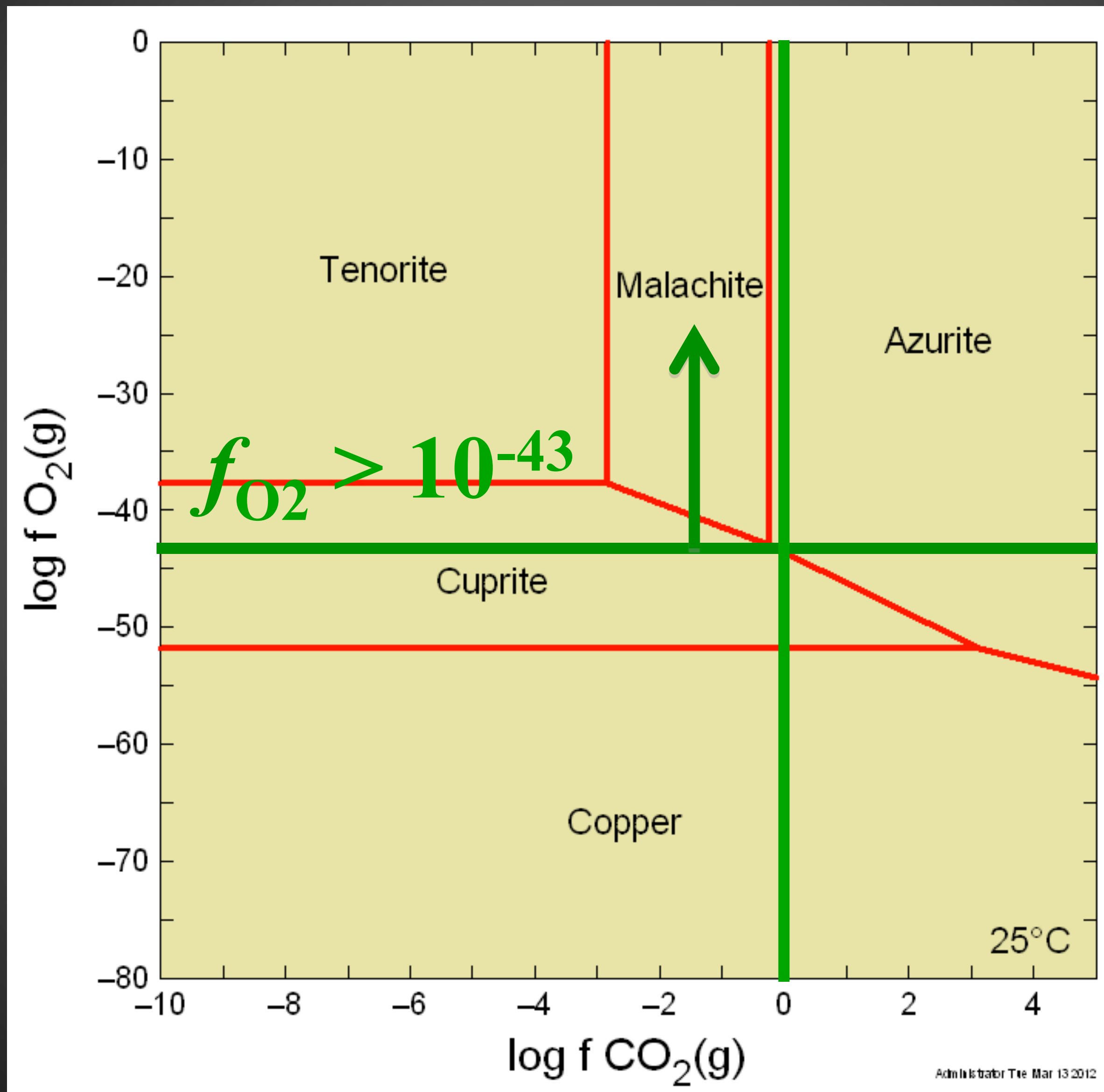
Precipitation of ferroan carbonates

What was the oxygen level in the Archean Eon?



Siderite
$FeCO_3$

What was the oxygen level in the Archean Eon?



Azurite

&

Malachite

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 Ga)

Cu^{2+} Copper minerals (256 of 321)

When did these minerals first appear?

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 Ga)

What mineral species won't form?

202 of 220 U minerals

319 of 451 Mn minerals

47 of 56 Ni minerals

582 of 790 Fe minerals


Piemontite


Garnierite

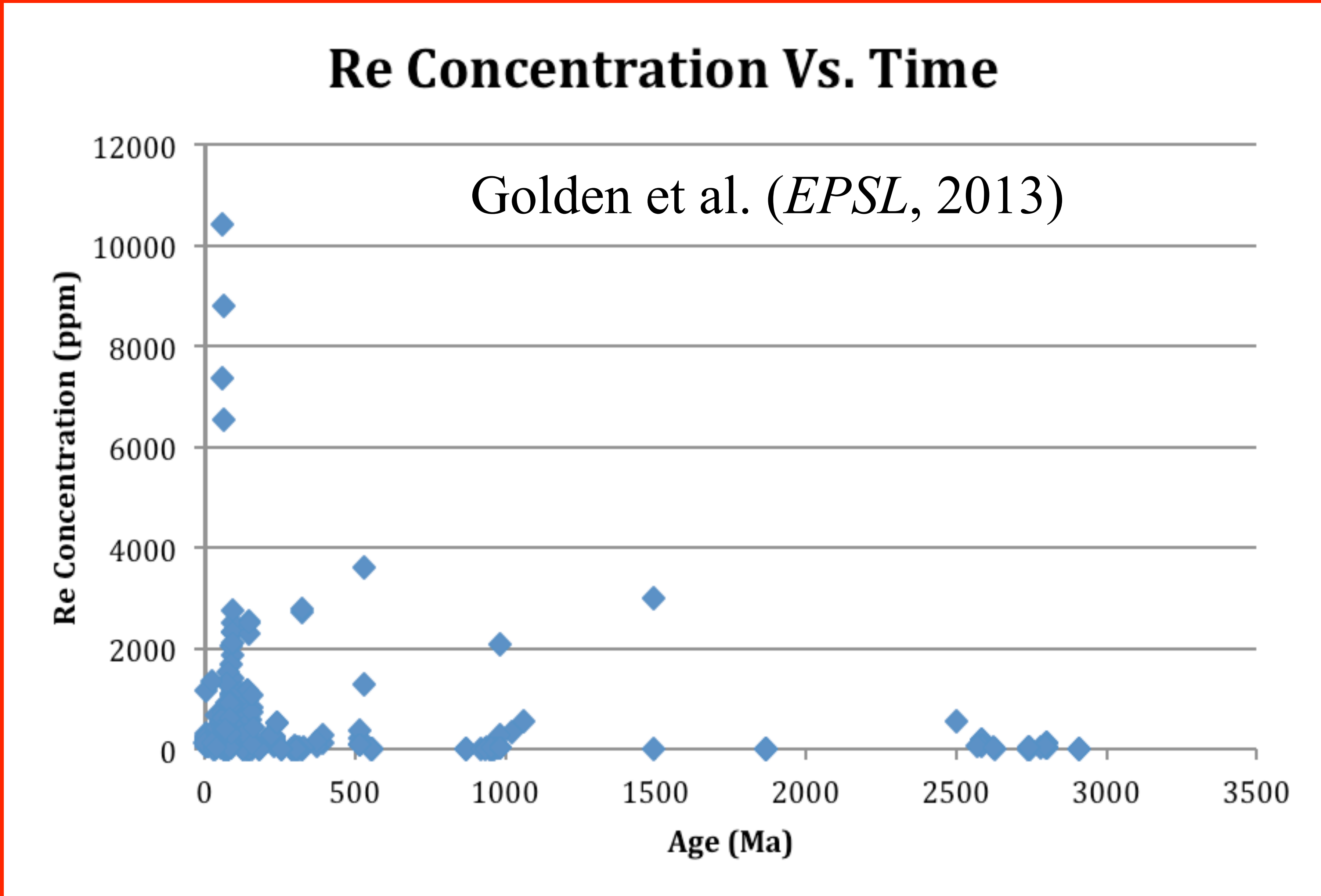

Xanthoxenite

Stages 6-10: Co-evolution of the geosphere and biosphere

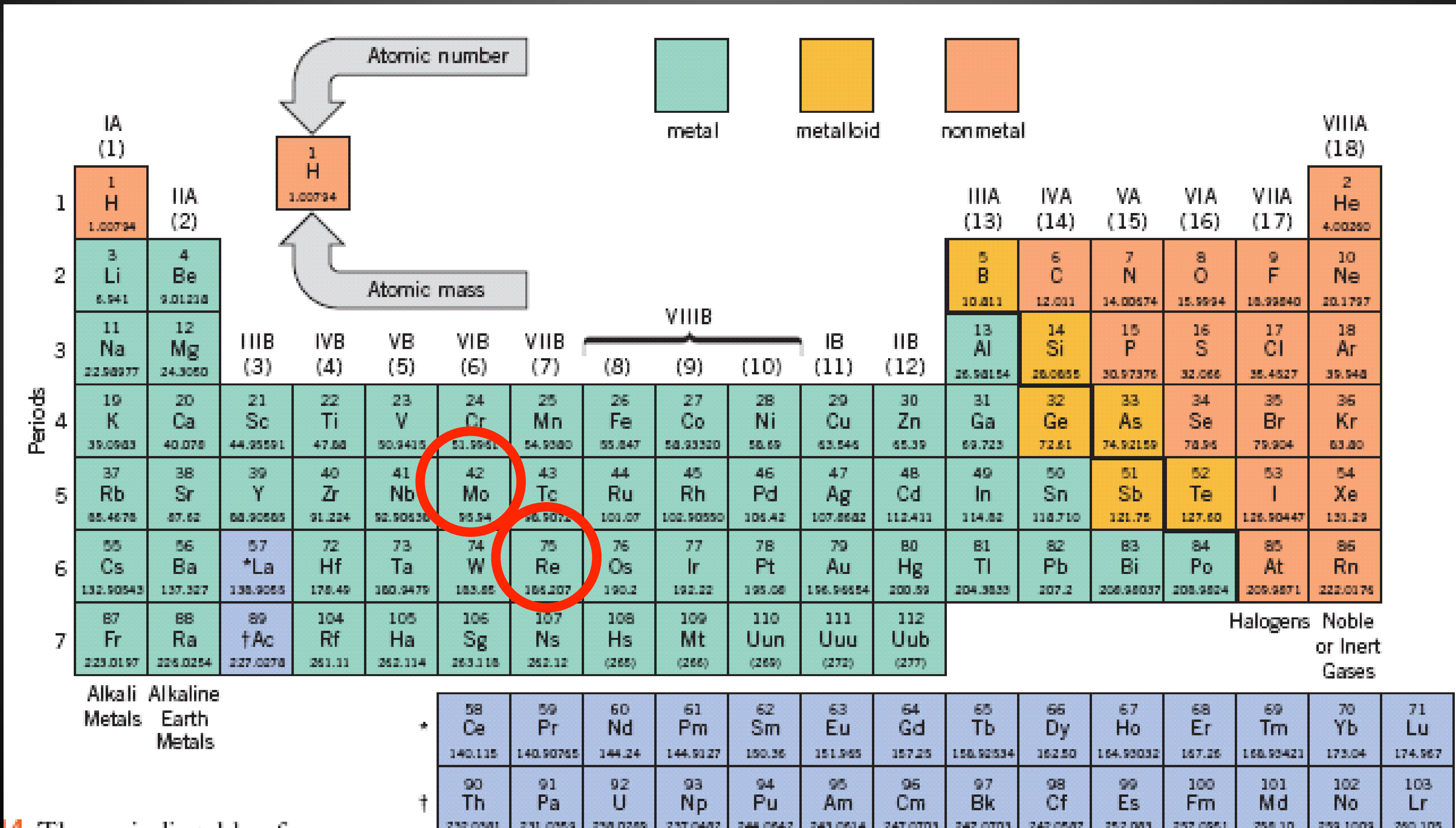
Changes in Earth's atmospheric composition at ~2.4 to 2.2 Ga represent the single most significant factor in our planet's mineralogical diversity.

>4500 mineral species

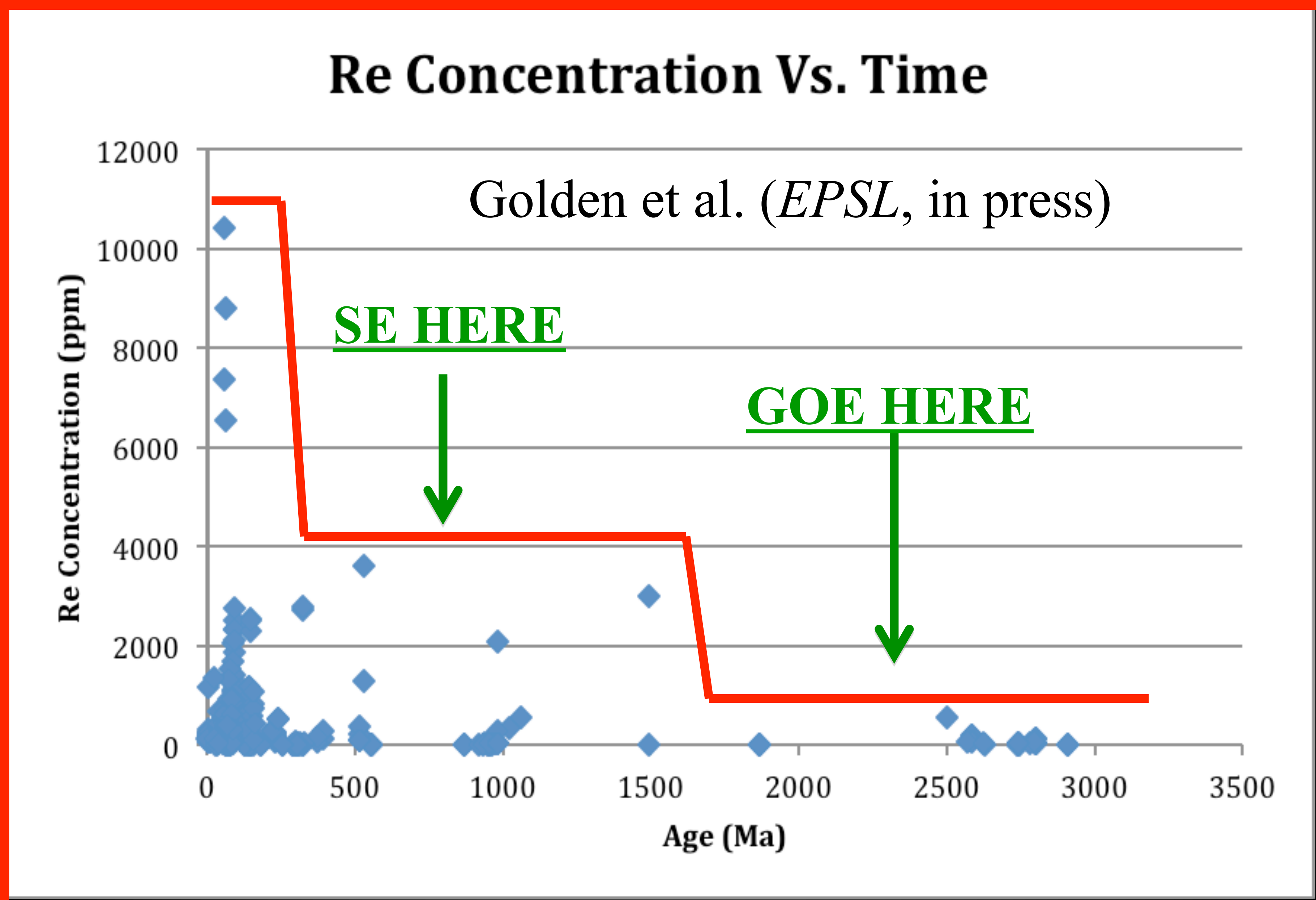
RESULTS: Molybdenite (MoS_2) through Time

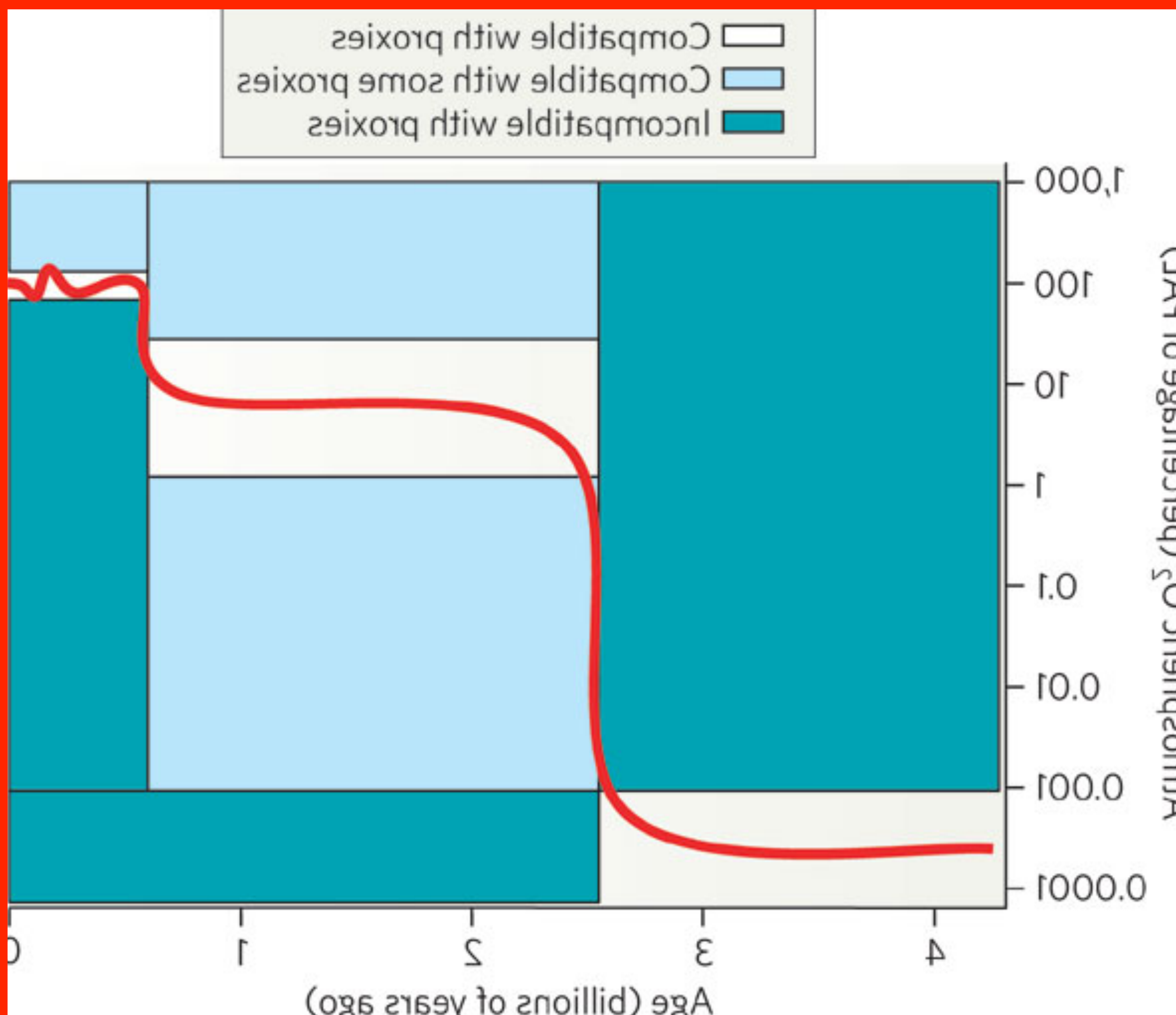


Mo & Re in Molybdenite



RESULTS: Molybdenite (MoS_2) through Time





Kump (2008) *Nature* 451, 277-278.

RESULTS: Molybdenite (MoS_2) through Time

Hypothesis: There was a protracted “Great Subsurface Oxidation Interval” that postdated the GOE by a billion years. This interval was the single most significant factor in Earth’s mineralogical diversificiation.

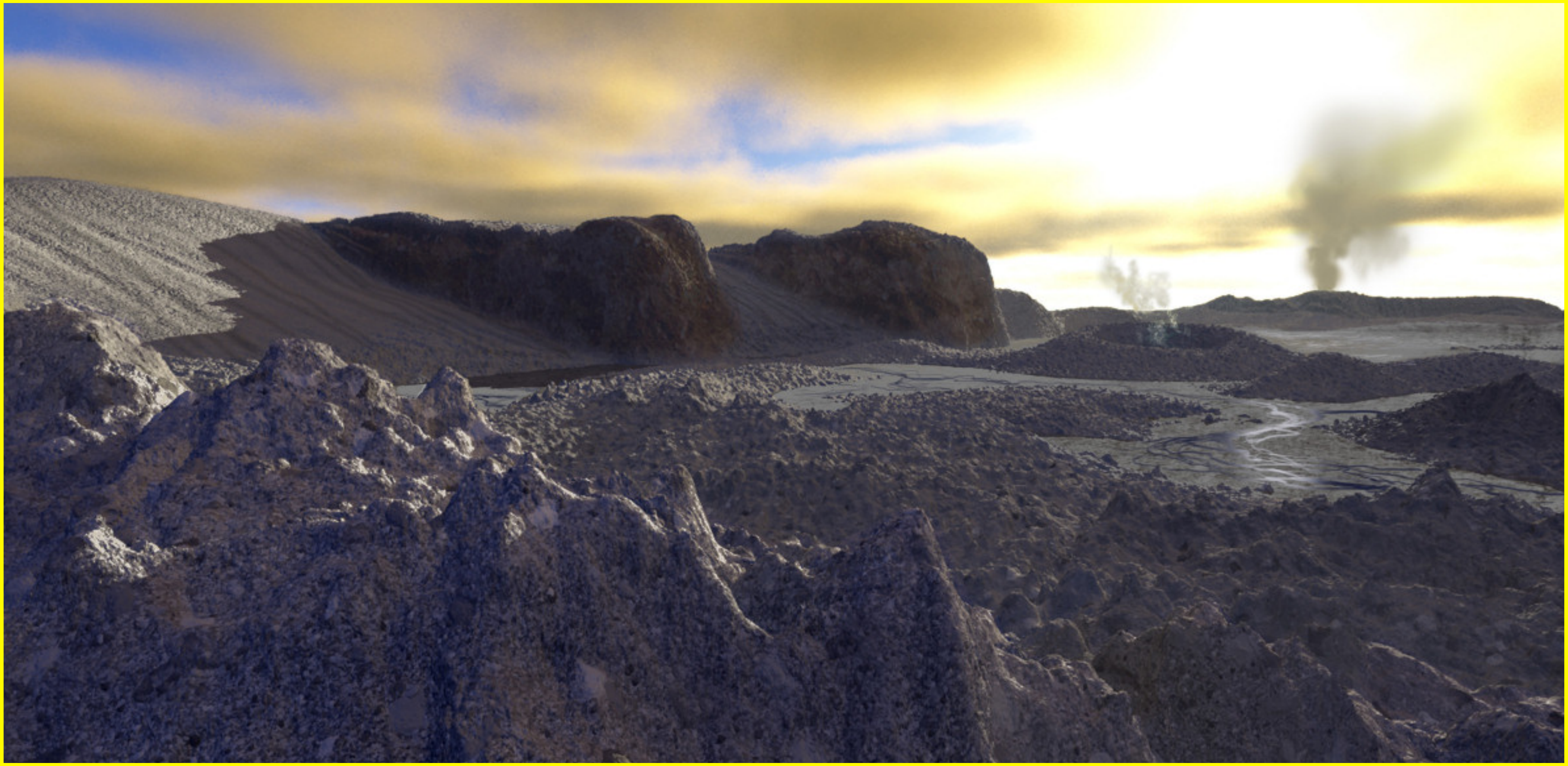
Stage 8: The "Intermediate Ocean" (1.85-0.85 Ga)

>4500 mineral species (few new species)

Oxidized surface ocean; deep-ocean anoxia.

Stage 9: Snowball Earth and Neoproterozoic Oxidation (0.85-0.542 Ga)

>4500 mineral species (few new species)



Glacial cycles triggered by albedo feedback.

Stage 10: Phanerozoic Biomineralization (<0.542 Ga)

>4,800 mineral species (Biominerals, clays)

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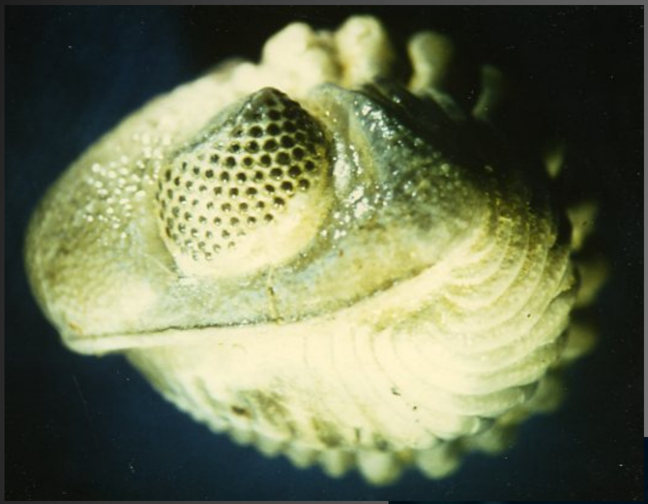
>4,800 mineral species



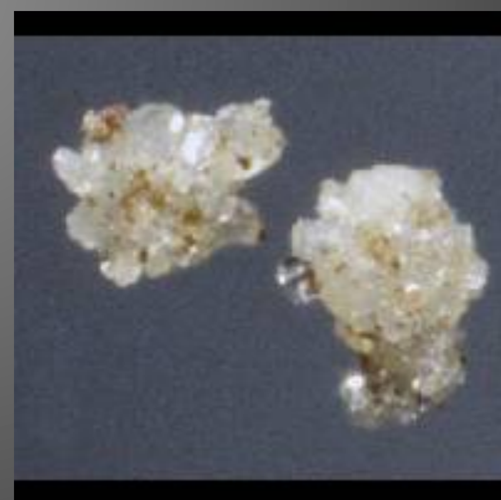
Stage 10: Phanerozoic Biomineralization

Abelsonite—$NiC_{31}H_{32}N_4$

Ravatite—$C_{24}H_{48}$

Evankite—$C_{24}H_{48}$

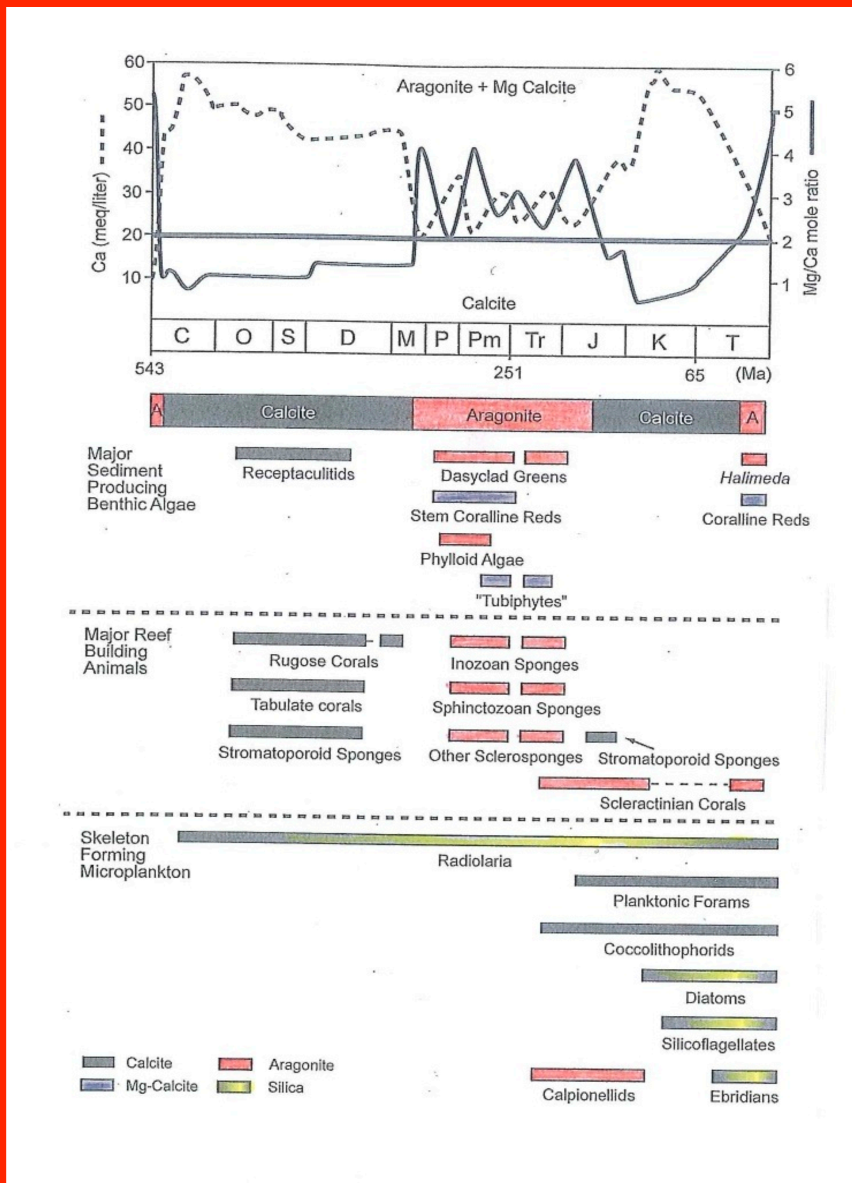
Dashkovaite—$Mg(HCOO)_2 \cdot 2H_2O$



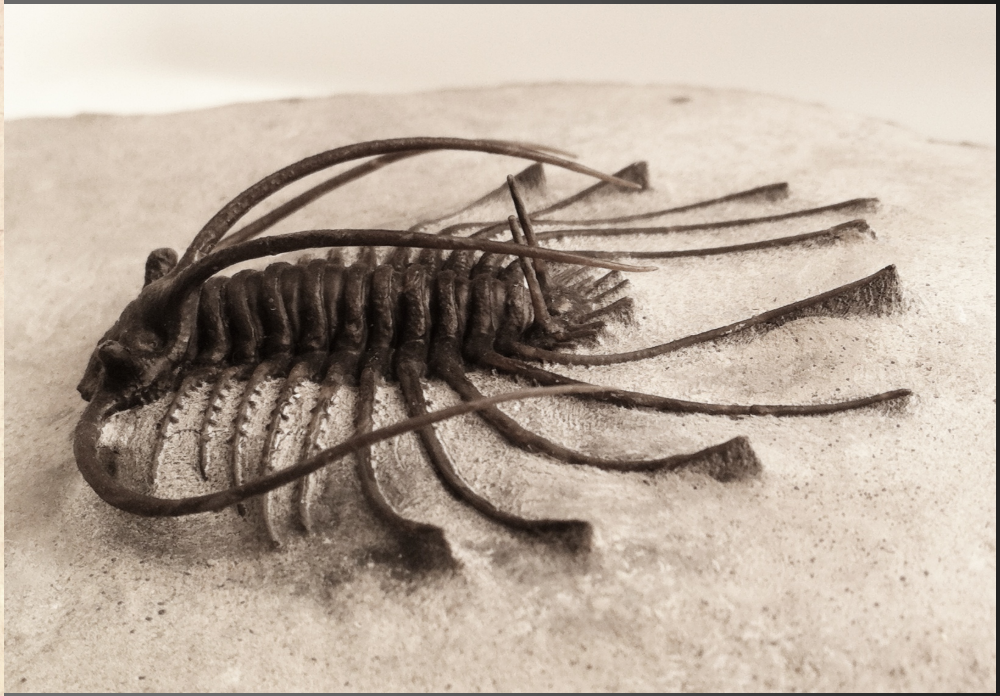
Oxammite—$(NH_4)(C_2O_4) \cdot H_2O$

> 50 Organic Mineral Species

Skeletal Biomineralization



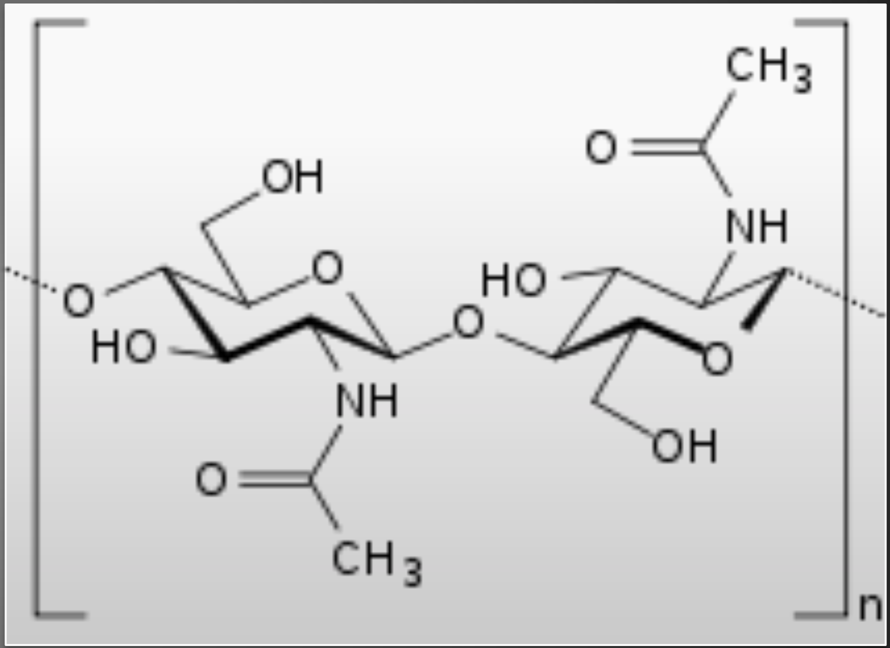
Stage 10: Phanerozoic Biomineralization



Apianurus nov. sp.

Walcott-Rust Quarry,
Moscow, New York.

Stage 10: Phanerozoic Biomineralization

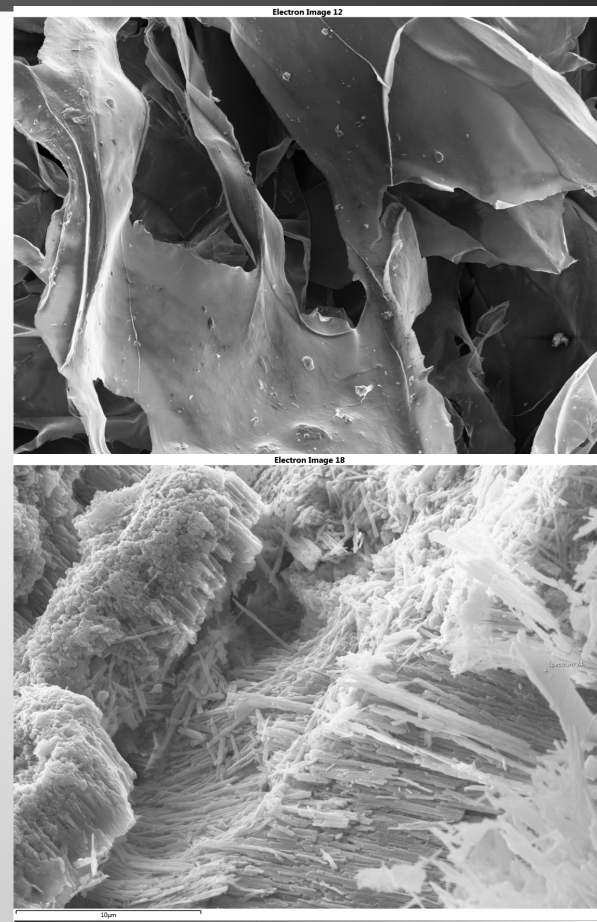


Apianurus nov. sp.

Walcott-Rust specimens preserve biomolecular fragments of chitin.

Stage 10: Phanerozoic Biomineralization

Ecphora



SEM images

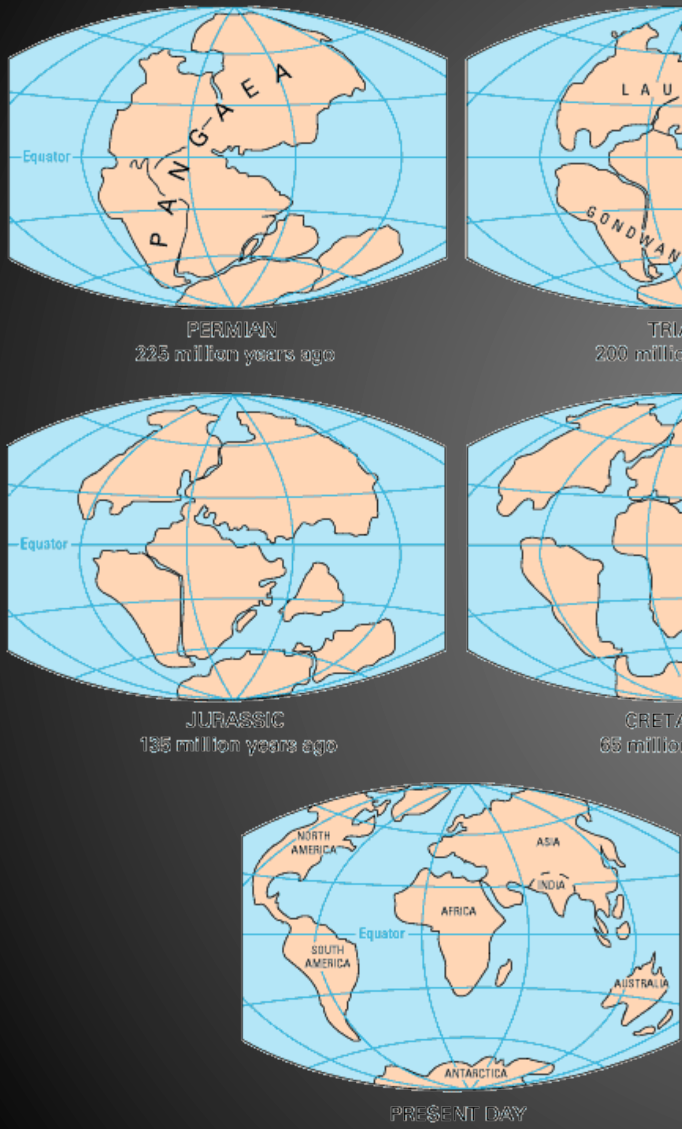
Calvert Cliffs specimens preserve the original 15 million year old shell-binding proteins!

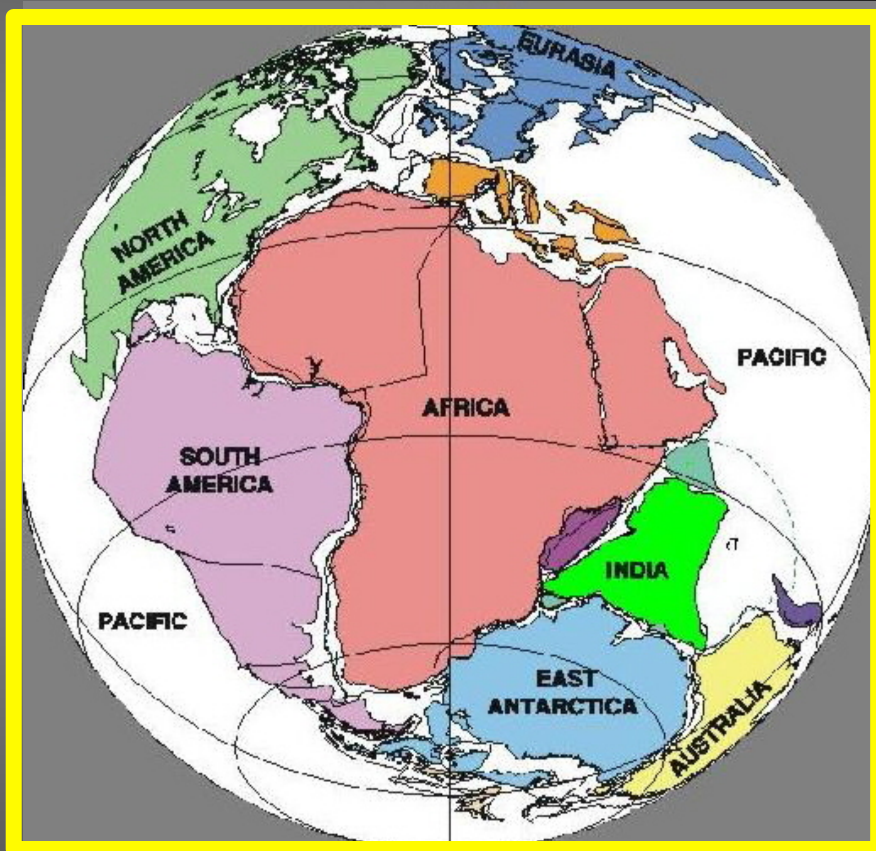
RECENT CONCLUSIONS

Previously unrecognized patterns in the distribution of minerals through Earth history reflect:

- **The supercontinent cycle.**
- **The rise of the terrestrial biosphere.**

The Supercontinent Cycle

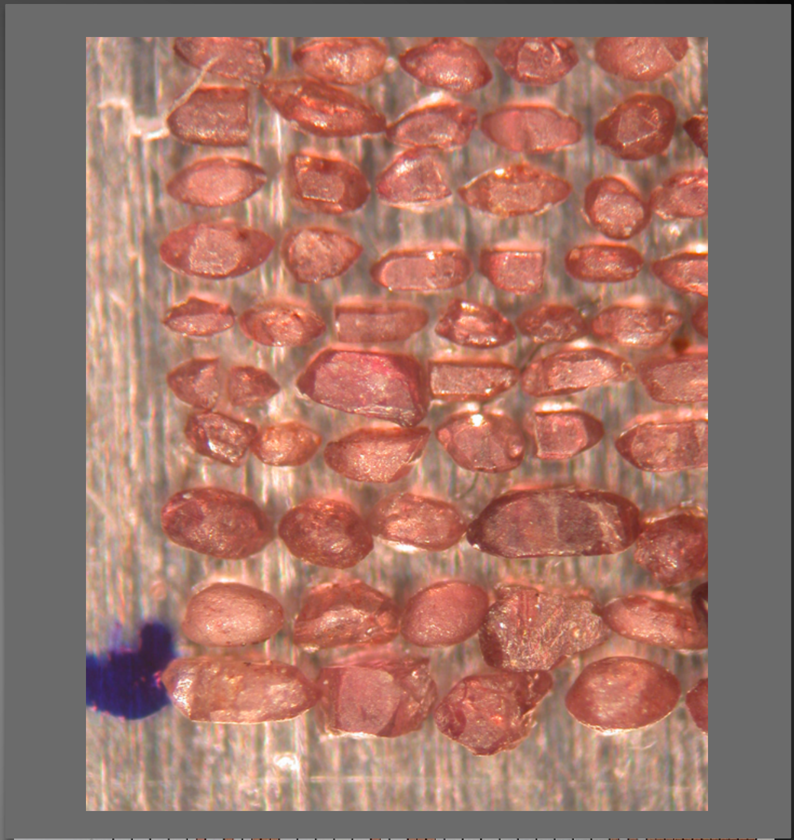


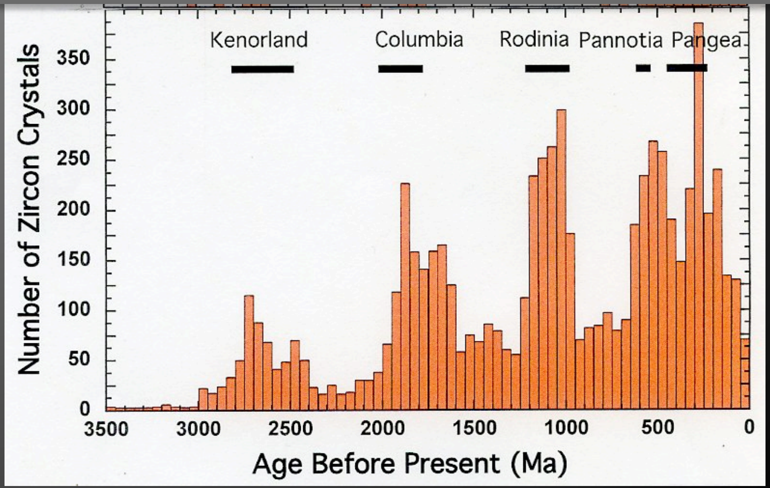


RESULTS: The Supercontinent CYCLE

The distribution of zircon crystals through time correlates with the supercontinent cycle over the past 3 billion years.

(Condie & Aster 2010; Hawksworth et al. 2010)

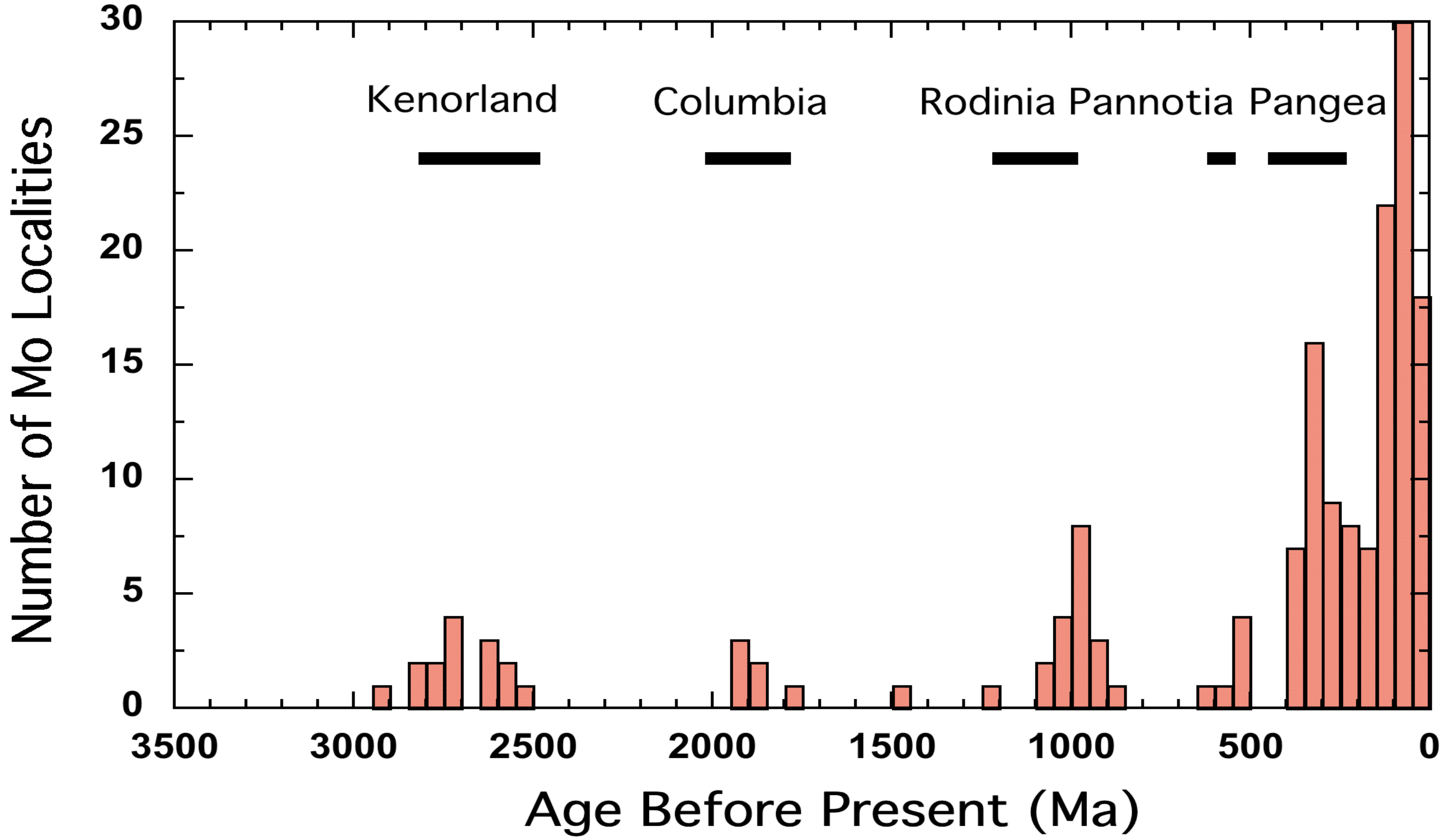




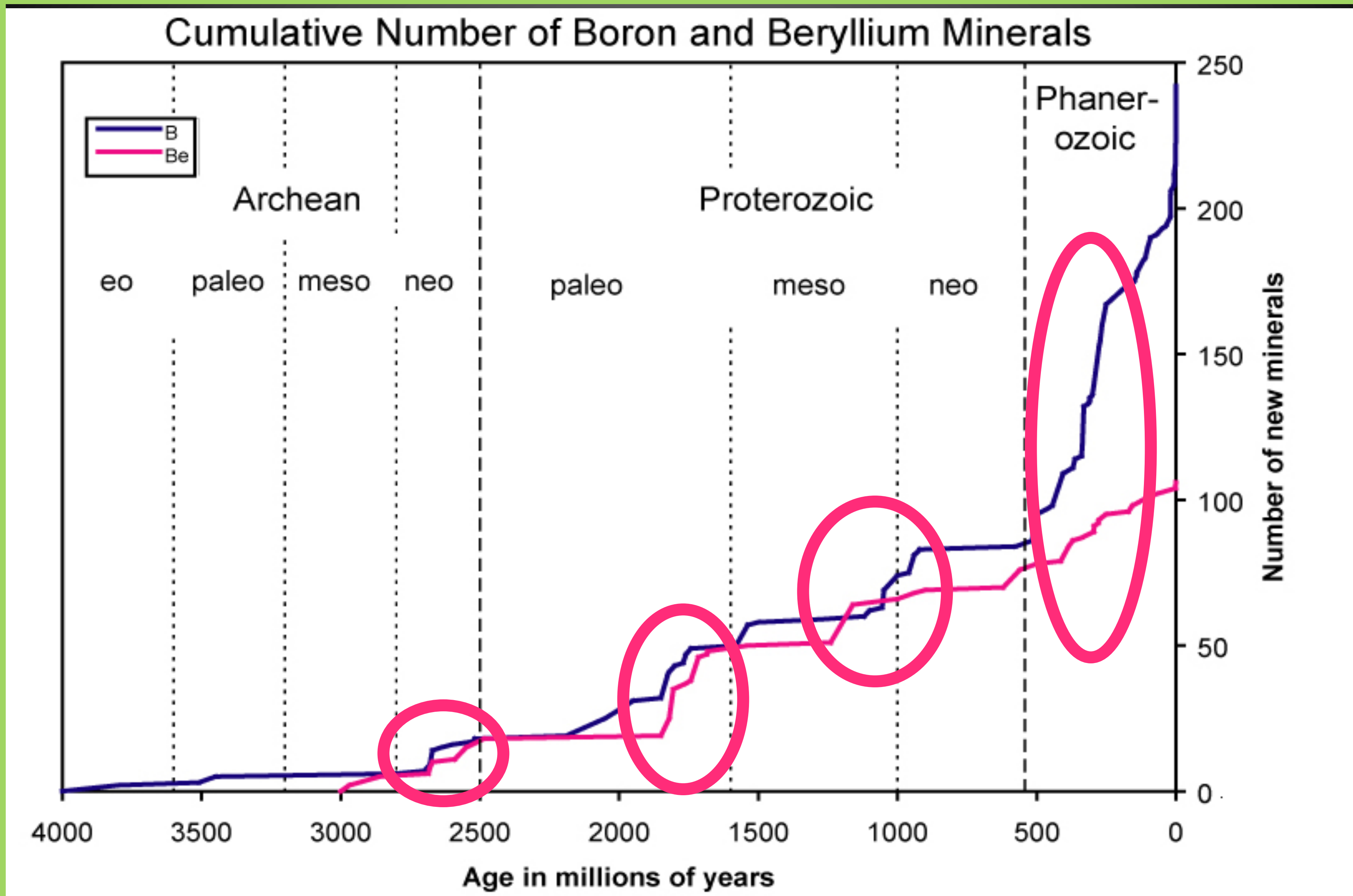
RESULTS: Mo Mineral Evolution

Temporal distribution of molybdenite (MoS_2)

Golden et al. (*EPSL*, in press)

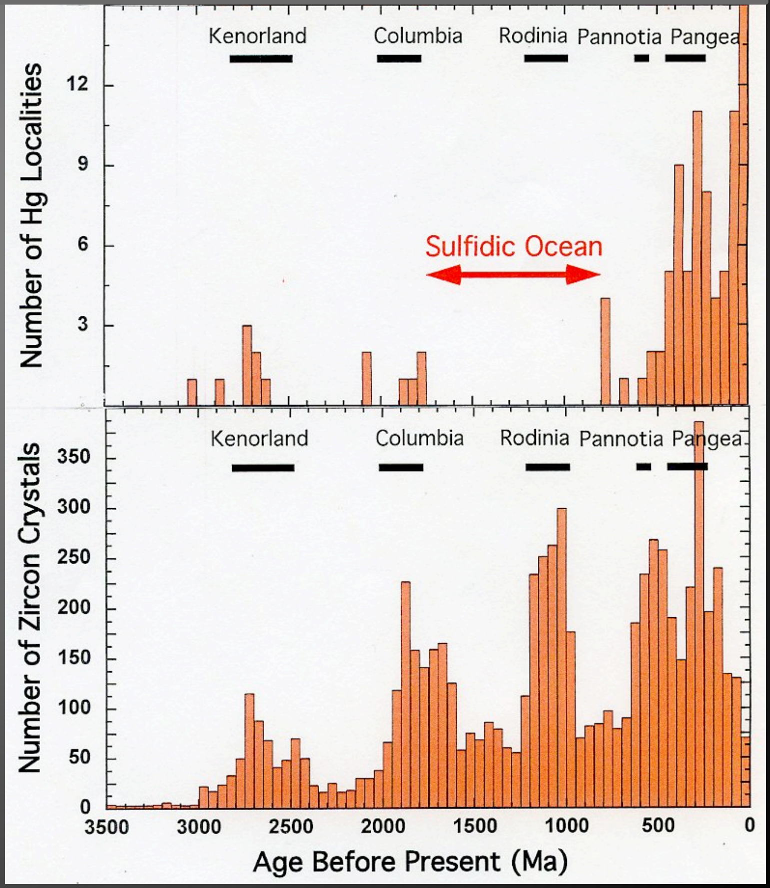


B and Be Minerals (Grew & Hazen 2009, 2010)



Hg Mineral Evolution

The distribution of mercury (Hg) minerals through time also correlates with the SC cycle over the past 3 billion years, but there's a gap during the "boring billion".



Hazen et al. (2012) *Amer. Mineral.*

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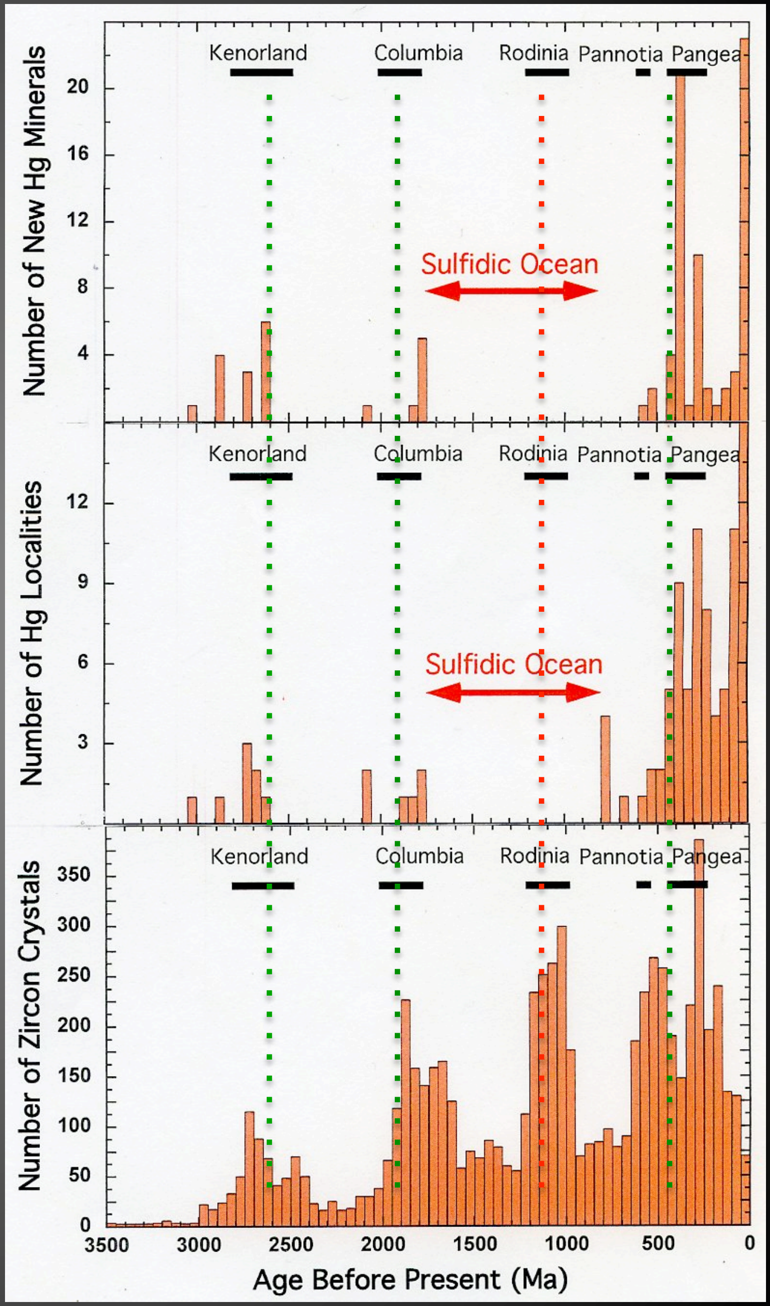
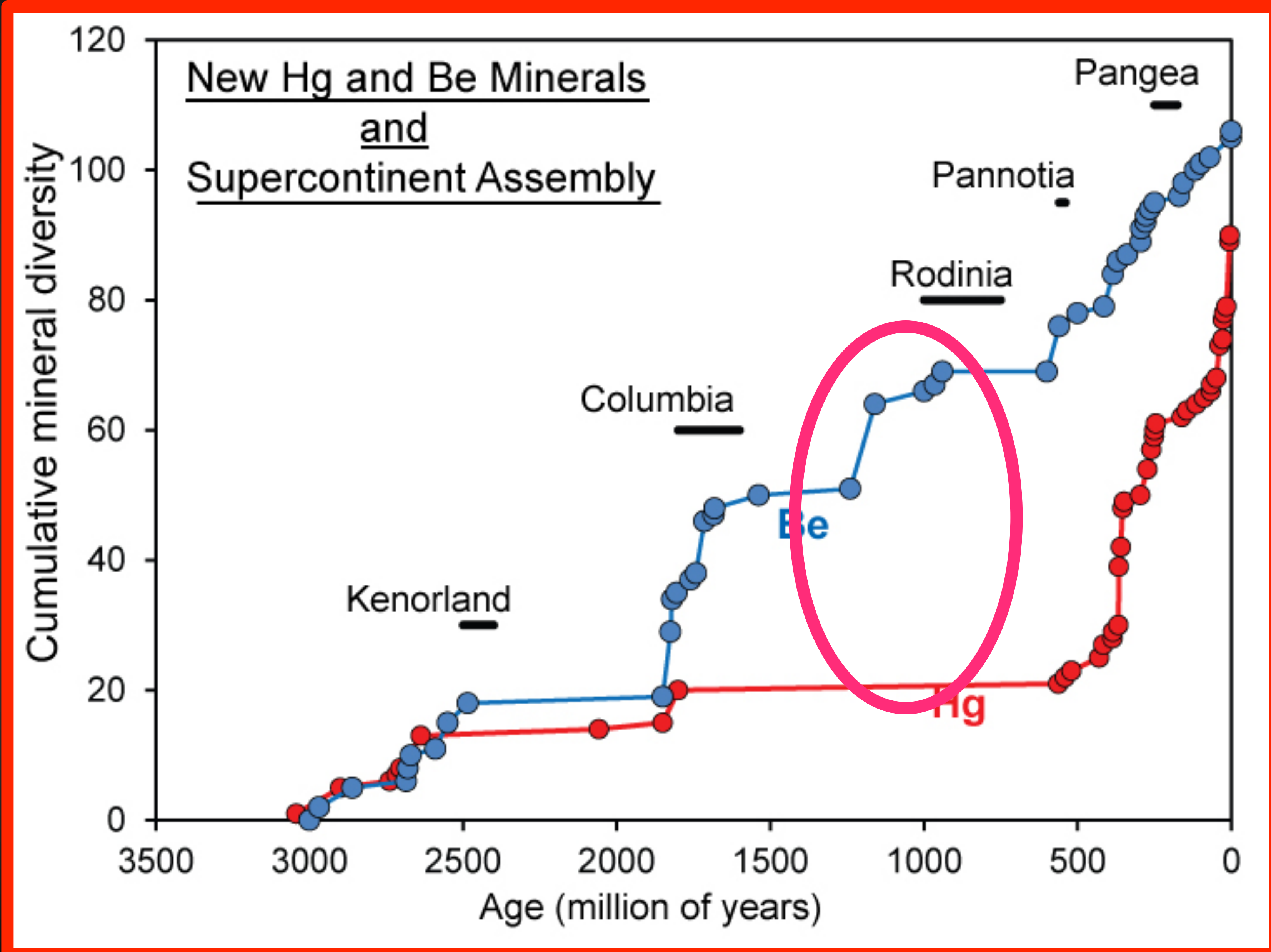


Hazen et al. (2012) *Amer. Mineral.*

RESULTS: Hg & Be Mineral Evolution



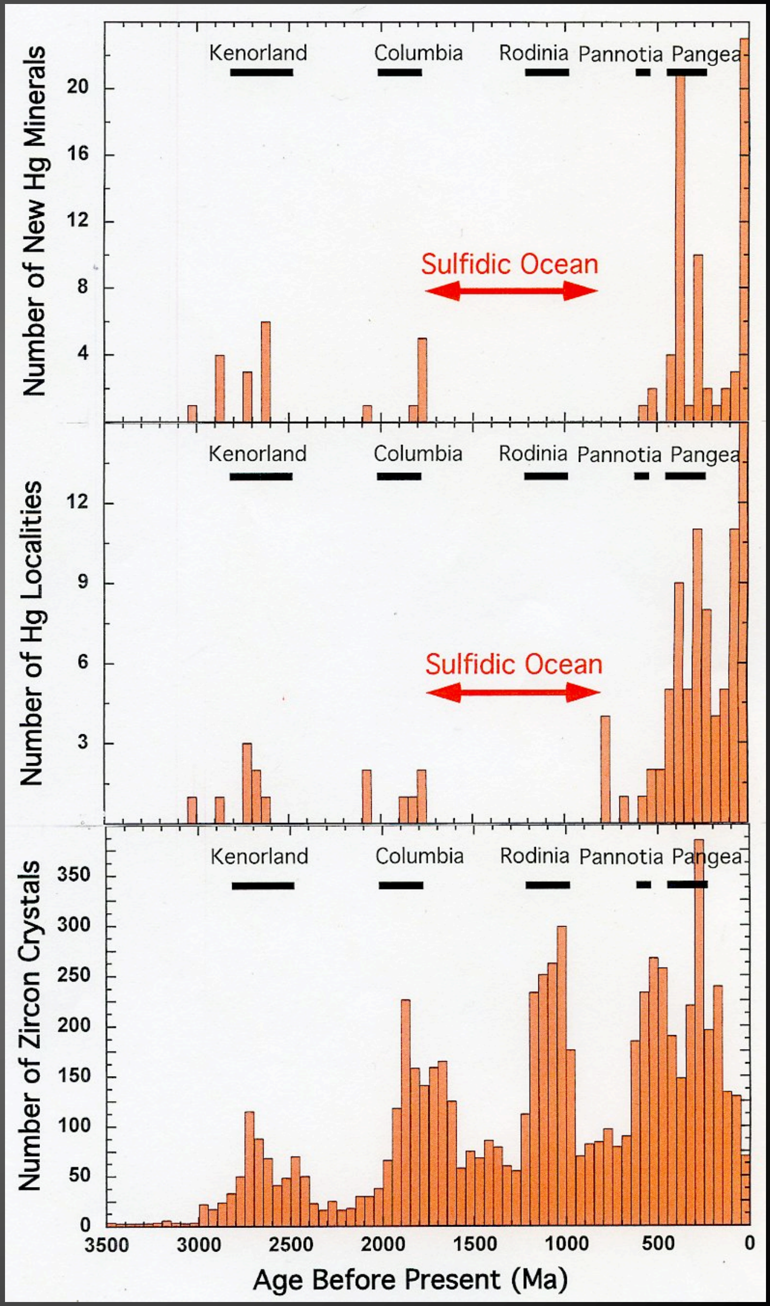
Hg Mineral Evolution

1. Was Hg sequestered as insoluble cinnabar?

2. Did microbial methylation play a role?

3. Is Hg in Mesoproterozoic Pb-Zn deposits?

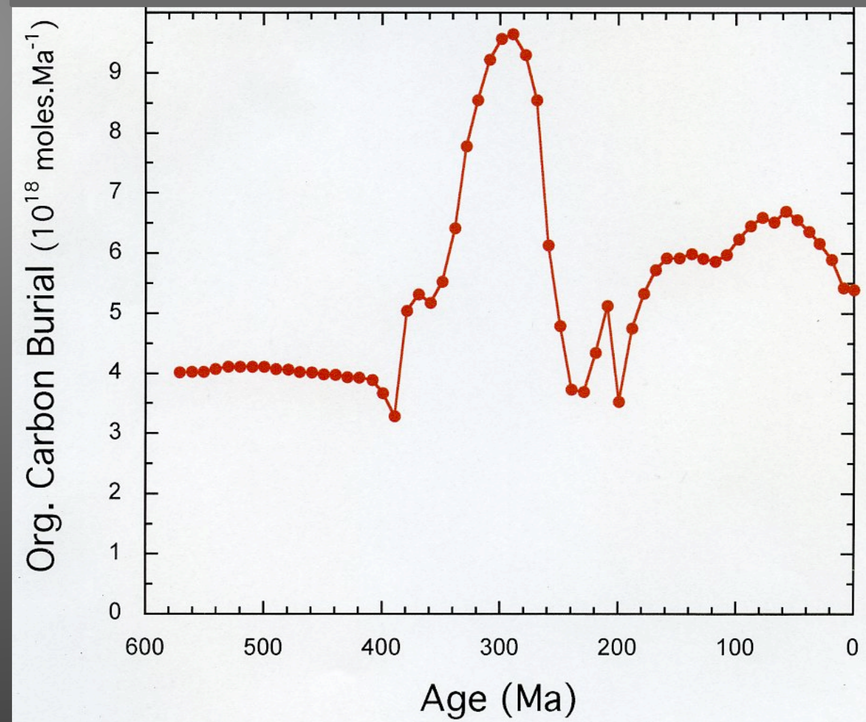
Hazen et al. (2012) *Amer. Mineral.*



Phanerozoic Biomineralization and the Terrestrial Biosphere (<542 Ma)

Hg Mineral Evolution

The distribution of mercury (Hg) minerals through the last 450 million years reflects changes in Earth's biosphere.



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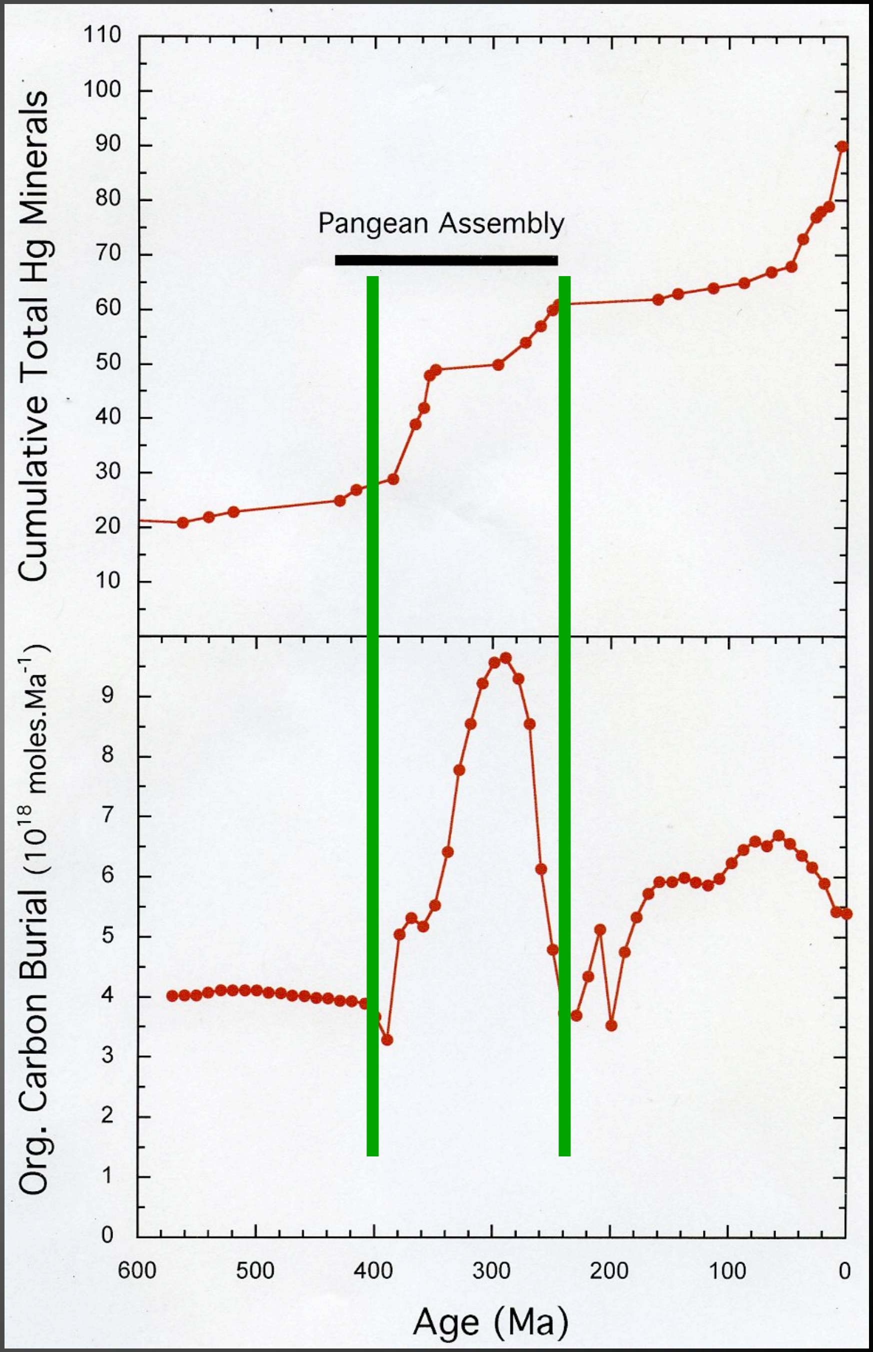

Conclusions

With mineral evolution, the science of mineralogy once again assumes its rightful place at the center of the Earth and planetary sciences.

Deep Carbon Observatory

NSF

NASA

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