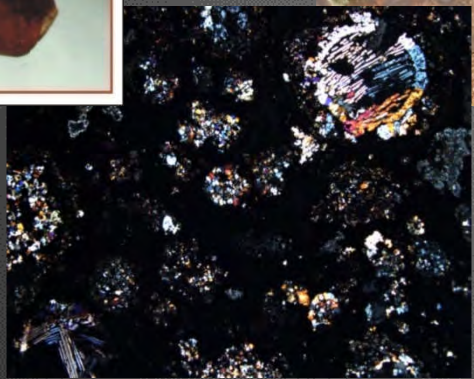
Mineralogical Co-Evolution of the Geo- and Biospheres




Mid-Atlantic Senior Physicists Group
October 17, 2012

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Deep Carbon Observatory

CARNEGIE INSTITUTION FOR SCIENCE

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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”

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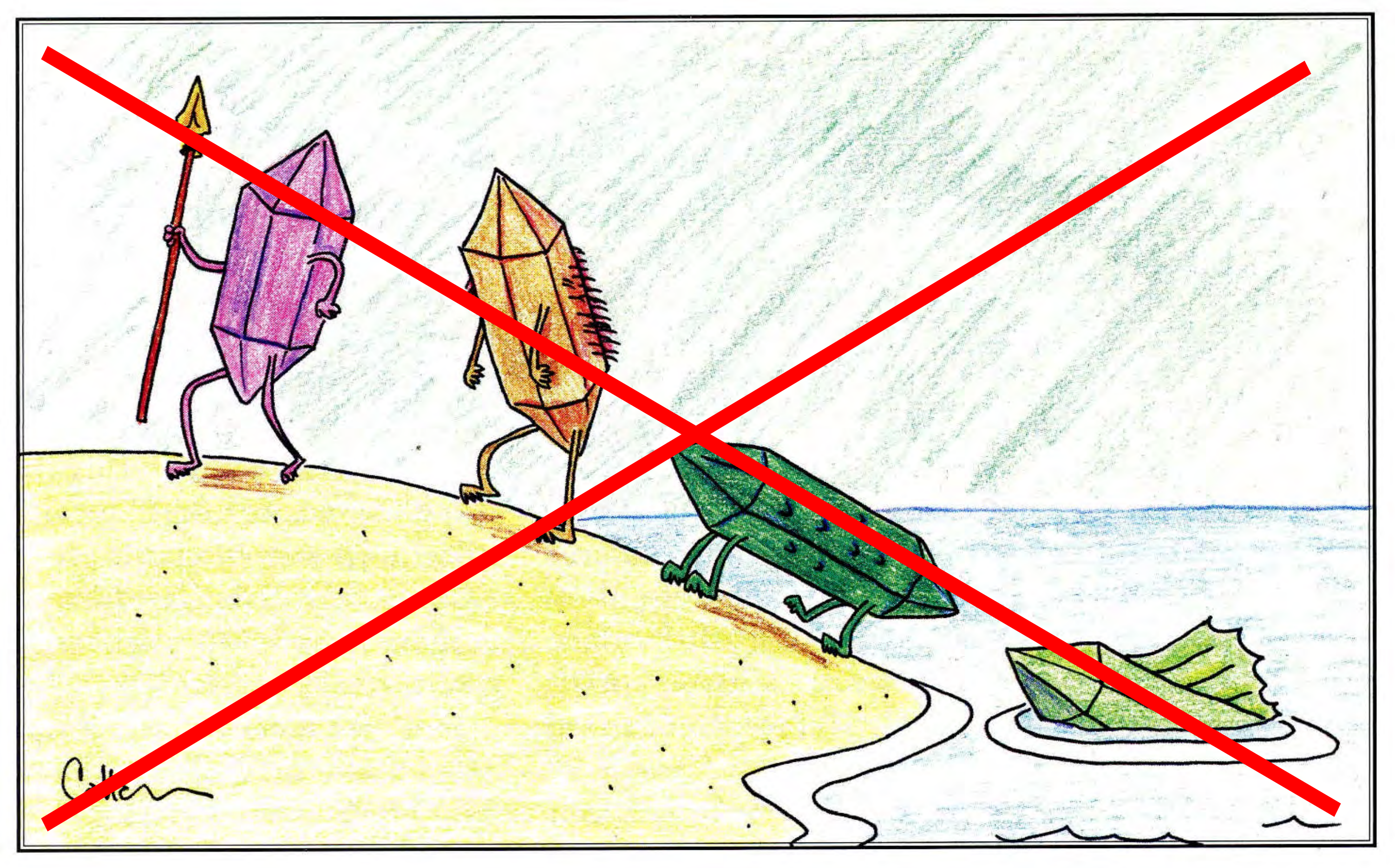

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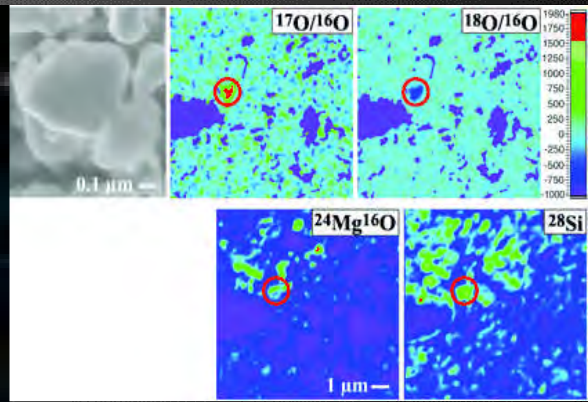
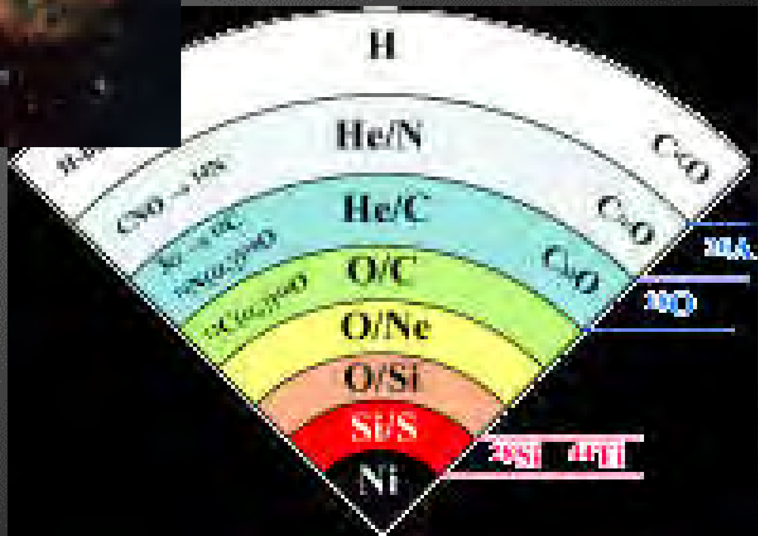
- But <u>NOT</u> Darwinian evolution!

“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).





Mineral Evolution:

How did we get from a dozen minerals to ~4500 on Earth today?

What does the distribution of minerals through time tell us about key tectonic, geochemical, and biological events?

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?

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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).**

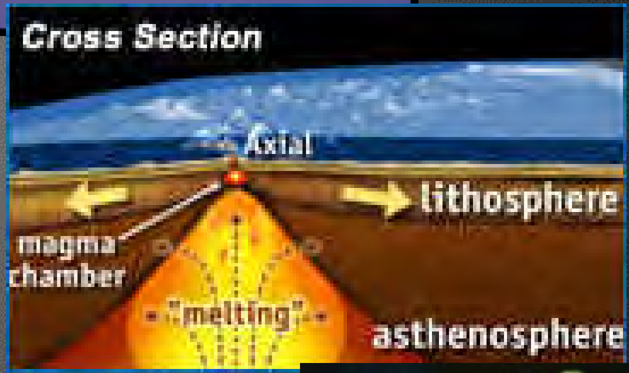
3. **The generation of far-from-equilibrium conditions by living systems.**

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**

Stage 1: Primary Chondrite Minerals

Minerals formed ~4.56 Ga in the Solar nebula "as a consequence of condensation, melt solidification or solid-state recrystallization" (MacPherson 2007)

~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

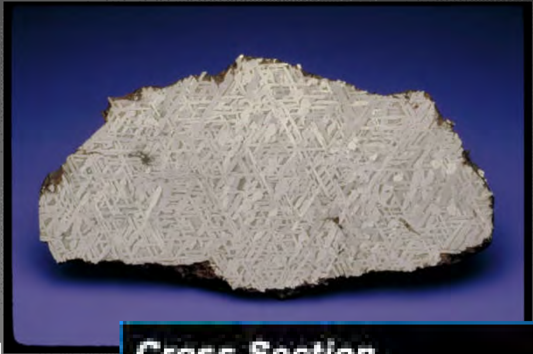
Stages 1 and 2: Planetary Accretion

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.

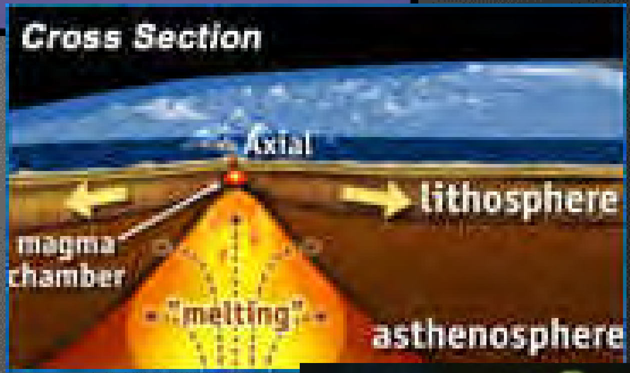
>250 mineral species

Three Eras of Earth's Mineral Evolution

1. The Era of Planetary Accretion

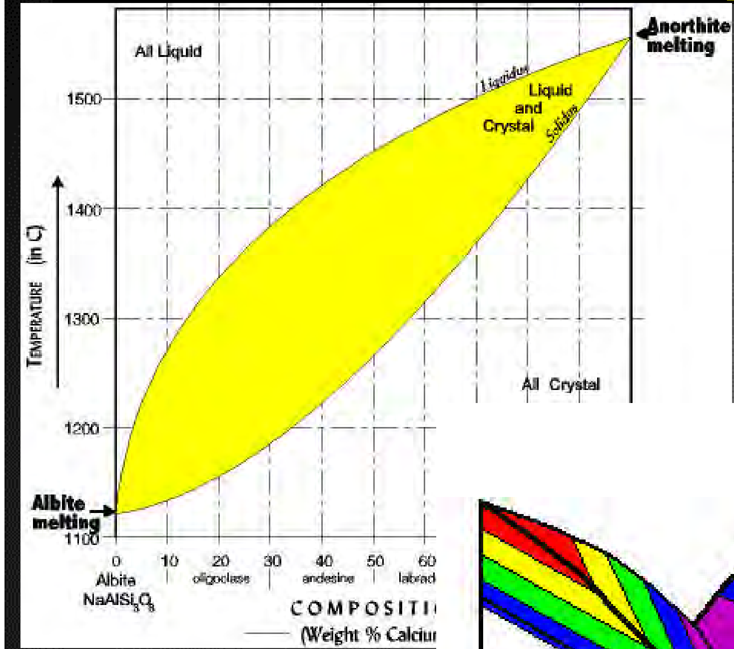


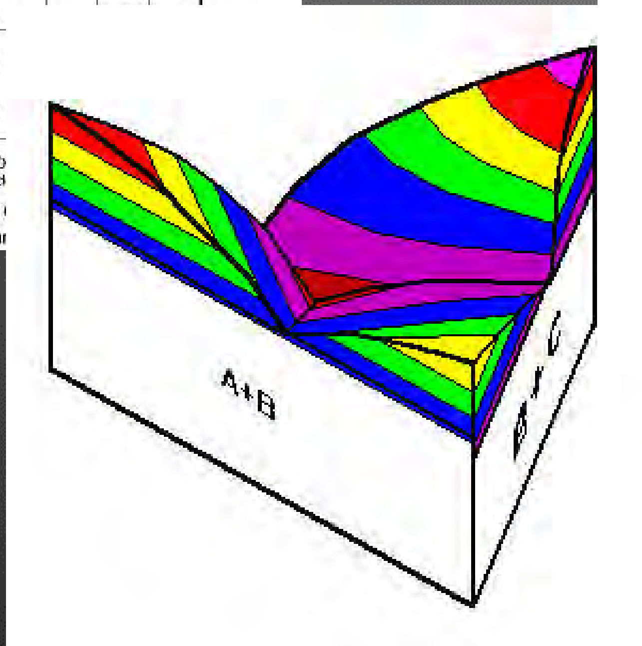
2. **The Era of Crust and Mantle Reworking**

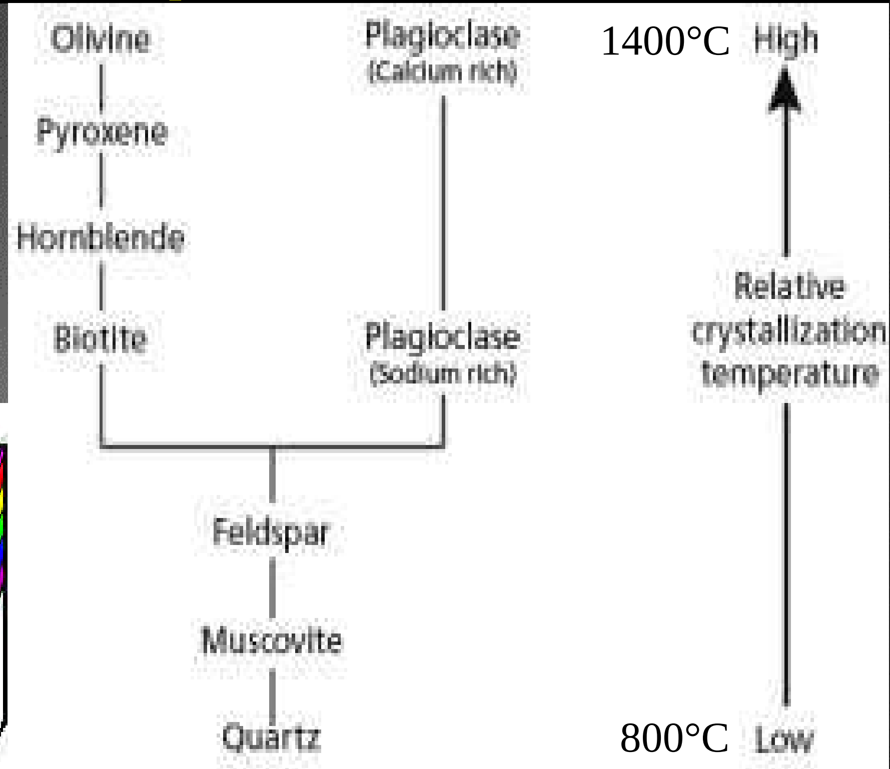


3. The Era of Bio-Mediated Mineralogy

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



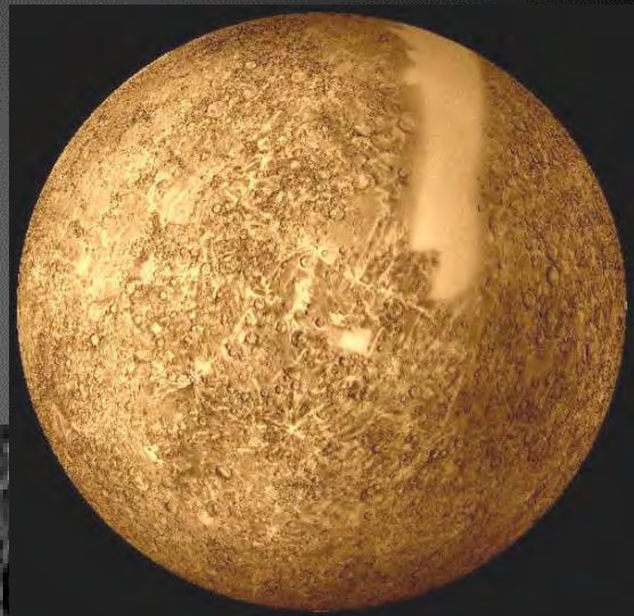




Partial melting, fractional crystallization and magma immiscibility

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

~350 mineral species?



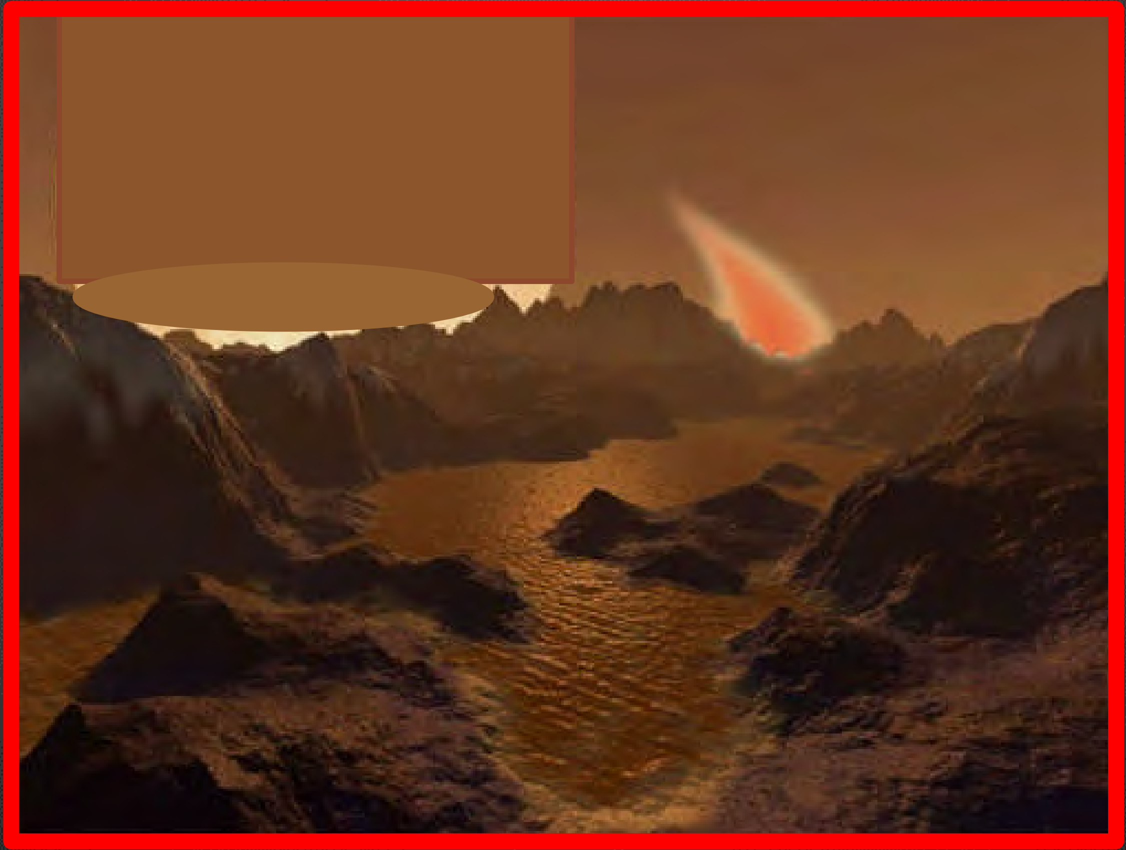
Is this the end point of the Moon and Mercury?

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

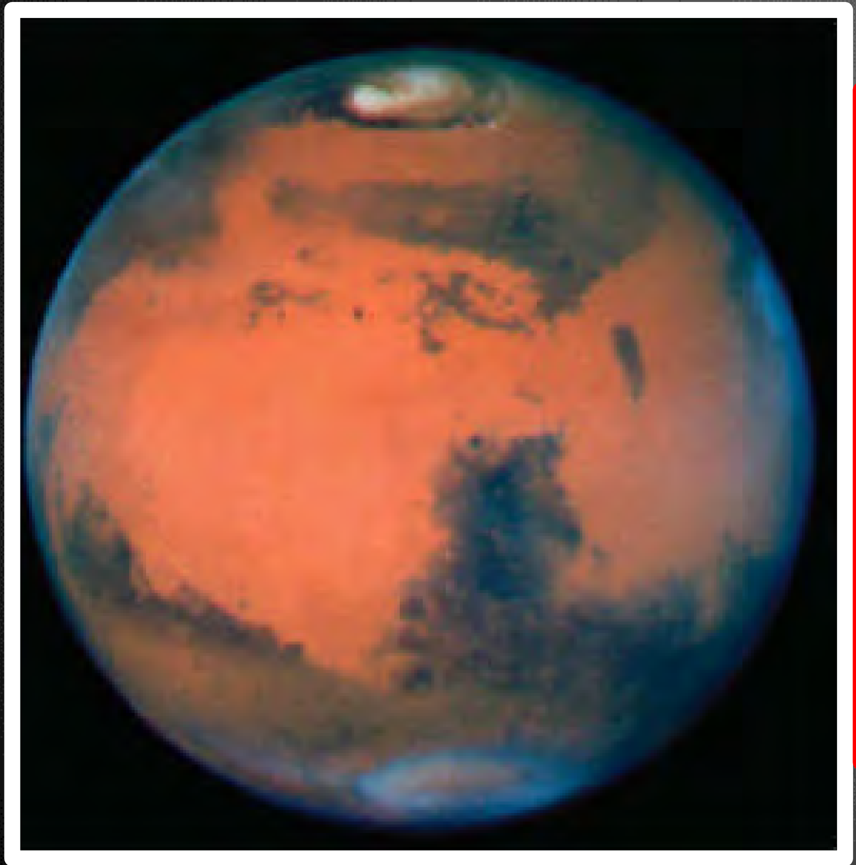
Stage 3: Initiation of Igneous Rock Evolution
Volatile-rich Body

>500 mineral species (hydroxides, clays)

Volcanism, outgasing, surface hydration, evaporites, ices.

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

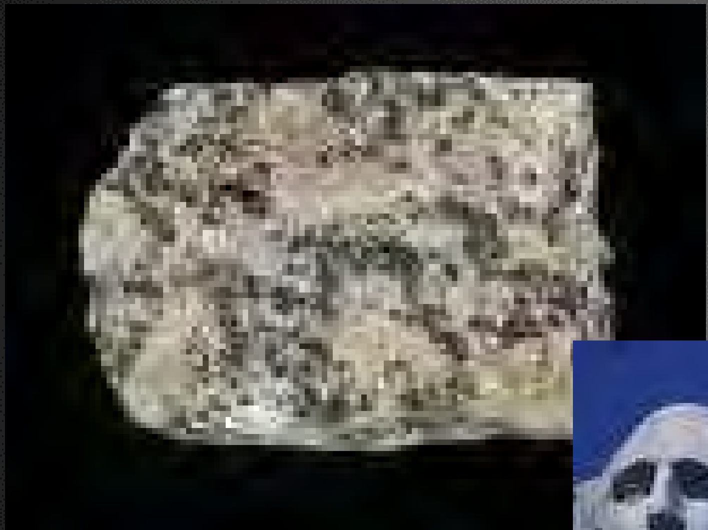
Is this the end point for Mars?



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: Granitoid Formation (>3.5 Ga)

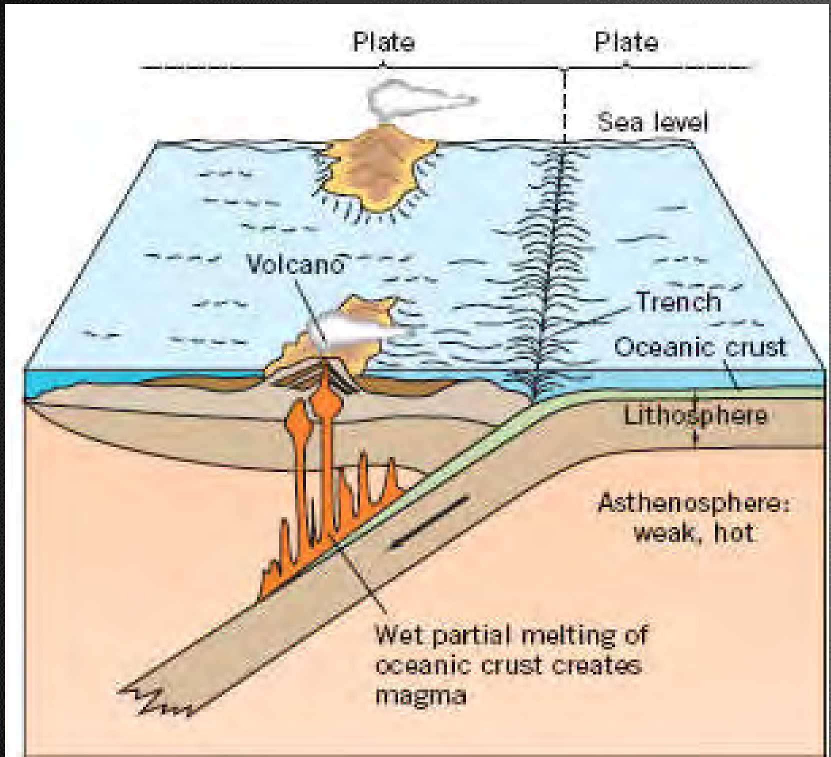
>1000 mineral species (pegmatites)

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)

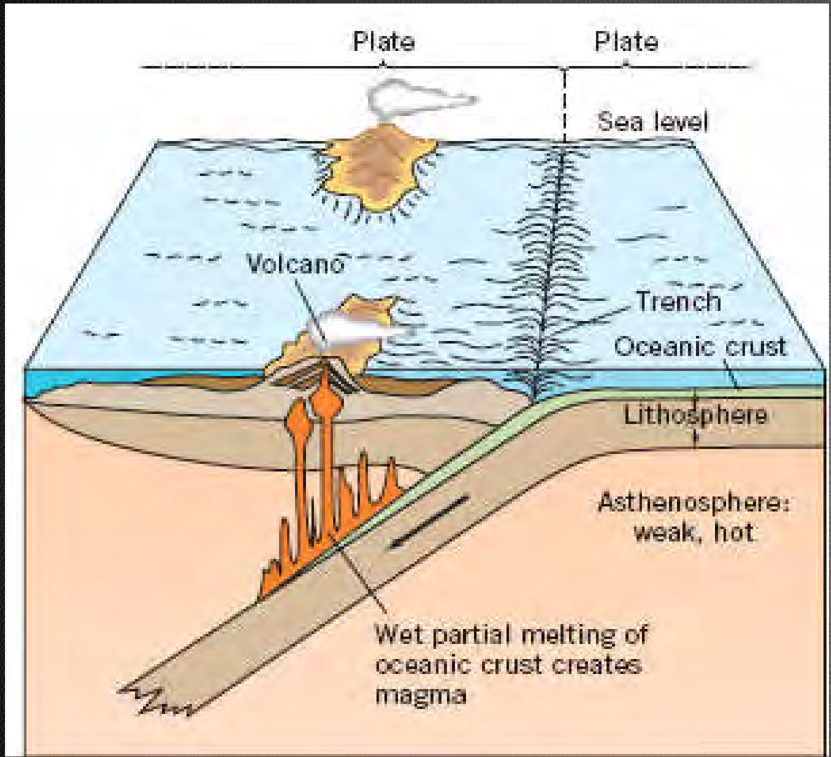


~10^8 km^3 of reworking

Mayon Volcano, Philippines

New modes of volcanism

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



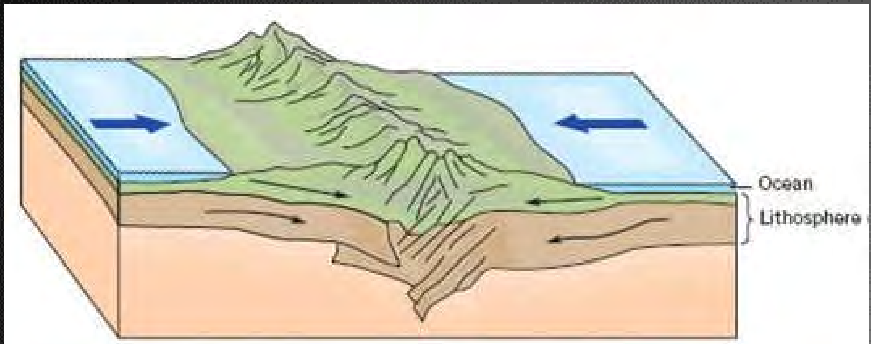
Rio Tinto. Spain

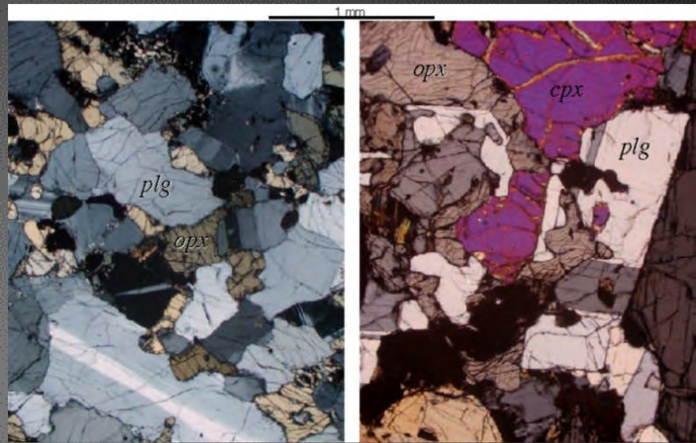
New modes of volcanism

Massive base metal deposits (sulfides, sulfosalts)

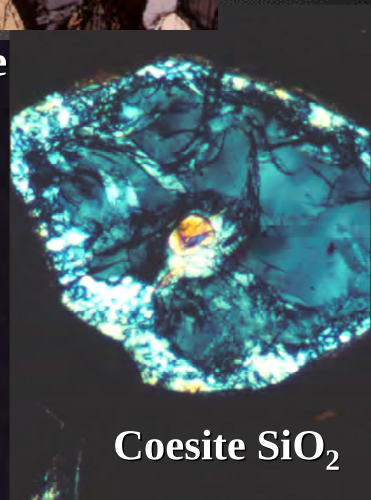
Stage 5: Plate tectonics and large-scale hydrothermal reworking of the crust (>3 Ga)

1,500 mineral species



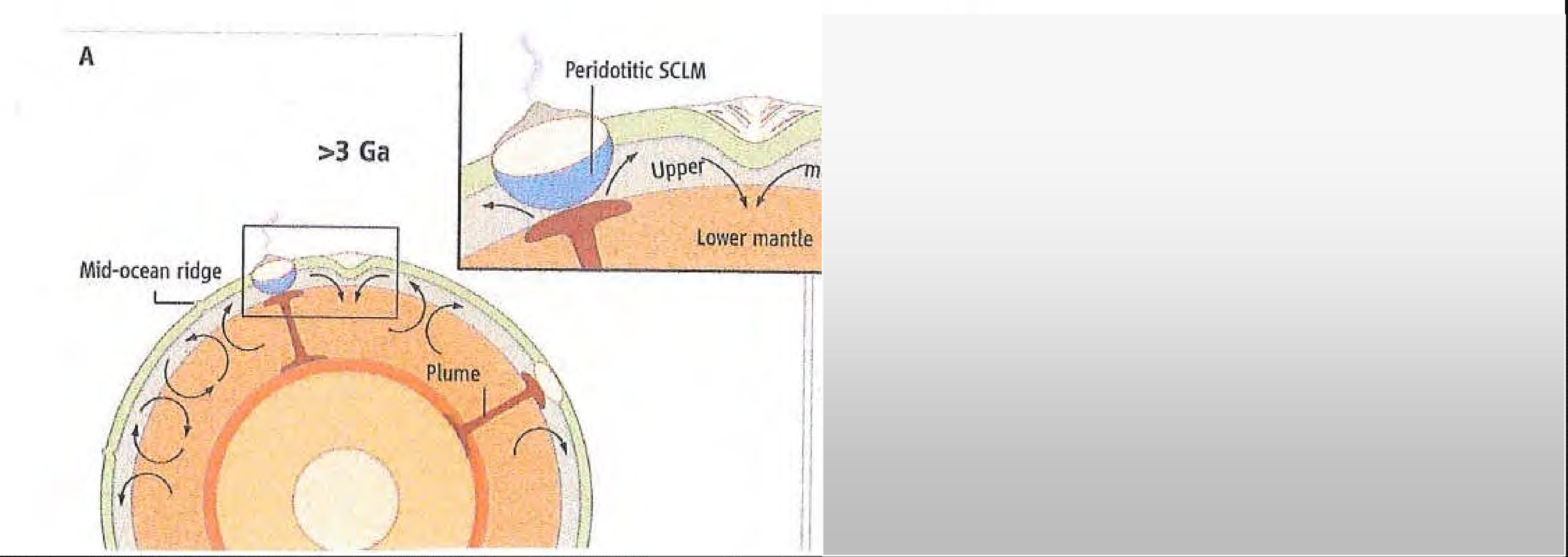


Glaucophane, Lawsonite, Jadeite



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

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

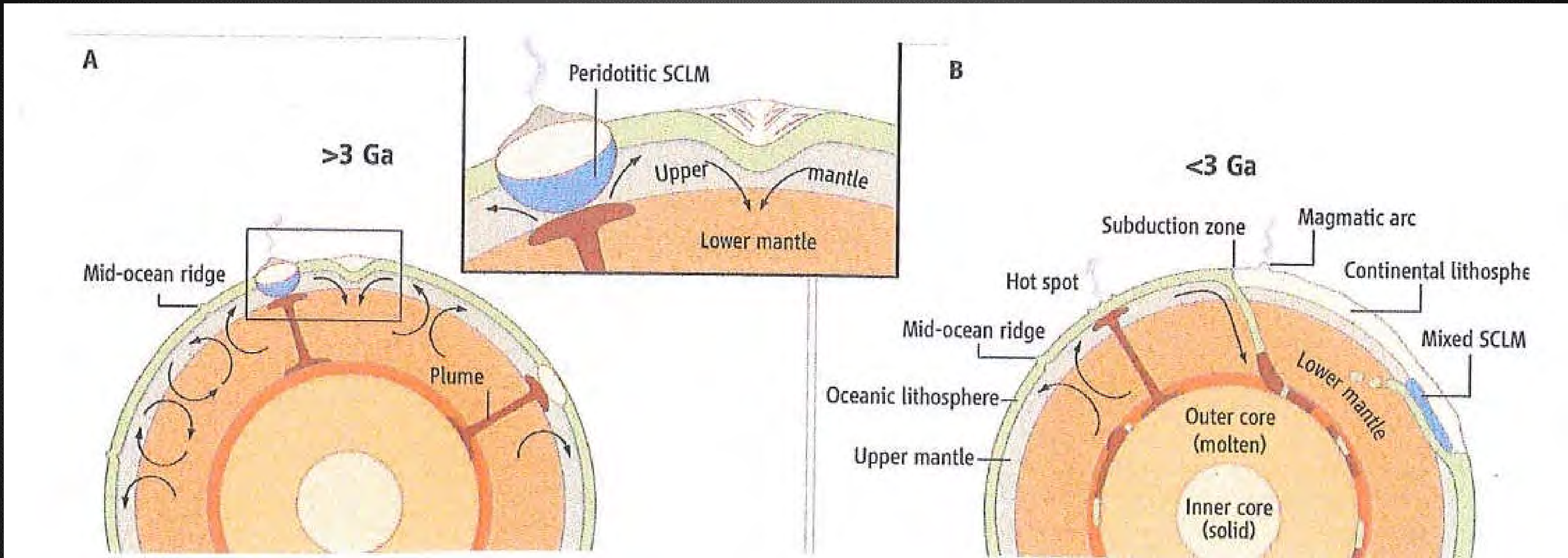


Van Kranendonk (2011)

> 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

Three Eras of Earth's Mineral Evolution

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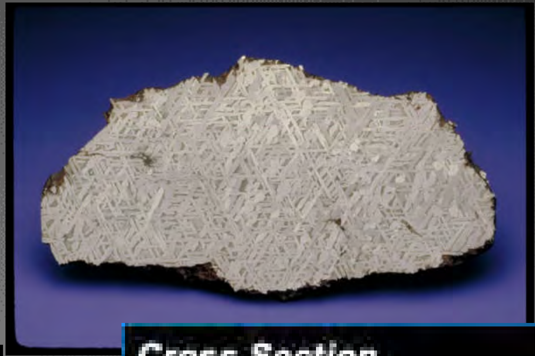
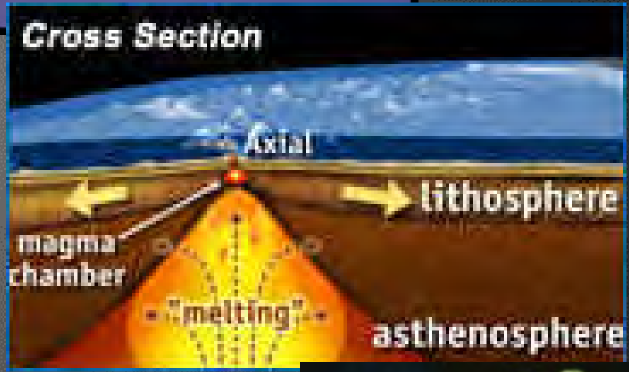


2. The Era of Crust and Mantle Reworking



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,

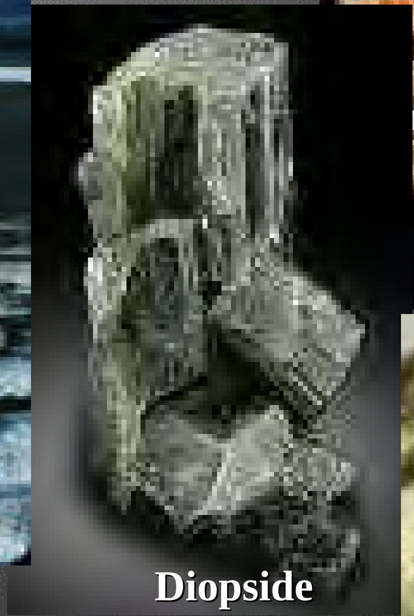
Photo credit: D. Papineau

Photo credit: F. Corsetti, USC

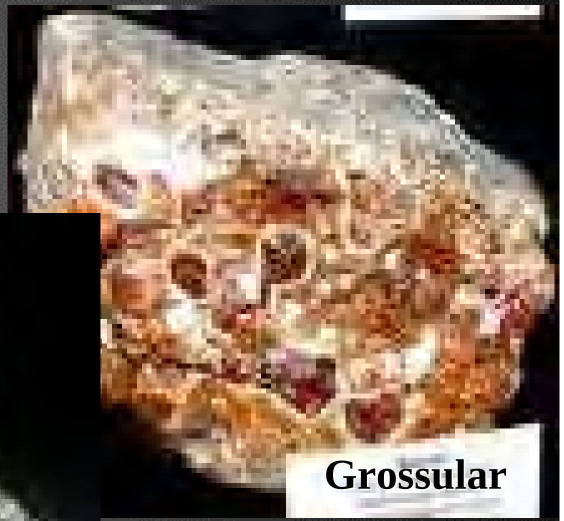
Stage 6: Anoxic Archean biosphere (3.9-2.5 Ga)

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

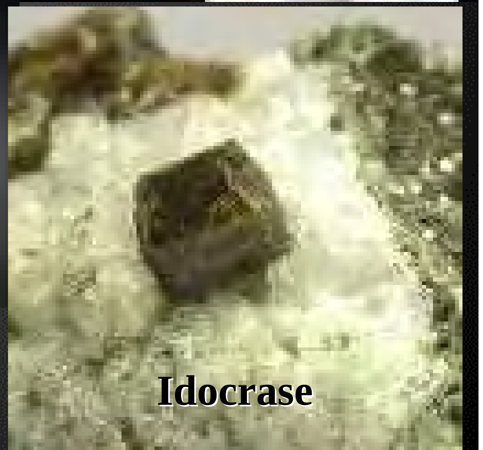
Death Valley evaporites (courtesy Smith College)



Diopside



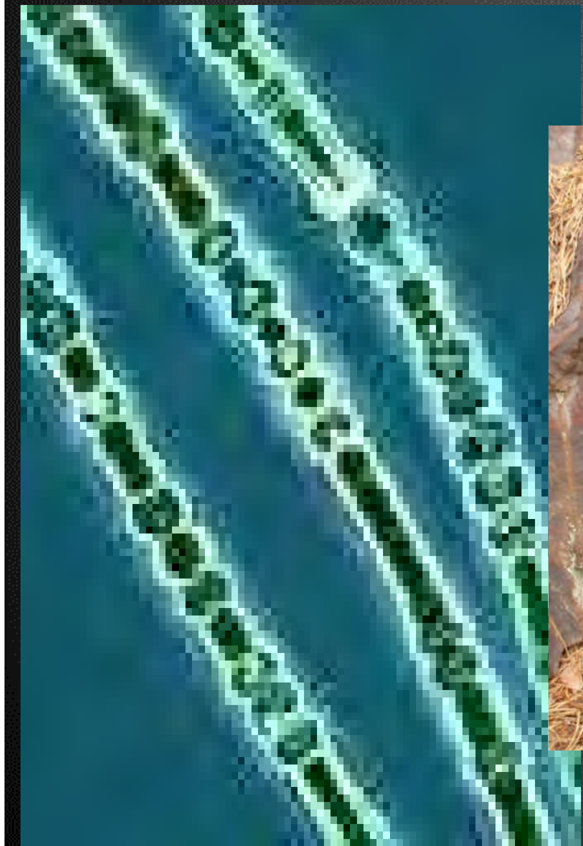
Grossular



Idocrase

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 Ga)

>4000 mineral species, including perhaps >2,000 new oxides/hydroxides



Rise of oxidative photosynthesis.

Stage 7: Paleoproterozoic Oxidation (2.5-1.85 Ga)

>4000 mineral species, including perhaps >2,000 new oxides/hydroxides

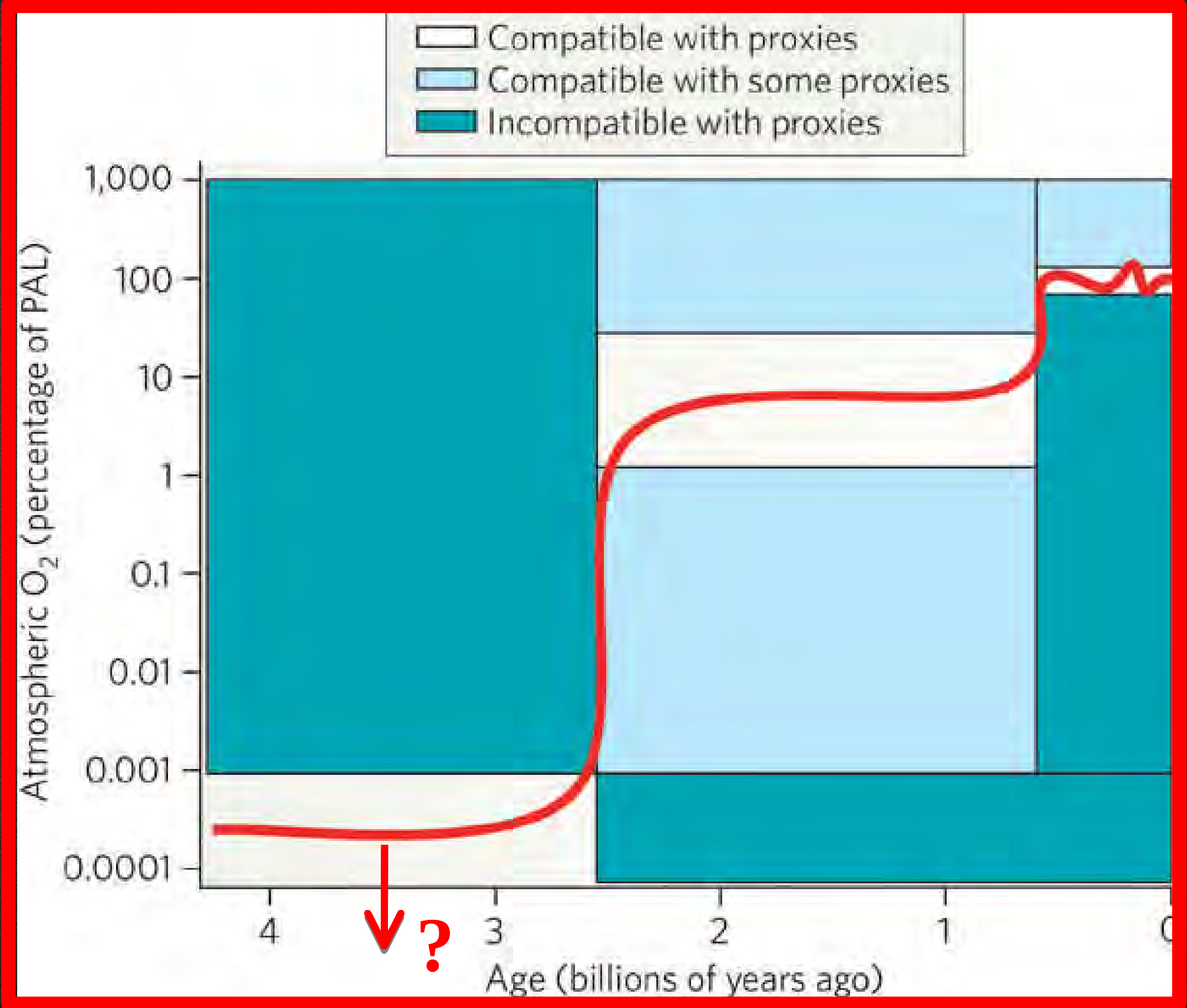
Rise of oxidative photosynthesis.

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 essentially anoxic Archean atmosphere.

What was the oxygen fugacity in the Archean?



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

What was the oxygen fugacity in the Archean?

Published estimates of Archean log fO_2

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 fugacity.

Detrital uraninite and pyrite

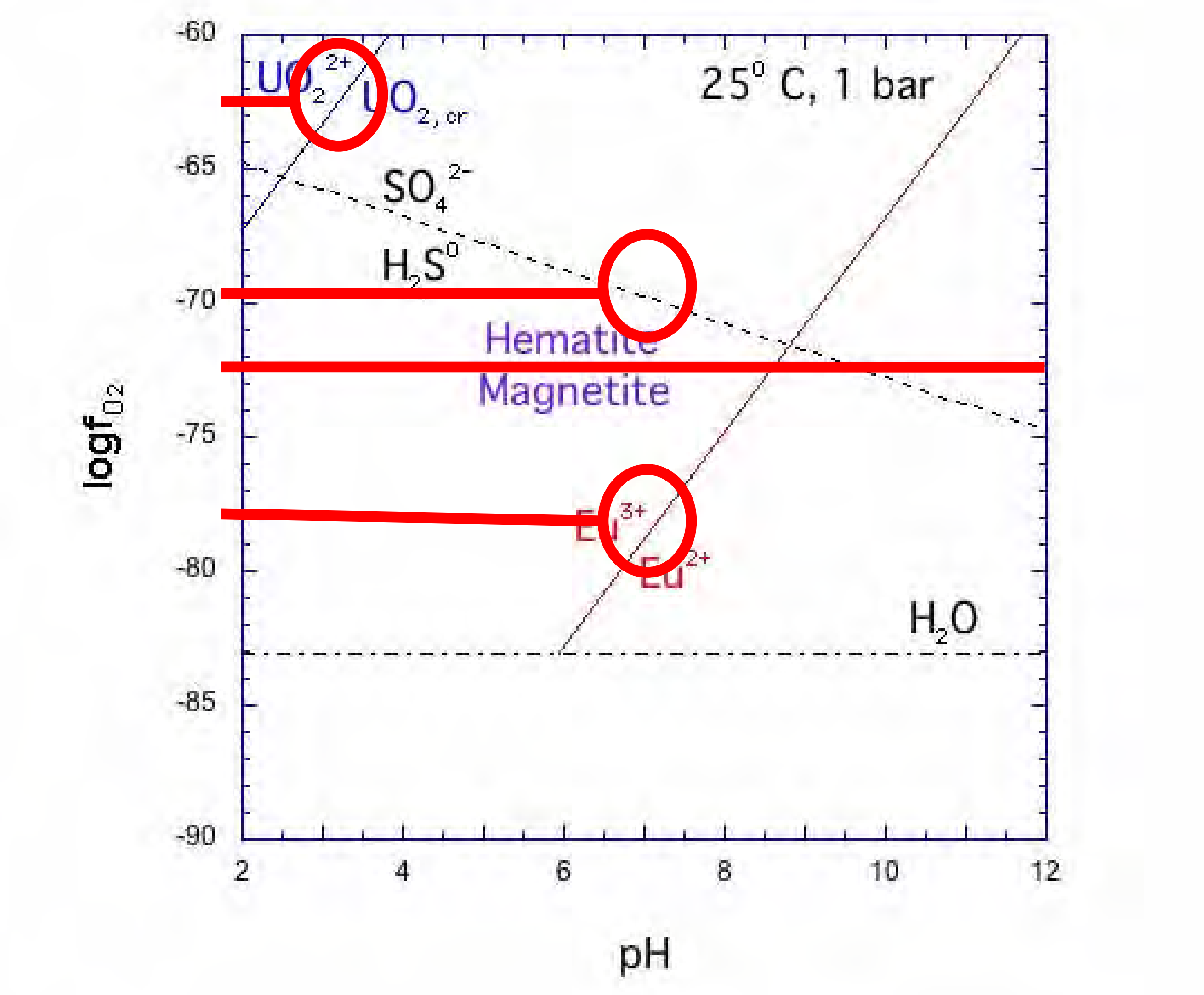
Paleosols lacking iron oxides

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

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

Eu^{2+} anomalies

What was the oxygen fugacity in the Archean?



Key constraints on Archean surface oxygen fugacity.

Detrital uraninite, pyrite and siderite

Paleosols lacking iron oxides

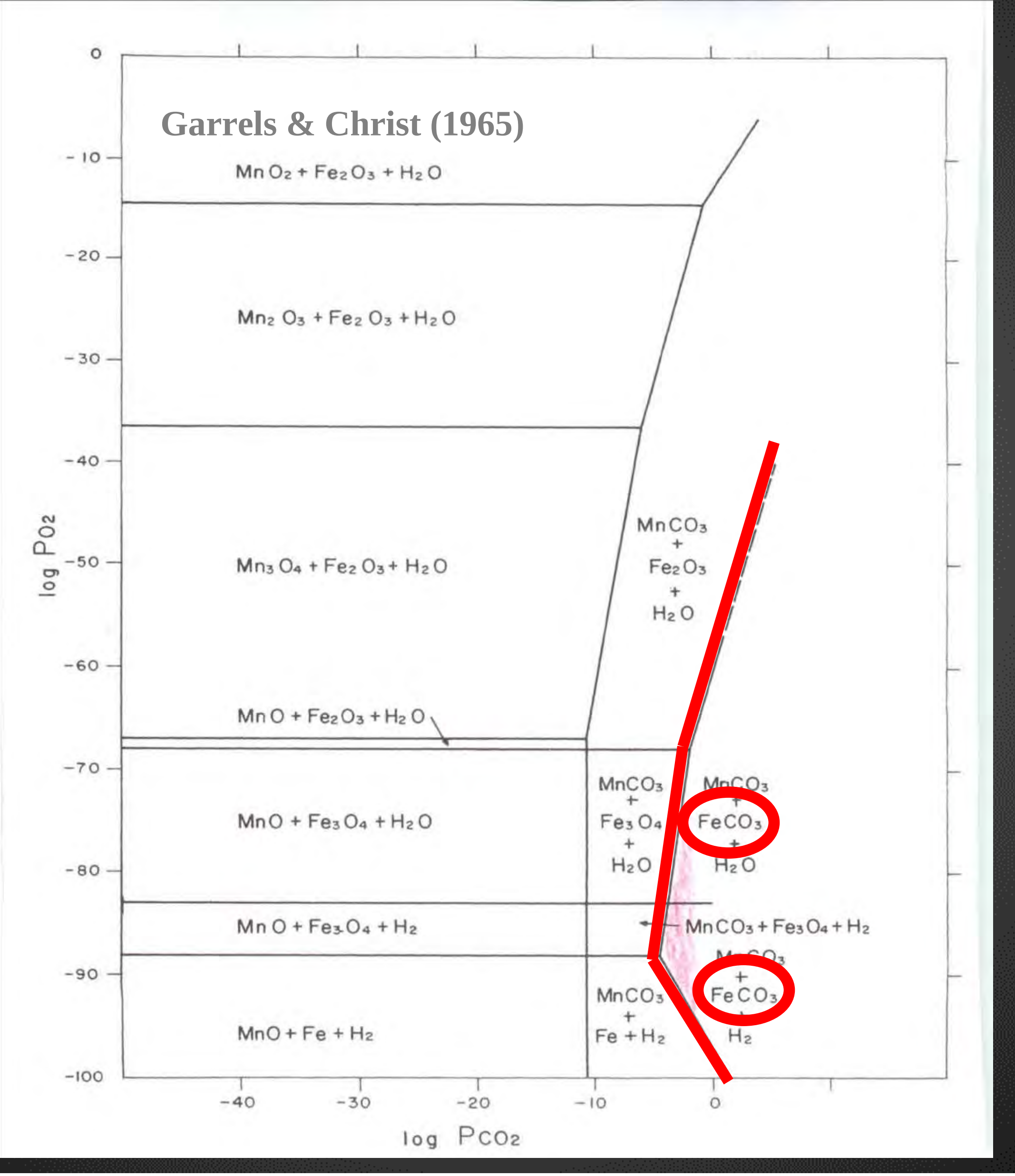
[Surface waters with aqueous Fe^{2+}]

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

Eu^{2+} anomalies

Precipitation of ferroan carbonates

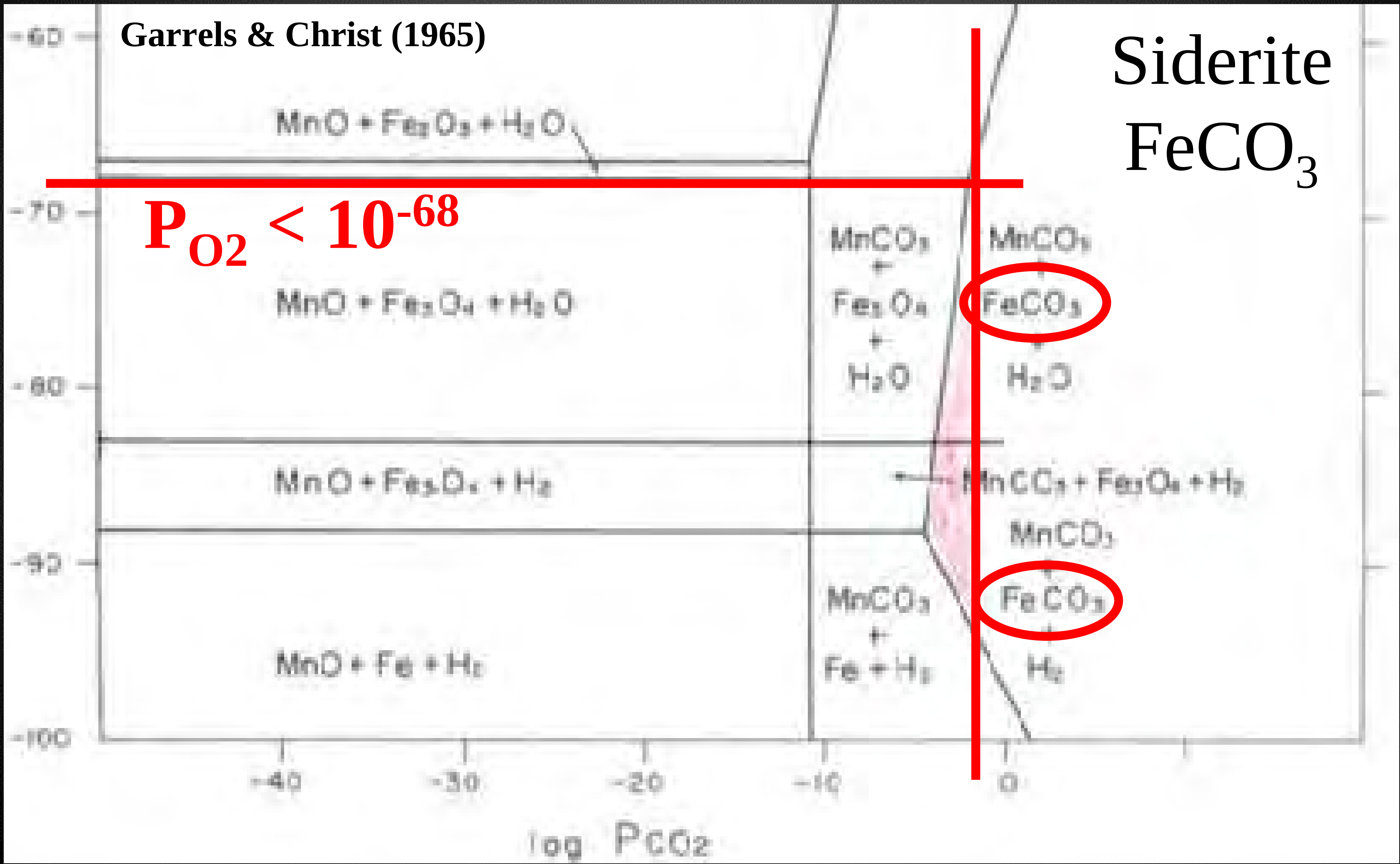
What was the oxygen fugacity in the Archean?



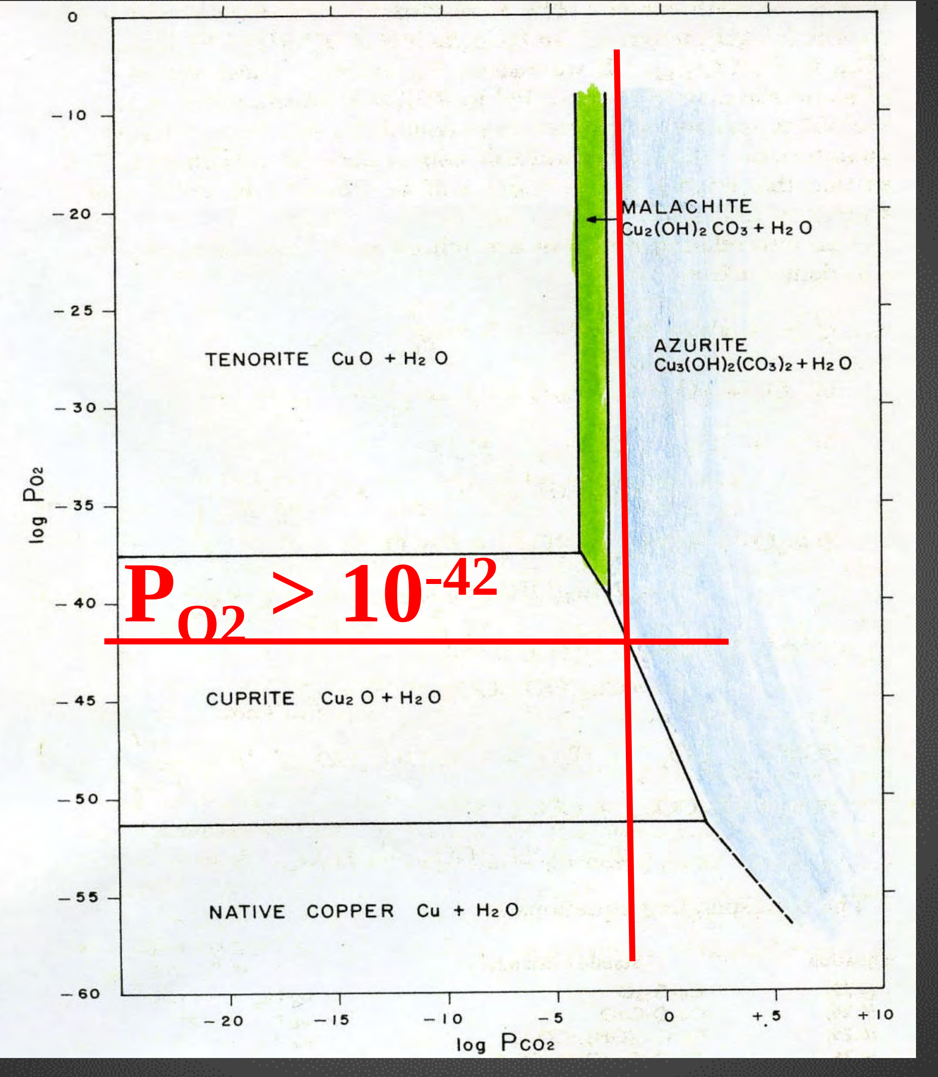
Siderite

$FeCO_3$

What was the oxygen fugacity in the Archean?



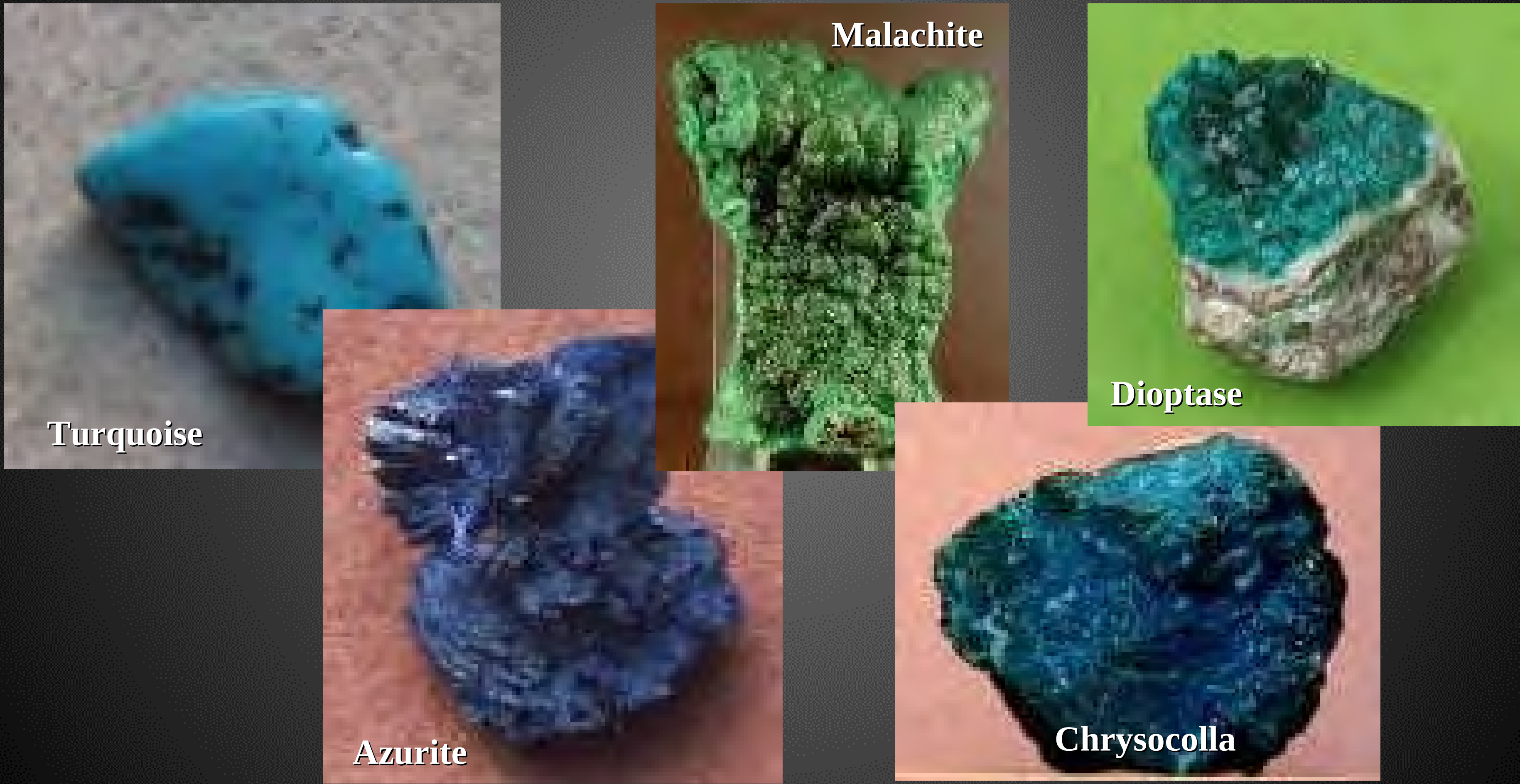
What minerals won't form?



If the effective log fO_2 ~ -70, then malachite, azurite and other Cu^{2+} minerals will not form.

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)

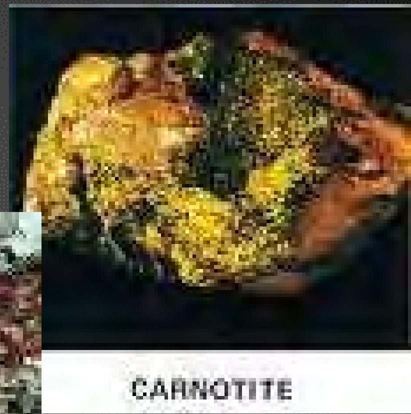
What mineral species won't form?

02 of 220 U minerals

19 of 451 Mn minerals

7 of 56 Ni minerals

32 of 790 Fe minerals




Piemontite


Garnierite

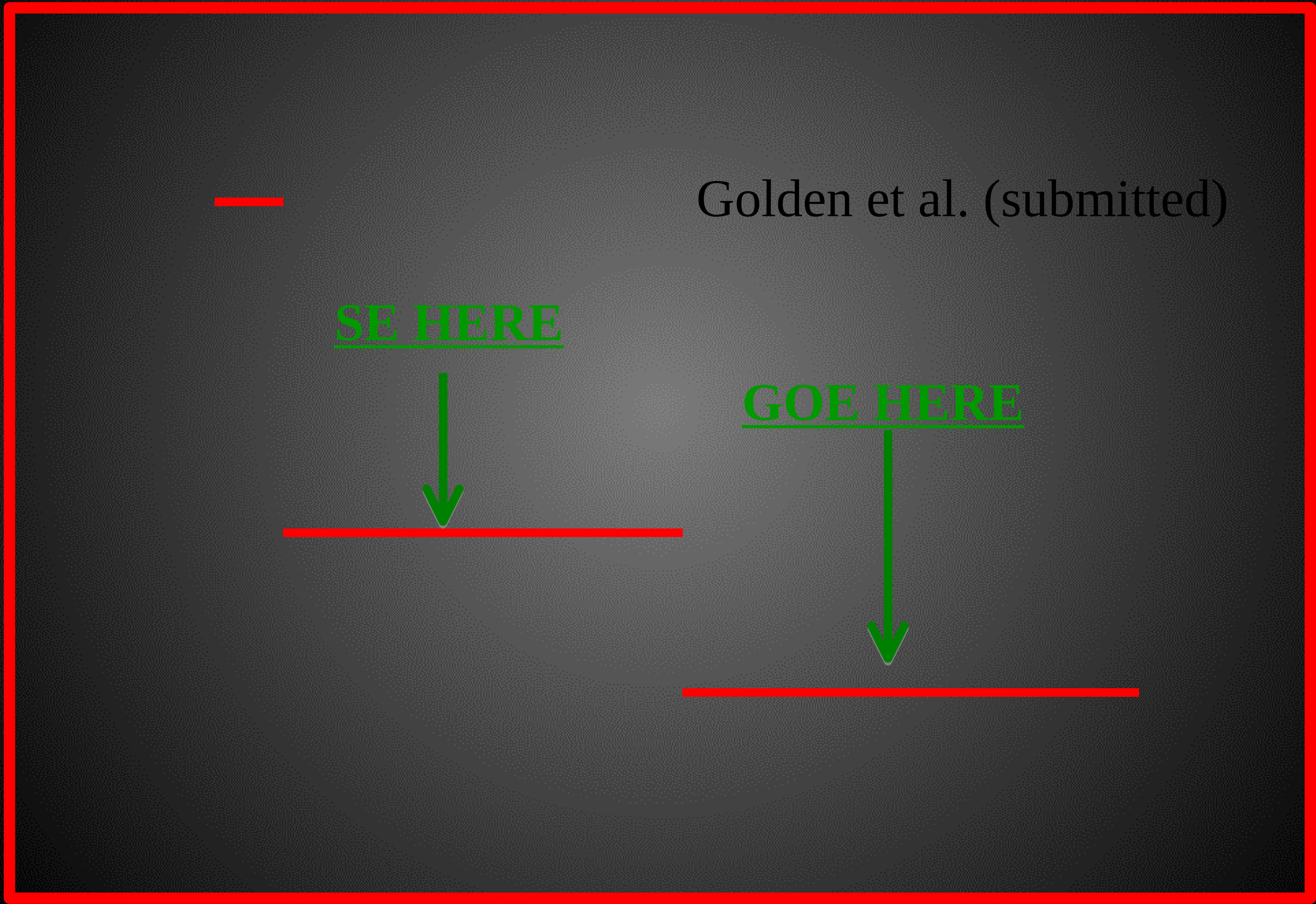

Xanthoxenite

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

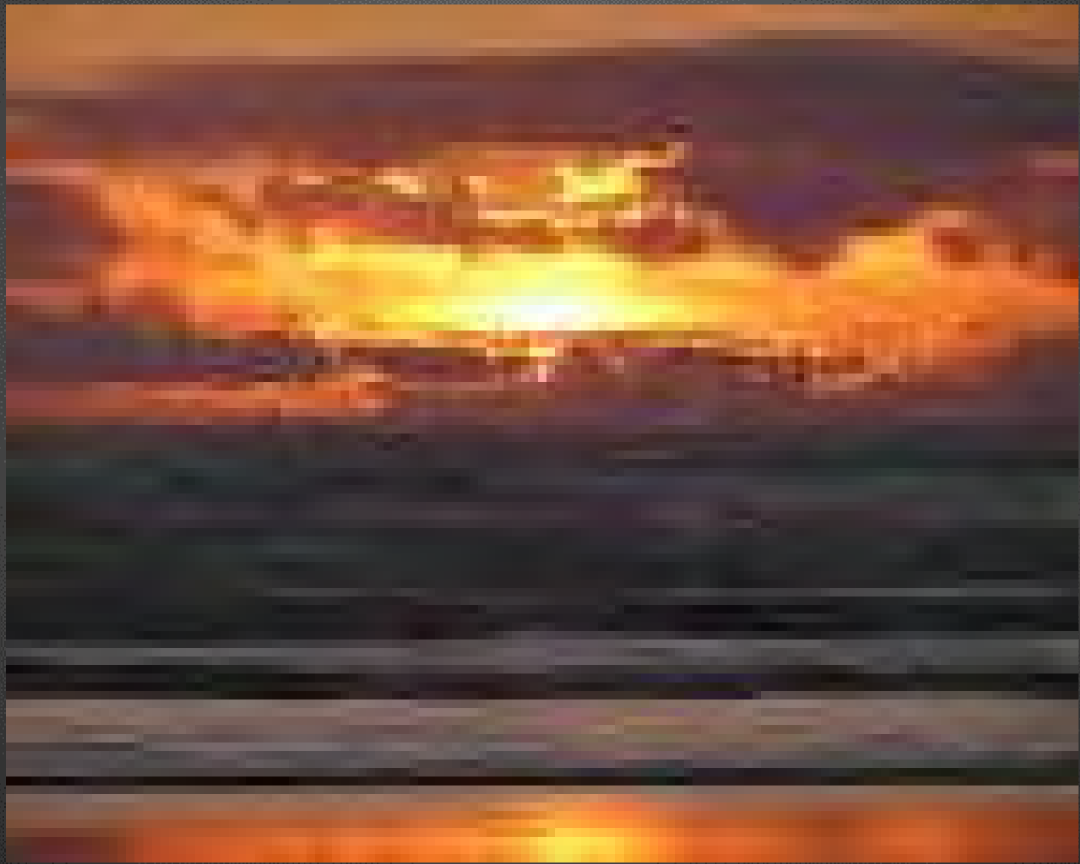


RESULTS: Molybdenite (MoS_2) through Time

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.

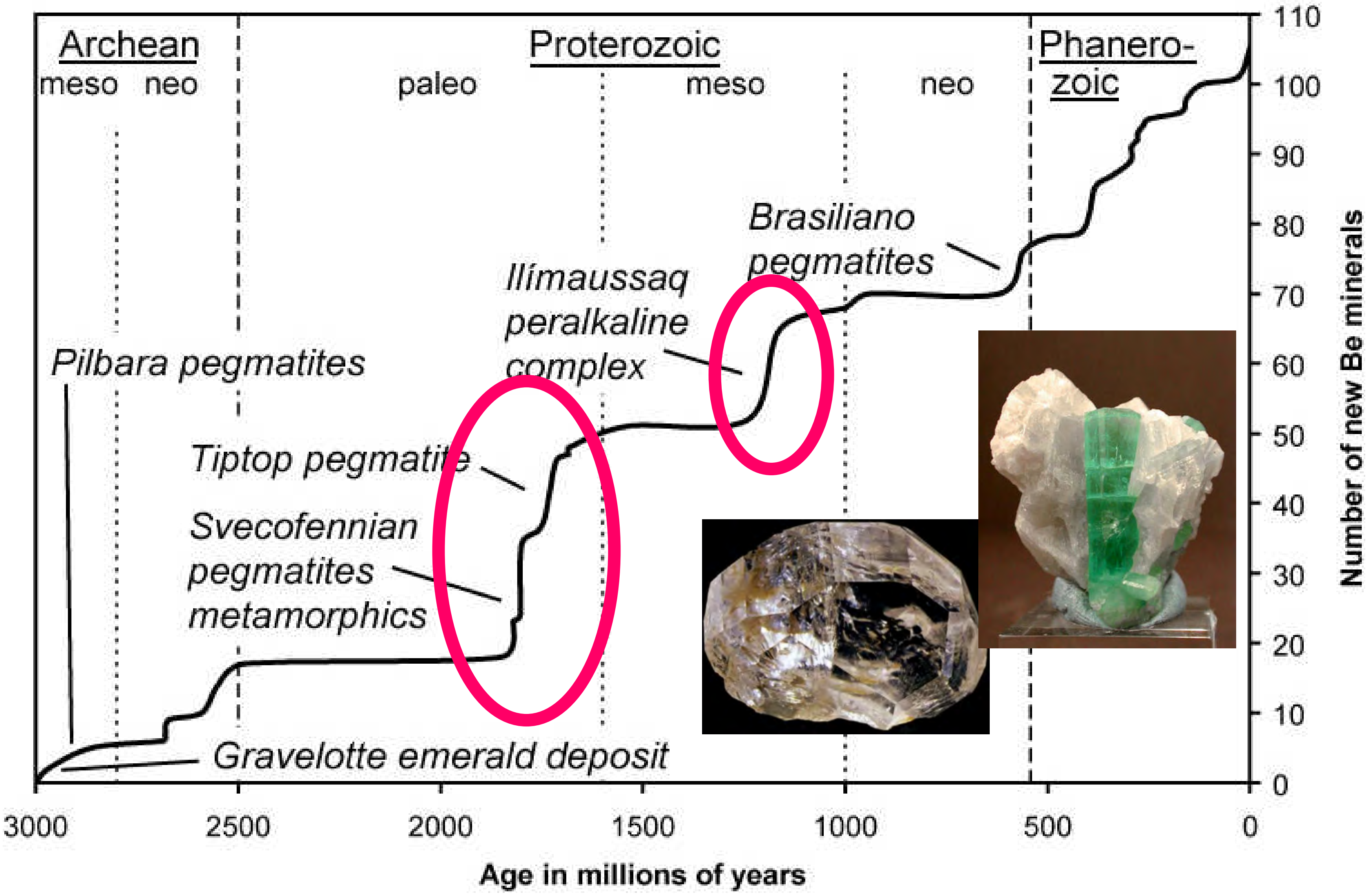
Stage 8: The “Intermediate Ocean” (1.85-0.85 Ga)

>4000 mineral species (few new species)



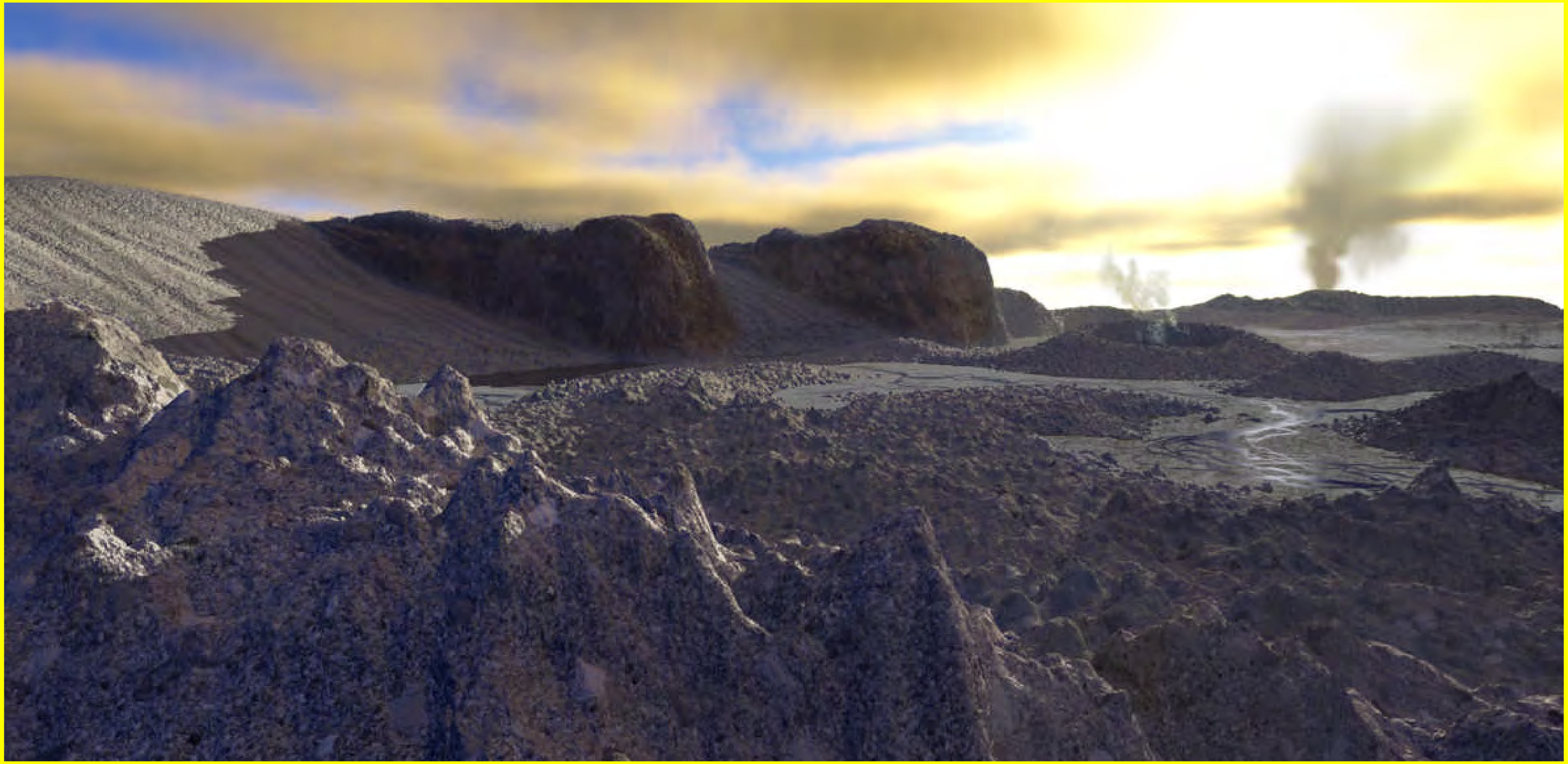
Oxidized surface ocean; deep-ocean anoxia.

Be Mineral Evolution (Grew & Hazen, 2009)



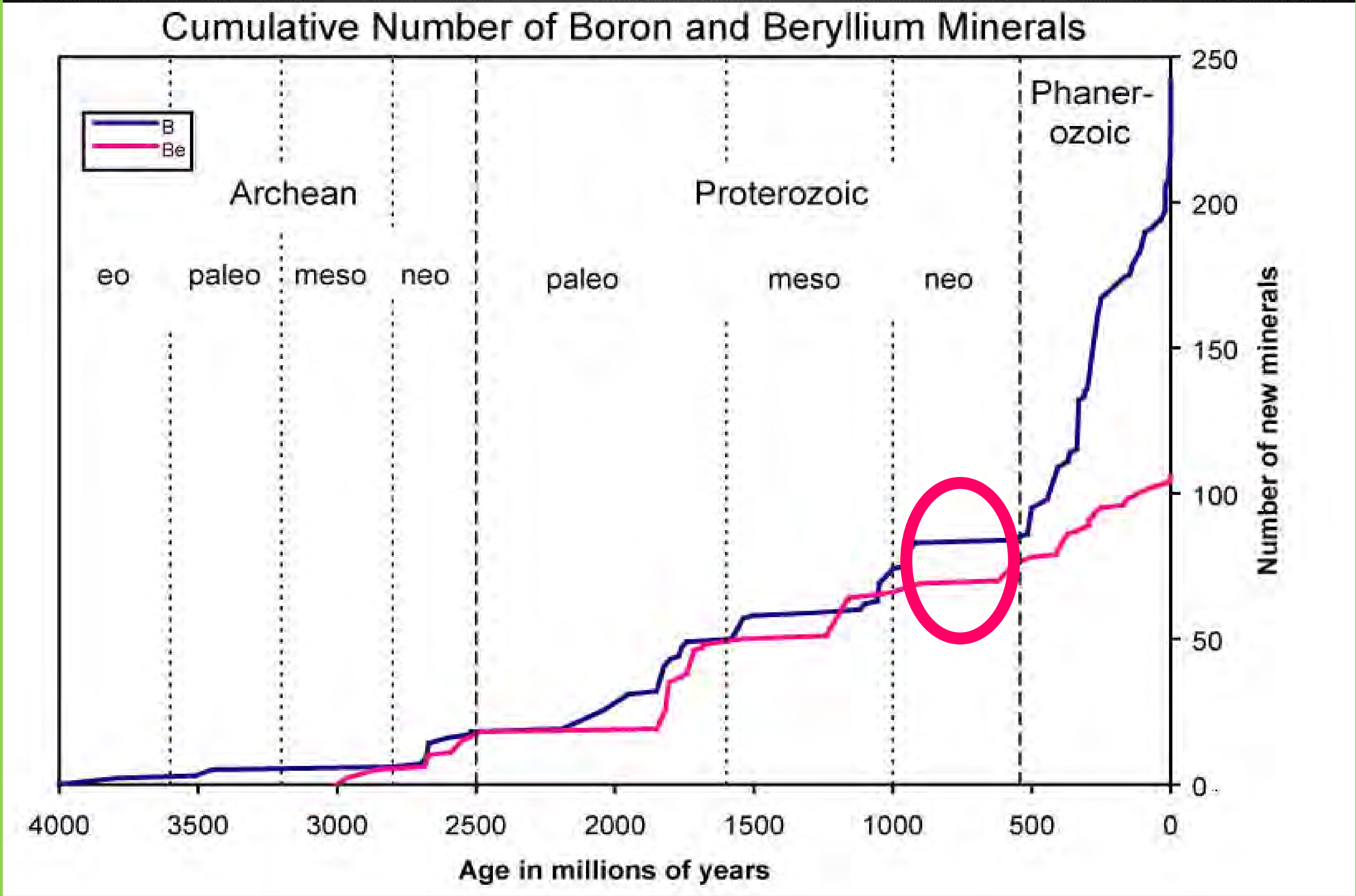
Stage 9: Snowball Earth and Neoproterozoic Oxidation (0.85-0.542 Ga)

>4000 mineral species (few new species)



Glacial cycles triggered by albedo feedback.

B Mineral Evolution (Grew & Hazen 2010)



Stage 10: Phanerozoic Biomineralization (<0.542 Ga)

>4,400 mineral species (Biominerals, clays)

Stage 10: Phanerozoic Biomineralization (<0.542 Ga)

>4,400 mineral species

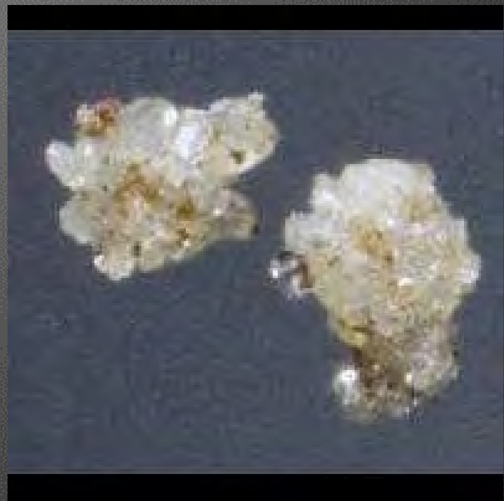
Stage 10: Phanerozoic Biomineralization

Abelsonite—$NiC_{31}H_{32}N_4$

Ravatite—$C_{24}H_{48}$

Evankite—$C_{24}H_{48}$

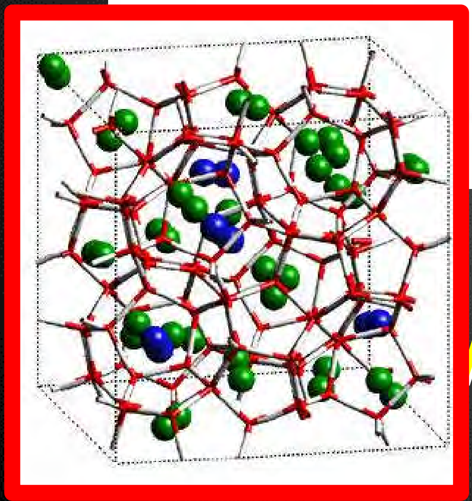
Dashkovaite—$Mg(HCOO)_2 \cdot 2H_2O$



Oxammite—$(NH_4)(C_2O_4) \cdot H_2O$

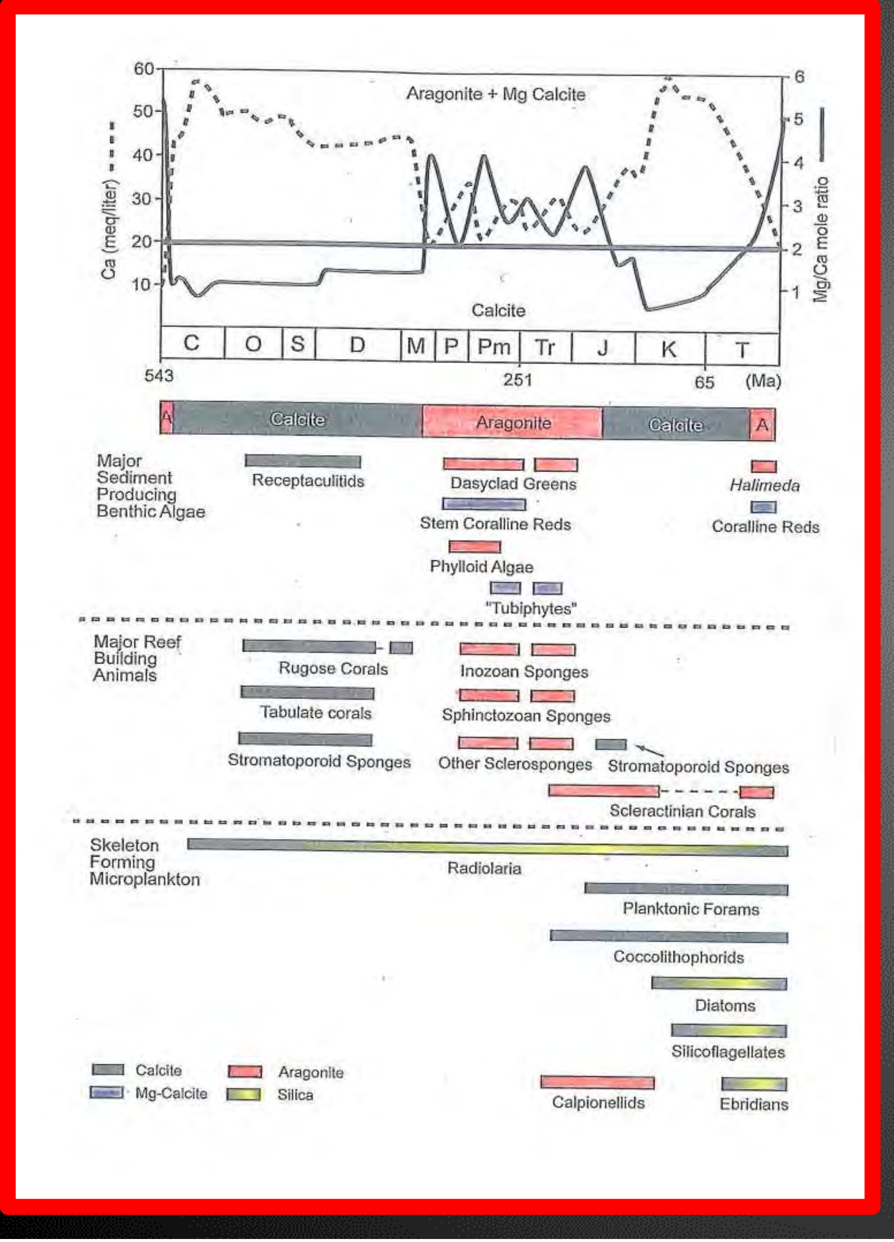
> 50 Organic Mineral Species

Stage 10: Phanerozoic Biomineralization

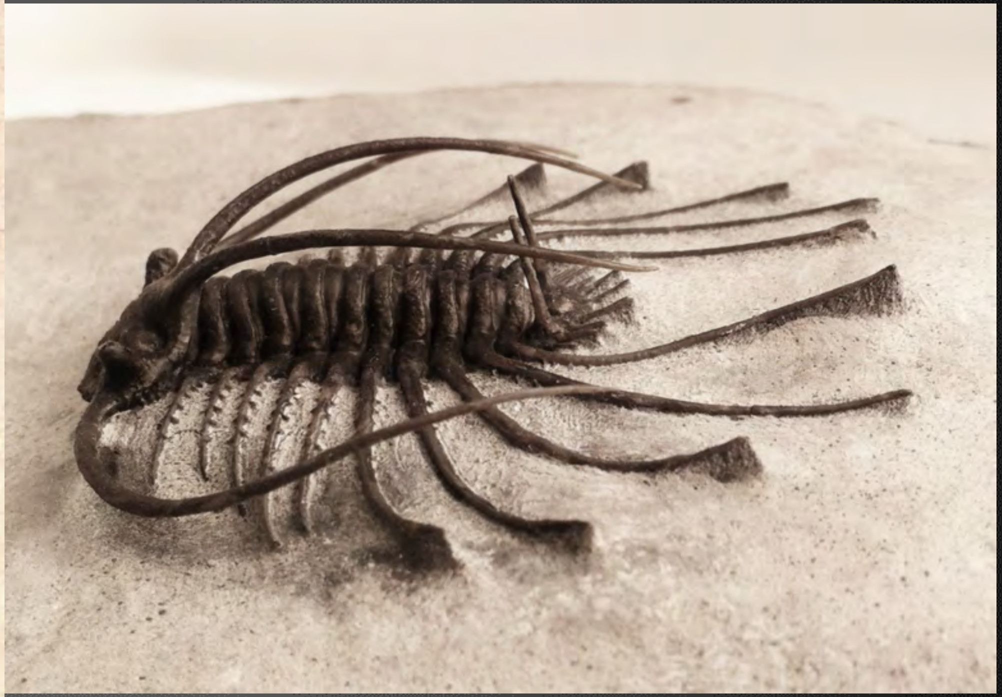


Methane Ice—$H_2O{\cdot}n[CH_4]$

Skeletal Biomineralization



Stage 10: Phanerozoic Biomineralization



Apianurus nov. sp.

Walcott-Rust Quarry, Moscow, New York.

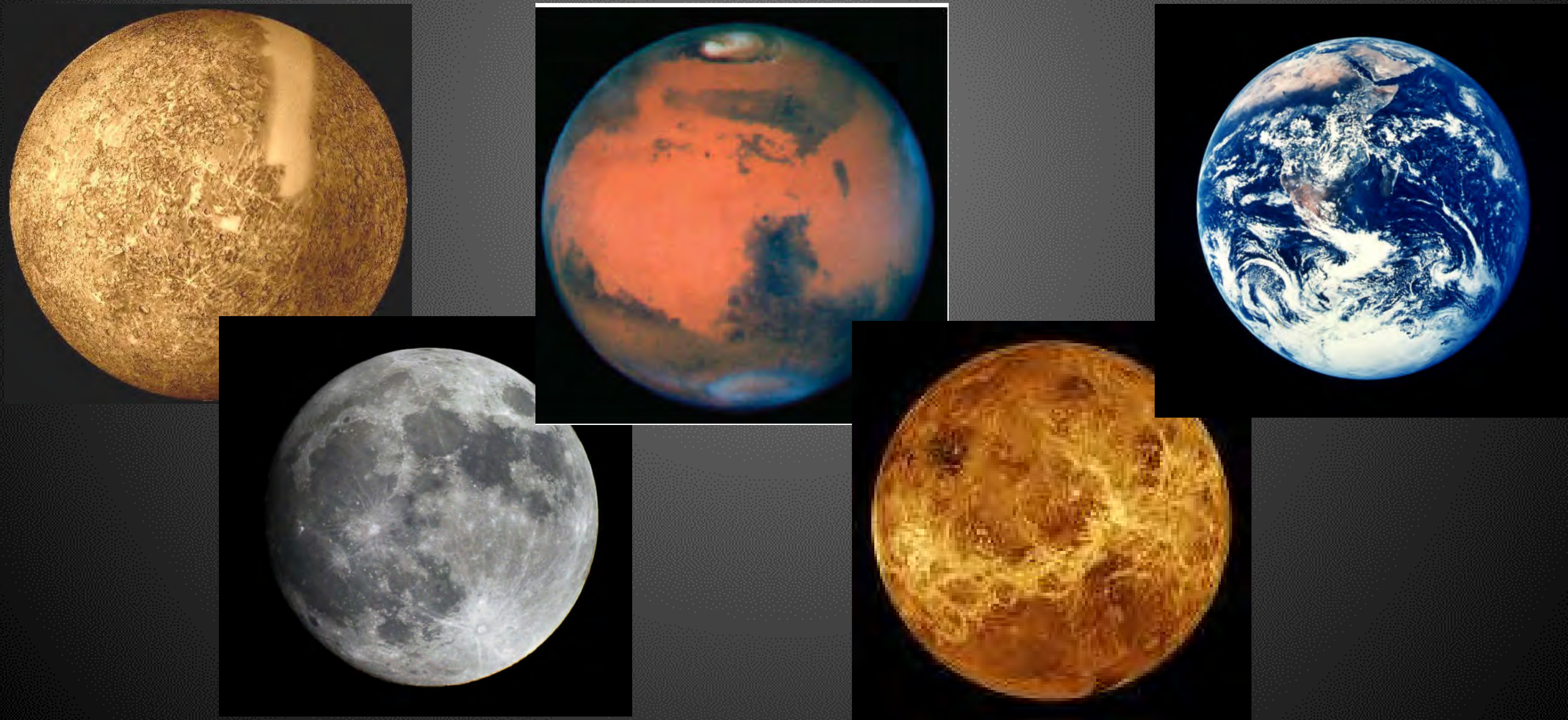
Stage 10: Phanerozoic Biomineralization

Apianurus nov. sp.

Walcott-Rust specimens preserve biomolecular fragments of chitin.

Implications of Mineral Evolution

1. Mineral evolution suggests a new way to compare and contrast terrestrial planets and moons.



Implications of Mineral Evolution

2. Mineral evolution points to NASA mission targets: mineral biosignatures (and abiosignatures).

- Granites (pegmatites)
- Massive sulfide deposits
- Carbonates
- Banded iron formations
- Evaporites

Implications of Mineral Evolution

3. Mineral evolution represents a new way to frame (and to teach) mineralogy.

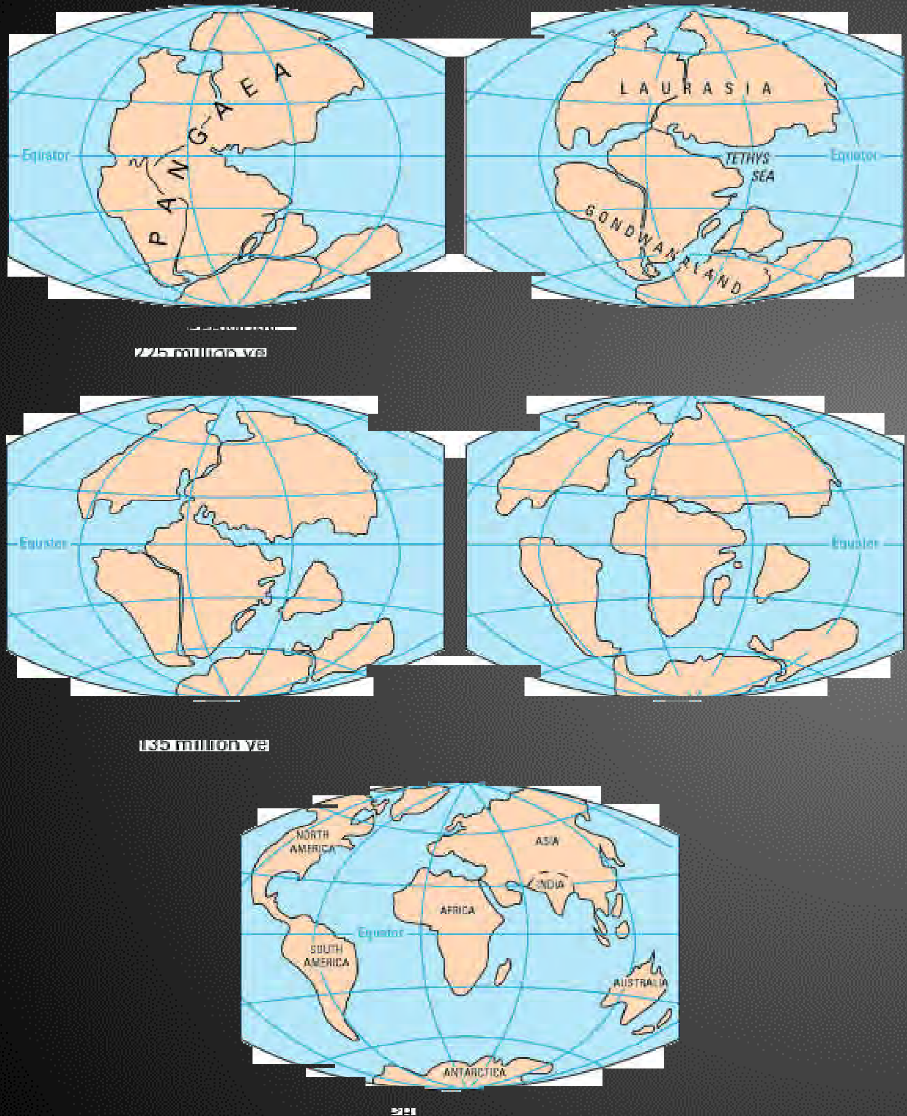
- Provides a narrative thrust to the presentation of minerals.

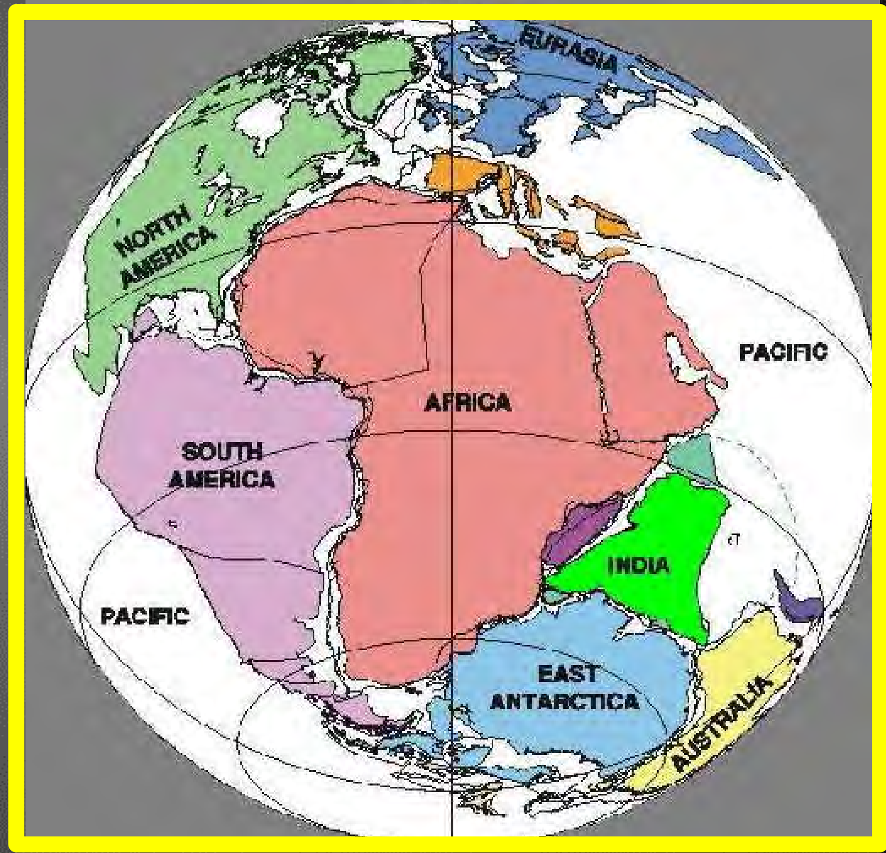
RECENT CONCLUSIONS

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

- **The supercontinent cycle.**
- **Changes in Earth’s near-surface oxidation state.**
- **Changing ocean chemistry.**
- **The rise of the terrestrial biosphere.**

The Supercontinent Cycle





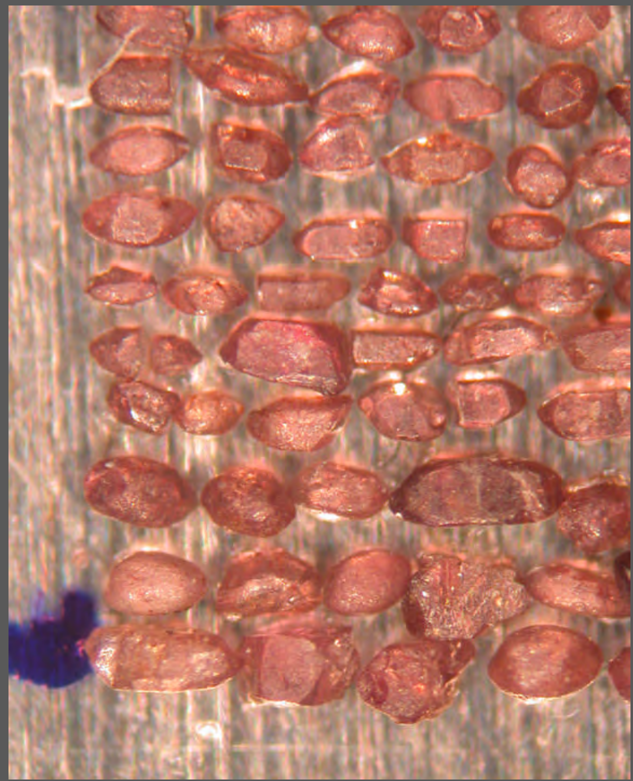
The Supercontinent Cycle

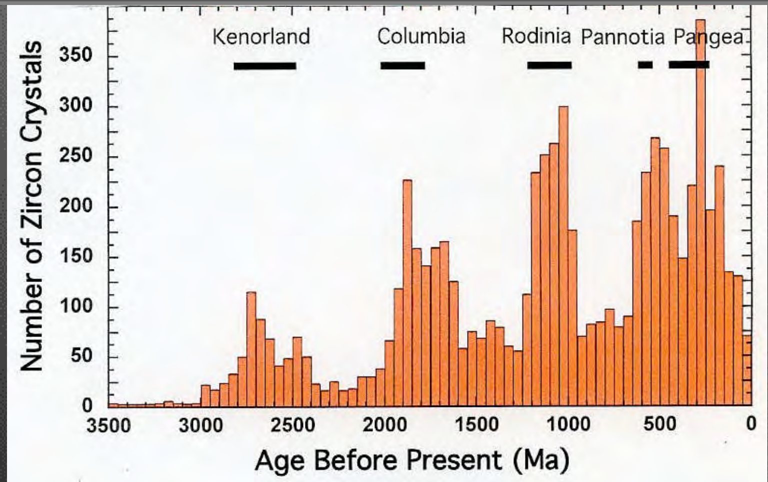
SUPERCONTINENT	STAGE	INTERVAL	DURATION
Kenorland (Superia)	Assembly	2.8-2.5	300
	Stable	2.5-2.4	100
	Breakup	2.4-2.0	400
Columbia (Nuna)	Assembly	2.0-1.8	200
	Stable	1.8-1.6	200
	Breakup	1.6-1.2	400
Rodinia	Assembly	1.2-1.0	200
	Stable	1.0-0.75	250
	Breakup	0.75-0.6	150
Pannotia	Assembly	0.6-0.56	40
	Stable	0.56-0.54	20
	Breakup	0.54-0.43	110
Pangaea	Assembly	0.43-0.25	180
	Stable	0.25-0.175	75
	Breakup	0.175-present	175

RESULTS: The Supercontinent CYCLE

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

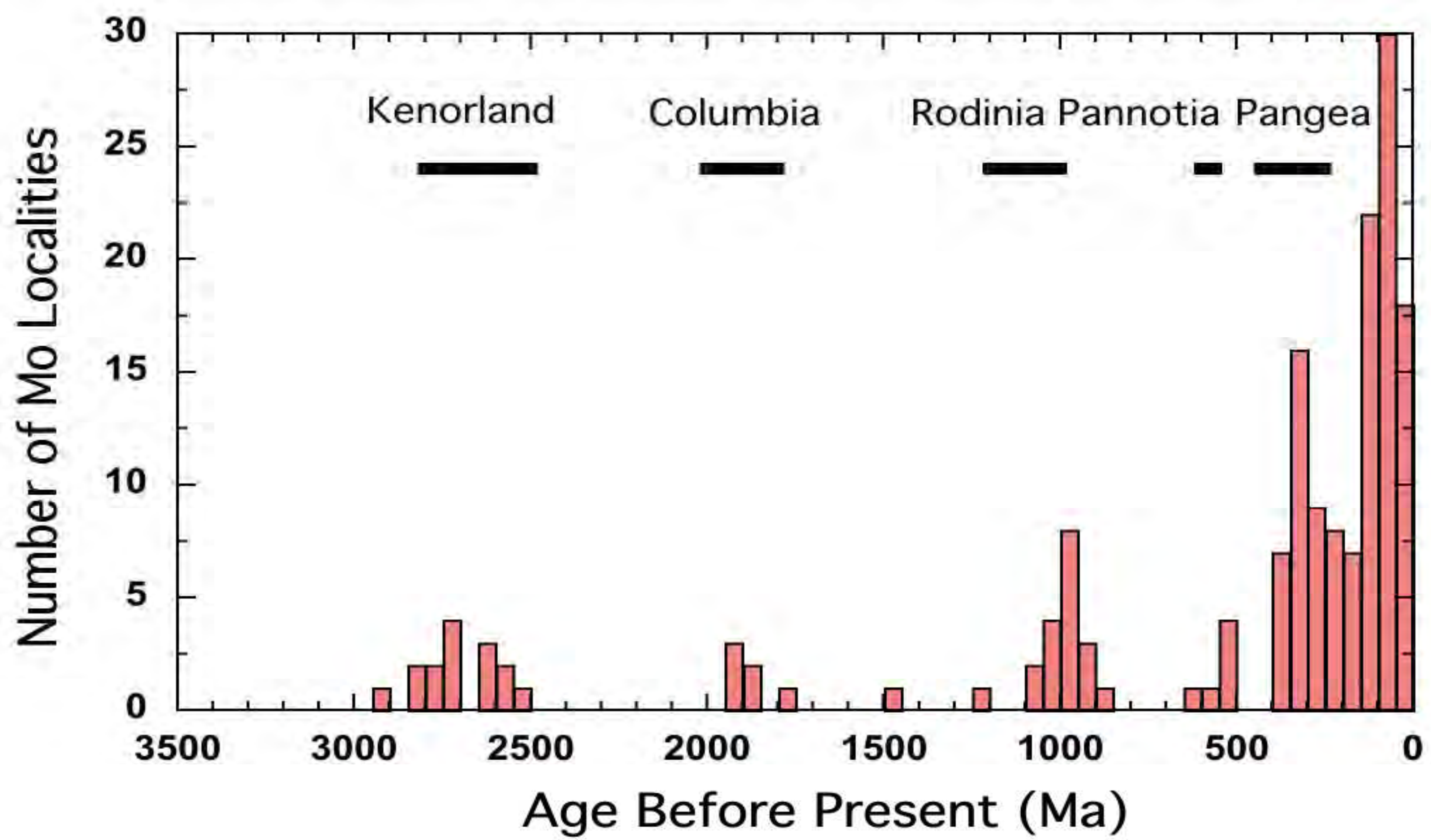
(Condie & Aster 2010; Hawksworth et al. 2010)



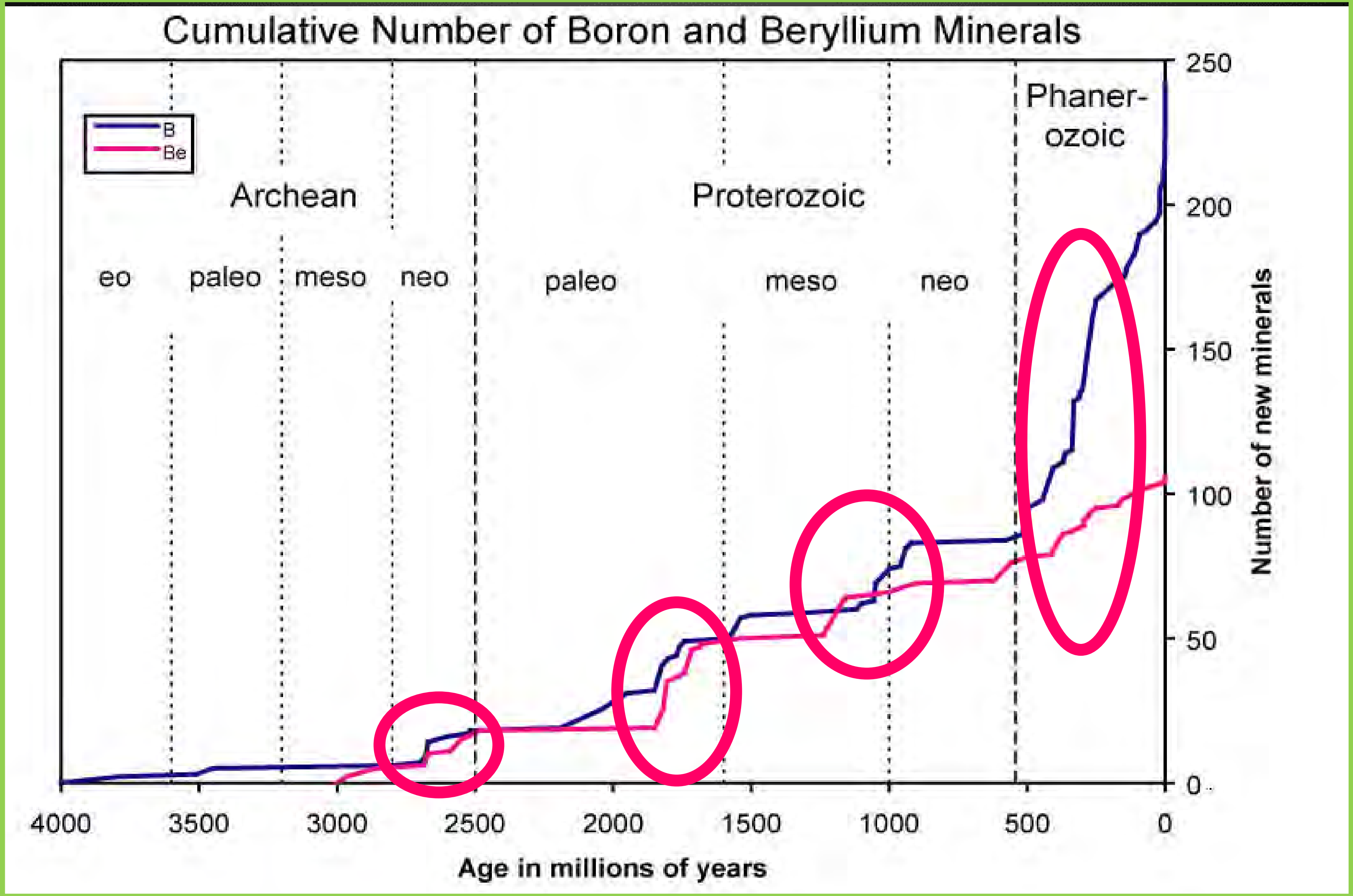


RESULTS: Mo Mineral Evolution

Temporal distribution of molybdenite (MoS_2)



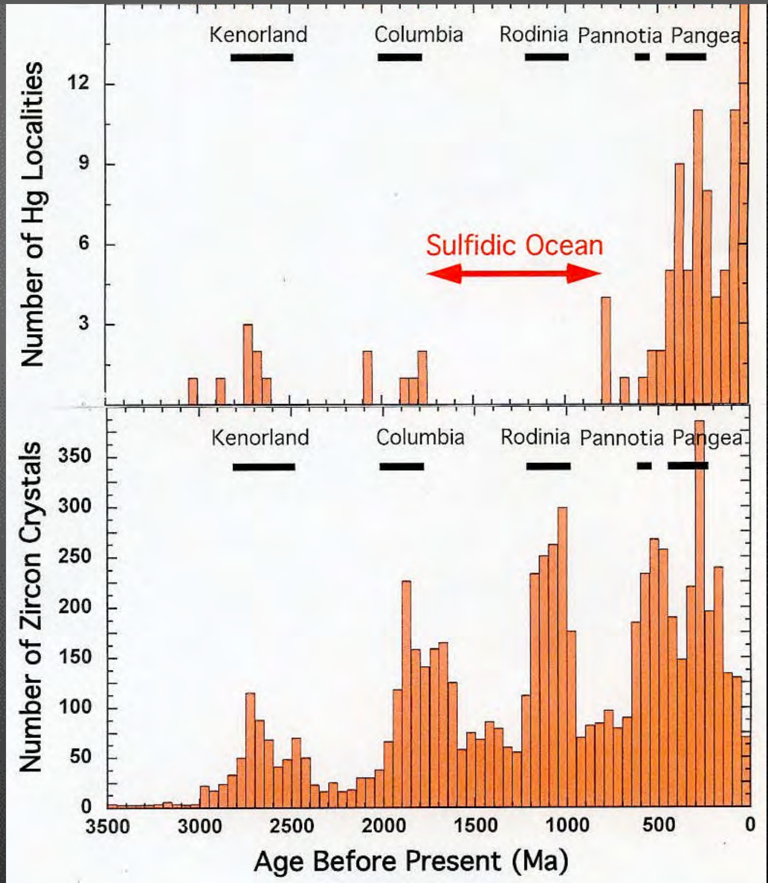
B and Be Minerals (Grew & Hazen 2010)



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.*, in press.



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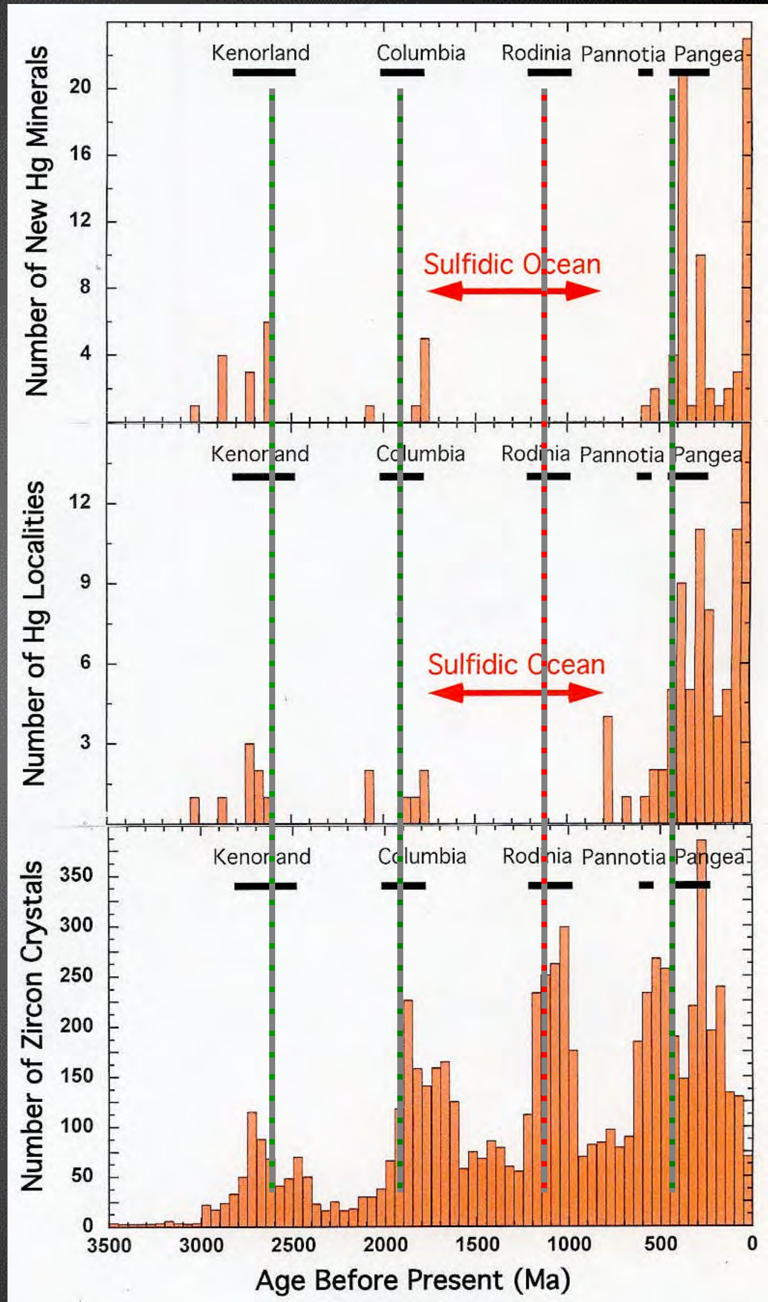

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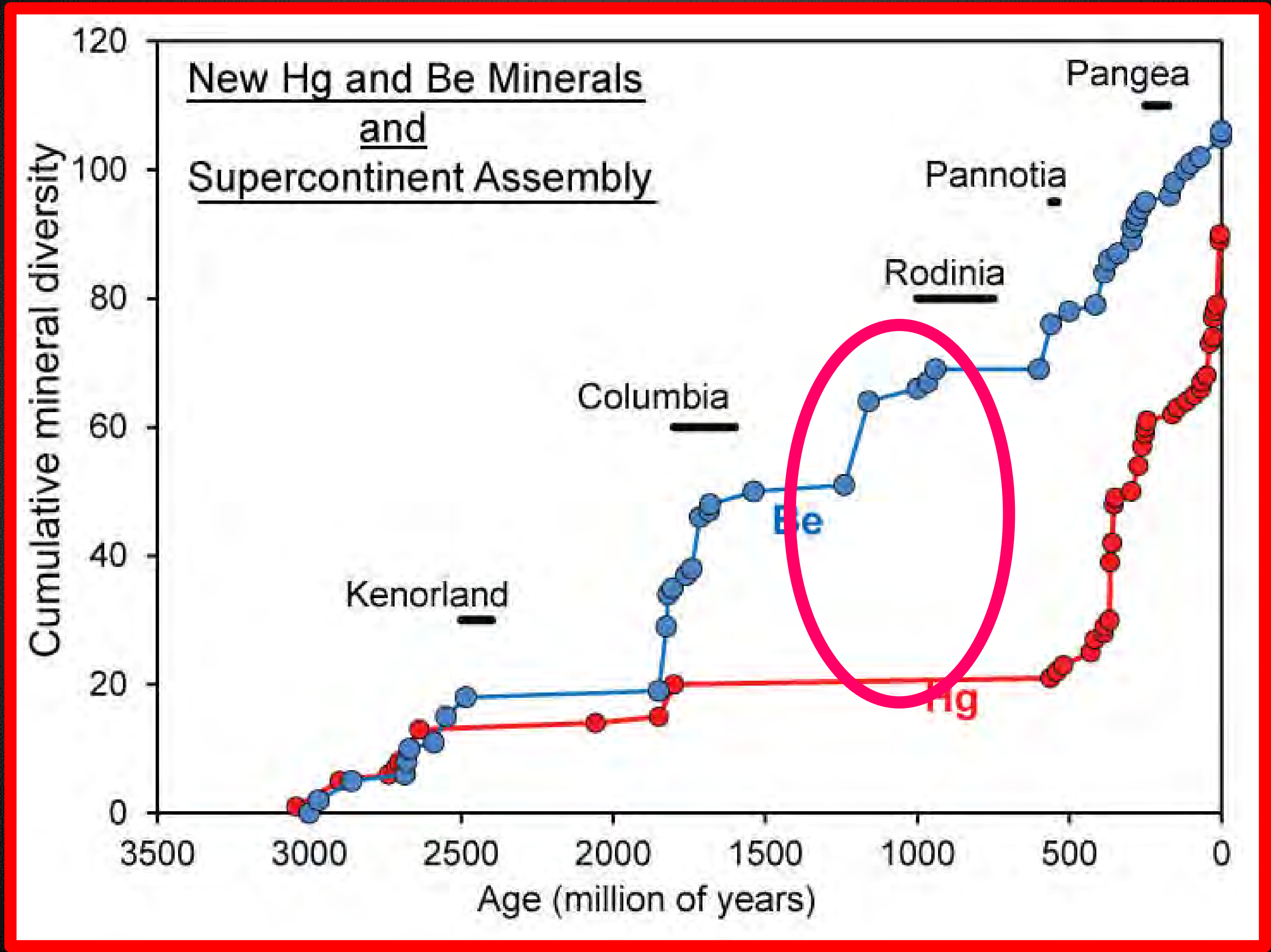
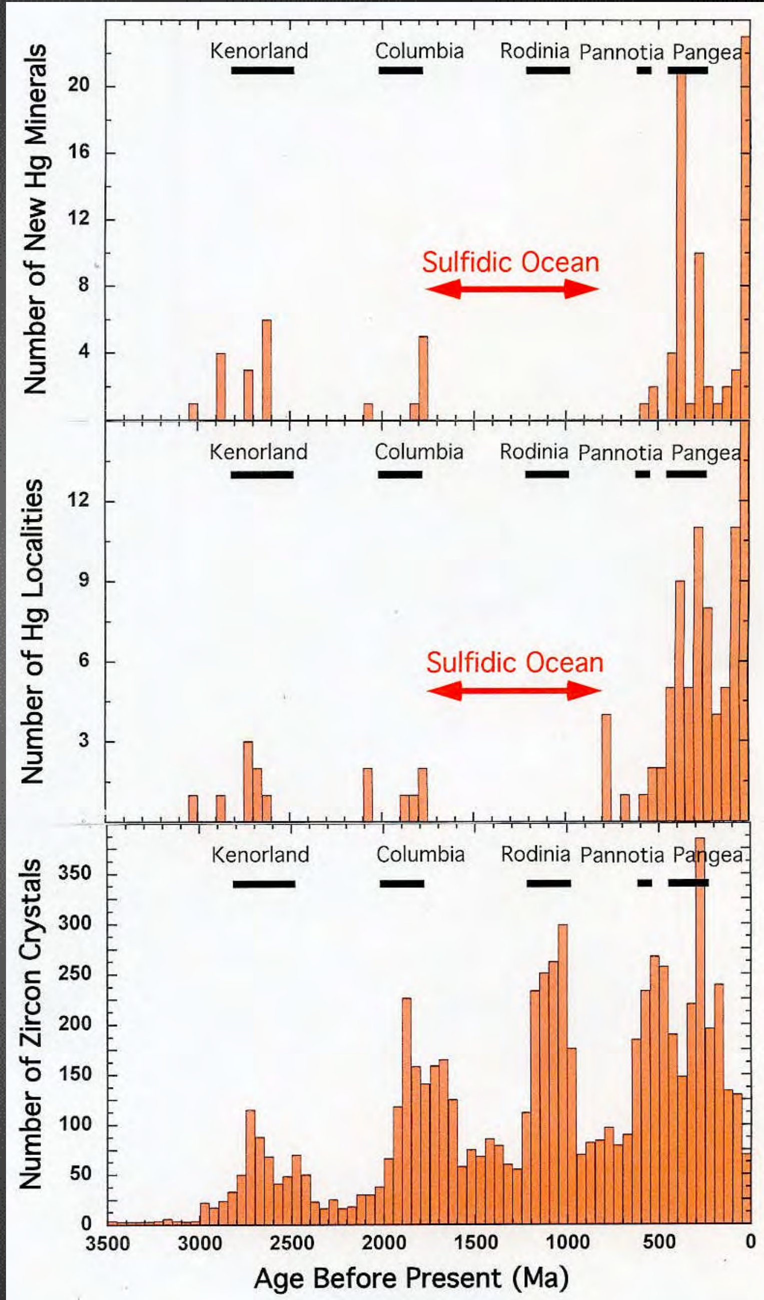
RESULTS: Hg & Be Mineral Evolution



Hg Mineral Evolution

We conclude that mercury was sequestered as insoluble cinnabar during the interval of the sulfidic ocean.

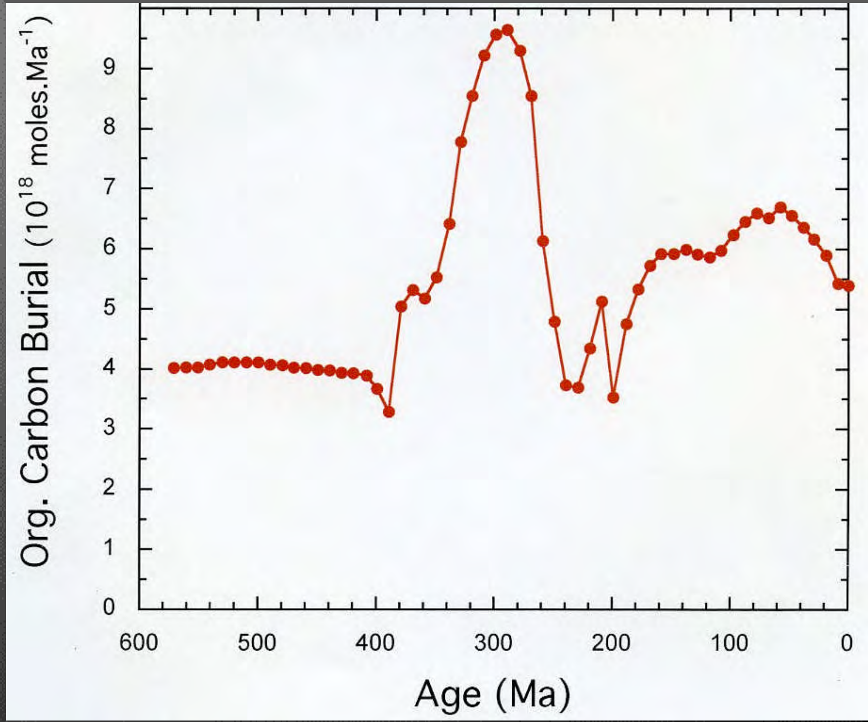
Hazen et al. (2012) *Amer. Mineral.*, in press.



Phanerozoic Biomineralization and the Terrestrial Biosphere (<542 Ma)

Hg Mineral Evolution

The distribution of mercury (Hg) minerals through the last 400 million years reflects changes in Earth's biosphere.



Hg Mineral Evolution

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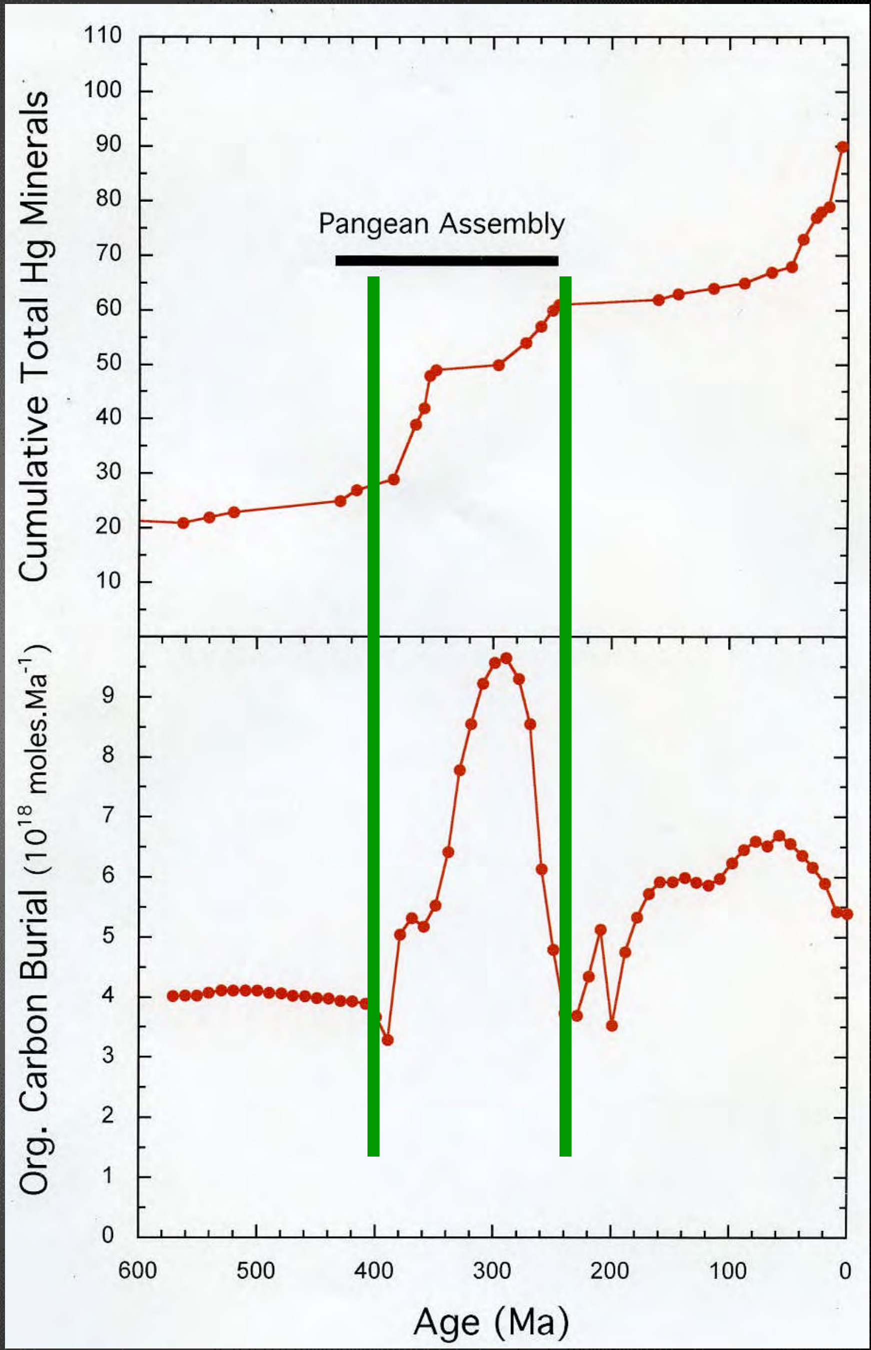

Conclusions

- **The mineralogy of terrestrial planets and moons evolves in both deterministic and stochastic ways.**

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.

Conclusions

- The mineralogy of terrestrial planets and moons evolves in both deterministic and stochastic ways.
- Different planets/moons achieve different stages of mineral evolution.

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Conclusions

- The mineralogy of terrestrial planets and moons evolves in both deterministic and stochastic ways.
- Different planets/moons achieve different stages of mineral evolution.
- Three principal mechanisms of change:
  1. Element segregation & concentration
  2. Increasing ranges of T, P and X
  3. Influence of living systems.

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.

Conclusions

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

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