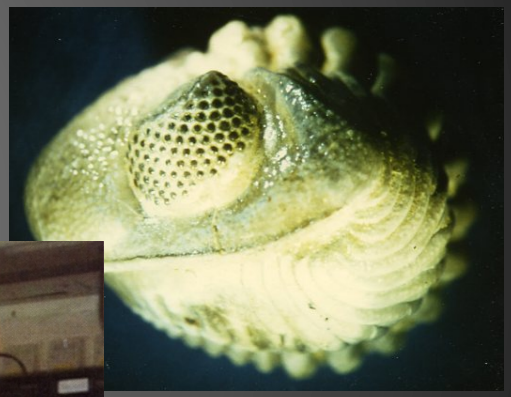
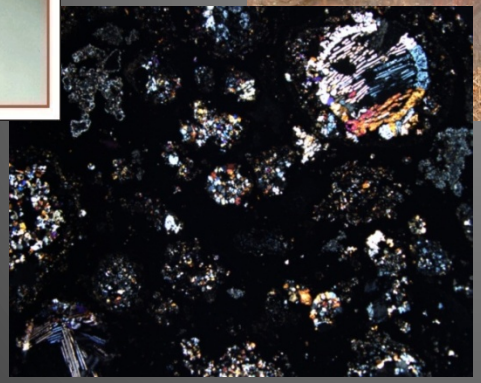
Paleomineralogy of the Hadean Eon: What Minerals Were Present at Life's Origins?





Robert M. Hazen—Geophysical Lab

1st ELSI International Symposium

Tokyo Institute of Technology

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Deep Carbon Observatory

CARNEGIE INSTITUTION FOR SCIENCE

CONCLUSIONS

As many as 90% of the 4700 known mineral species were not present on Earth prior to the origins of life before ~4.0 billion years ago.

Origins-of-life models that rely on minerals for catalysis, selection, concentration, protection, or other processes must employ plausible prebiotic mineral species.

List of 420 Mineral Species

R. M. Hazen (2013) “Paleomineralogy of the Hadean Eon: A Preliminary List” *American Journal of Science*, in press.

What Is Mineral Evolution?

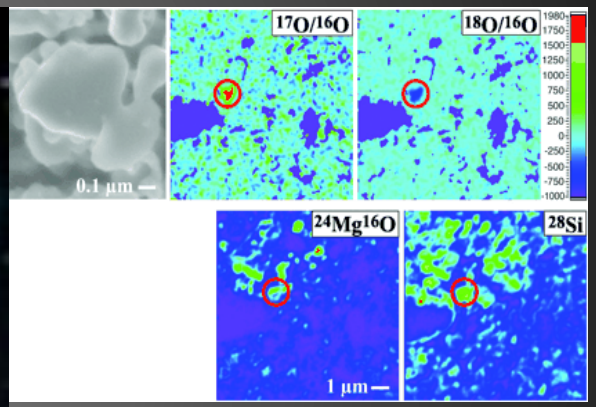
A change over time in:

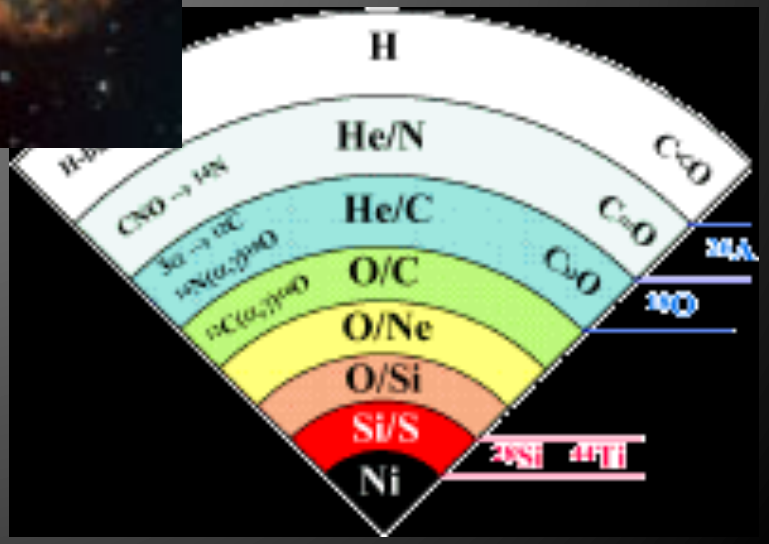
- The diversity of mineral species
- The relative abundances of minerals
- The compositional ranges of minerals
- The grain sizes and morphologies of minerals

"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).



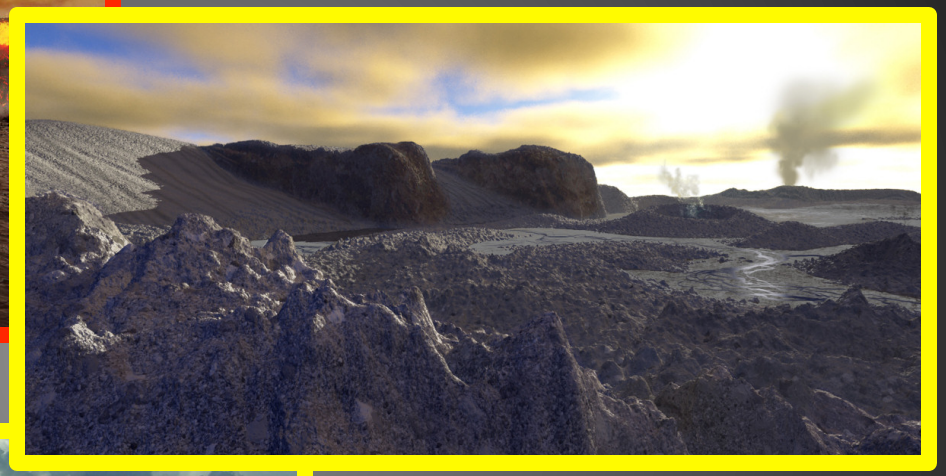


Mineral Evolution:

How did we get from a dozen minerals to >4700 on Earth today?

What minerals were not present at the origin of life (~4.0 Ga), and why?

Mineral Evolution



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.

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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).

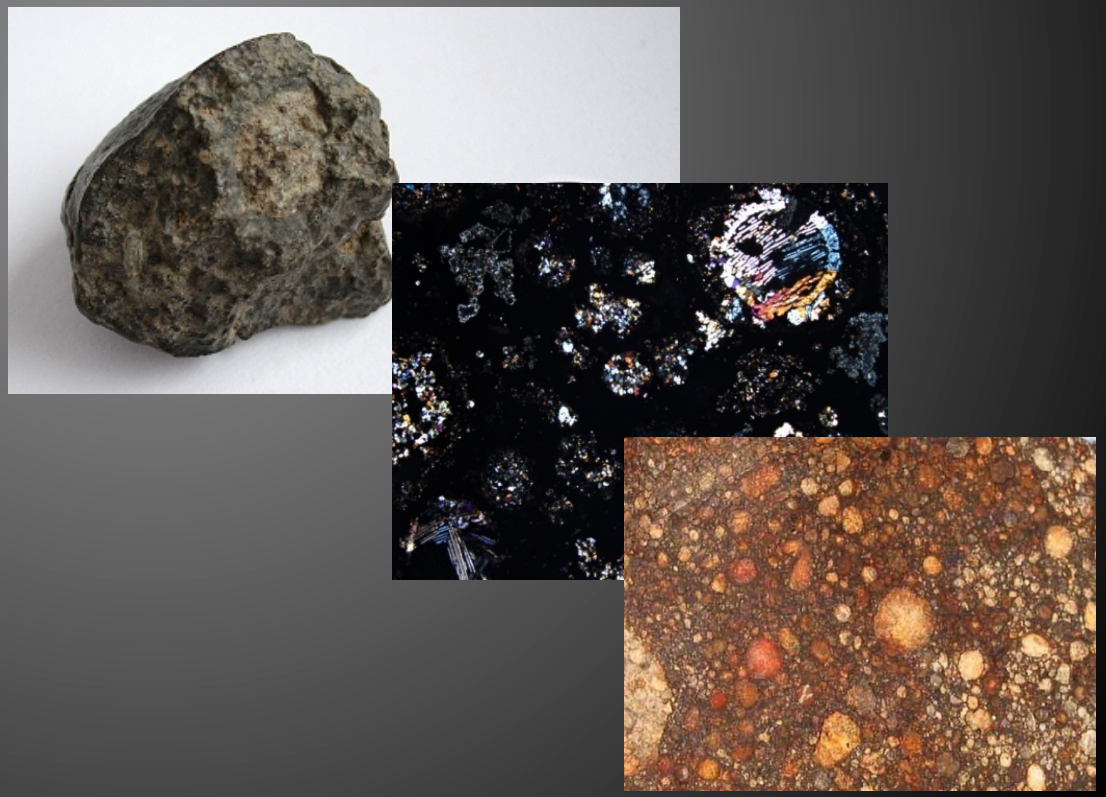
3. The generation of far-from-equilibrium conditions by living systems.

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

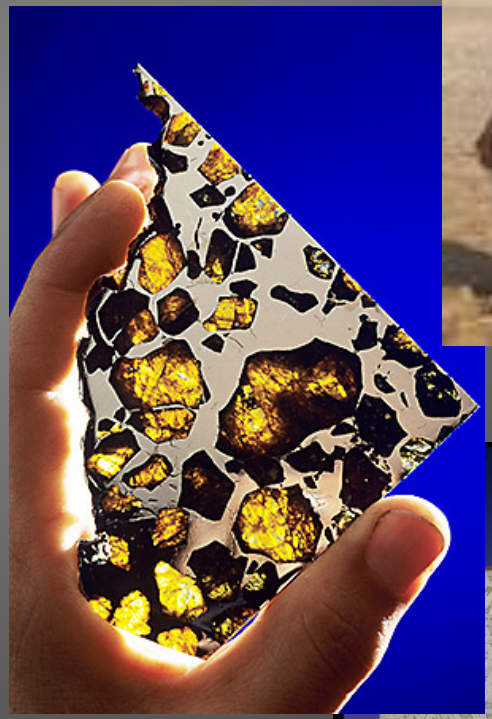
- CAIs
- Chondrules
- Silicate matrix
- Opaque phases



Stage 2: Aqueous alteration, metamorphism and differentiation of planetesimals

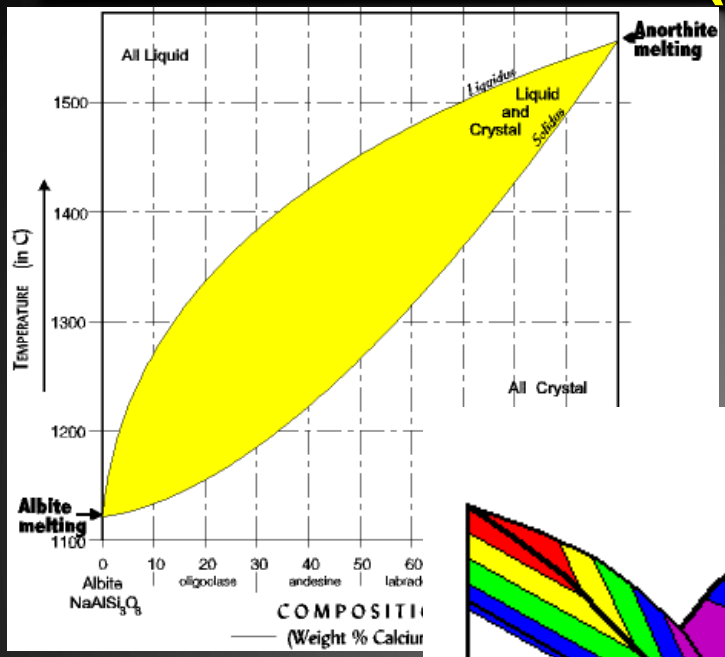
~250 mineral known species: 4.56-4.55 Ga

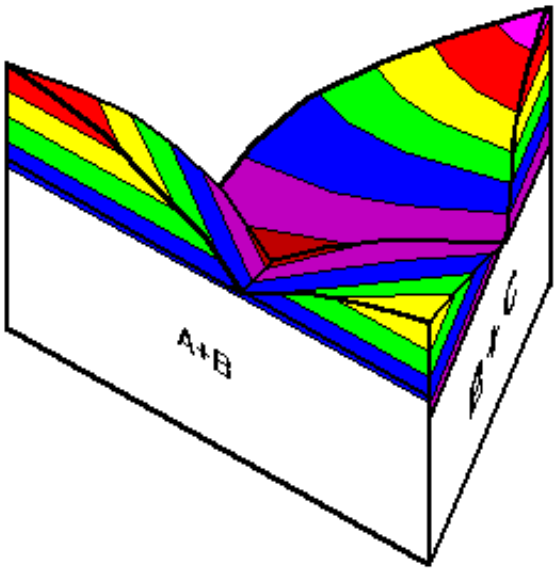
- First albite & K-spar
- First significant SiO_2
- Feldspathoids
- Hydrous biopyriboles
- Clay minerals
- Zircon
- Shock phases
- Carbonates

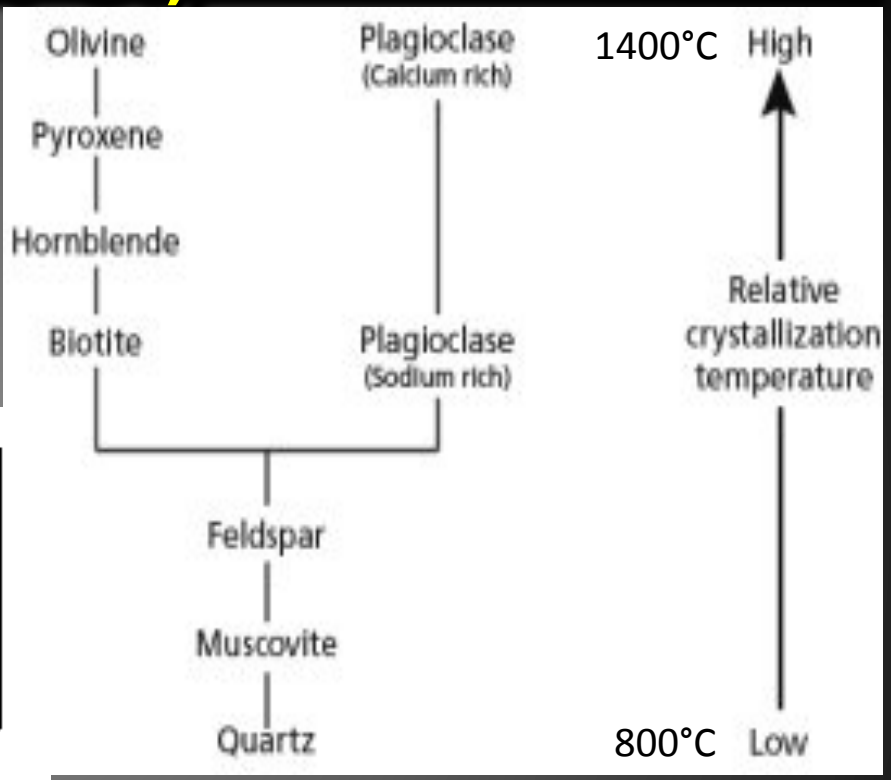


Stages 1 and 2: Planetary Accretion

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-rich Body

>400 mineral species (hydroxides, clays, Ices, evaporites, sulfates, carbonates)

Volcanism, outgasing, surface hydration, evaporites, ices.

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

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

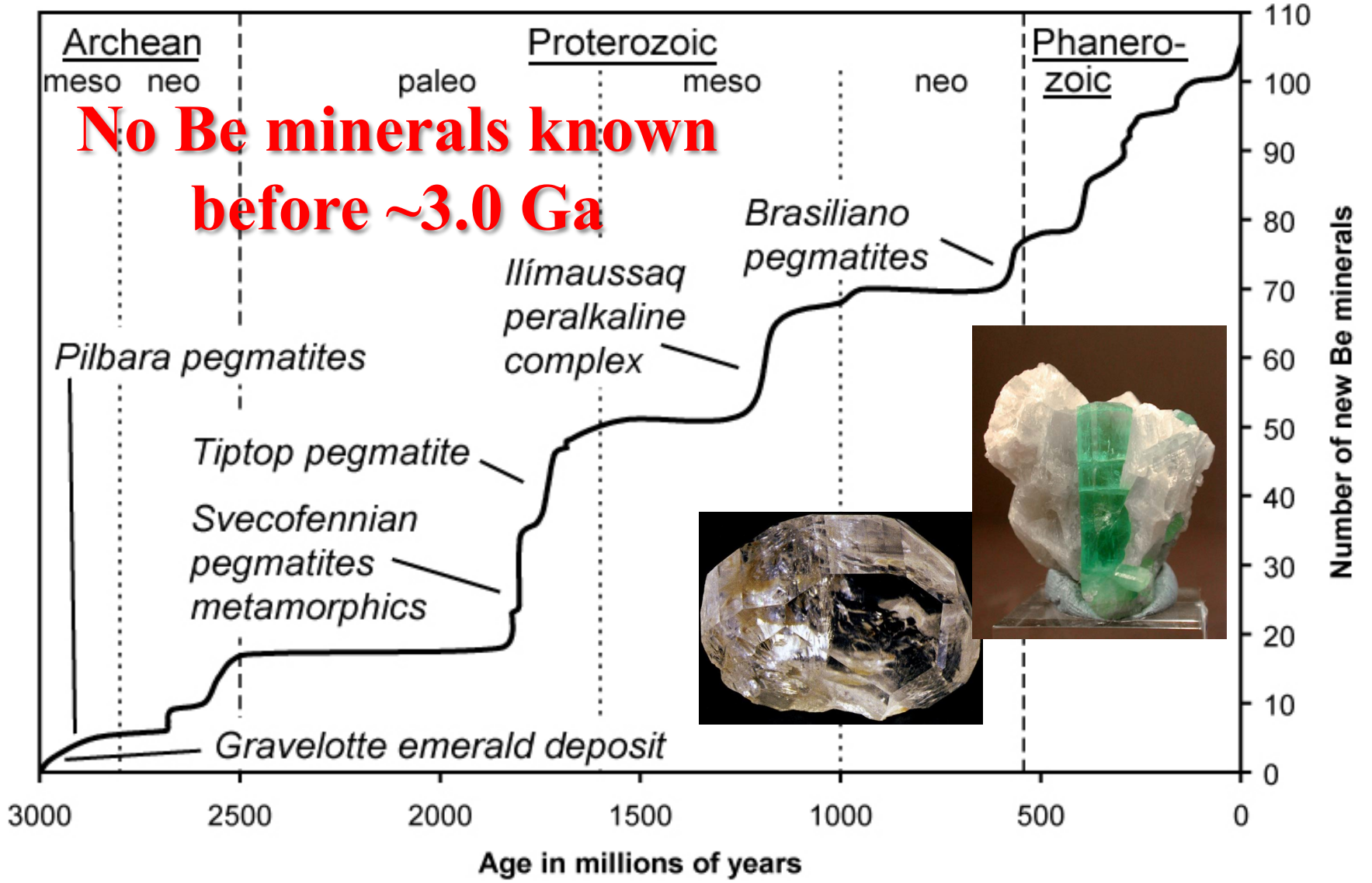
Pollucite

Tantalite

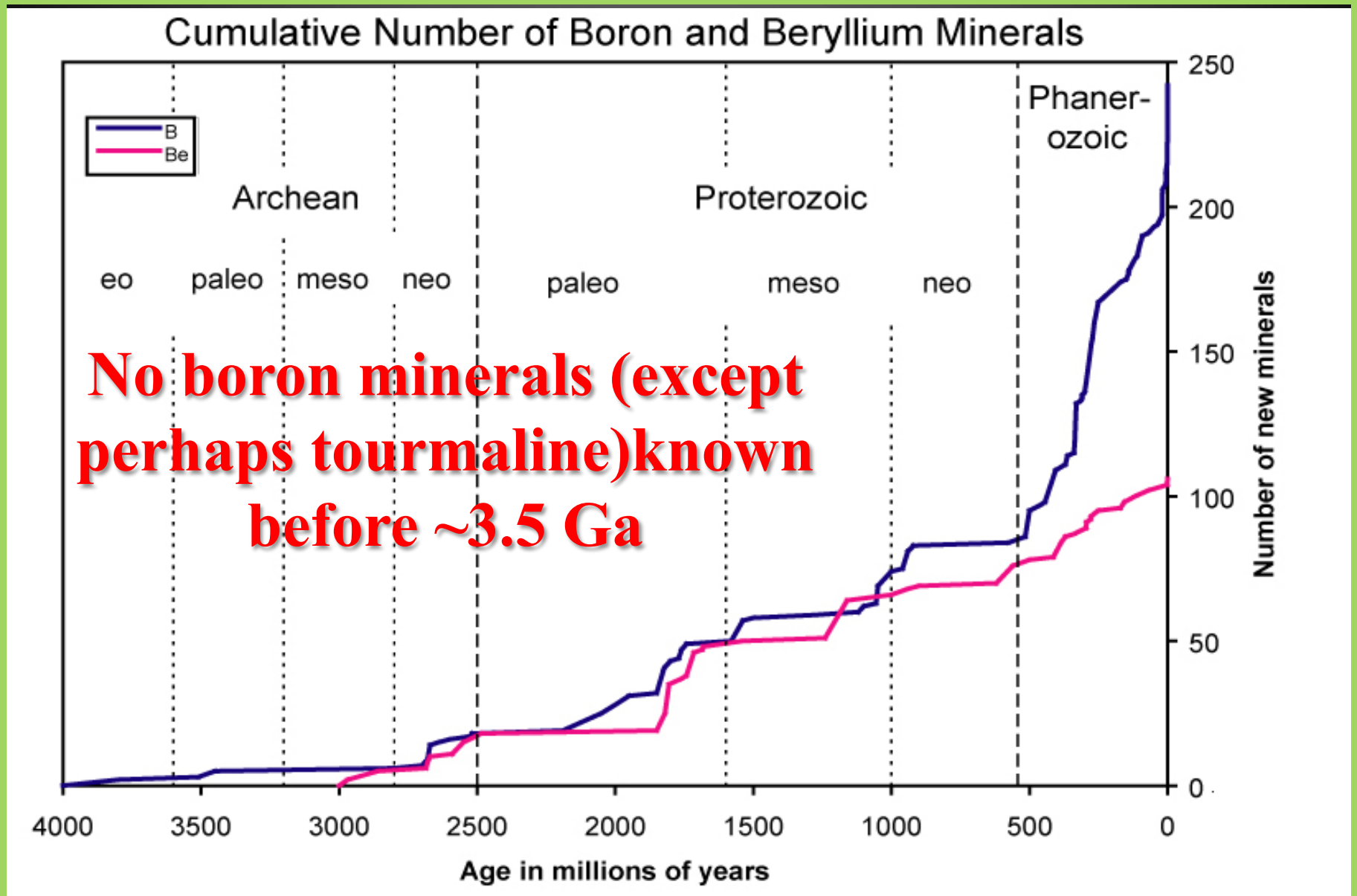
Complex pegmatites require multiple cycles of eutectic melting and fluid concentration.

All complex pegmatites are younger than 3.5 Ga.

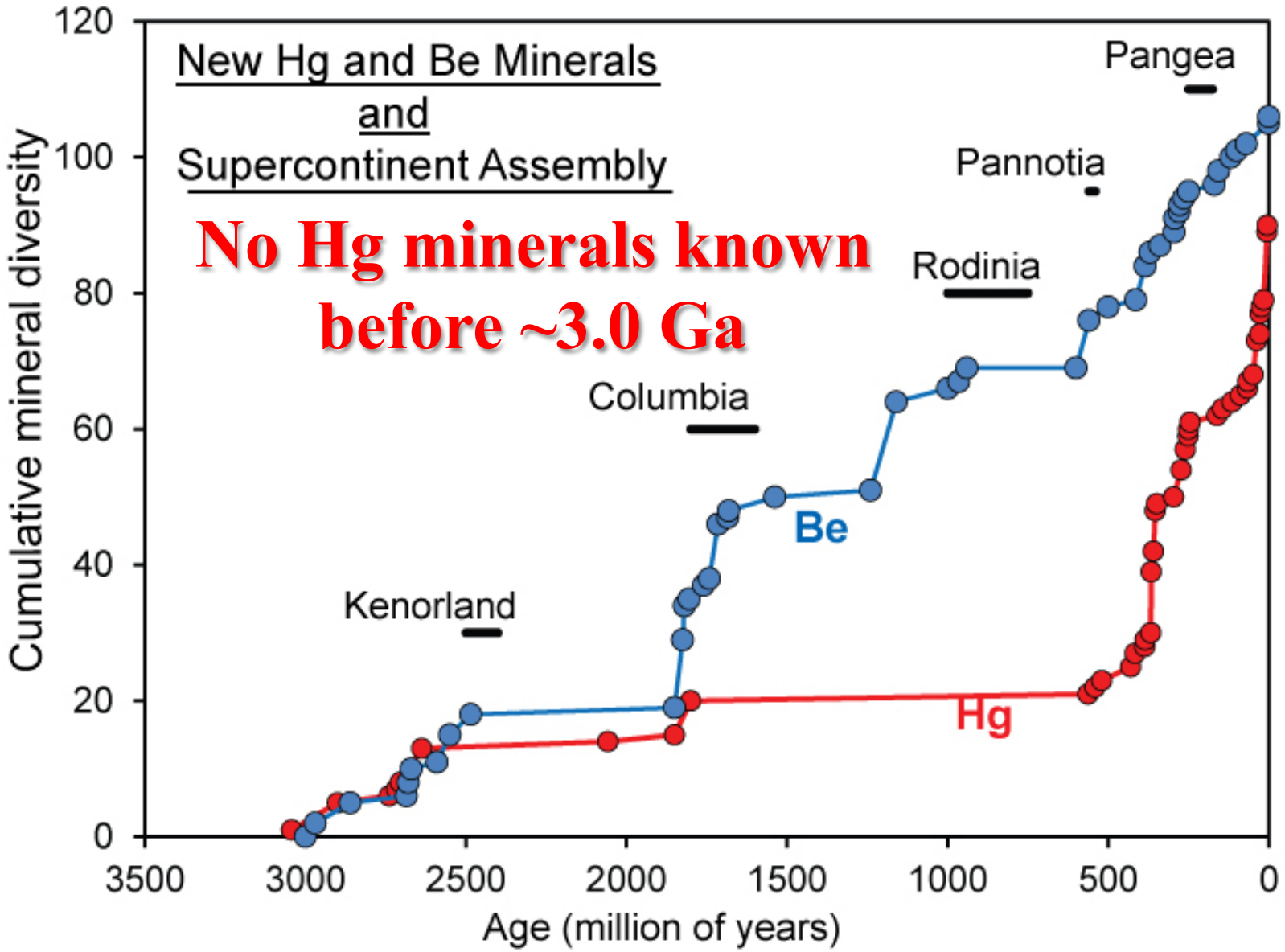
Be Mineral Evolution (Grew & Hazen, 2009)



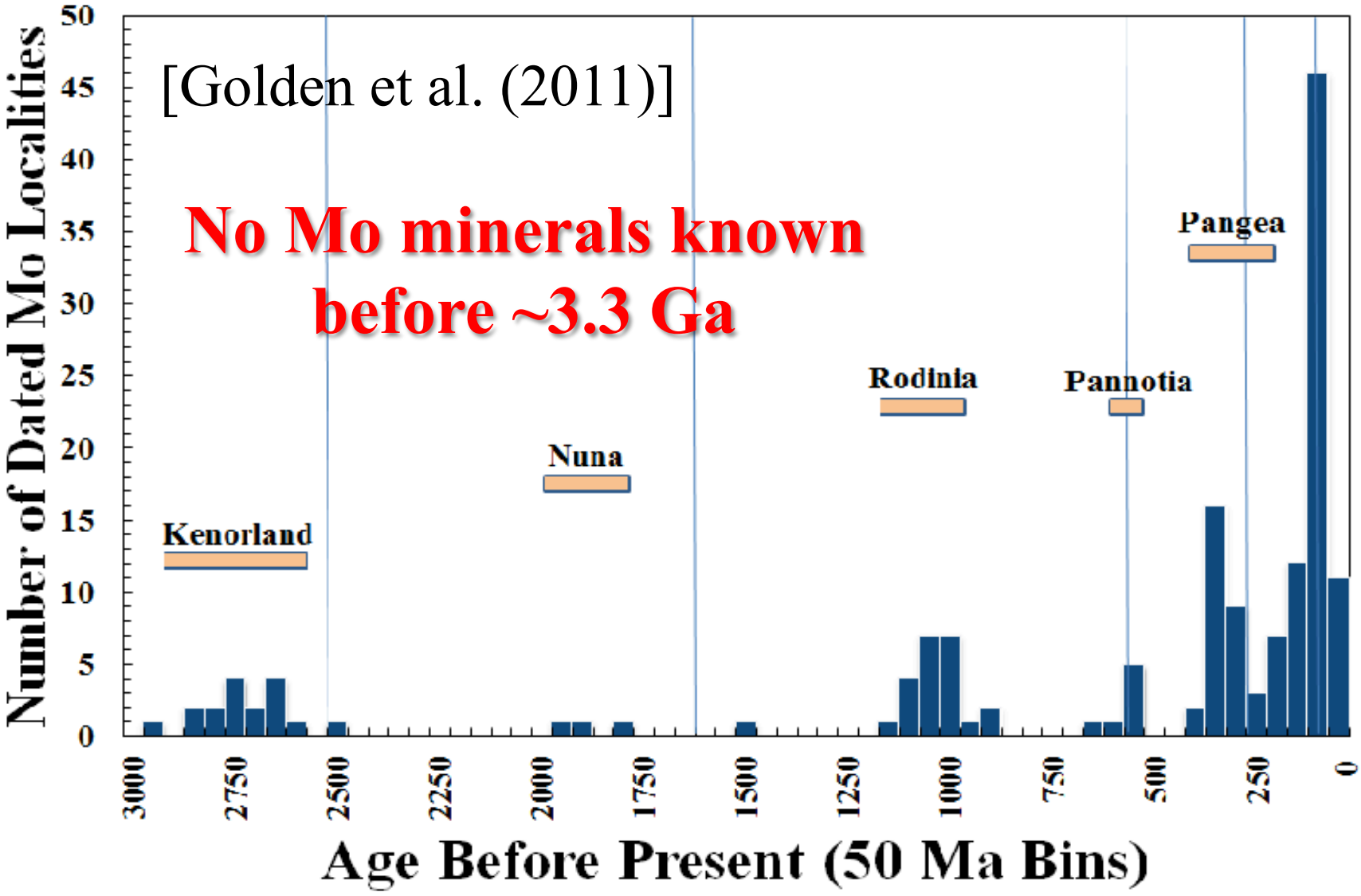
B Mineral Evolution (Grew & Hazen 2010)



RESULTS: Hg & Be Mineral Evolution

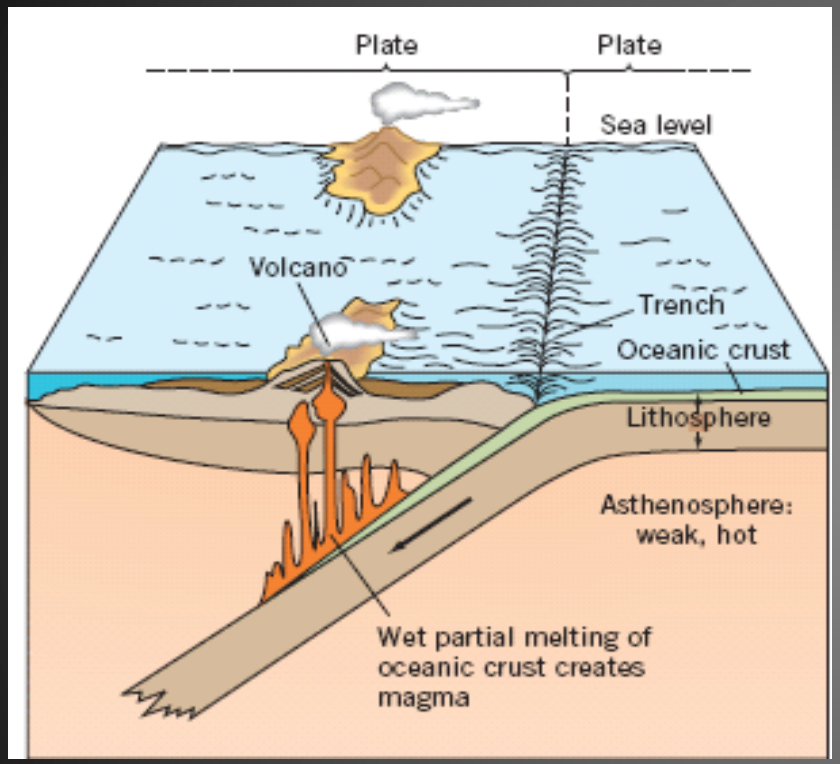


RESULTS: Molybdenite (MoS_2) through Time



RESULTS: Mo Mineral Evolution

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

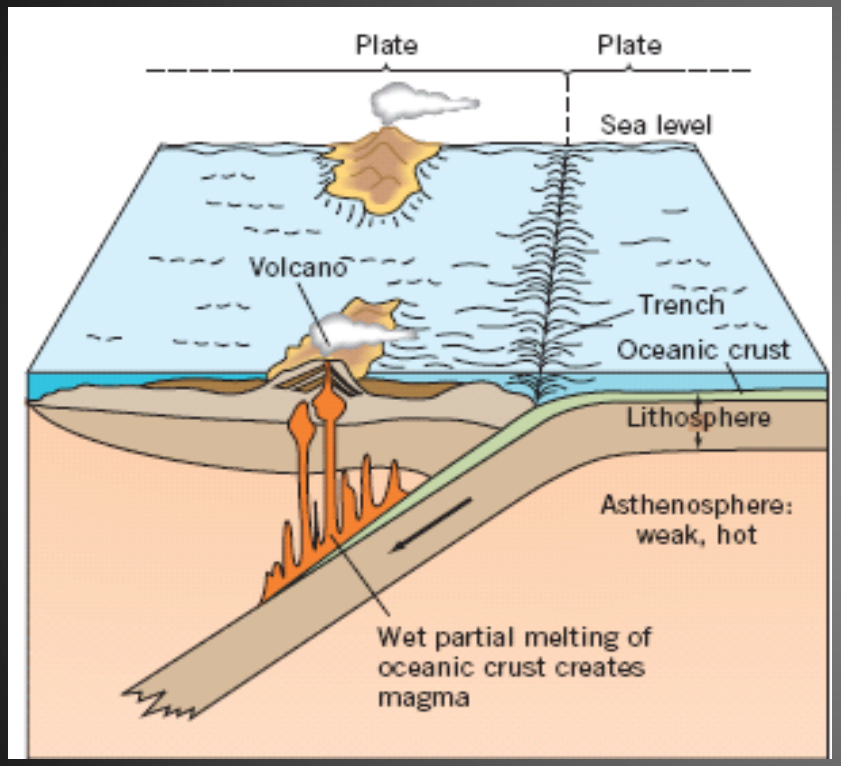


~10^8 km^3 of reworking

Mayon Volcano, Philippines

New modes of volcanism

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



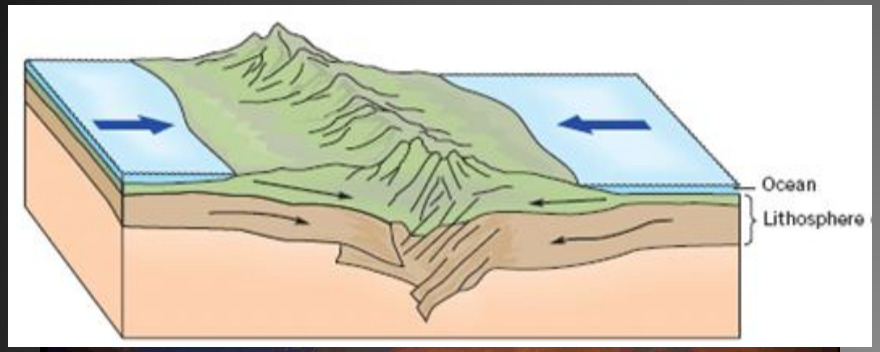
Rio Tinto. Spain

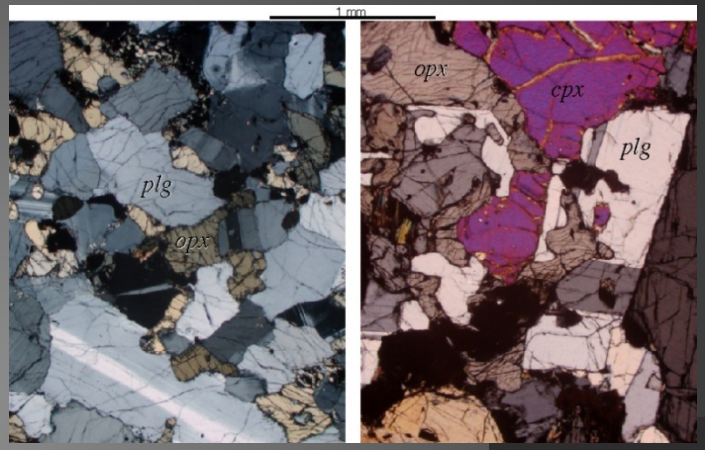
New modes of volcanism

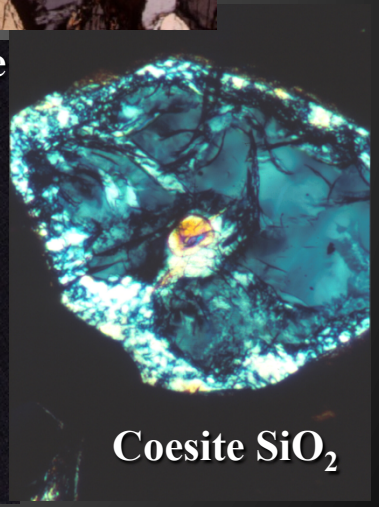
Massive base metal deposits (sulfides, sulfosalts)

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

1,500 mineral species

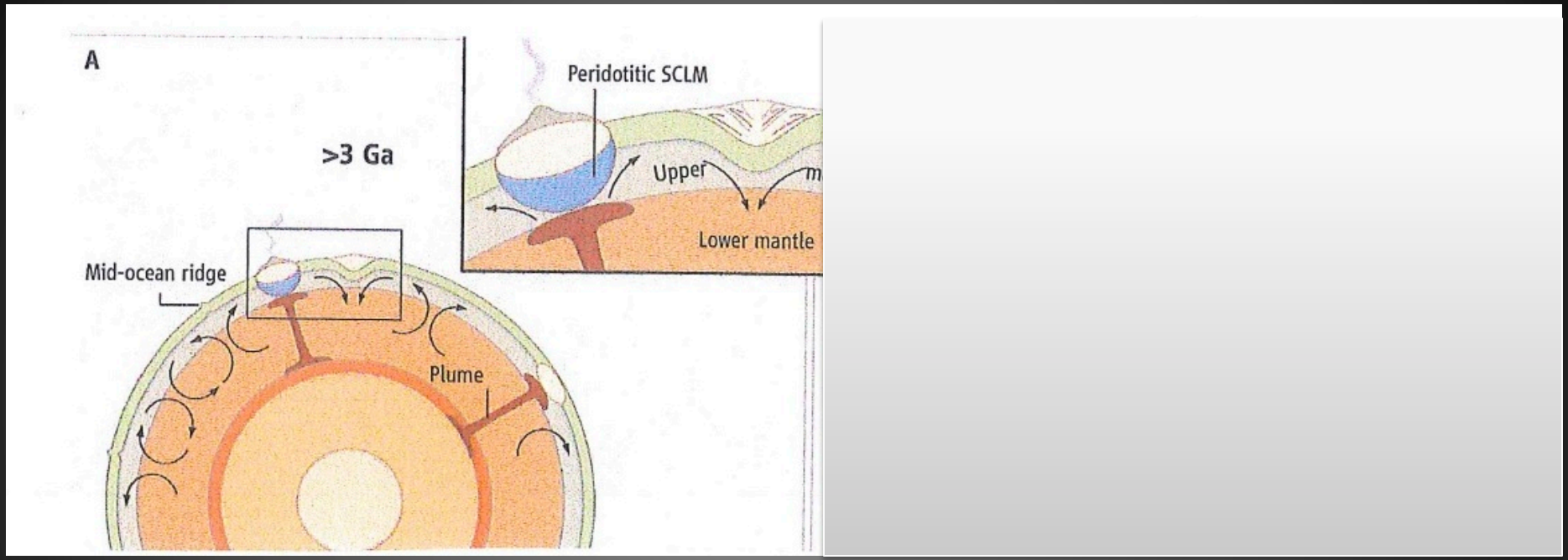






High-pressure metamorphic suites (blueschists; granulites; UHP phases)

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

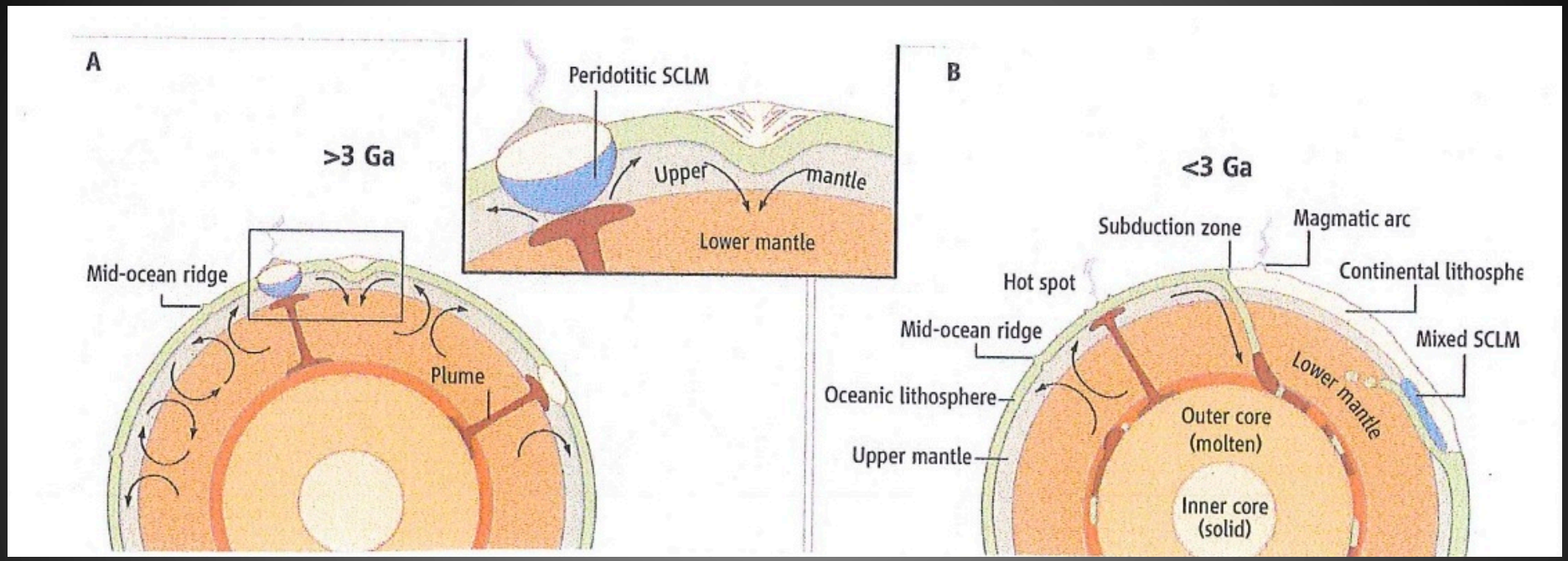


Van Kranendonk (2011)

> 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**

Recent research suggests that global-scale subduction did not begin until ~3 Ga.

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

Approximately 1500 mineral species form by Stages 3, 4, and 5 processes, but only ~420 of those species formed before 4.0 Ga.

What was the Role of Impacts?

1. Formation of shock minerals.

2. Excavation of deep igneous and metamorphic terrains.

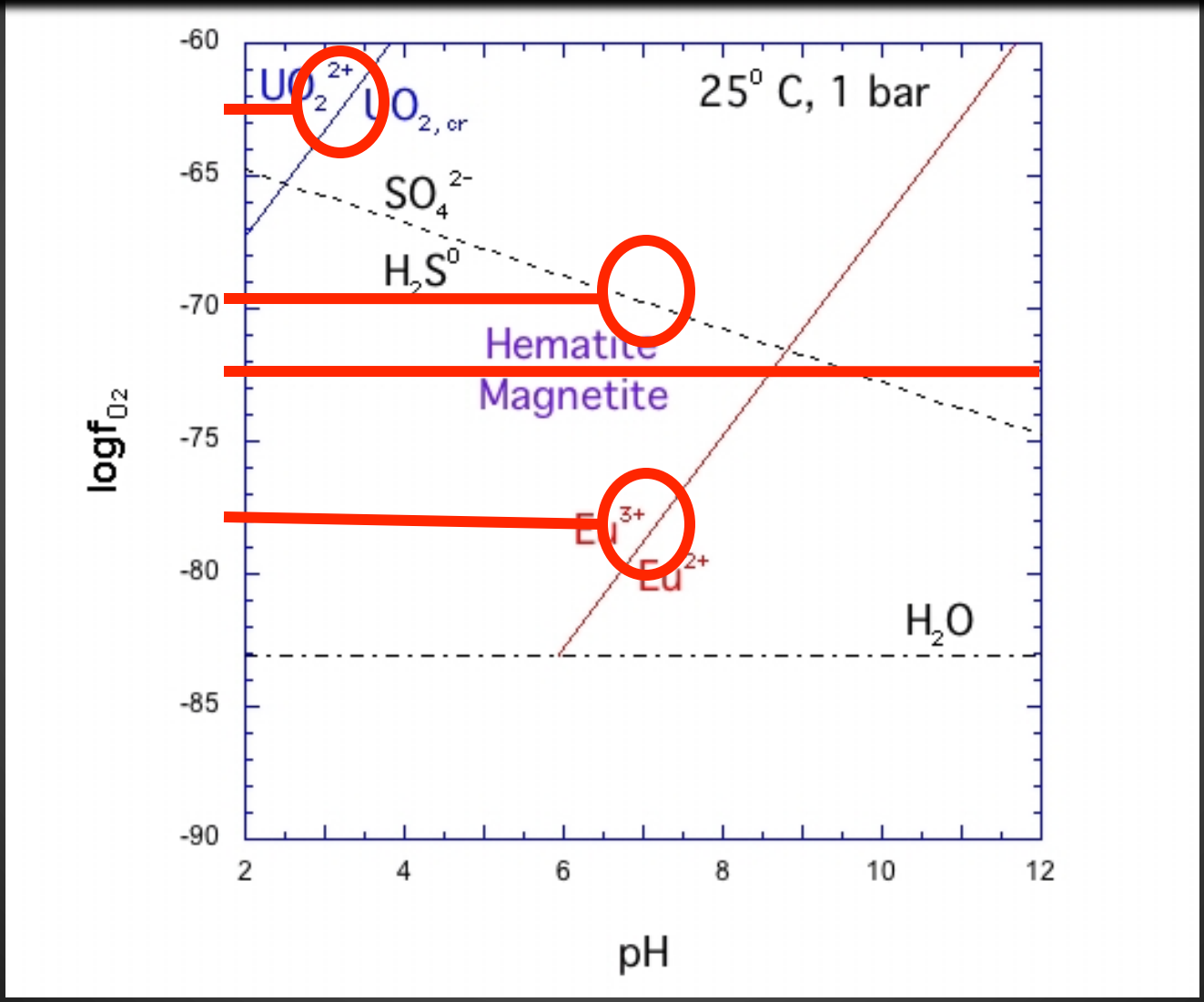
3. Creation of deep subsurface hydrothermal zones.

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 (ask me).

What was the oxygen fugacity in the Archean?



Key constraints on Archean surface oxygen fugacity.

Detrital uraninite, pyrite and siderite

Paleosols lacking iron oxides

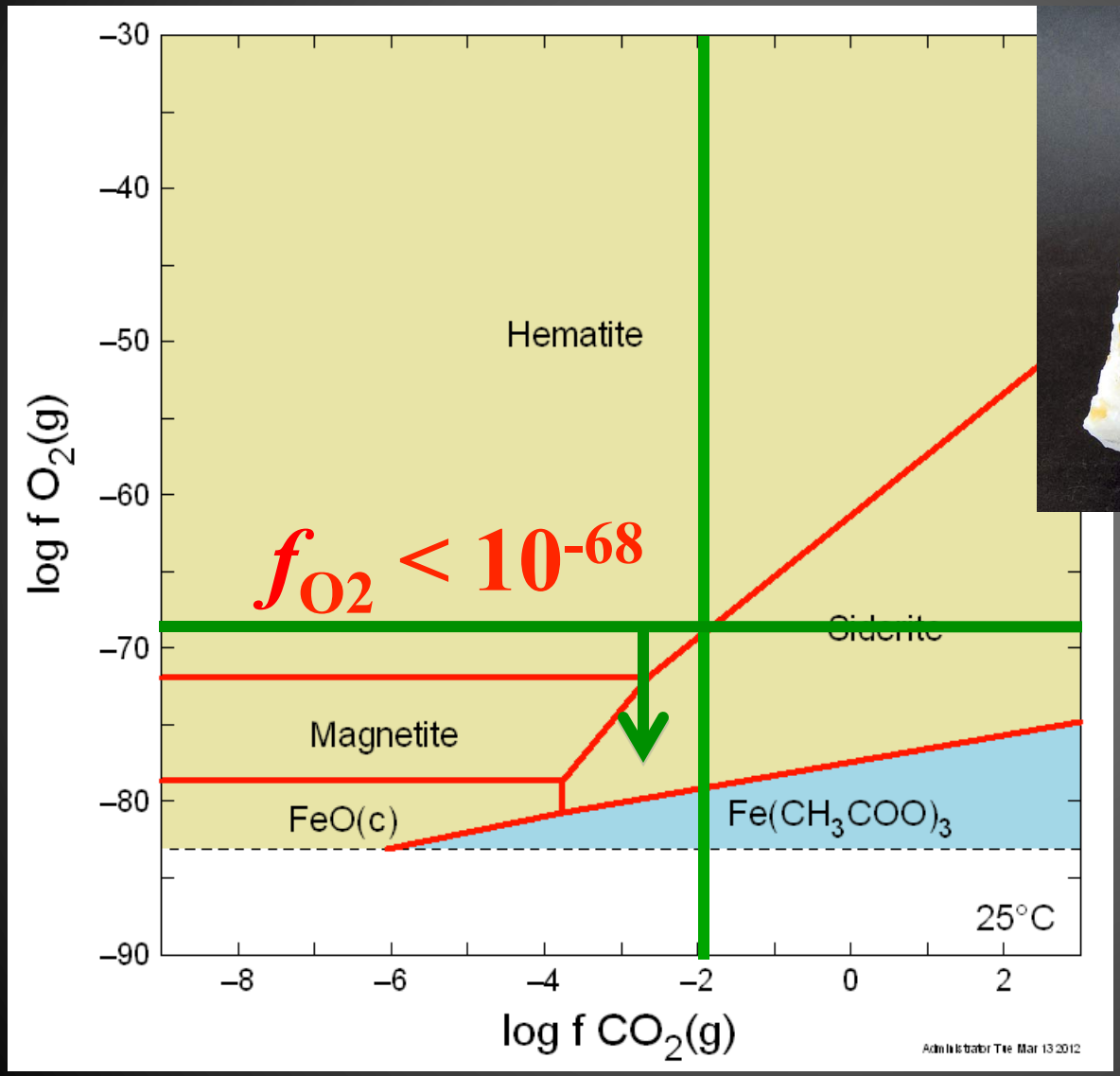
[Surface waters with aqueous Fe^{2+}]

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

Eu^{2+} anomalies

Precipitation of ferroan carbonates

What was the oxygen level in the Archean Eon?



Siderite
$FeCO_3$

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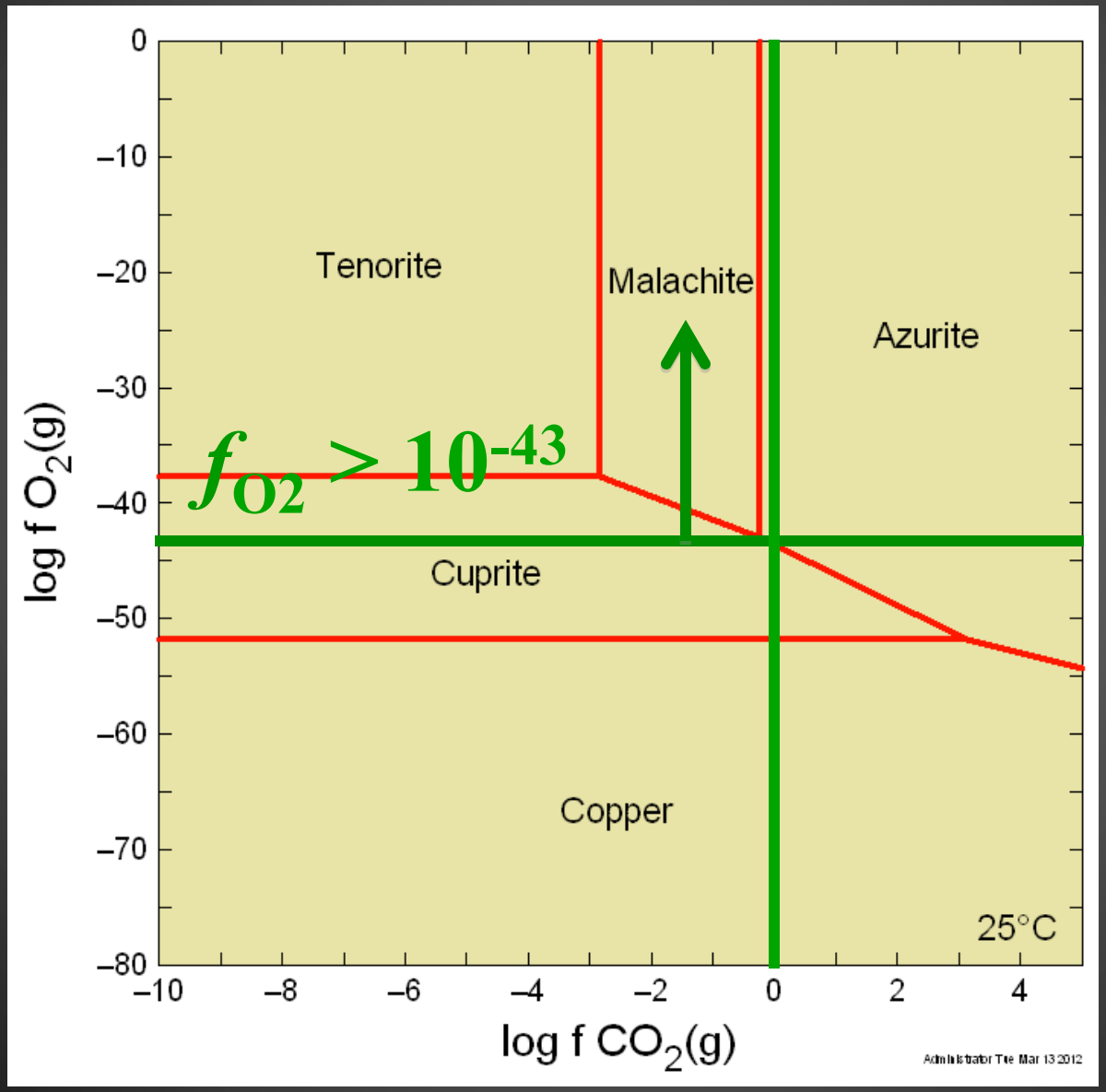


Azurite

&

Malachite

What minerals won't form?

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

What minerals 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

What minerals won't form?

Abelsonite—$NiC_{31}H_{32}N_4$

Ravatite—$C_{24}H_{48}$

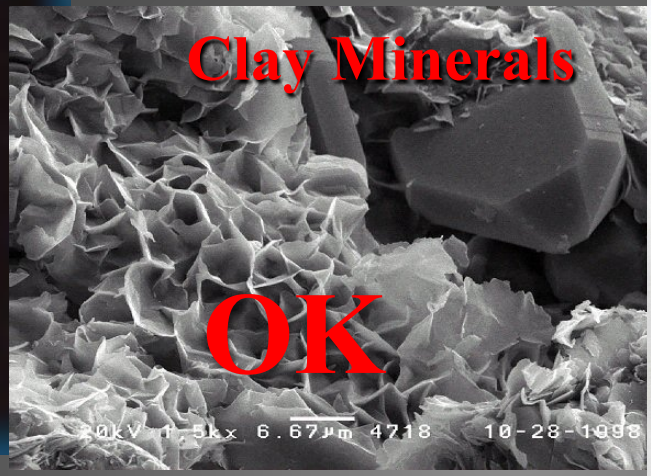
Evankite—$C_{24}H_{48}$

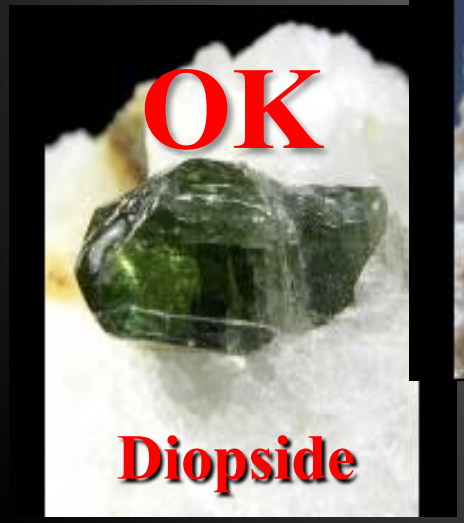
Dashkovaite—$Mg(HCOO)_2{\cdot}2H_2O$

Oxammite—$(NH_4)(C_2O_4){\cdot}H_2O$

> 50 Organic Mineral Species

So what minerals were present at the time of life's origins?





CONCLUSIONS

As many as 90% of the >4700 known mineral species were not present on Earth prior to the origins of life before ~4.0 billion years ago.

Origins-of-life models that rely on minerals for catalysis, selection, concentration, protection, or other processes must employ plausible prebiotic mineral species.

Unanswered Questions?

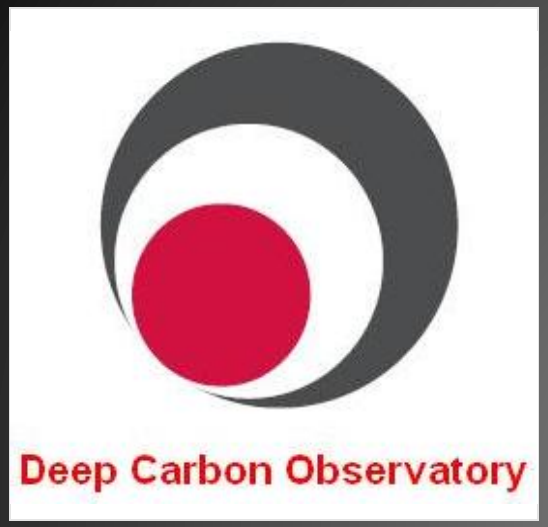
When did an ocean form and what were its physical and chemical characteristics?

When did continents form and what was the dominant lithology (TTG vs. anorthosite)?

When did plate tectonics begin?

What local reaction path mechanisms might have led to redox excursions?

What was the role of impacts?



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