Mineral Evolution of Terrestrial Planets

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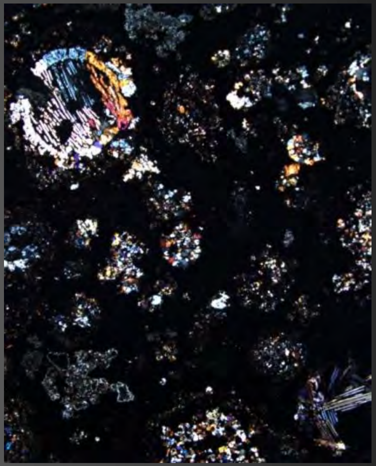


AbSciCon 2008 – Session 24
Biosignatures in Minerals
Wednesday, 16 April, 11:45 am

CARNEGIE INSTITUTION FOR SCIENCE

What Is Mineral Evolution?

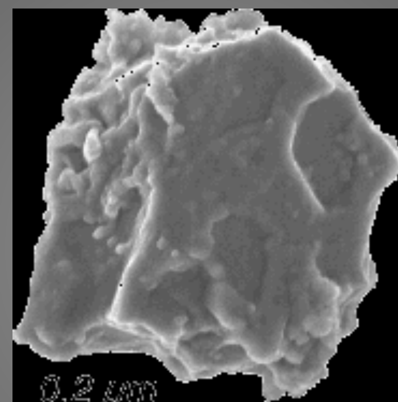
A change over time in:

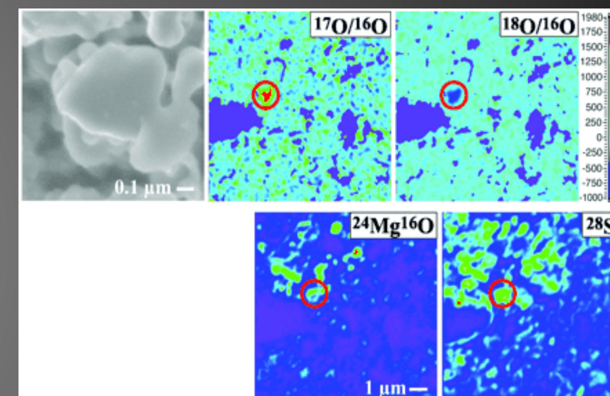
- The diversity of mineral species
- The relative abundances of minerals
- The compositional ranges of minerals
- The grain sizes and morphologies of minerals

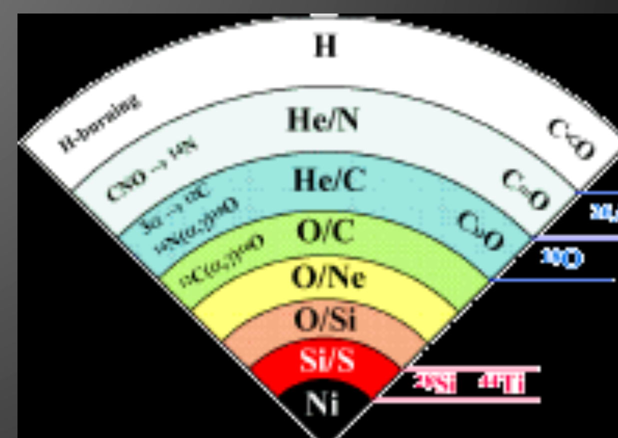
“Ur”-Mineralogy

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

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







How did we get from a dozen minerals to >4300 on Earth today?

(Focus on near-surface)

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.

Three Eras of Earth's Mineral Evolution

1. The Era of Planetary Accretion

2. The Era of Crust and Mantle Reworking

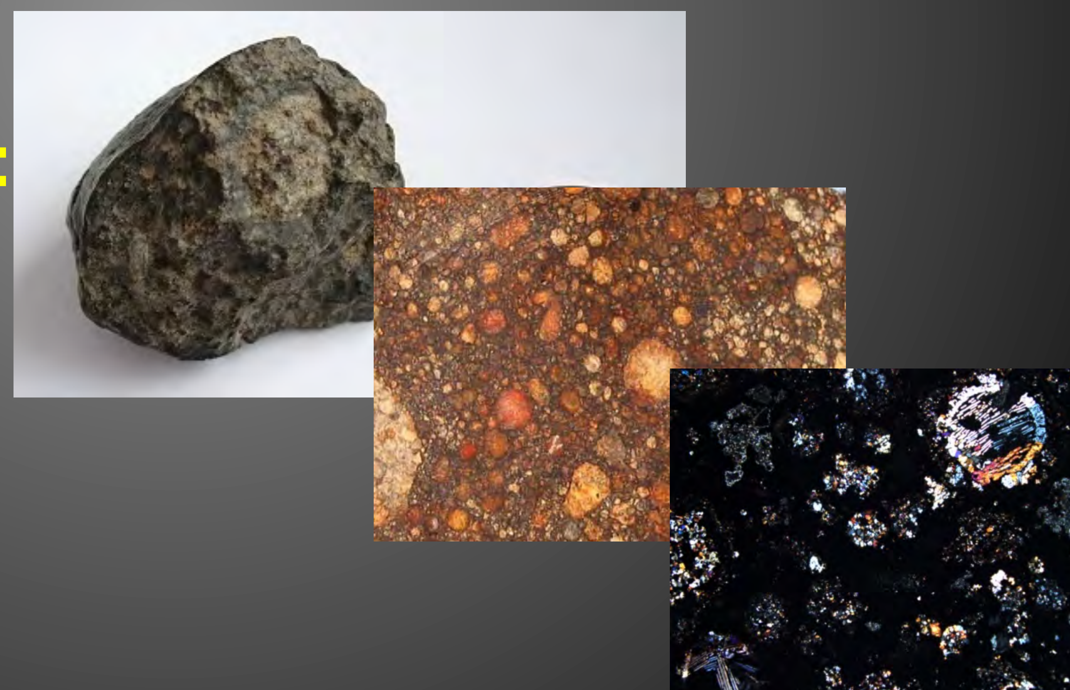
3. The Era of Bio-Mediated Mineralogy

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:

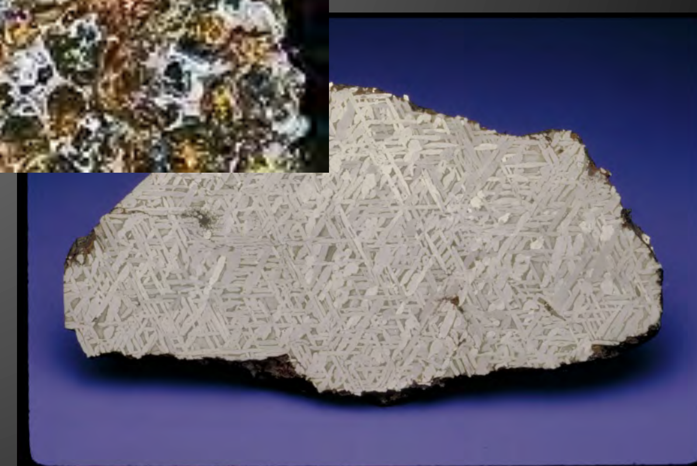
- CAIs
- Chondrules
- Silicate matrix
- Opaque phases



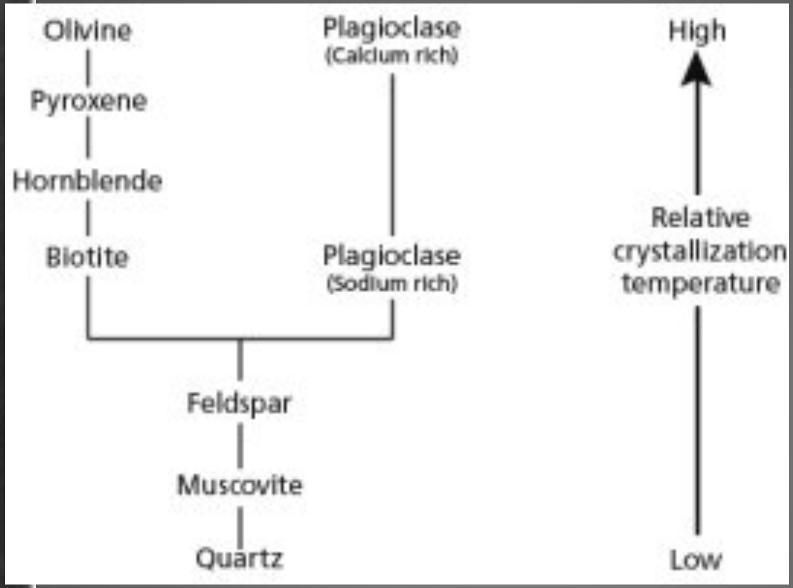
Stage 2: Aqueous alteration, metamorphism and differentiation of planetesimals

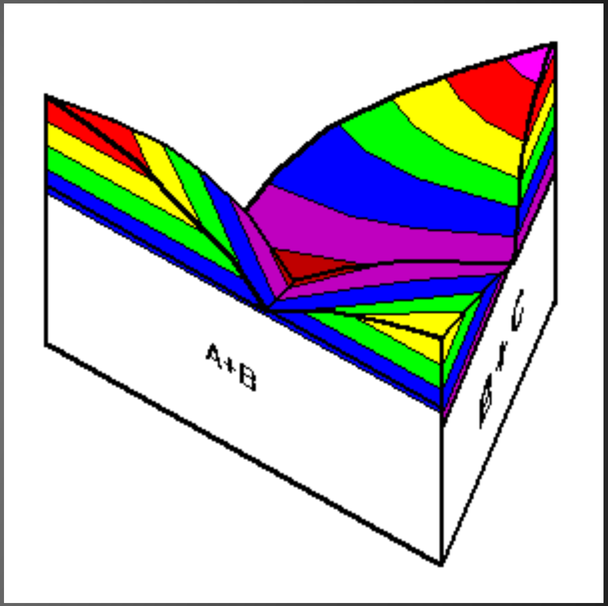
~250 mineral known species: 4.56-4.55 Ga

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



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

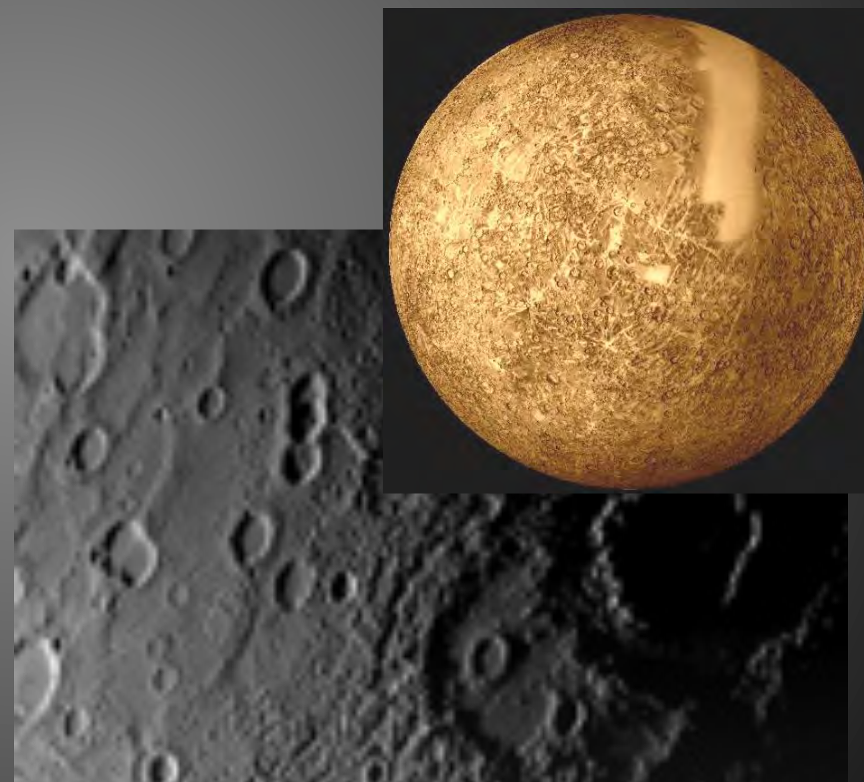




Partial melting, fractional crystallization and magma immiscibility

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

~350 mineral species?



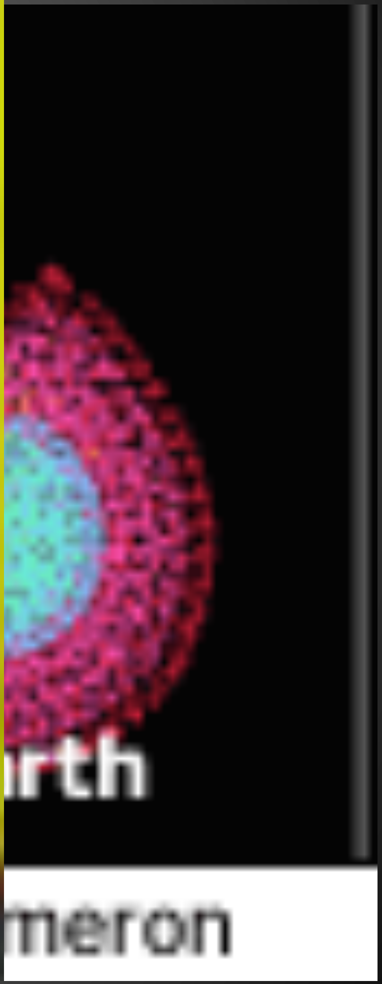
Is this the end point of the Moon and Mercury?

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

>500 mineral species (hydroxides, clays)

Volcanism, outgasing and surface hydration.

The Formation of the Moon



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

>500 mineral species (hydroxides, clays)

Volcanism, outgasing and surface hydration.

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

Is this as far as Mars or Venus progressed?

Volcanism, outgasing and surface hydration.

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)

Complex pegmatites require multiple cycles of eutectic melting and fluid concentration (i.e., younger than 3.5 Ga?).

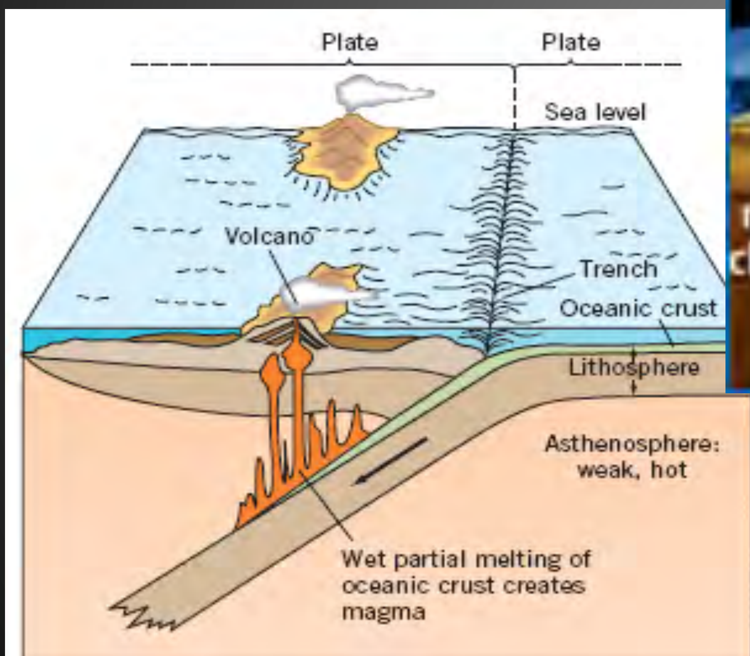
Stage 4: Granitoid Formation

Are there pegmatites on Mars?

Are there emeralds on Venus?

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

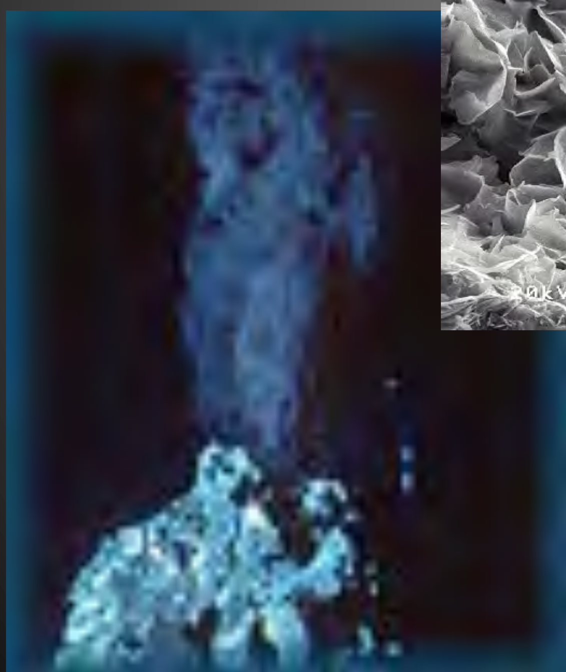
1,500 mineral species (sulfides, sulphosalts)

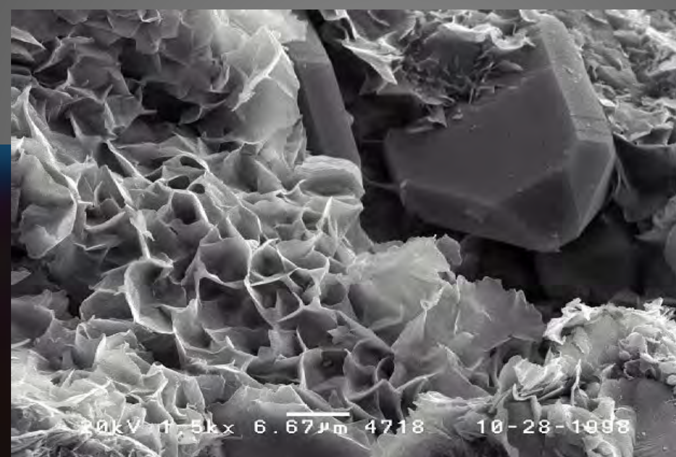


Massive base metal deposits; exposure of high-P metamorphic terrains; new hydrated minerals.

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

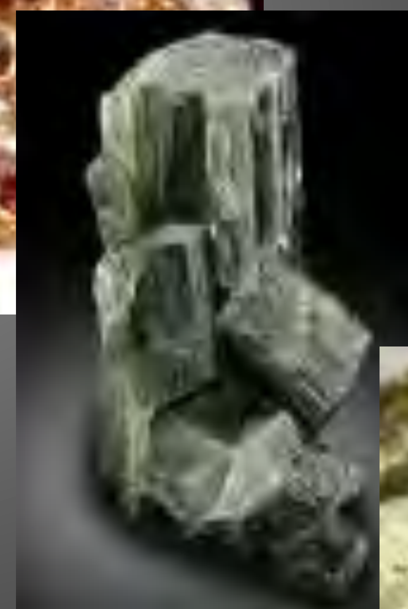
Does the origin of life require some minimal degree of mineral evolution?





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

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



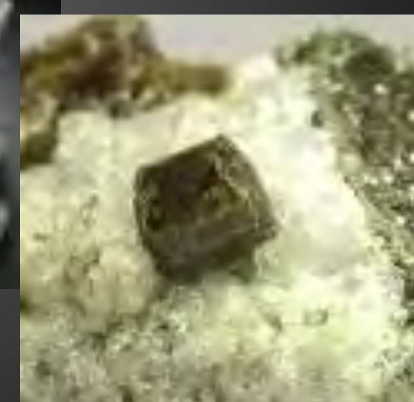


Photo credit: D. Papineau

Stage 7: Paleoproterozoic Oxidation (2.5-1.9 Ga)

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

Rise of oxidative photosynthesis.

Stage 7: Paleoproterozoic Oxidation (2.5-1.9 Ga)

>4000 mineral species (oxy-hydroxides)

202 of 220 U minerals

319 of 451 Mn minerals

47 of 56 Ni minerals

582 of 790 Fe minerals

Piedmontite

Garnierite

Xanthoxenite

Stage 7: Paleoproterozoic Oxidation (2.5-1.9 Ga)

Especially copper minerals!

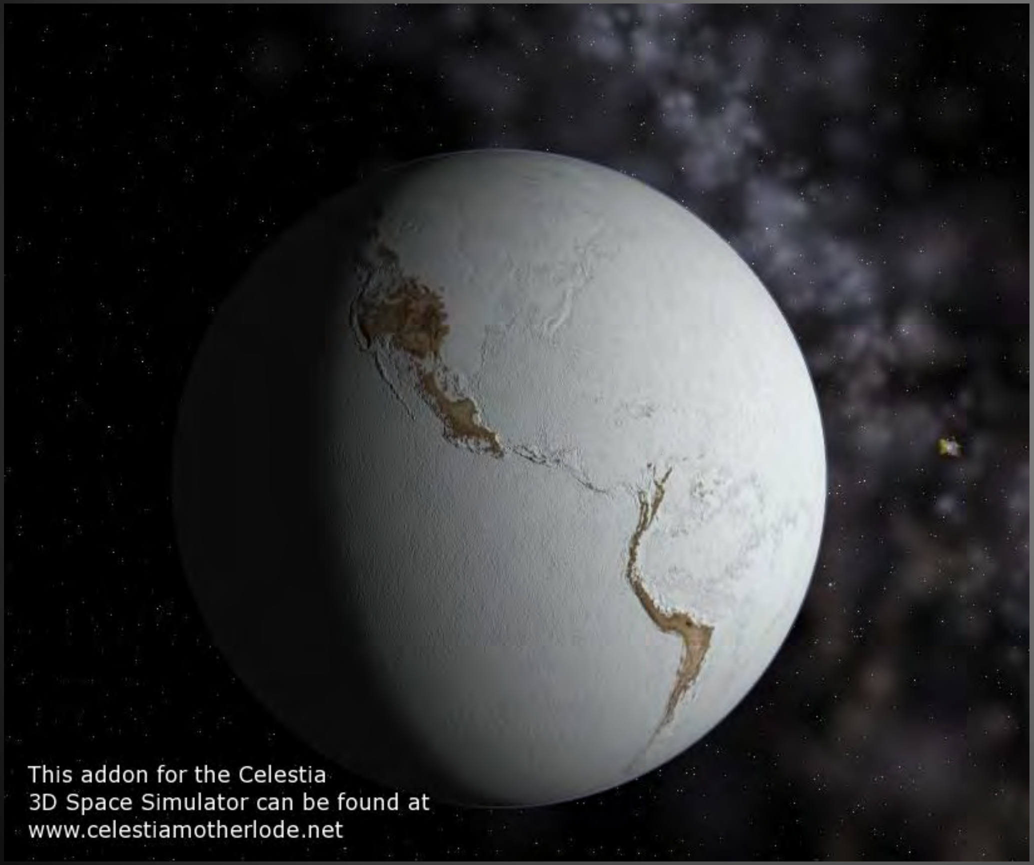
Stage 8: The "Intermediate Ocean" (1.9-1.0 Ga)

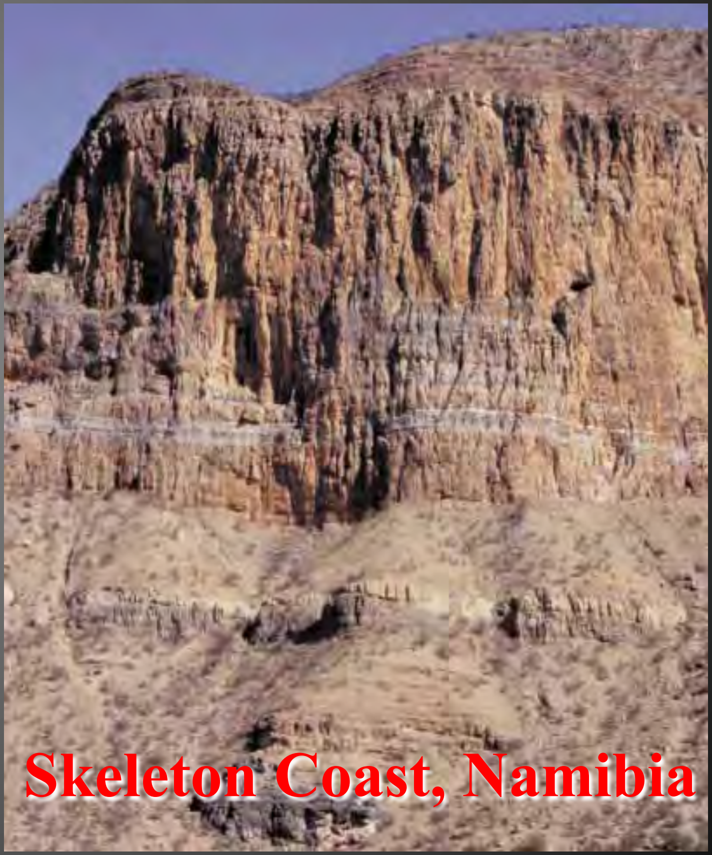
>4000 mineral species (few new species)

Oxidized surface ocean; deep-ocean anoxia.

Stage 9: Snowball Earth and Neoproterozoic Oxidation (1.0-0.542 Ga)

>4000 mineral species (few new species)





Glacial cycles triggered by albedo feedback.

Stage 10: Phanerozoic Biomineralization (<0.542 Ga)

>4,300 mineral species




Implications of Mineral Evolution

- Defines a way to categorize terrestrial planets and moons.
- Implies mission targets: mineral biosignatures (and abiosignatures).
- Provides insights on the evolution of complex systems.
- Represents a new way to frame (and to teach) mineralogy.

Conclusions

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

- Three principal mechanisms of change:
    1. Element segregation & concentration
    2. Increasing ranges of T, P and X
    3. Influence of living systems.

- Different bodies achieve different stages of mineral evolution.