Mineral Evolution

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"You are not in Kansas anymore"

- Robert Hazen and colleagues (2008) had a fundamental insight on mineralogical evolution.
- The mineralogy of terrestrial planets and moons evolves as a consequence of varied physical, chemical, and biological processes that lead to the formation of new mineral species.
- Mineral evolution is 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

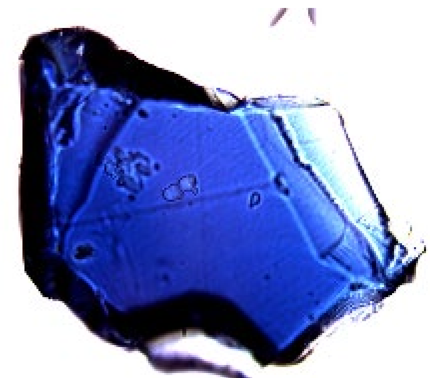
Autunite $Ca(UO_2)_2(PO_4)_2 \times 8\text{-}12\ H_2O$

A Few Definitions

- **Mineral:**
  - A crystalline compound with a fairly well-defined chemical composition and a specific crystal structure.
  - For example, water ice is a mineral.
- **Evolution:**
  - In biology the process by which different kinds of living organisms are thought to have developed and diversified from earlier forms during the history of the earth.
  - More broadly it is the gradual development of something from simple to more complex forms.
- What we will be talking about is a form of radiation where minerals react in changing chemical and physical environments.
  - The result are changes to their crystal structure along with their physical and chemical properties.

Take Olivine

- Olivine is one of the most abundant minerals in the solar system and the universe.
- Forsterite is the Mg-rich endmember: Mg_2SiO_4
  - Add water and time, it weathers to serpentine $Mg_3Si_2O_5(OH)_4$
  - Add high pressure the chemistry stays the same, but the crystal structure transforms to Ringwoodite.
  - Add more pressure and it decomposes to silicate perovskite $MgSiO_3$ and ferropericlase MgO
  - In silica-rich igneous systems it reacts to form orthopyroxene $Mg_2Si_2O_6$
  - Heat olivine under reducing conditions and you get enstatite $MgSiO_3$ plus free oxygen and pure Mg.
- So by changing the local chemistry, energy, or pressure, this mineral can "evolve" into 6 more minerals (actually a lot more).

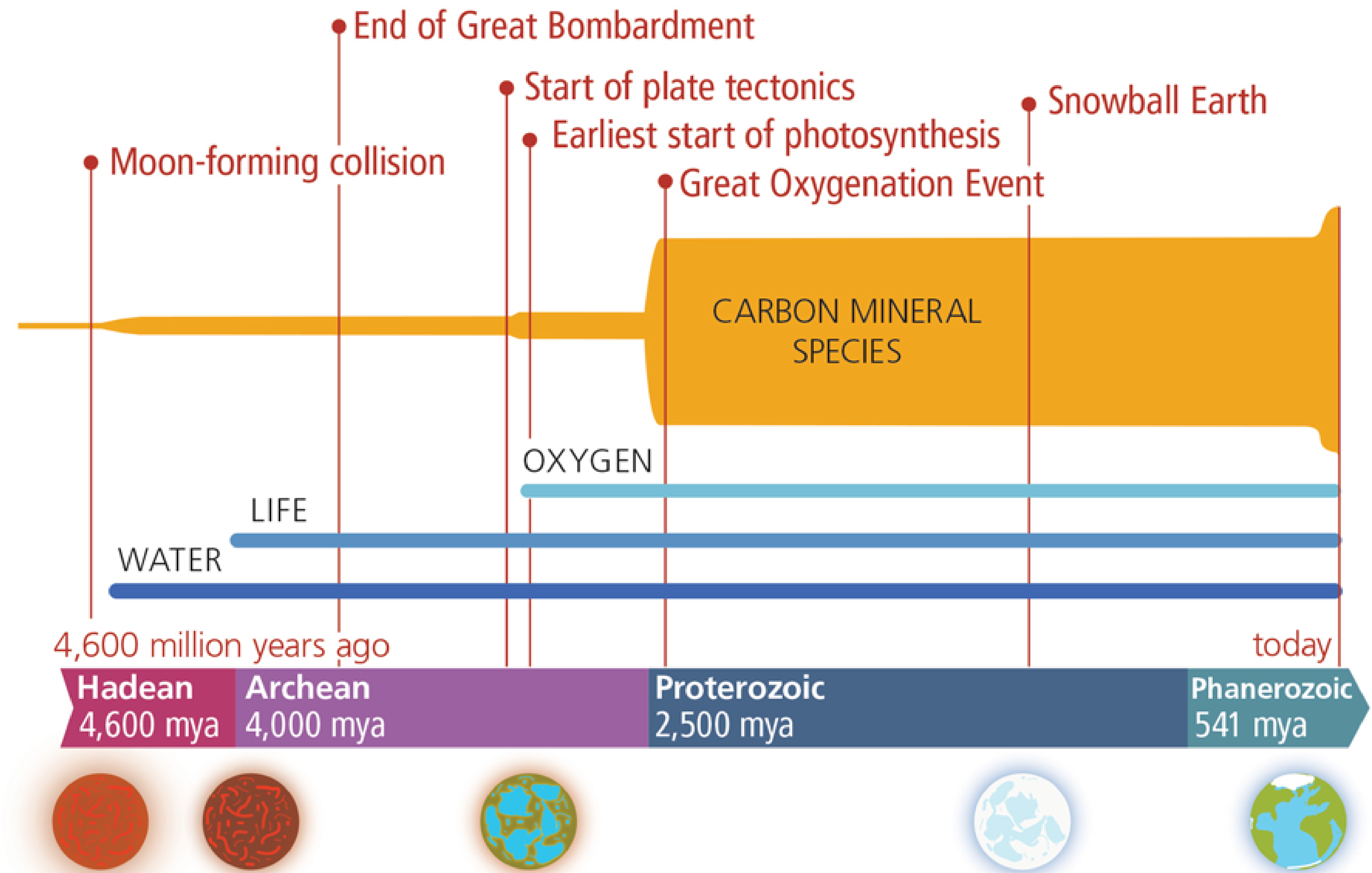

Ringwoodite


Serpentine

Mineral Evolution

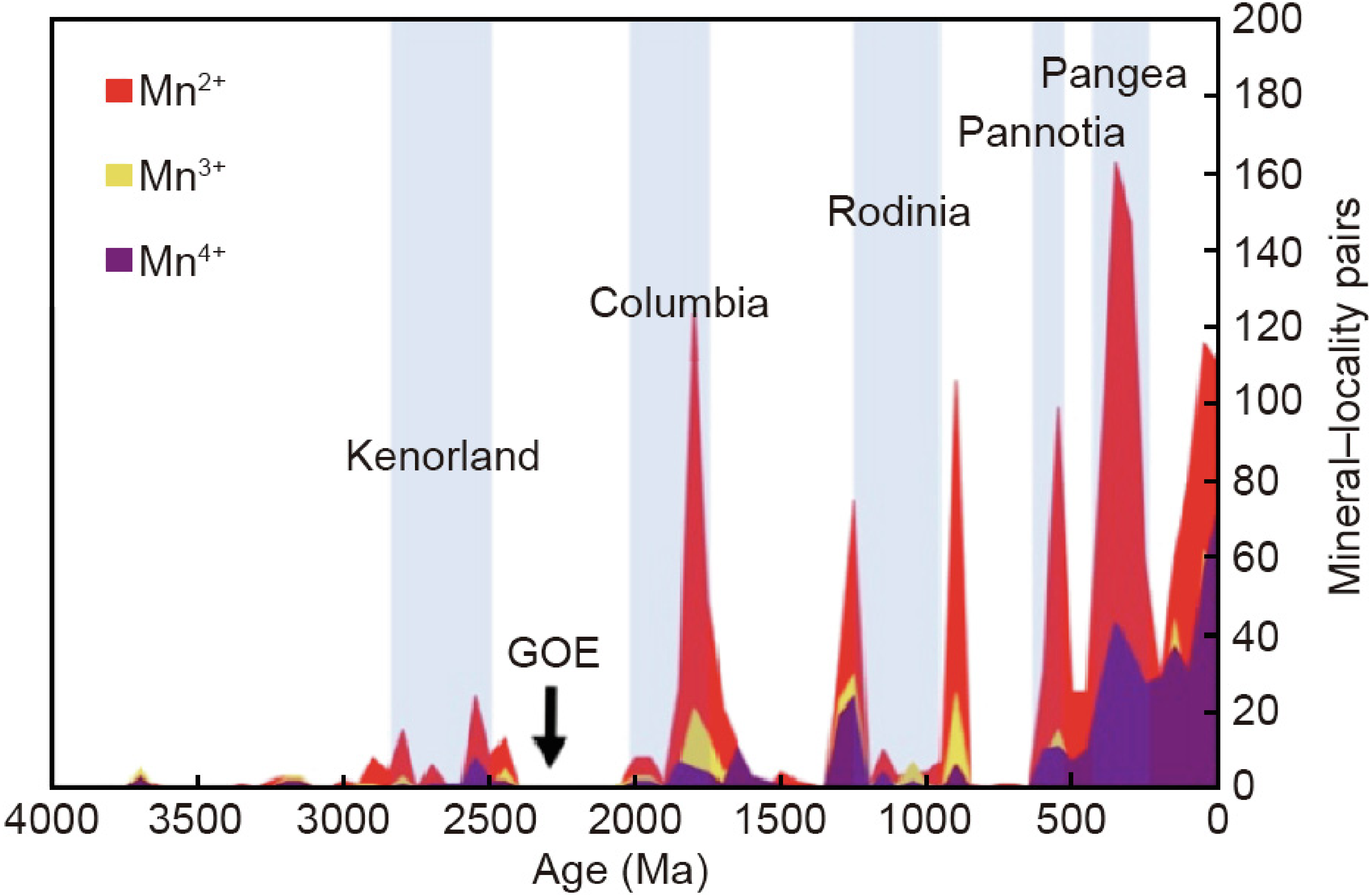
- **Mineral inventory of the solar system has gone from about a dozen minerals in the forming solar nebula to over 5400 currently identified on Earth (as of November).**
- **Three processes drive mineral evolution**
  - **The progressive separation and concentration of chemical elements from their original uniform distribution.**
  - **Greater ranges of temperature and pressure coupled with the action of volatiles.**
  - **The generation of far-from-equilibrium conditions by living systems.**
- **A few examples of mineral radiation over Earth history……**

Diversity of Carbon Minerals

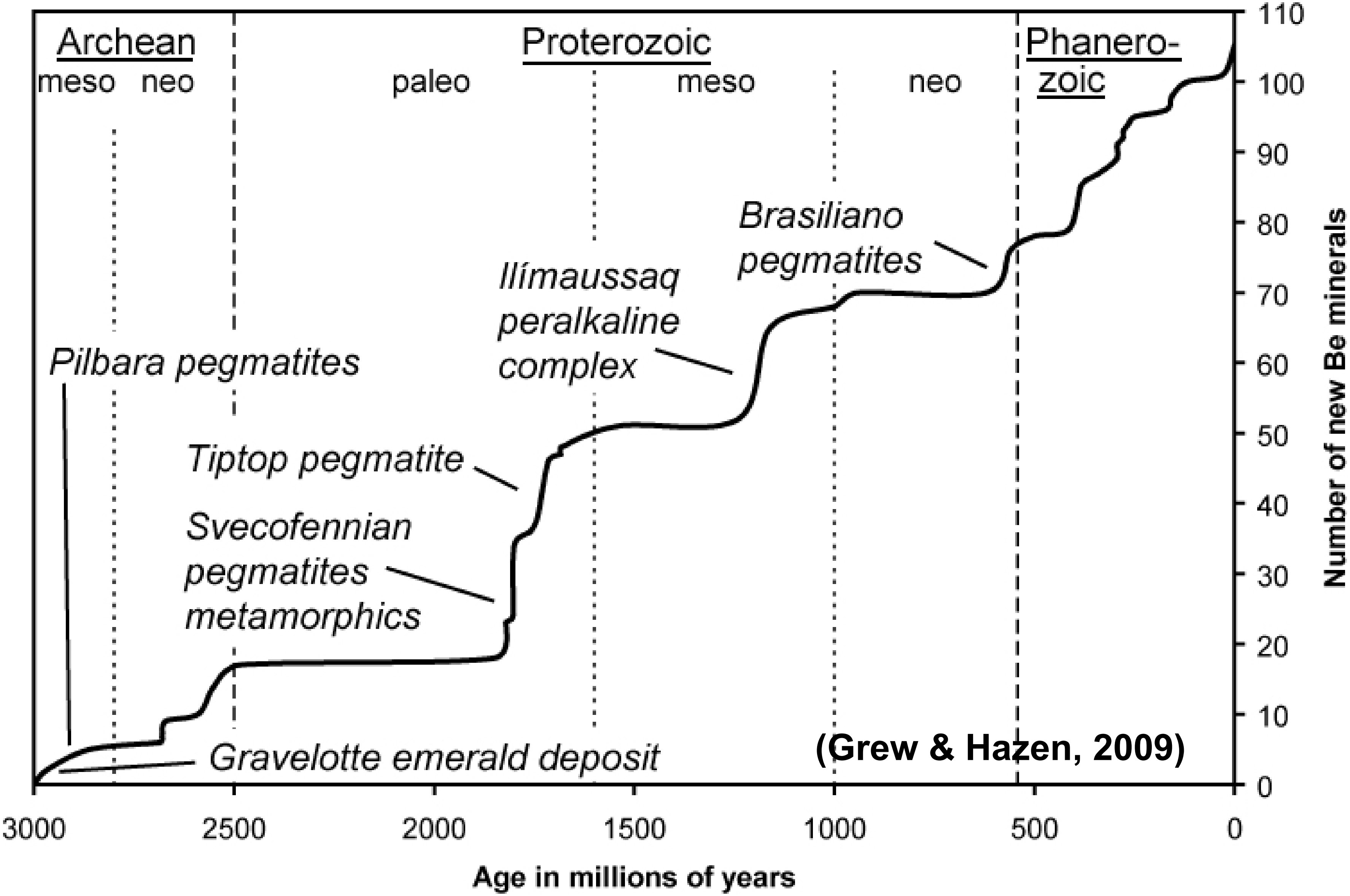


Credit: Deep Carbon Observatory/Josh Wood

The evolution of manganese minerals over time. Closely associated with the supercontinent cycle and the Earth's near-surface oxidation state. (Hazen et al., 2019)



No Beryllium Minerals Known Before ~3.0 Gys.



Stages of Mineral Evolution

Era/Stage	Age (Ga)	Cumulative no. of species
Prenebular "Ur-Minerals"	>4.6	12
Era of Planetary Accretion (>4.55 Ga)		
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetesimal alteration	>4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)		
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
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)		
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	4400+

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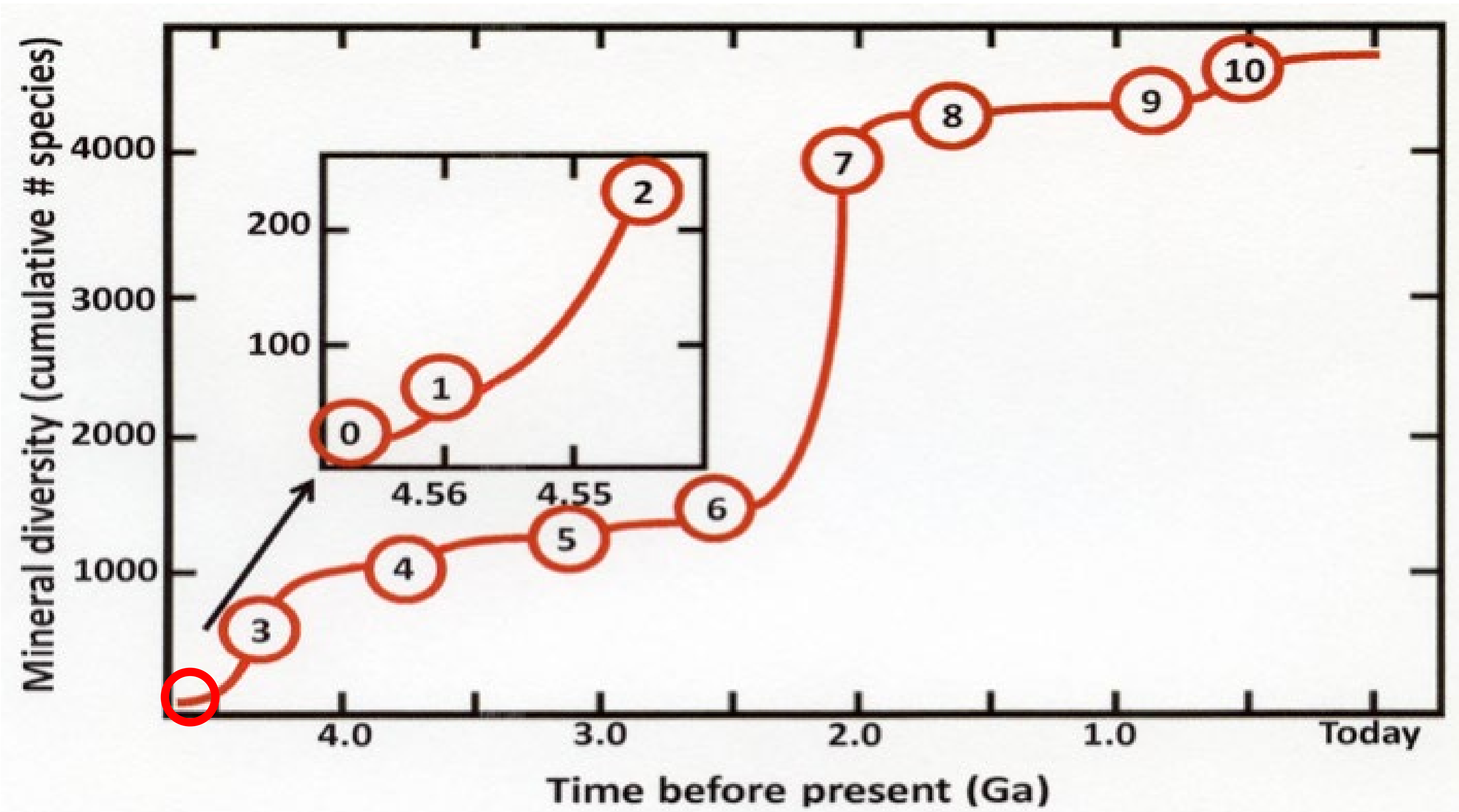
Planetary

Asteroid Line

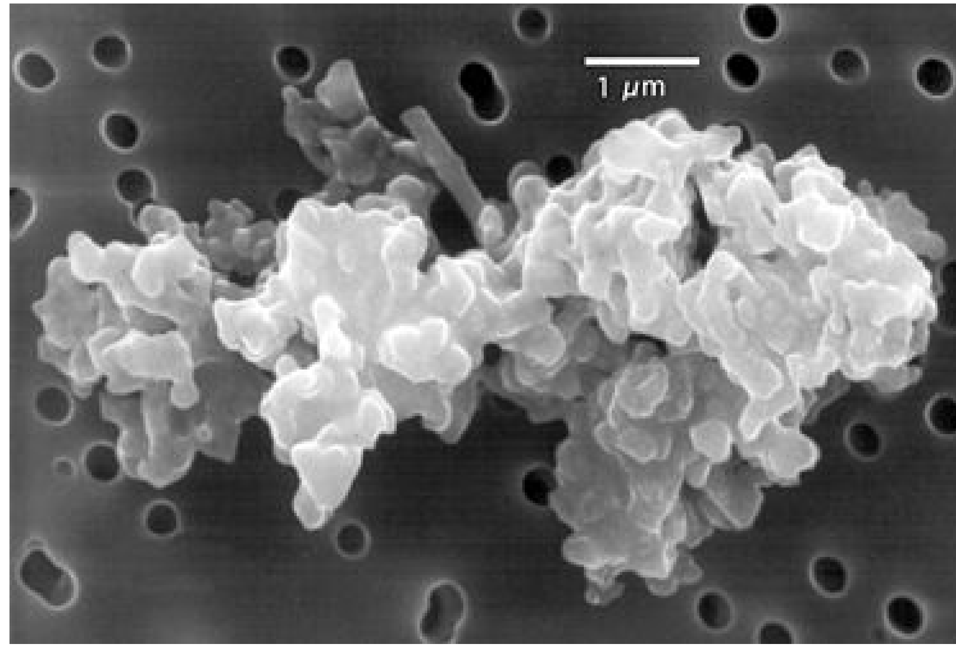
Lunar Line

Terrestrial


Mineral diversity (cumulative # species)
4000
3000
2000
1000
Time before present (Ga)
4.0
3.0
2.0
1.0
Today
200
100
4.56
4.55
0
1
2
3
4
5
6
7
8
9
10

Stage 0: Presolar Grains

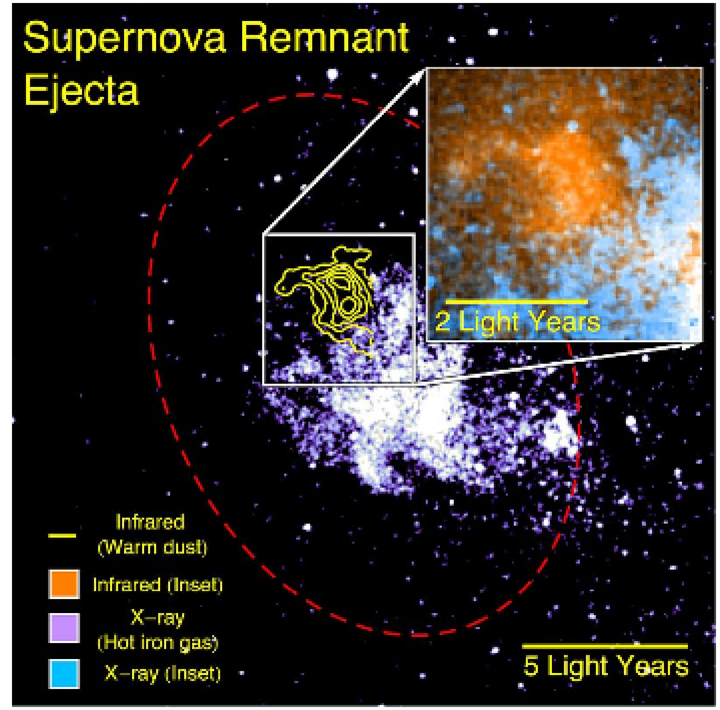
- **Presolar stardust grains comprise about 0.1 percent of the total mass of meteorites.**
- **nitrides**
  - Osbornite (TiN)
  - Nierite (α-Si_3N_4);
- **carbides**
  - Cohenite [(Fe,Ni,Co)3C]
  - Moissanite (SiC)
  - Titanium carbide (TiC)
  - Diamond, graphite (C)
- **Iron alloys**
  - Kamacite (Fe,Ni)
- **oxides**
  - Rutile (TiO_2)
  - Corundum (Al_2O_3)
  - Cpinel ($MgAl_2O_4$)
  - Hibonite ($CaAl_{12}O_{19}$)
- **Silicates**
  - Forsterite (Mg_2SiO_4)
  - Perovskite-structured $MgSiO_3$

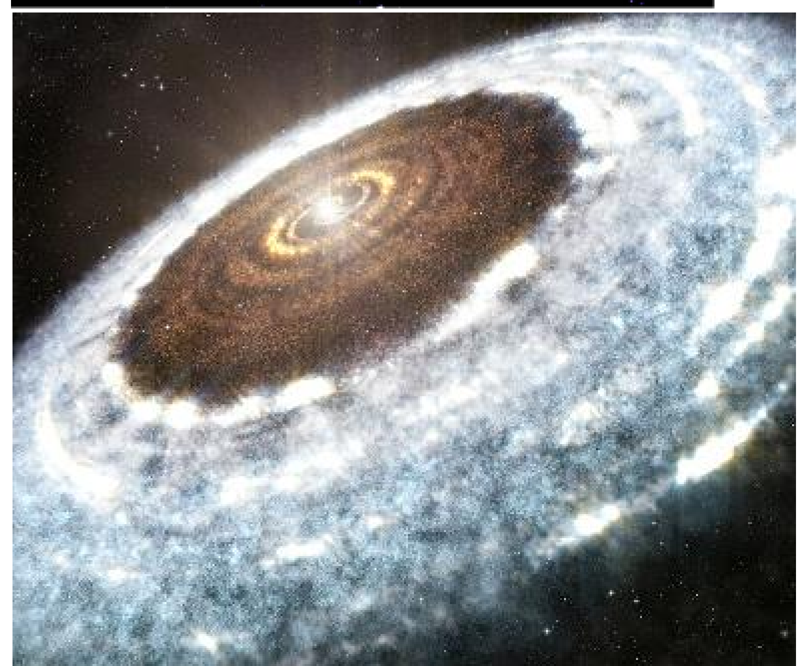


- **There are probably more minerals to be found.**
- **Much of the presolar material observed in IDPs and primitive chondrites is amorphous, nonstoichiometric, or partially crystalline.**
- **Suggests that a much more robust selection of minerals was accreted to form the early solar system.**

Solar System Formation

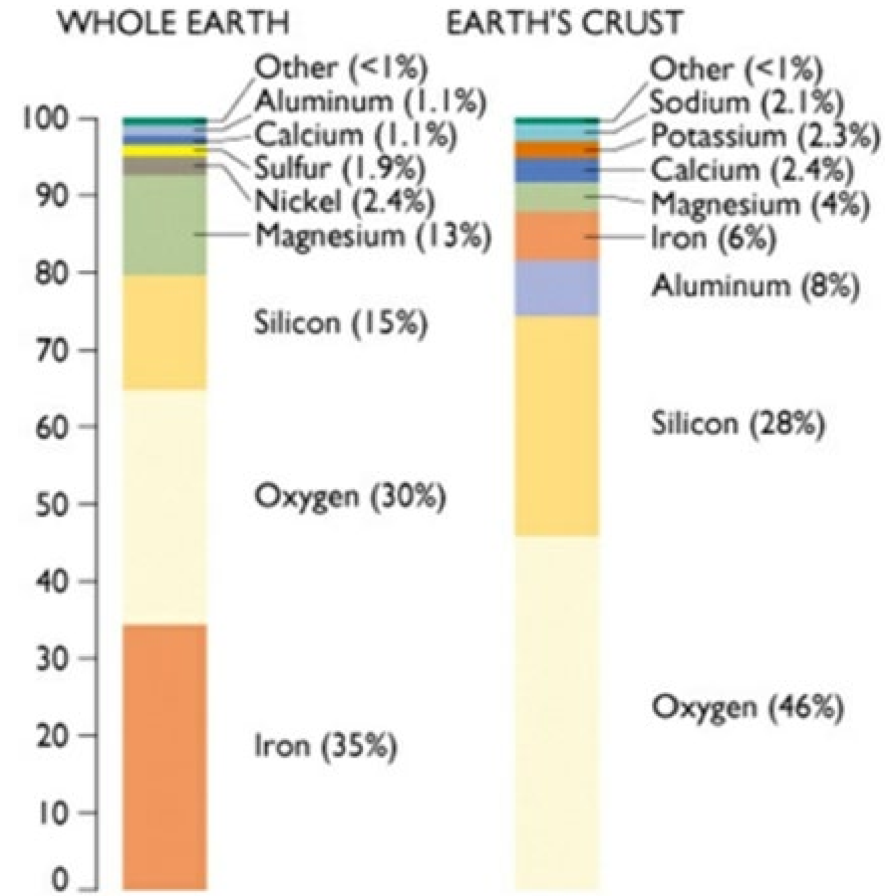
- Solar nebula collapses under self-gravity.
- The collapse heats the nebular material….amount depends on location.
- The protoplanetary nebula is seeded by nearly supernova with materials rich in short-lived radioisotopes.
  - Al_{26}
  - Fe_{60}

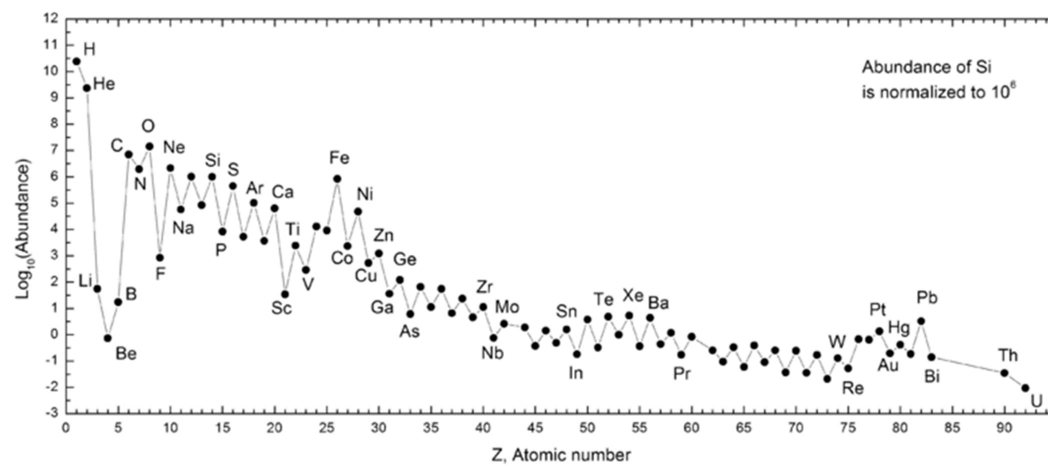




Elemental Abundances

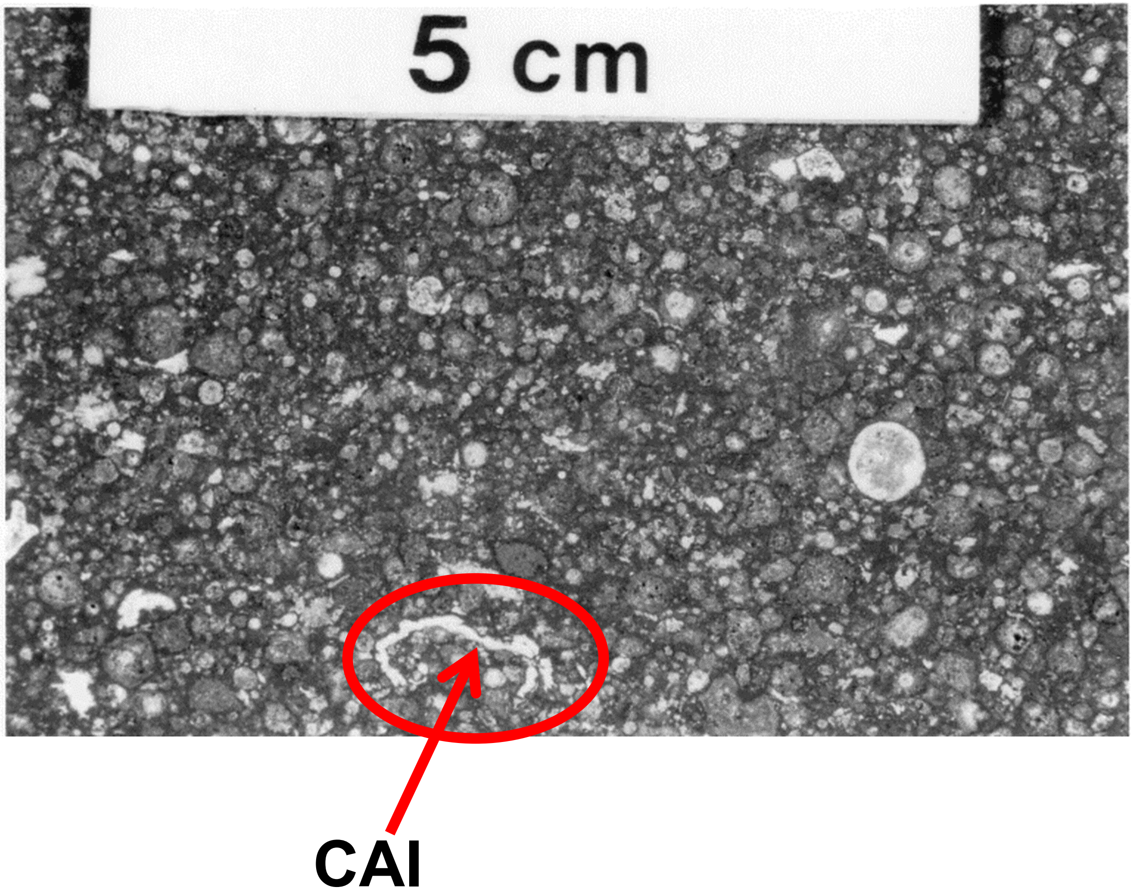
- What you can build from the nebula depends on what is available.
- What drives initial abundances is the saw-tooth pattern of Nucleosynthesis





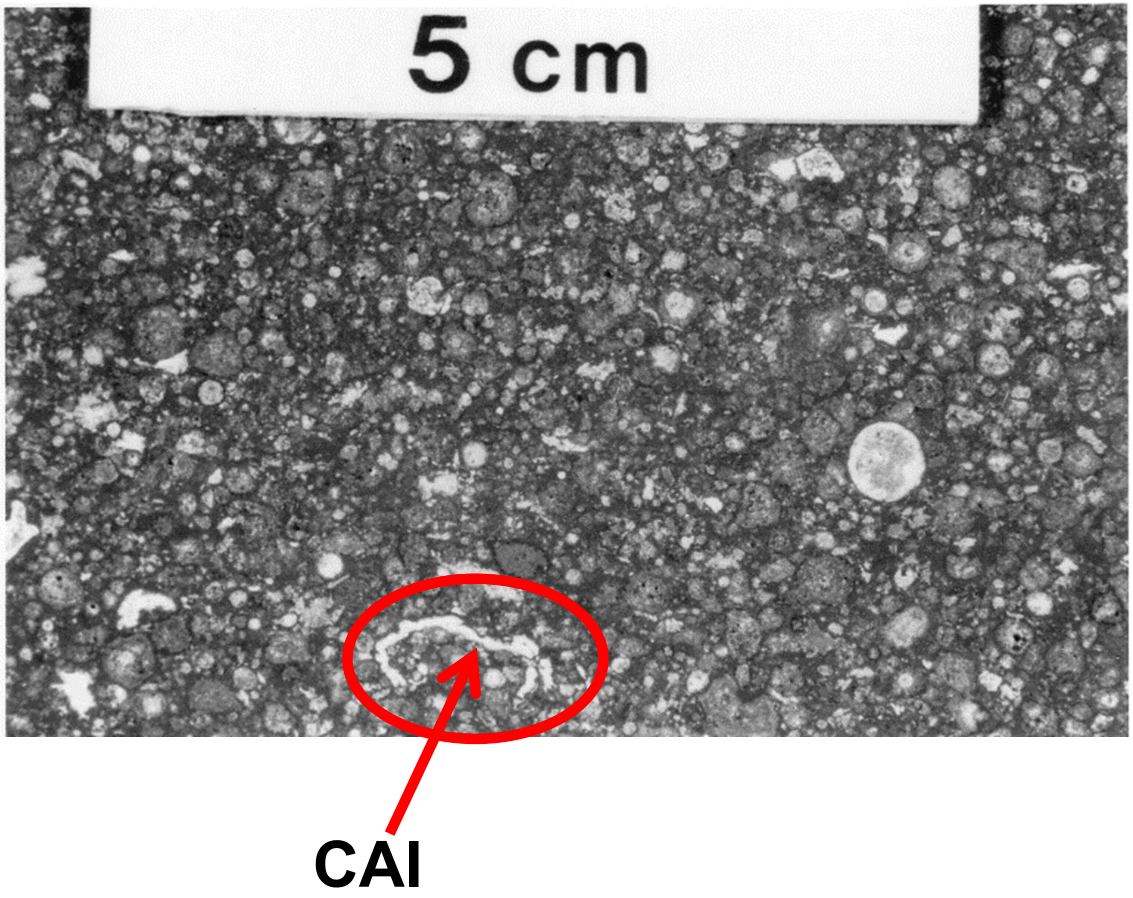
Stage 1:
Accretion and the Formation of Chondritic Minerals

- **Minerals condense out of the cooling solar nebula, with high-temperature minerals condensing first.**
- **These were the calcium–aluminum inclusions (CAIs) and include ~24 mineral phases:**
  - Spinel ($MgAl_2O_4$–$FeAl_2O_4$),
  - Melilite ($Ca_2Al_2SiO_7$) to ($Ca_2MgSi_2O_7$)
  - Perovskite ($CaTiO_3$)
  - Hibonite ($(Ca,Ce)(Al,Ti,Mg)_{12}O_{19}$)
  - Calcic pyroxene ($CaMgSi_2O_6$)
  - Anorthite ($CaAl_2Si_2O_8$)
  - Forsterite (Mg_2SiO_4)
- **How do we know? ~70,000 recovered meteorites.**



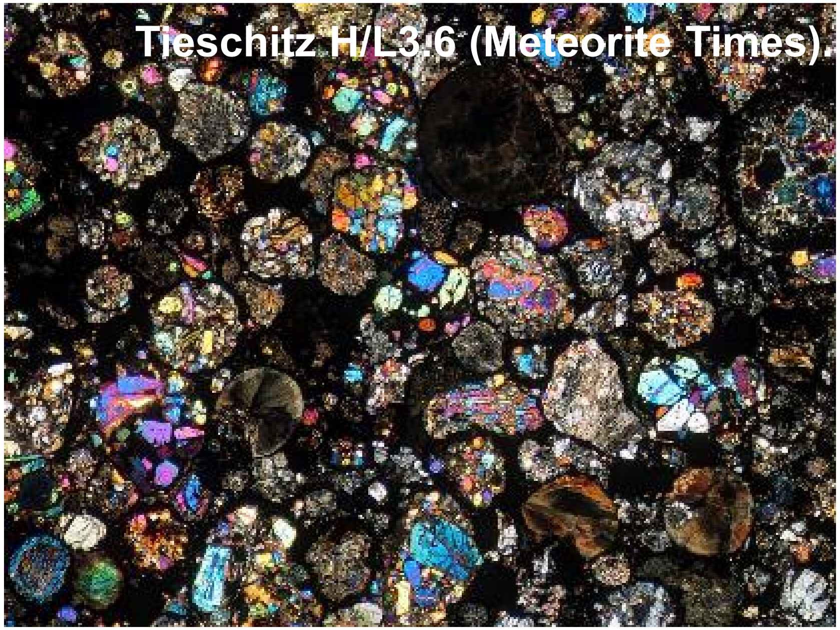
Stage 1:
Cooling and Condensation Continue

- The cooling nebula condenses progressively lower-temperature minerals.
- Chondrules dominate this stage.
- Chondrules are the sedimentary "sand" of the solar system….which make up the chondrite meteorites.
  - Millimeter sized spheres formed during flash melting in the solar nebula.
- Chondrites contain a diversity of metals, sulfides, oxides, and phosphates.



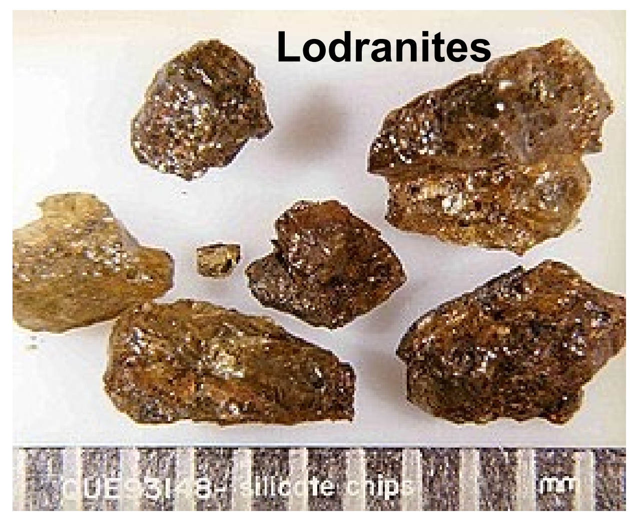
Stage 1: Primary Chondritic Minerals

- The mineral assemblage at this stage is ~60 minerals
- Formed under chemically diverse environments, particularly oxygen fugacity which ranges from highly reduced enstatite chondrites to the oxidized carbonaceous chondrites.
- Dominant minerals include:
  - Olivine
  - Pyroxene
  - Plagioclase
  - FeNi
  - Troilite
- Metamorphism, aqueous alteration, and shock will alter, modify, and diversify the chondrites.



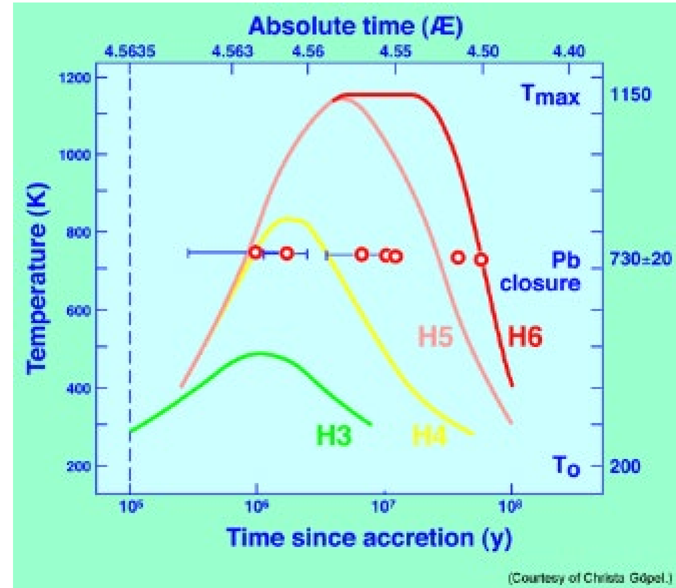
Stage 2
Achondrite and Planetesimal Alteration

- **Chondrules accrete into planetesimals, planetesimals accrete into planets over about 10 million years.**
- **The timing planetesimal growth depends on location and the local density of materials.**
- **Heating becomes a critical factor.**
- **Heat sources:**
  - **Gravitational potential energy from accretion**
  - **Radioactive isotopes**
  - **Core formation**
- **Remember that the nebula was seeded with material from a nearby supernova.**
  - **Included in the seeding was very short-lived nuclides including ^{26}Al (717,000 years) and ^{60}Fe (2.6 million years)**
  - **Because of the abundance and short half-life of ^{26}Al, its heat generation potential is about 1,000,000 times that of Uranium.**



Stage 2
Timing and Size are Key to Outcomes

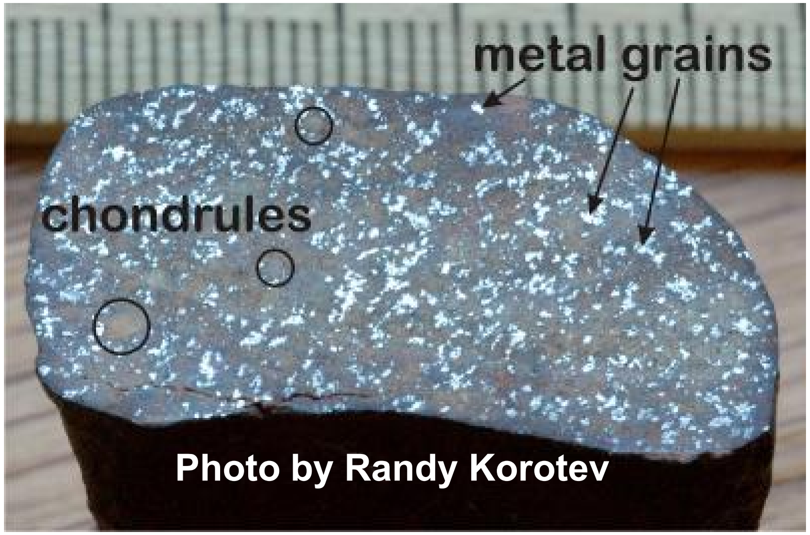
- **Planetesimals that accrete early (with lots of ^{26}Al) heat to melting and differentiate, producing igneous melts.**
- **With the short half-life of ^{26}Al it does not take much time before the isotope is depleted and the heating will only metamorphize the planetesimal.**
- **Dr. Steve Desch will talk about planetesimal accretion and timing in detail.**
- **Planetesimals that accrete outside the “frost line” will include frozen volatiles as well as minerals. Heating of this assemblage will produce aqueous alteration.**
- **Planetesimals that accrete outside the frost line and later do not heat much, producing comets that retain unaltered refractory minerals and ices.**



St Michel (L6)

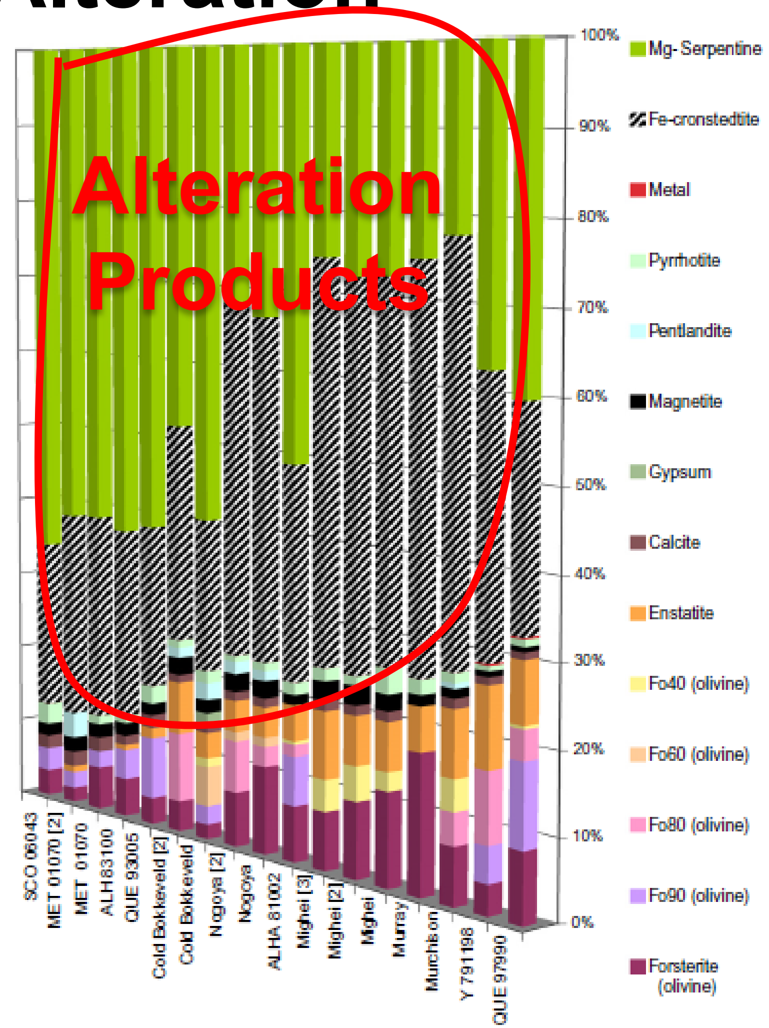
Stage 2: Metamorphism

- **Heating of anhydrous ordinary and enstatite chondrites produced new minerals from thermal metamorphism at temperatures up to ~950°C**
- **Phosphates**
  - **Apatite $Ca_5(PO_4)_3(F,Cl,OH)$**
  - **Merrillite $Ca_9NaMg(PO_4)_7$**
- **Silicates**
  - **Nepheline $(Na,K)AlSiO_4$**
- **Oxides**
  - **Rutile TiO_2**
  - **Quartz SiO_2 and its high-temperature polymorphs Cristobalite and Tridymite**



Stage 2: Aqueous Alteration

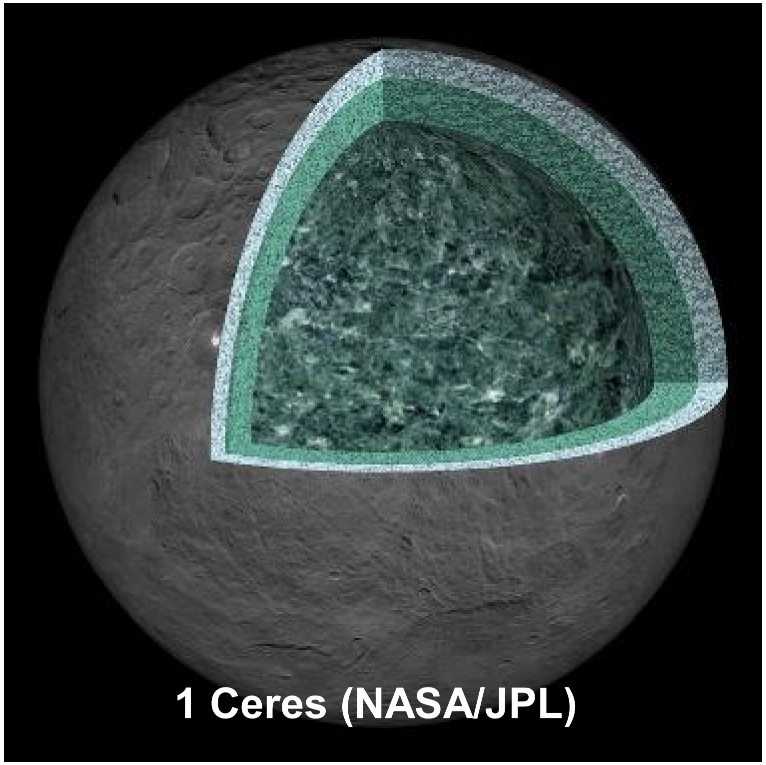
- The melting of ice and the subsequent alteration of chondrule silicates at low temperatures (<100°C) produced a range of new minerals
- Phyllosilicates
  - Montmorillonite $(Na,Ca_{0.5})_{0.33}(Al,Mg)_2Si_4O_{10}(OH)_2 \cdot nH_2O$
  - Chrysotile $Mg_3Si_2O_5(OH)_4$
  - Cronstedtite $(Fe_2{}^{2+},Fe^{3+})_3(Si,Fe^{3+})_2O_5(OH)_4$
- Oxides
  - Magnetite $Fe^{2+}Fe^{3+}{}_2O_4$
  - Ferrihydrite $5Fe_2O_3 \cdot 9H_2O$
- Sulfides
  - Pyrrhotite $Fe_{1-x}S$ (x = 0 to 0.2)
  - Pentlandite $(Fe,Ni)_9S_8$
- Carbonates
  - Dolomite $CaMg(CO_3)_2$
  - Calcite $CaCO_3$
- Sulfates
  - Gypsum $CaSO_4 \cdot 2H_2O$
  - Epsomite MgSO4·7H2O

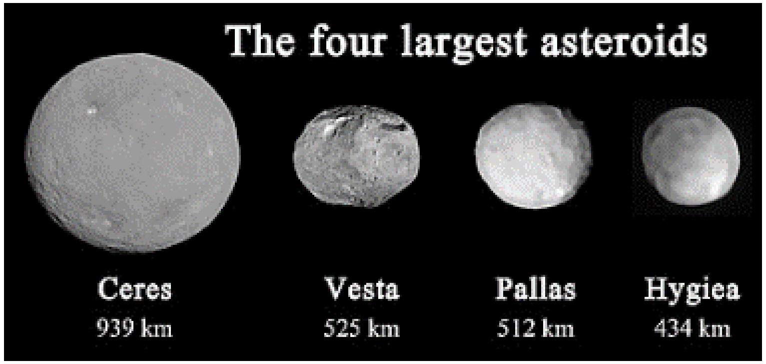


From Howard et al, 2011

Stage 2: Aqueous Alteration

- On small near-Earth asteroids the only surviving volatiles are in the mineral alteration products (hydrated phyllosilicates, sulfates, carbonates, oxides).
- Aqueous processes on most asteroids are short-lived and open system. Water not incorporated into minerals either migrated to the surface and sublimated or was retained as ice in the subsurface.
- The largest main-belt volatile-rich asteroids may have a mantle of hydrated rocks with a crust of ice, salts, and hydrated minerals. Salt-rich brines may be occasionally active. Ceres for example, the mantle is estimated to be 23-28 wt.% water.

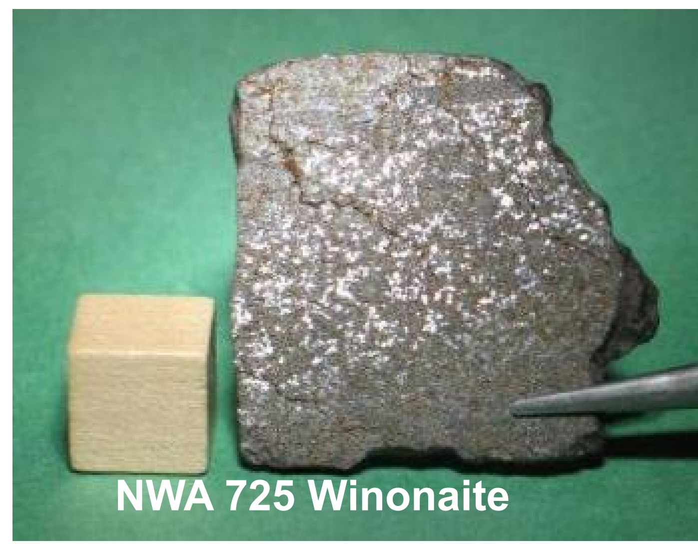




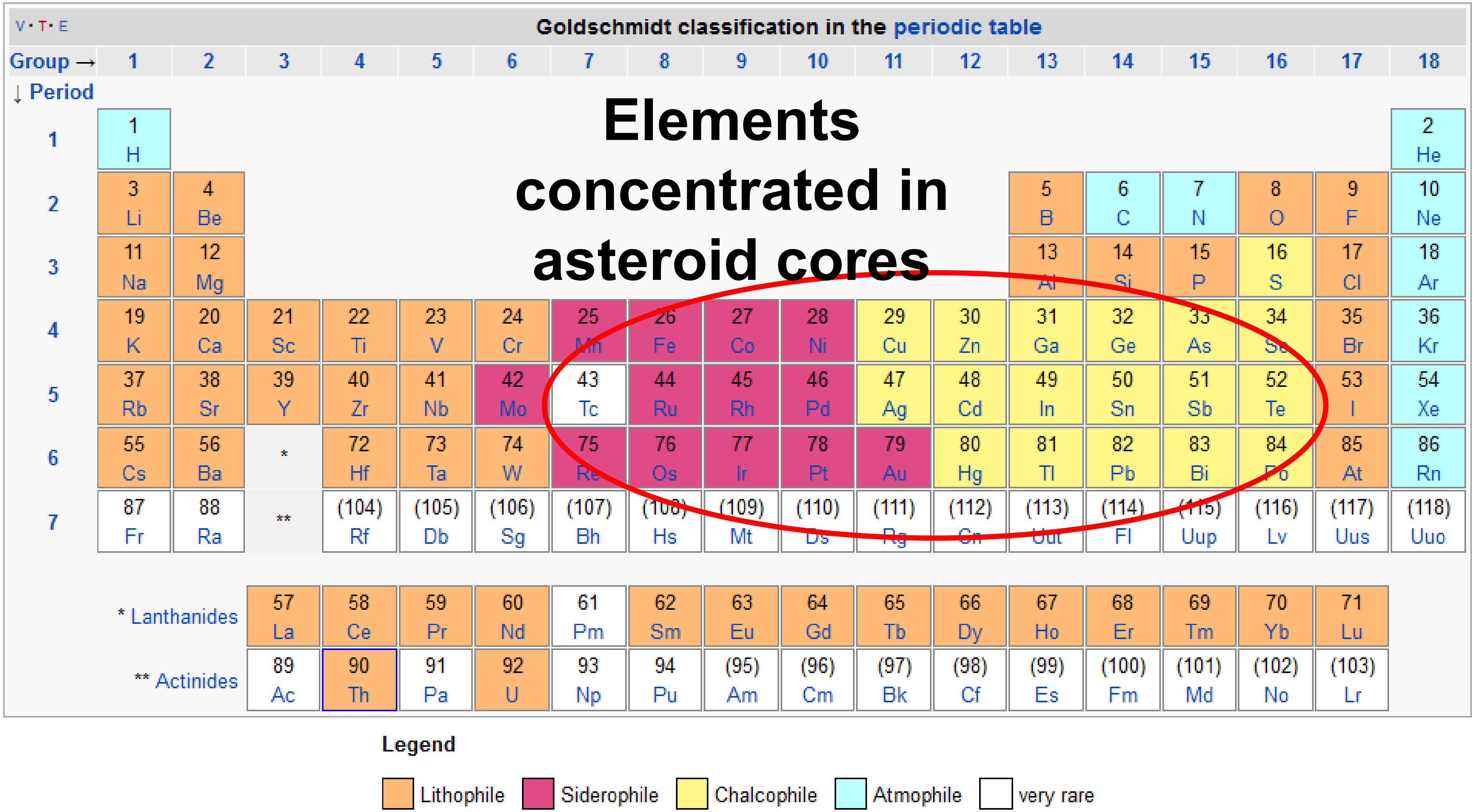
Stage 2: Igneous Alteration

- **In some planetesimals heating continued above ~950°C crossing the liquidus for early partial melts from FeNi metal and troilite.**
- **The early melts migrated through the unmelted silicates and form meteorites like acapulcoites, winonaites, and IAB irons.**
- **As the temperatures increased, silicate melting formed pyroxene–plagioclase-rich melts.**
  - **Residual rocks remaining after silicate melting are represented by meteorite groups like the ureilites and lodranites.**
- **The partial melts sequestered a range of incompatible elements, including phosphorus, sulfur, and carbon which reacted with unmelted silicates to form new minerals.**
  - **Phosphates: Na–Ca–Mg phosphates chladniite, panethite, brianite, and johnsomervilleite**
  - **Carbides: cohenite and haxonite $(Fe,Ni)_{23}C_6$.**

NWA 2989 Acapulcoite



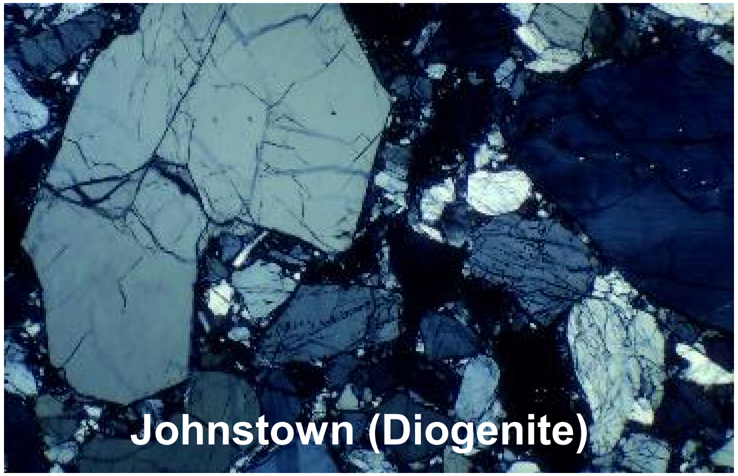
NWA 725 Winonaite

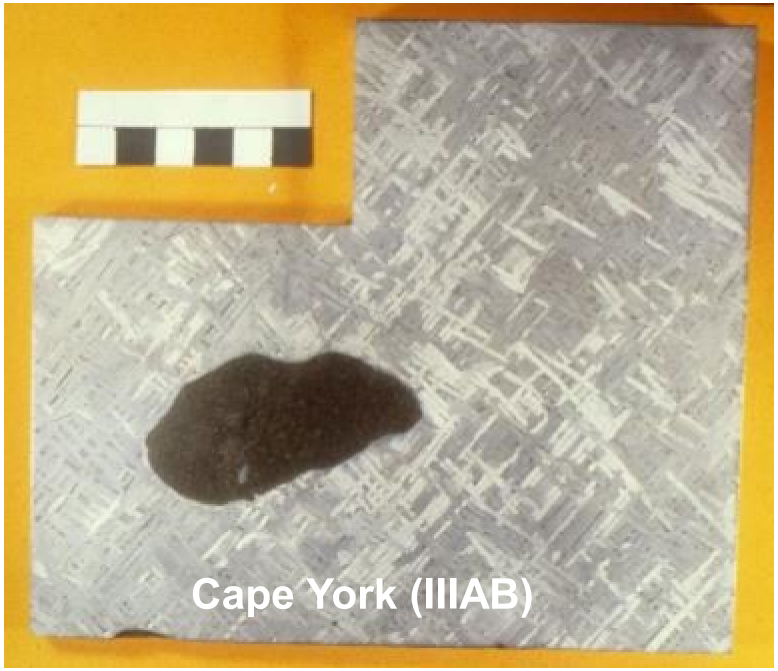


- **<u>Lithophile</u> (rock loving) elements remain on or close to the surface because they combine readily with oxygen, forming compounds that do not sink into the core.**
- **<u>Siderophile</u> (iron loving) elements are the high-density transition metals which tend to sink into the core because they dissolve readily in iron.**
- **<u>Chalcophile</u> (ore loving) elements that combine readily with sulfur and/or some other chalcogen other than oxygen.**
- **<u>Atmophile</u> (atmosphere loving) elements are either gases or form volatile hydrides.**

Stage 2: Igneous Alteration

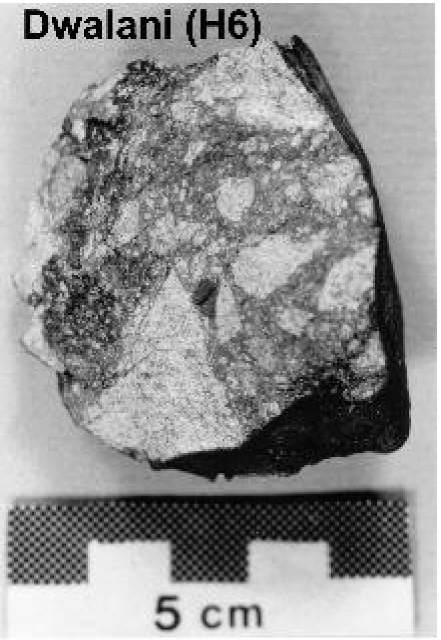
- **At high degrees of melting differentiation sequestered siderophile from lithophile elements that crystallized separately to form the crust, mantle, and core of the planetesimal.**
- **Within the crust more incompatible elements were concentrated.**
  - **Feldspar ($KAlSi_3O_8$), titanite ($CaTiSiO_5$), zircon ($ZrSiO_4$), and baddeleyite (ZrO_2) formed.**
- **In the core, mineralogical diversity was controlled both by fractional crystallization and solid-state transformations during cooling.**





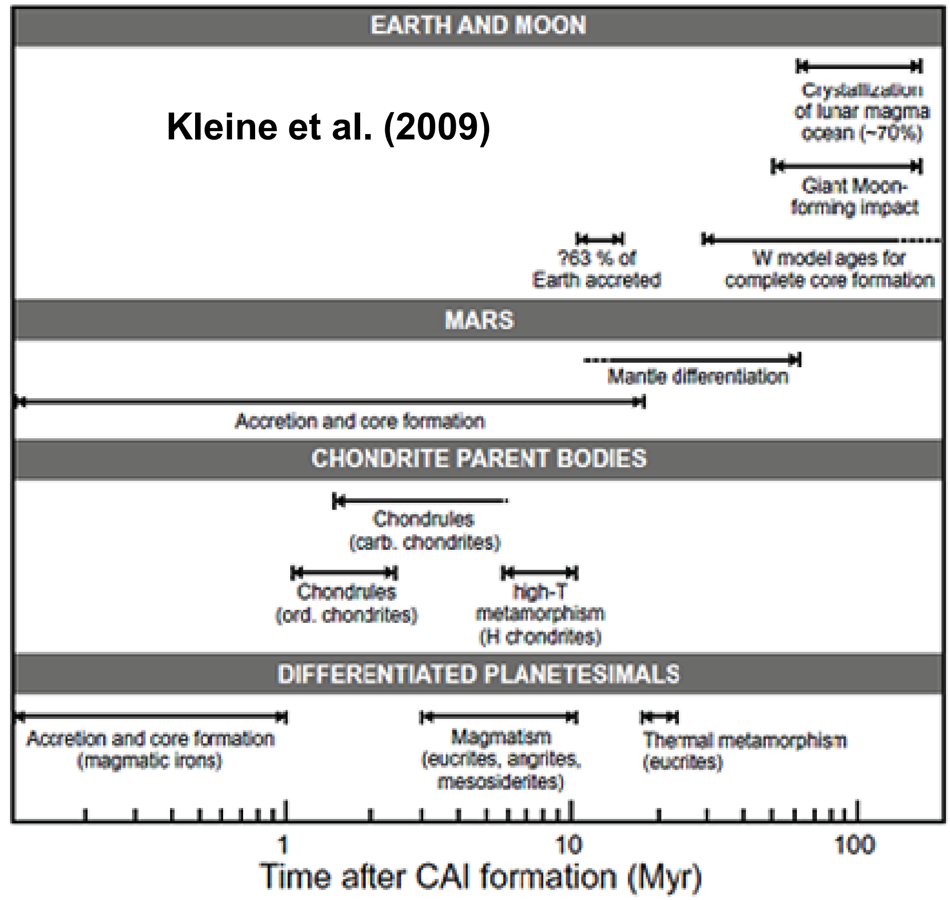
Impacts and Mineral Evolution

- **Formation of shock minerals.**
  - High-pressure minerals in meteorites are often polymorphs of lower pressure common minerals
  - Olivine → ringwoodite
  - Chondrite melt → majorite garnet
  - Magnesiowüstite
  - Enstatite → akimotoite
  - Plagioclase feldspar → maskelynite
- **For asteroids impact fracture and rubblize the bodies. Asteroids in near-Earth space are collisional fragments and probably rubble piles.**
- **On larger bodies, excavation of deep igneous and metamorphic terrains can initiate hydrothermal activity.**
- **Creation of deep subsurface hydrothermal zones (if there is water…..i.e. Mars).**



The End of Asteroid Mineral Evolution

- **In asteroids heat drives mineral evolution.**
- **But heat from accretion, core formation, and strong radioactive sources was exhausted early in solar system history.**
- **Metamorphism lasted longest on large asteroids, but ended within 20-30 Myr.**
- **After this period, the only mineralization action was impact-related.**
- **Between original mineralogy, aqueous, metamorphic, impact, and igneous evolution meteorites have about 250 minerals.**

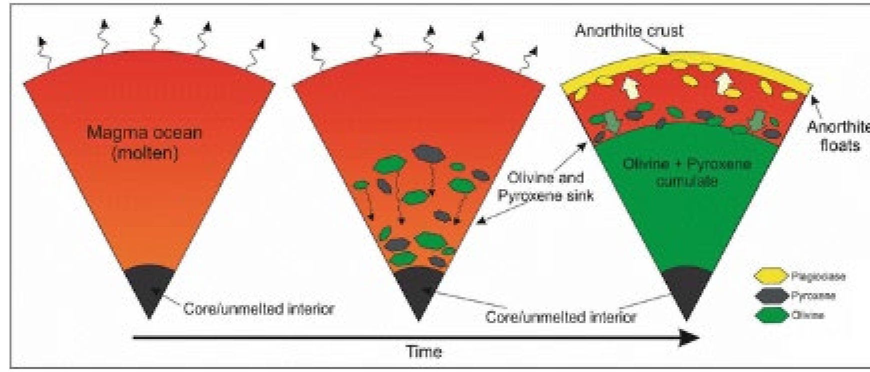


Stage 3: The Moon

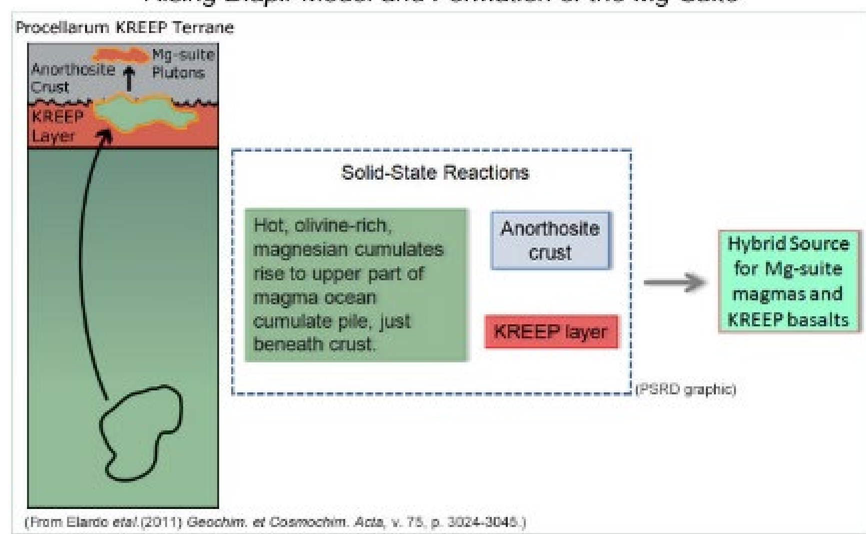
- The moon was the product of a giant impact that ripped off the crust and some of mantle of the early Earth.
- The giant impact was between two already differentiated planets.
- It was crust and mantle material that largely formed the Moon.
- That means the starting material was already depleted in siderophile elements.
- Volatiles would have been vaporized by the high impact temperatures.
- Accretional energy liberated during reaccretion would generate a magma ocean.

Stage 3: The Moon

- **Hot accretion meant that most of the Moon was initially molten.**
- **The magma ocean slowly cooled and differentiated. Tidal dissipation provided the energy to slow cooling.**
- **The ocean differentiated with denser olivine and pyroxene dropping to the bottom and less dense anorthite floating.**
- **Like igneous asteroids, high degrees of crystallization concentrated incompatible elements in the crust.**
  - **The KREEP (K for potassium, REE for rare-earth elements and P for phosphorus) source region in Procellarum was formed.**
- **Also like igneous asteroids mineralogical diversity comes from both by fractional crystallization and solid-state transformations during cooling.**

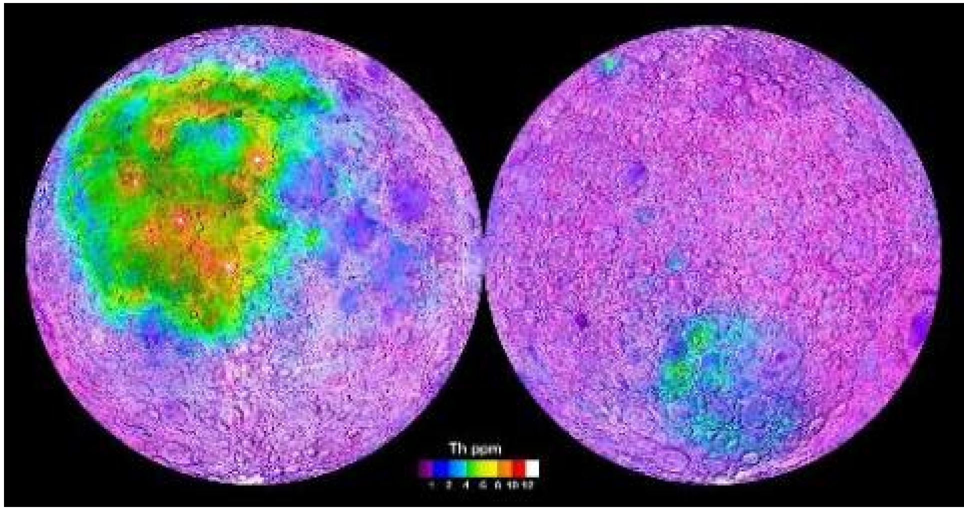


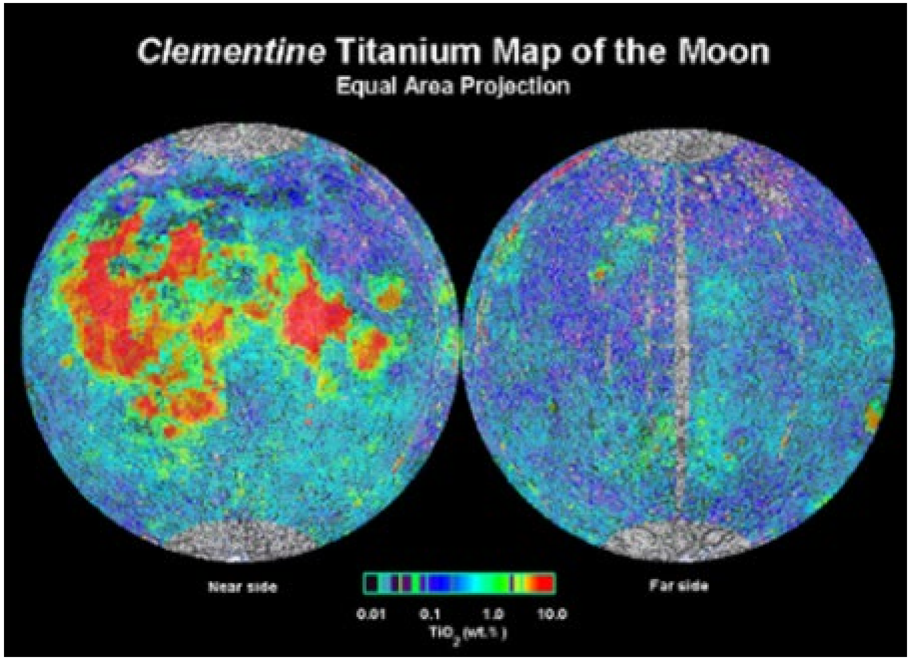
Rising Diapir Model and Formation of the Mg-Suite



Stage 3: The Moon

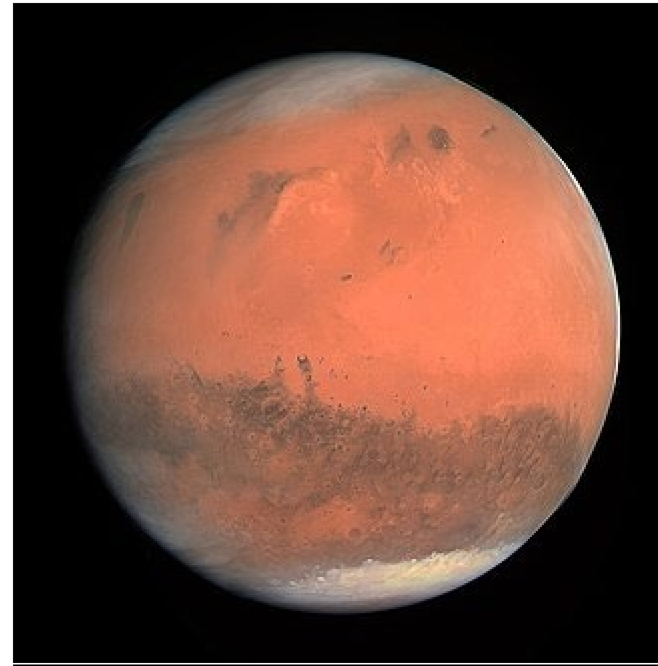
- The KREEP terrain is concentrated in Procellarum and Imbrium.
- A large proportion of the Moon's inventory of heat producing elements was incorporated into the KREEP.
- Mare volcanism between 4.2-3.16 Ga produced the Mare terrains seen on the Lunar near side.
- These basalts tapped the KREEP as part of their source region and material.
- A major difference between terrestrial and Lunar basalts is the near-total absence of water in the lunar basalts. As a result they erupt much hotter and more fluid than terrestrial basalts.

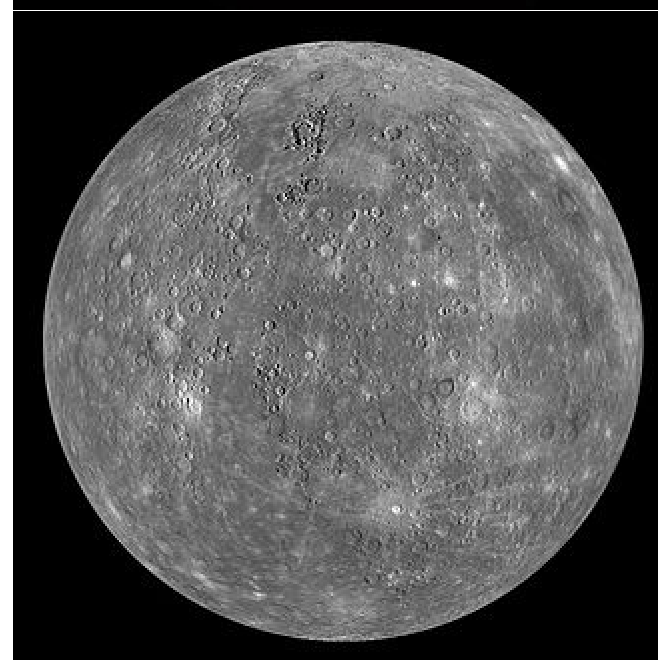




Stage 3: Planets

- All rocky planets and moons experience Stage 3 mineral forming igneous processes
- Even on a volatile-poor body like Mercury or the Moon, such processes yield as many as 350 different mineral species.
- If water and other volatiles are abundant, then the mineralogical diversity is enhanced by the development of hydroxides, hydrates, carbonates, and evaporite minerals—a total of approximately 500 mineral species.
- A once-wet Mars appears to have progressed this far in its mineral evolution.





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Prenebular "Ur-Minerals"	>4.6	12
Era of Planetary Accretion (>4.55 Ga)		
1. Primary chondrite minerals	>4.56 Ga	60
2. Achondrite and planetes-imal alteration	>4.56 to 4.55 Ga	250
Era of Crust and Mantle Reworking (4.55 to 2.5 Ga)		
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
Era of Biologically Mediated Mineralogy (>2.5 Ga to Present)		
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	4400+

Asteroid Line

Lunar Line

Terrestrial

Mineral Evolution: Stage 4 and 5
(All we do not see in Lunar and asteroid geology)

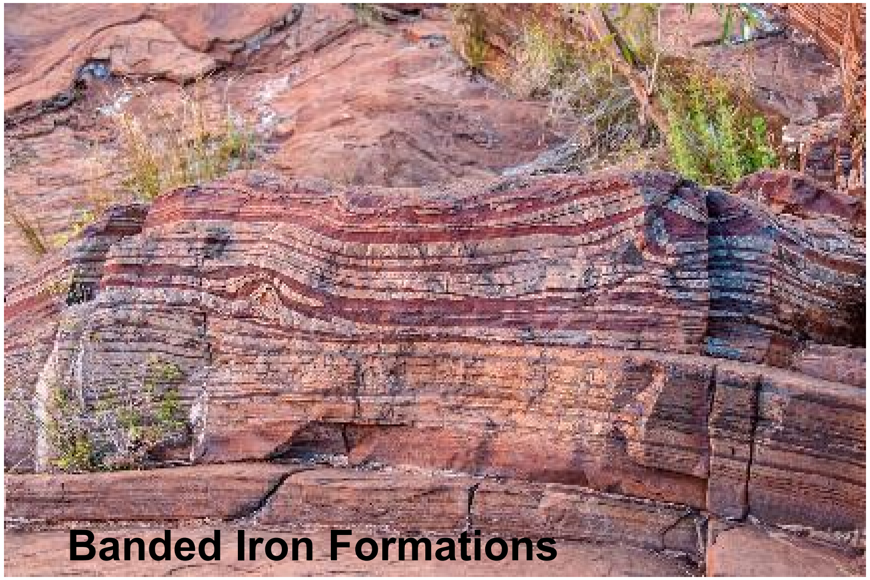
- **Stage 4: A planet has enough heat to remelt its initial basaltic crust**
  - **Forms granitoids from fractionation of the basalt.**
  - **<u>Repeated partial melting</u> and concentration of rare elements form pegmatites**
  - **Approximately 500 distinctive minerals of Li, Be,B, Nb, Ta, U, and a dozen other rare elements**
- **Stage 5: Onset of plate tectonics**
  - **Subduction of H_2O-rich crustal materials led to <u>fluid–rock interactions</u> and rare element concentration.**
  - **Uplift and erosion exposed new high-pressure, low-temperature minerals formed in subduction zones.**
  - **500 more minerals.**

Mineral Evolution: Stage 6 and 7

(All we do not see in Lunar and asteroid geology)

- **Stage 6: The anoxic biosphere interacts with the lithosphere**
  - Primitive microbes in the anoxic Archean Earth played a relatively minor role in mineralogy.
  - The 1500 mineral species would probably occur in any volatile-rich anoxic terrestrial planet.
- **Stage 7: Great Oxidation Event**
  - The rise of atmospheric oxygen paved the way for more than 2,500 new minerals.
  - Many were hydrated, oxidized weathering products of other minerals.
  - The planet rusted. Black basalt that turned red as the ferrous iron (Fe^{2+}) oxidized to hematite.

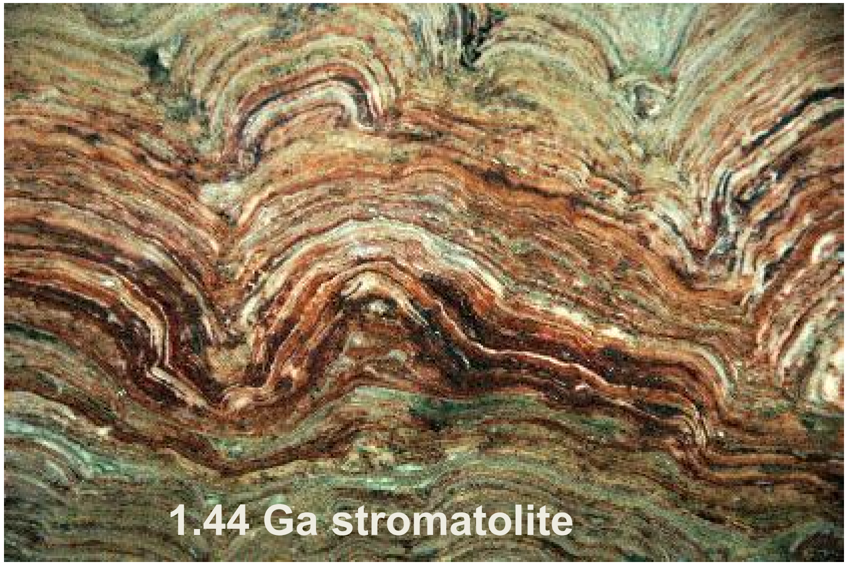
Turquoise $CuAl_6(PO_4)_4(OH)_8 \cdot 4H_2O$



Banded Iron Formations

Mineral Evolution: Stage 8 and 9
(All we do not see in Lunar and asteroid geology)

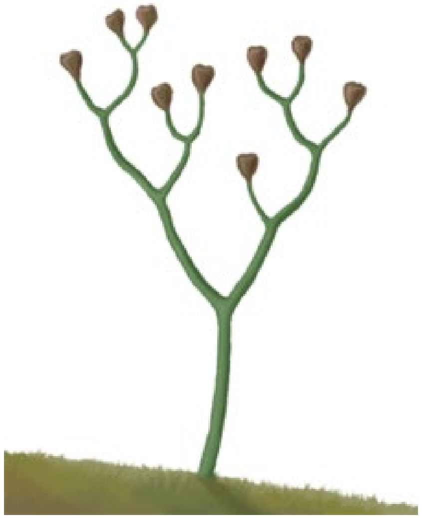
- **Stage 8: The intermediate ocean**
  - The "boring billion".
  - BIF ceased because the ocean chemistry reached an intermediate oxidation state.
  - Minimal mineralogical innovation.
- **Stage 9: Snowball Earth**
  - Fluctuations in climate and atmospheric chemistry produced at least two snowball Earth events.
  - During glaciation surface weathering slowed down allowing for volcanic CO_2 buildup and then rapid greenhouse deglaciation.
  - Glaciation enhanced weathering of sulfides and the production of clays.



1.44 Ga stromatolite

Mineral Evolution: Stage 10

- Creation of minerals by living organisms becomes widespread
- The buildup of atmospheric oxygen allowed the development of the stratospheric ozone layer, which shielding the surface from solar UV and allowed the start of a terrestrial biosphere.
- Allowed for rapid biochemical breakdown of rock.
- Increasing weathering rates of basalt, granite and limestone by an order of magnitude.
- The abundance of clay minerals and the rate of formation of soils increased vastly.



Cooksonia, the earliest vascular plant

To Wrap Up

- Mineral evolution are fundamentally different on the Moon and Asteroids vs. the Earth.
- Asteroids have about 250 minerals.
- The Moon has about 350 minerals.
- Geological concentration mechanisms that we depend on terrestrially for ores do not exist on the Moon and asteroids.
- On asteroids no high heat flow, no available fluids, no hydrothermal systems for the last ~4.5 billion years.
- On the Moon, no fluids or hydrothermal systems. What you get is Mare volcanism tapping KREEP source regions.
- Impacts and shock are the major drivers for most of solar system history.