Asteroid Minerology

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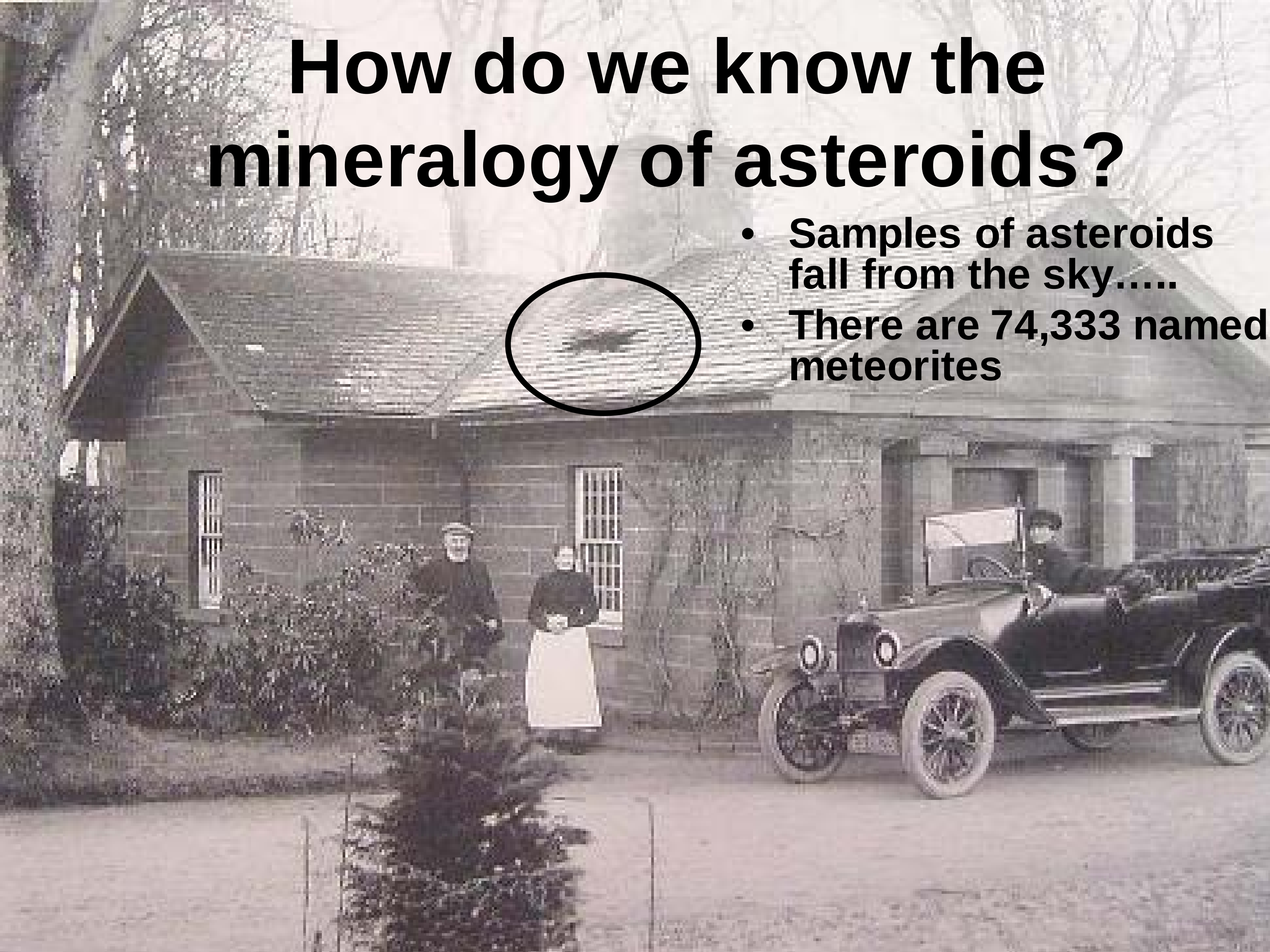
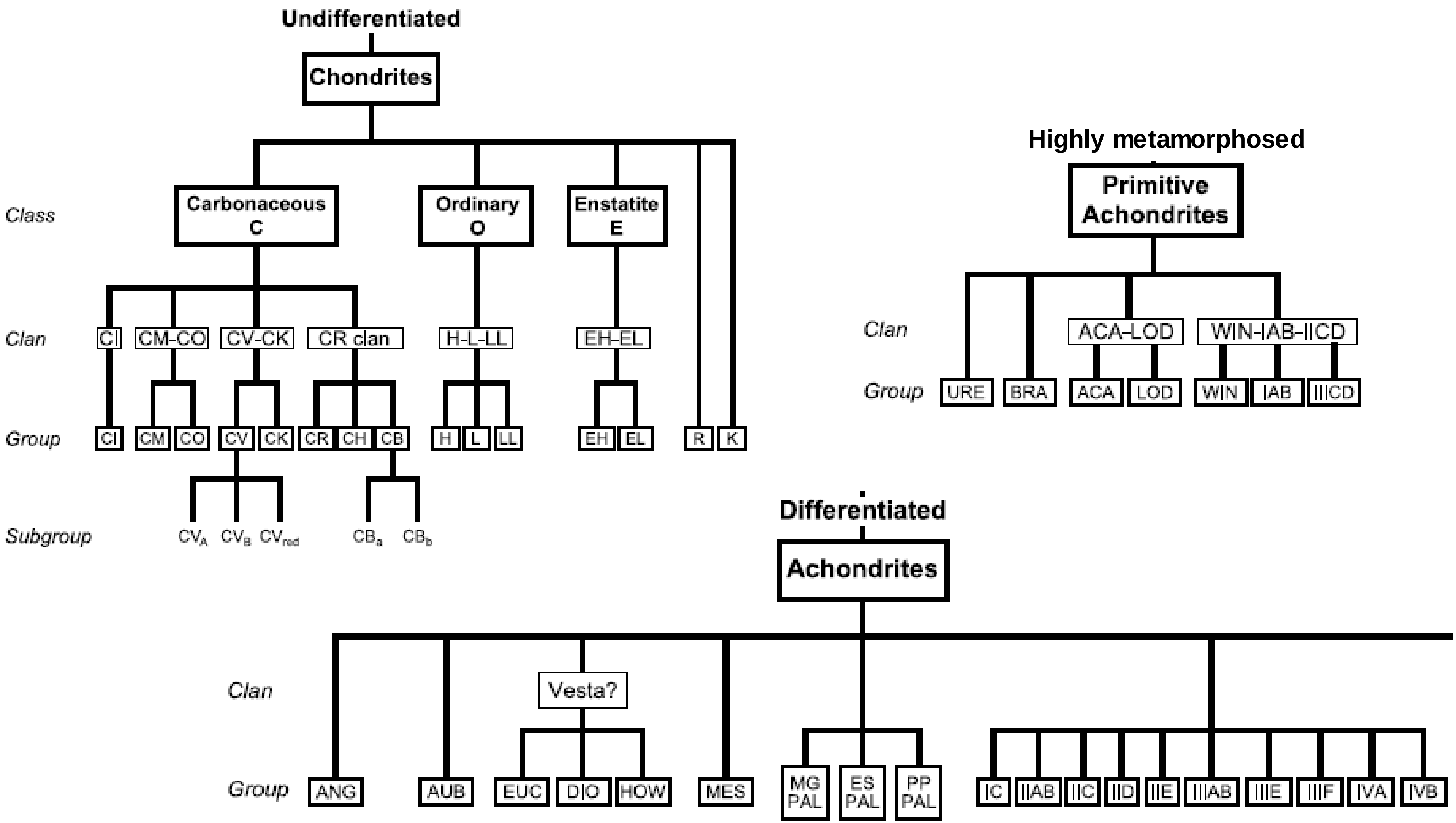
How do we know the mineralogy of asteroids?

- Samples of asteroids fall from the sky…..
- There are 74,333 named meteorites

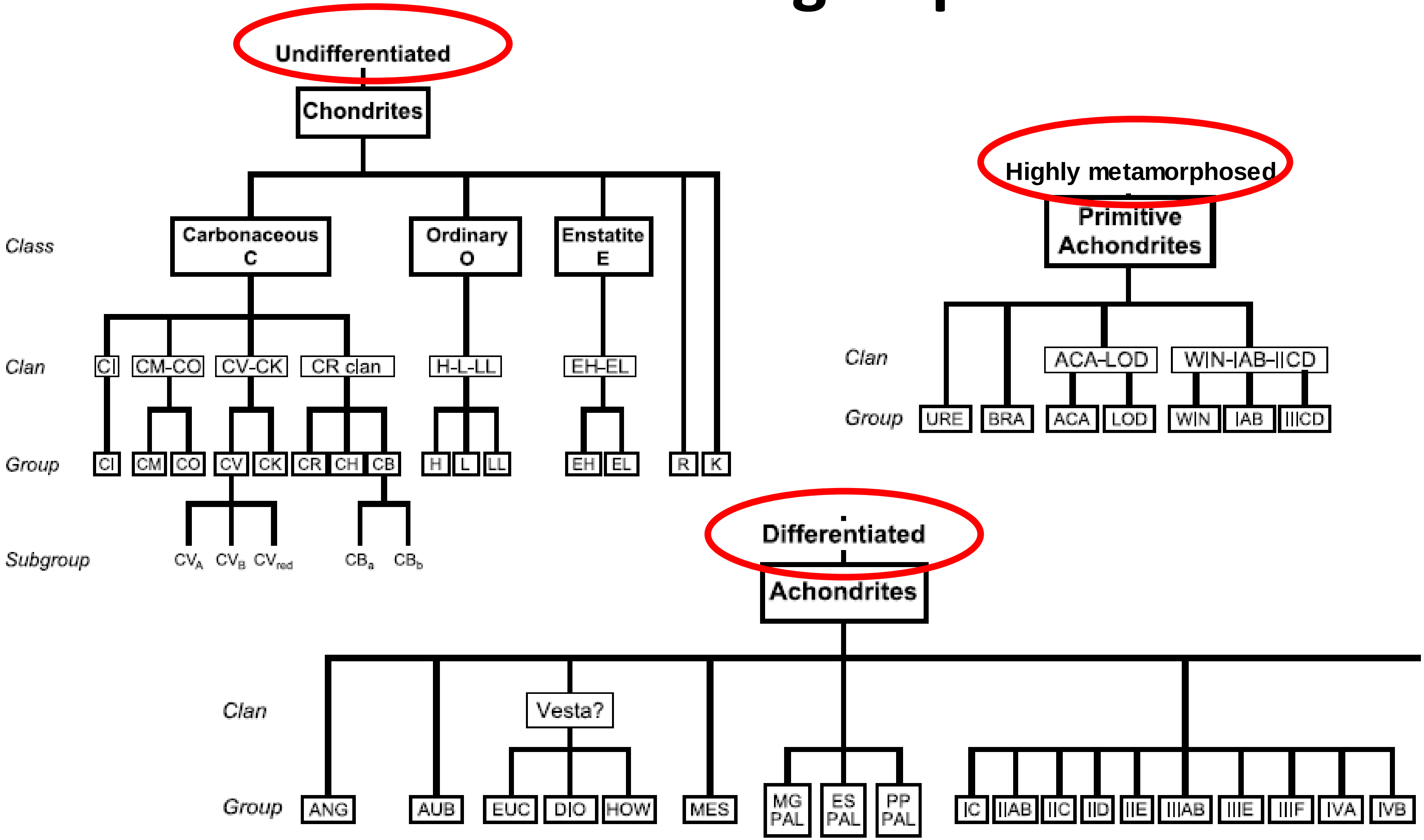


But they are in a seemly bewildering array of meteorite groups



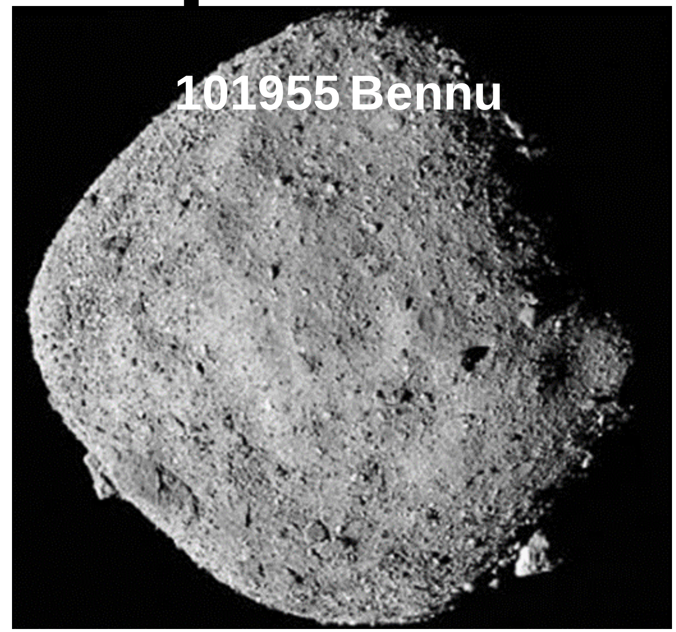
And don’t forget the “ungrouped” meteorites

But they are in a seemly bewildering array of meteorite groups



But asteroid mineralogy is actually pretty simple

- **There are about 4600 terrestrial mineral species.**
- **Asteroids get by with only about 250 minerals.**
- **Why?**
  - **Minerals "evolve" in response to changing chemical, physical, and even biological processes over time.**
  - **The complex terrestrial mineralogy is the result of 4.4 billion years of heat, pressure, crustal recycling, changing chemistry, and interaction with life.**
- **The processes that drive mineral evolution on Earth are either <u>very limited</u> or <u>entirely absent</u> on asteroids….hence a relatively simple mineralogy.**



NASA/Goddard/University of Arizona

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+

Hazen and Ferry, 2010

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Planetary

Terrestrial

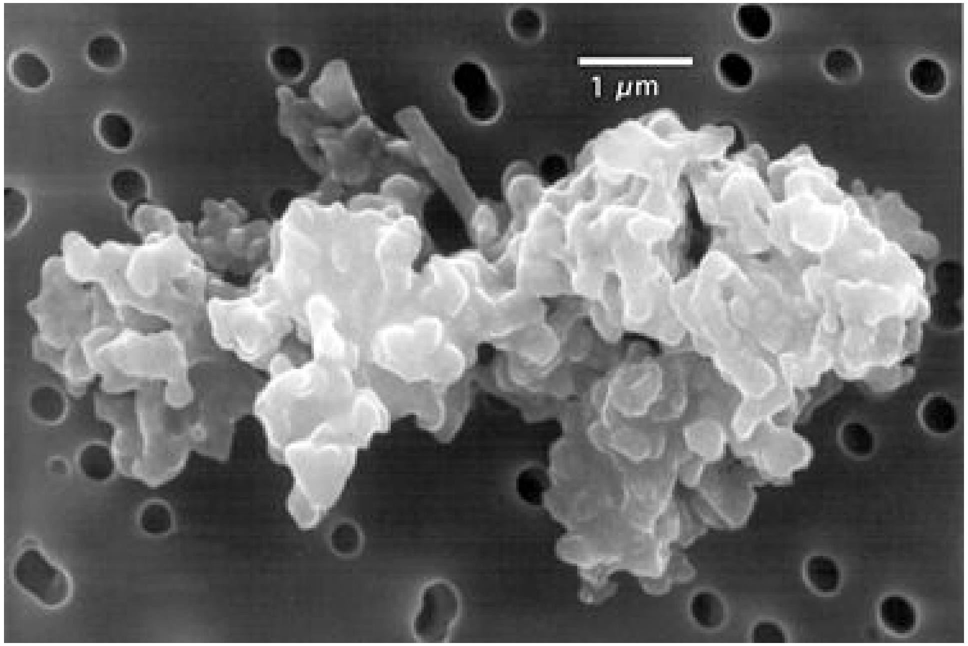
Asteroid Line

Lunar Line

Hazen and Ferry, 2010

Stage 0: Presolar Grains

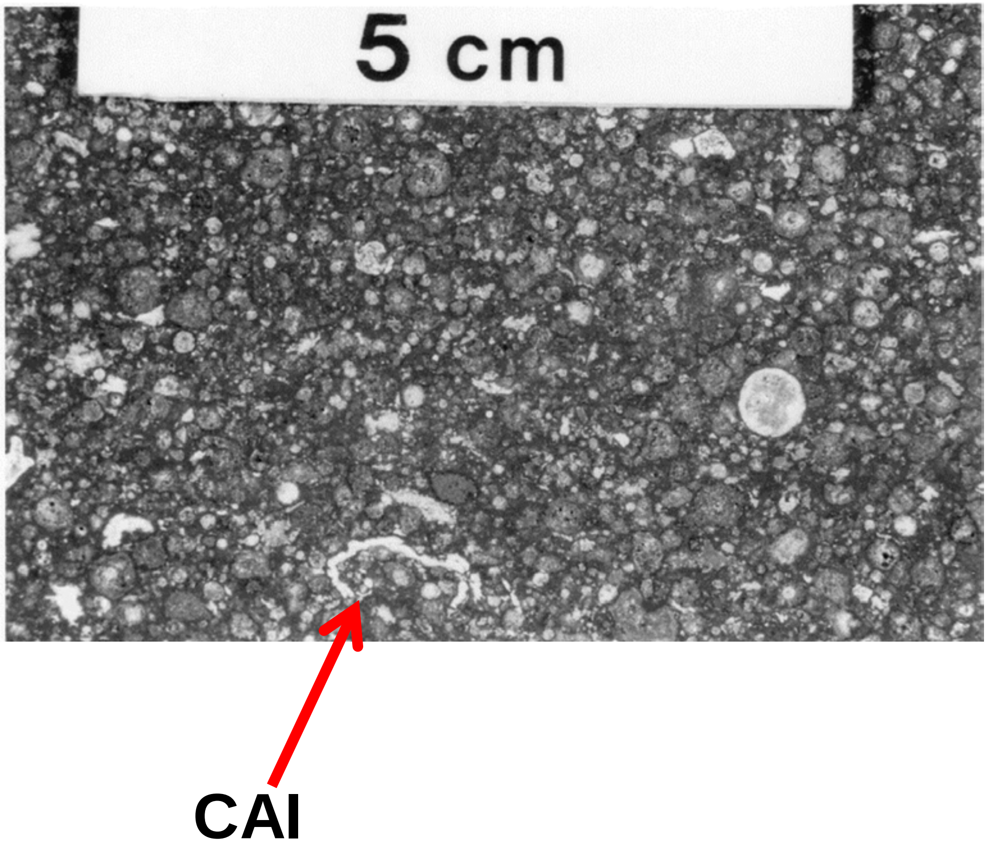
- **Presolar stardust grains comprise about 0.1 percent of the total mass of meteorites.**
- **nitrides**
  - **Osbornite (TiN)**
  - **Nierite (α-Si_3N_4);**
- **carbides**
  - **Cohenite [(Fe,Ni,Co)3C]**
  - **Moissanite (SiC)**
  - **Titanium carbide (TiC)**
  - **Diamond, graphite (C)**
- **Iron 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 $MgSiO_3$**



- **We have identified about a dozen, but there are probably a few more minerals to be found.**

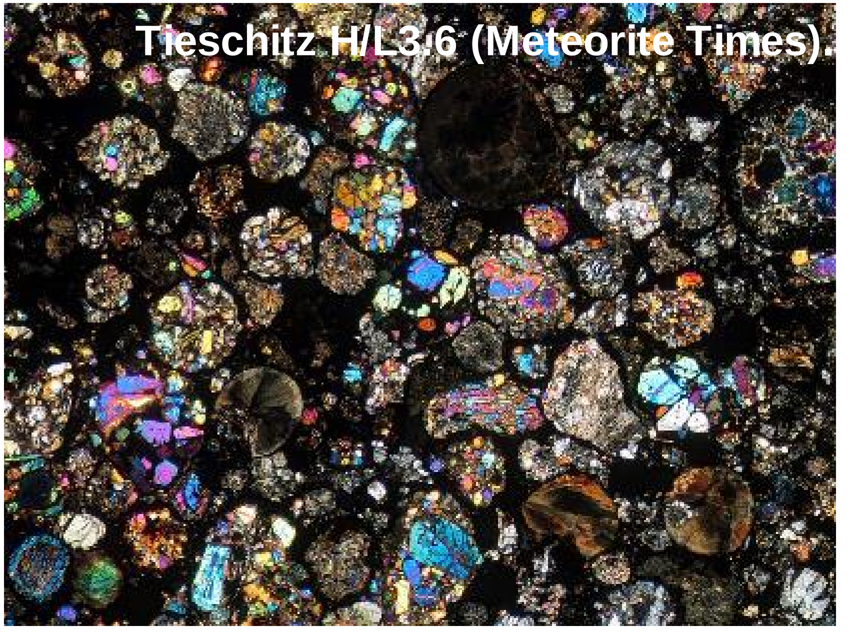
Stage 1:
Accretion and the Formation of Chondritic Minerals

- **Minerals condense out of the cooling solar nebula, with high-temperature minerals condensing first.**
  - **These include ~24 high-temperature mineral phases**
  - **The cooling nebula then condenses progressively lower-temperature minerals.**
- **Chondrules dominate this stage.**
  - **Millimeter sized spheres formed in the solar nebula.**
  - **Chondrules are the sedimentary "sand" of the solar system….which make up the chondrite meteorites.**
- **Chondrites contain a diversity of metals, sulfides, oxides, and phosphates.**
- **How do we know? ~75,000 recovered meteorites.**



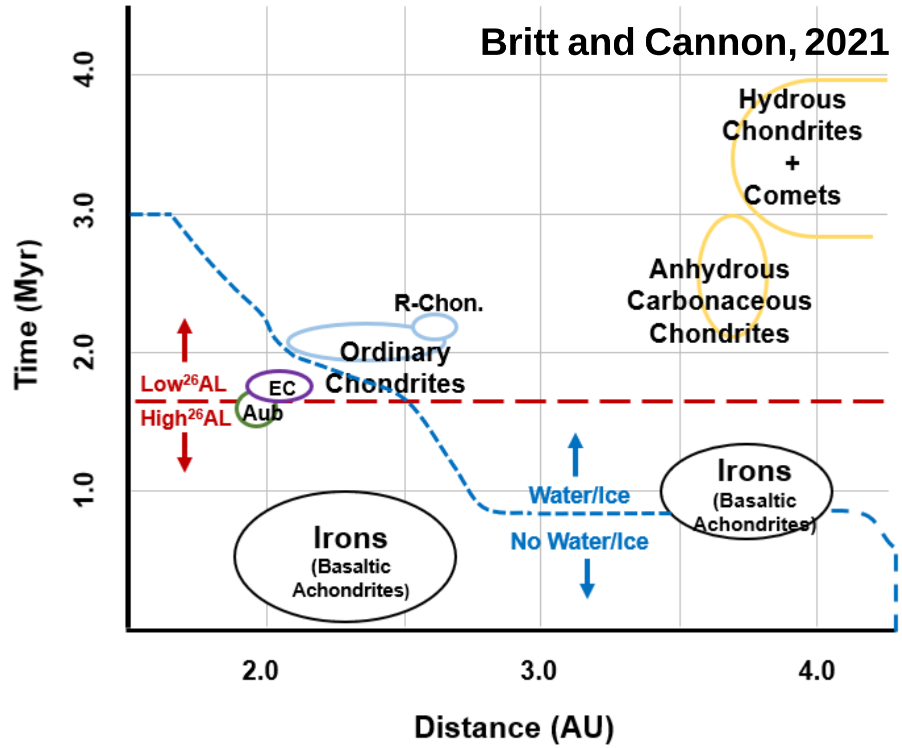
Stage 1: Primary Chondritic Minerals

- **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**
- **Melting, metamorphism, aqueous alteration, and shock will alter, modify, and diversify the chondrites.**



Timing and Location are Critical

- **<u>Asteroids got one major heating cycle and were done ~4.5 billion years ago</u>.**
- **Planetesimals that accrete early (with lots of ^{26}Al) heat to melting and differentiate, producing <u>igneous melts</u>.**
- **With the short half-life of ^{26}Al it does not take much time before the isotope is depleted and the heating will only <u>metamorphize</u> the planetesimal.**



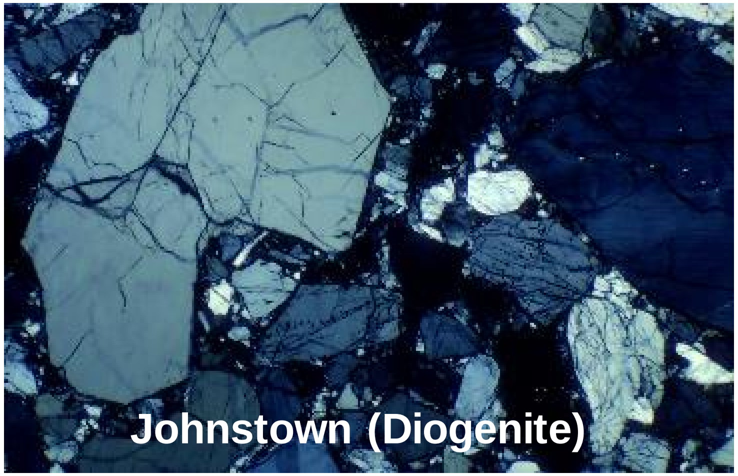
- **Planetesimals that accrete outside the "<u>frost line</u>" will include frozen volatiles and organics as well as minerals. Later heating of this assemblage produces <u>aqueous alteration</u>.**
- **Planetesimals that accrete outside the frost line <u>and</u> after several ^{26}Al half-lifes do not heat much, if at all. This produces comets, some Trojans, some of the Kuiper Belt that retain mixtures of unaltered refractory minerals, organics, and ices.**

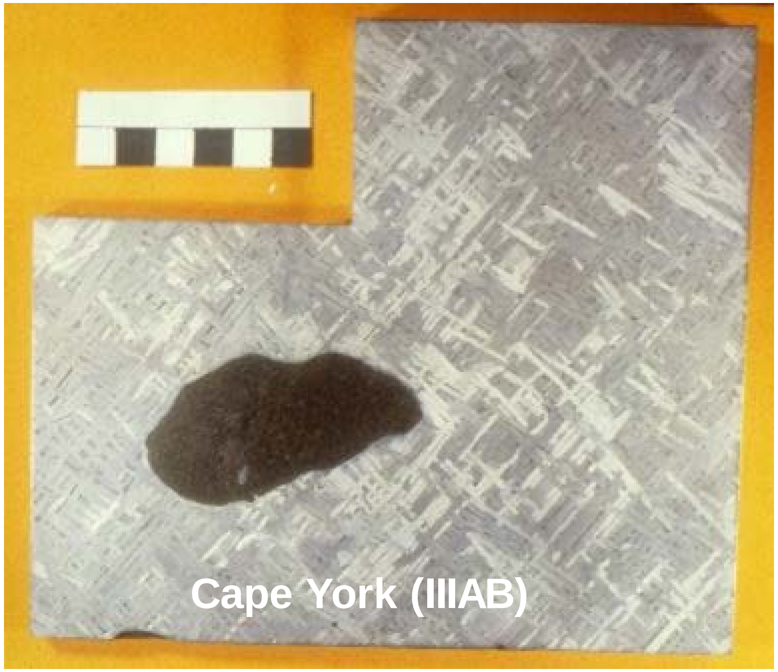
Stage 2: Igneous Alteration

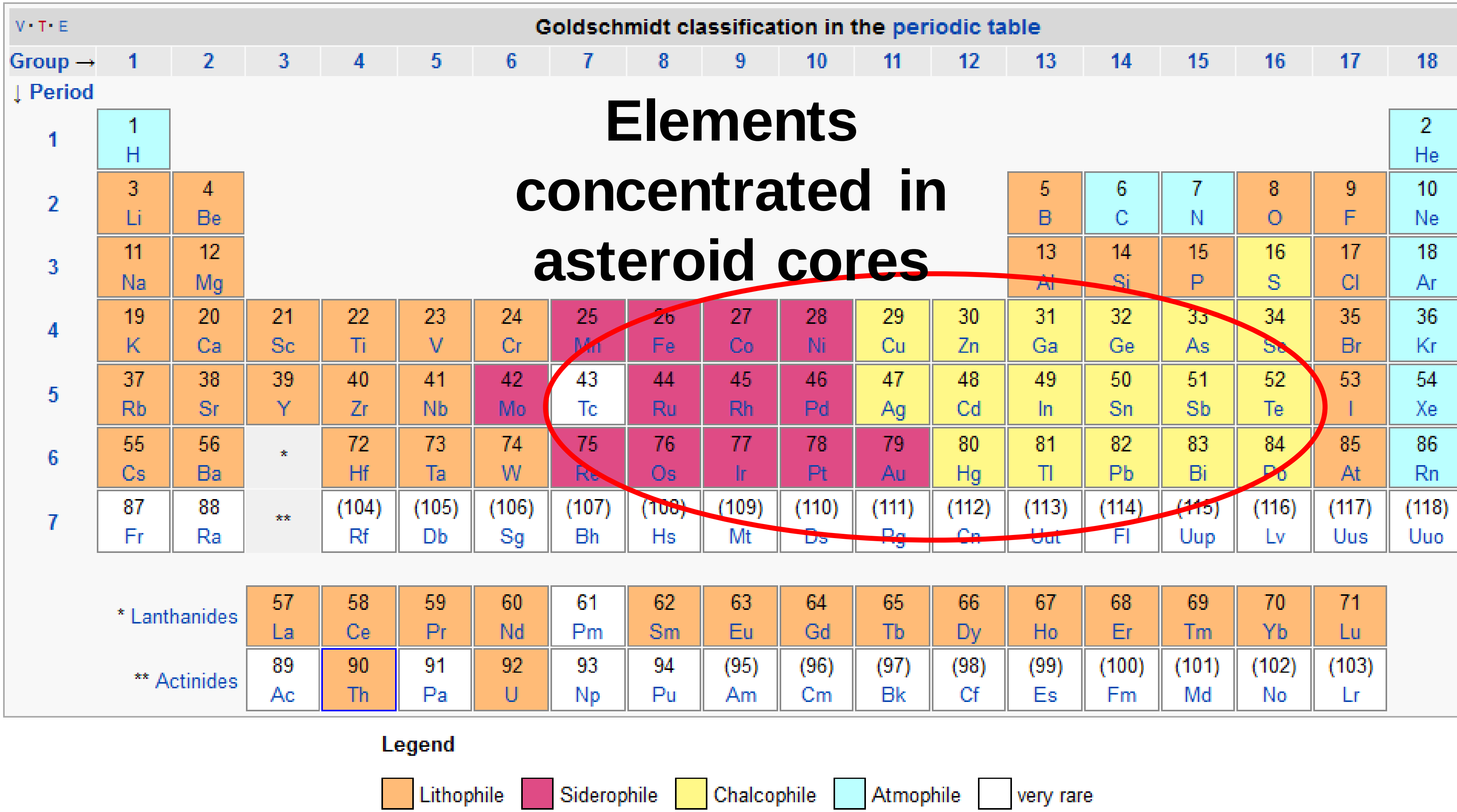
- In some planetesimals heated above ~950°C crossing the liquidus for early partial melts from FeNi metal and troilite.
- The early melts migrated through the unmelted silicates and form meteorites like acapulcoites, winonaites, and IAB irons.
- As the temperatures increased, silicate melting formed 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 $(Fe,Ni)_{23}C_6$.

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.**



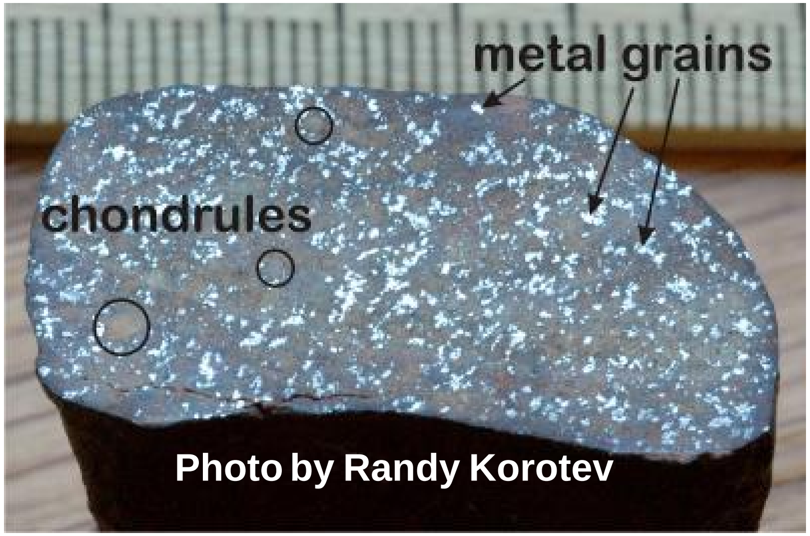




- **<u>Lithophile</u> (rock loving) elements remain on or close to the surface because they combine readily with oxygen, forming compounds that do not sink into the core.**
- **<u>Siderophile</u> (iron loving) elements are the high-density transition metals which tend to sink into the core because they 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.**

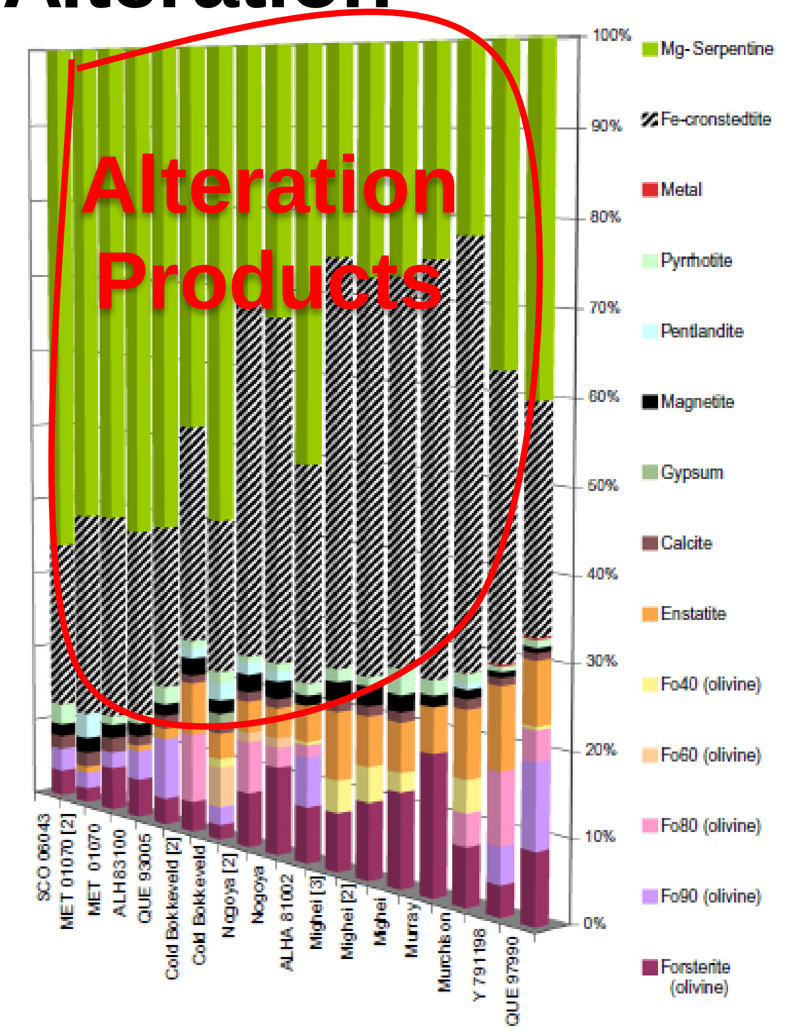
Stage 2: Metamorphism

- **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

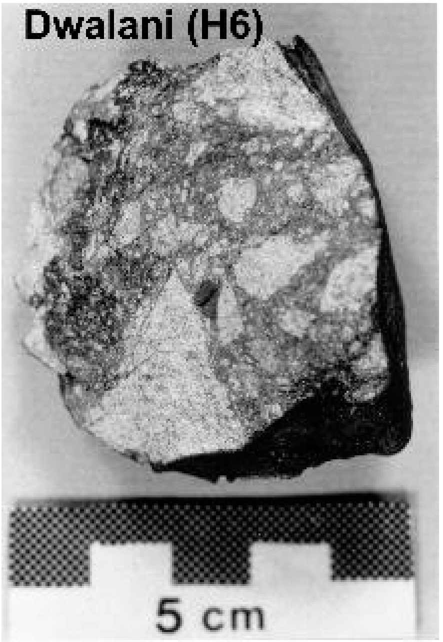
- **Late accretion outside the frost line with depleted radioactive elements resulted in only the melting of ice/volatiles and the subsequent alteration of chondrule silicates and organics at low temperatures (<100°C) producing a range of new minerals**
  - **Phyllosilicates**
  - **Oxides**
  - **Sulfides**
  - **Carbonates**
  - **Sulfates**
- **The organics also get "cooked" stripping hydrogen out of the carbon compounds, resulting in abundant low-hydrogen polycyclic aromatic hydrocarbons (PAHs).**



From Howard et al, 2011

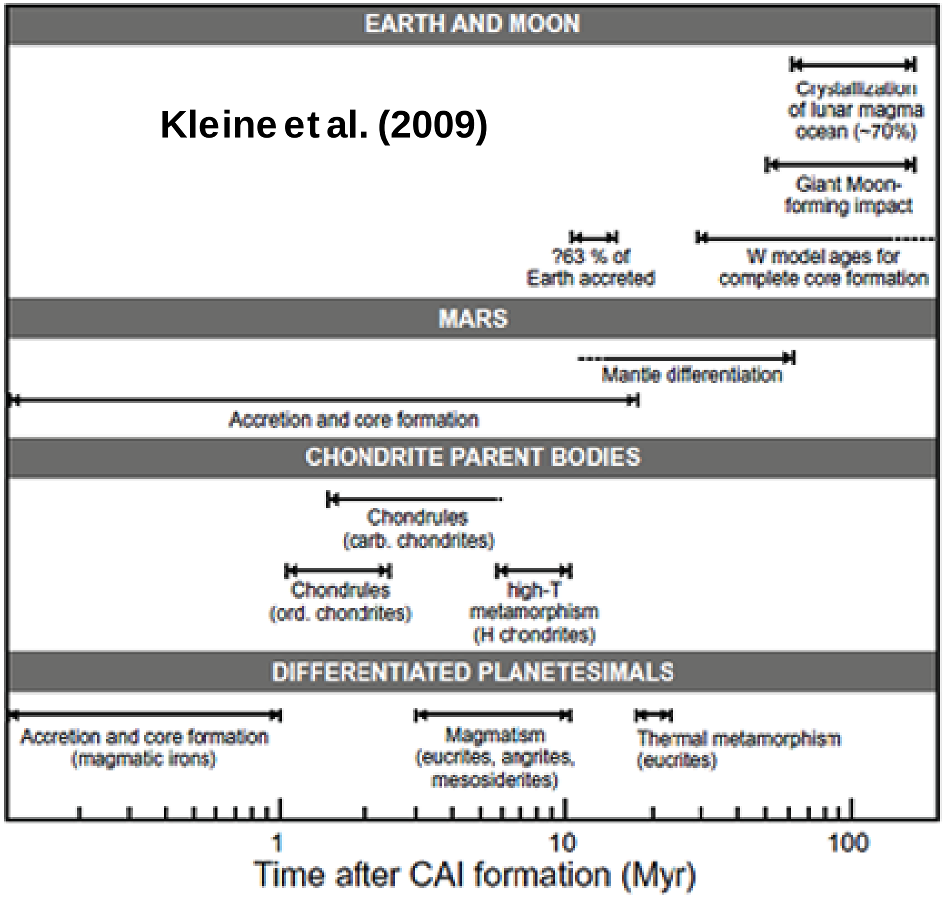
Impacts and Mineral Evolution

- For 99% of solar system history the only mineral evolution on asteroids is from impact shock effects.
- 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
- Impacts will fracture and rubblize the bodies.
- Asteroids in near-Earth space are collisional fragments and probably rubble piles.
- These represent multiple fragments of parent bodies that have been dynamically spread over the inner solar system.



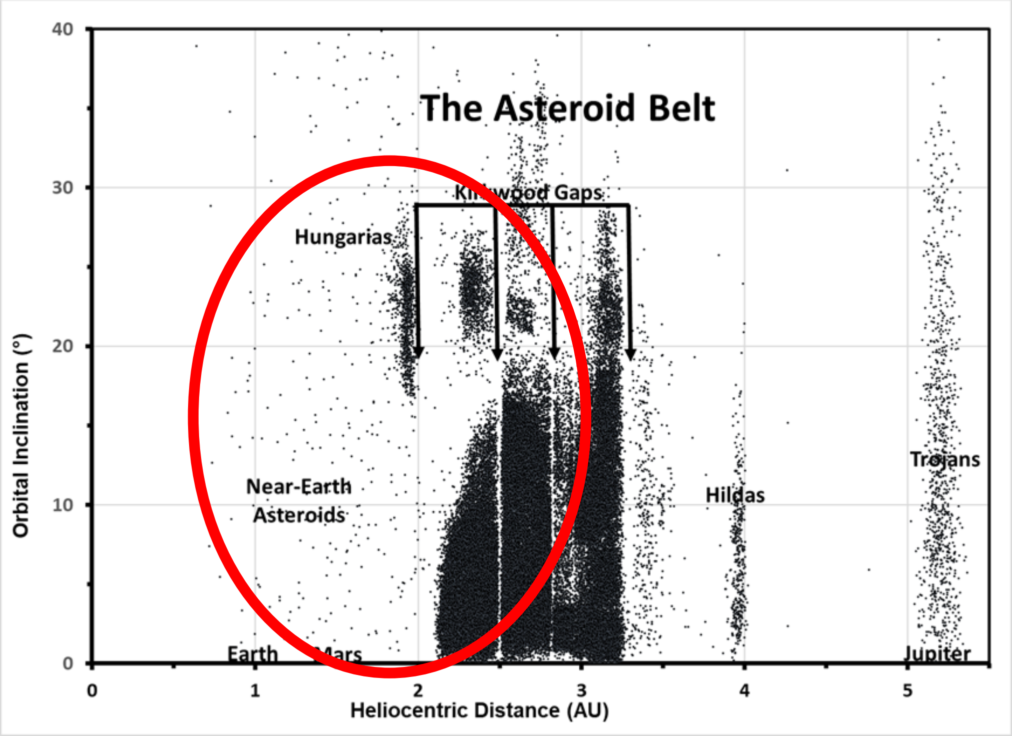
The End of Asteroid Mineral Evolution

- **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 (aside from dwarf planets).**
- **Between original mineralogy, aqueous, metamorphic, impact, and igneous evolution meteorites have about 250 minerals.**



What we know……

- On asteroids there are none of the drivers for terrestrial mineral diversity.
  - NO plate tectonics
  - Low lithostatic pressures.
  - No available fluids after 4.5 billion years.
  - Low to no heat internal heat flow after initial heating.
  - No long-lived hydrothermal systems.

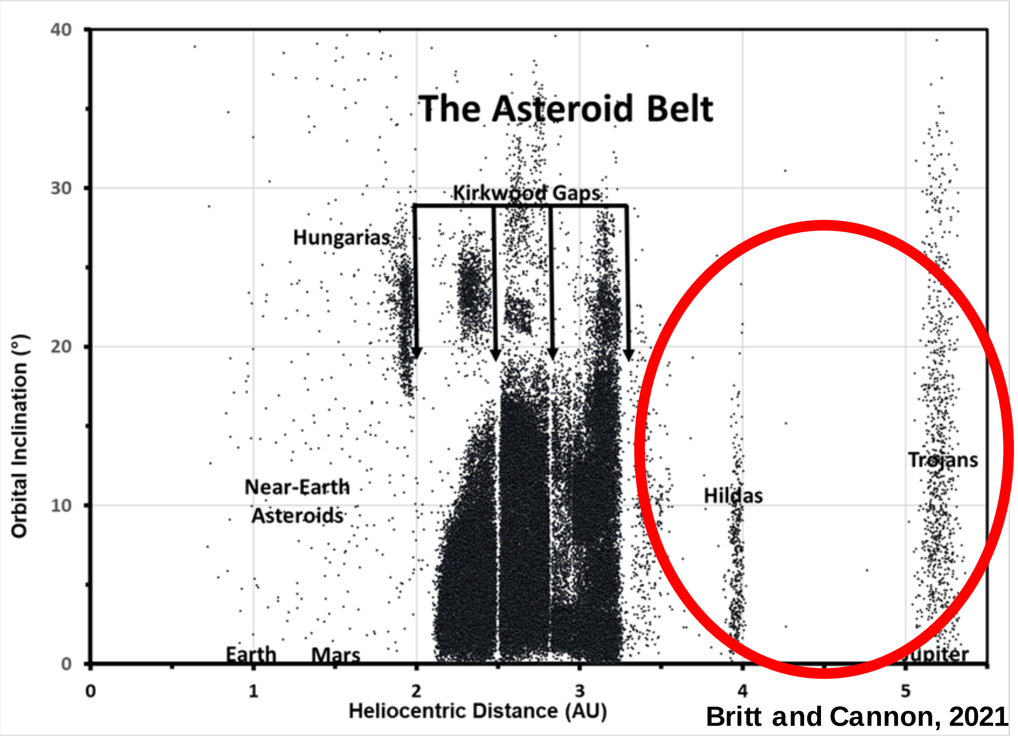


Britt and Cannon, 2021

- What we have is a relatively limited mineral suite that underwent short-lived thermal and aqueous processing.
- Meteorites in our collections are strongly biased, because of dynamics and atmospheric entry stresses, toward strong metamorphic and igneous materials from the inner asteroid belt.
- Organics in meteorites are “cooked” by the same thermal processing.

What we don’t know……

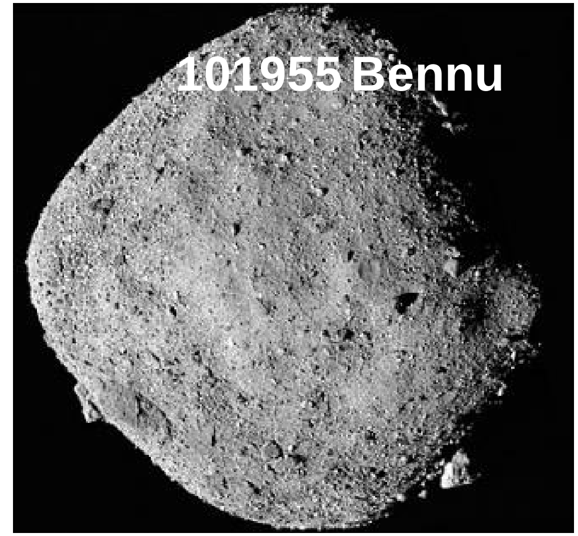
- **Dynamically distant (Hildas, Trojans, Kuiper Belt) and weak parent bodies are under-represented or <u>absent</u> in the meteorite collection.**



- **Late-accreting parent bodies which have not undergone thermal processing will likely have:**
  - **An even less diverse mineralogy. Probably limited to the ~60 minerals in the accretionary and pre-solar suite.**
  - **More (probably much more) diverse organic assemblage because of less or no thermal processing.**
  - **Again, these will be parent bodies in the outer belt and solar system.**

To Wrap Up

- Mineral evolution are fundamentally different on Asteroids vs. the Earth.
  - Asteroids have about 250 minerals vs. over 4600 for Earth.
- Geological concentration mechanisms, long-lived heat sources, and multiple mineral-forming events that we see on Earth do not exist on asteroids.
- Impacts, shock, and fragmentation are the major drivers for most of solar system history.
- NEAs and most inner asteroid belt objects are fragments of abundant populations of processed materials with limited mineral assemblages.
- Unique asteroid populations of astrobiological interest are very limited in the inner solar system.



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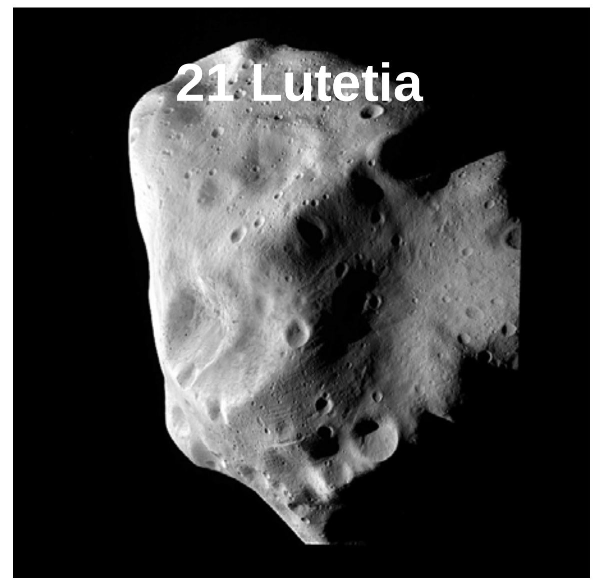

ESA 2010 MPS for OSIRIS Team MPS/UPD/LAM/IAA/RSSD/INTA/UPM/DASP/IDA