Meteorites and the Evolution of the Solar System

By

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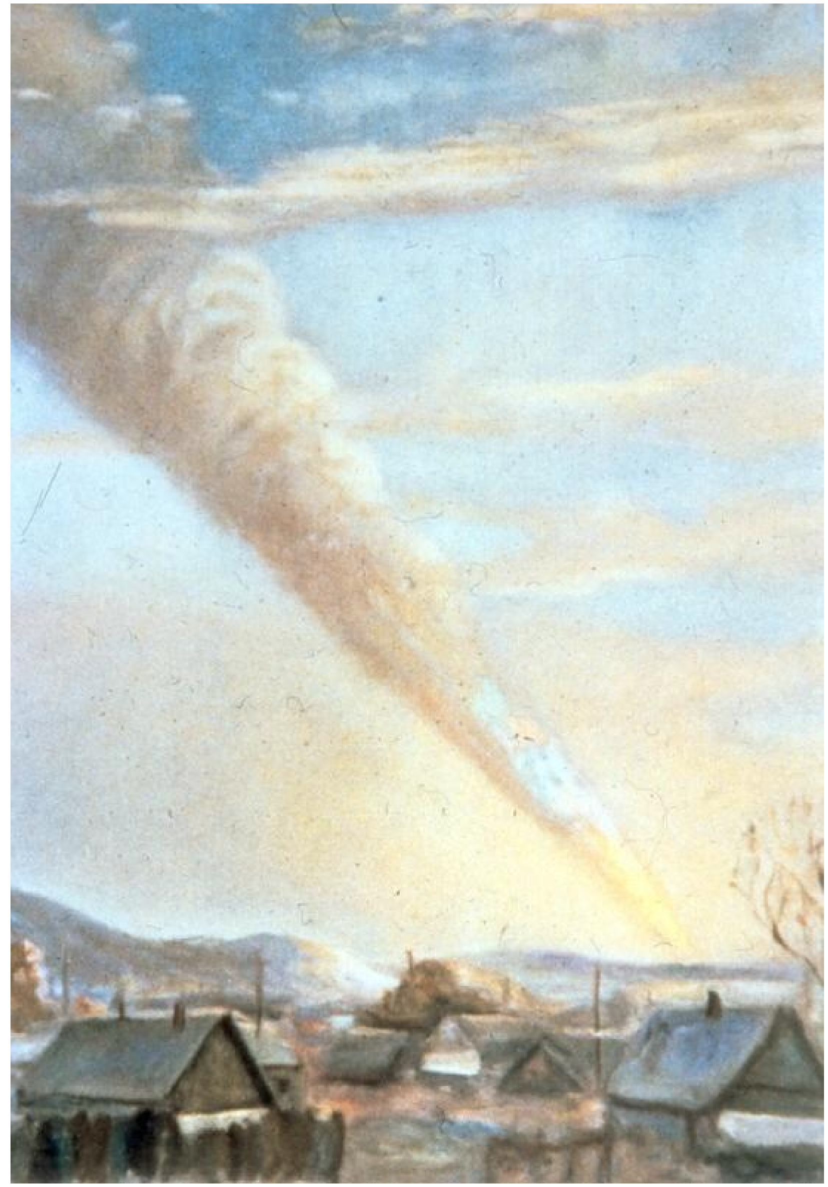
Some Definitions

- Meteoroid
- Meteor, fireball, bolide
- Meteorite
- Meteor shower
- Meteorite shower
- Falls and finds
- Fusion crust

Right: Sikhote-Alin fireball, Siberia, 12 February 1947: major fall of IIAB iron…

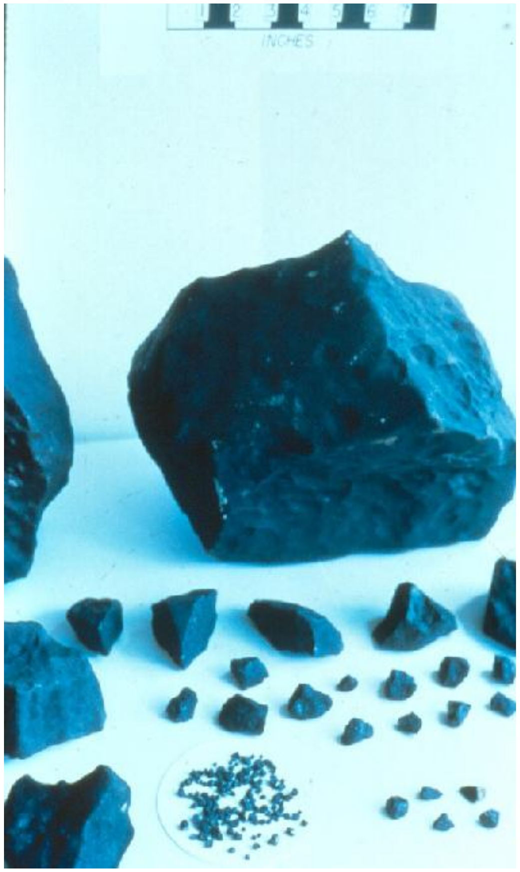


GSC/MIAC coll.

Right: fusion crust on small fragment of Chelyabinsk, a 2013 LL5 fall (Meteorite Market).

Arrival – falls

The arrival of the L'Aigle stony meteorite in France, on 26 April 1803, put an end to centuries of debate: rocks *could* fall from the sky!



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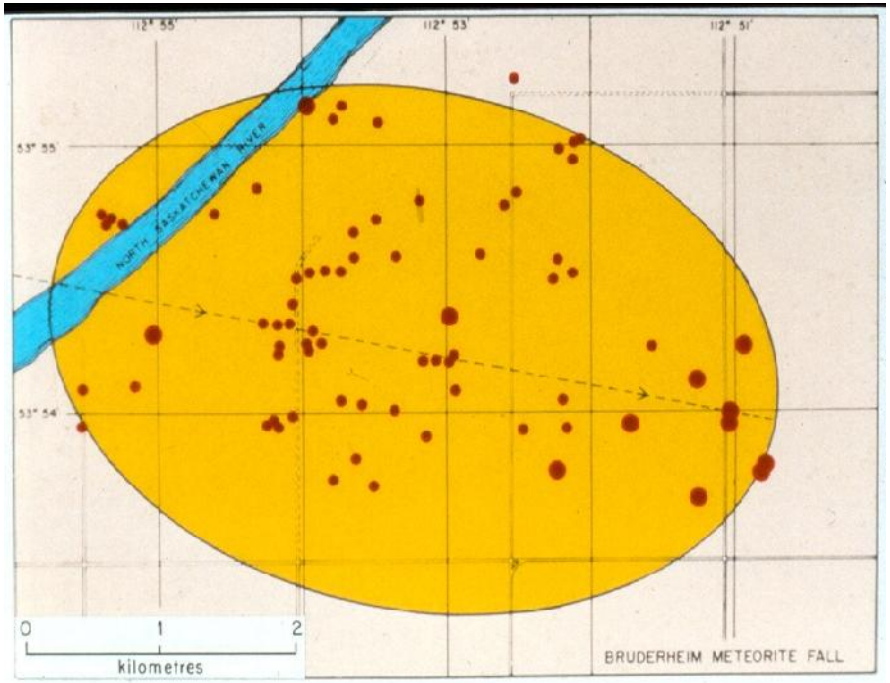


The Bruderheim L6 chondrite fall in Alberta, 1960. Largest confirmed * recovery in Canada – 303 kg. Above, strewnfield, with recovered individuals of meteorite shower.

* Recoveries of Buzzard Coulee (H4) fall of 2008 and the Whitecourt (IIIAB) finds (2007-) are also >200 kg.

Big arrivals – impact structures

The Hoba iron meteorite in Namibia is the largest single mass, at *circa* 60 tonnes. The largest meteorites (>3 or 4 tonnes) are all tough irons. Campo del Cielo in Argentina is the largest recovered fall (TKW *circa* 100 tonnes?) though the Cape York iron in Greenland is also huge.

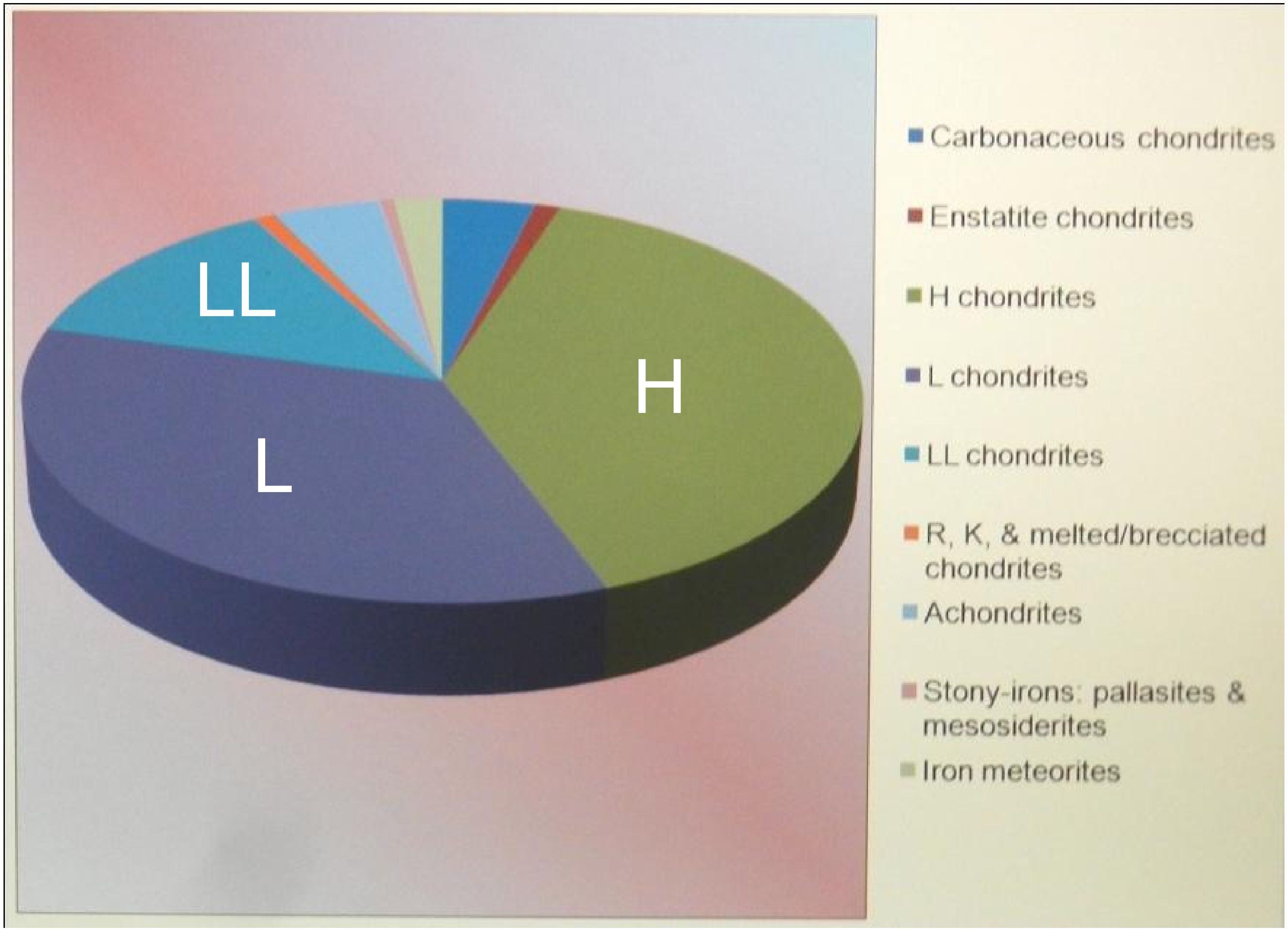
Can.Geog, Apr. 1990

Impactors larger than a few hundred tonnes are vapourized, but leave calling cards such as:

- Impact structures
- Shatter cones
- Spheroid (lapilli) layers
- Tektites
- Geochemical traces

(e.g., the iridium anomaly at the KT boundary).

Meteorites: the "cosmic booty" to date (Met.Bull., 05 January 2018)



58,858 classified meteorites offically recognized, *Met.Bull.*, 10 April 2018.

Meteorites are rocks:

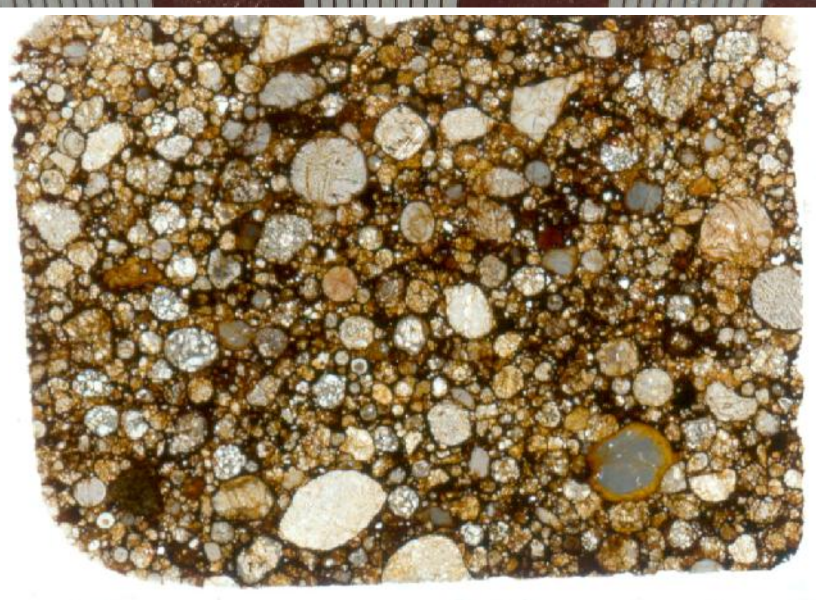
so, classify ‘em & then study the mineralogy and petrology

The hybrid science of **meteoritics** has furnished extraordinary analytical and theoretical details, and provided a window into time and space, extending beyond the formation of the solar system, *circa* 4567 Ma.

Meteorite Classification: a brief cookbook of protocols:

- Stony and stony-iron meteorites: petrography (mineralogy and textures) and mineral chemistry (especially EPM of OLIV, OPX, ± kamacite ± CPX, chromite, etc).
- Iron meteorites: metallography of lightly etched slices, including kamacite bandwidth (cooling rates), and INAA of Ni, Co, Ga, Ge, ± Ir, Pt, Au, As, Sb, Cr, Cu, Re, W.
- Other useful tools: XRD (cross-check on OLIV composition), magnetic susceptibility, oxygen isotopes, thermoluminescence.
- Not essential for classification, but SEM and Raman methods are very handy.

Chondrites

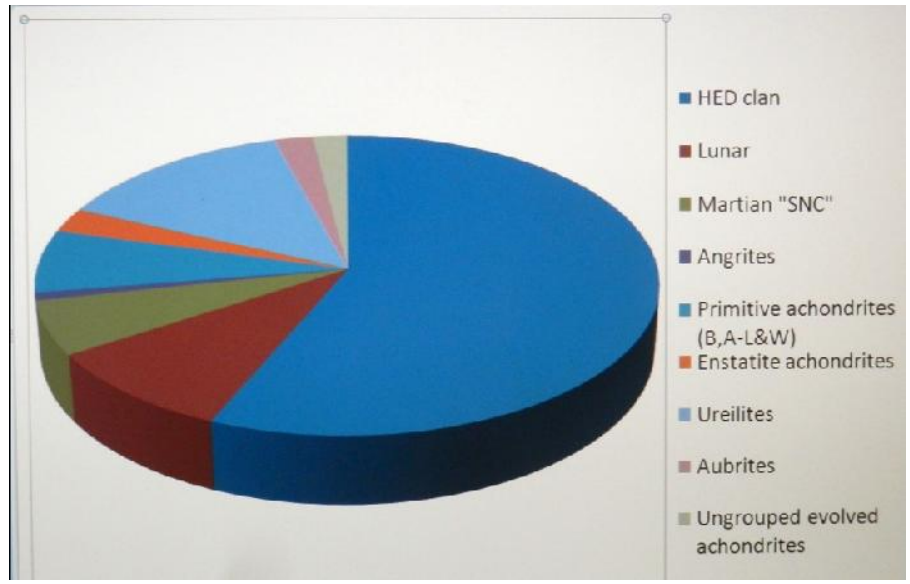


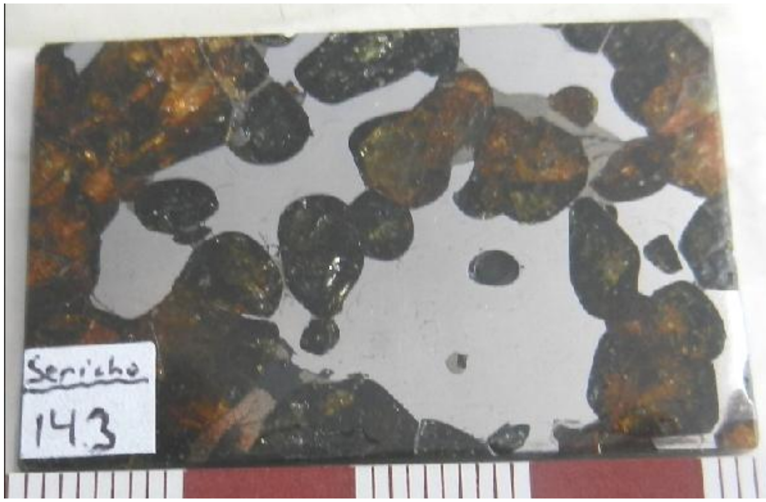
Left: the unequilibrated L3 ordinary chondrite NWA 7469. Petrologic grades 5 and above are equilibrated chondrites, and crystals are homogeneous. Zonation of minerals such as olivine typifies the unequilibrated ordinary chondrites and some carbonaceous chondrites, type 3 or below.

Lower left: a polished thin section of NWA 5731, LL3, 22x16 mm..

Achondrites

Look, no chondrules! Igneous silicate –dominated rocks. Left: Saricicek (Bingol) howardite, a polymict HED breccia. Lodranite NWA 11129 and (below) acapulcoite NWA 2871.





Stony-irons

Left and lower left: the Sericho and Springwater pallasites. Below: mesosiderite NWA 1242.

About 350, or one in every 160 meteorites, is a “stony-iron”. These occur in two distinct classes, shown here.

Iron meteorites

Left: Toluca (IAB-sLL). Below: Gibeon (IVA). Below left: the 15-tonne Willamette (IIIAB) at the AMNH.

Mineralogy brief

Olivine, pyroxenes (OPX, CPX)

Metal (alloy) phases

Sulphides

Phosphates

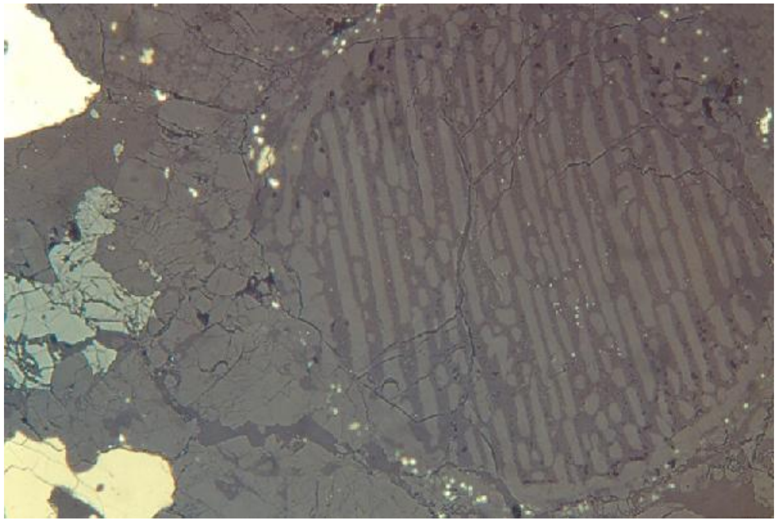
Phosphides, carbides, and nitrides

Minerals in "CAI" such as fassaite and spinel, anorthite, andradite and melilite

Copper, diamond, SiC, etc…

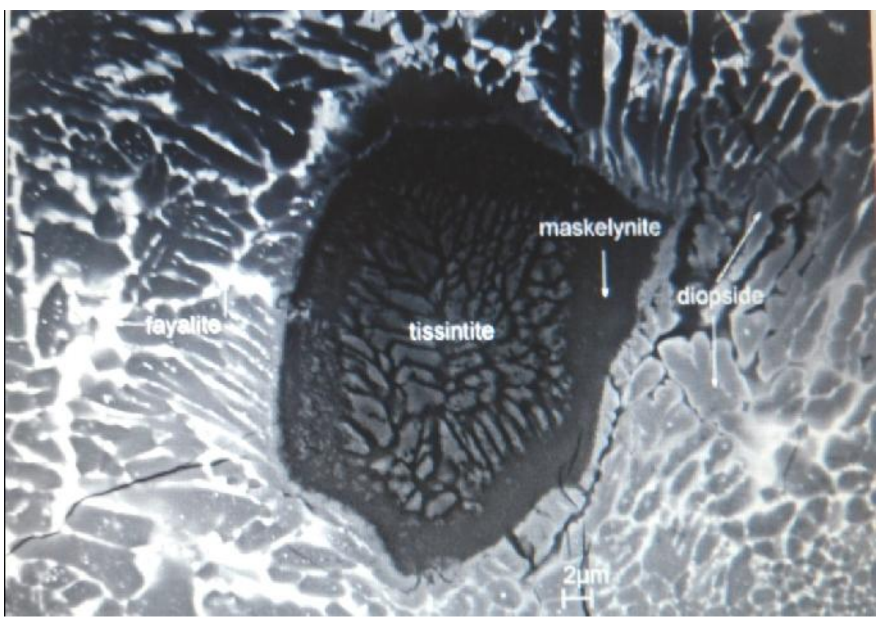
≈275 species (1997), now 435 species (Rubin and Ma, 2017), a 60% increase in 20 years!

Below:
kamacite(iron), chromite, troilite in the St-Robert H5 chondrite.



Some 8.3% of all known mineral species have been found in meteorites. IMA lists 5,208 valid species, Feb. 2017.

Olivine & tissintite: both "meteorite minerals"



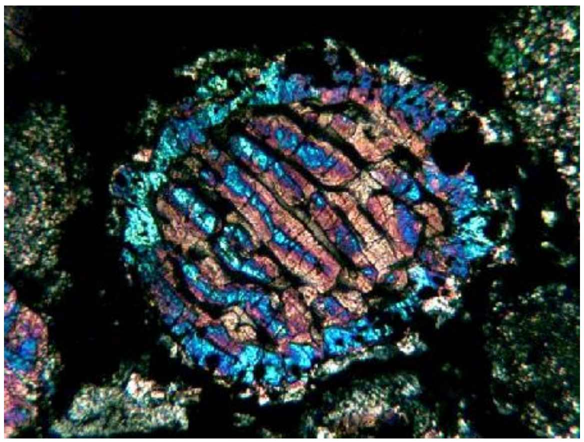
Left: olivine grains in NWA 6292, an ungrouped achondrite with affinities to brachinites. A meteoritic "rock- forming mineral".

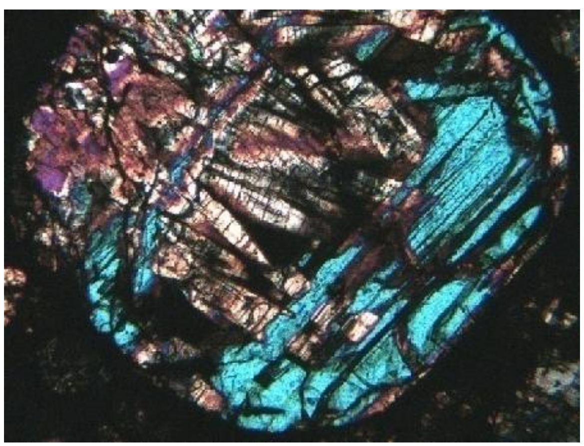
Below left: tissintite in the Tissint martian meteorite. The new mineral is a Ca analogue of jadeite, found in a shock melt pocket on the edge of an olivine grain. Here is tissintite in maskelynite (plagioclase glass), in diopside plus fayalite. Chi Ma *et al.*, LPSC 45, abs. 1222 (2013).

There are numerous high-pressure analogues of more familiar Earth minerals in shock veins and pockets in meteorites.

Synthesis in 7 slides (more or less)

1. Chondrules and matrix – petrologic grade and thermal metamorphism

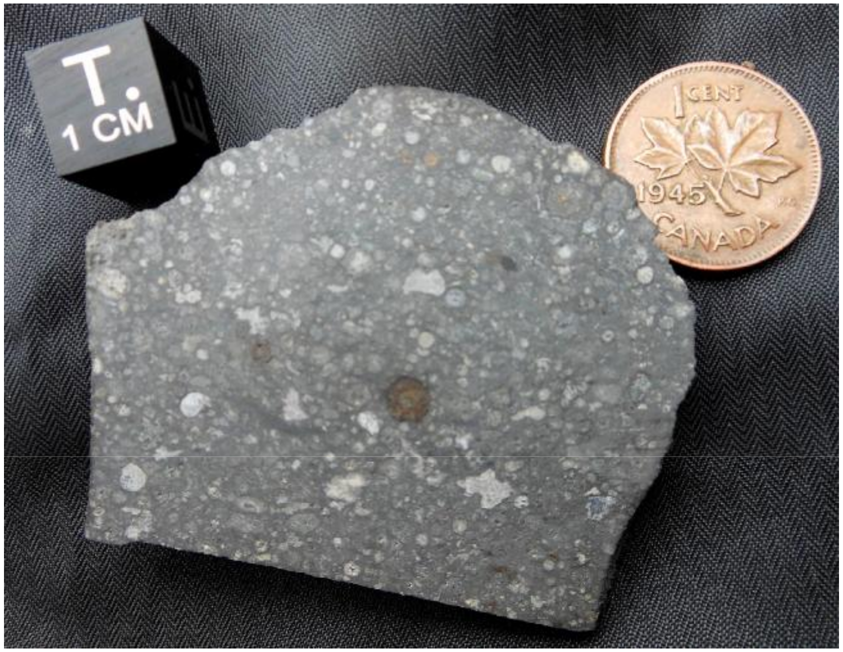




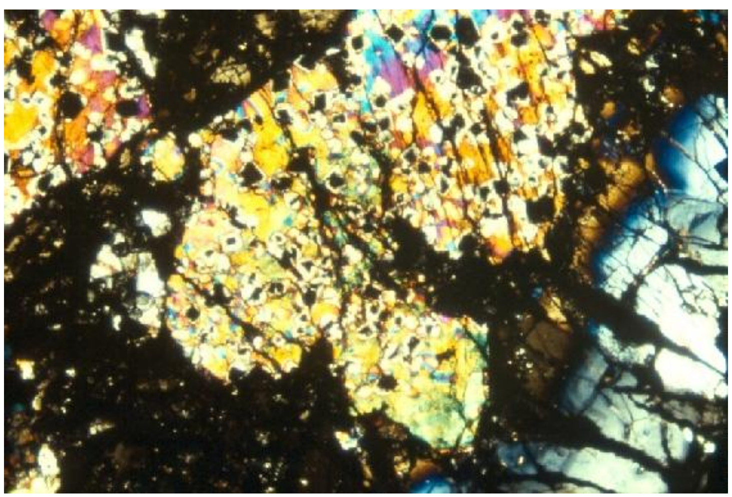
Left: Olivine and glass in a barred olivine chondrule, Moorabie L3.8 chondrite. Below left: NWA 5731 (LL3.2).

Chondrites have been through variable amounts of thermal metamorphism and aqueous alteration. The latter is obliterated by all but the lowest levels of thermal overprinting, analogous to the mineralogical changes on Earth, from sub-greenschist zeolite facies up to granulite metamorphism.

2. Calcium-aluminium inclusions (CAI)

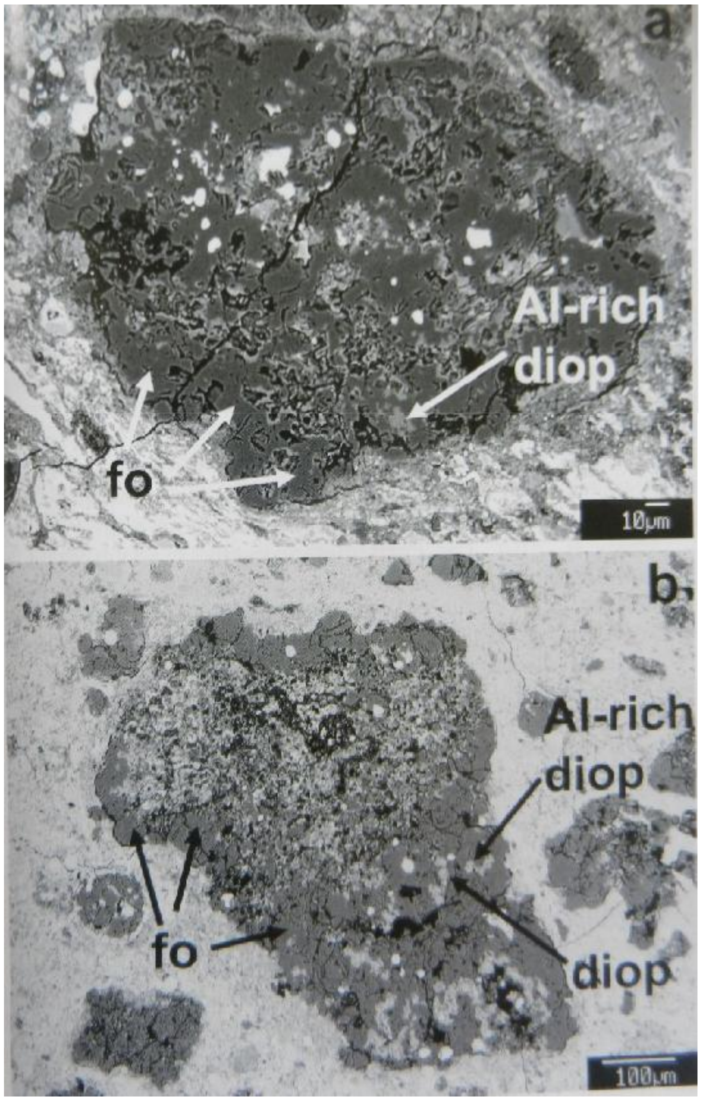


CAI are generally composed of refractory phases such as pyroxene, spinel, melilite and hibonite, $(Ca,Ce)(Al,Ti,Mg)_{12}O_{19}$, a rare hexagonal oxide found in Madagascar in 1953. CAI are perhaps the first objects to condense in the solar nebula, *generally* predating chondules by perhaps 1.5 Ma (but see Paris).



Above left: slice of the Allende CV3 chondrite. Note the mm-scale, irregular white CAI. Left: CAI 3655A, Smithsonian collection: melilite, fassaite and spinel

3. Amoeboid olivine aggregates or inclusions (AOA, AOI)



AOA are small, typically 50-500 μm wide, with 45-70% olivine. They comprise several percent of many carbonaceous chondrites, excepting the CI class, and also occur in LL3.0 (Semarkona). Best developed in CO3.0 chondrites. Forsteritic olivine plus a Ca,Al-rich component (anorthite, spinel, Al-diopside…). AOA seem to be formed from melts, though some have argued for a sintering process. May be subject to hydrothermal alteration…

Left: Paris CM chondrite, showing two AOA. Above: example composed largely of forsteritic olivine. Below: forsterite mantles diopside and (towards top) a porous area of diopsidic material. BSE images: Rubin (2015).

4. Hydrothermal alteration

Epsomite ($MgSO_4 \cdot 7H_2O$), gypsum, siderite, saponite after enstatite, magnetite, sulphides, nepheline, sodalite, andradite and wollastonite…

Found widely in the less-metamorphosed chondrites, especially carbonaceous chondrites: CI, CM, CV, CR, CO…

Kerridge and Bunch (1979) noted that ”aqueous activity may have been widespread on asteroids”.

Carbonaceous chondrites such as Orgueil (CI1) and Murray (CM2) formed by impact brecciation and hydrothermal alteration in the surfaces of at least two parent bodies.

Hydrothermal alteration is noted in the bedrocks of major terrestrial impact structures, such as Sudbury, Chicxulub, Bosumtwi and the Ries crater.

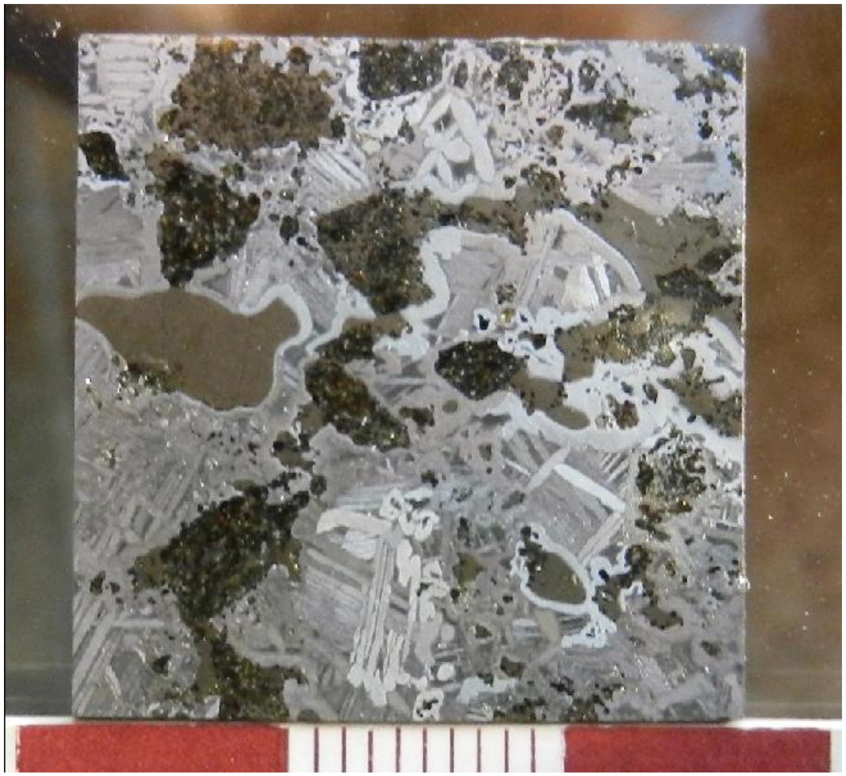
5. Breccias & Shock

Left: NWA 869, an L4-L6 breccia (W1, S3), a large find for an NWA meteorite, and for a chondrite, with “TKW” of 2-3 tonnes. The material displays cm-scale brecciation, chondrules, and mm-scale masses of Ni-Fe metal. The main slice is 20x12x0.55 cm (326 g). Below: “breccia facies” of Seymchan pallasite.

Left: shock melt veins in the Belly River H6.

6. Irons and stony-irons: silicate inclusions, metal veins, magmatic irons and more..

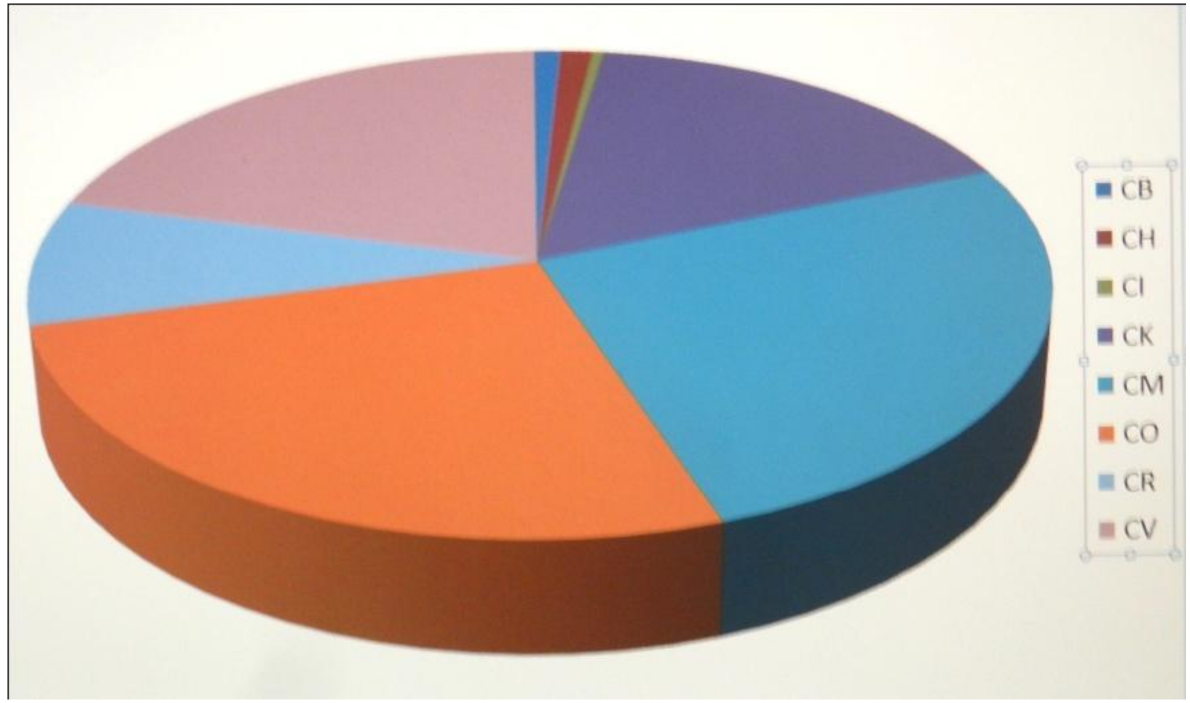
Left: Maslyanino (IAB).
Below: Seymchan pallasite

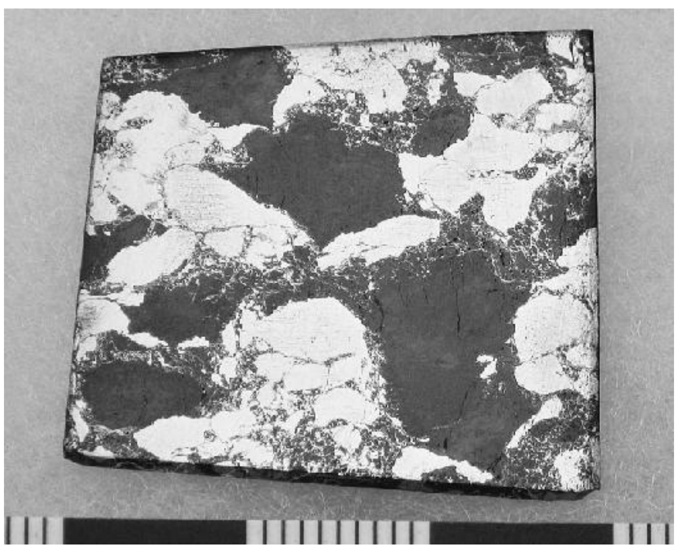


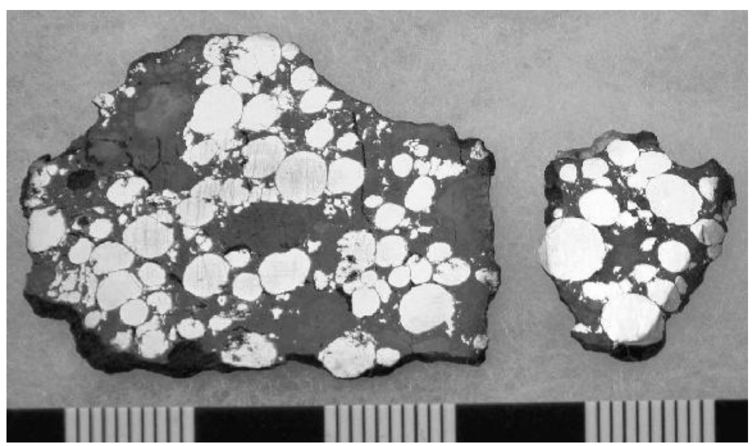
Irons are divided into *magmatic irons*, their chemistry indicative of fractional crystallization from a slowly-cooled melt, and *non-magmatic irons* (IAB, IIE, IIICD), which may contain silicate inclusions, some with relict chondrules, due to liquid immiscibility after impacts on the H-chondrite parent body, including an impact at *circa* 4500 Ma.

7. Carbonaceous chondrites

These meteorites have variable chondrule populations, variable reduced carbon content (up to 5.8 wt.%), and a few (CB, CH) are metal-rich. Some (CI such as Orgueil, and the ungrouped C2, Tagish Lake) are perhaps the most "primitive" material available. Some are hydrothermally altered, but many preserve presolar grains and also CAI from the early solar nebula.







Bencubbin (far left) & Gujba (left), two CBa chondrites.

Solar system evolution – introduction

Given that ordinary chondrites (H, L, LL) comprise 86.7% of all meteorites, and all the classes of chondrites are 92.5% of the total, it seems reasonable to presume that chondritic matter is the principal solid component of that part of the solar system represented by asteroids (and so meteorites).

One meteorite in 13 is something else: some kind of melt product, whether iron, stony-iron or achondrite.

Solar nebula "products":

Components:
crystals, CAI, chondrules, AOA, glass
es …

The Bigger Stuff:

- ❑ Main Belt asteroids
- ❑ Oort cloud comets
- ❑ Kuiper Belt
- ❑ Planets and satellites
- ❑ Comets
- ❑ Sun
- ❑ Earth-crossing asteroids

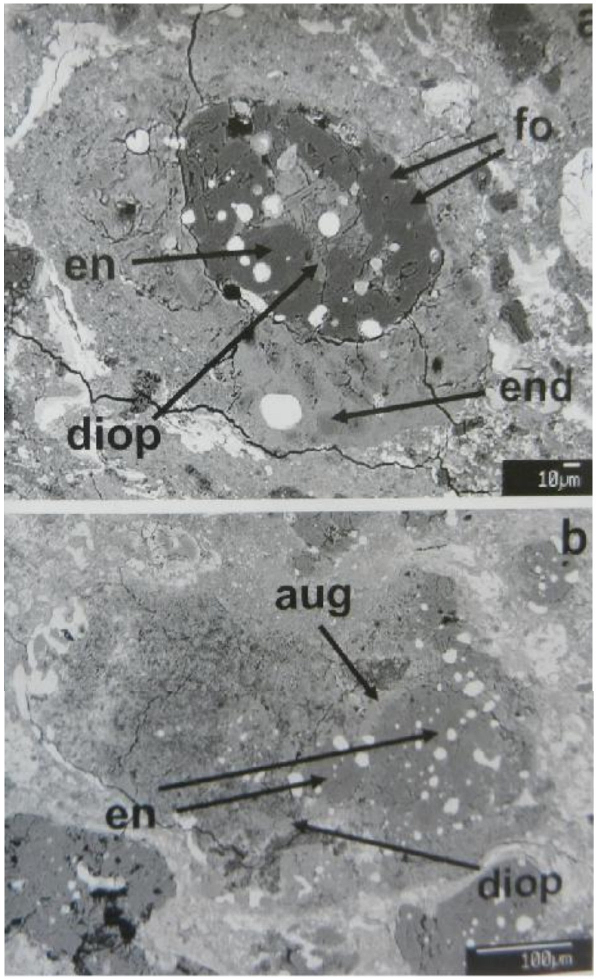
Role of meteoritics in advancing microanalysis and geochronology.

Left, raw material for study: a 30x25-mm slice of friable chondrite, the Saratov L4 that fell in Russia in 1918. Easy- to-separate chondrules and grains for analysis. *Circa* 5% metal shines amidst the chondrules and fine-grained matrix.

Applications in meteoritics and planetary science have driven, or been at the forefront of, many developments in analytical fields over the past 60 years, including EPM, SIMS, TIMS, and AMS.

CAI, chondrules, AOA…

A general sequence of **condensation** in a cooling solar nebula generated first CAI, and shortly after, chondrules and AOA (but see Paris, opposite). With much transient **heating** from short-lived isotopes injected into the nebula, especially ^{26}Al (half-life 0.7 Ma) the early planetesimals were often destined to melt, in whole or part.



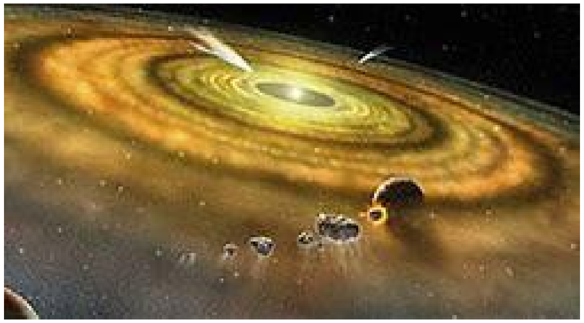
Above: Paris CM chondrite, showing olivine-pyroxene chondrule mantled by a CAI (above) and another chondrule with an accreted, later altered, CAI. BSE images: Rubin (2015).

Some notable dates:

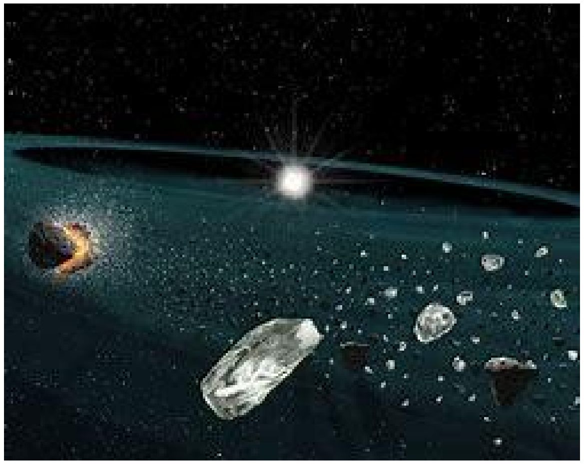
4567 Ma – CAI formation

4563 Ma – Zircon age of Vaca Muerta mesosiderite

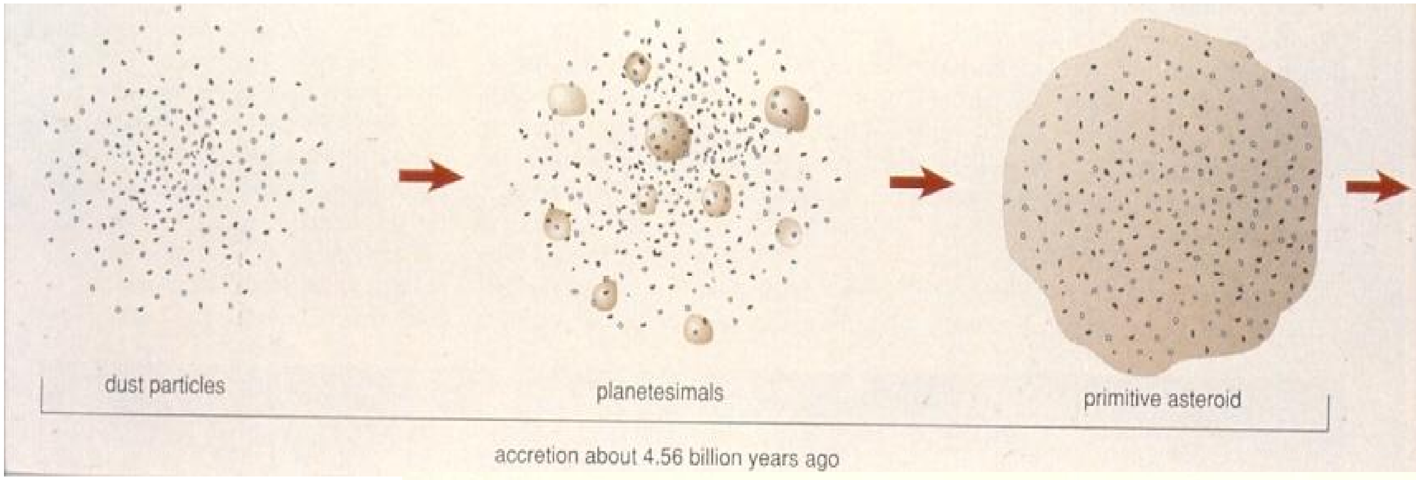
From the very small to the very large: sampling the solar system



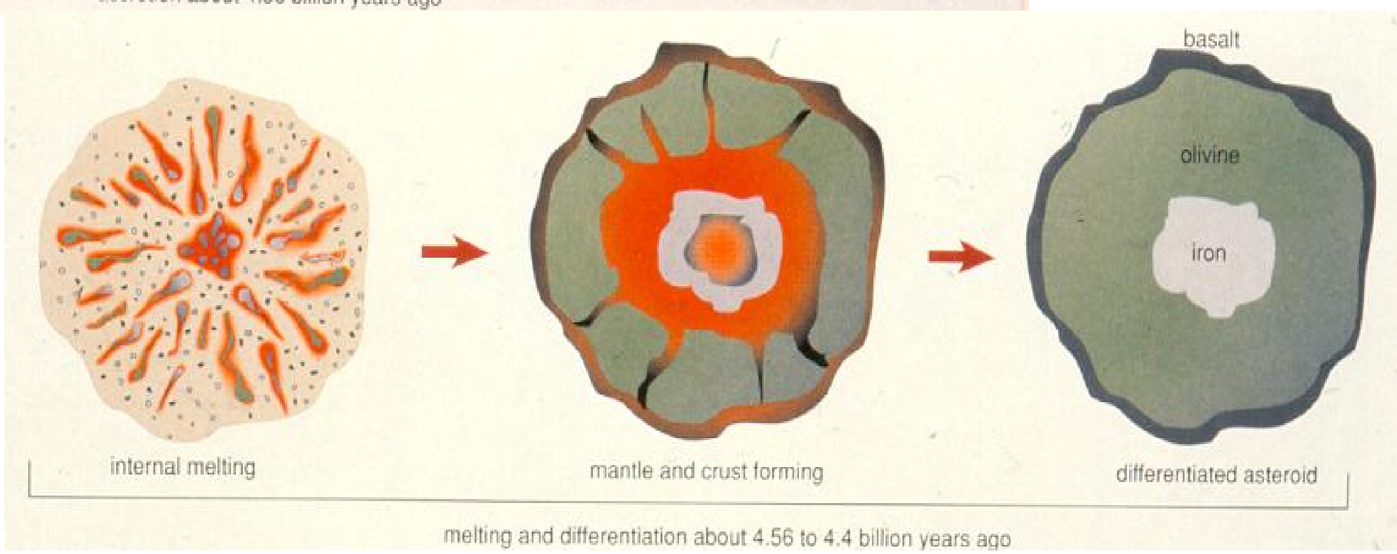
Below: coarse olivine on the edge of a 110-kg slab of the Seymchan pallasite, much of which turns out to be iron meteorite, with patches or veins of the pallasite “facies” (or is that iron dykes in a pool of pallasite?).



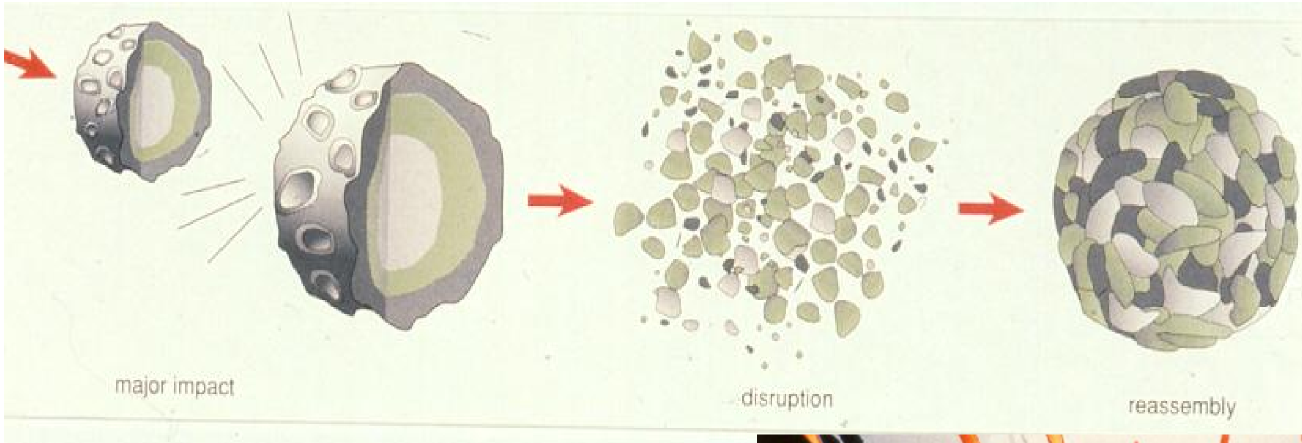
Larger Parent Bodies…



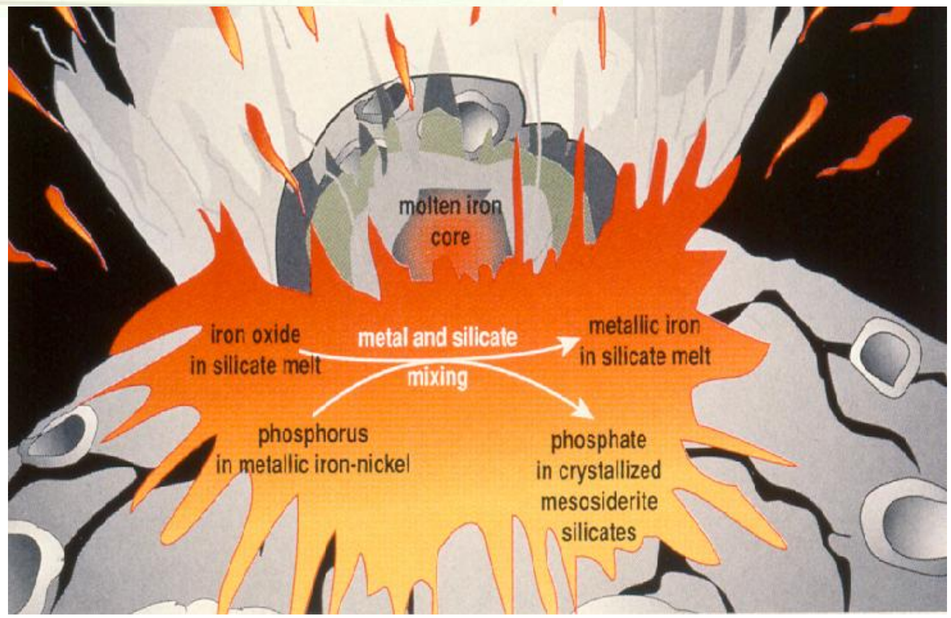
Formation of differentiated asteroids…



and Ancient Impacts…



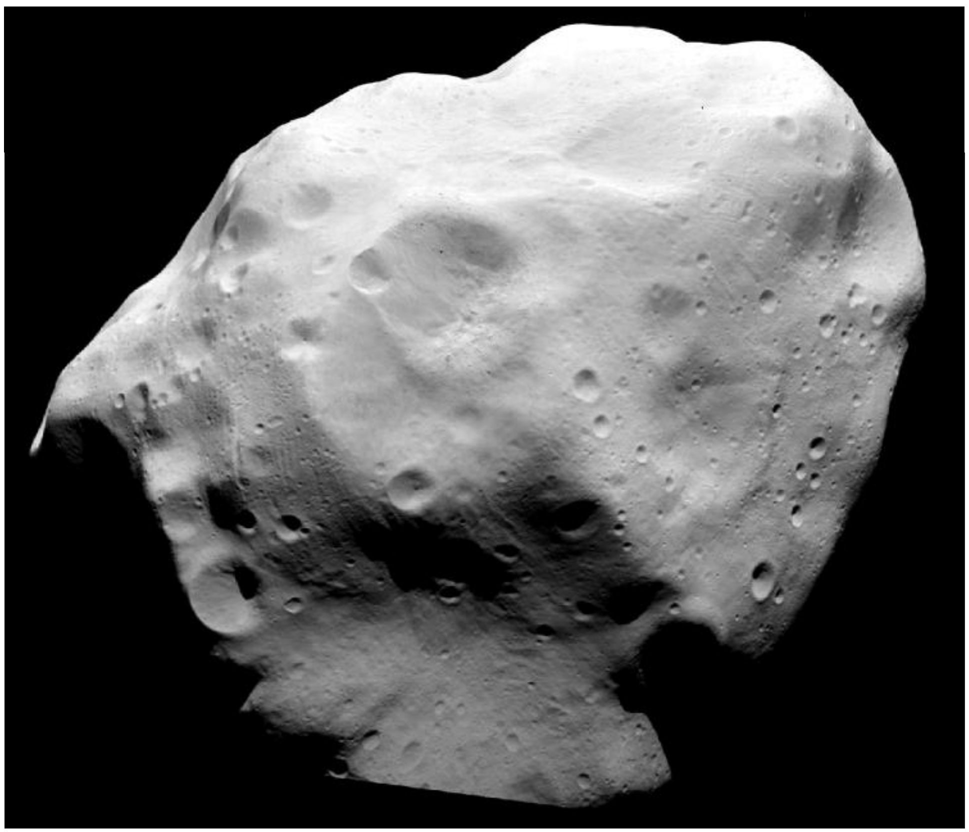
… and genesis of the mesosiderite class of stony-irons



Huff, in Rubin, Amer.Sci. 85 no.1, pp.26-35 (Jan. 1997)

Asteroids

Asteroid 1 Ceres was discovered on 01 January 1801. There are now estimated to be 1 million or more bodies ≥1 km in diameter, with 1,000 are >30 km in size, and >200 fall in the 100-1000 km range. Most are in the Main Belt between Mars and Jupiter. They are very diverse and apparently represent bodies that accumulated and evolved independently, albeit with many impact events early in solar system history.



Left: asteroid 21 Lutetia, 100 km in diameter, discovered in 1852 (Rosetta mission image).
Ceres, D≈930 km, contains an estimated 33% of the asteroid belt.

Astronomers classify asteroids by their orbits and their reflectance spectra. 14 or more classes are recognized.

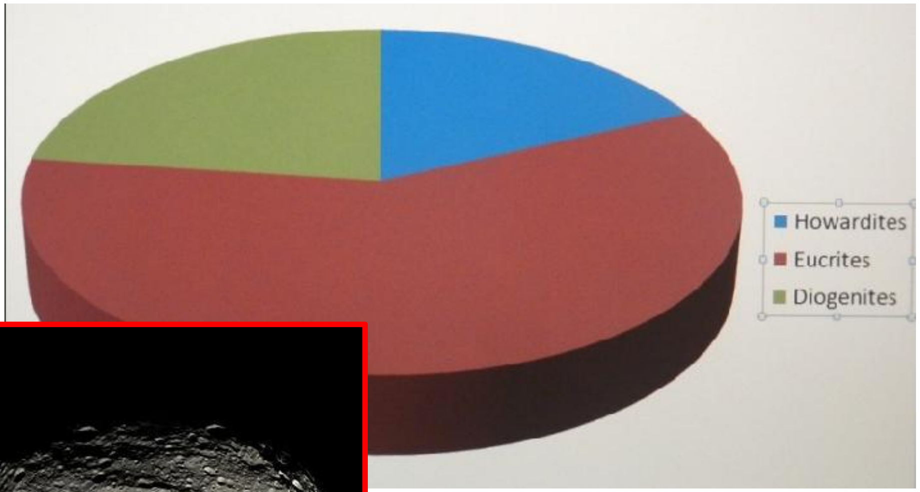
Meteorite-asteroid pairings

It is thought that meteorites in our global collection sample as many as 100-130 asteroids. Examples of classes and meteorite types are shown below.

Class	Asteroid	Associated meteorites
C	2 Pallas	Carbonaceous chondrites
S	3 Juno	Stony, *s.l.*
M	16 Psyche	Irons
V	4 Vesta	HED

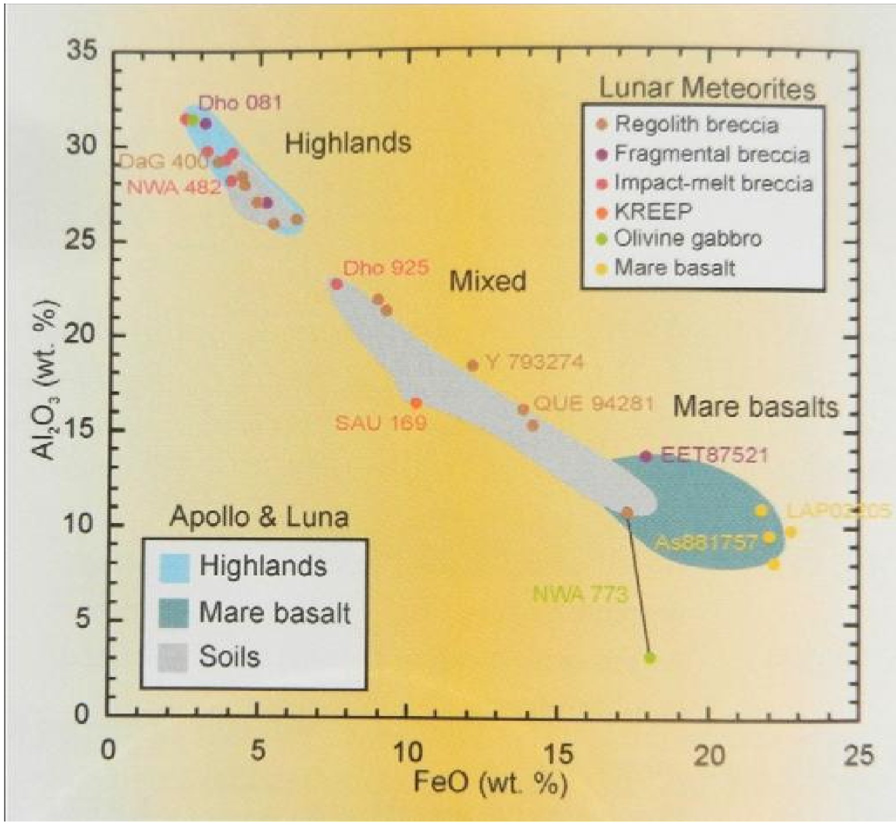
Below: the HED meteorites, by far the most numerous achondrites, are ascribed to asteroid 4 Vesta:

- Howardite regolith breccias
- Eucrite gabbroic crust
- Diogenite pyroxenites



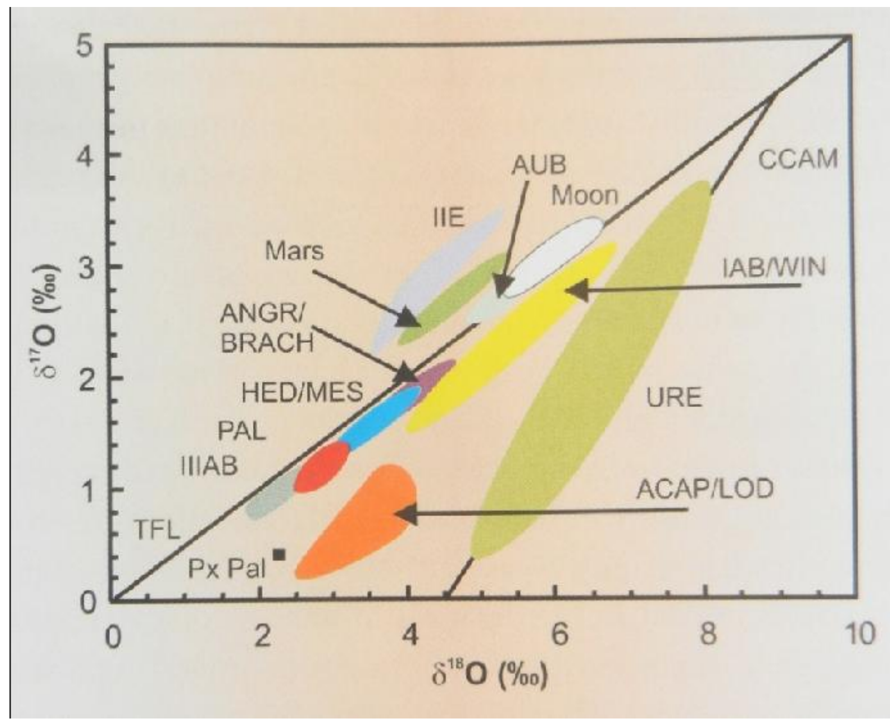
Left: 4 Vesta as seen by Dawn mission. Mean D=525 km. Estimated 9% of mass of asteroid belt.

Lunar meteorites

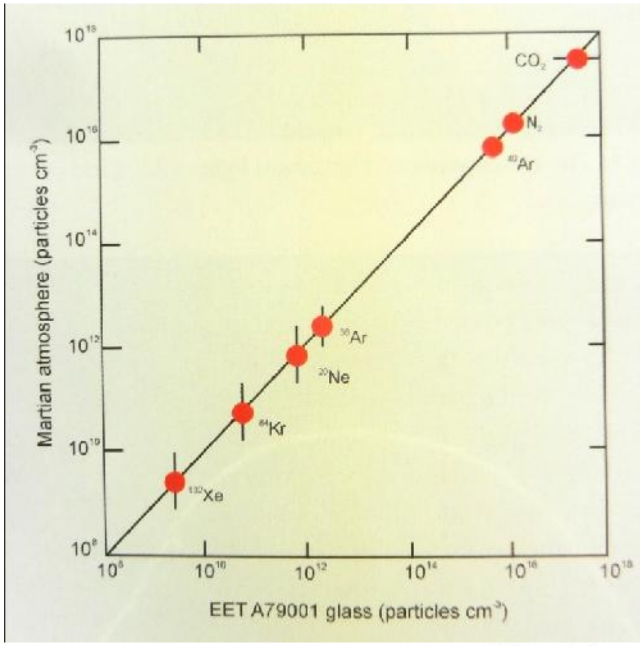


Below: O isotopes offer a "smoking gun" for Earth-Moon collisional origins, as the lunar meteorites are on the terrestrial fractionation line, unlike all other classes. Charts from Grady *et al.*, 2014.

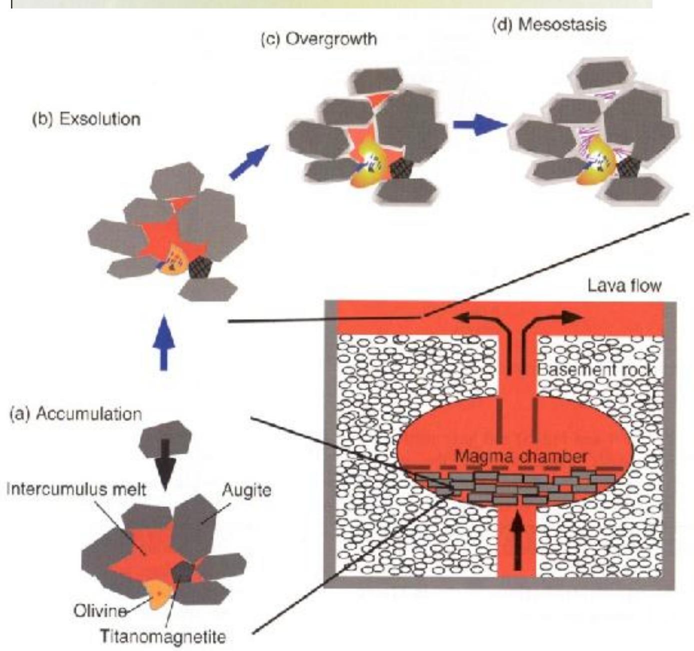
Above: we have some 381 kg of Moon rocks from the Apollo program, and a little more (0.3 kg) from other sites, from the Luna landers. Lunar meteorites plot in major-element space squarely atop the astronauts' basalt, regolith breccia, and soil samples.

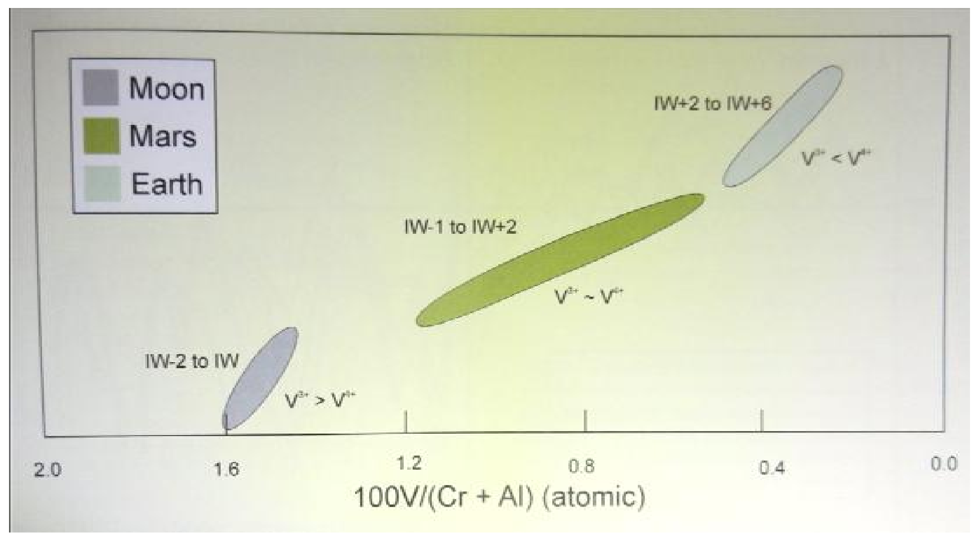


Martian meteorites



Above: shiny fusion crust on Tissint fragment (Arizona Skies Meteorites). Left: gases in martian atmosphere versus EETA 79001 meteorite. Below: chemistry of spinels from three parent bodies. Charts from Grady *et al.*, 2014. Lower left: nakhlite petrogenesis.

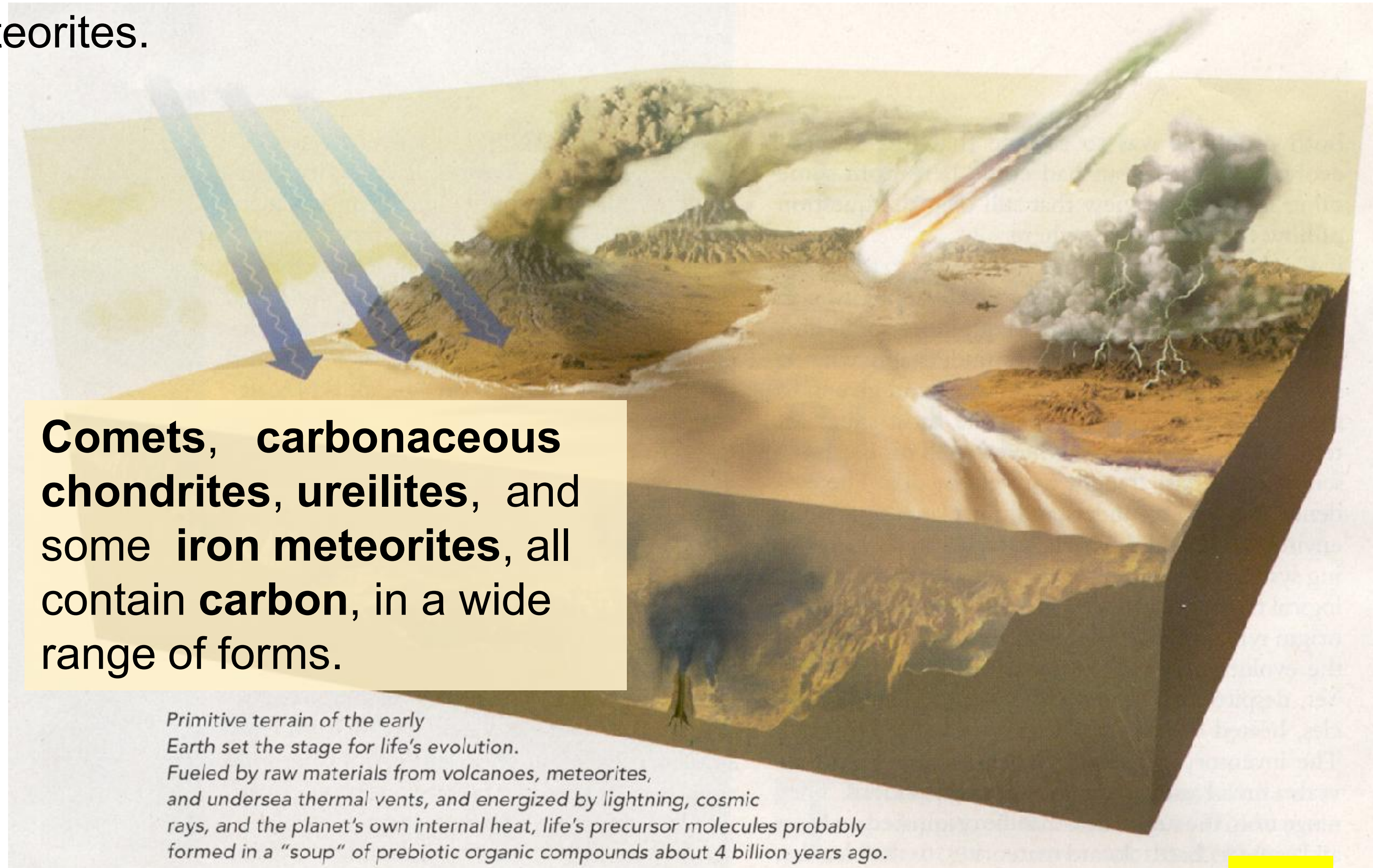




Imae *et al.*, MAPS 40, 1581-1598, 2005

Comets, organic compounds, life.

Reduced carbonaceous matter is abundant in certain meteorites. ‘Nuff said?



Comets, **carbonaceous chondrites**, **ureilites**, and some **iron meteorites**, all contain **carbon**, in a wide range of forms.

Natural History 115 no.1, p.38 (Feb.2006).

Presolar Grains

Scale bar is 1 μm. (Photo courtesy of S. Amari.)

Above: SEM view of 4-micron SiC grain isolated from the Murchison CM chondrite (S. Amari). This little beauty predates our solar system, and condensed in gas and dust shed from a star that may have died before our Sun was born!

Presolar grains, generally <1 to 30 µm in size, are refractory, simple minerals such as diamond and graphite (C), moissanite (SiC), and corundum(Al_2O_3). They appear to have condensed in the outer atmospheres of stars and been ejected by stellar winds, or during supernova events. Depending on the circumstances of their birth, they may exhibit “unearthly” isotope ratios of major elements such as Si, C and N.

Below: SN1987a / Tarantula Nebula. Astron. Soc. of the Pacific. This supernova was visible to the naked eye, at a distance of 168,000 light years!

Isotope anomalies & evidence of nucleosynthesis (seen at Oklo on Earth, but on an epic scale in UOC and CC!)

The evolution of the chemical elements, or **nucleosynthesis**, has been formulated by astrophysicists and nuclear chemists over the past 60 years or more, with an early, seminal review, "B^2FH", appearing in 1957, starting a spate of papers, many with constraints from isotope measurements in meteorites.

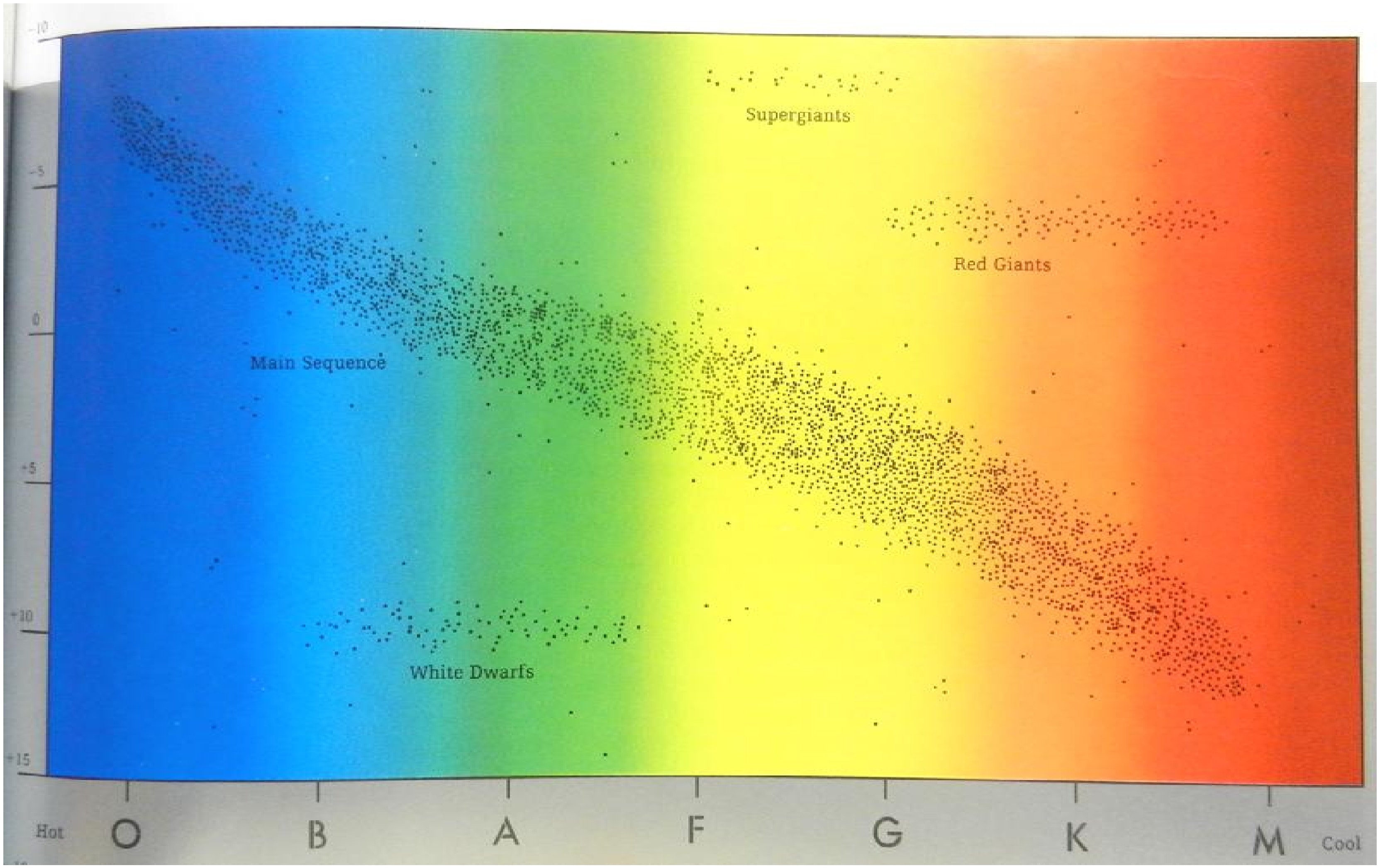
The cook book in brief:

- ❑ Big Bang: H + He (maybe a dab of Li, Be, B)
- ❑ Fusion to the iron peak (60 amu: Fe, Ni)
- ❑ More intense stellar environments, such as supernova shells, host r-, s- and p-processes for serial addition of neutrons and protons.

Selection of processes detectable in Moon rocks and meteorites :

- ❑ Decay of extinct radionuclides present in the early solar nebula, now represented by daughter products (e.g., ^{26}Al => ^{26}Mg, t½ = 0.72 Ma and ^{107}Pd => ^{107}Ag, t½ = 6.5 Ma)
- ❑ SCR and GCR spallation reactions forming cosmogenic nuclides
- ❑ Implantation of cosmic ray particles ("gardening" of lunar soils)

Atoms from where, you say?



Hertzsprung-Russell diagram from “Stars”, Time-Life Books, pp.30-31 (1988).

Atoms from where, you say? (II)

Environment	Processes	Elements	Evidence
Big Bang	Primordial	H, He (± Li, Be, B)	Astronomy
Main Sequence	Fusion	Up to Fe, 56-60 amu	Nuclear physics
Massive AGB (±Wolf-Rayet) Stars	Fusion and neutron-rich settings with ^{22}Ne neutron source	C, N, Si, and cosmogenic nuclides such as ^{26}Al, ^{60}Fe, ^{107}Pd	SiC in Murchison: see also novae
Novae	Fusion	C, N, ^{22}Na, ^{26}Al	C, N, Ne, Mg, Si in SiC, spinel, graphite
Supernovae	s-, r- and p-processes of neutron and proton capture	Heavy (heavier, larger) atoms, Z≥26	C, N, O, Si, Ca, Ti, etc in graphite
And other sources…		A quick look, from a cursory scan of author's MINLIB database, as of 2017.	

‘Oumuamua, interstellar asteroid, 2017

18 October 2017, a 400x40-m pencil-sized body, trajectory indicative of a fleeting, fast-moving visitor to the solar system, of uncertain origins: matching it to possible parent star associations suggests a very young age, maybe only 40 or 100 Ma.

Conclusions

- ❑ The scientific spin-offs from meteorite research are huge.
- ❑ The story continues, with sample return missions to comets and proposed recovery missions to metal-rich asteroids and other space objects.
- ❑ Not only that, but meteorites are cool (regardless of visual aesthetics)!

Barwell (1965) fireball over the Royal Albert Hall. The L5 fall, 44 kg, landed near Leicester, some 160 km north and west of this view.

Thank you for your Attention!

We'll end our voyage in far-west China

Armanty on exhibit in front of the Geology and Mineral Resource Museum of Xinjiang.

Aletai (Armanty)

The 28-tonne "Armanty" mass found in 1898 in northern Xinjiang. Some 51 tonnes of IIIE iron masses with elevated Au and Ir contents are known here.

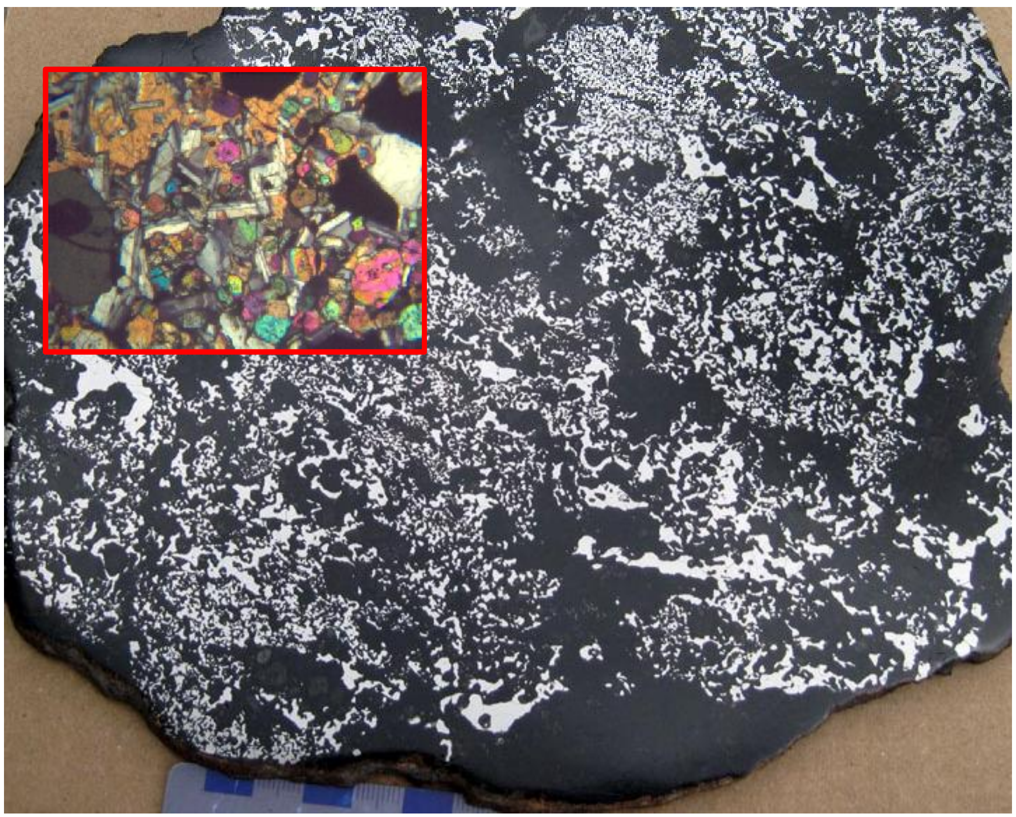
Extra slides on meteorites…

Last revised 18 Apr 2018: n=45+10

UNWA black chondrite, photo: Eric Wichmann.

``Meteorwrongs``

Some are very obvious, a few remain doubtful. A handful are so well-researched that they have been dubbed pseudometeorites. An example is Takysie Lake, a volcanic breccia from B.C. There is also Getafe, a refractory silicate slag(?) from Spain. Below, one of the best, a basalt with abundant native iron from the Putorana plateau, Siberia. It looks *soo* much like a mesosiderite!



Left: Putorana iron-bearing basalt. Below: typical slag samples.

Selected Readings

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Turnstone meteorite index (with 30-plus examples): http://www.turnstone.ca/turn-met.htm