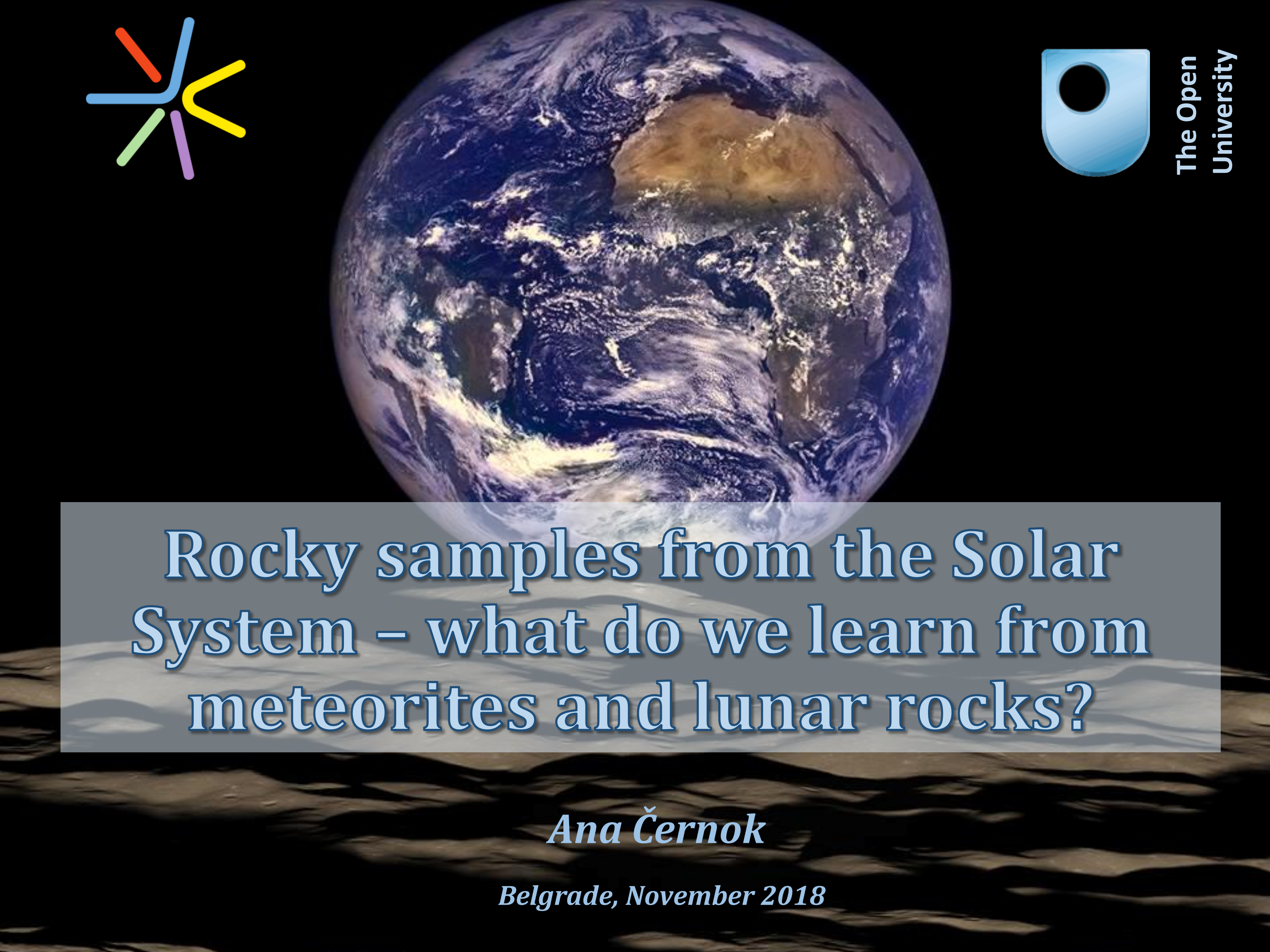


Rocky samples from the Solar System – what do we learn from meteorites and lunar rocks?

Ana Černok

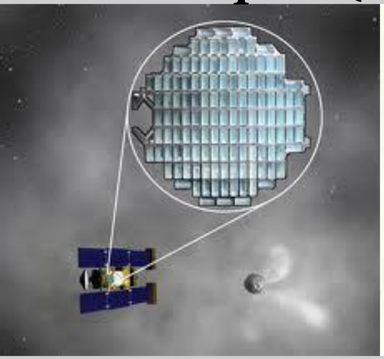
Belgrade, November 2018

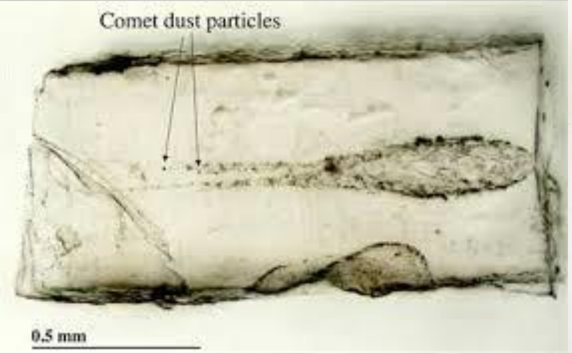
Extraterrestrial samples

- Small amount of extraterrestrial material
- Meteorites (~60 000)
- Composition of the Solar System objects
- Deep Earth objects
- Organic matter – signs of early life?
- Pre-solar grains, material older than the Solar System itself

Hayabusa
Asteroid Itokawa
2010

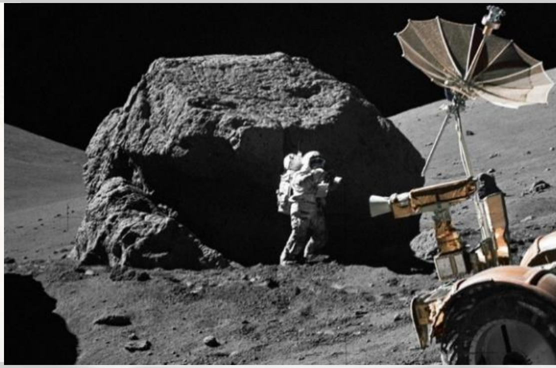
Stardust commet Wild 2 (2006)
and Tempel 1 (2011)



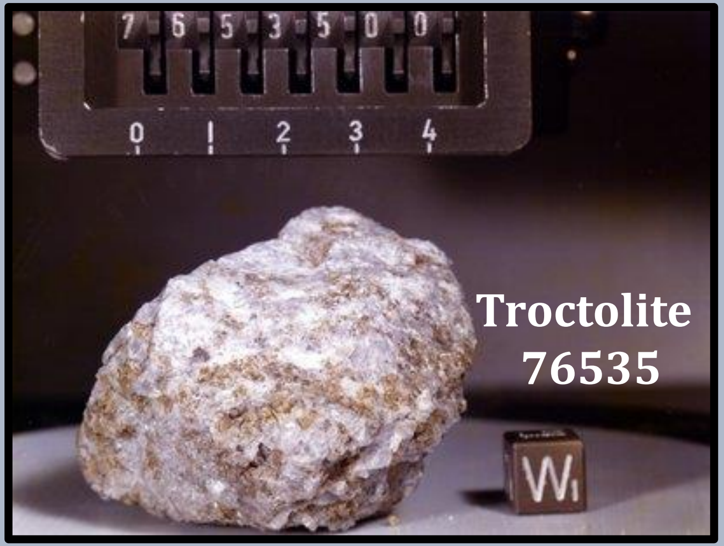


Tenham L6

Apollo & Luna (~380 kg)

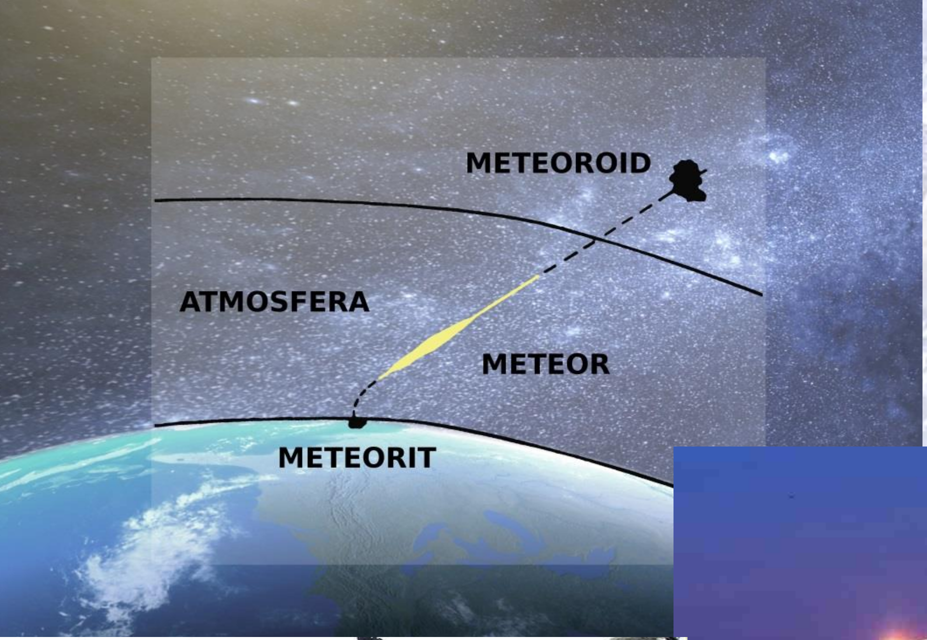


Meteorites



Lunar rocks

INTRO...



Meteoroid

Small rocky object in outer space, significantly smaller than asteroid

Meteor

A meteor is a meteoroid that has entered the earth's atmosphere and becomes brightly visible due to the ionized molecules in the upper atmosphere

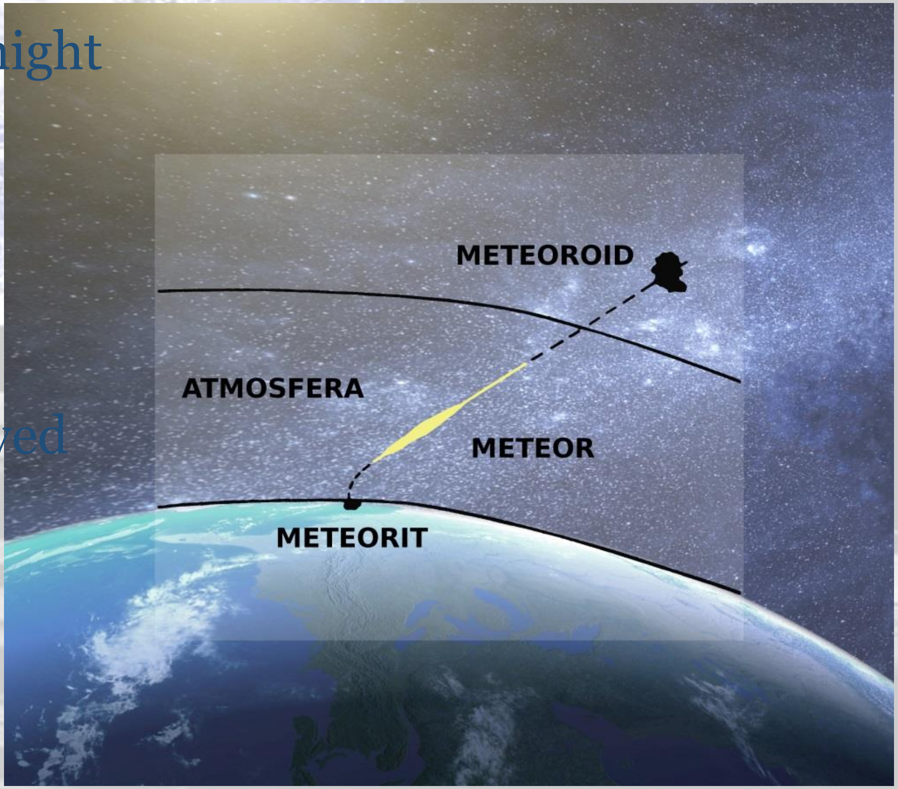
Meteorite

A meteoroid that reached surface of the Earth

Introduction

Meteorite: a meteoroid that survives that flight through the atmosphere **(~ minutes)** and reaches the surface of the Earth

- Enters Earth's atmosphere at speed 11-72 km/s
- Ionization begins at **100 km** of hight
- Fusion crust but **cold** surface
- Aerodinamical shape
- ***Pad*** *(Fall):* The flight was observed before collecting the meteorite **(Chelyiabinsk)**
- ***Nalaz*** *(Find):* all others



Fall 1877

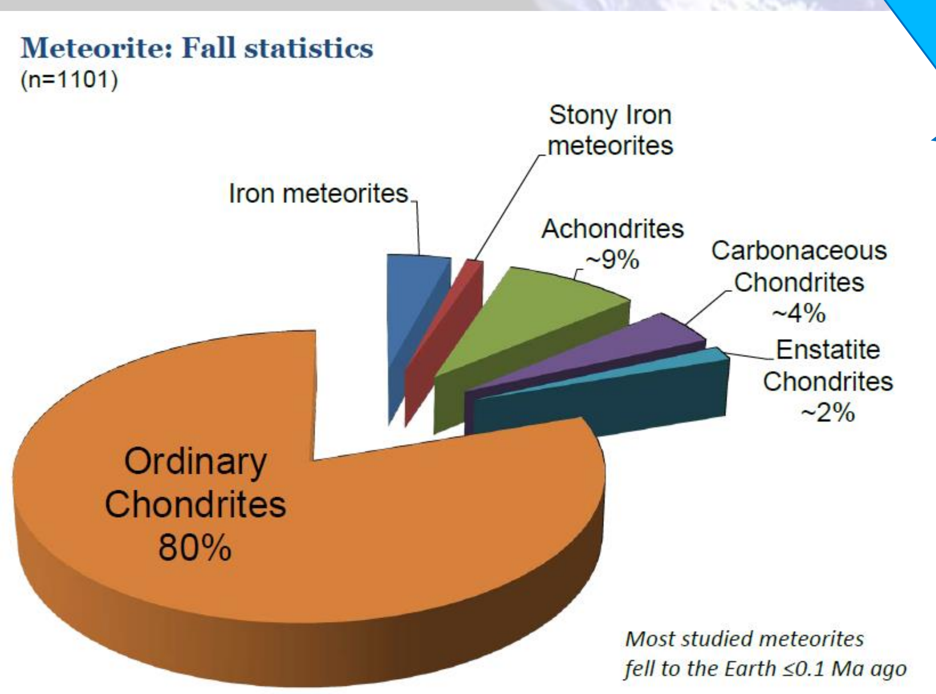
Josif Pančić, Soko-Banja prvi meteorit u Srbiji/ Glasnik Srpskog učenog društva, XLVIII (1880)

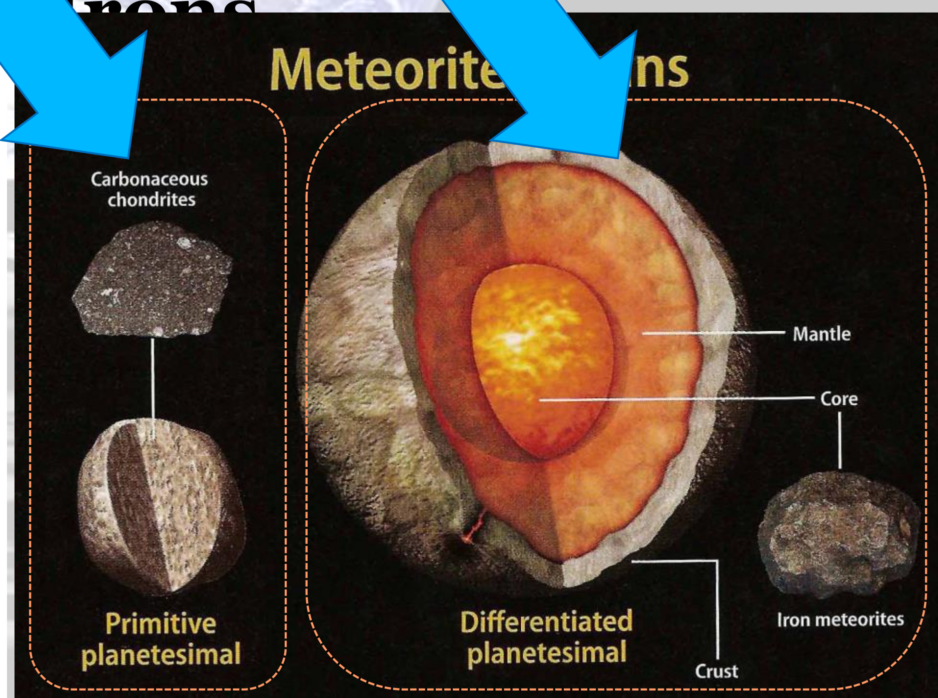
Find 1947

Meteorites

Undifferentiated | **Differentiated**

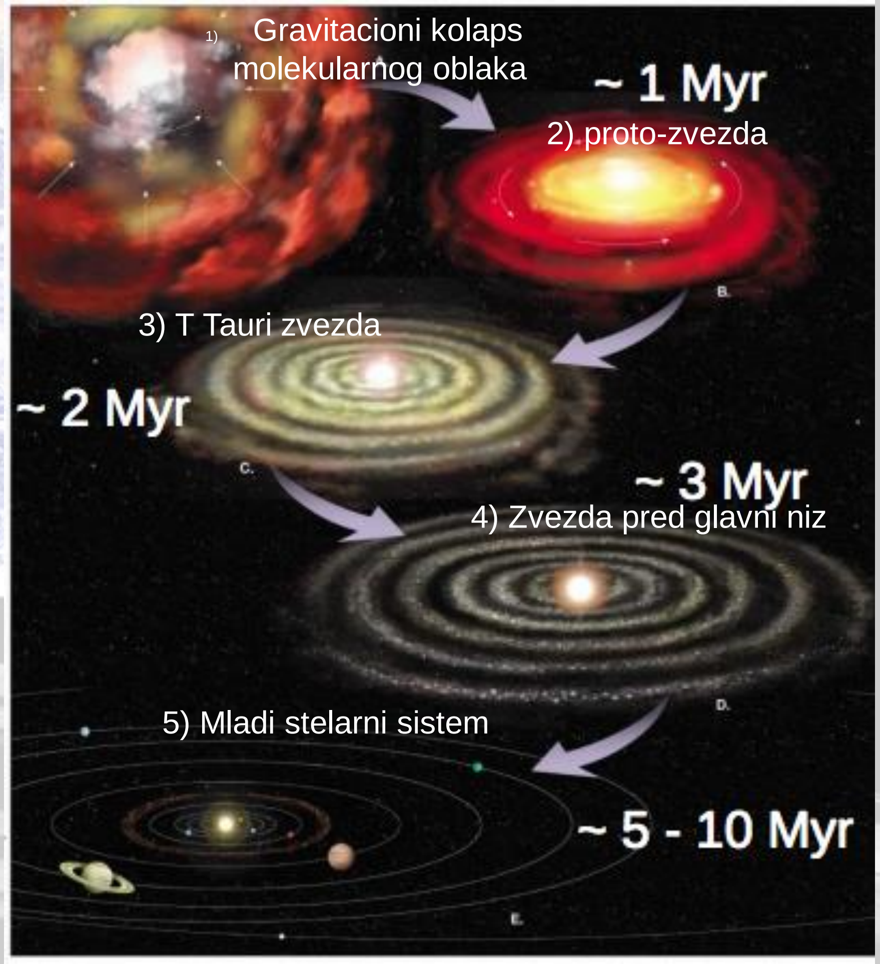
Stony Meteorites





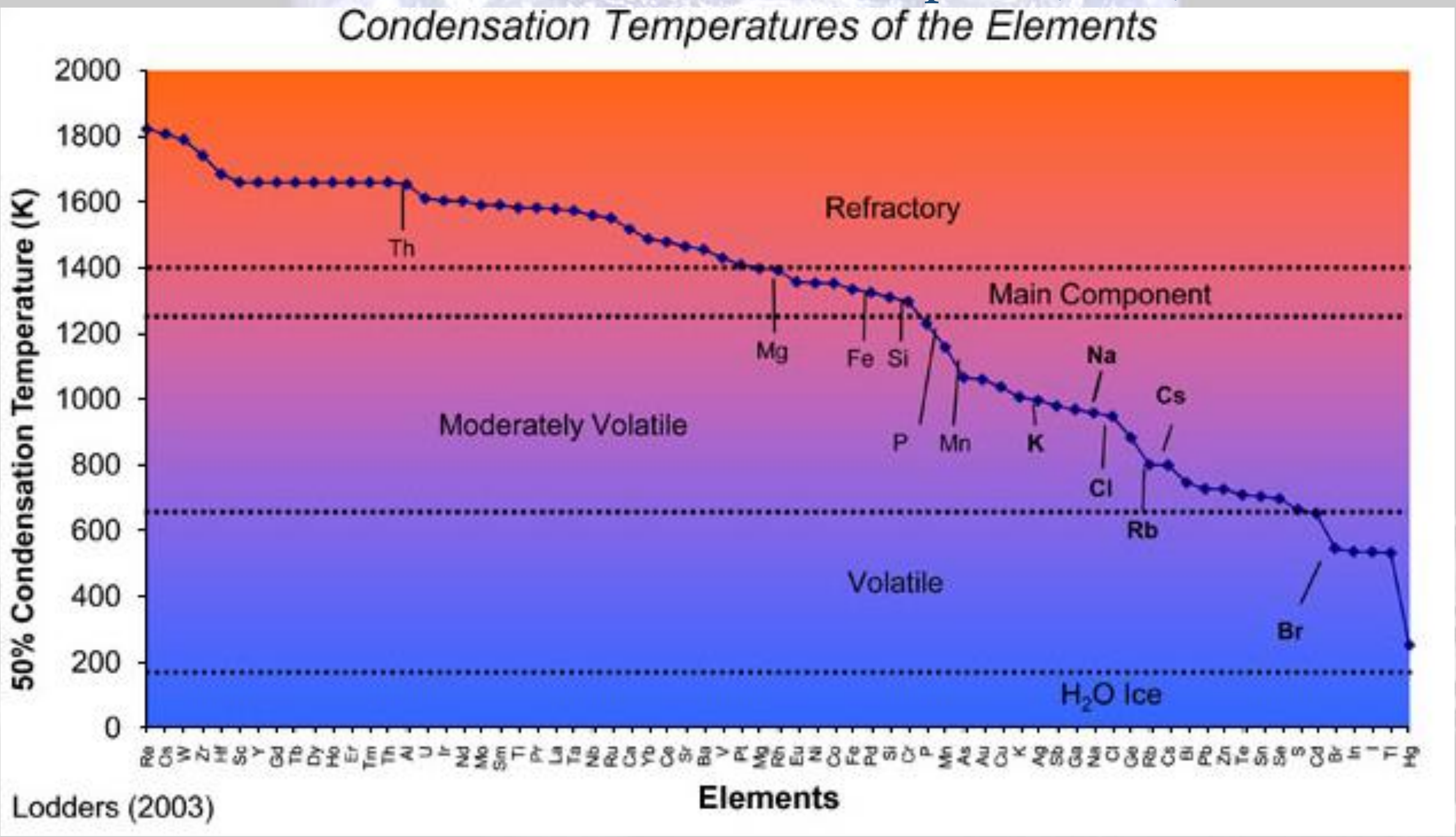
Early formation

- Solar System formation was initiated 4.56 billion years ago by collapse of the interstellar matter
- Protoplanetary disc was formed and early planetesimals (> 1km) accreted
- Further accretion led to planet formation
- Closer to the Sun: terrestrial planets – snow line – gas planets
- The **asteroid belt** – source of the meteorites



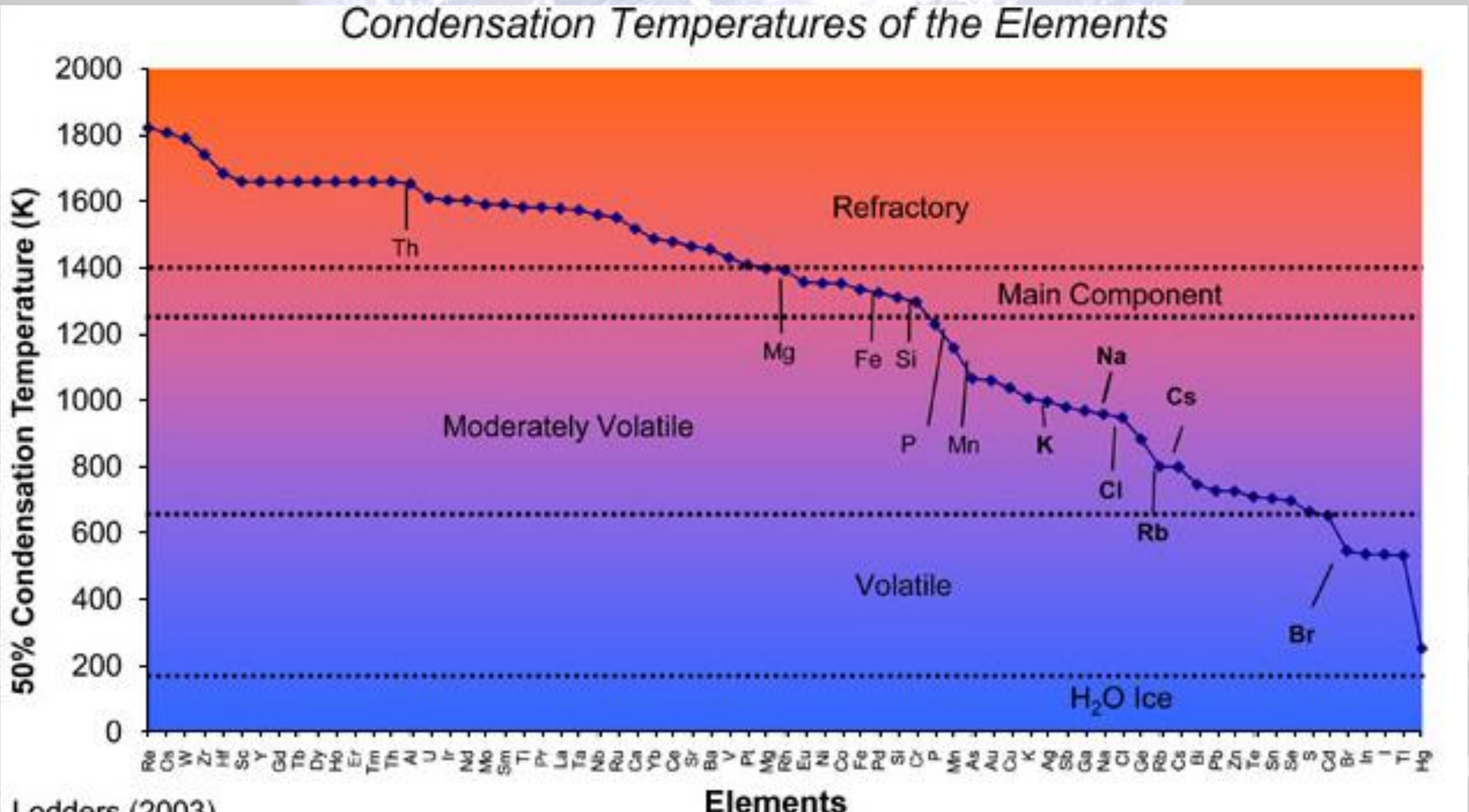
Early condensates: refractory droplets

- Refractory elements condensate first (> 1600 K)
- Local *flash heating*
- **Metals: Re, Os, Hf, W, Zr, Ir, Ru**
- Trace abundances – form small metal droplets (1mm)

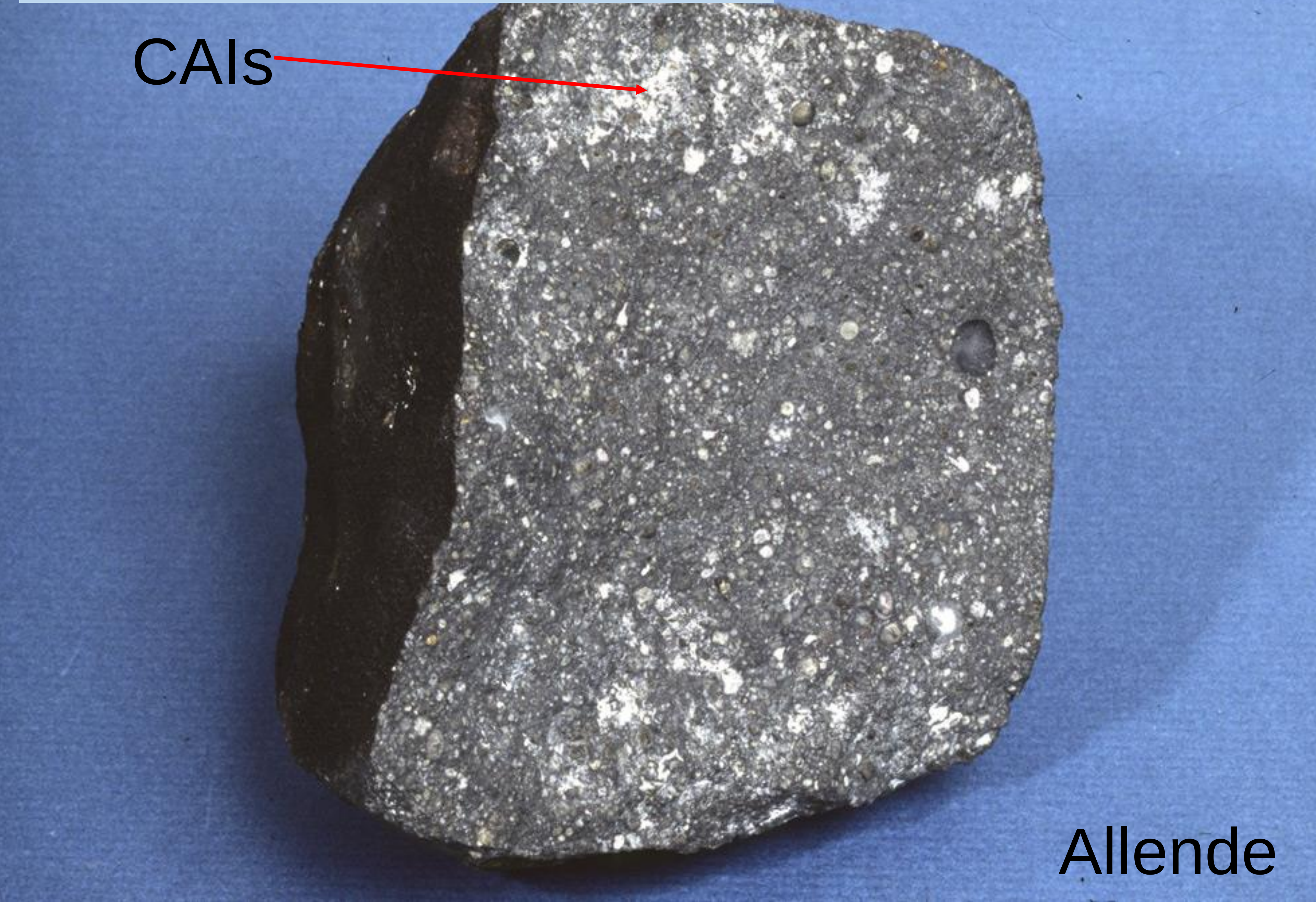


Early condensates: refractory inclusions

- Furter on **Ca, Al, Ti condensate** – forming **Ca-Al** inclusions ***(CAI)***
- High-T oxides (ceramics!): 1600 K
- The oldest dated material in the SS: 4567 (±2) million years-first solids in cooling protoplanetary disc
- Refractory droplets found within CAIs

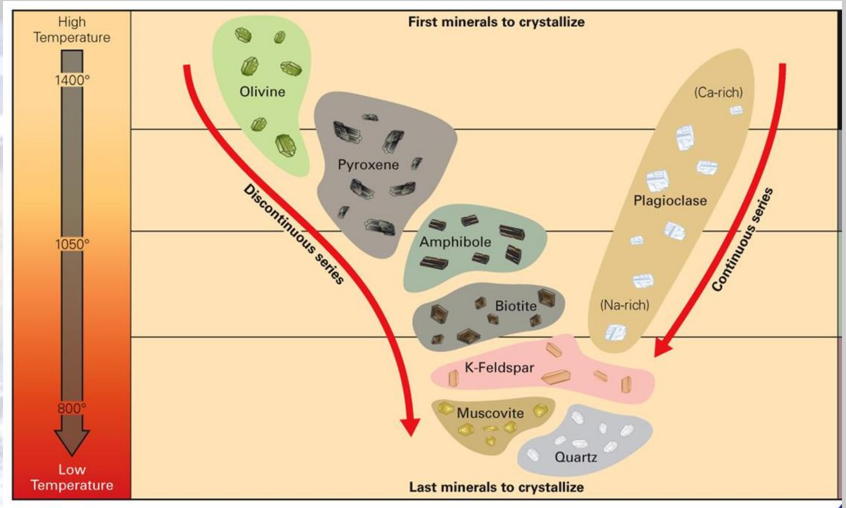


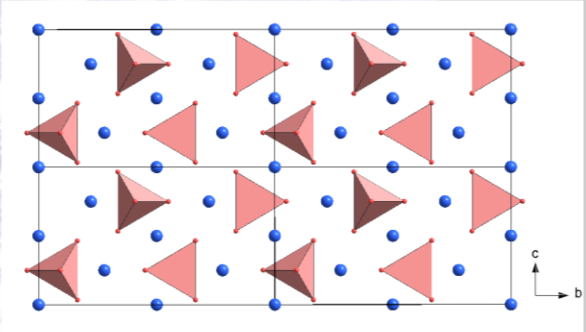
Allende Ca, Al-rich inclusion (CAI)

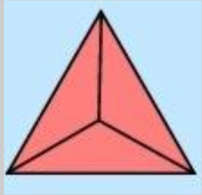


Early condensates:
chondrules

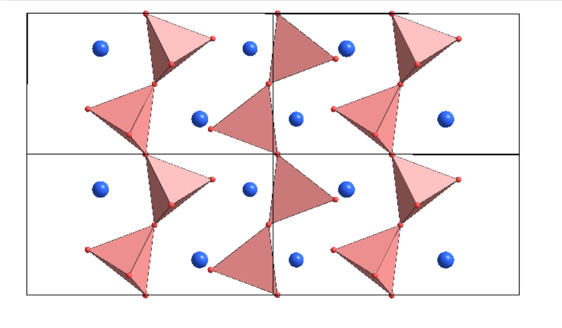
- Metals condensate: Fe, Mg and Si
- first *silicate* minerals
- **Olivine** $(Fe,Mg)_2SiO_4$
- **Piroxene** $(Mg,Fe)_2Si_2O_6$
- Chondrules: small (0.1-5 mm) silicate droplets that mostly contain olivine and pyroxene
- **First miny-rocks!**
- Formed 1 – 4 Myr after CAIs
- Other components: Ca-silicates, Fe-Ni metal…

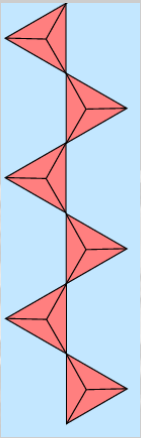




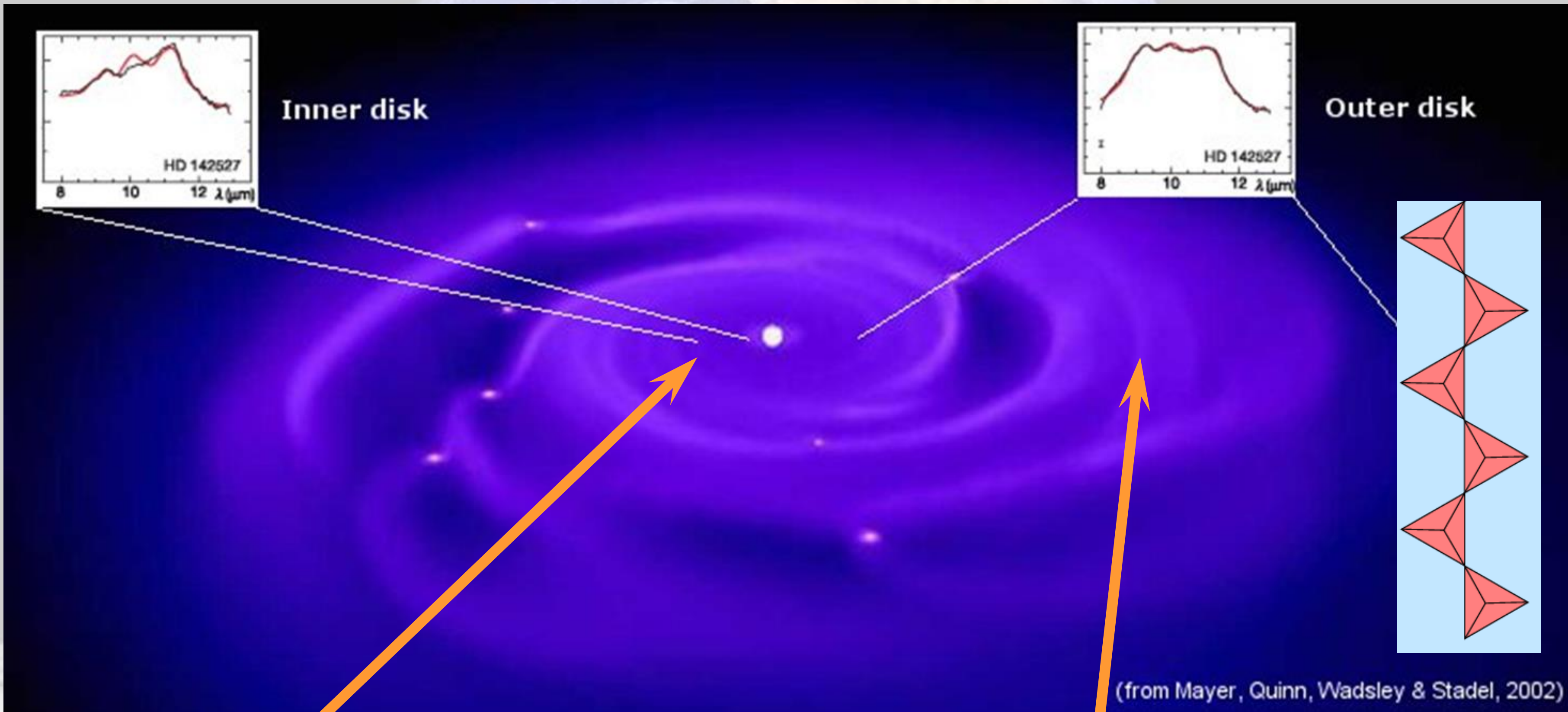


Olivin

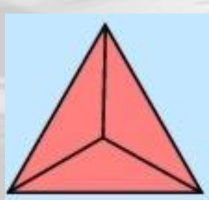




Piroxene

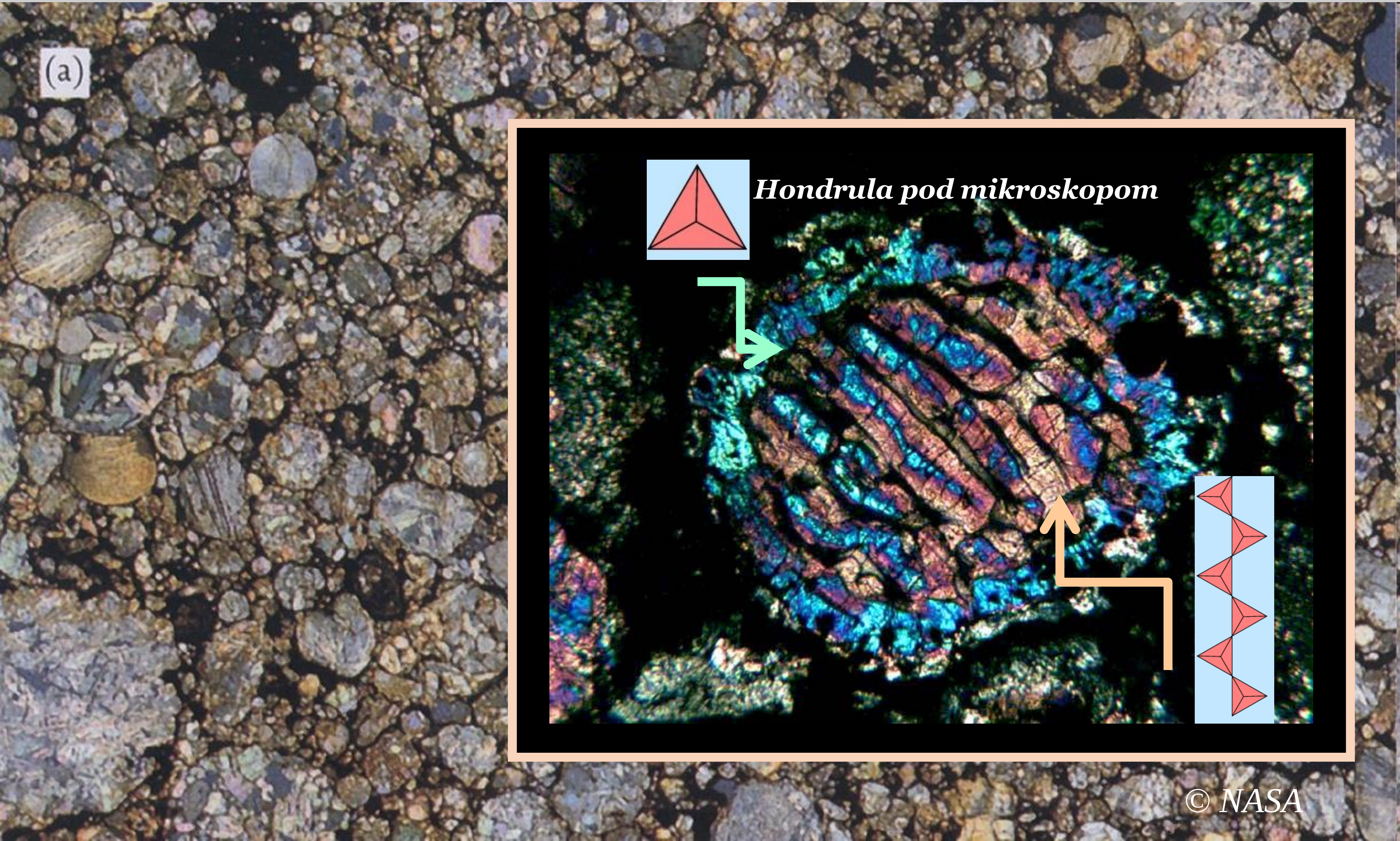


Olivin

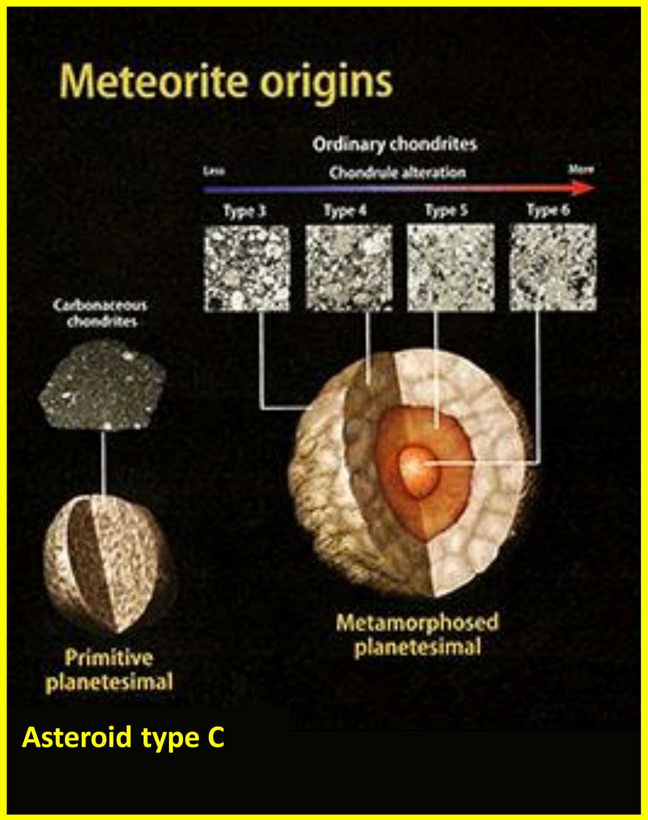


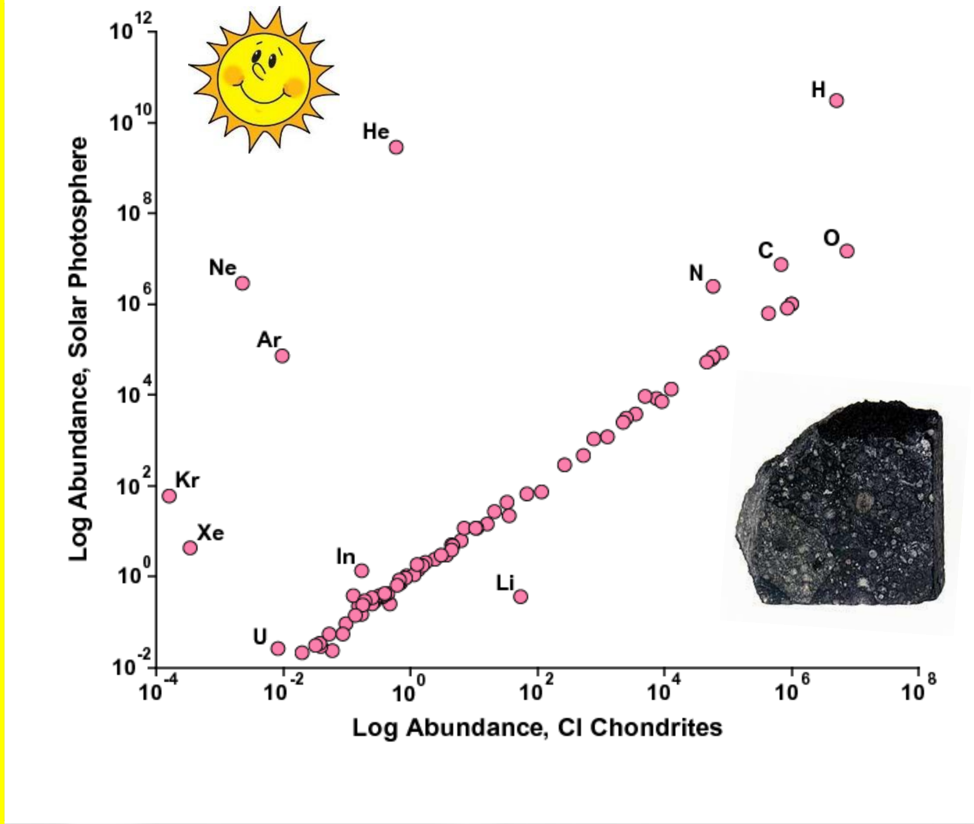
Olivin i piroksen

Chondrules: 1st silicate rocks



Undifferenciated meteorites: Chondrites

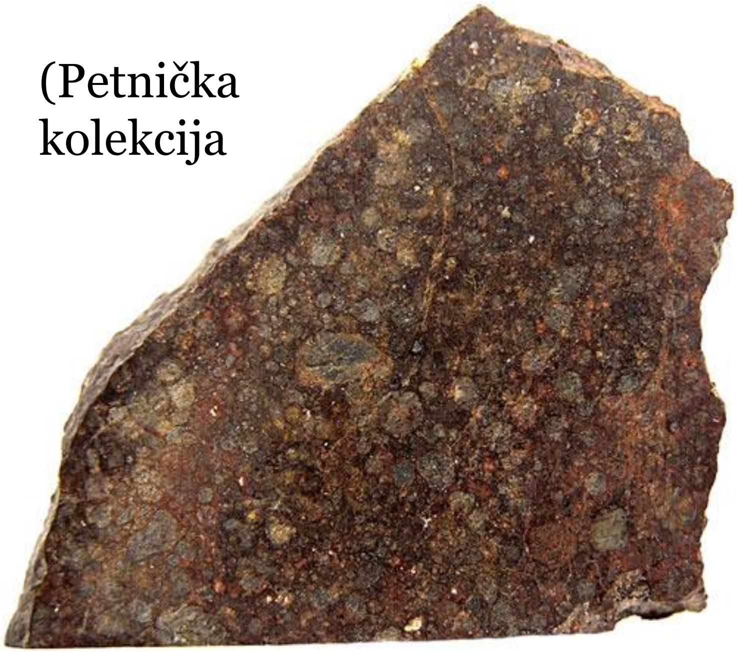




- The oldest meteorites in the SS
- Their bulk composition reflects the composition of the Sun
- Often used as reference material

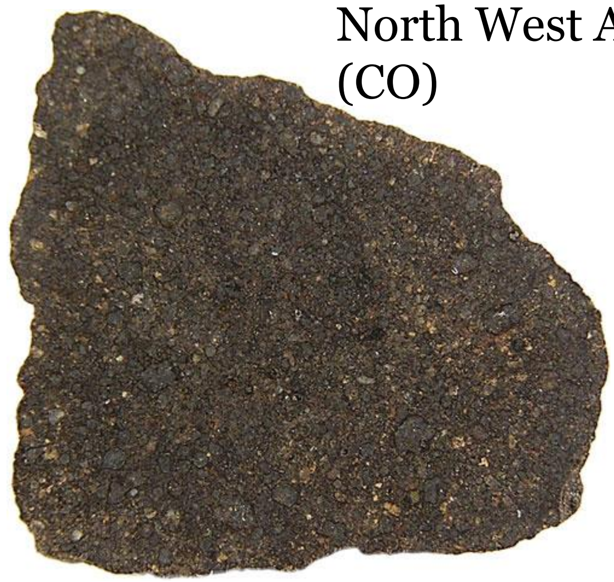
Dhofar
(Ordinary Chondrite H)

(Petnička
kolekcija

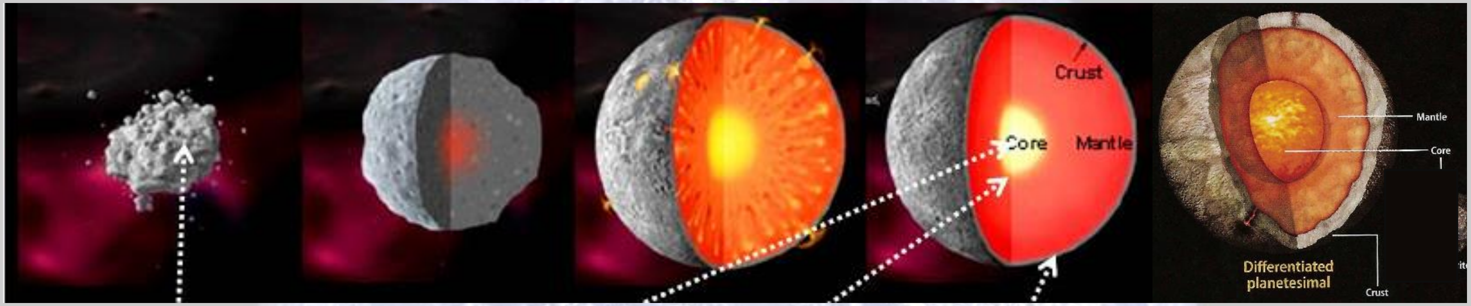


North West Africa
(Ordinary L)

North West Africa
(CO)



Planetesimal accretion

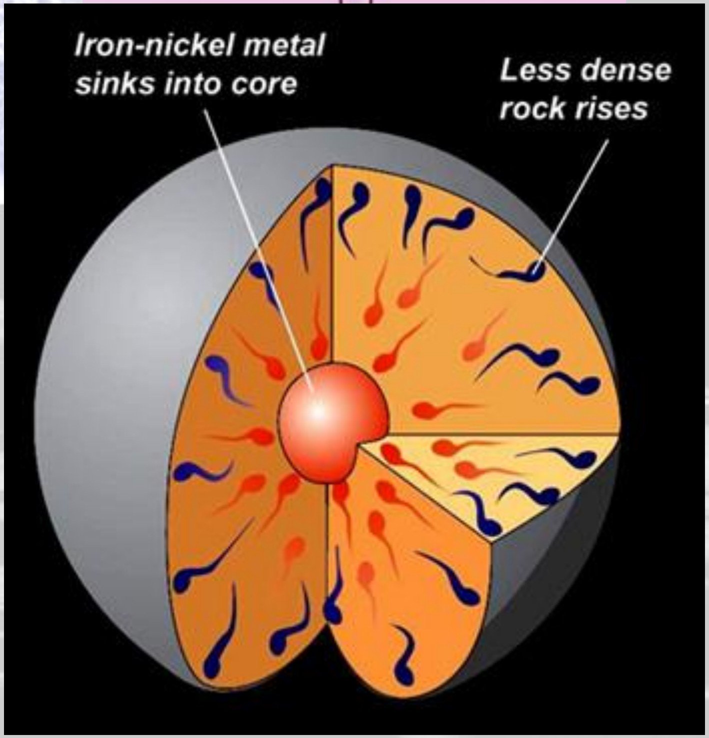


Differentiation

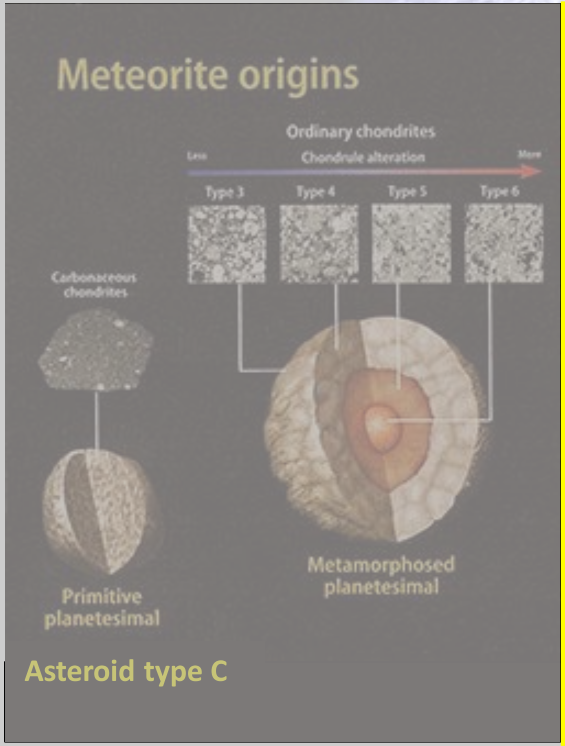
- Planetesimal accretion due to chaotic impacts – mass and size gorwth (up to 500 km in diameter)
- That leads to internal temperature increase
- ^{26}Al and other short-lived radioactive isotopes produce heat (e.g. daughter-isotope ^{26}Mg)
- Other sources of heat: impacts, collisions, gravitation & further accretion
- Melting of Fe-Ni (~1200K) and silicates (~1300K)

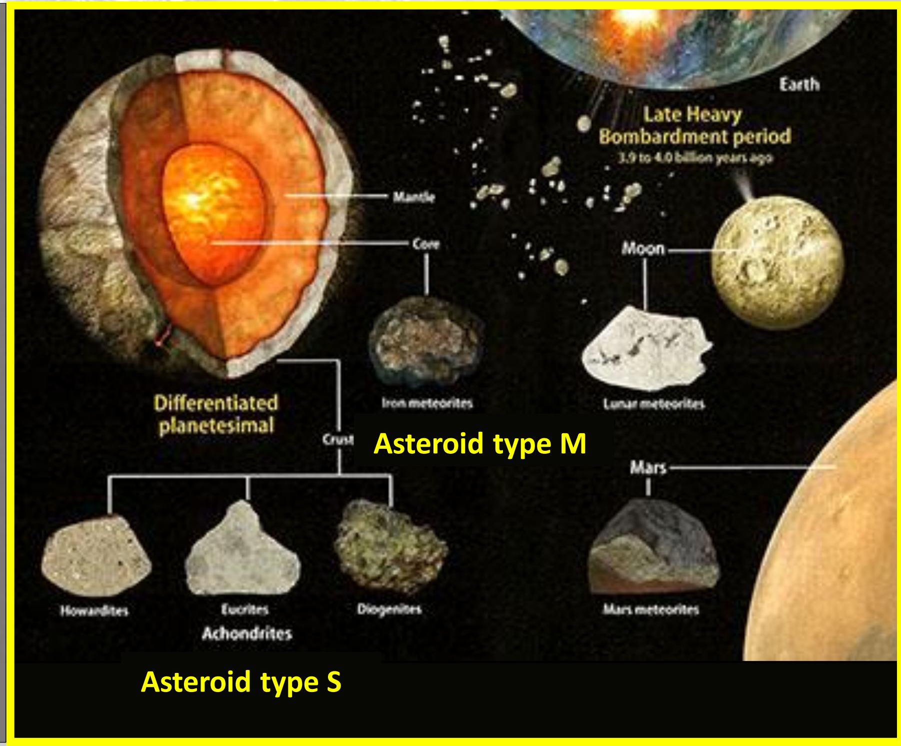
Formation of the protoplanets

- Silicate and metal liquids/melts are incompatible – causing separation and differentiation
- Metallic (Fe-Ni) melts are denser and sink to form a core
- Silicate melts (olivine, piroxene) melts migrate to the surface



Differentiated meteorites

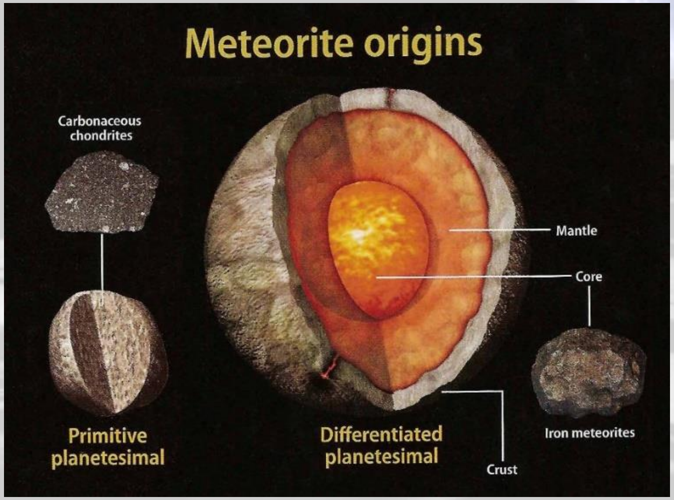




- Differentiated meteorites do not contain chondrules
- Only a minor (8%) group of total number of meteorites
- Mostly younger than chondrites

Differentiated meteorites: core and mantle

- Core and mantle of once existing protoplanets
- Core samples of destroyed protoplanets = **Iron meteorites**
- Mantle: contact of core and deep mantle
- Incompatible melts of metal and silicate:
- **Pallasite**(metal and olivine)
- **Mesosiderite** (rich in silicates)



Gibeon, oktaedrit, 1836
Widmanstätten-Pattern

Palasit Fukang, China, 2000
1003 kg

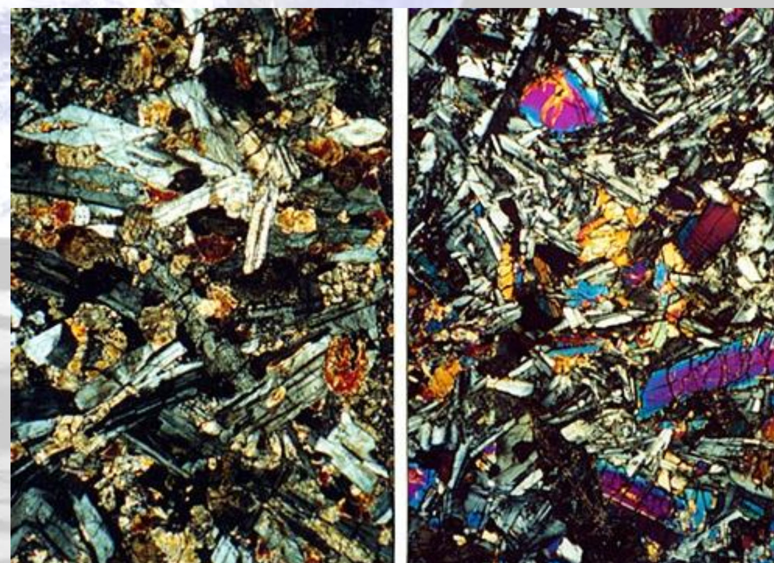
Differentiated meteorites: crust

- ***Achondrites:*** Meteorites sampling asteroids' surfaces

  HED (4 **Vesta**) Hovardite; Eucrite; Diogenite

- Originate from the surface of differentiated bodies – rich in silicates, depleted in metals

- Very similar to terrestrial basalts: volcanic textures



Asteroid 4 Vesta
(asteroid belt, 530 km diameter)

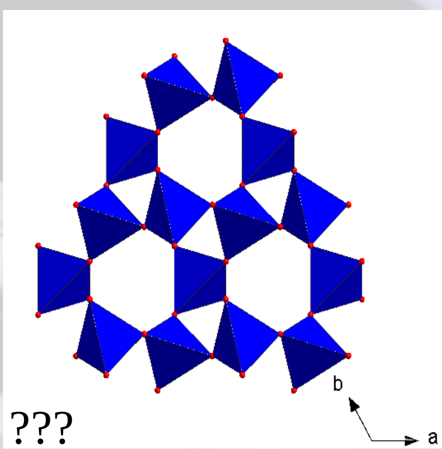
Textural similarity of the basaltic eucrite Stannern (left; pyroxenes white to gray; pyroxene, brown to buff) compared with a terrestrial basalt (right; same with highly colored olivine grains).

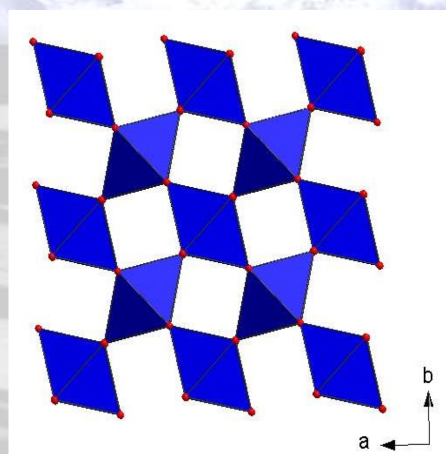
Differentiated meteorites: crust

- **Lunar & Martian meteorites**
- **Lunar (138** meteorites, 222 kg): blasted of <20 Ma ago, but mostly few hundred thousand, small craters
- Many originate far from PKT (low Th)
- **Martian (124):** wide range of crystallization ages, launched in last 20 Ma
- Noble gasses composition (Ar) confirmation of Mars atmosphere

Shergottite, Naklithe i Chassignite different groups

- *ExoMars possible sample return 2030*

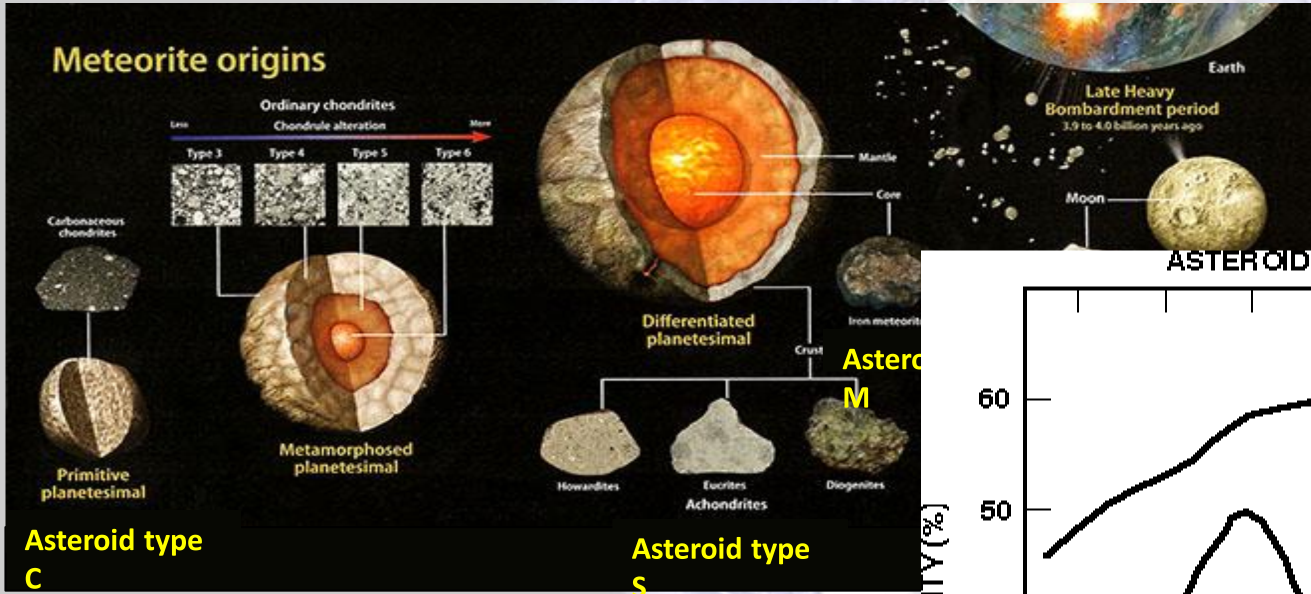




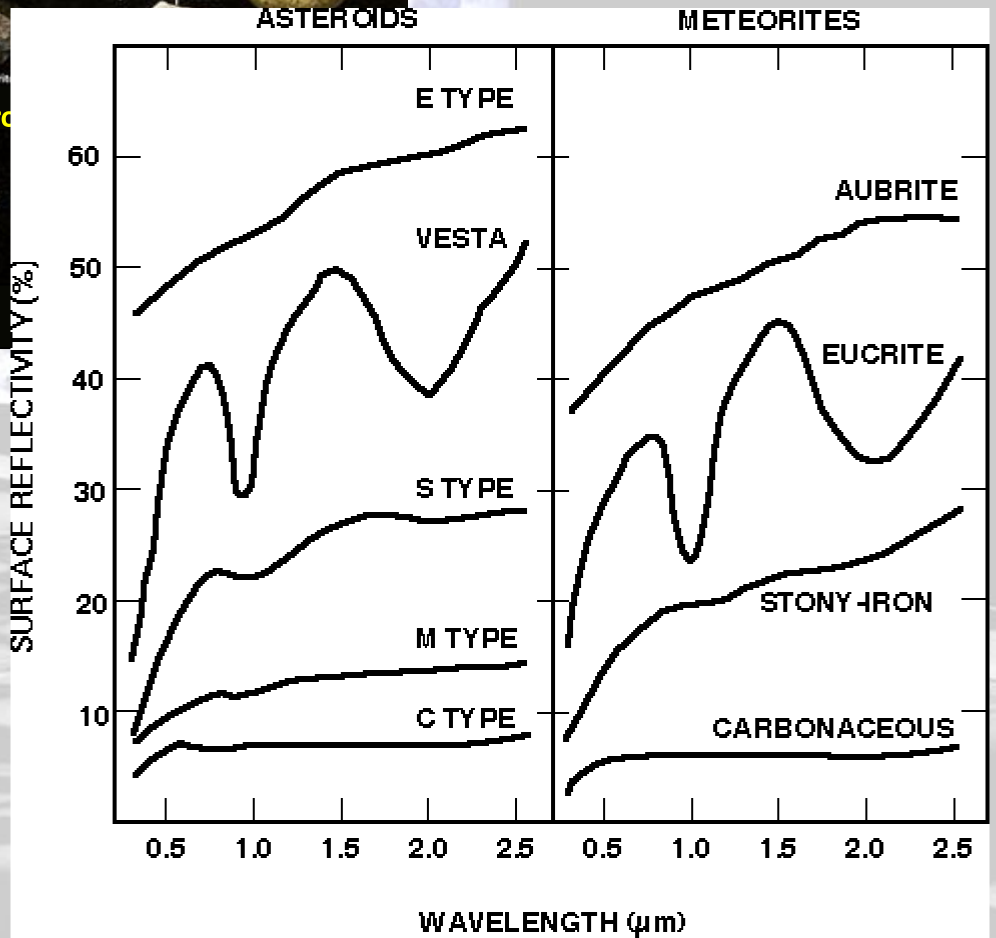
stishovite

Shocked quartz

SUMMARY

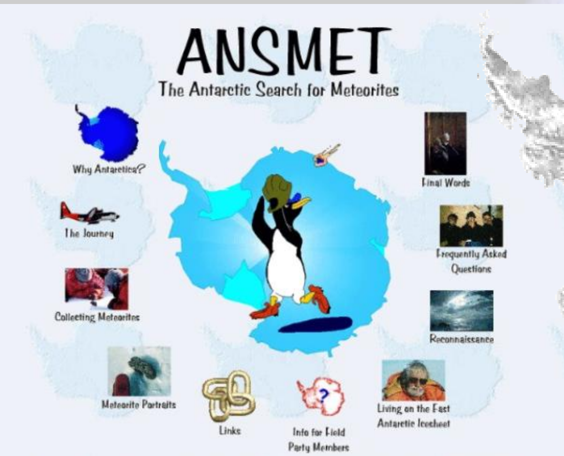


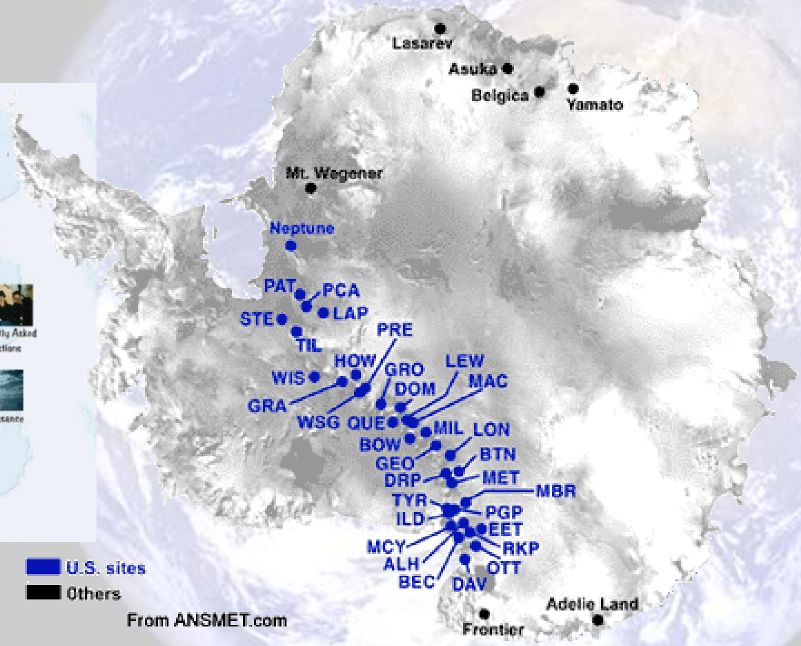
Meteorite origins
Ordinary chondrites
Chondrule alteration
Type 3
Type 4
Type 5
Type 6
Carbonaceous chondrites
Primitive planetesimal
Metamorphosed planetesimal
Differentiated planetesimal
Mantle
Core
Crust
Iron meteorites
Howardites
Eucrites
Diogenites
Achondrites
Earth
Late Heavy Bombardment period
3.9 to 4.0 billion years ago
Moon
Asteroid type C
Asteroid type S
Astero
M

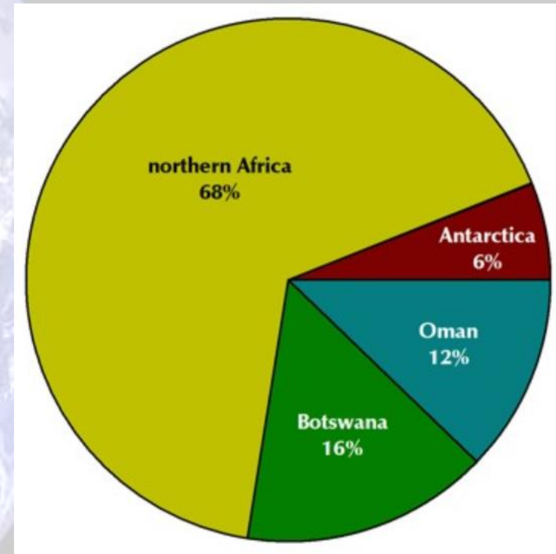


ASTEROIDS
METEORITES
E TYPE
VESTA
S TYPE
M TYPE
C TYPE
AUBRITE
EUCRITE
STONY-IRON
CARBONACEOUS
SURFACE REFLECTIVITY (%)
10
20
30
40
50
60
0.5
1.0
1.5
2.0
2.5
WAVELENGTH (μm)

Collecting meteorites systematically





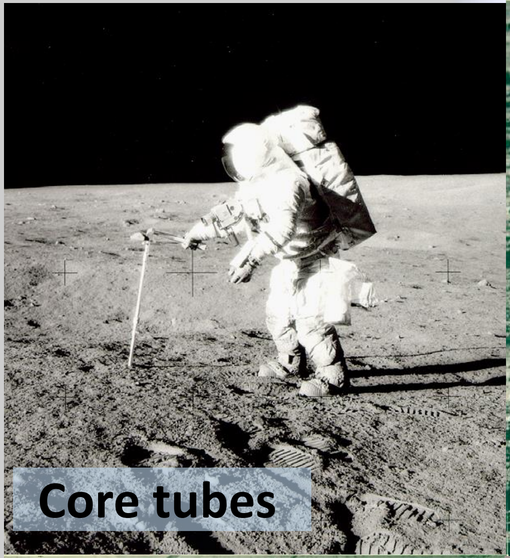


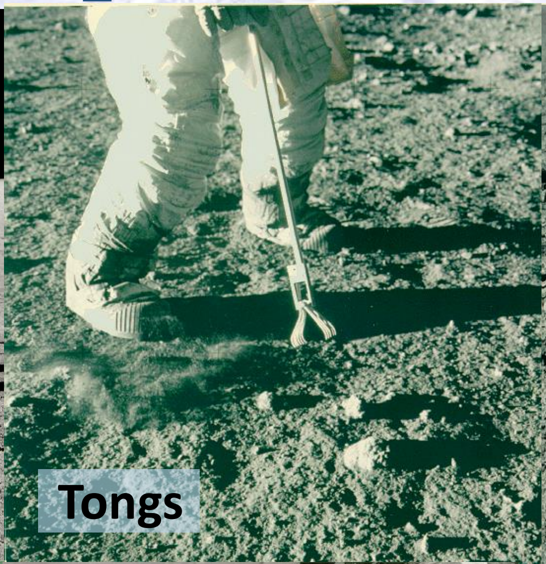
- Until 1978 only about 3000 meteorites around the world
- Antarctic, Sahara, Botswana missions
- Micrometeorites collected in snow ice and deep sea sediments

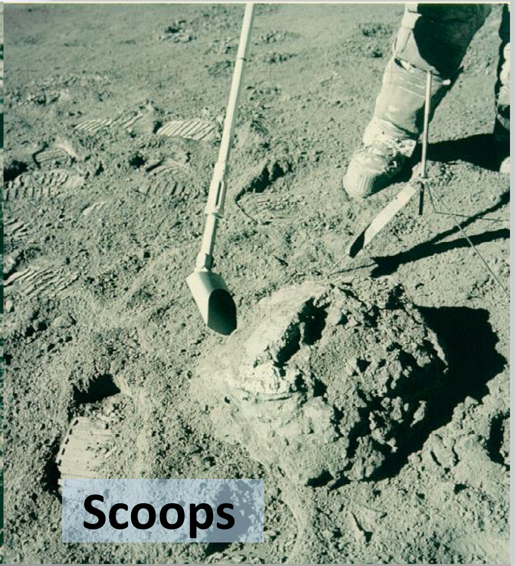
It was the year 1969…

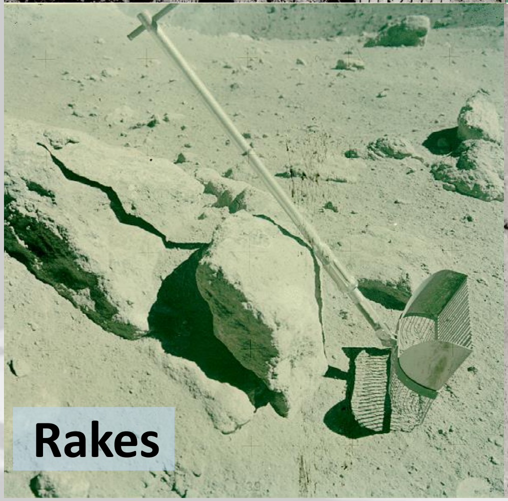
- Fireball Feb 8th 1969, Pueblito de Allende
- 2 tonns of meteorite (largest piece 110kg), covering 50km area
- Served as laboratory preparation for Apollo missions (Apollo 11 july 1969)
- Best studied meteorite CAIs & organic matter

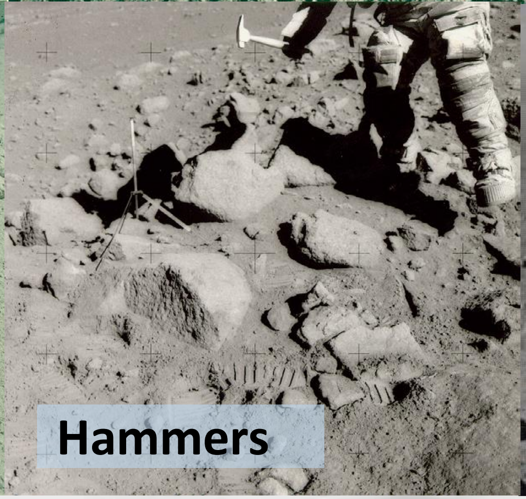
Lunar samples

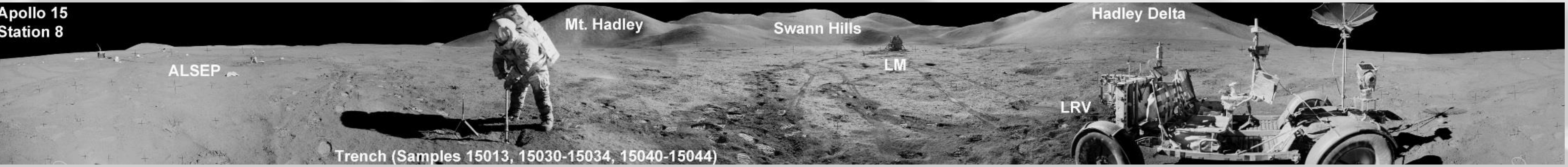






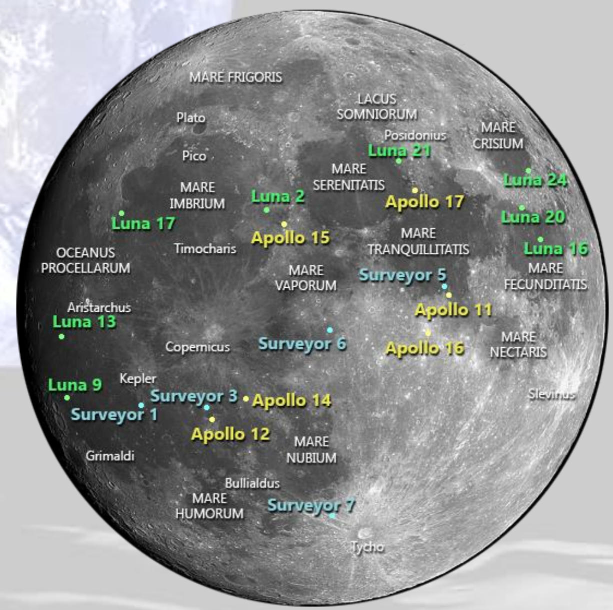






Sample return

- **Luna sample return:** Luna 16, 20 and 24 collected 0.3 kg of lunar soil
- **Apollo sample return:** Six Apollo missions ~382 kg of **rocks** and soil
  - Apollo 11 22kg (basalts and breccias)
  - Apollo 12 34 kg (almost all basalts)
  - Apollo 14 42 kg (mostly breccias)
  - Apollo 15 76 kg (basalts and breccias)
  - Apollo 16 96 kg (mostly breaccias)
  - Apollo 17 111 kg (highland samples and breccia)

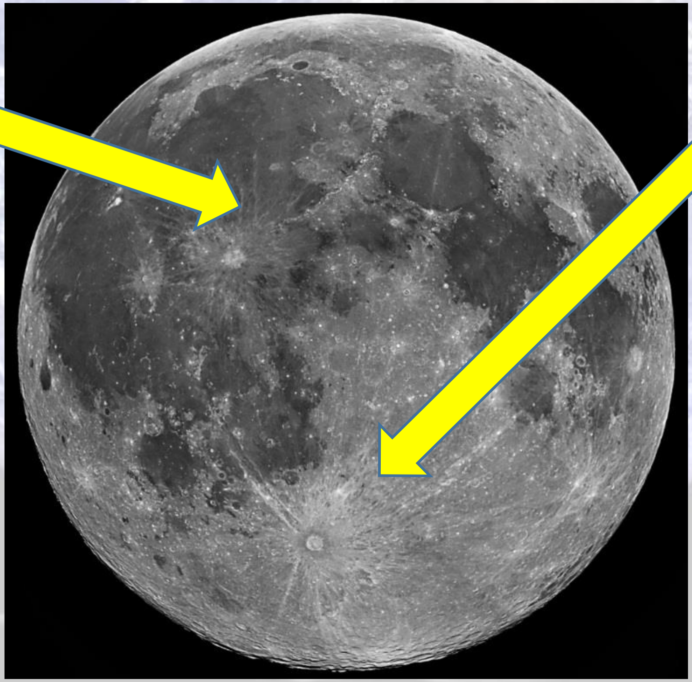


Apollo 17 – a geologist on board; focused selection of the acquired samples

Geology of the Moon

Maria:

- Dark in colour
- Basalts (cooled lava)
- Younger



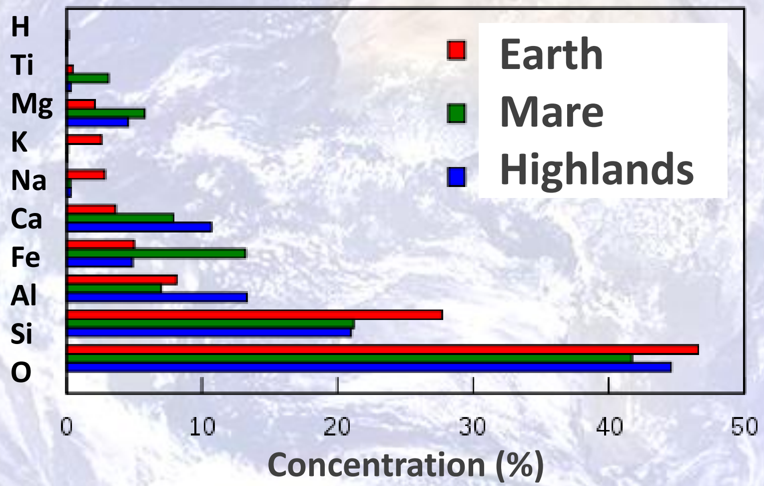
Highlands (crust)

- Light in colour
- Represent lunar crust
- Several different types of rocks
- Ancient

- To understand where the difference comes from, we have to consult mineralogy

Intro to mineralogy

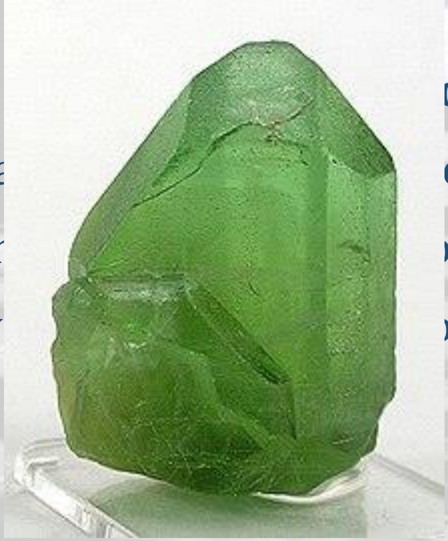
- These are the most abundant elements on Moon & Earth
- Elements are combined into inorganic (crystalline) compounds **i.e. minerals**
- Minerals join together to form a rock



- **Useful analogy:** letters form words, words form sentences
- Rocks are like sentences – we read geologic history by understanding the meaning of each word and their context

Important for … ock c…

- Si, Al, Fe, Ca a… omm… Moon
- Note the high… on (m…
- Note the low… on Mo… i.e. volatile)



Mineral (olivine) on its own

Mineral (olivine) with other minerals

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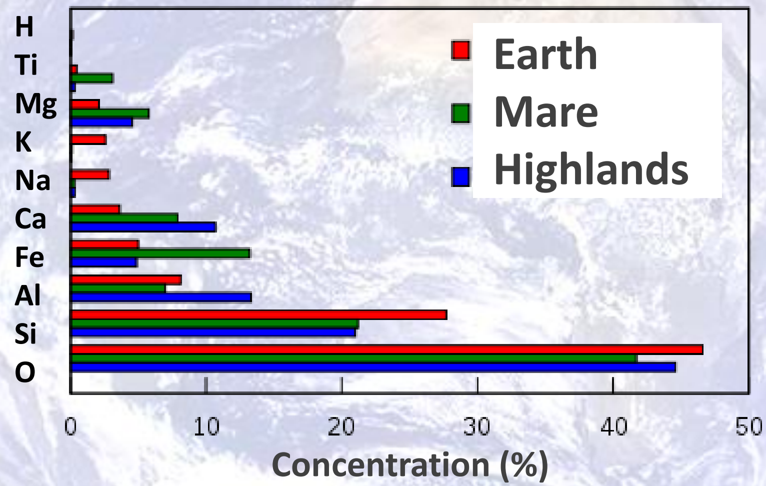

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Moon crust:

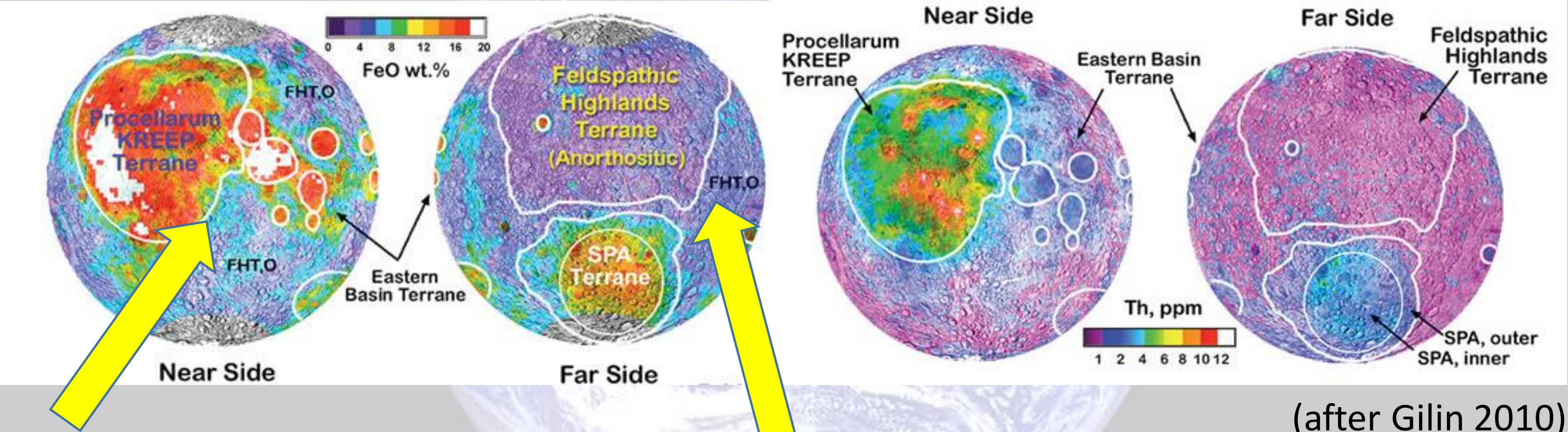
Common minerals:

Earth crust:

Common minerals:

- The fact that the **Moon has only a handful** of different minerals
- Moon’s history is frozen in time – processes in early Solar System

Surface rocks



(after Gilin 2010)

Maria (ca. ~3.9-3.2 Ga, and younger)

Minerals:

- Pyroxene (**black** or green)
- Ilmenite (**black**)
- Olivine (green)
- Some plagioclase (white)
- A **LOT** of accessory minerals

Rocks:

- Mare basalts, KREEP basalts, and volcanic glasses

Crust (ca. 4.5 – 3.9 Ga)

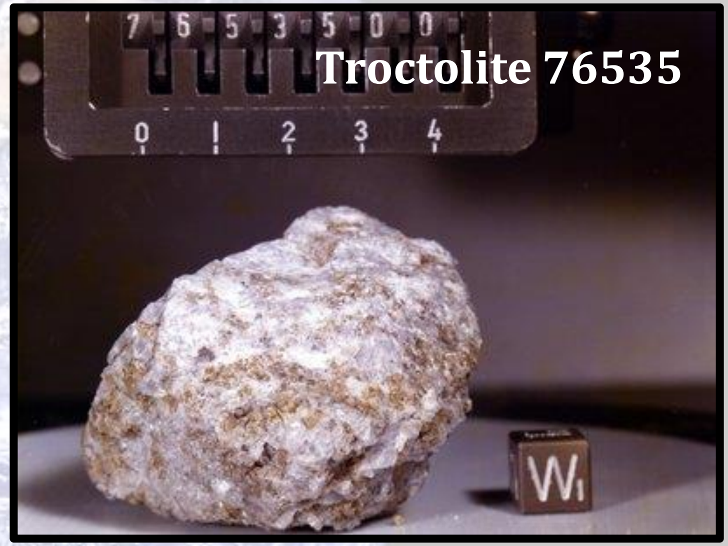
Minerals:

- Dominantly plagioclase (**white**)
- Some pyroxene (black or green)
- Some olivine (green)
- Some accessory minerals

Rocks:

- Primary crust – anorthosite (plagioclase)
- Secondary crust – Mg suite, alkali suite

Surface rocks



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Rocks:

- Mare basalts, KREEP basalts, and volcanic glasses

Crust (ca. 4.5 – 3.9 Ga)

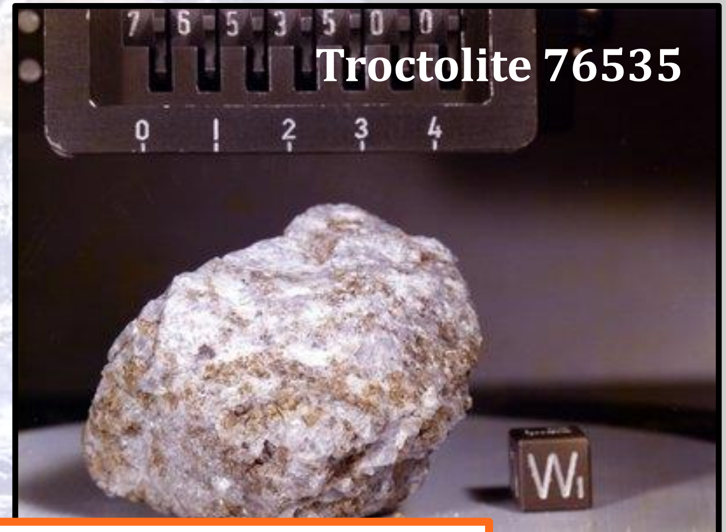
Minerals:

- Dominantly plagioclase (white)
- Some pyroxene (black or green)
- Some olivine (green)
- Some accessory minerals

Rocks:

- Primary crust – anorthosite
- Secondary crust – Mg suite, alkali suite

Surface rocks

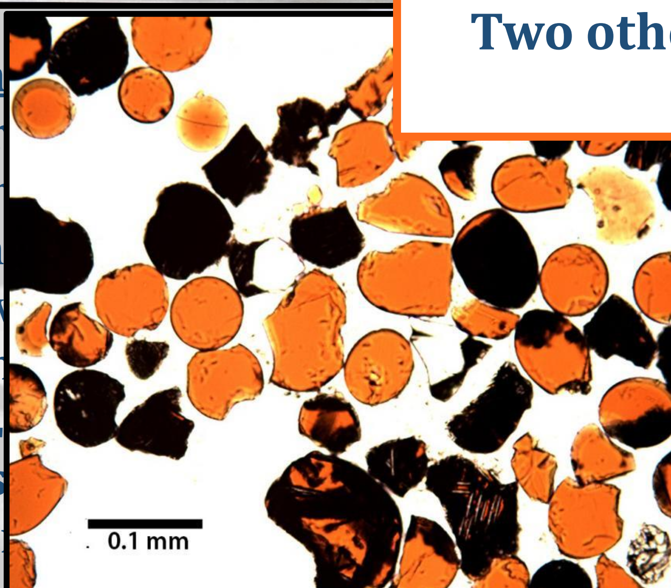


Two other important types of rocks

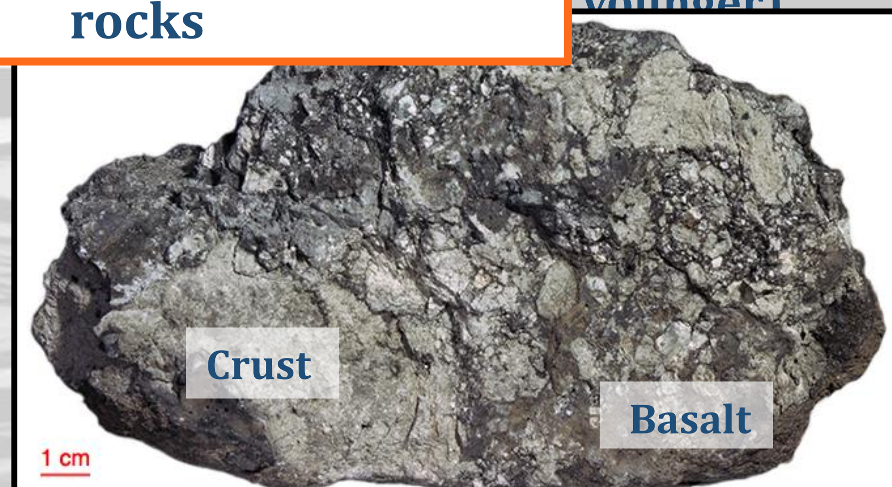
Maria ... younger)

Miner
- Pyr
- Ilm
- Oliv
- Son
- A L

Rocks
- Ma vol
- Var



Orange volcanic glass



Breccia

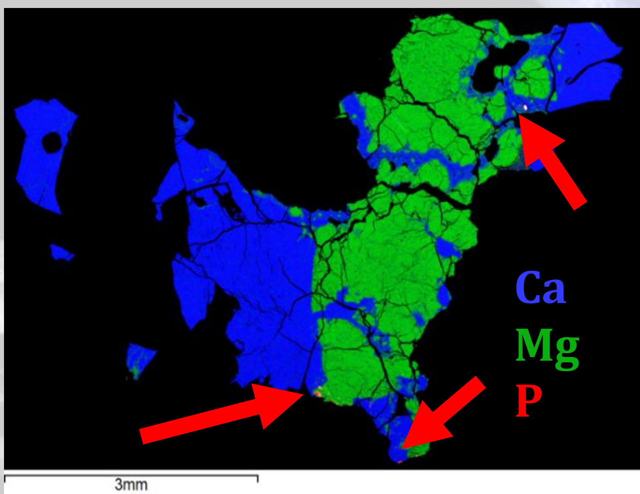
Analysing rocks

- Rocks are like sentences – we read geologic history by understanding the meaning of each word and its context
- **Thin-sections of rocks** to read the story
- **Texture, composition and reactions** (solid-state transformations)

https://www.virtualmicroscope.org/content/12039-45-pigeonite-basalt

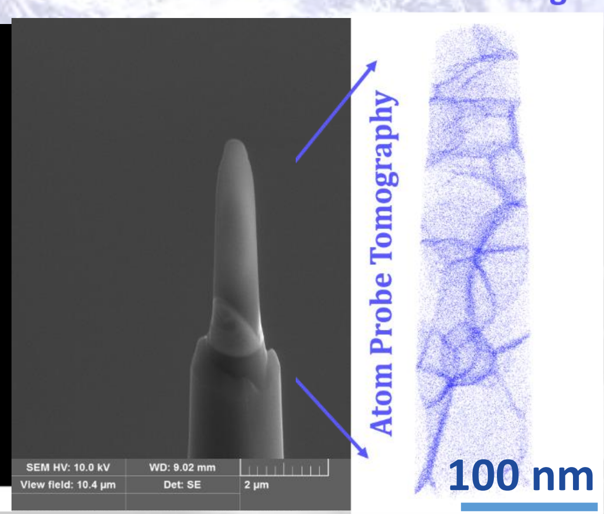
Analysing rocks

- ✓ Thin sections, *in situ* mineral analyses
- ✓ Secondary Electron Microscopy (SEM); Electron Microprobe Analyser (EPMA) – **elemental abundance**
- ✓ Electron Backscatter Diffraction (EBSD), Transmission Electron Microscopy (TEM) to understand (IR, Raman) **crystal structure**
- ✓ Secondary Ion Mass Spectrometry (SIMS) for **isotopic species (e.g. H and D; oxygen isotopes, U-Pb age)**
- ✓ Atom Probe Tomography (**nm-scale elemental & isotopic composition**)

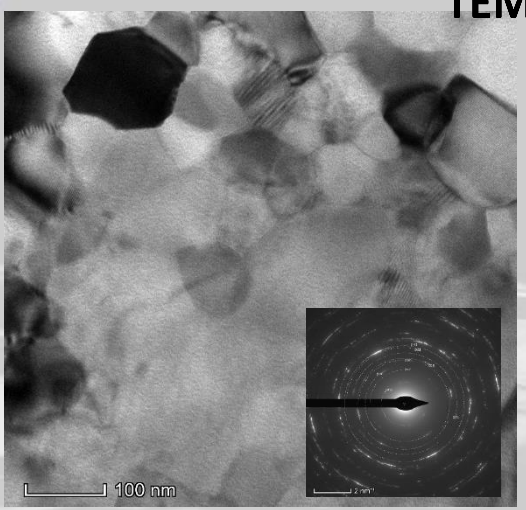


EDS

Mg

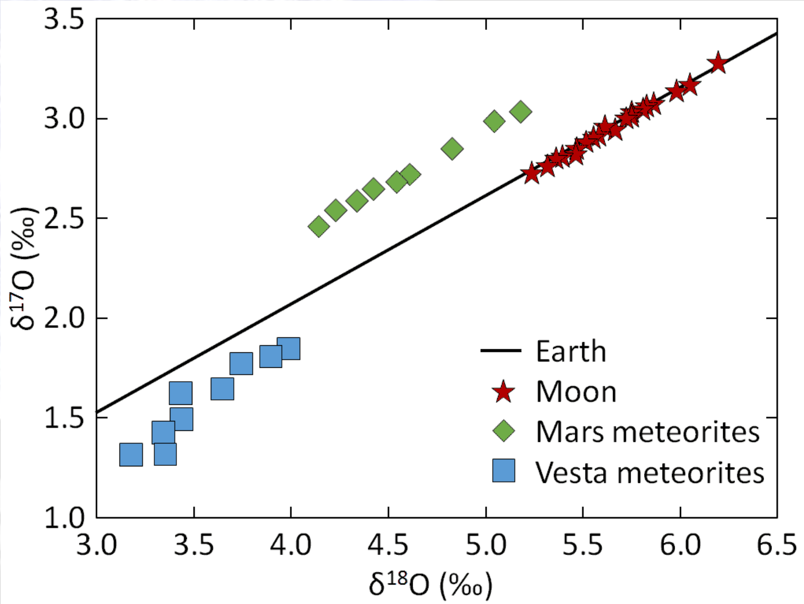


TEM



What do surface rocks tell us?

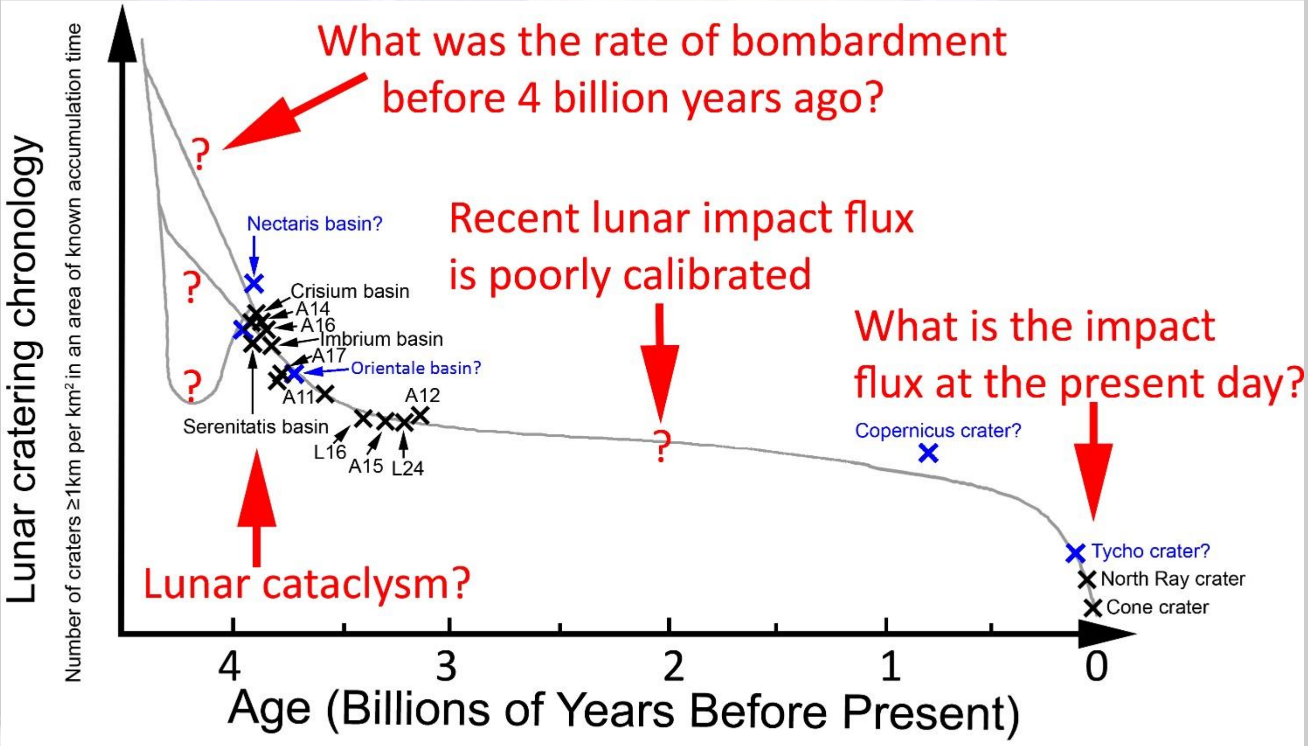
- **Constraints on the Moon-forming impact (e.g. oxygen isotopes)**
  - **<u>Pre-Apollo:</u>** Co-accretion; Fission; Capture
  - **<u>Post-Apollo:</u>** Giant-impact (with variations of impact-origin)



- Apollo samples have virtually identical isotopic signatures compared to Earth rocks for isotopes of O, Cr, Ti, K, Si and H (water), in contrast to all meteorites
- lunar rocks and terrestrial basalts show a 3 to 4 ppm (parts per million), statistically resolvable, difference in oxygen isotopes (Greenwood et al. 2018) – highest achievable precision up to date!

What do surface rocks tell us?

- **Derive the age of the crater forming and crater filling events**



Credit: K. Joy adapted from the Stoffler et al. (2006)

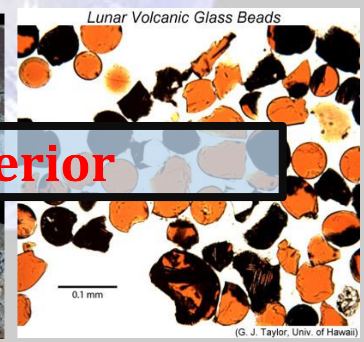
- Absolute ages on Apollo samples tied to specific lunar craters
- Concept of Late Heavy Bombardment (LHB)
- Application to age dating of surfaces of other bodies in the inner Solar System

What do surface rocks tell us?

- **New clues about water & volatile content of the lunar interior**

<u>Early-Apollo:</u> 'bone-dry' Moon (<1 ppb H_2O)

- Lack of hydrous minerals in Apollo and Luna samples (Papike et al. 1998)
- Any water detected considered terrestrial contamination (e.g., Epstein and Taylor, 1970)
- Lack of global remote sensing data & high-resolution mass spectrometry until recently



Water from the interior

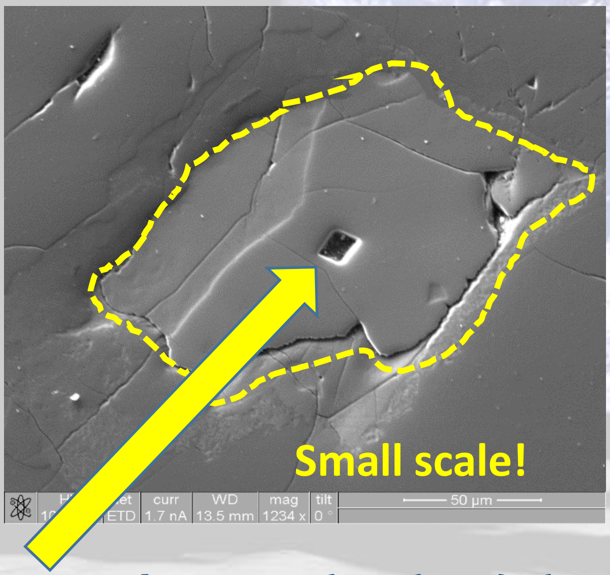
Water formed on the surface

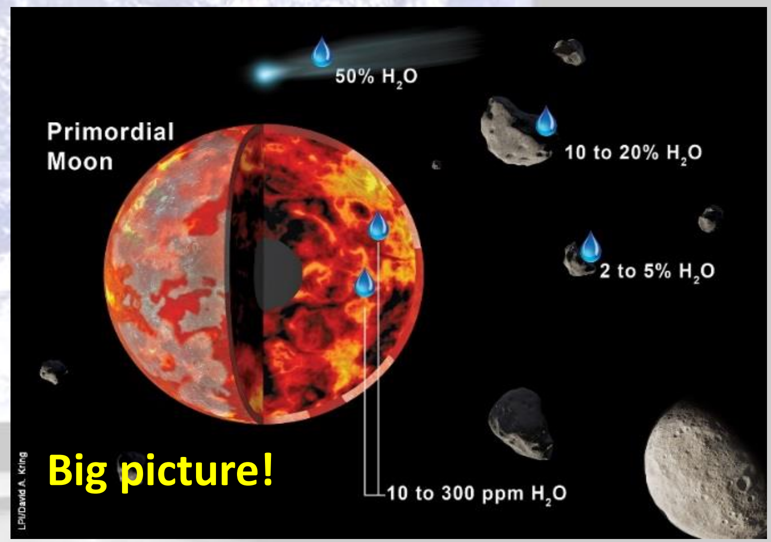
What do surface rocks tell us?

- **New clues about water & volatile content of lunar interior**

<u>Early-Apollo:</u> 'bone-dry' Moon's interior (<1 ppb H_2O)

<u>Current estimates:</u> > 10 – 300 ppm (Earth's mantle-like)





(e.g. Saal et al., 2008 Nature; Hauri et al. 2011 Science; Barnes et al. 2014; 2016; etc.)

Mineral apatite ($Ca_5(PO_4)_3(OH,Cl,F)$ contains H_2O)

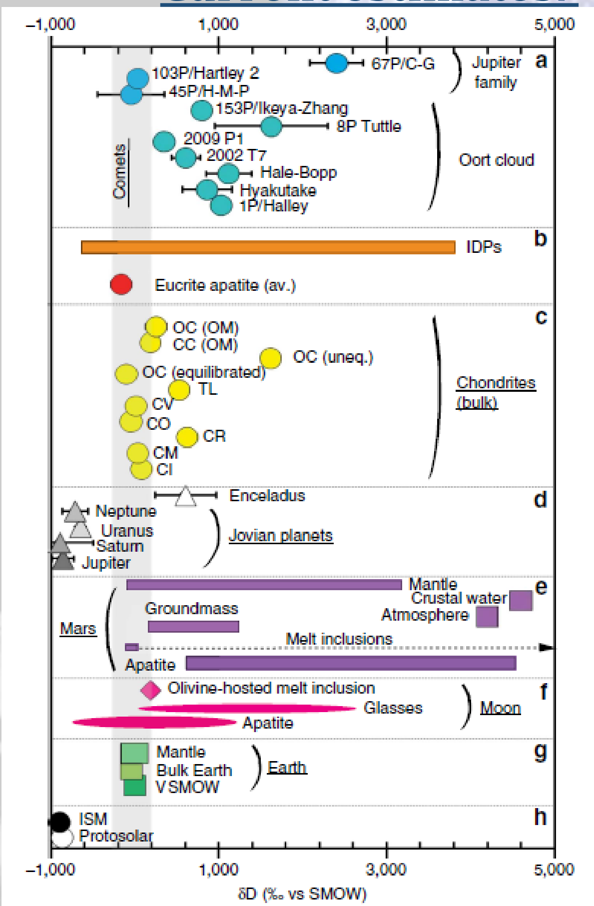
H_2O abundance was measured from this small 10x10 µm pit using very high-resolution mass-spectrometry (instrument named Nano-SIMS)

What do surface rocks tell us?

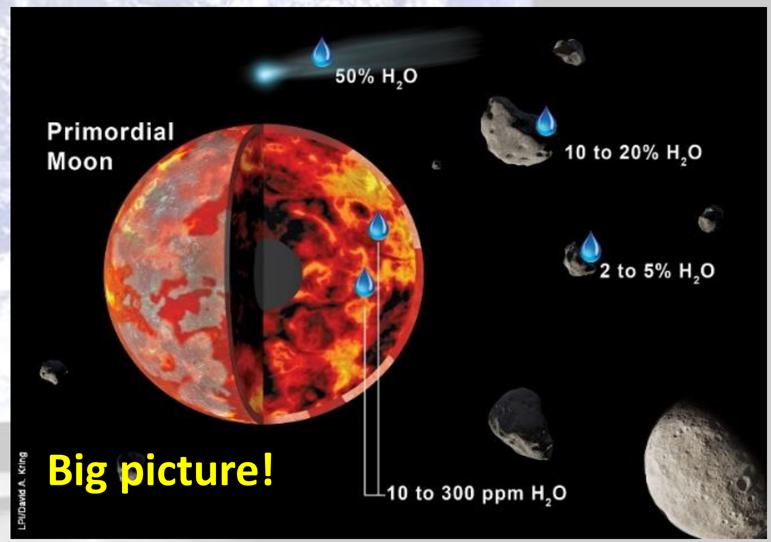
- **New clues about water & volatile content of lunar interior**

Pre-Apollo: 'bone-dry' Moon's interior (<1 ppb H_2O)

Current estimates: > 10 – 300 ppm (Earth's mantle-like)



Barnes et al. 2016



(e.g. Saal et al., 2008 Nature; Hauri et al. 2011 Science; Barnes et al. 2014; 2016; etc.)

- **Current data and models agree with the delivery of volatiles to the Moon mainly by C chondrite-type asteroids (=very primitive material) with minor input from comets**

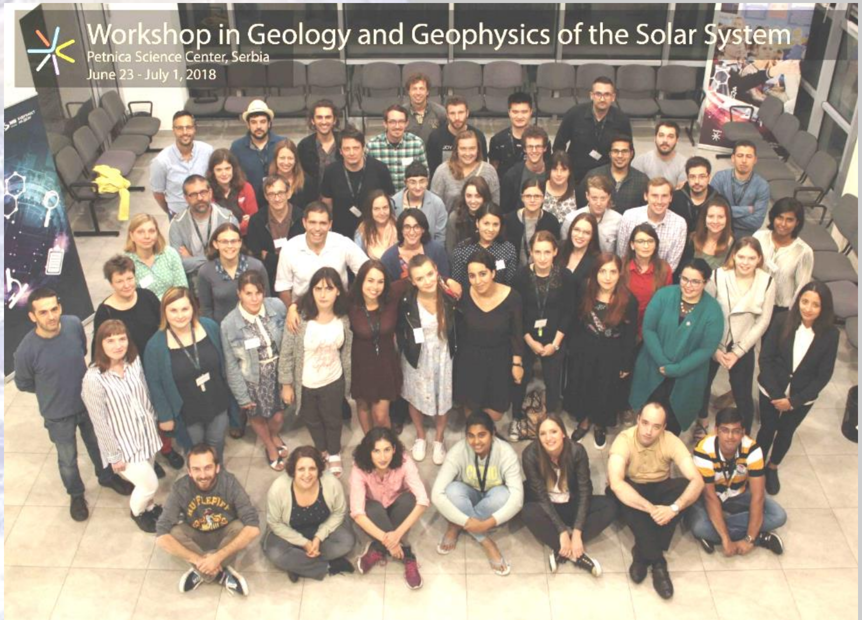
Summary and Future Directions

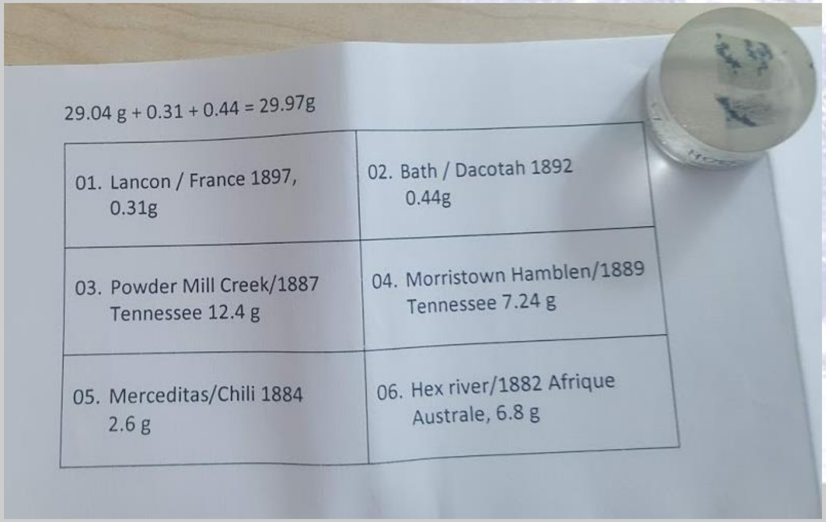
- Almost 50 years on, Apollo lunar samples continue to yield valuable data about the origin and evolution of the Moon and the inner Solar System.
- Major concepts (e.g., magma ocean; giant-impact; LHB) in Planetary Sciences have been developed through research on Apollo samples.
- **Uniformity of δD between mantles of Earth, Moon, and HED (Vesta) parent body argues for a common origin for water in the inner Solar System**
- Returned samples allowed remotely sensed data to be properly calibrated, interpreted and expanded to areas from which no samples have been yet returned
- **Information from these studies would provide key input to future sample return missions from different target bodies (e.g, Phobos, Moon, Mars, Benu).**
- Careful curation and distribution of Apollo sample by NASA CAPTEM has played a key role in maximising science outputs from analytical advances.
- A large proportion of Apollo samples remain sealed (e.g., drive tubes). Time to open some of these in light of recent research? **One core just got open!**

Reklame!

Školica u ISP

(planirano 2020)





Meteoriti na PMFu i izložba meteorita: Alena & Nataša

europlanet

Europlanet u Srbiji

Unique characteristics of lunar rocks:

- No unique chemical elements on Moon, but unique ratio and hence mineral composition
- Moon has a handful of major minerals; no major minerals that contain water (lice micas on Earth)
- Earth has more than 1000 minerals, and about 150 major minerals
- Moon has very low Na and K
- Moon has Fe^{2+} iron (Earth has mostly Fe^{3+})
- Abundant Ti
- Cosmogenic nuclides (CRE)

Thank you!

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