METEORITES: FREE SAMPLE DELIVERY FROM PRIMITIVE AND DIFFERENTIATED BODIES

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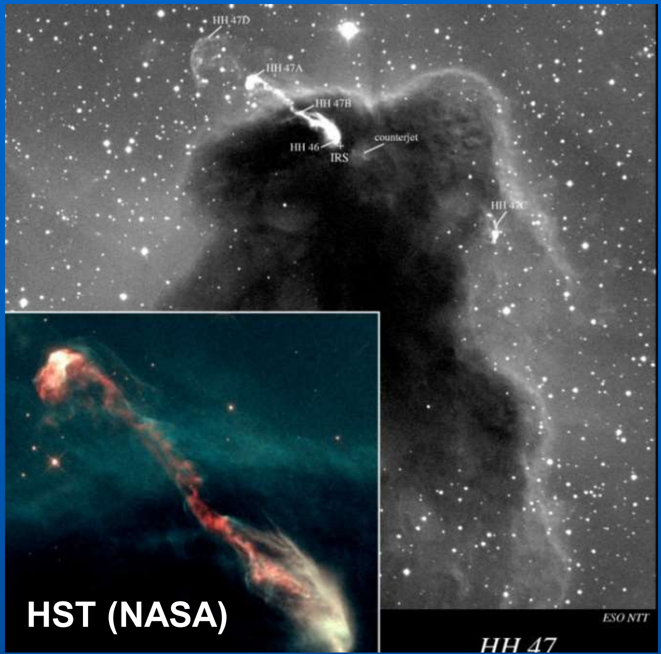
ANSMET meteorite recovery (NASA)

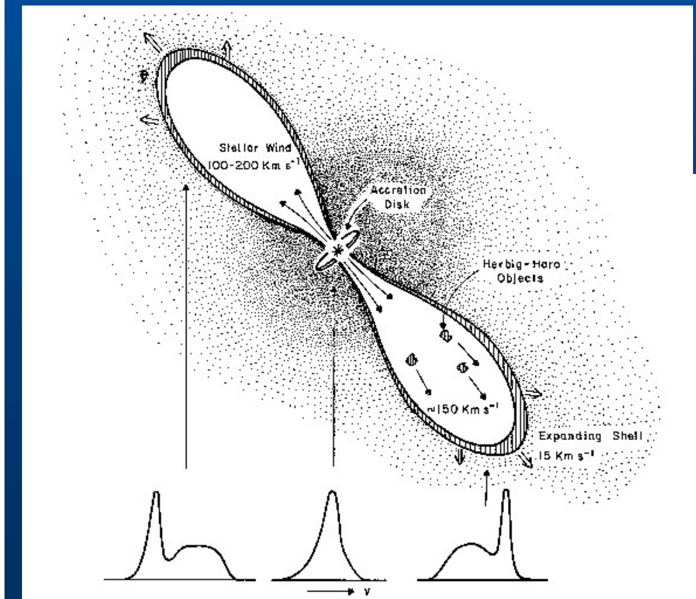
Don Dixon

OUTLINE

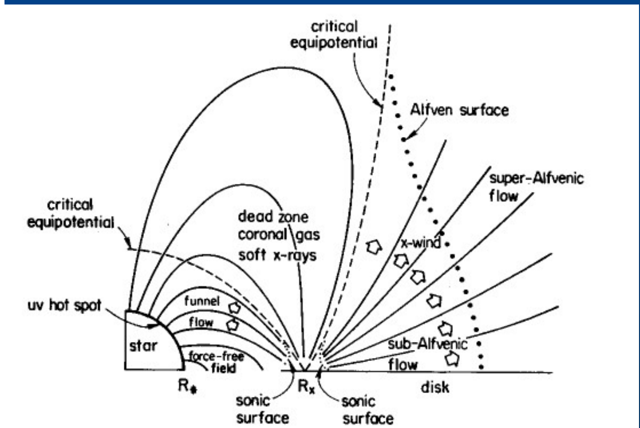
- Types of meteorites and their formation regions
- CHONDRITES: groups and reflectance properties
  - Main minerals and components forming chondrites
- The collisional processing (gardening) of asteroids
- Hydrothermal activity in primitive asteroids
  - – Aqueous alteration in carbonaceous chondrites
- Differentiated meteorites: ACHONDRITES
  - Main minerals forming achondrites
  - HED from asteroid Vesta and the Vestoids
  - Lunar meteorites
  - Martian meteorites: SNC achondrites
  - Rocky-iron and Iron meteorites as legacy of disrupted planets

YOUNG STELLAR OBJECTS (YSOs)





Snell et al. (1980)



Shu et al. (2001)

- These objects exemplify the violent environment that surrounds star formation
- Molecular clouds are enriched by nucleosynthesis products, and dust from previous stars
- Strong (100-200 km/s) stellar winds throw the materials continuously falling into unstable regions of the disk.
- Strong magnetic fields produce bipolar outflows that are characteristic of these objects
- The protoplanetary disk was formed in a gas-rich environment subject to strong and energetic stellar winds from the young Sun

THE METEORITICAL CONFIRMATION

NGC3603, adapted from HST image (NASA)

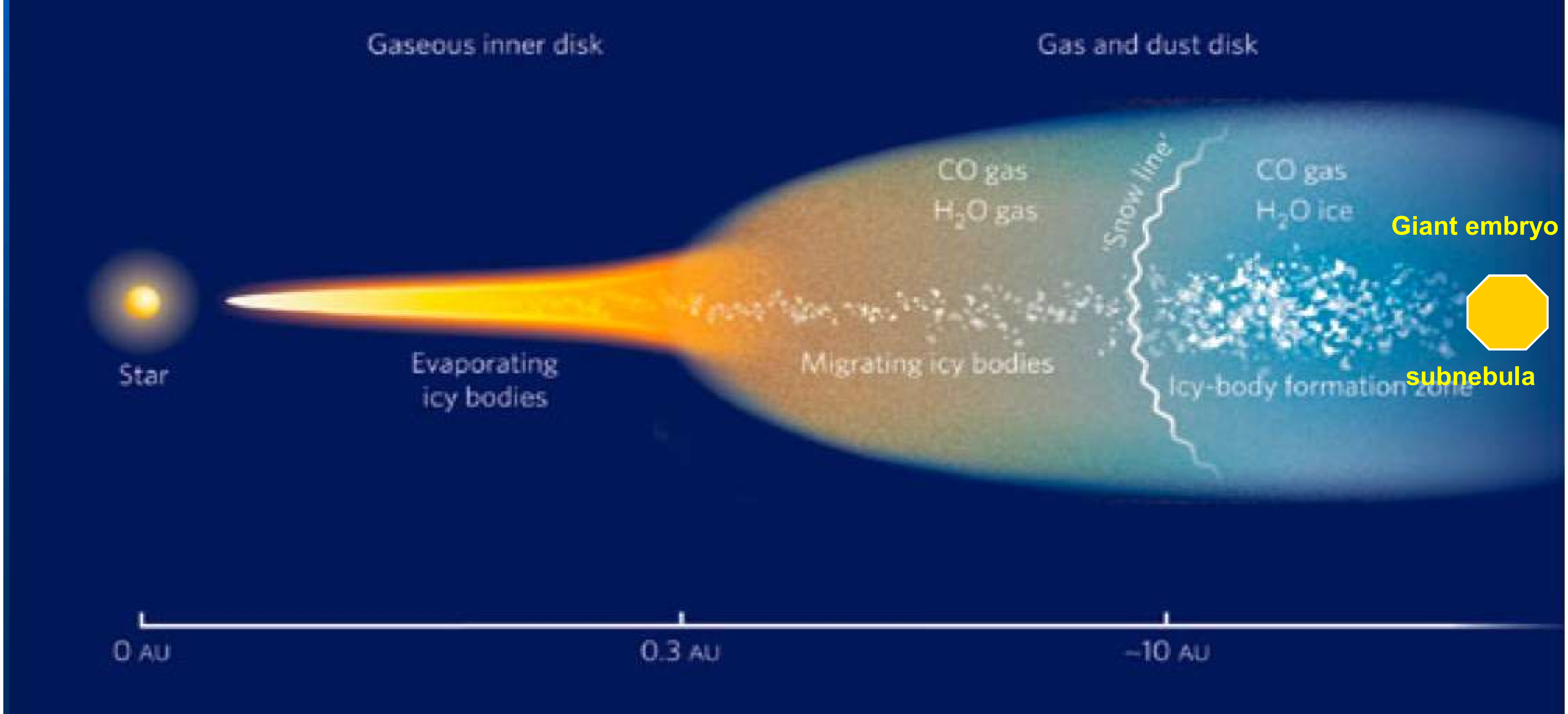
NASA

- **Solar System formation took place from the gravitational collapse of a molecular cloud (Cameron, 1962):**
  - **Primordial and stellar nucleosynthetic heritage from meteorite components**
  - **Remote observation of proplyds (Herbig, 1977) plus theoretical studies (Lynden-Bell & Pringle, 1974)**
- **First stellar grains in meteorites: a new age in laboratories (Bernatowicz et al., 1987)**
  - **Materials formed in stars during solar system formation (Anders, 1987; 1988)**
    - **Extreme isotopic anomalies**
  - ***Secondary Ion Mass Spectrometer (SIMS)* to get accurate isotopic abundances of components of meteorites (Ott, 1993; Bernatowicz & Zinner, 1997)**

THE INNER-DISK REGION

- **During the ESS gas drag produces fast migration of bodies**
  - **Icy bodies are evaporated in their approach to the Sun**
  - **The O availability depends on the formation region and time**
  - **Limited regions (e.g. around giant planets) had reducing environments**

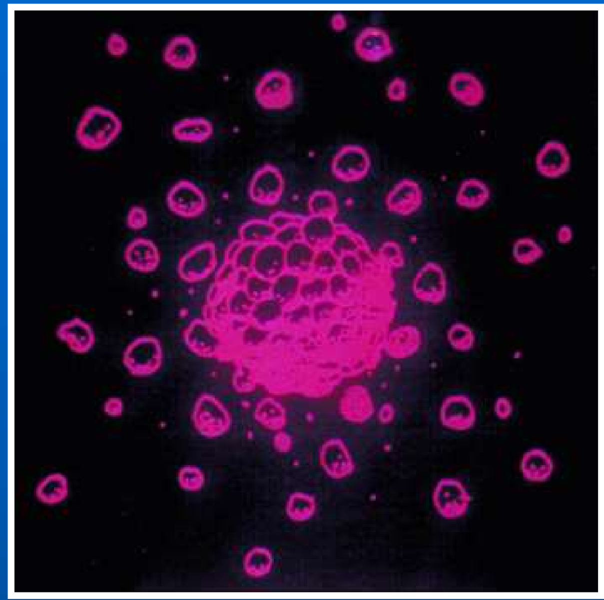
Adapted from Van Boekel (2007)



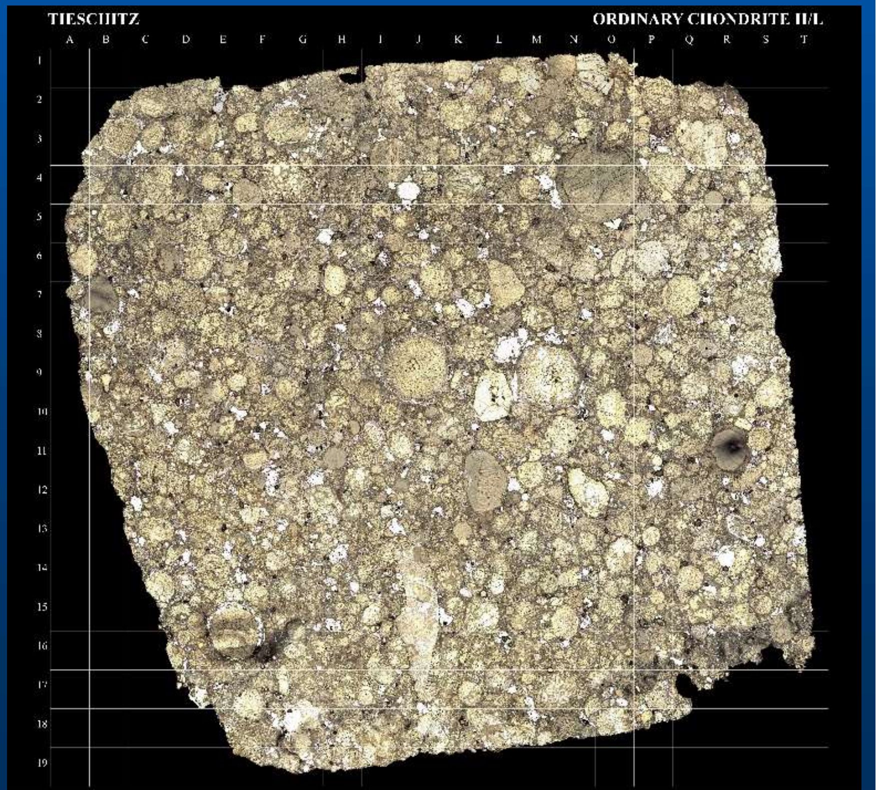
THE ACCRETION OF PLANETESIMALS

- **Encounters between low relative velocity particles with variable ratios of rocks/organics/ices formed primordial aggregates**
- **These highly porous materials were growing step by step by mutual collisions**
- **Consolidated bodies, with bulk composition related with their formation region, were affected by increasing impacts so they were compacted to different extent**
- **Pristine undifferentiated bodies were preserved if their diameters never overpass few hundred km**

-They are named "chondritic" (due to be mostly formed by igneous spherules or *chondrules*)

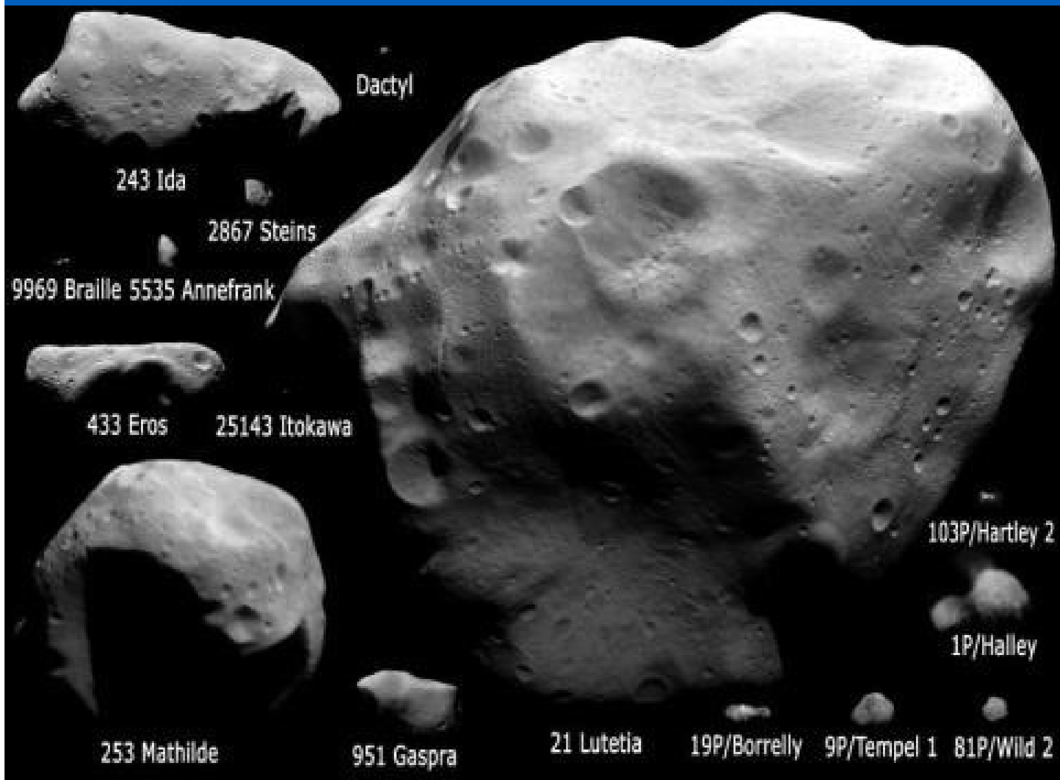


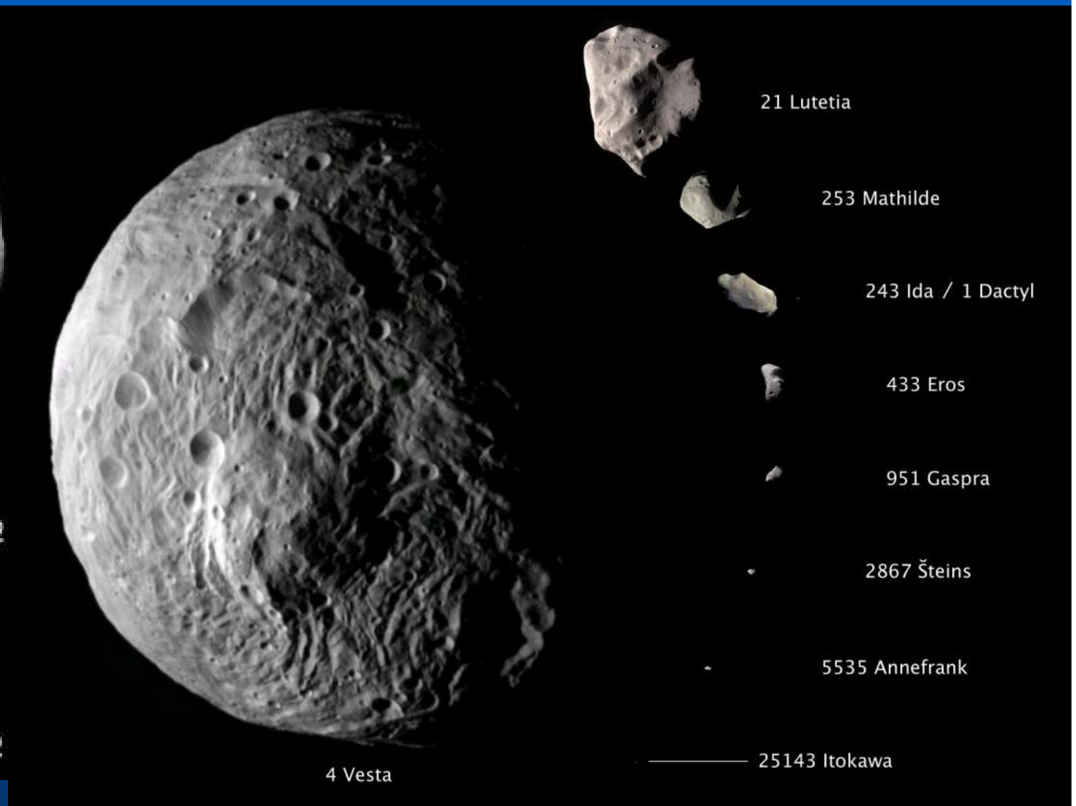
NASA



Tieschitz meteorite (Trigo-Rodríguez)

ASTEROIDS: a wide variety of physical & compositional properties





~100 km

~500 km

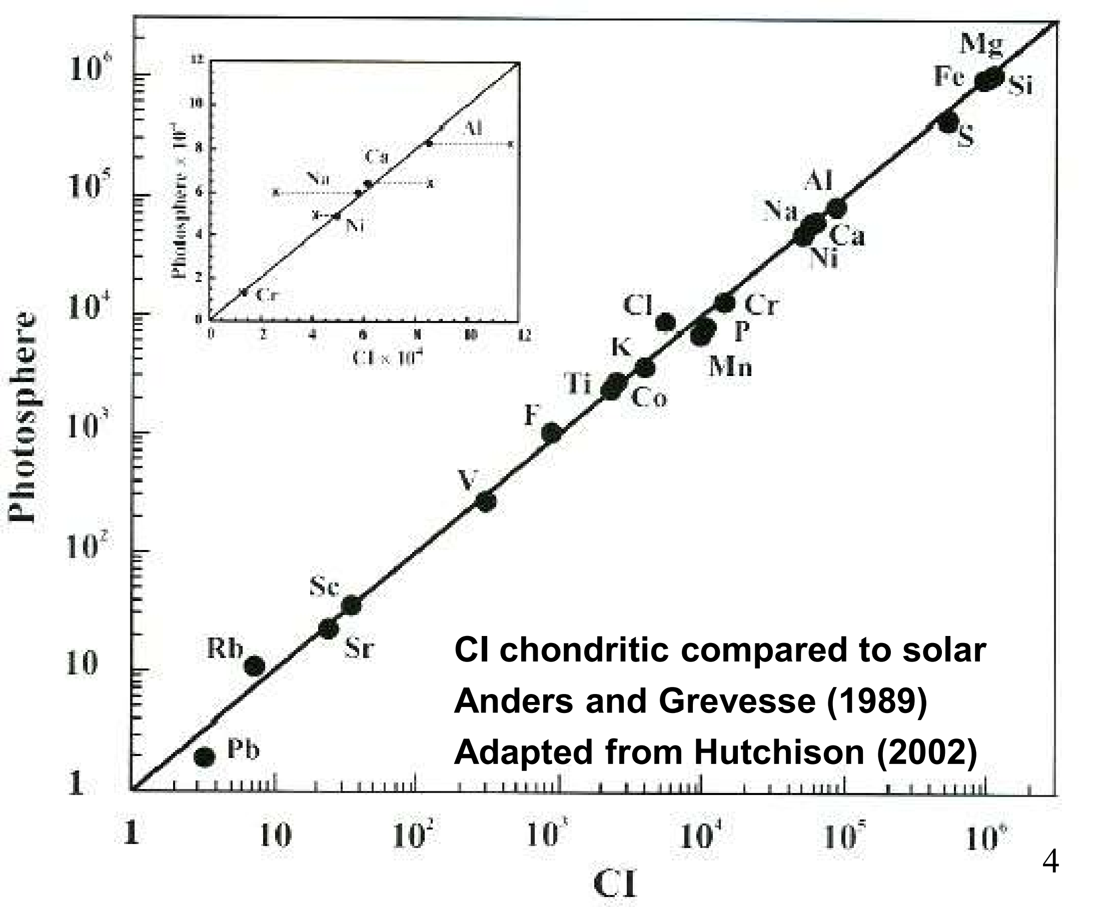
Chondrite parent bodies

Parent asteroids of achondrites

THE BUILDING BLOCKS OF PLANETS

- **Anders & Grevesse (1989) compared the chemical abundances measured in the solar photosphere with primitive meteorites (chondrites)**
  - **Extraordinary fit with carbonaceous chondrites of CI group (meteorite-type: Ivuna)**
- **In scientific literature is assumed that composition as "solar" since then**
- **The CI chondrites are among the most fragile materials, but they have suffered important aqueous alteration**
- **However, the enstatite and ordinary chondrites were probably the main building blocks of Earth on the basis of O isotope data**

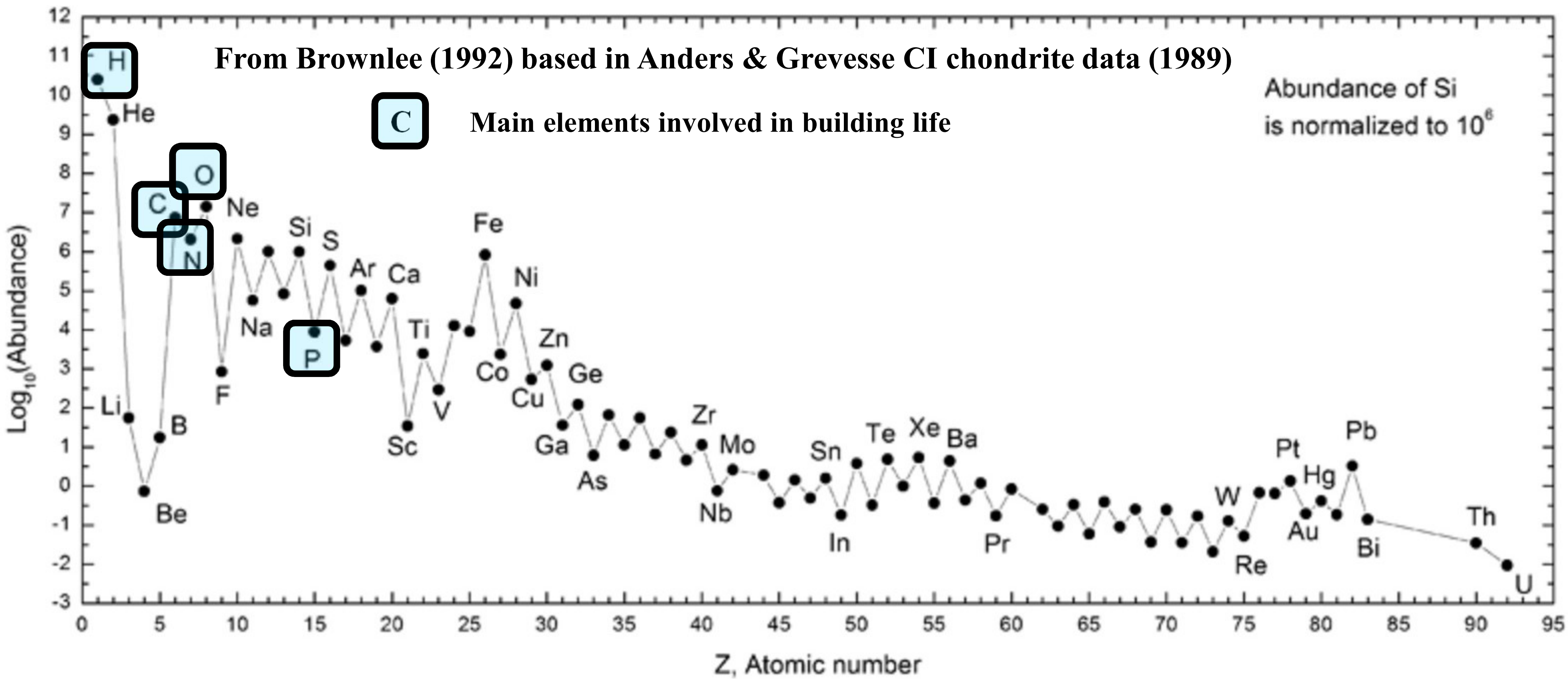
CI chondrite
Orgueil



CI chondritic compared to solar
Anders and Grevesse (1989)
Adapted from Hutchison (2002)

ELEMENTAL ABUNDANCES IN THE UNIVERSE

- The composition of our Solar System is the (local) legacy of the stellar nucleosynthetic products in our Milky Way neighborhood
- Inferred from the accurate measurements of CI carbonaceous chondrites (Anders & Grevesse, 1989)

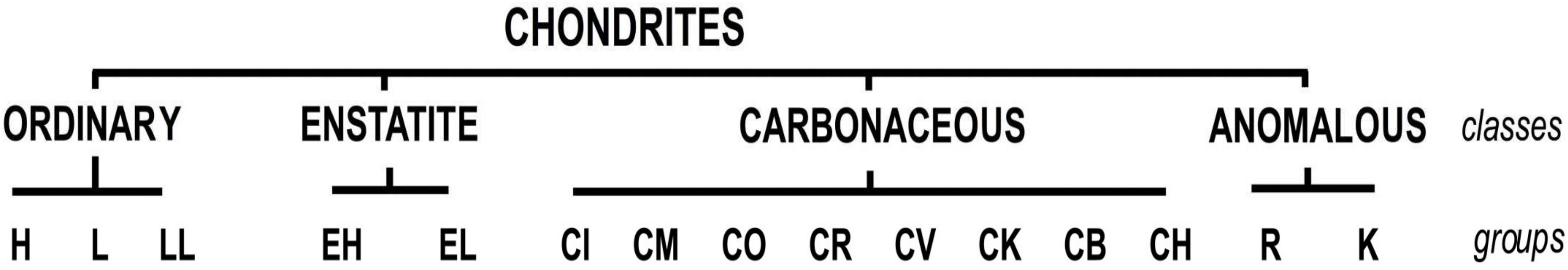


THE METEORITICAL BULLETIN DATABASE

- **It is an online catalog maintained by the Meteoritical Society, an international effort in which we contribute actively**
- **It contains 74812 valid meteorite names, and allow searches that can be made through this online database:**
  - **https://www.lpi.usra.edu/meteor/metbull.php**

Puerto Lapice eucrite

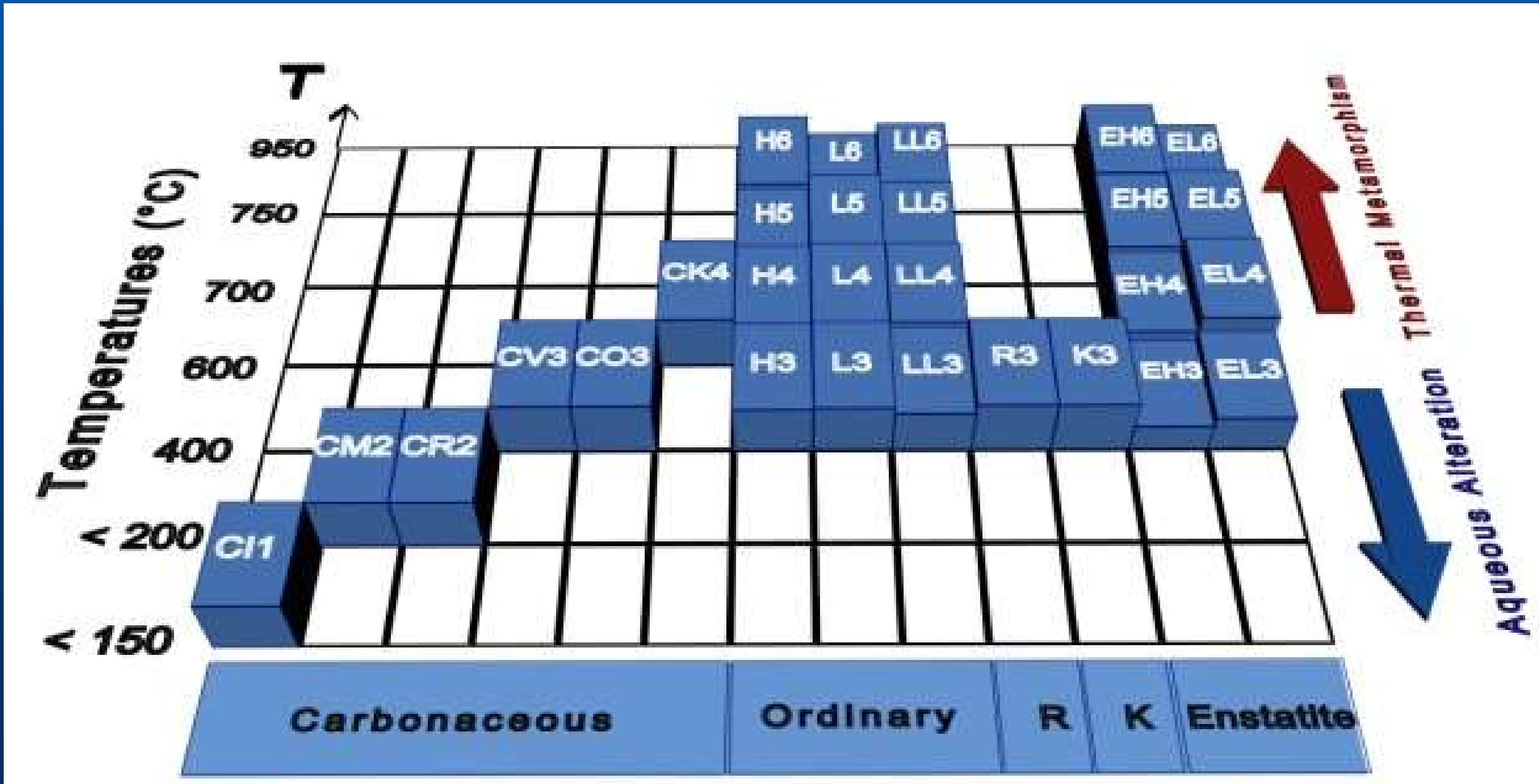
CHONDRITE CLASSES AND GROUPS



Adapted from Trigo-Rodríguez (2012)

PHYSICAL PROCESSES AFFECTING THEM

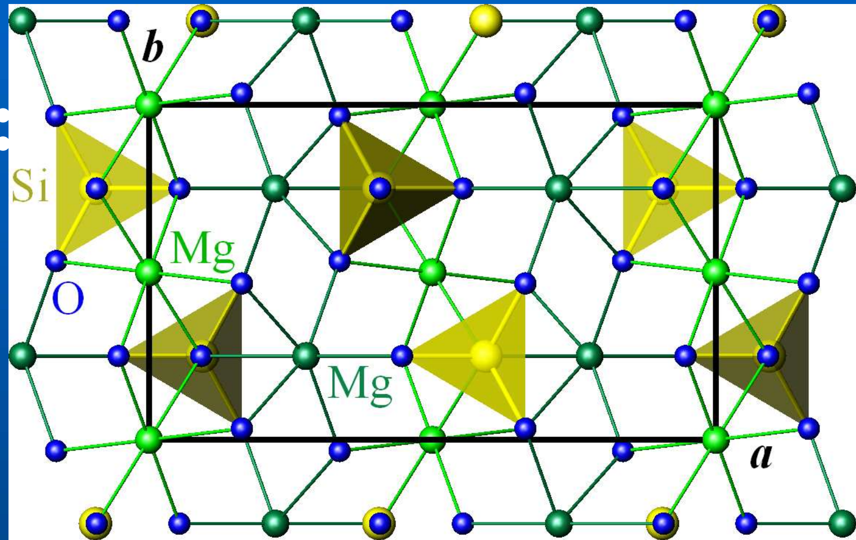
- **Different degrees of metamorphism (thermal processing) and aqueous alteration**
- **The chondrites are classified according the estimated thermal metamorphism and aqueous alteration required to produce the petrographic types**
- **The highest hydrated groups correspond to the carbonaceous chondrites, particularly the CMs, CRs, and CI groups.**



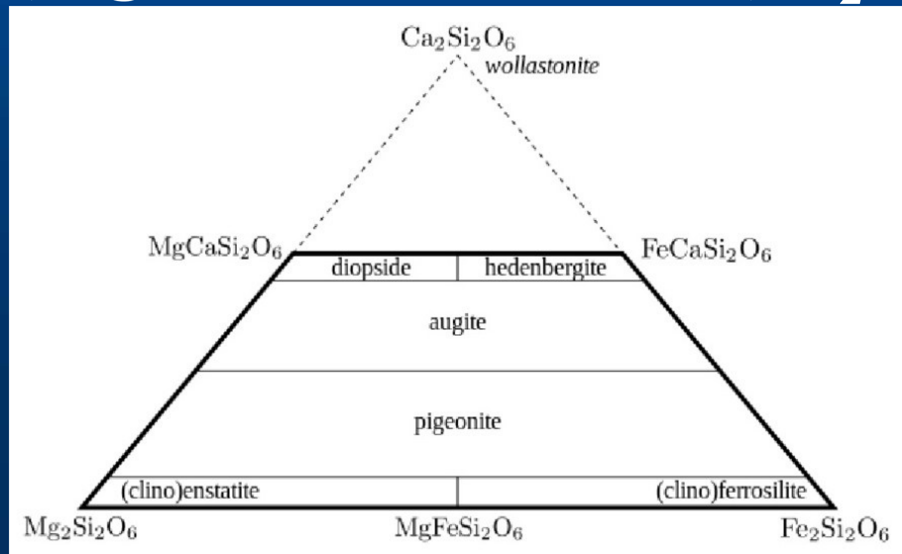
Dotto et al. (2005)

MAIN MINERALS IN CHONDRITES

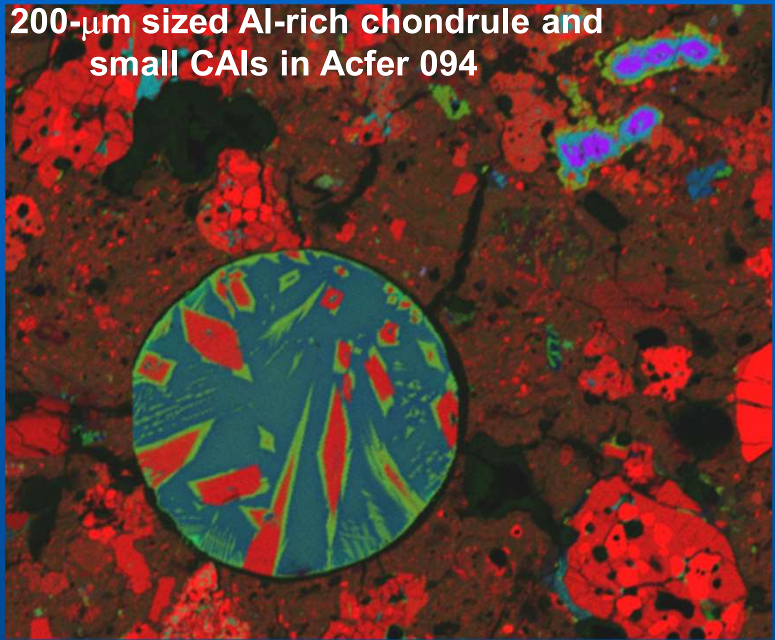
- Chondrites formed by chondrules, CAIs, metal grains and fine dust.
- Main rock-forming minerals:
  - Olivine: $(Mg, Fe)_2SiO_4$
    - Primordial olivine Mg_2SiO_4



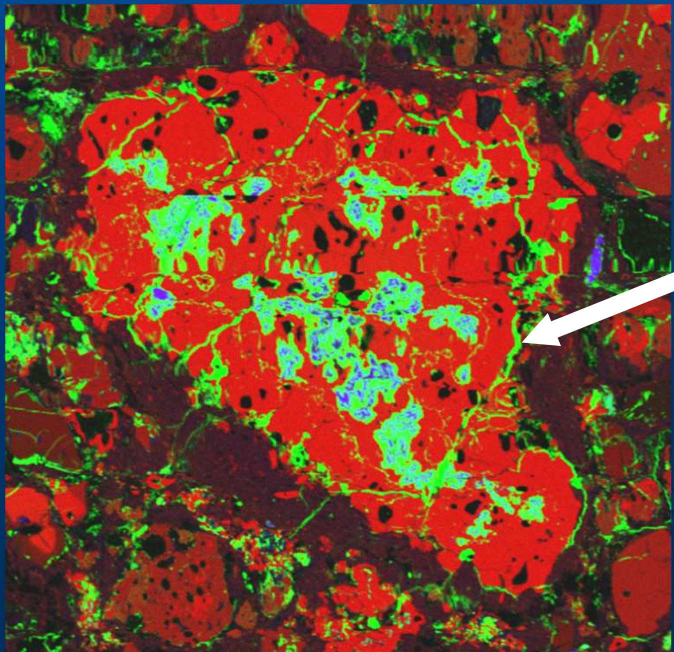
  - Pyroxene: $(Ca,Na,Mg \text{ or } Fe)(Mg,Fe, Ca,Cr, Mn, Al)Si_2O_6$
    - See right diagram for diverse mineral combinations
  - Enstatite: $MgSiO_3$
  - Plagioclase
  - Troilite: FeS



DISK COMPONENTS: CAIs, AOIs, CHONDRULES, FINE DUST



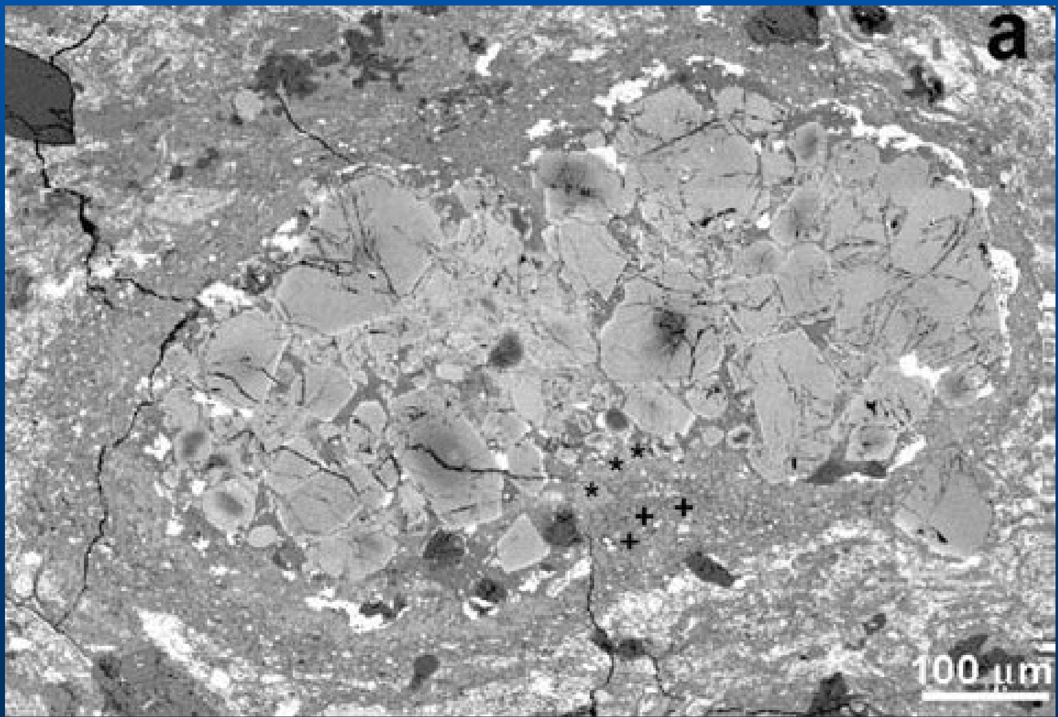
- **Ion microprobe: building X-ray maps to identify the mineral phases of chondritic components:**
  - **MgCaAl: red, green, blue**
  - **This technique, together with EDX, allows mineral identification**
- **The chondrules are the most ubiquitous components of chondrites, and are silicate-rich (originally forsterite rich)**
- **The Ca-Al rich Inclusions (CAIs)**
- **Ameboid Olivine Inclusions or Aggregates (AOIs - AOAs)**
- **MATRIX: Formed by fine-grained dusty materials, organic matter, chondrule fragments, etc…**



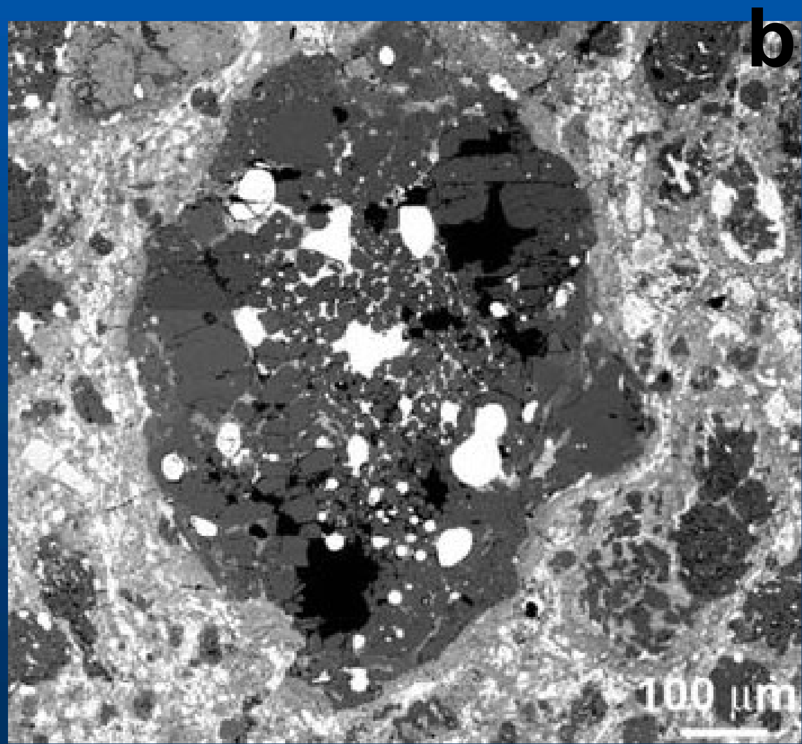
1-mm-sized AOIs in AH77307 (Trigo-Rodríguez et al., 2006)

CHONDRULES SEEN IN BSE (SEM)

- **Back-Scatter Electron Microscopy (BSE) images**
- **Igneous-textured particles composed mainly of olivine and low-Ca pyroxene crystals set in a feldespathic glass.**
- **Two types that evidence different mineralogy, but also a diversified forming environment, rich and poor in O:**
  - **Oxygen-isotopic compositions of large individual chondrules also suggest that they formed in different reservoirs (or at different times).**
  - **For comparison, CAIs formed in an environment richer in ^{16}O**

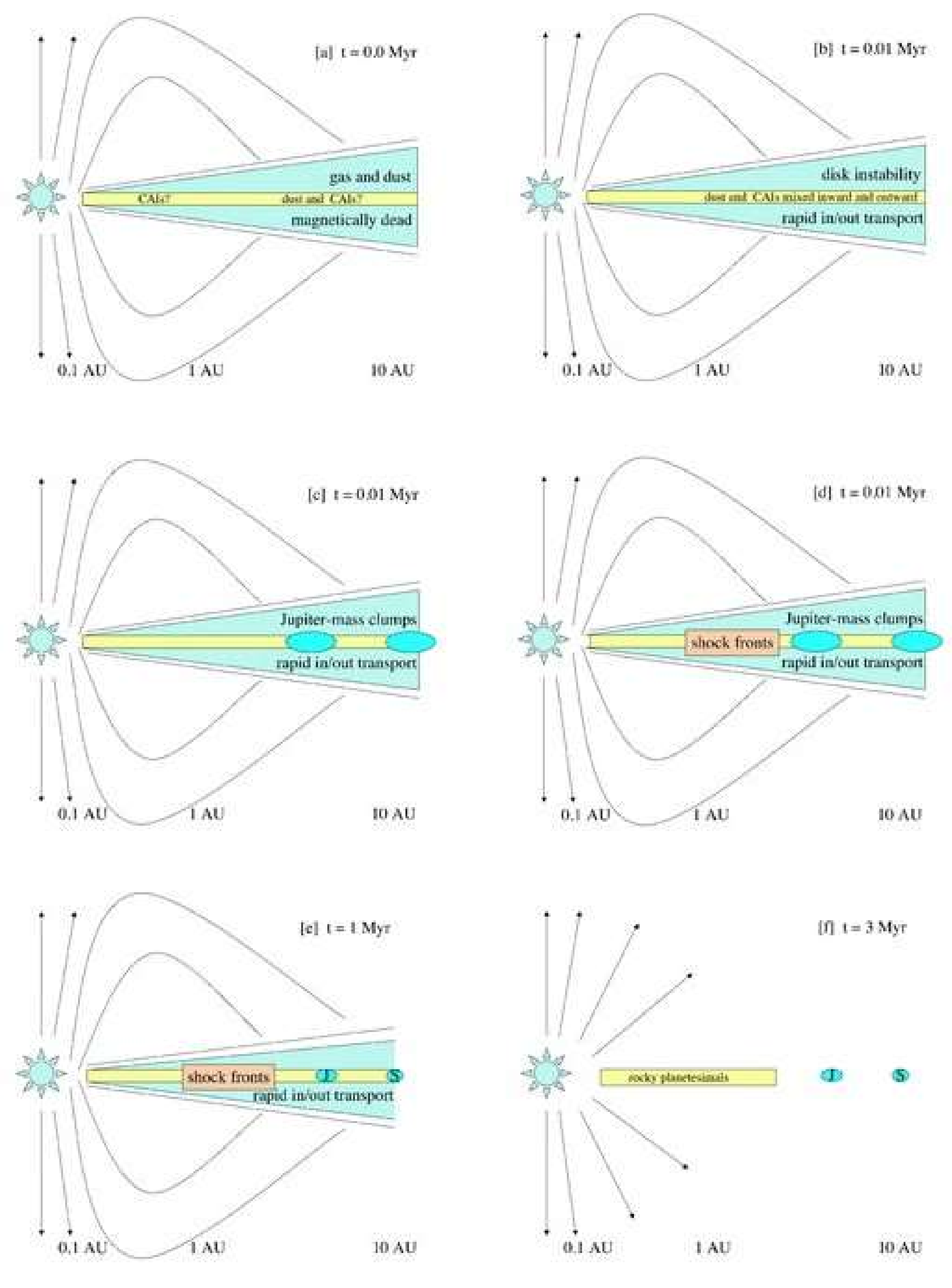


a) BSE image of high-FeO (type II) chondrule



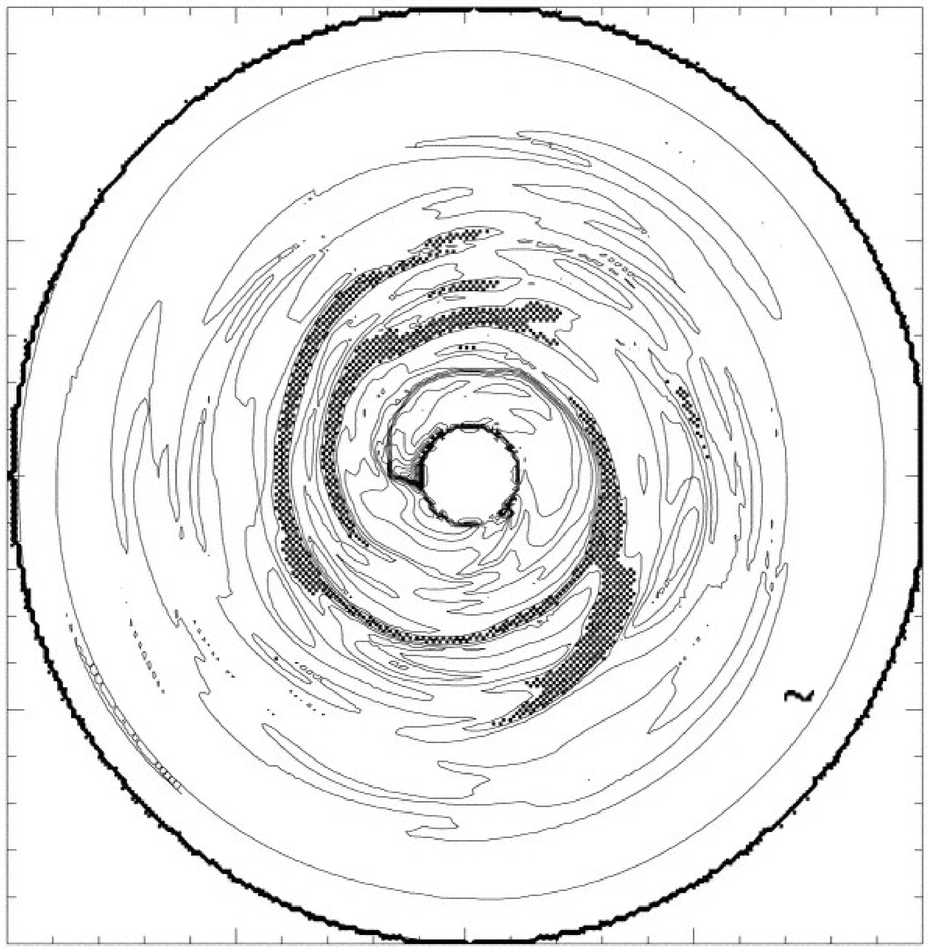
b) Low-FeO (type I) chondrule with metal grains

CHONDRULES FORMED IN SHOCK FRONTS?



20 AU

Boss et al. (2005)



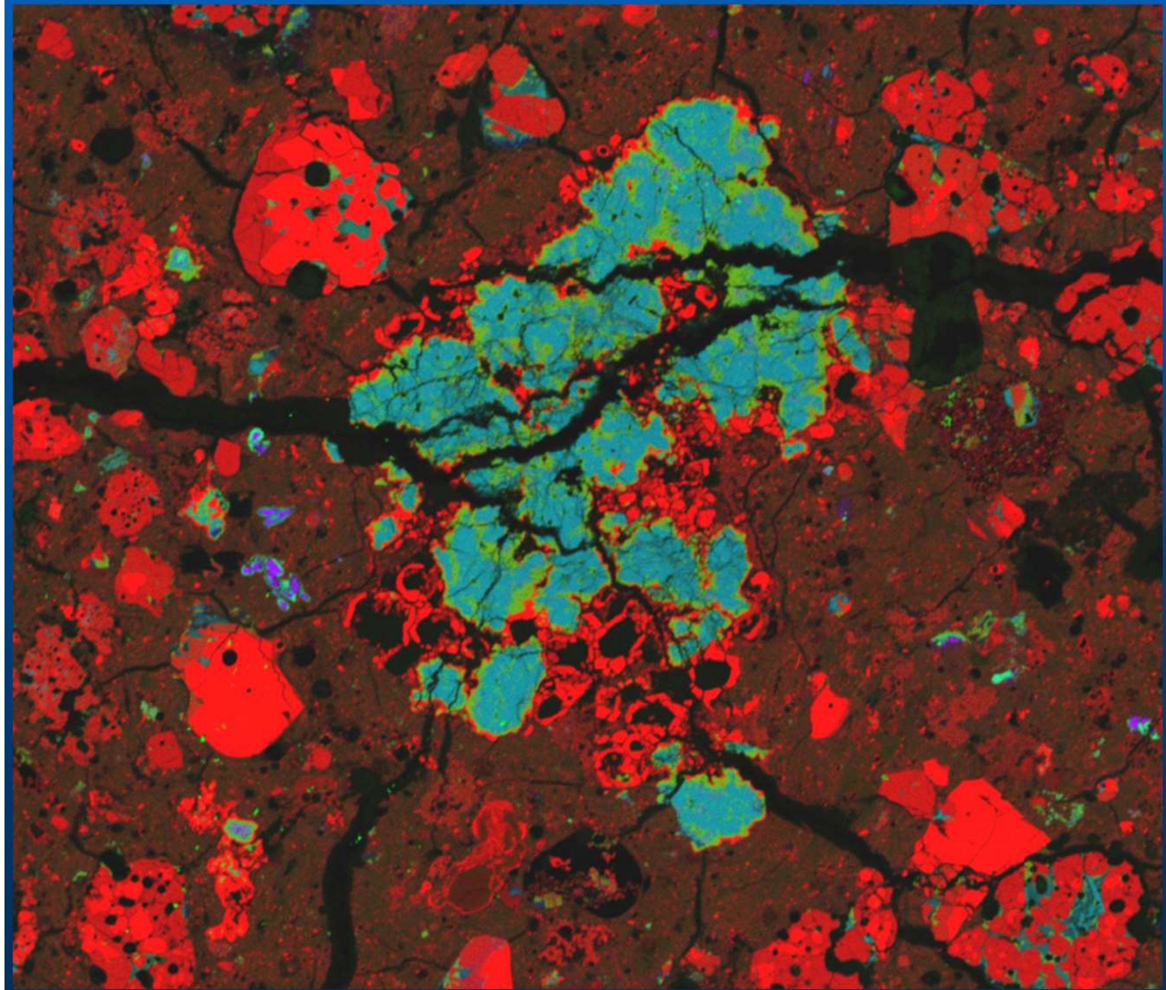
Density contours of a gravitationally unstable disk after 252 yr of evolution. A strong transient shock front appears outside the inner boundary at ~2 AU.

CAIs: THE OLDEST SS MATERIALS

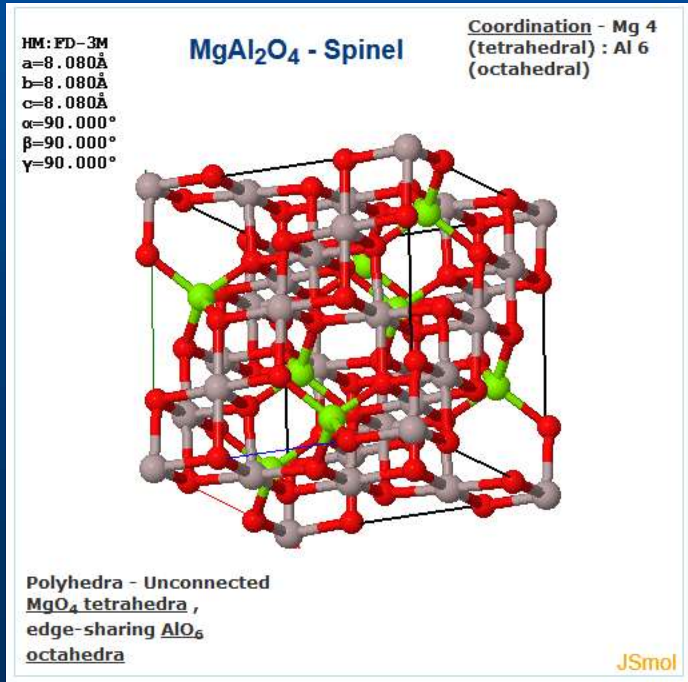
0.5 mm-sized CAI surrounded by chondrules and matrix In ACFER 094 (Trigo-Rodríguez, 2006)

RGB X-Ray mapping (each color for Mg, Ca, Al)

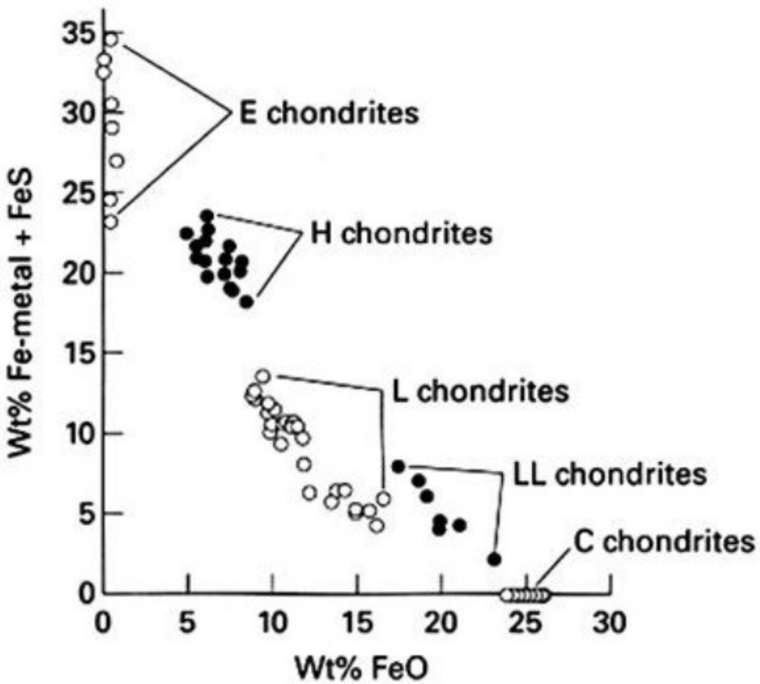
Note the relic aggregate-like structure

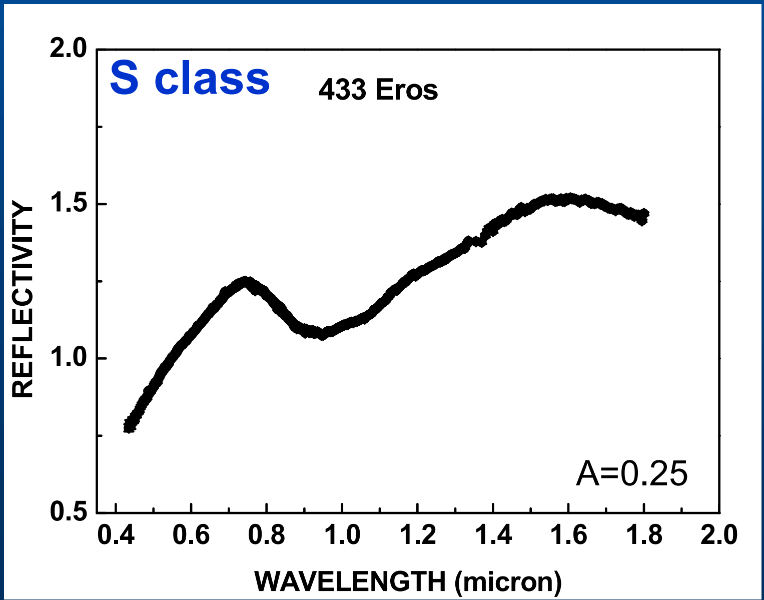


- The Ca-Al rich Inclusions (CAIs) are formed by refractory minerals:
  - Spinel:
    – $MgAl_2O_4$
  - Melilite:
    – $Ca_2Al_2SiO_7$
  - Hibonite:
    – $CaAl_{12}O_{19}$



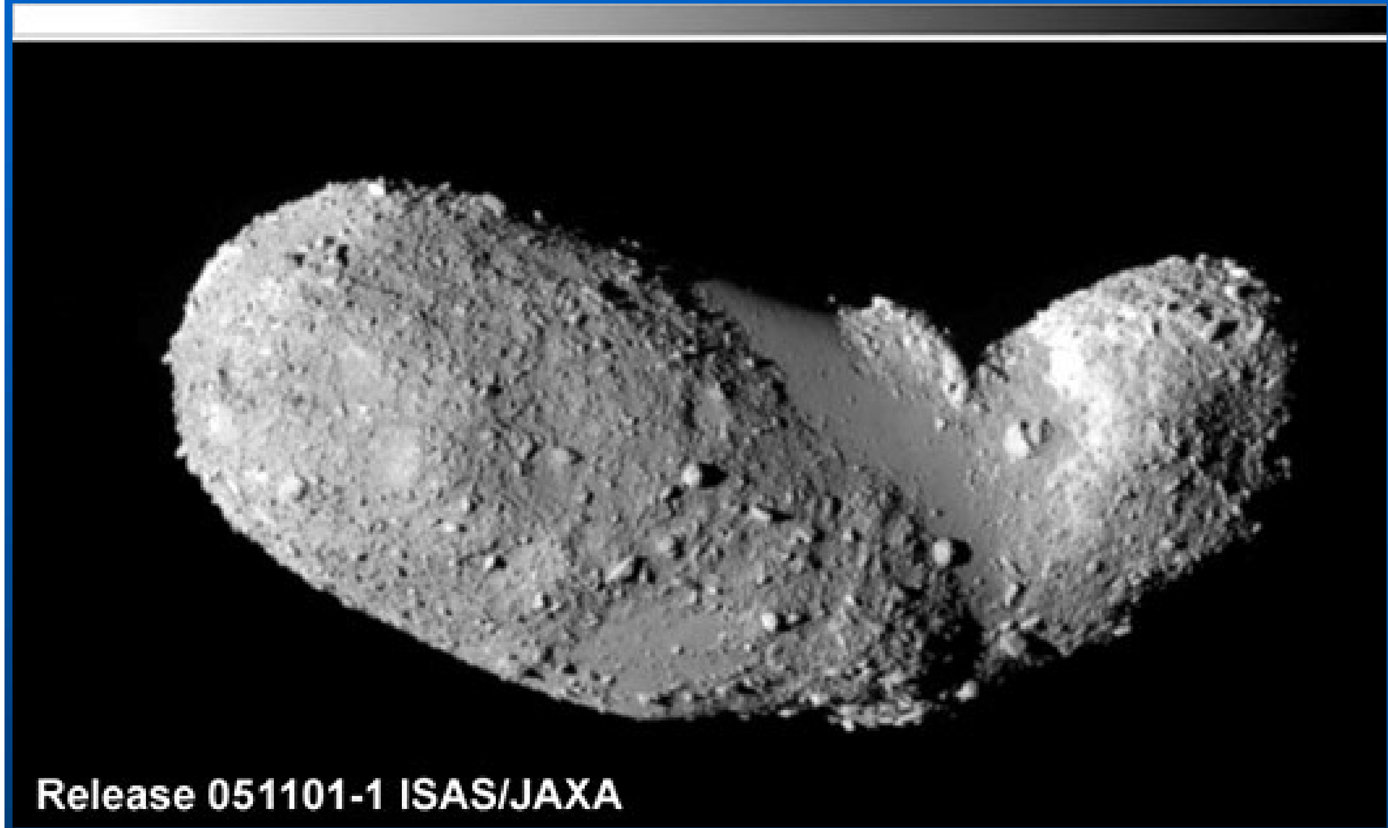
ORDINARY CHONDRITES

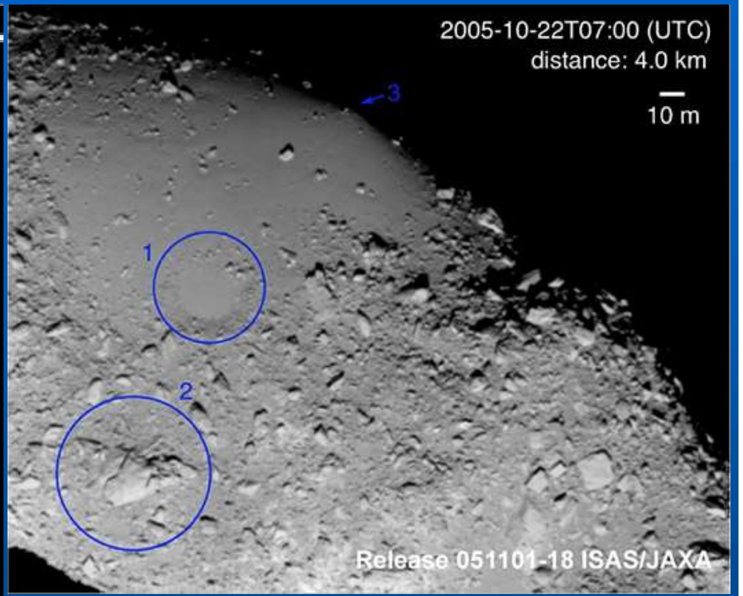




- The ordinary chondrites are subdivided into three groups based on different chemical criteria as e.g. the ratio of metallic to oxidized Fe (see Fig.).
- O isotopes also indicate a common origin between group members
- A spike in flux of L chondrites accumulated in Sweden Ordovician limestone (Schmitz et al., 1997, 2001, 2003)
  - Consistent with CREA data peak at ~500 Myr
- Plausible origin of the L group:
  - The Gefion asteroid family was born during a catastrophic collision ~485 Myr ago (Bottke et al., 2009)
  - The family is also next to the 5:2 resonance (!)

ITOKAWA AS AN EXAMPLE OF PARENT BODY OF ORDINARY CHONDRITES





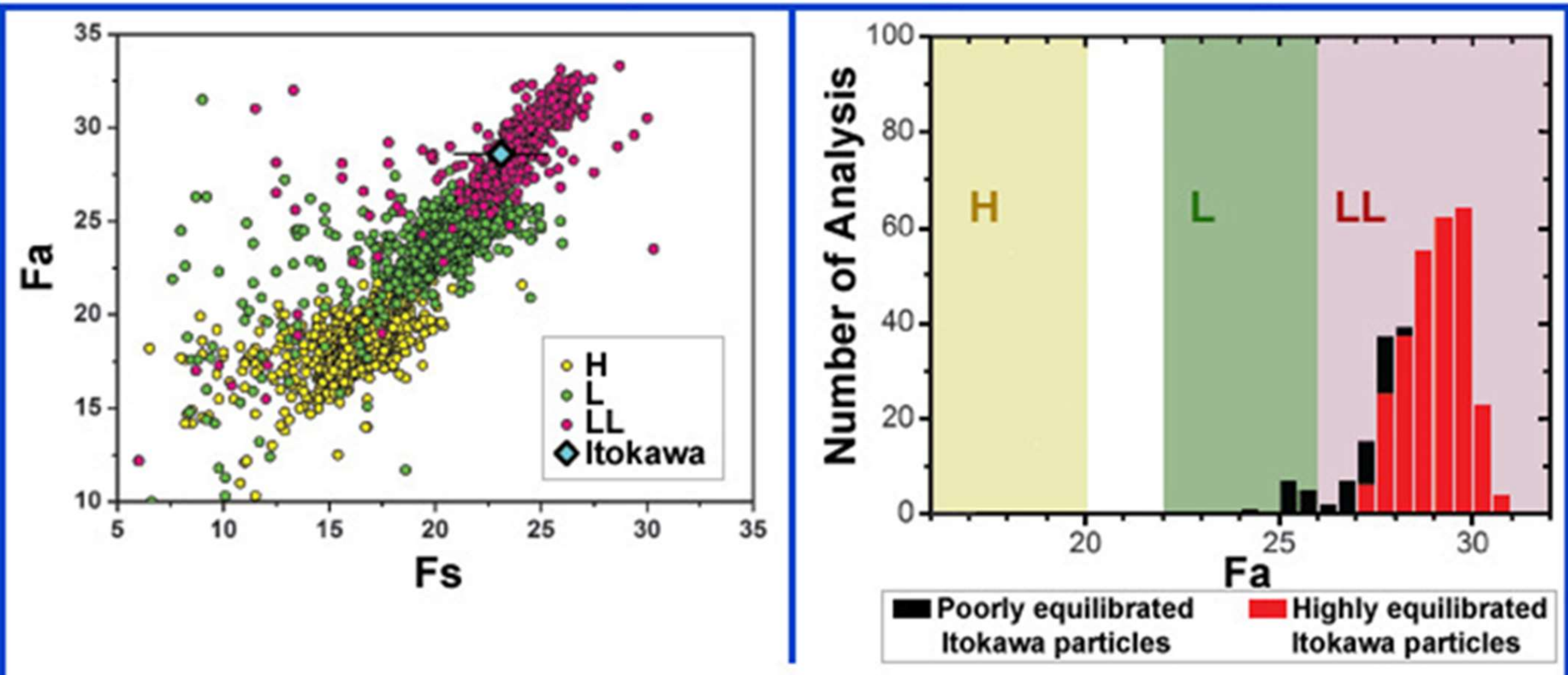
It is a nice example of rubble pile:

- **It is covered by fine-grained regolith, rocks and boulders that are the product of collisional gardening and space weathering (aging)**
- **Mineralogy associated with LL ordinary chondrites**

OCs vs. asteroid Itokawa

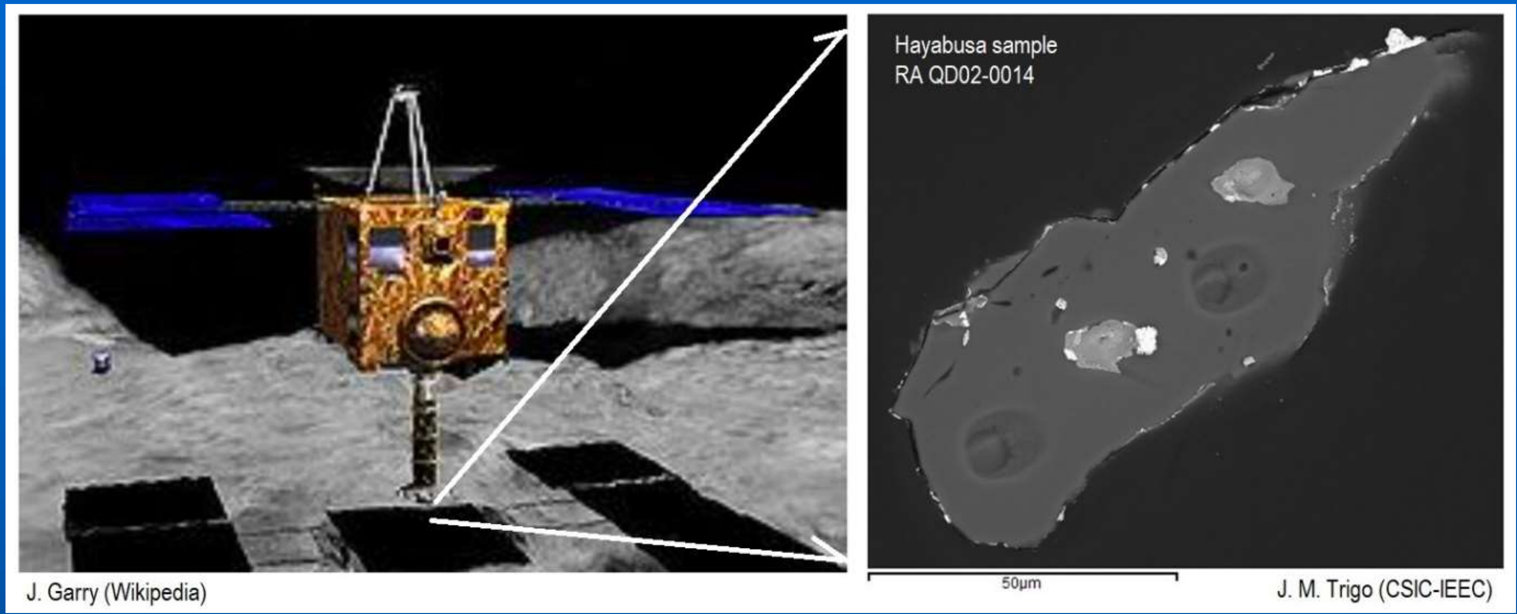
- The ordinary chondrites (OCs) are subdivided into 3 groups based on the ratio of metallic to oxidized Fe (see slide 14).
- Hayabusa (JAXA) mission achieved the sample return of regolith particles
- Fe-Mg content in Itokawa's olivine and pyroxene is in the range of LL OCs (Nakamura et al., 2011)

Itokawa Particles Compared to Ordinary Chondrite Groups



(From Nakamura *et al.*, 2011, *Science*, v. 333(6046), p. 1113-1116, Fig. 2A,B, doi: 10.1126/science.1207758.)

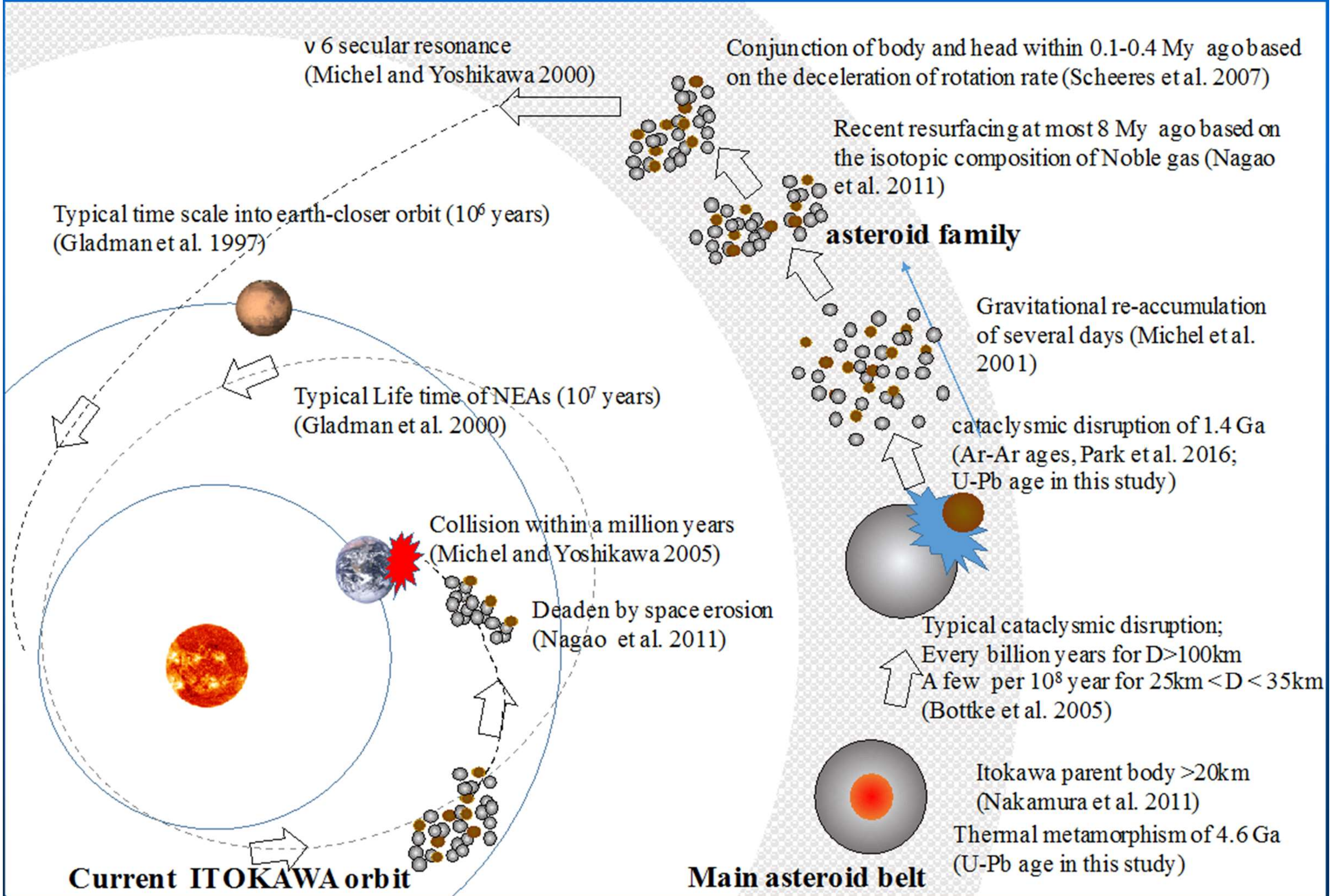
HAYABUSA MISION



- Several attempts at collecting samples from Itokawa during touch and go maneuvers, ended with thousands of regolith particles in one of the sample containers

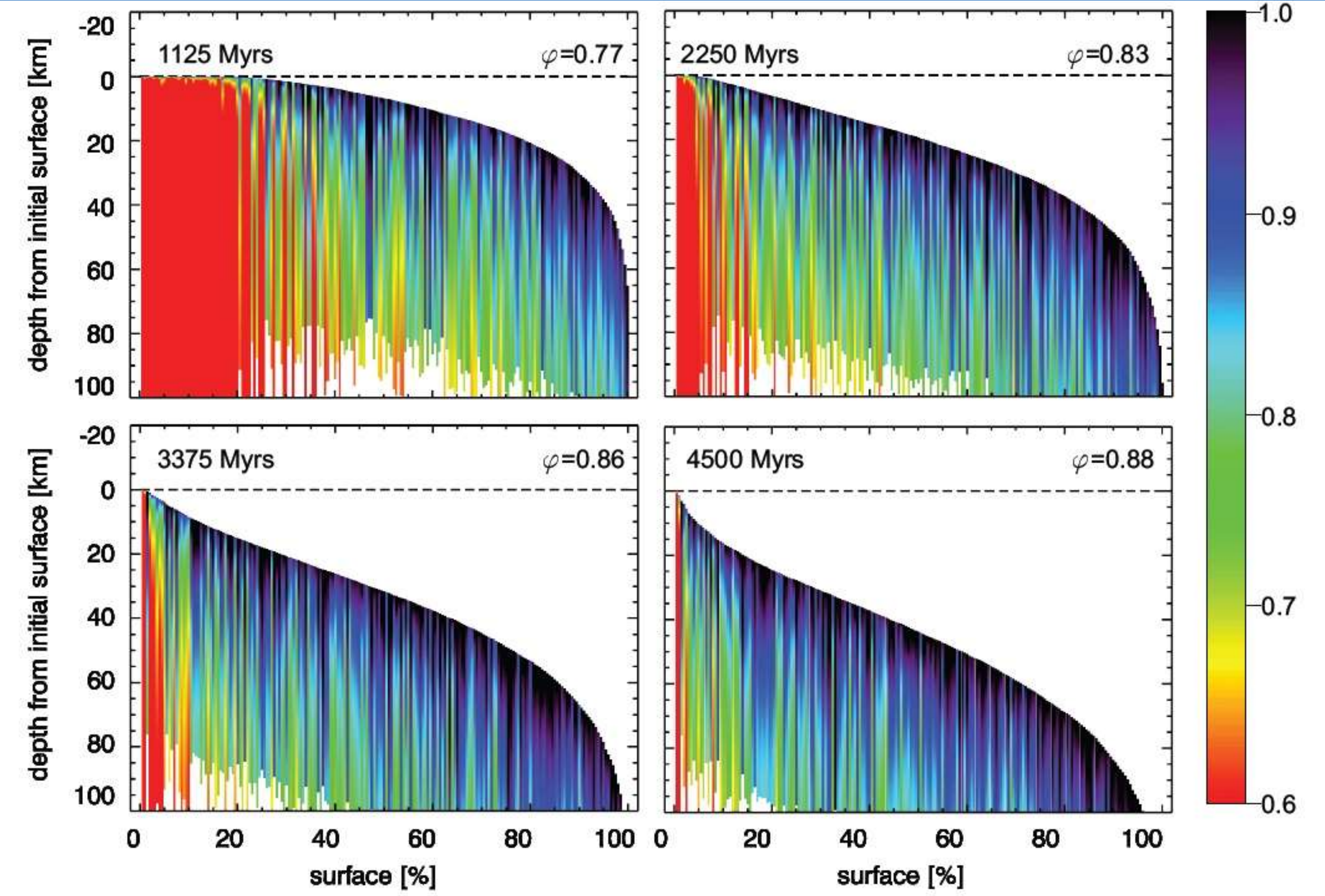
- We requested three Itokawa regolith particles to JAXA for the study of their physical properties

- It has been found recently that shock ages of Itokawa particles of 1.5 Ga obtained by Terada et al. (2018) are different from previously reported shock ages of shocked LL chondrites (4.2 Ga).
  - Itokawa had a time evolution different from that of the parent body of LL chondrites.


ν 6 secular resonance
(Michel and Yoshikawa 2000)
Conjunction of body and head within 0.1-0.4 My ago based on the deceleration of rotation rate (Scheeres et al. 2007)
Recent resurfacing at most 8 My ago based on the isotopic composition of Noble gas (Nagao et al. 2011)
Typical time scale into earth-closer orbit (10^6 years)
(Gladman et al. 1997)
asteroid family
Gravitational re-accumulation of several days (Michel et al. 2001)
Typical Life time of NEAs (10^7 years)
(Gladman et al. 2000)
cataclysmic disruption of 1.4 Ga
(Ar-Ar ages, Park et al. 2016;
U-Pb age in this study)
Collision within a million years
(Michel and Yoshikawa 2005)
Deaden by space erosion
(Nagao et al. 2011)
Typical cataclysmic disruption;
Every billion years for D>100km
A few per 10^8 year for 25km < D < 35km
(Bottke et al. 2005)
Itokawa parent body >20km
(Nakamura et al. 2011)
Thermal metamorphism of 4.6 Ga
(U-Pb age in this study)
Current ITOKAWA orbit
Main asteroid belt

COLLISIONAL EVOLUTION OF ASTEROIDS

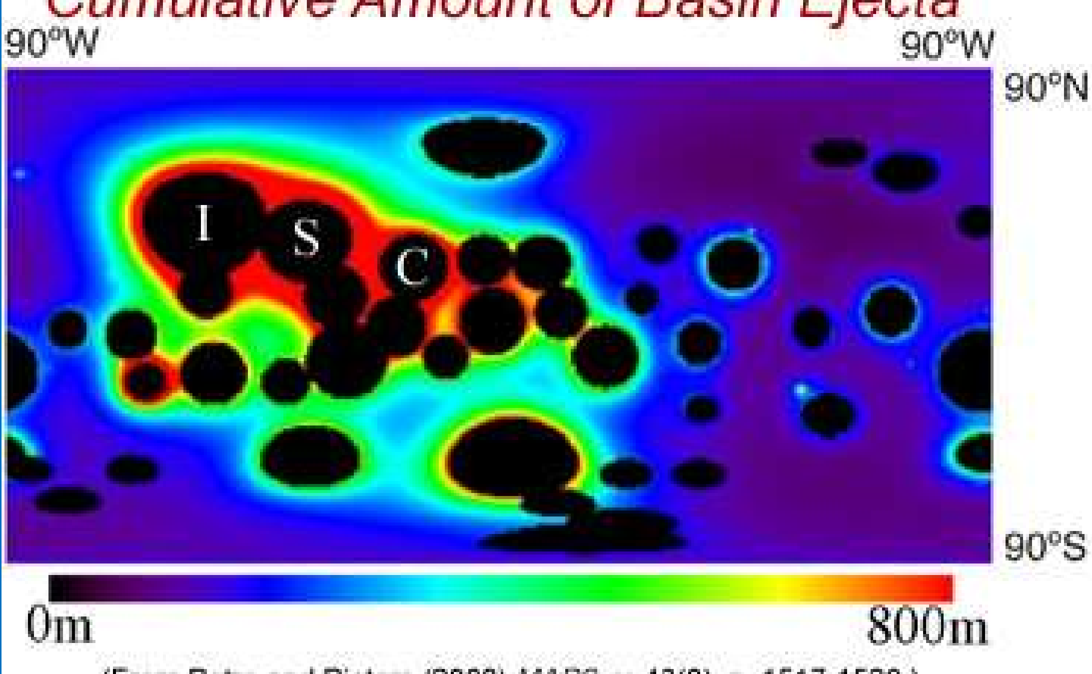
- Crater depth and compaction of an asteroid with ~100 km radius for times indicated in the upper left of the four panels.
- Collisional gardening lead to significant compaction of the PBs of carbonaceous chondrites (Blum et al., 2006)
- Progressive compaction by taking the difference in depth from the initial surface, and the higher volume filling factor.



Beitz et al. (2016) ApJ

IMPACT GARDENING

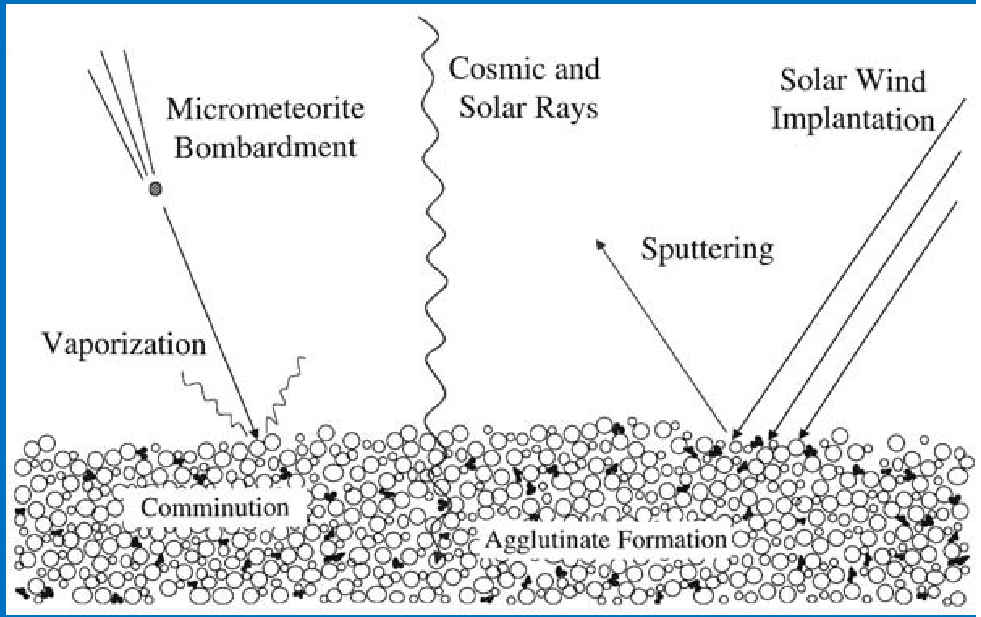
- Ejecta is excavated by the impacts and the excavated materials spread over the surface, being added to the regolith.
- This process mixes the upper layers of the regolith, depositing fresh material on the surface.
- As an example, around Lunar impact basins, the gardening can be huge: megaregolith

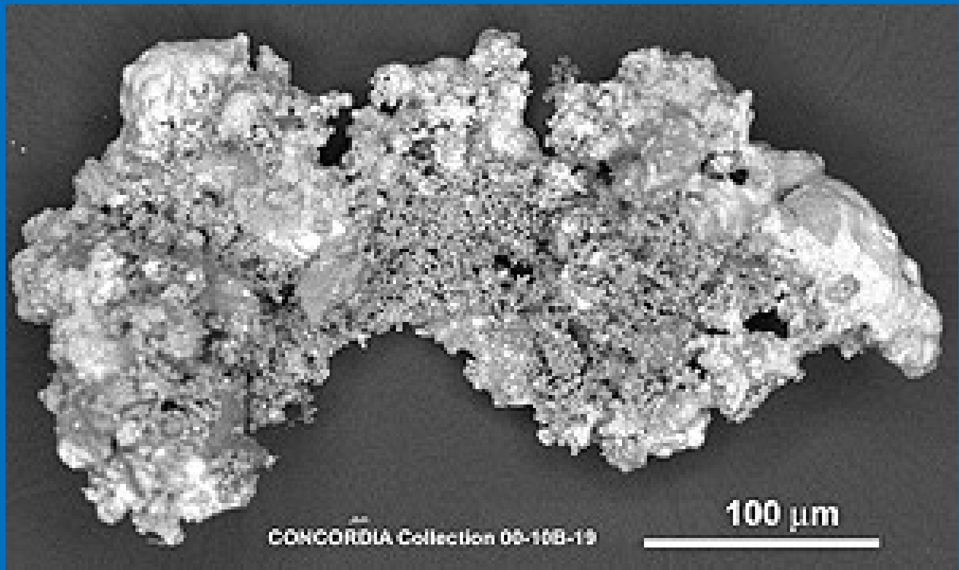


(From Petro and Pieters (2008) *MAPS*, v. 43(8), p. 1517-1529.)

Regolith Processes: Comminution

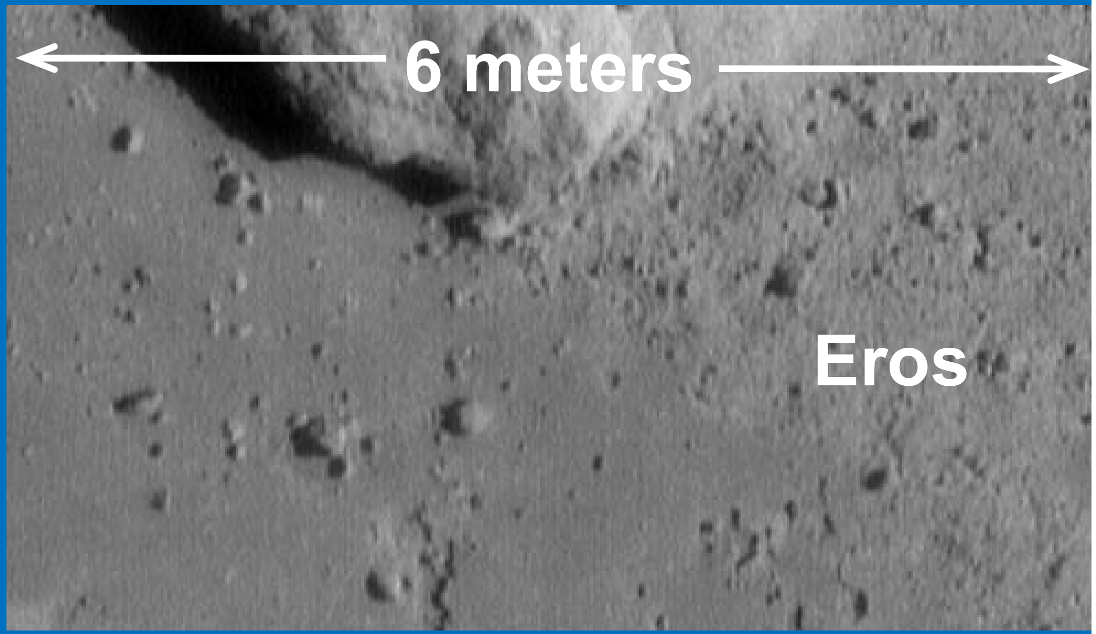
- Comminution: breaking of rocks and minerals into smaller particles
  - Impacts at all scales grind down particle size
  - Major impacts produce ejecta blocks and implantation
  - Micrometeorites grind down gravel and blocks to dust (remember they impact with an order of magnitude more energy than a bullet)
  - Implantation of volatiles

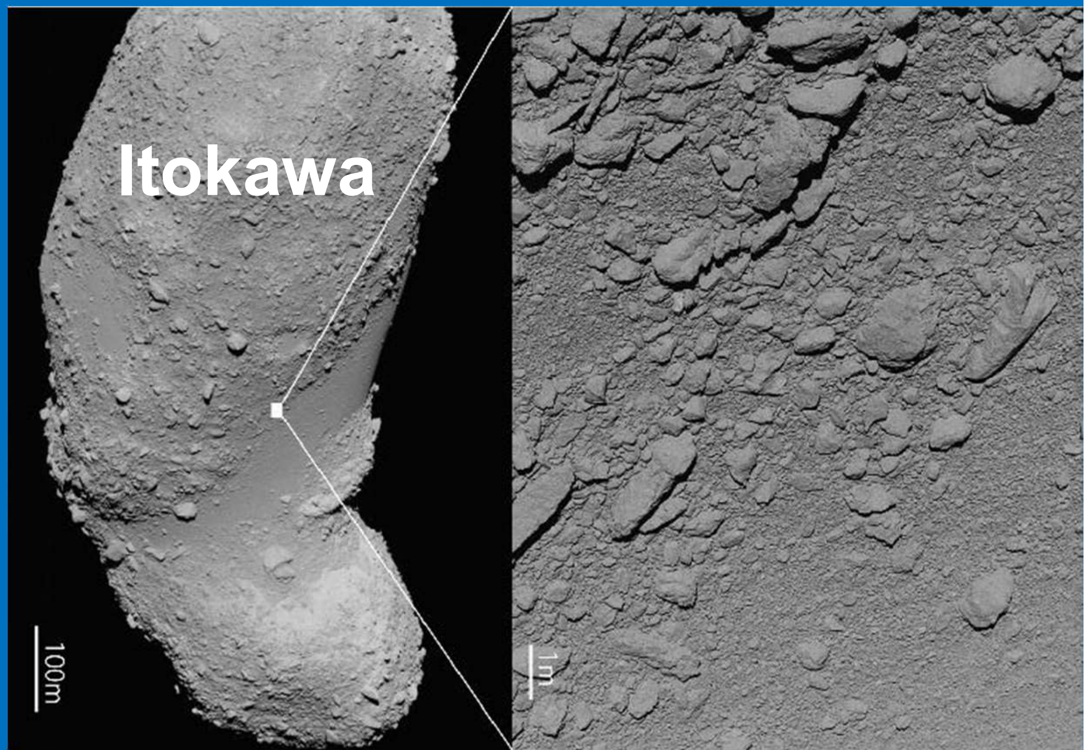




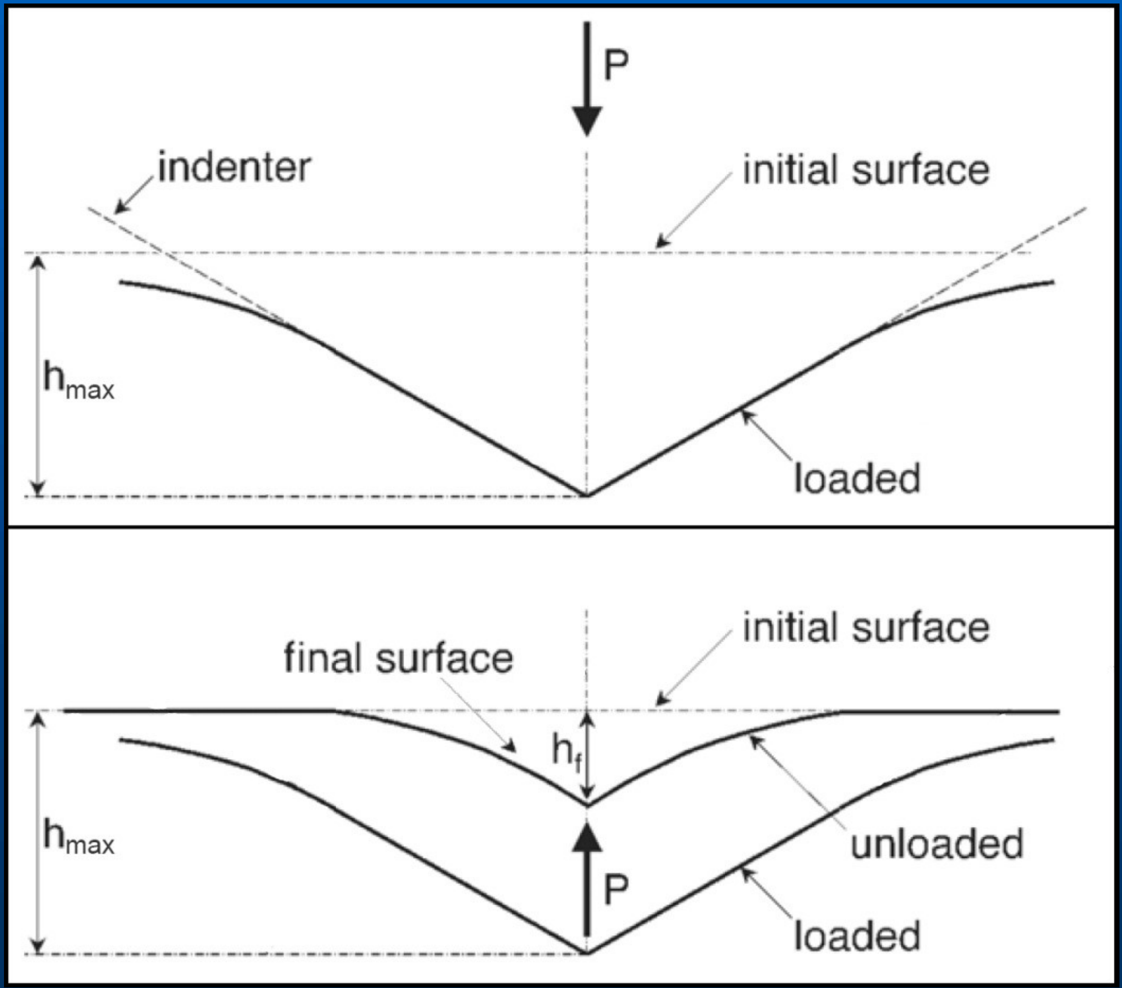
Asteroid Regolith Properties

- For small asteroids *comminution* plays a role:
  - Low gravity, low escape velocity
  - Much higher thermal inertia
  - Solar wind and impacts fracture the regolith
- As asteroids get smaller
  - Low gravity and porosity allows larger ejecta debris
  - Smaller asteroids have courser regolith soil with challenging properties
  - But *sample return missions* can bring these regolith particles for direct study in our labs (Tanbakouei et al., 2019: ICE studies on Itokawa).





- We first investigated the mechanical properties of Itokawa's forming materials: silicate chondrules, sulphides, etc
- Application of a controlled load (~20 μN-500 mN) through use of a hard indenter



- The indenter pushes the surface while increasing load, down to a maximum depth (h_{max} ~ few μm)
- Concurrent measurement of depth.
- Due to elasticity, the surface recovers when the indenter is unloaded

Nano-indentation results for 3 Itokawa particles

Tanbakouei, Trigo-Rodríguez, Sort, et al. (2019), A&A

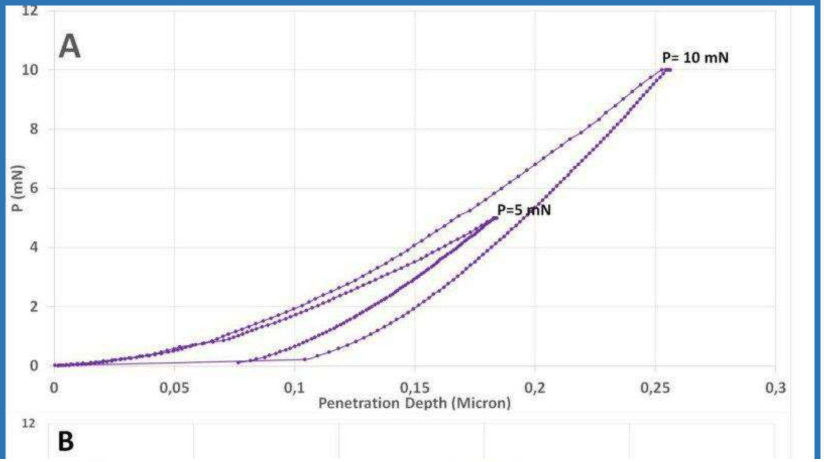
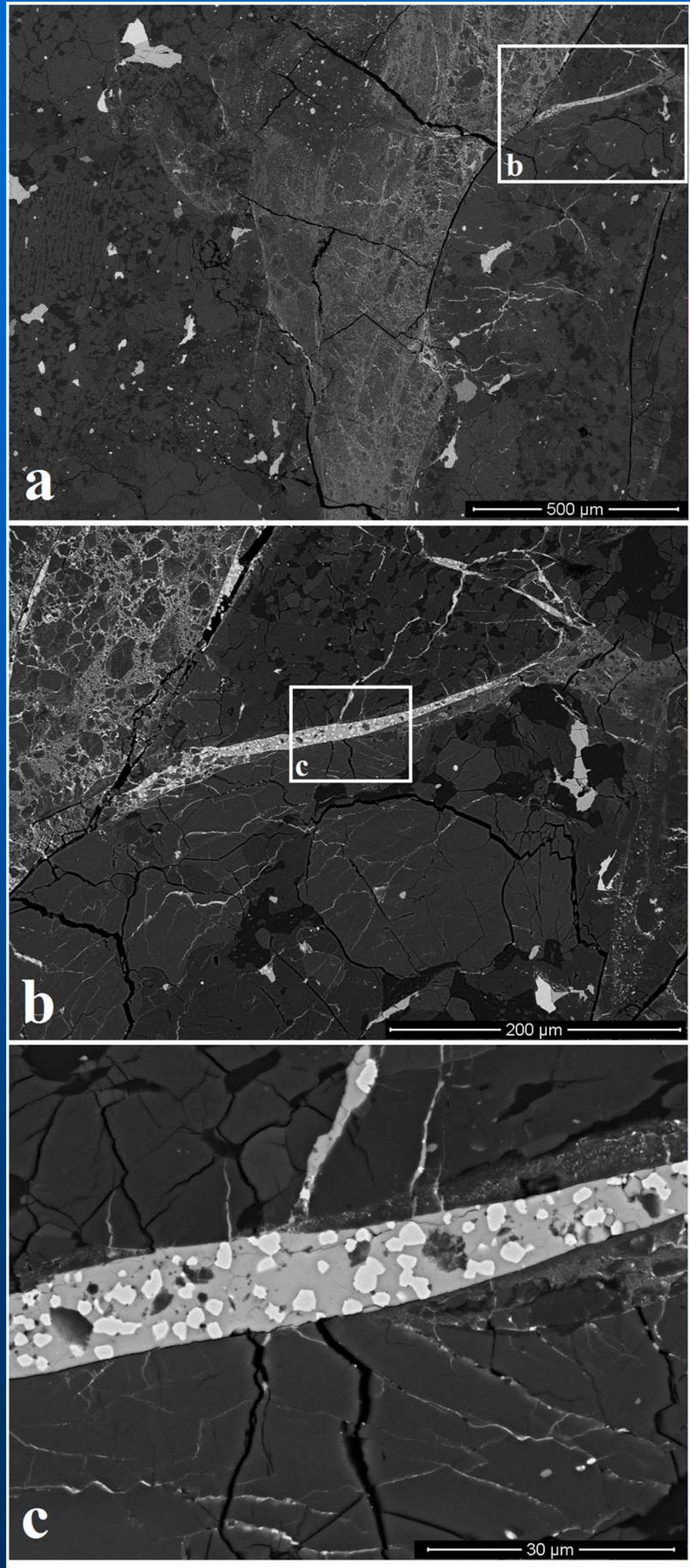


Table . Average mechanical properties of Itokawa regolith silicates in particles of given S#. Reduced Young's modulus (E_r), hardness (H), constant stiffness (S), elastic recovery (U_{el}/U_{tot}) and plasticity index (U_{pl}/U_{tot}) were calculated by averaging the results from two lines of indentations from the maximum applied force of 10 mN.

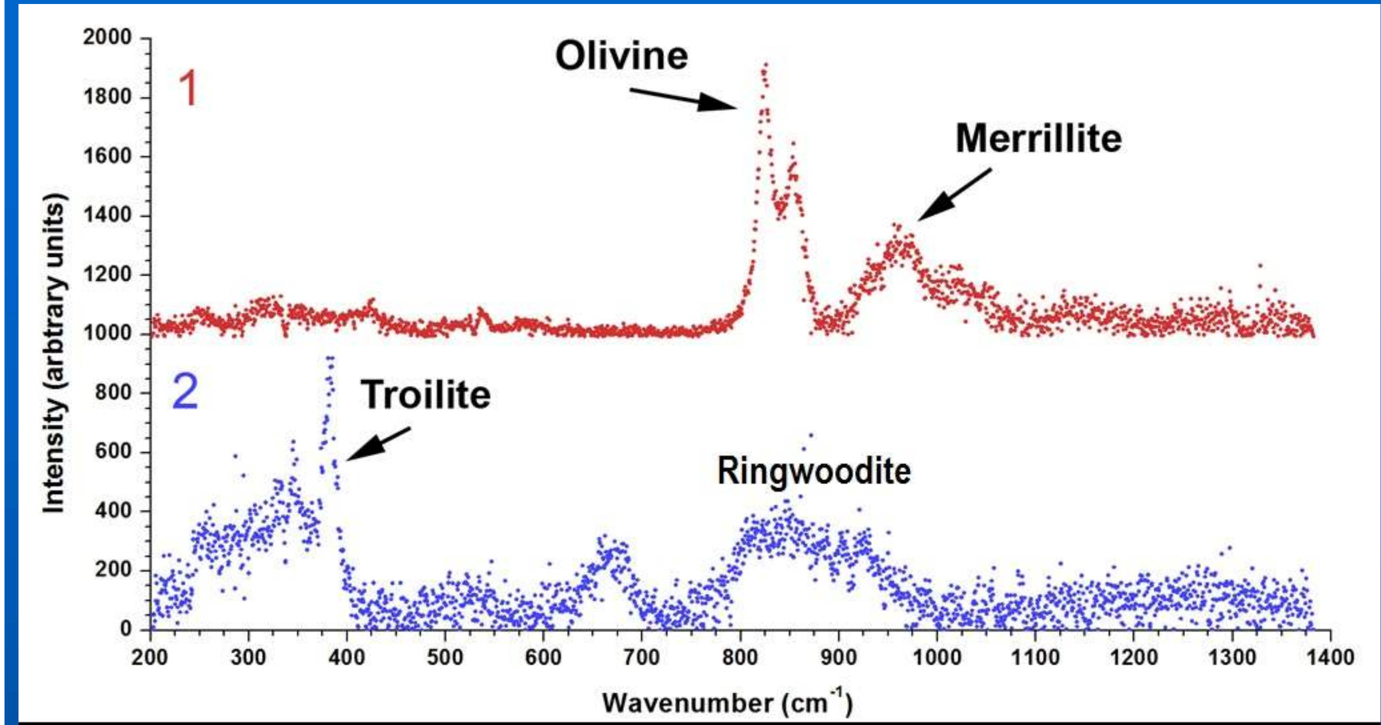
Sample	Applied Force (mN)	E_r (GPa)	H (GPa)	S (mN/µm)	U_{el}/U_{tot}	U_{pl}/U_{tot}
#14	5	83.01 ± 0.12	8.01 ± 0.01	77.01 ± 0.11	0.64 ± 0.01	0.36 ± 0.01
	10	86.00 ± 0.044	9.00 ± 0.014	105.00 ± 0.06	0.64 ± 0.01	0.34 ± 0.01
#23	5	111.01 ± 0.22	10.01 ± 0.02	92.00 ± 0.20	0.73 ± 0.07	0.27 ± 0.07
	10	101.00 ± 0.05	10.00 ± 0.01	117.00 ± 0.5	0.66 ± 0.05	0.35 ± 0.05
#47	5	86.01 ± 0.13	13.01 ± 0.03	62.01 ± 0.03	0.88 ± 0.01	0.13 ± 0.01
	10	82.00 ± 0.14	11.00 ± 0.02	91.01 ± 0.07	0.68 ± 0.01	0.33 ± 0.01

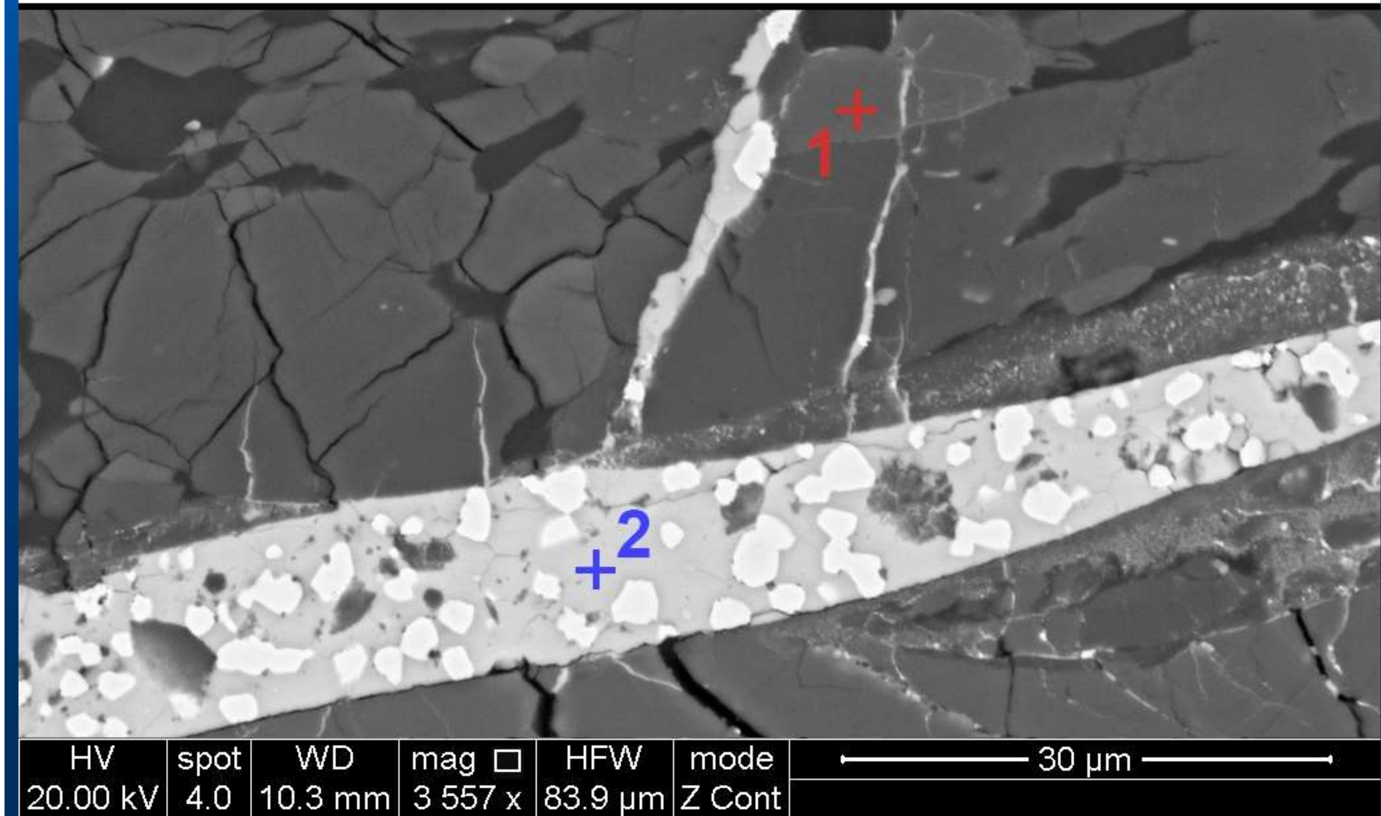
HIGH-PRESSURE TRANSFORMED MINERALS

- Severe collisional processing has been experienced by the Chelyabinsk meteorite
- Shock veins are present all over the meteorite.
- Impact melts and shock veins are filled with Fe-Ni and troilite
- This rock experienced shock-induced mineral transformations. Shock-darkened lithologies and clasts of impact melt breccias occur as (almost) opaque areas.



Increasing zoom BSE image around a shocked area to exemplify the degree of shock and complexity (Trigo-Rodríguez et al., 2014)

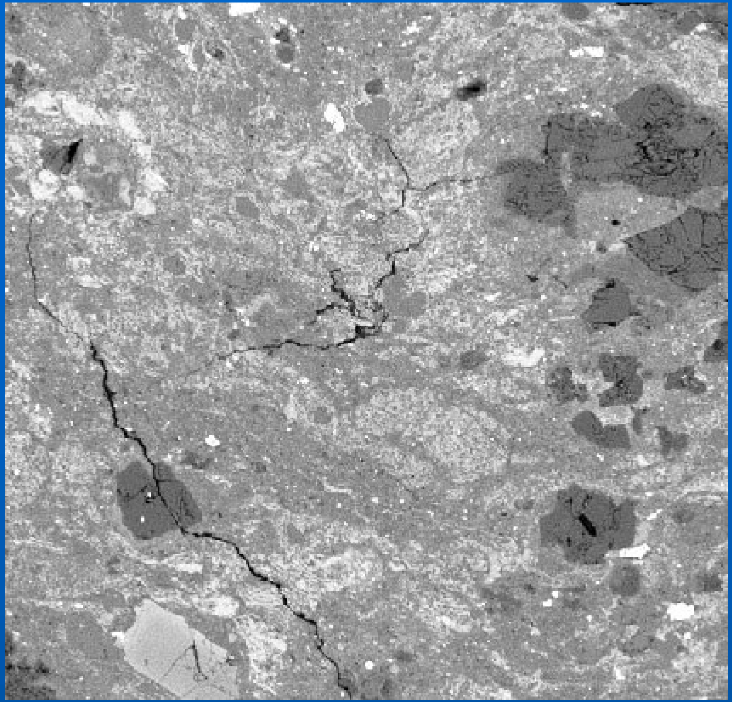




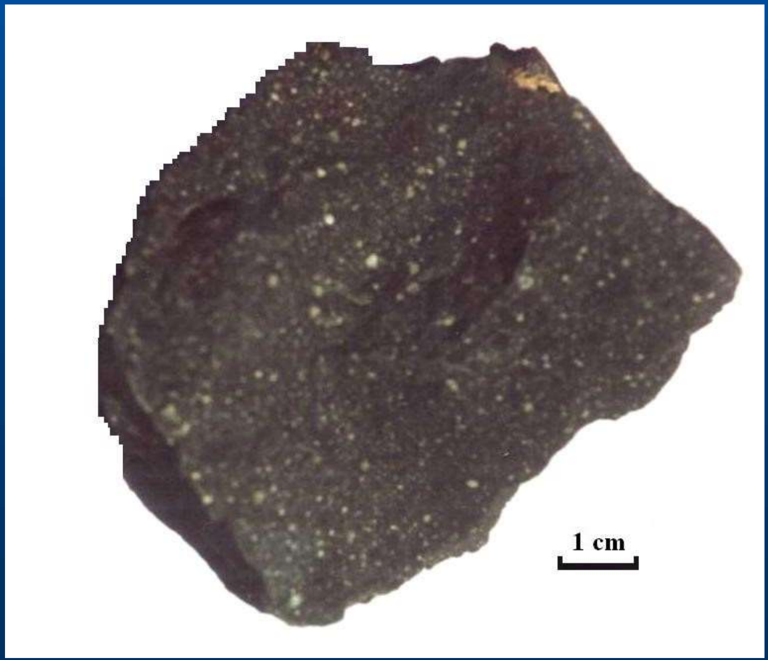
RAMAN SPECTRA OF SHOCKED MINERALS

- Ringwoodite, a high-P polymorph of olivine
- A high-pressure polymorph of merrillite, $Ca_9MgNa(PO_4)_7$ that has a trigonal structure γ-$Ca_3(PO_4)_2$ identified nearby shock veins.
- We have confirmed this by point-and-shoot Raman analyses that identified its characteristic intense peaks at 956 and 972 cm^{-1}.

CARBONACEOUS CHONDRITES



1 cm window SEM image of Y791198 CM2 (Trigo-Rodríguez et al., 2006)



Murchison CM2 chondrite

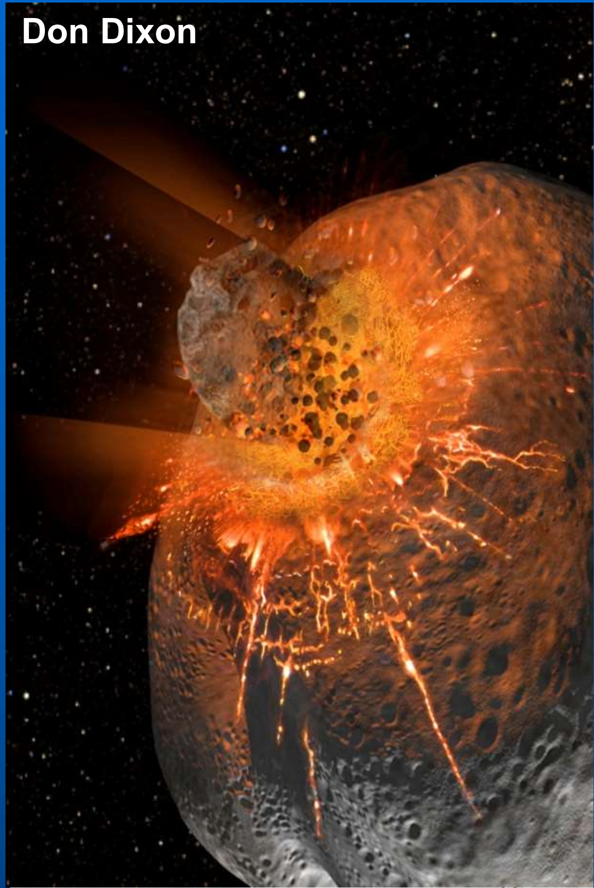
- They are among the most primitive rocks arrived to Earth
- Rocks from water-rich bodies containing chondrules, inclusions and fine dust materials:
  - Until 10% H_2O and 4% C in mass
- Some CCs experienced aqueous alteration to different degrees (McSween, 1979)
  - Many mineral phases are aqueous alteration products (Zolensky & McSween, 1988):
    - phyllosilicates, sulfides, carbonates, and oxides
- CCs chondrites suffered secondary processes after accretion (Brearley & Jones, 1998):
  - Aqueous alteration
  - Brecciation (consequence of impacts): amorphous C

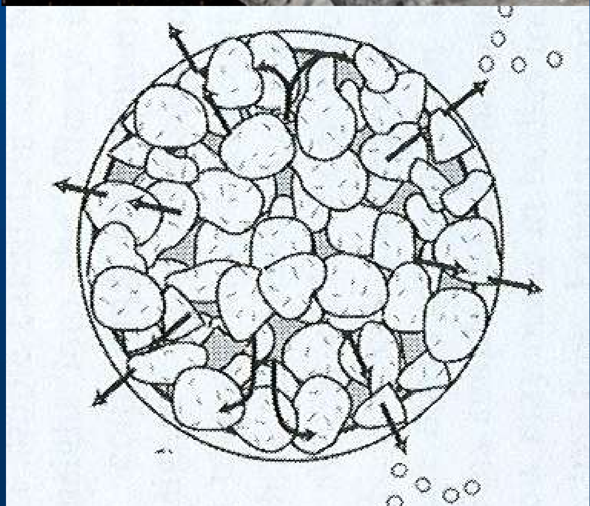
AQUEOUS ALTERATION

- Parent-body aqueous alteration:
  - T <400 K (Bunch & Chang, 1980)
  - Zolensky et al. (1993) estimated the conditions for aqueous alteration as a function of T, water/rock ratio and O fugacity

- The lenses found in CMs support water flow in parent bodies (Trigo-Rodríguez & Rubin, 2006):
  - Early exhalation or convection (Young et al., 2003)
  - Water mobilization as shock propagates after collisions, etc…

- Recent analyses of pristine CR2s found in Antarctica have revealed the existence of promising extraterrestrial environments to synthesize water-soluble compounds, particularly rich in N
  - Ammonia and amino acids are the most abundant components of matrix extracts of GRA 95229 (Pizzarello et al., 2011, PNAS)
    - High potential to evolve towards prebiotic chemistry!

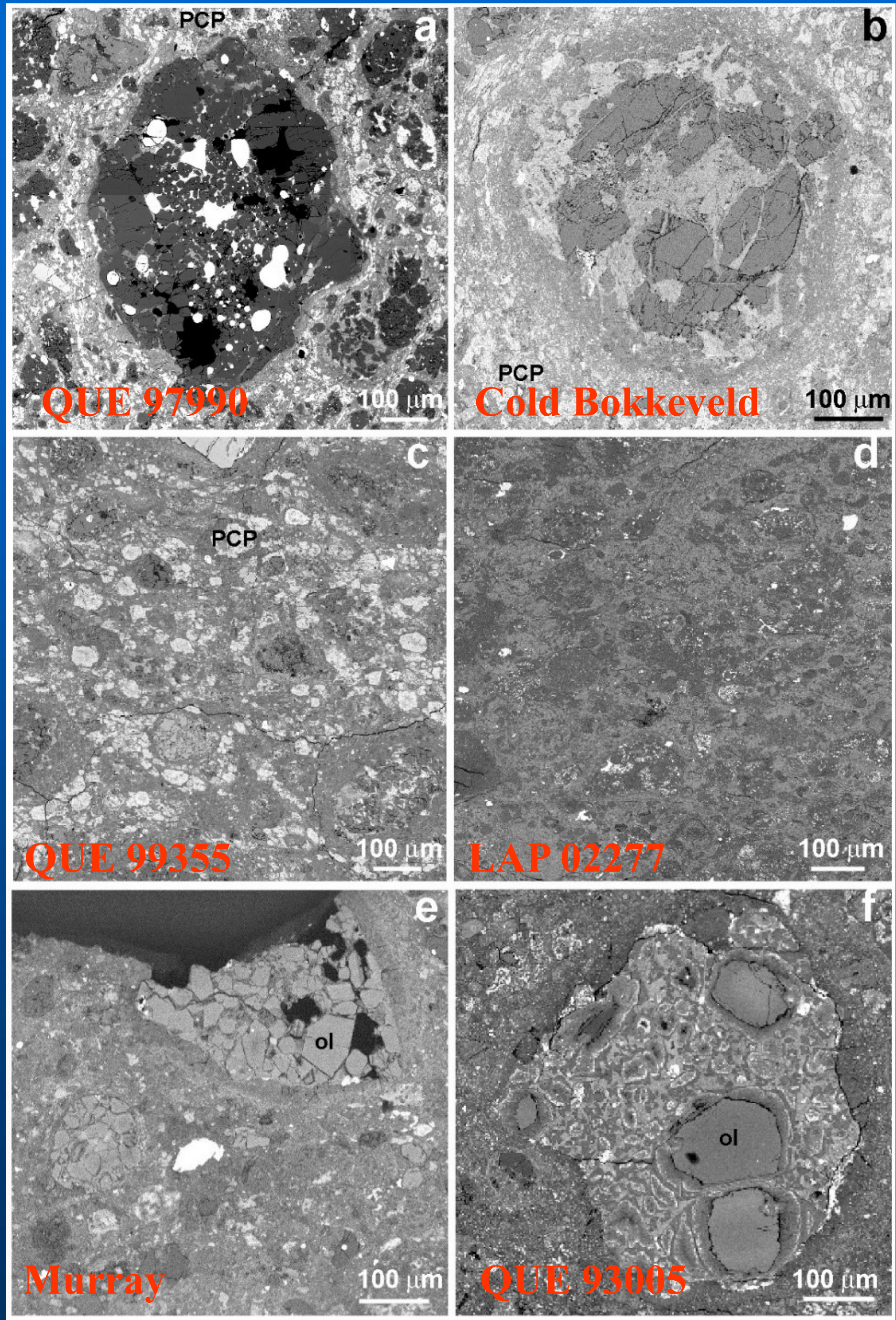




Exhalation (Young et al., 2003)

PROGRESSIVE AQUEOUS ALTERATION IN CMs

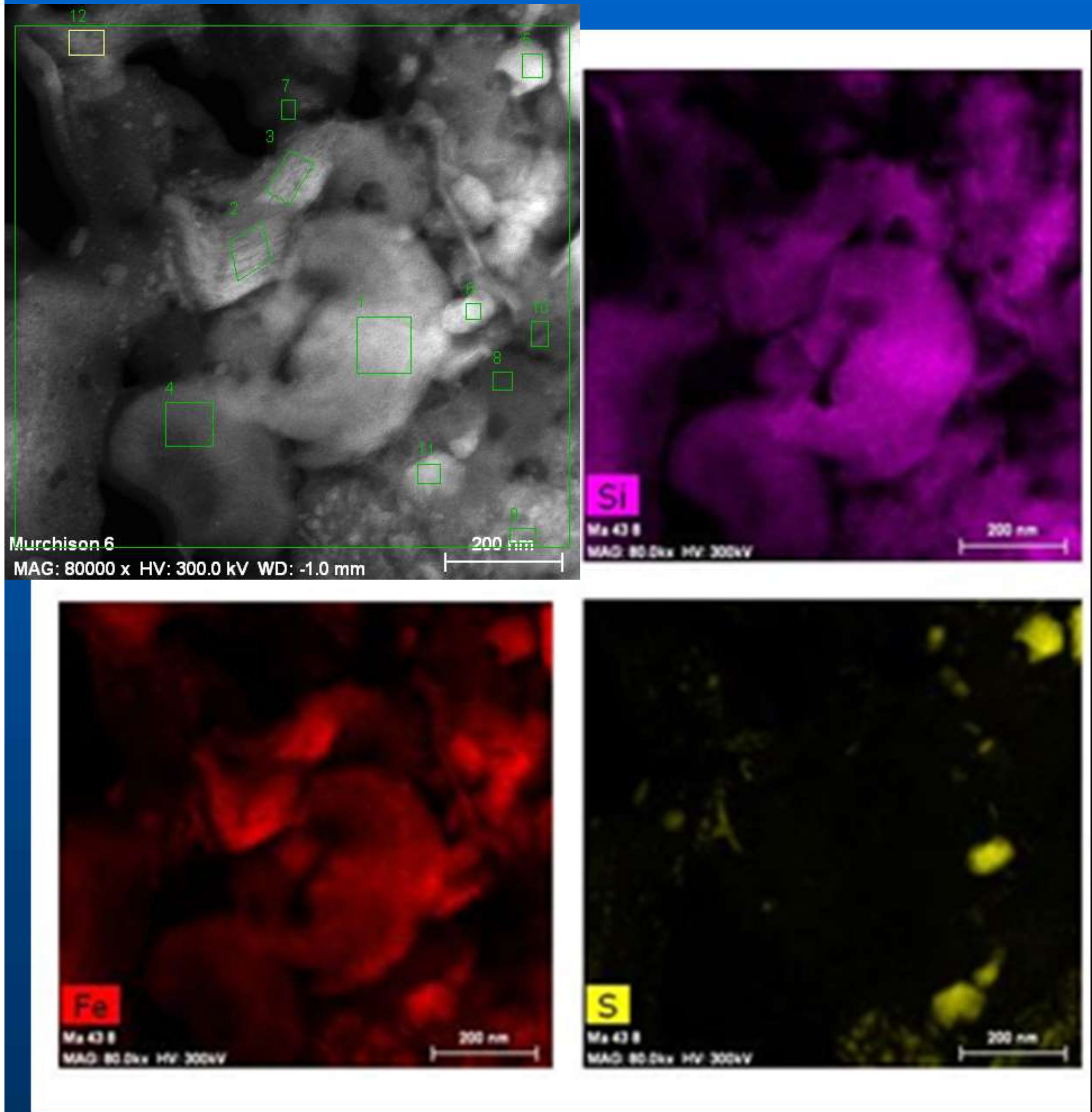
- Evidence for pre-terrestrial action of water in km-sized planetesimals
- We studied 10 CMs that span the range of moderate to extreme aqueous alteration (Trigo-Rodríguez et al., 2006)
- Many CMs are breccias containing clasts of different alteration stages (e.g., Cold Bokkeveld, Murray)
  - They were altered to different degrees, possibly due to their burial depth
  - The samples were later fragmented and compacted by impacts

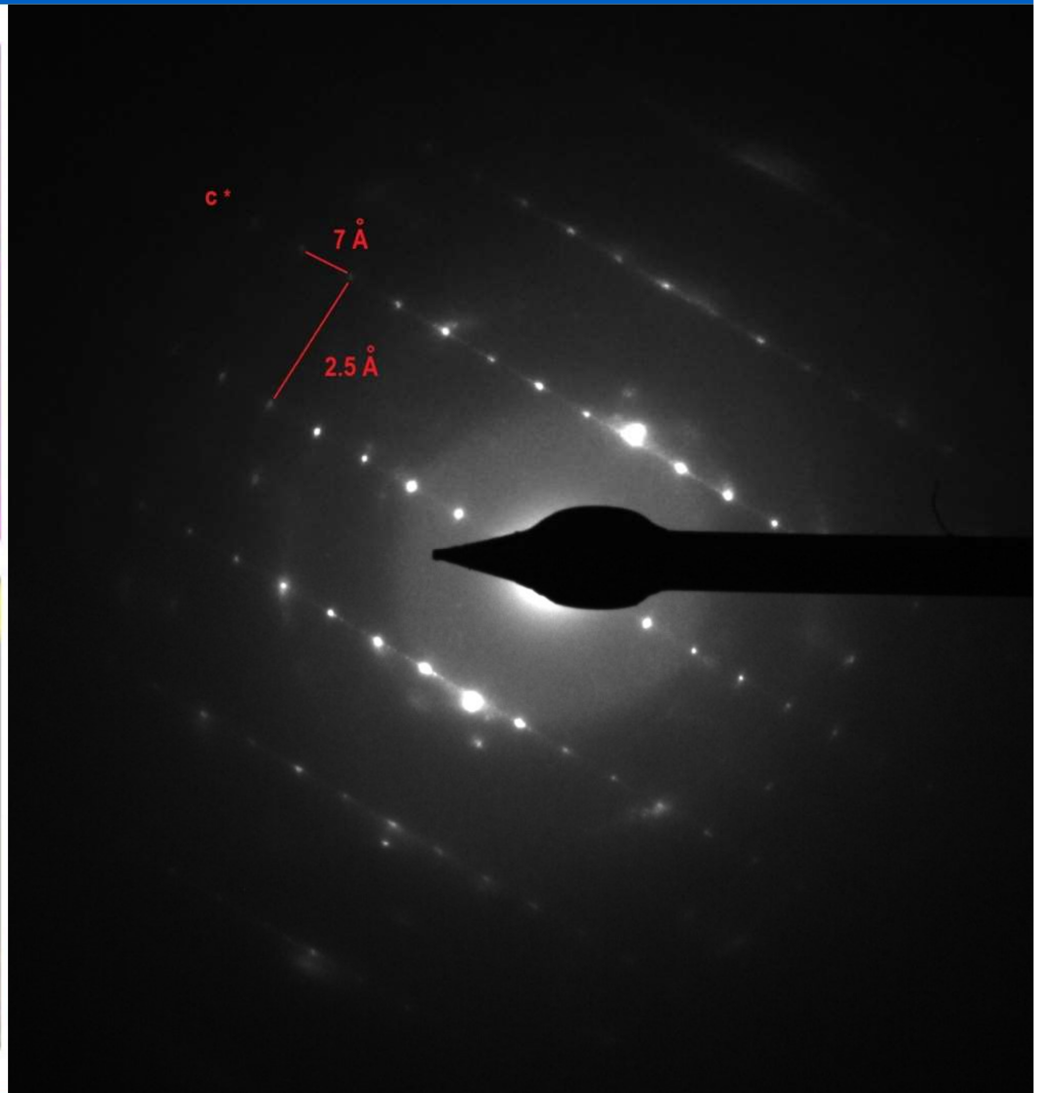


(Trigo-Rodriguez et al., GCA 4581 , 2006).

MURCHISON SEEN AT UHRTEM

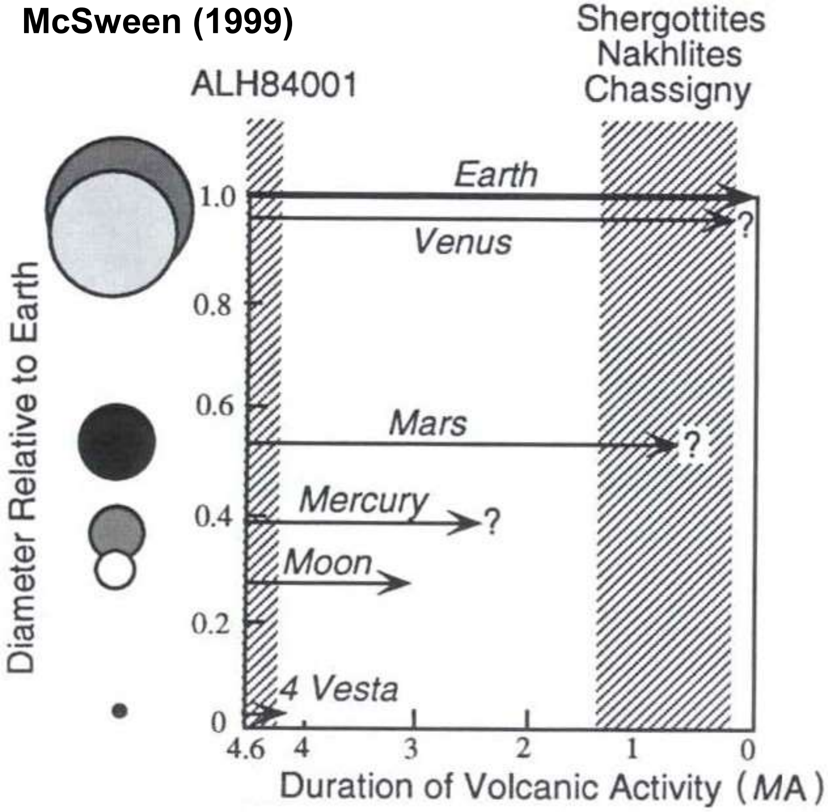
Trigo-Rodriguez et al. (2017, 2019)

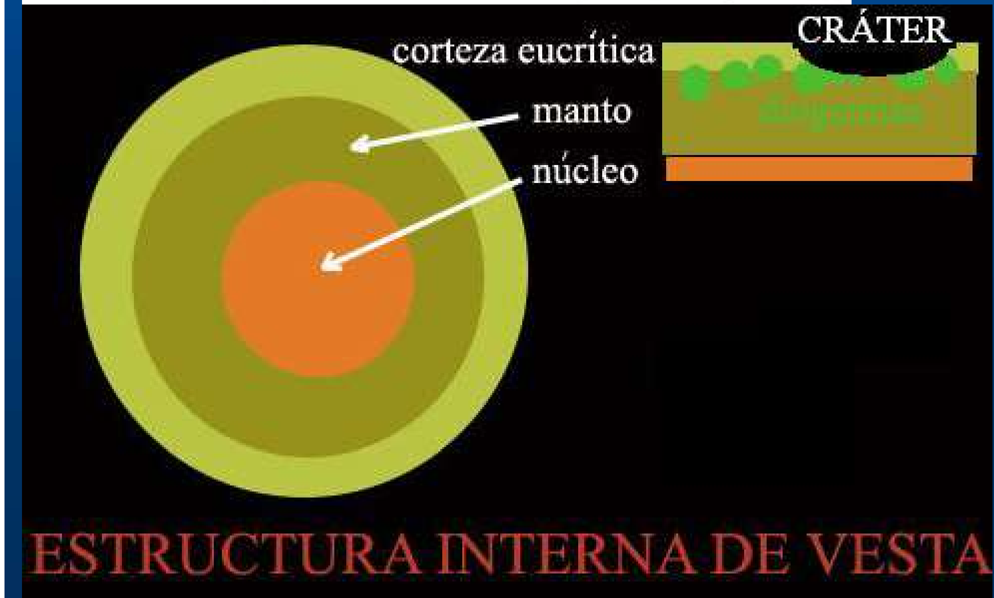




- **BOXES:** 1 & 4: lizardite, 2 & 3 mixture of serpentine with cronstedtite, 5 & 6 pentlandite, 8 carbonate, 11 pyrrhotite, and 12 pyroxene

ACHONDRITES

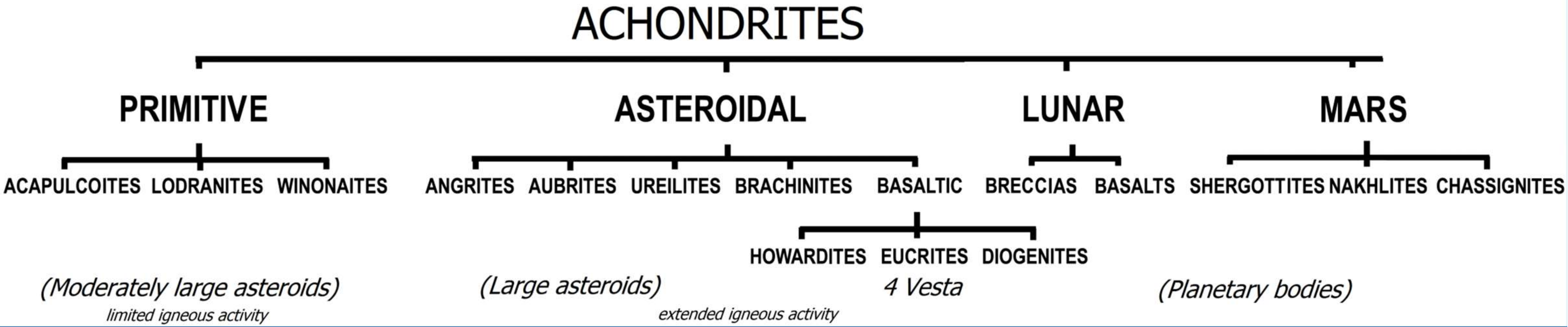




- They were formed by igneous processes in bodies of several hundred km in diameter
  - Most are producing igneous rocks of basaltic nature
  - Igneous activity had a different extent depending of the planetary body dimensions
- O isotopes allow us to associate these rocks with their sources

Puerto Lápice eucrite (Vesta)

ACHONDRITE DIVERSITY

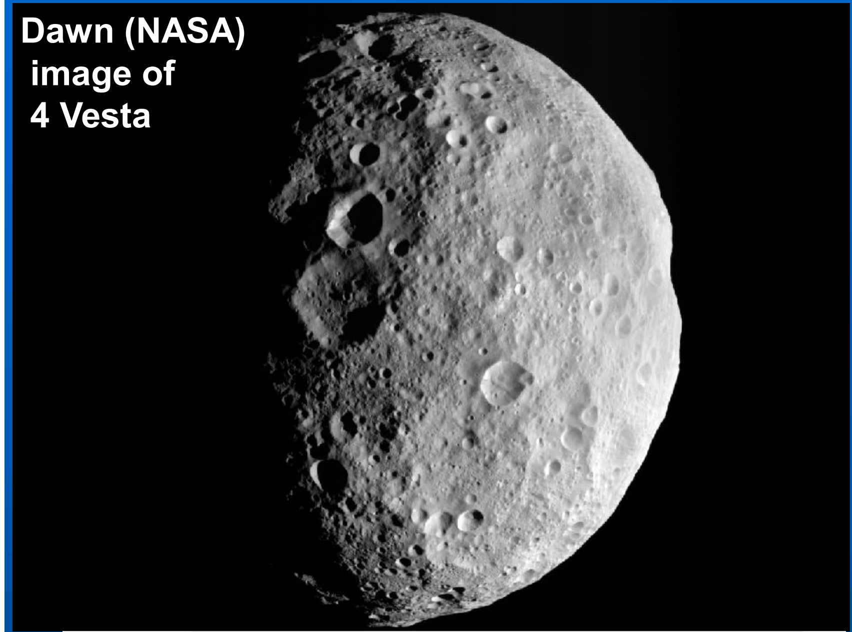


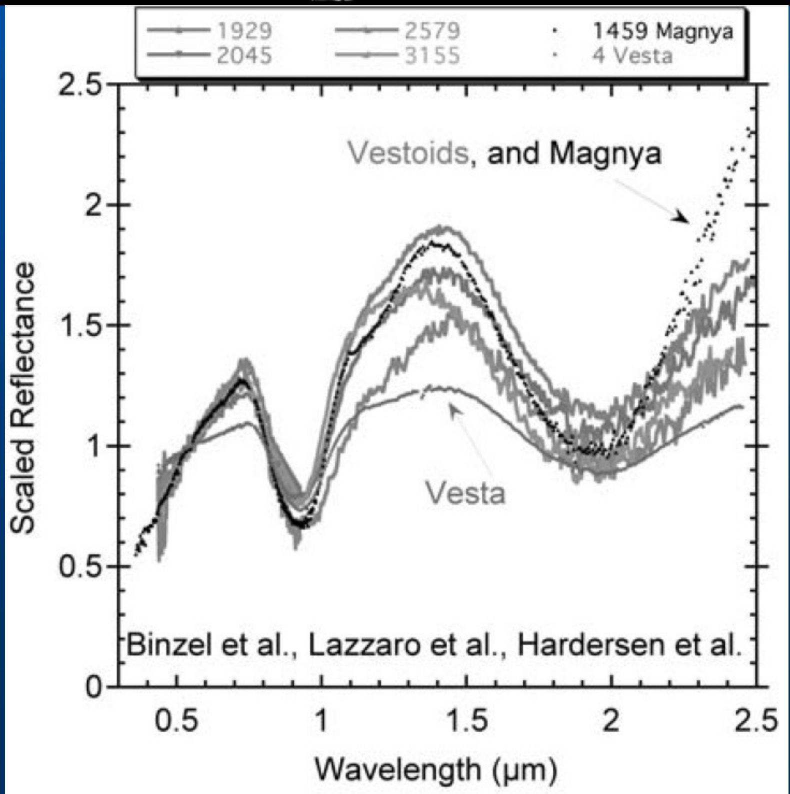
Adapted from Trigo-Rodríguez (2012)

Dhofar 125 (Acapulcoite)

Bilanga (diogenite from 4 Vesta)

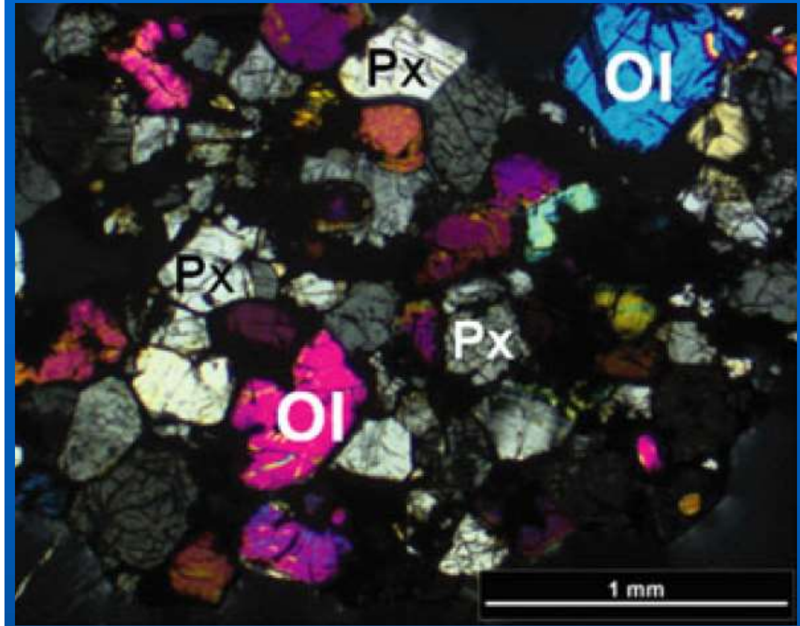
THE HED CLAN AND 4 VESTA





- The HED clan account for ~5% of the falls and ~60% of all achondrites arrived to Earth
- First match with eucrites (McCord et al., 1970)
- Pieters et al. (2005)
  - Vesta is the only "intact" basaltic asteroid. Although the smaller Vestoids and Magnya are basaltic in nature, the Vestoids are probably related to Vesta, but Magnya is not.
  - HEDs, NWA011, and Ibitira have very similar basaltic mineralogy, but appear to come from distinct parent bodies
- Now the Dawn (NASA) mission has revealed complex processes in this planetary embryo (McSween et al., 2012)

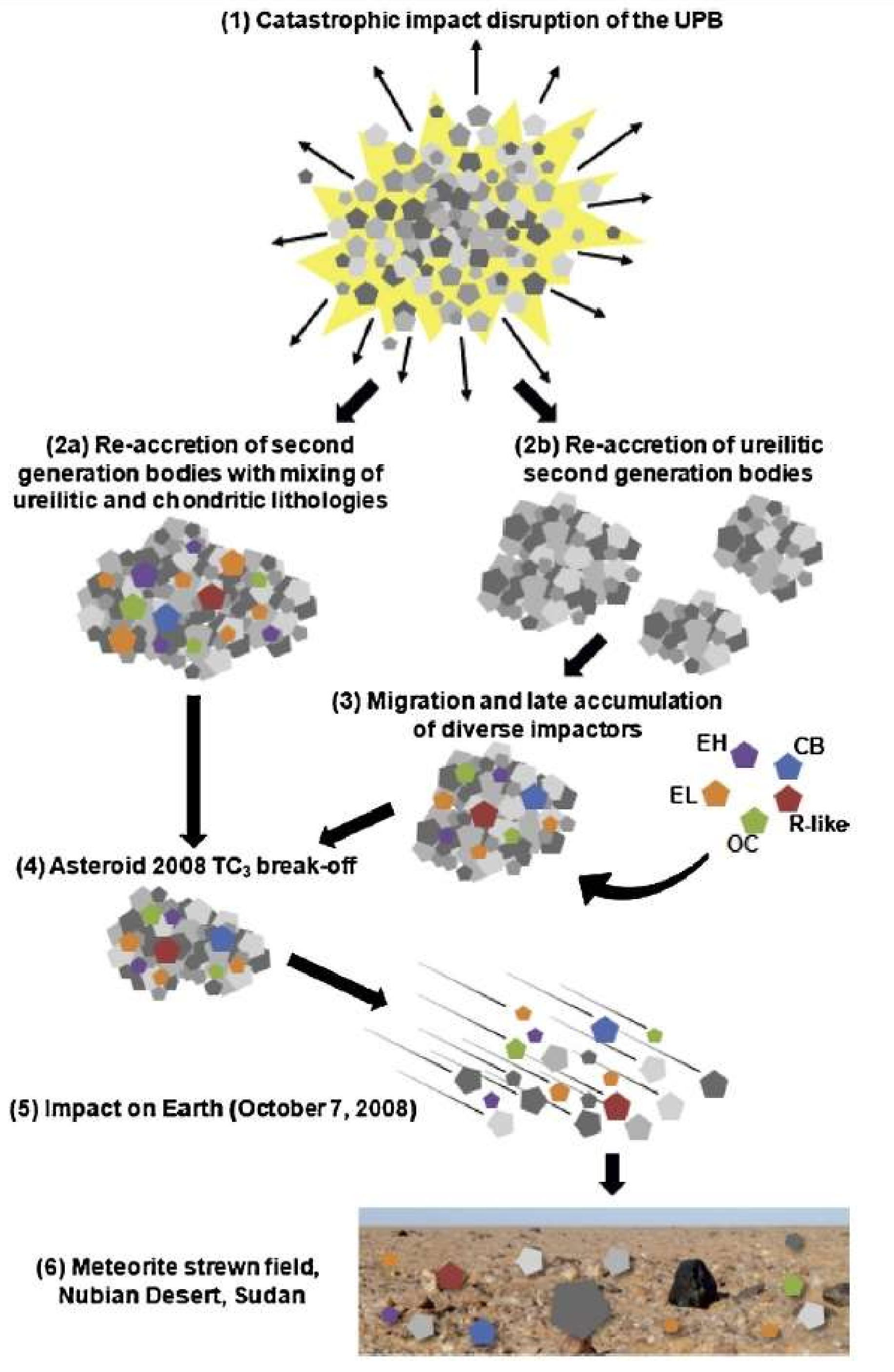
PRIMITIVE ACHONDRITES



Almahatta Sita ureilite (Bischoff et al, 2010)

Peña Blanca Springs (Trigo-Rodríguez, 2012)

- They presumably come from moderately large asteroids (few hundred-km in diameter) that experienced a short igneous period
- Basically the primitive achondrites are chondritic rocks that have been slightly modified by partial melting and recrystallization (Hutchison, 2004)
- The main classes:
  - Acapulcoite-Lodranite group
  - Winonaites; Coarse olivine and Ca-poor pyroxene
  - Ureilites: Olivine-pyroxene rocks with C-rich mesostases rich in noble gases
  - Aubrites are highly reduced, coarsed crystalline, enstatitic fragmental and regolith breccias with O isotope ratios linked with enstatite chondrites



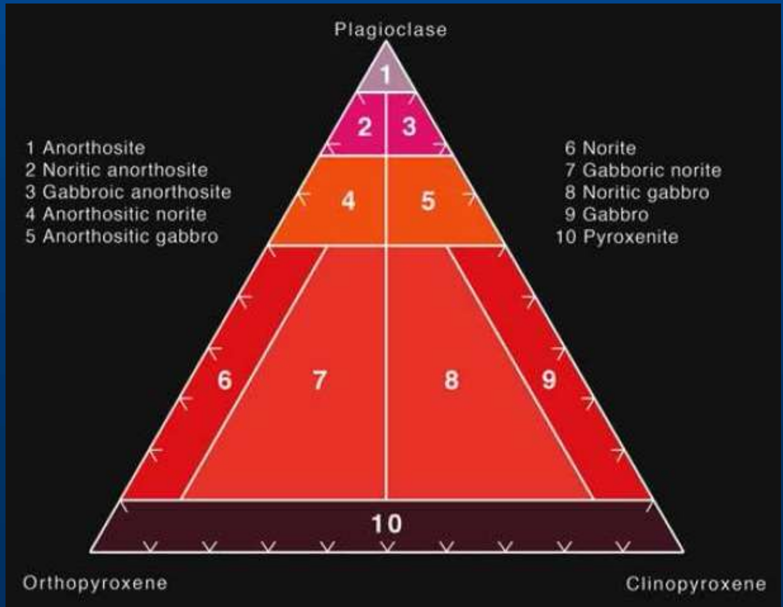
Almahatta Sita origin (Horstmann & Bischoff, 2014)

ALMAHATTA SITA: THE COMPLEX HISTORY OF ACHONDRITES

- Almahata Sitta was asteroid 2008 TC3 fell **over Sudan on Oct. 7th, 2008**
- This meteorite is not only a ureilite but a complex polymict breccia (Horstmann and Bischoff, 2014)
- It is a clastic sedimentary rock composed of angular clasts from different origin intermixed in a consolidated matrix, containing the lithologies:
  - Ureilites
  - Ordinary chondrites
  - Carbonaceous chondrites
  - Rumuruti-like: R chondrites

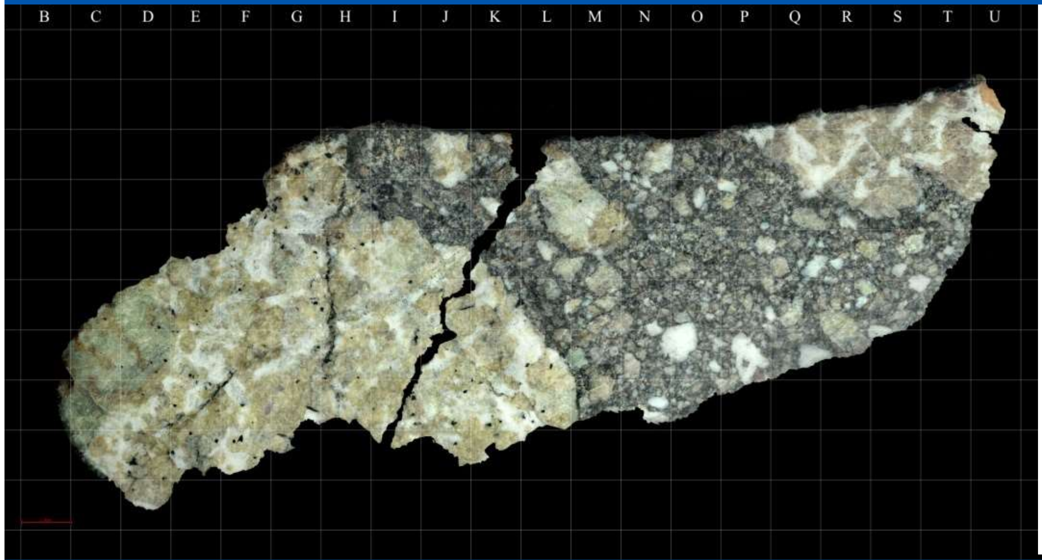
LUNAR ACHONDRITES

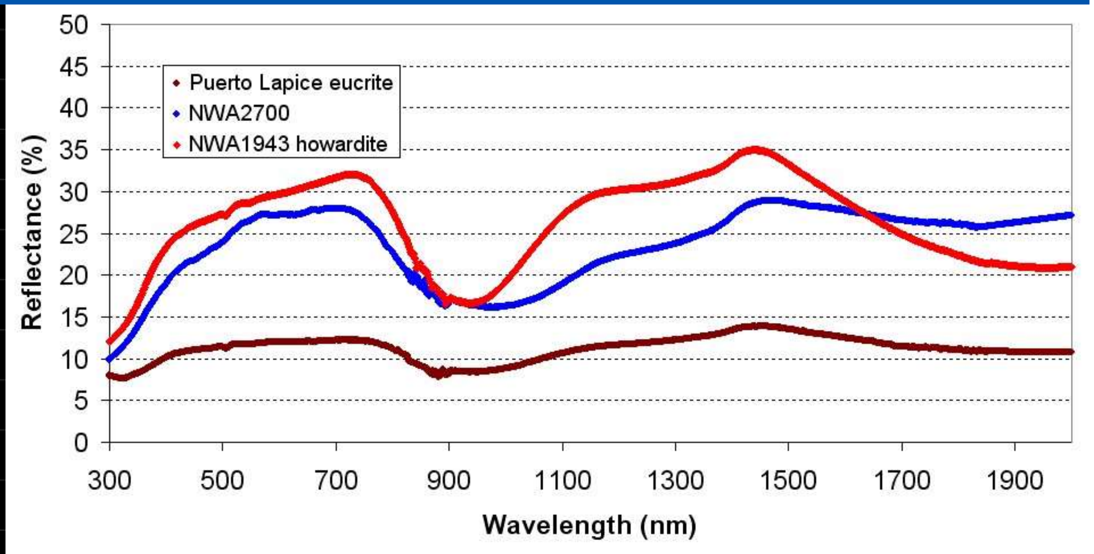
- The *Meteoritical Society* has 621 lunar meteorites
  - Formed 4.500 and 3.200 M.A. ago
- 99% recovered in cold or hot deserts
- Main types:
  - Basaltic: Lunar mare
  - Anortositic: High terrains (~90% plagioclase + pyroxene and olivine)
  - Others: gabbros and breccias
- Lunar rocks from space missions:
  - Apollo missions (382 kg) and Moon (0.3 kg)
    - RL 15555: Lava flow that formed the Mare Imbrium 3.310±30 MA ago (Podosek et al., 1972)



DISTINCTIVE SPECTRA OF DIFFERENTIATED METEORITES

- Just as an example of the plagioclase and pyroxene typical features of differentiated meteorites here are given the spectra of NWA2700 (a Lunar breccia characterized by our team), and a couple of HED meteorites





Cortés, Trigo-Rodríguez and Llorca (2012) LPS XLIII, abst. #1455.

- Note the distinctive absorption bands characteristic of silicates, and the higher reflectance compared with carbonaceous chondrites

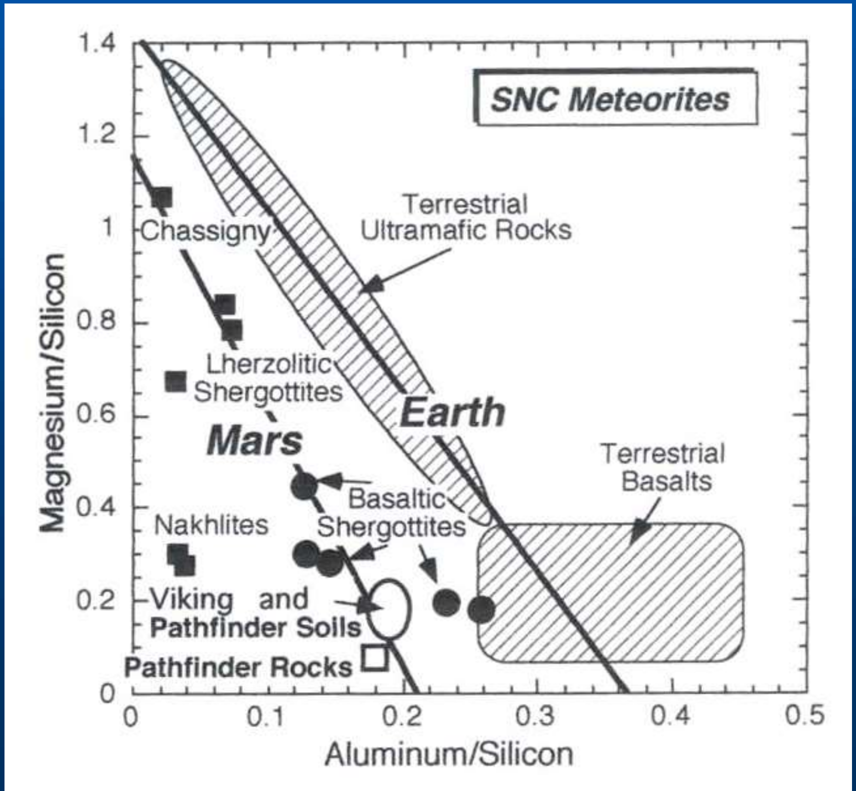
VIRTUAL POLARIZATION MICROSCOPE TO LEARN MINERALOGY

- Virtual Microscope of Moon rocks
- http://www.virtualmicroscope.org/content/moon-rocks
- Anorthosite (15415) – plag (twin) -2
- Troctolite (76535) – ol + plag - 1
- Norite (78235) plag + px - 2
- High-Ti basalt (70017) ilm + px - 2
- Low-Ti basalt (12002) – ol, Px (ex)- 1

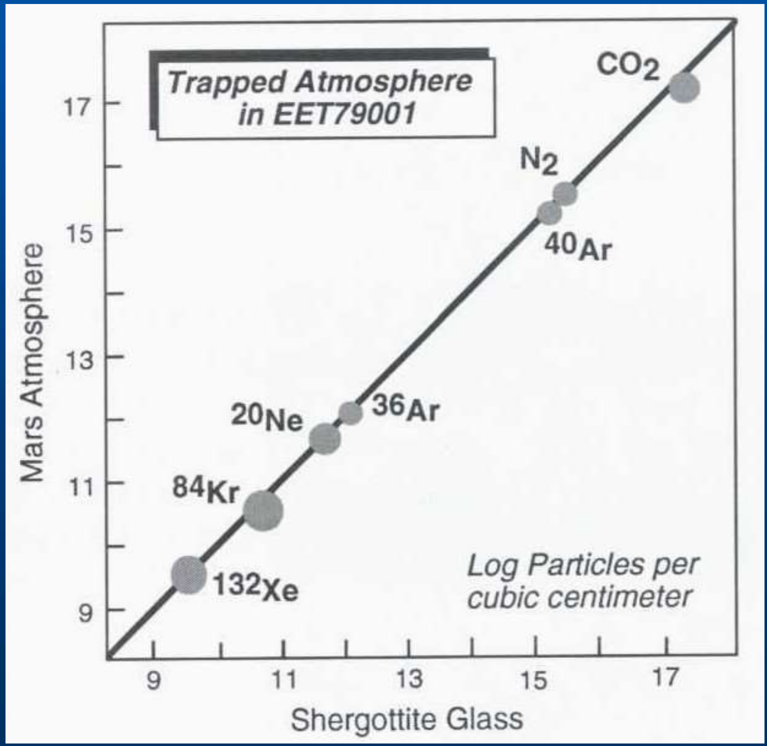
SNC METEORITES FROM MARS

- 354 Martian meteorites catalogued by the Meteoritical Society
- Clearly distinguishable by Al/Si and Mg/Si ratios, different from terrestrial rocks as measured by Viking landers
- Also called generically SNC meteorites:
  - Acronym of the meteorites-type of 3 main identified groups: Shergotty (India, 1865), Nakhla (Egipto, 1911)& Chassigny (Francia, 1915)
- Final confirmation of their origin in Mars came from the study of trapped gases during crystallization of the EET 79001 Shergottite

EET 79001



McSween (1999)

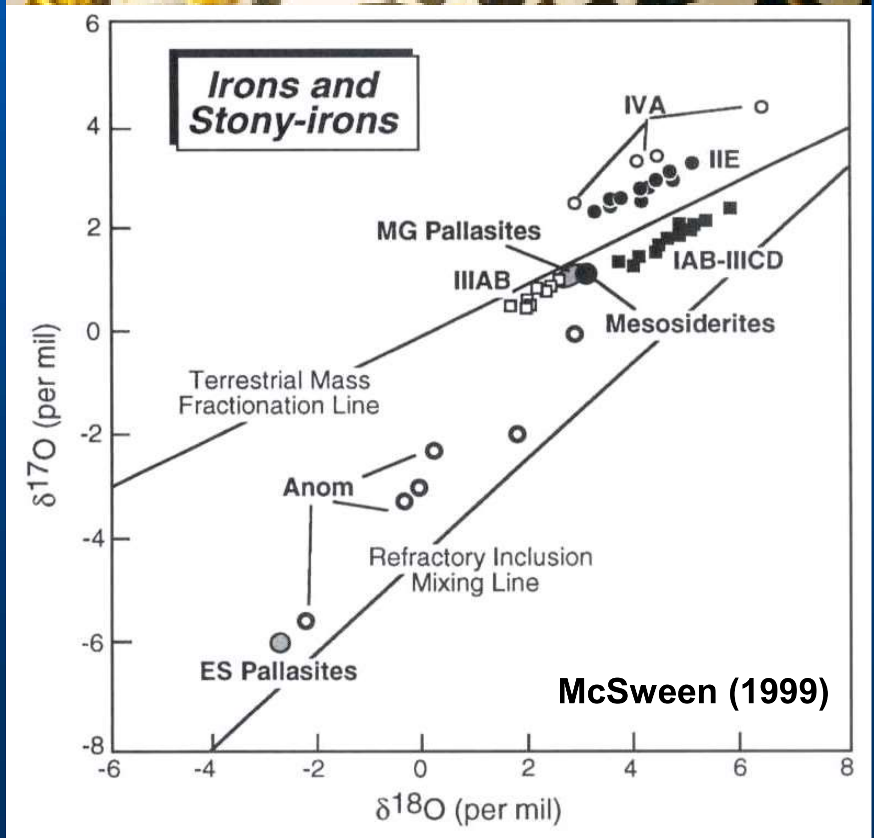


Adapted from Bogard & Johnson (1983)

STONY-IRON METEORITES

- Stony-irons are rare samples
  - They are from differentiated asteroids
  - About ~ 1% of falls (Grady, 2000)
  - Representative of inner regions
    - Interphase among metallic core and mantle
- Mesosiderites: Breccias composed by similar proportions of silicates and Fe-Ni alloys, plus troilite (FeS)
- Pallasites: Fe-Ni alloys plus olivine (35-85% in vol.)
  - As a function of the olivine content and O isotopic ratios we distinguish two types:
    - Mg-rich olivine Pallasites
      - Associated with IIIAb group of irons
    - Eagle Station Pallasites (ES) with olivine crystals rich in Fe

Imilac (MetSoc)



McSween (1999)

FASCINATING PALLASITES

- Just a type of stony-iron meteorites
- cm-sized olivine crystals embedded in Fe-Ni alloy

Esquel (Trigo-Rodríguez, 2012b, CSIC-IEEC)

IRON METEORITES FROM MANTLE-DEPLETED ASTEROIDS

- They are differentiated meteorites
  - About ~ 6% of falls belong to this class
- They are sampling asteroidal interiors
  - Representative materials of metallic cores
- Composed by Fe-Ni alloys with small quantities of Fe sulfides, graphite, silicates and other minerals:
  - Characteristic Widmanstätten pattern under diluted HNO_3 action
  - Future exploratory missions to explore (16) Psyche and other metal-rich asteroids
- As a function of Ni concentration (also Ga, Ge and Ir) are classified in 13 groups (Wasson, 1974)
  - They are coming from a similar number of parent bodies

BIBLIOGRAPHY

- Bischoff A. et al. (2010) Meteorit. Planet. Sci. 45, 1638-1656. [Almahata Sitta]
- DeMeo F. et al. (2009) Icarus 202, 160-180 [asteroids taxonomy]
- Grady M. (2000) Catalogue of meteorites. CUP, Cambridge, UK.
- Horstmann M. and A. Bischoff (2014) Chemie der Erde 74, 149-183.
- Hutchison R. (2004) Meteorites: A Petrologic, chemical and isotopic synthesis, Cambridge University Press (CUP), Cambridge, UK. [meteorite classes]
- Kieffer H.H. et al. (eds.) (1992) Mars, The Univ. Arizona Press, AZ, USA.
- Llorca J. (2004) Meteoritos y cráteres. Editorial Milenio, Madrid.
- McSween H. (1999) Meteorites and their parent planets. CUP, Cambridge, UK.
- McSween H. and G. Huss (2010) Cosmochemistry. CUP, Cambridge, UK.
- Melosh J. (2011) Planetary Surface Processes, CUP, Cambridge, UK.
- Oró J. et al. (1970) Organogenic Elements and Compounds in Surface Samples from the Sea of Tranquillity. Science 167, 765-767.
- Papike J.J. et al. (1998) Lunar samples. In Planetary Materials, Rev. In Mineralogy 36, chap. 5, 234 pp., Mineralogical Soc. America, Washington, US
- Trigo-Rodríguez J.M. (2012b) Meteoritos, Editorial Catarata-CSIC, Madrid.
- Trigo-Rodríguez J.M. et al. (2019) Space Science Reviews 215:18, 27 pp.
- Wasson J. (1985) Meteorites: their record of early Solar System History, W.H. Freeman, NY, USA.