MECHANICAL AND MAGNETIC PROPERTIES OF MICRON-SIZED REGOLITH FROM THE STUDY OF ITOKAWA SAMPLES

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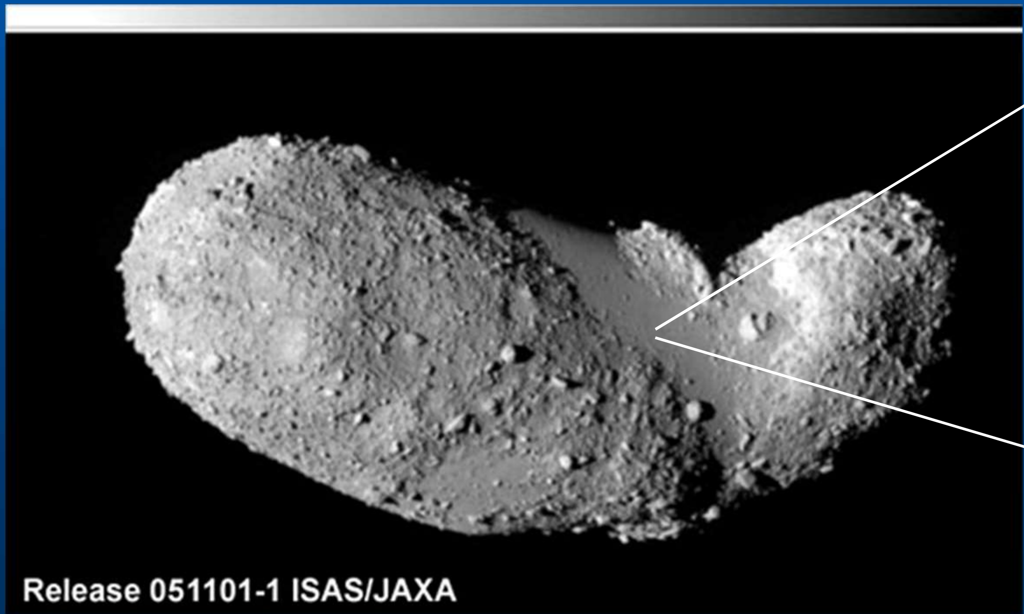
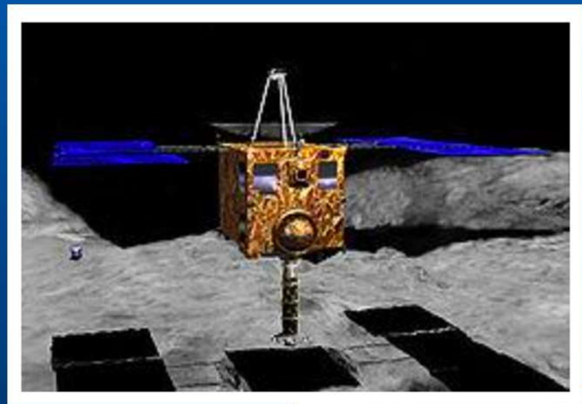
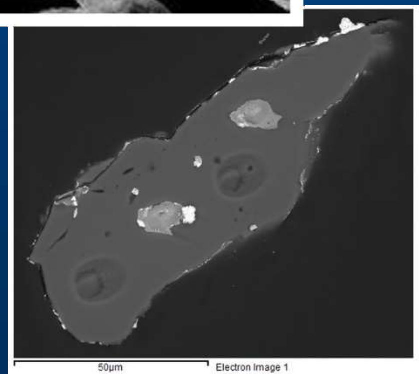






HERA workshop, 15-16 Nov. 2018, Berlin

METEORITES, MINOR BODIES & PL. SCIENCES

- Research group at the Institute of Space Sciences (IEEC-CSIC), specialized in space missions: www.ice.csic.es
  - PI: Josep M. Trigo-Rodríguez, Tenured scientist CSIC
  - Dr. Ivan Lloro
  - Dr. Jordi Ibáñez (ICTJA/CSIC)
  - PhD. Safoura Tanbakouei and M. Moreno-Ibáñez
  - Plus master students: M. Herrero

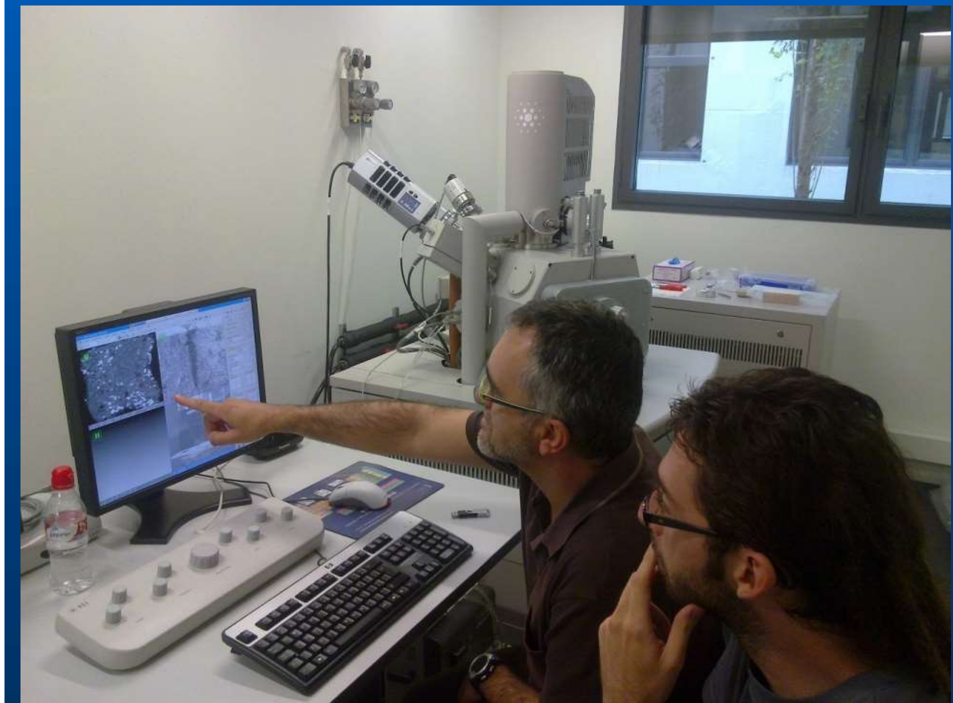
The ICE building at UAB campus

- Research group main lines:
  - Laboratory experiments to gain insight about processes affecting asteroids and comets:
    - How these processes affected the structure, composition and reflectivity of asteroids?
    - Evidence, constrains and implications for impact shock, and space exposure in meteorites
  - Recovery and characterization of new meteorites
  - Determination of fireball trajectories and meteoroid orbits from the SPMN network: www.spmn.uji.es
  - Photometric follow-up of comets and NEOs

Joan Oró robotic Telescope at OAdM

TECNIQUES AND INSTRUMENTS USED

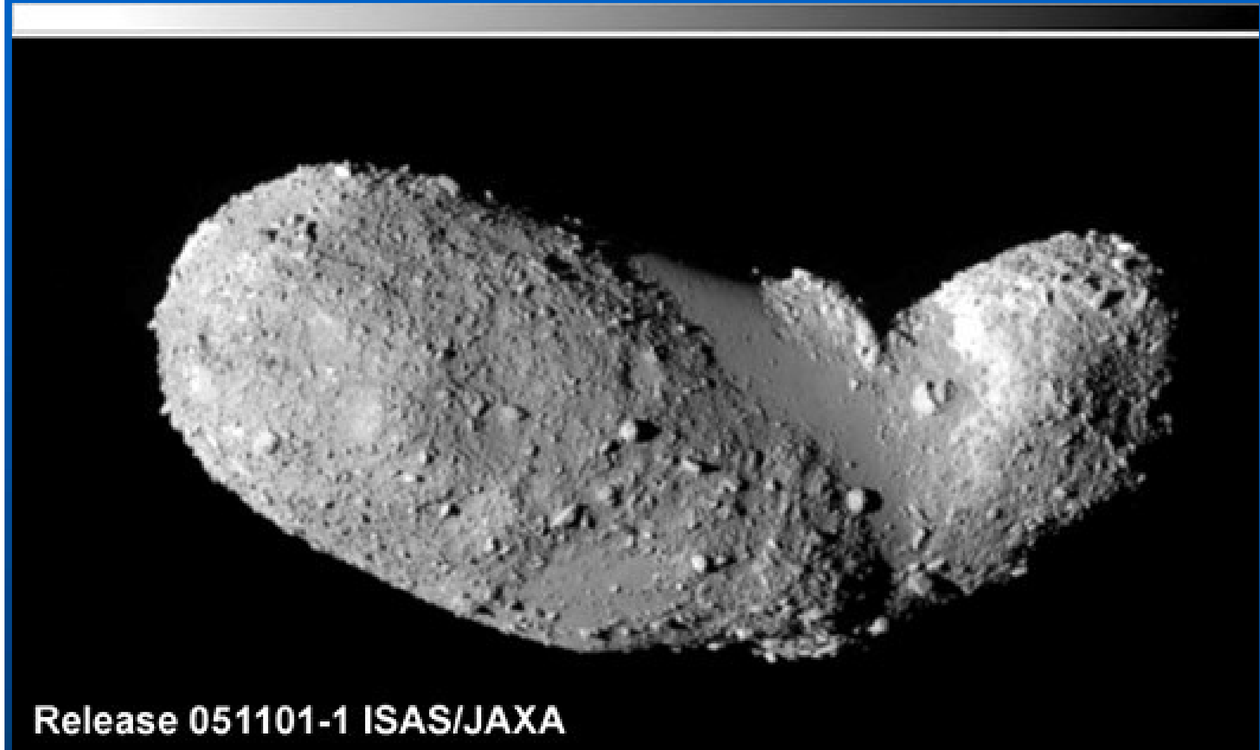
- **We are applying different techniques to study meteorites and returned samples:**
  - **Petrographic and polarization microscopy (thin sections' integral mapping) at CSIC-IEEC**
  - **Scanning Electron Microscopy and Energy Dispersive X-ray microscopy**
  - **Transmission Electron Microscopy (TEM)**
  - **Shimadzu UV-3600 spectrometer (0.2-2.6 μm), and IR ATR Nicolet spectrometer (2-40 μm) at UPC**
  - **ICP Atomic Emission Spectroscopy (ICP-AES) and Mass Spectrometry (ICP-MS) ThermoElectron**
  - **UMIS indenter from Fischer Cripps Laboratories for nano-indentation**
  - **Vibrating Sample Magnetometers (VSM) for magnetic properties**

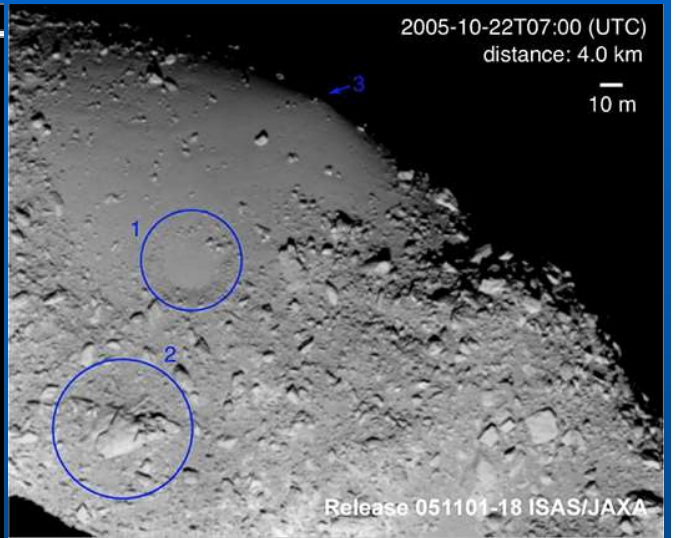


SEM+EDX microscopy at CIN2-CSIC

Ar-ion laser with a Jobin-Yvon T-64000 Raman spectrometer of 1 μm res.) at ICMAB-CSIC

ITOKAWA AS SEEN BY HAYABUSA

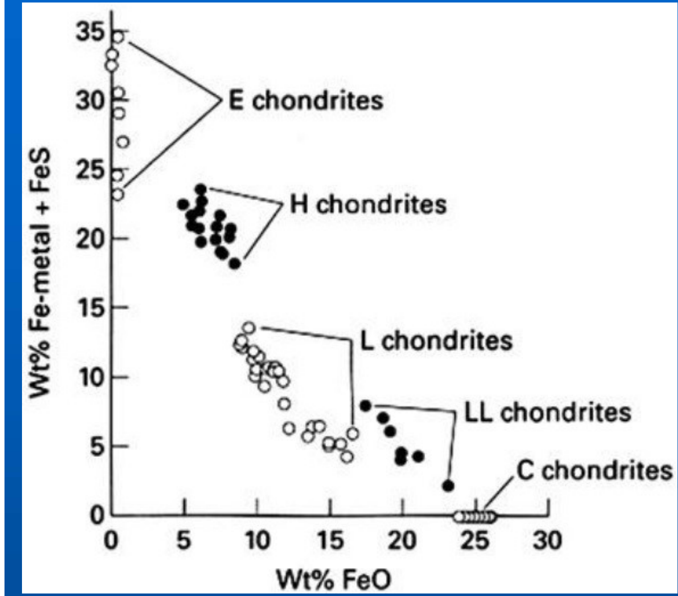




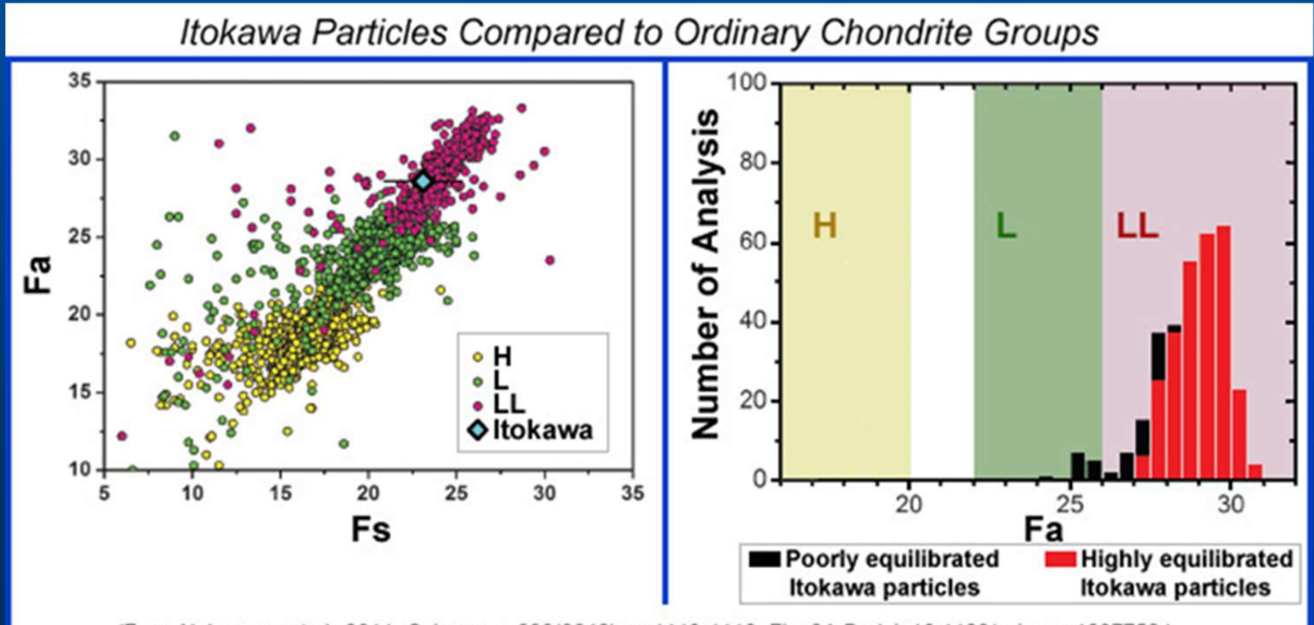
It is a nice example of rubble pile:

- It is covered by fine-grained regolith, rocks and boulders that are the product of collisional gardening and space weathering (aging)

ORDINARY CHONDRITES

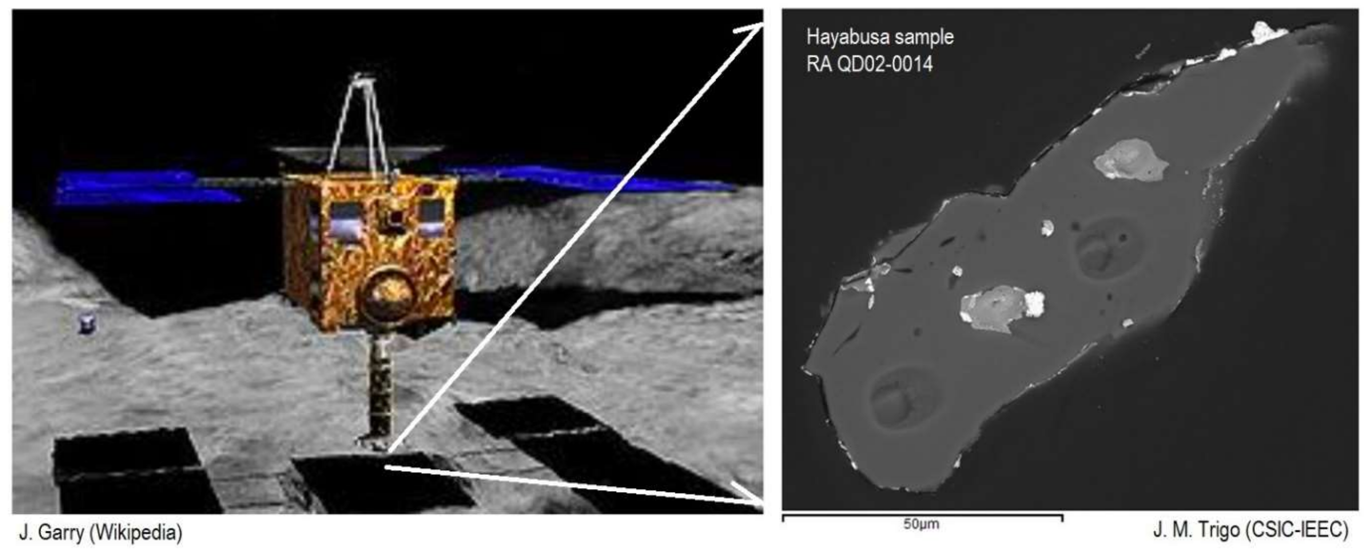


- The ordinary chondrites are subdivided into 3 groups based on different chemical criteria as e.g. the ratio of metallic to oxidized Fe (see Fig.).
- O isotopes also indicate a common origin between group members
- Fe-Mg content in Itokawa's olivine and pyroxene is in the range of LL OCs (Nakamura et al., 2011)

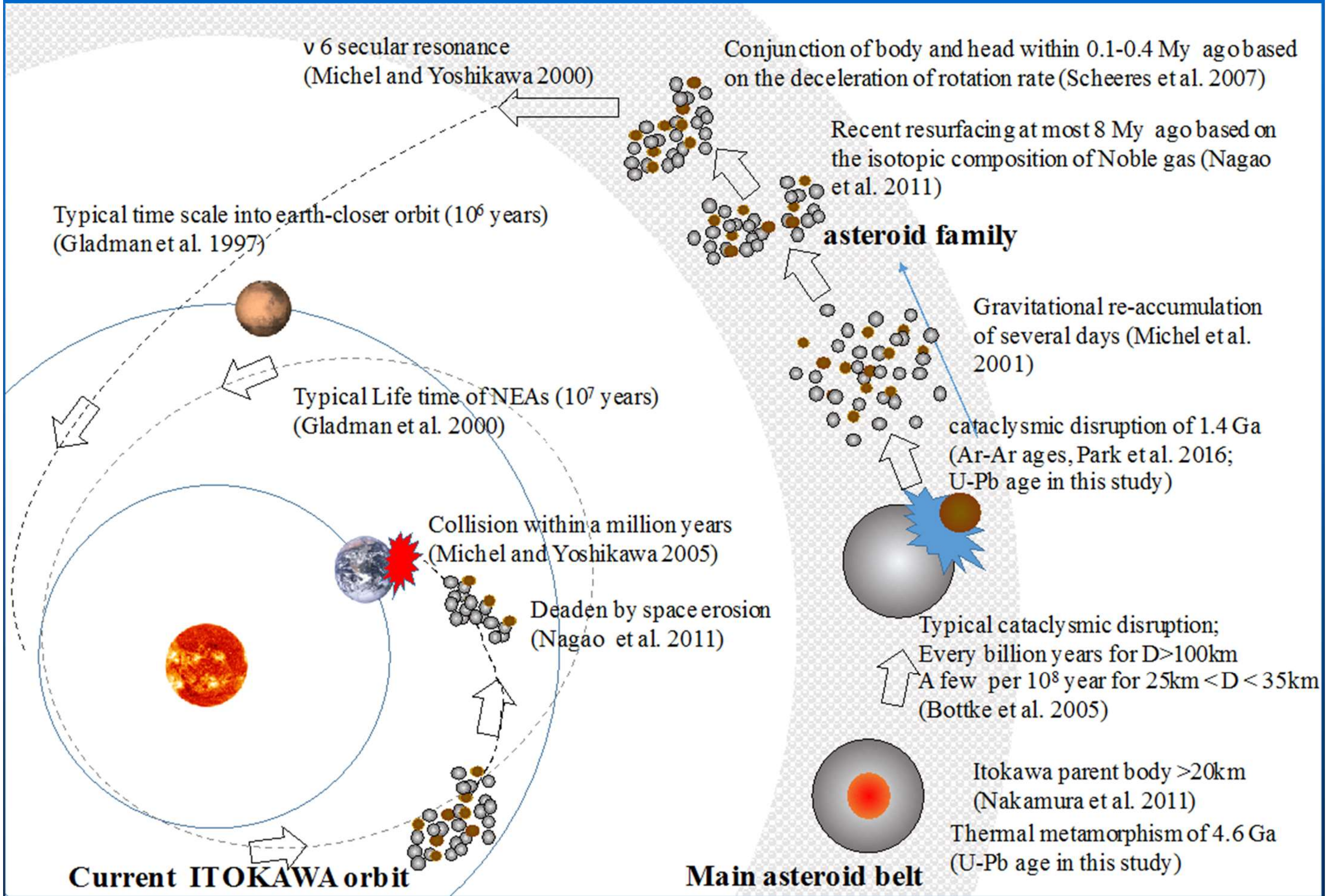


(From Nakamura *et al.*, 2011, *Science*, v. 333(6046), p. 1113-1116, Fig. 2A,B, doi: 10.1126/science.1207758.)

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)
asteroid family
Typical time scale into earth-closer orbit (10^6 years)
(Gladman et al. 1997)
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

NANOINDENTATION

- What are the consequences of this collisional history for the physical properties of Itokawa materials?
- Experiments made at the Autonomous University of Barcelona (UAB) with the support of the Group of Smart Nanoengineered Materials, Nanomechanics, and Nanomagnetism (Prof. Jordi Sort)

- Indenter:
  - UMIS indenter from Fischer Cripps Laboratories
  - Diamond tip with Berkovich pyramidal geometry
  - Working at load control mode

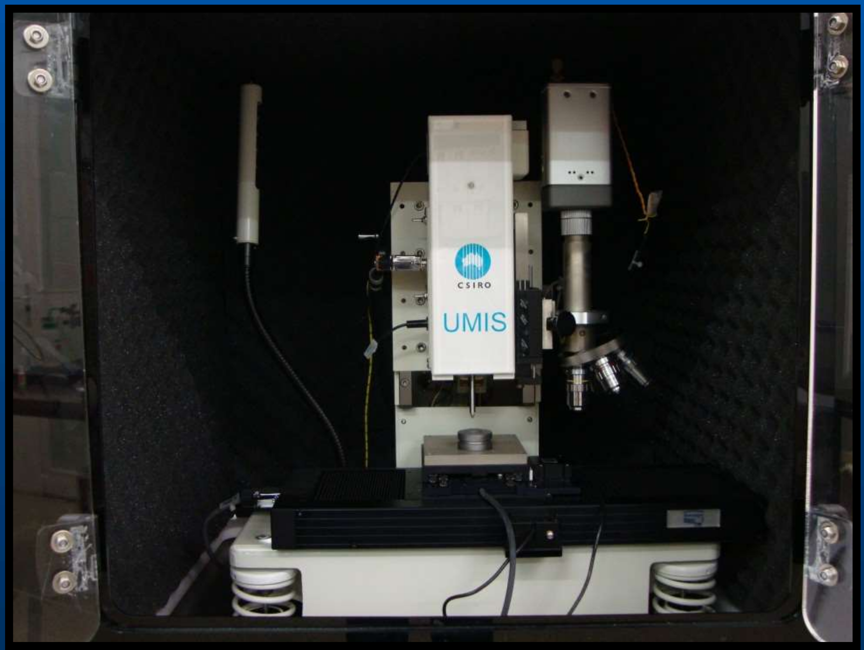
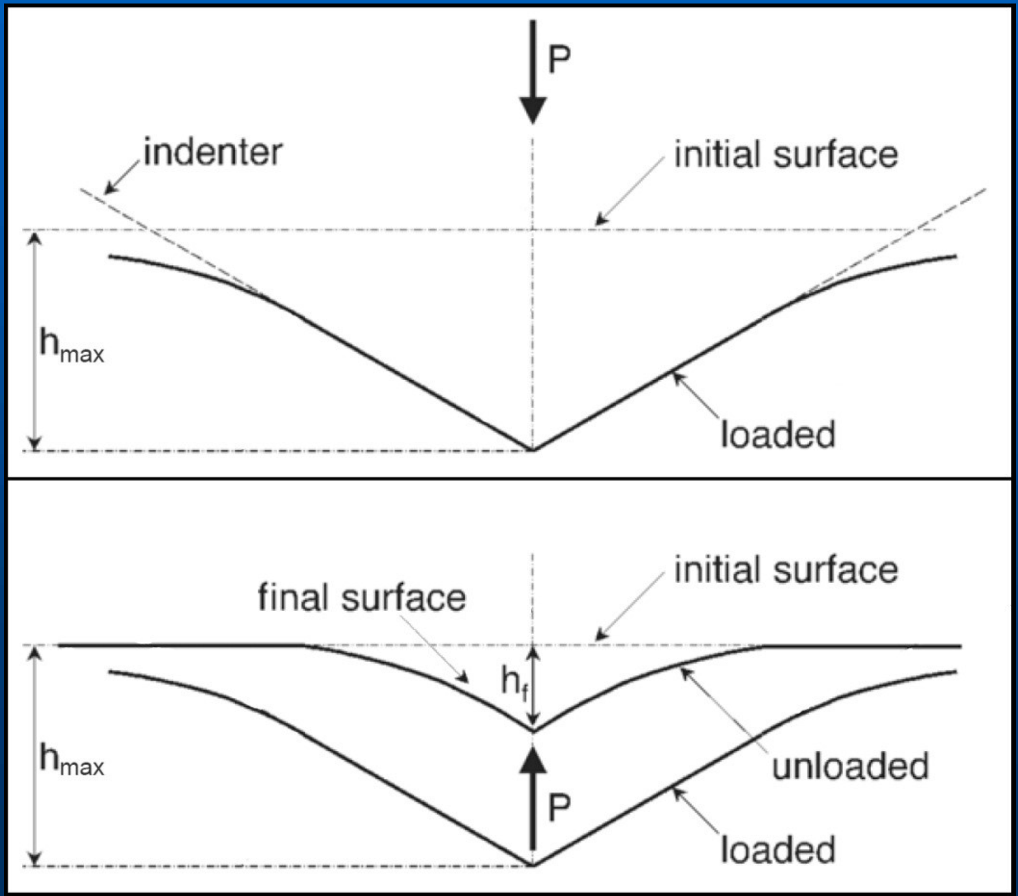
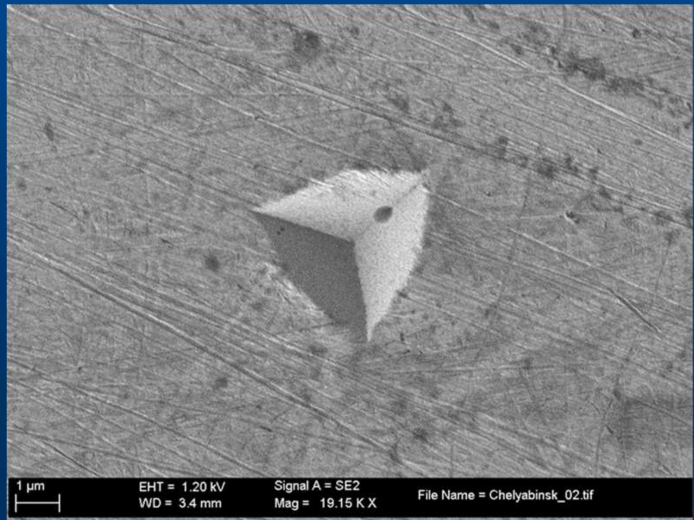


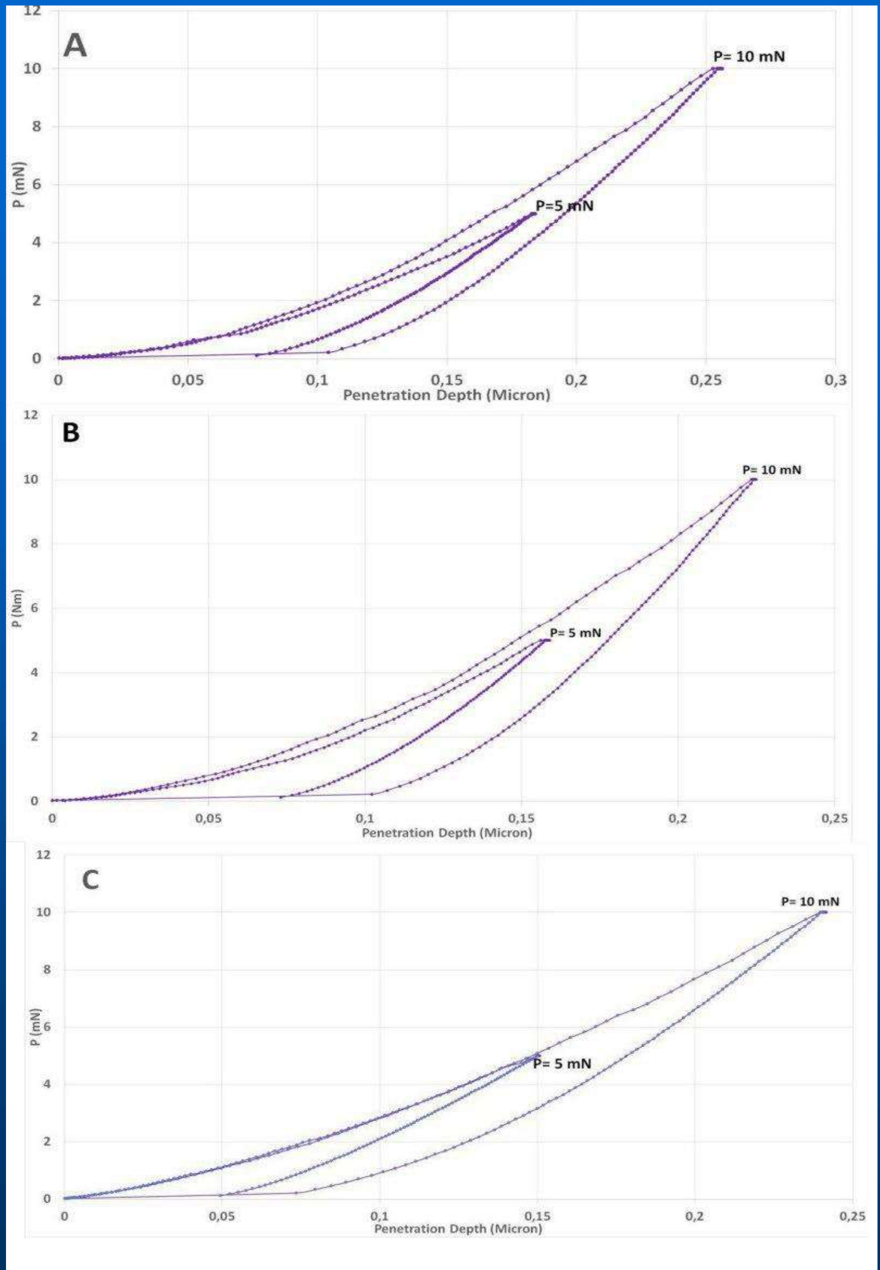
Image of one of the UMIS indenters used

- **Investigation of mechanical properties on Chelyabinsk forming materials: silicate chondrules, metal grains, veins, etc**
- **Application of a controlled load (~20 µN-500 mN) through use of a hard indenter**



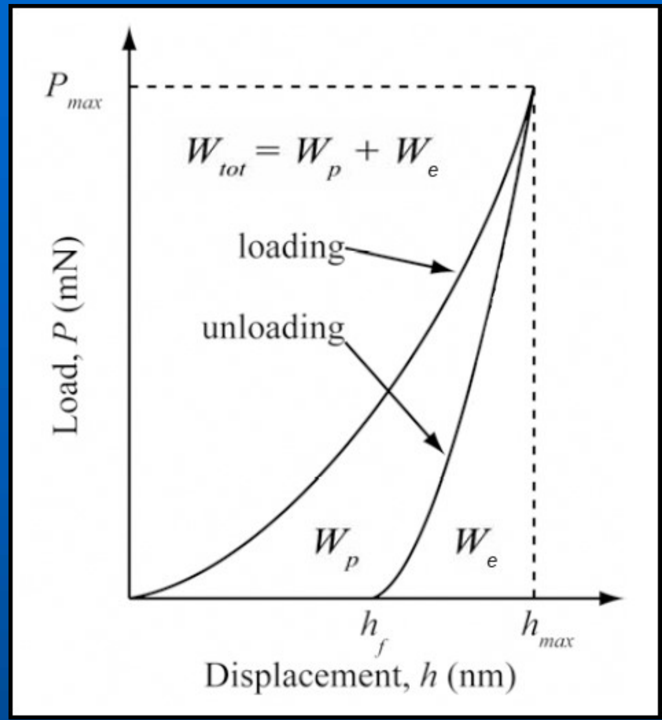
- **The indenter pushes the surface while increasing load, down to a maximum depth (h_{max} ~ few µm)**
- **Concurrent measurement of depth.**
- **Due to elasticity, the surface partially recovers when the indenter is unloaded**





Load-displacement curves of three olivine-rich regolith particles of Itokawa under applied forces of 5 and 10 mN (Tanbakouei et al., 2018)

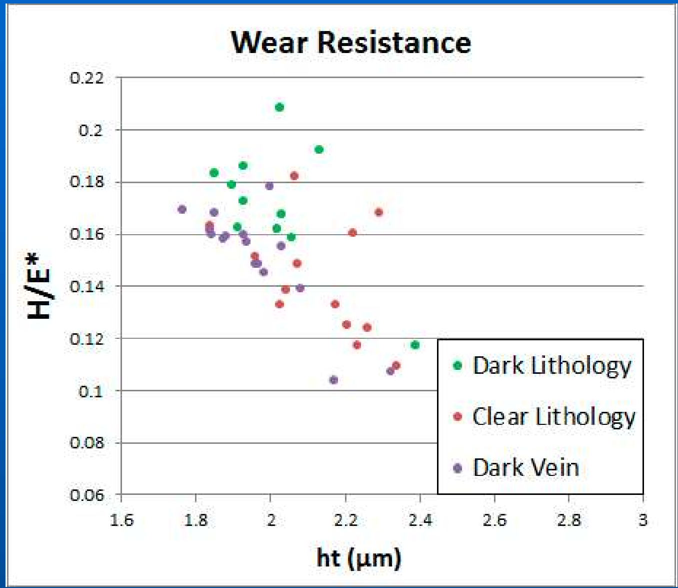
- **Load-displacement curve**



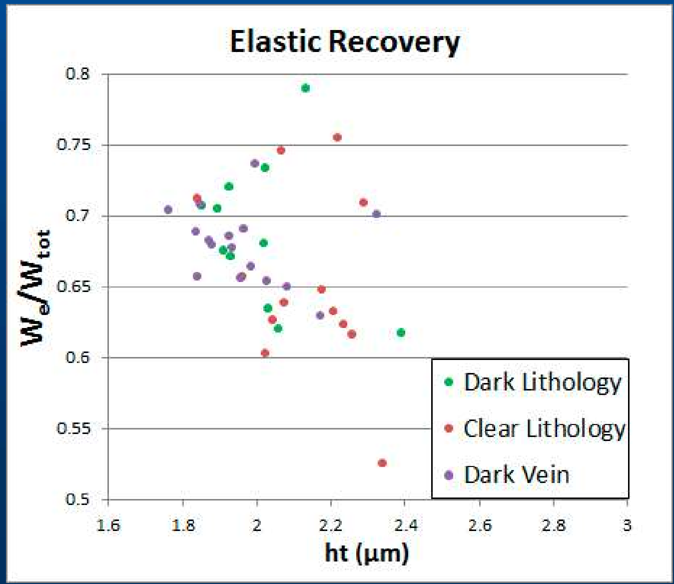
The curve shows plastic (W_p) and elastic (W_e) works

- **Loading -> Deformation mechanisms: elastic, plastic and phase transformations**
- **Unloading -> Mainly elastic recovery**

- **Oliver & Pharr (2004) analysis (indentation software), provides:**
  - **Hardness (H)**
  - **Reduced Young's modulus (E*)**
  - **Plastic Work (W_p)**
  - **Elastic Work (W_e)**



- **Relative properties:**
  - **Indirect assessment of the Wear Resistance (H/E*)**
  - **Elastic recovery and Plasticity Index (W_e/W_{tot} & W_p/W_{tot})**



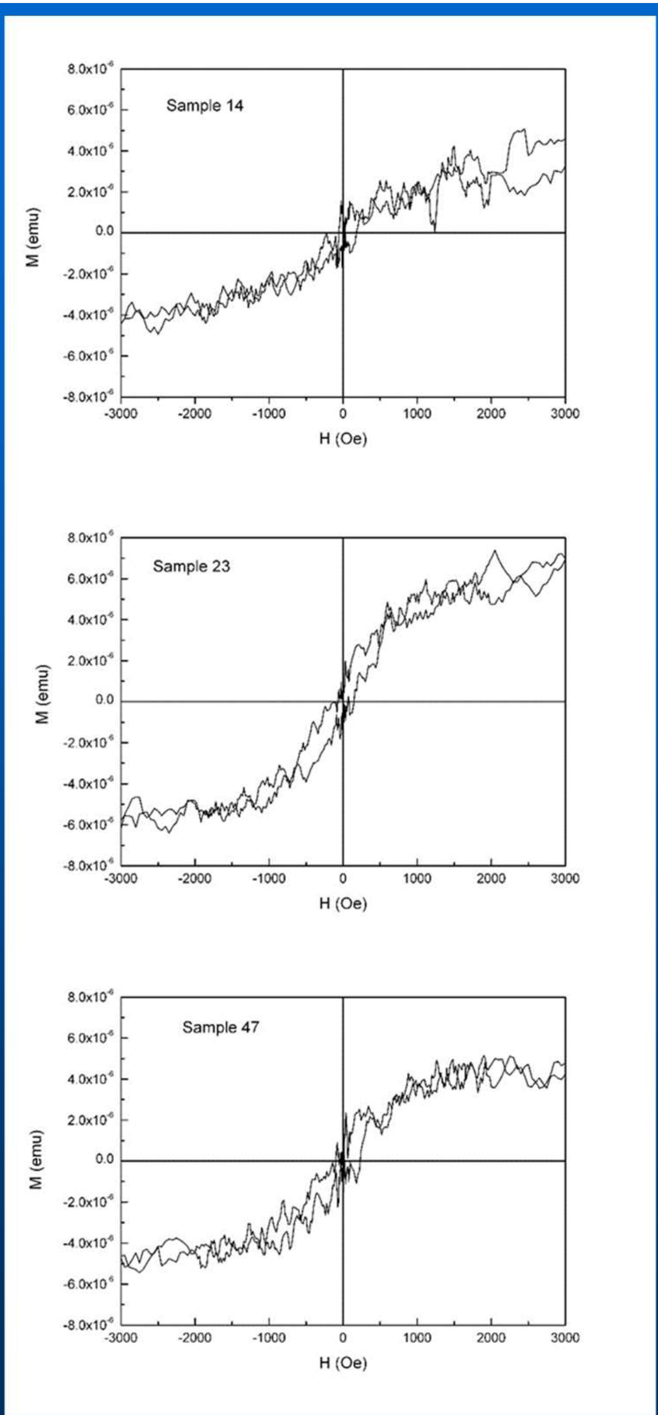
Indirect Wear Resistance and Elastic Recovery for the two different Chelyabinsk lithologies, and in the dark vein .

MECHANICAL BEHAVIOUR

- **Reduced Young's modulus (Er), hardness (H), constant stiffness (S), elastic recovery (Uel/Utot) and plasticity index (Upl/Utot) were calculated by averaging the results from two lines of indentations for a maximum applied force of 5 mN**

Sample#	Er (GPa)	H (GPa)	S (mN/ micron)	U_{el}/ U_{tot}	U_{pl}/ U_{tot}
14	83.01 ± 0.12	8.01 ± 0.01	77.01 ± 0.11	0.64 ± 0.01	0.36 ± 0.01
23	111.01 ± 0.22	10.01 ± 0.02	92.00 ± 0.20	0.73 ± 0.07	0.27 ± 0.07
47	86.01 ± 0.13	13.01 ± 0.03	62.01 ± 0.03	0.88 ± 0.01	0.13 ± 0.01

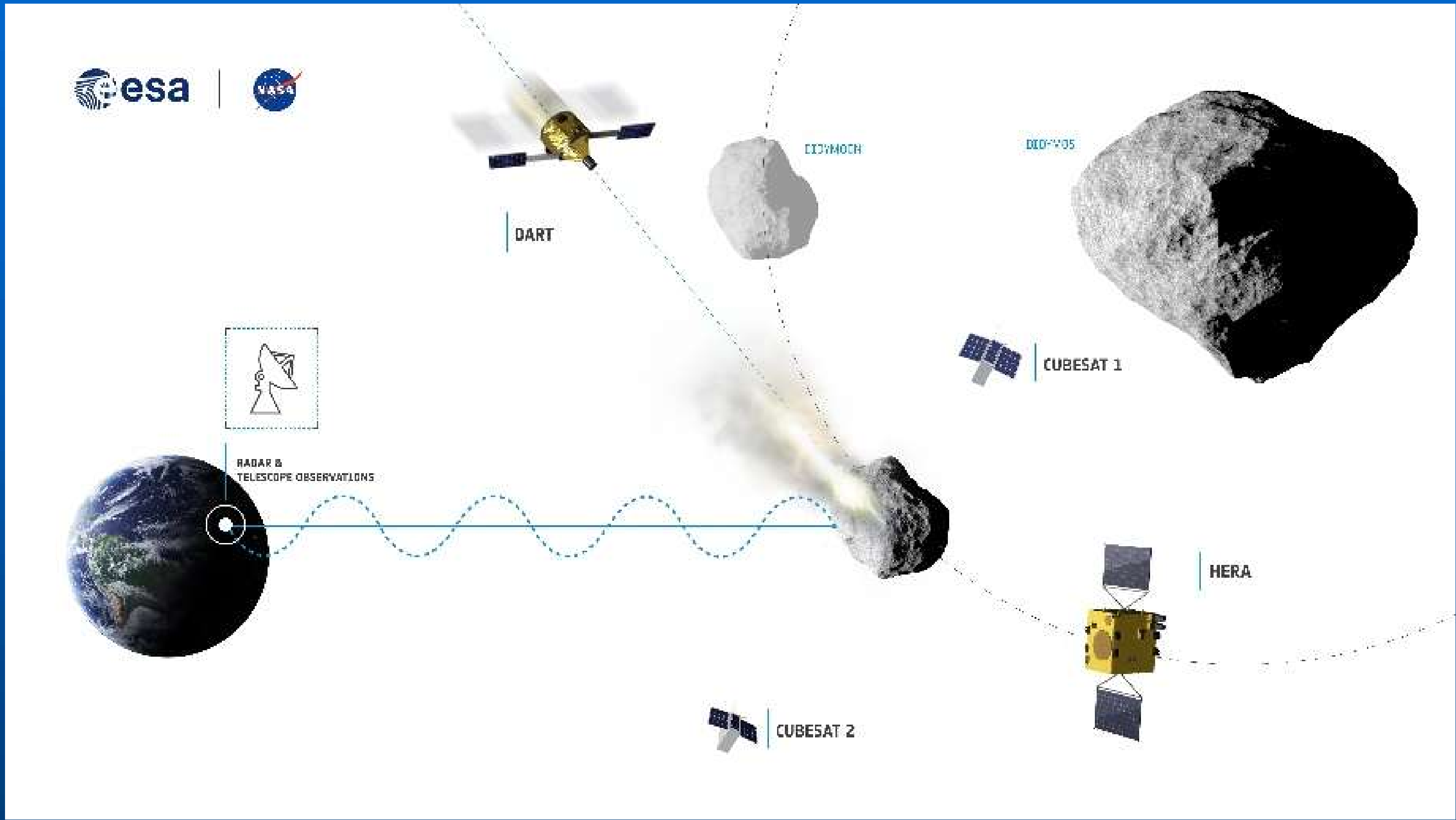
- **The mechanical properties of Itokawa's regolith particles are comparable with silicates forming LL chondrites.**
- **Despite of it, the elastic recovery of minerals in the Chelyabinsk chondrite (Moyano-Cambero et al., 2017, ApJ) is lower than that measured for the Itokawa samples.**
- **There is difference in the Young's modulus but hardness values are similar.**



MAGNETIC PROPERTIES

- The magnetic properties were measured by using a vibrating sample magnetometer (VSM) from MicroSense (LOT-Quantum Design). Hysteresis loops were recorded at room temperature with a maximum magnetic field of 20 kOe.
- We found a soft magnetic behavior with a coercivity of around 70 Oe.
- As we see in the figure, for the same magnetic field, sample 23 has at higher signal than the other two
- This magnetic behavior is consistent with the presence of tiny Fe and Ni inclusions in the samples, as was detected by energy-dispersive X-ray (EDX) analyses, indicating the possible presence of FeNi, FeO or FeS_2, among others.

OUR CONTRIBUTION TO HERA



- As members of a cubesat proposal for Hera we plan to participate in the interpretation of the surface properties of Didymoon, the release of regolith by crater excavation, and the study of the regolith size and expected properties

CONCLUSIONS

- Asteroids formed by ordinary chondrites are the result of the fragmentation of larger progenitors (Beitz et al., 2013)
- The rubble piles materials studied so far, like e.g. Itokawa or chondritic meteorites, experienced significant shock metamorphism
- The mechanical properties of Itokawa's regolith particles are comparable with silicates forming LL chondrites, but with some differences. For example, the elastic recovery of minerals in the Chelyabinsk chondrite (Moyano-Cambero et al., 2017, ApJ) is lower than that measured for the Itokawa samples. There is also difference in the Young's modulus but hardness values are similar.
- Nanoindentation provides valuable information about the material response to impacts in the diverse lithologies and shock veins
- Itokawa's µm-sized regolith has a soft magnetic behavior with a coercivity of around 70 Oe. It is consistent with the presence of tiny Fe and Ni inclusions, and other magnetic minerals in the samples
- From these experiments we plan to better understand the answer of asteroid regolith to impacts used to deflect future Potentially Hazardous Asteroids