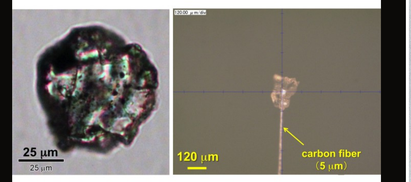
Preliminary Examination Results of ITOKAWA

Itokawa Particles

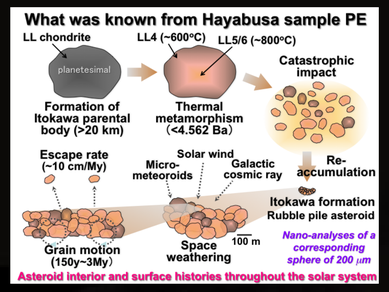


Very beautiful as jueries
(because not oxidized by the atmosphere)

Science, 26 August 2011

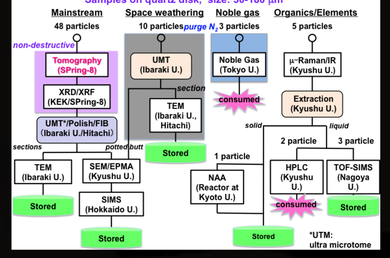
Nakamura et al.
Itokawa Dust Particles: A Direct Link Between S-Type Asteroids and Ordinary Chondrites
Yurimoto et al.
Oxygen Isotopic Compositions of Asteroidal Materials Returned from Itokawa by the Hayabusa Mission
Ebihara et al.
Neutron Activation Analysis of a Particle Returned from Asteroid Itokawa
Tsuchiyama et al.
Three-Dimensional Structure of Hayabusa Samples: Origin and Evolution of Itokawa Regolith
Nagao et al.
Irradiation History of Itokawa Regolith Material Deduced from Noble Gases in the Hayabusa Samples
Noguchi et al.
Incipient Space Weathering Observed on the Surface of Itokawa Dust Particles

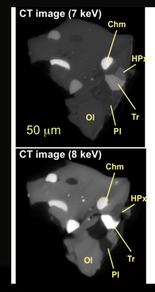
What was known from Hayabusa sample PE



Outline of PE analysis flows (60 particles)

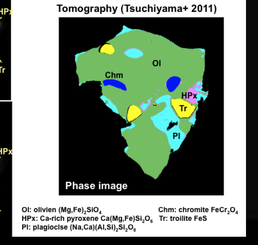
Samples on quartz disk, size: 30-180 μm





3D mineral distributions by micro-tomography

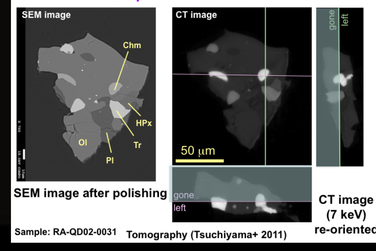
Tomography (Tsuchiyama+ 2011)



Ol: olivien (Mg,Fe)$_2$SiO$_4$
HPx: Ca-rich pyroxene Ca(Mg,Fe)Si$_2$O$_6$
Pl: plagioclase (Na,Ca)(Al,Si)$_4$Si$_2$O$_8$
Chm: chromite FeCr$_2$O$_4$
Tr: troilite FeS

Design for Later Destructive Analyses

For optimal cross section



SEM image after polishing

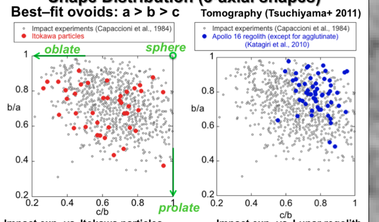
CT image (7 keV) re-oriented

Sample: RA-QD02-0031 Tomography (Tsuchiyama+ 2011)

Shape Distribution (3-axial shapes)

Best–fit ovoids: a > b > c

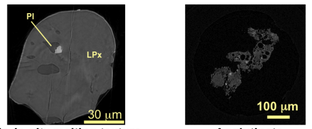
Tomography (Tsuchiyama+ 2011)



Impact exp. *vs.* Itokawa particles
P=0.17 (Kolmogorov-Smirnov (K-S) test)
⇒ Itokawa particle: impact fragments
(residence time: < ~a few My.)

Impact exp. *vs.* Lunar regolith
P=0.00 (K-S test)
⇒ Lunar regolith evolved
(residence time: ~1 By.)

No particles showing *in-situ* melting



No *in-situ* melting texture in Itokawa regolith (Tsuchiyama et al., 2011)
☜ Small impact velocities typically relative velocity among asteroids: ~5 km/s

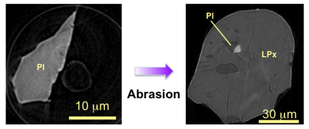
Agglutinate in lunar regolith (Apollo 16) (Katagiri et al., 2010)
☜ Large impact velocities exceeding escape velocity from the Earth : >~10 km/s

Tomography (Tsuchiyama+ 2011)

Surface : edges

Sharp edges
35 particles (73%)

Rounded edges
13 particles (27%)
External shapes also spherical.

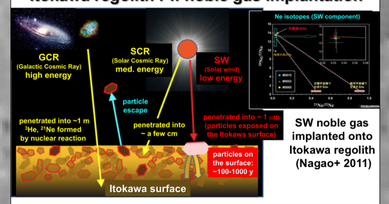


CT image (7 keV) RA-QD02-0025-2

CT image (7 keV) RA-QD02-0042

Tomography (Tsuchiyama+ 2011)

Itokawa regolith P.: noble gas implantation



SW noble gas implanted onto Itokawa regolith (Nagao+ 2011)

・SW noble gas detected ⇒ Particle on the surface: ~100-1000 y
・GCR noble gas not detected ⇒ Regolith age : <~3 My
⇒Particle escape rate: ~10 cm/1 My (Itokawa life time: ~1 By)

*Science*誌：2011年のブレークスルーに選出

THE RUNNERS-UP

Asteroid Dust Solves Color Conundrum

This year the first samples returned from another planetary body in 35 years settled a decades-old planetary mystery: why the most common meteorites that fall to Earth didn't seem to come from the most common asteroids in the asteroid belt. It turns out they do. By examining bits of asteroid Itokawa brought back by Japan's Hayabusa spacecraft, researchers discovered that the solar wind had been discoloring asteroids enough to cause a massive case of mistaken identity.

Hayabusa's odyssey to and from the 535-meter-long Itokawa was as harrowing as anything in Homer. En route, the spacecraft lost two of its three gyroscopelike reaction wheels that controlled its attitude, so it had to fall back on small rockets normally used for course corrections. A tiny rover meant to explore Itokawa's surface instead wound up being launched into deep space. Before the return trip, the spacecraft's attitude-control thrusters sprang a fuel leak; the spacecraft lost its proper orientation, breaking off communications, losing solar power, short-circuiting its batteries, and sinking into a deep freeze.

In a stunningly successful rescue mission, Hayabusa's controllers managed to pull the spacecraft back from the brink of disaster. It returned in June 2010, 3 years late and carrying only a dusting of Itokawa particles—but that was enough. Analyzing 52 particles, each less than 100 micrometers in diameter, Japanese researchers showed that the elements and minerals that make up Itokawa—a member of the largest class of asteroids, the S types—match the composition of the most abundant type of meteorite, ordinary chondrites. Researchers had long been inferring the composition of asteroids from their remotely recorded spectral colors. But the S types looked too red to be the source of the ordinary chondrites. Sophisticated spectroscopic analyses eventually showed that the tint was misleading and the link real. This year, Hayabusa's wispy cargo of asteroid dust closed the case for good.

Probing further, researchers used scanning transmission electron microscopy to look beneath the surface of Itokawa particles. There they could see tiny "nanoblobs" of metallic iron small enough to scatter sunlight and redden the asteroid's surface. Most of the nanoblobs probably formed when charged particles such as protons blowing in the solar wind penetrated the particles on Itokawa's surface. Mission accomplished, Hayabusa.

Made it! Touchdown on Itokawa, as portrayed in the Japanese movie *Hayabusa: Back to the Earth.*

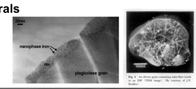
DOWNLOADED FROM WWW.SCIENCEMAG.ORG on December 22, 2011

Evidences of Itokawa sample: What we should analyze?

1. Comparison with meteorites
   (1) Mineral assemblage and abundances*
   (2) Chemical composition of minerals*

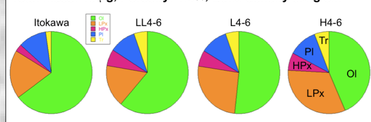
2. Definitive evidences
   (1) Isotope compositions
      (a) Oxygen : Not on the terrestrial fractionation line*
      (b) Noble gases*
         Solar wind* and/or cosmic ray components
      (c) Other isotopic anomalies
   (2) Micro-textures of minerals
      (a) Space weathering*
      (b) Solar flare tracks

* Results by PE



3D petrology: Modal Mineral Abundances

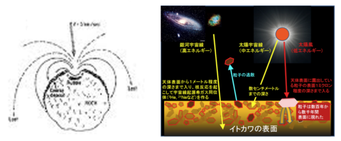
Total volume : 4.2x10^6 μm^3 (corresponding sphere of ~200 μm)
Total mass: 15 μg, Porosity: 1.4%, Bulk: density 3.4 g/cm^3



✓ Modal abundances (40 particles): ~LL chondrites
✓ Bulk density (3.4 g/cm^3)
Bulk porosity of Itokawa : ~39 ± 6 %
(☞ Bulk density of Itokawa:1.9 g/cm^3)
⇒ Reconfirmation of rubble pile model (Fujiwara+ 2006)

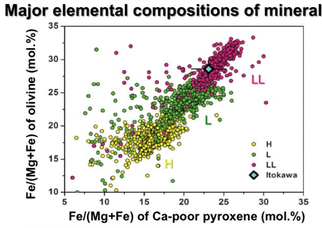
Tomography (Tsuchiyama+ 2011)

Itokawa particles as regolith



✓ Are Itokawa particles fragments of small body impacts?
✓ Are there any evidences of solar wind and cosmic ray irradiations?
✓ Are there any space weathering due to cosmic dust bombardment and solar wind implantation?

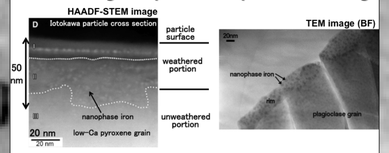
Major elemental compositions of minerals



olivine, pyroxene, chromite
plagioclase, kamacite
⇒ LL chondrite

EPMA (Nakamura+ 2011)

Itokawa regolith particles: space weathering

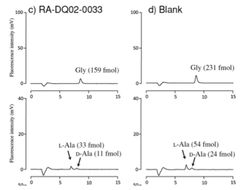


Space weathering found on Itokawa particle surface (Noguchi+ 2011)

Space weathering on Lunar regolith surface (Keller+ 1999)

⇒ Proof of space weathering on Itokawa which is responsible for reddening and darkening of Itokawa spectrum

Carbonaceous and organic materials: Exotic materials fallen onto the asteroid



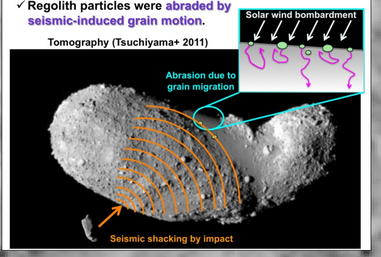
Extraction of organics ⇒ Not detected

Naraoka et al. (2012) *Geochem. J.*

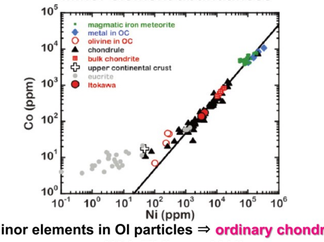
Mechanical abrasion by grain motion

✓ Regolith particles were abraded by seismic-induced grain motion.

Tomography (Tsuchiyama+ 2011)



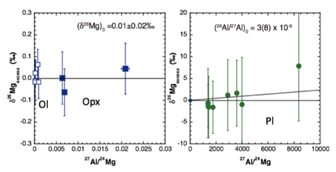
Minor element abundances



Minor elements in OI particles ⇒ ordinary chondrite

NAA (Ebihara+ 2011)

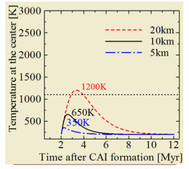
^{26}Al-^{24}Mg isochron



Al-Mg system ⇒ Metamorphism age < 4.562 Ba

SIMS (Yurimoto+ 2011)

Thermal history (Nakamura+ 2011)



We assume formation at 2 Myr after CAIs

Heat source : ^{26}Al
Abundance of Al: 1.18 wt%
Initial temperature: 200K
Thermal conductivity: 2 Jm^{-1}s^{-1}K^{-1}
Specific heat: 600 Jkg^{-1}K^{-1}
Density: 3000 kgm^{-3}

Crystallization during temp rise
・Plagioclase thermometry (Smith, 1972, Nakamuta+ 1999)

0010	575 °C
0025-1	560 °C
0055	575 °C
0013	820 °C

Metamorphic temperature
・Two pyroxene thermometery (Lindsley, 1983)

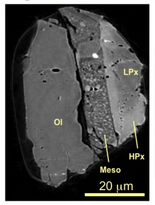
0024	817 ± 20 °C
0013	785 ± 13 °C
0010	839 ± 9 °C

Cooling rate
・Ol-Sp speedometry (Ozawa, 1984)
0030 0031
~ 5x 10^{-4} °C /yr at 600 °C

Nakamura+ (2011)

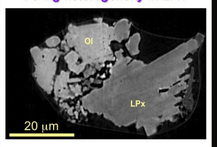
Particles with less-equilibrated textures

Fragment of a chondrule?



CT image (7 keV) RA-QD02-0048

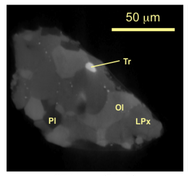
Fe-Mg heterogeneity in LPx



CT image (8 keV) RA-QD02-0060

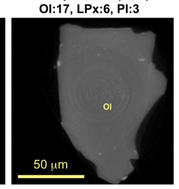
Particles with equilibrated textures:

Polymineralic
22/48 particles (46%)



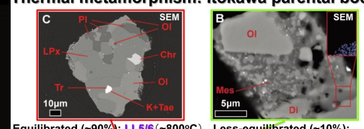
CT image (8 keV) RA-QD02-0030

(Almost) Monomineralic
26/48 particles (54%)
Ol:17, LPx:6, Pl:3



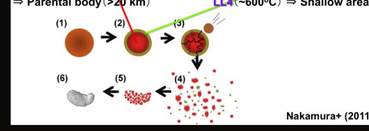
CT image (7 keV) RA-QD02-0023

Thermal metamorphism: Itokawa parental body



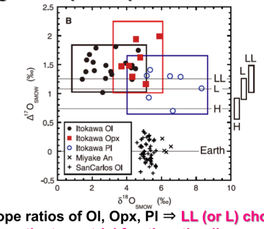
Equilibrated (~90%): LL5/6 (~800°C)
⇒ Parental body (>20 km)

Less-equilibrated (~10%): LL4 (~600°C) ⇒ Shallow area



Nakamura+ (2011)

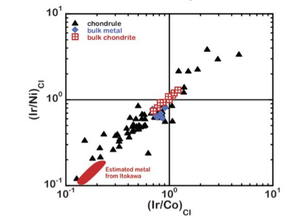
Oxygen isotope compositions of minerals



• Isotope ratios of Ol, Opx, Pl ⇒ LL (or L) chondrite
Not on the terrestrial fractionation line

SIMS (Yurimoto+ 2011)

Minor element compositions-2



Ir ⇒ Elemental fractionation in the early solar system

NAA (Ebihara+ 2011)