# The mass, morphology, and internal structures of three particles from the Hayabusa sample return mission, analyzed with synchrotron radiation X-ray tomographic microscopy

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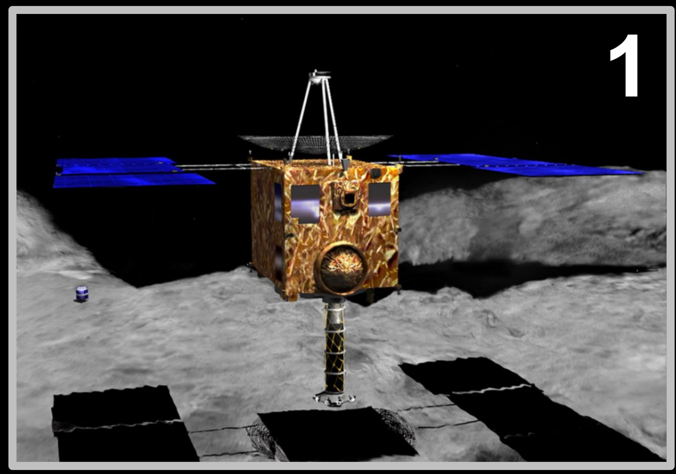
**Introduction** On June 13th 2010, the „Hayabusa" mission by the Japanese Aerospace Exploration Agency (JAXA) came to a successful end when the first samples from an asteroid (Itokawa) were returned to Earth. More than 1000 grains have been recovered from the upper regolith of Itokawa, and made available to international researchers.
One goal of our consortium is to measure the inventory of cosmogenic He and Ne in Itokawa grains [1]. To achieve that goal, a precise determination of mass via volume and density (mineralogy) is necessary, which we attempt here by analyzing the grains with SRXTM.



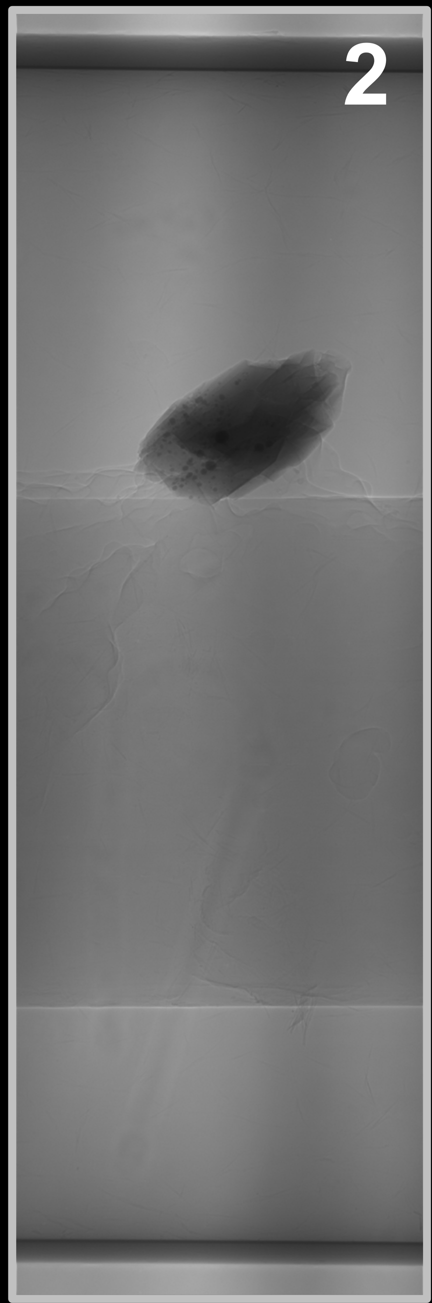
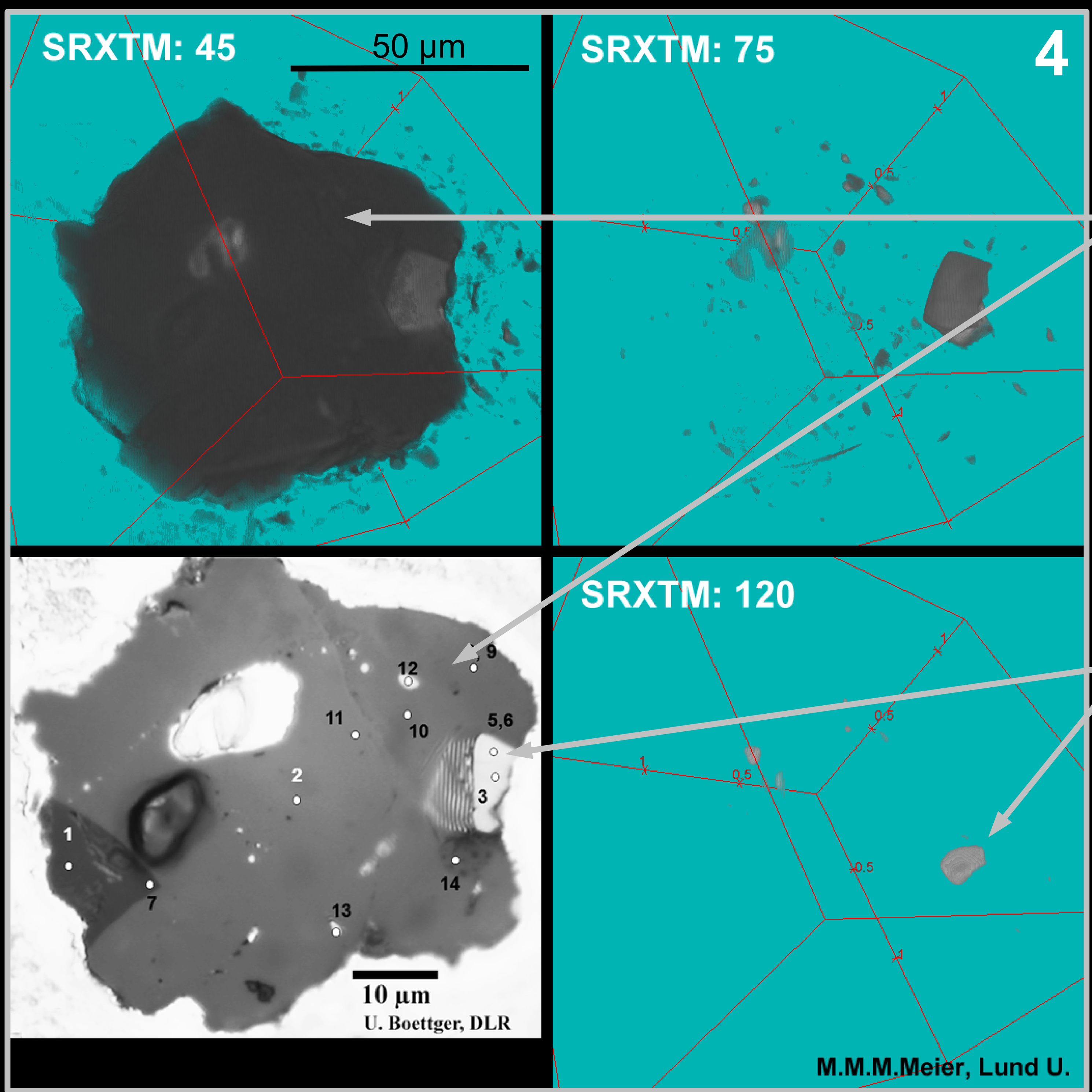
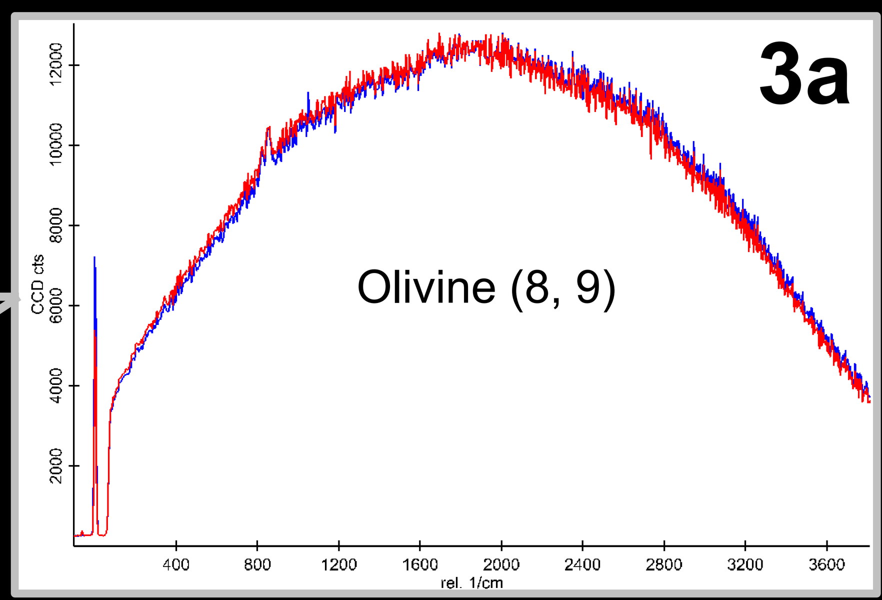
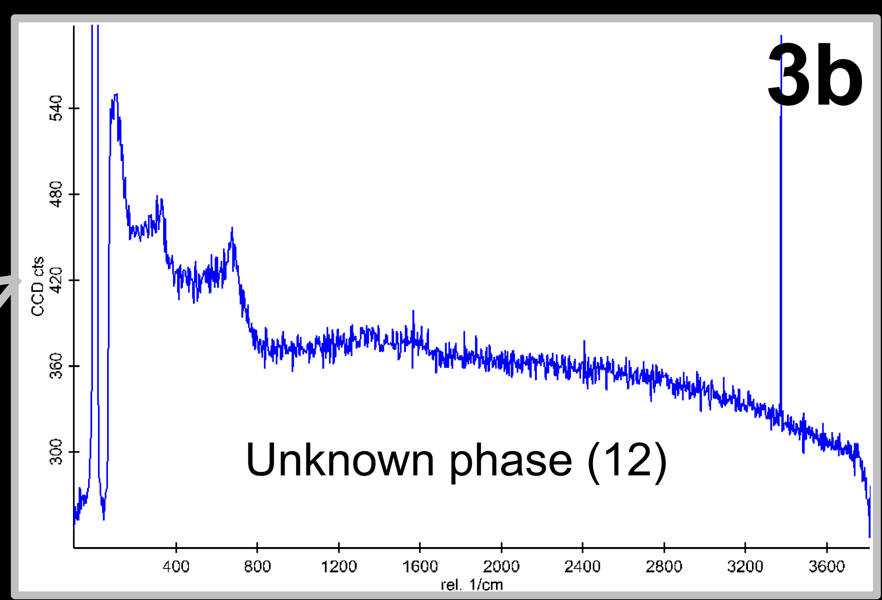




**Figure 1**, top: Hayabusa at Itokawa. **Figure 2**, right: Grain 0049-1 sitting on thread in SRXTM image.

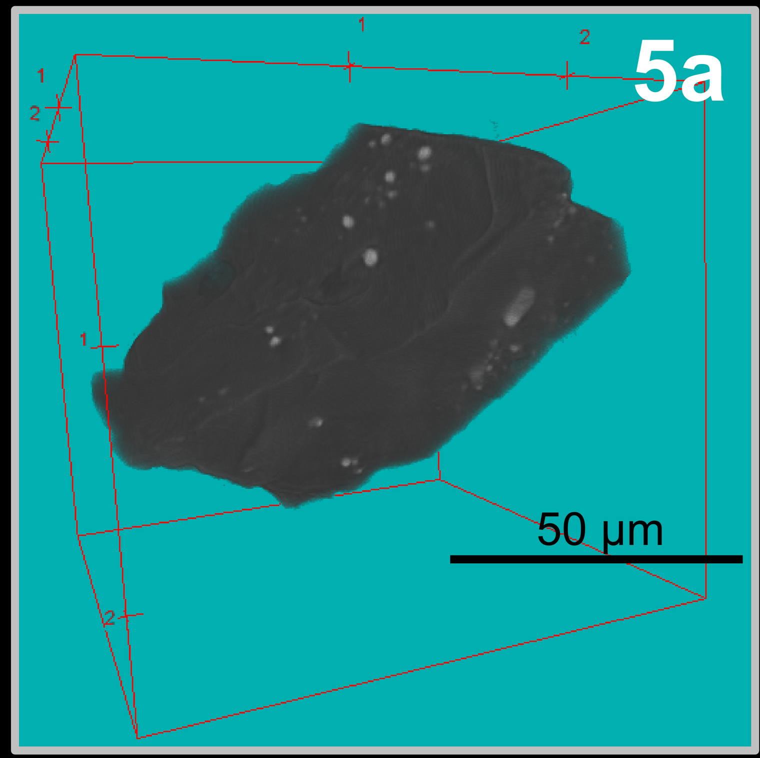
**Samples & Methods** Three of the seven grains allocated to our consortium were fixed with heptane-disolvable glue to a fluorocarbon thread, which was inserted into a capillary made of X-ray transparent boron glass. The grains were imaged using „Synchrotron Radiation X-Ray Tomographic Microscopy (SRXTM) at the TOMCAT beamline of the Swiss Light Source (SLS) at the Paul-Scherer-Institute (PSI) in Villigen, CH. The images were run through a 3D-reconstruction procedure [2], resulting in a series of virtual slices. The cubic voxel size of a 3D image is 0.325 µm.

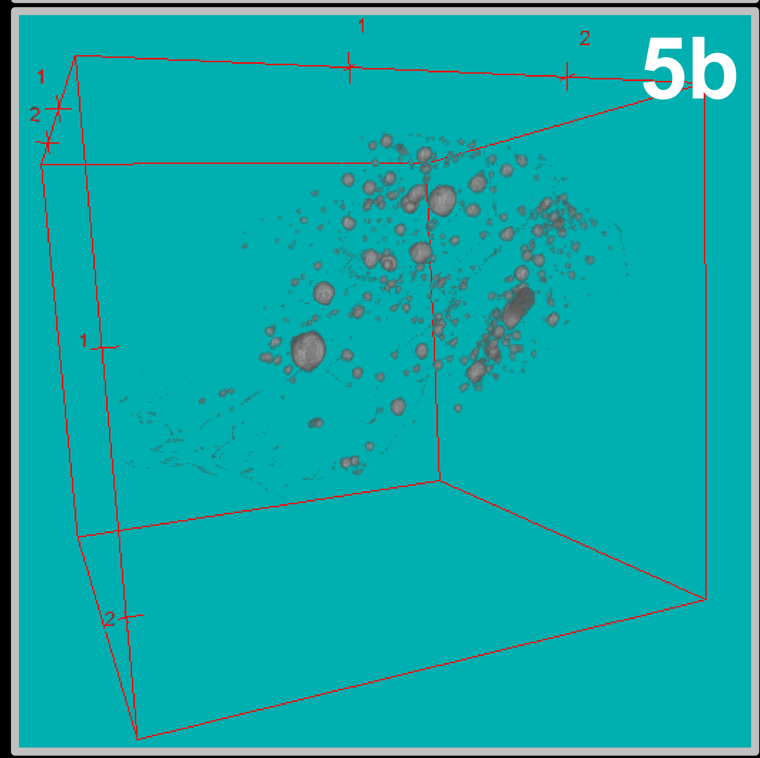


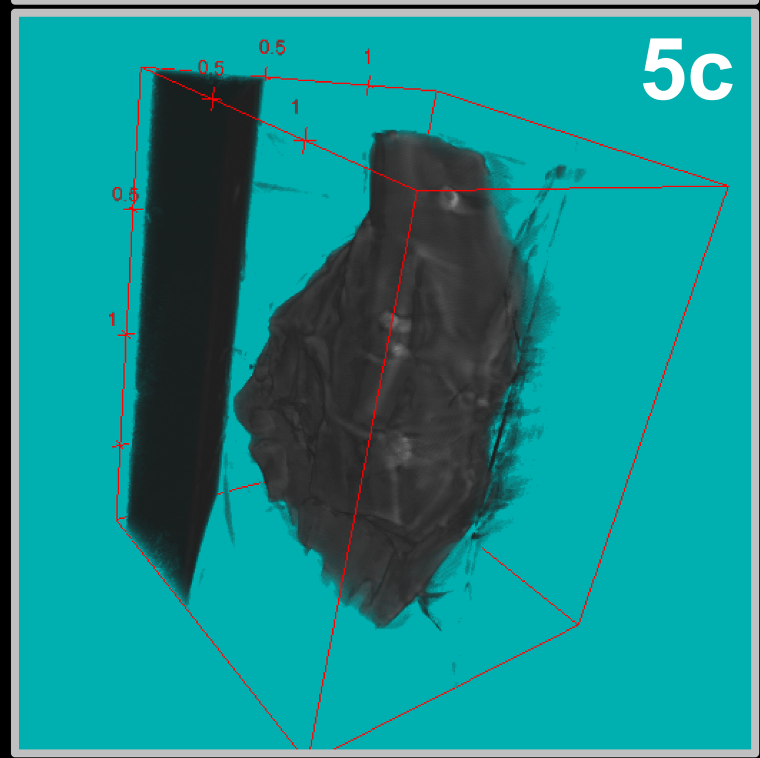



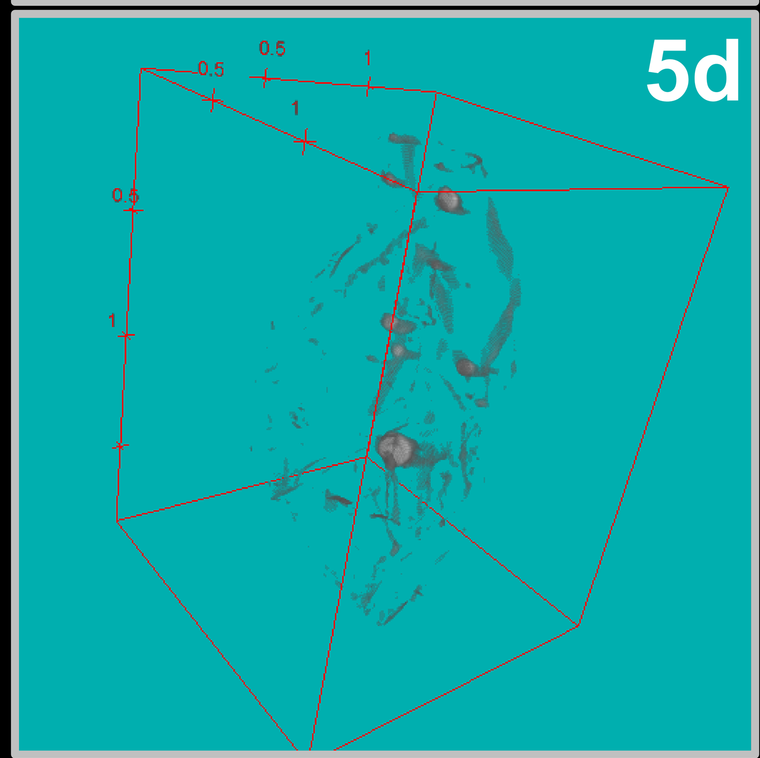




**Figures 3a, 3b** (top)
Raman spectra of the two mineral phases present in particle 0035.




**Results for RA-QD02-0035** The virtual slices were reconstructed to 3D images using the free, open-source program Fiji (ImageJ) [3] and the „3D object counter" plugin [4] for Fiji. By adjusting the gray-scale threshold, mineral phases with different X-ray attenuation coefficients can be made visible and rotated in 3D. In **Figure 4** (top), grain 0035 has been oriented such that the view is orthogonal onto the polished surface of the grain. The same surface has previously been analyzed with Raman spectroscopy [5], and different mineral phases have been identified. The grain is almost monomineralic, consisting of olivine with a small addition (<1 vol%) of a metal-rich phase, which could so far not be identified using standard materials, but is probably Fe,Ni metal, or troilite. The phase is readily visible in the lower-right panel of Figure 4 (with grayscale threshold 120).

**References** [1] Busemann H. et al., 2013, LPSC abstr. #2243 (this meeting); [2] Marone F. & Stampanoni M. 2012, *J. Synchrotron Rad.* 19, 1029; [3] Schindelin J. et al., 2012, *Nature Methods* 9, 676. [4] Bolte S. & Cordelières F.P., 2006, *J. Microsc.* 224, 213; [5] Boettger, U. et al., 2013, LPSC abstr. #2092 (this meeting); [6] Nakamura T. et al., 2011, *Science* 333, 1113; [7] Leya I. & Masarik J., 2009, *Meteorit. Planet. Sci.* 44, 1061.

**Conclusion** Synchrotron X-ray tomographic microscopy (SRXTM) can be used in combination with Raman spectroscopy and FTIR to determine very precisely the volumes, surfaces, densities, masses, mineral phases and internal structures of ~50 µm sized grains.

**Results for RA-QD02-0049-1 and RA-QD02-0049-4 – and determination of particle mass**
Similar 3D reconstructions were done for grains 0049-1 and 0049-4 as well (**Figure 5a - 5d**, left. Shown are the whole grains (5a, 5c) and the high-density phases (5b, 5d). Notice also the capillary wall visible in panel 5c). These grains, which are both fragments from a once larger grain (0049), show a similar internal structure as grain 0035: they are dominated by a single mineral (presumably olivine), with the addition of a presumably metal-rich phase with a high X-ray attenuation coefficient forming micron-sized „droplets". The fractional volume of that secondary phase is similar as in grain 0035 (<1%). Since grains 0049-1 and 0049-4 have been neutron-activated before [6], they cannot be used for cosmic-ray exposure age determination. Instead, they will be used to determine precise concentrations of solar wind-derived He, Ne and possibly Ar (0049-4), as well as Kr, Xe (0049-1).
The mass of the particles was determined by calculating their volume first (**Figure 6**, below). While the calculated volume depends on the gray scale threshold, values between 25 and 45 (on a gray scale between 0 and 255) form a „plateau", from which the volume was calculated. The density has so far been calculated using nominal Fo values [6], but this will be adjusted as soon as measured Fo values (Raman [5], FTIR [1]) are available for these grains. This will result in slightly different values from the ones given in **Table 1**.
The mass of the grains will be used to determine the (maximum) He, Ne cosmic-ray exposure age of the grains. For this, the information on the mineral phases present in the grains, and the resulting mass of the grain, will be combined with an elemental production rate model of cosmogenic $^{3}$He and $^{21}$Ne [7].

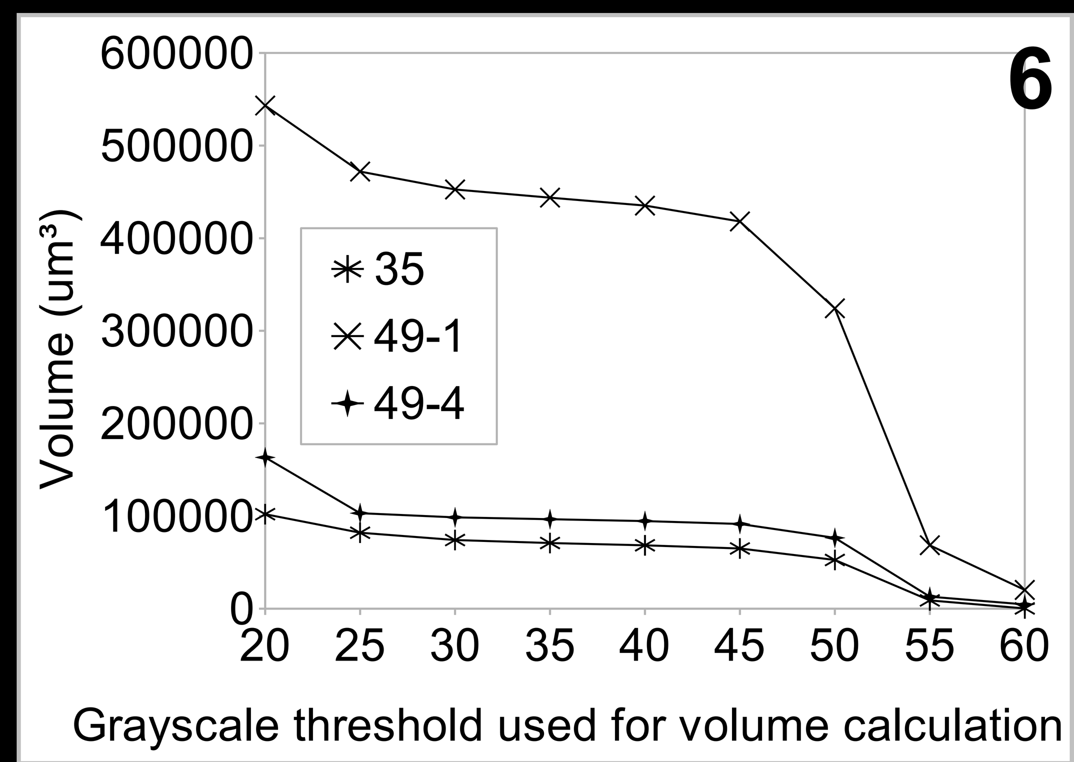



*Table 1: Volumes, densities and masses*

| Grain | V (1000 um³) | ρ (g/cm³) | M (µg) |
|---|---|---|---|
| 35 | 72.1±2.9 | 3.63±0.03 | 0.26±0.01 |
| 49-1 | 444±9 | | 1.61±0.04 |
| 49-4 | 96.9±1.9 | | 0.35±0.01 |