Quantitative analysis of minerals in meteorite chips by SR-X-ray microcomputed tomography

Recently, X-ray micro-CT has become one of the important methods of observing extraterrestrial materials such as meteorites, Antarctic micrometeorites, interplanetary dust particles, and materials of sample-return missions [1]. Synchrotron radiation (SR) provides particularly high flux density monochromatic X-rays, which enables the quantitative determination of materials with a spatial resolution of approximately 1 μm. We applied SR-X-ray CT to the non-destructive analyses of meteorites including the quantitative analysis of chemical composition using Linear Attenuation Coefficient (LAC, μ) [2].

Experiments were carried out at beamline **BL20B2**. The X-ray beam is monochromatized using a double-crystal monochromator. Samples were fixed on a rotational stage by clay. Transmitted and direct X-ray images were converted into visible light by a powder P43 ($Gd_2O_2S:Tb^+$) scintillator with thicknesses of 7 μm and 10 μm in the X-ray beam monitor. The effective pixel sizes of the detector, δ, were 2.74 μm and 3.14 μm.

Figure 1 shows CT images of meteorites. The spherical shape of chondrules, which are igneous spherules in meteorites, as well as their texture and fine grained rims around them are well defined in the CT images, with a few microns of spatial resolution. In Fig. 1B, the radial texture of a chondrule is clearly visible in an enlarged image and a 3D cut-off image.

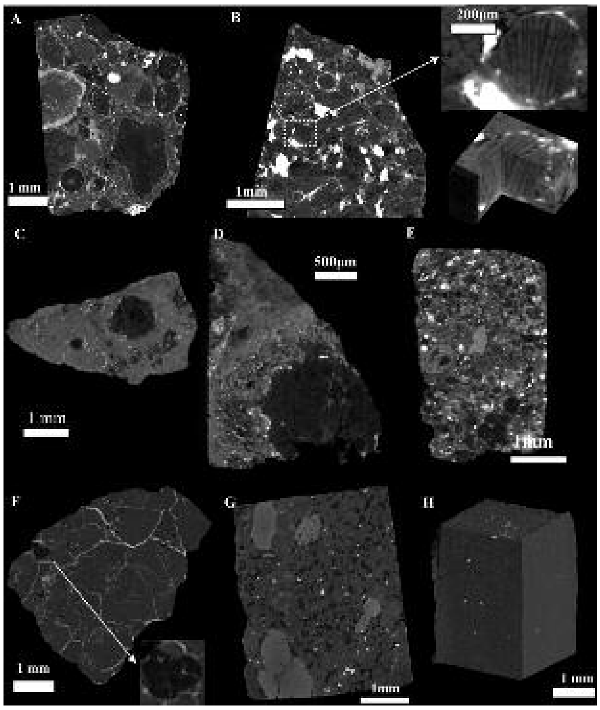

Fig. 1. CT images of various meteorite chips obtained using optimized experimental conditions. Except for D and H, the X-ray energy is 30 keV. A: Y-790448 (ordinary chondrite, LL3), B: ALH 78084 (ordinary chondrite, H3), enlarged image of a radial chondrule and 3D cut-off image of the radial chondrule, C: Allende (carbonaceous chondrite, CV3), D: Allende (23 keV), E: Y-81020 (carbonaceous chondrite, CO3), F: Y-791538 (Ureilite), G: DaG 476 (Martian meteorite, Shergottite), H: 3D distribution of voids in Gibeon (iron meteorite, 60 keV).

CT images of differentiated meteorites (ureilite, shergottite, and iron) are also shown in Fig. 1. Figure 1G displays an image of a Martian meteorite, DaG 476 (shergottite). The CT image displays distinct crystals such as olivine phenocryst (large light-gray objects), groundmass of pyroxene (gray matrix in CT image), and plagioclase (dark gray objects between pyroxene), and opaque phases including chromite grains (white objects). Figure 1H shows a bird's eye view image of the Gibeon iron meteorite. Gibeon shows no structure in the CT image, but the 3D distribution of voids (~20 μm in diameter) inside the meteorite is visible. A previous study has suggested the possibility that these voids are the carriers of noble gases in iron meteorites.

Figure 2 shows a magnified image of Fig. 1G (DaG 476) with a line profile of μ taken along the rectangle in the CT image. The line profile is the average value of 10 pixels perpendicular to the long side in the rectangle. We can observe the zoning of the olivine phenocryst, roughly from 8.1 to 10.0 cm^{-1} in μ. This range of μ is equivalent to a fayalite range (the iron content of olivine ranges from 0 to 100) of Fa_{29-39} for μ of olivine crystal. From a previous study, it appears that an olivine phenocryst in DaG 476 shows igneous zoning as Fa_{24-37} [3]. The range of Fa number shows good agreement with the Fa number obtained with μ.

Figure 3 shows the histograms of μ obtained using 30 keV X-rays. The count number is normalized to the total number of voxels of the meteorite chip. From the peak position of the histograms, we can deduce the internal components and their chemical composition. All the histograms of LL chondrites show peaks at almost the same position. For example, the histogram of Y-790448 shows peaks at 4.9 and 6.4 cm^{-1}. The peaks correspond to low-Fe silicates, which are mainly included in chondrules. The value of 6.4 cm^{-1} is equivalent to Fa_{20} for olivine and Fs_{29} for low-Ca pyroxene (Fs shows iron contents of low-Ca pyroxene), and 4.9 cm^{-1} is equivalent to Fa_{12} for olivine and Fs_{17} for low-Ca pyroxene. Peaks of iron inclusions, such as troilite (FeS, ~29 cm^{-1}) and metallic iron (~64 cm^{-1}), also appear in Fig. 3.

The histogram profile of DaG 476 shows a peak at around 6.4 cm^{-1}, which is equivalent to Fs_{29}. From polished section observations, the groundmass pyroxene in DaG 476 is Fs_{21-30} [3] and is consistent with the peak. The peak of the groundmass pyroxene is associated with two different peaks, 3.9 cm^{-1} (plagioclase, 3.5 cm^{-1} for anorthite) and 9.1 cm^{-1} (olivine phenocryst, equivalent to Fa_{34}). The compositional range of olivine crystals obtained by polished section observation is Fa_{24-42}. The peaks of chromite can be observed in the histogram. We can also observe a peak of ferrihydrite, which would be products of terrestrial weathering.

These results show that we can observe the texture in CT images, and obtain chemical compositions of individual minerals quantitatively by combining the textural information without destruction of the samples. We can also estimate the average chemical compositions of major and minor minerals in the meteorites from the peak position of the histogram. The method can be applied effectively to the initial observation of materials that will be obtained by future sample-return missions. CT data in this paper lacks higher and lower petrologic types and some reduced chondrites, such as E and CR. By increasing the number of data, we can increase the reliability of the classification of meteorite using X-ray CT.

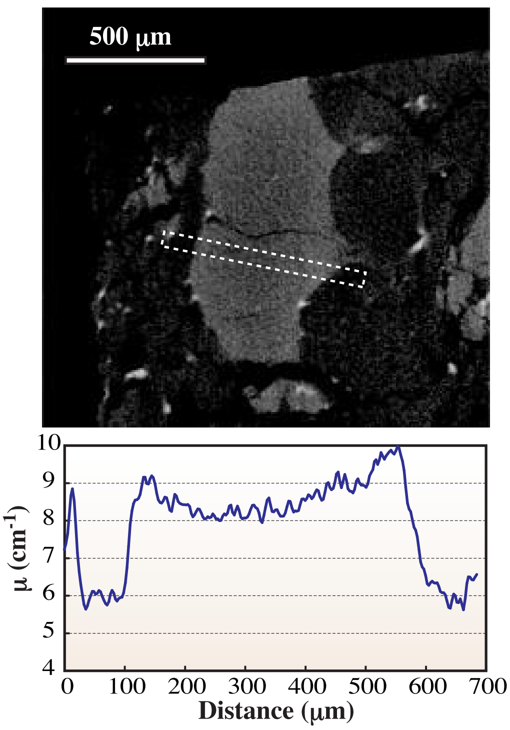

Fig. 2. An enlarged CT image of Fig. 1G (DaG 476) together with a line profile along the white rectangle in the image. The line profile is averaged perpendicular to the long side of the rectangle. We can observe igneous zoning of the olivine phenocryst in the range of 8.1–10.0 cm^{-1}, which is equivalent to Fa_{29-39}.

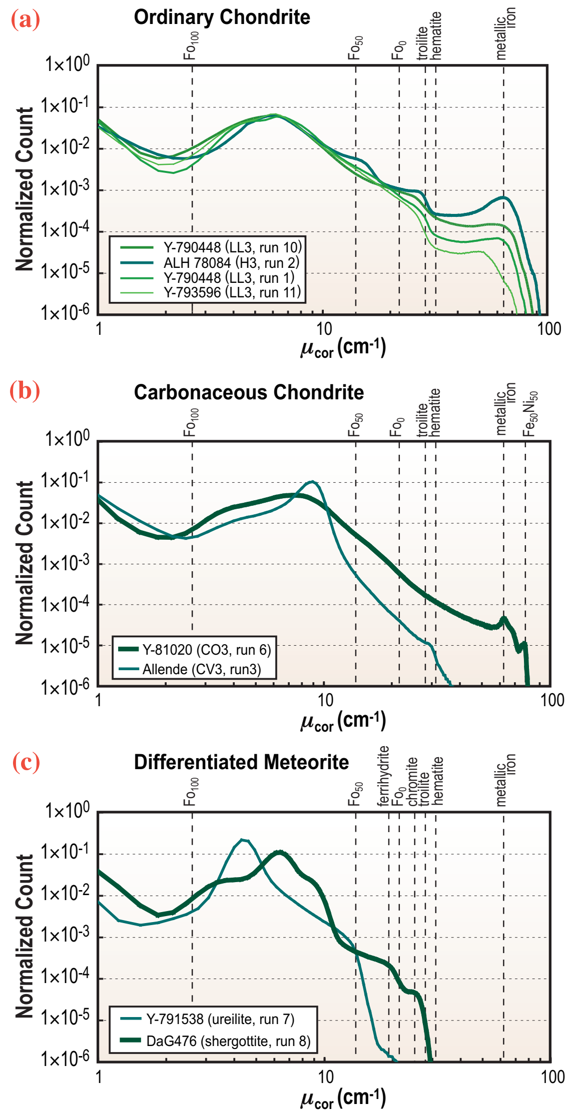

Fig. 3. Histograms of various classes of meteorites, obtained from CT data recorded using 30 keV X-rays. **(a)** Ordinary chondrites. **(b)** Carbonaceous chondrites. **(c)** Differentiated meteorites.

Masayuki Uesugi[a,*,†], Kentaro Uesugi[b] and Mayumi Oka[c]

[a] Dept. of Adaptive Machine Systems, Osaka University
[b] SPring-8/JASRI
[c] Dept. of Earth and Space Science, Osaka University

*E-mail: uesugi@planeta.sci.isas.jaxa.jp

[†] Present address: JAXA/JSPEC

References

[1] T. Nakamura *et al*.: Science **321** (2008) 1664.
[2] *M. Uesugi, K. Uesugi, M. Oka: Earth and Planetary Science Lett.* ***299*** *(2010) 359.*
[3] T. Mikouchi *et al*.: Meteorit. Planet. Sci. **36** (2001) 531.