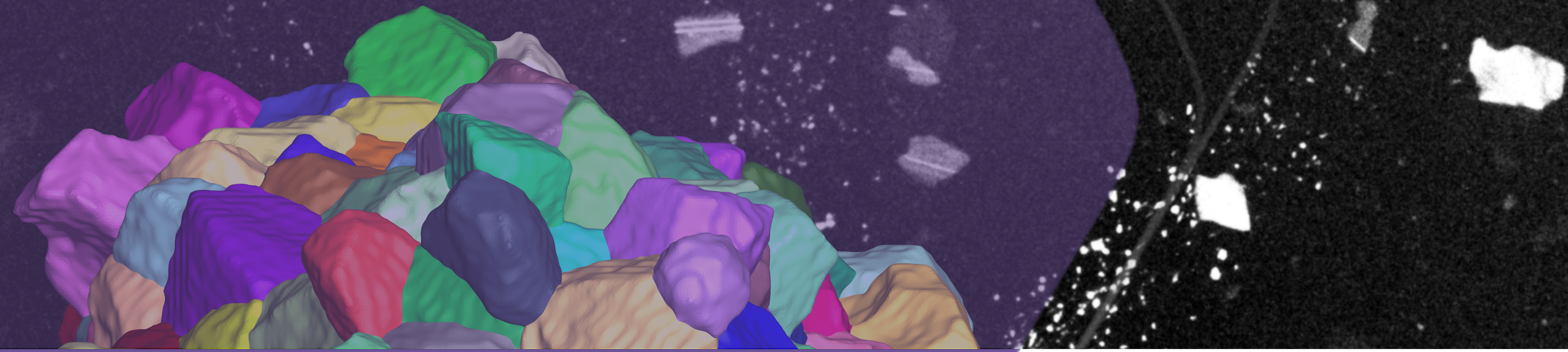

Application Note

Meteorite thermal history accessed by multimodal imaging

Chondrites, olivine and crystal zoning

Chondrites are among the oldest solid materials in the solar system. These 4.56 billion-year-old rocks fall to Earth as meteorites. They are identified by their spherical, silicate-rich particles, called chondrules. The mm-sized chondrules rapidly crystallized from molten droplets that formed during collisions in the solar nebula. The origin of chondrules makes them an ideal material to investigate the physics of the early solar system.

A chondrule's thermal history is reflected by its mineral content, composition, and texture, but interpretation requires knowledge of the timescales involved. This can be gained from the compositional zoning in crystals of olivine, $(Mg,Fe)_2SiO_4$, a constituent mineral in chondrules. Olivine zoning represents crystal layers richer in Mg or Fe and can be deciphered like growth rings of trees. At elevated temperatures during collisional events, some Fe and Mg diffused across layer boundaries, causing these to become chemical gradients. When cooling stopped diffusion, the gradients were left preserved in olivine crystals. Timescales of olivine thermal histories can be recovered by measuring the gradient profiles, however, Fe-Mg diffusion in olivine is anisotropic and six-times faster along the crystal *c*-axis compared to the *a*- and *b*-axes. Therefore, determining the crystallographic orientation of olivine is essential to accurately measure the chemical profiles.

Conventionally, diffusion timescales are modeled using data collected from 2D microscopy on cut and polished meteorite sections. This is both destructive and time-consuming, it does not guarantee a cross-section through the crystal center and rarely gives access to diffusion profiles precisely along a crystal axis. Here, we use non-destructive 3D multimodal X-ray imaging to overcome these limitations.

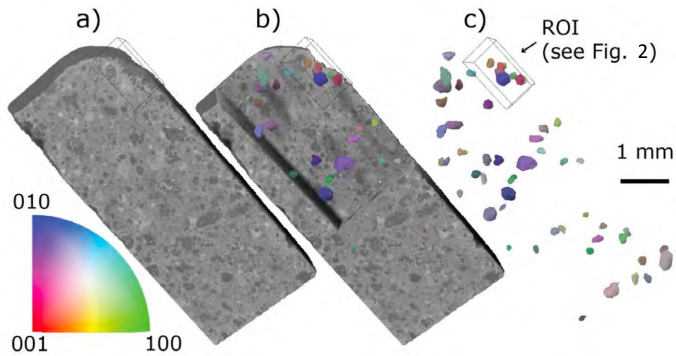

Fig. 1 *NWA 11346 carbonaceous chondrite. Overview scan of the 0.8 × 2.5 × 5.0 mm³ sample. (a) Absorption CT reconstruction. (b) Olivine grains reconstructed from DCT data, colored by IPF relative to the long-axis of the sample and shown inside the virtually-cropped absorption volume. (c) 52 olivine grains >100 µm. The highlighted region of interest contains a chondrule shown in Fig. 2.*

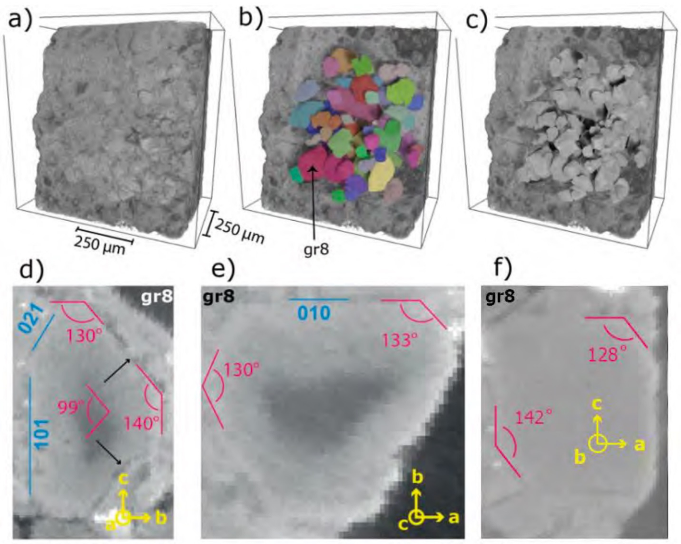

Fig. 2 *High-resolution scan of the 0.9 × 0.9 × 0.5 mm³ chondrule region. (a) Absorption CT reconstruction. 77 olivine grains >50 µm reconstructed from DCT data are shown inside the virtually-cropped absorption volume and colored by (b) IPF highlighting grain 8 (c.f. Fig. 1) and (c) absorption density. (d)-(f) Orthogonal slices through the absorption volume at the center of grain 8 after rotating into the crystallographic reference frame of the grain itself as indicated. The absorption density shows strong Mg-Fe zoning.*

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Combining absorption CT and DCT

A piece of the Northwest Africa (NWA) 11346 carbonaceous chondrite has been investigated using correlative, lab-based absorption (ACT) and diffraction contrast tomography (DCT). Two imaging experiments were performed in the lab: an overview scan covering the entire sample (Fig. 1), and one covering a chondrule at higher resolution (Fig. 2). The chondrule was also scanned with monochromatic synchrotron-ACT to calibrate density information.

It was first shown that the density information obtained through ACT on a Zeiss Xradia Versa 520 compares well to calculations using the monochromatic data, and later the relationship between density and the Mg/Fe ratio in olivine was also confirmed with energy dispersive spectroscopy (EDS). The LabDCT Pro module on the Versa was used to measure the crystallographic orientations, shapes, and locations of 77 olivine grains larger than 50 µm in the studied chondrule (Fig. 2b). Finally, the 3D tomography data were rotated to align the XYZ axes with the orthorhombic crystallographic axes of each olivine grain, which made virtual profile cuts through the grain centers straightforward, accurate and reproducible (Fig. 2d-f).

Zonation intensity

Plotting the chemical range present within each of the grains in the chondrule against the rank of this range in Fig. 3 shows three zoning groups. It is evident that the largest grains are also most strongly zoned. The 3D grain map shows that these grains have similar crystallographic orientations and form a band through the center of the chondrule.

The crystallographic context acquired through the lab-based experiment combined with a calibration of the olivine forsterite (Fo: Mg_2SiO_4) content (based on density) reveals new 3D insights into the diversity of olivine zoning in chondrules. It also shows that some grains experienced a more complicated thermal history involving remelting and recrystallization, setting the stage for 3D diffusion studies.

Future advances in 3D petrography

Correlating ACT with DCT results allowed us to generate crystallographically oriented 3D chemical zoning profiles of 77 individual olivine grains within the chondrule. This provides an opportunity to not only deliver a more accurate assessment of individual grain histories but also to do so for a statistically significant number of grains, which will better establish details of chondrules' thermal histories. An important future step will be to interpret 3D zoning profiles in the context of crystal growth and diffusion models that will benefit from the full 3D chemical, textural and crystallographic information.

Because data collection required next to no sample preparation and left the sample intact for further analysis, traditional 2D measurements may be replaced within the rich contexts established in 3D if desired. This collectively speaks in favor of placing multimodal X-ray imaging as a natural first step in future 3D petrographic workflows, especially for precious materials like sample return missions from space.

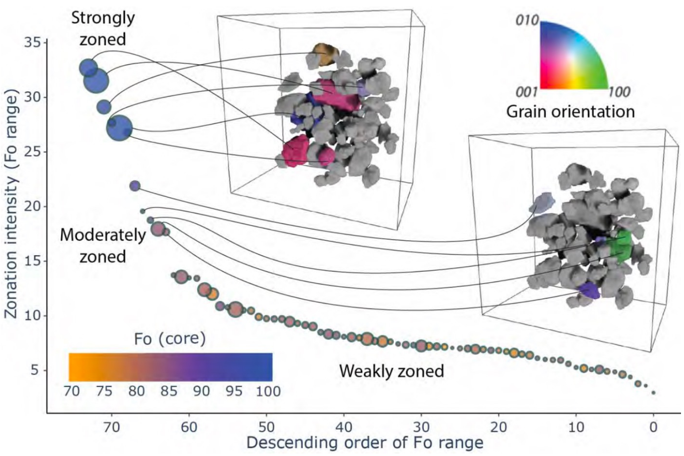

Fig. 3 *Zonation intensity of the 77 olivine grains in the NWA 11346 chondrule measured as forsterite (Mg-olivine) range within individual grains plotted against rank order (0 to 76) with marker sizes representing relative grain sizes. The groups of strongly and moderately zoned grains have been correlated to the grain map for context on grain shape, crystallographic orientation and spatial location.*

References:

[1] M.J. Pankhurst et al., https://doi.org/10.2138/am-2023-9213 (2025)

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