Meteorite 3-Dimensional Synchrotron Microtomography: Methods and Applications
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DVD-Figs-Captions: These figures (DVD-Figs) total 644 MB space on disk.

Fig 1: Al Rais: This rare CR chondrite is rich in multiply-layered chondrules.

Fig1a,b: AlRais1-ts1-Y.mpg, Z.mpg: The entire 1.444g specimen (AMNH 4168) was imaged at 17.11 µm/pixel. Movies are orthogonal to y and z axes of the sample.

Fig1c: AlRais-B2-2ts1-Y.mpg: Sample B2 is a smaller piece cut from Al Rais tomography volume 1, and imaged at 6.56 µm/pxl (426x426x1431 x-y-z pixels). Movie is orthogonal to y axis of subsection B2. At this higher resolution, chondrule layering is strikingly detailed and textural variations between chondrule core and rim layers can be accurately measured.

Fig 2: Itqiy: File Itquy1-ts1-Y.mpg This anomalous EH chondrite illustrates a limit in metal content, beyond which sample density appears to precludes microtomography. This movie through the sample volume is orthogonal to the tomographic y axis. Although x-ray 'shadows' cast by metal create artifacts that hinder interpretation of the data, equigranular enstatite (dark), and metal (bright) form obvious triple junctions with measurable geometries. Sulfides in intergranular 'corners' cannot be discerned. The scaling factor of the initial grayscale range of the data prior to image reconstruction has been reduced from the usual 10^6, so that the cores of large metal accumulations do not have a brightness (x-ray attenuation) that is beyond the 32-bit range of the final density structure.

Fig 3: chondrules

Fig3a-Renazzo1-C1toC8: Each of 8 sub-directories contains a complete stack of -bit tiff images cut through each of 8 chondrules.

Fig3b-Renazzo1-cc1: Compound chondrule in a subvolume of a piece of Renazzo (for complete volume, see CD-Fig8).

Ren1wcR45c-cc1.volume A NETcdf format volume file of the subvolume.

Ren1wcR45c-cc1-Xtif8, Ytif8, Ztif8 Tiff format (8-bit) stacks of compund chondrule orthogonal to x, y, and z axes.

Fig3c-Allende-BB: Compound chondrule removed from Allende.

AlBB1-X8-mosaic1-gs300.tif: Representative sequence of x-axis slices 100 to 350, with lines to locate fracture intersection points.

AlBB1-Z8-mosaic1-gs300.tif: Representative sequence of z-axis slices 50 to 475, with lines to locate fracture intersection points, indicated by small circles in frames 175-350.

AlBB2-els-gs300.tif: Element x-ray maps and BSE image of chondrule BB2.

Al1BB2-2c-ts2_Y.mpg: Movie through chondrule BB2.

AlBB1_w-ts1_Y, Z.mpg: Movies through chondrule BB1.

septumBB3-Y-gs150.tif: Successive slices through septum between compound chondrules. Every 25th slice (239 µm apart) is shown. Period before slice label marks the lower left corner of each image frame. Smooth curve to upper left is the imprint of chondrule BB1.

Fig3d-Bjurbole-ch7c-ts1-Y.mpg: Movie through Bjurbole barred olivine chondrule, on y axis.

Fig3e-KaroondaK30-3-raw.mpg: 'Raw' x-ray movie of rotating pophyritic olivine chondrule from Karoonda. This is the only movie of this type here, and shows how the chondrule looks as it rotates through a half-circle, looking toward the x-ray beam.

Fig3f-KaroondaKr30-3-ts1-Y.mpg: The chondrule of Fig 3f, as a movie through the volume.
Fig3g-KaroondaKr18c-ts1-Z.mpg: Barred olivine chondrule from Karoonda with a thick rim.
Fig3h-KaroondaKr22c-ts1-Z.mpg: Porphyritic olivine chondrule from Karoonda.
Fig3i-KaroondaKr11-2c-ts1-Z.mpg: Thickly-rimmed concentrically zoned chondrule from Karoonda.
Fig3j-Ren1-ch1-metal.avi: Renazzo chondrule #1 (see CD-Fig3a), thresholded to reveal only metal grains (blue), and rotated.

Fig 4: Zagami (SNC): Tomographic image movie (Zagami1-ts1-Y.mpg) passing through a rectilinear piece (~5 x 7 x 18mm, 0.255 g.) cut from this basaltic Shergottite (AMNH 4709). Pyroxene morphology and chemical zoning are visible. Homogeneous magnesian cores are darker (less attenuating) than FeO-enriched, zoned rims. Grain size and orientation can be determined to a high degree of accuracy. Also visible are the 3D sizes, abundance, distribution and associations of oxide grains in the tomographic data.

Fig 5: Allende (CV3, ox): This data was produced from a single tomographic sample, #2 of four we have imaged. Dark Mg-silicate chondrules, bright metal and sulfide, and irregular dark gray CAIs are easily seen against light-gray, FeO-rich matrix.
Fig5a-Allende2-ts1-X8: Stack of 8-bit tiff virtual slices through volume of Allende (sample 2).
Fig5b-Al2ps3-BSEMCAtomo1.gif: Comparison of BSE, x-ray map composite RGB (Mg-Ca-Al), and tomography images, for serial section 3 through Allende sample 2. The actual cut surface mapped in BSE and x-ray intensities does not exactly correspond to the virtual slice (x_066) that is identified in tomography. The serial sections are cut sub-parallel to the tomographic slices orthogonal to the x-axis of the tomography volume. None of the images are at their original resolution in this gif picture.
Fig5c-Al2ps3-TomoThresh1.tif: Thresholded virtual slice corresponding approximately to Fig 5b. For determining chondrule/matrix ratios, volumes were cropped to eliminate all surrounding black (air) that is visible in Fig 5a.
Fig5d-Al-slicer3D-1-rgb72.tif: Images in 3D prepared using 'slicer3d' IDL software, from the volume from which Figs. 5a,e,f,g are made. The chondrule/matrix ratios obtained from thresholding and voxel counting are noted (Schoenbeck and Ebel 2003).
Fig5e -Allende2-ts1-X.mpg: Movie through the volume along X direction.
Fig5f-Allende2-X-threshWCZ.mpg: Movie through thresholded volume (as Fig5c), along X. The view point in this seqence is inverted from that in Fig5e.

Fig 6: Semarkona (LL3.0): A 2.32 g. fusion-crusted sample was chosen for tomographic analysis (AMNH 4128). Five stacked volumes 4.5 mm apart were imaged at 17.073 micron/pixel, in a 650x309 pixel field of view, at 42 keV, 0.8sec exposure time, with a Mitutoyo 5x lens. The five volumes combine to a total of 1365 pixels (2.33cm) in the vertical dimension. This sample illustrates the difficulty in extracting quantitative results from tomographic data on ordinary chondrites.

One interesting object clearly visible in tomography and in the cut section is a large, zoned chondrule. High resolution maps of this object reveal concentric layers differently enriched in metal, zoned in composition. This find illustrates the utility of tomography for locating interesting objects in chondrites. Possession of 3D information allows the full volumetric textural relations of such objects to be understood. In this case, the extent of dust-rich rims, and their concentricity around the central object, are easily observed and can be measured volumetrically.

Fig6a-Sem2-sample.gif: Sample geometry in the tomography run, and comparison of BSE and tomographic images of the flat surface of the sample, after polishing. Note that alignment in 3D of polished surface to virtual slice is not exact.

Fig6b-f, -Sem1ps1c_Si.tif, Fe, Mg, Al, BSE: Surface x-ray intensity maps for elements, and BSE image, for cut sample, at 5 micron/pixel resolution.

Fig6g-Sem2wc-ts2-X_0007w.tif: Tomography image of approximately the same surface, at 17.1 micron/pixel resolution. Surrounding air has been rendered in white.

Fig6h-Semarkona2-ts1-X.mpg: Movie through the Semarkona volume orthogonal to x axis.

Fig 7: Krymka (LL3.1): A single fragment (0.240g) of Krymka (AMNH 4847) was imaged at 10.2 5 micron/pixel resolution. Movies through the volume are orthogonal to x, y, and z axes. Many features known from thin-section analysis are revealed in 3D, including the predominance of metal as large inter-chondrule grains, the presence of void spaces in chondrule interiors, the rarity of thickly-rimmed chondrules, and the high degree of compaction. Type I (FeO-poor) and II (FeO-rich) chondrules are darker, and lighter gray, respectively.

Fig7a-Krymka-1-ts1-Z.mpg: Movie through the Krymka volume orthogonal to z (long) axis.

Fig7b-Krymka-1-ts1-Y.mpg: Movie through the Krymka volume orthogonal to y axis.

Fig 8: Renazzo (CR2): This sample (#1) is a roughly tetragonal prismatic fragment (~8x8x15 mm, 1.636 g., AMNH 588), imaged at 17.11 micron/pixel. Bright metal grains are evident, surrounding and included inside chondrules. Apparent compound chondrule pairs can be seen, and also multiply-layered chondrules.

Fig8a-Renazzo1-ts1-Y8: Stack of 8-bit tiff virtual slices through volume of Renazzo. The volume has been rotated a quarter turn about z, relative to the original data, so that the volume takes up minimal space (sides of sample sub-parallel to boundaries of volume).

Fig8b-c, Renazzo1-ts1-X,Z.mpg: Orthogonal movies through the volume of Fig. 8a. Movies are orthogonal to x and y axes of the volume.

Fig8d-i, -Ren1psA1a-Si, Fe, Ca, Mg, Al, BSE: Surface x-ray intensity maps for elements, and BSE image, for cut sample, at 4 micron/pixel resolution.

Fig8j-Rnzo1secA-4-gs300.tif: Detail of section through Renazzo piece, including locations of some chondrules of CD-Fig3a, and comparison with tomographic images.

Fig 9: Acfer 139 (CR2): A long slender fragment (0.635g) of Acfer 139 (AMNH 4793), and an adjacent piece (0.684g), were both imaged at 10.50 micron/pixel resolution in 4 volumes separated by 4.70mm, then stitched together and cropped to make single volumes, 375x502x1829 and 372x454x1829 x-y-z pixels. This weathered desert sample shows similar features as Renazzo, but with an overprint of rust that appears as high-attenuation fracture-fillings.

Fig9a-Acfer139-cut-rgb72.tif: Documentation of cutting for two pieces of Acfer 139.

Fig9b-Acfer139-1-ts1-X.mpg: Movie through volume of piece #1, orthogonal to x axis.

Fig9c-Acfer139-2-ts1-Y.mpg: Movie through volume of piece #2, orthogonal to y axis.

Fig 10: NWA487 (LL3): A sample ~6x6x35mm was cut from a slab (AMNH 5021), and imaged at 17.036 micron/pixel, for a cropped image 450x450x1365 x-y-z pixels. NWA487-1-wcts1_X.mpg is an mpeg format movie along the x axis, and NWA487-1x-wcrop_Z.mpg is along the z axis). The full data set is from 5 volumes collected sequentially along the z axis, resulting in minimally perceptible discontinuities at sutures between the volumes. The mounting medium (crystal bond) is visible at the bottom edge the sample.

Fig 11: Allende CAI-1

Fig11a-b, -AllendeCAI1-ts1-X, Y.mpg: Orthogonal movies through the volume of CAI.

Fig11c-mellilite_trial_1a.tif: Results of thresholding and segmentation of mellilite in CAI, using the Imaris software. Mellilite and fassaitic pyroxene make up most of the CAI volume.

Fig11d-UH_close_up_void_1.gif: Animated gif format close-up of thresholded void space in the interior of the CAI (black in CD-Figs 11a-c). The volume was cropped to remove intersections with the outer CAI surface.

Fig11e-lower_half_surface.tif: Thresholded surface-rendering of the lower half of the CAI, illustrating texture of the surface.

Fig11f-mostdense_test_1.gif: Animated gif format video of thresholded metal (white) in the CAI (red). Voids and outer surface morphology are also evident.

Fig11g-CAI-halfvolume.gif: Animated gif format of a virtual half of the CAI, created using the Imaris software tool. The texture of the outer surface of the CAI is visible. Interior sulfide grains are visible on the flat virtual cut.

Fig 12: Leoville (CV3, reduced): A tabular piece (0.522g) of Leoville (AMNH 4337) was imaged at 10.50 micron/pixel resolution in 3 volumes separated by 3.50mm, then stitched together and cropped to make a single volume, 360x450x1154 x-y-z pixels. Weathering shows as Fe oxides filling fractures. Figure Leoville1-ts1-Y.mpg is a movie through Leoville sample (#1), orthogonal to the tomographic y axis.

Fig 13: Aerogel: These are tomography images of tiles like those returned by the STARDUST mission, shot with dust (v = ~ 6 km/sec) from the Allende meteorite, by analogy to the expected cometary dust in the returned samples.

Fig13a-AeroB1-ts2_Y.mpg: Movie through aerogel tile shot with Allende dust, imaged at 12 keV, at 14.5 micron/voxel edge resolution. Particle tracks throught the aerogel are visible, as are particle fragments.

Fig13b-B1-pB1-ts3-Y.mpg: Partial volume of Fig13a, cropped to isolate tracks, in Y direction.

Fig13c-B1-pB1-ts3-Z.mpg: Partial volume of Fig13a, cropped to isolate tracks, in Z direction.

Fig 14: Lunar Spherules: This movie of 1.96 micron/pixel data reveals the existence of a single spherule containing an olivine phenocryst. The tomography volume has been cropped from the original field of view, to contain all the sample but less air surrounding it during data collection. OG1C-c1w-t1_X.mpg is a pass through the volume.

Fig 15: Techniques

Fig15a-Wiresaw1-rgb300.tif : Sample assembly for wire saw. Wires 20, 30 or 50 microns in diameter were used to cut tomography samples with minimum loss.