ACQUISITION AND ONLINE DISPLAY OF HIGH-RESOLUTION BACKSCATTERED ELECTRON AND X-RAY MAPS OF METEORITE SECTIONS. R. C. Ogliore. Department of Physics, Washington University in St. Louis, St. Louis, MO 63130, USA.

Introduction: In recent years there have been efforts to make raw scientific data publicly available online. Many astronomy and planetary science data sets are available for any interested scientist to analyze. These open data sets allow for greater transparency of published work and exploration of data in novel ways by people outside of the main community. Open data sets also facilitate a "first look" into an interesting scientific question, with more in-depth studies that follow. Open data sets in cosmochemistry and meteoritics include the presolar grain database [1] and NASA's Astromaterials 3D [2].

The "first look" data that is most often critical for cosmochemists is a detailed mineralogic and petrographic description of the sample. For a sample prepared as a thin or thick section, backscattered electron and elemental maps acquired at the effective resolution limit for these two modalities (50 nm/pixel and 2 μm/pixel, respectively) are critical for determining if a given sample can answer a given scientific question. However, thin sections of precious extraterrestrial samples are rare and often difficult to acquire and expensive or logistically challenging to analyze by FEG-SEM techniques. Here I describe a technique to acquire BSE maps and the associated elemental maps of an entire one-inch section, and display these maps conveniently online.

Methods: The meteorite section is mounted on a large SEM stub with clips to ensure the sample does not move during the long acquisition. The SEM is tuned for optimal BSE image acquisition at high magnification and 15–30 kV accelerating voltage. First, we acquire a "focus map" before the high-resolution BSE acquisition. The sample is scanned over a coarse grid ($\sim$50$\times$50 images) using the Image Snapper software on a Tescan Mira3 FEG-SEM with the SEM's autofocus function enabled. The optimal working distances for the images (recorded in header files) are used to build a focus map that is sampled at each position in a coarse grid. Outliers are removed, then the remaining points are fit to a two-dimensional, second-order polynomial (to account for curvature and tile of the sample from polishing and mounting). The x, y and working distance values are then calculated for the full-resolution BSE scan from this polynomial (including a user-defined overlap fraction, $\sim$20%). These coordinates are fed into a Matlab function that writes an Image Snapper acquisition file for collection of the high-resolution BSE scan. Images are only acquired over the actual sample (defined as the perimeter of points that the user defined in the focus map), minimizing wasted acquisition time. Each

individual tile is a 16-bit BSE image in png format, 2048$\times$2048 pixels, 100–200 μm field of view, and 2–4 μs/pixel dwell time.

Next, we optimize BSE brightness and contrast for the sample we are analyzing. With auto-working-distance and auto-brightness-contrast disabled, we acquire BSE images over the entire sample using Image Snapper and the acquisition file written in the previous step (acquisition takes $\sim$3 days). After acquisition, images are renamed to their locations in the scan grid.

We then re-optimize the SEM conditions for X-ray acquisition (higher beam current, 15 mm working distance). We acquire a new focus map and write a multi-field acquisition file using Matlab for the EDAX TEAM software. We acquire a 512$\times$400 pixel imagesover a 1024$\times$800 μm field of view (2 μm/pixel). It takes 5–10 days to acquire X-ray maps over the entire thin section using the 30-mm^2 SDD X-ray detector on our SEM.
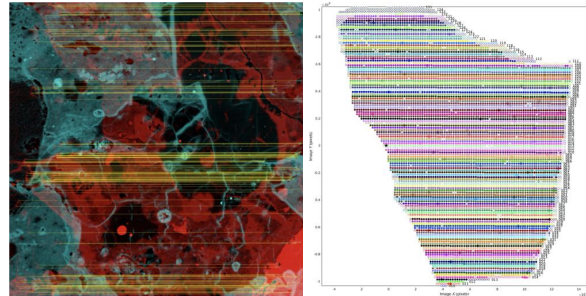

Figure 1: Left) Two neighboring BSE images (red and turquoise) and their matches indicated by yellow lines (field-of-view=150μm). Right) Positions of individual tiles of an assembled mosaic.

Individual images are then assembled using a Matlab script. Identifying features in the overlap regions of neighboring images are found using detectBRISK-Features which uses uses the Binary Robust Invariant Scalable Keypoints algorithm to detect multi-scale corner features. Neighboring images are matched using a similarity transformation matrix. The matching features are assigned a transformation error value based on how well the set of matched features maps from one image to its neighbor. The brightness of overlapping regions is calculated for a shading correction in the final mosaic. The entire set of $\sim$10,000 individual tiles are mapped back to an origin tile near the middle of the image. The path from this origin image to an arbitrary tile image is calculated via a bidirectional graph where the edge weights (distances between nodes) are proportional to the transformation error. Outlier images with large er-

rors are assigned infinite weight. The transformation for outlier images is calculated via 2d interpolation from the surrounding images. A text file is written where each row is a tile image filename, the components of the transformation matrix, and a shading correction offset. The computation time for this process is a few hours. The BSE image that is acquired along with the X-ray maps is stitched using the same method, then this map is transformed again to match the high-resolution BSE map. The same transformations are then applied to the X-ray maps so that they are warped to align with the high-resolution BSE map. RGB maps with histogram equalization for each channel, such as Ca-Al-Si or Fe-S-O, are also created.

The image transformation list is then fed to a Python script which uses vips [3], a demand-driven, horizontally threaded image processing library, to apply the transformation and brightness corrections, and assemble the tiles into the final mosaic. Vips is able to stitch together ∼100-gigapixel images by pixel streaming where the entire final image is never loaded into memory. The BSE and registered X-ray maps are saved as dzi image pyramids. These images can be viewed seamlessly (panning and zooming) online using OpenSeaDragon, with javascript code that allows for easy switching between BSE and X-ray maps. Various tools are added to the web display of the image, including a scale bar. Each field-of-view has a unique url so the positions of interesting features can be recorded and shared with colleagues.

Results: An example map can be viewed here [4] and several more are available on our lab's website [5].

Our lab has used these maps to identify cosmic symplectite in Acfer 094, search for cosmic symplectite in other meteorites, and to locate carbonaceous-chondrite-like clasts in the howardite Kapoeta. We have identified an unusual Ti-, V-rich sulfide mineral in Acfer 182 (CH3) [6] that would have been nearly impossible to find without these maps.

The code to acquire, assemble, and display these maps is available [7].

Conclusions: I have presented a method for an online "virtual SEM" of meteorite thin sections. Data acquisition is lengthy, 1–2 weeks, but it is unsupervised and requires only minimal setup. Data processing is also mostly unsupervised. The investment in effort and SEM time is worthwhile for important samples where mm- to μm-scale mineralogic context is critical for targeting subsequent *in-situ* micro-analyses such as FIB-TEM and and SIMS.

This technique can play an important curation role for the next generation of returned samples. Hayabusa2 returned mm-sized and larger stones from Ryugu that may
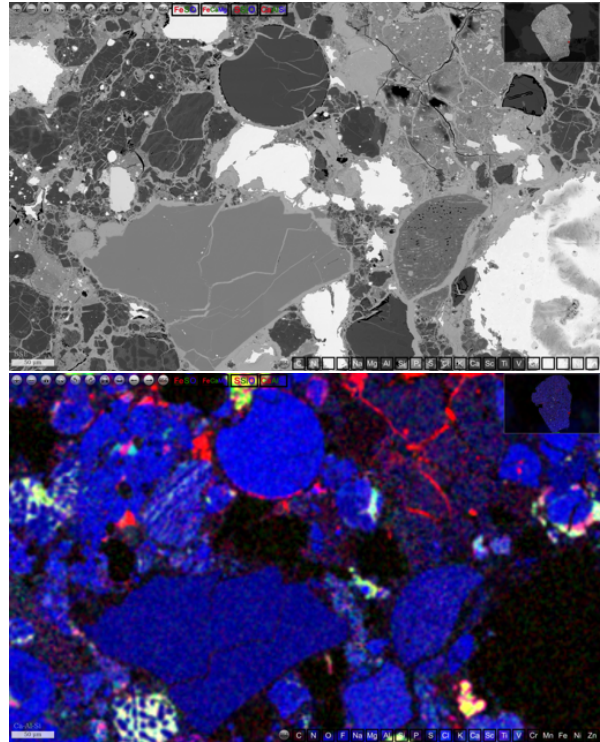

Figure 2: BSE image (top) and Ca-Al-Si RGB image of a portion of a 160 gigapixel image of Acfer 182 (CH3). 50 μm scale bar is visible at lower-left

possibly be prepared in thin section. OSIRIS-REx will likely return stones from Bennu at least this large that may also allow for thin sections. The characterization of Ryugu and Bennu samples with this technique will allow for researchers all over the world to simultaneously analyze thin sections and target particular samples for more detailed analysis.

References: [1] T Stephan et al. *LPI* 2326 (2020), 2140. [2] https://ares.jsc.nasa.gov/astromaterials3d. [3] K. Martinez and J. Cupitt. *IEEE International Conference on Image Processing 2005*. Vol. 2. IEEE. 2005, pp. II–574. [4] https://presolar.physics.wustl.edu/maps/lpsc2021. [5] https://presolar.physics.wustl.edu/meteorite-deep-zoom. [6] https://presolar.physics.wustl.edu/maps/Acfer182TiVsulfide. [7] https://github.com/ogliore/DeepZoomSEM.