

GIGAPIXEL OPTICAL MICROSCOPY FOR METEORITE CHARACTERIZATION R. C. Ogliore¹, C. E. Jilly¹, ¹Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI 96822, USA.

Introduction

Optical microscopy is the first method used to characterize meteorite thin sections. To properly classify a meteorite, modal abundances of features (such as chondrules, clasts, inclusions, or matrix material) and the size distribution of chondrules are typically acquired under reflected light microscopy to make a preliminary identification of the meteorite group (for typical chondritic meteorite characteristics, see [1]). The degree of terrestrial weathering, shock stage, and other characteristics of the sample can be ascertained using optical microscopy. High-resolution optical imaging provides direction for other analytical techniques, and digitally recording optical information allows for further analysis of this data after the sample is coated.

Here we describe an automated microscopy setup for the acquisition, creation, and display of optical micrographs at ~ 385 nm/pixel for typical meteorite thin sections up to a few cm in size, resulting in a total image size of up to a few billion pixels. Our system employs focus stacking and exposure fusion to properly image variable-height and high-contrast samples. Using free software available for Windows and Macintosh, these images can be shared and viewed easily in a web browser, allowing for smooth zooming and panning. The result is a "virtual microscope" in which all of the optical characteristics of the meteorite thin section can be examined without the operator having to sit in front of the microscope with the sample in hand. The software for our system is entirely open source and can be improved upon and adapted for a wide range of applications. The system we describe is entirely automated and can be set up on any optical microscope with a computer-controlled stage and modern consumer-grade digital camera.

Optical Microscopy Setup

The optical microscope we use is a Nikon AZ100 Multizoom Research Microscope System with 0.5 \times , 1 \times , and 4 \times objective lenses. The microscope is capable of both reflected and transmitted light, in addition to plane-polarized and cross-polarized illumination using custom-designed polarizing-film holders. A motorized, computer controlled stage (Prior Optiscan II) is capable of 1 μm step size in the x- and y- dimensions and focus steps of 0.1 μm in z. We use a Canon T2i digital SLR to capture still images using the camera's live video feed at 1056 \times 704 pixels, which at 32 \times magnification corresponds to ~ 385 nm per pixel (407 μm \times 271 μm field of view). The camera is computer-controlled through

a USB 2.0 connection using the *libgphoto2* library and the *gphoto2* command-line client, and the stage is controlled via serial connection with the terminal emulator *minicom*. An eight-core Fedora Linux computer with 8 GB RAM runs the entire system.

The user specifies the four corners of the sample plane, and *Matlab* computes the least-squares fit plane and generates a grid of mosaic points at which individual image tiles are acquired. Then *Matlab* writes a *Tcl* script that coordinates the stage movement, camera control, and stitching commands over all the points in this grid. The user simply runs this script to acquire, stitch, and prepare the gigapixel image for online viewing.

Focus Stacking and Exposure Fusion

The depth of field for the 32 \times magnification of our microscope used to acquire individual mosaic images is only several μm . Small errors in defining the plane of the sample to be imaged can lead to acquiring out-of-focus images. Additionally, unpolished sections may contain topography outside of the depth-of-field that the user wishes to record in a single image. For these reasons we acquire a "focus stack" of images at each point in the plane of the microscope's stage. A focus stack combines the in-focus parts of a number of images captured at different focal plane depths into one image. We employ the command-line utility *enfuse* which uses the Mertens-Kautz-Van Reeth exposure fusion algorithm [2] to merge the in-focus regions (defined by high pixel-by-pixel contrast) of a stack of images taken at various depths into a single image.

What we see through the eyepieces of a microscope spans a larger dynamic range of brightness than what is possible to capture by a single digital camera exposure (typically 8-bits per color channel). However, we can capture several digital images with varying brightness levels and use an algorithm to assemble these into one image with a perceived increase in dynamic range. In addition to focus stacking, we acquire a range of images with different values of exposure compensation, typically -2, -1, 0, +1, and +2 eV. We use exposure blending as employed by *enfuse* to merge the best-exposed (not too dark and not too bright) parts of these individual images together into one well-exposed image. A single field of view in a meteorite thin section can contain metal grains (very bright in reflected light) and fine-grained matrix (very dark in reflected light). A single digital image capture will saturate the pixels in either the metal or matrix, whereas an exposure-fused image will record information in both these constituents.

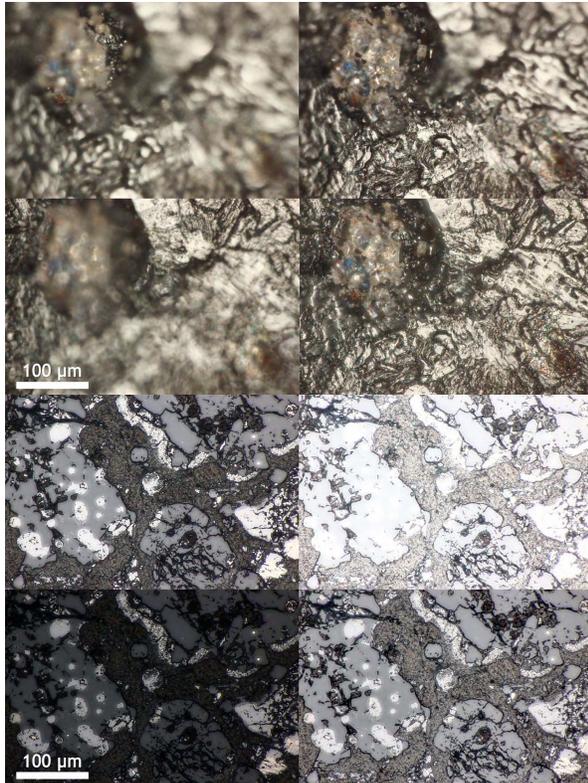


Figure 1: **Top:** Single-focus optical micrographs at varying focus depths of an unpolished piece of the achondritic diogenite meteorite, Tatahouine, are shown along with the focus-stacked image at lower-right. **Bottom:** Optical micrographs of the CO3 meteorite EET 90043 with exposure compensation values of -2 , 0 , and $+2$ eV are shown with the exposure-blended image at lower-right.

Creating and Viewing the Gigapixel Image

We record individual focus-stacked and exposure-blended image tiles in a $407\mu\text{m} \times 271\mu\text{m}$ field-of-view across a meteorite thin section with 40% overlap between neighboring tiles. The images then need to be stitched together and blended to produce one large seamless image. For stitching we use the scriptable, open-source package Hugin (<http://hugin.sourceforge.net>). The final stitched and blended mosaic image shows neither stitching seams nor brightness changes across the mosaic.

We stitch together each row of image tiles immediately after that row of tiles has been acquired. After all of the image tiles have been acquired and row images stitched, we then stitch together these individual rows to create the final mosaic. A row of ~ 60 images takes ~ 13 min to stitch (conveniently, a bit shorter than the time it usually takes to acquire a row of images, each with 10

focus steps and 5 exposures). The final gigapixel mosaic (~ 60 rows) takes ~ 3 hrs to stitch and is a ~ 1 gigapixel tiff image that is ~ 3.0 gigabytes in size.

We would like to smoothly pan and zoom the image, as well as easily share it with collaborators. We employ Microsoft hdmake and HD View to view our gigapixel images online. This free software creates and displays image tiles at different resolutions and provides javascript callback functions that we used to create a scale bar that dynamically resizes with the user-specified zoom level.

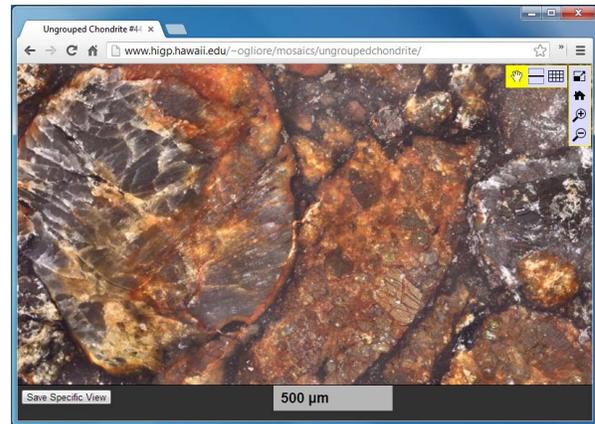


Figure 2: Web page screen capture of Microsoft HD View which is used to smoothly display the gigapixel images online. The scale bar changes as the user zooms in and out of the image (or resizes the browser window). The “Save Specific View” button displays a link that can be copied and returns the view to the location and zoom level currently displayed. Buttons in the top-right are used to move the view, change tone adjustment, and zoom in and out of the image.

Availability of Software and Examples

We have imaged several meteorite thin sections of various types using this gigapixel optical microscopy setup. These images can be viewed online: <http://www.higp.hawaii.edu/~ogliore/mosaics/>.

We provide the scripts used to acquire and assemble gigapixel images as open source software (free to use, modify, and share). The code is stored at <http://www.higp.hawaii.edu/~ogliore/mosaics/software/>. Familiarity with Linux scripting, *Matlab*, and the Hugin package is recommended to use and modify the software effectively.

References: [1] M. Weisberg, et al. (2006) *Meteorites and the early solar system II* 1:19. [2] T. Mertens, et al. (2009) *Computer Graphics Forum* 28(1):161.