X-RAY COMPUTED MICROTOMOGRAPHY AND FLUORESCENCE MICROTOMOGRAPHY: NON-INVASIVE SCREENING TOOLS FOR RETURNED ROCK AND CORE SAMPLES FROM MARS AND OTHER SOLAR SYSTEM BODIES. George J. Flynn, Dept of Physics, SUNY-Plattsburgh, 101 Broad St. Plattsburgh NY 12901 (George.flynn@plattsburgh.edu).

Introduction: NASA's Mars Exploration Program includes plans for a 2018 mission carrying a NASA rover that would collect and cache rock samples for potential delivery to Earth by a future mission. In addition, NASA's recently selected OSIRIS-Rex mission is expected to deliver to Earth rock fragments from the surface of an organic-rich asteroid "1999 RQ36" in 2023. In each case the samples are expected to be small (~ cm-size or less). A sensitive, non-invasive screeing of these rock samples to identify fluid inclusions, gas-filled inclusions, and possibly fossils is desirable to support the search for life. Fluids and gasses may contain important clues to prior conditions on Mars or RQ36 that constrain or identify the presence of life.

Unless the location of these inclusions is determined prior to cutting or breaking the rock the valuable fluids or gasses can be lost. The X-ray Computed MicroTomography (CMT) and Fluorescence MicroTomography (FMT) are sensitive, non-invasive screeing tools having high spatial resolution that are particularly well suited to the preliminary screening of these samples.

Techniques: We have performed CMT on meteorite samples [1] and FMT on interplanetary dust particles (IDPs) [2] with results that demonstrate the applicability of these techniques to the prescreening of extraterrestrial samples returned from Mars and other Solar System bodies.

Computed MicroTomography (CMT). We performed CMT analyses on the bending magnet beamline of the GeoSoilEnvironmentalCARS at the Advanced Photon Source (Argonne National Laboratory). This beamline provides x-rays ranging from 5 to ~100 keV. A Si (220) channel-cut monochrometer was used to provide a monochromatic beam, which illuminated the enture sample. X-ray transmission images were collected by viewing a YAG scintillation screen, located downstream from the sample, with a Princeton Instruments Pentamax CCD camera. We collected 360 transmission images in 0.5 degree steps covering 180 degrees of rotation.

Meteorite cores and small whole stones ranging from ~1/3 to 1 cm in diameter were analyzed. A 40 keV monochromatic x-ray beam, an energy sufficient to penetrate a 1 cm stone, was used. Each voxel in the reconstructed image was ~30 micrometers in each linear dimension. Sufficient contrast was obtained to identify cracks, high-Z inclusions, and vugs in an ~½ cm stone in ~45 minutes per sample. Improvements to the imaging system should provide at least 4 times better spatial resolution by the time of Mars of RQ36 sample delivery.

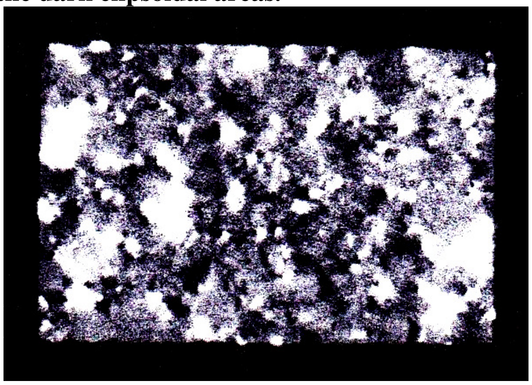
Fluorescence MicroTomography (FMT). We performed FMT analyses on the undulator beamline of the GeoSoilEnvironmentalCARS at the Advanced Photon Source (Argonne National Laboratory). The x-rays were focused to an ~3 micrometer spot using Kirkpatrick-Baez mirrors. The fluorescence tomography data were obtained by translating the particle, which was mounted on the end of a silica fiber with clean silicone oil, through the x-ray beam in 2 micrometer steps. At each position the fluorescence spectrum was collected with a solid state energy dispersive x-ray detector, which allows multiple elements to be detected simultaneously. The sample was then rotated by 0.5 degrees about the vertical axis and the line scan was repeated. The process was continued until the particle had been rotaed through 180 degrees, sampling a 2D plane through the particle. By successively translating the particle vertically by 2 micrometers and repeating the procedure at each height a full 3D fluorescence map of the particle was obtained.

One complication in this element-specific imaging technique is the escape depth of the fluorescent x-rays. In chondritic material the 1/e escape depths for the K-line fluorescence x-rays are ~0.2 micrometers for C, ~6 micrometers for Si, ~10 micrometers for S, ~30 micrometers for Ca, and ~100 micrometers for Fe. Thus, for the light elements the data reduction requires an iterative procedure in which successive element distributions and their appropriate absorption corrections are determined. In larger particles mapping the distriburttion of heavy trace elements that exhibit the same chemical behavior as certain light elements allows inference of the distribution of elements whose fluorescence x-ray are severely absorbed (e.g., Sr serves as a proxy for Ca and Se serves as a proxy for S).

Results: The results from our analyses of meteorites and interplanetary dust particles demonstrate the utility of CMT and FMT as non-invasive screening tools to search for evidence of life on Mars.

Identification of Gas-Filled or Fluid Inclusions: Minute amounts of Martian atmosphere trapped in inclusions in glass from the Martian meteorite ETTA 79001 provided evidence that the SNC meteorites were from Mars, and demonstrated that samples of Mars'

Figure 1: CMT virtual slice through an ~1x1x2 cm block of the Mt. Tazerzite meteorite showing vugs as the dark elipsoidal areas.



atmosphere are preserved in the rocks. More recently, the discovery of fluid inclusions in salt crystals in the Monahans and ZAG meteorites provided the opportunity to analyze liquid water from asteroids. The analysis of these fluids and atmospheric gas samples can have important implications for past life. For example, the presence of large amounts of oxygen in a planet's atmosphere has been proposed as a strong indicator of life [3].

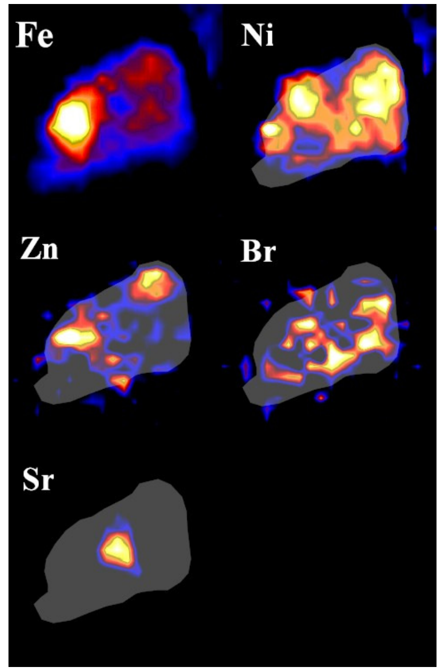
However, the analyses of trapped fluids or gases requires the identification of the subunit of the sample containing the fluid or gas before breaking the wall of the inclusion. While fluid- or gas-filled inclusions can sometimes be identified in thin section, if they are rare a large amount of sample can be consumed in this preparation.

CMT provides a quick, efficient tool to search for fluid or gas inclusions in centimeter-size samples. CMT images we obtained on the Mt. Tazerzite meteorite identified vugs as small as 2 voxels in size [1], as shown in Figure 1.

Identification of Fossils: If the density or average atomic weight of a fossil differs significantly from the host rock, CMT is an efficient tool for identifying and imaging fossils in rock samples. For example, propagation phase contrast X-ray synchrotron imaging was used to identify invisible fossil inclusions in fully opaque amber [4].

Element mapping: FMT provides a 3-D image of the distribution of elements in the sample, as shown in Figure 2 for an ~30 micometer interplanetary dust particle. If any fluid inclusions are identified by CMT, FMT can produce a preliminary elemental characterization of the heavier elements in the fluid, providing clues to its origin. FMT on fossils could provide better contrast between the fossil and the host rock as well as information on the composition and structure of the fossil.

Figure 2: Fluorescence microtomogtaphy (FMT) images of the distributions of Fe, Ni, Zn, Br, and Sr (a proxy for S) in a virtual slice through the ~30 micrometer interplanetary dust particle L2036H19. The gray aera is the outline of the particle.



Conclusions: CMT is a useful, non-invasive screening tool for cm-size samples, including samples collected by an initial Mars Sample Return mission and samples of the organic-rich asteroid 1999 RQ36. CMT is an efficicient, non-destructive technique to identify vugs, potentially containing fluids or gases from an earlier era on the parent body, as well as fossils in these samples. FMT, although limited by fluorescence absorption to smaller samples, ~200 micrometers, can provide elemental analyses of the fluids and fossils identified by CMT.

References: [1] Flynn, G. J., Rivers, M., and Sutton, S. R. (2000) X-Ray Computed Microtomography (CMT): A Non-Invasive Screening Tool for Charac terization of Returned Rock Cores from Mars and Other Solar System Bodies, *Lunar & Planetary Sci. XXXI*, Abstract #1893. [2] Sutton, S. R., Flynn, G. J., Rivers, M., Newville, M., and Eng, P. (2000) X-Ray Fluorescence Microtomography of Individual Interplanetary Dust Particles, *Lunar & Planetary Sci. XXXI*, Abstract #1857. [3] Kump, L. R. (2008), The Rise of Atmospheric Oxygen, *Nature,* 451, 277-278. [4] Lak M, Néraudeau D, Nel A, Cloetens P, Perrichot V, Tafforeau P. (2008) Phase contrast X-ray synchrotron imaging: opening access to fossil inclusions in opaque amber, *Microscopy* and *Microanalysis*, 14(3), 251-9.