LABORATORY CT: A REVOLUTION IN PLANETARY SAMPLE PETROLOGY.

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Introduction: High-resolution, non-synchrotron computed tomography or "laboratory CT" has rapidly become a standard method of sample characterization since being described as "a breakthrough technology for earth scientists" [1]. Most such systems are "cone beam" with helical instruments as a variant. In the USA, lab CT was pioneered in 1999 at U. Texas, Austin as an NSF-supported national shared multi-user facility [2, note web resources]. Tomography has become a topic with its own workshops (e.g., [3], with 8 instrument and 2 software vendors]. Tomography for Scientific Advancement (ToScA) is in its 7th year and will soon become a stand-alone society [4].

It is a good rule never to apply a single technique like CT to *all* of a sample. [8] reviews best practices for CT on natural history specimens, with lists of hardware and software vendors. Recent investigations have established that while x-ray CT induces thermoluminescence [5], it does not have measurable effects on amino acid chemistry [6,7].

While some vendors have a historical focus on research (e.g., XRE, spun off U. Ghent 2017, purchased by TESCAN 2018; SkyScan founded 1996 in Belgium, acquired by Bruker 2012), others (e.g., NSI) began focused on industrial metrology. The penetrating power (kV), resolution (nm, µm, mm per voxel edge) and specimen size accommodation within the shielded instrument volume are all critical in deciding on the best instrument for specific applications. Scan resolution depends on sample size; however, the unique optics of the ZEISS Xradia allow higher resolution scanning of subvolumes (UTCT has had one since 2008). The Johnson Space Center (Houston, USA) Curation Facility recently purchased a Nikon XT H 320 micro focus instrument with interchangeable 180, 225 and 320 tubes to characterize meteorites, clasts in lunar breccias, etc. Their policy is never to scan > 70% of any lunar rocks without very careful review, and to only scan smaller fractions of other samples (e.g., chondrites).

CT at AMNH: The AMNH purchased a GE/Phoenix VtomX S dual tube scanner in 2010 with NSF support. The instrument has interchangeable 35-180 kV and 40-250 kV tubes capable of imaging a wide range of materials. In a typical year with 260 days of operation, 5% were used by Earth and Planetary Science, 63% by Paleontology, 30% by zoology and 2% by Anthropology. Curators travel or send specimens to other locations for specialized imaging. Advantages of an "in house" CT facility include 1) proximity - travel is unnecessary, 2) no need to apply for synchrotron time, 3) lower risk to rare, sensitive samples. Disadvantages include competition for instrument time.

The technique: Interpretable data shows x-ray attenuation per volume element (voxel) [9]. Useful quantitative information from CT scans depends on segmentation. While determining porosity [10], object (chondrule) sizes [11], metal grain [12,13] and chondrule [14-17] orientations, and rim thicknesses [18] currently requires significant manual labor, CT represents a fundamental shift from the previous 150 years of understanding based on 2D slices of rocks as thin sections. We can now cut surfaces for 2D chemical analysis with precise 3D prior knowledge [19].

Challenges: Among the most pressing challenges are improving the ability to integrate (match) 3D data with electron beam, ion beam and other data on 2D surfaces. Composition based only on x-ray attenuation places inherent limits requiring 2D information. Visualization challenges depend on 3D segmentation quality, where automated neural networks (machine learning) are now being applied (e.g., by Marsh of ORS in [3]). Data size is also a growing barrier, particularly for the most cutting-edge applications (e.g., De Carlo in [3], 20 TB in 9 hours).

Outlook: Many laboratory CT vendor choices exist, each with a range of instruments. Improvements in workflow and machine learning will improve data extraction. Software packages [8, app. 8.3] allow for very hands-on data segmentation. The future of both synchrotron and laboratory CT looks bright [20]!

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