VERSATILE *IN SITU* X-RAY MICRO COMPUTED TOMOGRAPHY INSTRUMENT FOR PLANETARY EXPLORATION.

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Introduction: An innovative X-ray Micro Computed Tomography (XCT) instrument developed for planetary exploration is useful for multiple mission concepts and poised to provide a ground-breaking technology demonstration of micromorphological analysis in-situ on another planetary surface.

XCT, sometimes called microCT, is a non-destructive technique for analyzing fine-scale internal features of a multiphase sample with spatial resolution down to several microns. An X-ray source and detector are positioned on opposite sides of a sample, and a series of high-resolution radiographic images of a sample are collected at small angular steps around the vertical axis. In the X-ray attenuation images, contrast is based on X-ray absorption of each phase and is a function of atomic number and density.

These collected images are used to reconstruct a 3D volume of the sample in which phases and voids can be distinguished by their grayscale (voids are black; the higher the atomic number of a phase or particle, the lighter it is). Quantitative data, including particle and void sizes, 3D particle shape parameters (e.g., aspect ratio, sphericity), and modal volumes and pore geometry can be derived from the resulting 3D reconstructions [1;2] and, with complementary techniques such as X-ray diffraction and X-ray fluorescence, for phase identification.

Planetary XCT instrument design: The XCT design for planetary use is based on cone-beam X-ray geometry and a simple architecture combining a microfocused X-ray tube, a sample scanning stage, and an X-ray image sensor (Fig. 1).

XCT prototypes were built utilizing commercial microfocus X-ray tubes (6 - 60 µm spot sizes), stepper-motor based sample rotation stages, and X-ray cameras based on CMOS sensors coupled with a CsI scintillator with a fiber optic plate. Attenuation images are collected at steps of 0.225, 0.45, or 0.9° over a full revolution with acquisition times of 1-10 seconds for each position.

High-quality reconstructed XCT images require stable and well-known system geometry. The instruments are designed with limited fine alignment capabilities. ConeTom software was developed for 3D reconstruction of planetary XCT data and works on a complex misaligned system [3]. It includes a method for retrieving the geometric parameters of the cone-beam tomography system by analyzing the trajectory of a marker-spheres at two heights [3; 4].

Preprocessing steps include flat-field correction, beam hardening correction, zinger removal, and ring artifact removal [3]. The cone-beam reconstruction method is based on filtered back-projection and back-projection filtering that incorporate the geometric parameters of a cone-beam system (e.g., pitch, roll, and position of the rotation axis; X-ray source positions; source-detector distance).

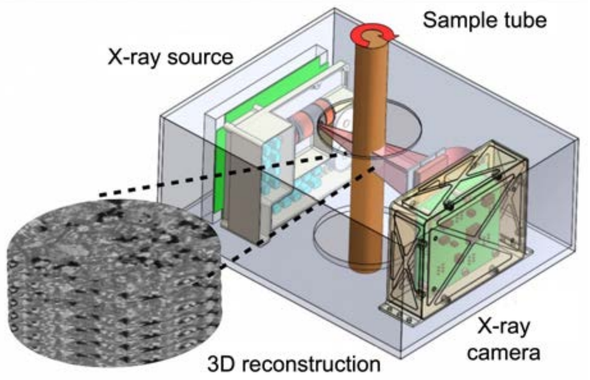

Fig. 1: Schematic geometry of a planetary XCT instrument. An X-ray source, sample rotation stage and X-ray detector with reconstructed 3D data volume.

Reconstruction generates 2D gray-scale slices (TIF images) stacked in the axial direction to produce the 3D volume. Figure 2 shows an example of one slice each of two Gruithuisen Dome analog materials (Novarupta, Alaska rhyolite pumice and Quizapu, Chile dacite lava) obtained using a prototype spaceflight XCT instrument and compared to those obtained from a laboratory microCT instrument.

Planetary applications: The limited size, weight, and power of the planetary XCT instrument concept enables a variety of in-situ planetary deployments.

Lunar Gruithuisen Domes. The recent PRISM-II Lunar CLPS opportunity has as one of its objectives the in-situ investigation of the Gruithuisen Domes, features thought to be remnants of late-stage silicic volcanism. The proposed science payload of Mineralogical, Elemental and Tomographic Reconnaissance Investigation for CLPS ("METRIC") [7] includes an XCT instrument, alongside an X-ray Diffraction/X-ray Fluorescence (XRD/XRF) instrument, four cameras to provide geologic context, and a regolith collection and delivery system [8].

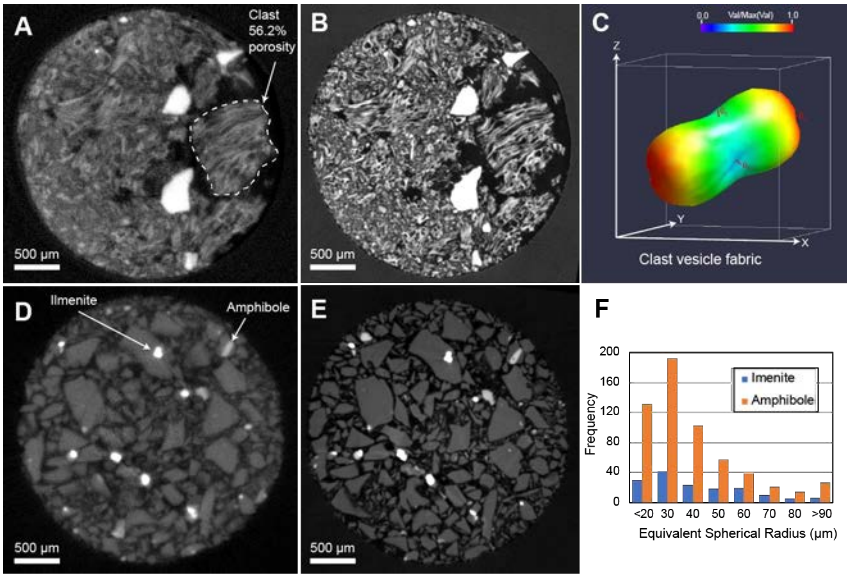

Fig. 2: Single slice of 3D XCT data of terrestrial rhyolite pumice (A, B) and dacite lava (D,E). Slice from METRIC XCT prototype on left (A, D), and from Zeiss Versa 620 of the same sample with similar acquisition conditions on right. The METRIC XCT system is capable of distinguishing minerals, textures, and porosity. Clast outlined in A was digitally isolated in 3D using Dragonfly, its porosity quantified (56.2%), and the fabric of vesicles measured (C) with Quant3D [5] showing an elongated, prolate texture. Phases in (D) were identified using the METRIC XRD system [6] on the same sample (dark gray phase is a mixture of amorphous material and plagioclase). (F) shows the particle size distribution of ilmenite and amphibole from the full METRIC XCT dataset, derived using Blob3D [5].

The XCT instrument will determine the 3D internal micromorphology of a lunar soil sample pneumatically delivered into a 3 mm internal diameter graphite tube installed on a rotation stage. METRIC XCT is based on existing high TRL components developed initially for XRD (CCD camera, 25 kV X-ray source) reducing the cost and schedule risk normally associated with development of a new instrument. METRIC XCT will resolve mineral grains, rocks, and pore and vesicle sizes and geometry down to 30 µm (Fig. 2).

Mars North Polar Layered Deposits (NPLD). Micro In Situ Tomography (MIST) is a coupled ice-coring and microCT-analysis system being developed to characterize the porosity and distribution of dust in the Mars NPLD from a lander or rover [9]. The NPLD are a multi-kilometer thick sequence of dust-ice layers thought to record previous climate conditions much like Earth's ice sheets. Deciphering this polar record has been, and remains today, a major goal of Mars research [10]. In this XCT implementation, a coring drill captures a sample core 2.5 cm in diameter and 0.5 – 1 m in length in an X-ray transparent carbon fiber tube. The tube is lifted through the XCT system, which rotates around the core. A 1 m core of the Mars NPLD sampled by MIST would provide information about approximately 1000 Martian years of climate history. MicroCT has also been recommended as the first technique to be applied to returned Mars samples [11].

Rock-core XCT analysis on Mars, Venus, the Moon. PIXI (Planetary In-situ X-ray Imager), a development targeting applications to rock samples collected with a coring drill, will enable 3D-reconstructions of rock cores, to evaluate grain size distribution, mineral spatial distribution, porosity, fragmentation etc. An additional challenge with rock cores is the increased absorption of a solid sample 8-12 mm in diameter and its coring tube. Because higher energy X-rays are required, this work includes the development of a space-deployable 50 kV microfocused source. The study of rock microstructures will elucidate rock formation processes and reveal potential biogenic origins. [12]

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