X-ray Computed Tomography of Tranquility Base Moon Rock

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Technique Background:
• X-ray Computed Tomography (CT) is very similar to Medical “CAT” scans
• An x-ray source creates a “cone beam” which enables geometric magnification
• A series of 2D radiographs are taken at precise angle steps as the part rotates
• Feldkamp filtered back-projection algorithm is applied to image “projections” to create 3D reconstructed “volume”

Main Components:
• 7-axis motion/manipulator system, up to 100lb capacity on rotation stage
• Detector: Dexela 7529 CMOS with CsI scintillator
  – 75 µm pitch, 3888 x 3072 pixel array
• X-ray Source: Yxlon FXE-225.99 Dual Head Microfocus: 225kV
• Installed in radiation shielded room
• North Star Imaging and VG Studio Max software
• Reconstruction PC with 4 Tesla GPU computing

GSFC X-Ray CT System
(Code 541 NDE Laboratory)
GSFC CT Examples - Composites

Impact Damage in Structural Composite

Experimental “Topological Core” Composite Structure
GSFC CT Examples – Metallic Parts

- Europa: Additively Manufactured “Venturi” with stress relief crack
- JWST: ISIM Structure 3D Welded Joint
- ISS: Cracked magnet in EMU FPS Rotor Assembly
GSFC CT Examples – Circuit Boards/Components

Full Circuit Board

Circuit Board Interior
Wiring Plane

HV801 Diode Terminals
GSFC CT Examples – Reverse Engineering / 3D Reproduction

JWST: CT Scan of Transition Link Assembly (fuse wire, ~1cm)

3D Model “Surfacing” to export as STL file for CAD/FEA/3D printer

3D printed replica of actual TLA (lower) at 10x scale
Apollo 11 Mission Background

The following text was sourced, with minor edits, from the NASA site:

- ‘The Lunar Module landed at 20:17:40 UT (4:17:40 p.m. EDT) on 20 July 1969 in the region known as Mare Tranquilitatis (the Sea of Tranquility) at 0.6741 degrees N latitude, 23.4730 degrees E longitude’
- ‘Armstrong reporting, "Houston, Tranquility Base here - the Eagle has landed".’
- ‘Neil Armstrong stepped onto the lunar surface at 02:56:15 UT on 21 July (10:56:15 p.m. July 20 EDT), stating "That's one small step for man, one giant leap for mankind".’
- ‘The astronauts deployed the EASEP and other instruments, took photographs, and collected 21.55 kg [47lbs] of lunar rock and soil.’
- ‘The astronauts traversed a total distance of about 250 meters, both ranging up to about 100 meters from the LM.’
Lunar Sample 10057

- The Apollo 11 Moon Rocks discussed here are basalts, similar to those on Earth but high TiO_2 and low SiO_2.
- This sample (10057) is described as high K, VHT (very high titanium), fine grained, and has about 10% vesicle content (pores)
- This sample is 3.63 billion years old
- In 1976, Sample 10057 was sectioned into multiple smaller samples

http://www.lpi.usra.edu/lunar/samples/atlas/compendium/10057.pdf
Lunar Sample 10057-[XX]

Figure 6: Space Window at US National Cathedral in Washington DC with piece of 10057 located in center of rose window.

http://www.lpi.usra.edu/lunar/samples/atlas/compendium/10057.pdf
Lunar Sample 10057-30

Lunar Sample 10057-30

Lunar Sample 10057-30, CT Results
Lunar Sample 10057-30, CT Results
Lunar Sample 10057-30, CT Results

Vesicles; trapped gas bubbles

len=2.025 in

len=10 mm
Could it really be made of “Green Cheese”??
Lunar Sample 10057-30, CT Results
Lunar Sample 10057-30, CT Results

Video, go to: 160406_Garvin_MOONROCK_10057-30_Slices.avi
Lunar Sample 10057-30, CT Results

2D Radiograph Image (i.e. raw data)

Linear “Needle-like” features observed both in 2D and 3D data

Ion = 0.1 in 2.3 mm
Lunar Sample 10057-30, CT Results

Very large tabular bundles, or lamellae, observed.
Lunar Sample 10057-30, CT Results

2.8 mm width

len=9 mm
Lunar Sample 10057-30, CT Results
Lunar Sample 10057-30, CT Results

Video, go to: 160413_Garvin_MOONROCK_10057-30_ZoomInPlate_S-Ilmenite.avi
Lunar Sample 10057-30, CT Results

Video, go to: 160413 Garvin MOONROCK 10057-30 ZoomInPlate Ilmenite.avi
Lunar Sample 10057-30, CT Results

Ilmenite needles and tabular bundles in lunar basalt sample 10057,30

9 mm

3.8 mm

2.8 mm

XCT scan by Jones et al.
Lunar Sample 10057-30, CT Results
Longer, “archival” scan revealed more detail

Video, go to: 160506_Garvin_MOONROCK_10057-30_LongScan_IImnenite.avi
Lunar Sample 10057-30, CT Results

Longer, “archival” scan revealed more detail

Video, go to: 160506_Garvin_MOONROCK_10057-30_LongScan_Ortho.avi
Lunar Sample 10057-30, Possible Mineral Content: Ilmenite

Ilmenite

Ilmenite from Miass, Ilmen Mts, Chelyabinsk Oblast, Southern Ural, Urals Region, Russia. 4.5 x 4.3 x 1.5 cm

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<thead>
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<td><strong>Crystal system</strong></td>
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**Identification**
- **Color**: Iron-black; gray with a brownish tint in reflected light
- **Crystal habit**: Granular to massive and lamellar exsolutions in hematite or magnetite

https://en.wikipedia.org/wiki/Ilmenite
Lunar Sample 10057, Prior Petrology

Vesicles very similar to those observed with CT

Needles similar, but orders of magnitude smaller than those observed with CT

Mission: Apollo 11
Sample: 10057
Split: 0
Photo Number: S69-59408
Film Type: Black & White
Description: Black and white Thin Section photograph of Apollo 11 Sample(s) 10057.
Source: NASA/JSC

Mission: Apollo 11
Sample: 10057
Split: 35
Photo Number: JSC04223
Lithology: basalt
Image Type: reflected light microscope image
Thin Section Type: standard thin section
Field of View: 0.70 mm
Magnification: 10x
Source: JSC

http://www.lpi.usra.edu/lunar/samples/atlas/detail/?mission=Apollo%2011&sample=10057
Conclusions

- We are reporting the first micro-CT scan results from the Apollo Lunar Sample #10057.30
- This non-destructive evaluation of one of the most primitive types of rocks in the solar system has discovered a 3D distribution of needle-like and tabular crystals; likely Fe-Ti oxides (possibly ilmenite).
  - These crystals are much larger than previously observed, which carries geological implications for how 3.63 billion year old erupted lunar lavas may have formed and even “flowed”.
  - An “archival scan” using higher frame averaging and more projections revealed an even higher number of very large grained ilmenite.
- Ongoing efforts to quantify size, distribution, and map orientations of these features, which will help us better understand the Moon’s evolution.
- Ongoing efforts to acquire new, smaller Lunar Samples in order to achieve higher resolution scans (down to ~5 µm). This could resolve the interconnectivity of the oxides in the matrix of silicate minerals.
- Possible next steps:
  - IRAD Feasibility study for on-board x-ray CT for future spacecraft (ISS or Mars rovers)
  - xCT study for other interesting samples: Martian meteorites, Shocked vs Unshocked Sandstone from Meteor Impact Site at Coconino, Deep Crustal (upper mantel) rock from Iceland volcano, Asteroid return samples
  - Working with Mars Science team to research 3D topo imagers to replace MaHLI for Mars2020 mission.
Thanks for your time!