X-ray Computed Tomography of Tranquility Base Moon Rock

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

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
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
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 TiO₂ and low SiO₂.
- 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.
Lunar Sample 10057-30

Lunar Sample 10057-30

GSFC X-Ray CT Setup
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
Lunar Sample 10057-30, CT Results

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

Length = 0.1 in

2.8 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

3.8 mm

2.8 mm

9 mm

18 um resolution
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_Ilmenite.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 Urals, Urals Region, Russia. 4.5 x 4.3 x 1.5 cm

**General**

**Category**
Oxide mineral

**Formula**
iron titanium oxide,
FeTiO$_3$

**Strunz classification**
4.CB.05

**Dana classification**
04.03.05.01

**Crystal system**
Trigonal - rhombohedral

**Unit cell**
a = 5.08854(7) Å, c = 14.0924(3) Å; Z=6

**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

<table>
<thead>
<tr>
<th>Mission</th>
<th>Apollo 11</th>
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<tbody>
<tr>
<td>Sample</td>
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<td>Description</td>
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<td>Source</td>
<td>NASA/JSC</td>
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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!