X-ray Computed Tomography of Tranquility Base Moon Rock

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**GSFC X-Ray CT System**
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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
Impact Damage in Structural Composite

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

JWST: ISIM Structure 3D Welded Joint

ISS: Cracked magnet in EMU FPS Rotor Assembly

Europa: Additively Manufactured “Venturi” with stress relief crack
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.’
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]

http://www.lpi.usra.edu/lunar/samples/atlas/compendium/10057.pdf

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
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

Ion = 0.1 in

2.5 mm
Lunar Sample 10057-30, CT Results

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

2.8 mm wide

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

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_Ilmnenite.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

**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
Vesicles very similar to those observed with CT.

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

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!