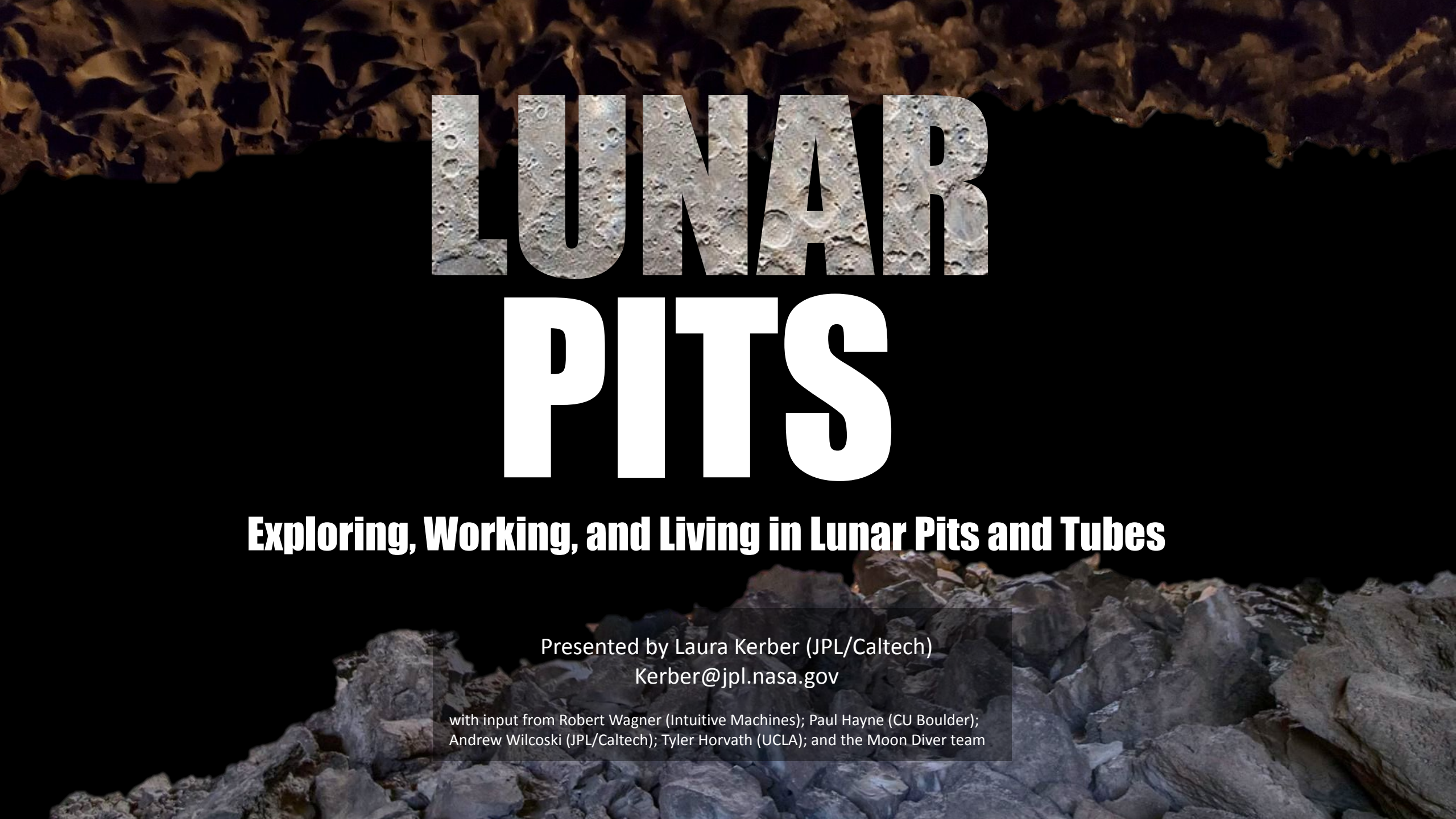






LUNAR PITS

Exploring, Working, and Living in Lunar Pits and Tubes

Presented by Laura Kerber (JPL/Caltech)
Kerber@jpl.nasa.gov

with input from Robert Wagner (Intuitive Machines); Paul Hayne (CU Boulder);
Andrew Wilcoski (JPL/Caltech); Tyler Horvath (UCLA); and the Moon Diver team

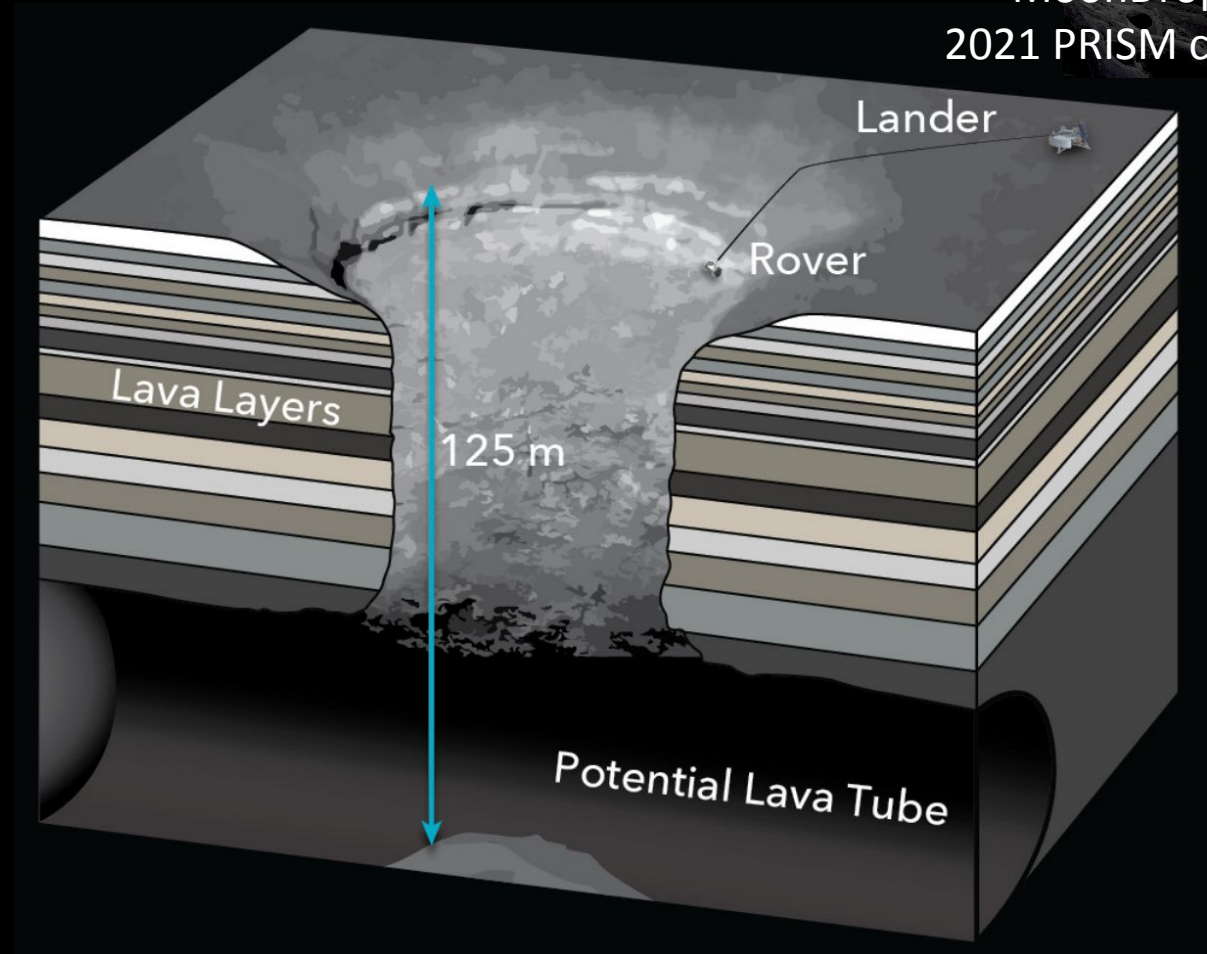


A little about myself...

Research Scientist; Volcanologist; PI of
Moon Diver and MoonDrop concepts



MoonDrop was a
2021 PRISM concept



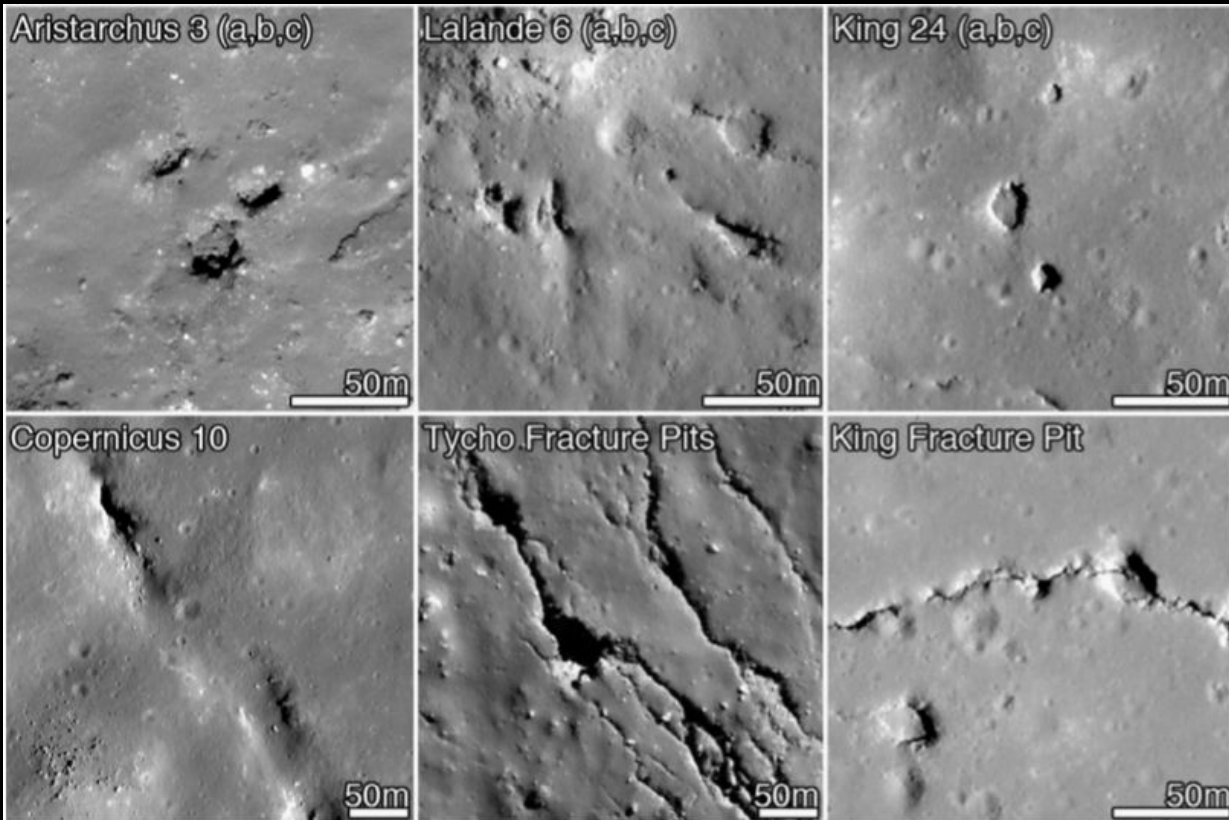
Moon Diver was a 2019 Discovery Concept to
explore a pit in Mare Tranquillitatis

Plan for the Talk

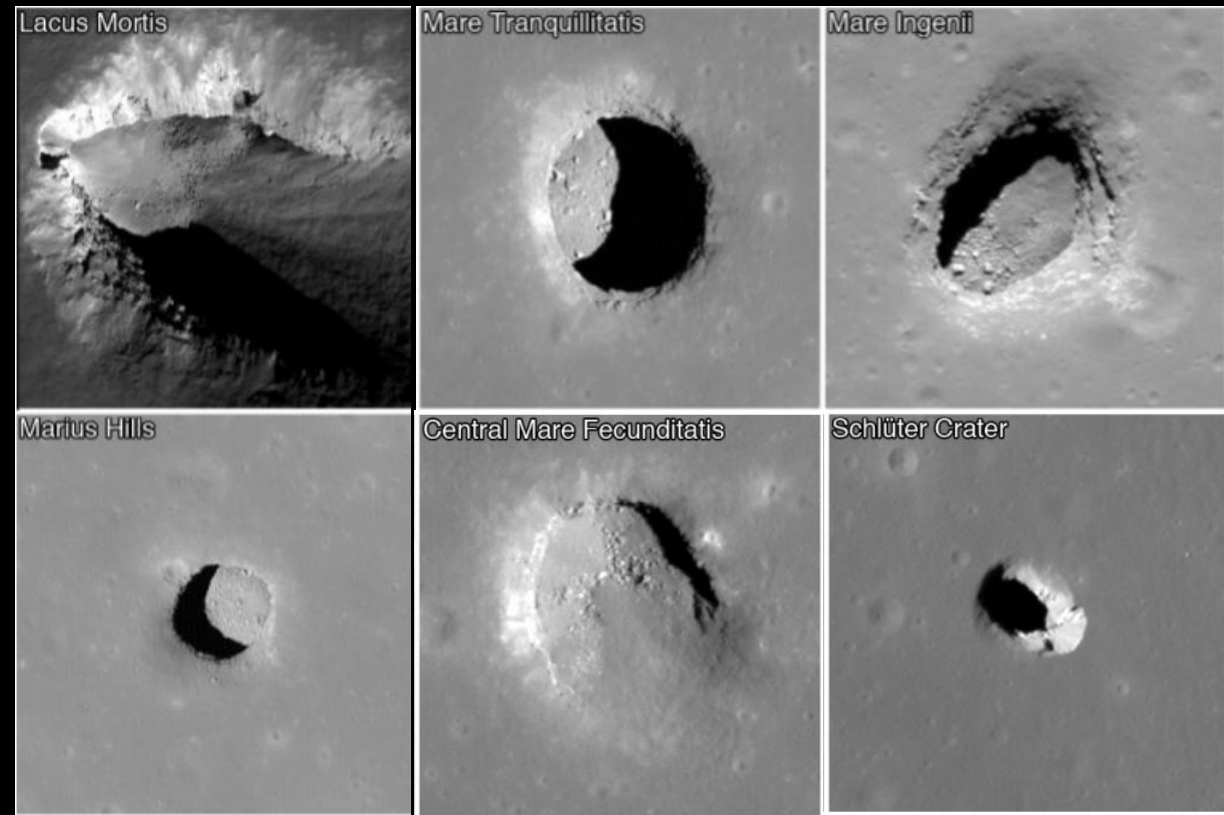
- Pit Basics: Types and Distribution
- Caves, Pits, and Lunar Hazards: Radiation, Thermal Swings, Micrometeorites, Dust, Vacuum
- Pros and Cons of Specific Sites
- What Can Humans Do Best? (and how can robots help?)
- Access and Stability
- References

Pit Basics: Impact Melt Pits vs Deep Pits

Impact Melt Pits (257)



Mare (15) and Highland (6) Pits

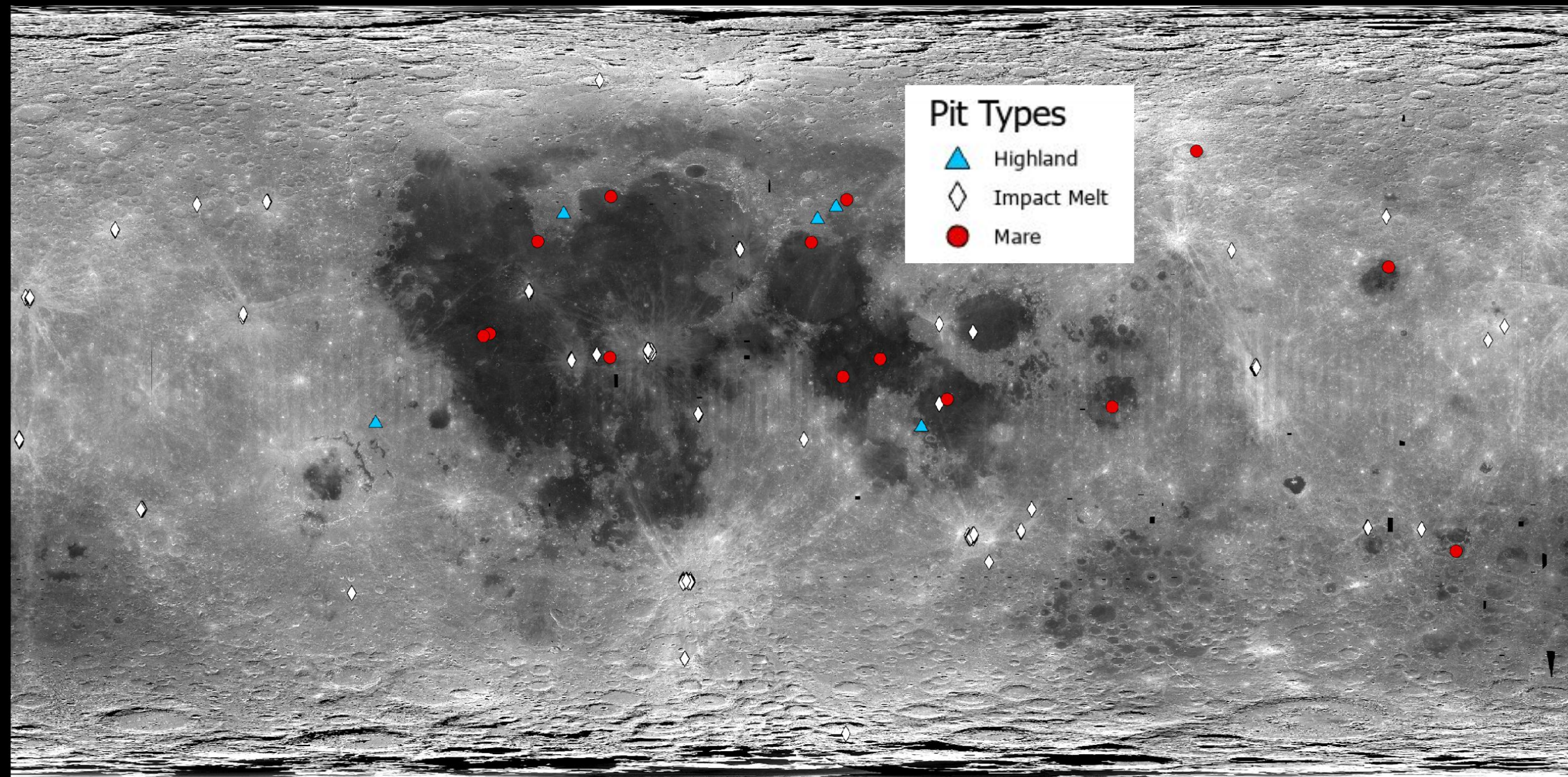


Wagner and Robinson, 2014

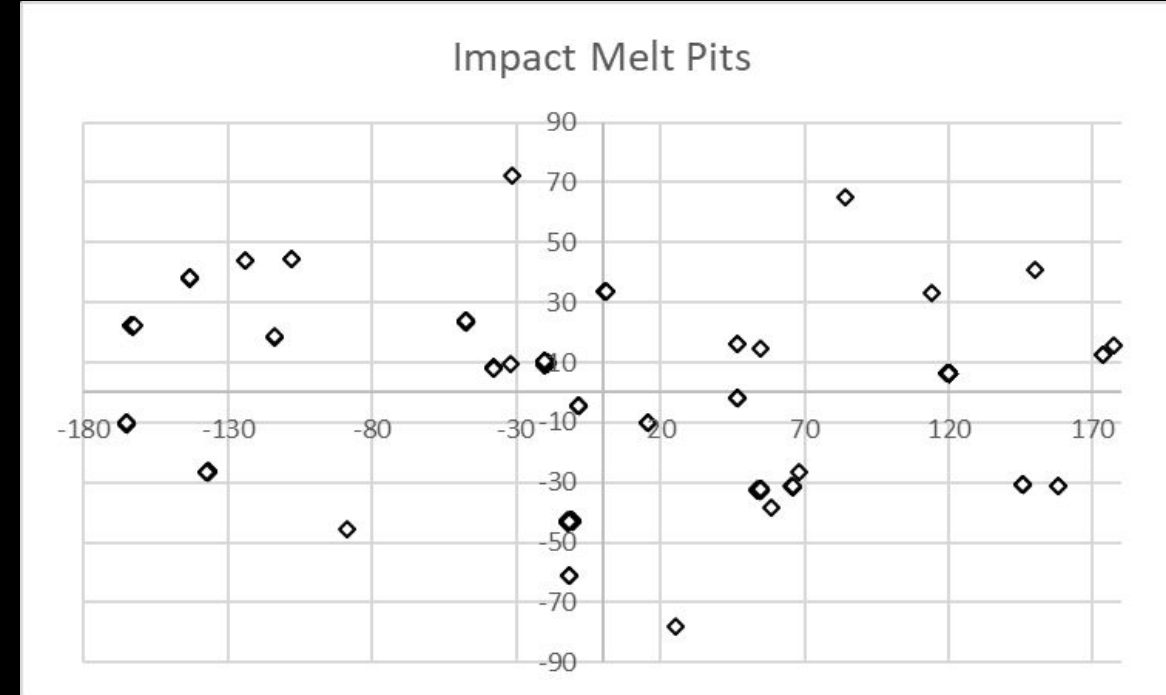
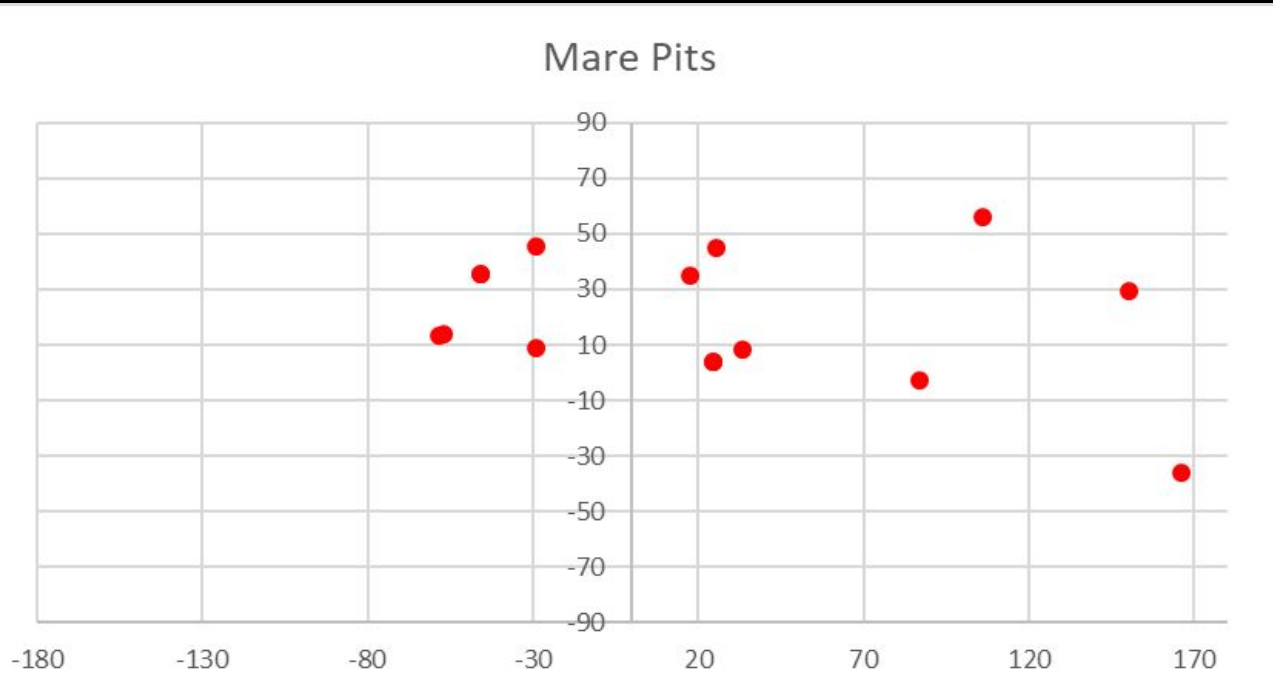
Important Points:

Impact Melt pits are numerous but small (median diameter: 15 m). Mare pits are few but large. 256 total pits measured [by Wagner et al., 2017], 178-194 are at least large enough to host a 3-person habitat. 30-40% of measured pits have some kind of “ramp”. Only a handful of pits are likely to have caves (mostly mare pits). Impact melt pits are much less scientifically interesting than mare pits. Consult the LRO Pit Atlas for more details!! <https://lroc.im-ldi.com/atlas/pits>

Pit Distribution

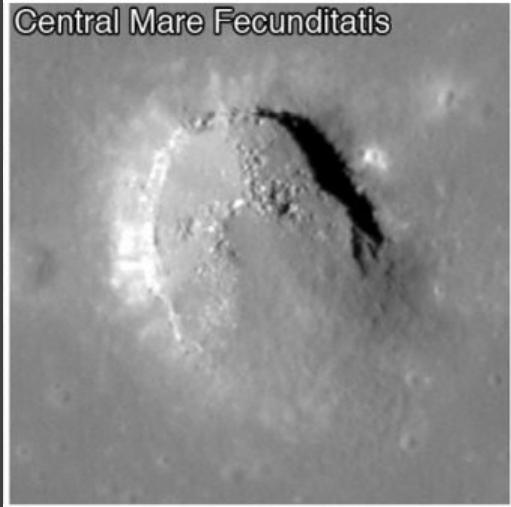


Pit Distribution



The Big 5

Central Mare Fecunditatis



Lacus Mortis



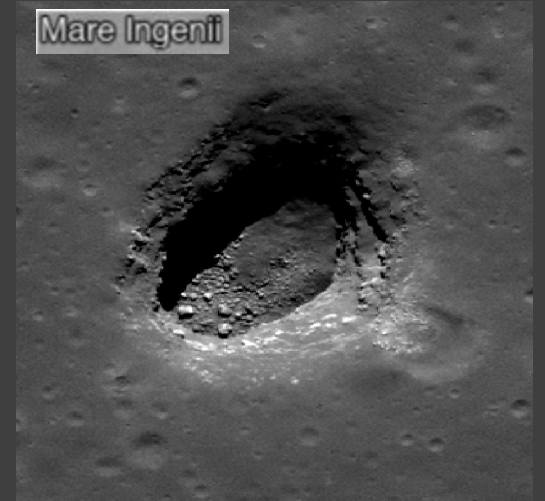
Mare Tranquillitatis



Marius Hills



Mare Ingenii



Presence of a Ramp
Presence of a Cave

Science

Regolith Examining the regolith/bedrock interface
(in-situ)

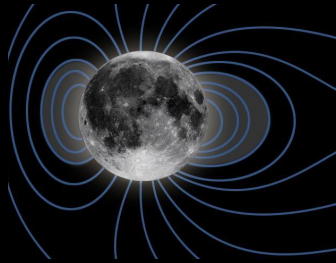
Physical Volcanism Determining how magmas are transported to the surface on the Moon (in-situ and sample return for absolute chronology)

Petrology Determining the structure of the Moon's interior (in-situ or sample return)

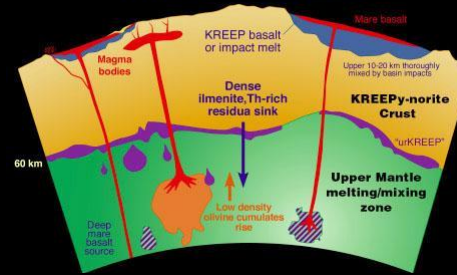
History of the Magnetic Field
(in-situ or sample return)

Solar History (shallow paleoregolith sample return)

Galactic History (deeper paleoregolith sample return)



Thick or thin?



LUNAR HAZARDS

RADIATION

**MICRO-
METEORITES**

**THERMAL
SWINGS**

DUST

VACUUM

RADIATION

MICRO-METEORITES

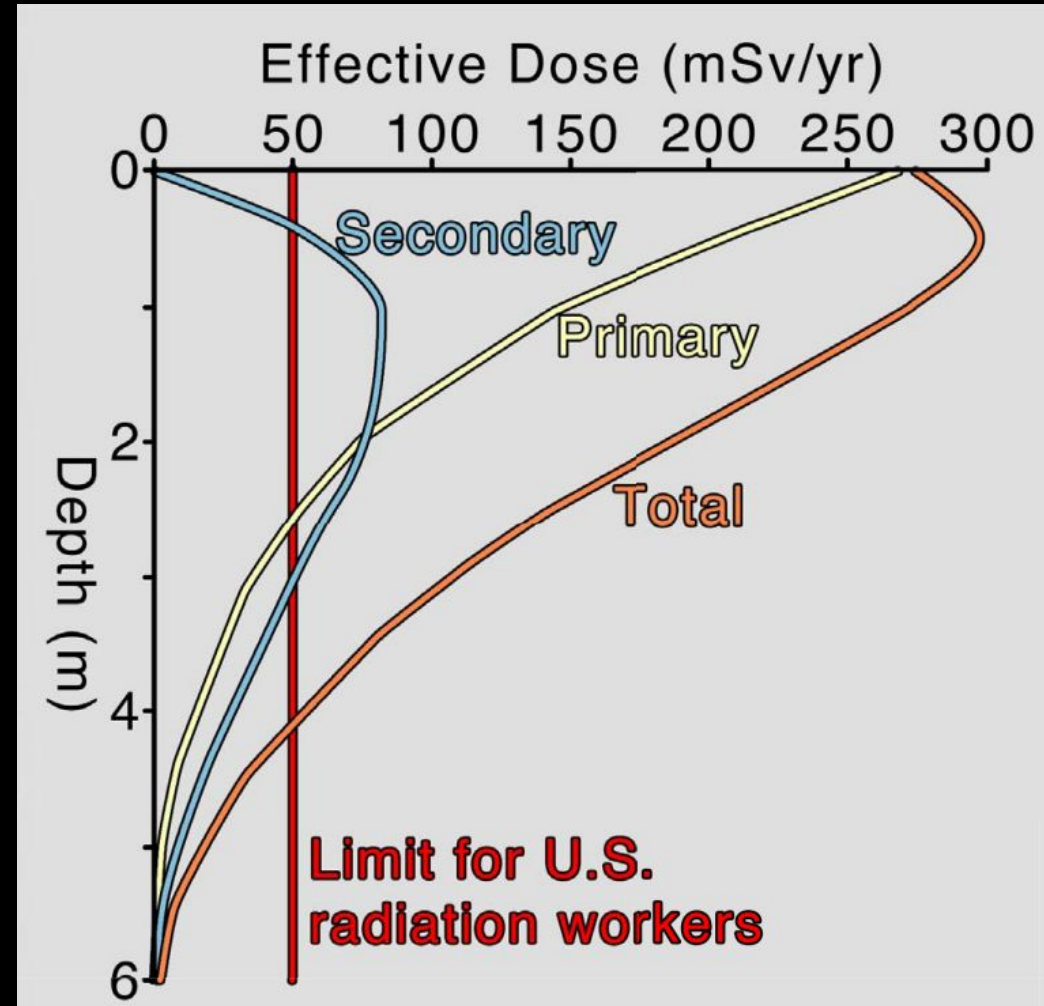
THERMAL SWINGS

DUST

VACUUM

- Radiation is a major limiting factor for long-term stays on the Moon. The annual radiation dose on the Moon is ~11% of NASA's career dose limit for an astronaut (and ~25% of ESA's), before accounting for solar flares [1,2,3].
- There are two major sources of radiation on the Moon: Solar radiation and cosmic ray nuclei.

Wagner et al., 2017



Modified by Wagner et al. from De Angelis, G. et al. (2007)

RADIATION

**MICRO-
METEORITES**

**THERMAL
SWINGS**

DUST

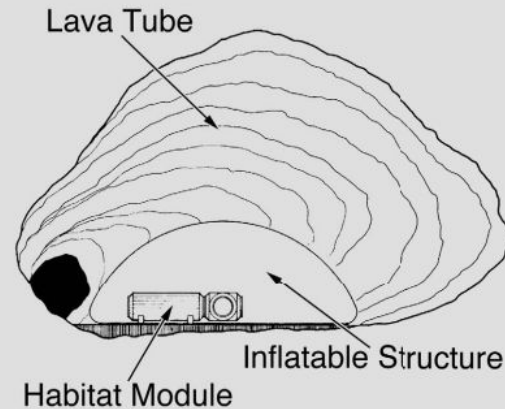
VACUUM



ESA/Foster + Partners

Regolith Shielding

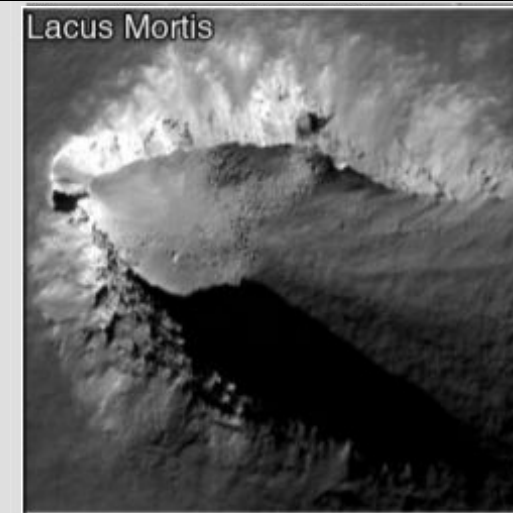
- Can build anywhere
- Full protection requires moving 4+ m of regolith into place
- Complex engineering and materials simulation needed
- Difficult to expand



Adapted from Daga and Daga (1992)

Caves

- Limited to places with caves
- Extremely good protection
- Easy to use inflatable habitats
- Can't conclusively identify cave entrances from orbit



Pits

- More common than cave access
- Moderate protection
- Likely easier access than caves
- Often limited interior space
- Limited line-of-sight to Earth for communication

RADIATION

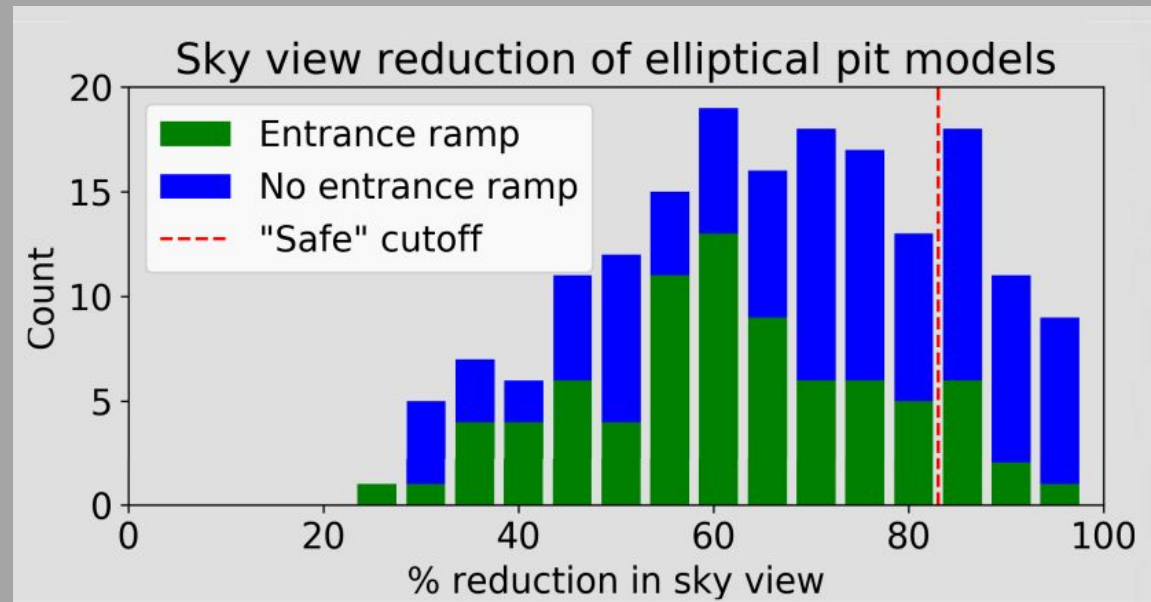
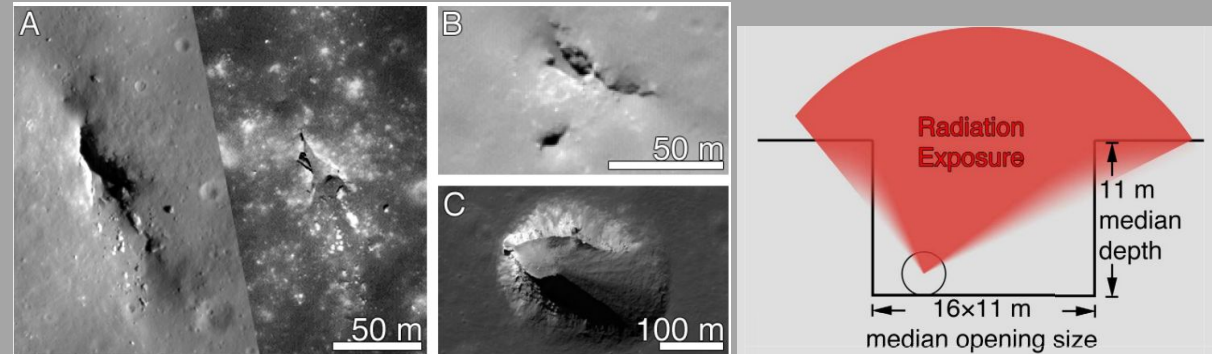
MICRO-METEORITES

THERMAL SWINGS

DUST

VACUUM

- Of the 256 measured pits, 178-194 are large enough to hold a three-astronaut habitat module (depending on model shape). 40-49 of these pits reduce radiation by 83% or more, corresponding to an annual dosage of less than 50 mSv (the limit for U.S. radiation workers [2]).
- Some pits (~43%) have an additional feature that would be useful for astronauts: a collapsed wall that provides possible access by driving, rather than building an elevator.
- Unfortunately, pits with these collapses are rarely narrow and deep enough to provide good protection. Of the pits with <50 mSv/yr exposure, only ~8 have possible entrance ramps.



RADIATION

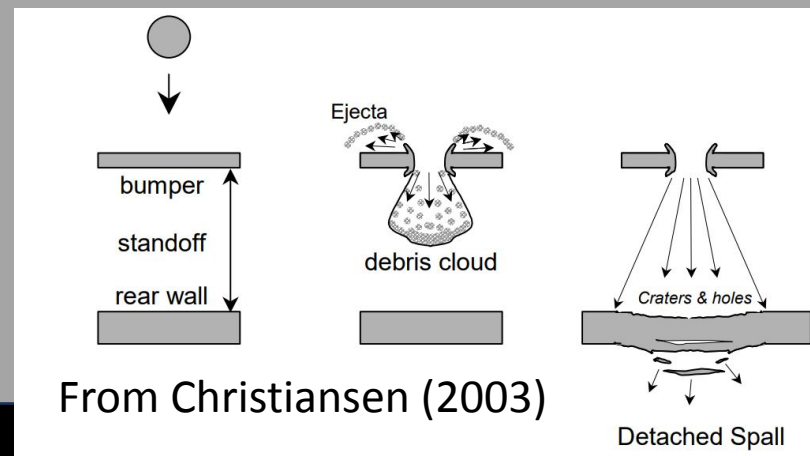
MICRO-METEORITES

THERMAL SWINGS

DUST

VACUUM

- The Grun Lunar flux model estimates that a micrometeoroid with a mass equal to one microgram will impact the lunar surface twice per square meter per year, causing damage ranging from catastrophic failure to partial penetration and pitting, local deformation, and material degradation. [Allende et al., 2020]
- Protection is also needed from nearby rocket blasts



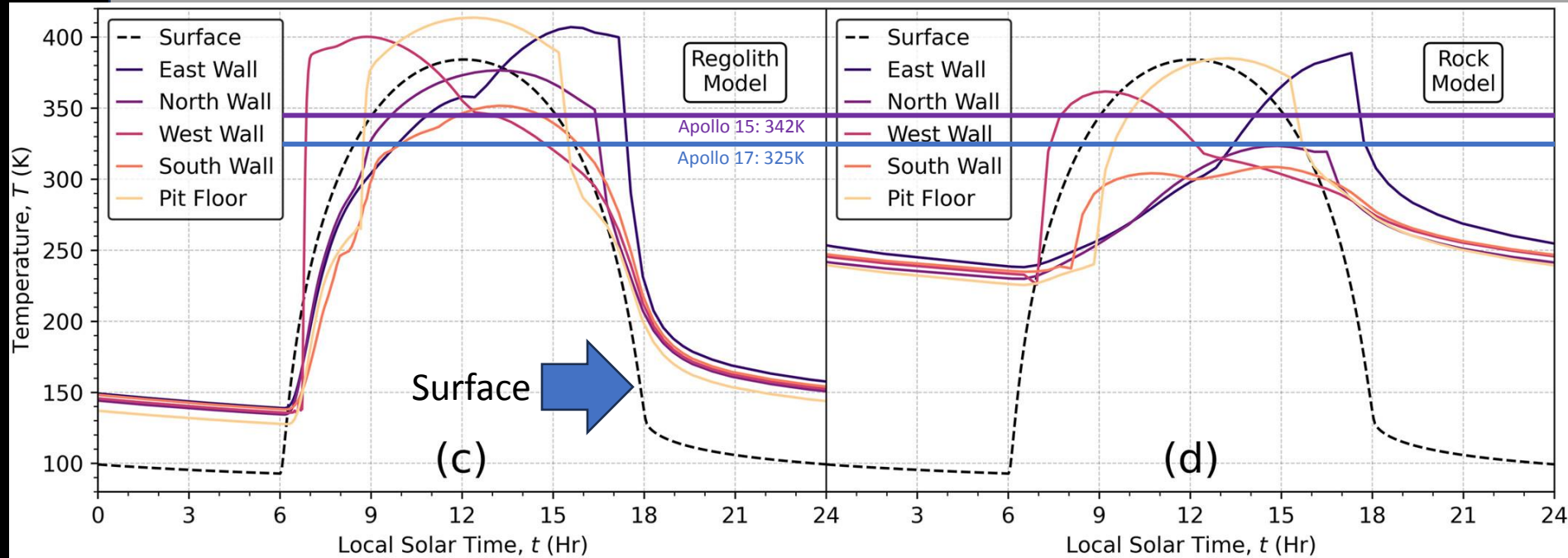
RADIATION

**MICRO-
METEORITES**

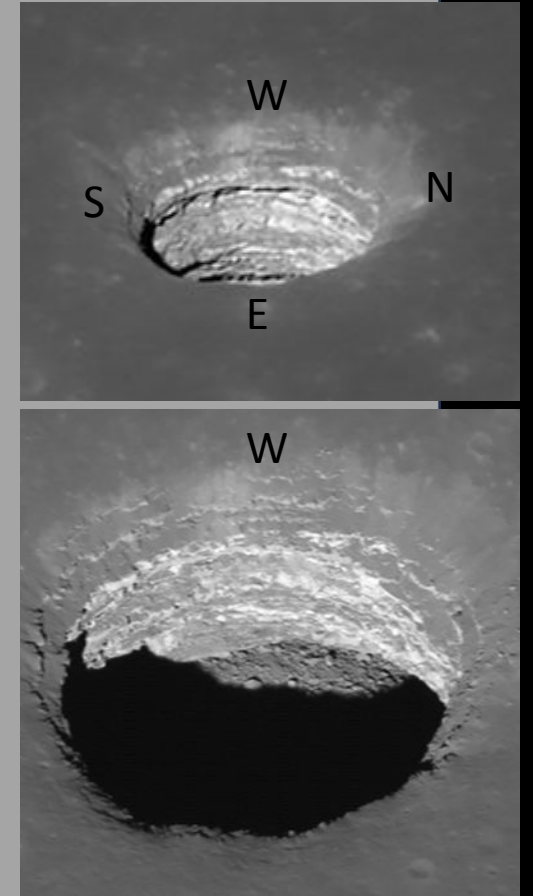
**THERMAL
SWINGS**

DUST

VACUUM



Horvath et al., 2022



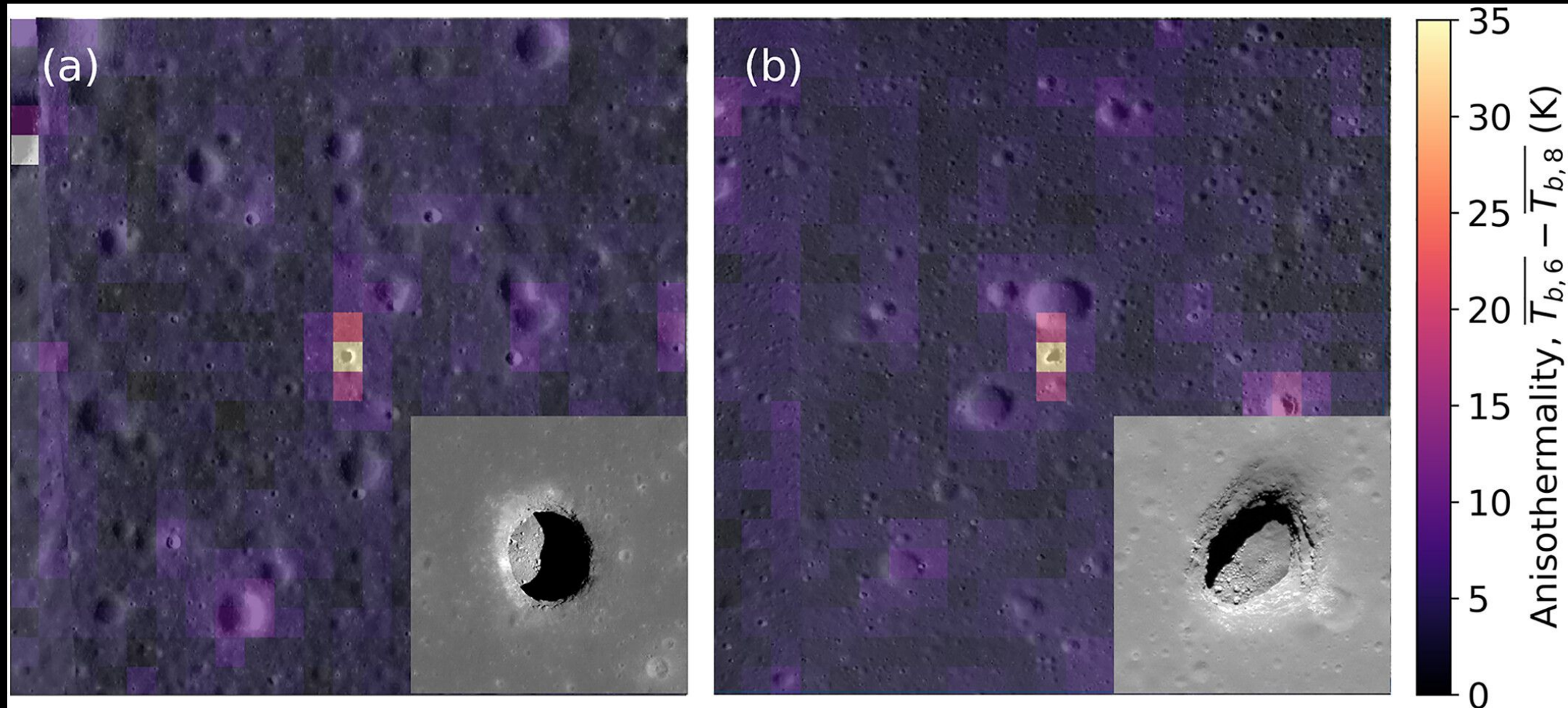
RADIATION

**MICRO-
METEORITES**

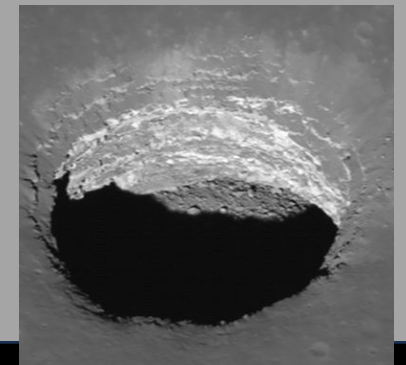
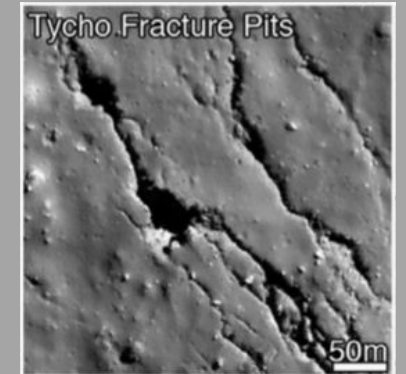
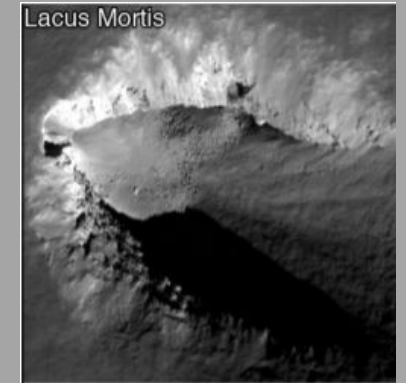
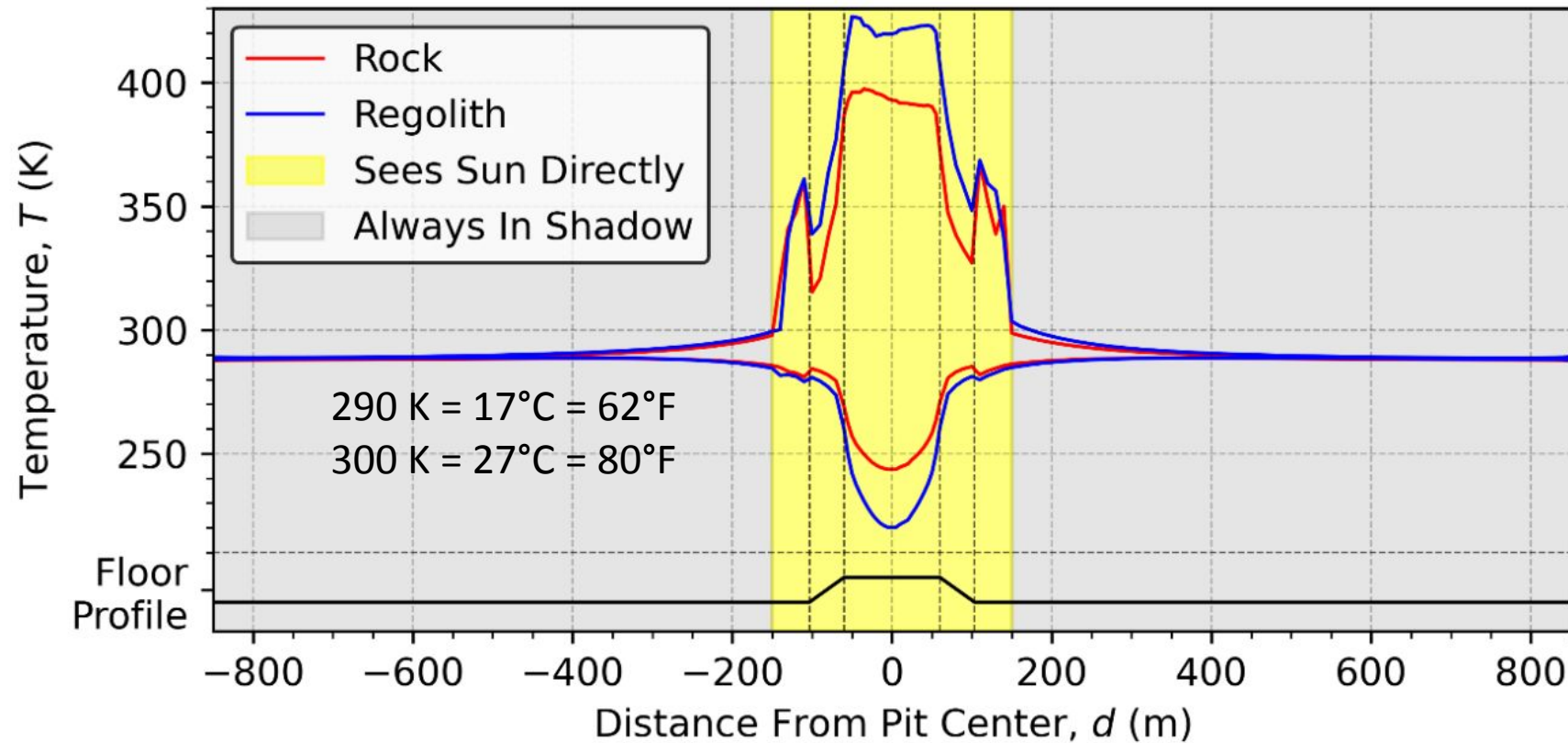
**THERMAL
SWINGS**

DUST

VACUUM



Horvath et al., 2022

RADIATION**MICRO-
METEORITES****THERMAL
SWINGS****DUST****VACUUM**

Horvath, Hayne, and Paige (2022). Thermal and Illumination Environments of Lunar Pits and Caves: Models and Observations from the Diviner Lunar Radiometer experiment

RADIATION

**MICRO-
METEORITES**

**THERMAL
SWINGS**

DUST

VACUUM

- The floor of lunar pits are likely to have slightly more dust than their surroundings (because dust can fall in but it cannot get out)
- There will be little to no dust actually inside the tubes.



Kazumura Cave, Hawai'i (65 km long)

RADIATION

**MICRO-
METEORITES**

**THERMAL
SWINGS**

DUST

VACUUM

Can lava tubes be hermetically sealed?

No; but....



Porosity- Lavas vary greatly in porosity, with high porosities seen near the tops of lava units. However, individual pores are not always connected.

Permeability- Instead, permeability in lavas comes mostly from a combination of boundaries between lavas (horizontal) and jointing from cooling (vertical). Dense lava cores have very low permeability.

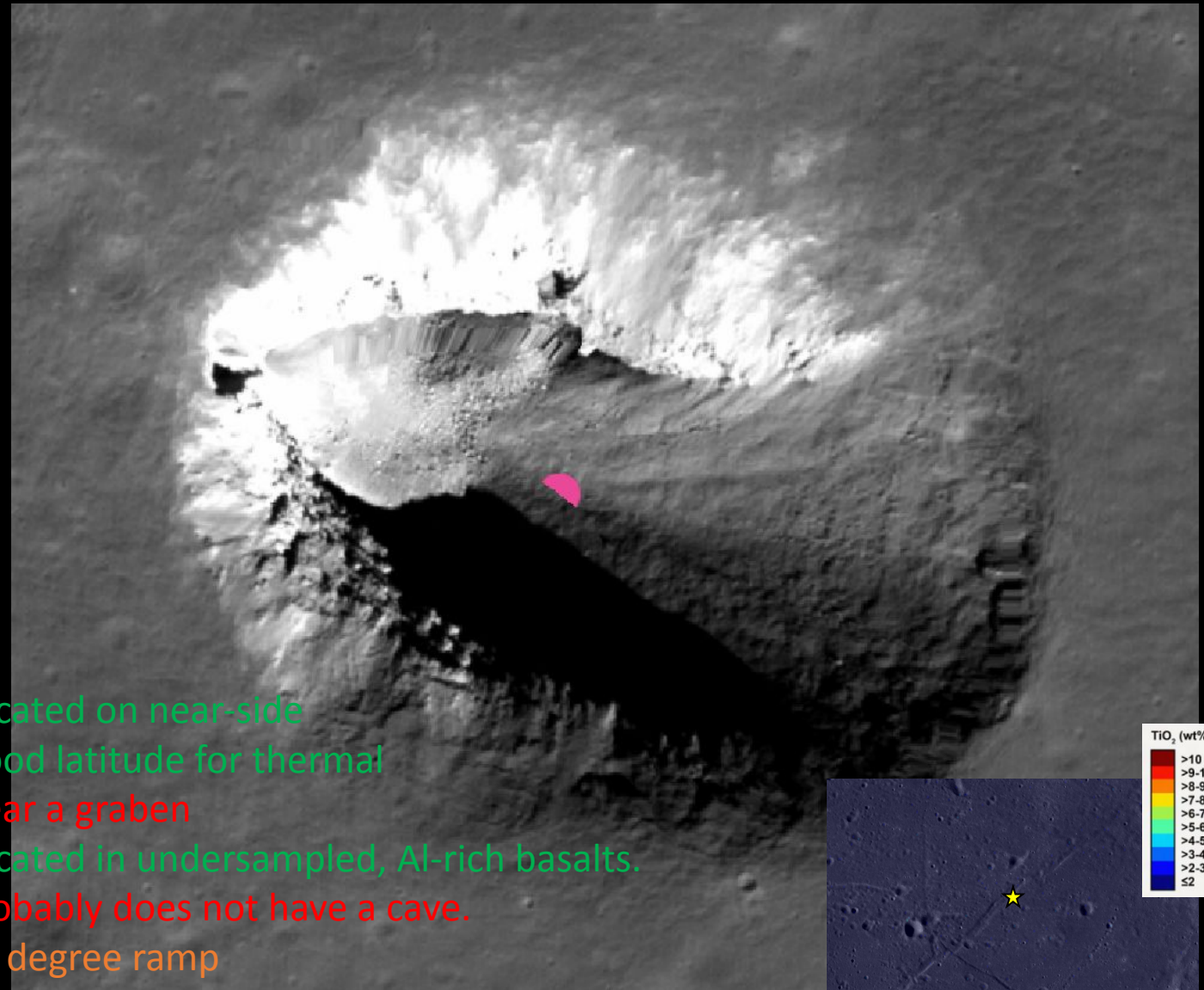
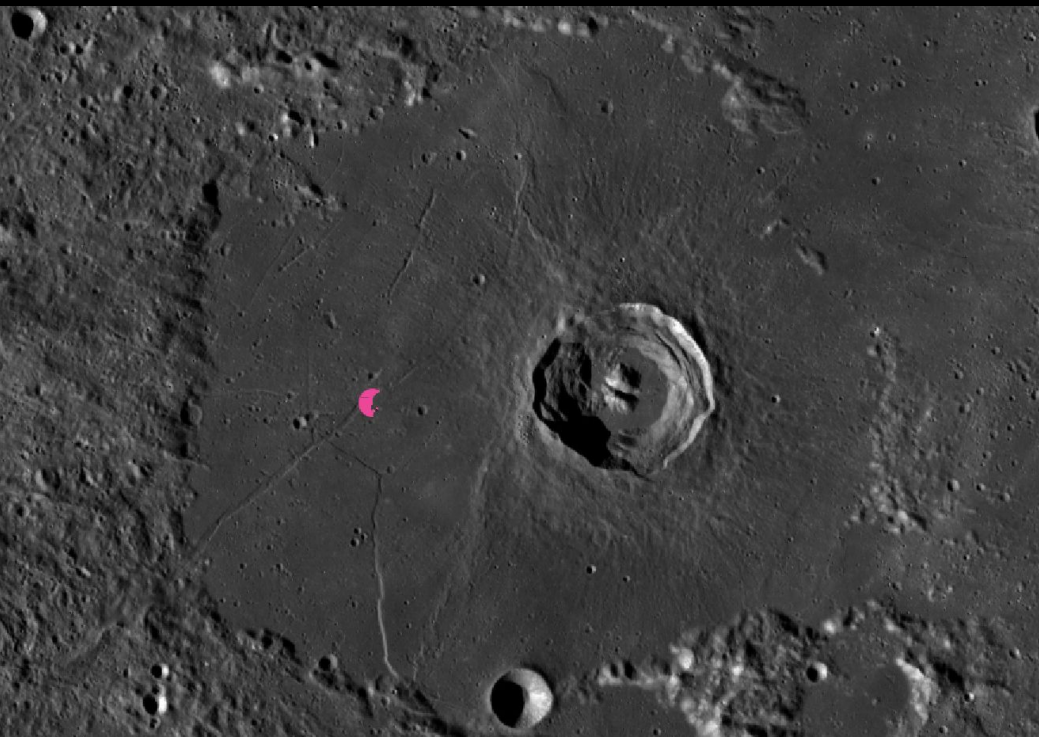
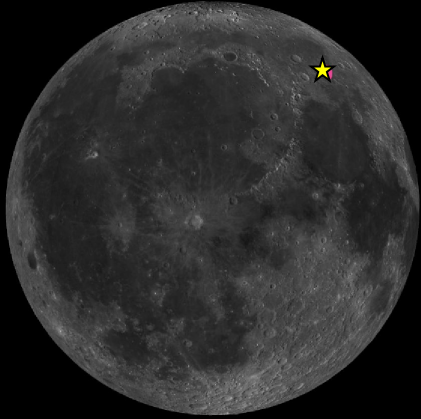
Cracks- On Earth, cracks often form during cooling and then widen later due to infiltration by water, earthquakes, and tectonic stresses.



Cueva de los Verdes, Laura Kerber

Someone should try it...

Lacus Mortis Pit



Located on near-side

Good latitude for thermal

Near a graben

Located in undersampled, Al-rich basalts.

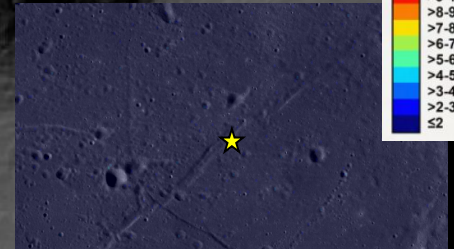
Probably does not have a cave.

22 degree ramp

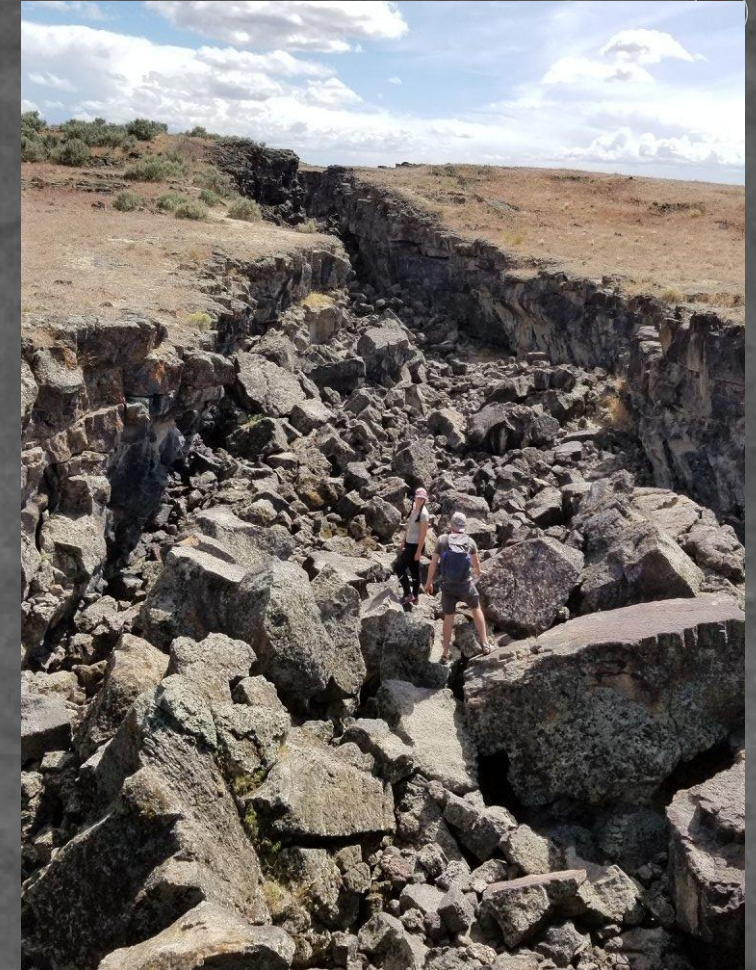
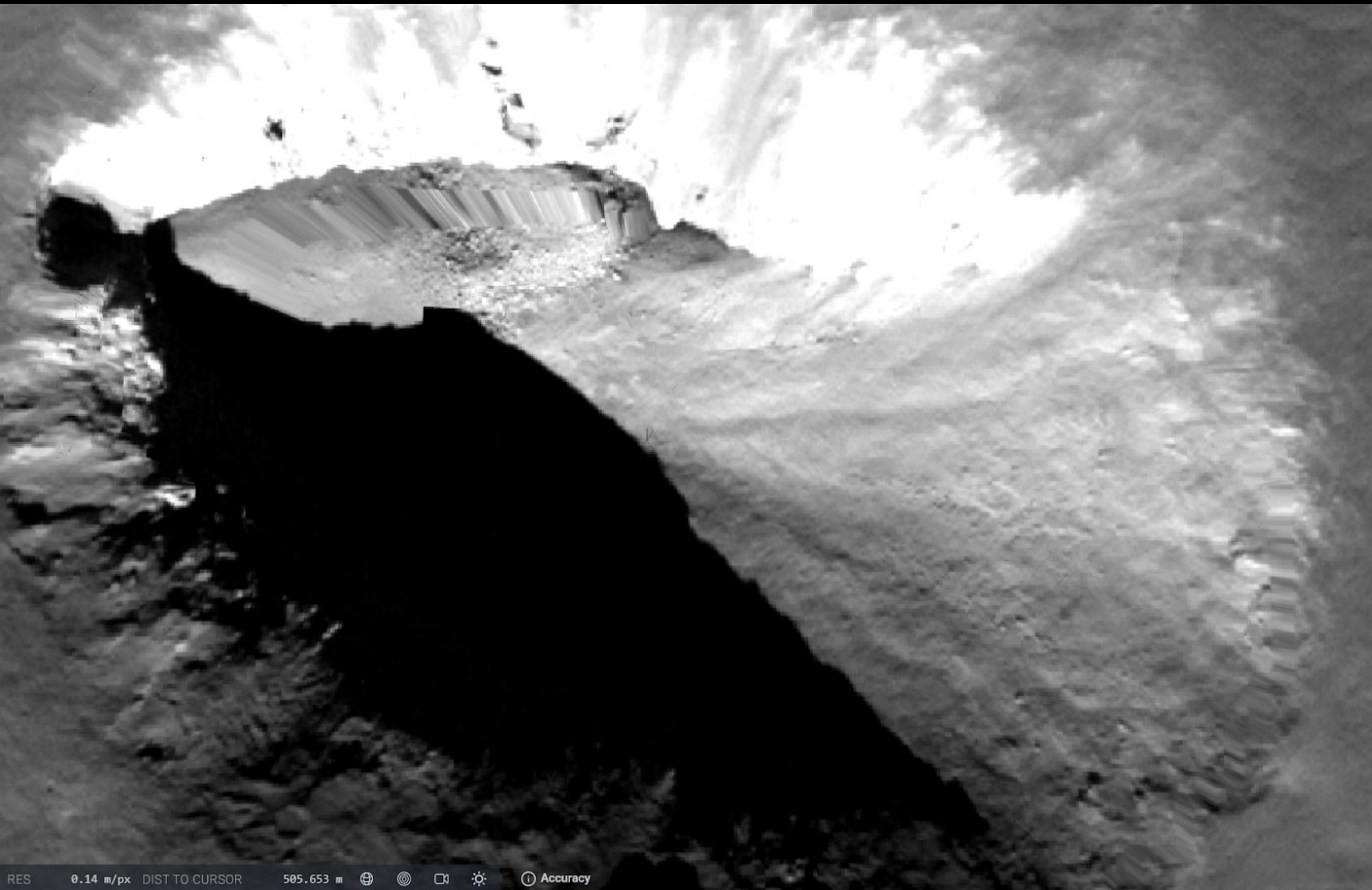
Some thermal advantage during the day (southern shaded wall); not at night.

Sufficient radiation shielding.

Low iron, low titanium



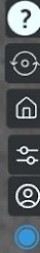
Lacus Mortis



Tabernacle Hill, UT; Laura Kerber

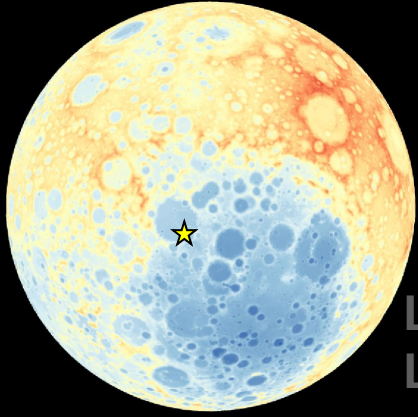
20 m

RES 0.14 m/px DIST TO CURSOR 505.653 m Accuracy

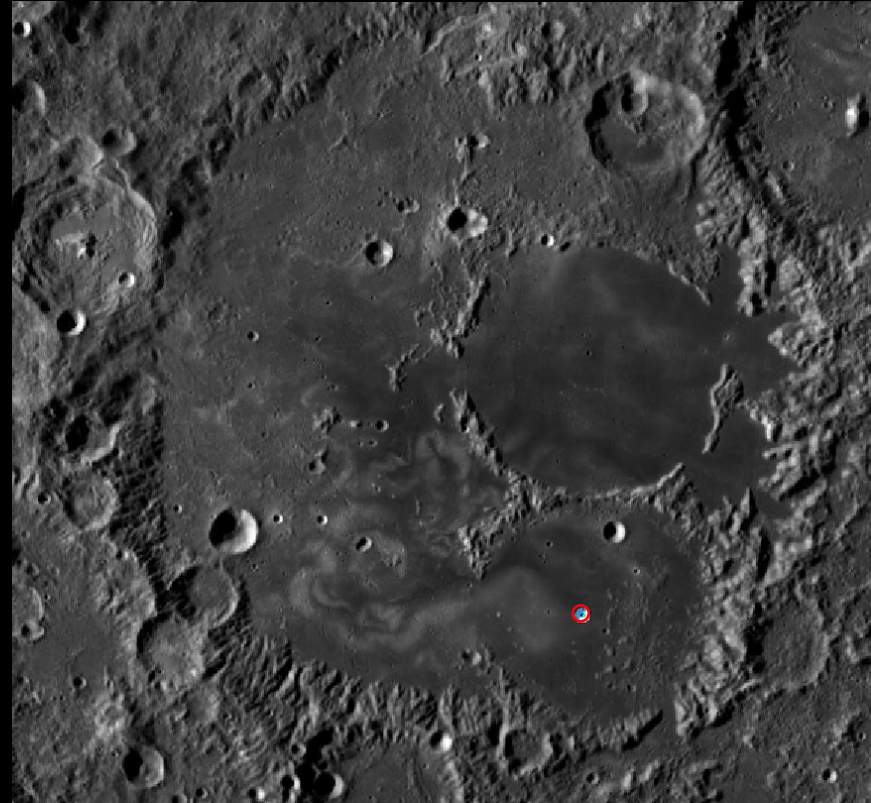


The devil is in the details on ramps: we need higher resolution imagery!

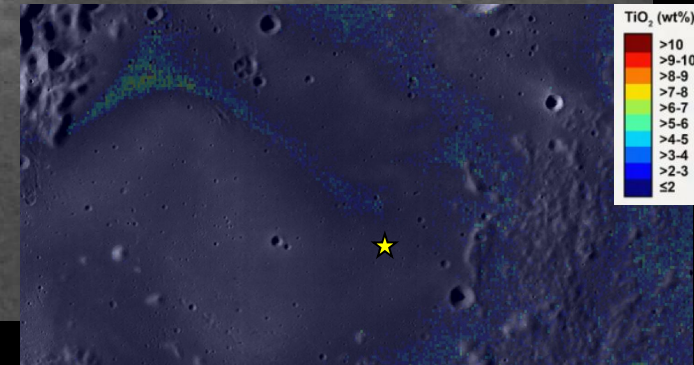
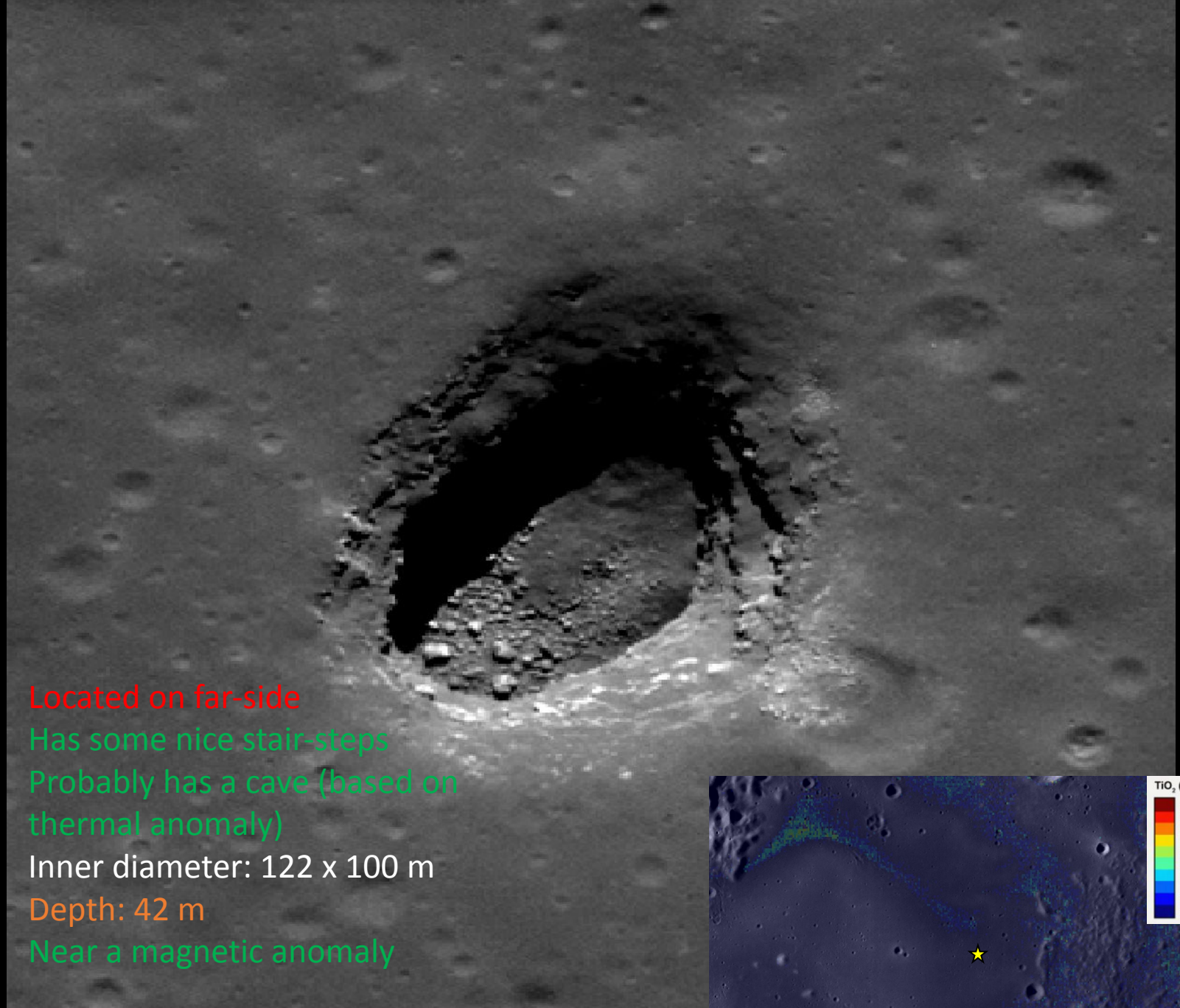
Mare Ingenii Pit



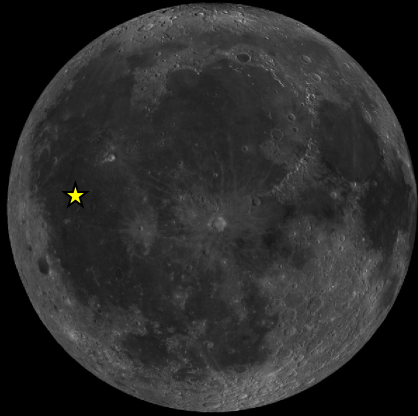
Lat -35.949
Lon 166.056



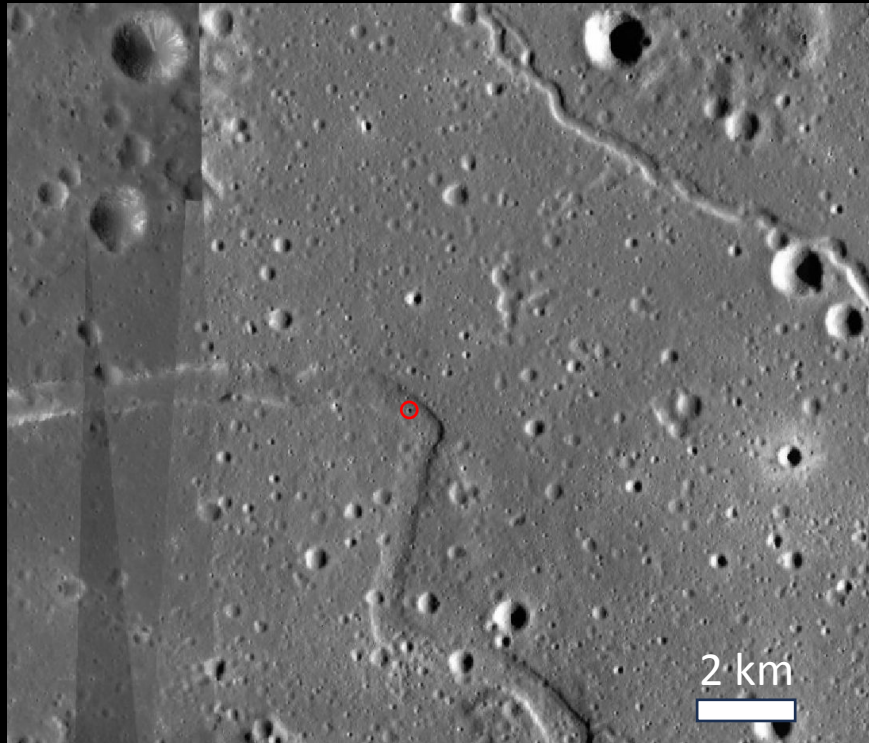
Located on far-side
Has some nice stair-steps
Probably has a cave (based on
thermal anomaly)
Inner diameter: 122 x 100 m
Depth: 42 m
Near a magnetic anomaly



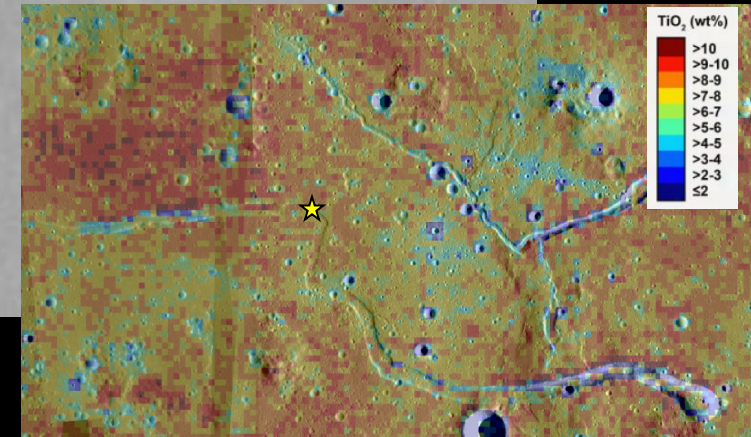
Marius Hills Pit



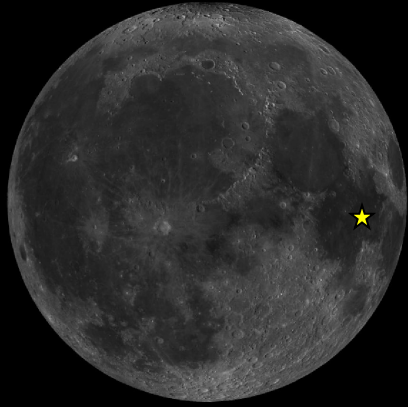
Lat 14.0917
Lon 303.2299



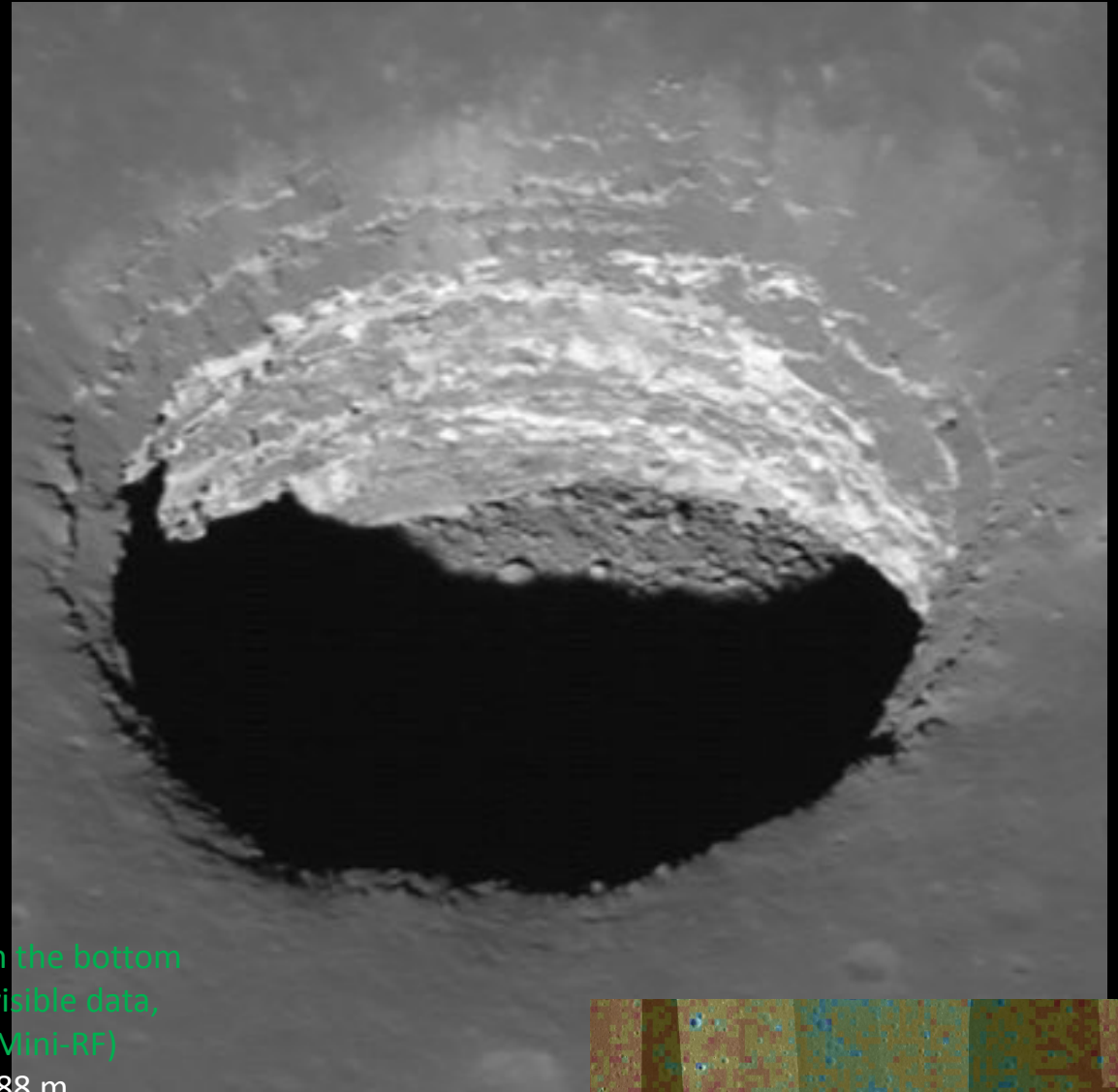
Located on near-side
Probably has a cave (based on visible data, context, and thermal anomaly)
Inner diameter: 55 x 49 m
Depth: 40 m
100 km from magnetic anomaly
Close to interesting dome features and rille
Previous Apollo and Constellation site (before pit was known)
High Titanium lavas (7-10% TiO_2)
High Iron lavas (18-20% FeO)



Tranquillitatis Pit



Lat 8.3355.
Lon 33.222



Located on near-side
Best quality imagery
Can see the Earth from the bottom
Has a cave (based on visible data,
thermal anomaly and Mini-RF)

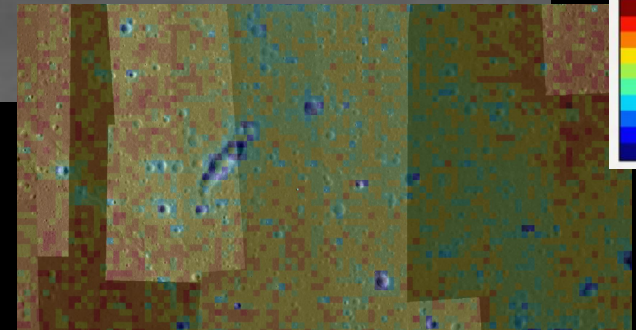
Inner diameter: 100 x 88 m

Depth: 105 m

Close to intersection of two lava units

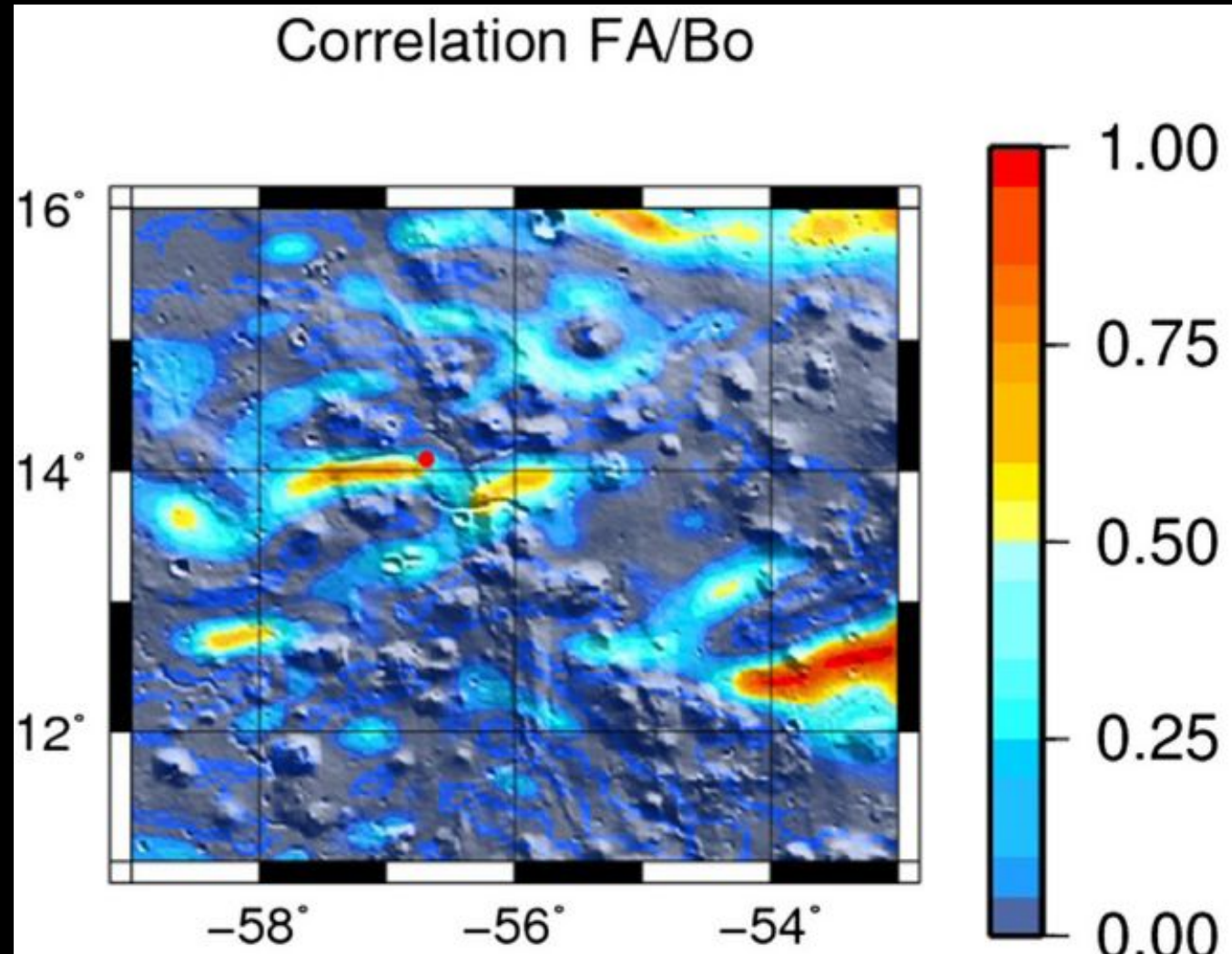
High titanium lavas (6-8% TiO_2)

High iron lavas (17.5-19.5% FeO)

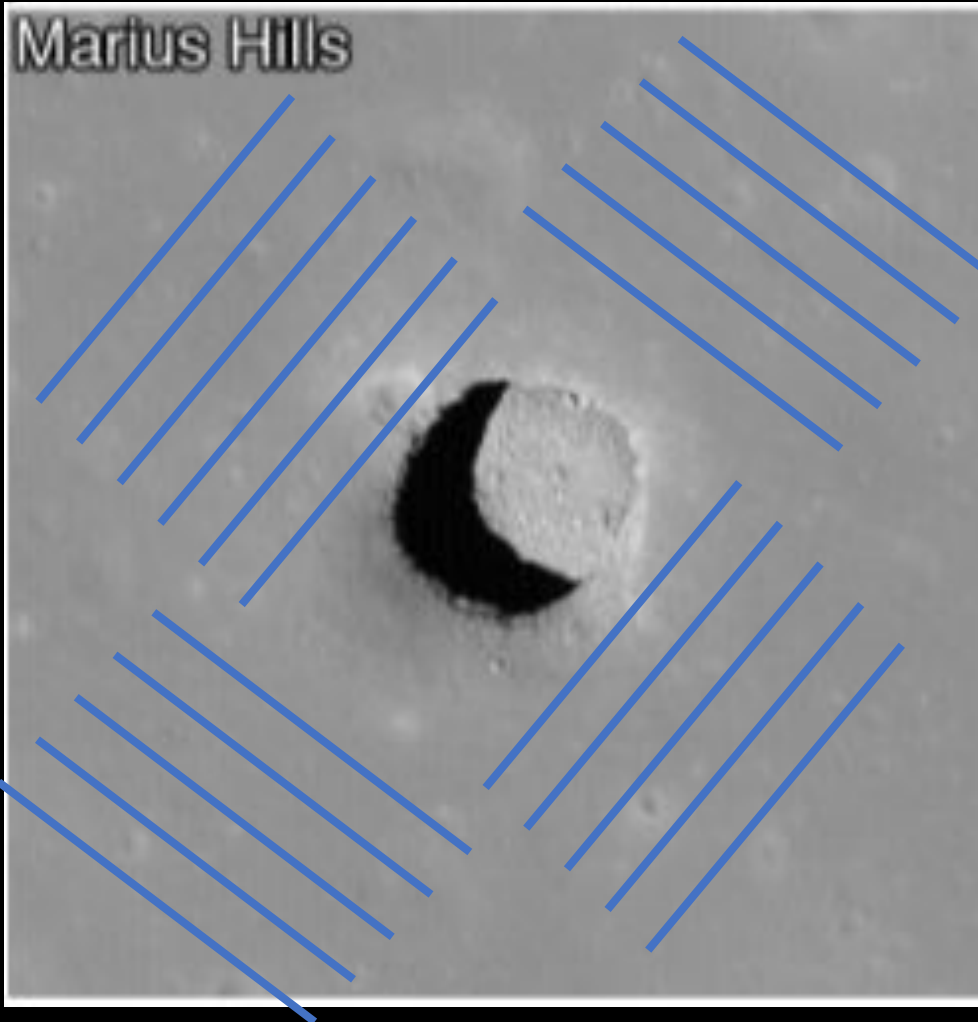


Attempted Ways to Confirm a Cave

- Looking with LRO off-nadir (at least 20 m of overhang at Tranquillitatis; at least 14 m at Marius Hills; at least 10-20 on the W and S sides of Ingenii; Wagner and Robinson, 2014).
- Thermal anomaly (confirmed at Tranquillitatis and Ingenii) with Diviner (Horvath et al., 2022)
- Radar (SELENE radar and Mini-RF Kaku et al.; Carrer et al., 2024)
- Gravity (Chappaz et al., 2017)

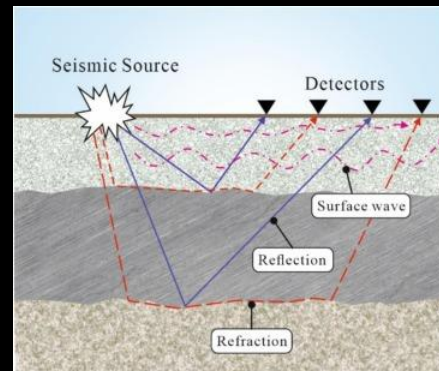


What Can Humans Do? Step 1



Surface-based exploration:

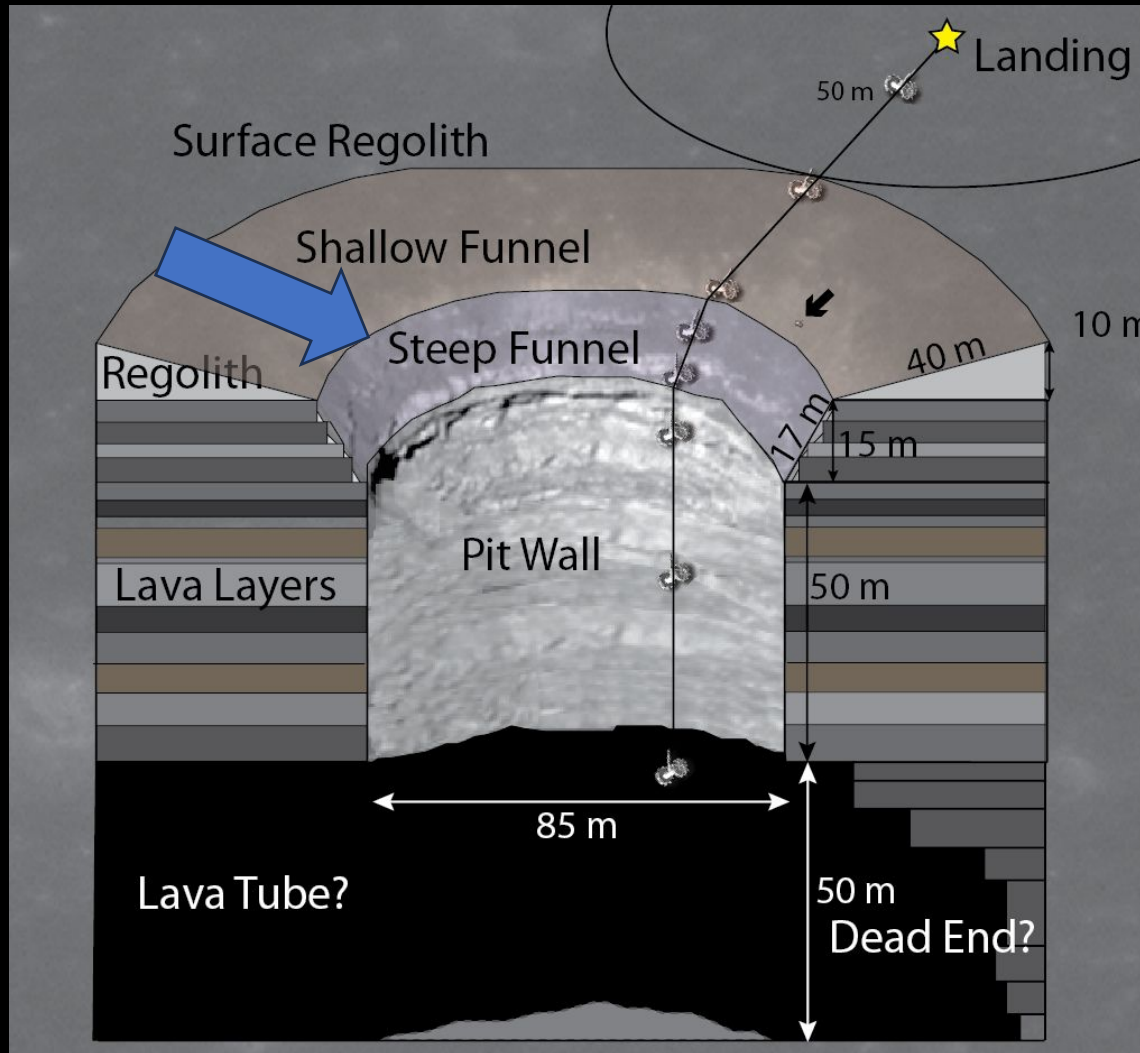
- Geophones/seismic
- Mortars/thumpers
- Ground penetrating radar
- Magnetic surveys
- Gravimeters



Measure subsurface void

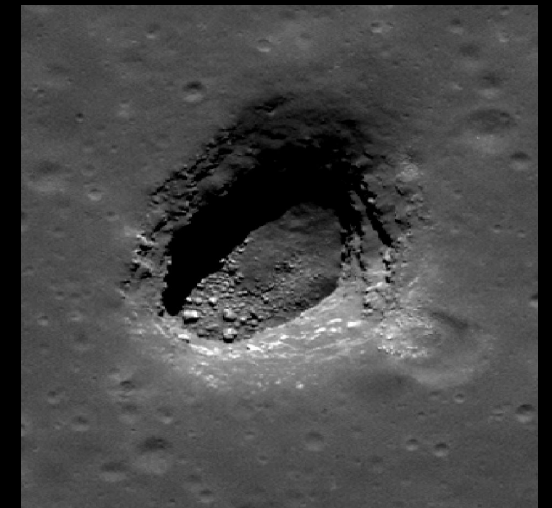
Compare geophysical data of lava and regolith layers and compare with ground-truth in outcrop

What Can Humans Do? Step 2



Funnel-based Exploration:

- Tethered drilling and exploration
- Examination of the regolith-to-bedrock transition



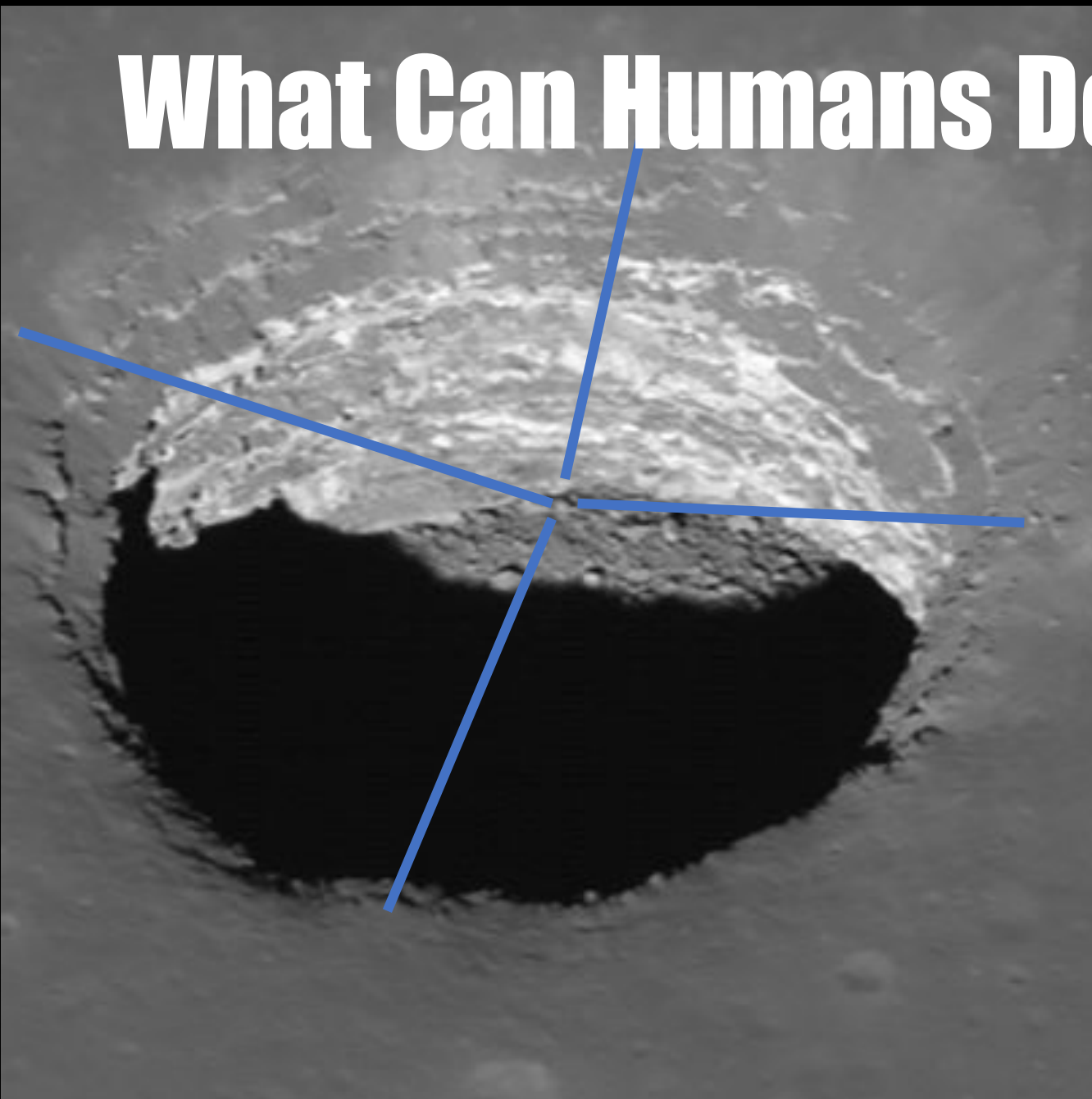


30-40 m across (~100 ft)



Use your car as an anchor!

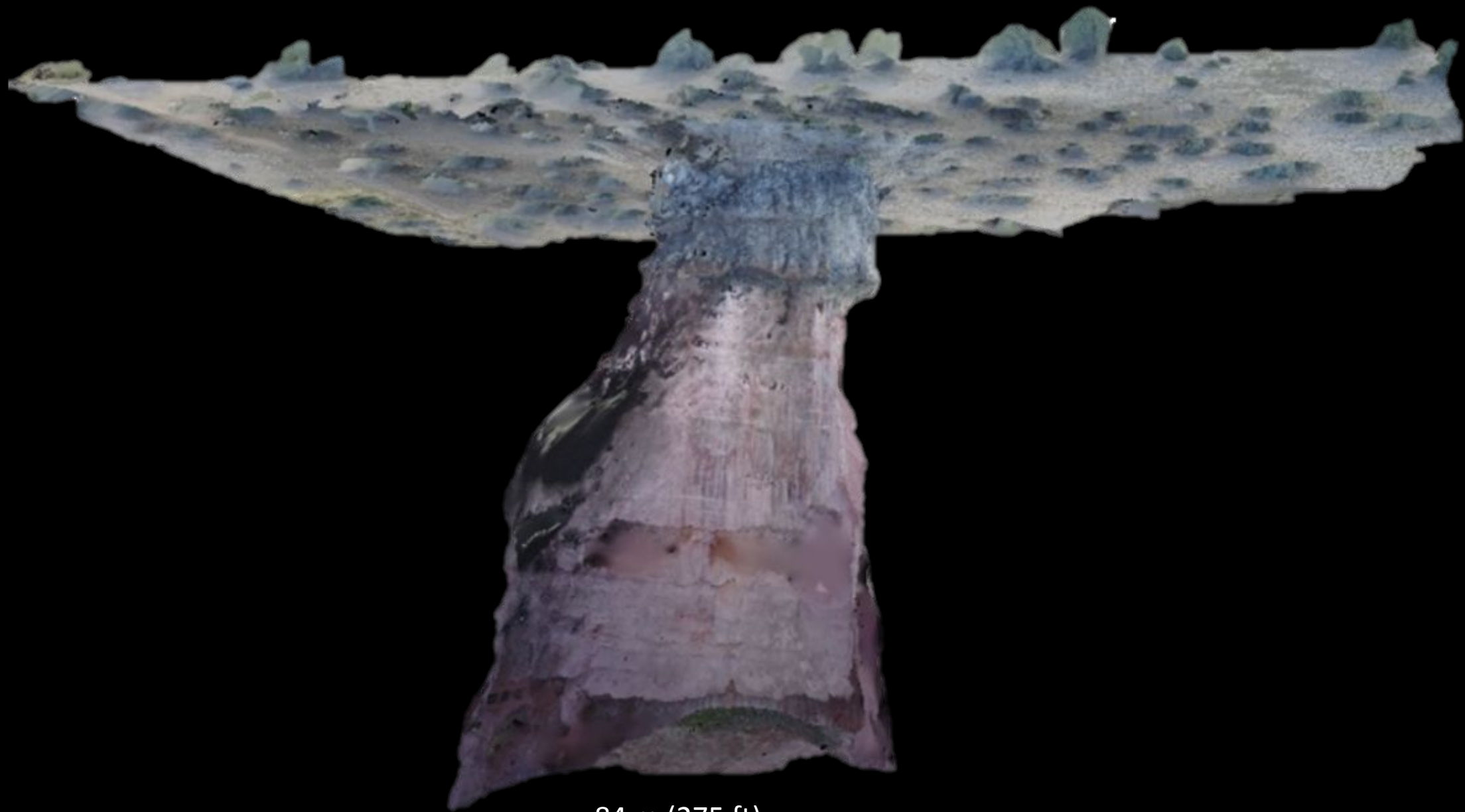
What Can Humans Do? Step 3



Pit-Based Exploration

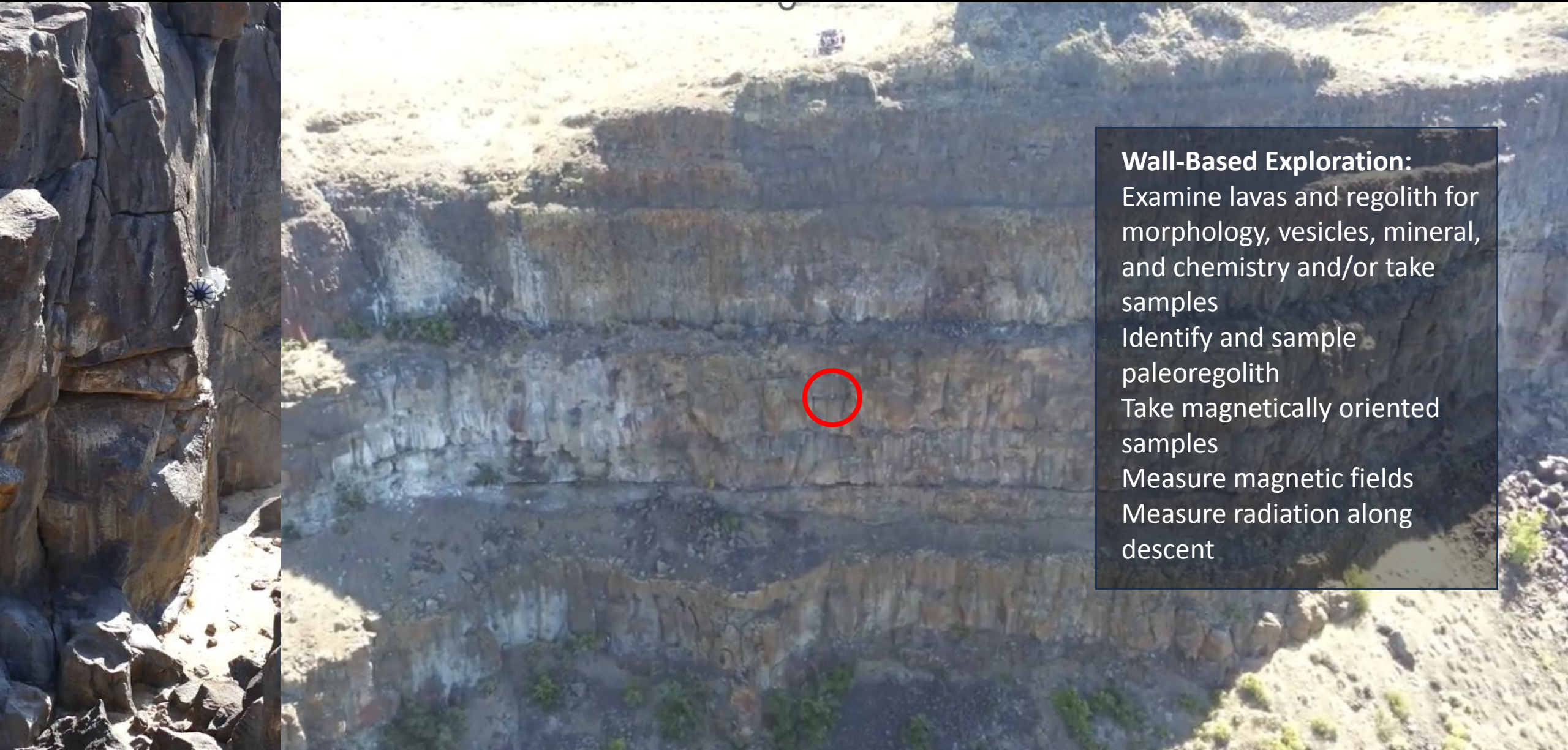
Humans could install a hovering camera, similar to the SkyCam and SpiderCams used by the NFL. Humans are good at setting anchors!

Humans could also fly a hopper in real time to explore and map the cave interior.



84 m (275 ft)

What Can Humans Do? Step 4



Wall-Based Exploration:

Examine lavas and regolith for morphology, vesicles, mineral, and chemistry and/or take samples

Identify and sample paleoregolith

Take magnetically oriented samples

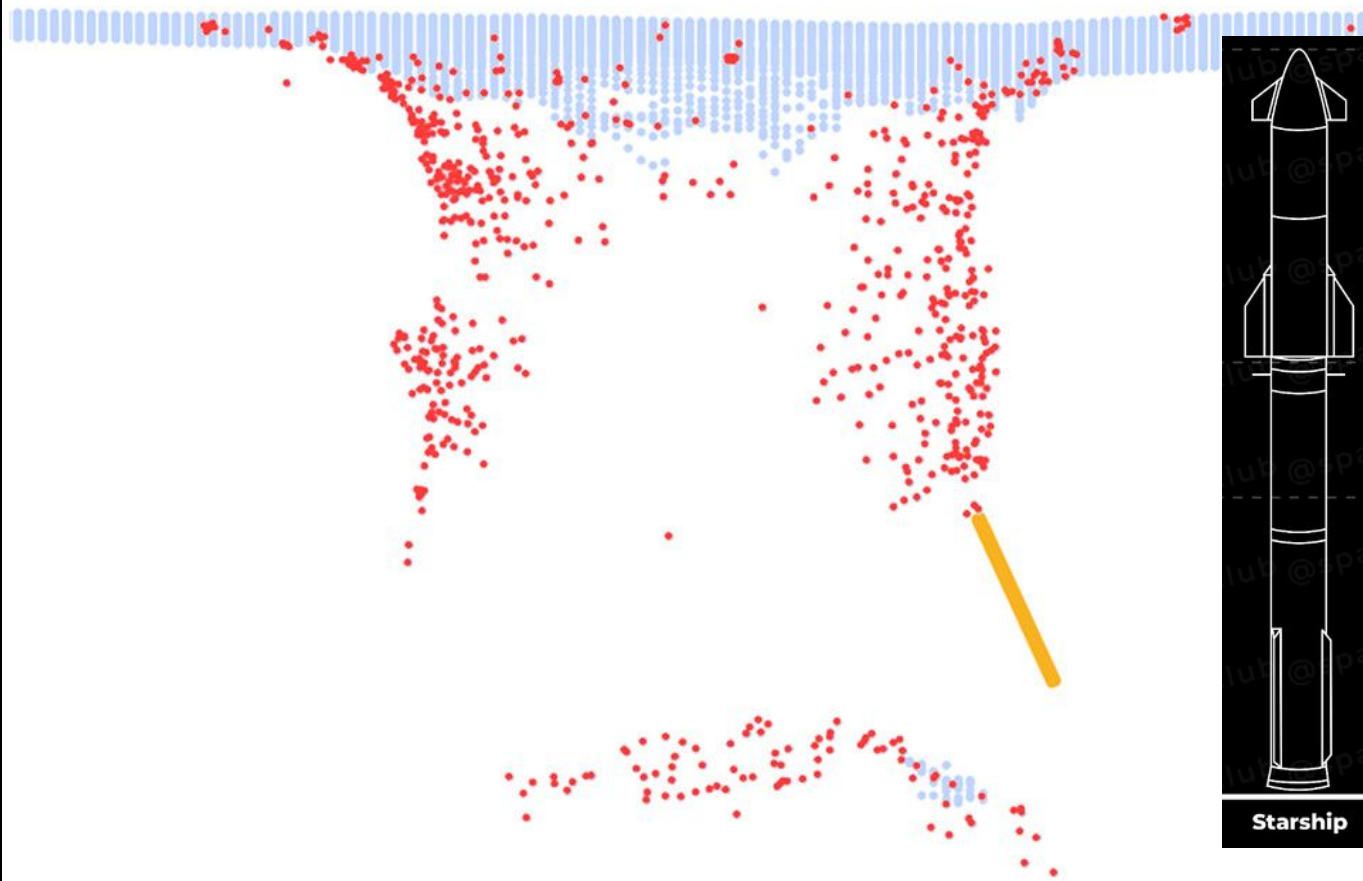
Measure magnetic fields

Measure radiation along descent

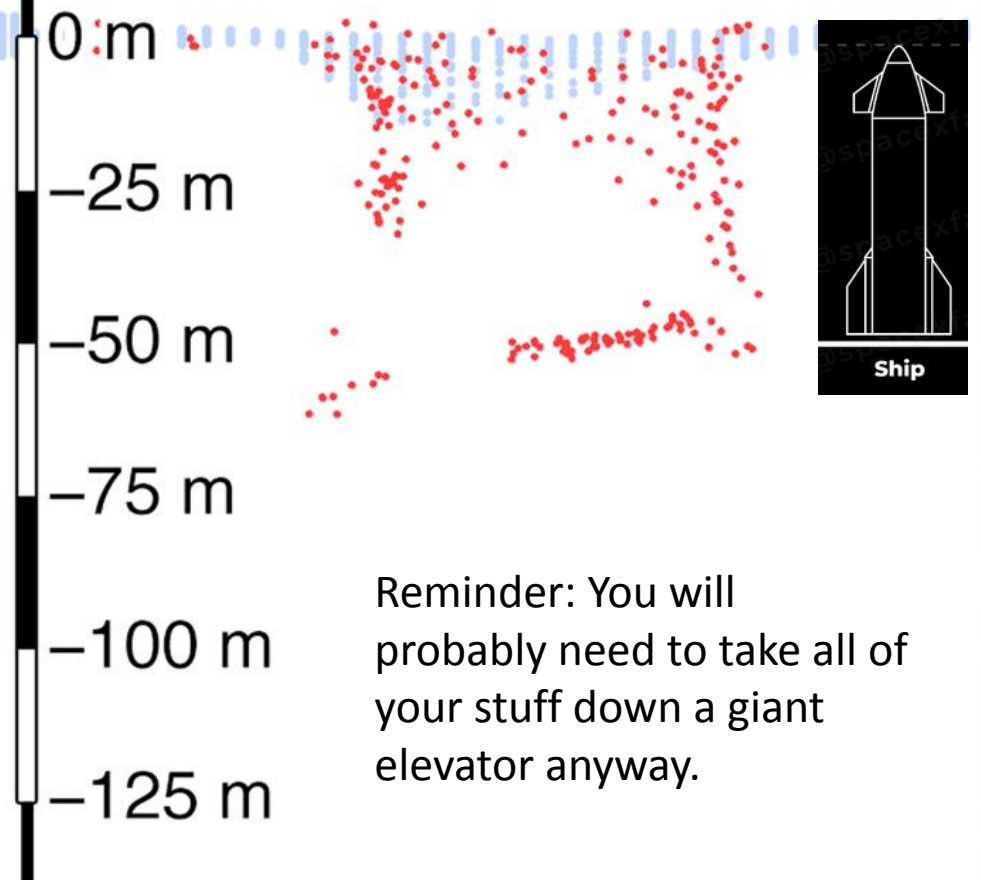


What Can Humans Do? Step 5

a. Mare Tranquillitatis Pit (MTP)



b. Marius Hills Pit (MHP)



But Laura: I don't want to carry all of my stuff down there!

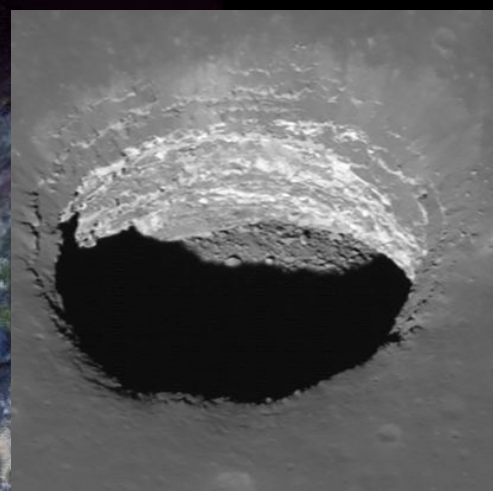


SS

100 m deep

Person

168 m deep





People rappel into these pits on Earth fairly frequently.

Things we worry about when we do that:

- Material falling down from above
- Overhangs
- Standing on unstable ledges

Advantages:

Humans are very good at setting anchors!

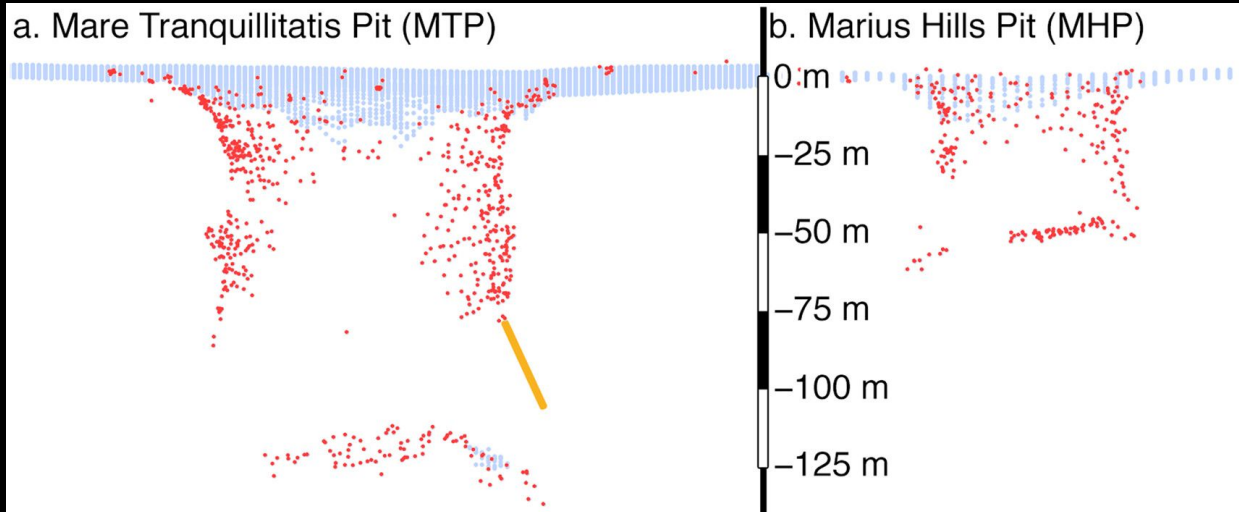
Humans are very good at drilling into walls!

Humans are very good at rappelling!

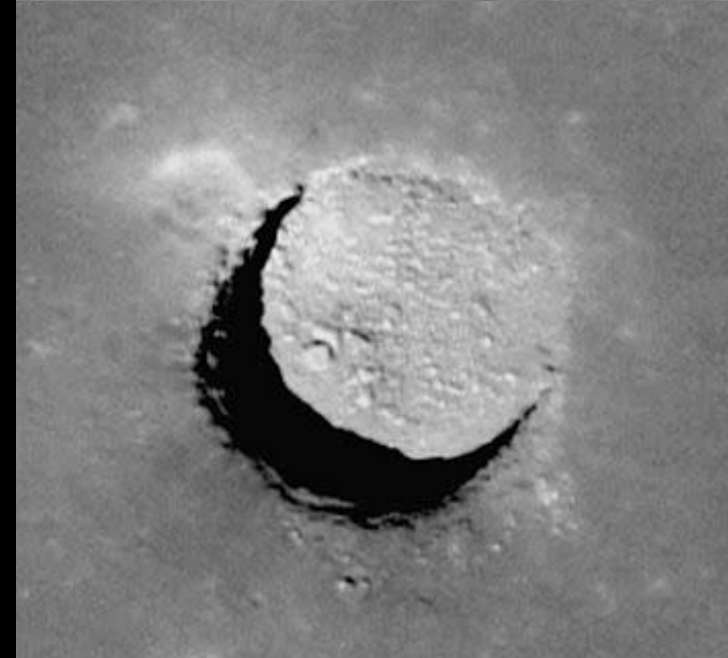
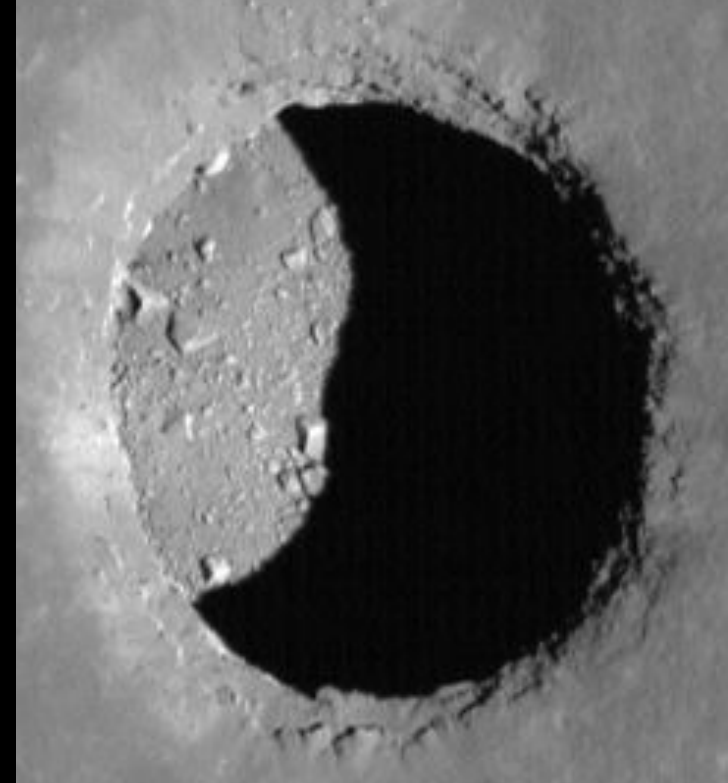


PIT FLOOR

The floor of pits are covered in giant boulders. It is scary, but humans are also actually pretty good at this.



Wagner and
Robinson,



LAVA TUBE FLOOR



© Arizona Public Radio

Lava River Cave, Arizona



Photo: Lanny Wagner
El Malpais, NM

Is it Safe to Live Here?









STABILITY

Pretty Stable, All Things Considered

Types of Instability:

Blocks— Mitigation: Inspection, Tilt-meters

Gravel and Sand— Mitigation: Inspection, Mortar, and Resin

Plates— Mitigation: Inspection, Bolts if needed

Span—Mitigation: Inspection, Modeling

Inspections at major tourist caves are mostly done after major events such as earthquakes, floods, and volcanic eruptions.

These instabilities are less likely to be a problem on the Moon in the absence of water and chemical weathering. For example, the fall of gravel and sand is mostly due to chemical weathering of the rocks due to water flowing through cracks.



Mount Fuji Lava Tubes (Kerber)

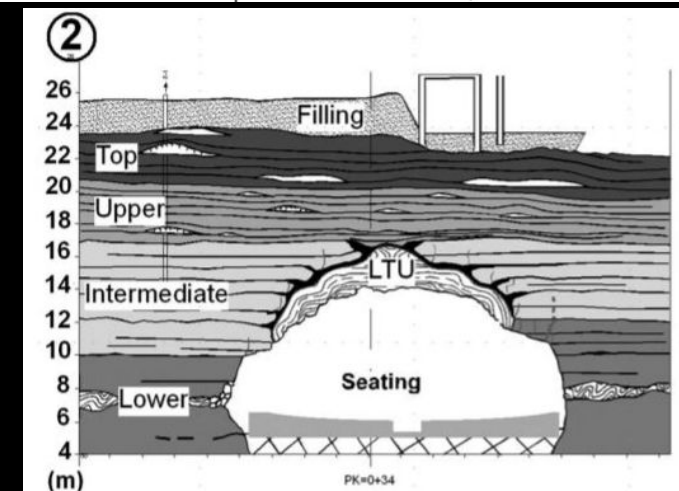
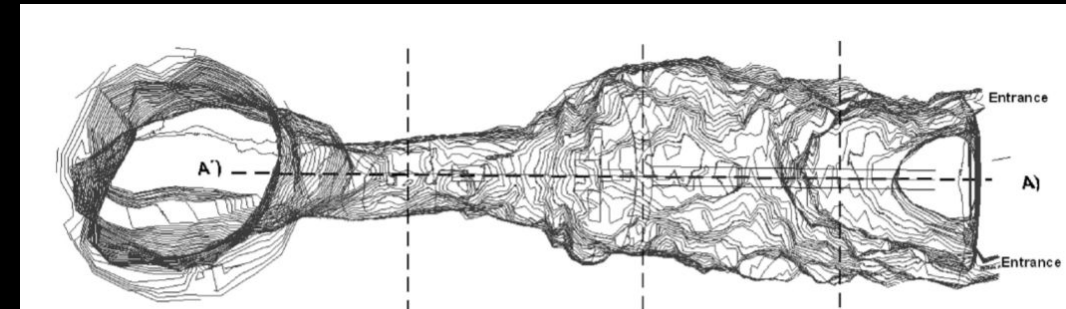


Hengifoss, Iceland

STABILITY

Things to observe and measure:

- Are the lavas thick or thin? (tens of cm vs meters vs decameters)—thick lava flows will be more stable than thin ones
- Are the lavas porous or dense?
- Are the lavas a'a or pahoehoe? A'a is thicker and denser, except at the boundaries between lavas. Pahoehoe is what forms tubes.
- Are there granular layers between lavas? (paleoregolith; clinkers)
- Are the original lava tube textures still present? (lavacicles, flows on the floor, glazed walls)
- What is the density (and orientation) of cracks?
- How much break-down is there? (fallen ceiling blocks, blocks covering the floor)



Signorelli et al., 2019

Conclusions

- Lunar pits are a desirable non-polar landing site for planetary science, astrophysics, heliophysics, biological and physical sciences, and applied sciences.
- There are many possible pits that can be visited, but the most attractive scientifically and for a long-term base are the large mare pits, especially those with caves. There is no known pit with both a ramp and a “known” cave.
- More information is needed before we can commit to building a habitat in a lunar pit, including internal geometry, amount of breakdown, lava types, thermal and radiation environment measurements.
- Humans are typically very good at the types of activities that would be needed (geophysical surveys, setting anchors, rappelling, rock-hopping).
- It would be useful to have some precursor information about the detailed geometry of the pit to be visited, if possible.

Applied Sciences

Goal	Measurements	Mission Requirement
Determine size and shape of cave	Local seismic, magnetic, gravimeter, radar	Surface is ok
Determine size and shape of cave (high quality)	Lidar	Peek into cave (descend to overhang)
Determine stability of cave	Images of cave to see if there is breakdown vs pristine lava-tube structures, assessment of thick or thin lava layers	Peek into cave (descend to overhang)
Determine entrance geometry	Images of cave or lidar	Peek into cave; further entrance may be needed
Determine density/porosity of lavas	Close-up examination of lavas in wall	Access to wall
Identify paleoregolith (for stability reasons)	Images of walls	Top of funnel
Understand the regolith/bedrock interface (for ISRU)	Geophysical measurements; direct imaging	Surface; top of funnel

Goal	Measurements	Mission Requirement
Determine thickness and morphology of lava	Images of walls	Close-up flyover is ok; access to walls is preferred
Determine rheology of lavas	Bulk elemental composition; bubble and crystal distributions	Access to walls, can be done in-situ, samples would be better
Understand the regolith/bedrock interface		Peek into cave (descend to overhang)
Determine entrance geometry	Images of cave or lidar	Peek into cave; further entrance may be needed
Determine density/porosity of lavas	Close-up examination of lavas in wall	Access to wall
Identify paleoregolith	Images of walls	Top of funnel





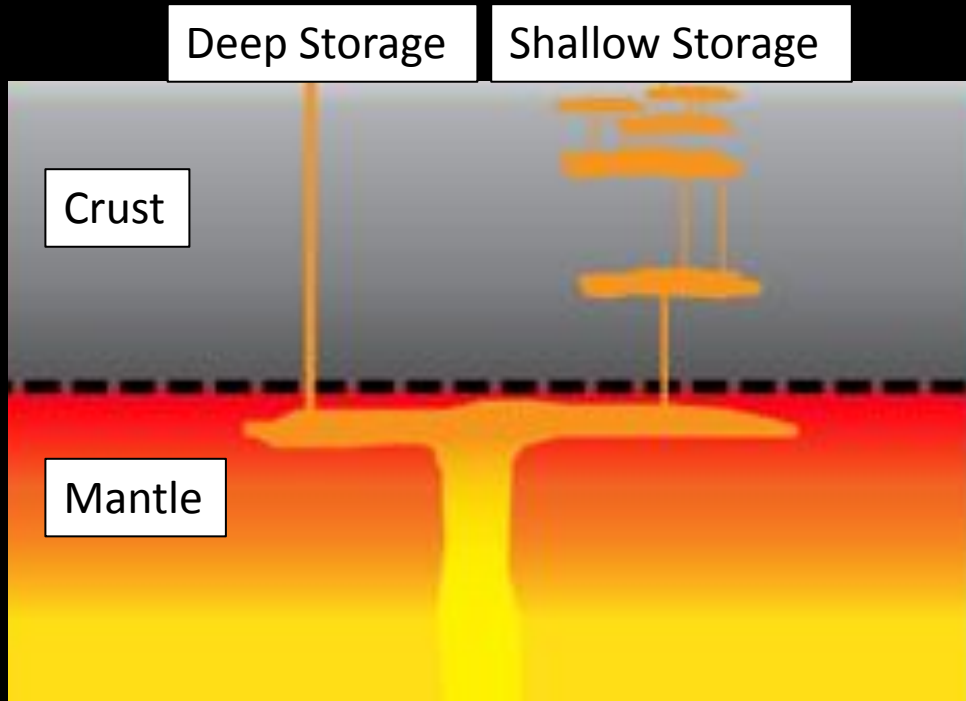
More References

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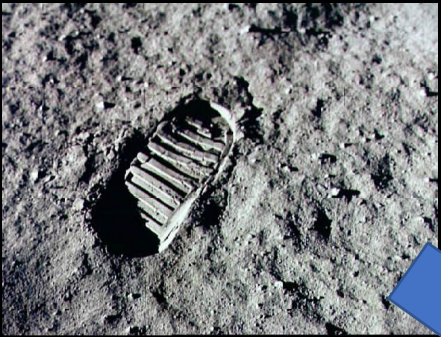
Science

- **Physical Volcanism:** Determining how magmas are transported to the surface on the Moon



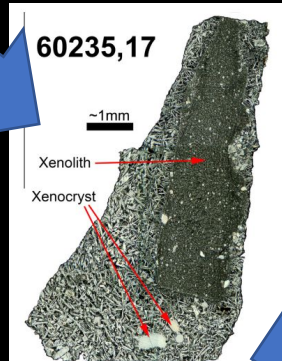
Science

- **Petrology:** Piecing together the structure of the lunar mantle and crust with petrology



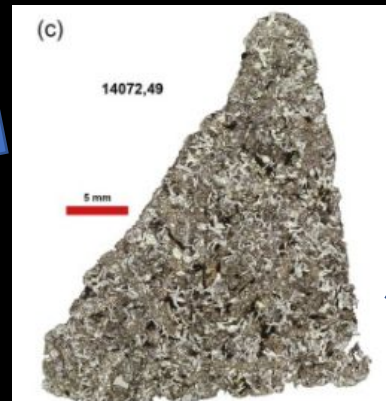
Is it local?

Is it representative?



Neal et al., 2015

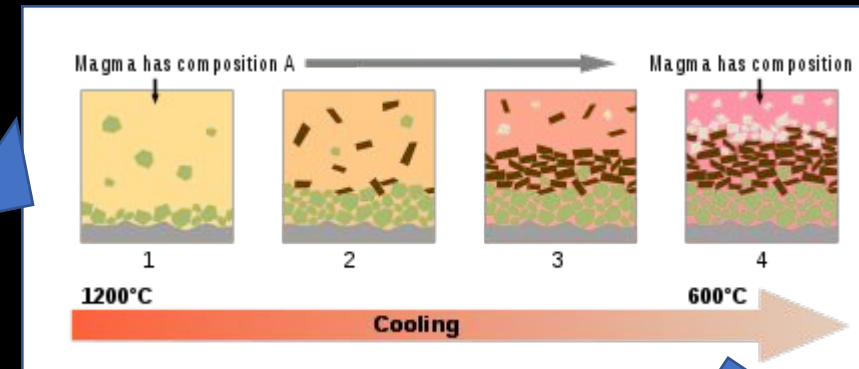
Is it an igneous rock?



Neal et al., 2015

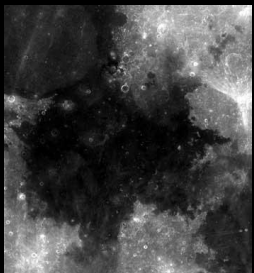
Is it a liquid composition?

Is it a primary composition?

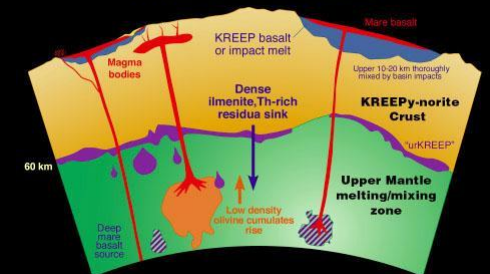


Where in the lava does it come from?

KNOWLEDGE OF PLANETARY VOLCANISM!



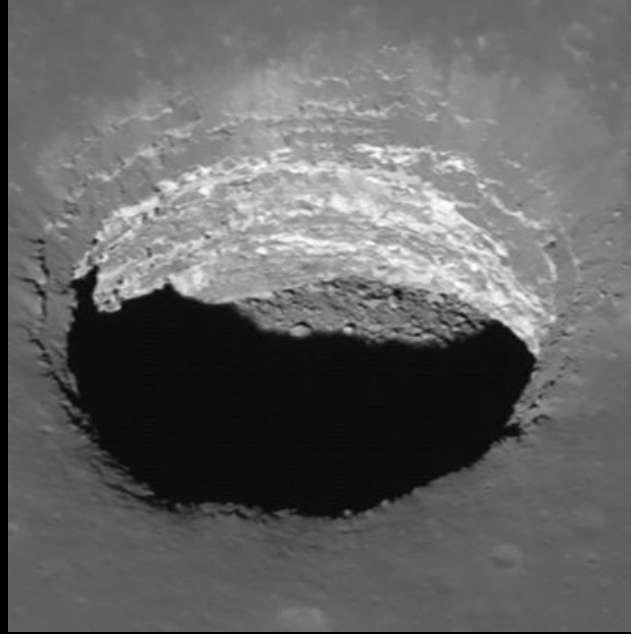
KNOWLEDGE OF THE LUNAR INTERIOR!



(Graphic by Brooks G. Bays, Jr. based on diagram by Brad Jolliffe)

Science

- **Regolith:** Exploring the regolith/bedrock interface and process of regolith formation
- Comparing the surface regolith to the underlying layers to determine its representativeness



Science

Lunar Magnetism: Did the lunar crust have a late dynamo?

Paleoregolith: What was the density of the ancient solar wind?

