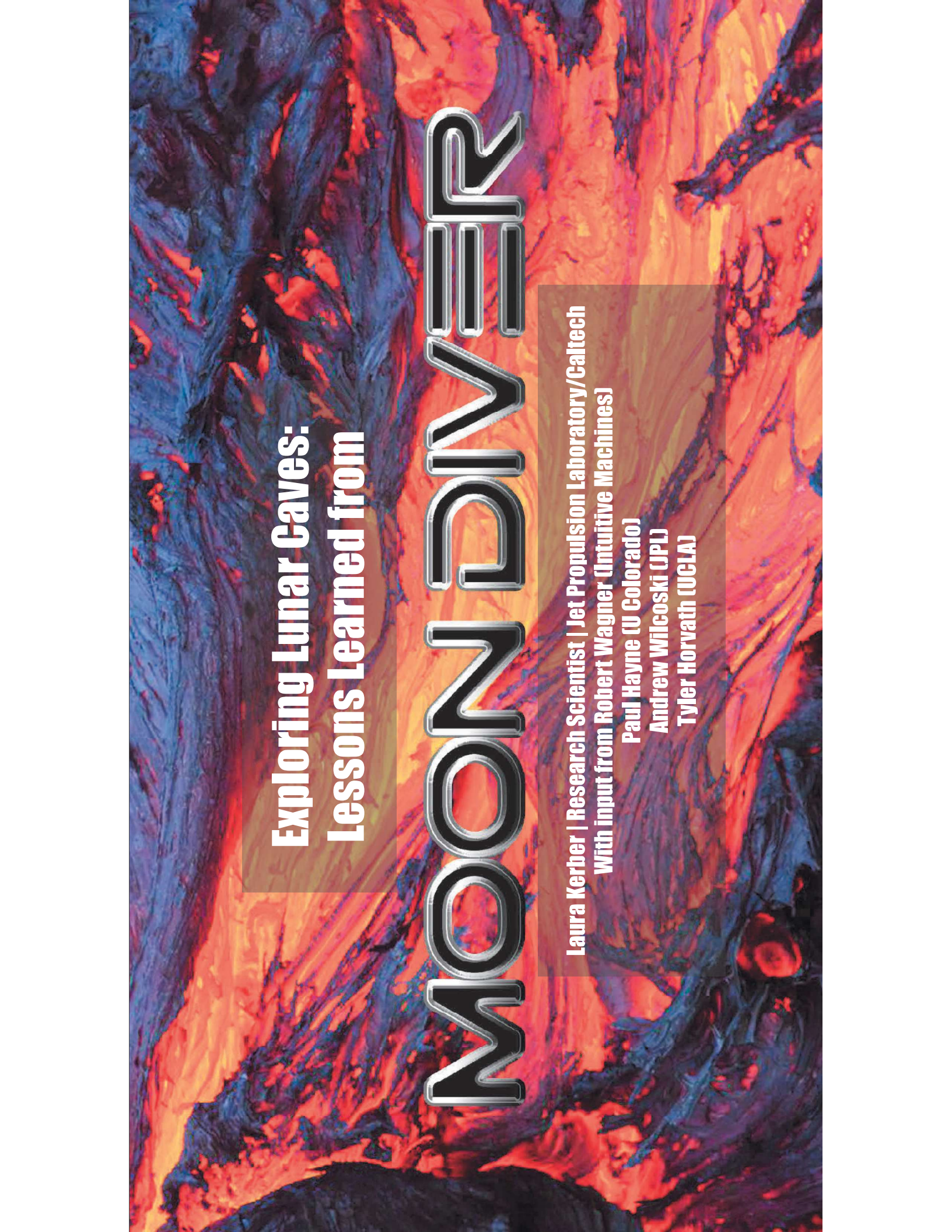






**Exploring Lunar Caves:
Lessons Learned from**

MOON DIVER

Laura Kerber | Research Scientist | Jet Propulsion Laboratory/Caltech

With input from Robert Wagner (Intuitive Machines)

Paul Hayne (U Colorado)

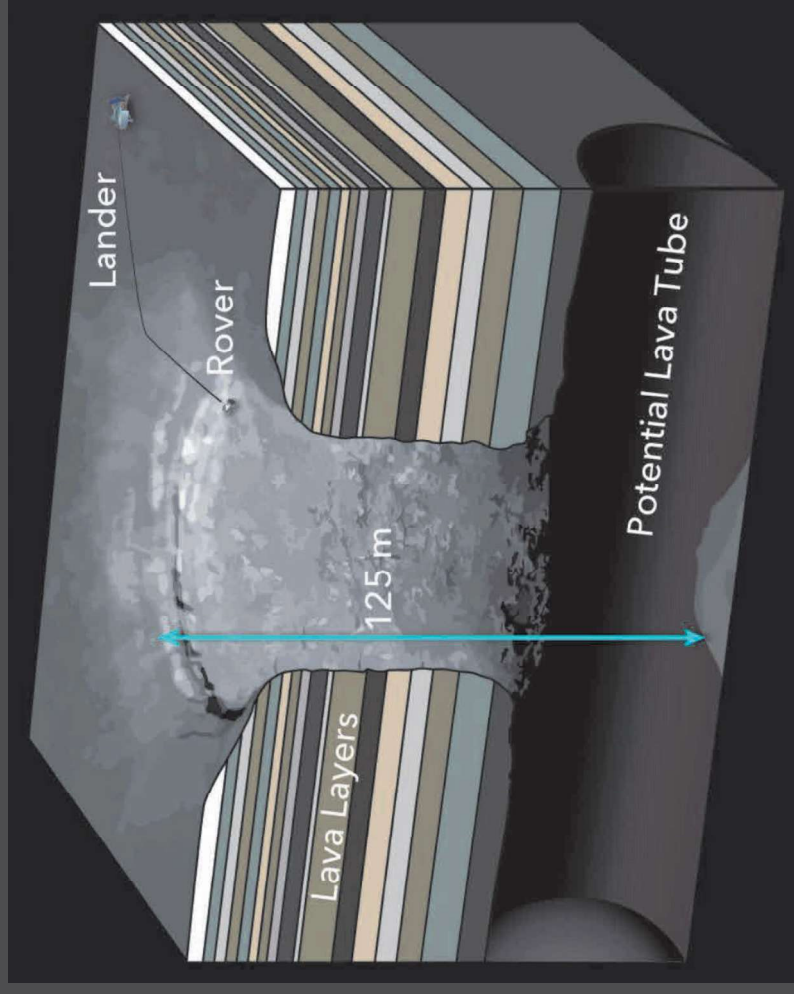
Andrew Wilcoski (JPL)

Tyler Horvath (UCLA)



A little about myself...

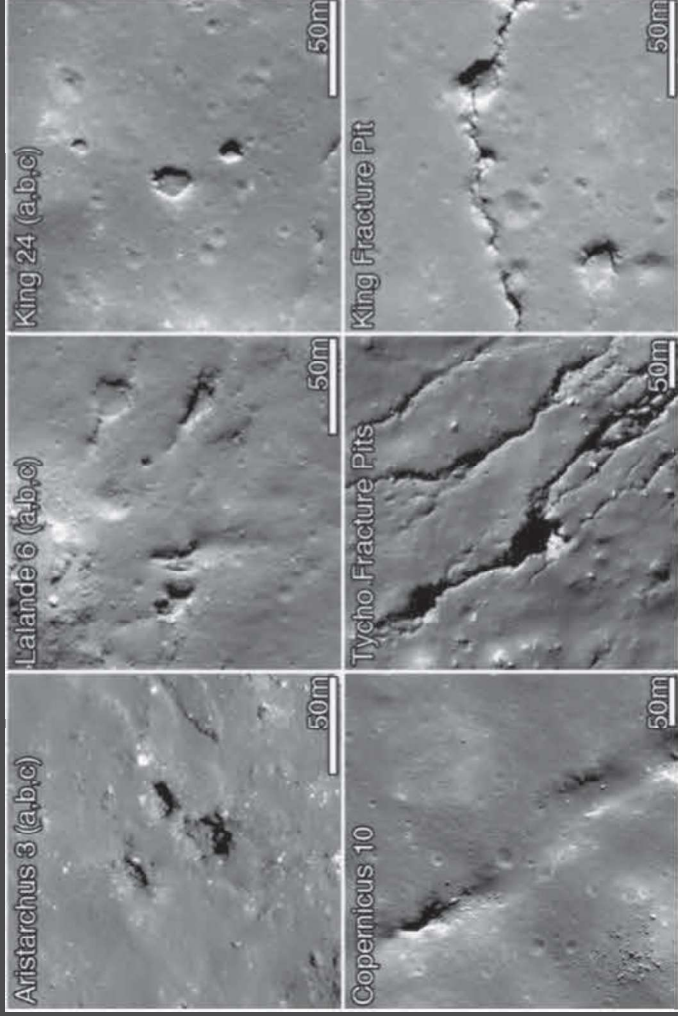
JPL Research Scientist; Volcanologist; PI of Moon Diver Concept



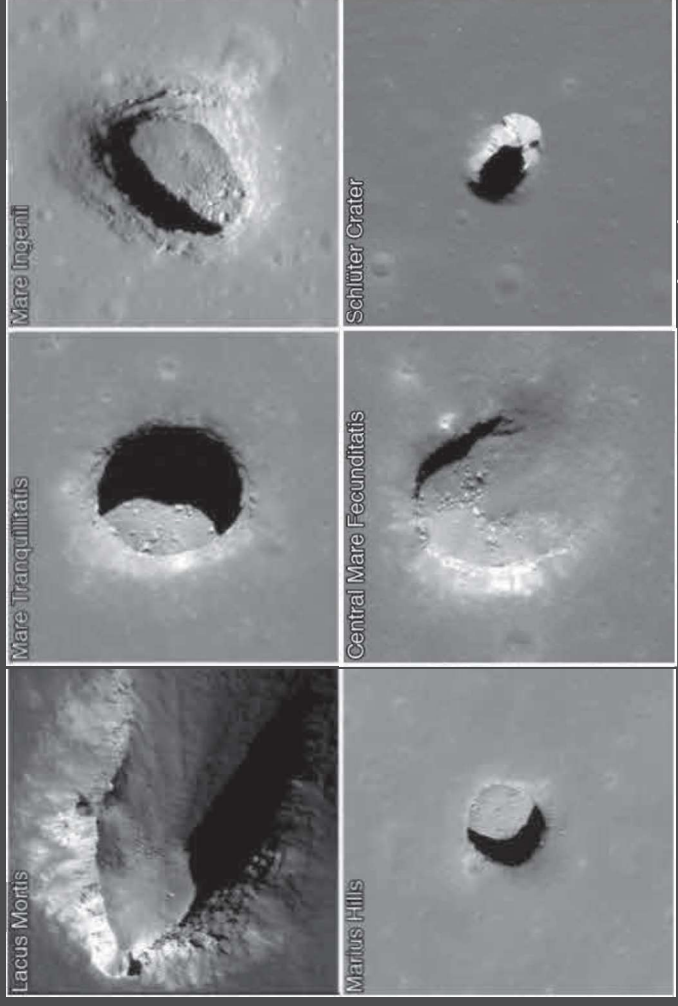
Moon Diver was a 2019 Discovery Concept to explore a pit in Mare Tranquillitatis

Pit Basics: Impact Melt Pits vs Deep Pits

Impact Melt Pits (257)



Mare (15) and Highland (6) Pits



Consult the LRO Pit Atlas for more details!! <https://lroc.im-ldi.com/atlas/pits>

Wagner and Robinson, 2014

- No known pits in the polar regions (as defined for this study)
- Thermal modeling suggests that no lunar pits host long-lived water
- Very few pits that are likely to lead to significant caves
- We can see the Earth from the bottom of the Mare Tranquillitatis Pit

Pit 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)

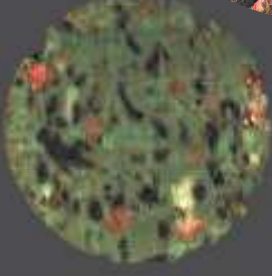
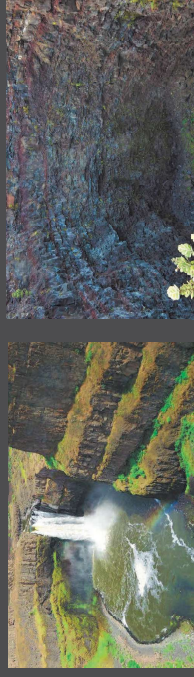
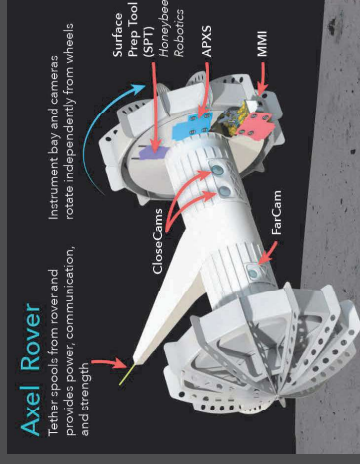
Petrology Determining the structure of the Moon's interior
(in-situ or sample return)

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

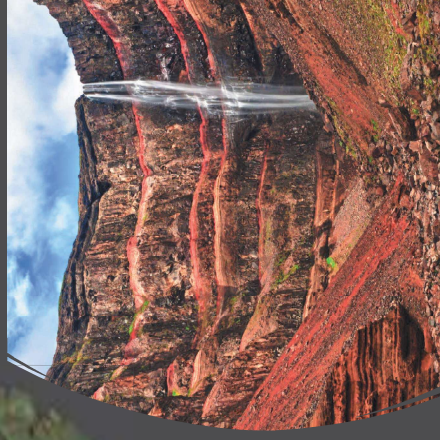
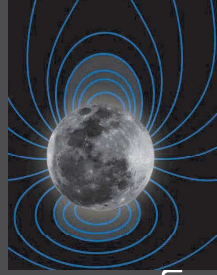
Solar History (shallow paleoregolith sample return)

Galactic History (deeper paleoregolith sample return)

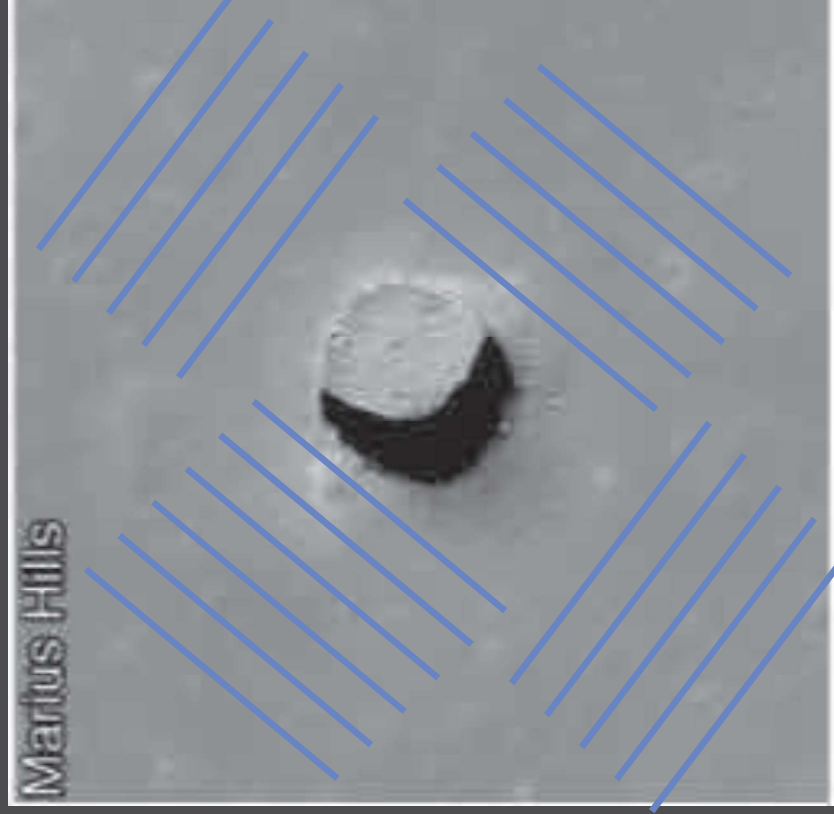
Dark Matter Detection (in-situ detector in cave)



Thick or thin?



What Can Humans Do? **Surface**

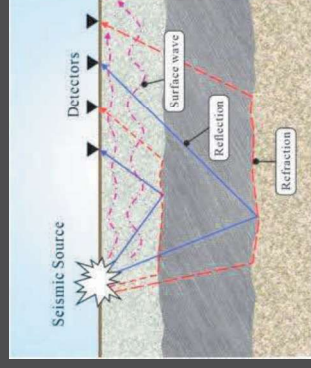


Surface-based exploration:

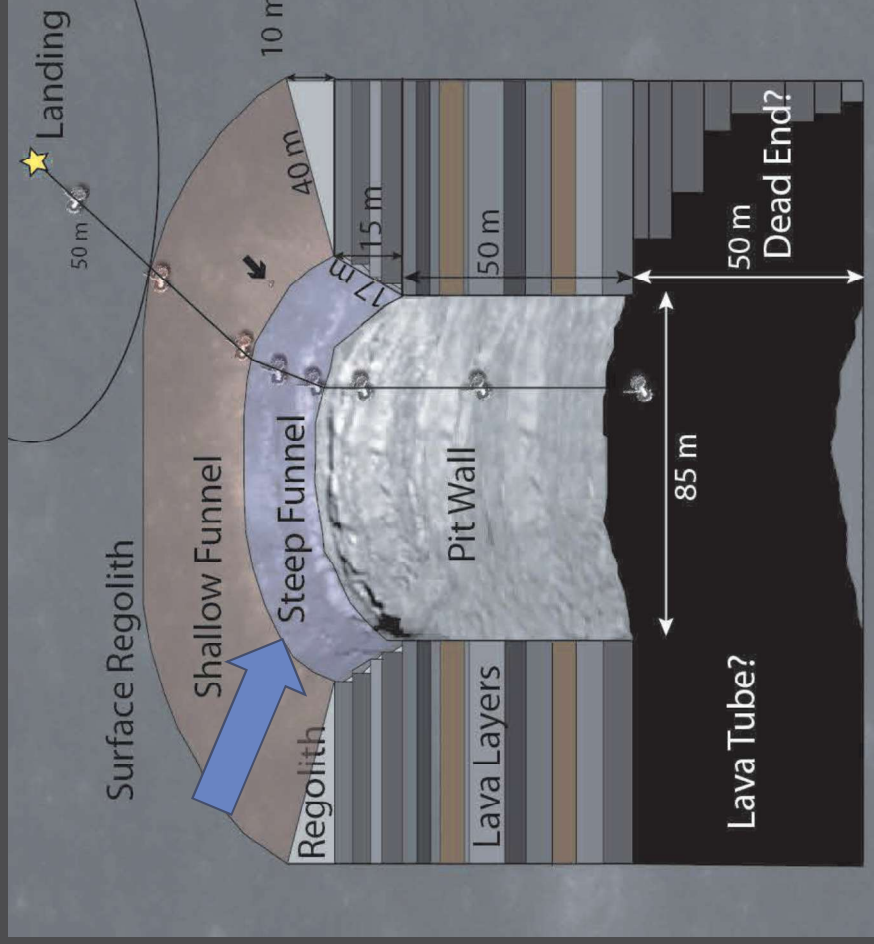
- Geophones/seismic
- Mortars/thumpers
- Ground penetrating radar
- Magnetic surveys
- Gravimeters

Measure subsurface void

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

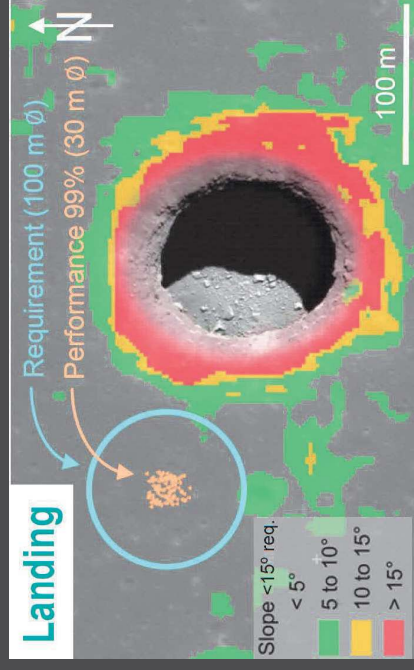


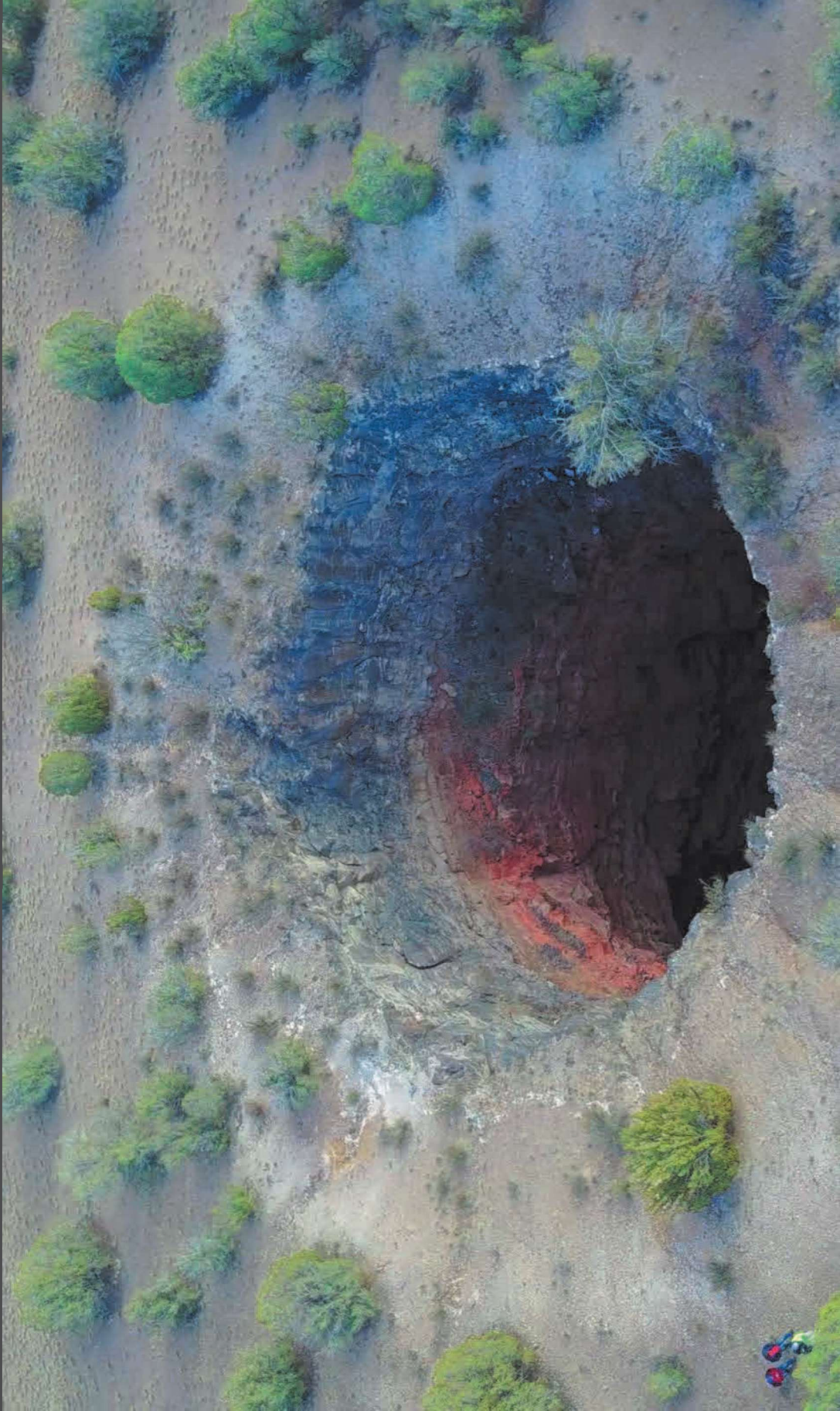
What Can Humans Do? **Funnel**



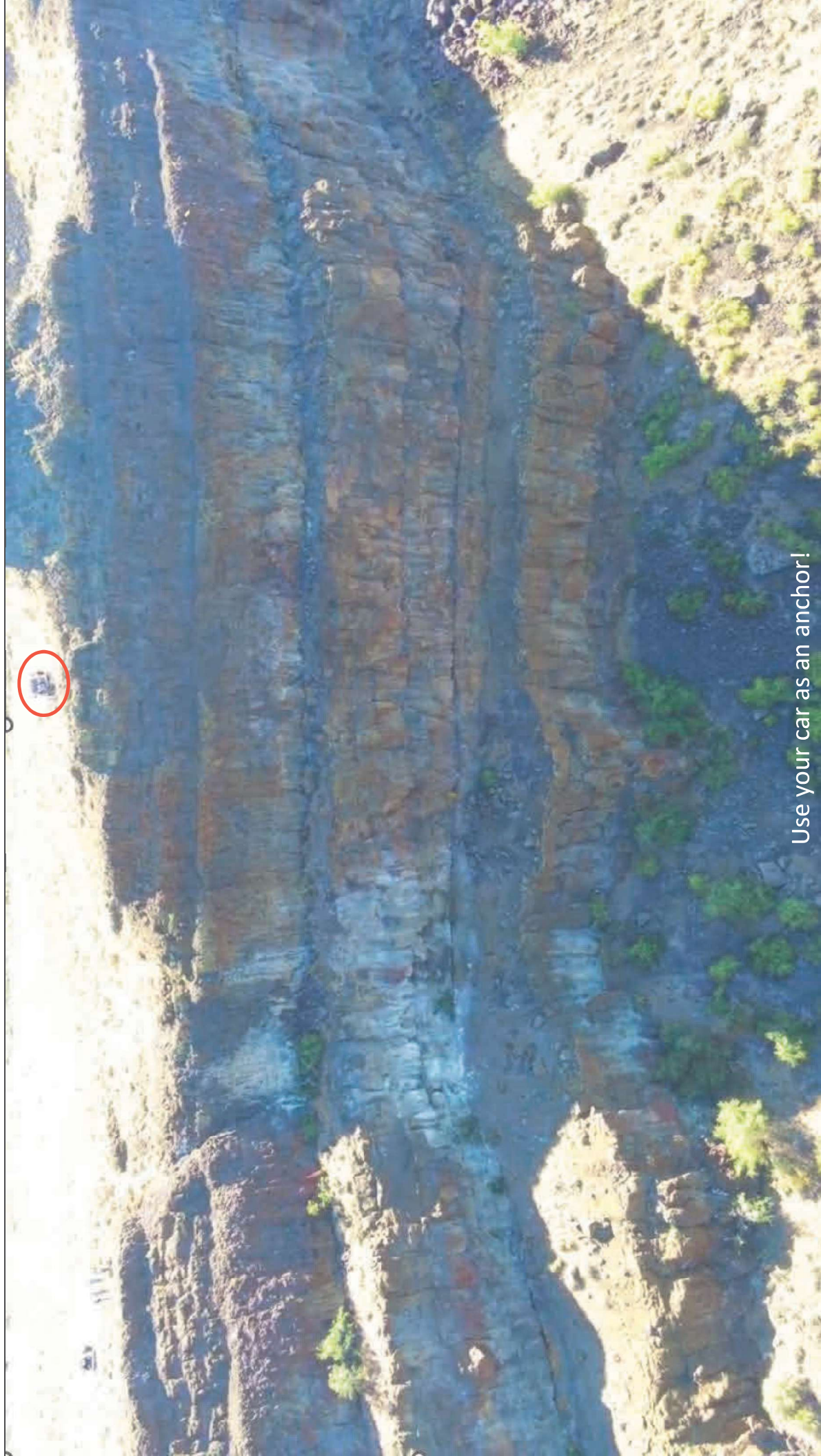
Funnel-based Exploration:

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





30-40 m across (~100 ft)

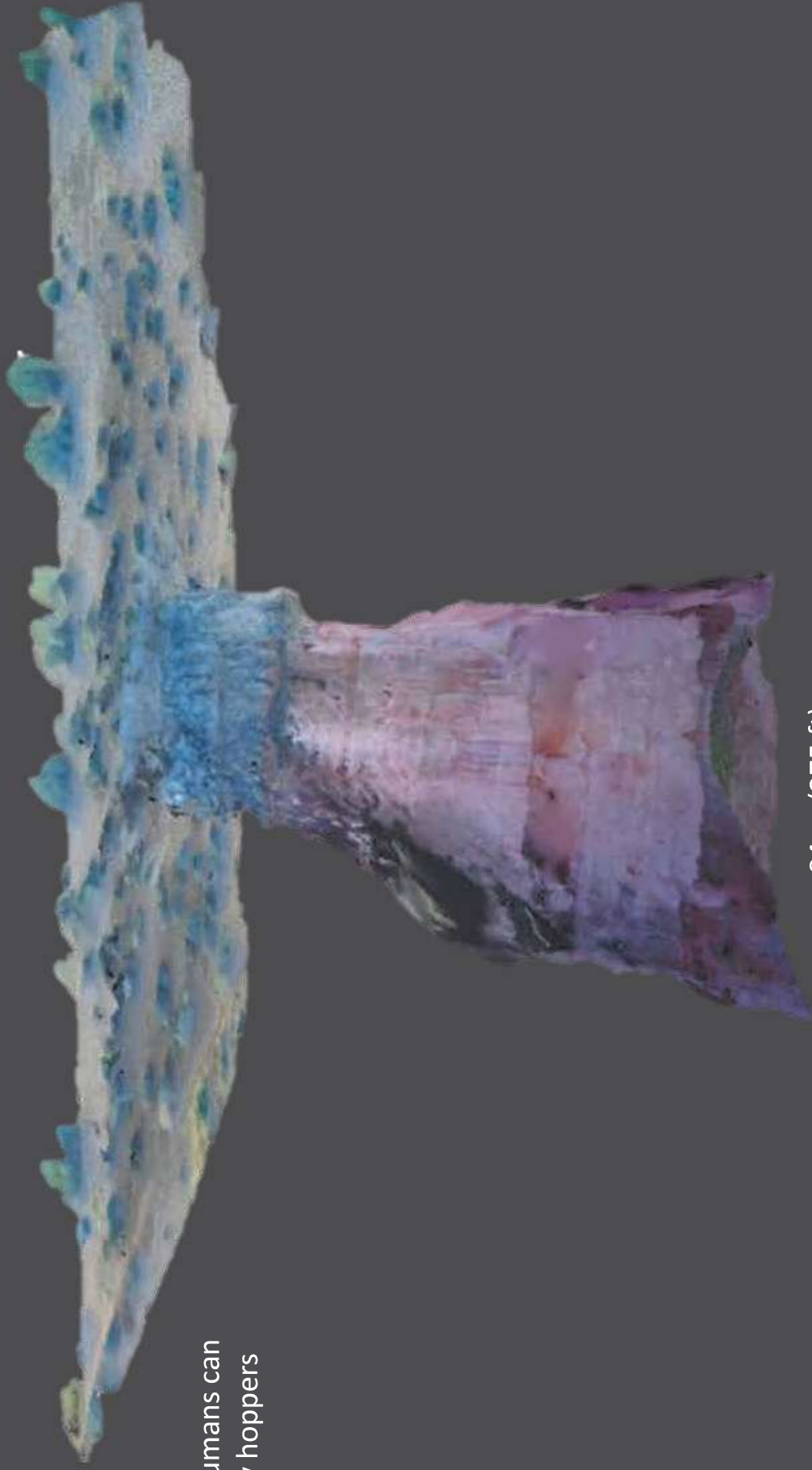


Use your car as an anchor!

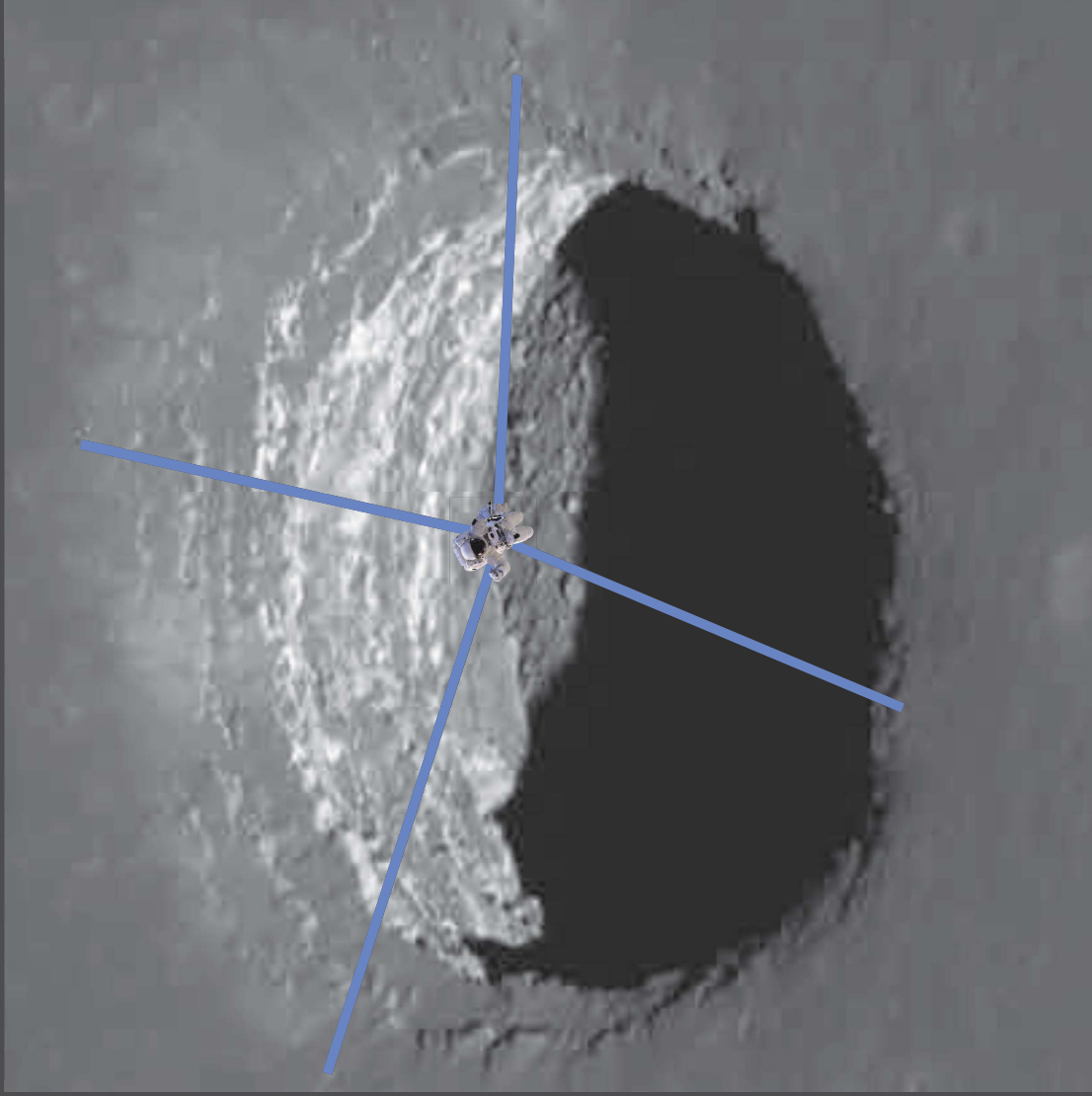
Humans can
operate
robots in
real time



Humans can
fly hoppers



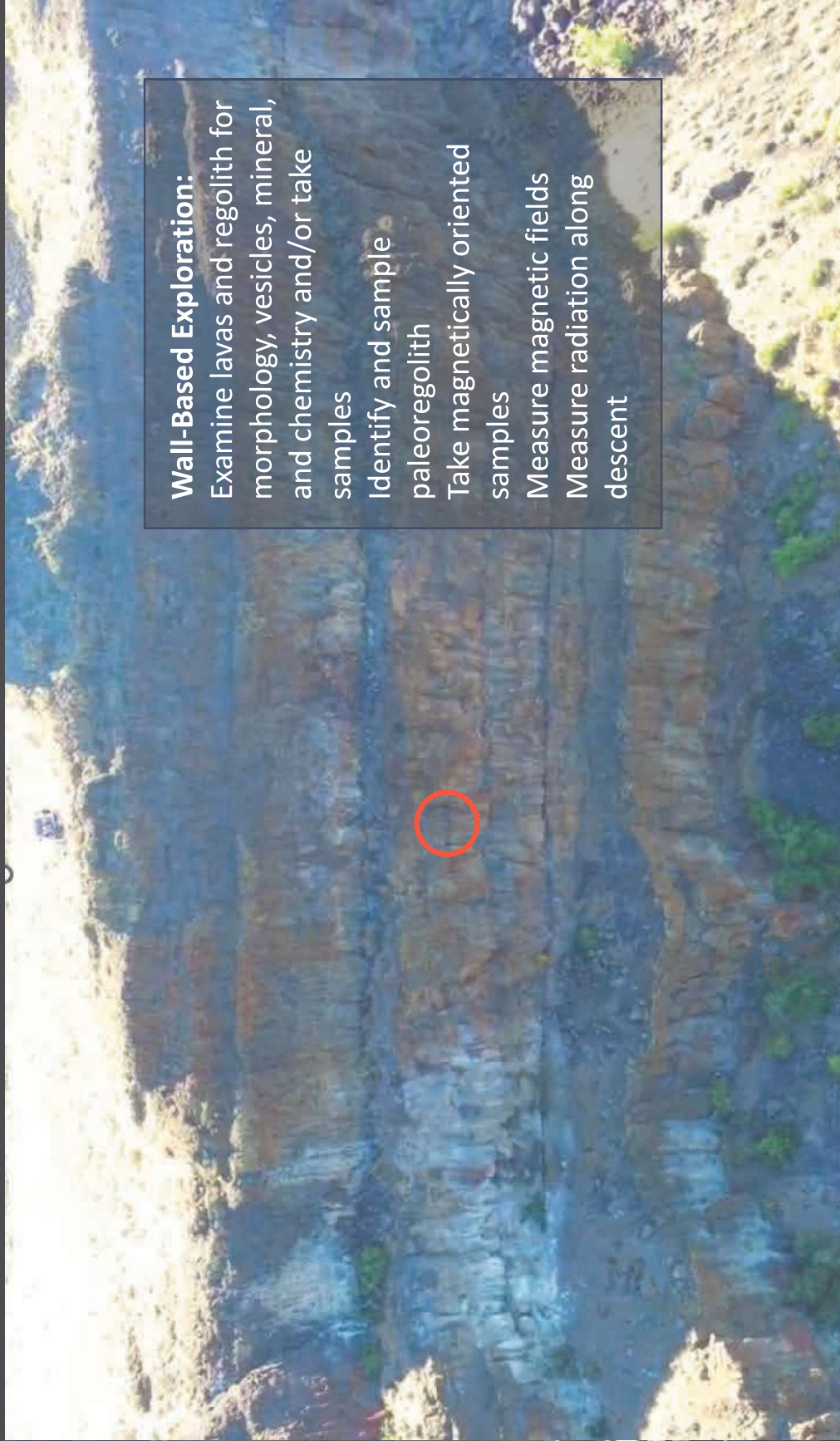
84 m (275 ft)



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!

What Can Humans Do? Wall



Wall-Based Exploration:

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

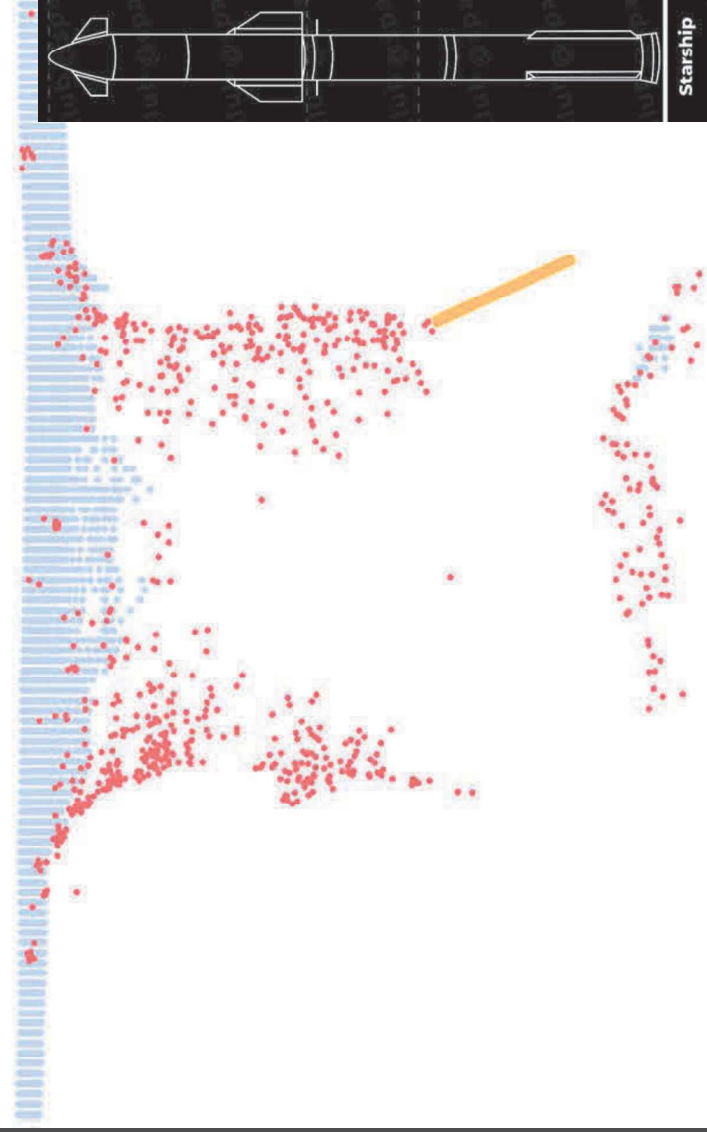
Identify and sample paleoregolith

Take magnetically oriented samples

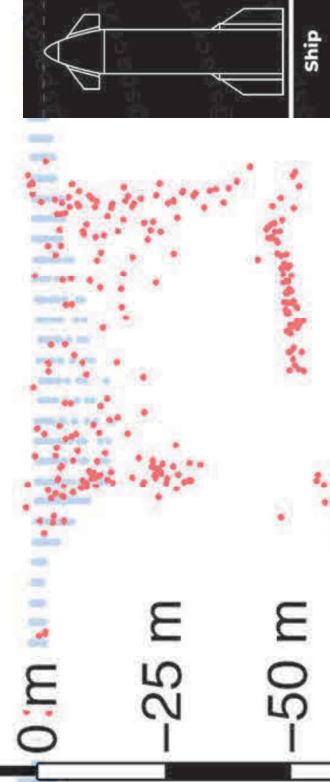
Measure magnetic fields

Measure radiation along descent

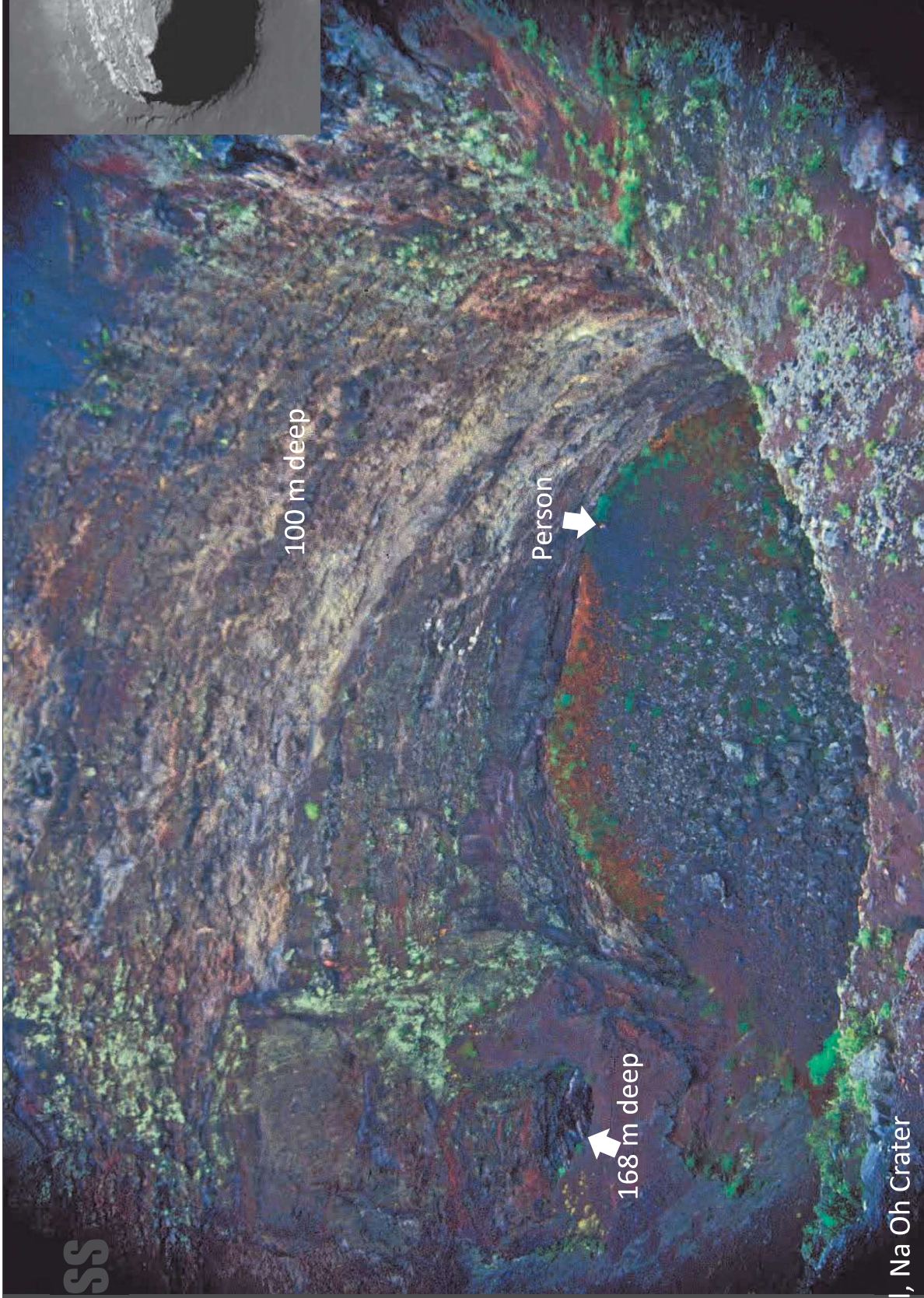
a. Mare Tranquillitatis Pit (MTP)



b. Marius Hills Pit (MHP)



Reminder: You will probably need to take all of your stuff down a giant elevator anyway.



SS

100 m deep

Person

168 m deep

Dave Bunnell, Na Oh Crater



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!

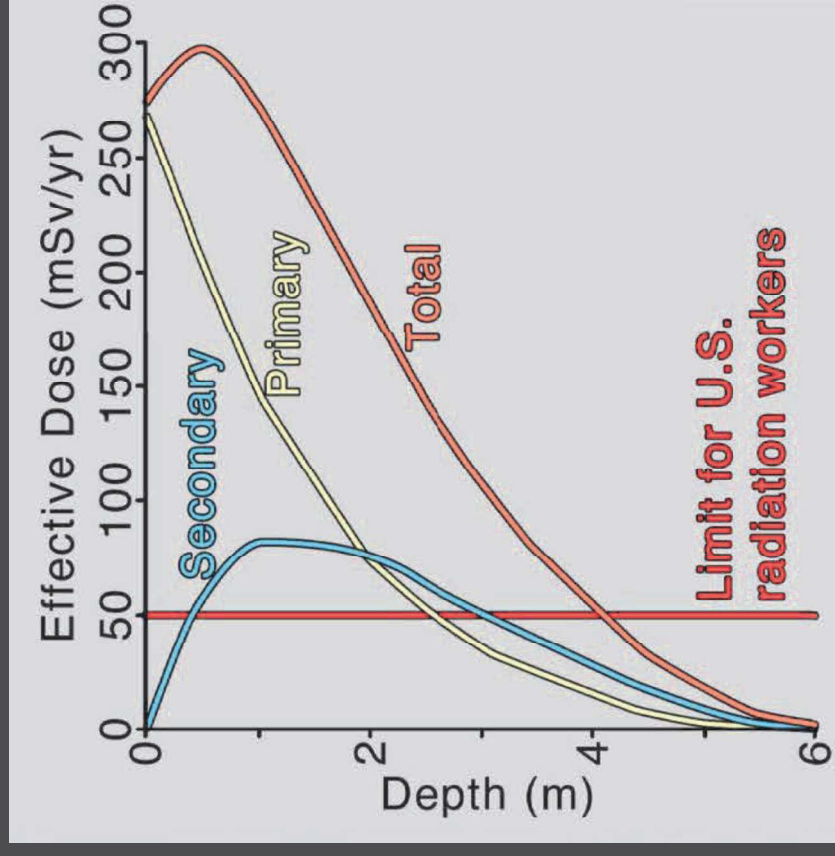
Humans are very good at rappelling!



What Can Humans Do? Cave

- 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

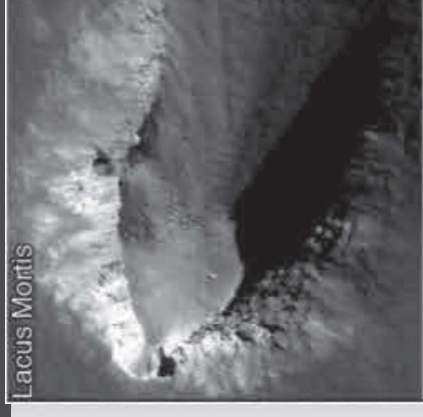


Modified by Wagner et al. from De Angelis, G. et al. (2007)



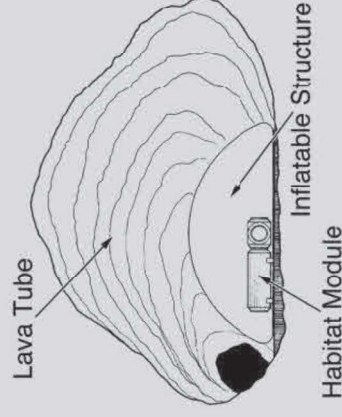
Regolith Shielding

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



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



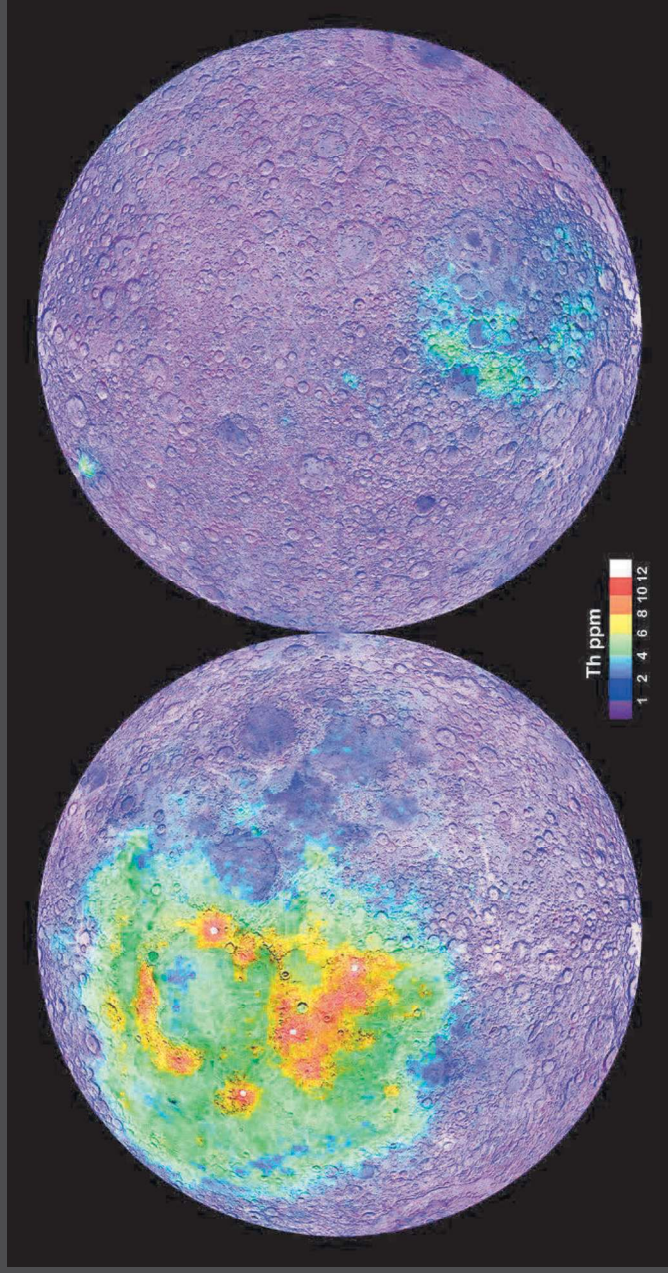
Adapted from Dogai and Dagg (1992).

Caves

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

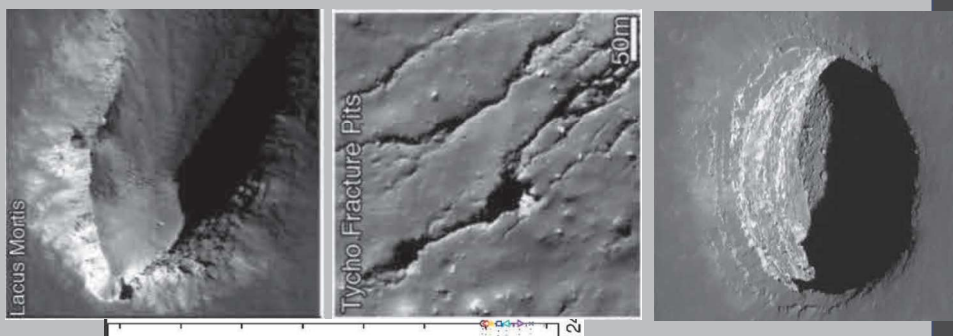
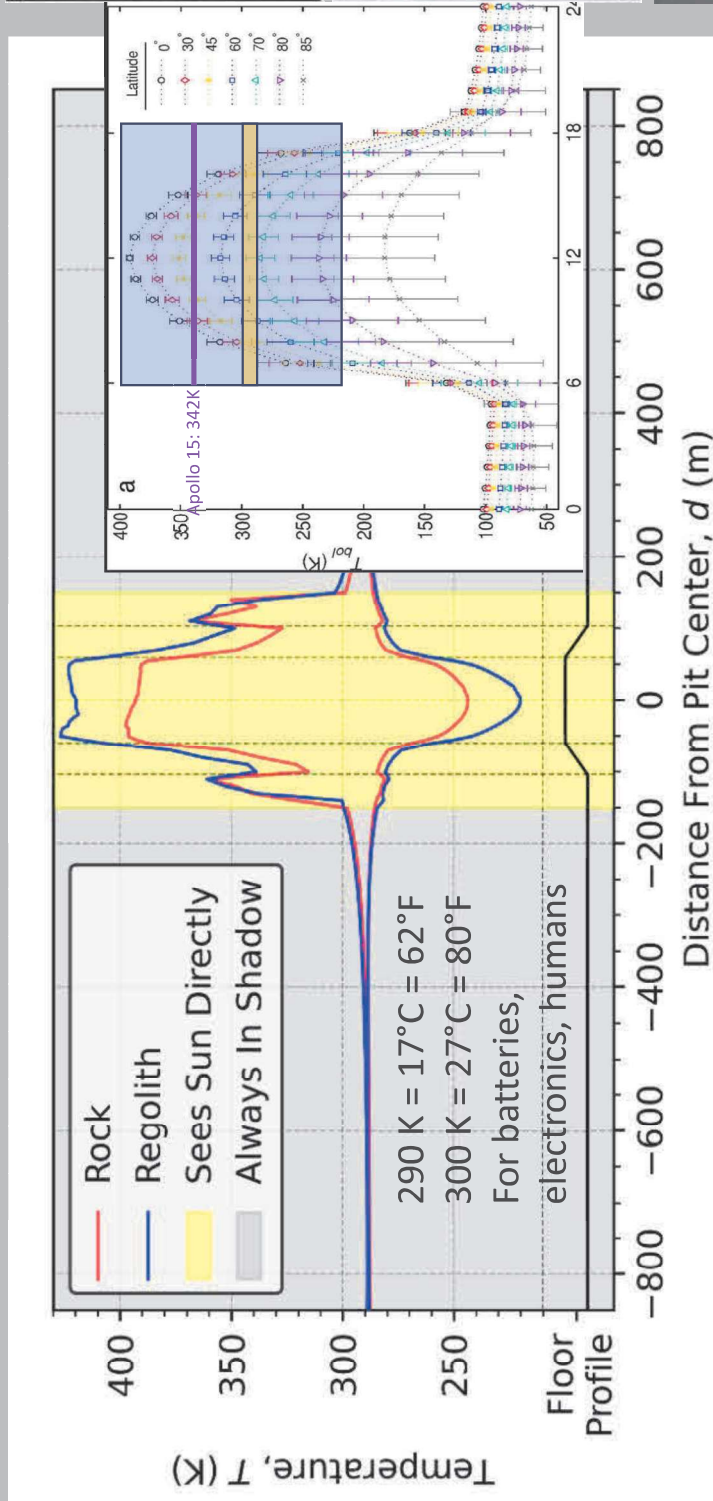


Secondary radiation from
illuminated walls

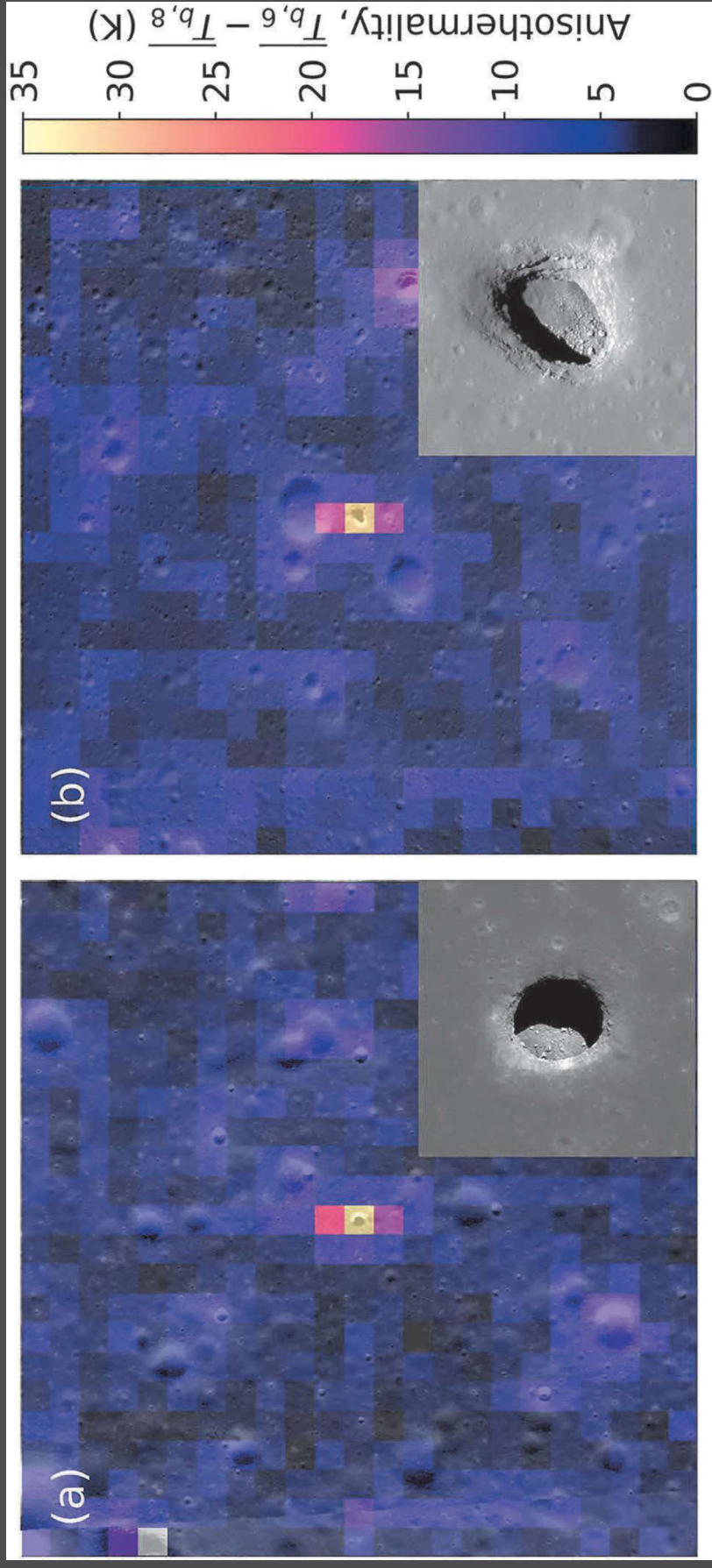


Intrinsic Radiation from Rocks

Caves Provide a Stable Thermal Environment (for humans and plants?)



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



Horvath et al., 2022

Assessing a Cave Resource

- **Impact Hazards:** Humans can set up devices to measure meteorite impact flux and impact effects from rocket blasts
- **Thermal Environment:** Humans can measure the thermal environment of the pit and cave using thermal cameras and in-situ sensors
- **Stability:** Humans can assess the stability of the cave using cameras to observe crack patterns and presence or absence of break-down. Caves are generally stable on human lifespans, especially on the Moon.
- **Dust:** Humans can characterize the amount of dust at the pit bottom and inside the cave
- **Radiation Environment:** As a radiation shelter or permanent shelter for humans, plants, and supplies

Goals for Assessing a Cave

Goal	Measurements	Mission Requirement
Determine size and shape of cave (low quality)	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 (source of instability)	Images of walls	Top of funnel
Understand the regolith/bedrock interface (for ISRU)	Geophysical measurements; direct imaging	Surface; top of funnel
Characterize thermal environment	Thermal imaging, thermocouples	Surface to cave interior
Characterize radiation environment	Dosimeters, radiation	Surface to inside cave

Planetary Science, Astrophysics, Heliophysics

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	Image of transition; composition of surface regolith and underlying layers	Access to funnel (may need to sweep off interface)
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
Sample ancient solar wind	Samples of paleoregolith layers, cms deep	Access to wall
Understand ancient galaxy	Samples of paleoregolith layers, m deep	Access to wall
Directly measure dark matter	Install detector in cave	Access to cave



Extra Slides



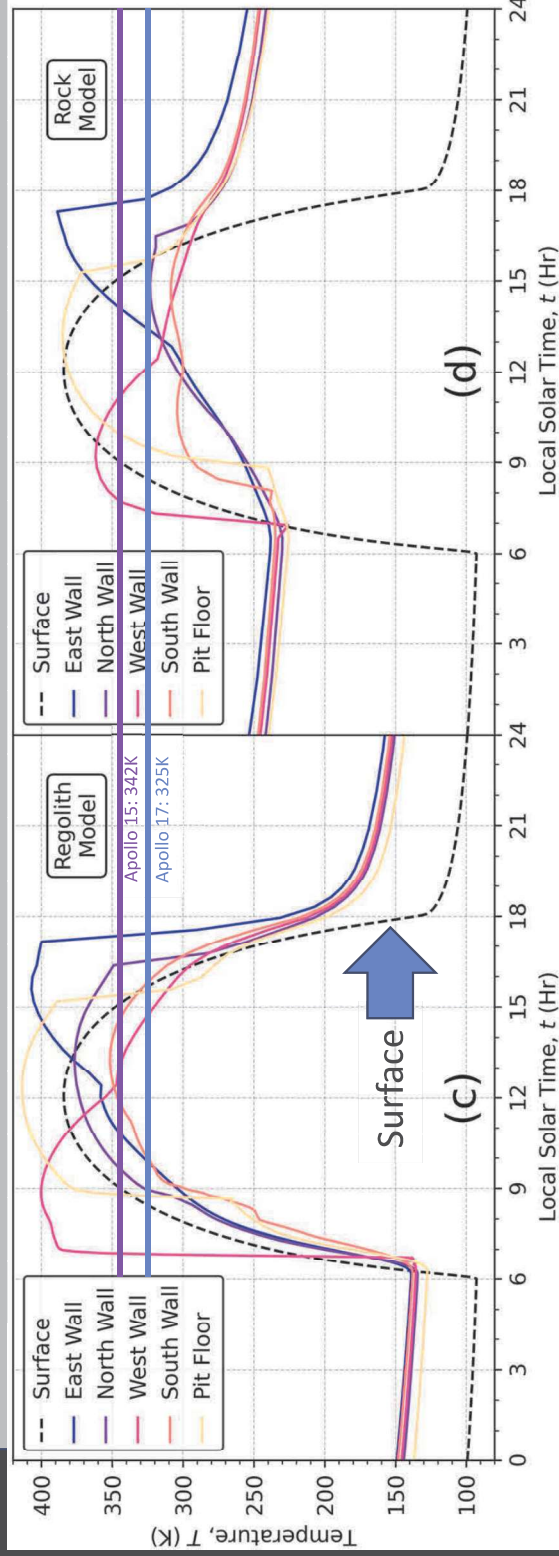
RADIATION

MICRO-METEORITES

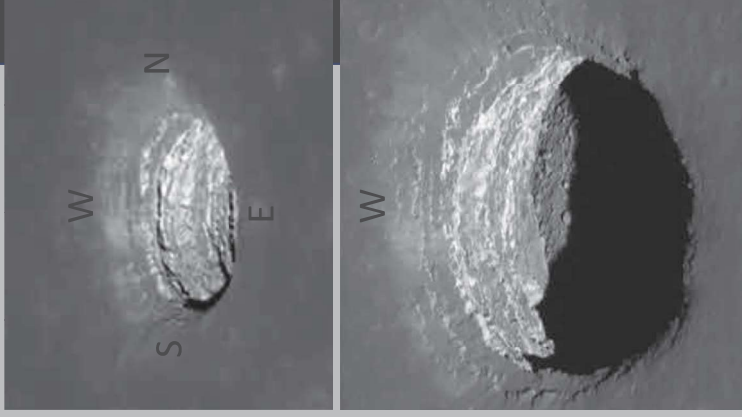
THERMAL SWINGS

DUST

VACUUM



Horvath et al., 2022



<https://www.nasa.gov/history/alsj/WOTM/WOTM-ThermalEnvrnmnt.html>

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....

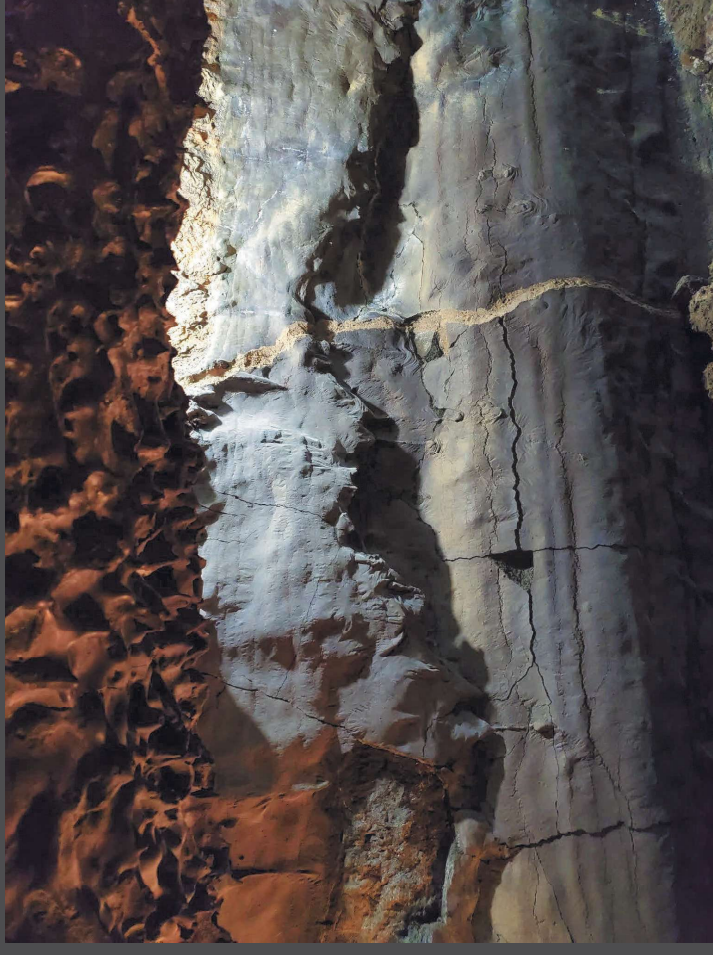


Porosity- Lavas vary greatly in porosity, with high porosities seen near the tops of lava units. However, individual pores are not always connected.

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.

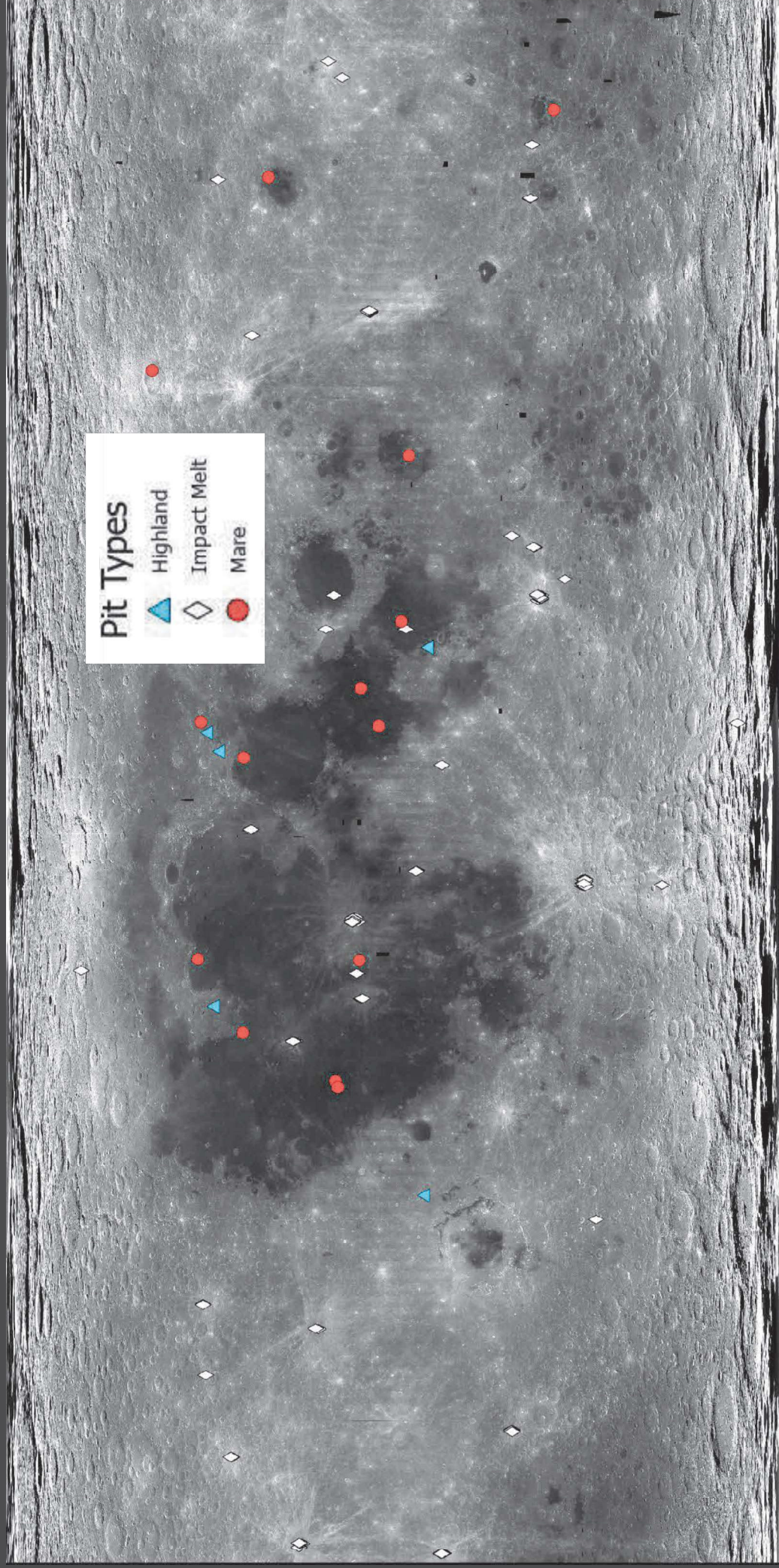
Cracks- On Earth, cracks often form during cooling and then widen later due to infiltration by water, earthquakes, and tectonic stresses.

Someone should try it...

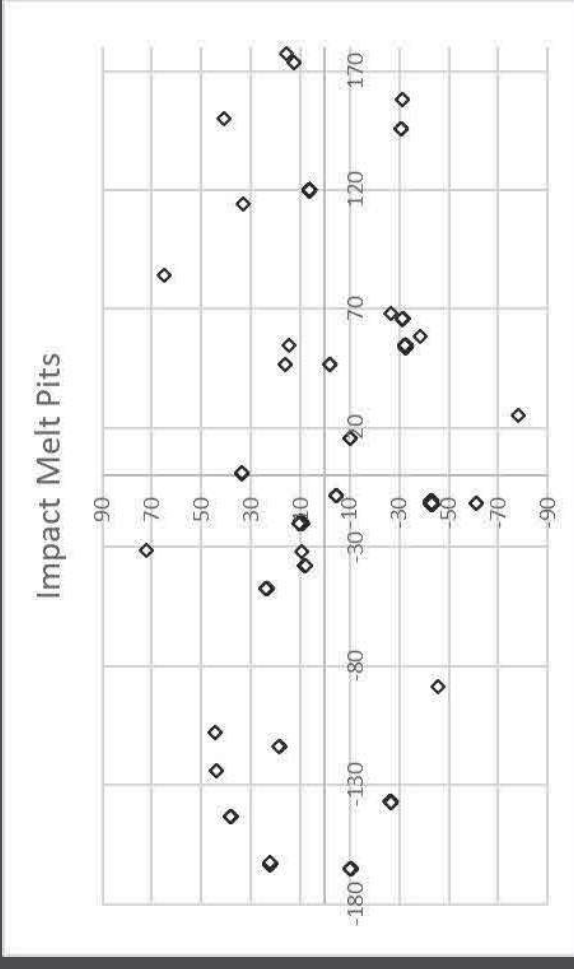
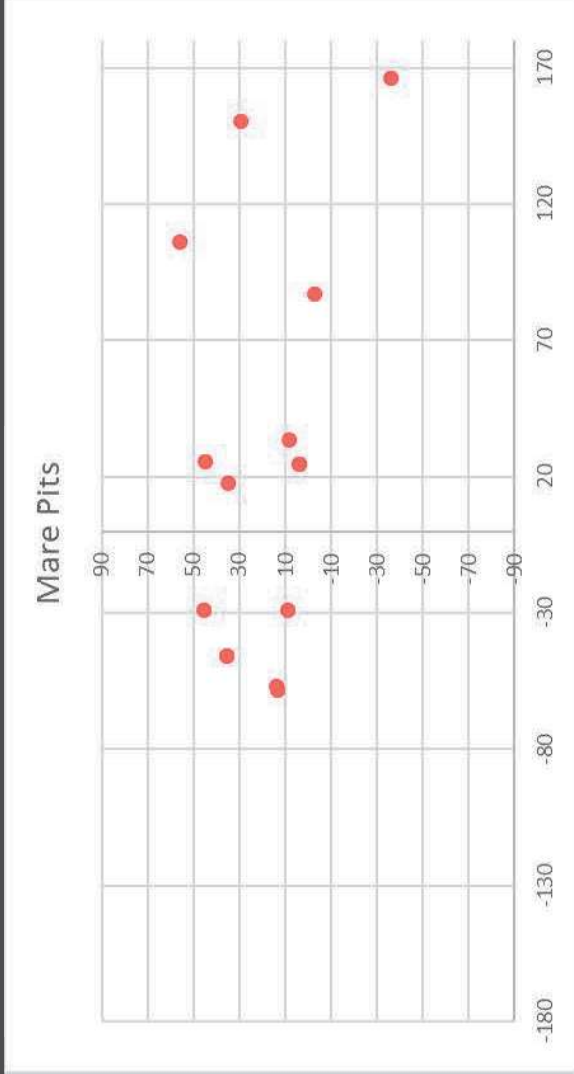


Cueva de los Verdes, Laura Kerber

Pit Distribution

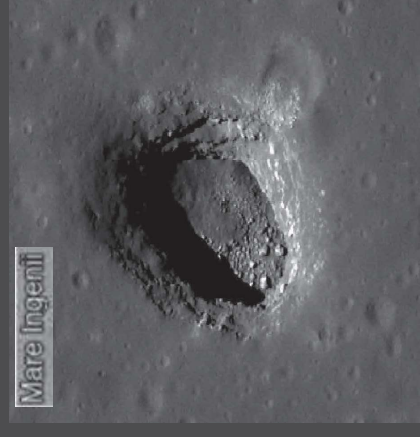
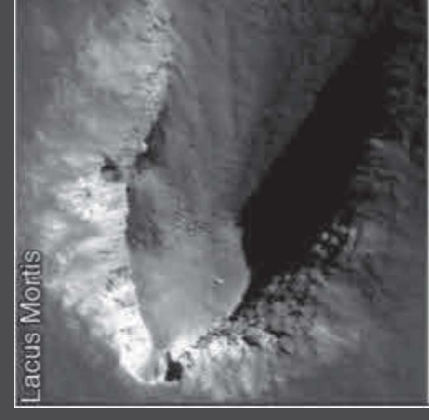


Pit Distribution



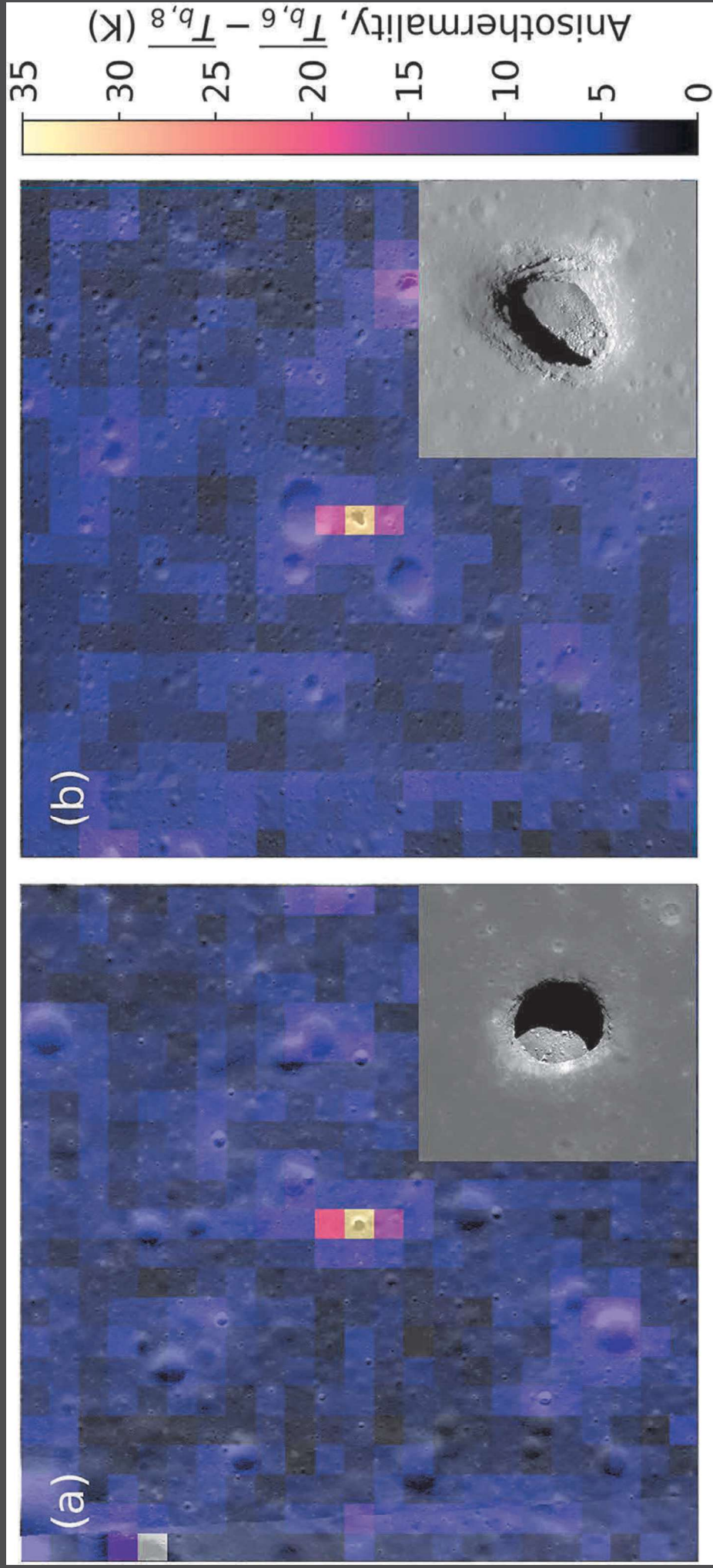
Important Points:

- There are no confirmed pits in the polar regions ($>84^\circ$ latitude)
- For Mare Pits, it is because there is no mare!
- For Impact Melt Pits, it is hard to confirm them
- Even Pascal Lee's northern pits are outside the polar region ($\sim 73^\circ\text{N}$)
- Pits are not expected to contain water ice (even if they are at high latitudes) (Wilcoski et al., 2023); however, water left by humans could persist for some time.



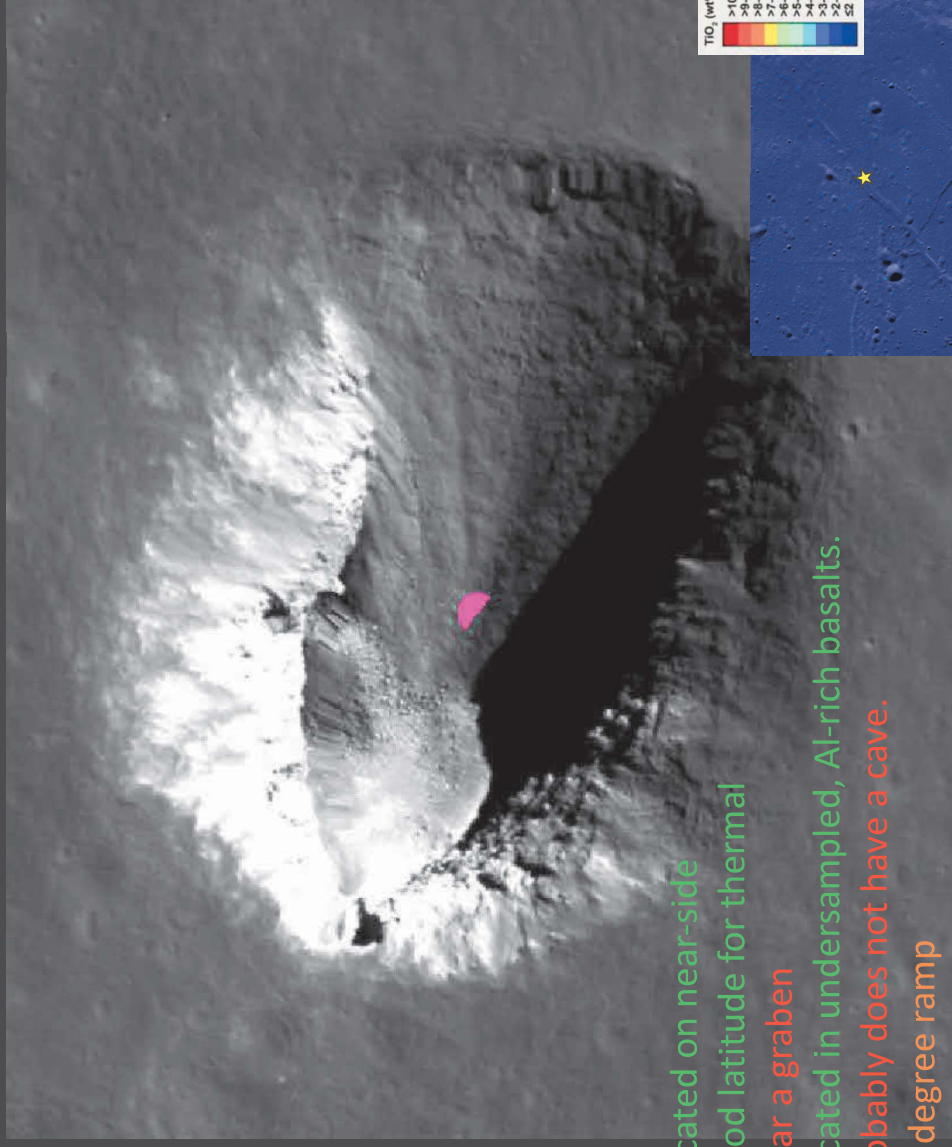
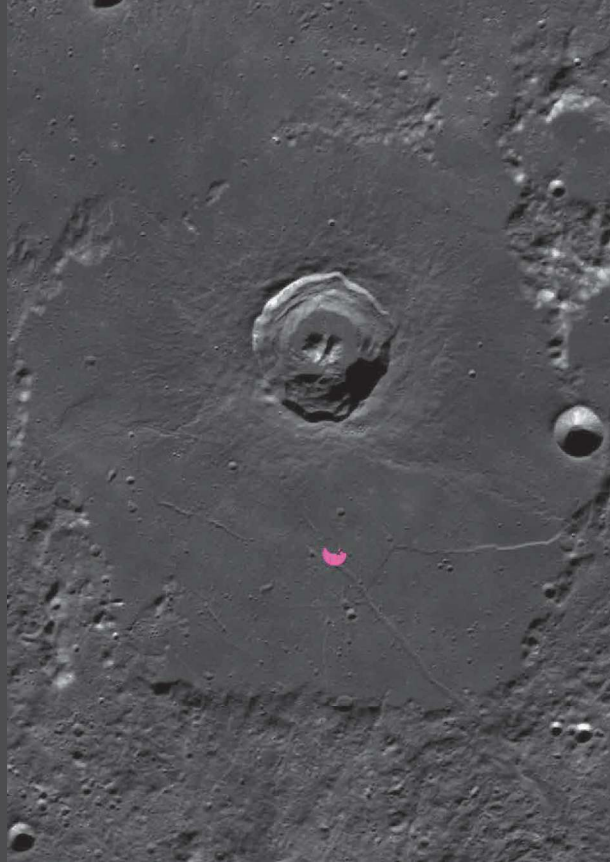
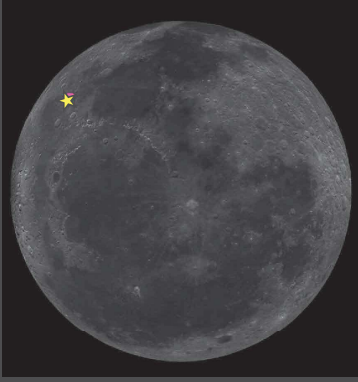
The Big 5





Horvath et al., 2022

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.

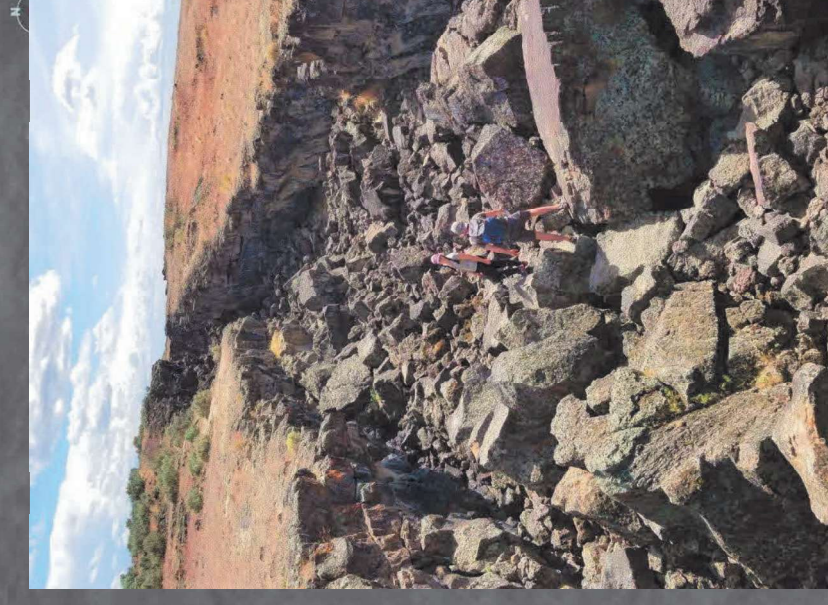
22 degree ramp

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

Sufficient radiation shielding.

Low iron, low titanium

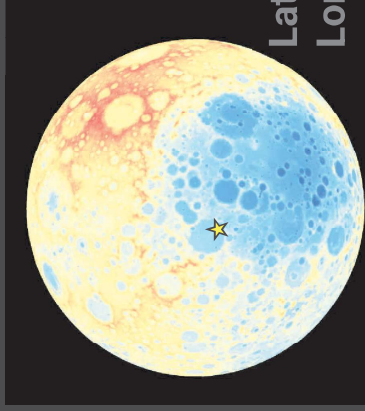
Lacus Mortis



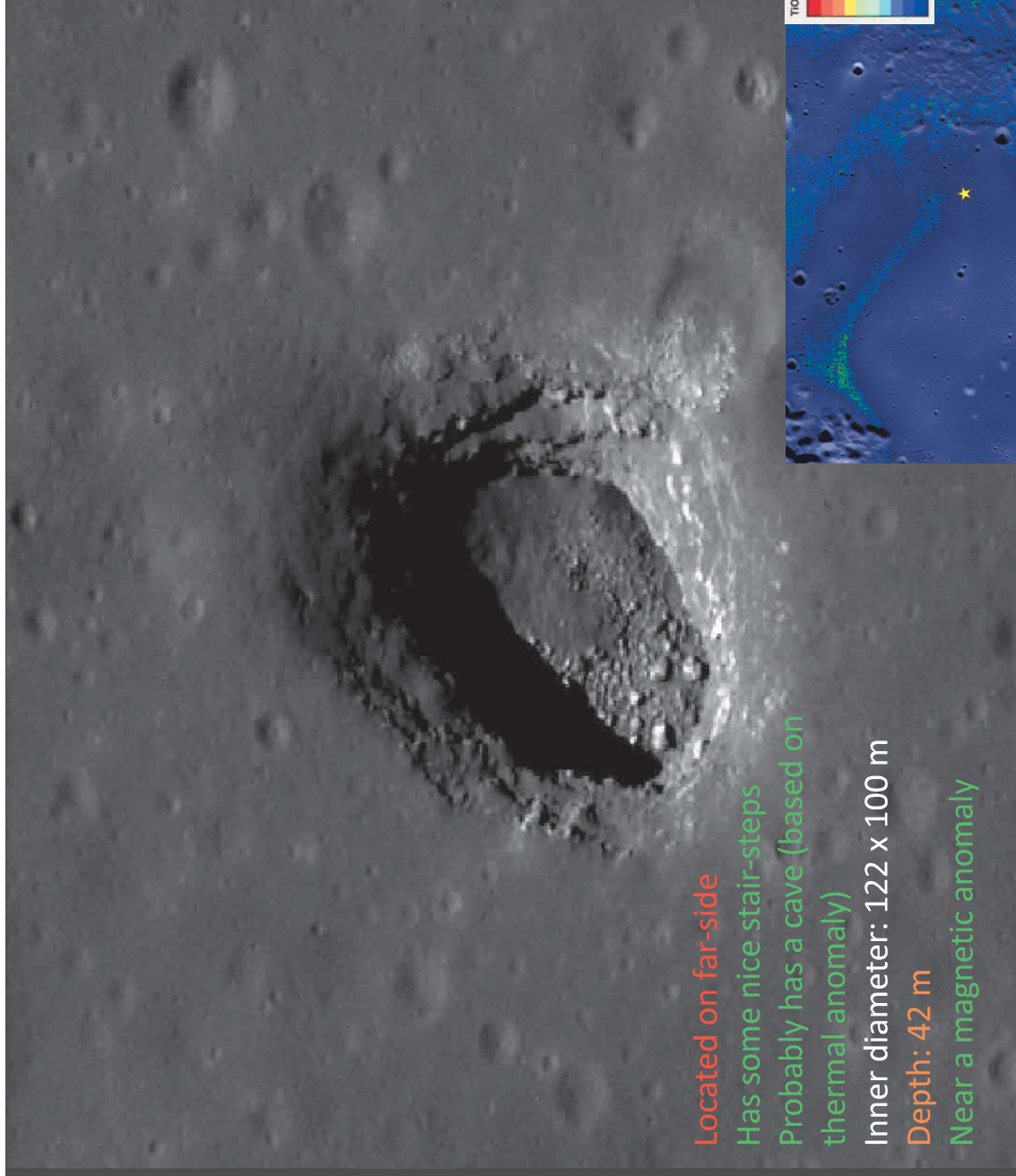
Tabernacle Hill, UT; Laura Kerber

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

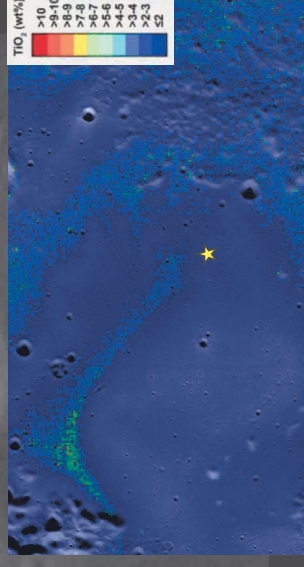
Has some nice stair-steps

Probably has a cave (based on thermal anomaly)

Inner diameter: 122 x 100 m

Depth: 42 m

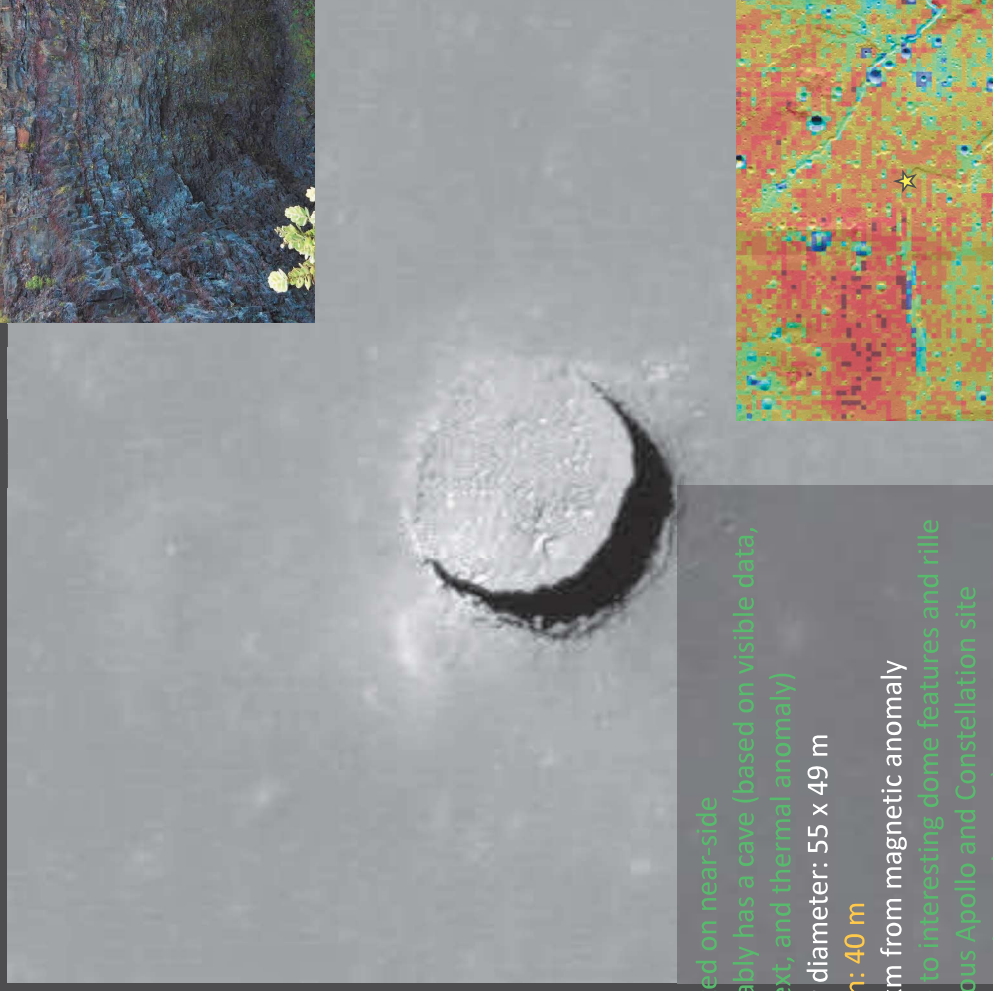
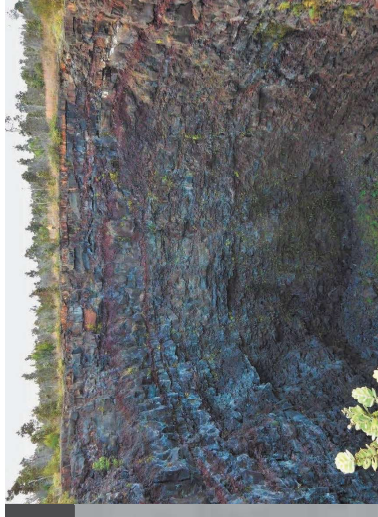
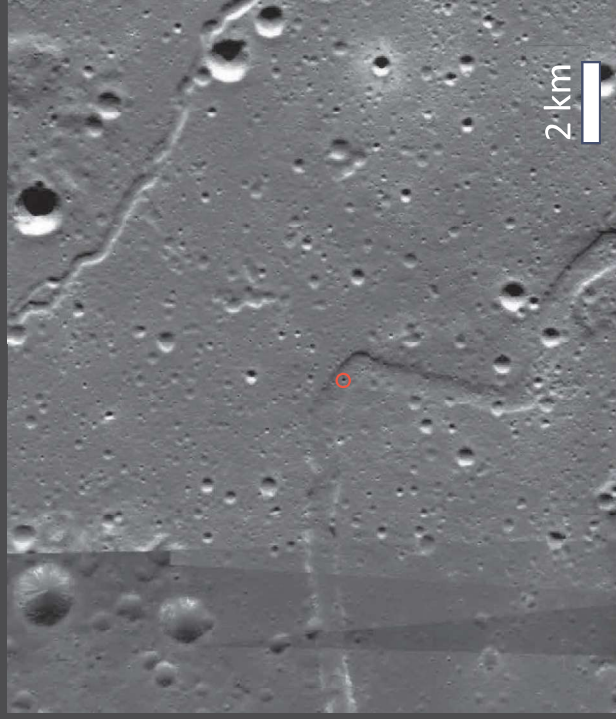
Near a magnetic anomaly



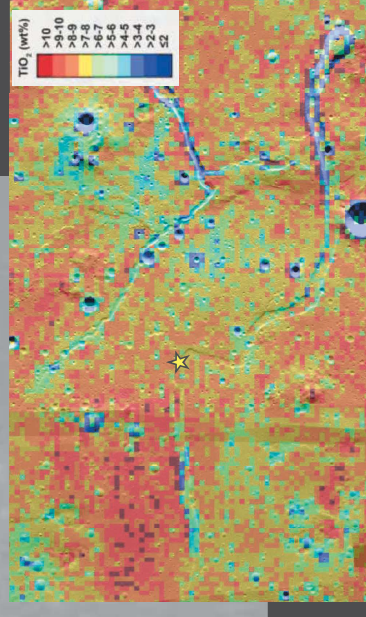
Marius Hills Pit



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) He_3 ?
High Iron lavas (18-20% FeO)

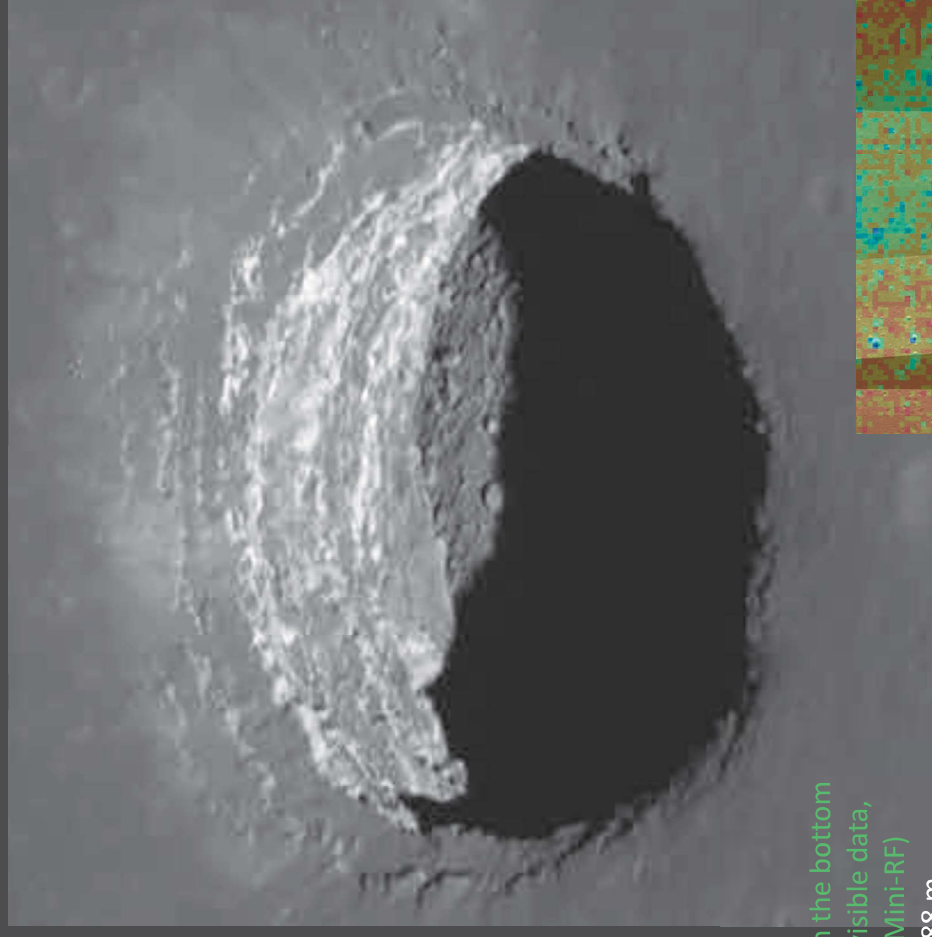


Tranquillitatis Pit



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)

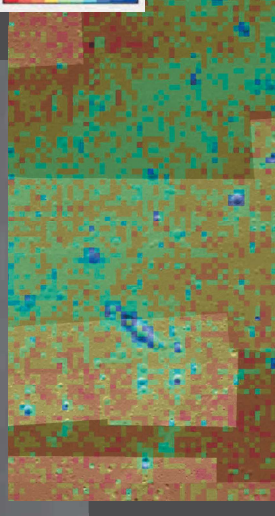
Inner diameter: 100 x 88 m

Depth: 105 m

Close to intersection of two lava units

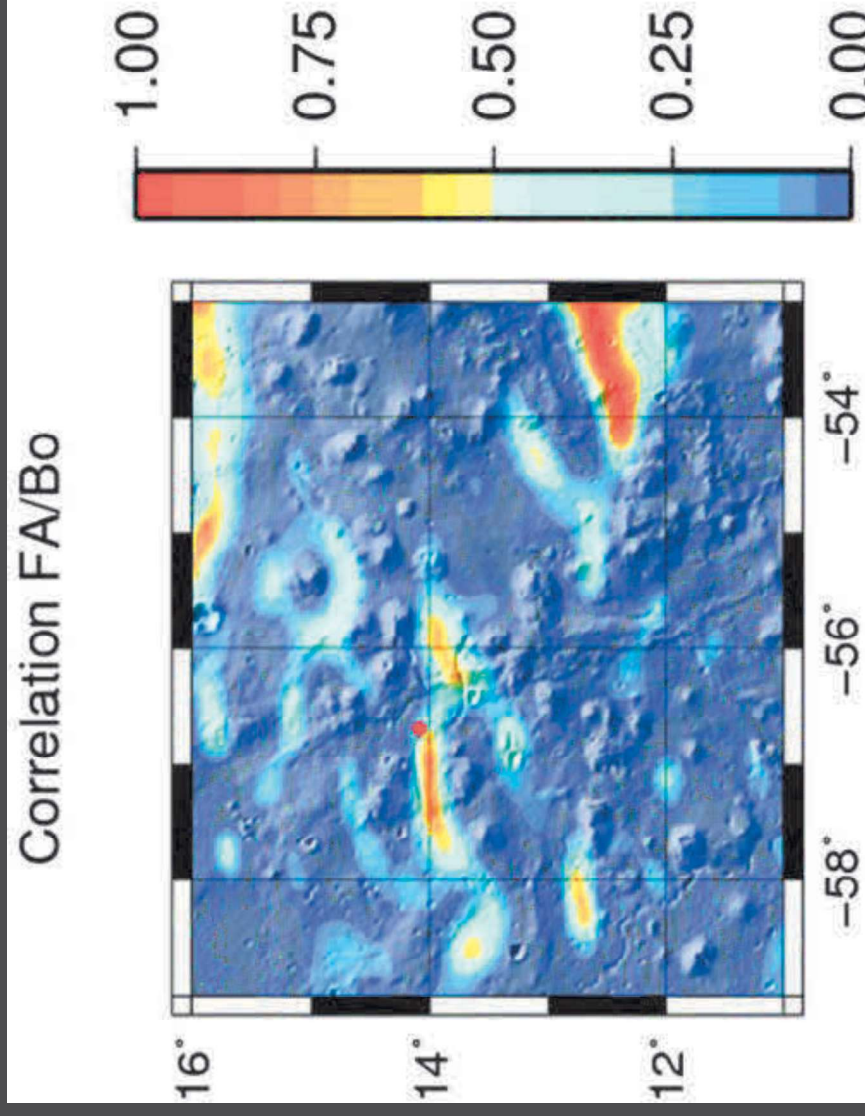
High titanium lavas (6-8% TiO_2)

High iron lavas (17.5-19.5% FeO)



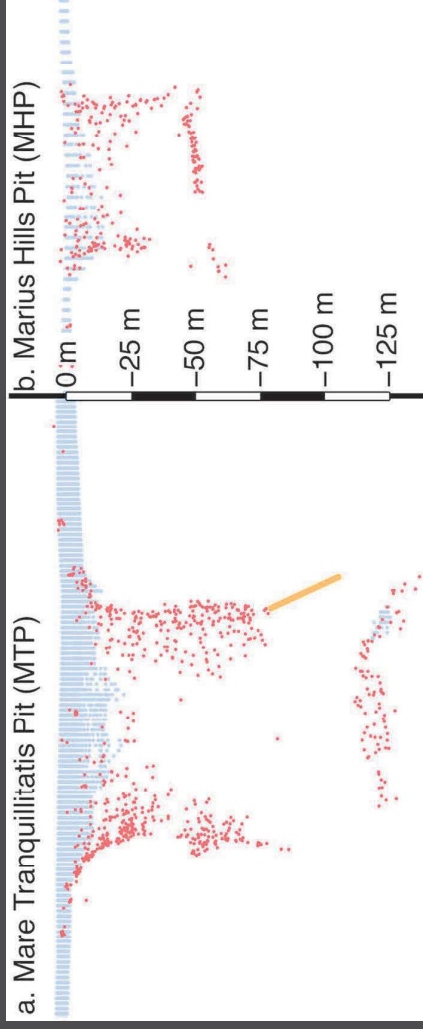
Attempted Ways to Confirm a Cave

- 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)



PIT FLOOR

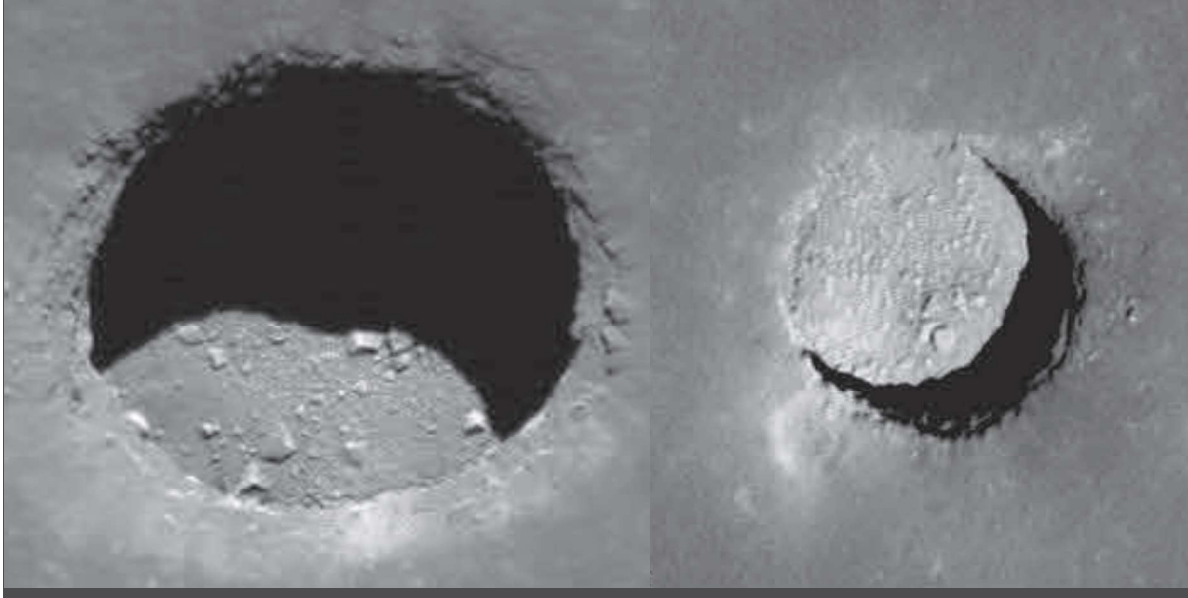
The floor of pits are covered in giant boulders. It is scary, but humans are also actually pretty good at this.



Wagner and Robinson,



Photo: David Bunnell



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)

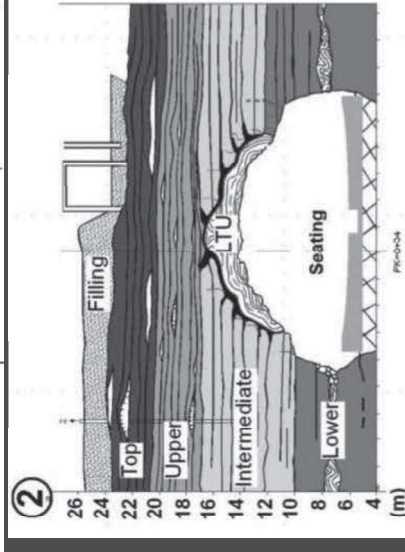
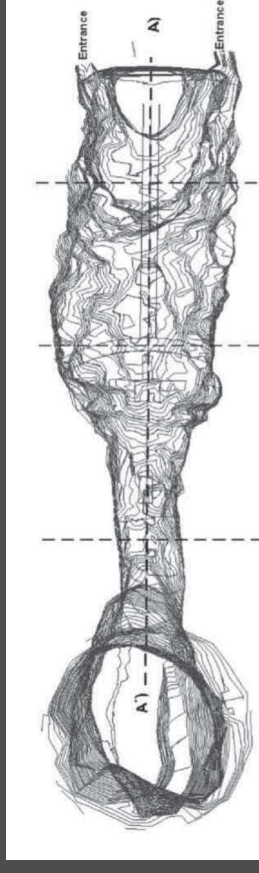
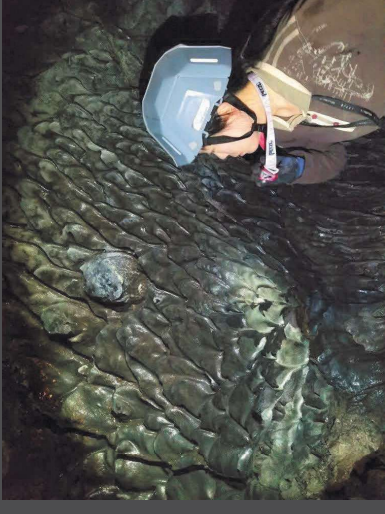


Hengifoss, Iceland

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

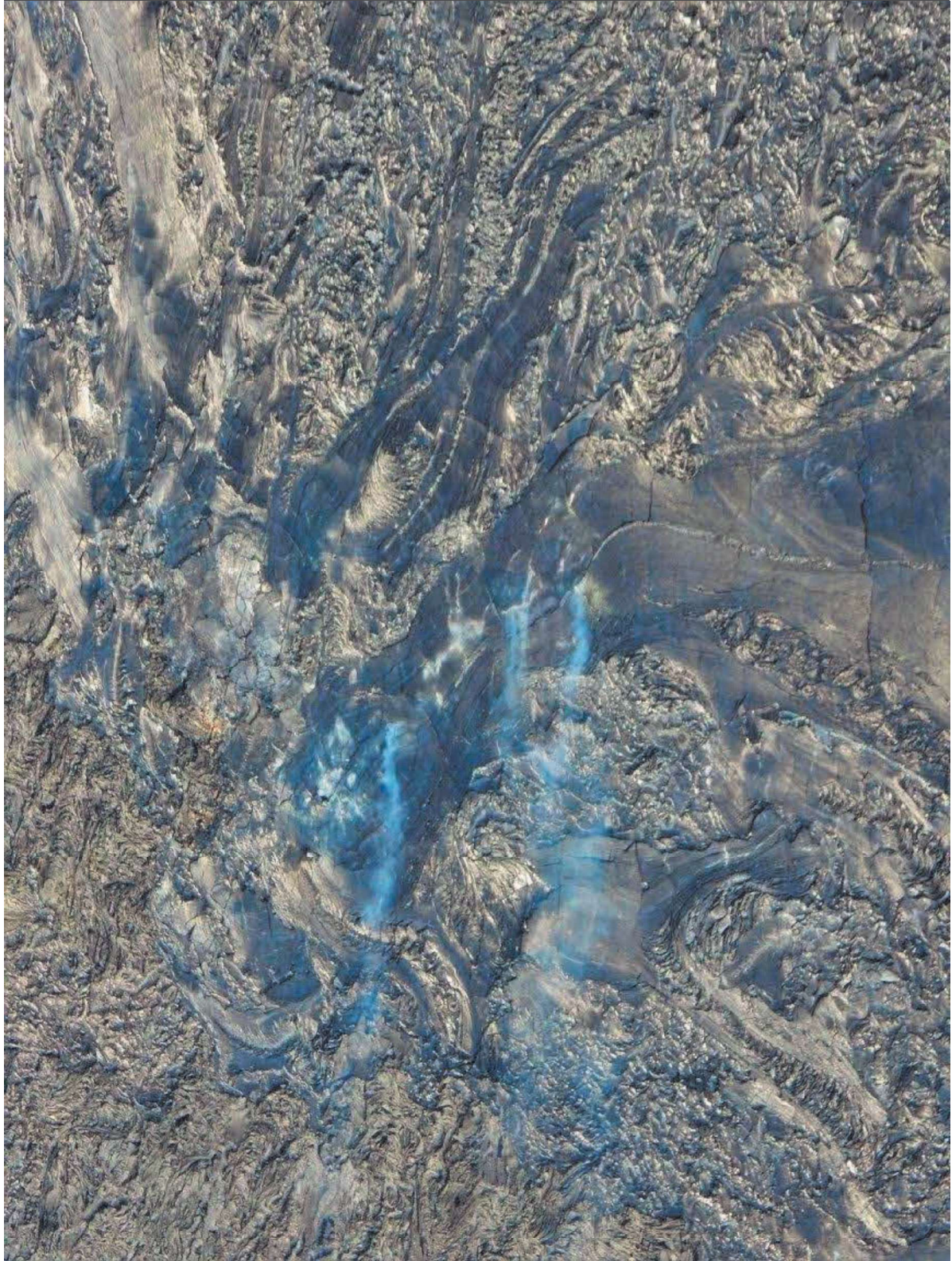
Conclusions

- 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 higher resolution images of ramps/pit floors, 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.



More References

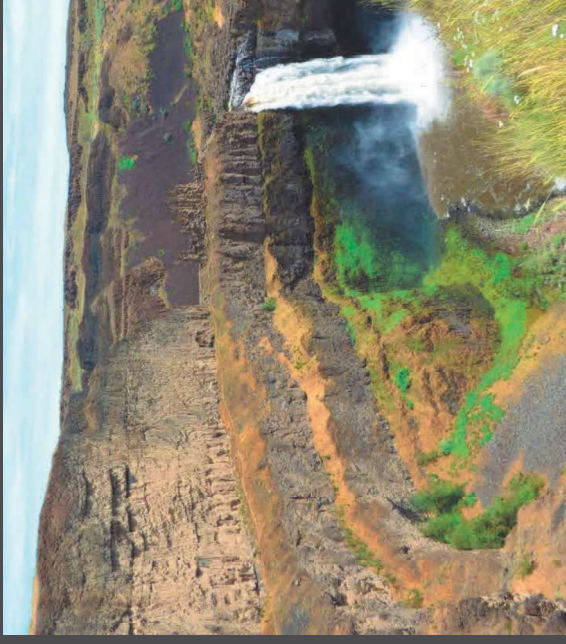
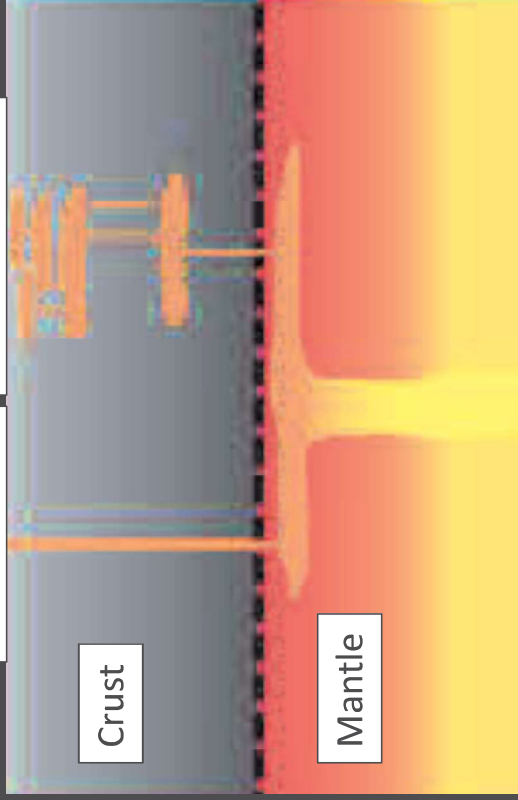
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Science

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

Deep Storage Shallow Storage



60235, 17

~ 1 mm

Xenolith

Xenocryst

Is it local?

Where in the lava does it come from?

The diagram illustrates the evolution of magma composition during cooling. It shows four stages (1, 2, 3, 4) of crystallization. Stage 1 is a homogeneous yellow liquid at 1200°C. Stage 2 shows the first crystals (green) forming. Stage 3 shows more crystals (green and brown) forming. Stage 4 shows a high concentration of crystals (green and brown) at 600°C. A vertical arrow on the right indicates 'Cooling' from 1200°C to 600°C. A horizontal arrow at the top indicates 'Magma has composition A' for stages 1 and 2, and 'Magma has composition B' for stages 3 and 4.

KREEP basalt of impact melt

KREEP-mantle melting/mixing zone

Upper mantle melting/mixing zone

KREEP Crust

Densest lithic residue sink

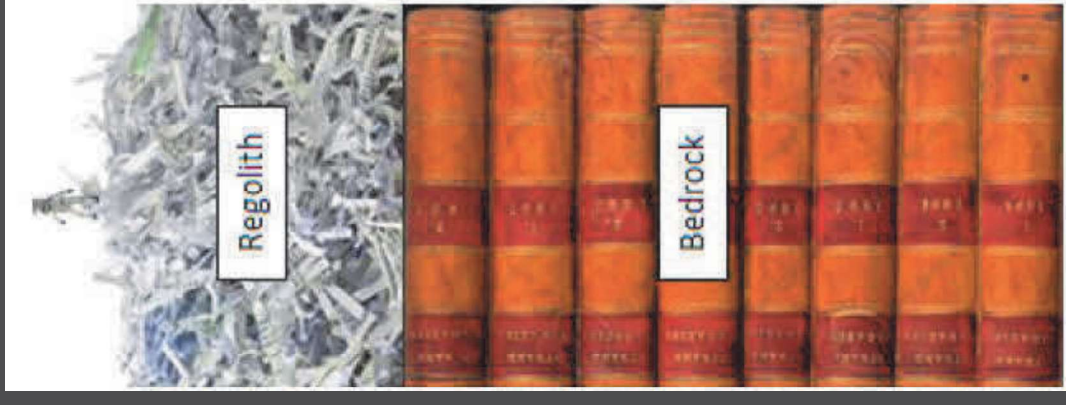
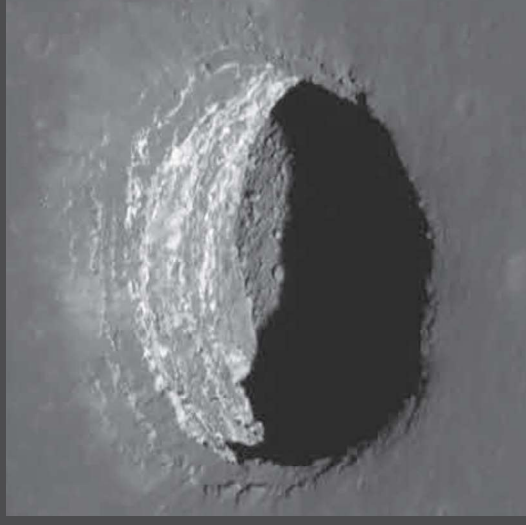
Magma bodies

50 km

(Credit: by Ruzicki, C. E., 1997, based on diagram by B. Feghly)

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?



