Using the TRIDENT Drill to Assess Geotechnical Properties of Probable Icy Lunar Regolith on Upcoming South Pole Missions

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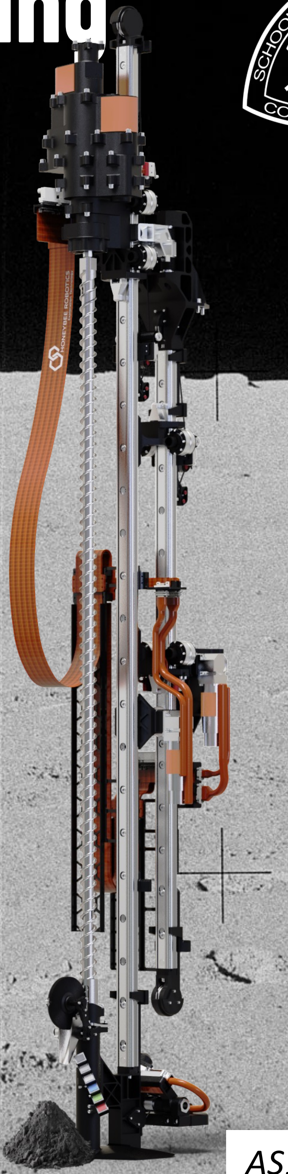

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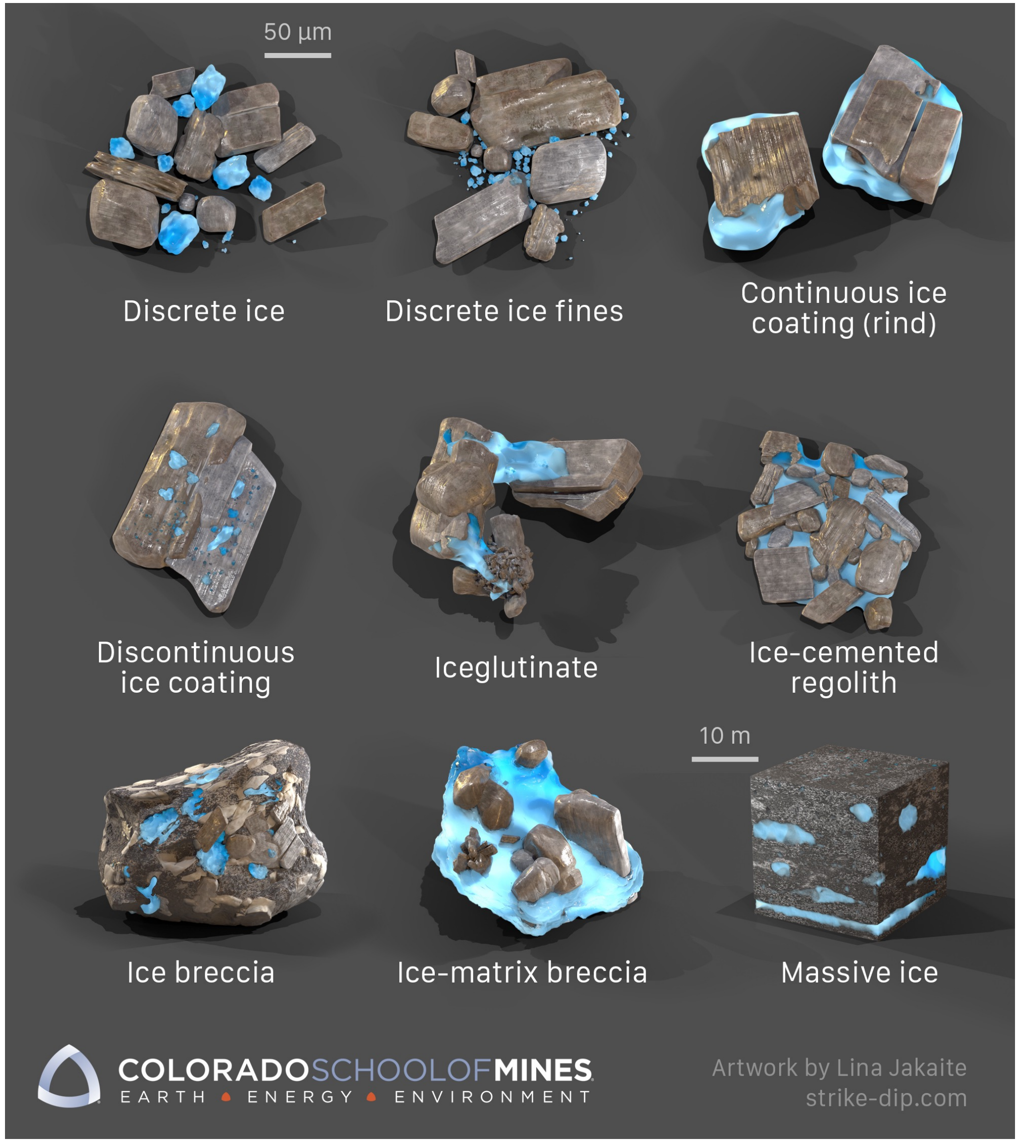
What We (Don't) Know About Lunar Ice



Remote sensing, lunar volatile transport models, and LCROSS point to water ice deposits in the lunar south pole

Extent, concentration, and texture of the regolith-ice mixture are unknown

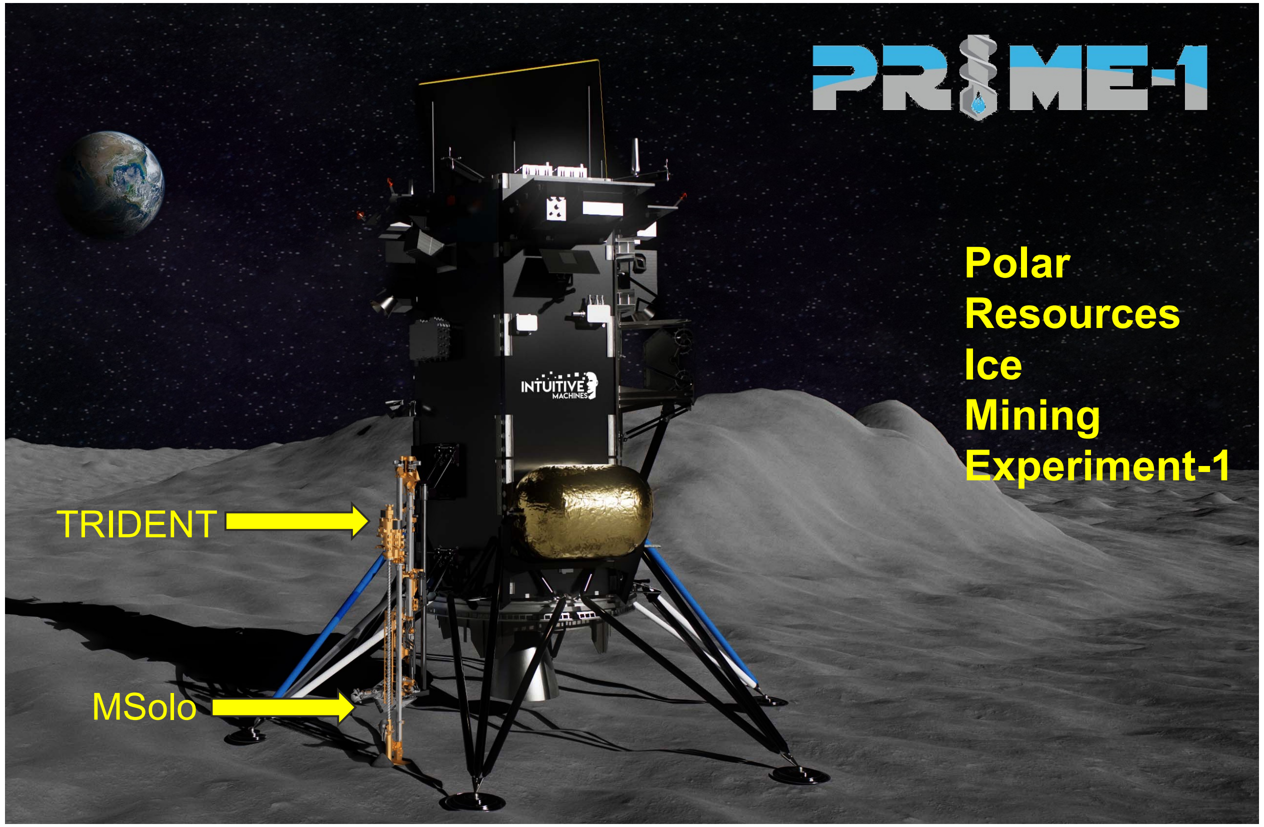
This information has major implications for ISRU

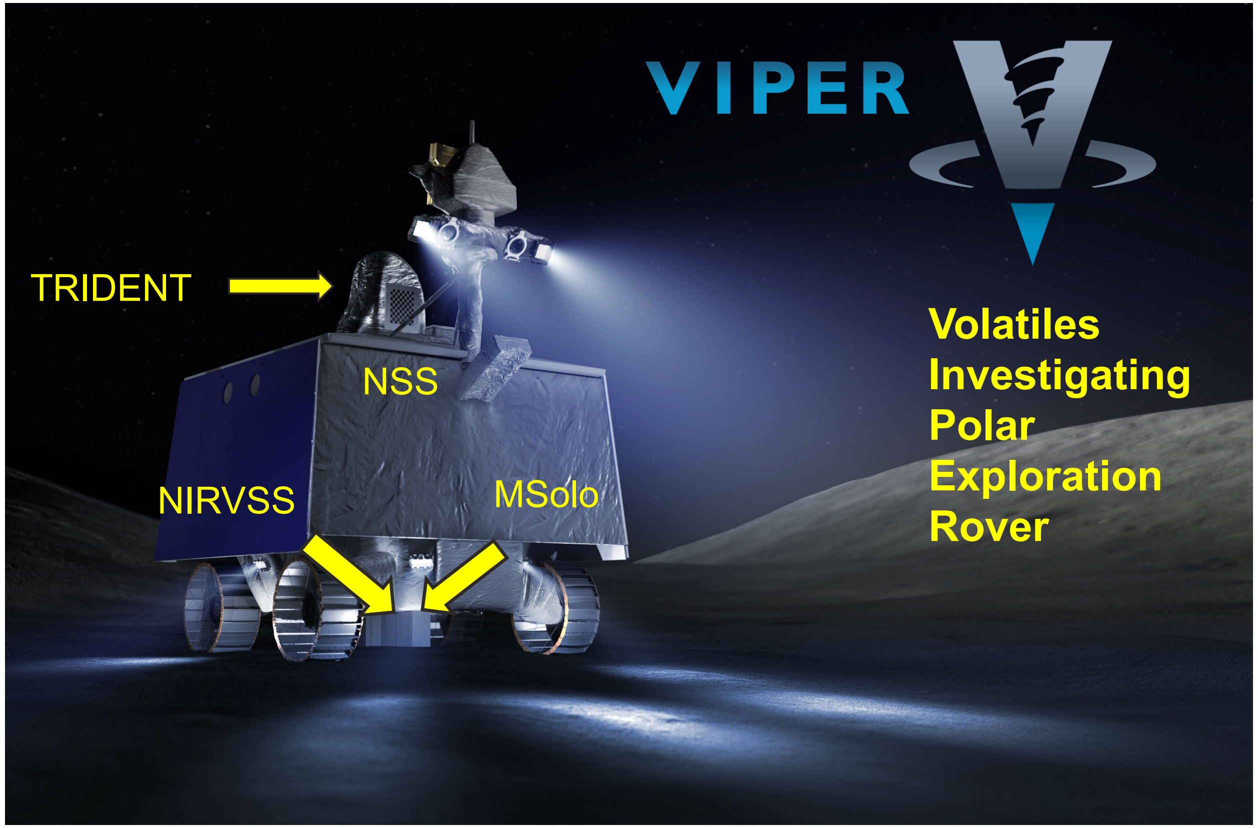
PRIME-1 and VIPER Missions

Goal: determine distribution and abundance of lunar polar volatiles

Instrumentation:

- Neutron Spectrometer System (NSS) for hydrogen;
- Mass Spectrometer Observing Lunar Operations (MSolo) for volatile characterization
- Near-Infrared Volatiles Spectrometer System (NIRVSS) for volatile and mineralogical characterization
- The Regolith and Ice Drill Exploring New Terrains (TRIDENT) for bringing cuttings from the subsurface … and more





TRIDENT Overview & ConOps

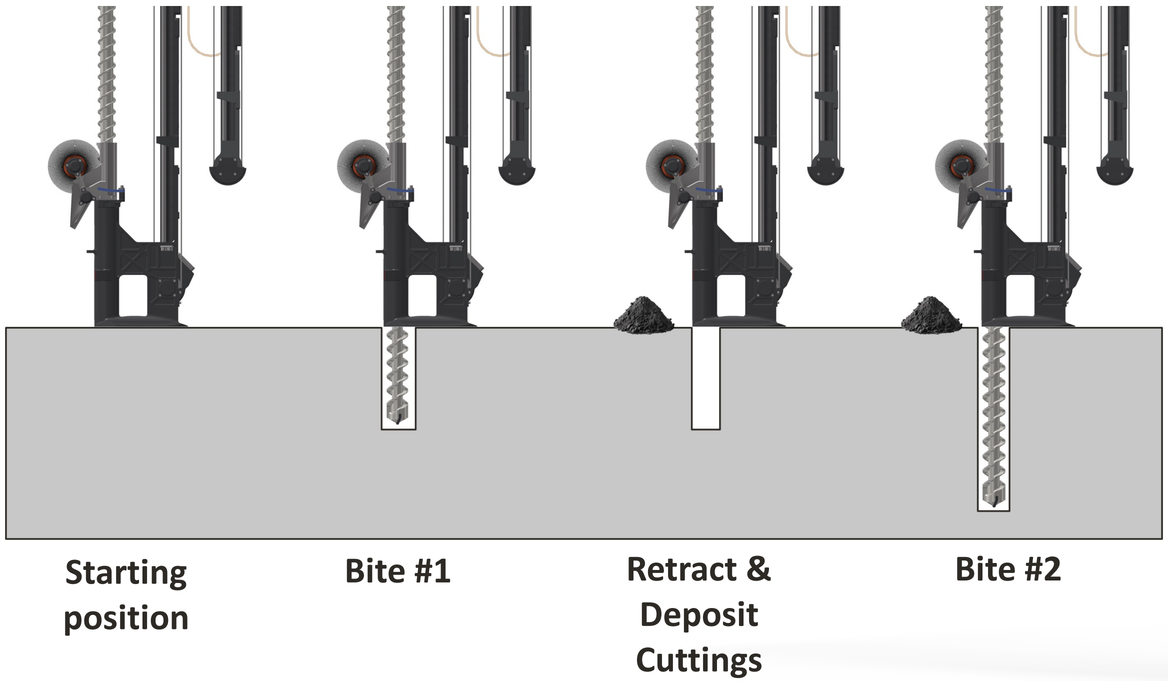
Key Facts:

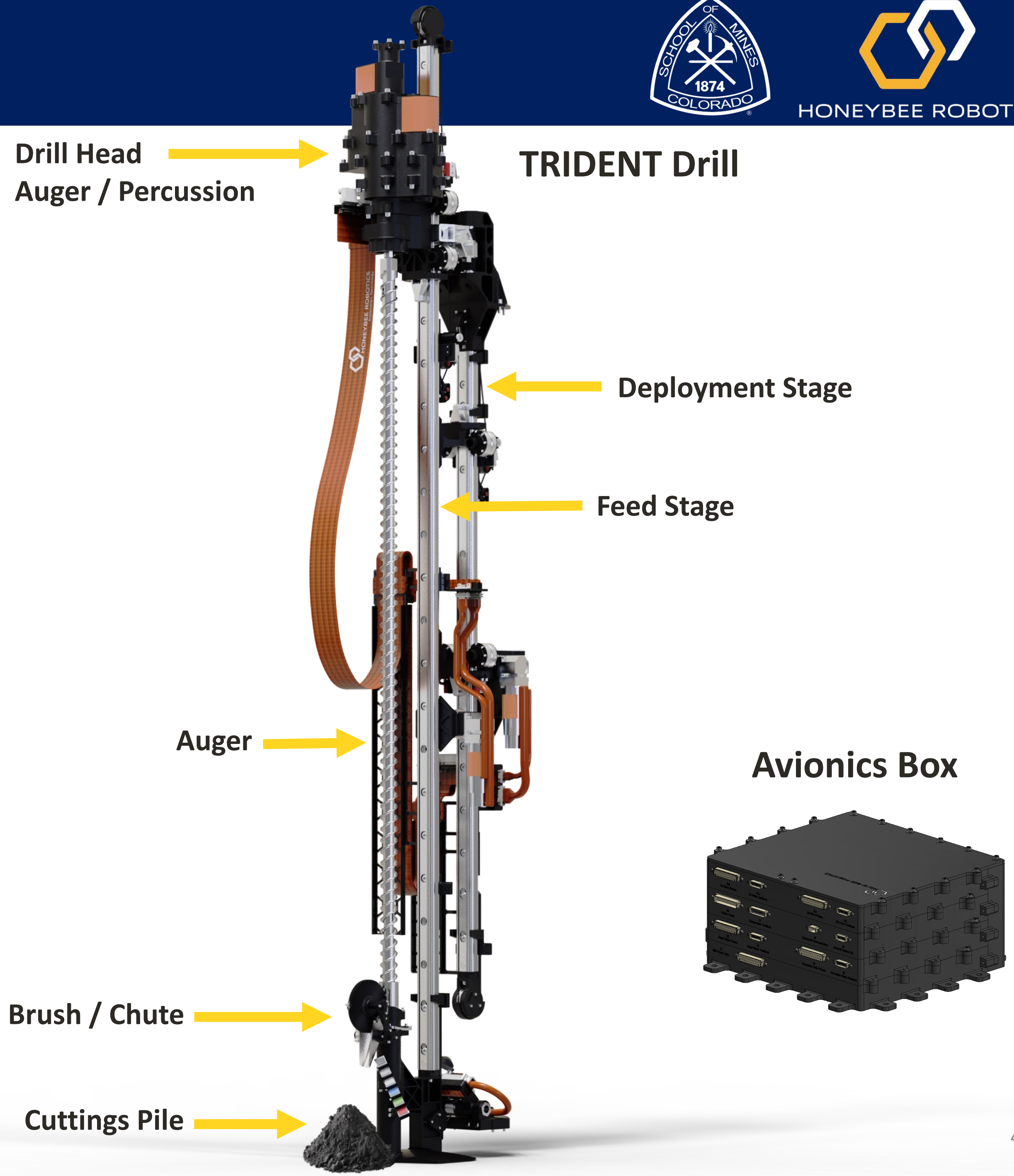
1-meter rotary percussive drill

Two linear stages: drill head travels up/down feed stage, feed stage travels up/down deployment stage

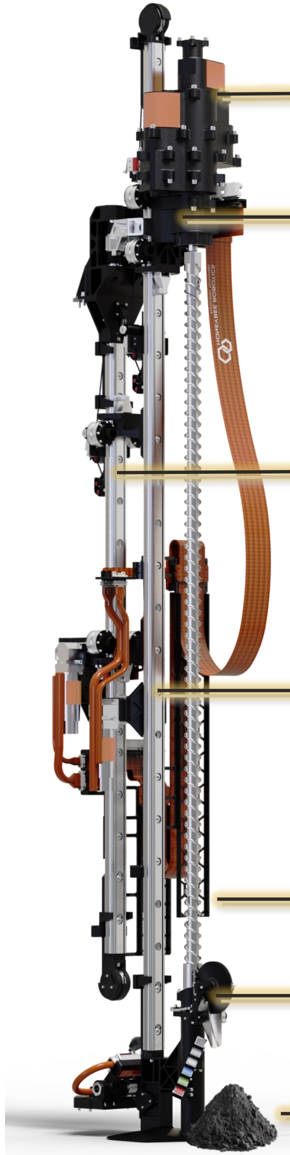
Footpad at the end of the feed stage deploys to bring the drill to the ground

Bite Sampling



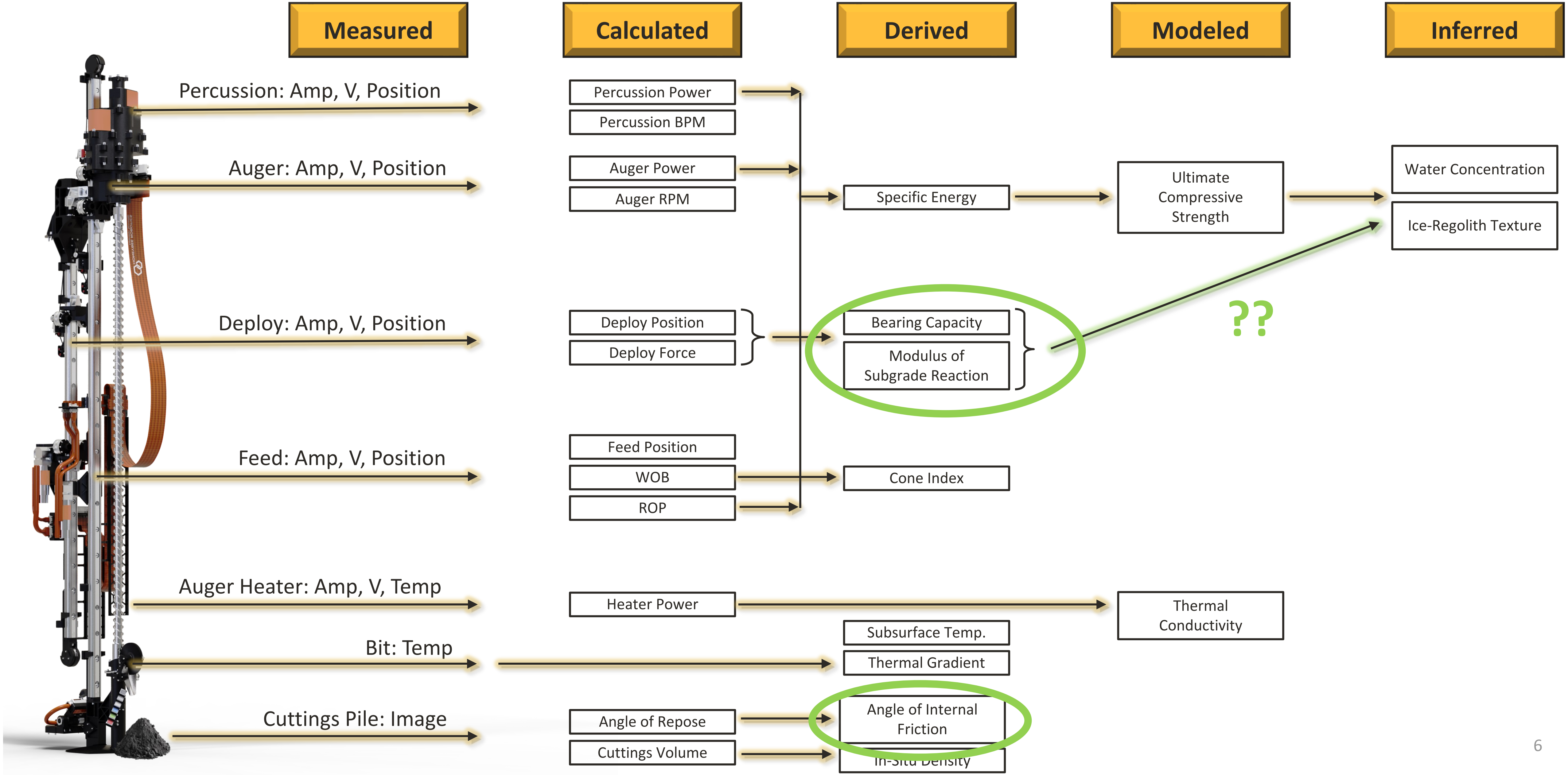


TRIDENT as an Instrument



Measured	Calculated	Derived	Modeled	Inferred
Percussion: Amp, V, Position	Percussion Power Percussion BPM			
Auger: Amp, V, Position	Auger Power Auger RPM	Specific Energy	Ultimate Compressive Strength	Water Concentration Ice-Regolith Texture
Deploy: Amp, V, Position	Deploy Position Deploy Force	Bearing Capacity Modulus of Subgrade Reaction		
Feed: Amp, V, Position	Feed Position WOB ROP	Cone Index		
Auger Heater: Amp, V, Temp	Heater Power		Thermal Conductivity	
Bit: Temp		Subsurface Temp. Thermal Gradient		
Cuttings Pile: Image	Angle of Repose Cuttings Volume	Angle of Internal Friction In-Situ Density		

TRIDENT as an Instrument

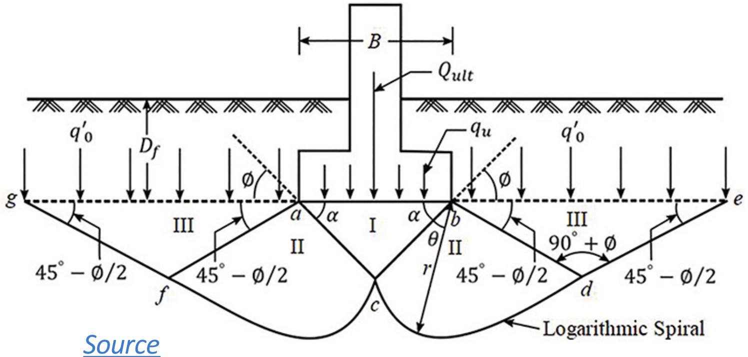


Key Definitions

These properties are routinely measured and used in civil/geotechnical engineering applications on Earth

On the Moon, these are useful in both engineering design and geological interpretation

Geotechnical Property	Explanation
Bearing Capacity	You will sink in a dry granular medium until your bearing pressure (F/A) is equal to the bearing capacity (q) of the soil
Modulus of Subgrade Reaction	An estimated stiffness or spring force of the soil
Angle of Internal Friction	Measure of a soil’s ability to withstand shear



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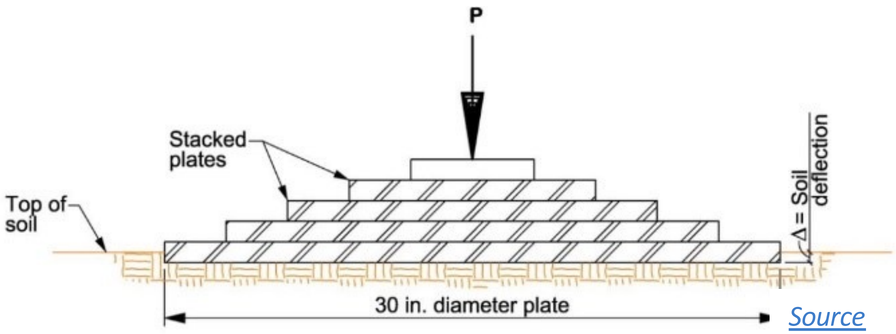

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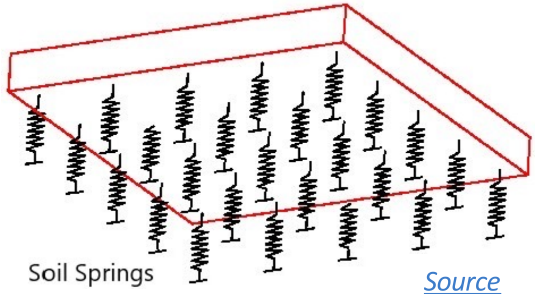

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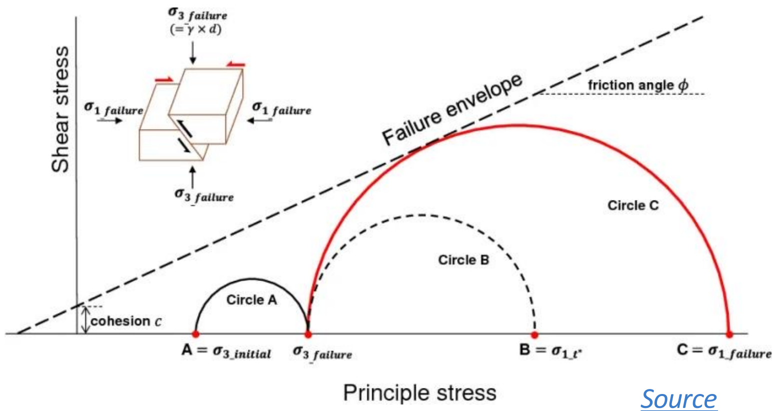

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Apollo Bootprints

Image Credit: NASA

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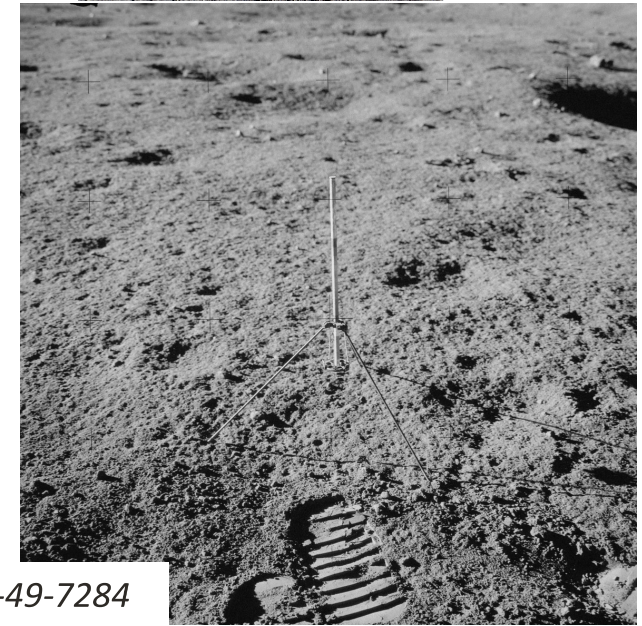

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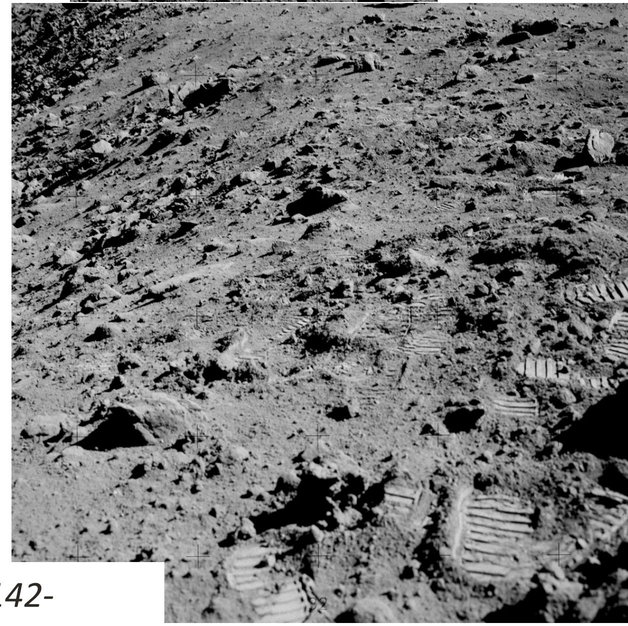

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Expectations in Lunar PSRs

Will geotechnical properties in PSRs be any different than Apollo landing sites?

Competing theories: surface-level ice or lack of thermal cycling could result in differences, but estimates of bearing capacity from boulder tracks look very similar to elsewhere on the Moon

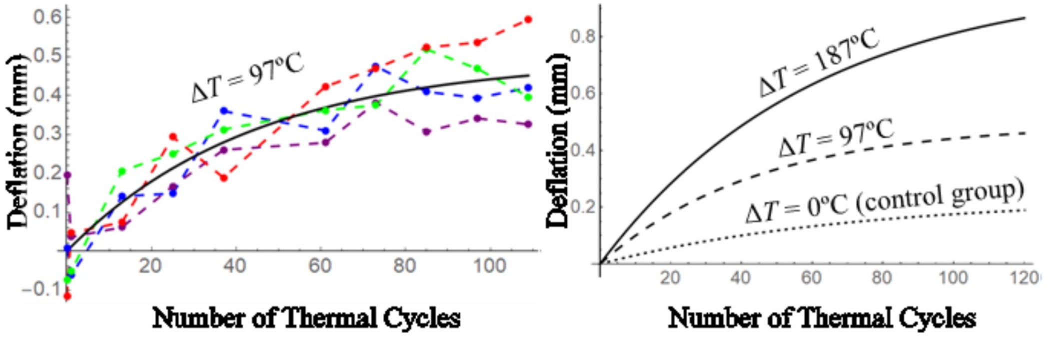
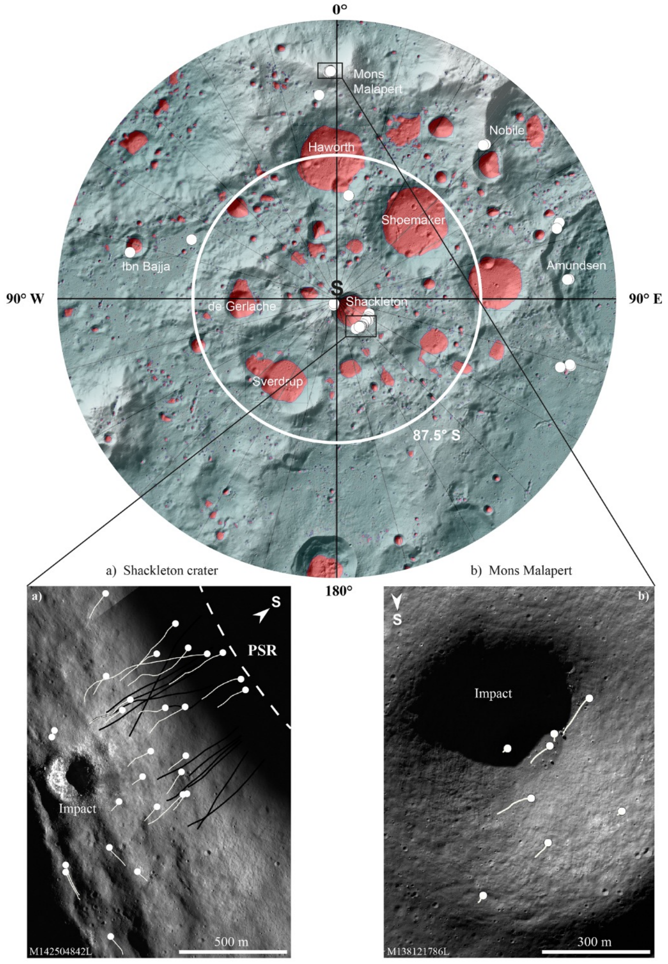
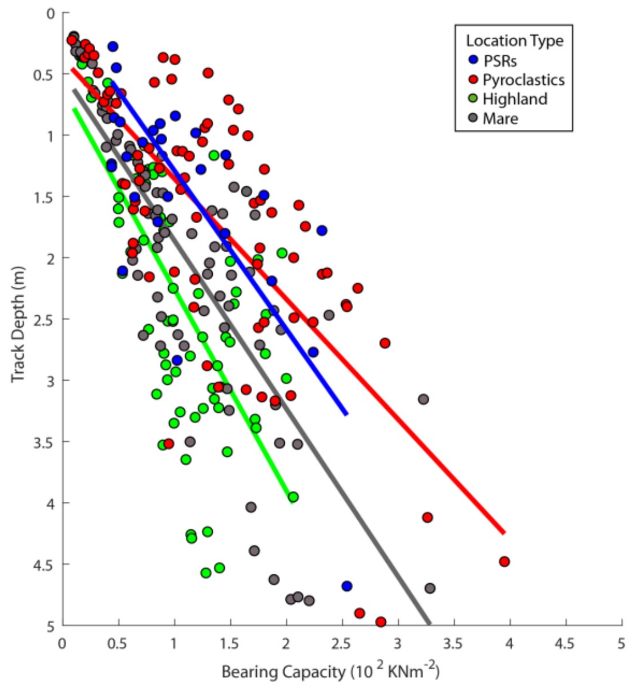


Figure 2. Results of Thermal Cycling. Left: For the $\Delta T = 97$ ºC case, four samples in dashed colors with the fitted function in solid black. Right: the fitted functions for three cases, $\Delta T = 187$ ºC, 97 ºC, and 0 ºC (the control group) that included all sample handling but no oven power).

Source: Metzger et al. (2018)



Source: Bickel et al. (2020)

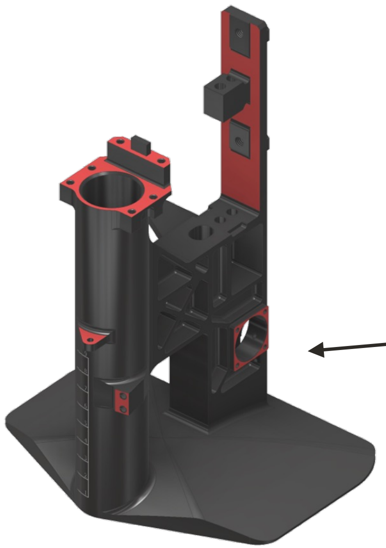


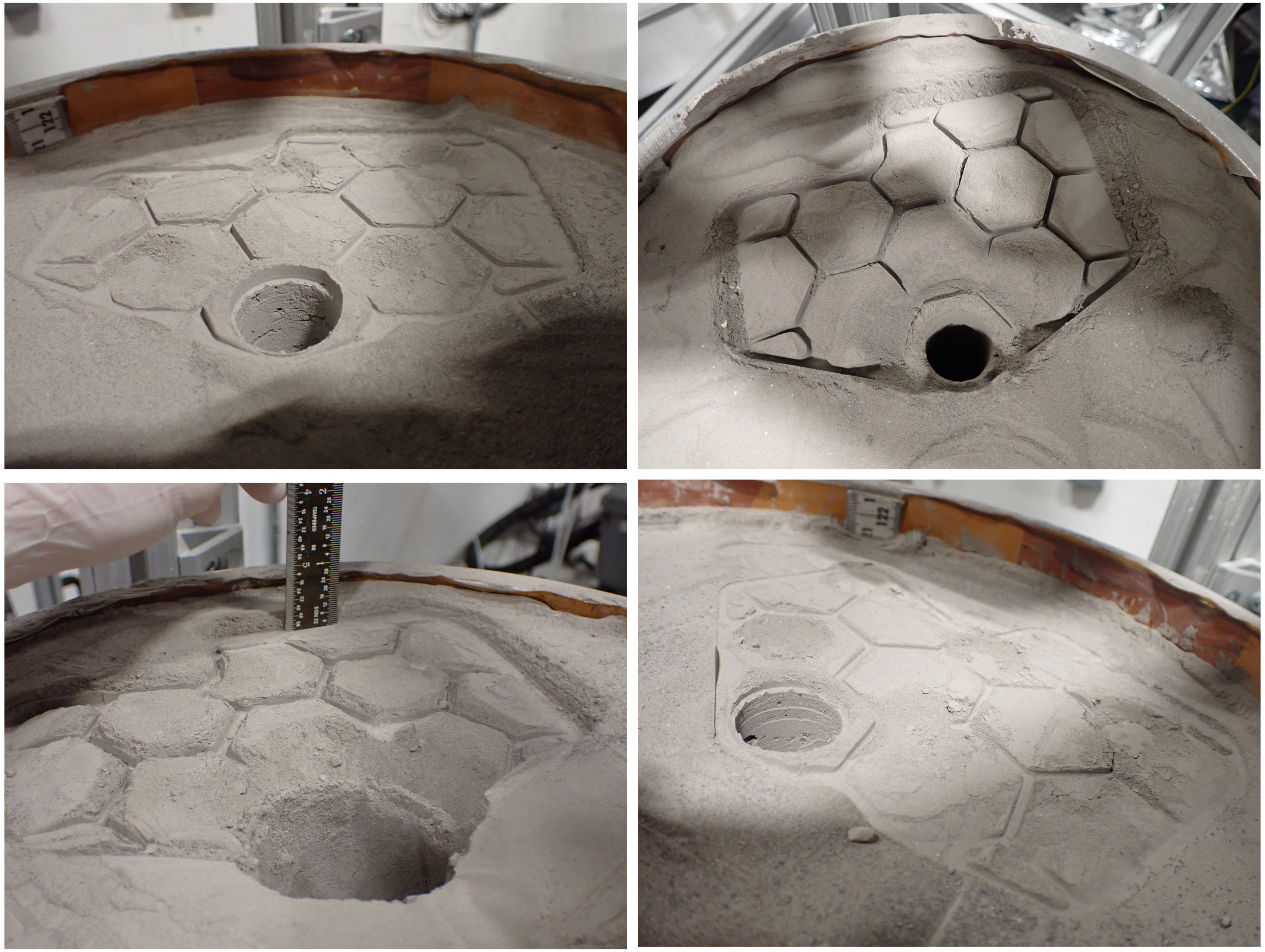
Source: Sargeant et al. (2019)

TRIDENT Footpad Prints

TRIDENT enables more precise measurements: known force and displacement

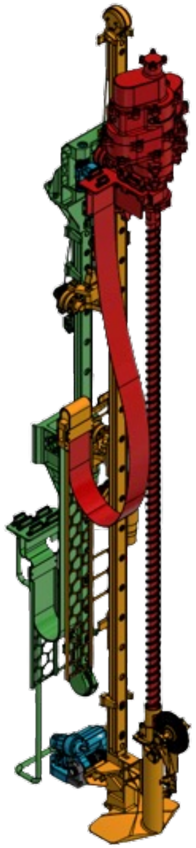
Possible experiment on VIPER: two-stage footpad deployment





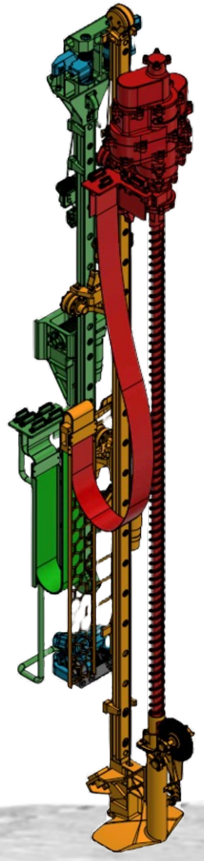
Two-Stage Footpad Deployment

1. Drill stowed on lander/rover



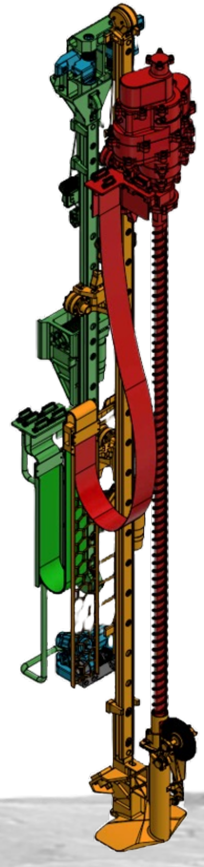
Yellow rail travels along green rail to place footpad on the ground

2. Command footpad to deploy to min. preload (47 N)



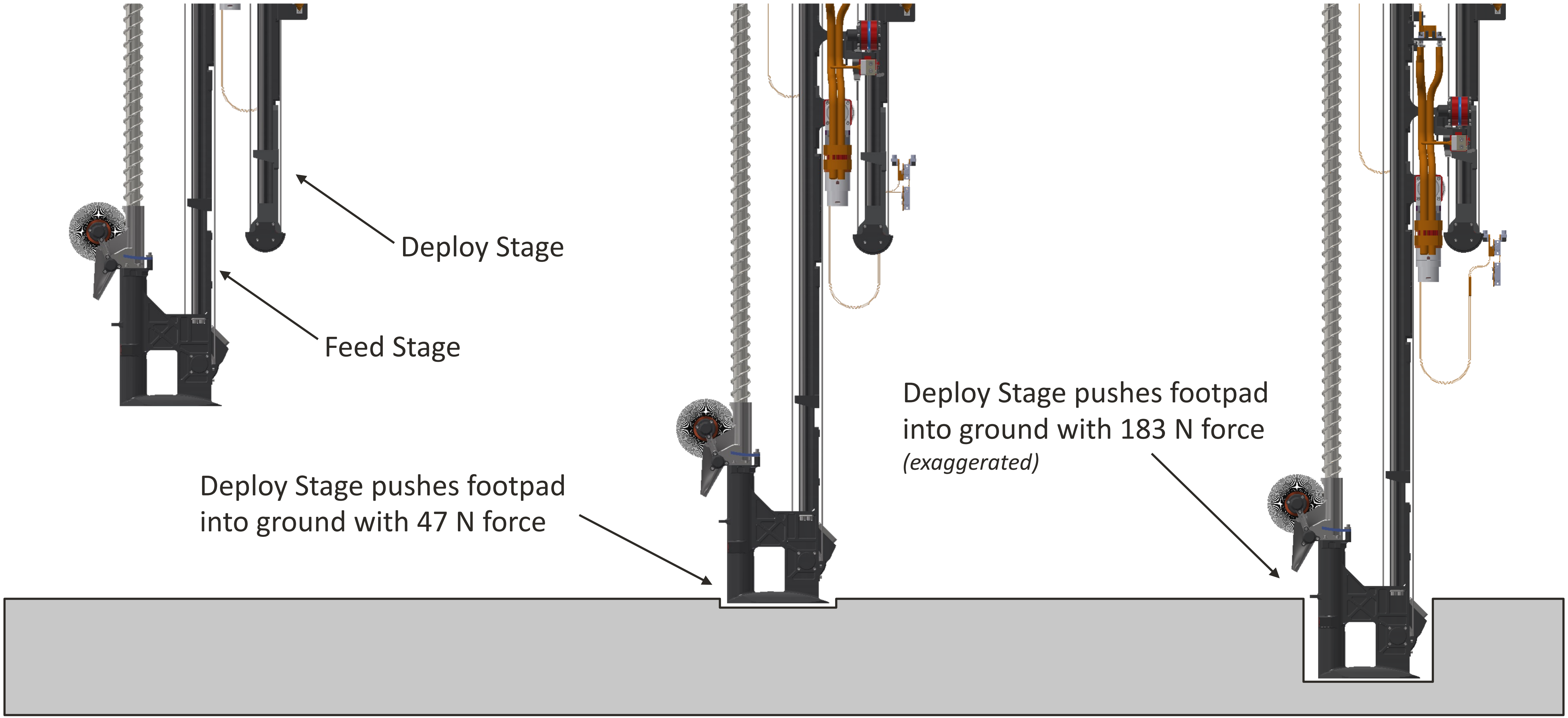
Yellow rail travels along green rail to sink footpad further into ground, typically +3-5 mm

3. Command footpad to deploy to max. preload (183 N)



Two-Stage Footpad Deployment

STOWED **MIN. DEPLOY** **MAX. DEPLOY**



Experimental Results – Dry/Ambient NU-LHT-2M

MODULUS OF SUBGRADE REACTION

Test ID	d (mm)	k ($kN/m^2/m$)
006B	4.55	2860.8
008B	4.23	3080.9
007	4.72	2762.2
008	3.09	4216.0
009	4.72	2762.2
010	4.39	2966.8
011	3.25	4005.2
012	3.58	3641.0
013	3.41	3814.4
014	4.06	3204.1
015	4.07	3204.1
017	4.88	2670.1
019	4.88	2670.1
020	4.39	2966.8
021	4.55	2860.8
022	3.74	3482.7
024	4.07	3204.1
Avg:	*4.15*	*3198.4*

BEARING CAPACITY

$$q = \frac{F}{A}$$

At 4.15 mm depth, our simulant has the following bearing capacity:

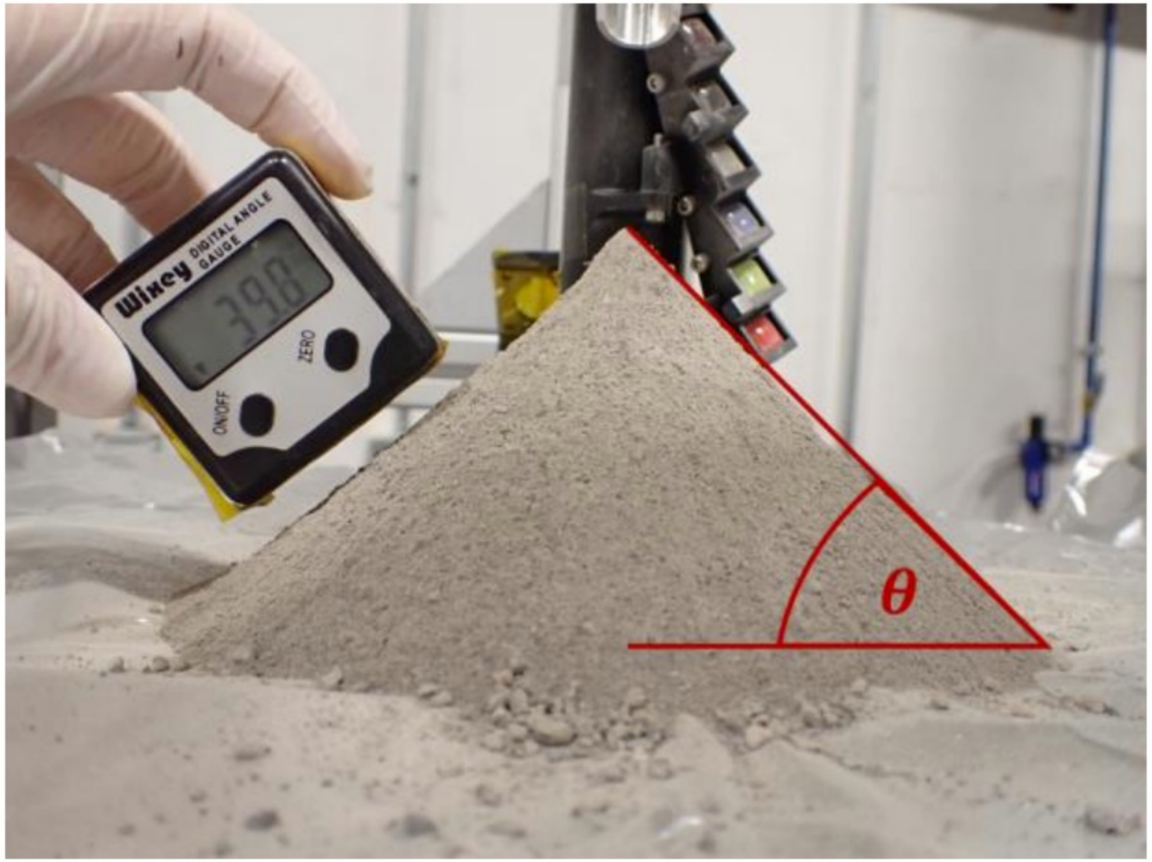
$$q = \frac{183}{140\ cm^2} = 13.07\ kPa$$

Angle of Internal Friction

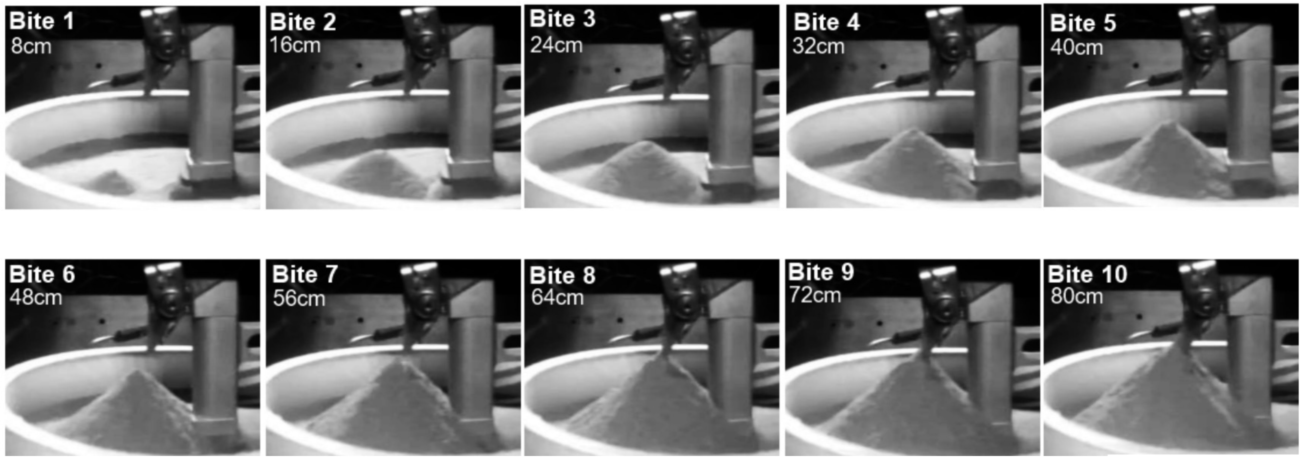
Angle of repose is a good approximation for angle of internal friction, which is a fundamental soil property

Estimation of cuttings pile angle of repose possible from planned images

Apollo regolith estimates were 35-50 degrees



Cuttings pile after 10 bites into NU-LHT-2M at HBR lab



Cuttings pile growth over 10 bites in TVac testing at NASA GRC

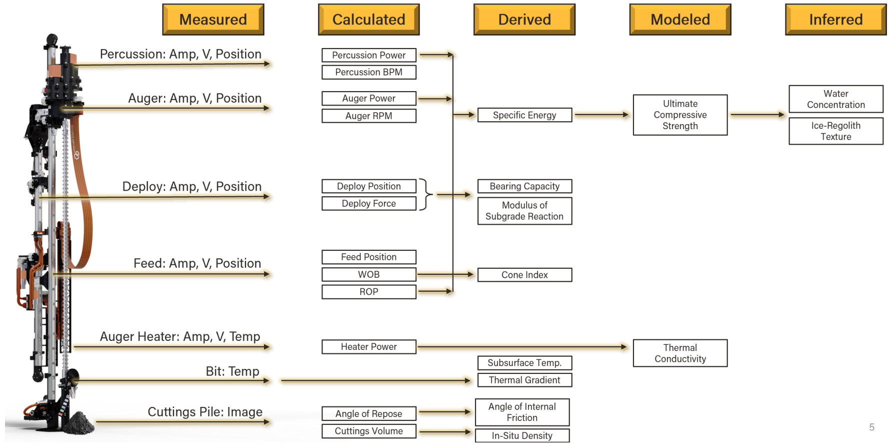
Future Work

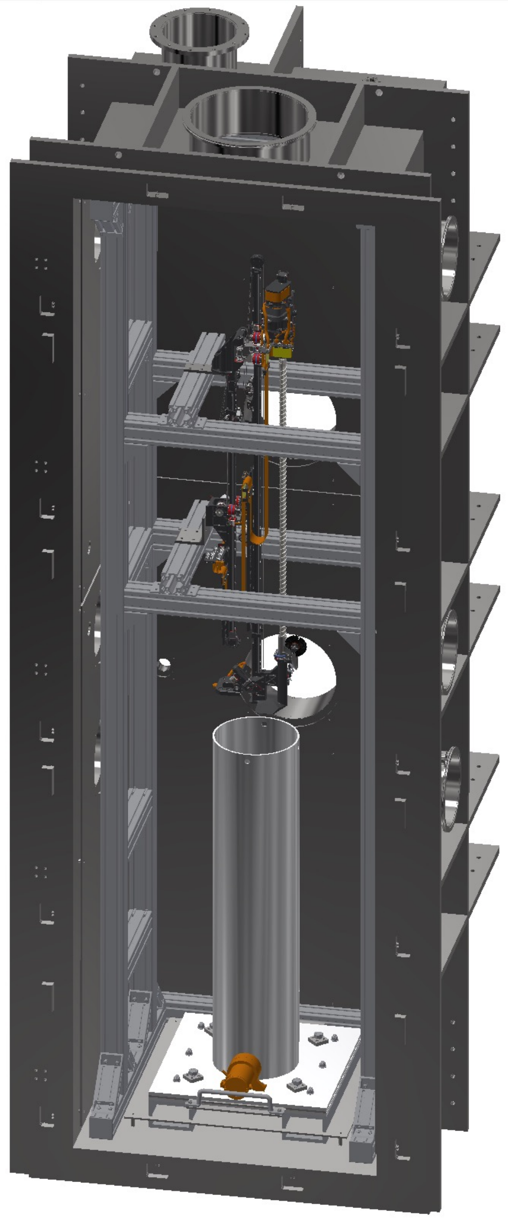
TRIDENT EU test campaign is ongoing

- Only ambient testing in NU-LHT-2M thus far
- TVac testing in varying texture and concentration ice to come
- More cohesive LSP simulant to come

Comparison to other measurements: VIPER's rover team is making similar engineering measurements, ex. wheels for bearing capacity

Make these measurements on the Moon! Provide novel insights into the geotechnical properties of probable icy lunar regolith in PSRs





HONEYBEE ROBOTICS

SCHOOL OF MINES
1874
COLORADO