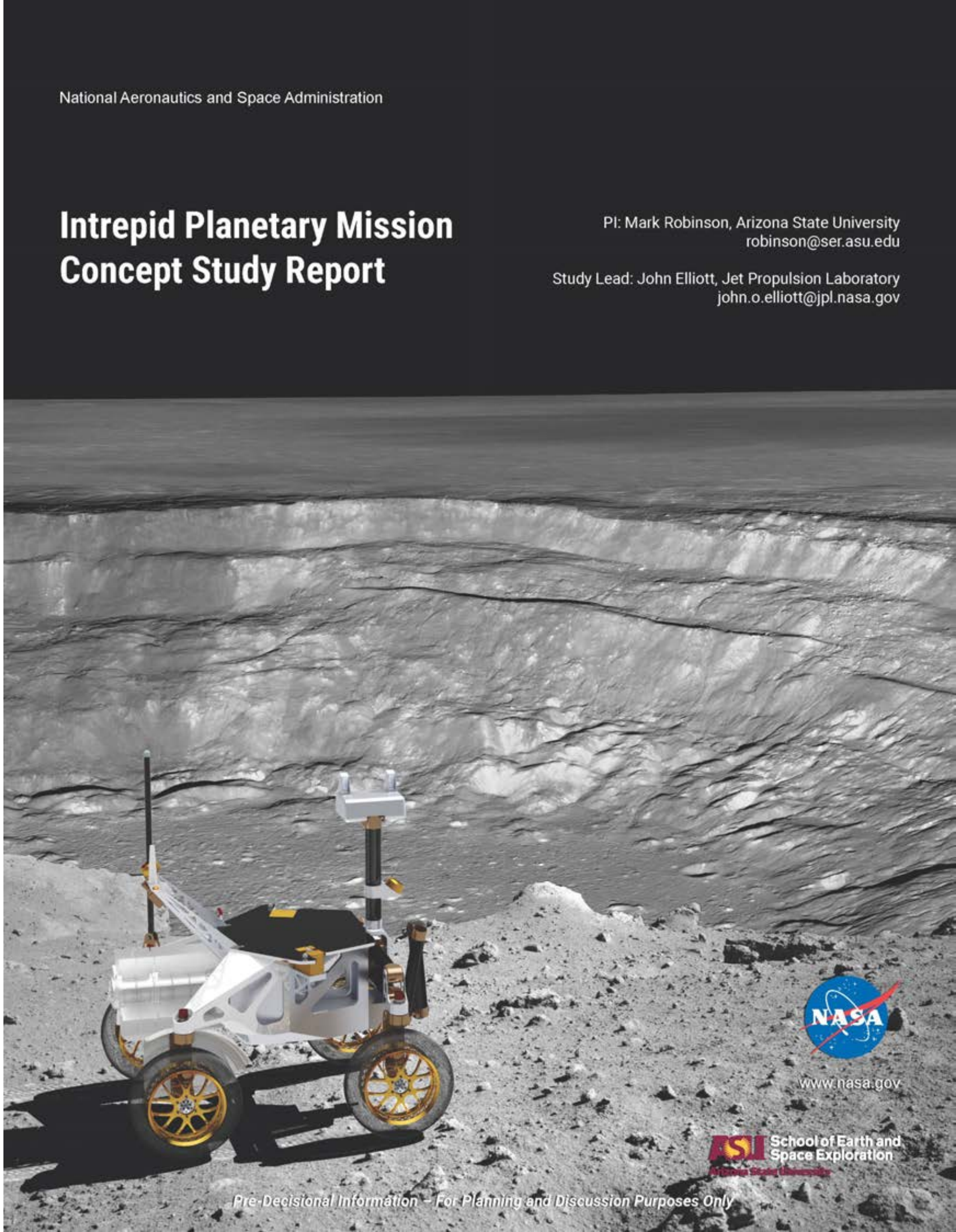
Intrepid

Unraveling Four Billion Years of Lunar *Magmatism*

Decadal Survey on Planetary Science and Astrobiology: Steering Group
27 May 2021

PI: Mark Robinson, ASU
Study lead: John Elliott, JPL



Intrepid PMCS Team

Amazing team!

- Mark Robinson, ASU
- Brian Anderson, JHUAPL
- David Blewett, JHUAPL
- Brett Denevi, JHUAPL
- Michael Fitzgerald, First Mode
- Terry Fong, Ames
- Elizabeth Frank, First Mode
- Lee Graham, JSC
- Peter Illsley, First Mode
- Brad Jolliff, WUSTL
- David Lawrence, JHUAPL
- Sam Lawrence, JSC
- Kevin Lewis, JHU
- Prasun Mahanti, ASU
- Heather Meyer, JHUAPL
- Elizabeth Rampe, JSC
- Harlan Spence, UNH
- Emerson Speyerer, ASU
- Julie Stopar, LPI
- Sonia Tikoo-Schantz, Stanford
- Chris Voorhees, First Mode
- Robert Wagner, ASU
- David Wettergreen, CMU

JPL PMCS Team

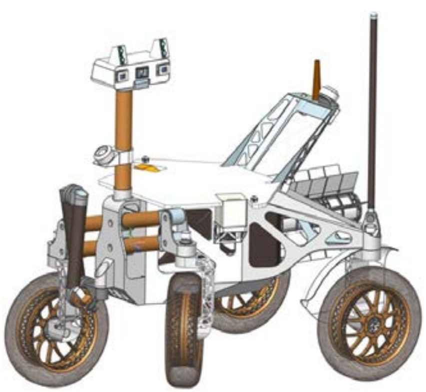
- Catherine Elder, JPL
- John Elliott, JPL
- Rudranarayan Mukherjee, JPL
- Raul Polit-Casillas, JPL
- Issa Nesnas, JPL
- Kim Reh, JPL
- A Team and Team X, JPL
- And many others!

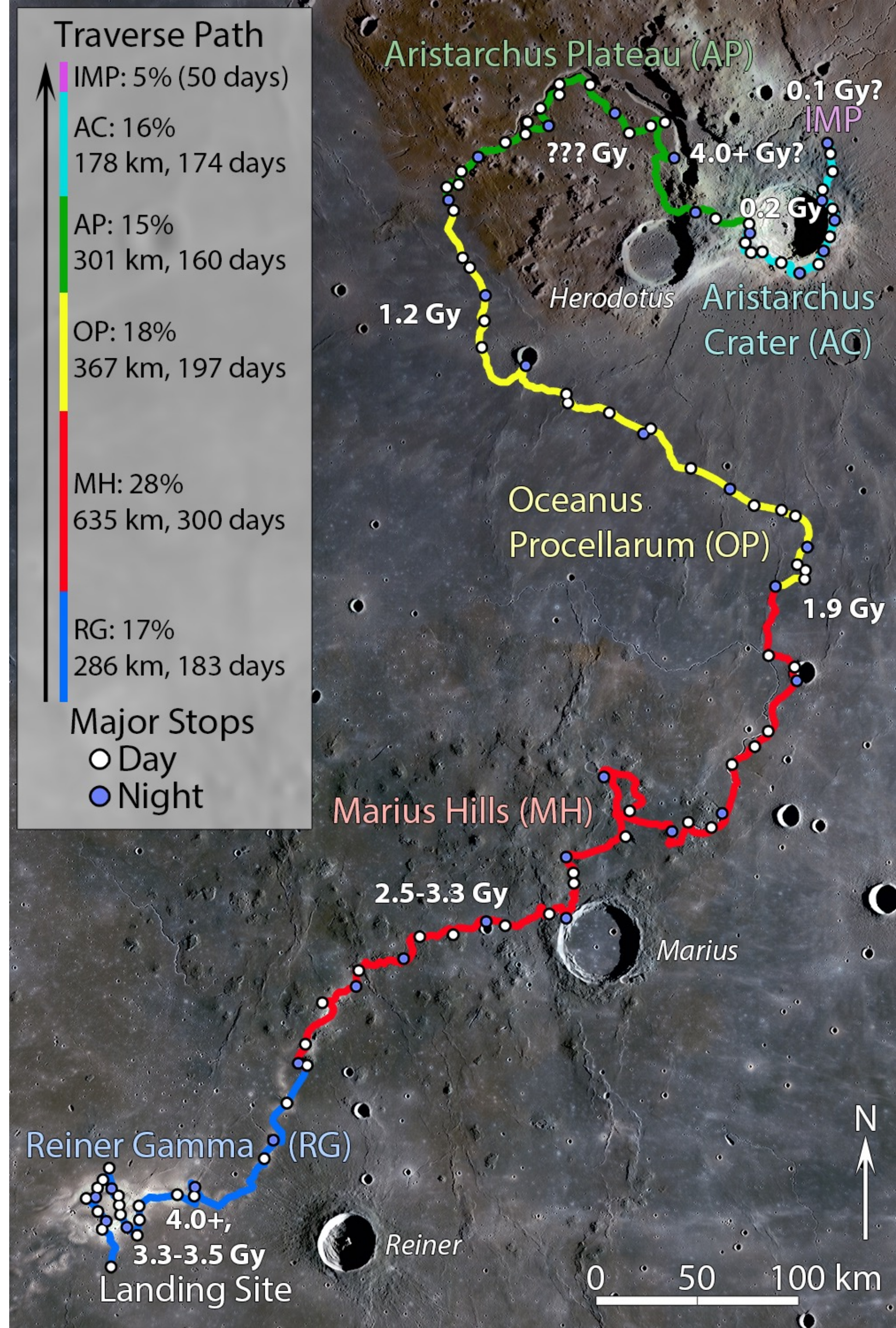
Intrepid

Traverse Six Key Geologic Regions in the Procellarum KREEP Terrain (PKT)

Three Science Themes
Twelve Objectives
How solid planets evolve

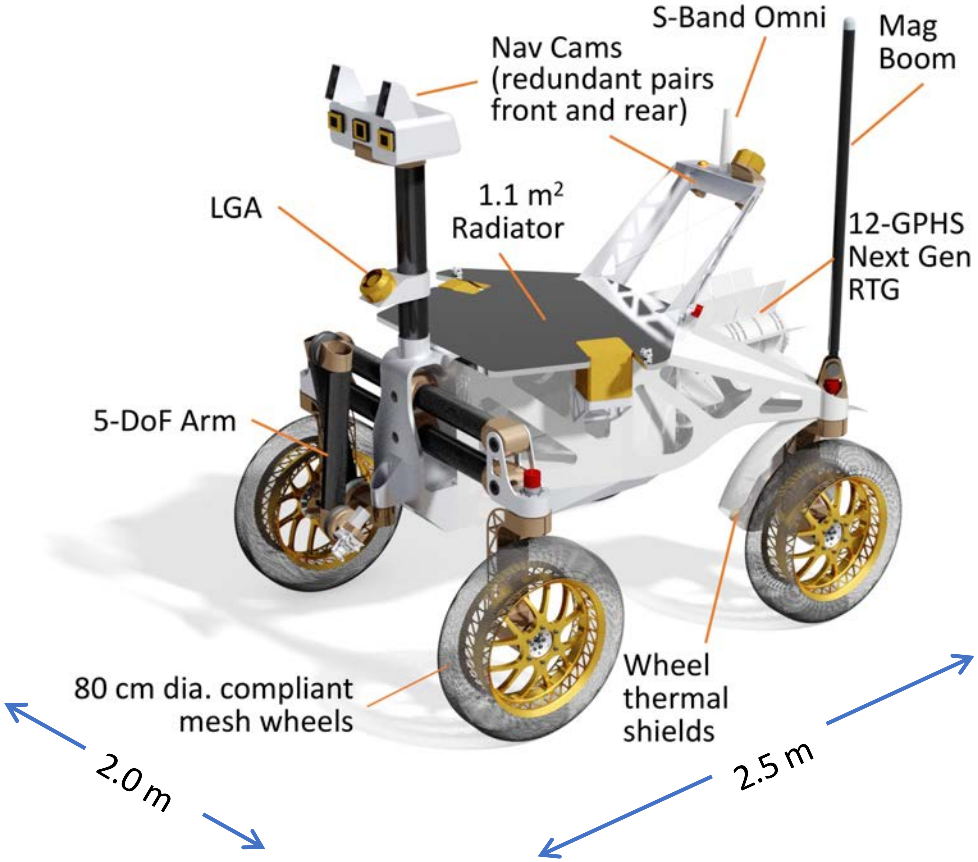
1800 km traverse





Intrepid RTG-Powered Rover

New Frontiers Class Mission ($1049M, A-D margined)



- Designed for operation in day *and night* conditions
- Range >1800 km
- High level of autonomy ←
- Lifetime >4 years
- Capable of slopes up to 15°
  - All wheels driven, all wheels steered
- 0.6 m ground clearance
- 5 degrees of freedom robotic arm
- Powered by 300 W (BOL) 12-GPHS Next-Gen RTG
- Mass (margined, 1.43 x CBE): 423 kg
  - Includes ~24 kg science payload

Solar powered version (590 kg, $997M A-D) requires 3 extra years of operation for same science return; hunker down survive the night ☹

Unraveling Four Billion Years of Lunar Magmatism

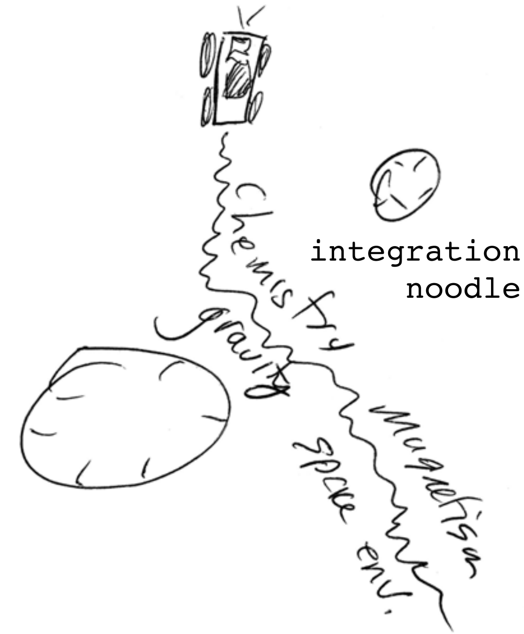
- **Evolution of the lunar interior, nature of the Procellarum KREEP Terrane**
  - Determine the cause of extended volcanism in the Procellarum region
  - Determine the cause of the lunar crustal asymmetry
  - Determine the origin of non-mare volcanism
  - Determine composition of deep mantle from pyroclastic deposits
  - Characterize decline of core dynamo and magnetic field over time
- **Diversity of styles of magmatism**
  - Characterize flood basalt emplacement, rilles, vents, flows, tubes
  - Determine origin(s) and composition(s) of cones, domes and shields
  - Characterize the compositions and physical state (grain size, glass content) of pyroclastic materials
  - Determine the nature of intrusive volcanism and relation to effusive deposits
- **Post emplacement modifications**
  - Test hypotheses of crater impact formation, ballistic sedimentation, ray formation, and physical properties of regolith outward from impact
  - Determine target material influence on crater characteristics and impact mechanics
  - Characterize variations in space weathering across a variety of geologic regions and ages (relationship to radiation environment, H abundance, magnetic anomalies, swirls)

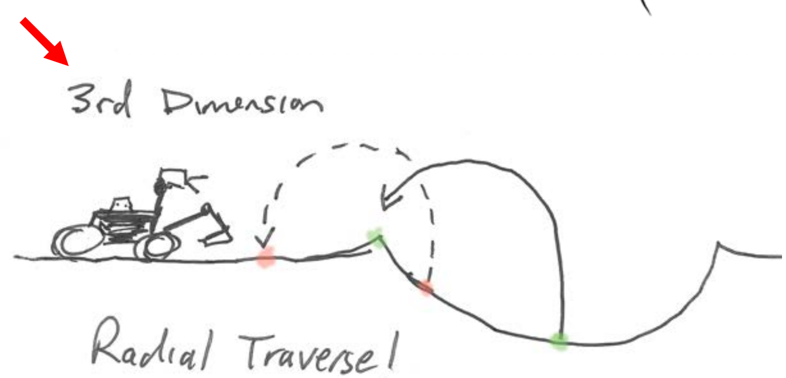
Responsive to current Decadal (and next)

High degree of synergy with human exploration

Measurement Overview

- Mineralogy/Petrology
  - Anorthite, olivine, pyroxenes (opx, cpx), ilmenite, glass
- Elemental Abundance
  - Determine major element chemistry (Fe, Mg, Ti, Si, O, Al, Ca)
  - Determine minor element chemistry (K, Th, U, H, OH), including magmatic volatiles (Zn, Fl, Cl)
- Magnetic environment
  - Characterize magnetic field (strength, orientation, polarity) over meter spatial scales
- Crustal density
  - Determine local gravitational acceleration
- Solar wind charged and neutral particles
  - Measure species and intensity
- Radiation environment >10 MeV
  - Galactic cosmic rays and solar energetic particles
- Regolith Structure
  - Estimate depth of regolith, discontinuities (macro-scale)
  - Document grain size, shape and color (micro-scale),
  - Geotechnical properties
- Maturity of regolith
  - Optical maturity, physical state
- Landform morphometry
  - Shapes of flow forms, crater forms, vents, etc



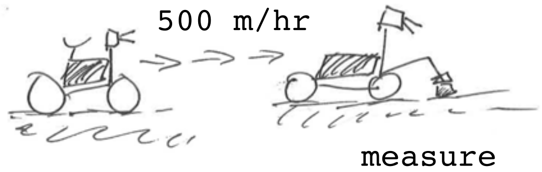


Low Risk Instrument Suite

Instrument	Deployment	Measures	Peak Power (W)	Standby Power (W)	Mass
ARMAS (LET)	Body fixed pointed up	Galactic and solar cosmic ray >10 MeV	0.3	0.3	1
Magnetometer	One time deploy boom	Magnetic field strength orientation	1.7	1.7	0.5
Gamma Ray Neutron Spectrometer (GRNS)	Body fixed pointed down	Elemental abundance	4	4	4
TriCam Stereo RGB Imager + BW telescopic FarCam (electronics shared with PS, HLI)	Mast mounted, two degrees of freedom (*electronics box inside rover*)	Reflectance (BW, color, and stereo imaging)	12	9	5.0 (3.5 kg on mast)
Point Spectrometer (PS) uses FarCam telescope	Mast	Reflectance (300 to 1400 nm)	4	4	2 (1 kg on mast)
Hand Lens Imager (HLI)	Arm deployable	Reflectance (400 to 1000 nm)	12	1	0.7
Alpha Particle X-Ray Spectrometer (APXS)	Arm deployable	Elemental abundance	8	8	1.7 (0.4 on arm)
Electrostatic Analyzer (EA)	Body fixed pointed up	Solar wind (electrons, protons)	2	2	2
Laser Retro-Reflector Array (LRA)	Body fixed pointed up, passive instrument	Location (x,y,z) of rover from orbiter	0	0	0.2
		TOTALS		30	17.1

Power and mass estimates from high TRL instruments, except point spectrometer (margin not included).
Note: TriCam, PS and HLI share same electronics box inside rover -- only one rover interface for power and data for these three instruments.

Concept of Operations Basics



- CLPS class lander delivers rover to the Moon
- Rover egresses lander, initiates checkout and operations
- Rover travels to investigation sites along *pre-determined* traverse
  - Autonomous operations between sites and at investigation sites
  - Focused Investigation Sites, 12 to 48 hrs (daytime), longer at night
- Health and safety data transmitted while rover is moving
- Science data is transmitted at high rate while stationary
- Rover progresses and takes measurements during the *2 weeks of sunlight*
  - Rover travels 500 m/hr over sustained distances autonomously
  - Continuous operation while roving (GRNS, Magnetometer, Electrostatic Analyzer, ARMAS)
  - Point spectra and images every 10 minutes (~80 meters)
  - Stops every 4 hrs (2 km) for 1 hr to document traverse (***Interval Stop***)
- During periods of *darkness rover traverse progress limited*, focuses on long integration measurements and downlink
  - Limited movement in terms of speed (50 m/hr) and distance (2 km) at night
- *Rover stops are pre-planned* taking into account science and traversibility and time of day
- Current mission design includes 131 major, and 981 minor sites over 3 Earth years (plus one year margin, 4 years total), traverses 1800+ km

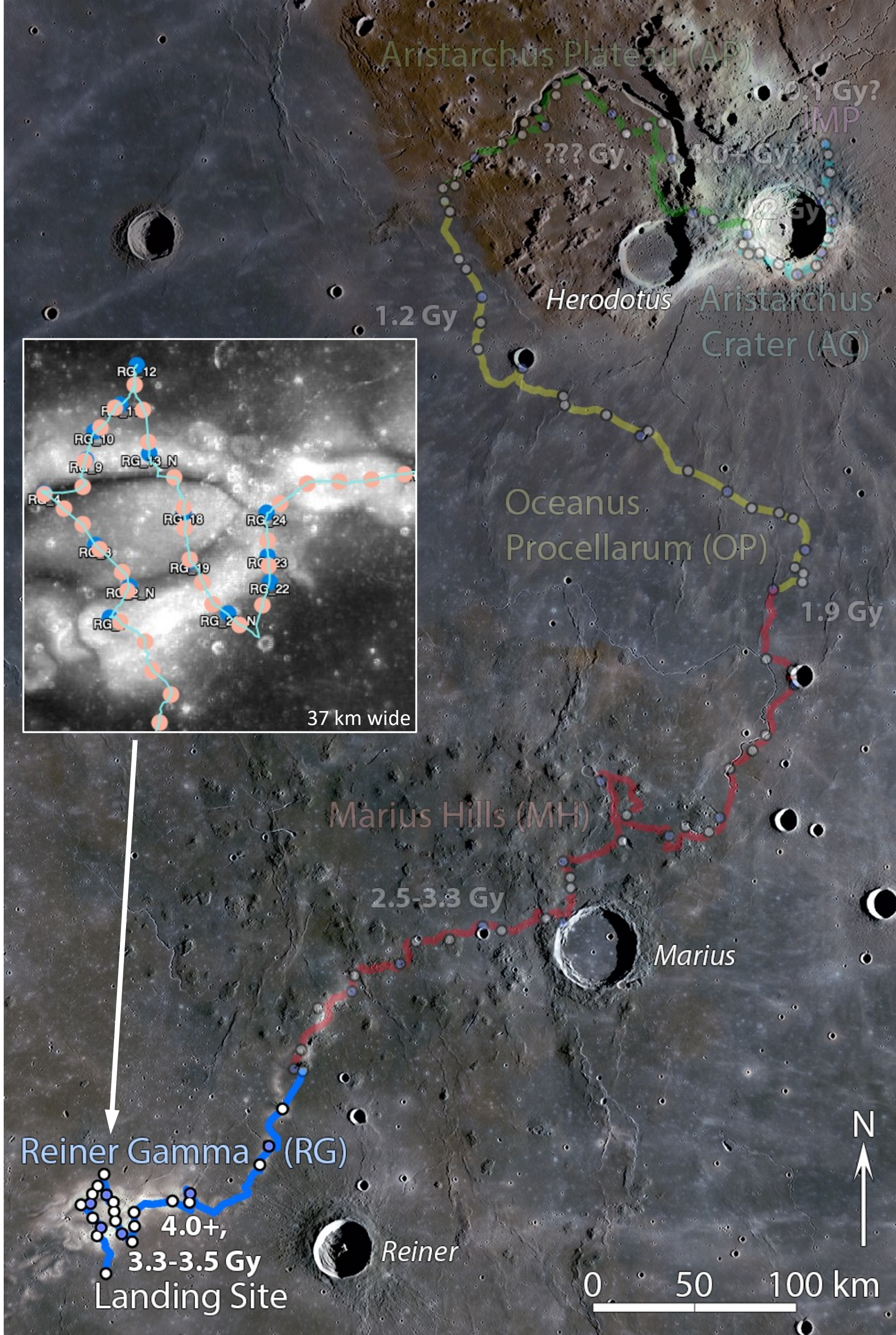
Mission requires high degree of *rover autonomy...*
New way of thinking about rover operations, get the measurements and continue on!

Reiner Gamma

30+1 major stops, 131 interval stops, 259 km, 6 lunations

- Multiple passes across swirl
- Magnetic environment
- Space environment interaction with surface
- 3.3 to 3.5 Gy mare surface
- Mare composition as function of depth
- Regolith development
- Cratering mechanics

Knowledge of magnetic field orientation, strength and spatial variation will discriminate between dike, metal-rich impactor, basin ejecta, and cometary hypotheses for the origin of the magnetic anomaly.

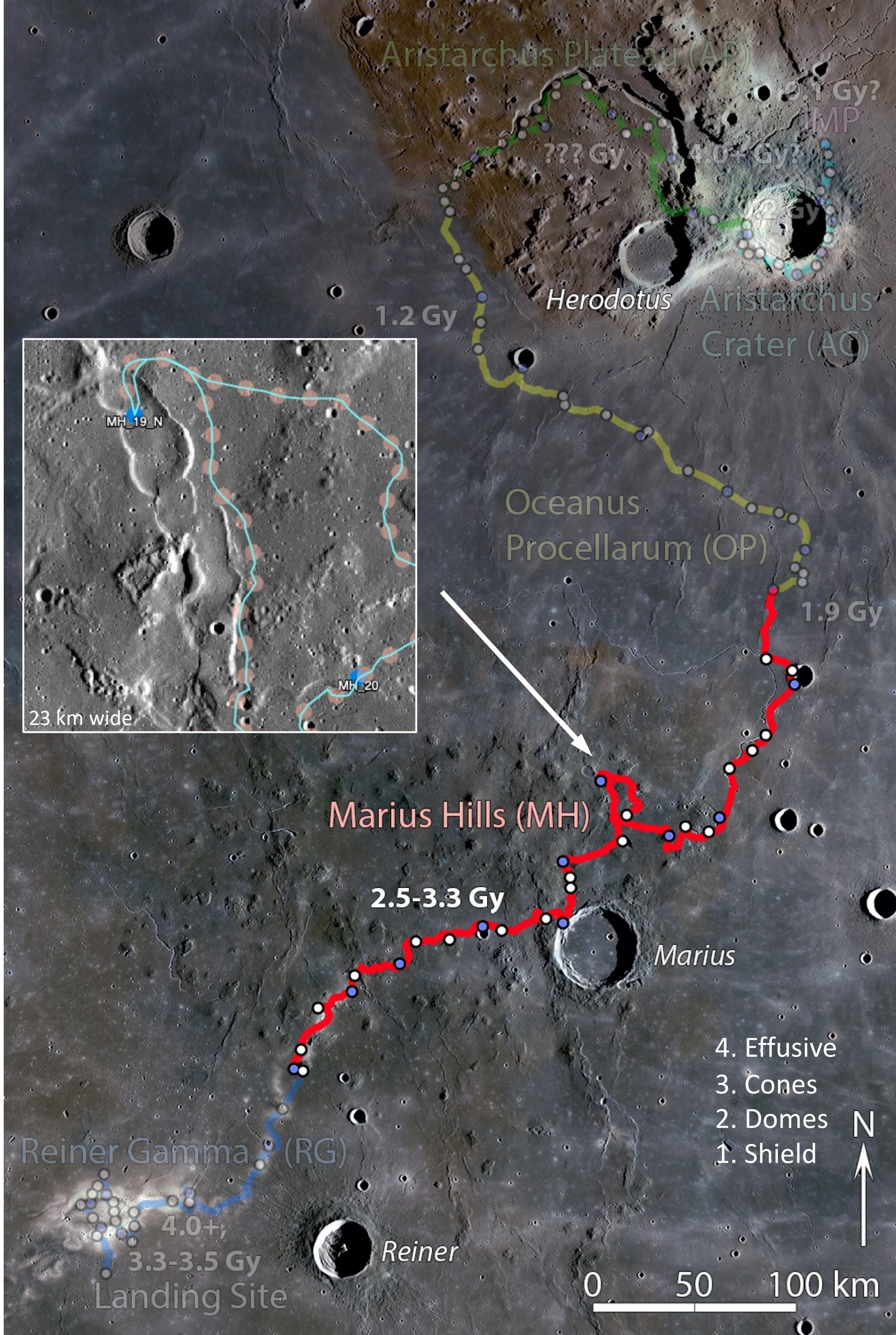


Marius Hills

31 major stops, 290 interval stops, 608 km, 10 lunations

- Search for intrusive bodies
- Magnetic environment
- Space environment interaction with surface
- Domes, cones, rille, vents, tubes, pyroclastics
- Non-mare volcanism?
- 2.5 to 3.3 Gy mare surface
- Mare composition as function of depth and along length of flows
- Regolith development
- Cratering mechanics

Test hypotheses for variations in volcanic morphologies: composition, volatile content, effusion rate



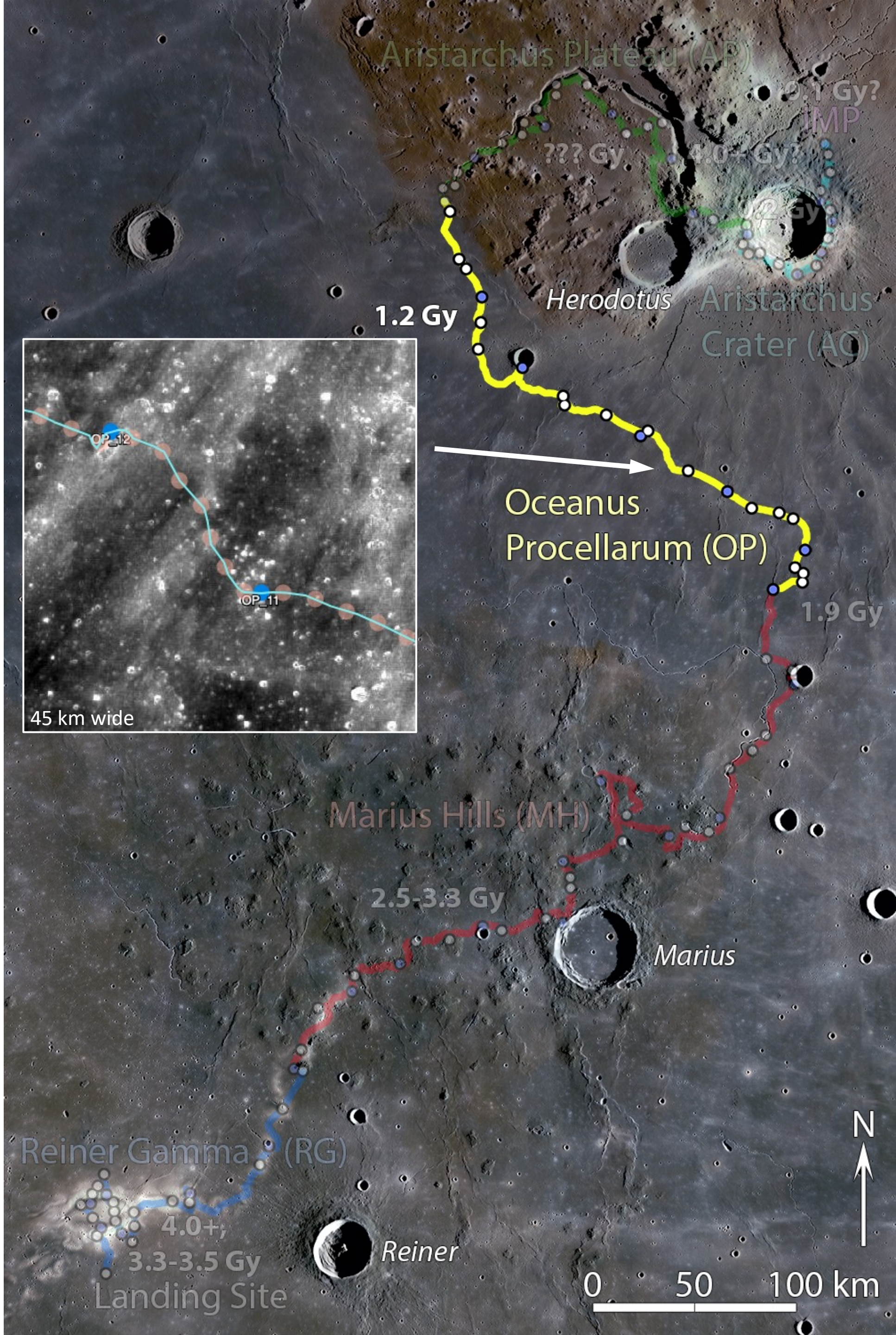
Oceanus Procellarum

24 major stops, 196 interval stops, 405 km, 7 lunations

- 1.2 to 1.9 Gy mare surface
- Radiogenic (Th, K) content of basalts
- Magnetic environment with time
- Shield volcano
- Intrusive body
- Ray mixing systematics
- Mare composition as function of depth
- Regolith development
- Cratering mechanics

Measure basalt and Aristarchus ray compositions to test ray formation hypotheses (% local vs ejected material) and KREEP (ejecta vs erupted).

Magnetic field through time (3.5 to 1.2 Gy) reveals evolution of core dynamo decline (rapid vs slow).

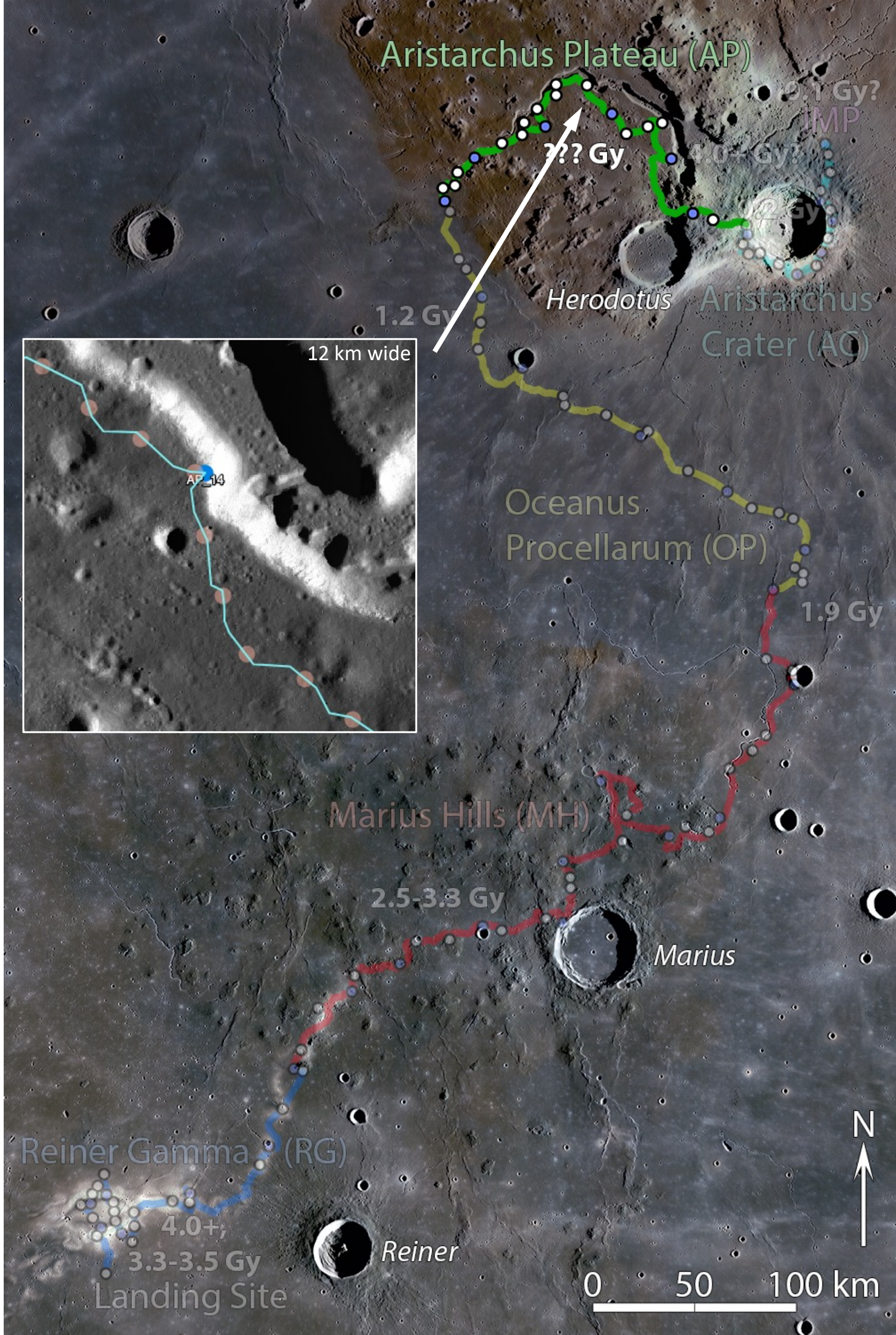


Aristarchus Plateau

22 major stops, 171 interval stops, 310 km, 5 lunations

- Large pyroclastic deposit (2 - 3 Gy?), physical state and composition as distance from vent and vertically
- Super size rille and vent, double nested rille
- Intrusive body
- Non mare volcanism?
- Regolith development (pyroclastics)
- Cratering mechanics (pyroclastics)

Determine composition of pyroclastic deposit; implications for mantle heterogeneity, and resource potential of the volcanic glass deposit.



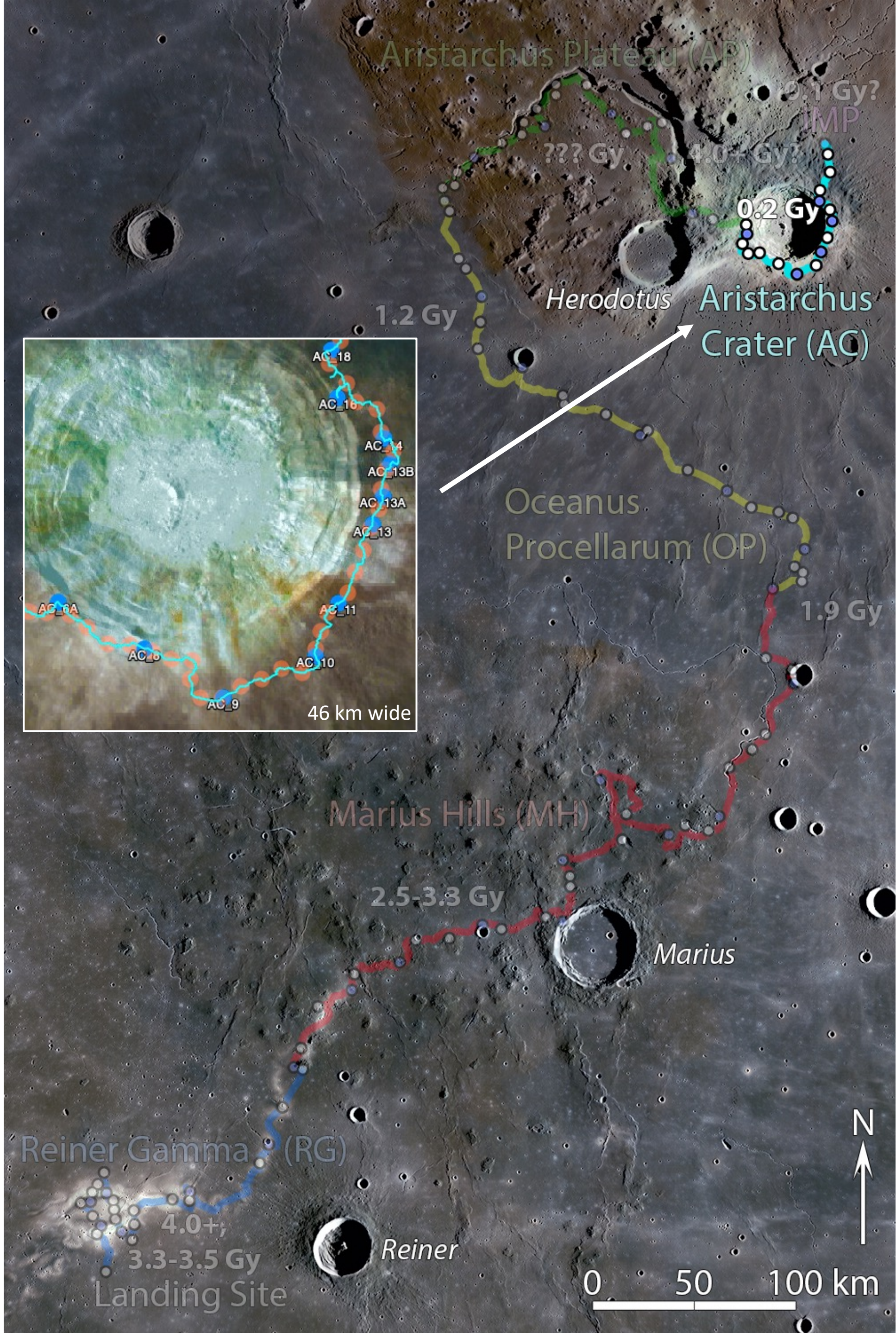
Aristarchus Crater

20 major stops, 171 interval stops, 182 km, 6 lunations

- 45 km diameter Copernican crater
- Procellarum KREEP Terrain crustal materials (range of compositions ejected from crater)
- Intrusive body
- Non-mare volcanism
- Regolith development (young impact melt units and granular ejecta)
- Cratering mechanics (ditto)

Test hypothesis that Aristarchus Crater excavated a silicic volcanic complex or other unknown ancient crustal material.

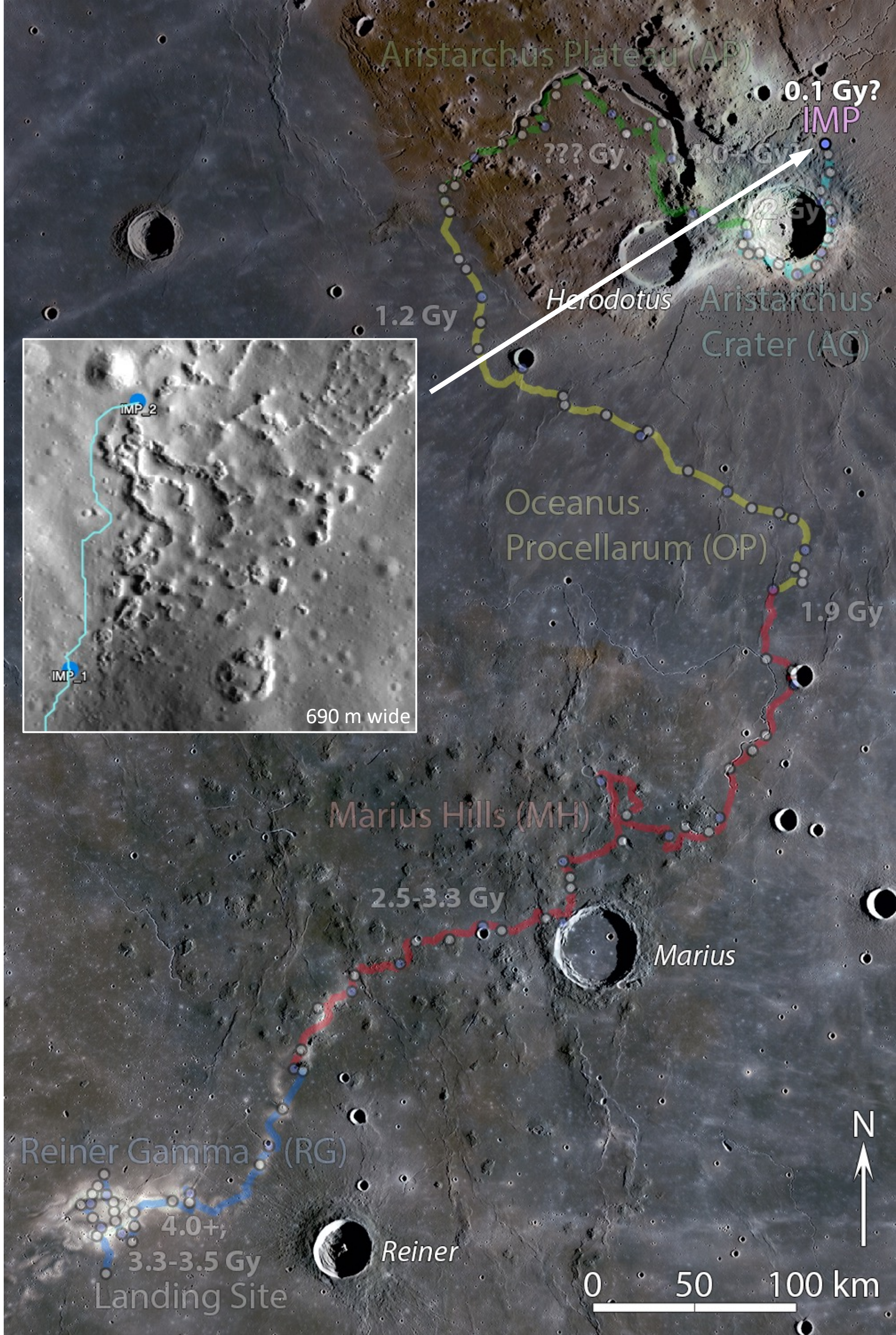
Test basaltic underplating as mechanism for tertiary crust formation.



Irregular Mare Patch (IMP)
2 major stops, 4 interval stops, 5 km, 1 lunation

- Origin and relative age
- Nature of materials
  - Composition
  - Physical state
- Non mare volcanism?
- Regolith development (young or anomalous old surface)
- Cratering mechanics (ditto)

Intrepid will characterize the contact of the IMP and AC ejecta thus determining relative age of IMP – young <0.2 Gy, or older than AC



New Paradigm

- The lunar night is your friend
- Long distance roving is your friend
- Excavated material provides is key
- Autonomy, autonomy, autonomy
- Pre-planning traverse and observations ensures maximum science return!

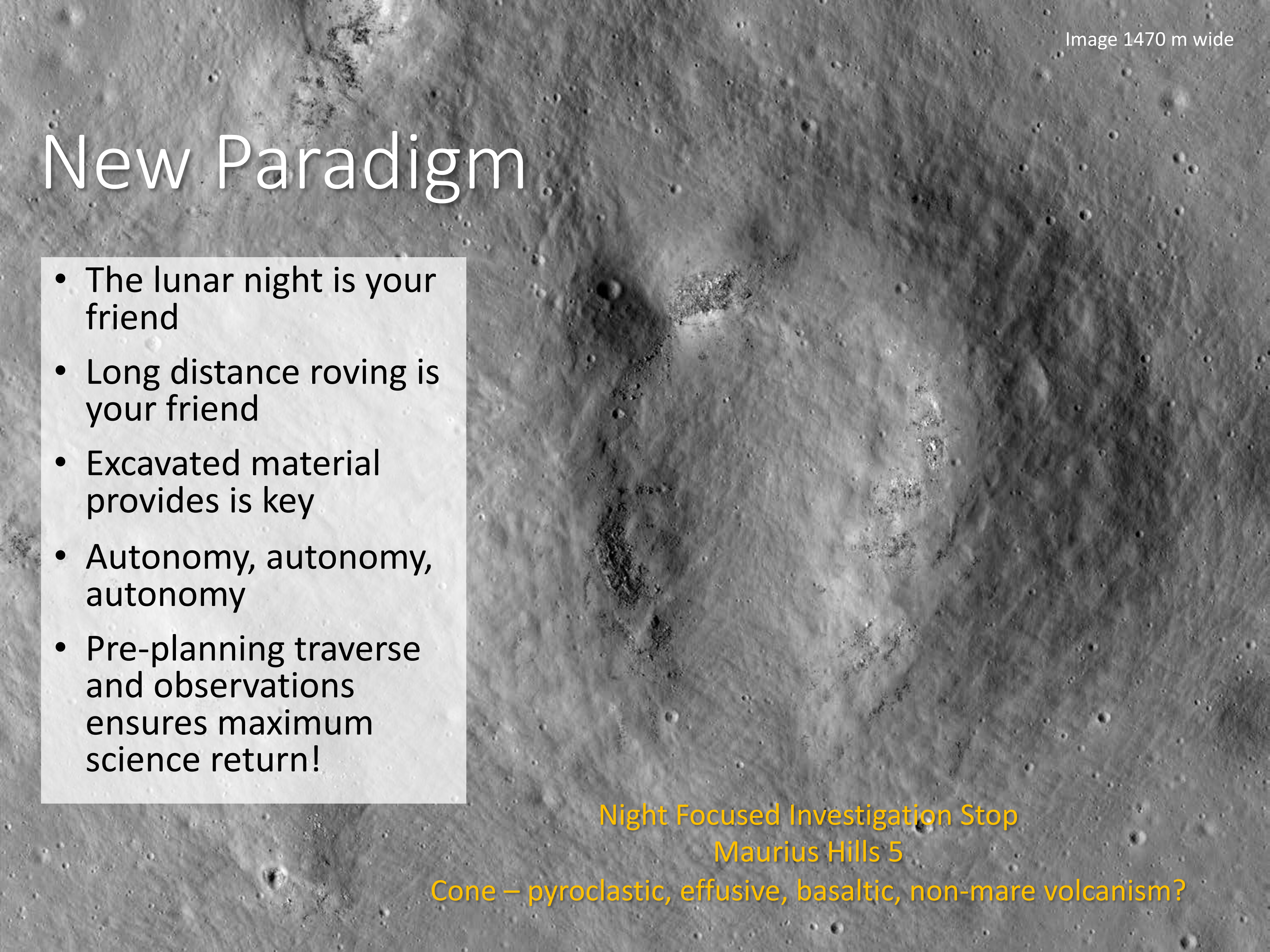
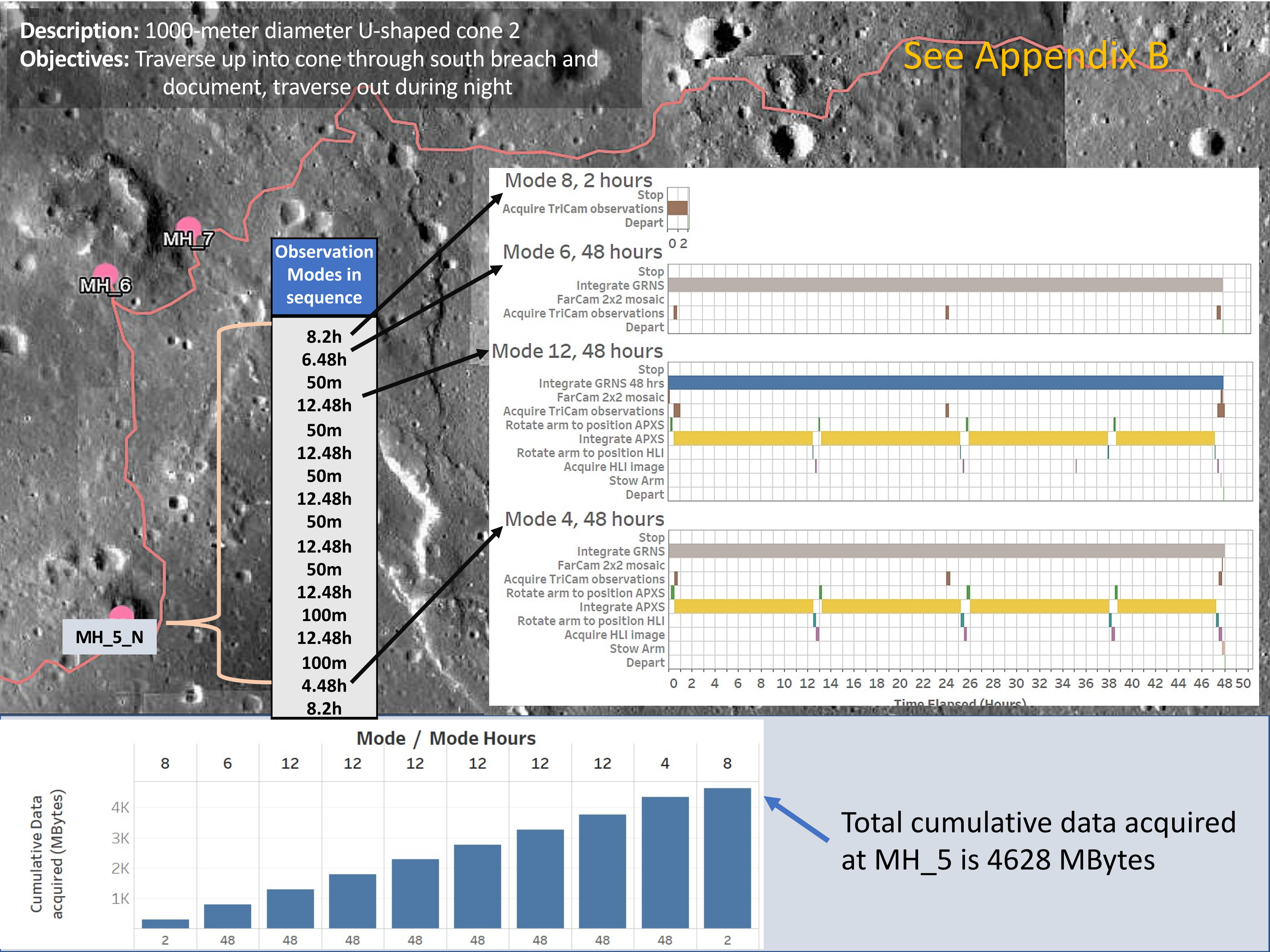


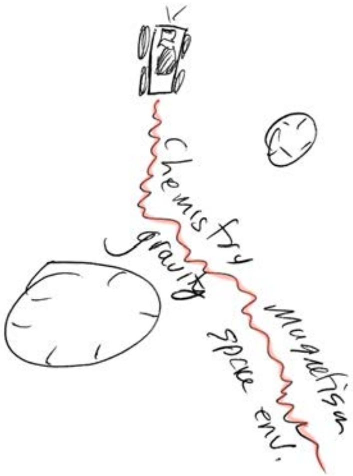
Image 1470 m wide

Night Focused Investigation Stop
Maurius Hills 5
Cone – pyroclastic, effusive, basaltic, non-mare volcanism?


Description: 1000-meter diameter U-shaped cone 2
Objectives: Traverse up into cone through south breach and document, traverse out during night
See Appendix B
MH_7
MH_6
MH_5_N
Observation Modes in sequence
8.2h
6.48h
50m
12.48h
50m
12.48h
50m
12.48h
50m
12.48h
50m
12.48h
100m
12.48h
100m
4.48h
8.2h
Mode 8, 2 hours
Stop
Acquire TriCam observations
Depart
0 2
Mode 6, 48 hours
Stop
Integrate GRNS
FarCam 2x2 mosaic
Acquire TriCam observations
Depart
Mode 12, 48 hours
Stop
Integrate GRNS 48 hrs
FarCam 2x2 mosaic
Acquire TriCam observations
Rotate arm to position APXS
Integrate APXS
Rotate arm to position HLI
Acquire HLI image
Stow Arm
Depart
Mode 4, 48 hours
Stop
Integrate GRNS
FarCam 2x2 mosaic
Acquire TriCam observations
Rotate arm to position APXS
Integrate APXS
Rotate arm to position HLI
Acquire HLI image
Stow Arm
Depart
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50
Time Elapsed (Hours)
Mode / Mode Hours
8 6 12 12 12 12 12 12 4 8
Cumulative Data acquired (MBytes)
4K
3K
2K
1K
2 48 48 48 48 48 48 48 48 2
Total cumulative data acquired at MH_5 is 4628 MBytes

Summary of Stops and Measurements

Integration
noodle



- Focused Investigation Stops: 133
- Overnight Stops: 35 of 133
- Interval Stops: 981
- >1800 km of "integration noodles"
    - Continuous roving observations (GRNS, magnetometer, electrostatic analyzer, ARMAS); slice and dice as appropriate
- Total Number of FI and Interval Observations
    - APXS 2013; HLI 2103; PS 69,198; FarCam 48,002 ; Color stereo pairs 35,307
- While driving: 31,400 observations with 1 PS spectrum and 1 lossy greyscale stereo pair.
- Total science data 1.1 TeraBytes with 2.0 Terabytes of available science downlink

Detailed inventory of observations critical to power, computing, and downlink allocations -- as well as documenting data sufficiency (Appendix B)

Science Return Time Line

	Reiner Gamma	Marius Hills	Oceanus Procellarum	Aristarchus Plateau	Aristarchus Crater	IMP
1.1 Extended volcanism Proc region		x	x	x	x	x
1.2 Crustal asymmetry		x	x	x	x	
1.3 Origin of nonmare volcanism		x?			x	
1.4 Deep mantle composition		x		x		
1.5 Decline of core dynamo	x	x	x			x?
2.1 Flood basalt emplacement	x	x	x	x		
2.2 Origin composition domes, cones, shields		x	x			x?
2.3 Pyroclastic processes		x		x		x?
2.4 Nature of intrusive volcanism	x			x	x	
3.1 Crater formation and processes	x	x	x	x	x	x
3.2 Target material influence	x	x	x	x	x	x
3.3 Space weathering	x	x	x	x	x	x

Mission elapsed time →

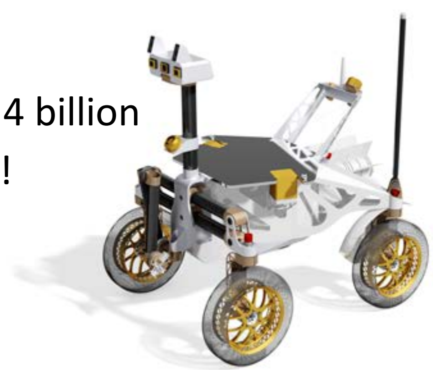
Some objectives require observations from the full traverse (all six regions) while others require observations from fewer regions. Mission progresses from left to right.; “x” indicates regions where required measurements are acquired.

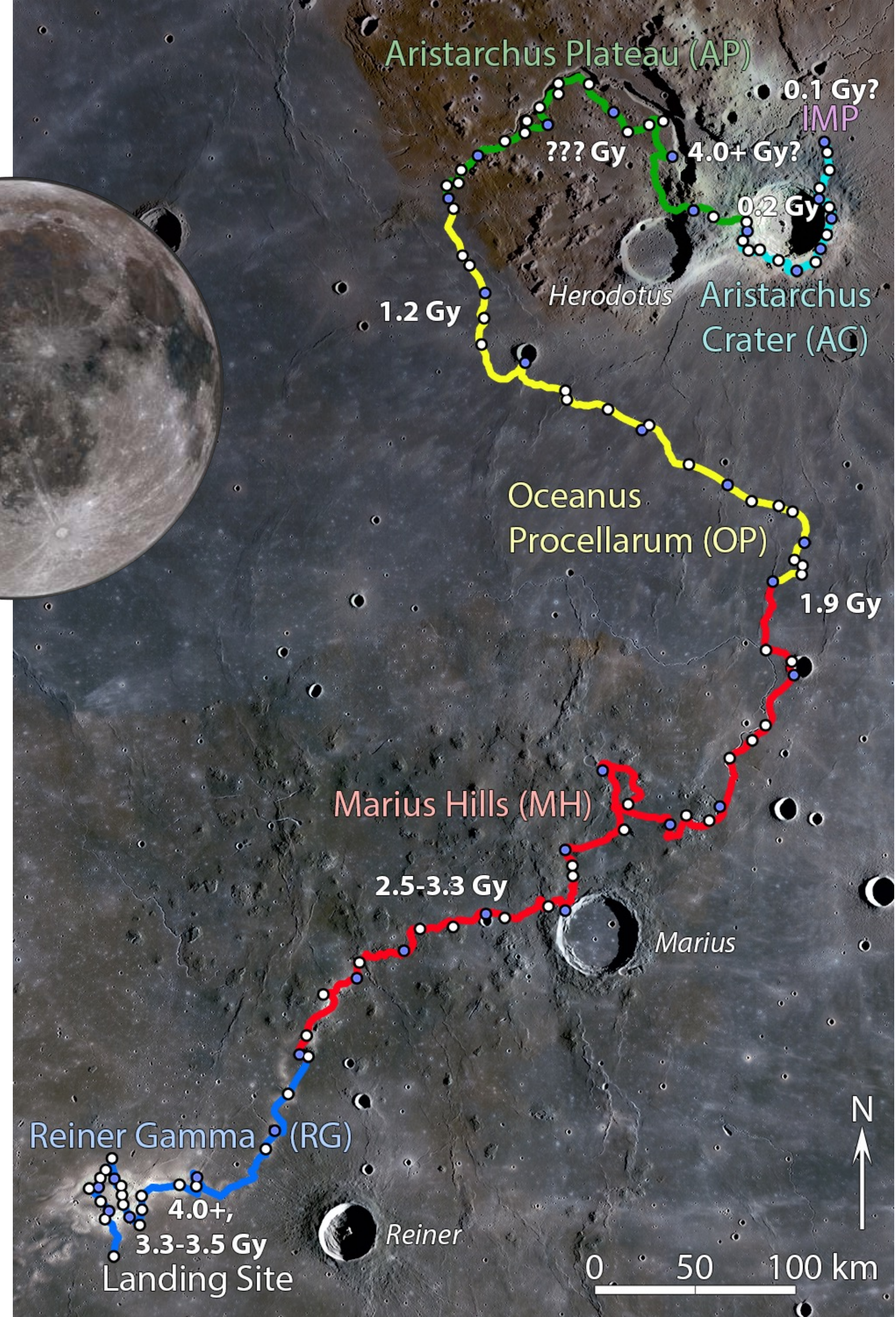
Why 1800 kilometer traverse?

The current traverse is the shortest route to interrogate 4 billion years of magmatic materials emplaced via a broad range of mechanisms.

Need full time spectrum to begin a holistic understanding of lunar magmatism, a key to unraveling the formation and evolution of the Moon (Earth-Moon system) and early evolution of differentiated silicate bodies.

Small distance to traverse 4 billion years of lunar magmatism!



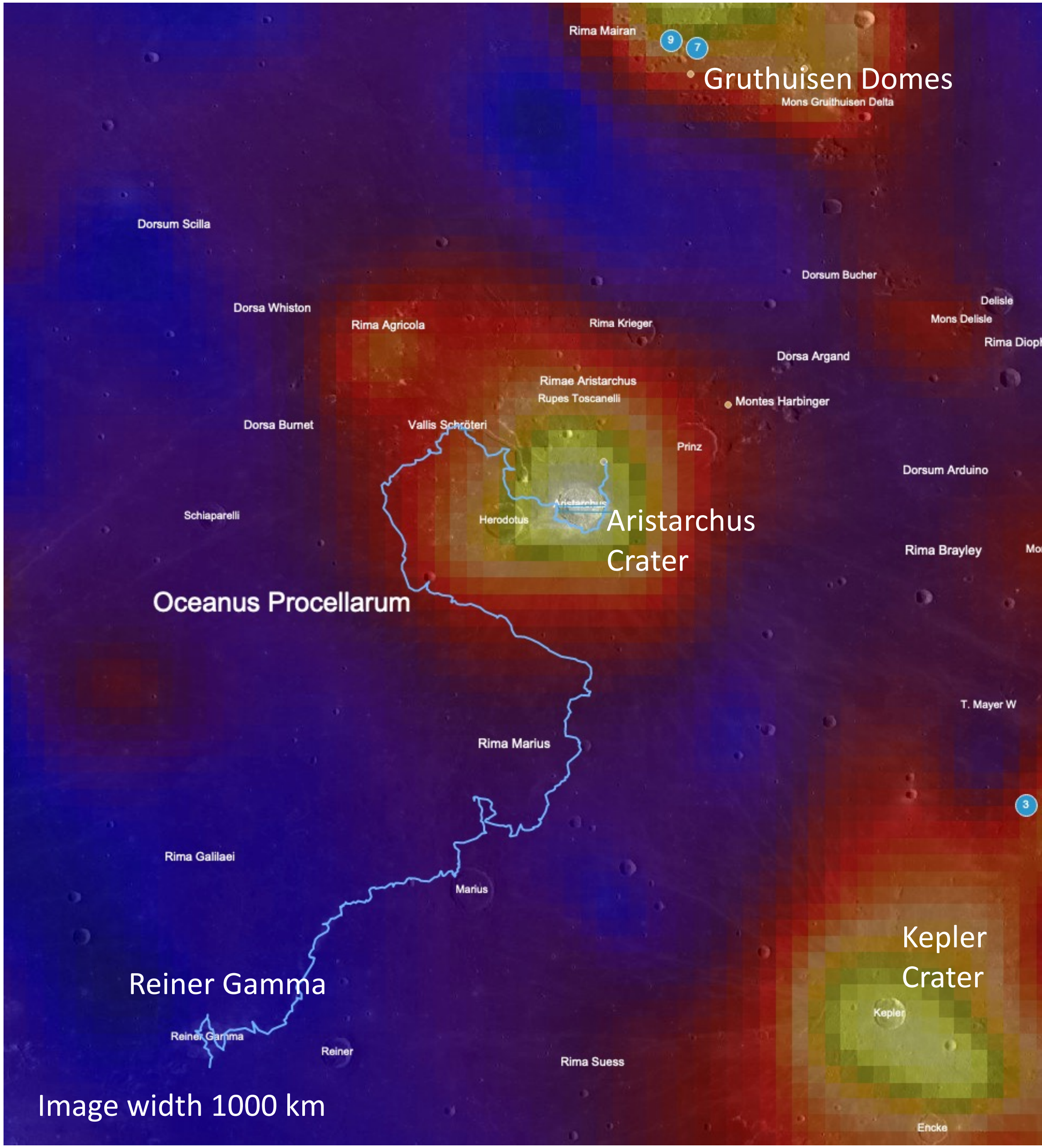


Backup Slides

Nature of PKT?

- Is the Th signature from highland material?
- Are there KREEPy basalts?
- KREEPy non-mare volcanism?
- Measure Th etc from surface and sub-surface to gain 3-D picture of KREEP source (small crater ejecta)
- Extended mission to Gruithuisen domes *extends* range of non-mare volcanic materials measured and provides second highland terrane traverse

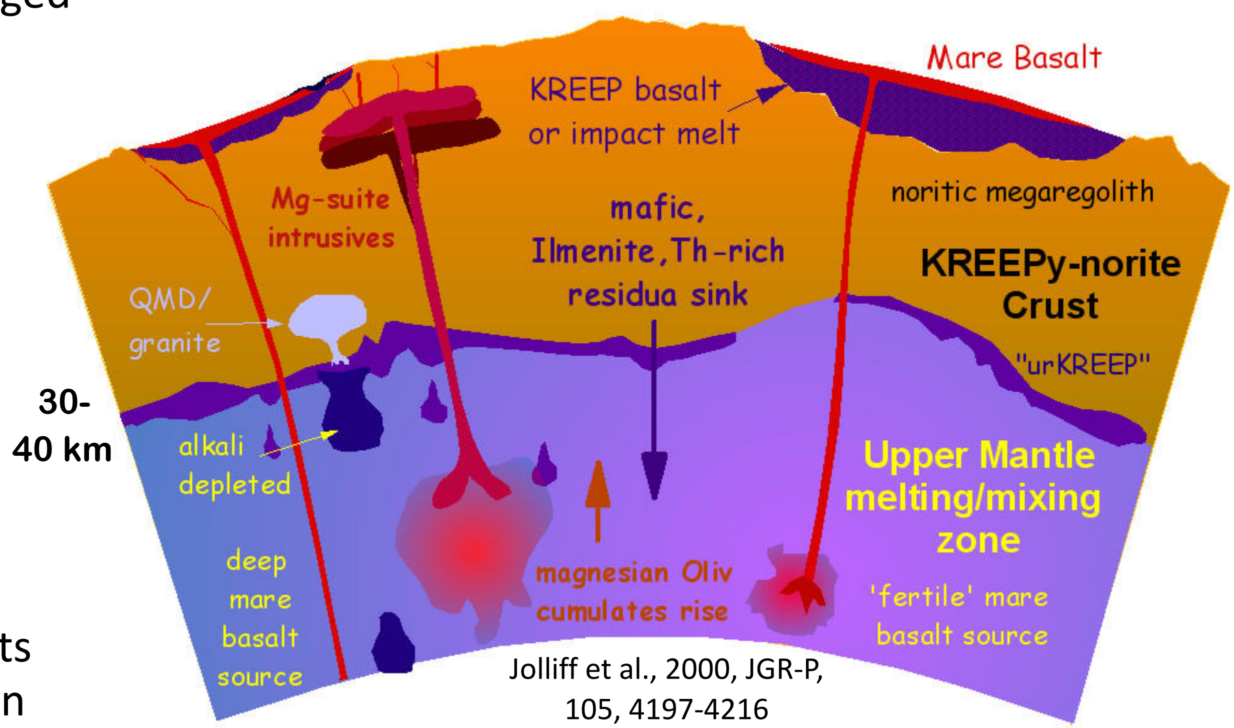
Lunar Prospector Thorium Map, Intrepid Traverse



Mantle Overturn

- Is the PKT an area of prolonged volcanic activity because of mantle overturn?
- From compositions of basalt, we can infer characteristics of the mantle beneath this region of the Moon.
  - Mineralogy
  - Chemical composition
  - Depth of melting
- Variations with age of basalts will reveal if mantle overturn led to the intense volcanic activity of this region.

Procellarum KREEP Terrane



Jolliff et al., 2000, JGR-P, 105, 4197-4216

Procellarum KREEP Terrane (PKT) may be a site of prolonged volcanism owing to mantle overturn, which would have caused early olivine cumulates to rise from depth and mix with sinking, late-stage Ti- and KREEP-rich LMO residua, producing "fertile" source regions for partial melting at a variety of depths.

Intrepid Traceability to Key NASA Planning Documents

1. **Evolution of the lunar interior over 4 Gy (requires diversity of ages and compositions)**
   1.1. Composition of basaltic volcanism through time, heterogeneity/evolution of mantle (shallow), end of volcanism
   1.2. Test for presence, extent, and composition of ancient crust in PKT, crustal asymmetry
   1.3. Test for presence, extent, composition of non-mare volcanism
   1.4. Determine composition of deep mantle from pyroclastic glass
   1.5. Decline of core dynamo and magnetic field over time

Traceability themes:

Decadal 1.1.2 (interior volatiles); 1.2.1 (magmatic evolution; interior); 1.2.2 (core dynamo); 1.3.1 (landforms); 1.3.3(volcanism)

SCEM and ASM-SAT: Concepts 2 (interior), 3 (crustal rock diversity); 5 (volcanism and thermal evolution)

NEXT-SAT objectives: 1 (ages of units), 3 (interior), 4 (magnetic anomalies)

2. **Diversity of styles of magmatism (requires diversity of landforms/deposits: flood basalts, shield volcanism, Marius Hills, pyroclastic eruption, rille, intrusive/dike):**
   2.1. Flood basalt emplacement, rilles, vents, flows, tubes
   2.2. Origin(s) and composition(s) of cones, domes and shields
   2.3. Pyroclastic volcanism processes, composition and physical state (grain size, glass content)
   2.4. Intrusive volcanism and relation to effusive deposits

Traceability themes:

Decadal 1.1.2 (interior volatiles); 1.2.1 (magmatic evolution); 1.3.1 (landforms); 1.3.3 (volcanism)

SCEM and ASM-SAT: Concepts 5 (volcanism and thermal evolution), 11 (tectonism)

NEXT-SAT objectives: 5 (volcanism), 7 (resources)

LEAG SKGs: 1 (DMD volatiles)

Intrepid Class Rover Enables Many Missions

New Frontiers class science missions

Gather decisional data for human exploration sites

Collect and document contextualized samples and bring to human site for return to Earth

Work with humans exploring a given site

Explore after humans leave

Explore towards next human site...

NASA Illustration

Intrepid Traceability to Key NASA Planning Documents

3. Post emplacement modifications (also requires diversity of terrains to assess variations):

3.1. Nature of impact cratering processes, ballistic sedimentation, ray formation, physical properties of the regolith around the impact

3.2. Target material dependence of crater formation and key landforms diagnostic of impact mechanics

3.3. Variations in space weathering in variety of terrains/ages and relationships to radiation environment, H-abundance, and magnetic anomalies

Traceability themes:

Decadal 1.1.2 (volatile budget on surface & in exosphere); 1.3.1 (surface modification); 1.3.2 (sources/timing impacts); Human (radiation)

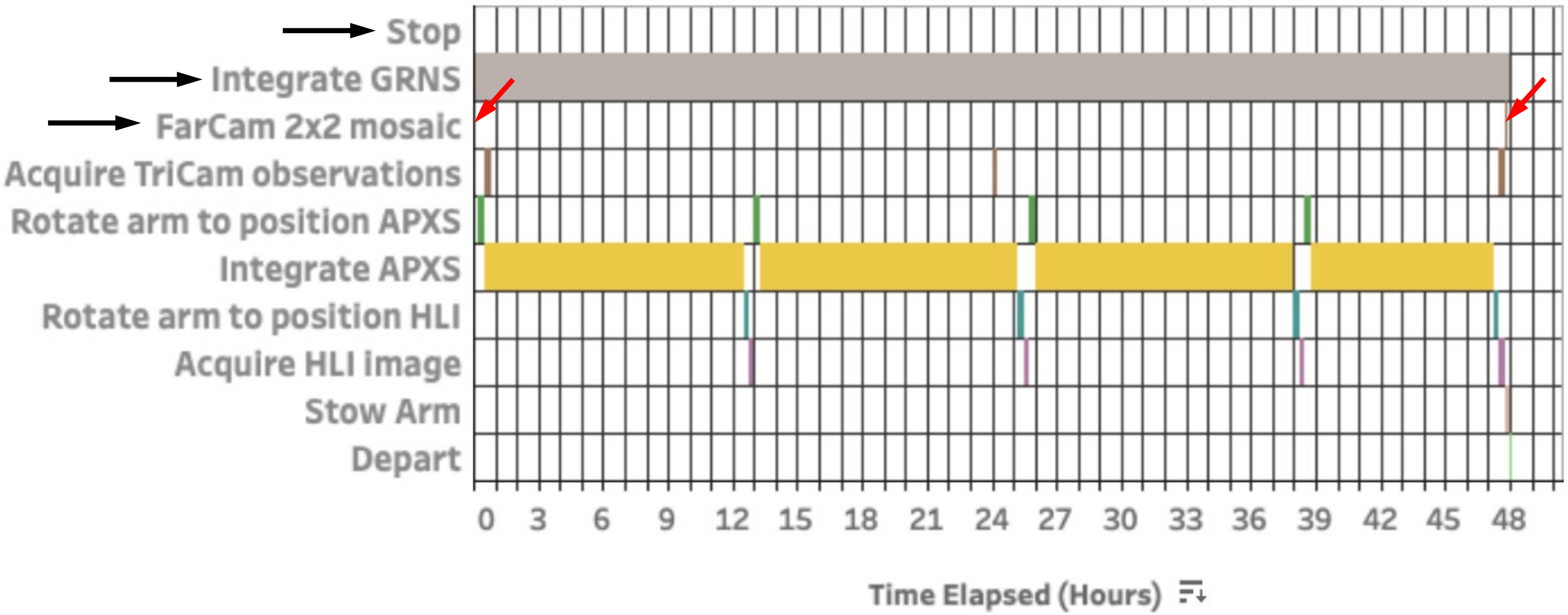
SCEM and ASM-SAT: Concepts 1 (bombardment history), 6 (impact lab), 7 (regolith and weathering lab), 11 (tectonism)

NEXT-SAT objectives: 4 (magnetic anomalies)

LEAG SKGs: 1 (regolith volatiles); 2 (radiation & environment)

All Stops Are pre-Planned

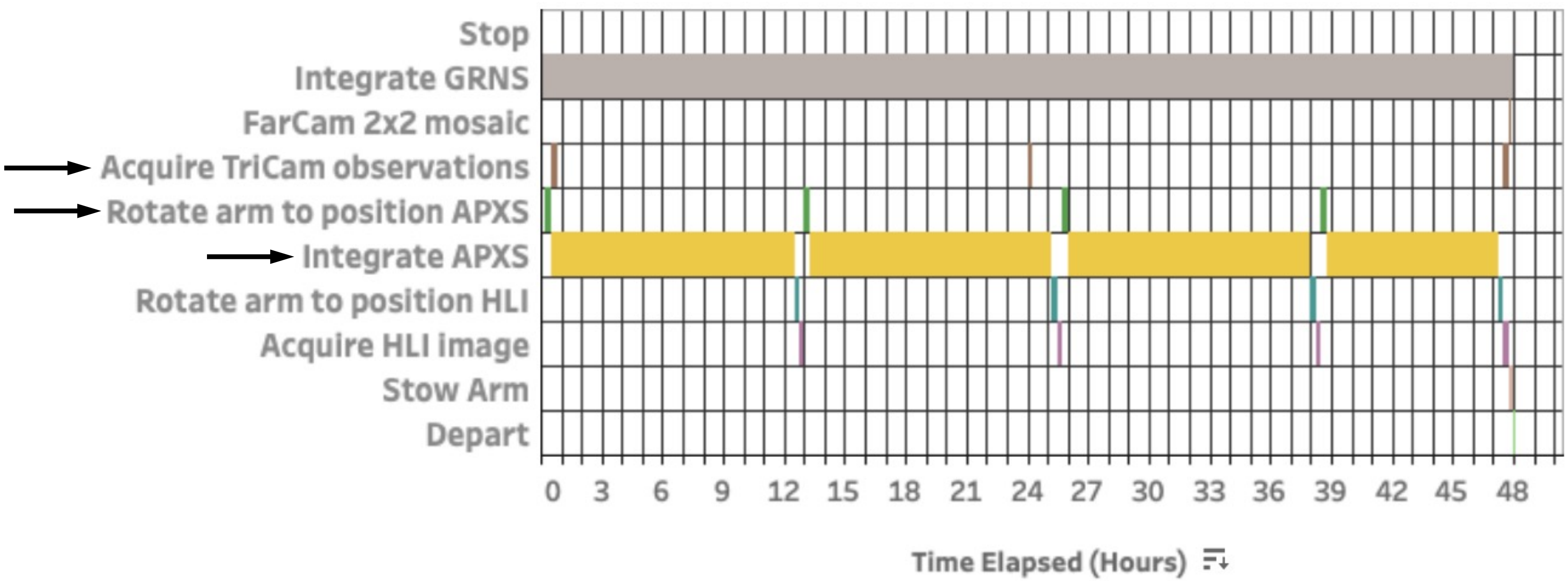
Example 48 hr Focused Investigation Site



T=0.00 hr Integrate GRNS for 48 hours
T=0.00 hr FarCam 2x2 mosaic "APXS area"
T=0.00 hr Mag/ARMAS/ELAN continue to integrate
T=0.50 hr Start first 12 hour APXS integration
T=0.50 hr Collect TriCam observations
T=12.75 hr Acquire HLI image
T=13.25 hr Start second 12 hour APXS integration
T=24.00 hr Collect TriCam observations
T=25.50 hr Acquire HLI image
T=26.00 hr Start third 12 hour APXS integration
T=38.15 hr Acquire HLI image
T=38.75 hr Start fourth 8.5 hour APXS integration
T=47.50 hr Acquire HLI image
T=47.50 hr Collect TriCam observations
T=47.75 hr FarCam 2x2 mosaic

All Stops Are pre-Planned

Example 48 hr Focused Investigation Site



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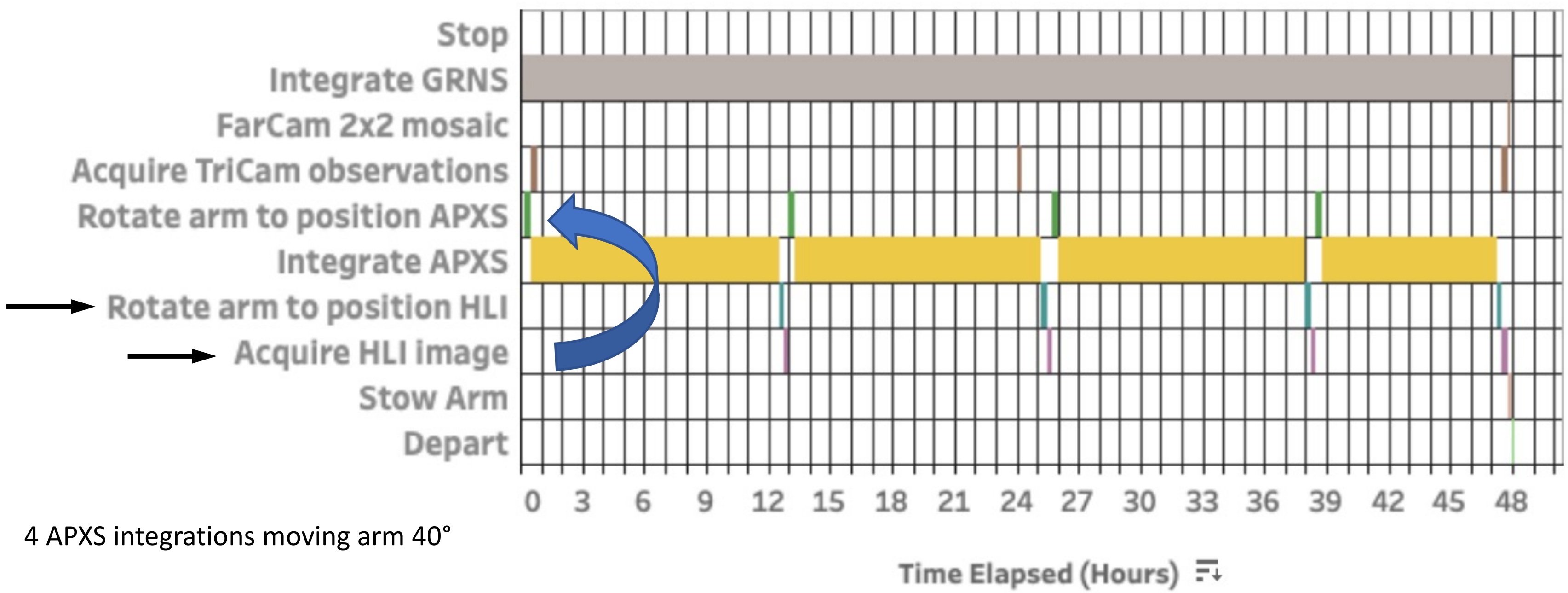
T=12.75 hr Acquire HLI image
T=13.25 hr Start second 12 hour APXS integration
T=24.00 hr Collect TriCam observations
T=25.50 hr Acquire HLI image
T=26.00 hr Start third 12 hour APXS integration
T=38.15 hr Acquire HLI image
T=38.75 hr Start fourth 8.5 hour APXS integration
T=47.50 hr Acquire HLI image
T=47.50 hr Collect TriCam observations
T=47.75 hr FarCam 2x2 mosaic

All Stops Are pre-Planned
Example 48 hr Focused Investigation Site



4 APXS integrations moving arm 40°

T=0.00 hr Integrate GRNS for 48 hours
T=0.00 hr FarCam 2x2 mosaic
T=0.00 hr Mag/ARMAS/ELAN continue to integrate
T=0.50 hr Start first 12 hour APXS integration
T=0.50 hr Collect TriCam observations
T=12.75 hr Acquire HLI image
T=13.25 hr Start second 12 hour APXS integration
T=24.00 hr Collect TriCam observations
T=25.50 hr Acquire HLI image
T=26.00 hr Start third 12 hour APXS integration
T=38.15 hr Acquire HLI image
T=38.75 hr Start fourth 8.5 hour APXS integration
T=47.50 hr Acquire HLI image
T=47.50 hr Collect TriCam observations
T=47.75 hr FarCam 2x2 mosaic

All Stops Are pre-Planned

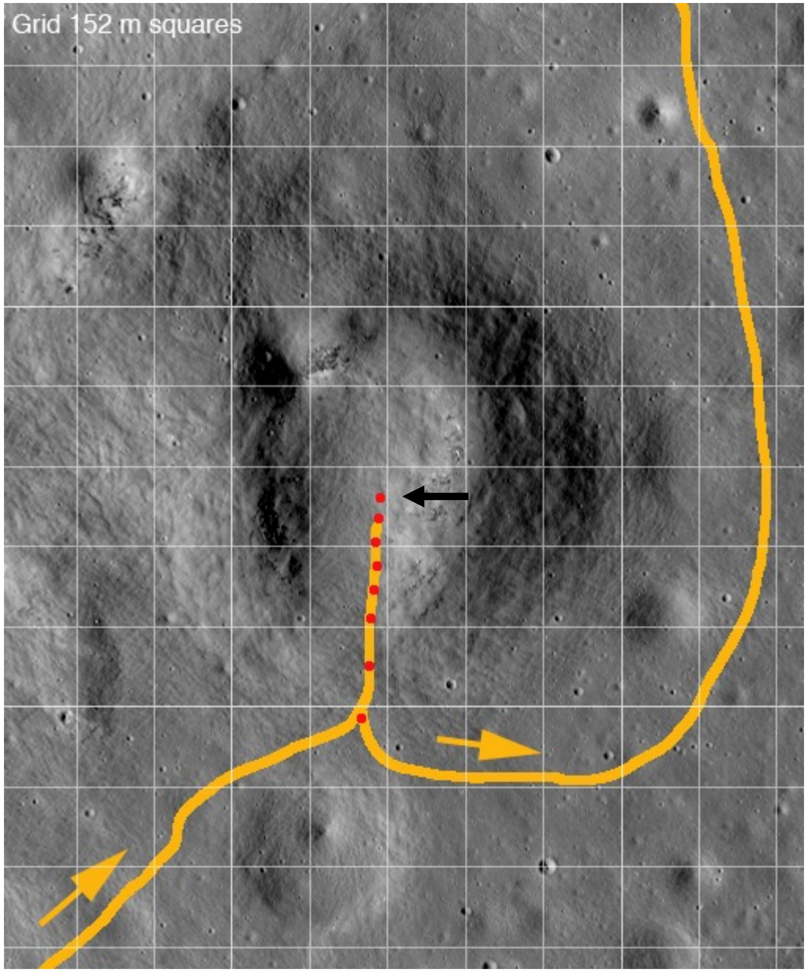
Example 48 hr Focused Investigation Site

T=0.00 hr Integrate GRNS for 48 hours
T=0.00 hr FarCam 2x2 mosaic
T=0.00 hr Mag/ARMAS/ELAN continue to integrate
T=0.50 hr Start first 12 hour APXS integration
T=0.50 hr Collect TriCam observations
T=12.75 hr Acquire HLI image
T=13.25 hr Start second 12 hour APXS integration
T=24.00 hr Collect TriCam observations
T=25.50 hr Acquire HLI image
T=26.00 hr Start third 12 hour APXS integration
T=38.15 hr Acquire HLI image
T=38.75 hr Start fourth 8.5 hour APXS integration
T=47.50 hr Acquire HLI image
T=47.50 hr Collect TriCam observations
T=47.75 hr FarCam 2x2 mosaic

Typical Night Stop

Drive to furthest point laying down night tracks (arrival 14.90 solar time)

1) BW telephoto panorama, stereo color panorama, PS mosaic, 48 hr int, drive 50 m
2) Sunset
3) 48 hour integration, 50 m (x5)
4) 48 hour integration, 100 m (x2)
5) Sunrise
6) Large BW telephoto mosaic stereo panorama, 48 hr int
7) Depart when solar angle 10° above horizon



Marius Hills cone (11.138°N, 305.132°E), map 1600 m wide, cone rises ~100 m above surroundings, max slope of night path 10°.

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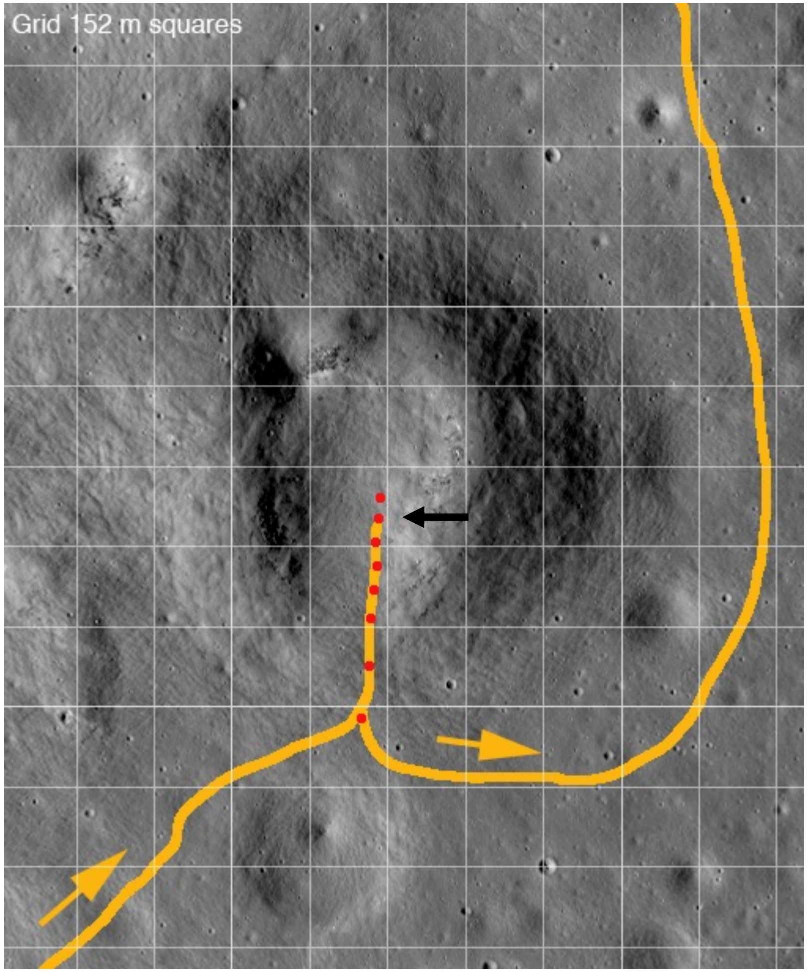

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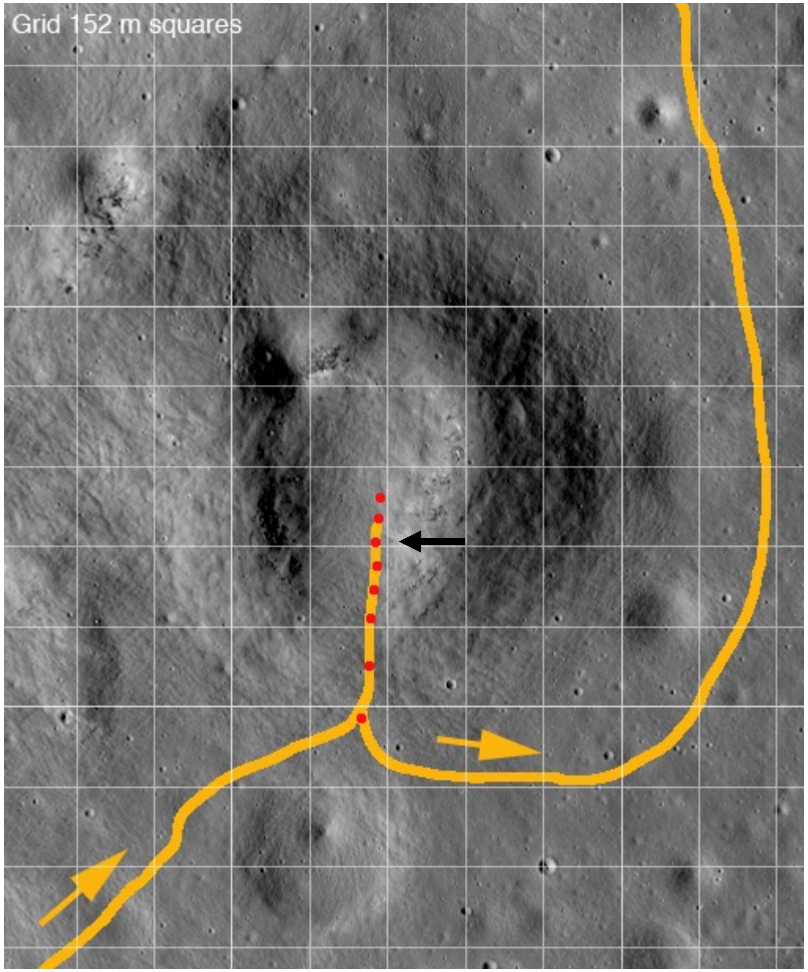

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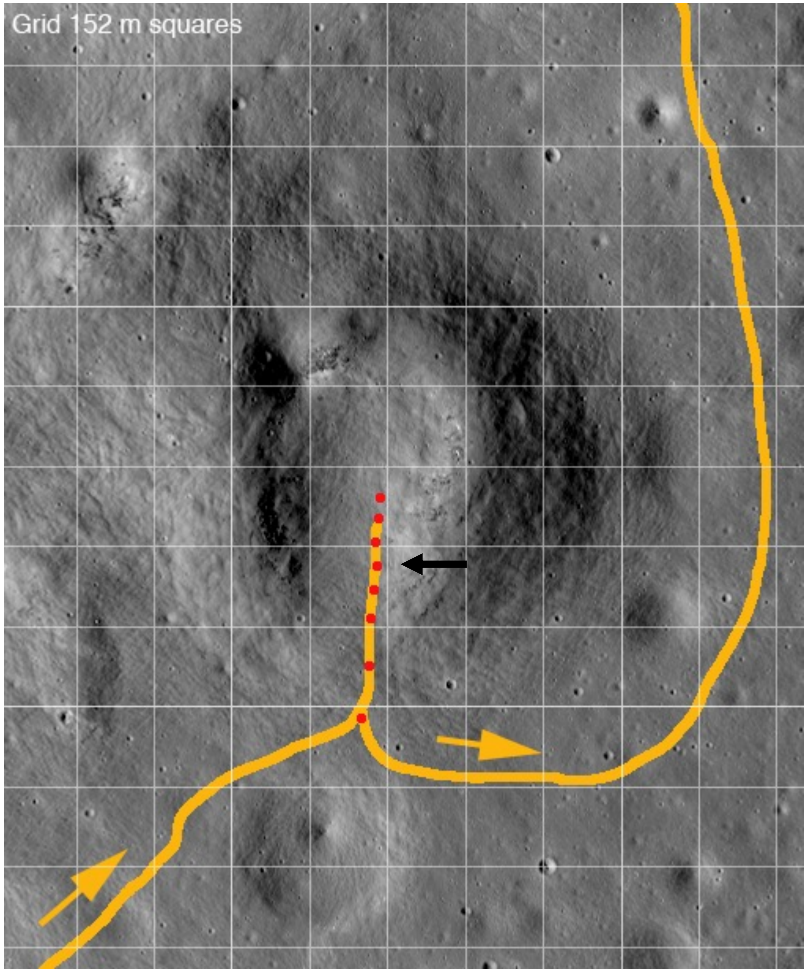

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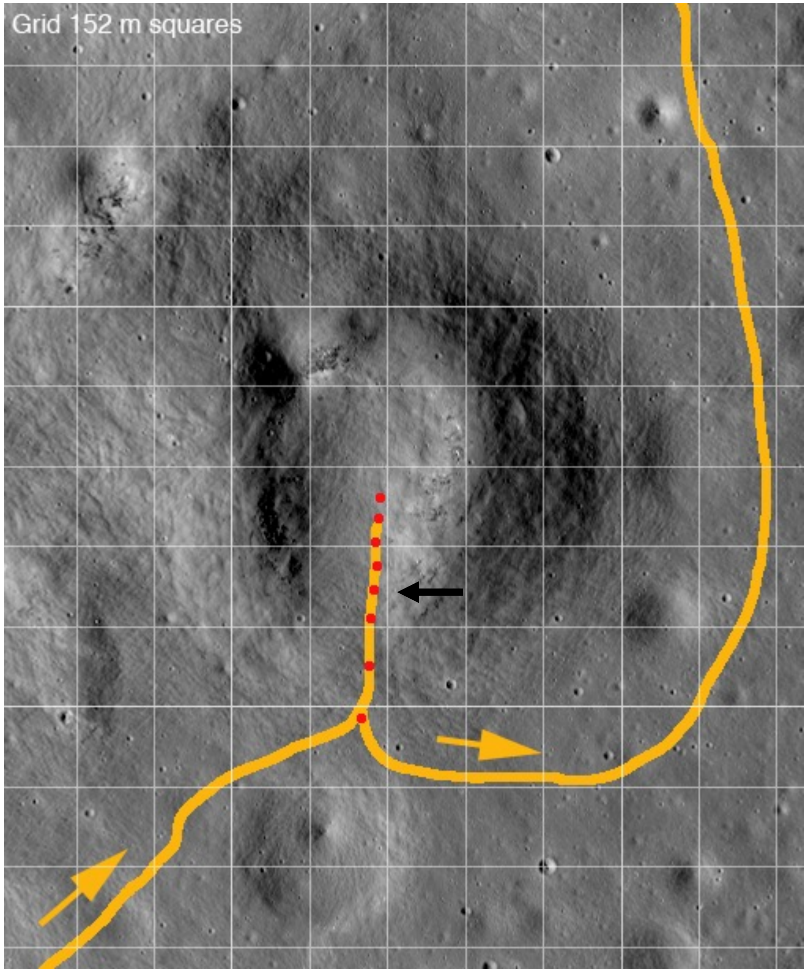

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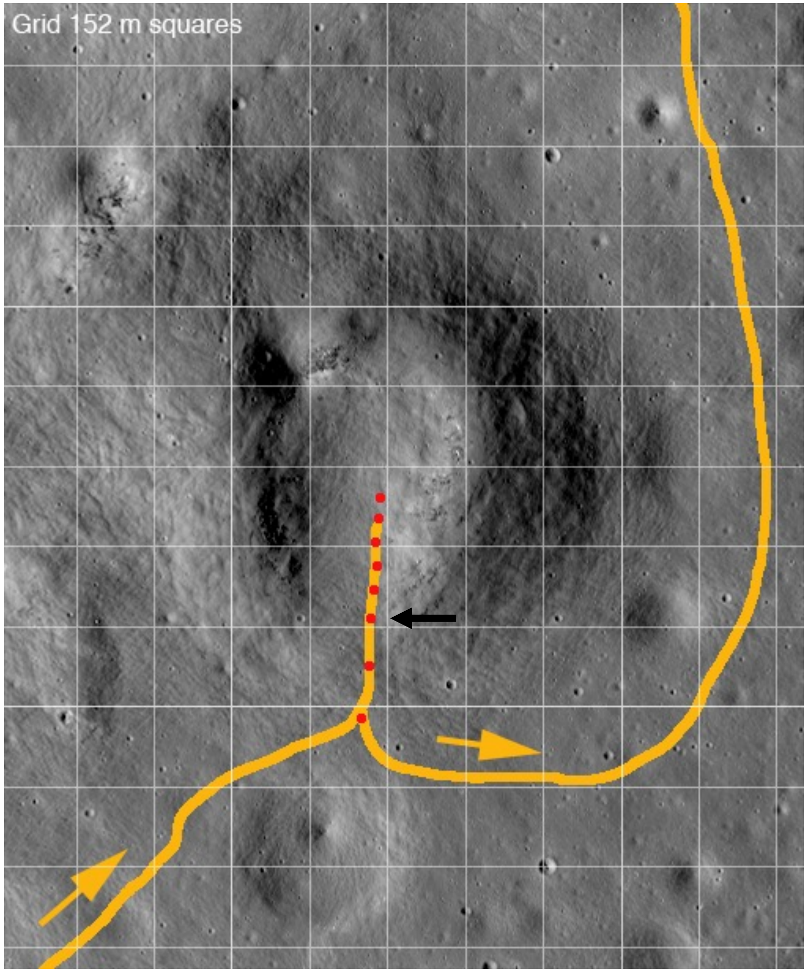

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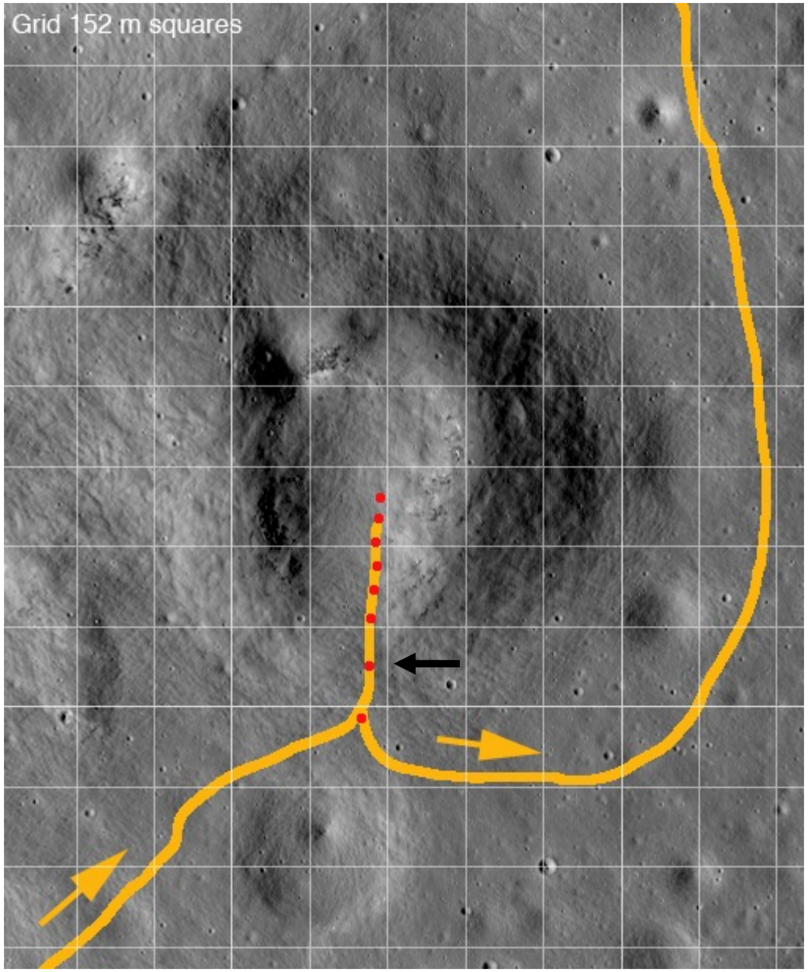

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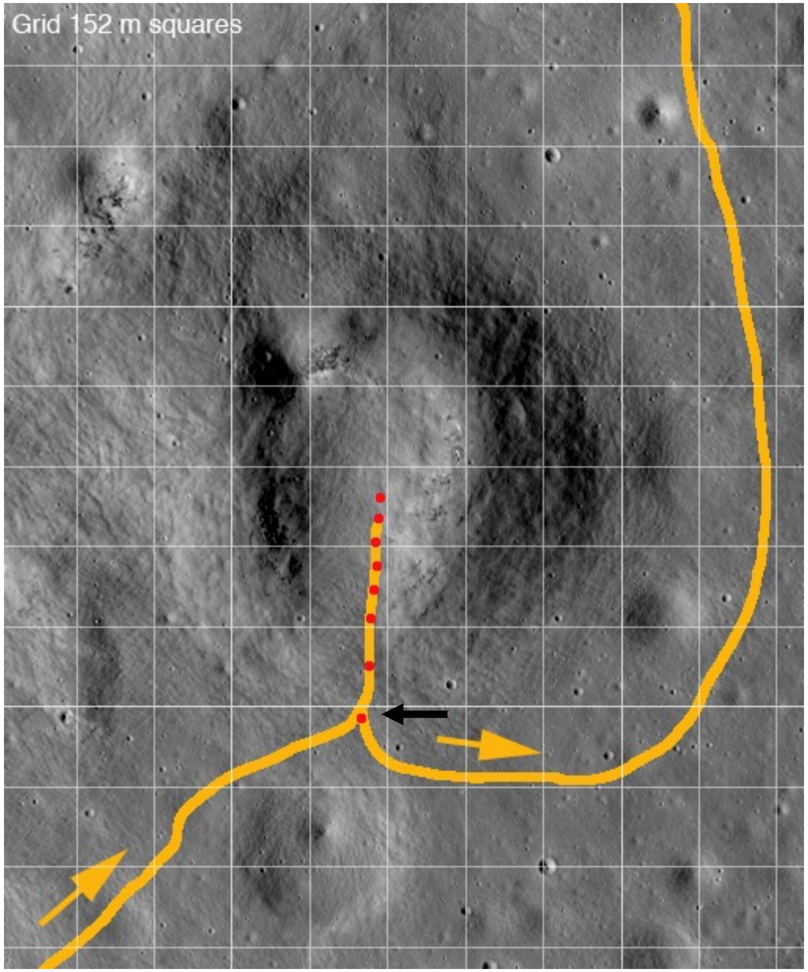

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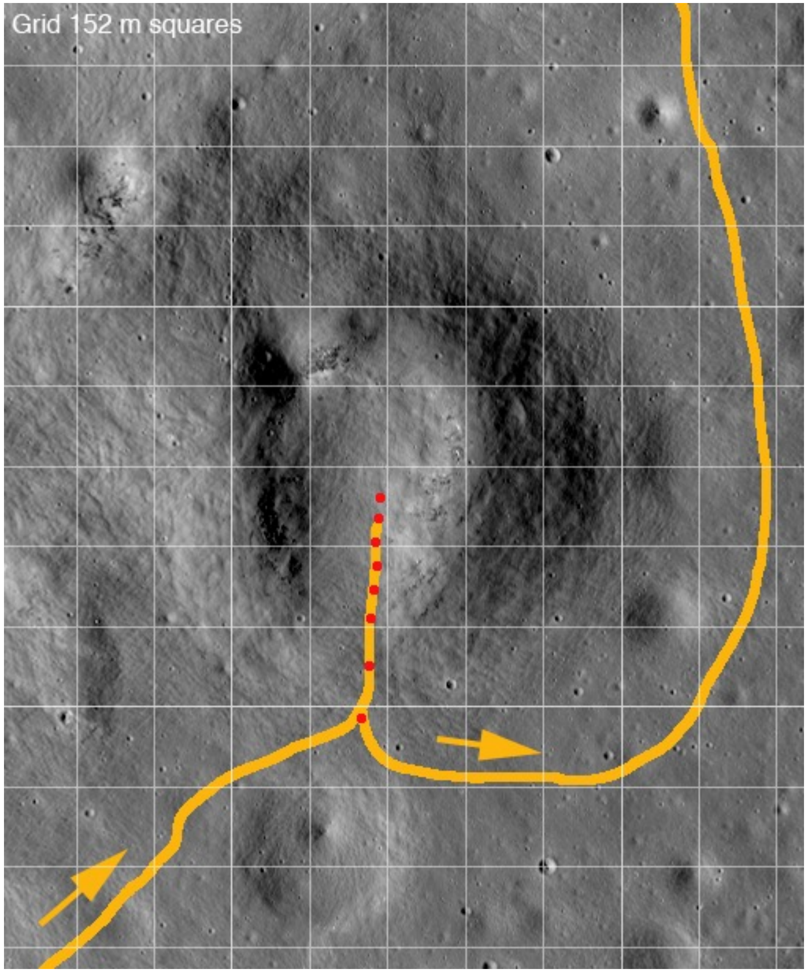


Marius Hills cone (11.138°N, 305.132°E), map 1600 m wide, cone rises ~100 m above surroundings, max slope of night path 10°.

Measurements Come Full Circle

1) Determine the cause of extended volcanism in the Procellarum region: Test for variations in mineralogical and chemical composition of basalts from very old (Marius Hills) to very young (IMP). Test the hypothesis that extended volcanism is related to variations in the composition of the basalt source regions, e.g., radiogenic elements (K, U, Th), Fe/(Fe+Mg), and reflected by mineralogy such as olivine content and Fe content of olivine (forsterite vs. Fe-rich olivine).

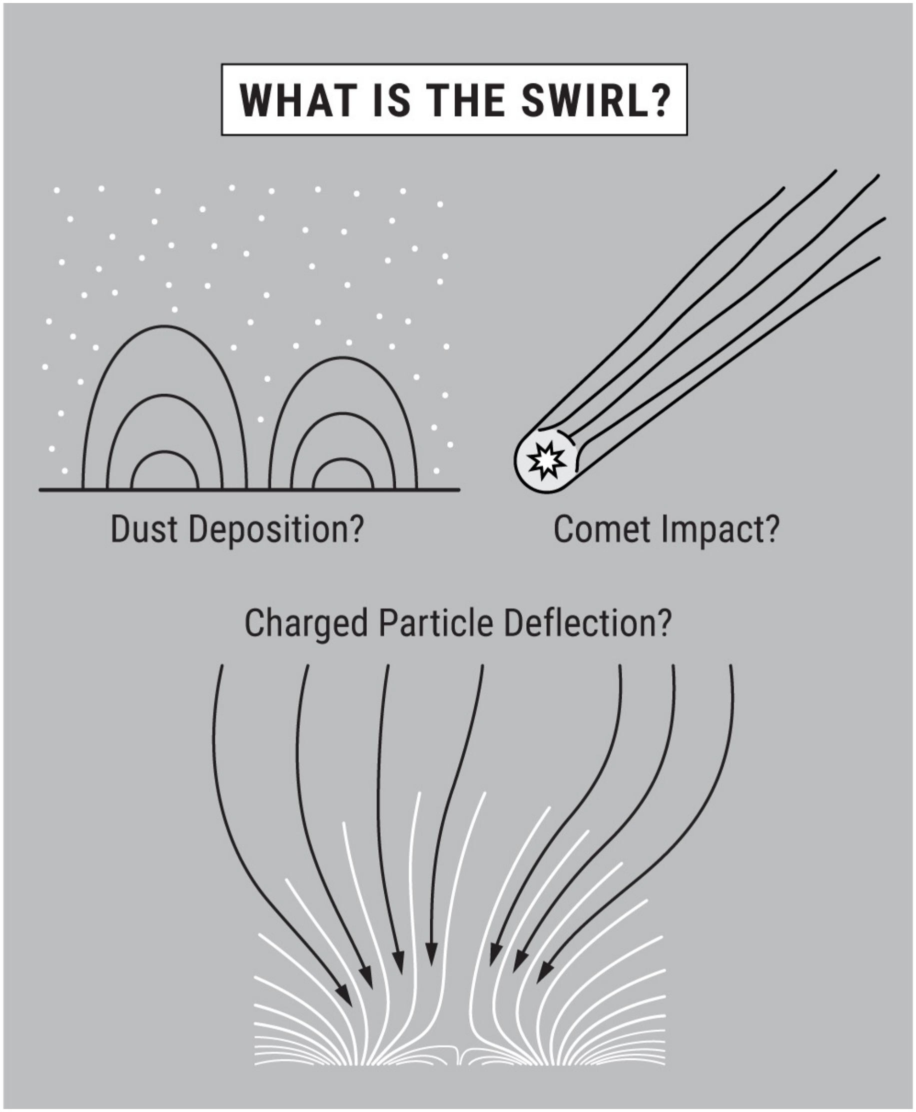
2) Determine the cause of lunar crustal asymmetry: Related to (1) – why is there so much more volcanism on the nearside and why was volcanism prolonged on the nearside compared to the farside? Test hypothesis that extended volcanism is related to the higher concentration of radiogenic heat-producing elements, using K, Th, and U measurements directly.

3) Determine the origin of nonmare volcanism: This objective will be accomplished as Intrepid approaches Aristarchus crater. Mineralogical and compositional (chemical) measurements will identify the silicic volcanic components that will be increasingly abundant as Intrepid nears Aristarchus and crosses crater rays of Aristarchus materials. The distribution of these silicic volcanic materials as Intrepid roves up onto the Aristarchus Plateau can be used to test the hypothesis of bimodal volcanism as the origin of silicic volcanics on the Moon, i.e., if we find only silicic (rhyolitic) materials and basaltic materials, but no intermediate compositions (andesite, dacite), then the hypothesis of bimodal volcanism is supported. Compare compositions of excavated OP basalts from range of crater sizes to regolith compositions.

4) Determine composition of deep mantle from pyroclastic deposits: By measuring the chemical composition of the Aristarchus Plateau pyroclastics, we will have a direct measure of material derived from partial melting in the mantle, and with major elements, can use petrologic modeling to determine the likely depth of origin. We can then compare the materials with Apollo 15 green glass and Apollo 17 orange glass.

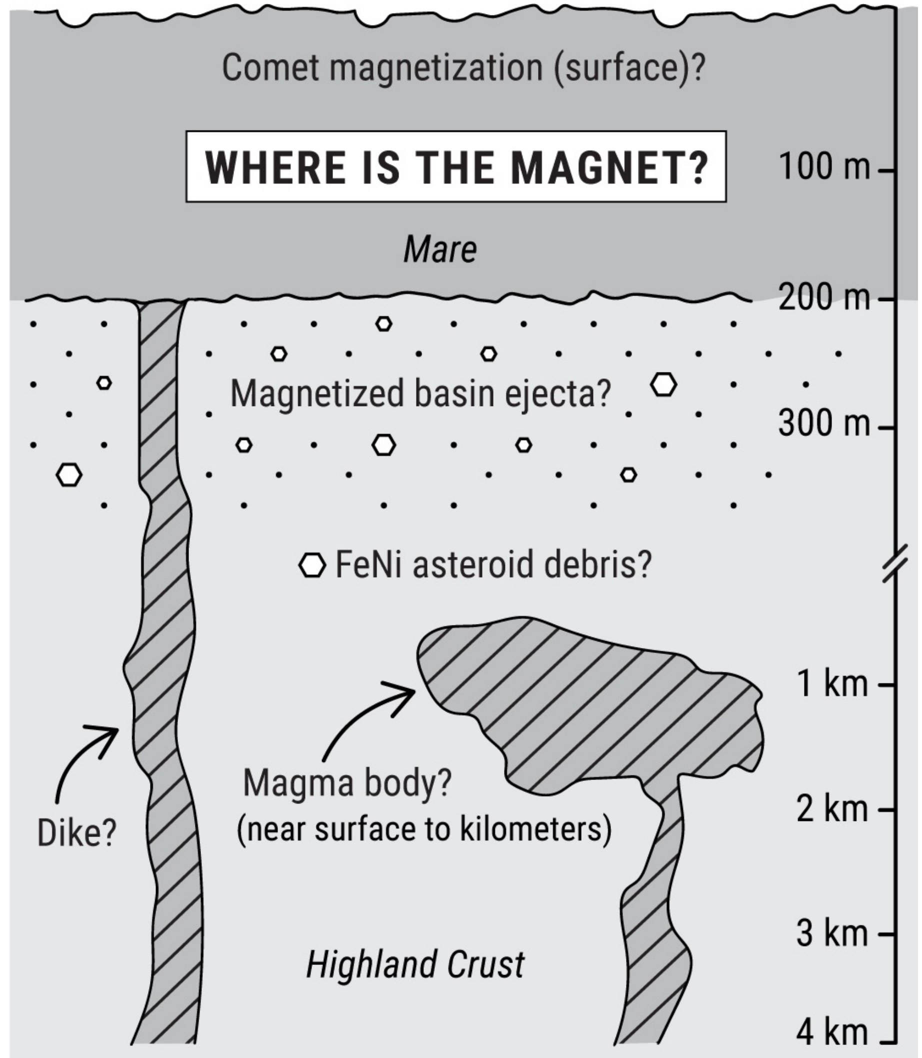
Test hypotheses of swirl formation

1. Transported dust
2. Solar wind shielding
3. Cometary impact and grain sorting/compaction



Test magnetic anomaly formation hypotheses

1. Comet magnetization
2. Magnetized basin ejecta
3. FeNi asteroid debris
4. Magnetized intrusives



Executive Summary

Total Cost Comparison

OPTION 1: RTG

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Res.	PBE
Project Cost		$1158.7 M	30%	$1511.1 M
Launch Vehicle		$220.0 M	0%	$220.0 M
Project Cost (w/o LV)		$938.7 M	38%	$1291.1 M
Development Cost		$722.4 M	50%	$1048.7 M
Phase A		$7.2 M	50%	$10.5 M
Phase B		$65.0 M	50%	$94.4 M
Phase C/D		$650.2 M	50%	$943.8 M
Operations Cost		$216.2 M	15%	$242.4 M

OPTION 2: Solar

COST SUMMARY (FY2025 $M)	Generate ProPricer Input	Team X Estimate CBE	Res.	PBE
Project Cost		$1173.9 M	32%	$1546.9 M
Launch Vehicle		$200.0 M	0%	$200.0 M
Project Cost (w/o LV)		$973.9 M	38%	$1346.9 M
Development Cost		$664.8 M	50%	$997.2 M
Phase A		$6.6 M	50%	$10.0 M
Phase B		$59.8 M	50%	$89.7 M
Phase C/D		$598.3 M	50%	$897.5 M
Operations Cost		$309.1 M	13%	$349.7 M