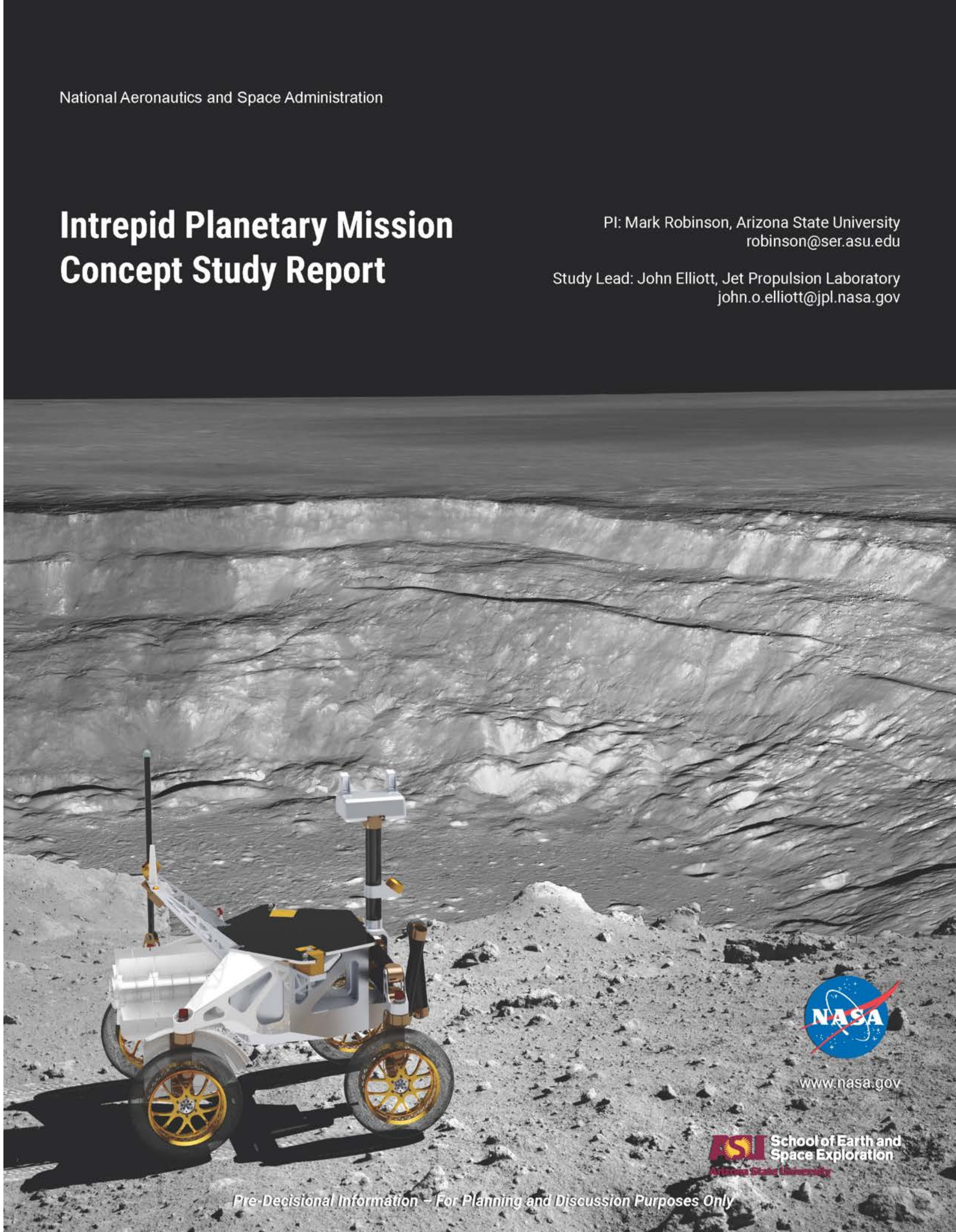
Intrepid

Unraveling Four Billion Years of Lunar *Magmatism*

Planetary Mission Concept Study

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

https://science.nasa.gov/solar-system/documents



Intrepid PMCS Team

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- Brian Anderson, JHUAPL
- David Blewett, JHUAPL
- Brett Denevi, JHUAPL
- Michael Fitzgerald, First Mode
- Terry Fong, Ames
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JPL PMCS Team

- Catherine Elder, JPL
- John Elliott, JPL (study lead)
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- Issa Nesnas, JPL
- Kim Reh, JPL
- A Team and Team X, JPL
- And many others!

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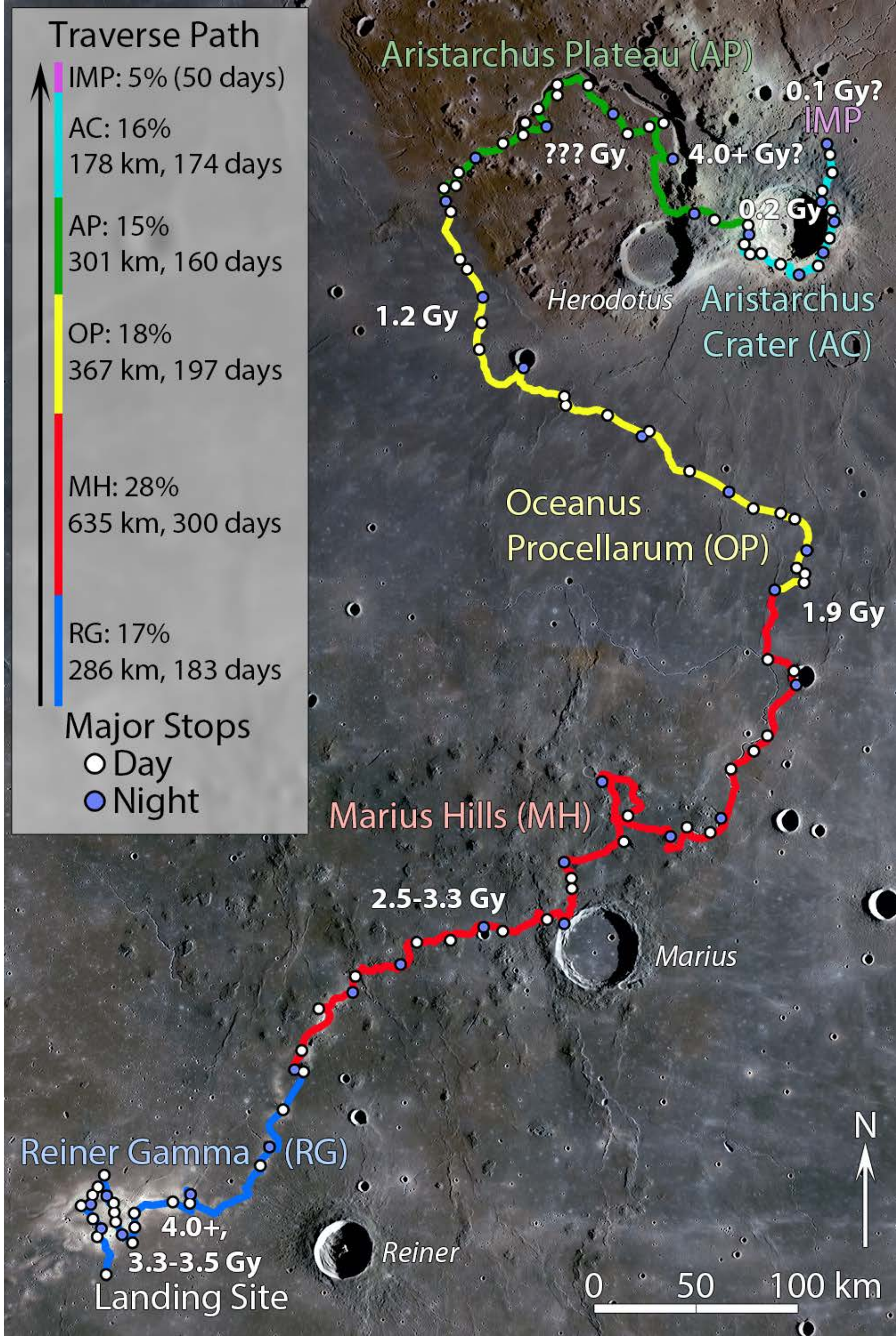
Traverse through 4 billion years of lunar magmatism

Evolution of the lunar interior, nature of the global asymmetry

Diversity of styles of magmatism

Post-emplacement modification

Mobility is key! Autonomy is key!



Unraveling Four Billion Years of Lunar Magmatism

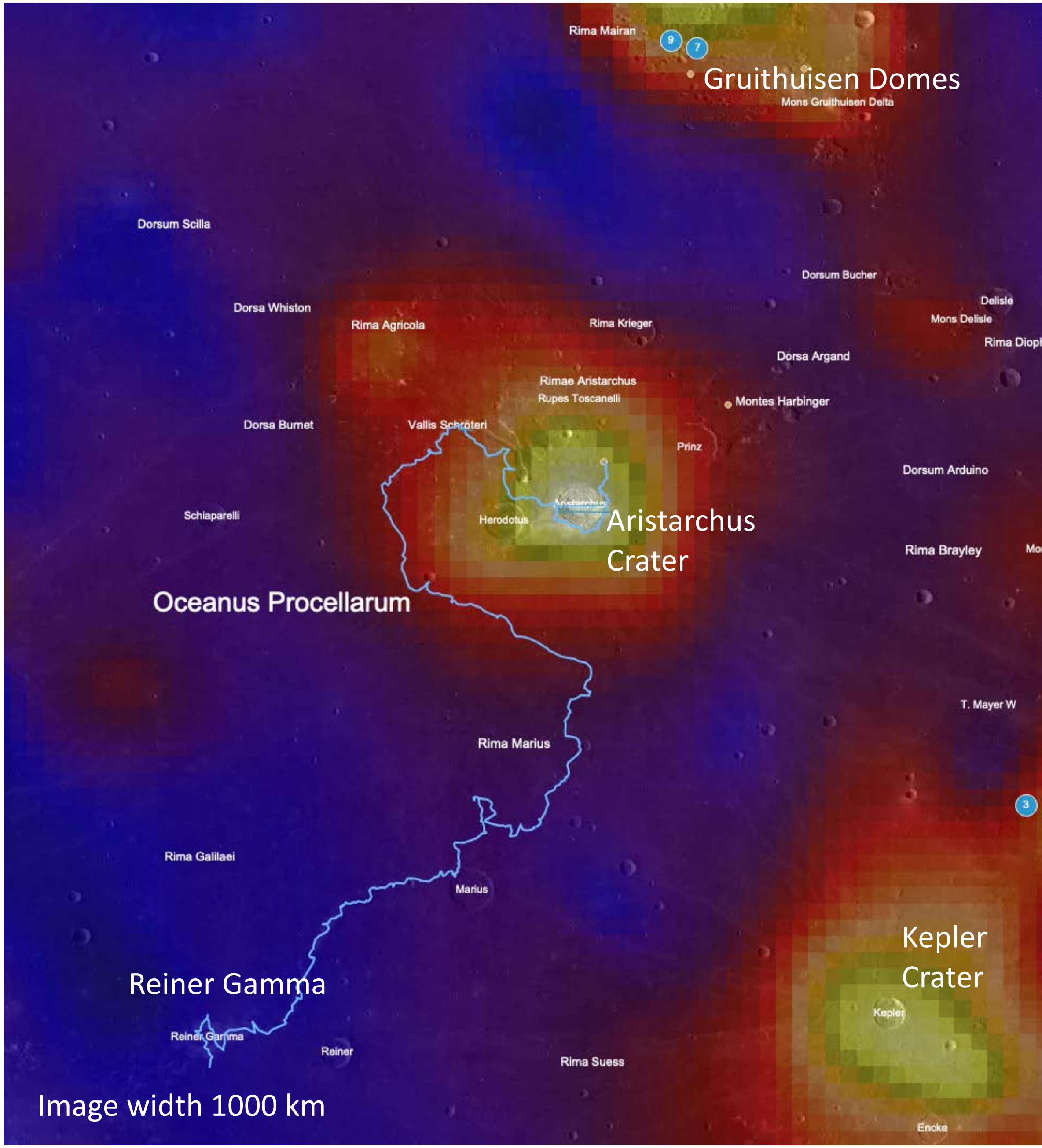
Responsive to current Decadal

1. **Evolution of the lunar interior over 4 Gy**
    1. Composition of basaltic volcanism through time, heterogeneity/evolution of mantle (shallow), end of volcanism
    2. Primitive composition of mantle (deep) from pyroclastics
    3. Nature and extent of non-mare volcanism
    4. Nature of Procellarum KREEP terrane crust
    5. Decline of core dynamo and magnetic field over time
2. **Diversity of styles of magmatism**
    1. Flood basalt emplacement, rilles, vents, flows, tubes
    2. Origin(s) and composition(s) of cones, domes and shields
    3. Pyroclastic volcanism processes, composition and physical properties (grain size, glass content)
    4. Intrusive bodies and relation to effusive deposits
3. **Post emplacement modifications**
    1. Nature of crater impact formation, ballistic sedimentation, ray formation, and physical properties of regolith outward from impact
    2. Target material dependence of crater characteristics and impact mechanics
    3. Variations in space weathering across a variety of geologic materials and ages (relationship to radiation environment, H abundance, magnetic anomalies)

1.4 Nature of PKT?

- Is the Th signature from highland material?
- Do large scale KREEPy basalt deposits exist?
- KREEPy non-mare volcanism?
- Measure Th and friends from surface and sub-surface to gain 3-D picture of KREEP source
- *<u>Extended Mission</u>* to Gruithuisen domes *extends* range of non-mare volcanic materials measured and provides second highland terrane traverse

Lunar Prospector Thorium Map, Intrepid Traverse



Intrepid

ConOps Requires Different Mindset

Autonomous driving (waypoints)

1 km/hour is not scary

Averaging 500 m/hr. is doable

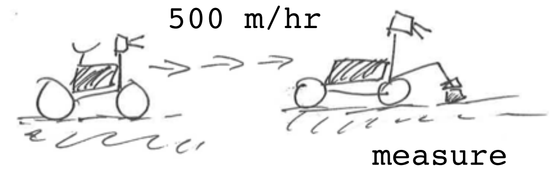
Night is your friend

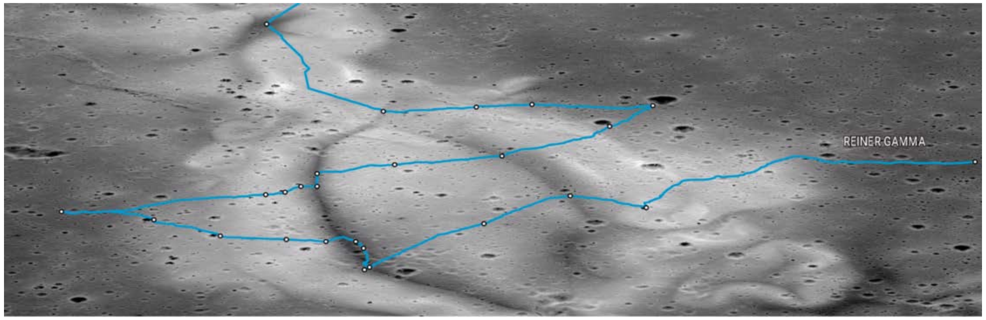
Pre-planned traverse down to individual measurement scale enables great science

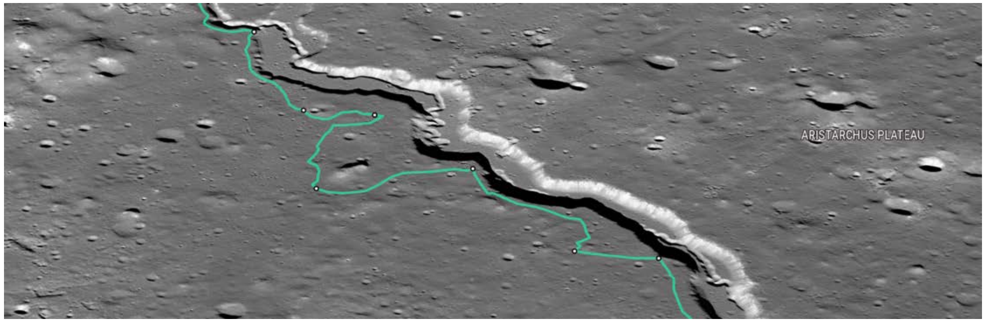
In motion observations enable key science (geologic noodle)

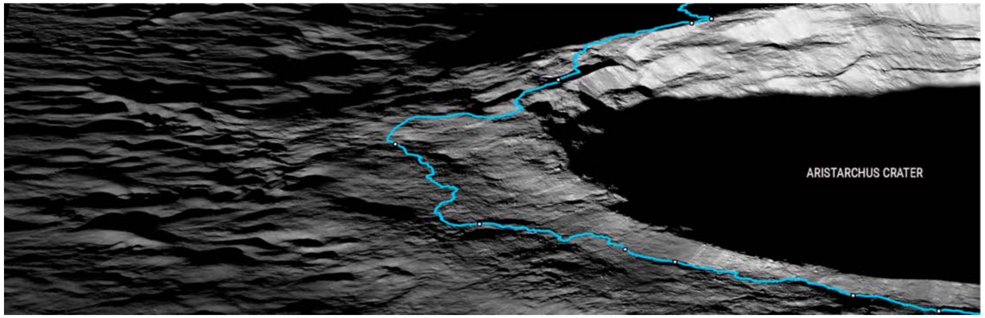
New way of thinking about rover operations, get the measurements and continue on!

Mobility enabled by autonomy





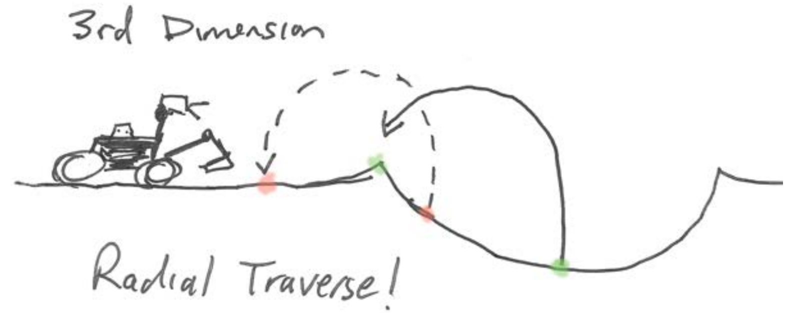




Focused Investigations (major stop), interval stops every 4 hrs (2 km)

Natural Drill Holes Reveal 3D Geology

- Radial traverse provides sampling with depth as Intrepid approaches crater rim (same strategy used at Cone crater, Apollo 14)



- Traverse observations* interrogate broad scale ejecta (i.e. Kepler and Aristarchus craters) as well as small local crater ejecta

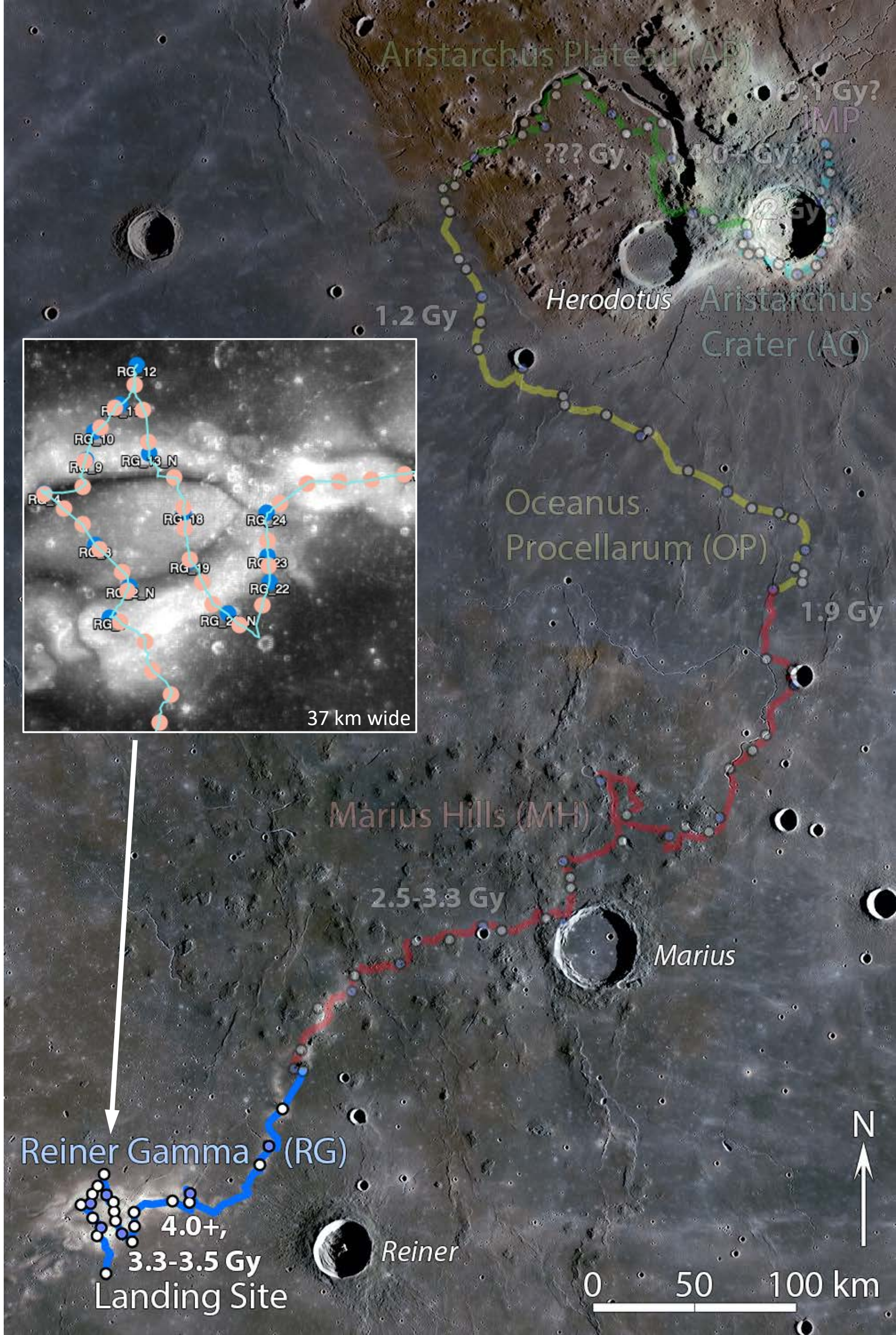
*Color images, point spectra, GRNS, magnetometer, APXS (interval stops)

Reiner Gamma

31 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.

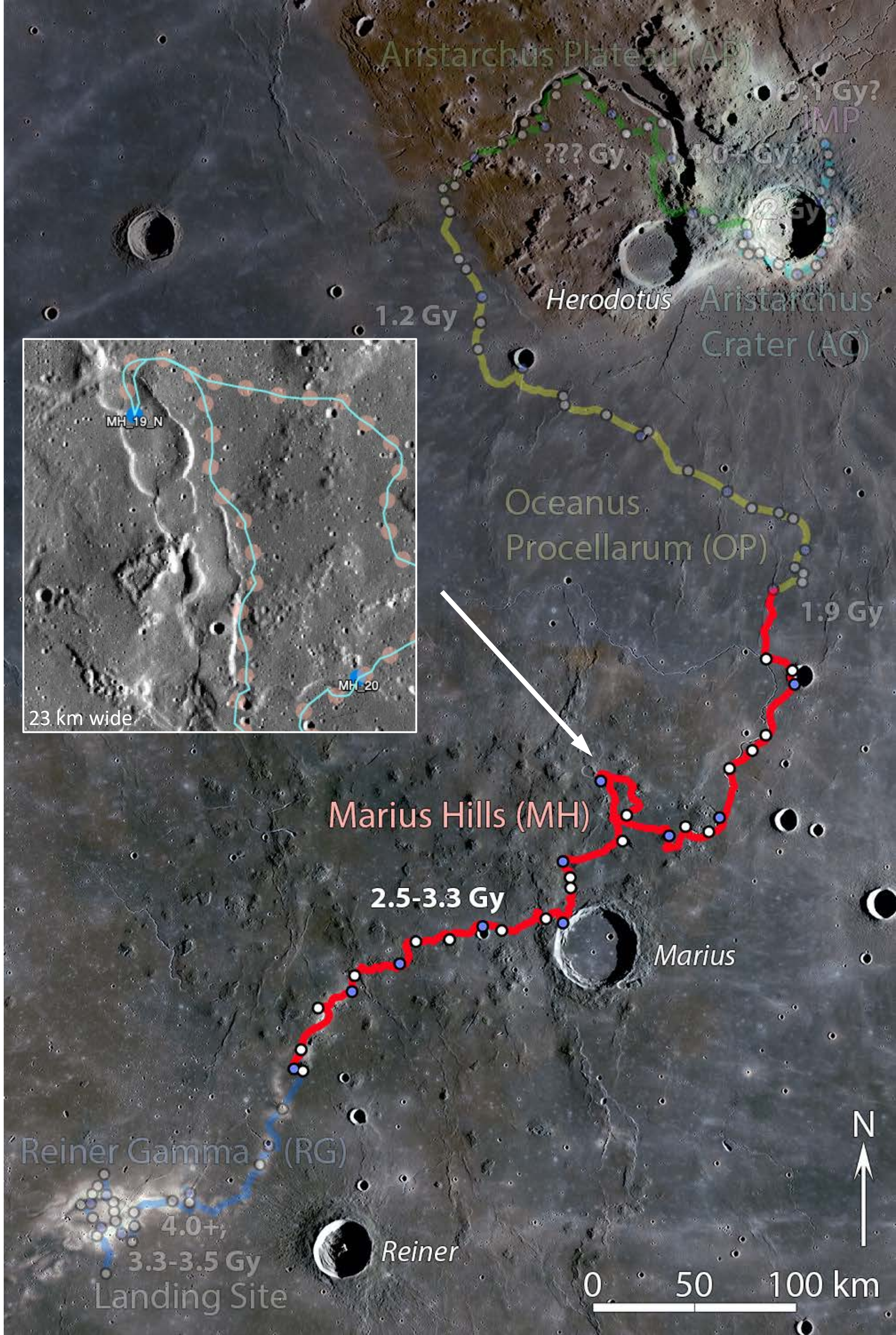


Marius Hills

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 causes of variations in volcanic morphologies: composition, volatile content, effusion rate



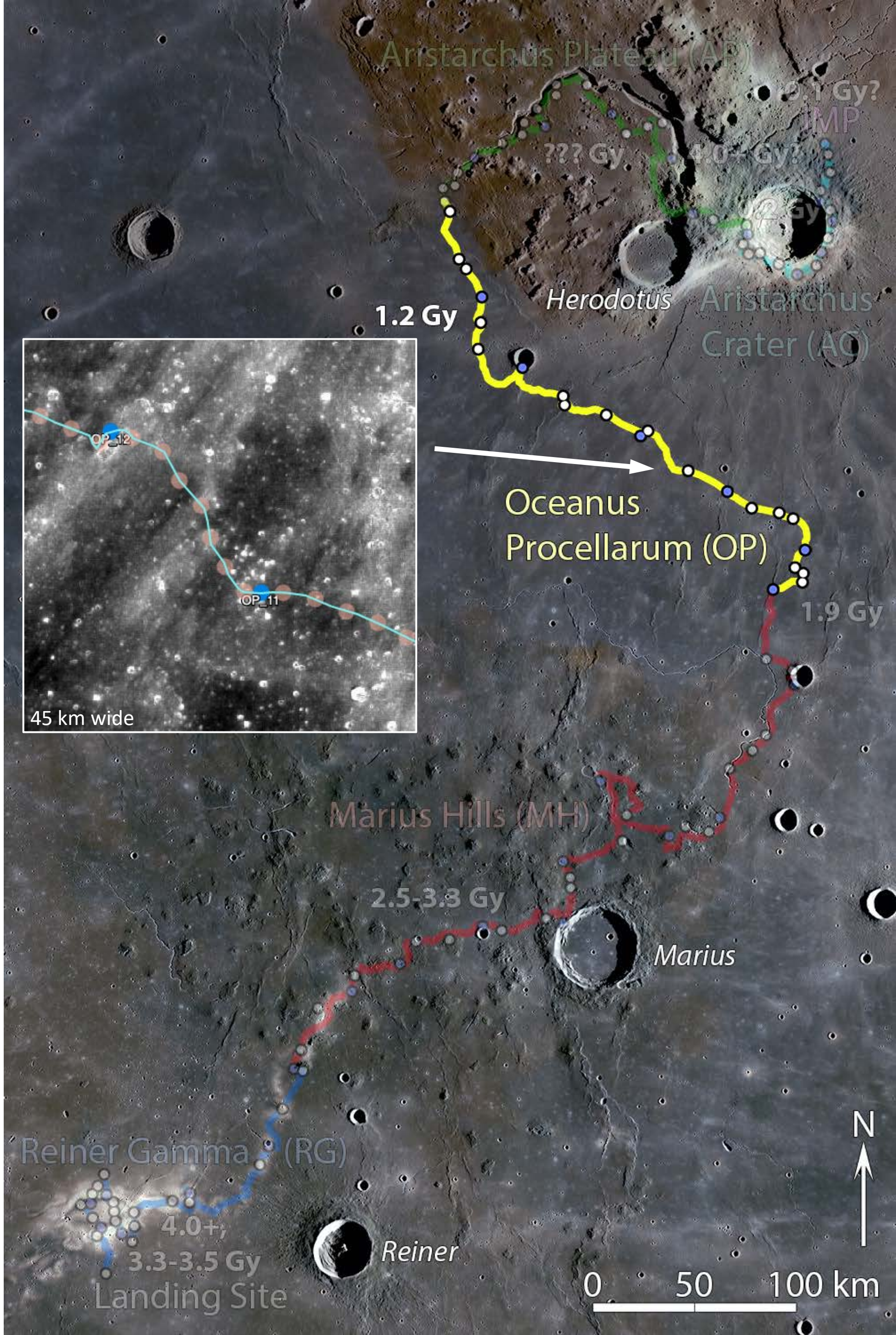
Oceanus Procellarum

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

- 1.2 to 1.9 Gy mare surface
- Radiogenic 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 Aristarchus ray composition to test ray formation hypotheses (local vs ejected material).

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

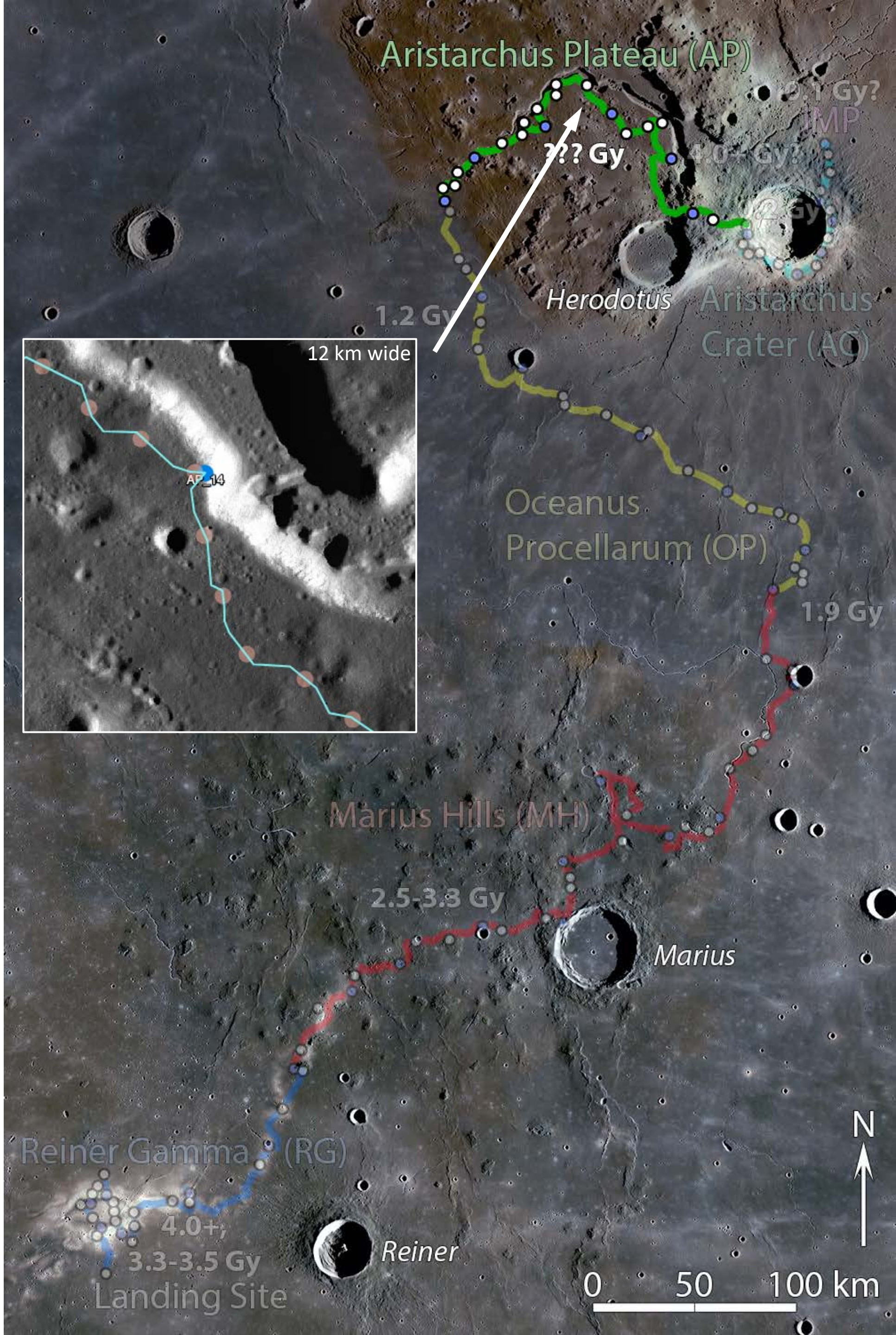


Aristarchus Plateau

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.



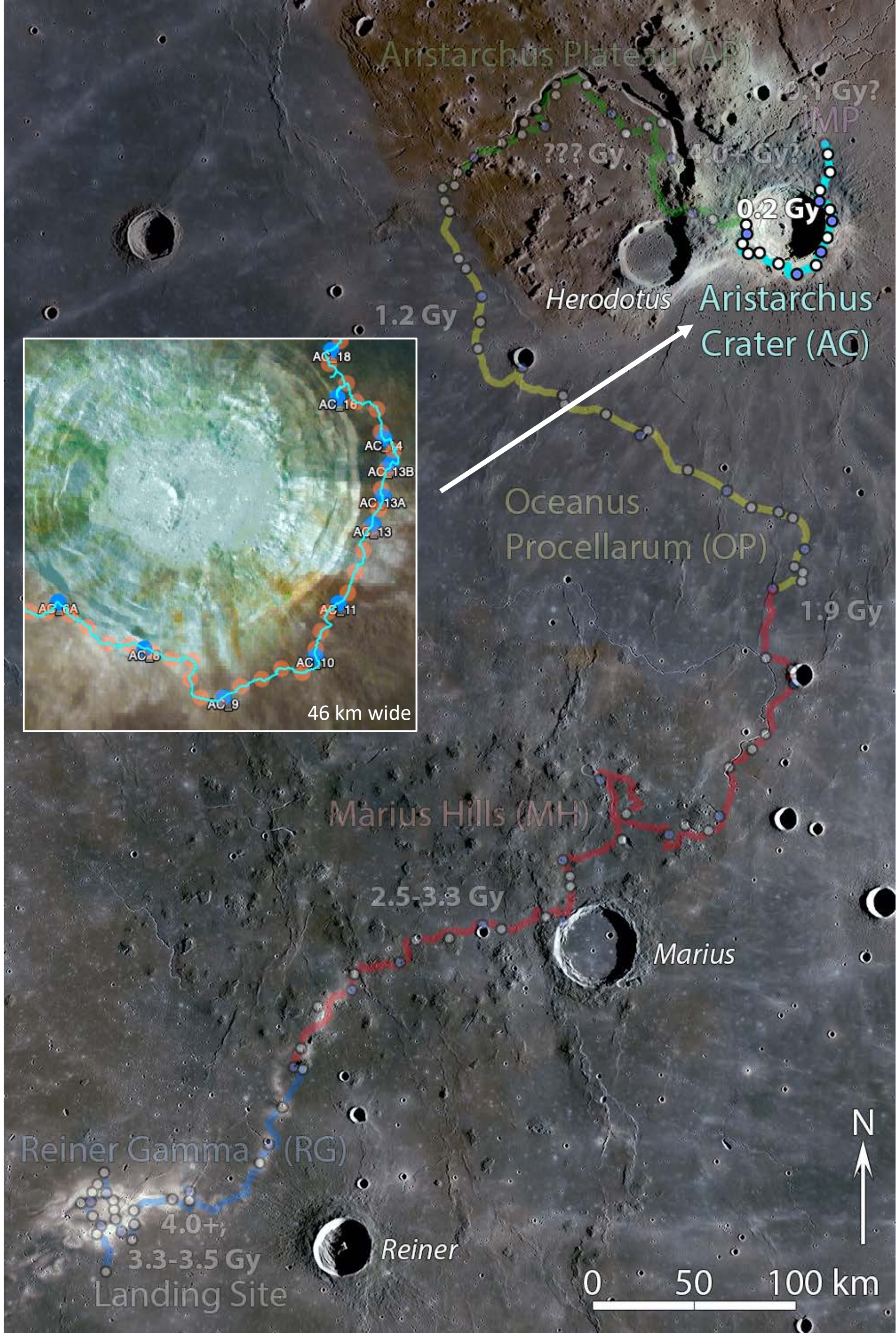
Aristarchus Crater

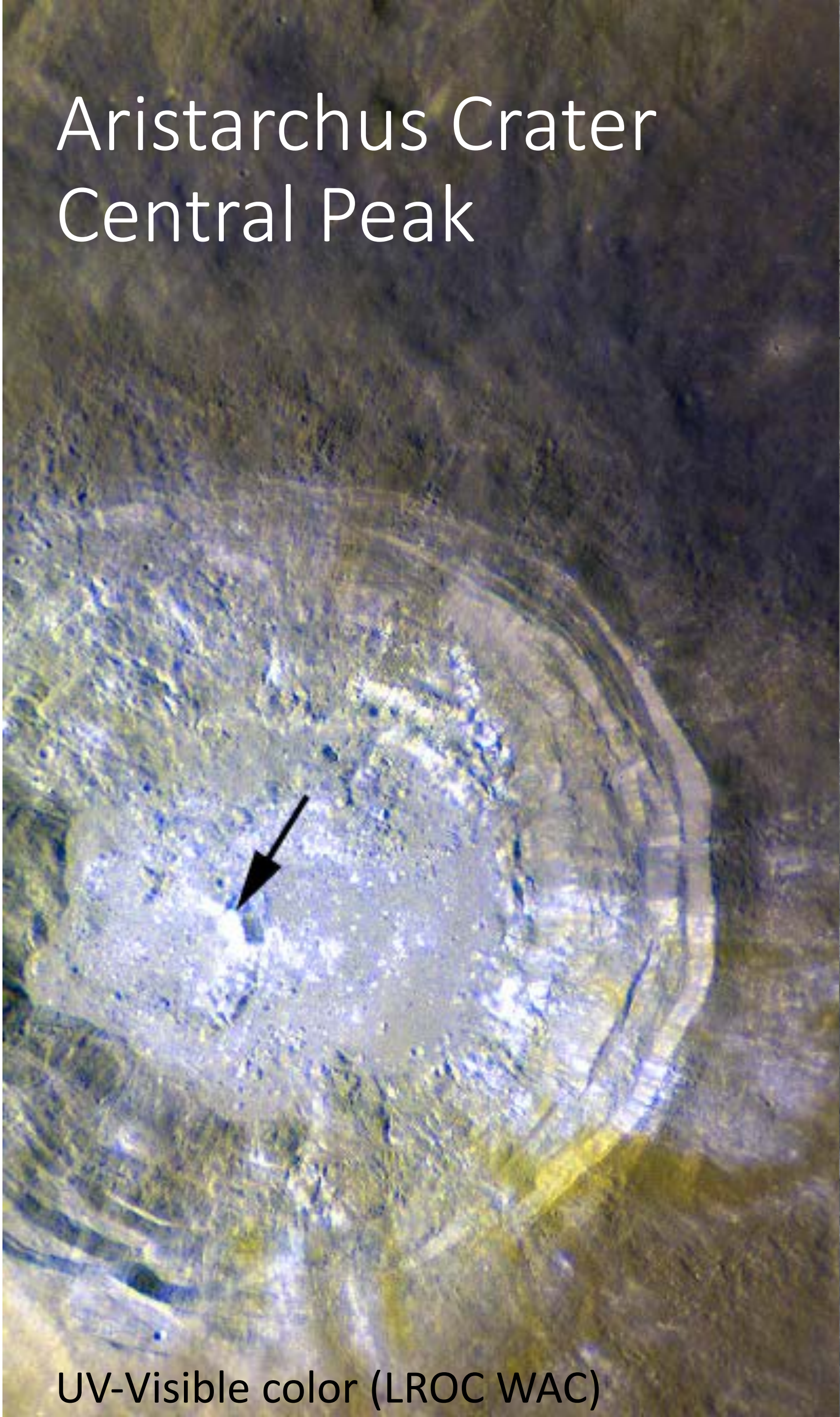
20 major stops, 171 interval stops, 182 km, 6 lunations

- 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.



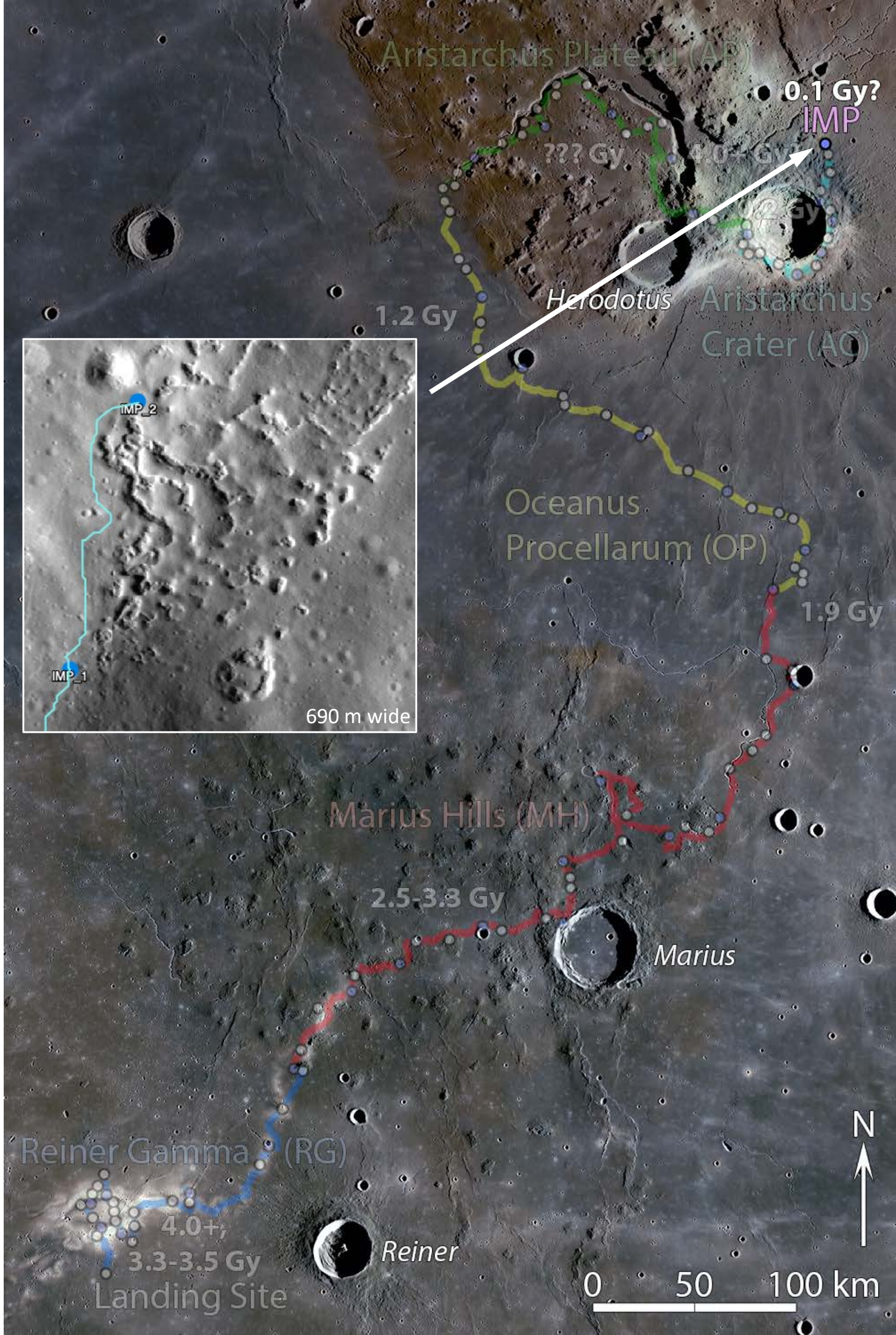

Aristarchus Crater
Central Peak
UV-Visible color (LROC WAC)


Layered Intrusions?
1 kilometer

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

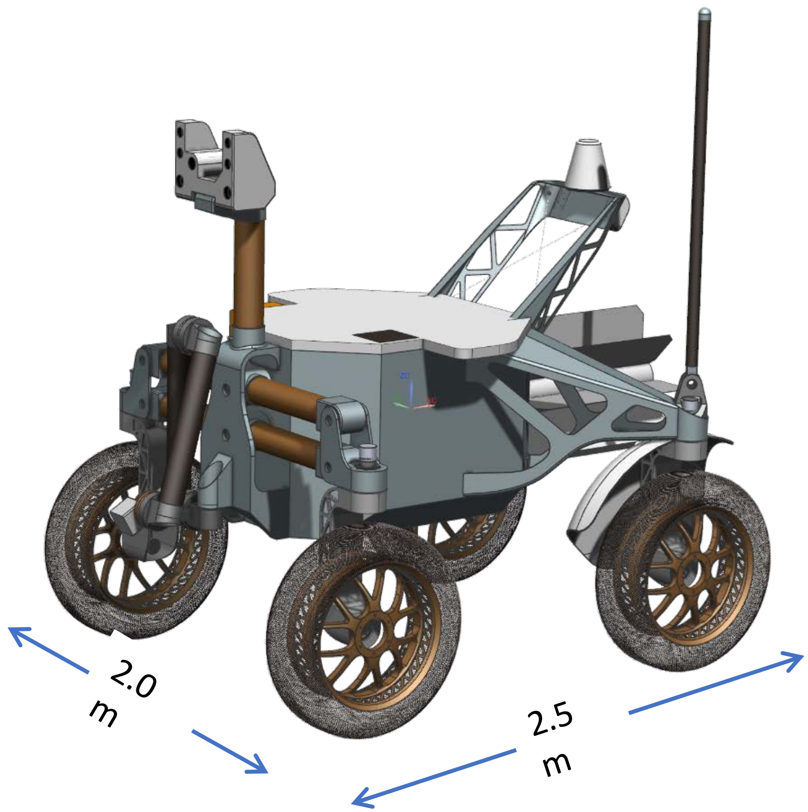
- Origin and relative age
- Nature of materials
  - Composition
  - Physical state
- Non mare volcanism?
- Regolith development (young or anomalous old surface)
- Cratering mechanics (ditto)

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



Intrepid RTG-Powered Rover

New Frontiers Class Mission



- Designed for operation in day and night conditions
- Range >1800 km
- <u>High level of autonomy</u>
- 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 (fully margined): 415 kg
  - Includes ~24 kg science payload

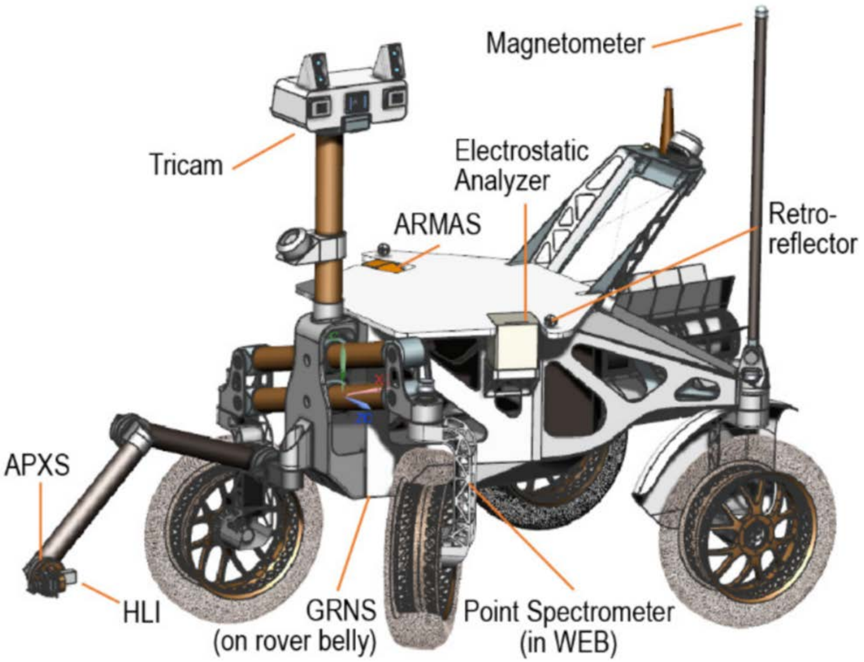
JPL PMCS Design

Solar powered version requires 3 extra years of operation for same science return

Low Risk Instrument Suite

Instrument	Measures
ARMAS (LET)	Galactic and solar cosmic ray >10 MeV
Magnetometer	Magnetic field strength orientation
Gamma Ray Neutron Spectrometer (GRNS)	Elemental abundance
TriCam Stereo RGB Imager + BW telescopic FarCam (electronics shared with PS, HLI)	Reflectance (BW, color, and stereo imaging)
Point Spectrometer (PS) uses FarCam telescope	Reflectance (300 to 1400 nm)
Hand Lens Imager (HLI)	Reflectance (400 to 1000 nm)
Alpha Particle X-Ray Spectrometer (APXS)	Elemental abundance
Electrostatic Analyzer (EA)	Solar wind (electrons, protons)
Laser Retro-Reflector Array (LRA)	Location (x,y,z) of rover from orbiter

Total payload mass: 17 kg
(24 kg with 40% margin)



Intrepid autonomously finds target and positions APXS and HLI with arm

ARMAS, Mag, GRNS, EA continuously integrate during traverse

Images and Point Spectra acquired at set intervals during traverse

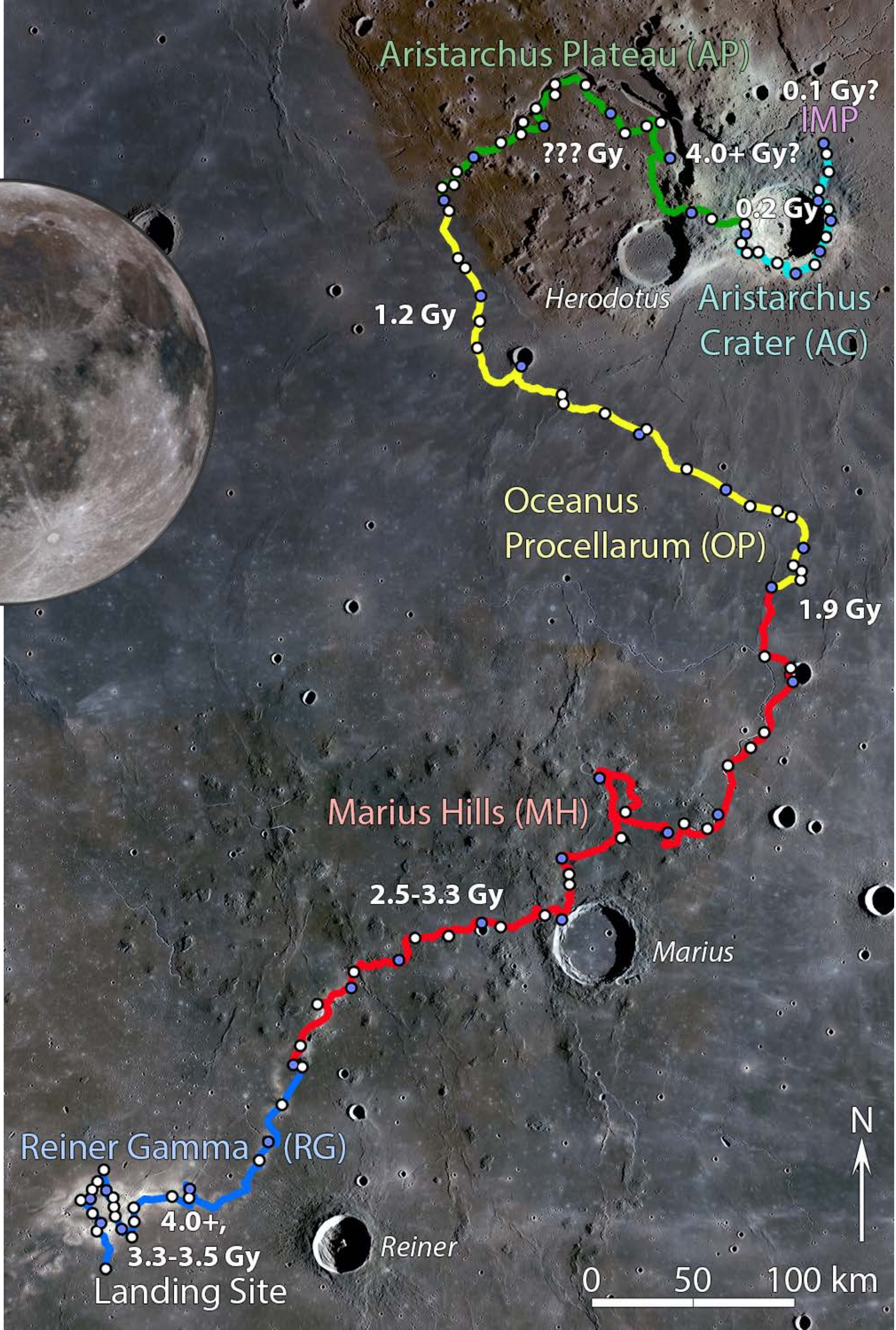
Why 1800 kilometer traverse?

The current traverse is the shortest route to interrogate up to 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!

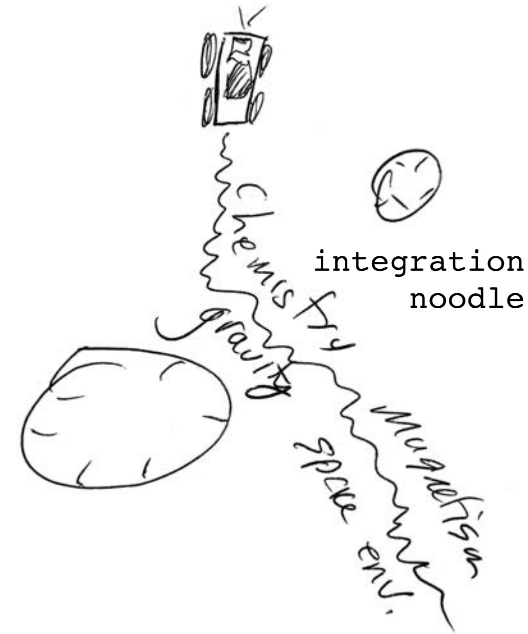
Same distance as Phoenix to Houston!

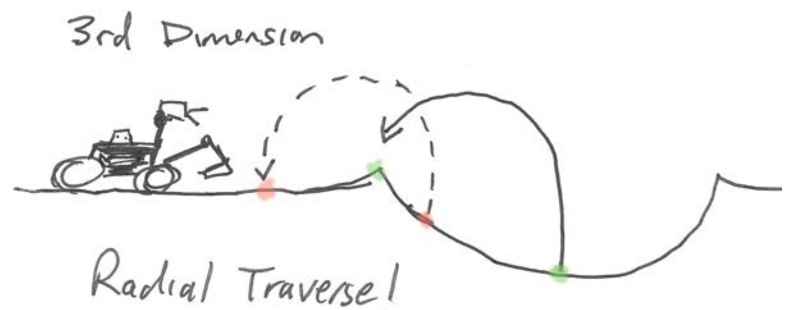


Backup Slides

Measurement Overview

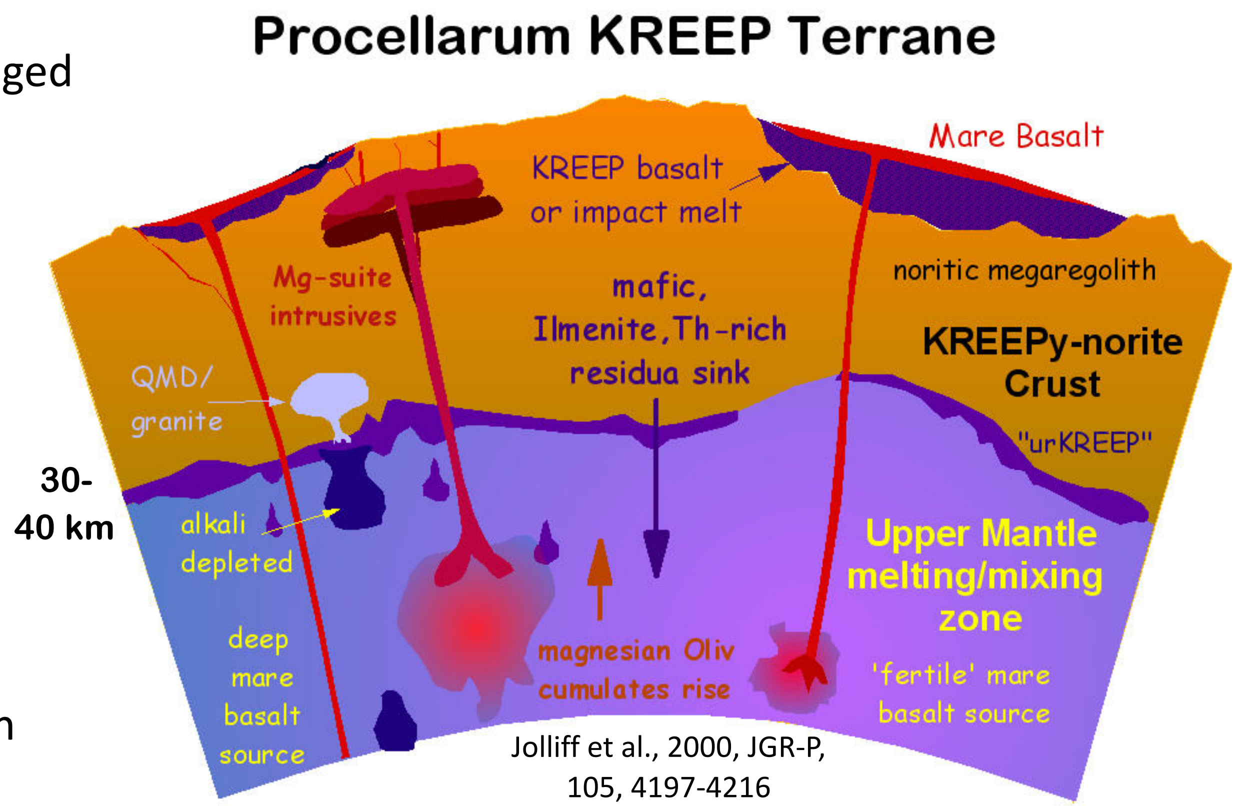
- Mineralogy/Petrology
  - Anorthite, olivine, pyroxenes (opx, cpx), ilmenite, glass
- Elemental Abundance
  - Determine major element chemistry (Fe, Mg, Ti, Si, O, Al, Ca)
  - Determine minor element chemistry (K, Th, U, H, OH), including magmatic volatiles (Zn, Fl, Cl)
- Magnetic environment
  - Characterize 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
- Probe Regolith Structure
  - Estimate depth of regolith, discontinuities (macro-scale)
  - Document grain size, shape and color (micro-scale),
  - Geotechnical properties
- Estimate maturity of regolith
  - Optical maturity, physical state
- Characterize landform morphometry
  - Shapes of flow forms, crater forms, vents, etc





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
- Geochemical variations with age of basalts will reveal if mantle overturn led to the intense and prolonged volcanic activity of this region.



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.

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

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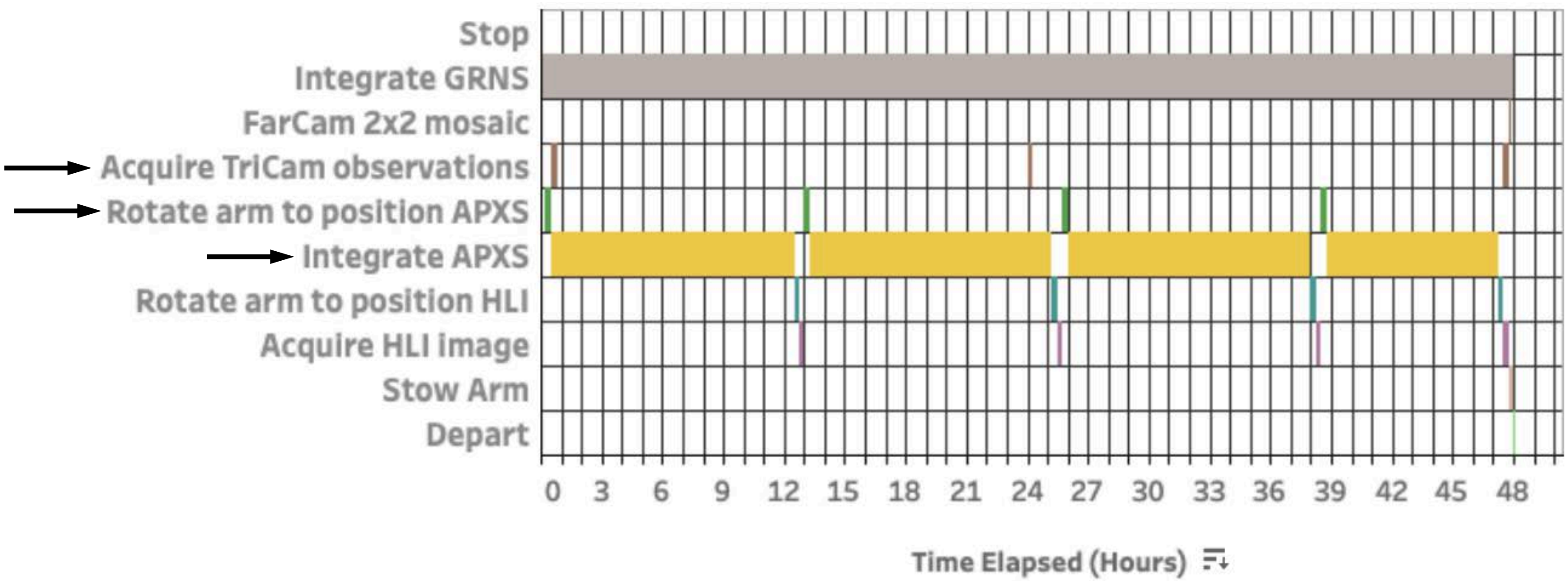

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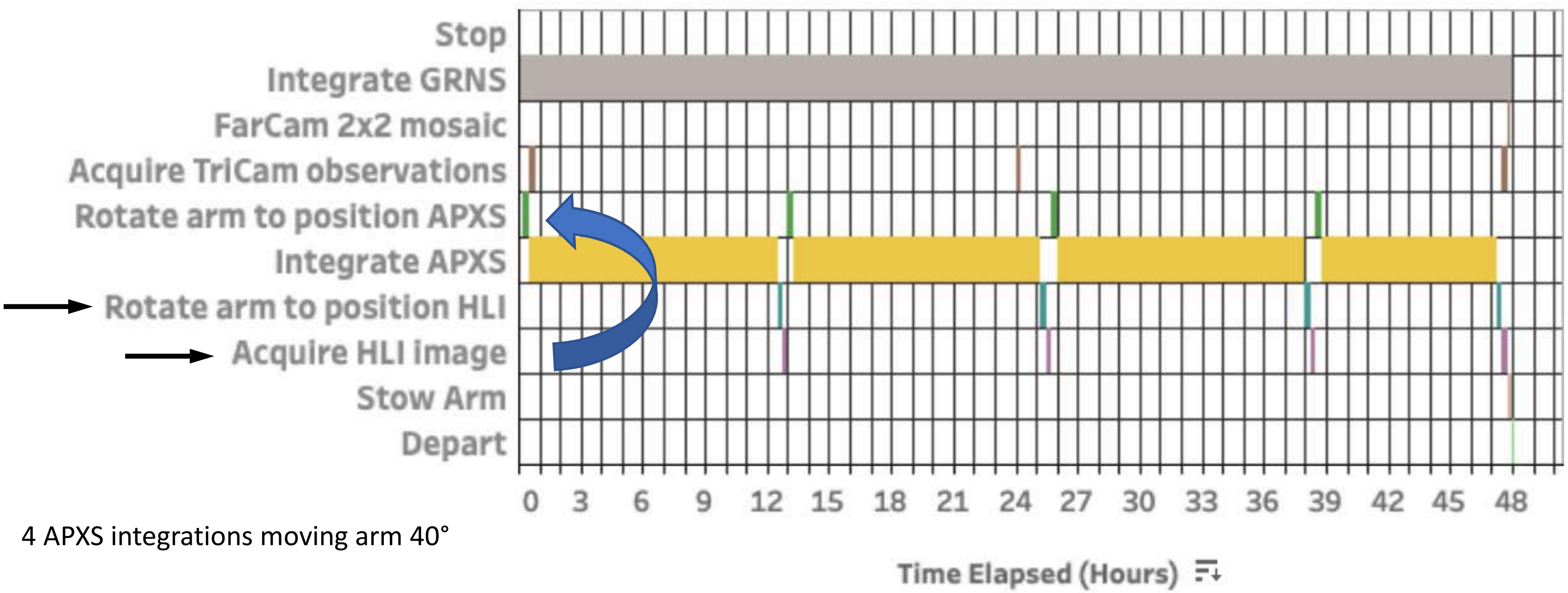

4 APXS integrations moving arm 40°

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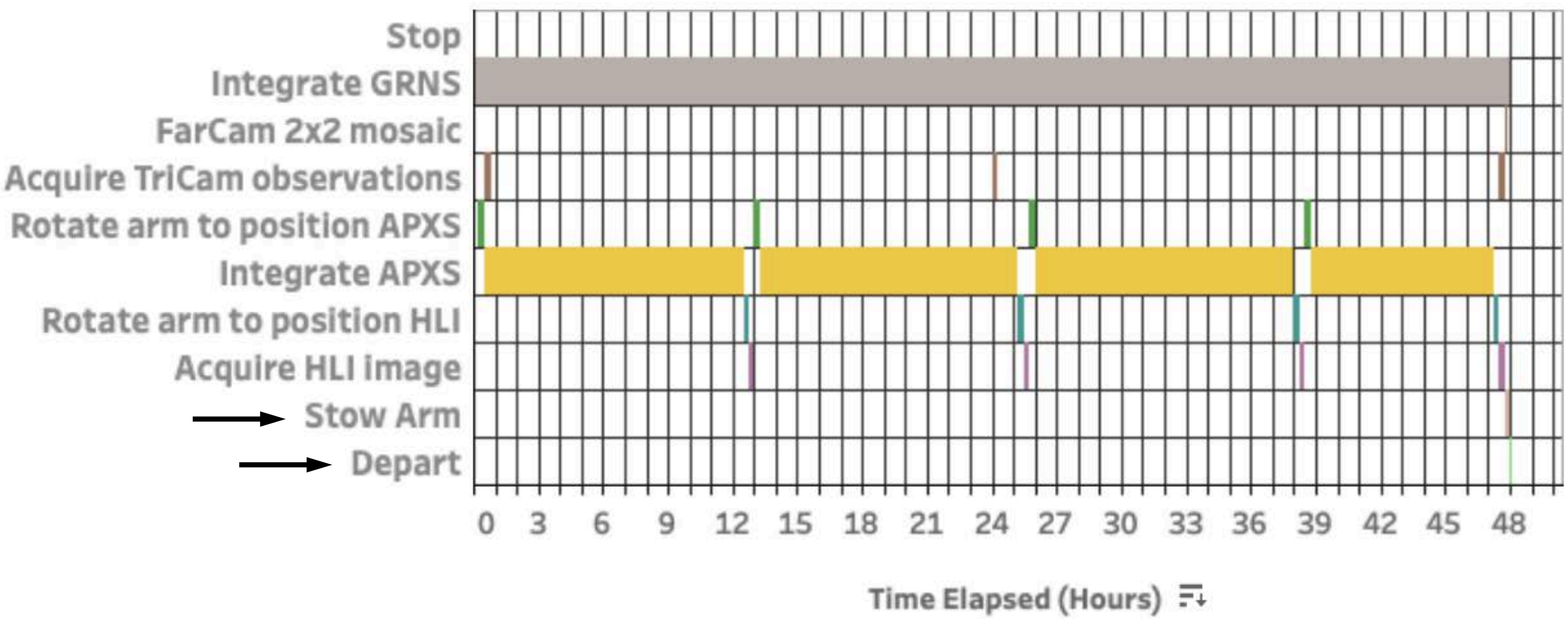

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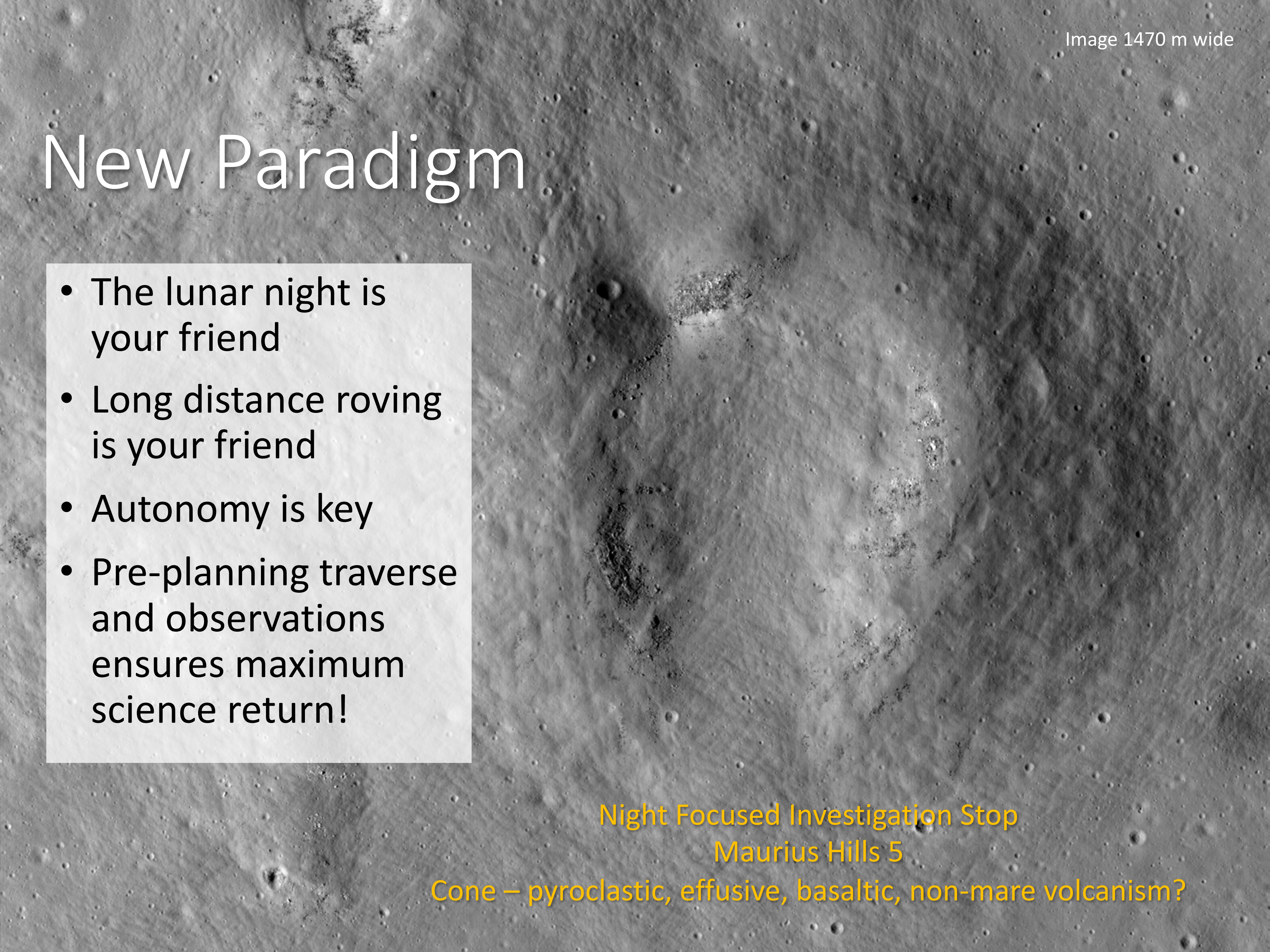
New Paradigm

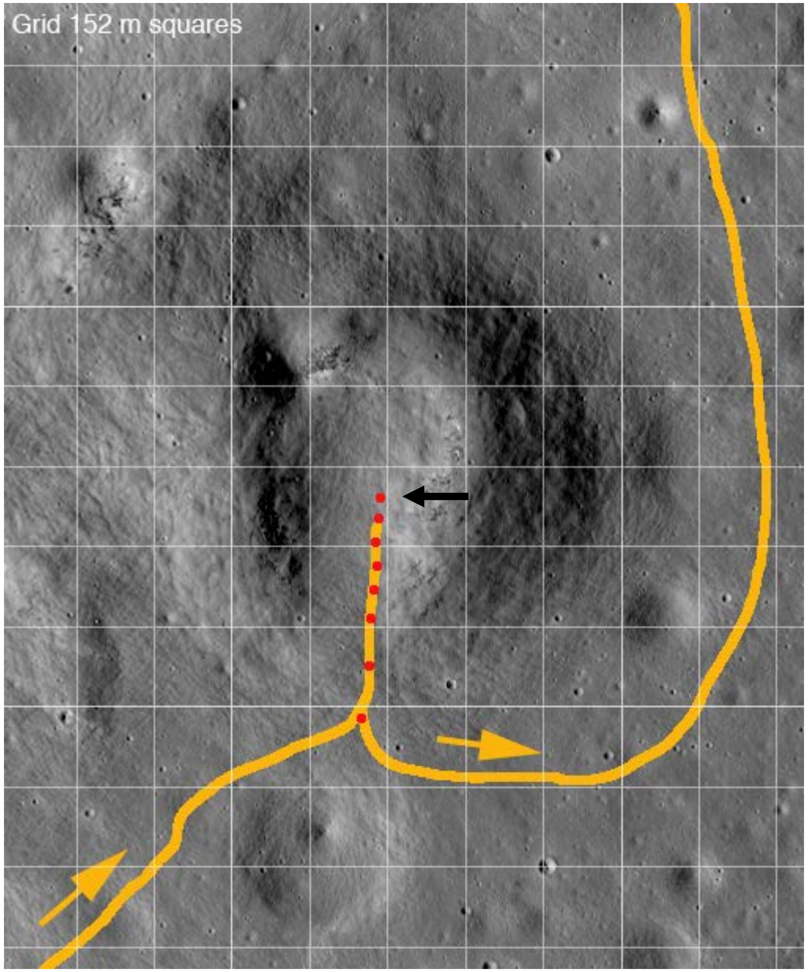
- The lunar night is your friend
- Long distance roving is your friend
- Autonomy is key
- Pre-planning traverse and observations ensures maximum science return!



Typical Night Stop

Drive to furthest point at a night site 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 inc. = 10°



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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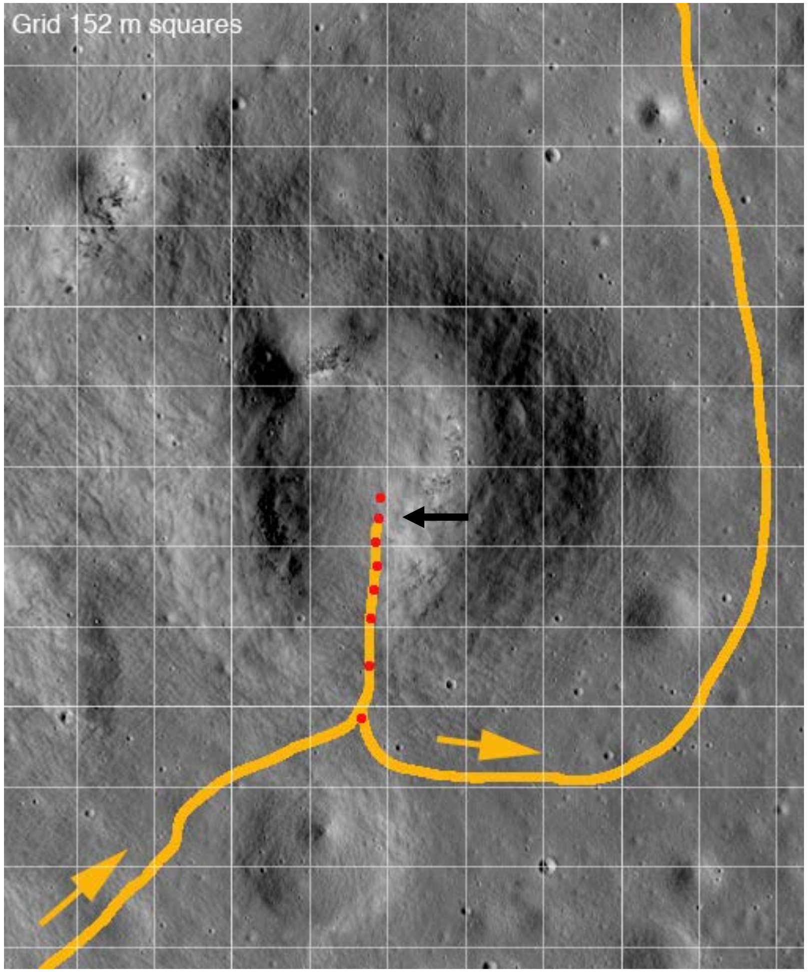

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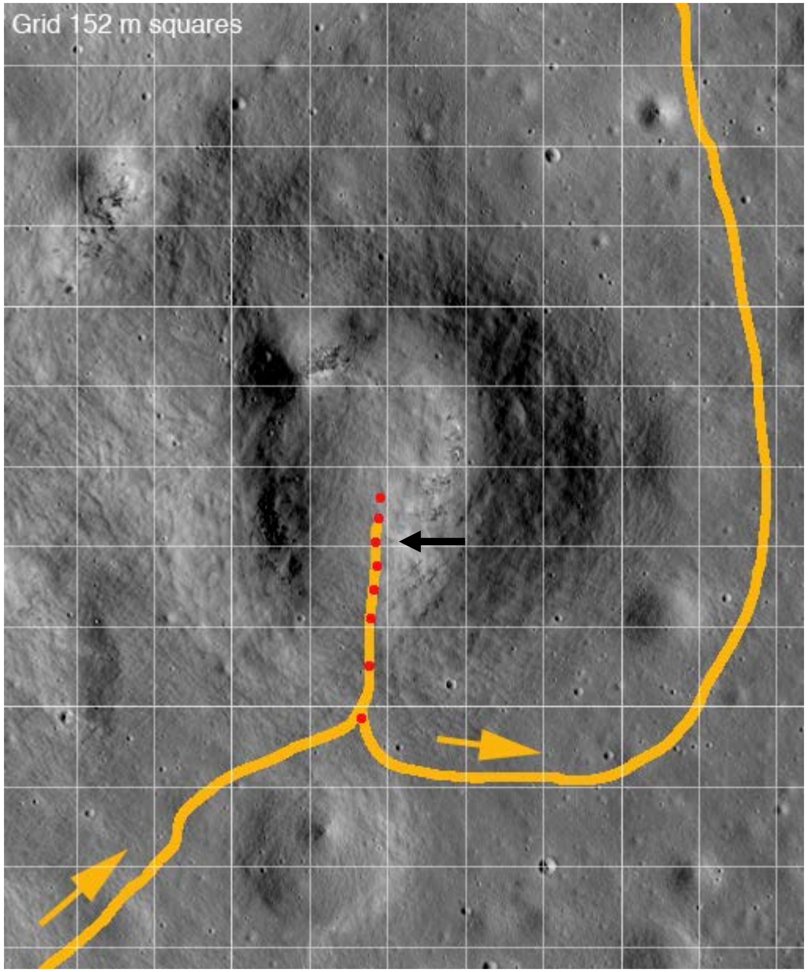

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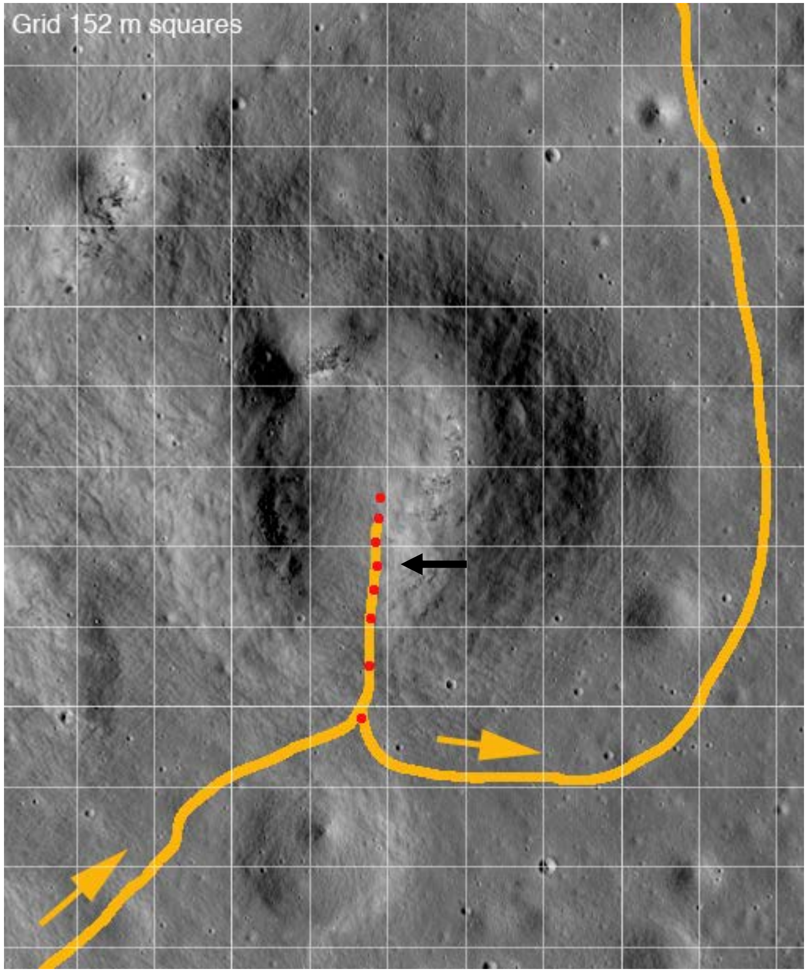

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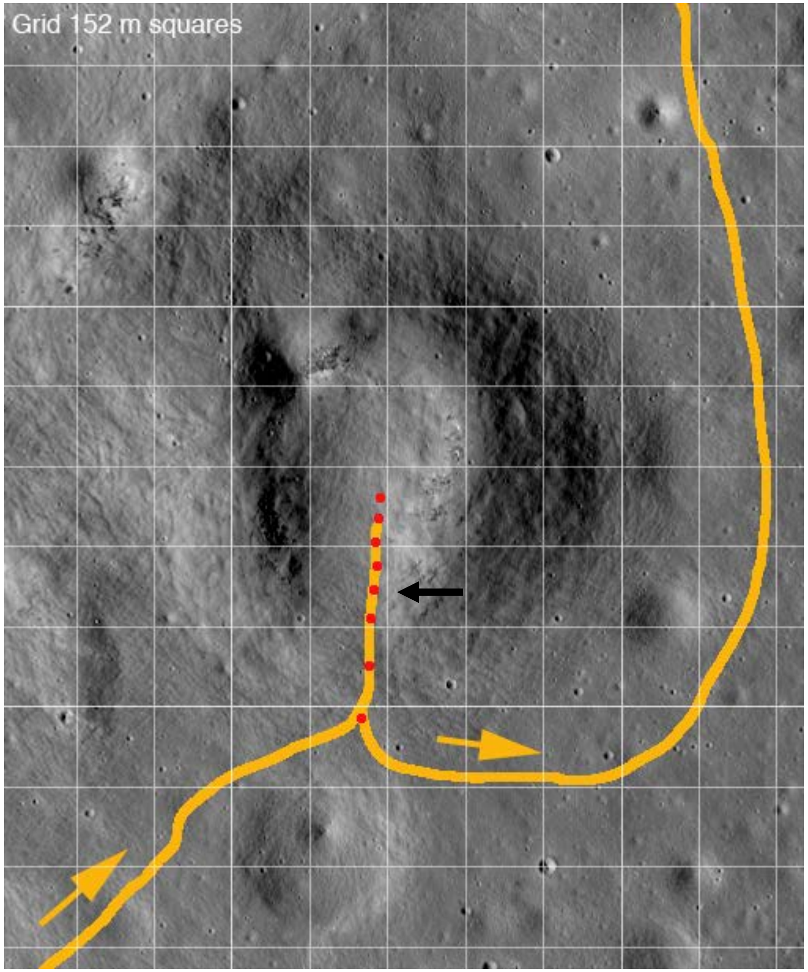

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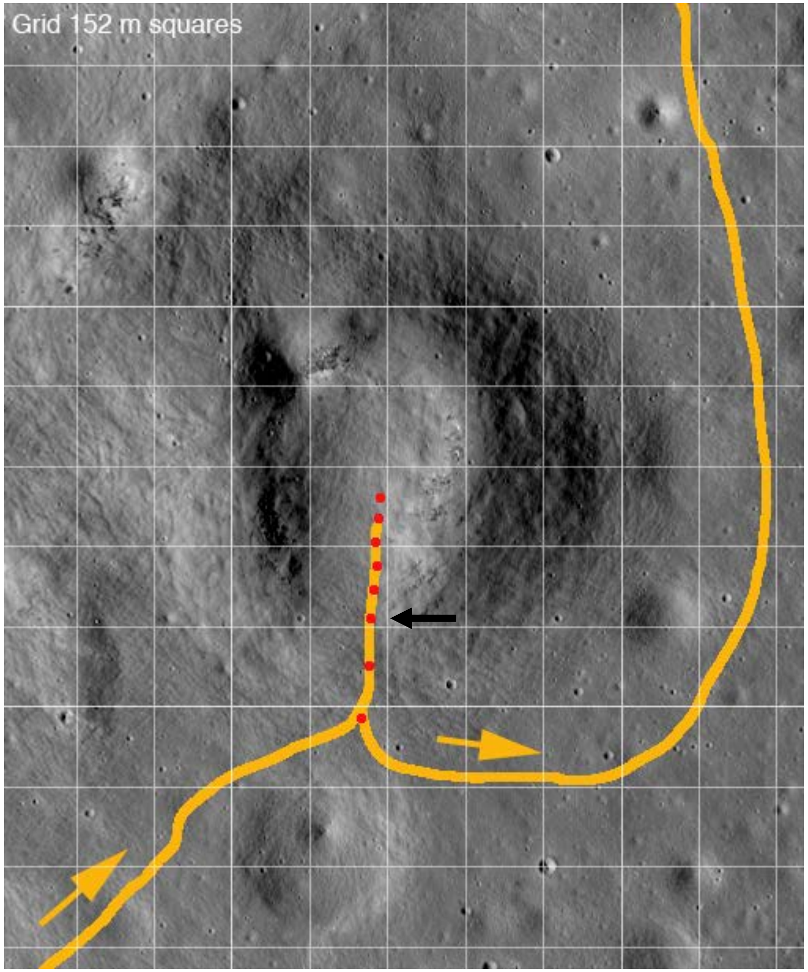

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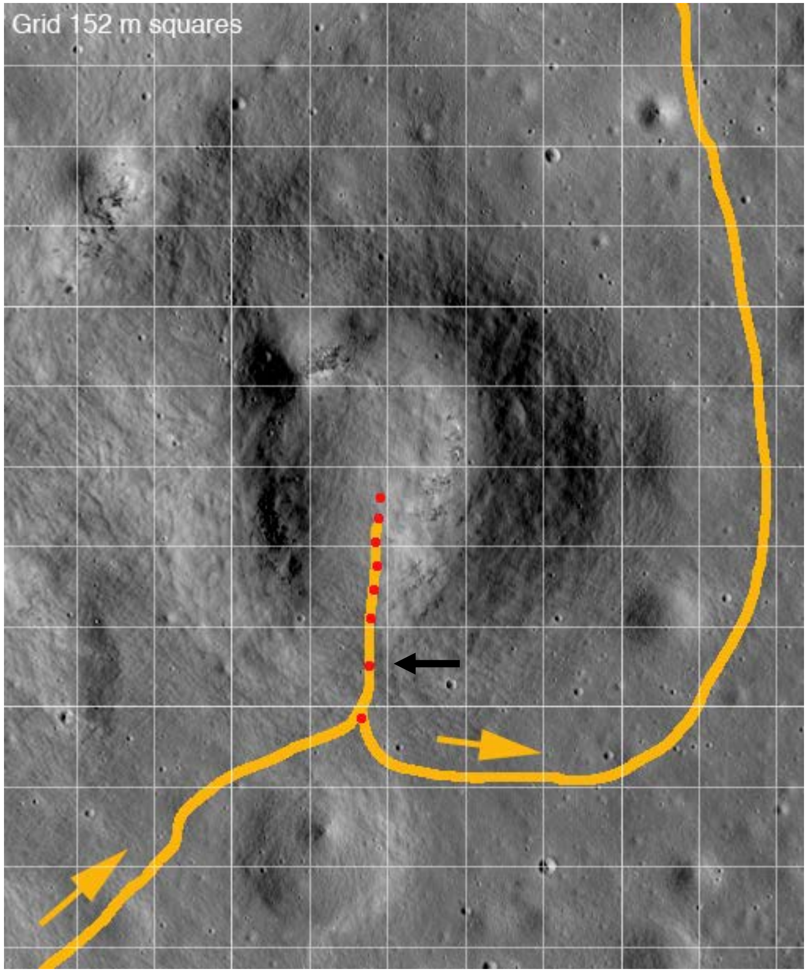
3) 48 hour integration, 50 m (x5)
4) 48 hour integration, 100 m (x2)
5) Sunrise
6) Large BW telephoto mosaic stereo panorama, 48 hr int
7) Depart when inc. = 10°

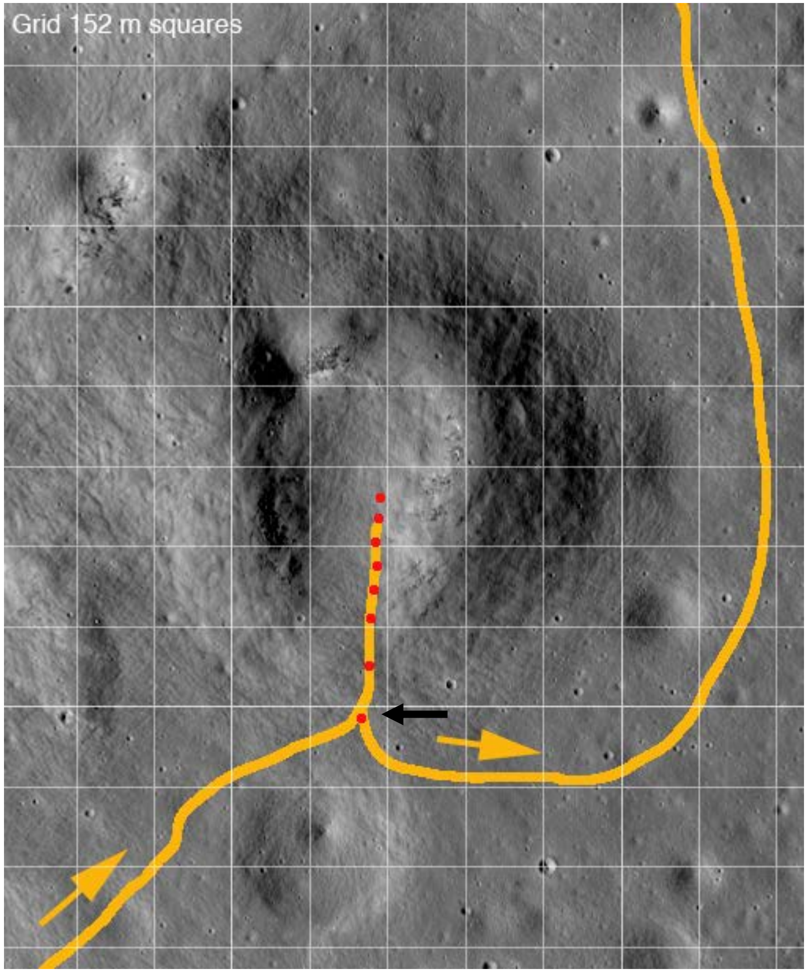


Marius Hills cone (11.138°N, 305.132°E), map 1600 m wide, cone rises ~100 m above surroundings, max slope of night path 10°.

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, 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 inc. = 10°



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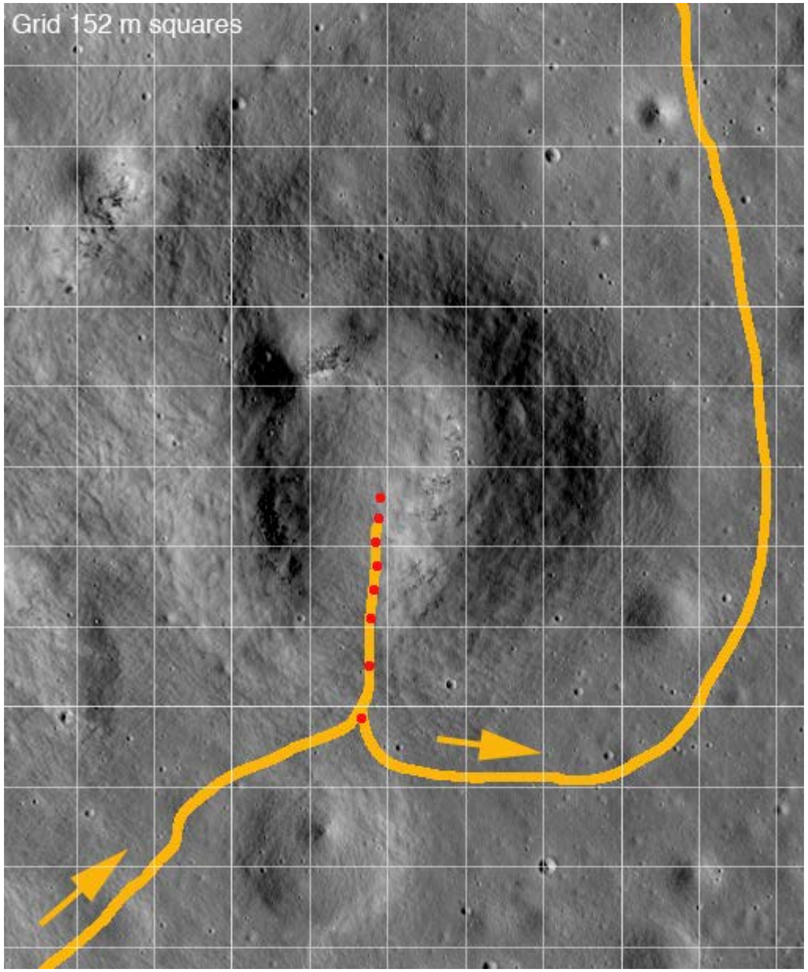
4) 48 hour integration, 100 m (x2)
5) Sunrise
6) Large BW telephoto mosaic stereo panorama, 48 hr int
7) Depart when solar angle 10° above horizon



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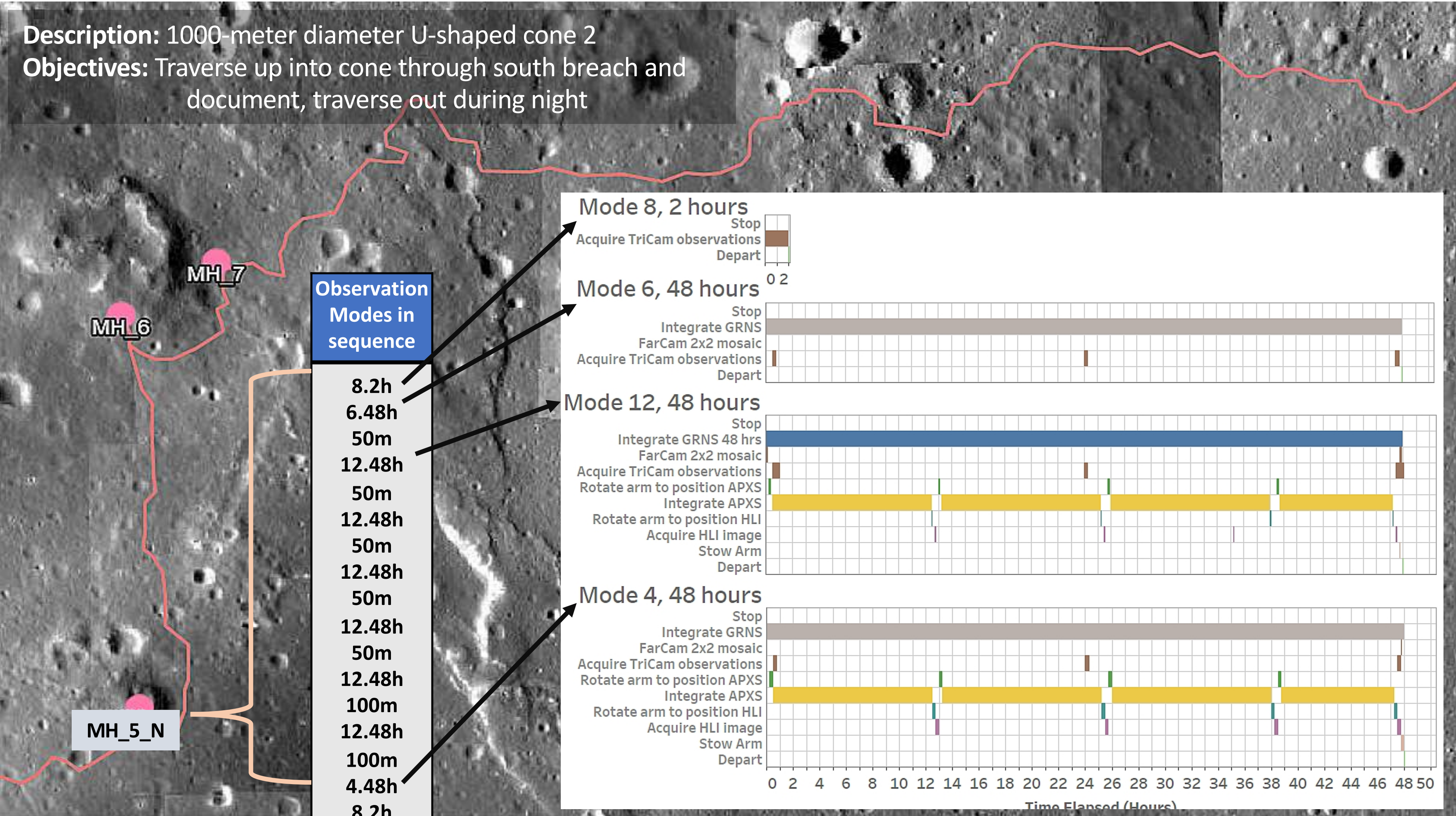
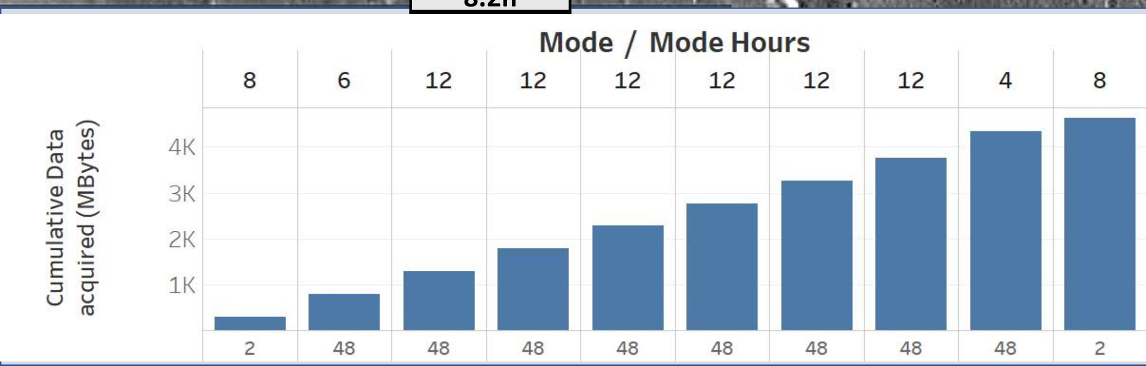
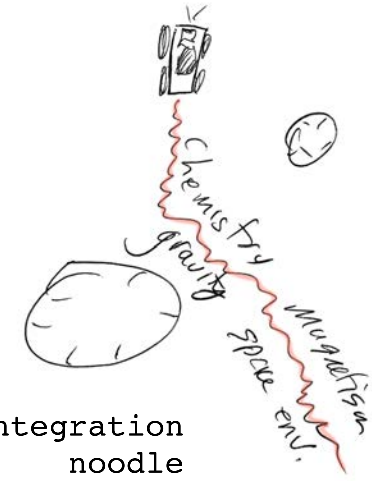




Total cumulative data acquired at MH_5 is 4628 MBytes

Summary of Stops and Measurements

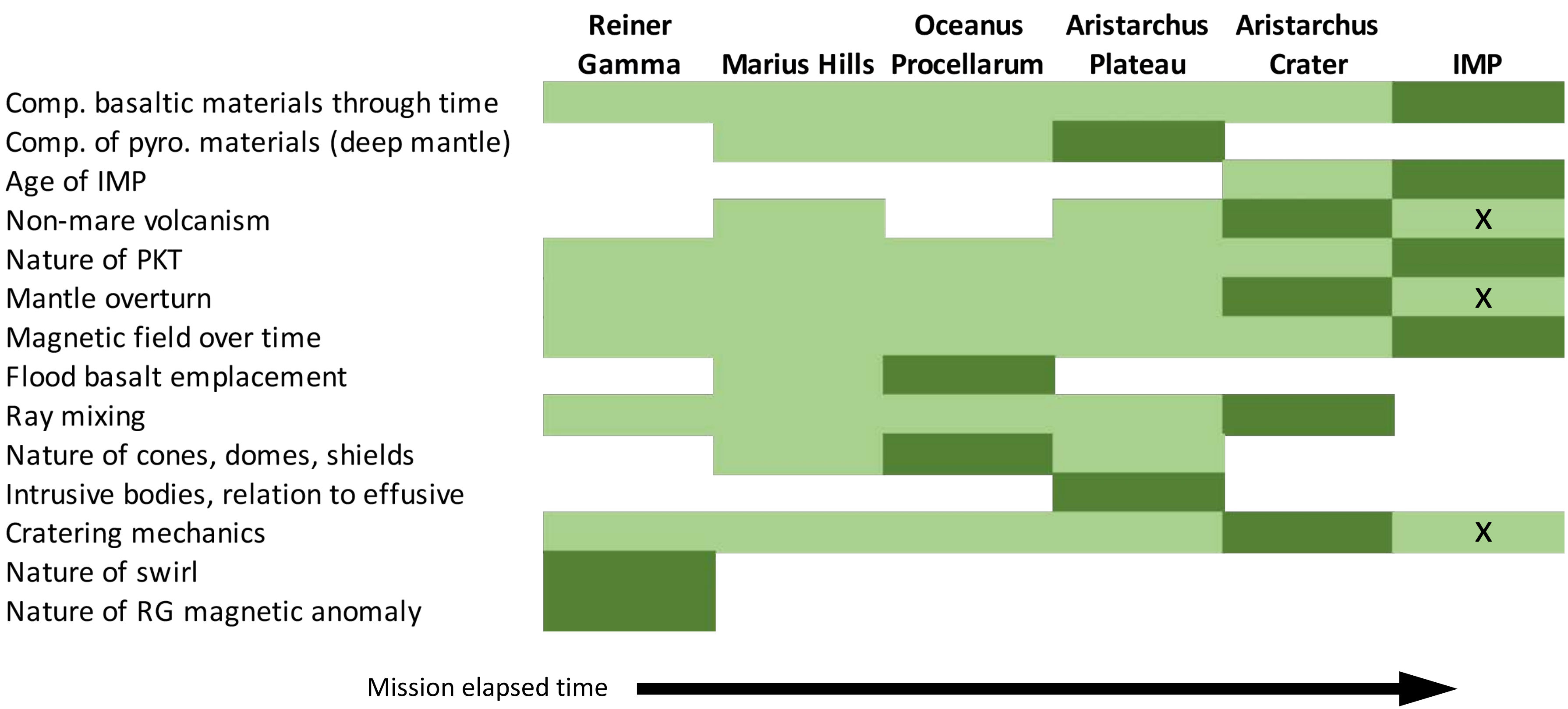


Integration noodle

- Focused Investigation Stops: 131
- Overnight Stops: 35 of 131
- 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 at 1 PS spectrum and 1 lossy greyscale stereo pair each.
- 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

Science Return Timeline



Some questions require full traverse

Light green indicates relevant measurements acquired, dark green indicates task baseline (following light green (e**X**tra) measurements potentially enhances return)

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 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)

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