Planetary Terramechanics

Big Picture

Phoenix and MER Case Studies

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Washington University in Saint Louis
KISS xTerramechanics Workshop
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With input from the Athena and Phoenix Science Teams,
Mars Exploration Rover Mobility Engineers.
and Phoenix Robotic Arm Team

Planetary Terramechanics

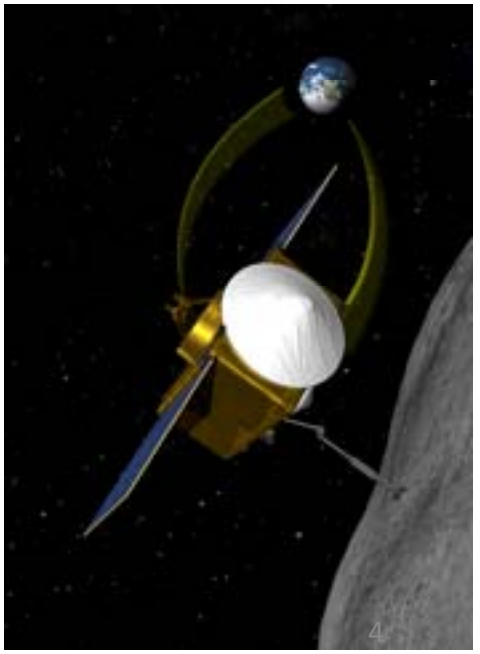
- Interaction of spacecraft systems with planetary surfaces, e.g., during
  - Hard landing (penetrometer)
  - Soft landing (rockets, air bags, “sky crane”)
  - Hopping (Proposed Comet Hopper)
  - Roving (MER, MSL, ExoMars, MAX-C)
  - Digging and sampling (Phoenix, MER)
  - Drilling and sampling (MSL, ExoMars, MAX-C)

All Missions Below Have Terramechanics Elements

- Spirit (2004-2011) and Opportunity Rovers (2004 to now)
- Phoenix Lander (May to November, 2008)
- Mars Science Laboratory – Curiosity (lands August 2012)
- NASA/ESA ExoMars and/or MAX-C rovers (2018?)
- New Frontiers – OSIRIS-Rex 2016 launch to return samples from near Earth Asteroid 1999 RQ36 in 2020
- Discovery Selection (to be down-selected to one mission)
  - Geophysical Monitoring Station (GEMS) determines structure and interior of Mars
  - Titan Mare Explorer (TiME) floats on Titan's methane-ethane sea
  - Comet Hopper lands on comet multiple times, making measurements as surface interacts with sunlight

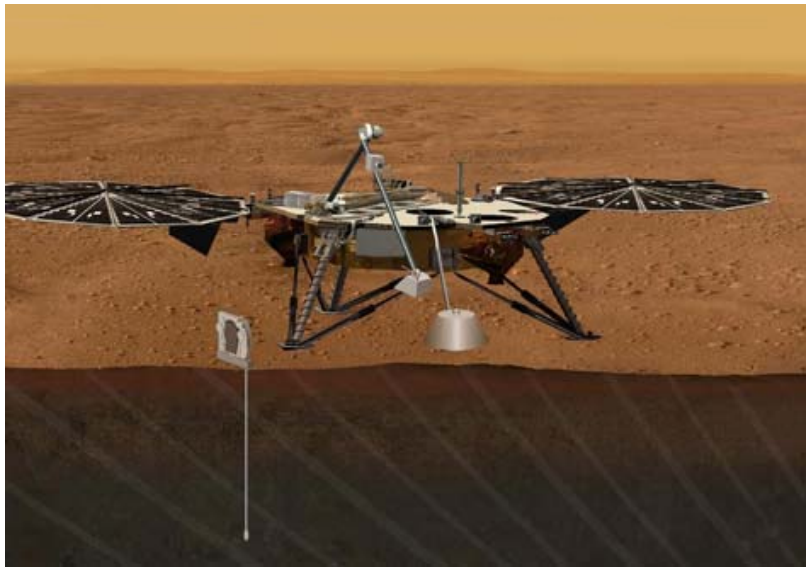
New Frontiers Mission OSIRIS-REX

- **Launch 2016; encounter with asteroid 1999RQ36 in 2020; sample return in 2023.**
  PI: Michael Drake, University of Arizona
- **Purpose and approach:**
  - **Spend up to 505 days mapping the properties, chemistry, and mineralogy of the asteroid to characterize its geologic and dynamic history and provide context for the returned samples.**
  - **Obtain and return at least 60 g of pristine regolith and a surface sample to study the nature, history, and distribution of its constituent minerals and organic material.**
  - **Document the texture, morphology, geochemistry, and spectral properties of the regolith at the sampling site *in situ* at scales down to the submillimeter.**
  - **Measure the Yarkovsky effect on a potentially hazardous asteroid and constrain the asteroid properties that contribute to this effect.**
  - **Characterize the integrated global properties of the asteroid to allow for direct comparison with ground-based telescopic data of the entire asteroid population.**
- **Instruments:**
  - **OCAMS (camera suite)**
  - **OVIRS (visible-IR spectrometer)**
  - **OTES (thermal emission spectrometer)**
  - **OLA (laser altimeter)**
  - **TAGSAM (touch-and-go sample acquisition mechanism)**
  - **Radio Science**



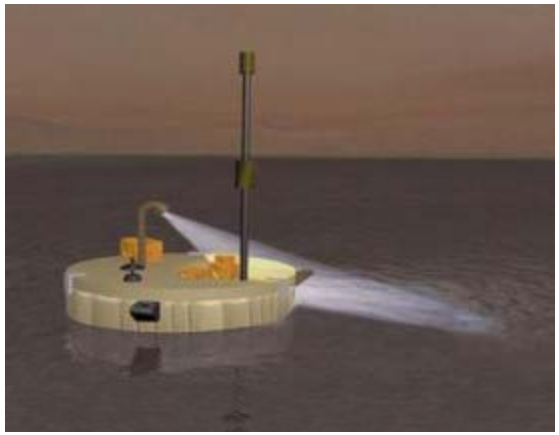
Discovery Proposal GEMS Geophysical Monitoring Station

- **Launch 2016. PI: Bruce Banerdt, Jet Propulsion Laboratory**
- **Goal: In-situ investigation of Mars' interior to understand its present tectonic activity and impact flux.**
- **Science objectives:**
  - **Determine the size, composition and physical state of the core**
  - **Determine the thickness and structure of the crust**
  - **Determine the composition and structure of the mantle**
  - **Determine the thermal state of the interior**
  - **Measure the rate and distribution of internal seismic activity**
  - **Measure the rate of impacts on the surface**
- **Instruments:**
  - **SEIS, a 6-component very-broad-band seismometer**
  - **HP^3 (Heat Flow and Physical Properties Package), a self-penetrating mole system that trails a string of temperature sensors**
  - **RISE (Rotation and Interior Structure Experiment), precision tracking through spacecraft X-band communication system**
  - **Instrument Deployment Arm with Instrument Deployment Camera**



Discovery Proposal TiME
Titan Mare Explorer

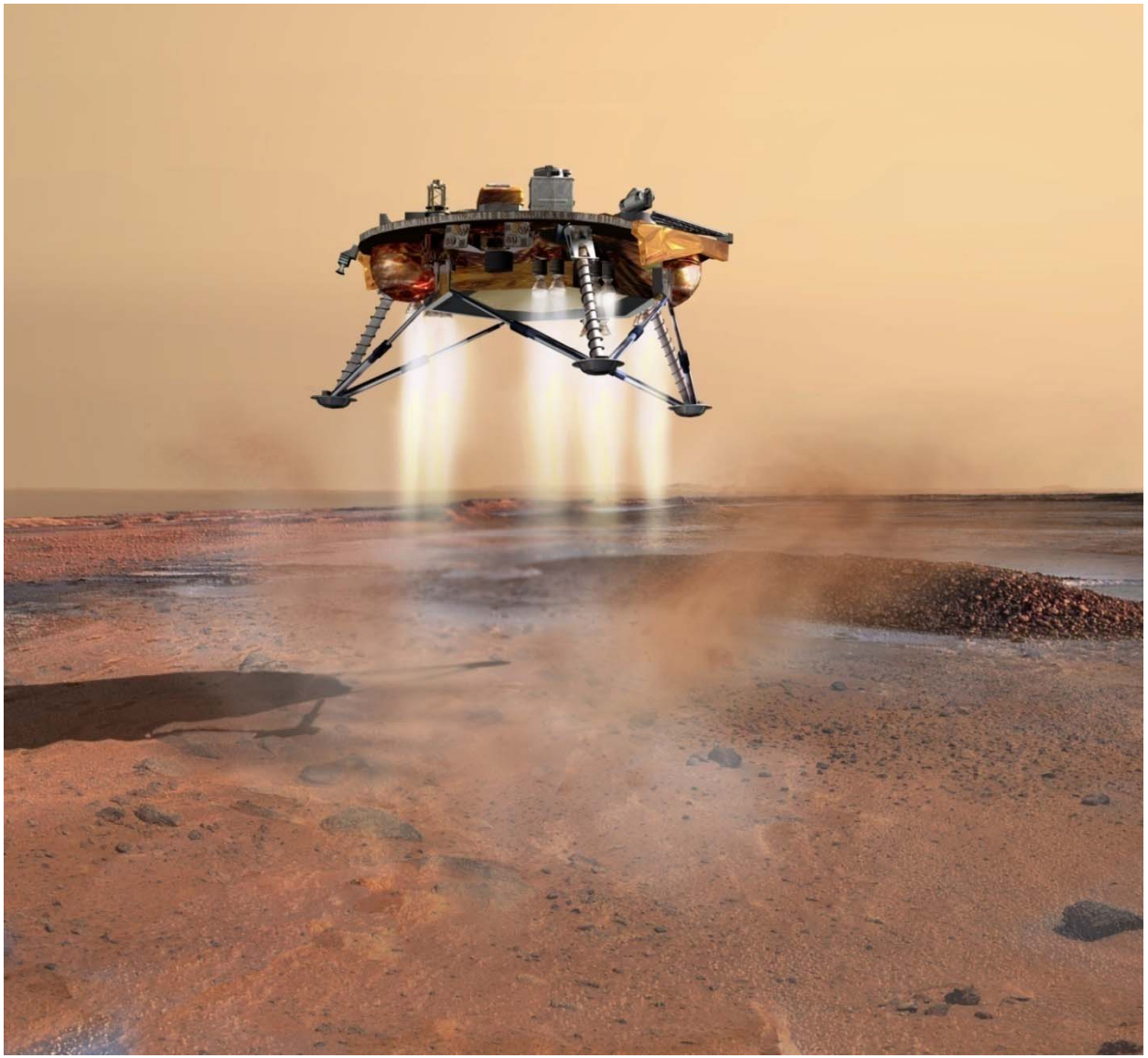
- **Launch 2016, reach Saturn's moon Titan in 2023, land and spend 96 days floating on a large methane-ethane sea, Ligeia Mare. PI: Ellen Stofan, Proxemy Research.**
- **Goals:**
  - **Understand Titan's methane cycle through study of a Titan sea.**
  - **Investigate the history of Titan and explore the limits of life.**
- **Science objectives:**
  - **Determine the chemistry of seas to constrain Titan's methane cycle, look for patterns in the abundance of constituents in the liquids and analyze noble gases. Determine the depth of the Titan sea to determine sea volumes, and thus, organic inventory.**
  - **Investigate Titan's lake-related processes by characterizing physical properties of its liquid seas, and how they vary with depth.**
  - **Determine how the local meteorology over the seas ties to the global cycling of methane on seasonal and longer timescales.**
  - **Analyze the nature of the sea surface and if possible, shorelines, to determine physical properties of sea liquids and better understand the origin, evolution, and subsurface methane/ethane hydrology of Titan lakes and seas.**
- **Instruments:**
  - **MS (mass spectrometer)**
  - **MP3 (Meteorology and Physical Properties Package)**
  - **Imaging system including a Descent Imager and Surface Imager**



Discovery Proposal Comet Hopper (CHopper)

- **Launch 2016, encounter with Comet Wirtanen in 2022, mission duration 7.3 years. PI: Jessica Sunshine, University of Maryland**
- **Purpose and approach:**
  - **Remote mapping of gas and dust emissions and surface solids**
  - **Landing and multiple surface hops as comet approaches the sun, recording surface changes as comet becomes more active**
- **Instruments:**
  - **CHIRS (CHopper Infrared Spectrometer)**
  - **CHIMS (CHopper Ion/Neutral Mass Spectrometer)**
  - **CHI (CHopper Imager)**
  - **CHEX (CHopper Heating Experiment)**
  - **PanCams (Panoramic Cameras)**

Mars Phoenix Lander Mission

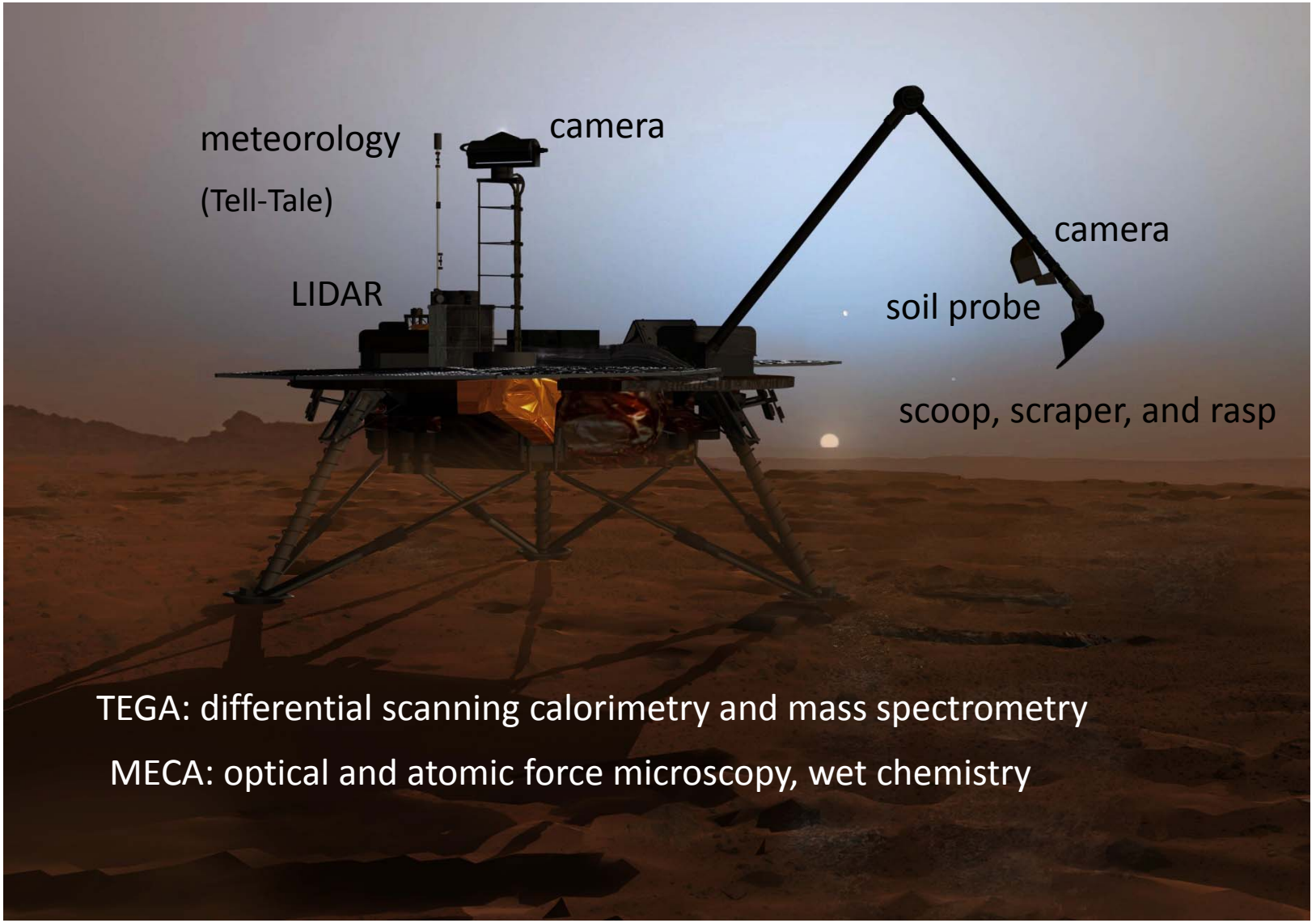


Touched down
5/25/08 on
high northern plains
to analyze soil and icy
soil: “Follow the Water”

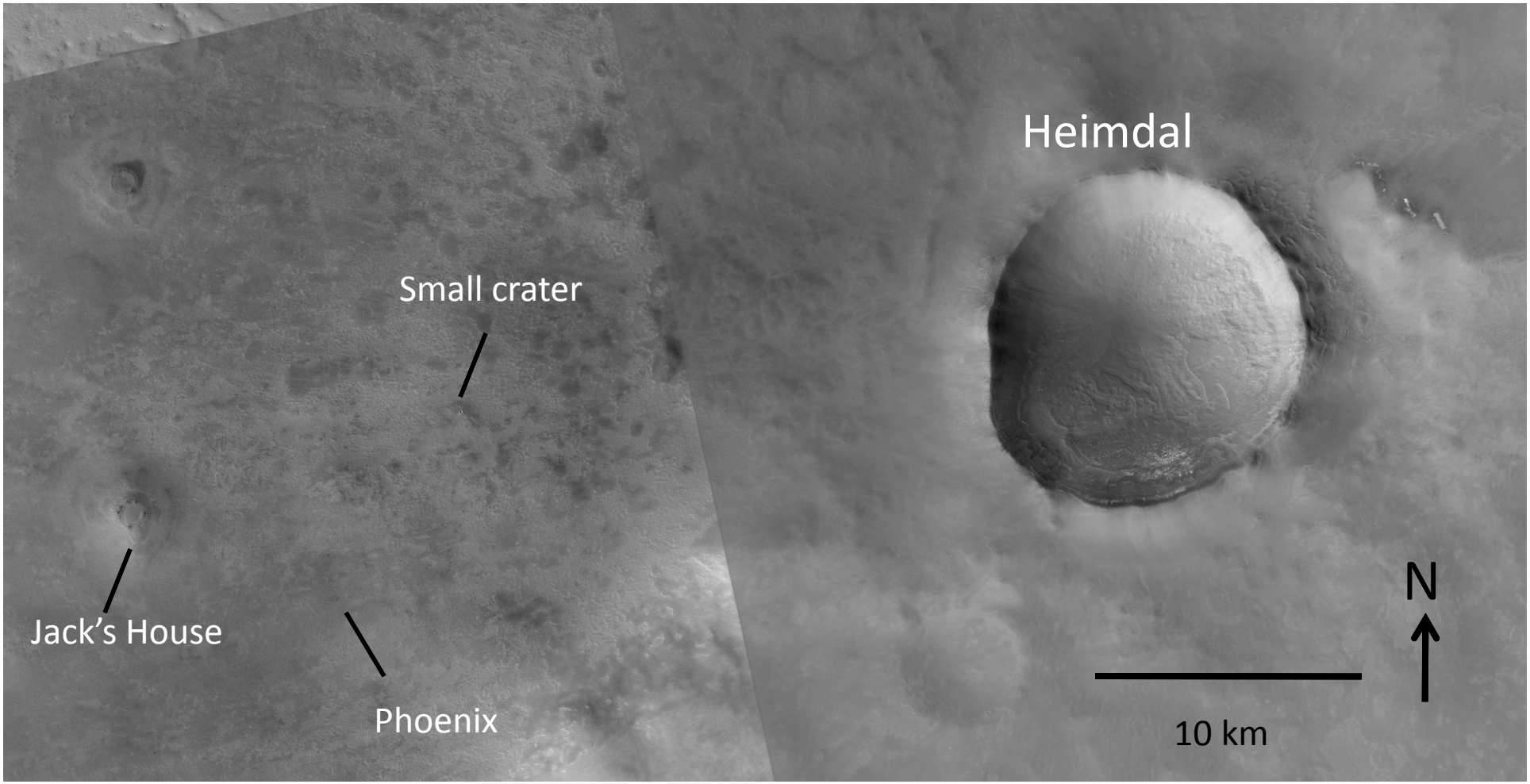
Also monitor
atmosphere, conduct
geomorphic and physical
properties experiments

Operated until 11/2/08

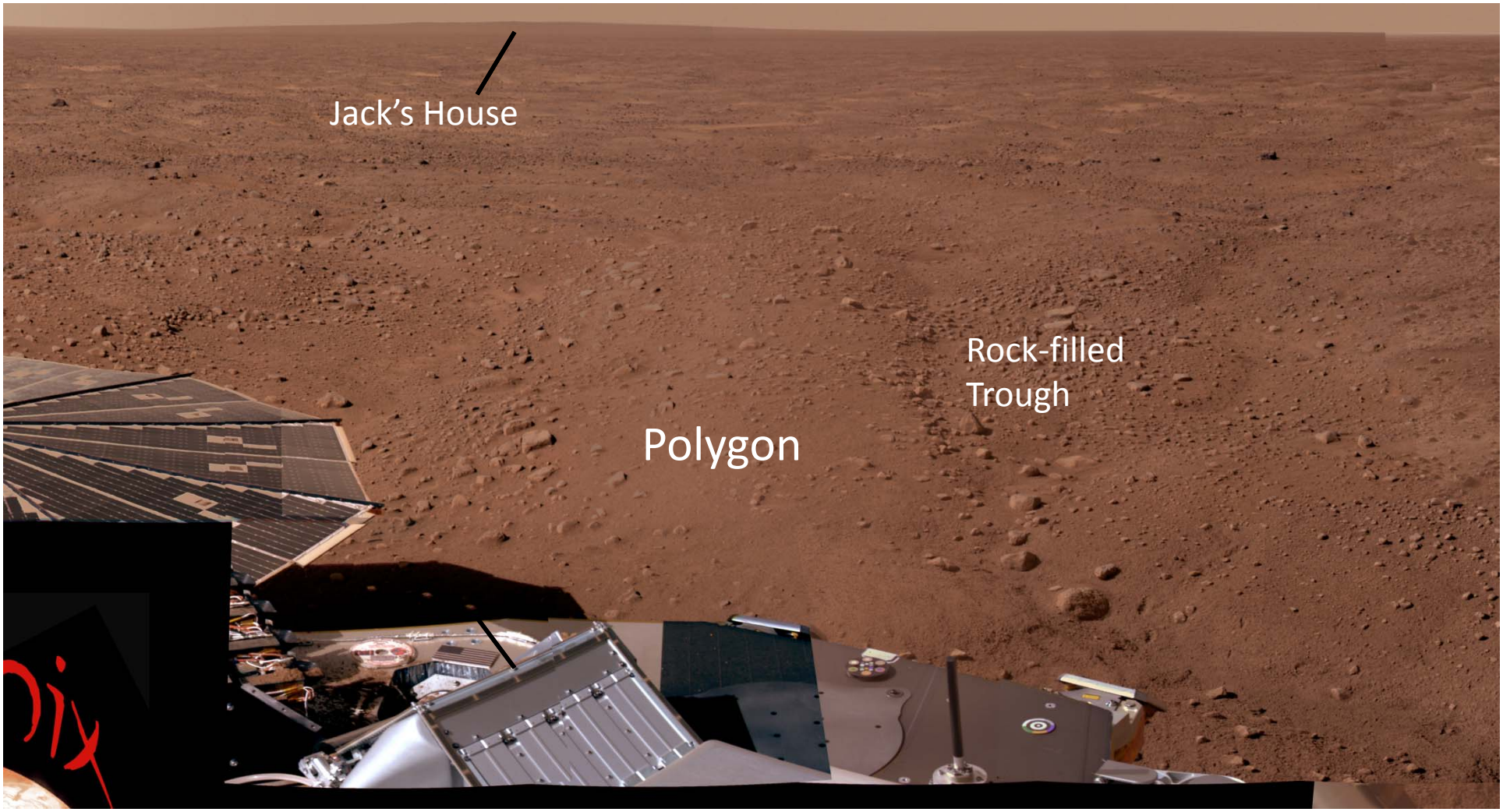
Mars Phoenix Lander Mission



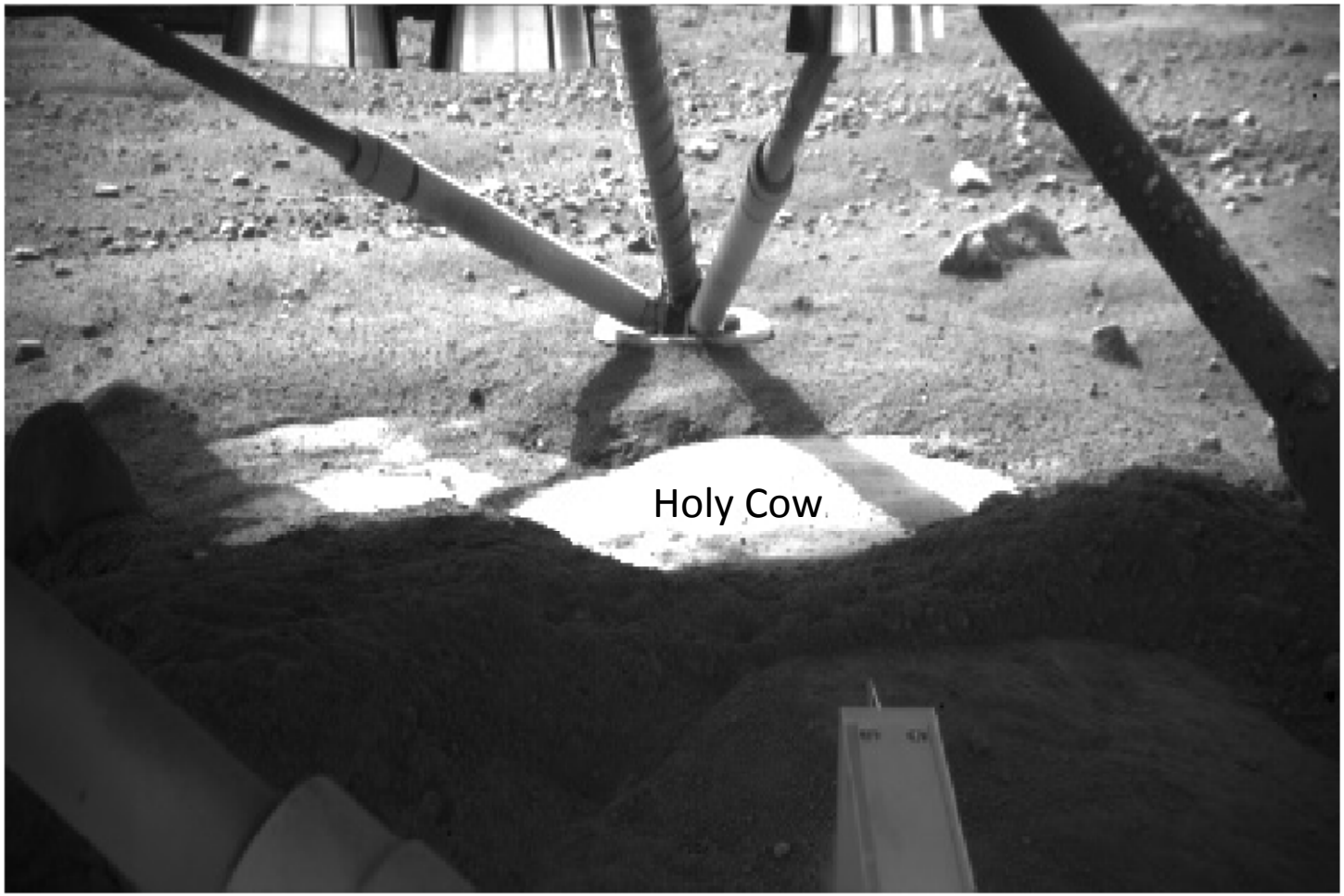
Context Imager Mosaic From Data Acquired After Landing



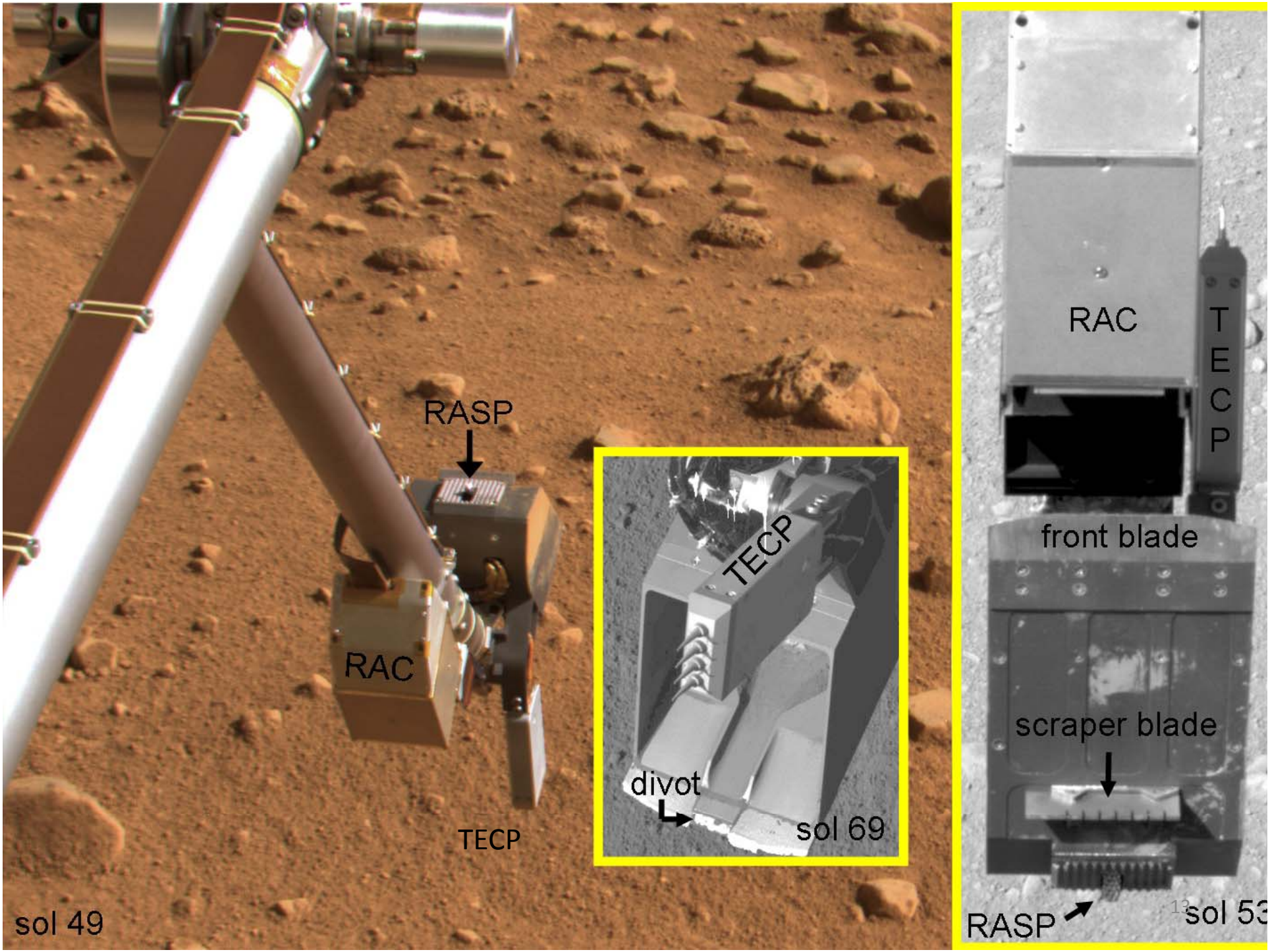
Initial Panoramic Image

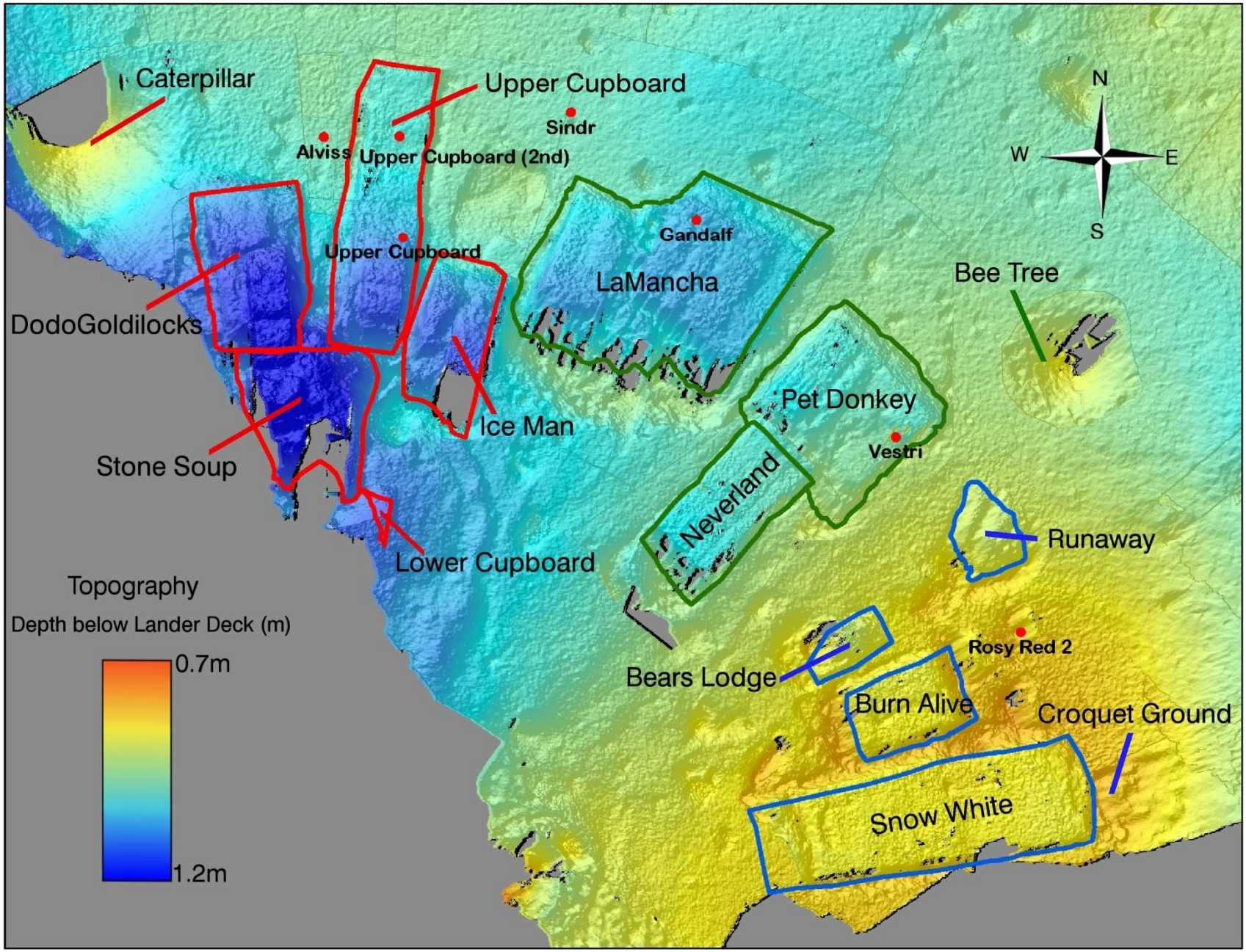


Phoenix Robotic Arm Image Taken Under Lander

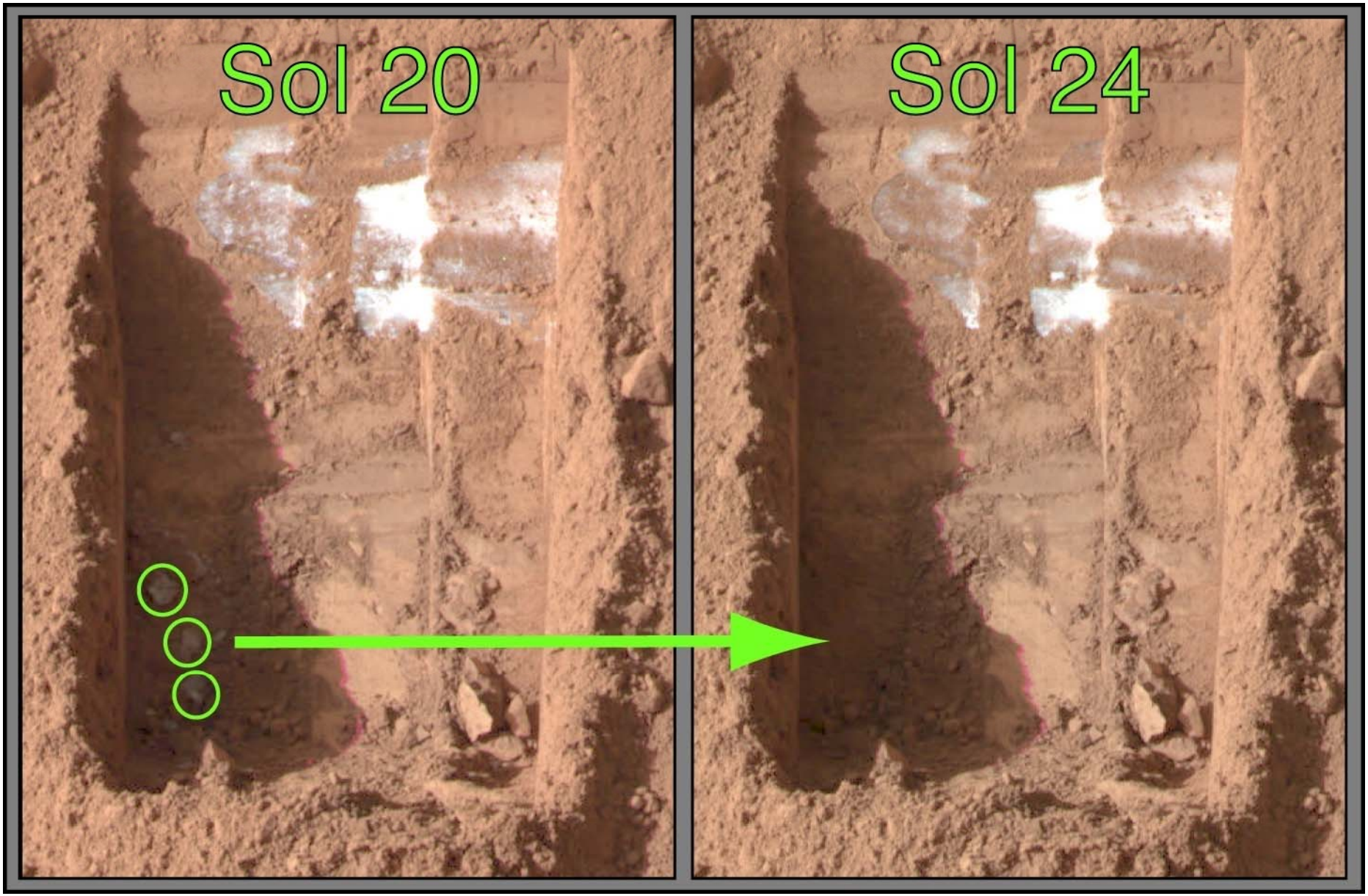


Soil blown away by retrorockets, exposing icy soils

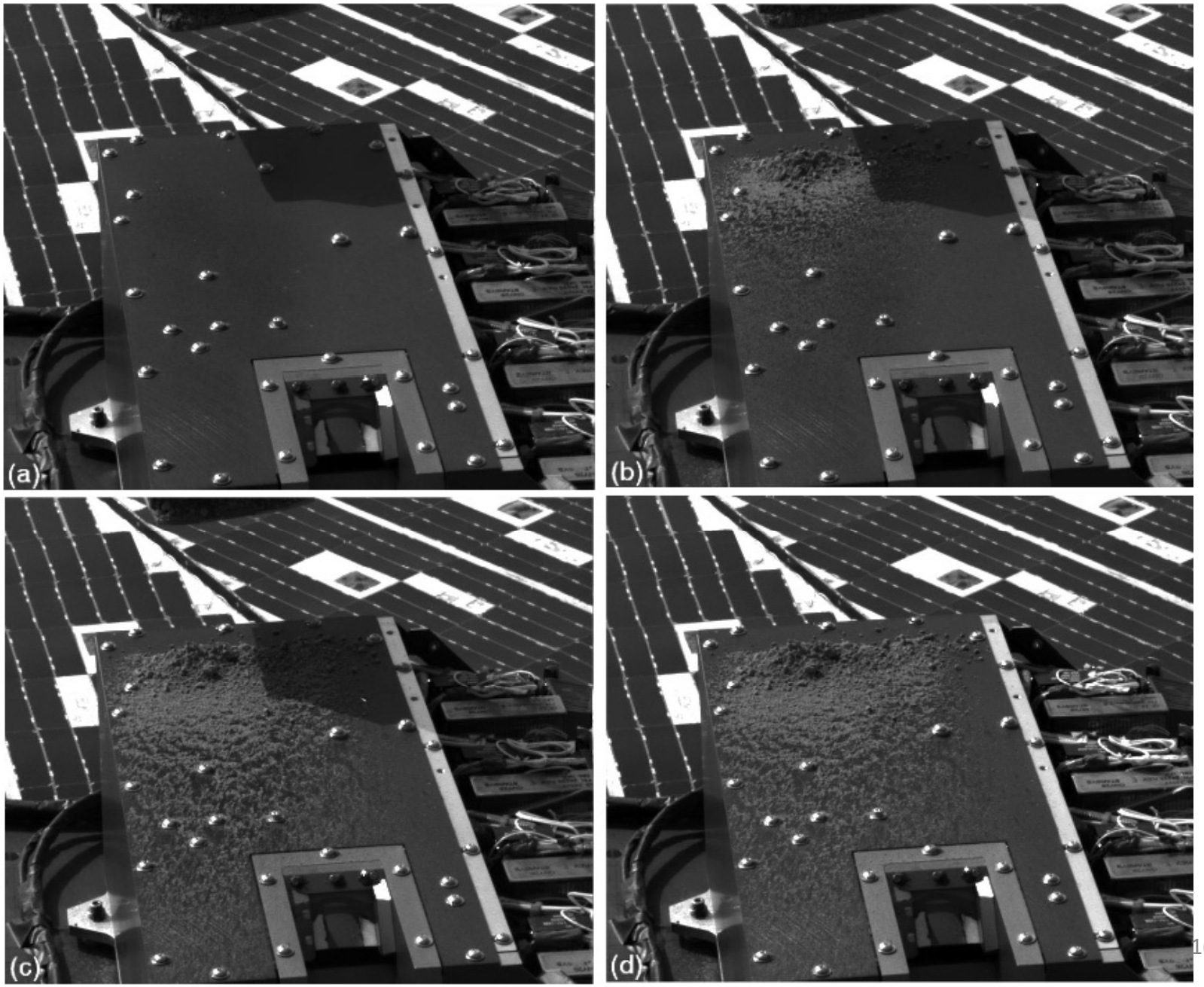

RASP
RAC
TECP
sol 49
TECP
divot
sol 69
RAC
TECP
front blade
scraper blade
RASP
sol 53


Caterpillar
Upper Cupboard
Sindr
Alviss
Upper Cupboard (2nd)
N
W
E
S
Gandalf
Upper Cupboard
LaMancha
Bee Tree
DodoGoldilocks
Pet Donkey
Ice Man
Vestri
Stone Soup
Neverland
Runaway
Lower Cupboard
Topography
Depth below Lander Deck (m)
0.7m
Rosy Red 2
Bears Lodge
Burn Alive
Croquet Ground
Snow White
1.2m

DodoGoldilocks Ice Sublimation Time Series

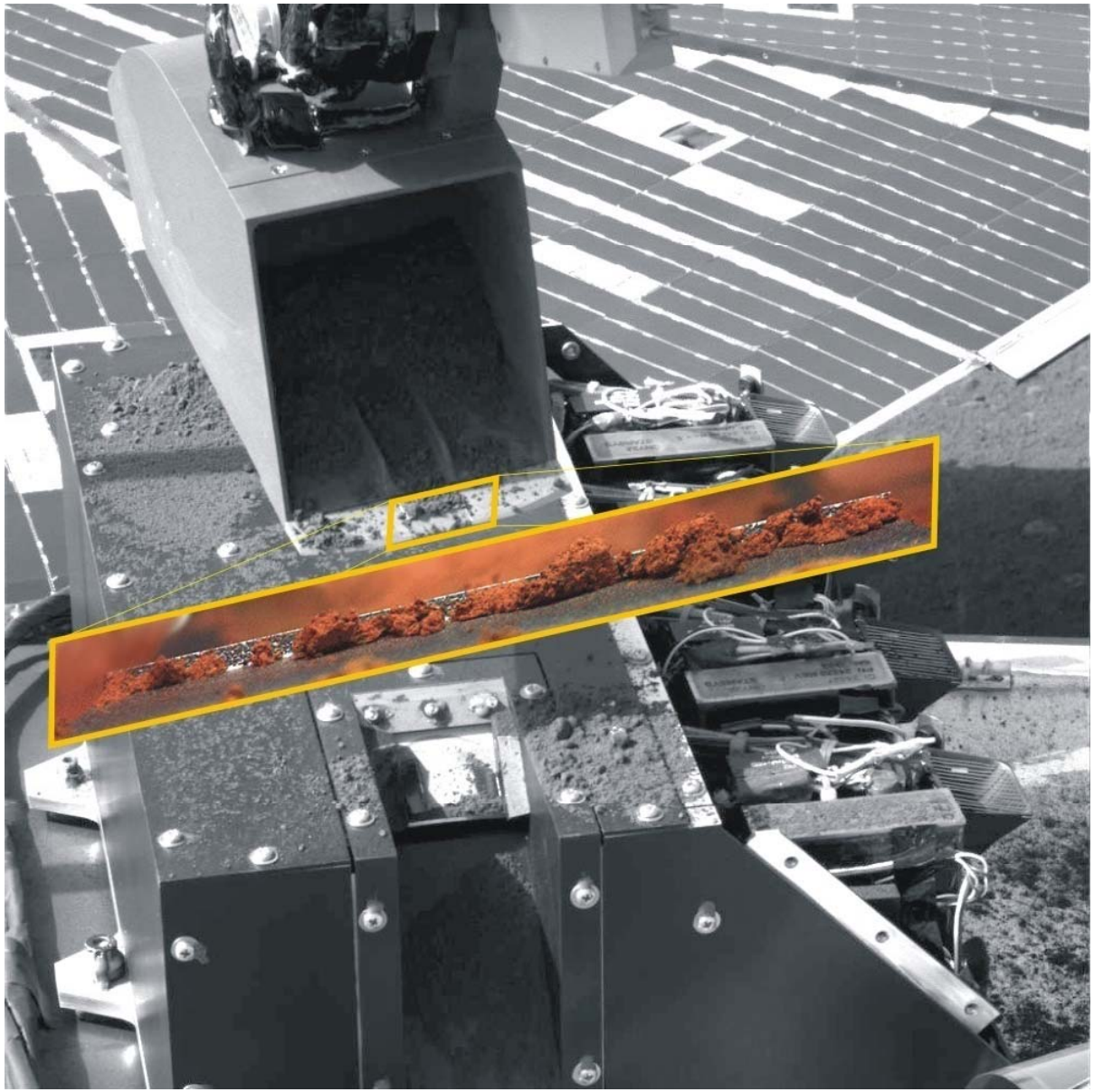


Sprinkle Delivery to Break-up Cloddy Soils



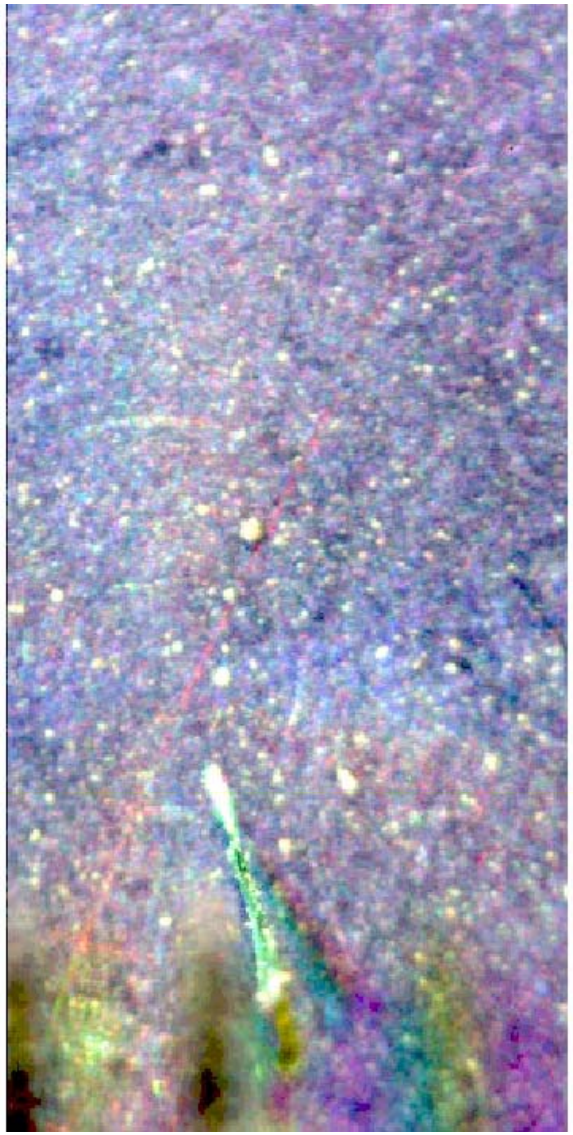
Scoop over
MECA
OM port

RAC divot
Image showing
Soil details



Sol 21 Momma Bear Soil Optical Microscope Image

Before sprinkle delivery

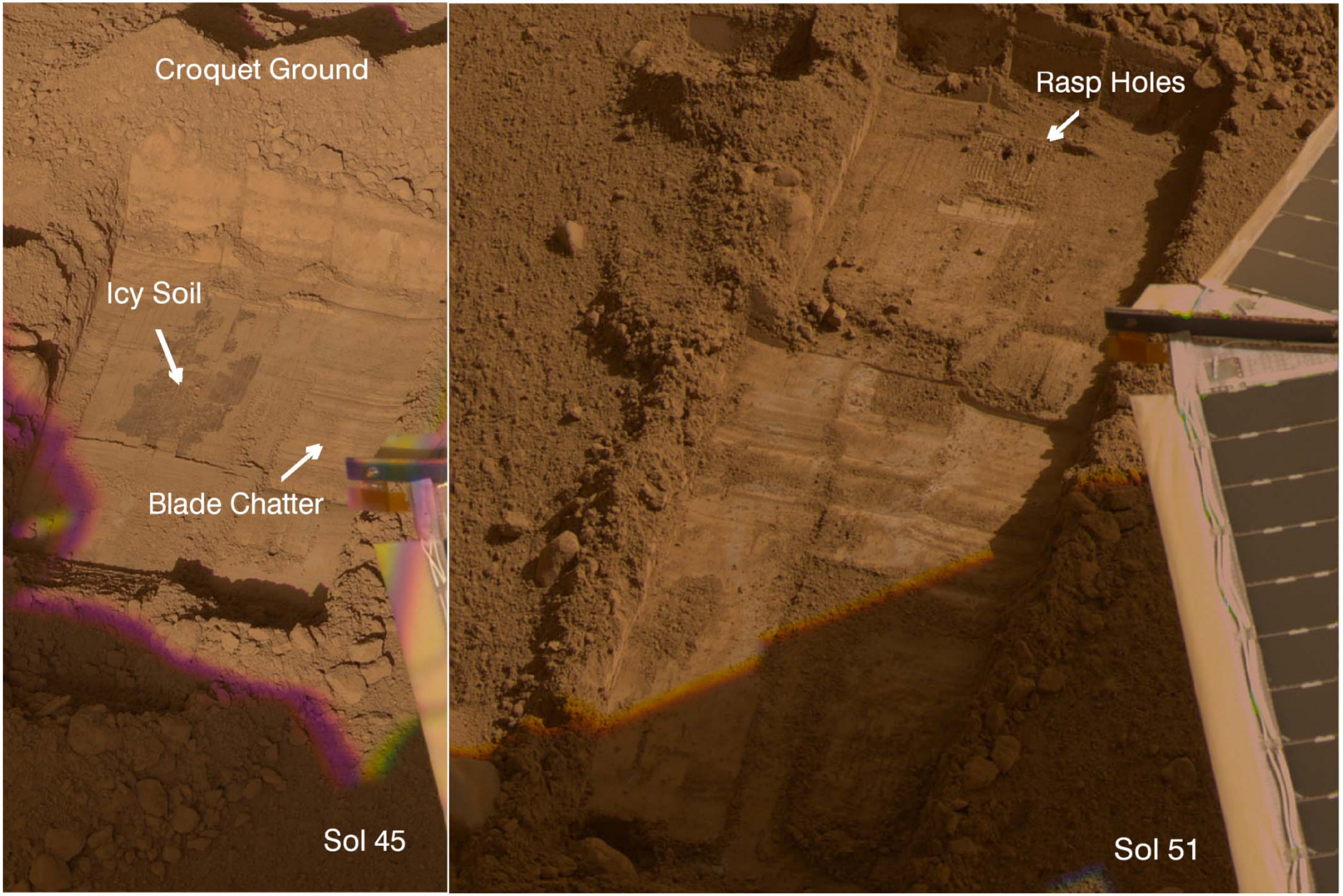


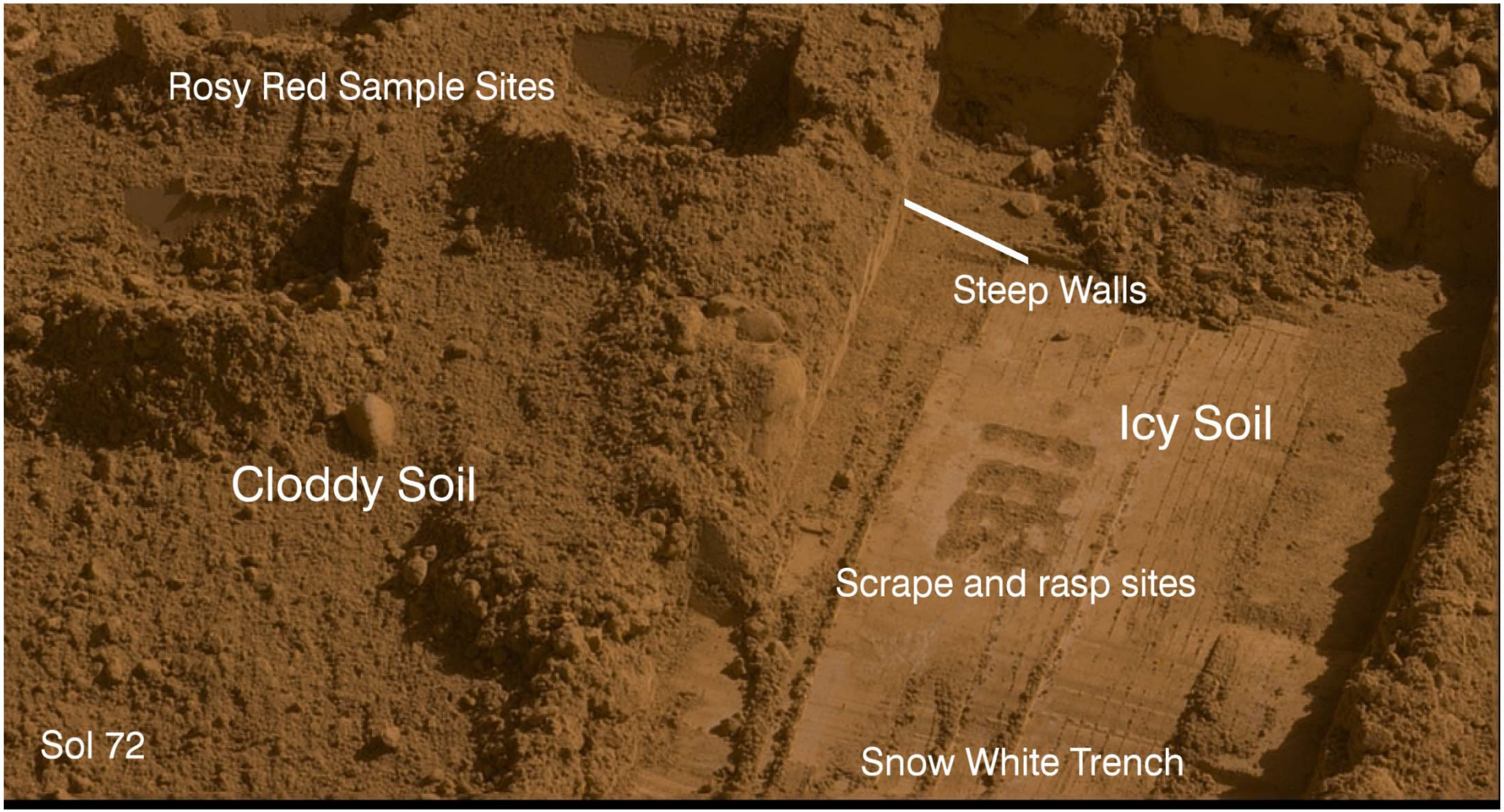
After sprinkle delivery

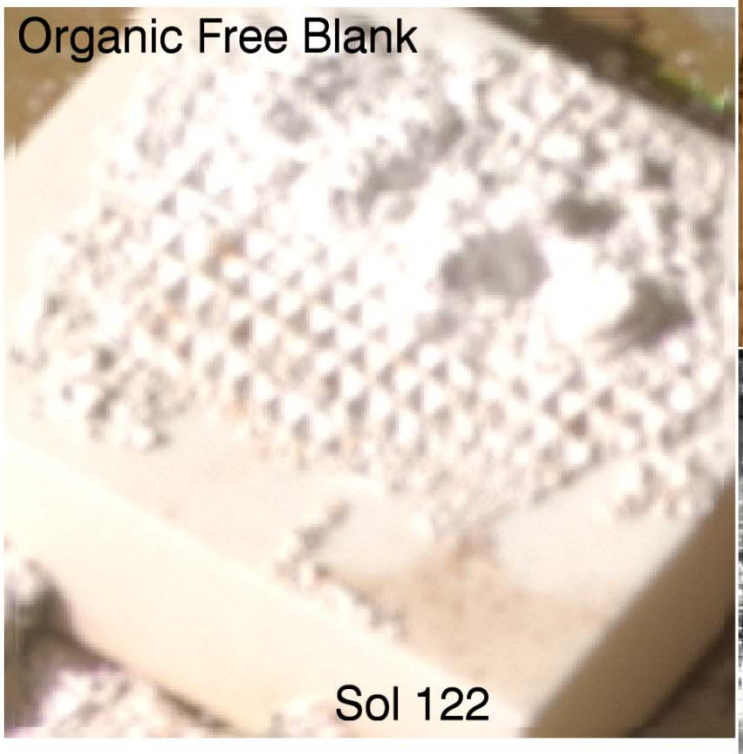
Weak magnet

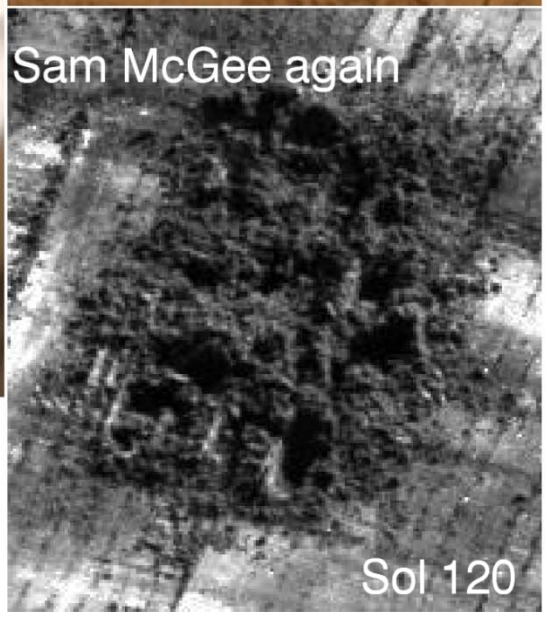
2 mm top to bottom

Deck on Sol 142

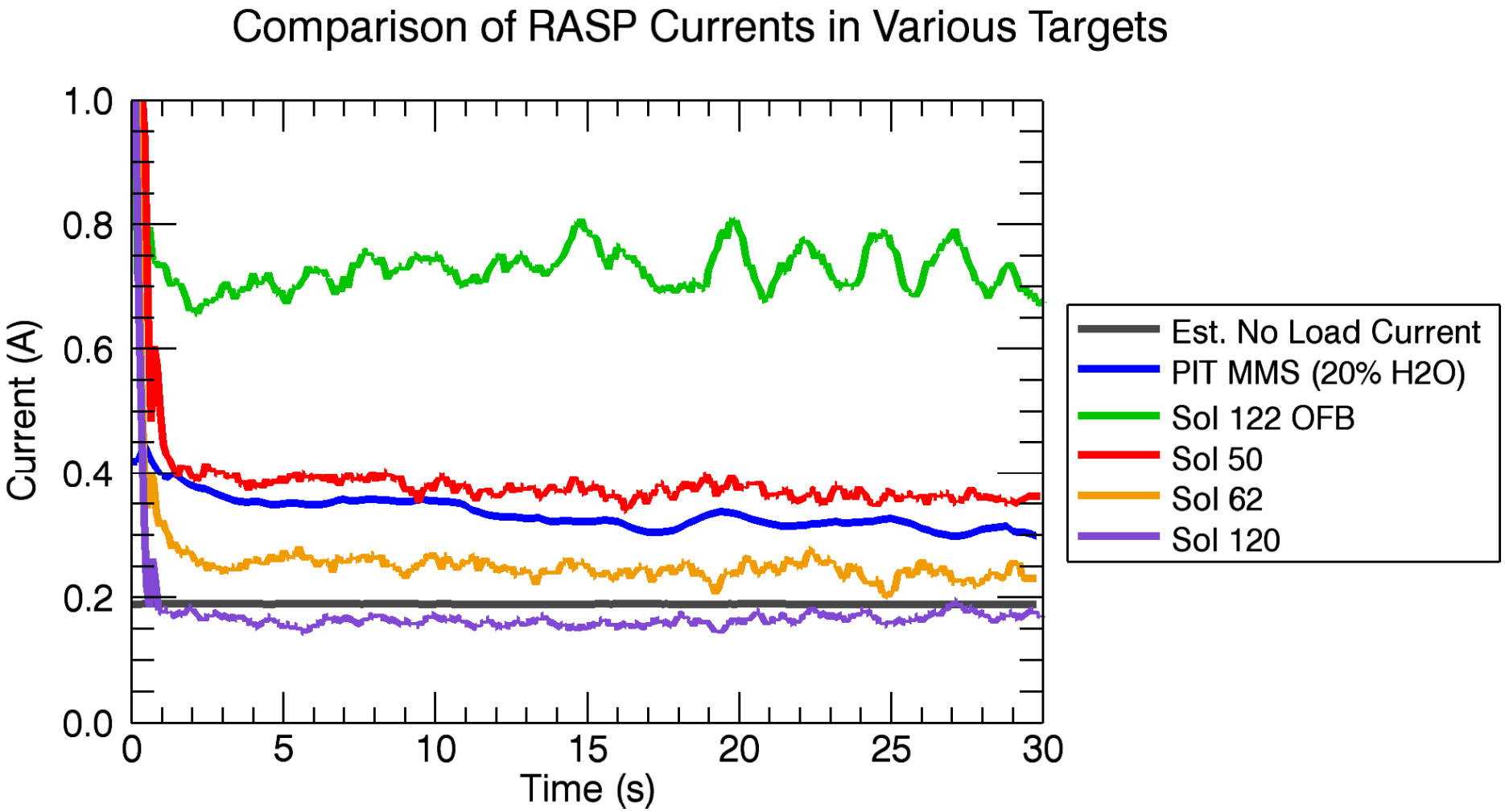

Croquet Ground
Icy Soil
Blade Chatter
Sol 45
Rasp Holes
Sol 51


Rosy Red Sample Sites
Steep Walls
Icy Soil
Cloddy Soil
Scrape and rasp sites
Sol 72
Snow White Trench

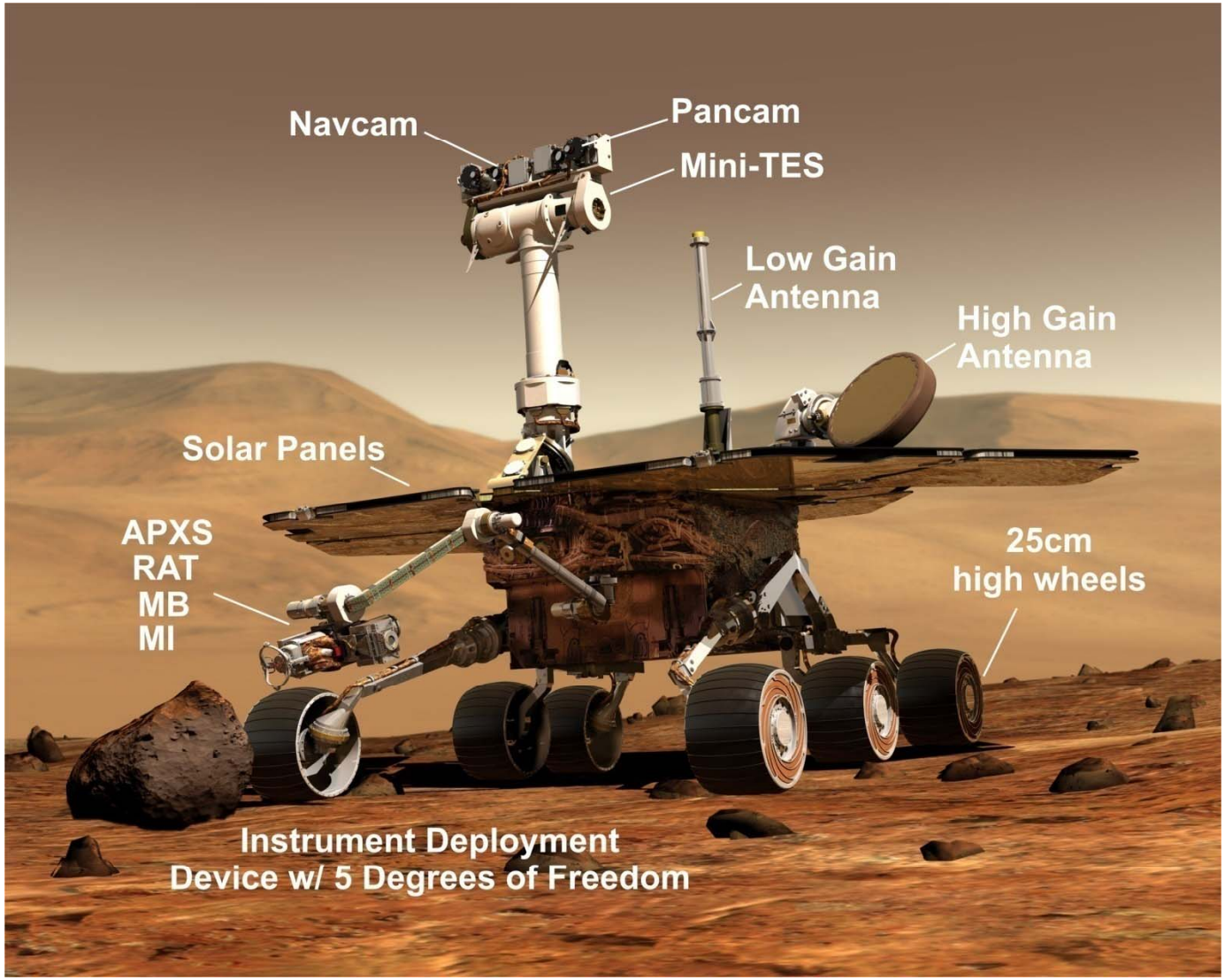




344 Mpa compressive strength

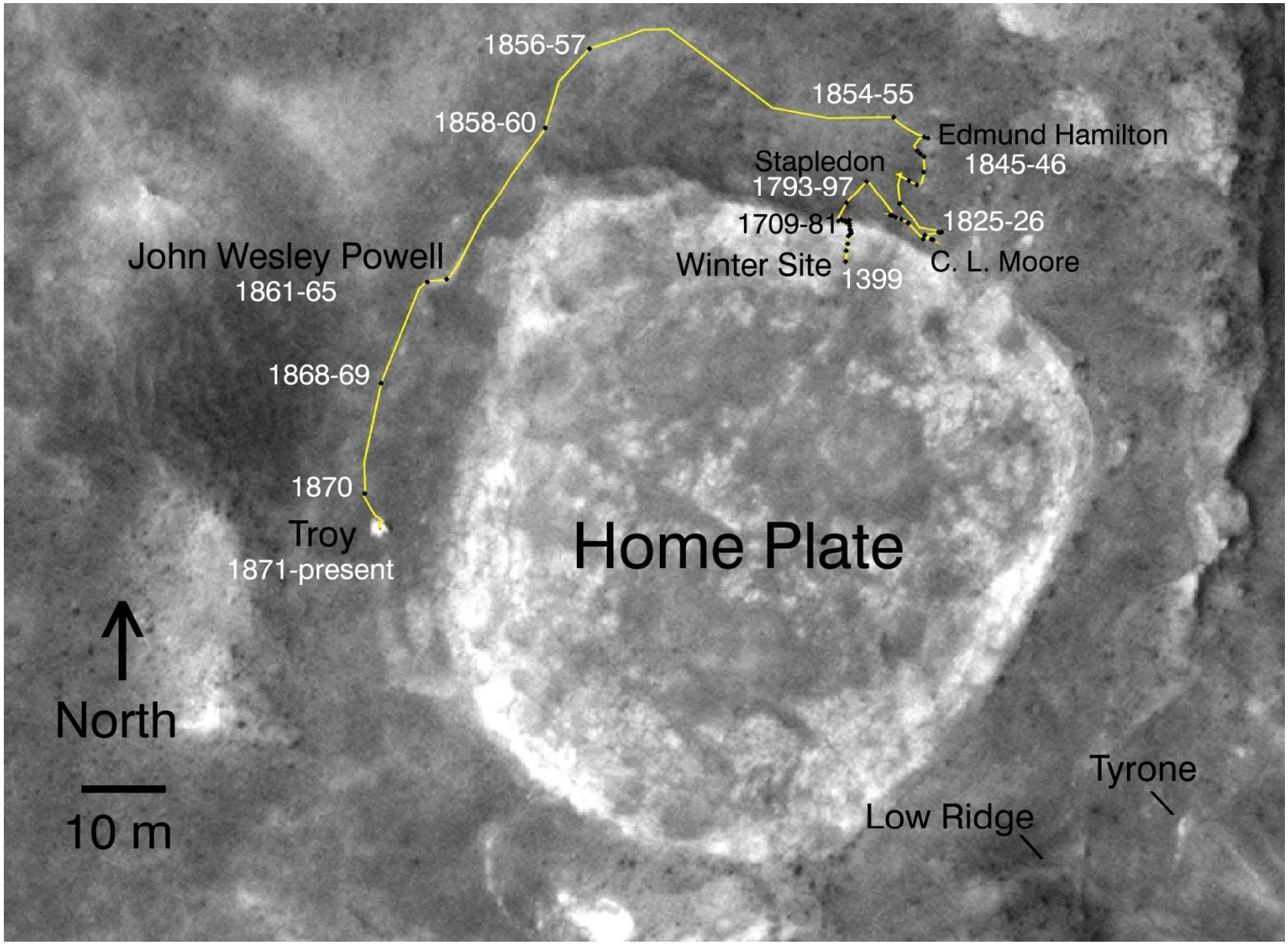

Comparison of RASP Currents in Various Targets
Current (A)
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
25
30
Time (s)
Est. No Load Current
PIT MMS (20% H2O)
Sol 122 OFB
Sol 50
Sol 62
Sol 120

Spirit Rover



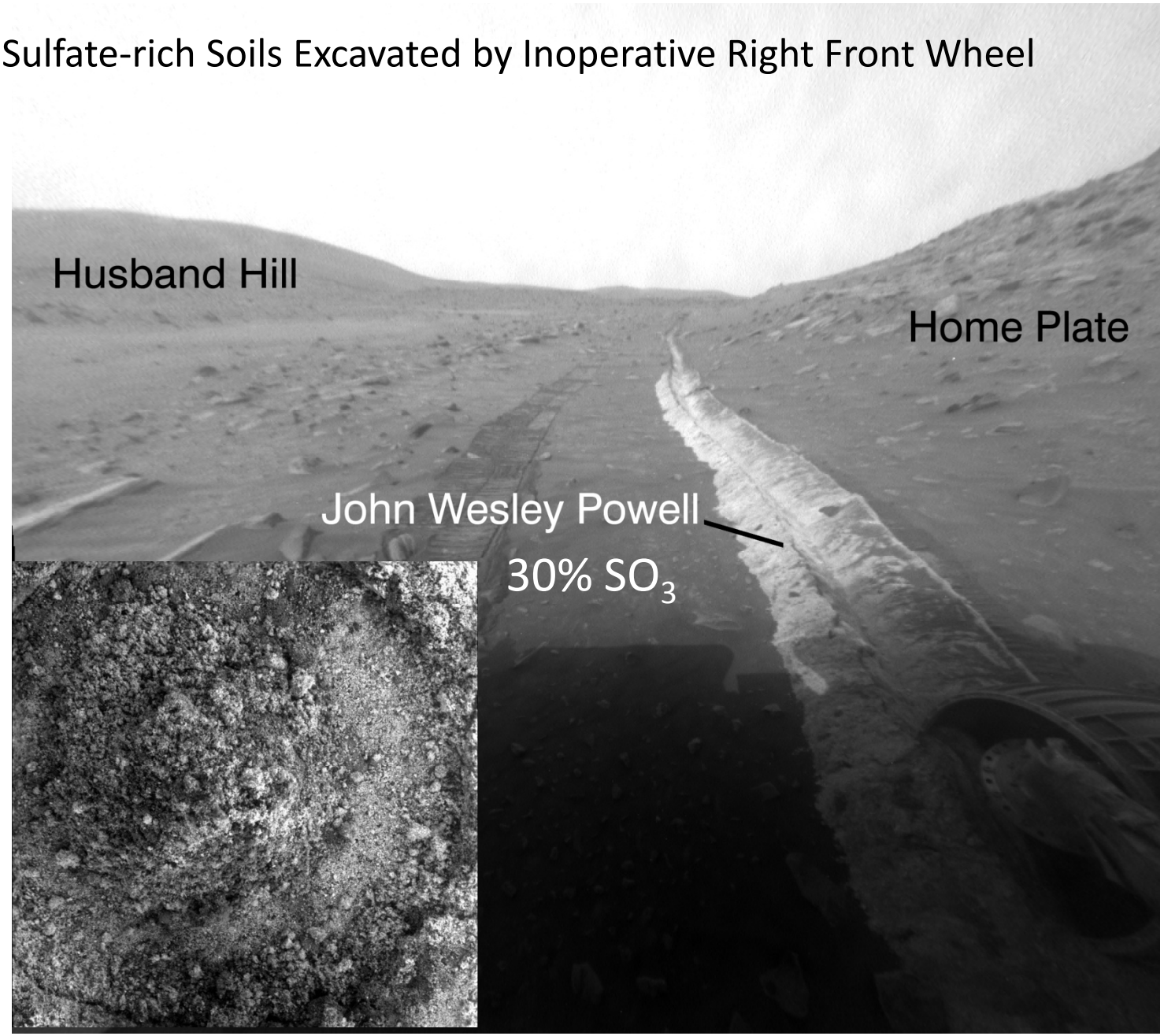
- Right front wheel drive actuator failed on sol 779 so subsequent drives caused rotations about that wheel
- Embedded in sands of Troy after breaking through soil crust
- Extrication stopped Sol 2169 to prepare for winter
- Last communication March 2010

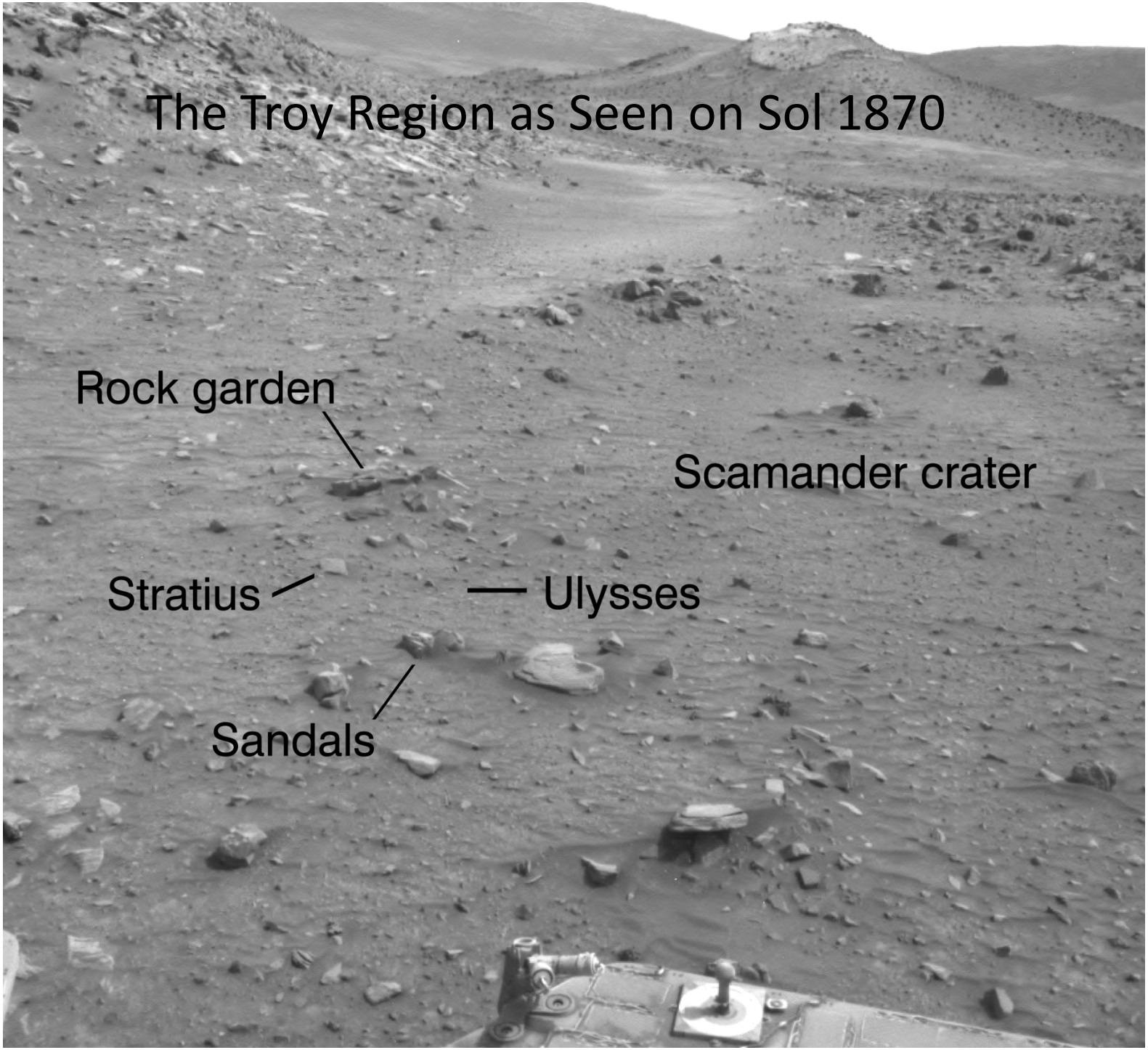
Spirit's Traverses Since Leaving the Third Winter Site

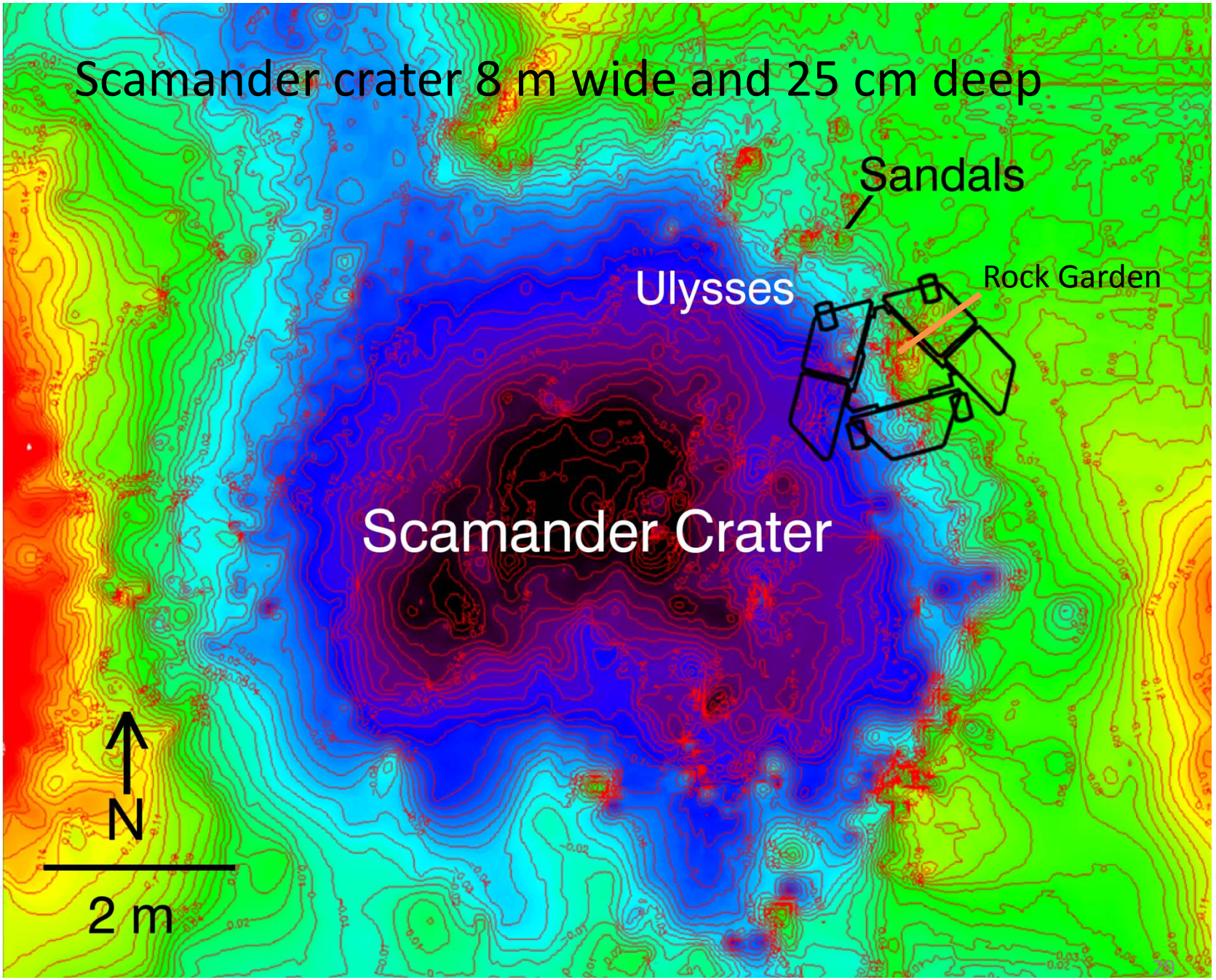


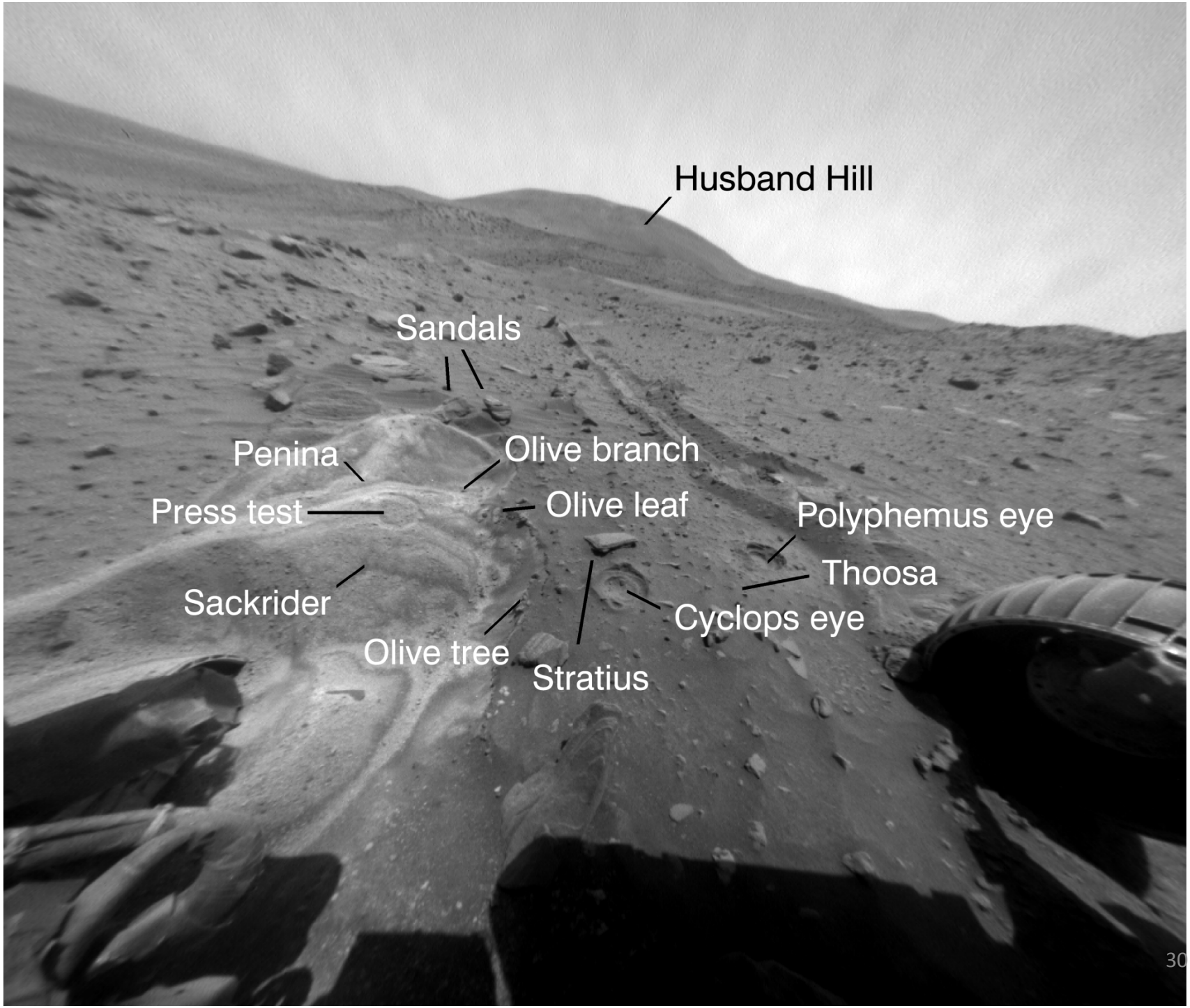
Stapledon Nodular Rock Clast Close to Winter Site

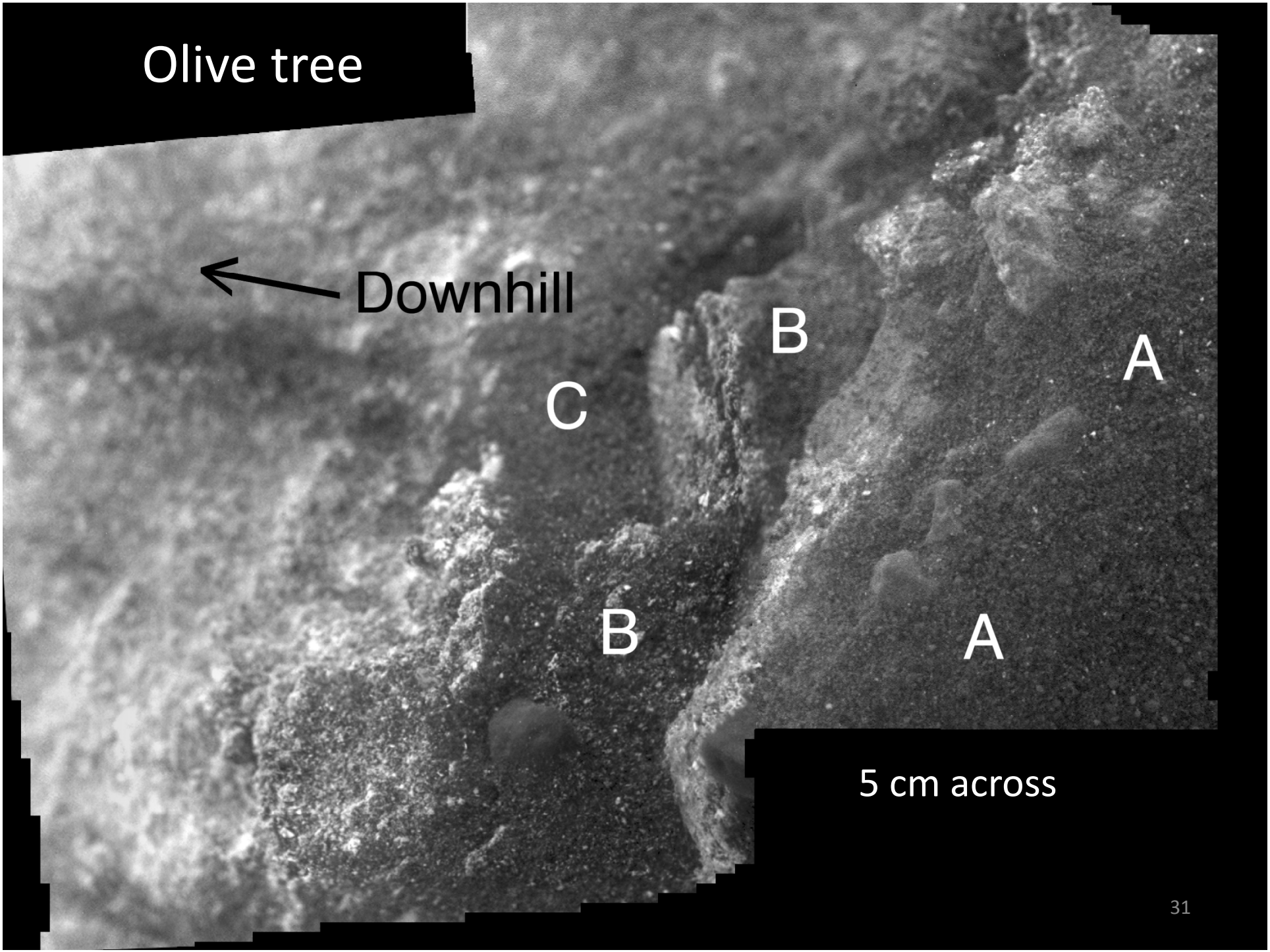
Sulfate-rich Soils Excavated by Inoperative Right Front Wheel

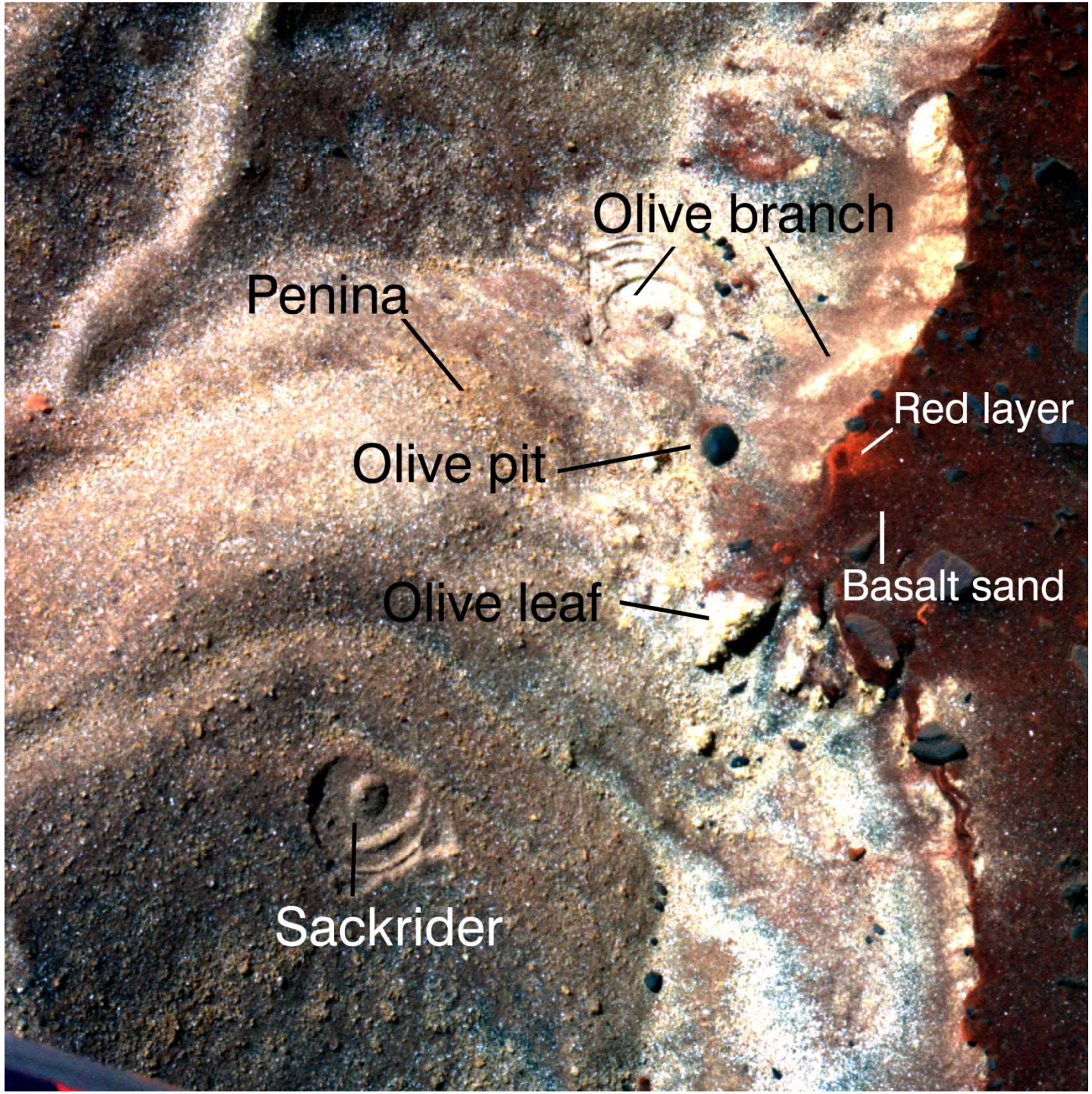


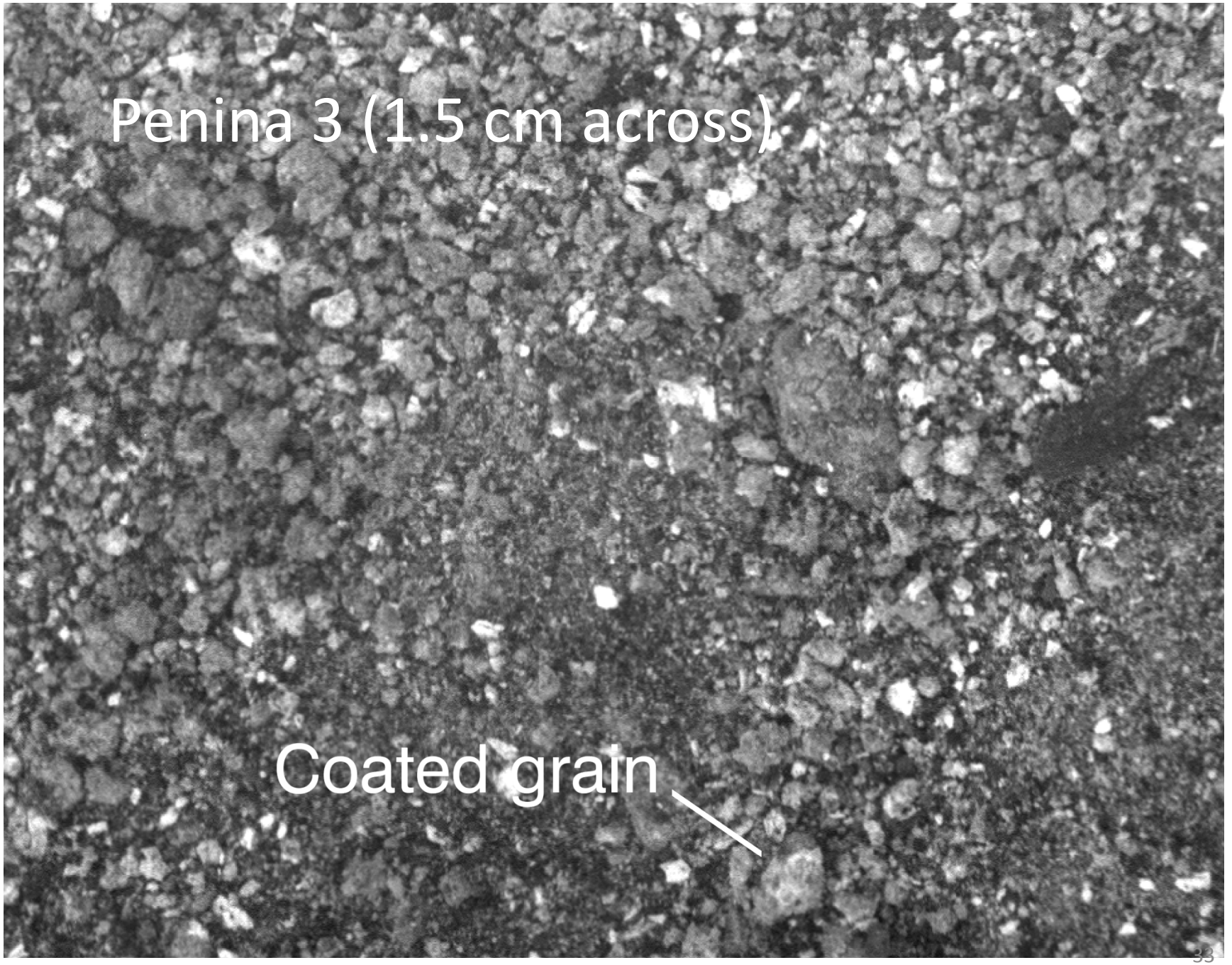

The Troy Region as Seen on Sol 1870
Rock garden
Scamander crater
Stratius
Ulysses
Sandals


Scamander crater 8 m wide and 25 cm deep
Sandals
Ulysses
Rock Garden
Scamander Crater
N
2 m


Husband Hill
Sandals
Penina
Olive branch
Press test
Olive leaf
Polyphemus eye
Thoosa
Sackrider
Cyclops eye
Olive tree
Stratius


Olive tree
Downhill
B
A
C
B
A
5 cm across


Olive branch
Penina
Red layer
Olive pit
Basalt sand
Olive leaf
Sackrider


Penina 3 (1.5 cm across)
Coated grain

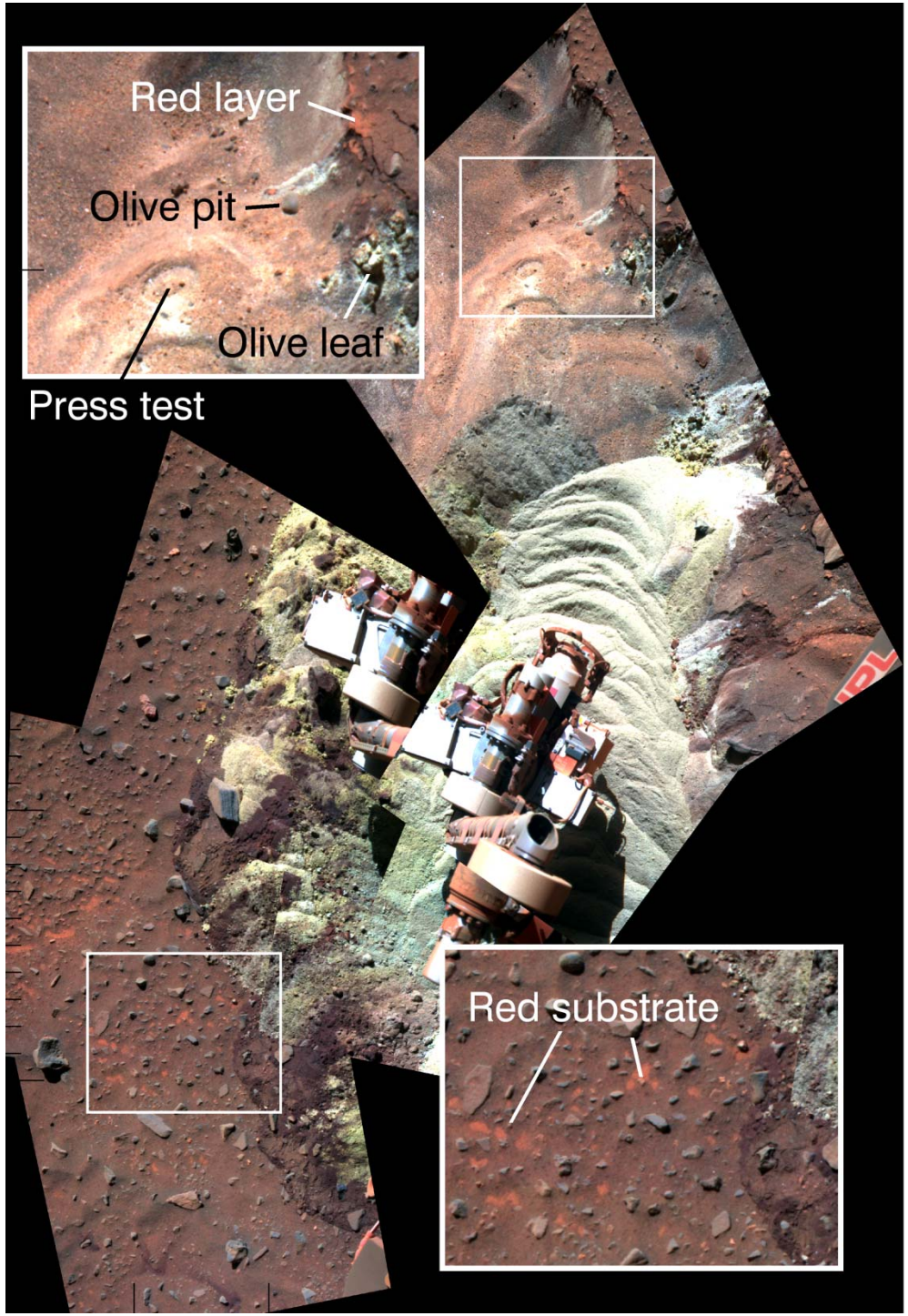
Cyclops eye RAT Holes

Sol 1906

Sol 1967

Sol 1990

Pancam
False color mosaic after IDD and extrication efforts stopped for winter



“Breast Stroke” Maneuver Moves Spirit ~35 cm over last drives

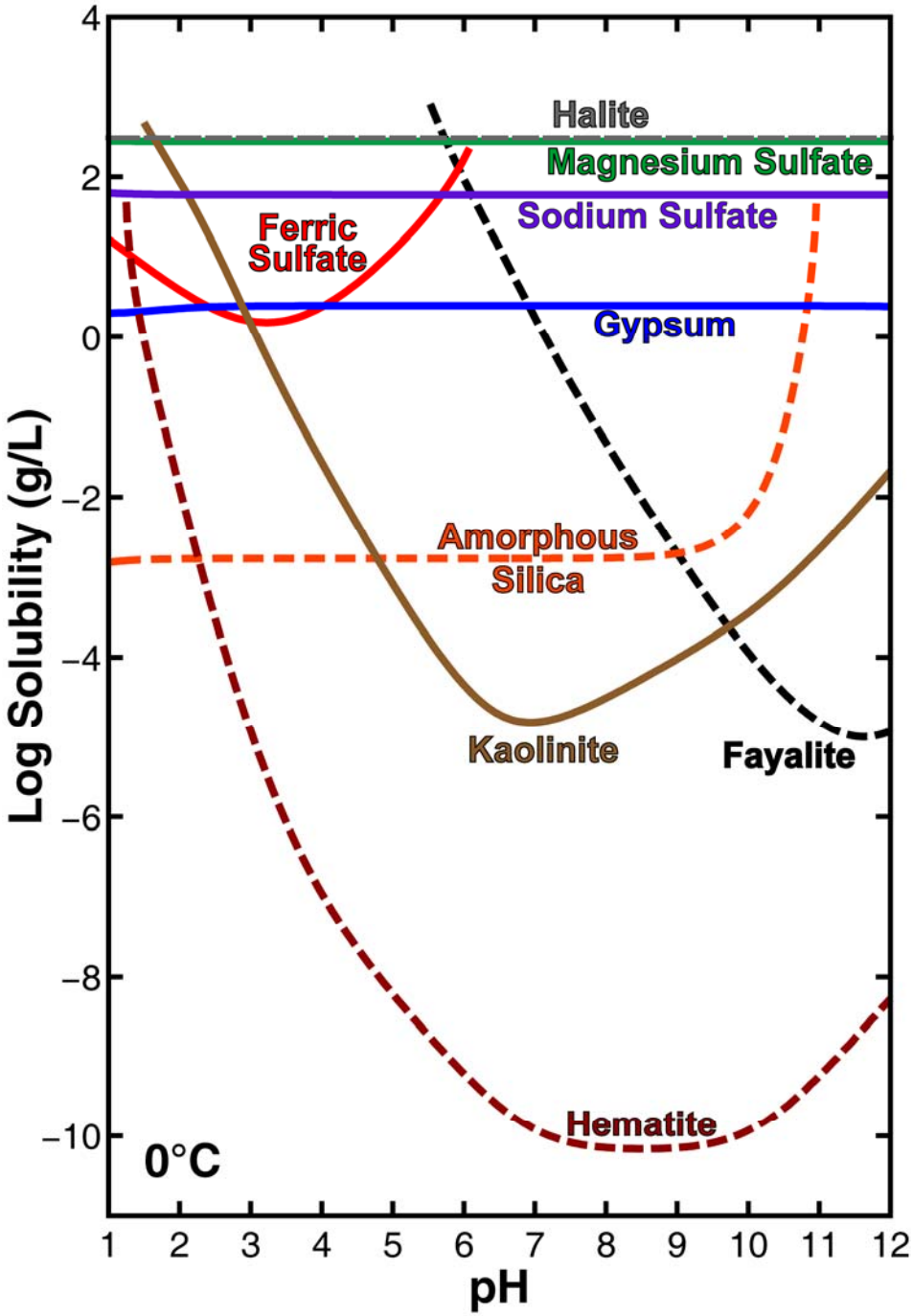
“Punch Line”

•Relatively insoluble minerals concentrated toward top of Troy soil section with ferric sulfate “lenses”

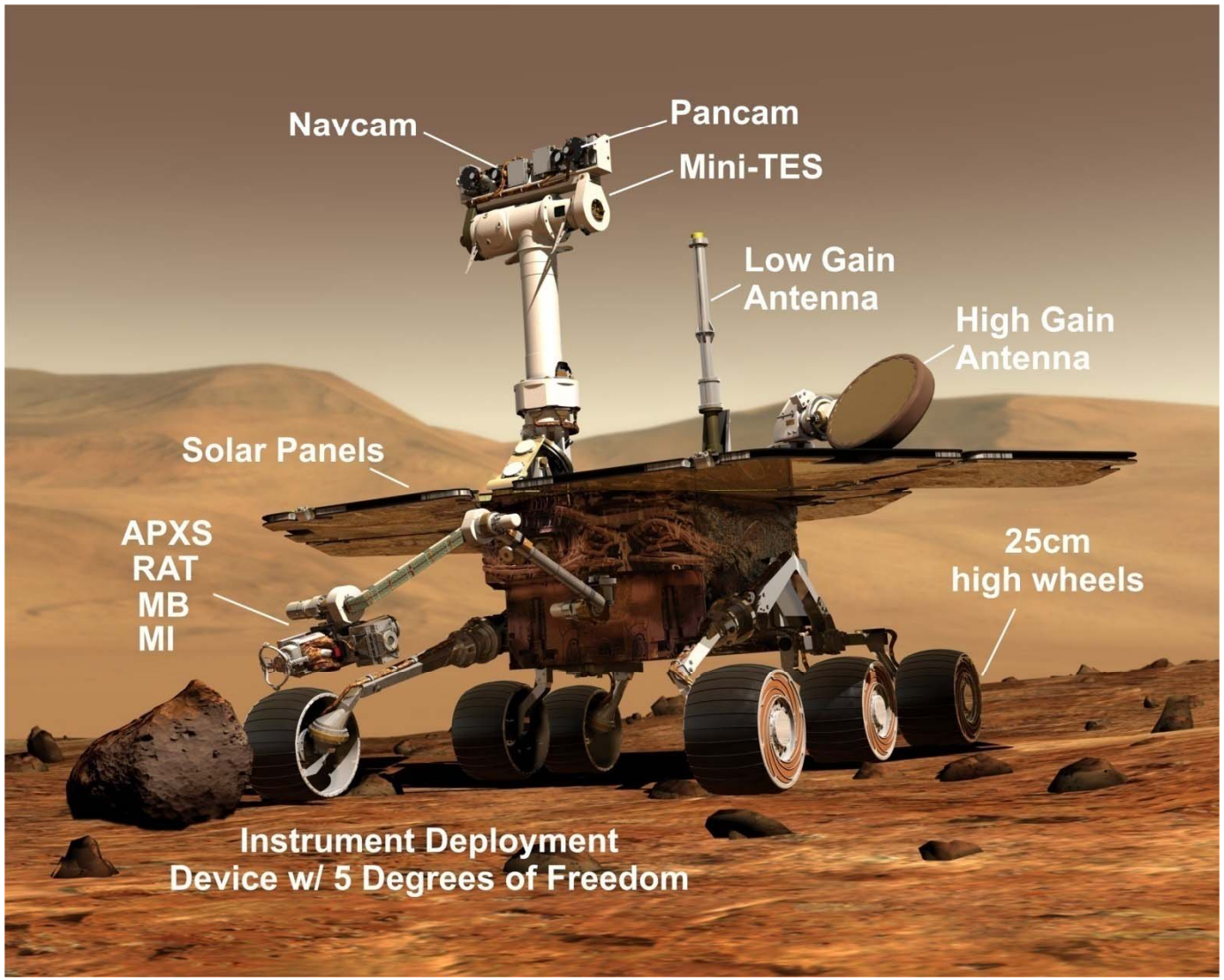
•Generate sulfates during Inner Basin volcanic period

•Wind erosion and transport mix sulfates and basaltic materials, e.g., infilling Scamander Crater

•On-going wetting (frosts, snowpack) moves soluble species down-section, without complete re-equilibration



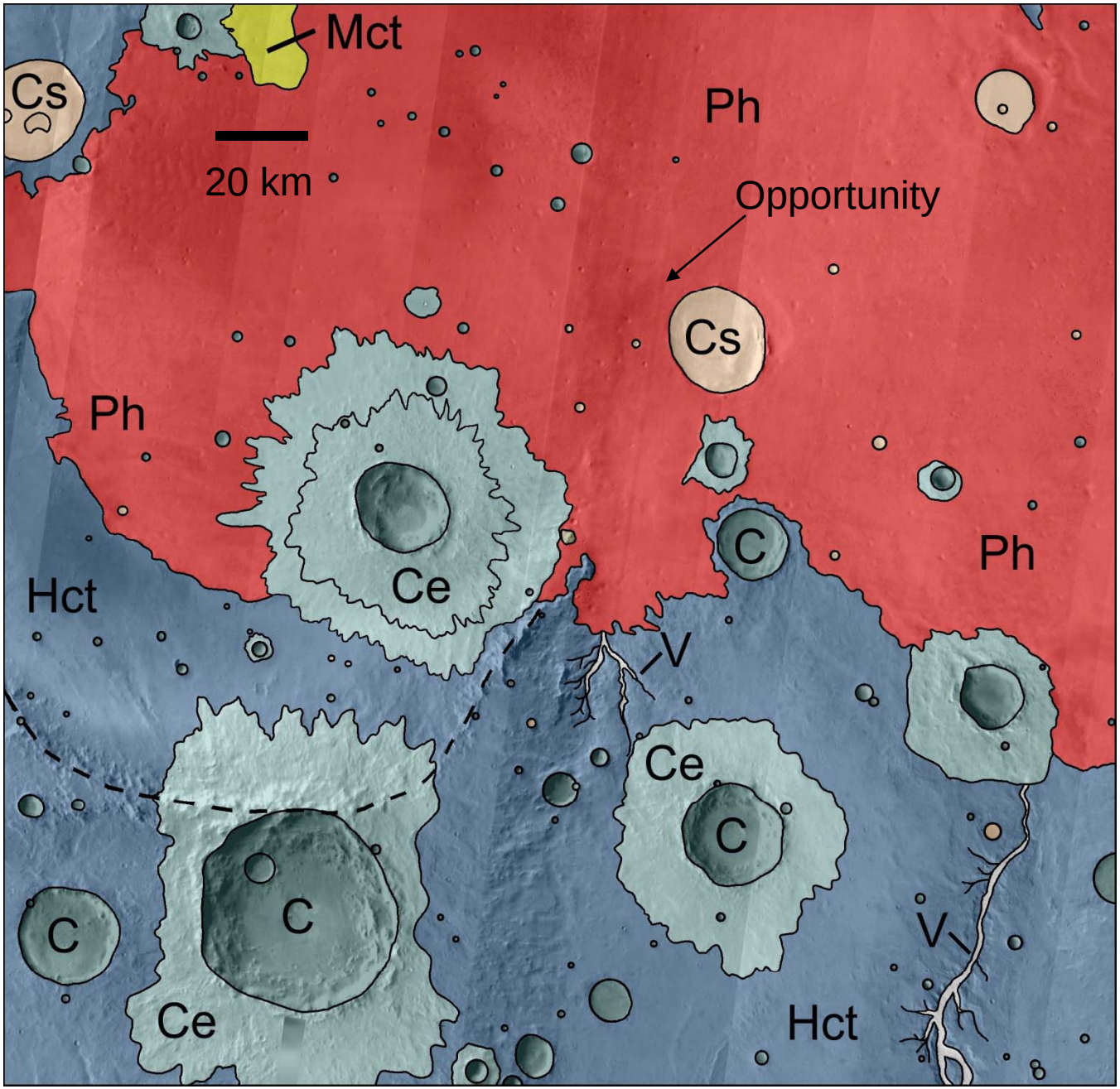
Opportunity Rover



- Right front wheel left rotated ~8 deg inward when azimuthal actuator failed

- Shoulder IDD actuator failed so driving uses "fishing stow" and have limited deployment work space

- Mini-TES no longer responding

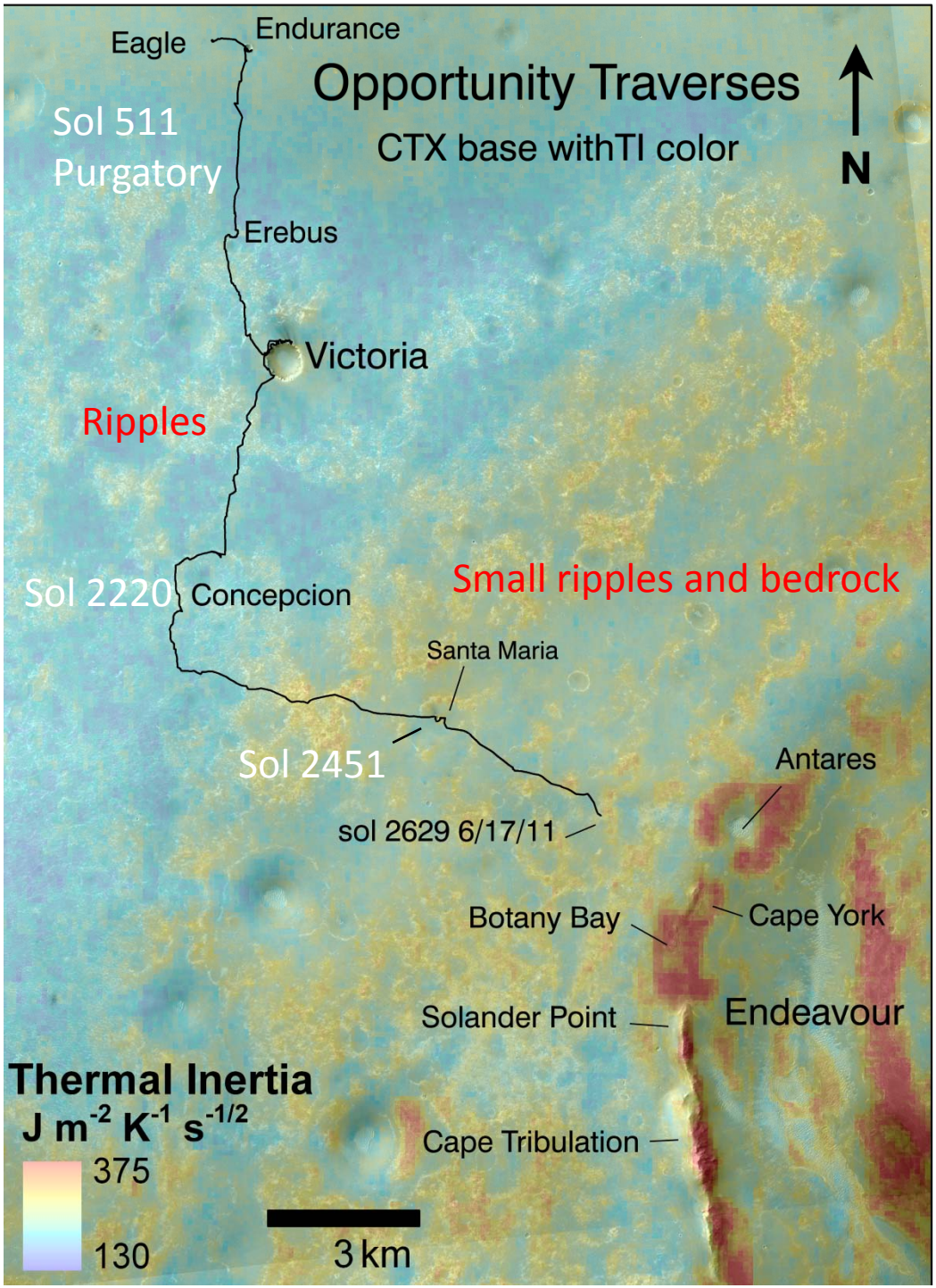


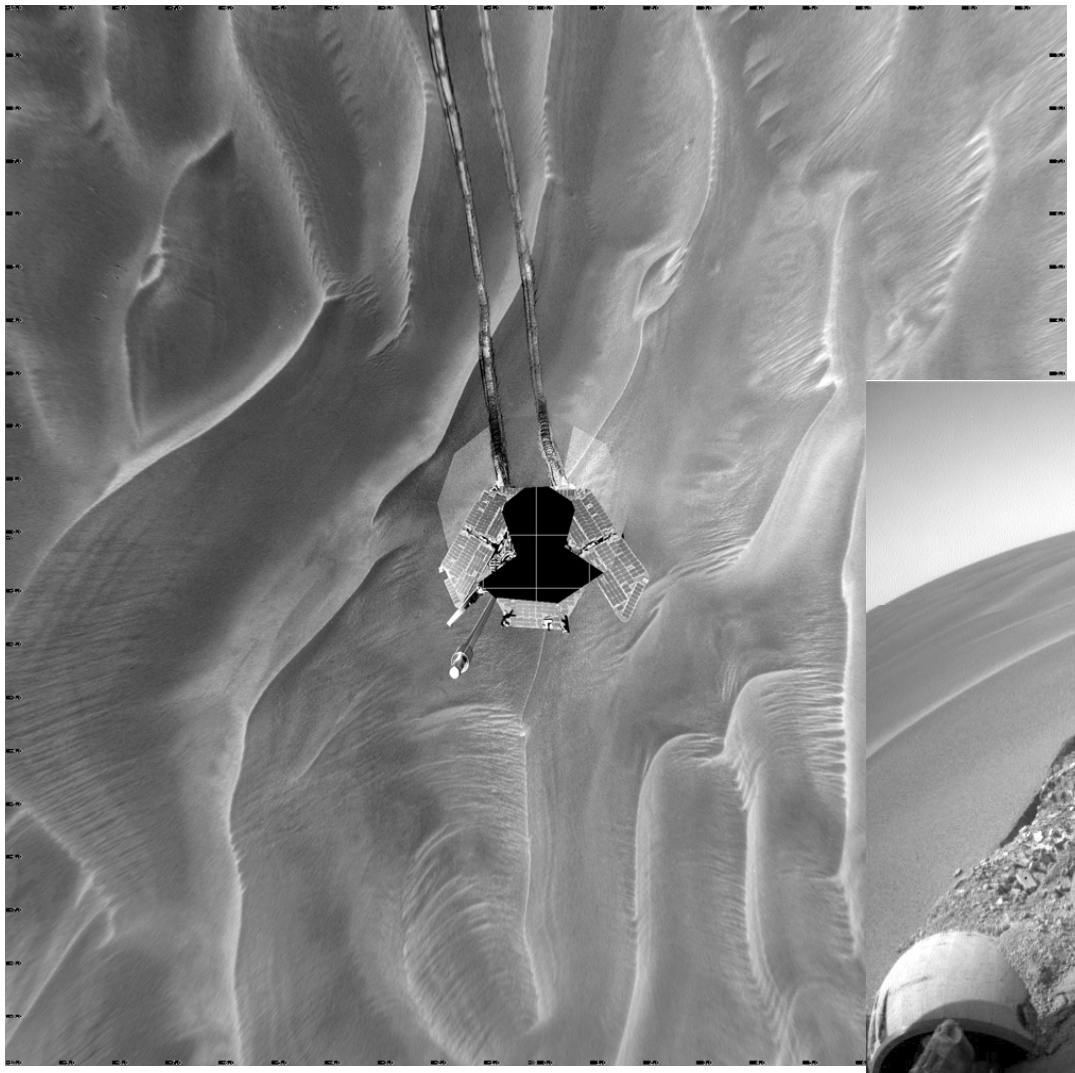
Units & Symbols

- C — Crater
- Ce — Crater ejecta
- Cs — Crater, subdued
- Ph — Hematite-bearing Plains
- V — Valley
- Hct — Cratered Highlands
- Mct — Mantled Terrain
- – – – Ridgeline trace

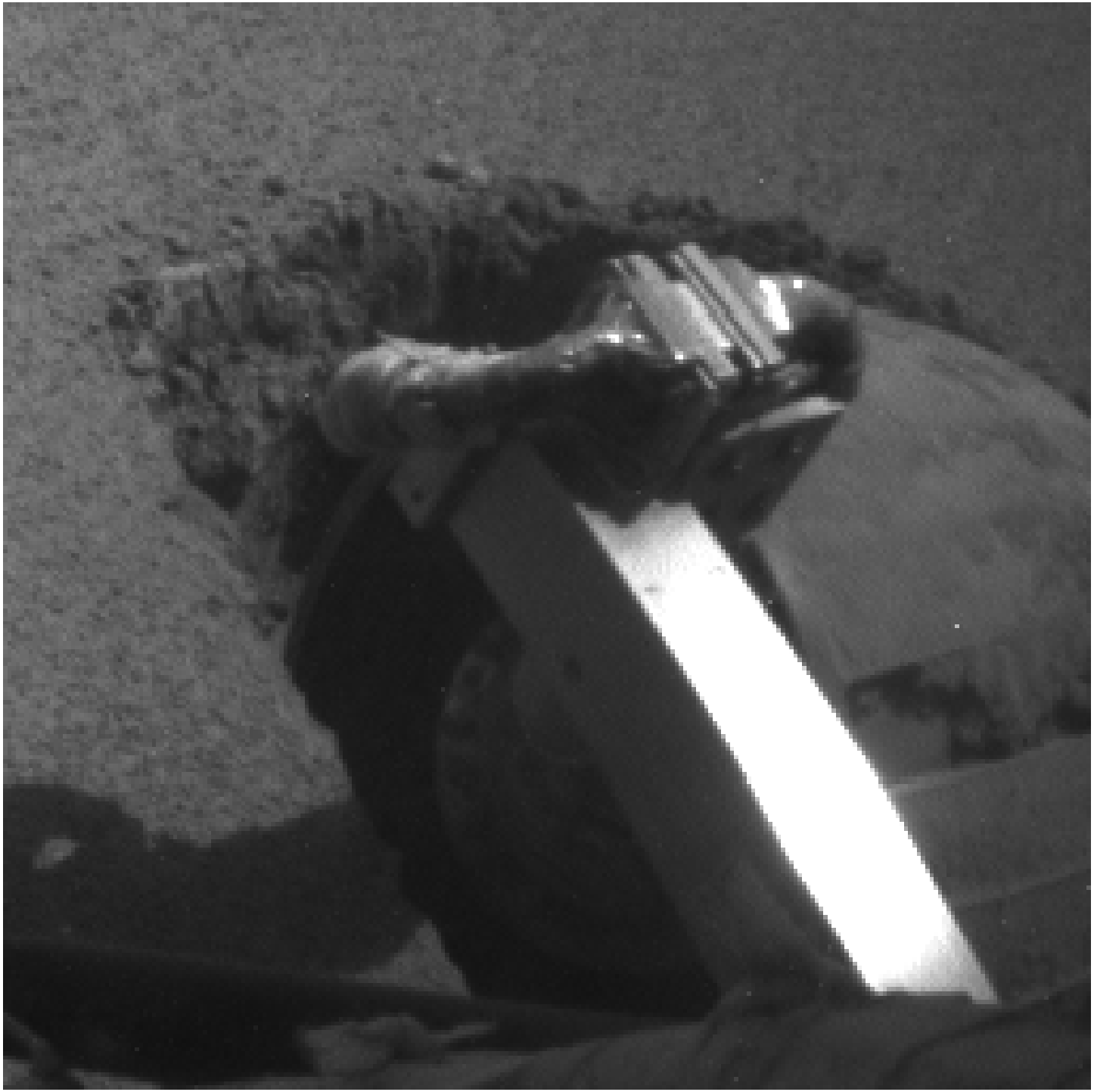
Thermal Inertia

- Predawn THEMIS thermal IR observations used to derive thermal inertia:
  - $TI=(K\rho c)^{1/2}$
  - K=thermal conductivity
  - ρc = heat capacity
  - Values indicate dominance by soil cover for Mars
- Integrated effect over thermal skin depth (cm's)
  - $\text{Skin depth}=K/\rho c\ (P/\pi)^{1/2}$
  - P=period of observation, typically diurnal

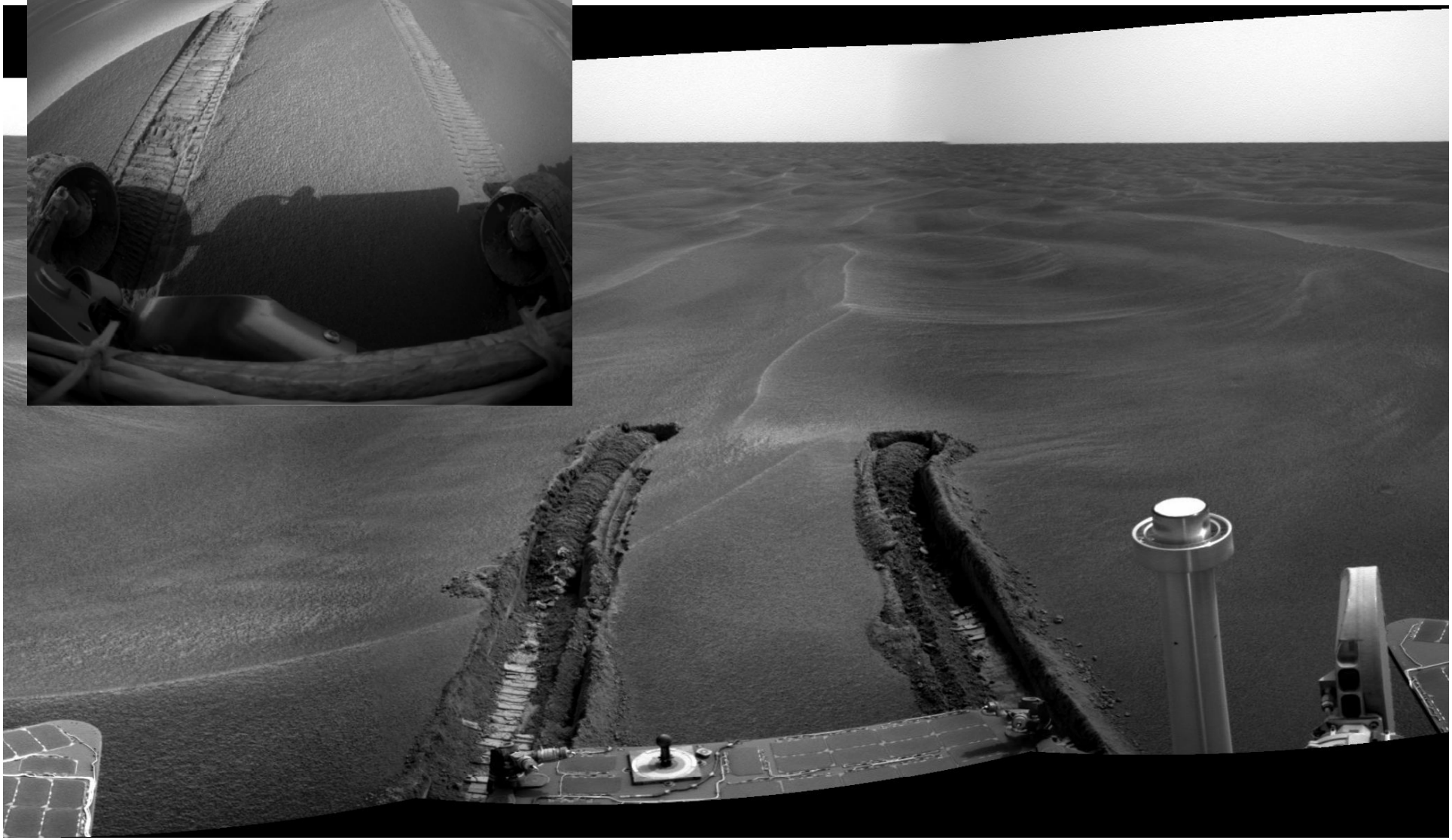

Opportunity Traverses
CTX base withTI color
N
Eagle
Endurance
Sol 511
Purgatory
Erebus
Victoria
Ripples
Sol 2220
Concepcion
Small ripples and bedrock
Santa Maria
Sol 2451
Antares
sol 2629 6/17/11
Botany Bay
Cape York
Solander Point
Endeavour
Cape Tribulation
Thermal Inertia
J m-2 K-1 s-1/2
375
130
3 km

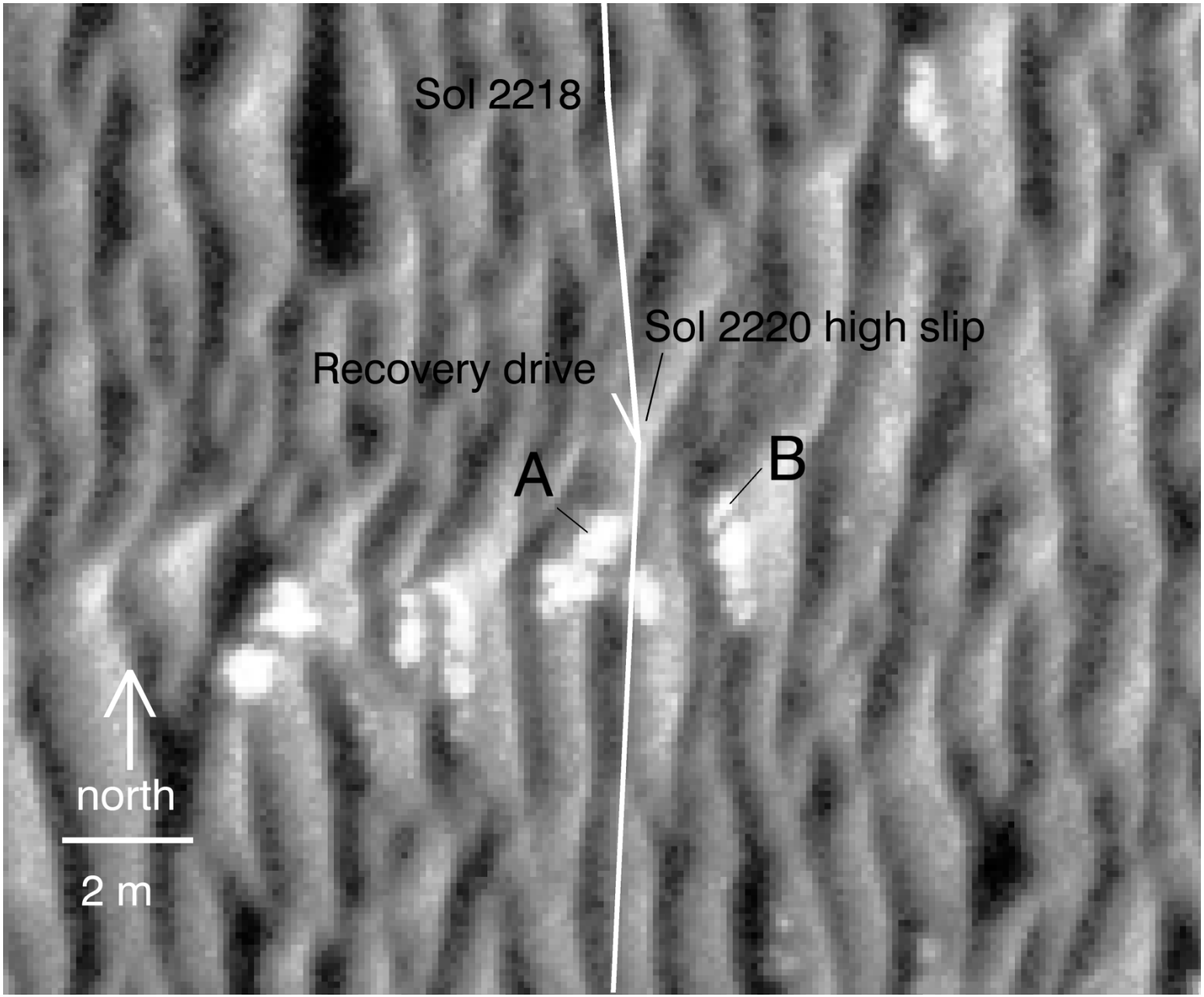


Purgatory ripple

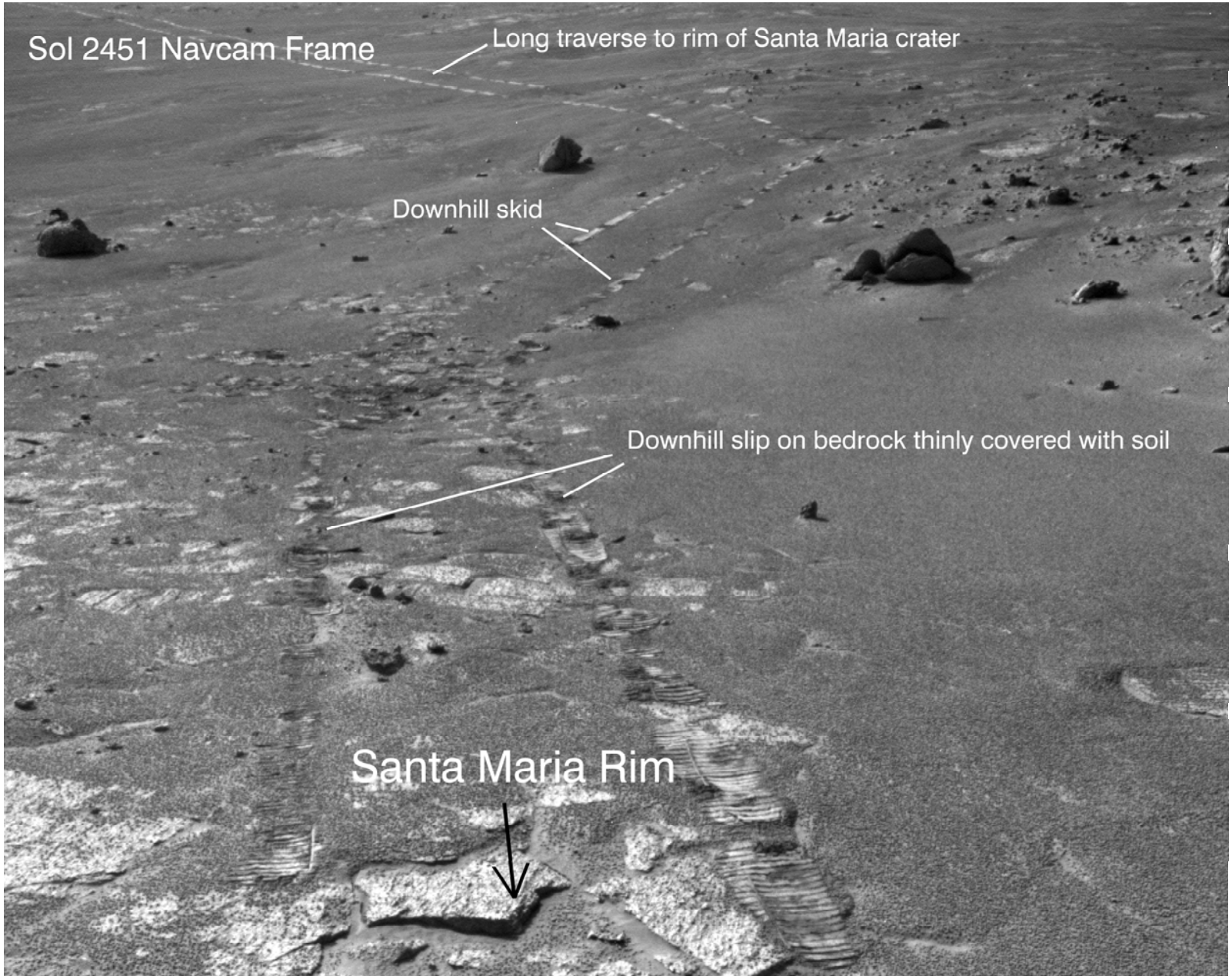


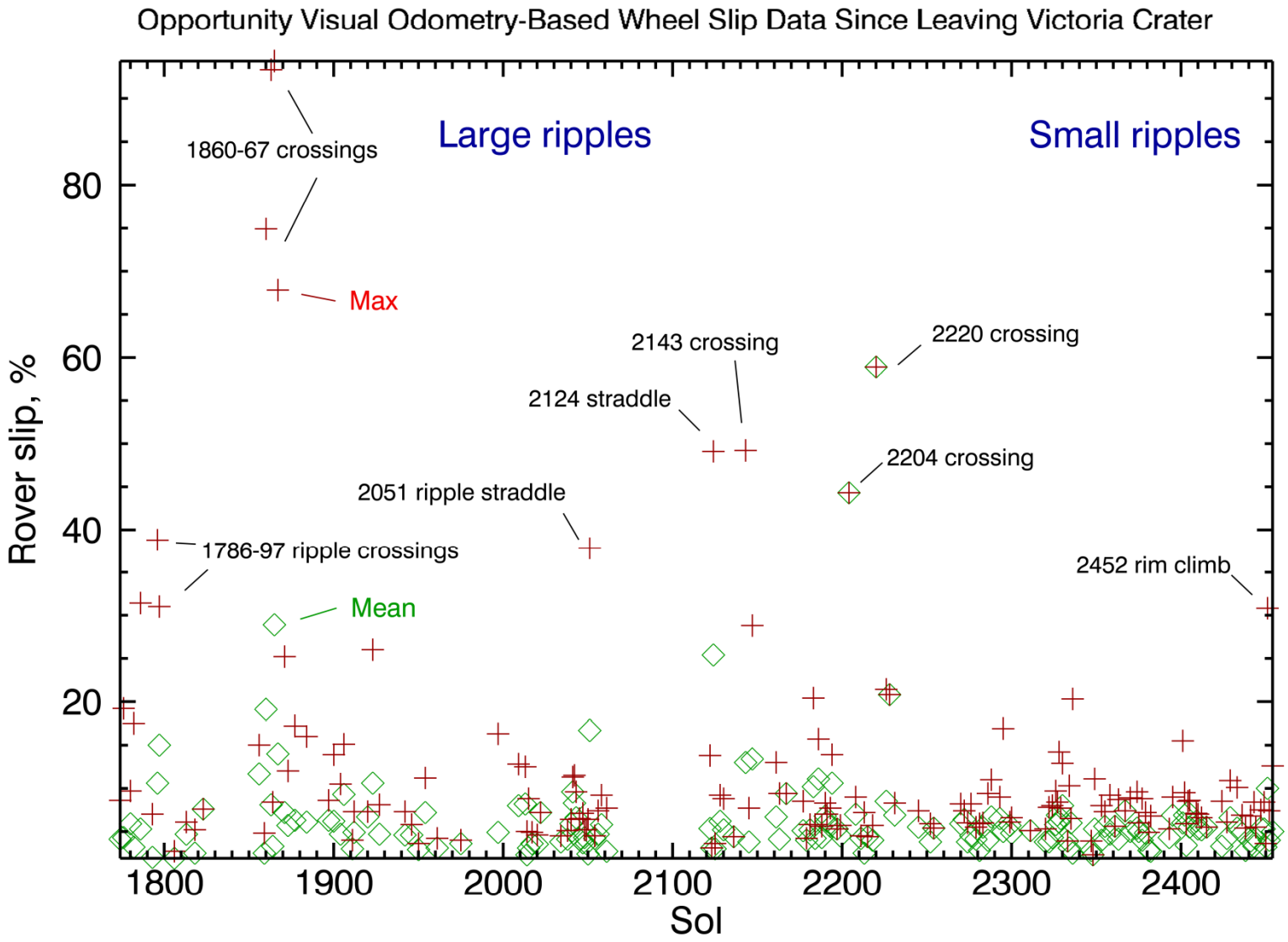
After backing out of Purgatory Ripple

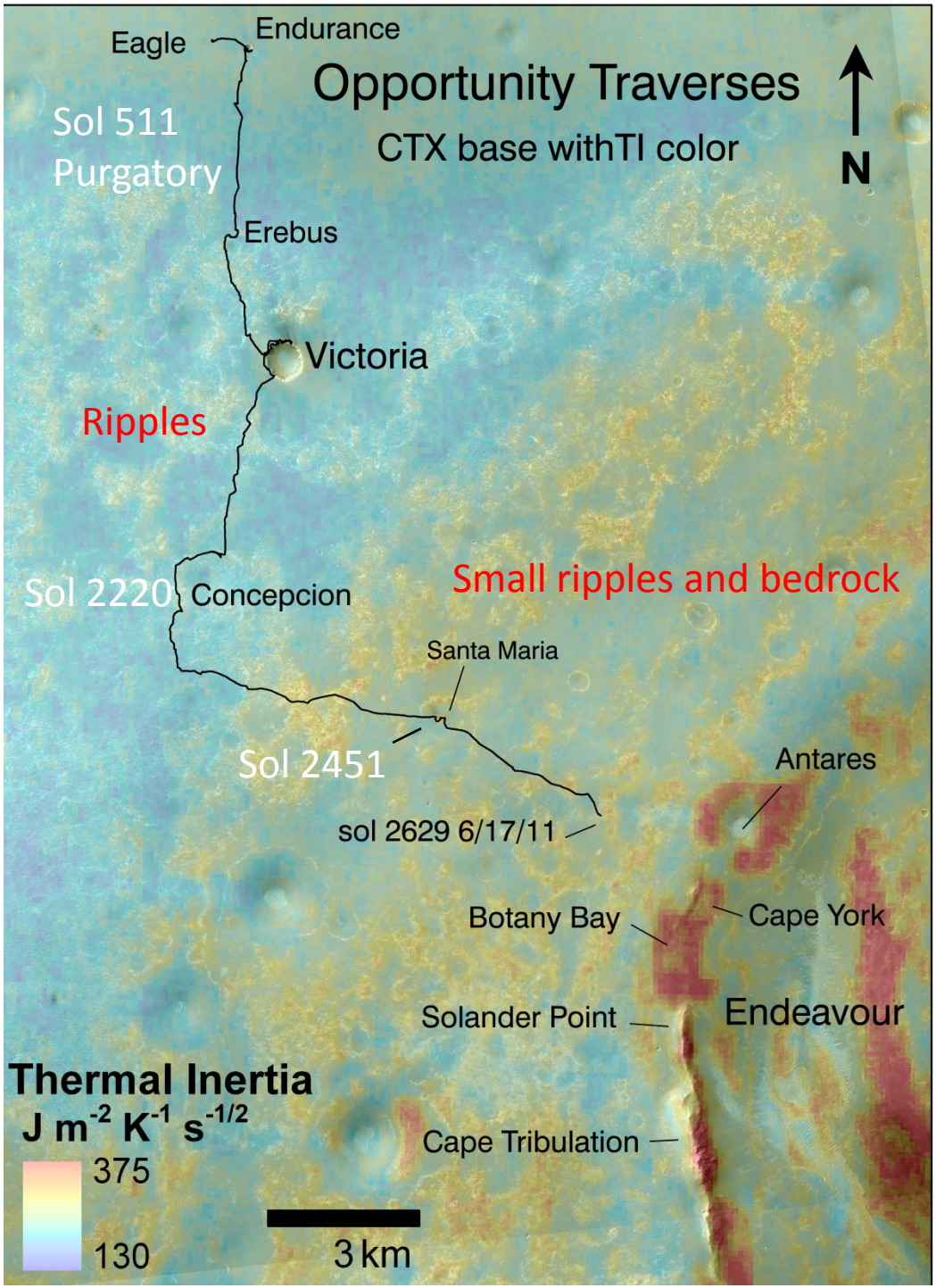


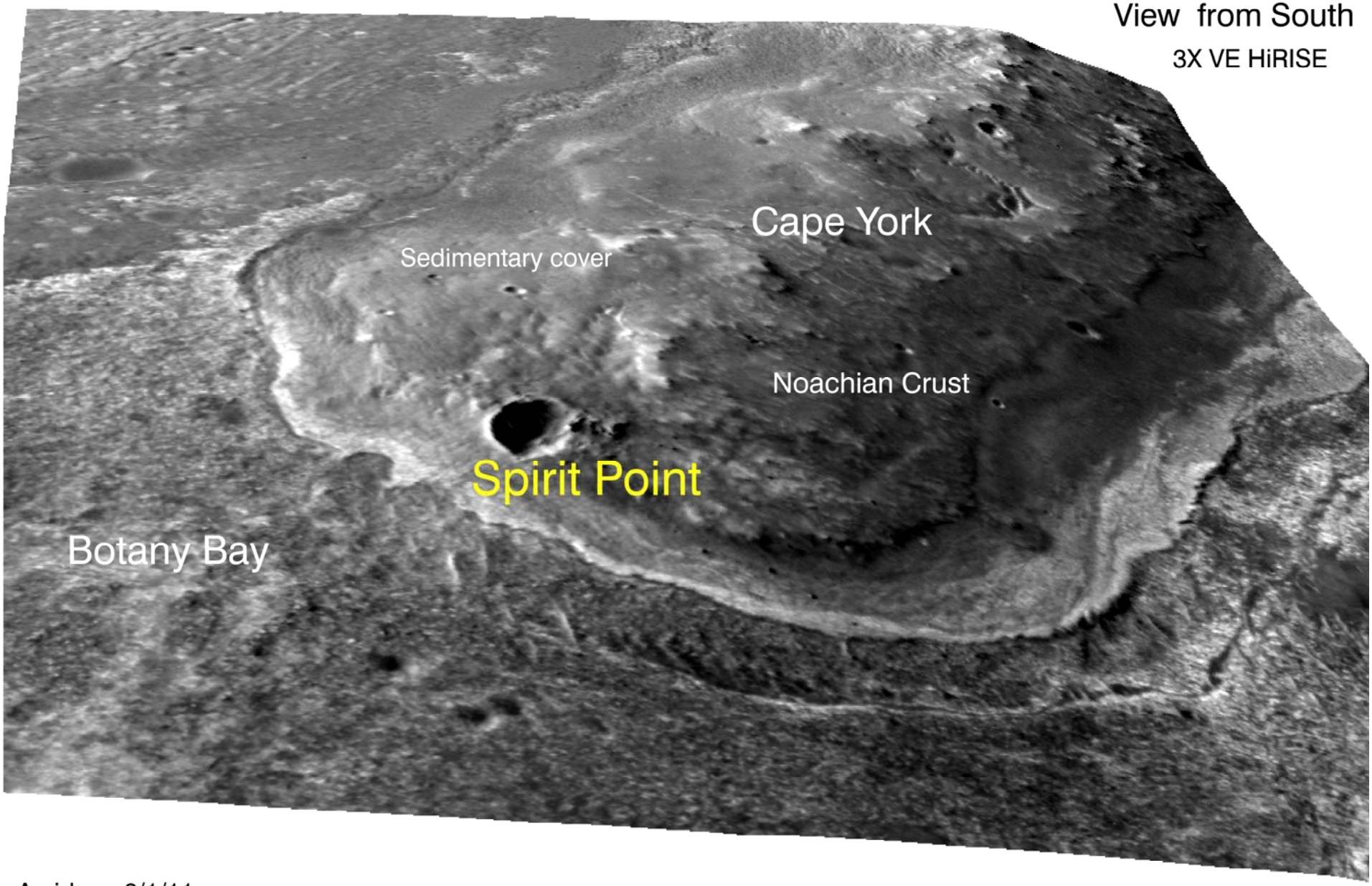

Sol 2218
Sol 2220 high slip
Recovery drive
A
B
north
2 m


Sol 2220 Ripple Slip of ~58% and sinkage of ~5 cm
B
A
Right rear wheel maximum extent
25 deg attack angle
Recovery drive tracks
Front wheel track


Sol 2451 Navcam Frame
Long traverse to rim of Santa Maria crater
Downhill skid
Downhill slip on bedrock thinly covered with soil
Santa Maria Rim


Opportunity Visual Odometry-Based Wheel Slip Data Since Leaving Victoria Crater
Large ripples
Small ripples
1860-67 crossings
Max
2143 crossing
2220 crossing
2124 straddle
2204 crossing
2051 ripple straddle
1786-97 ripple crossings
2452 rim climb
Mean
Rover slip, %
80
60
40
20
1800
1900
2000
2100
2200
2300
2400
Sol


Opportunity Traverses
CTX base withTI color
N
Eagle
Endurance
Sol 511
Purgatory
Erebus
Victoria
Ripples
Sol 2220
Concepcion
Small ripples and bedrock
Santa Maria
Sol 2451
Antares
sol 2629 6/17/11
Botany Bay
Cape York
Solander Point
Endeavour
Cape Tribulation
Thermal Inertia
J m-2 K-1 s-1/2
375
130
3 km



Arvidson 6/1/11

HiRISE image and associated DEM with OSU processing