Jet Propulsion Laboratory
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Mars Landing Site Selection

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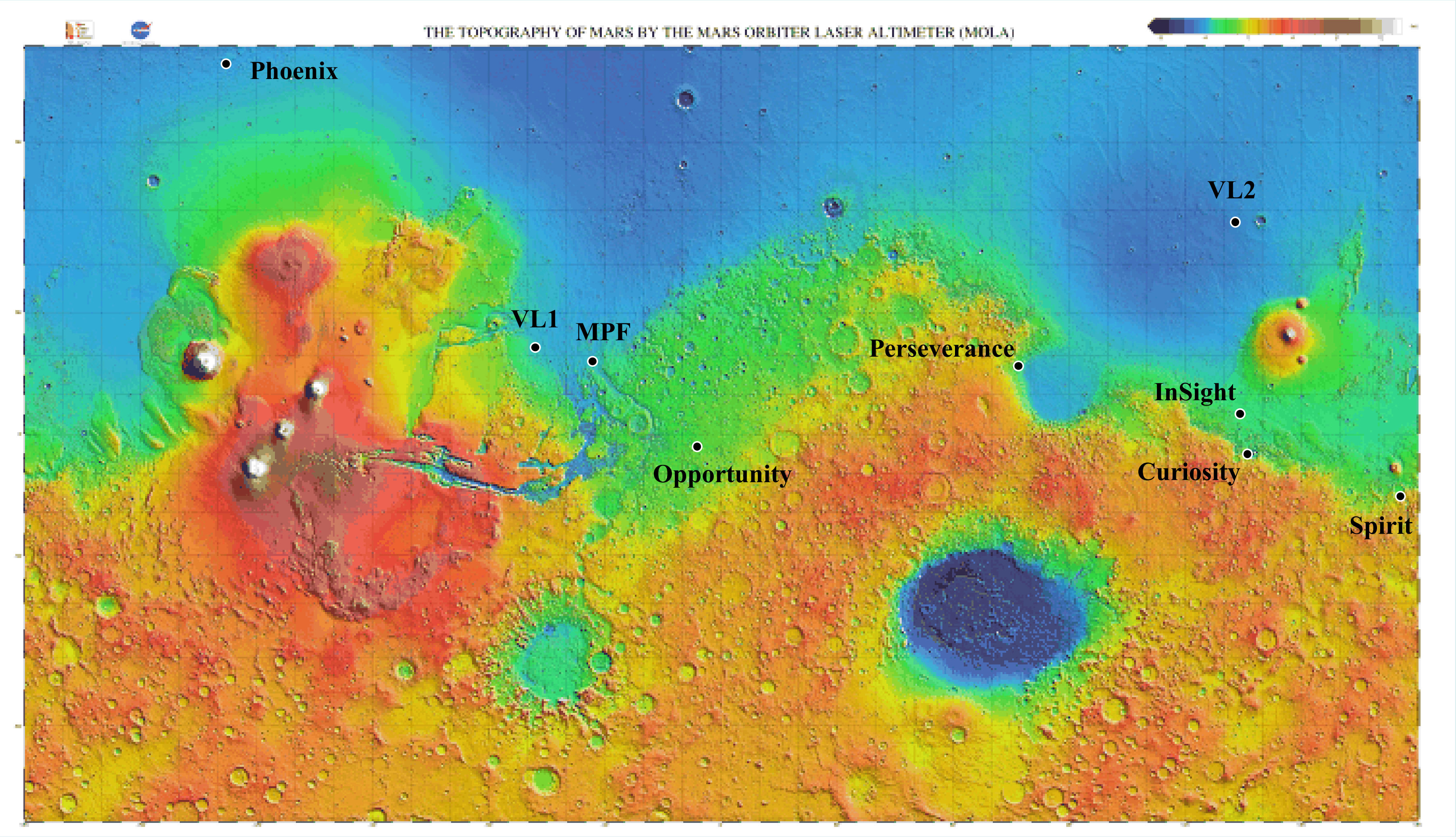
National Academy, Meeting
Committee on Planetary Protection
March 25, 2021

… Select a Landing Site?

- **Why?**
  - Because the Mission will Fail if Don’t Land Safely
  - Because the Mission Costs a Lot of Time, Energy & Money
- **When?**
  - During Project Development, Spacecraft Capabilities Change
- **How?**
  - Map Engineering Constraints onto Mars, Define Acceptable Sites
  - Gather Information to Certify Sites
- **What?**
  - Smooth, Flat “Boring” Rock Free Plain - Safe for Landing [and Roving]
  - Address Science Objectives of Mission, Complies with Planetary Protection
- **~7 Selection Efforts in Modern Era – Past 30 Years**
  - MPF – Educated Guess – Highest Res Images could ID Stadium
  - MER – Targeted MGS MOC - 3 m/pixel images
  - PHX – “what you can’t see can hurt you” – 25 cm/pixel HiRISE Images
  - MSL – No Surprises
  - InSight – No Science Requirements, 5 m of fragmented material
  - M2020 – Avoid Hazards, Collect Samples
- **Remote Sensing Predictions Generally Correct**
  - Physical Properties/Engineering Constraints Correctly Predicted
  - Science aspects mostly correct
  - Planetary Protection compliant

Landing Sites on Mars



Latitude & Elevation – Low & Equatorial

Process

- **Project Led Activity**
  - Project Organizes/Leads Activity
  - Can be Project Scientist, Co-I, EDL Engineer …
  - Develops Engineering Constraints
  - Coordinates with Project Scientist and Science Team (lead science aspects)
- **Council of Terrains, Council of Atmospheres**
  - Groups of Experts Characterize Surface and Atmosphere
  - Critical Data Products Announcement of Opportunity
- **NASA Landing Site Steering Committee**
  - Open Landing Site Workshops (4-5 over 3+ years)
  - External Science Community Members
  - Discuss Science (mostly) of Sites – Provide Input
- **Progressive Downselection of Sites**
  - Start with broad call for Sites
  - Gather Remote Sensing Data of Sites (especially high-resolution images)
  - Downselect based on Safety and Science Priority
- **Selection of Landing Site**
  - Includes Planetary Protection Review and Acceptance
  - NASA Associate Administrator for Space Science
  - PI of Competed/Discovery Mission

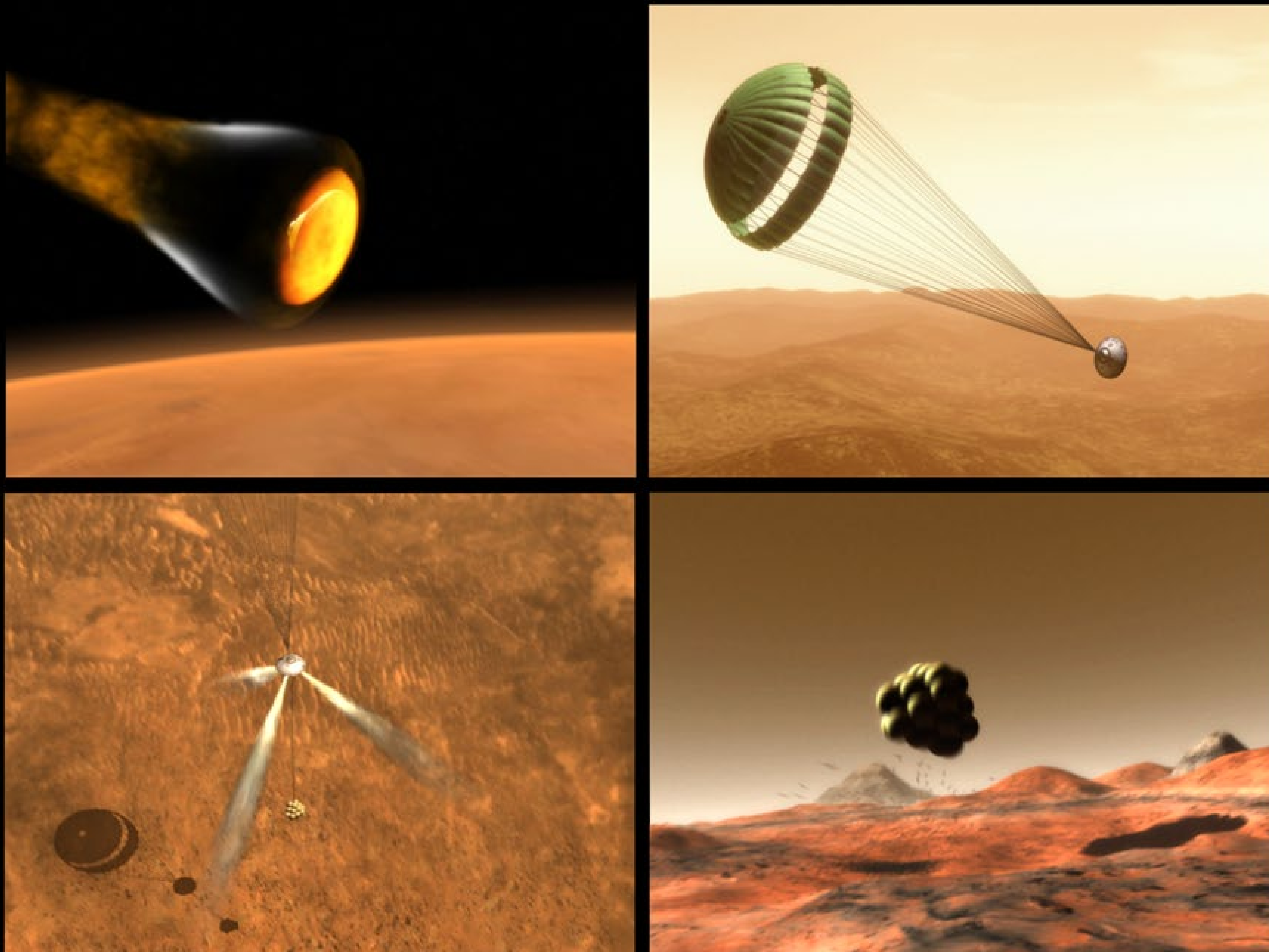
Outline

- **Engineering Constraints**
  - Elevation, Latitude & Ellipse Size
  - Topography/Slopes, Physical Properties, Rocks
- **Science**
  - Science Objectives of Mission
  - Instruments, Observations, Measurements
  - Geology, Setting, Features, Deposits, Rocks
  - Accessed during traverse
- **Planetary Protection Requirements**
  - Spacecraft designated Category IVa
  - No Life Detection, Not bound for Special Region
  - Interactions during project & Planetary Protection Review

Engineering Constraints

- Requires close collaboration between engineers and scientists
- Engineers design and build spacecraft
  - May have limited knowledge about Mars
- Scientists know about Mars
  - Must translate engineering constraints to Mars
  - Must define the environment
- What makes spacecraft fail?
- What is safe?
- How do measure it on Mars?

MER EDL

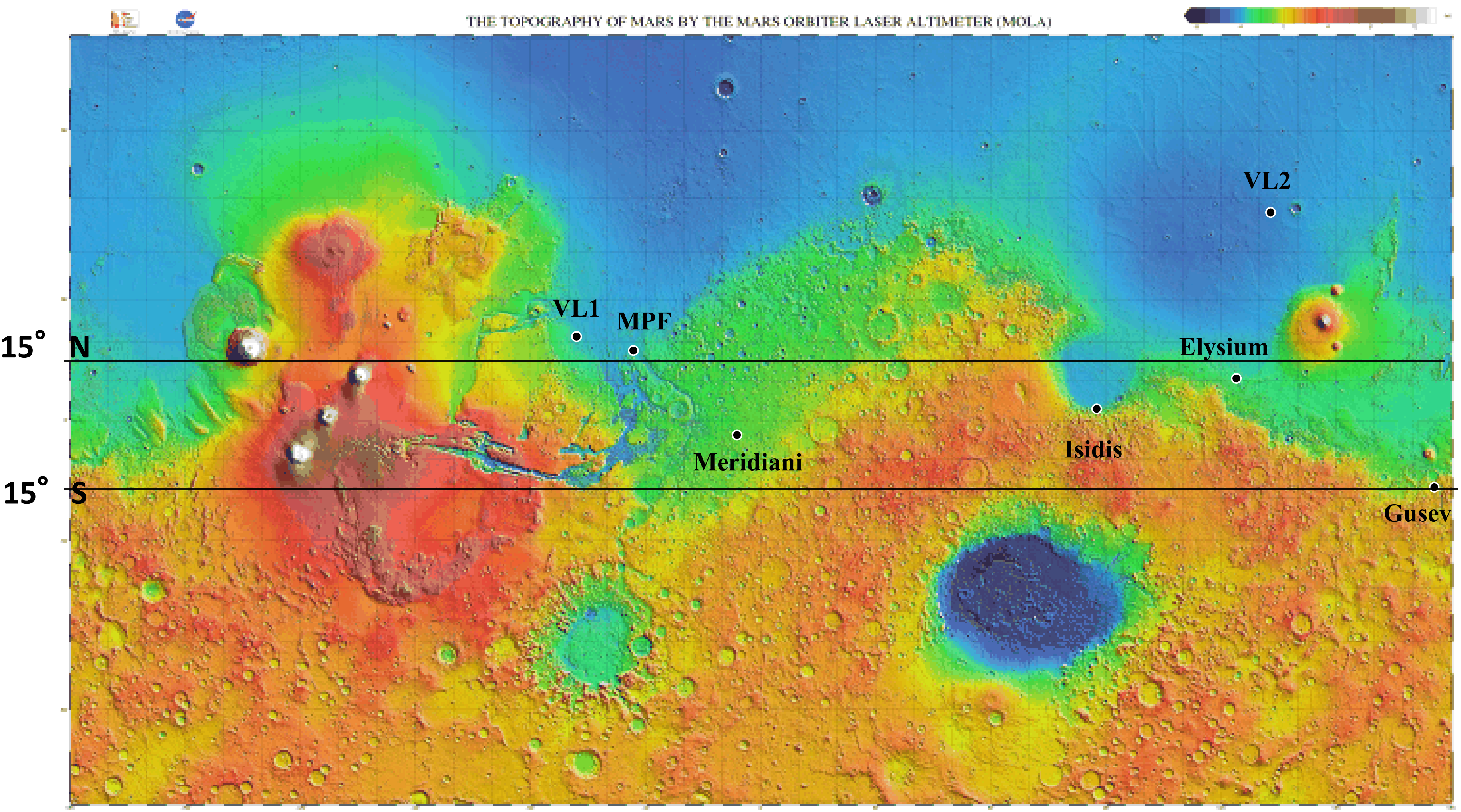


Preliminary MER Engineering Constraints

- **ATMOSPHERE - ELEVATION**
  - Must be <-1.3 km [wrt MOLA geoid] for Parachute
  - Atmospheric Column Density, Low-Altitude Winds <20 m/s
- **LATITUDE 5° N TO 15° S for MER-A and 15° N to 5° S for MER-B**
  - Solar Power, Temperature, Thermal Management, Sub-Solar Latitude; 37° Lander Separation
  - Ellipse Size and Orientation, Lat. Dep. – Varied w/simulations
- **ELLIPSE SIZE**
  - **340 to 80 km by 30 km**
- **SURFACE SLOPES <6° RMS (<15°)**
  - Mesa Failure Scenario; Radar Spoof; Lander Bounce/Roll; Rover Deploy; Power; Later <2° at 1 km; <5° at 100 m; <15° at 3-10 m
- **ROCKS**
  - <1% Area Covered by Rocks >0.5 m High for Landing
  - Athena Rover Trafficability - Total Rock Abundance of <20%
  - Athena Wants Rocks – It is a Rock Mission
- **DUST**
  - Must Have Radar Reflective Surface – Descent Altimeter
  - Load Bearing and Trafficable Surface
  - Reduce Lifetime, Coat Solar Panels, Rocks & Instruments

Golombek et al. 2003

MER Landing Sites on Mars



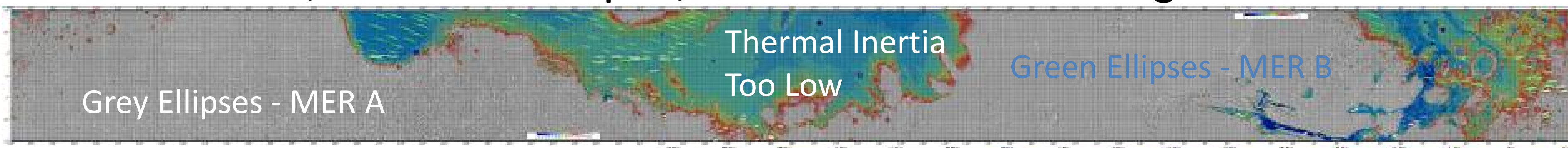
±15° Latitude, Below -1.4 km Elevation

Golombek et al. 2003

MER Landing Sites

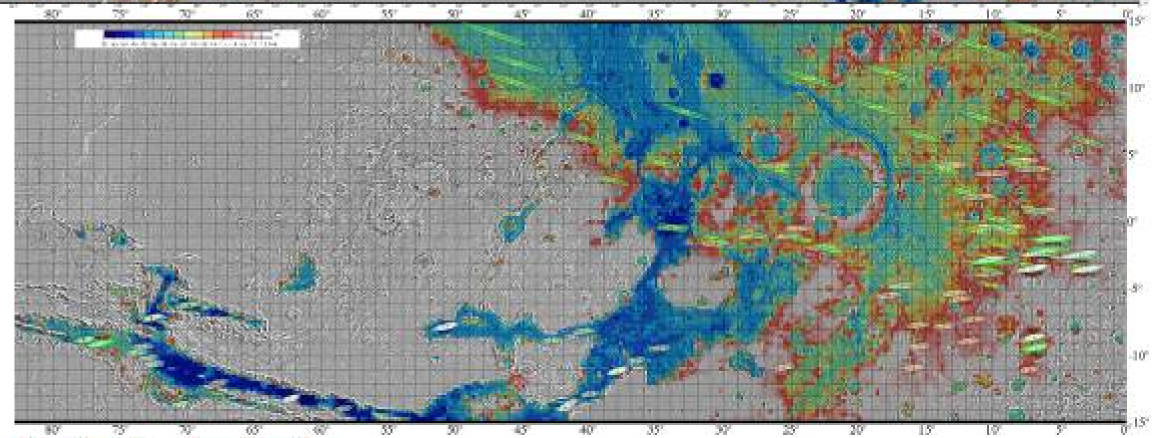
±15° Latitude Band, <-1.3 km Elevation; ~5% of Surface

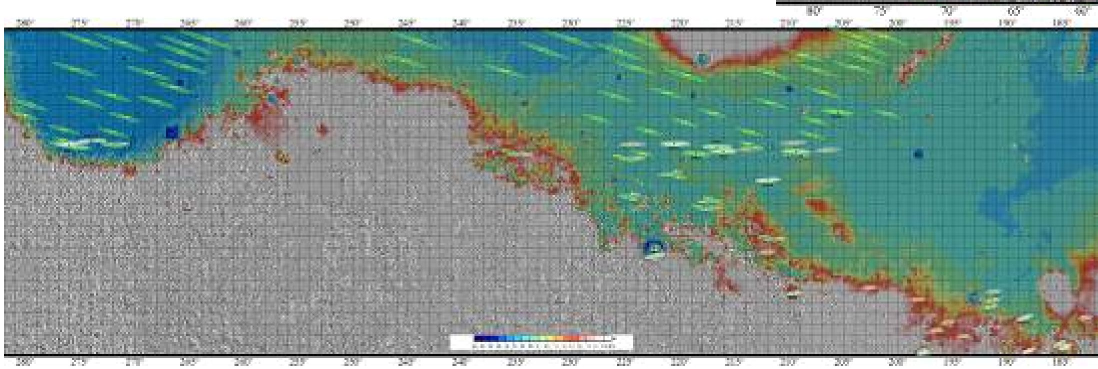
Smooth, Flat Over Ellipse, ~155 Possible Landing Sites



Western Hemisphere

Hematite, Melas, Eos





Eastern Hemisphere

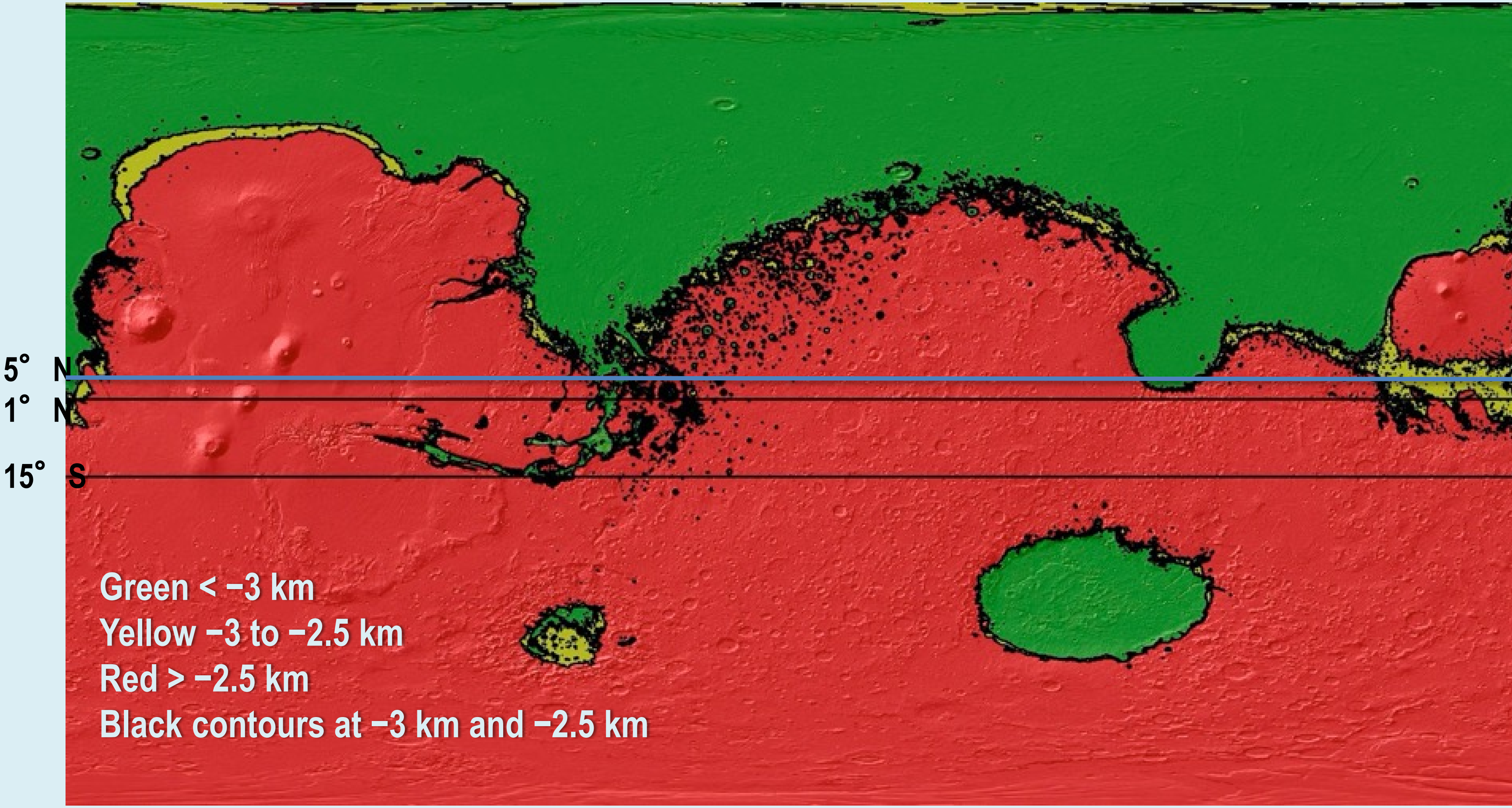
Gusev, Gale

Athabasca, Isidis

Low Wind Elysium

Number of Ellipses Scales with Size

Global Latitude and Elevation - InSight

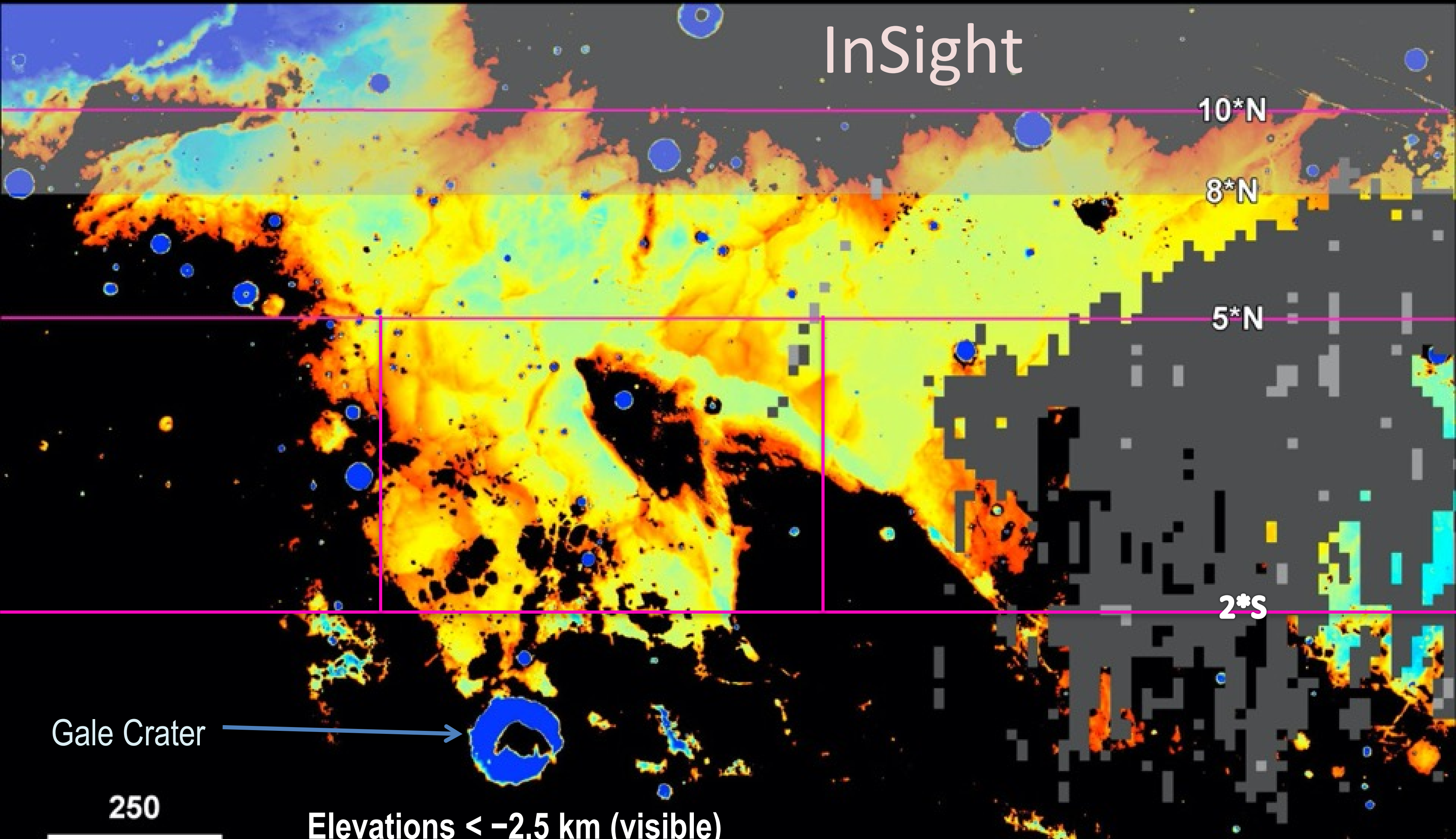


Valles Marineris & S Chryse Outflow
S Isidis Planitia
Both Rocky
Elysium

Expect S Chryse and Isidis Windy
GCMs Storm Tracks High N Lat.
Valles Marineris Canyons Windy
S Elysium Low Winds

Golombek et al. 2017

Elysium Planitia Elevation, Latitude & Thermal Inertia



Elevations < −2.5 km (visible)
Thermal inertia < 100 $Jm^{-2}K^{-1}s^{-1/2}$ (light gray mask)
Thermal inertia <140 $Jm^{-2}K^{-1}s^{-1/2}$ (dark gray mask)

Golombek et al. 2017

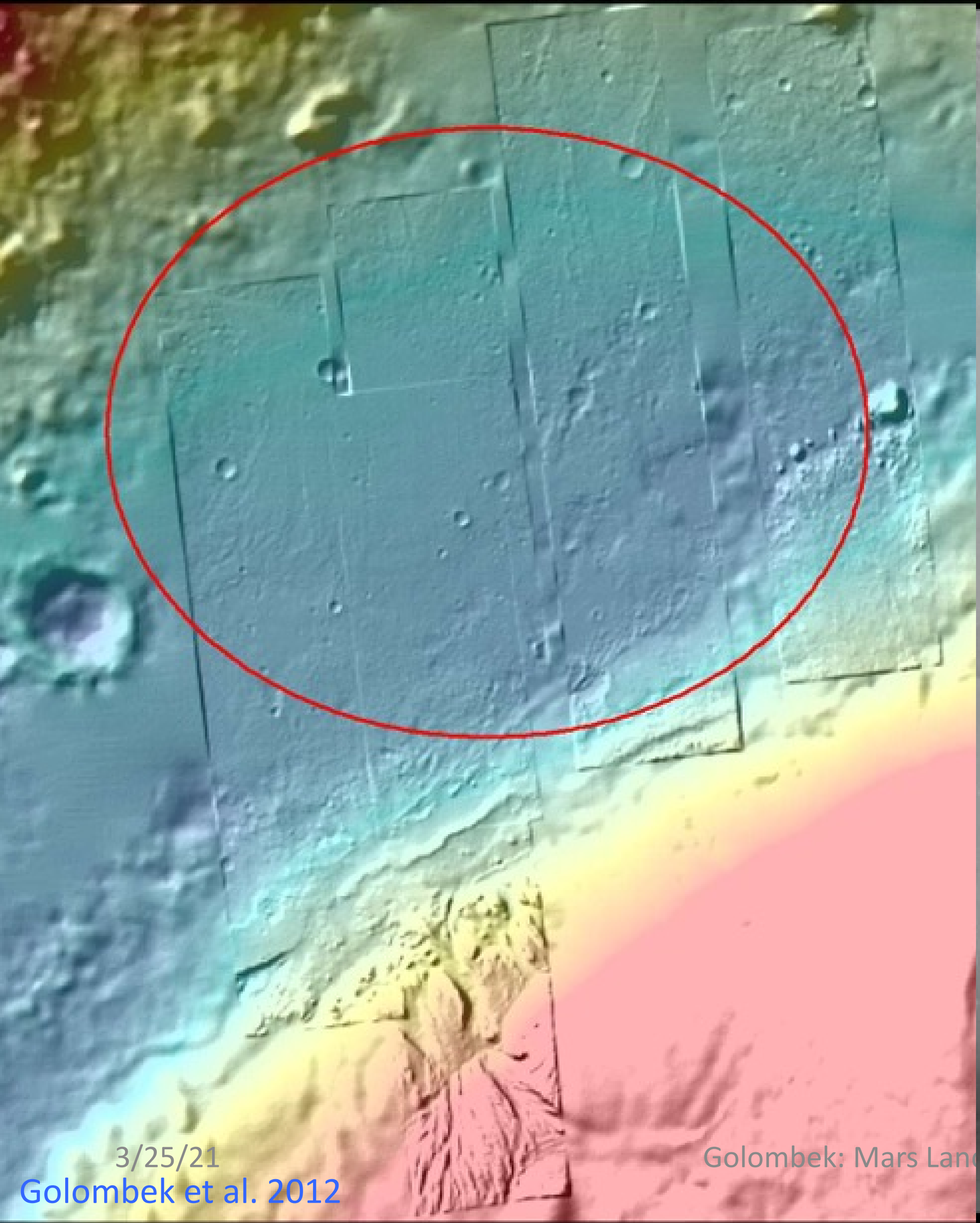
Topography

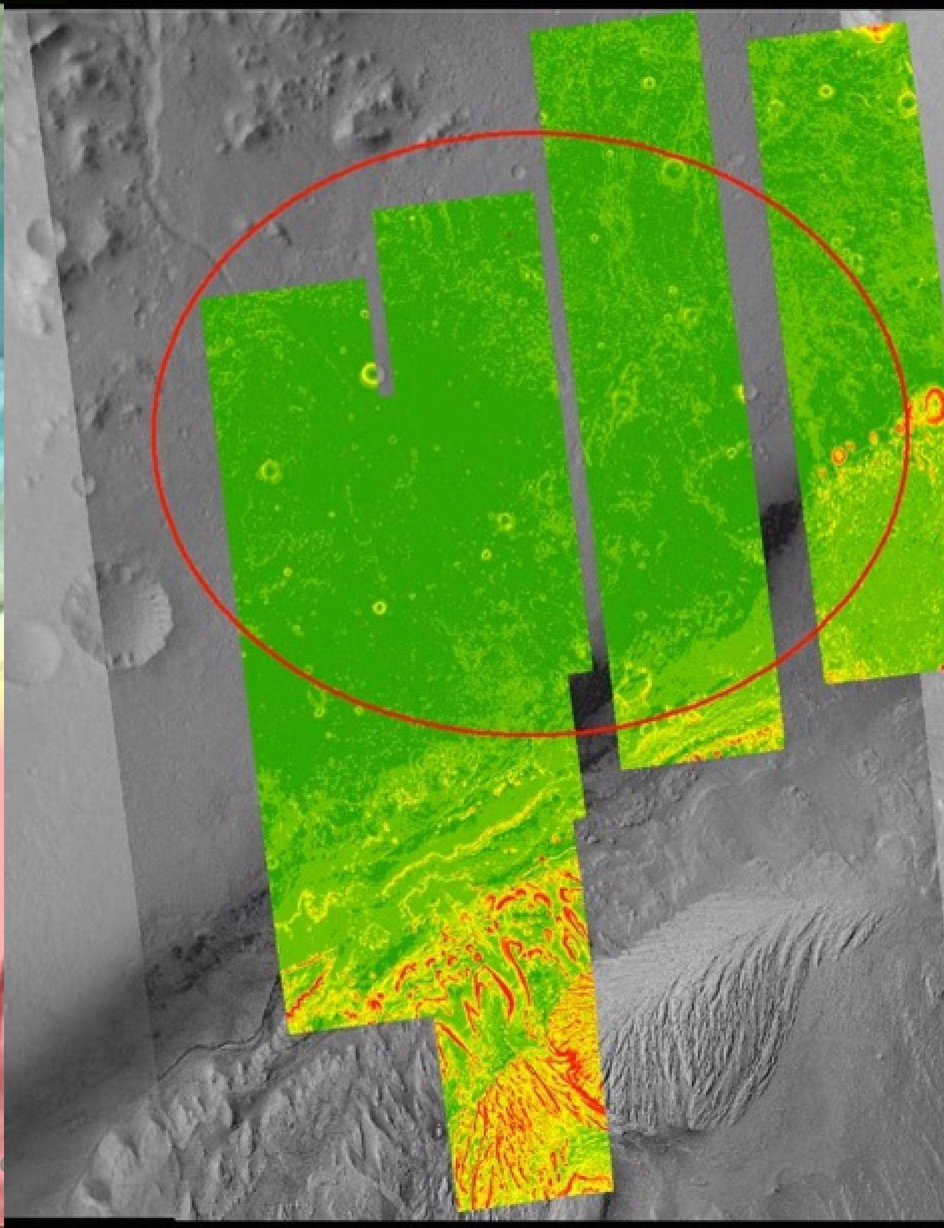
Thermal Inertia

Rocks

Gale Topography & Slope

Hierarchically georeferenced MOLA (km), HRSC (50 m), CTX (20 m), HiRISE (1 m)





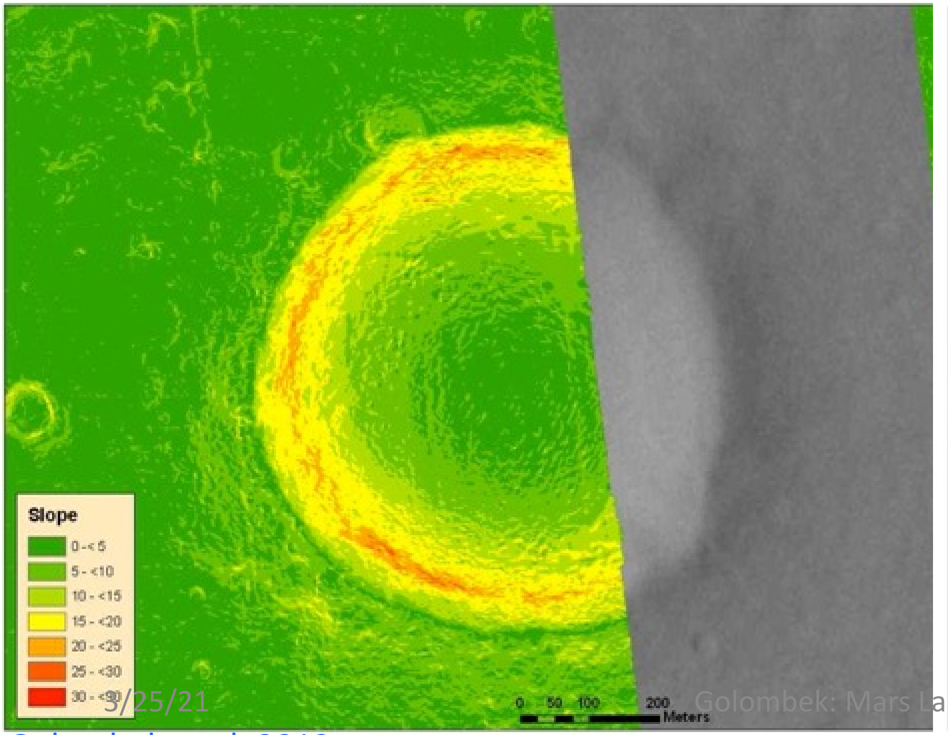
Golombek et al. 2012

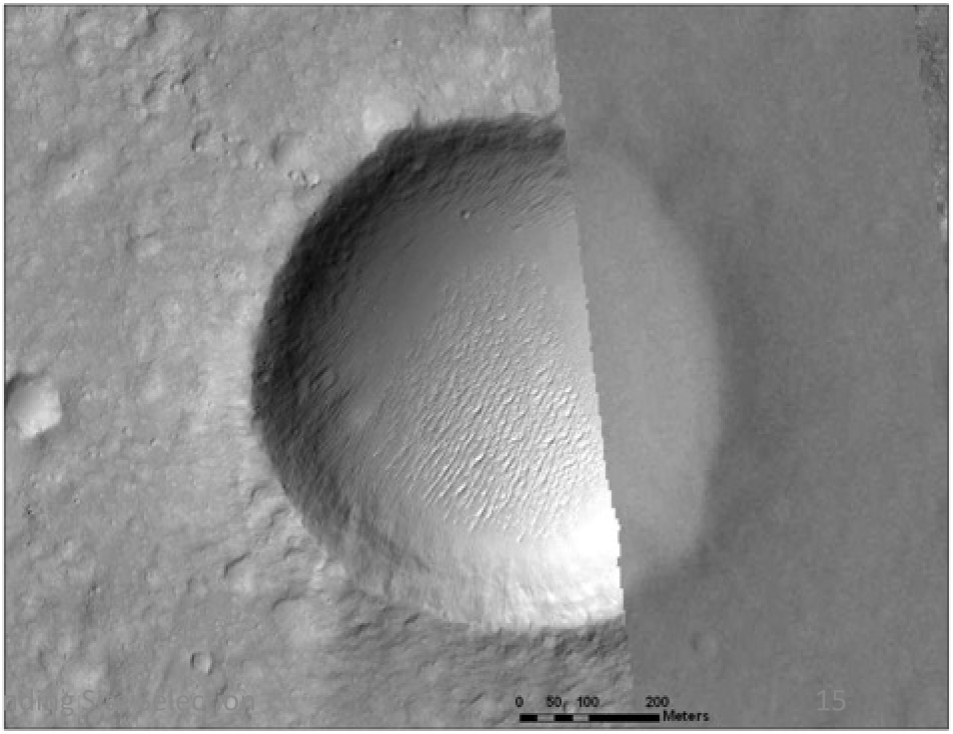
Gale ID. 2

Land Safely Inside Crater
Could not Get Out

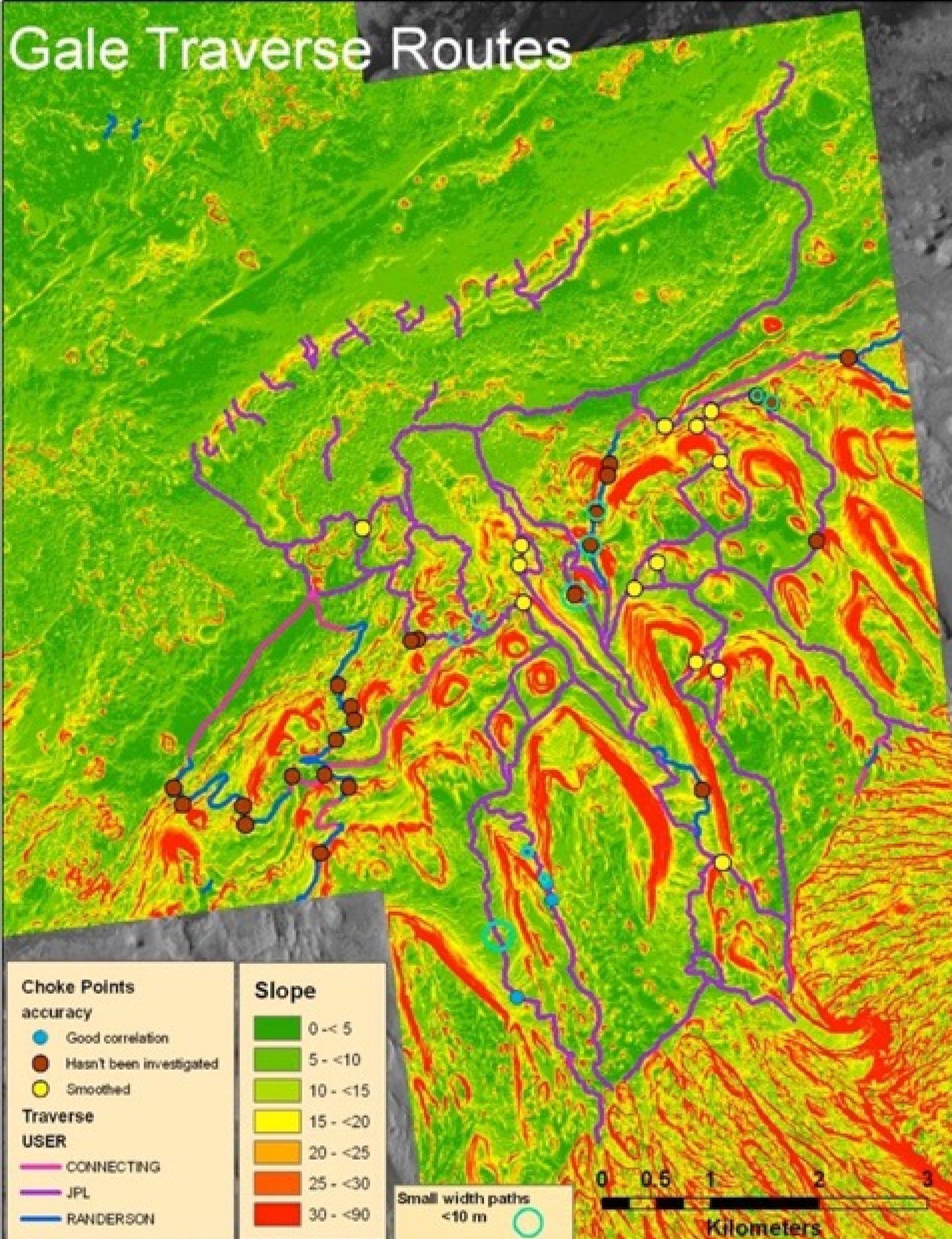
- Crater, 740 m diameter
- >15 to 30° slopes
- Degraded, sandy

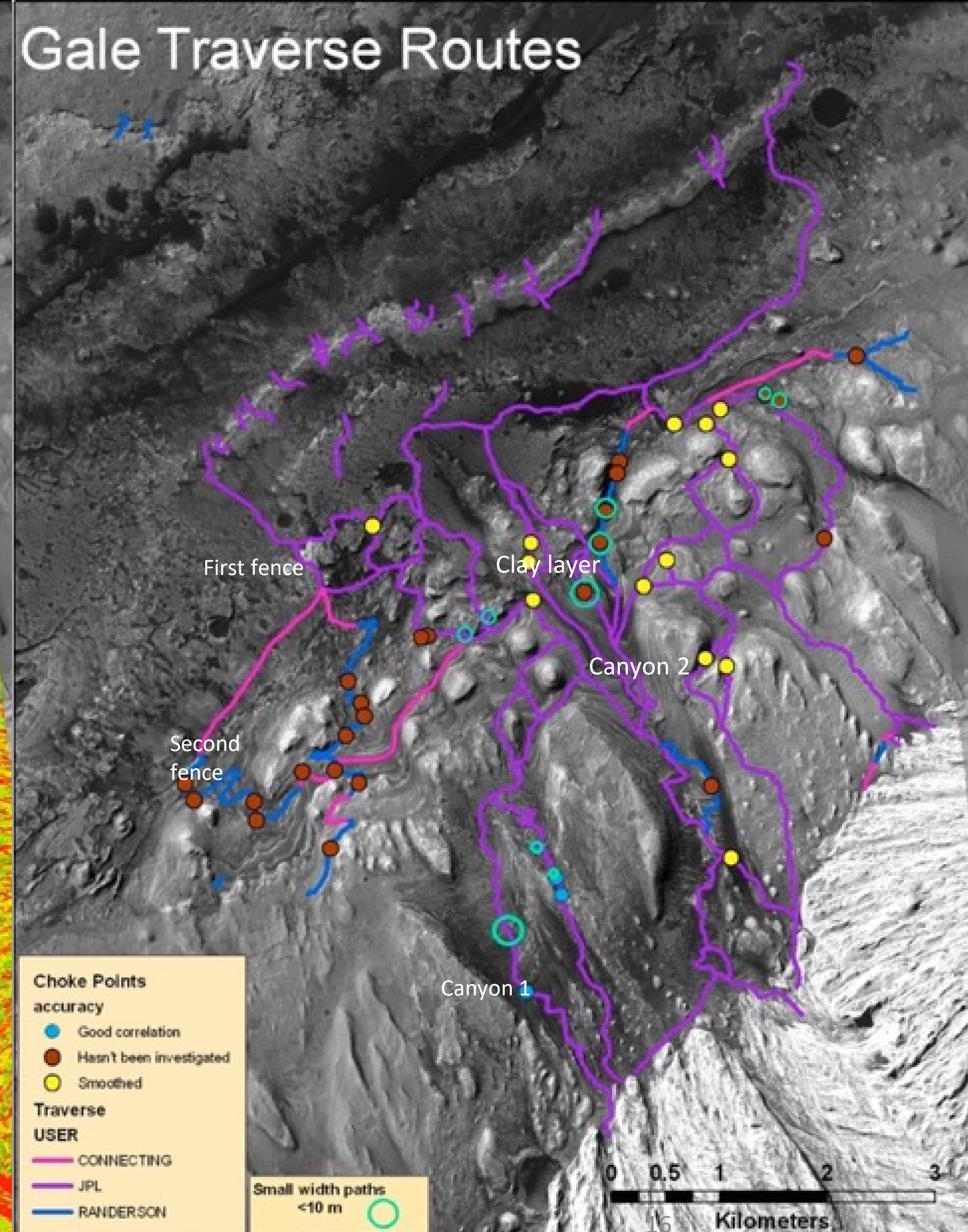
- Probably inescapable
- Based on slopes >15^{O} and sandy materials





Golombek et al. 2012

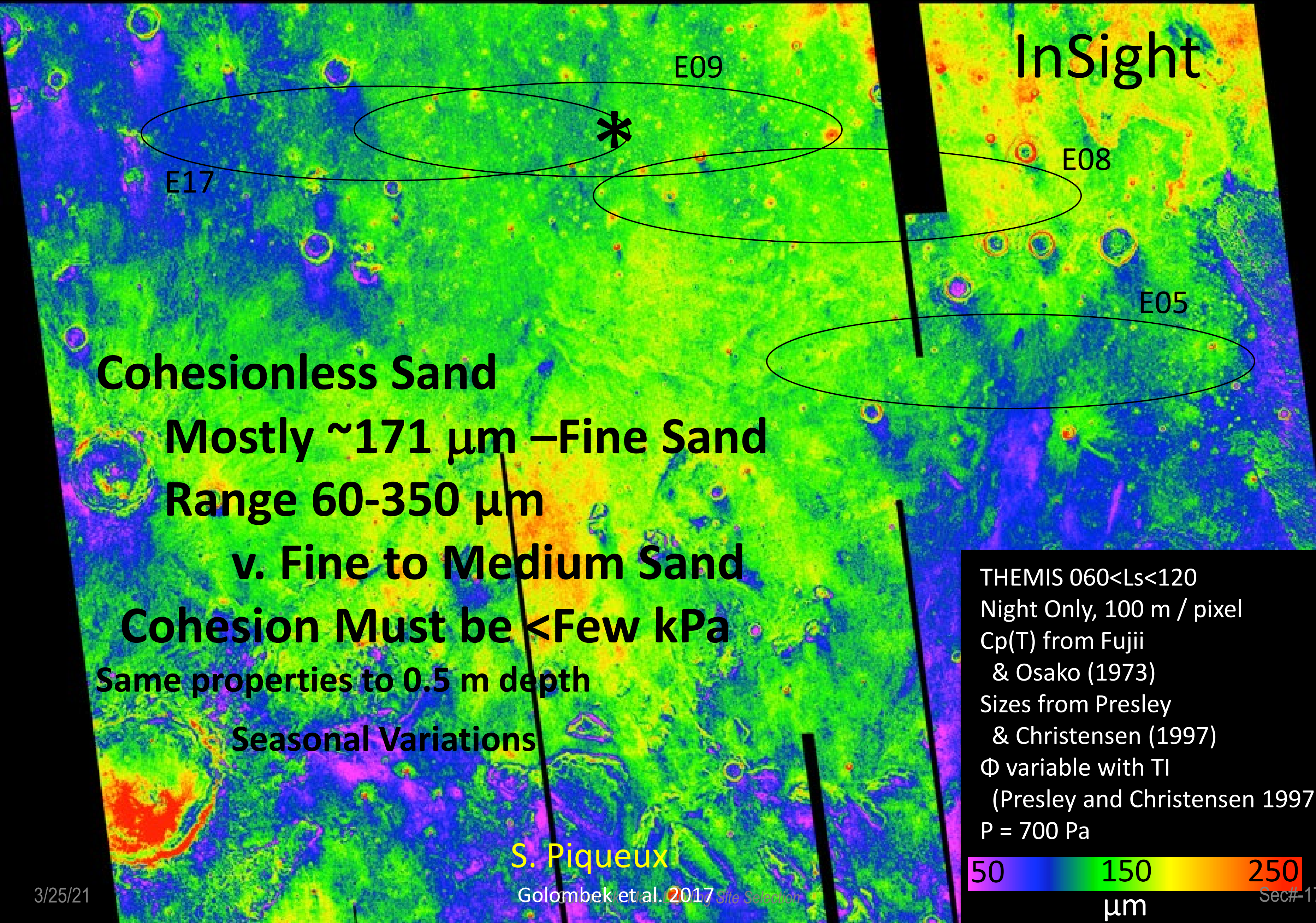




Slopes, Rock, Soil, Traversability

Golombek et al. 2012

Thermophysical Properties: Grain Sizes



Cohesionless Sand

- **Mostly ~171 µm –Fine Sand**
- **Range 60-350 µm**
  - **v. Fine to Medium Sand**

Cohesion Must be <Few kPa

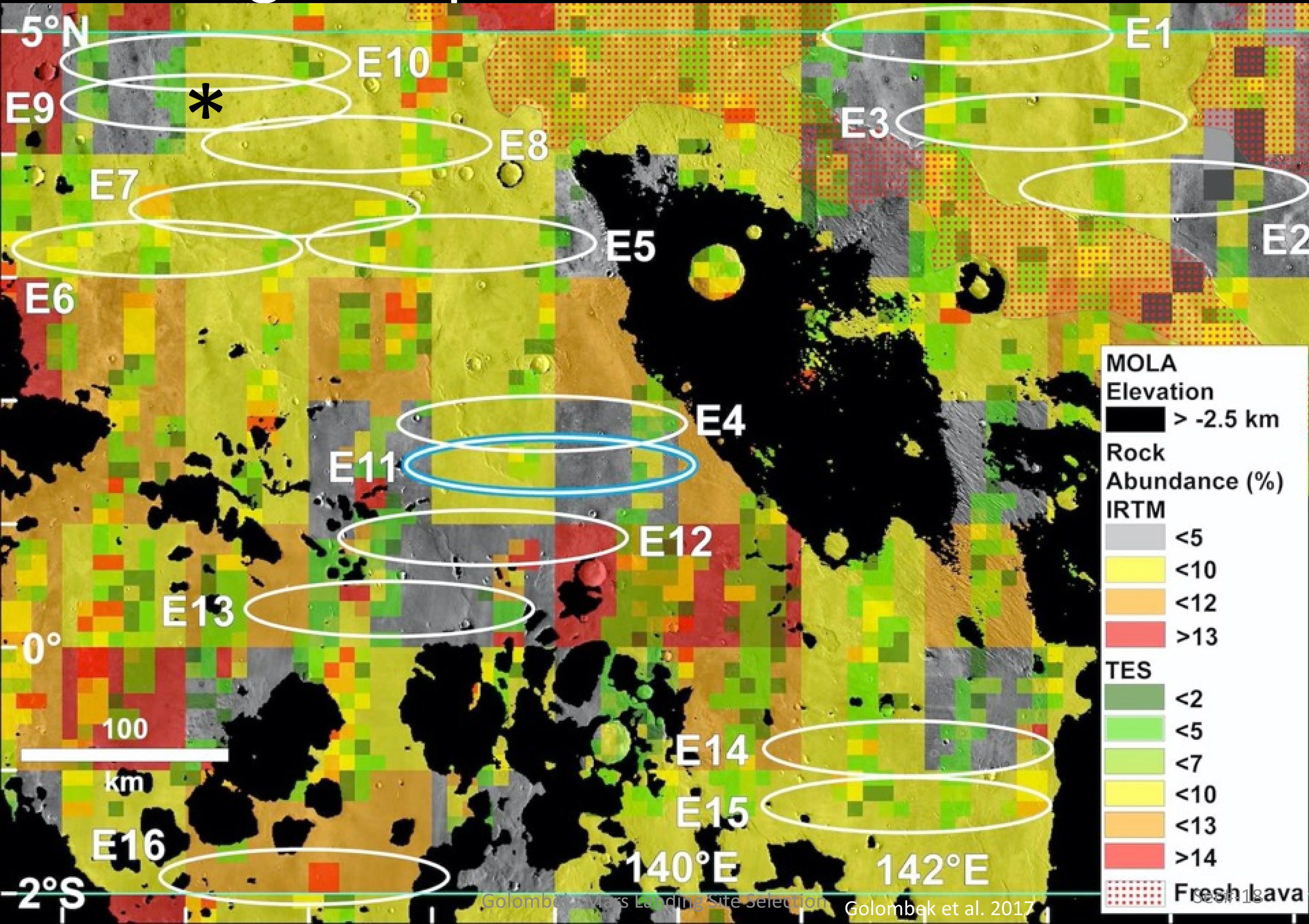
Same properties to 0.5 m depth

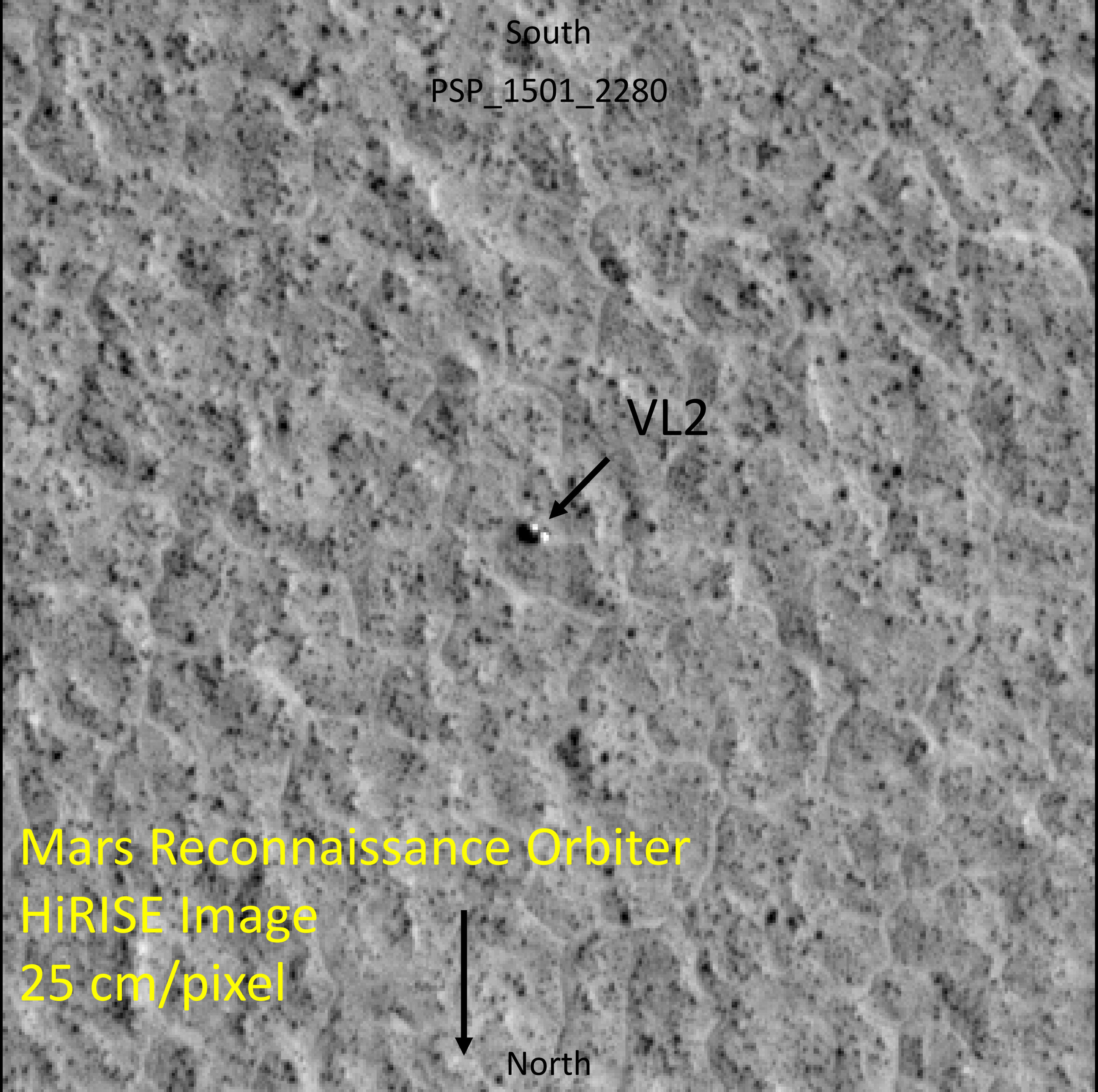
Seasonal Variations

S. Piqueux

Golombek et al. 2017

InSight Ellipses – Rock Abundance





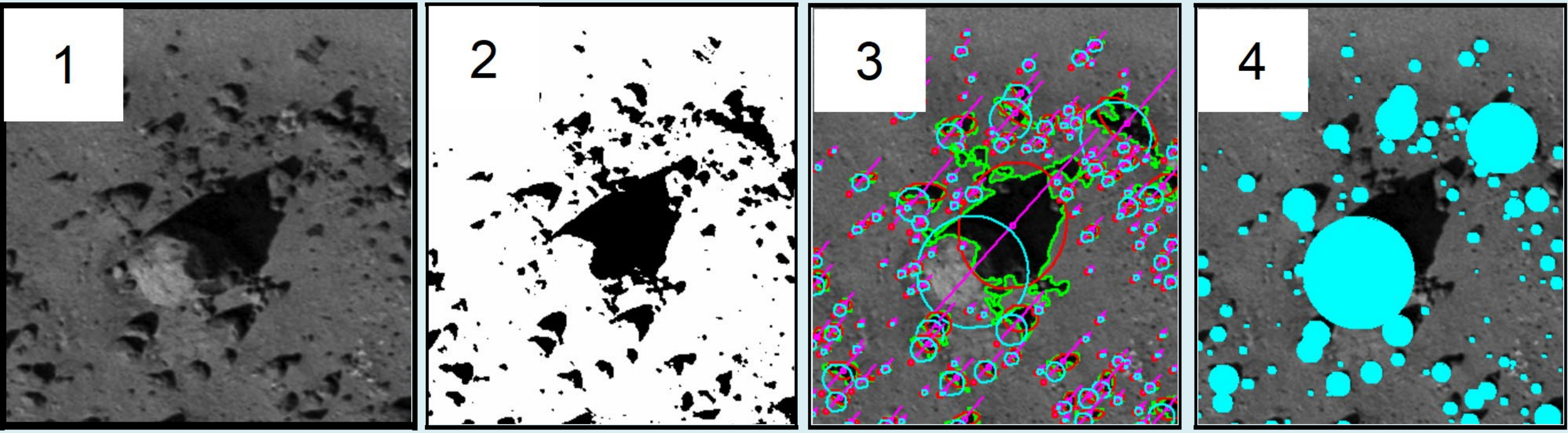
VL2

Can See Rocks Directly in HiRISE

Correlate Large Rocks in HiRISE with those Seen from Lander at All Landing Sites

Golombek et al. 2008

Semi-Automated Rock Counting



1) Image

A. Huertas

2) Software Segments Shadow
3) Fits Ellipse to Shadow - Width is Rock Width
4) Fits Cylinder to Rock - Diameter is Rock Diameter

Height is Rock Height from Shadow Length

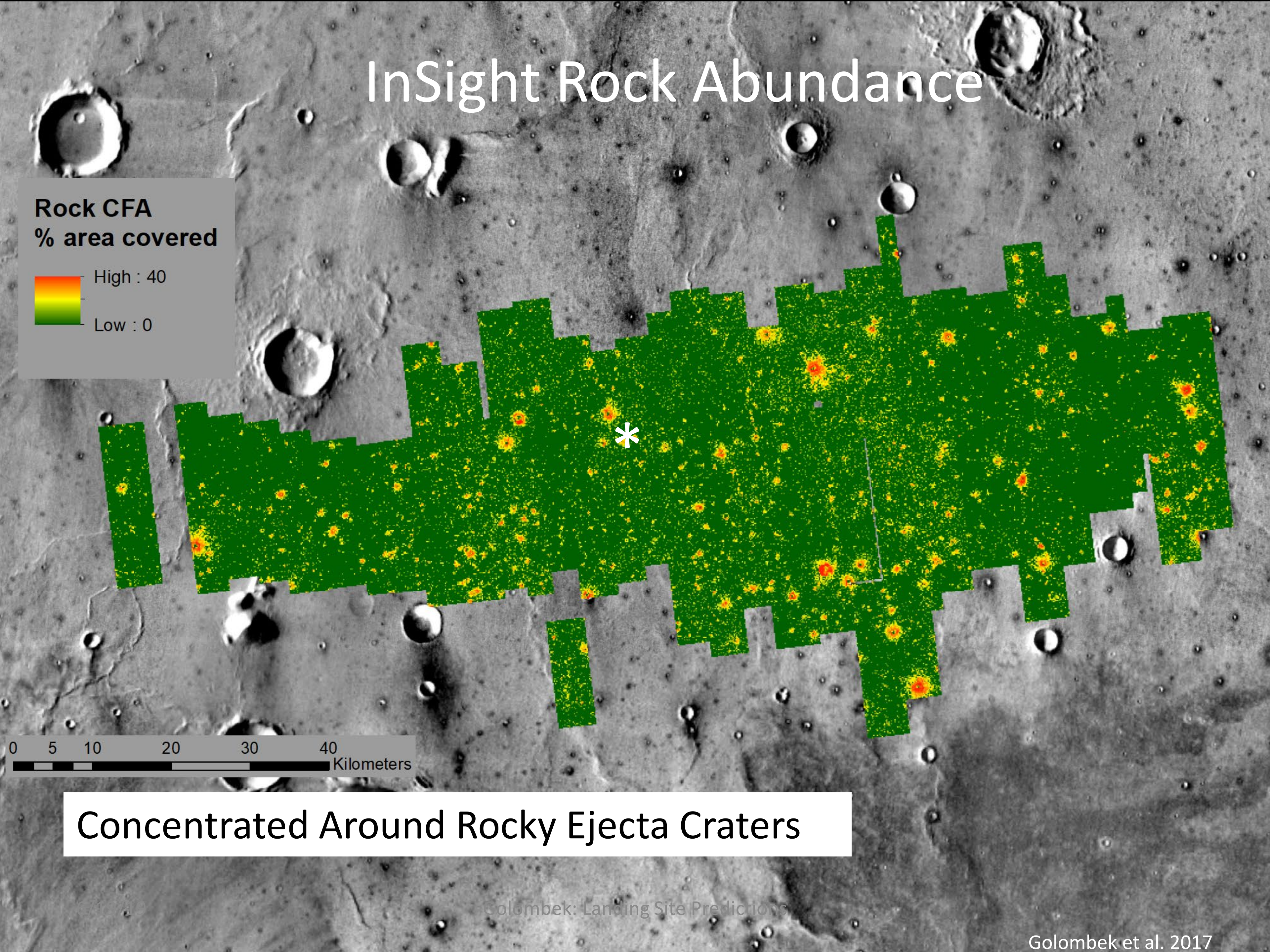
Results Match Hand Counts

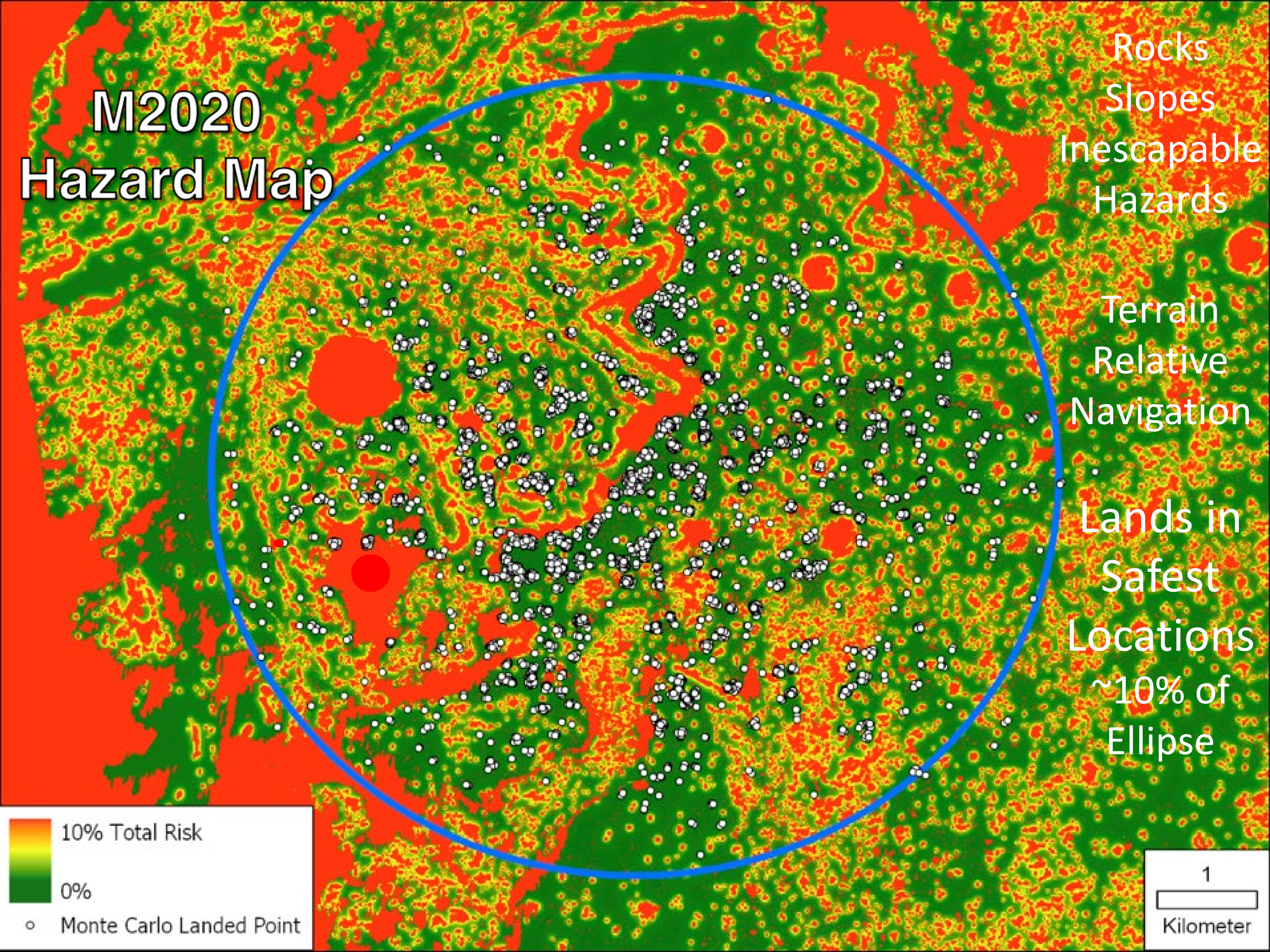
Results for Lander and Rovers of Known Size Generally ±1 pixel

Used to Map ~10 million rocks >1500 km^2 of the Northern Plains

Certified Phoenix Landing Site

Golombek et al. 2008


InSight Rock Abundance
Rock CFA
% area covered
High : 40
Low : 0
0
5
10
20
30
40
Kilometers
Concentrated Around Rocky Ejecta Craters
Golombek et al. 2017



M2020
Hazard Map
Rocks
Slopes
Inescapable
Hazards
Terrain
Relative
Navigation
Lands in
Safest
Locations
~10% of
Ellipse
10% Total Risk
0%
Monte Carlo Landed Point
1
Kilometer

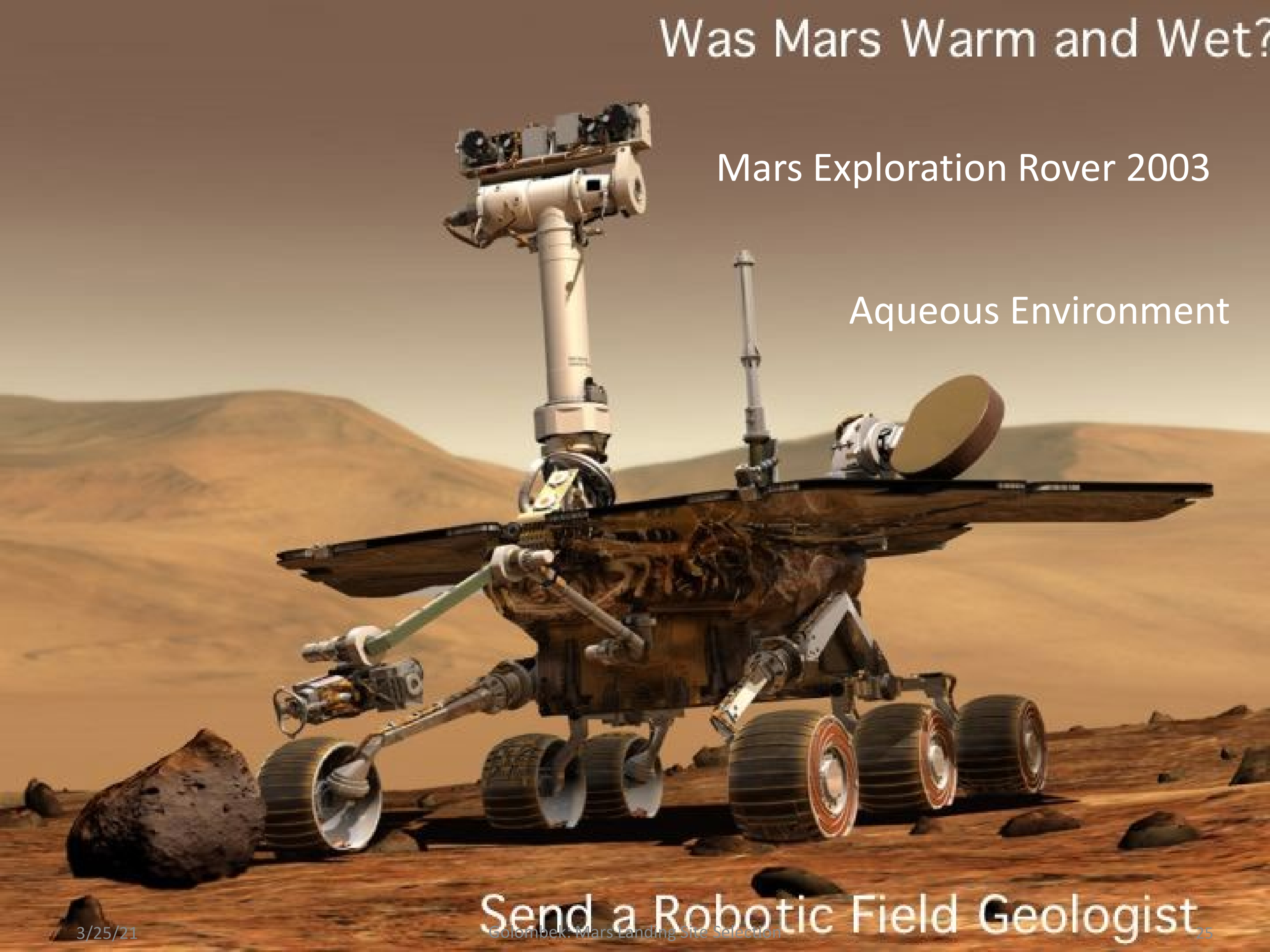
Engineering Constraints & Safety

- Increasingly sophisticated analysis of remote sensing data
- Characterize
  - Slopes
  - Rocks
  - Physical Properties
- Accurately predicted all 7 landing sites

Science

- Science Objectives of Mission
- Instruments
- Observations, Measurements
- Where can go to address?
- Geology – Geologic Setting, Deposits, Rocks
- Access via rover

Was Mars Warm and Wet?

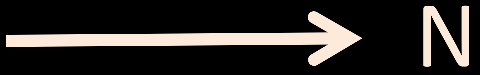


Mars Exploration Rover 2003

Aqueous Environment

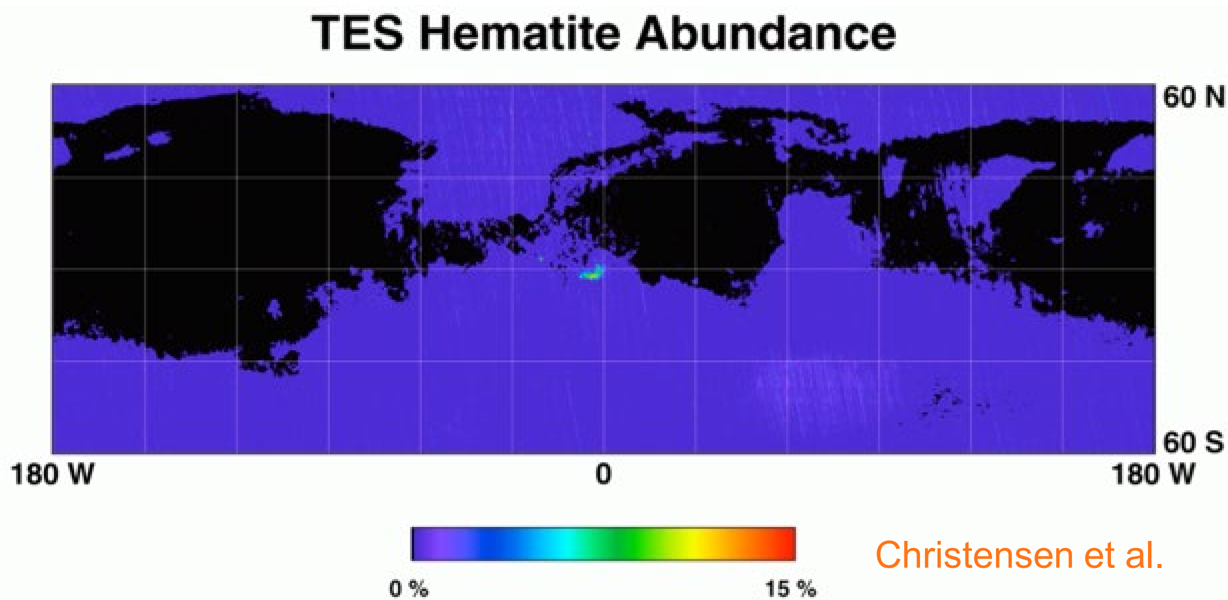
Send a Robotic Field Geologist

Ma'adim Vallis and Gusev Crater

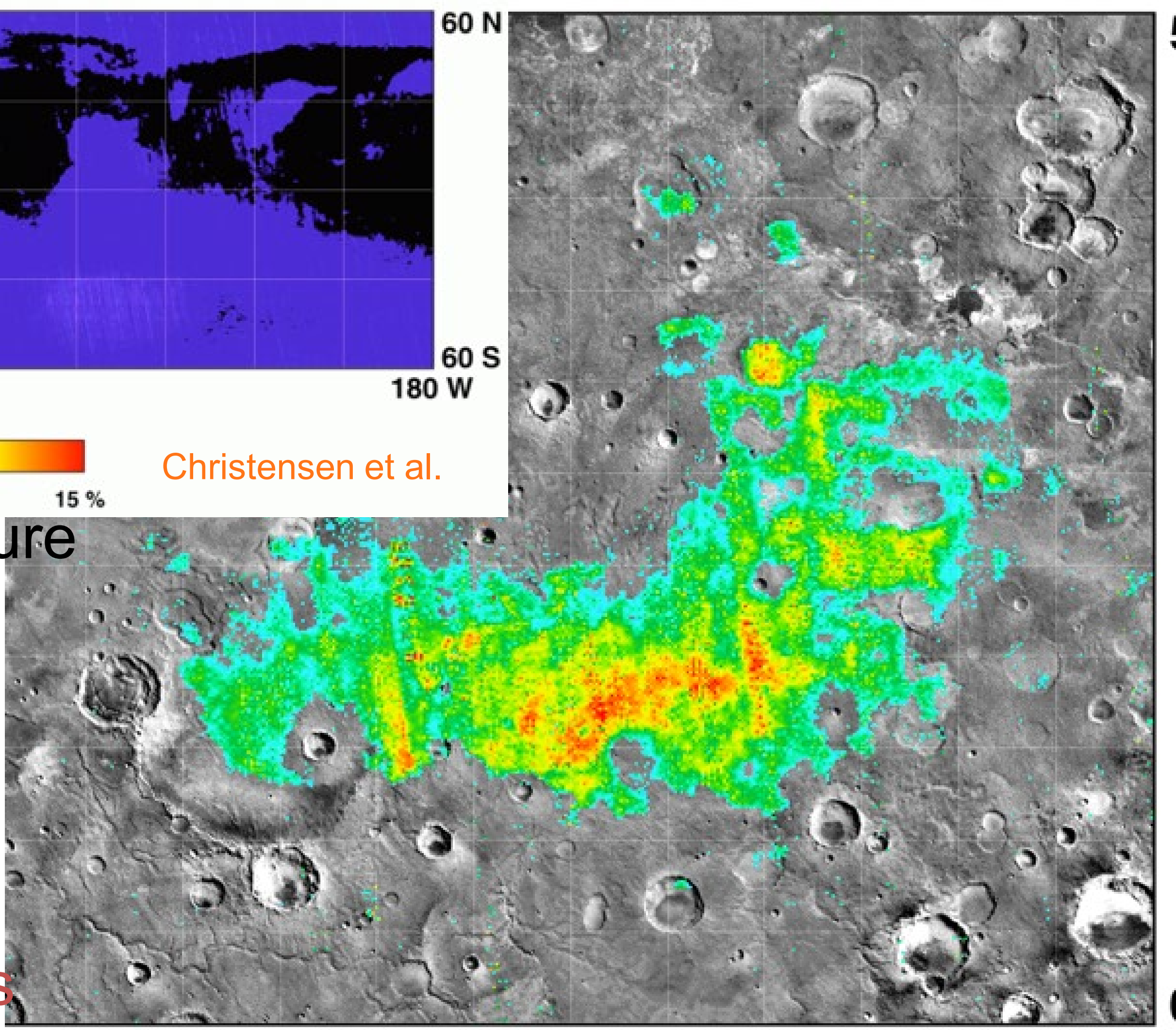


Golombek et al. 2003

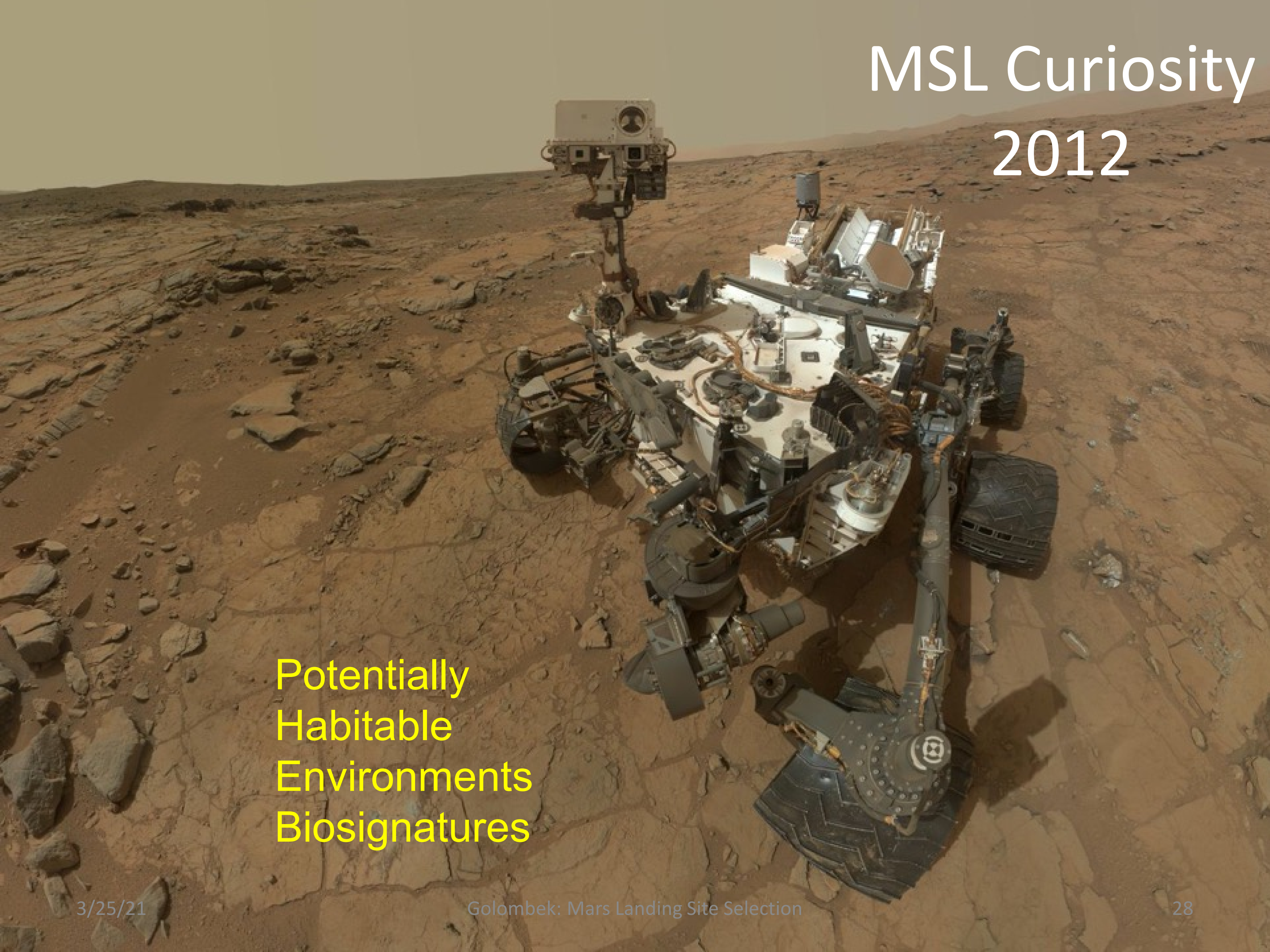
Meridiani Planum



Unique Hematite Signature
Deposited in Water or Hydrothermal Alteration
IRS H_20 Concentration
Basalt Also Present
Exhumed Stack of Noachian Geologic Units

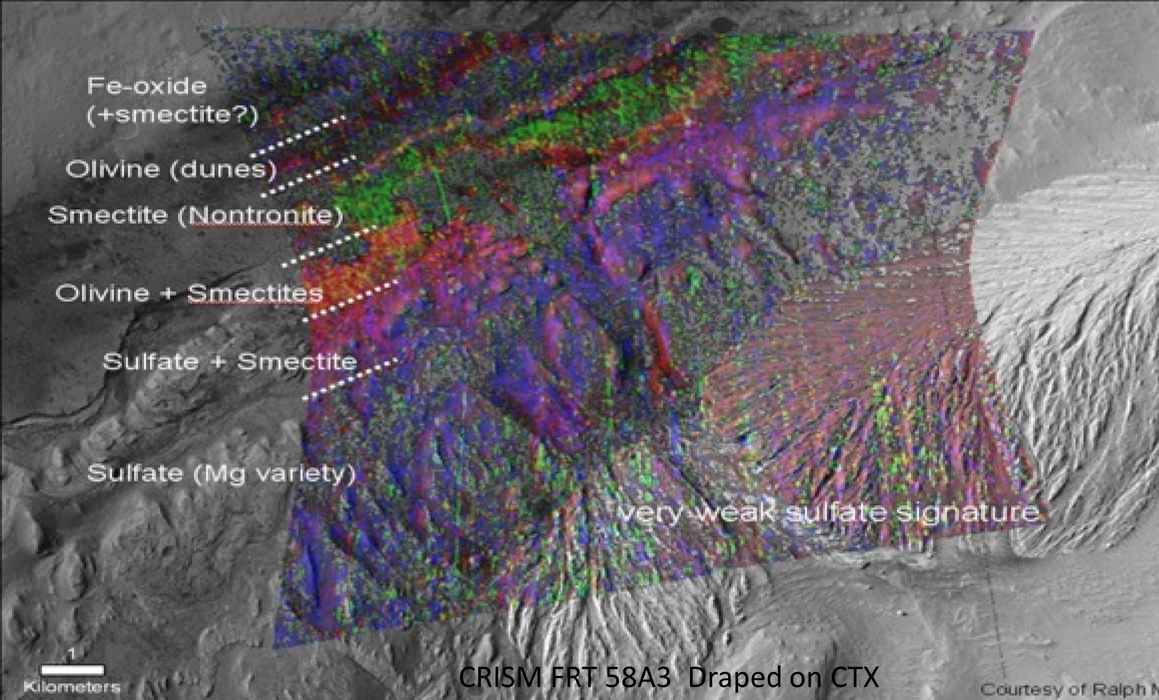


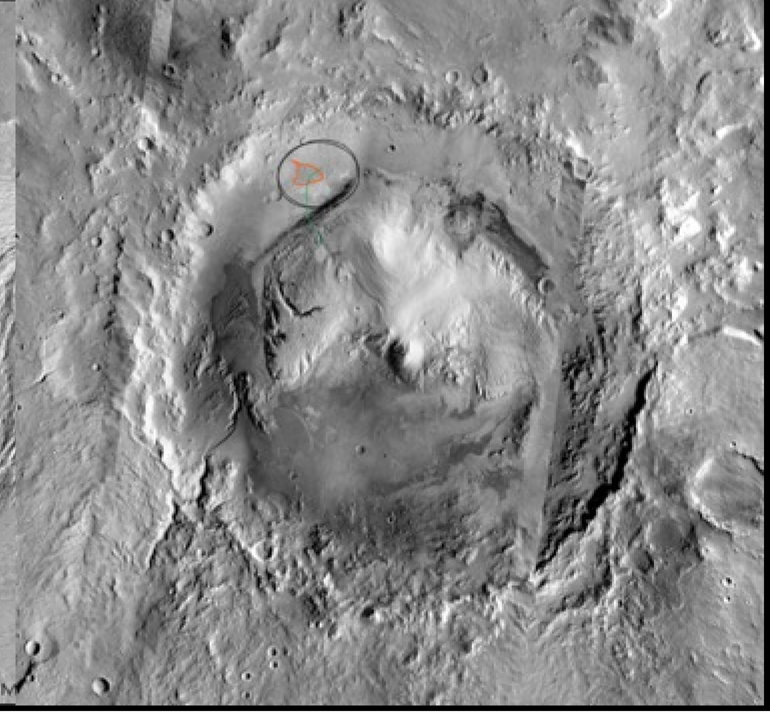
Mineralogical Evidence for Water



MSL Curiosity 2012

Potentially Habitable Environments
Biosignatures





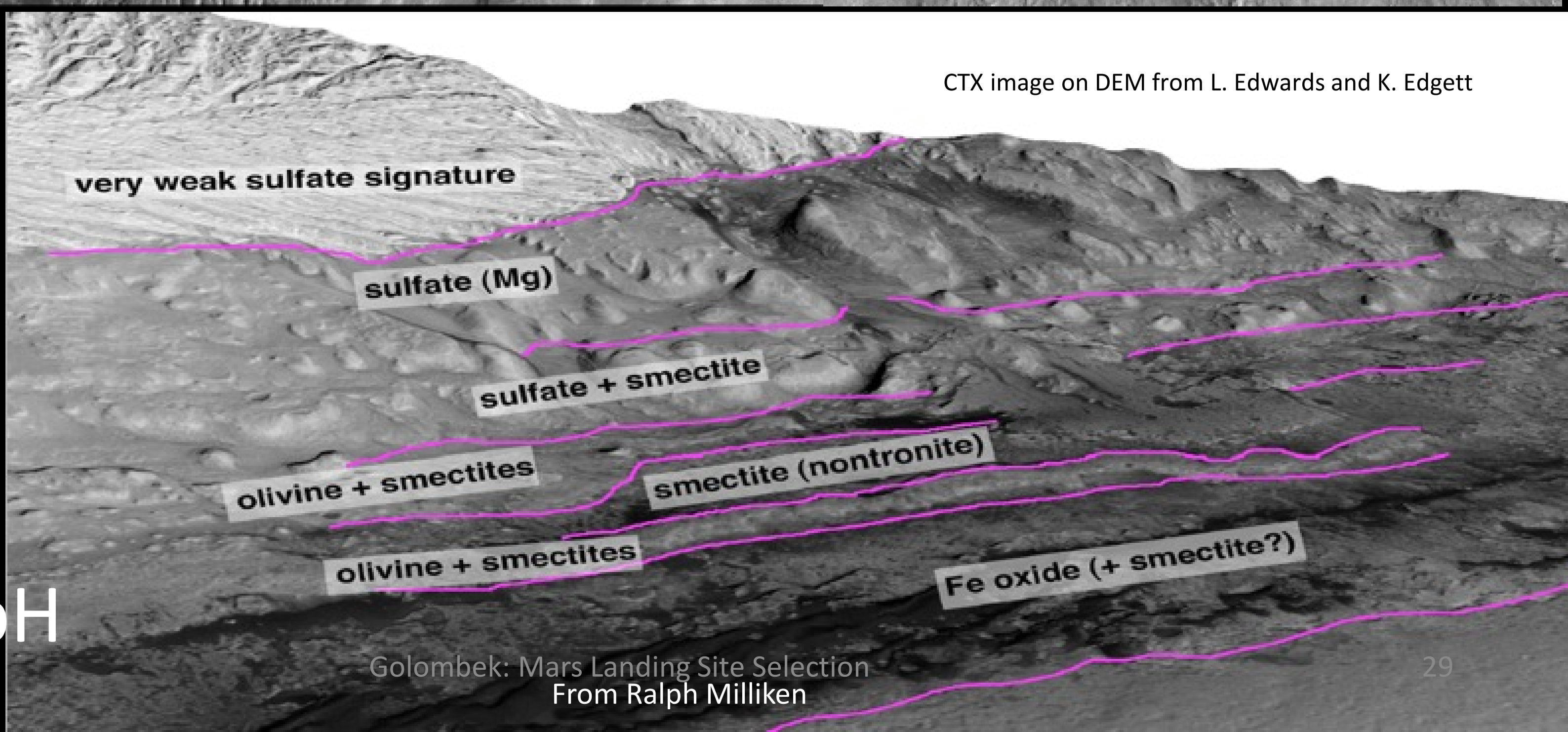
Gale Crater

Sulfate

Acidic

Clays

Neutral pH



From Ralph Milliken

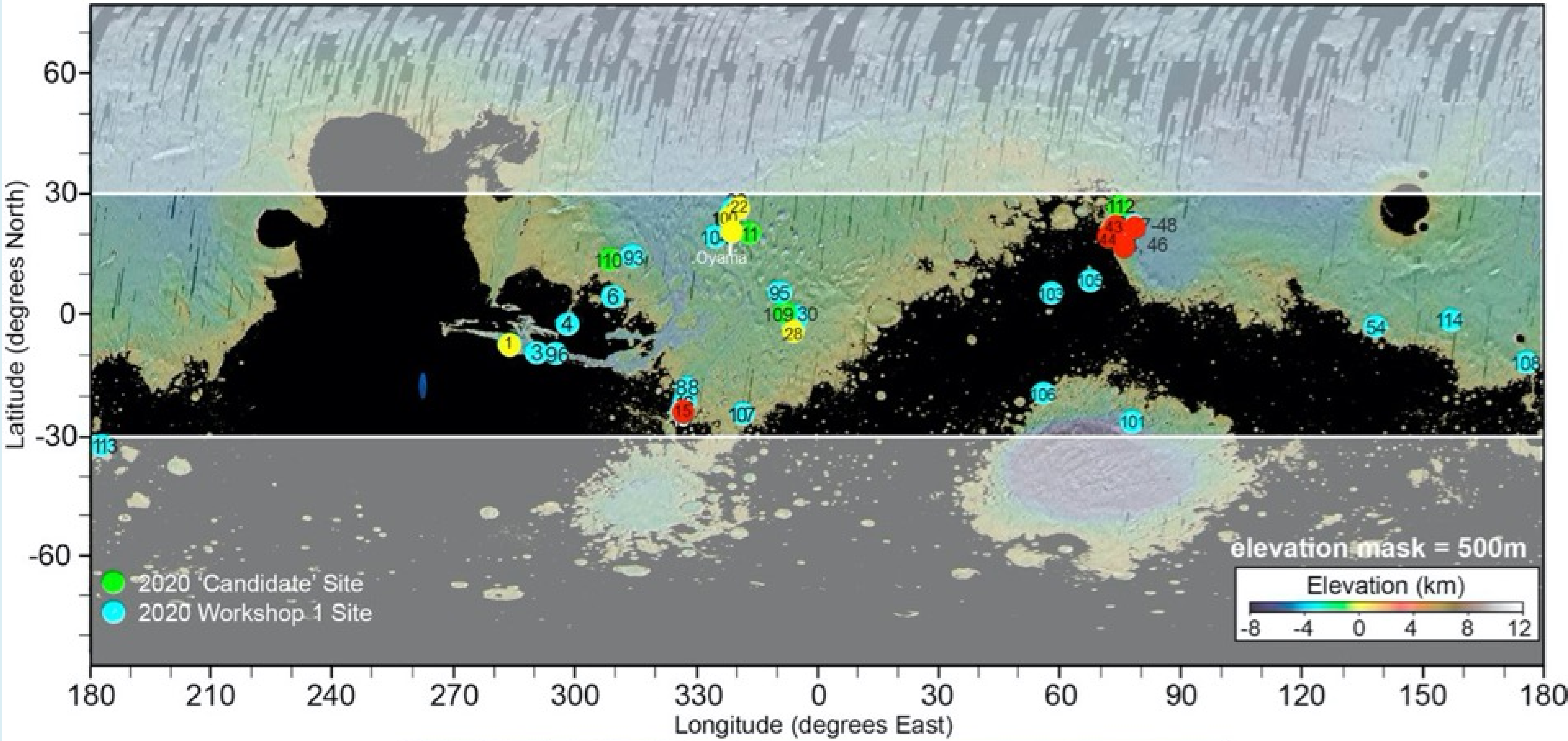
Mars 2020 Rover

Cache
Diversity
Samples
Potential
Return
to Earth

Habitable
Environment
Preservation

Four
Workshops
May 2014
Aug. 2015
Feb. 2017
Oct. 2018

M2020 Landing Sites



MARS 2020 WORKSHOP SITES (listed in order of presentation schedule, BLUE DOTS)

Dot 100: McLaughlin Crater (Michalski, J. et al.)
Dot 103: Leighton Crater (Michalski, J. et al.)
Dot 22: Mawrth Vallis (Loizeau, D. et al.)
Dot 104: Oxia Planum (Thollot, P., et al.)
Dot 43: Nili Fossae Trough (Mustard, J. F. et al.)
Dot 48: Nili Fossae Carbonates (Ehlmann, B., et al.)
Dot 44: NE Syrtis Major (Mustard, J. F., et al.)
Dot 105: Nili Patera (Skok, J. R., et al.) *(2020 Candidate Site from Skok, J. R., et al.)*
Dot 106: Hellas (NoeDobrea, E. Z., et al.)
Dot 3: Melas Chasma (Miyamoto et al.) *(2020 Candidate Site from S. M. R. Turner, et al.)*
Dot 4: Juventae Chasma (Miyamoto et al.)
Dot 1: Melas Basin (Williams, R. M. E., et al.)
Dot 96: Coprates Chasma (Quantin, C., et al.)
Dot 6: Hypanis delta in Xanthe Terra (Gupta, S., et al.)

Dot 16: Eberswalde Crater (Irwin, R. P., III)
Dot 46: Jezero Crater (Gupta, S., et al. and Ehlmann, B. L., et al.)
Dot 88: Ladon Valles (Weitz, C., et al.)
Dot 93: Sabrina Vallis (Platz, T., et al.)
Dot 113: Eridania Basin (Noe Dobrea, E. Z., et al.)
Dot 107: Kashira crater (Edgett et al.) *(2020 Candidate Site from M. R. Salvatore)*
Dot 28: Eastern Margaritifer Terra (Christensen, P., et al.)
Dot 101: Hadriacus Palus (Skinner, J. A., et al.,)
Dot 95: Firsoff Crater (Pondrelli, M., et al.) *(2020 Candidate Site from Pondrelli et al.)*
Dot 108: Gusev Crater (Ruff, S. W. et al.; Longo, A.; Rice, J.) *(2020 Cand. Site from Cabrol et al.)*
Dot 54: Gale Crater (Grant, J.)
Dot 30: Meridiani Planum (M. Golombek)
Dot 15: Holden Crater (Irwin, R.)
Dot 114: Aeolis (Yakovlev, V)

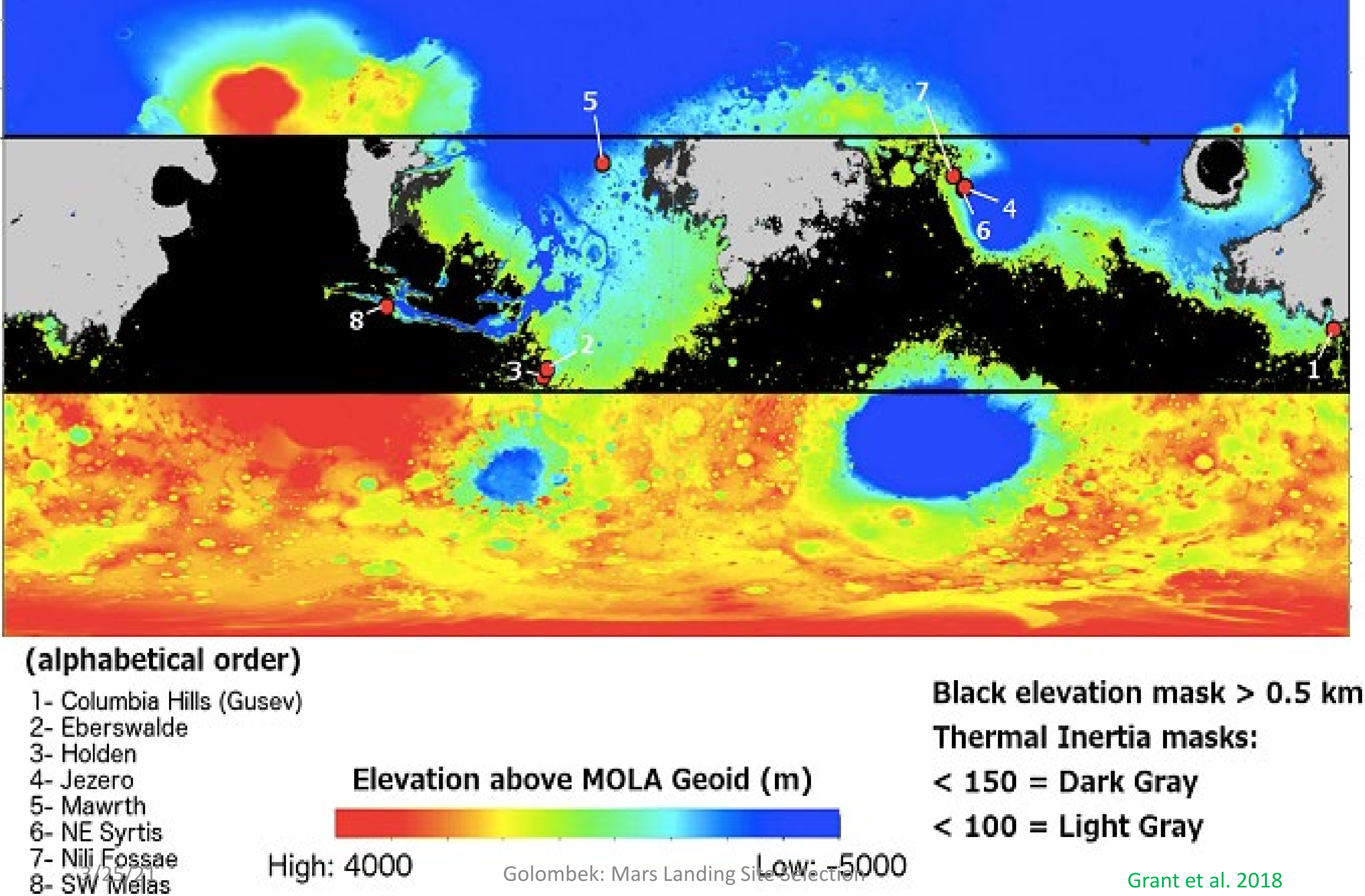
MARS 2020 CANDIDATE SITES (GREEN DOTS)

Dot 109: Farthest West Meridiani (Edgett et al.)
Dot 110: Vistula Valles/Chryse (Edgett et al.)
Dot 111: Intercrater West Arabia (Edgett et al.)
Dot 112: Nilosyrtis crater (Saper, L.)

~30 Sites Proposed

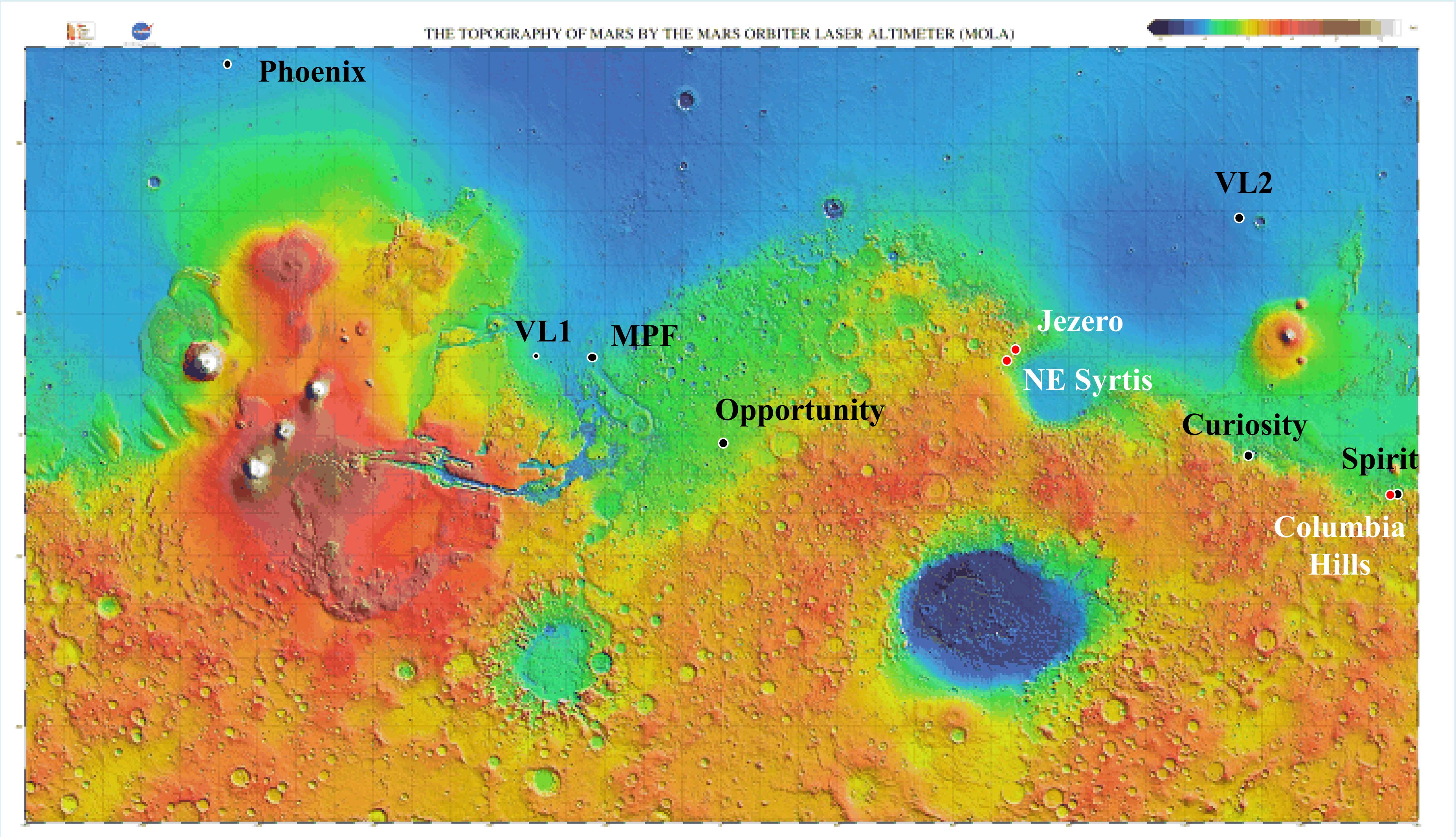
Grant et al. 2018

8 Mars 2020 Landing Sites 2nd Workshop



Grant et al. 2018

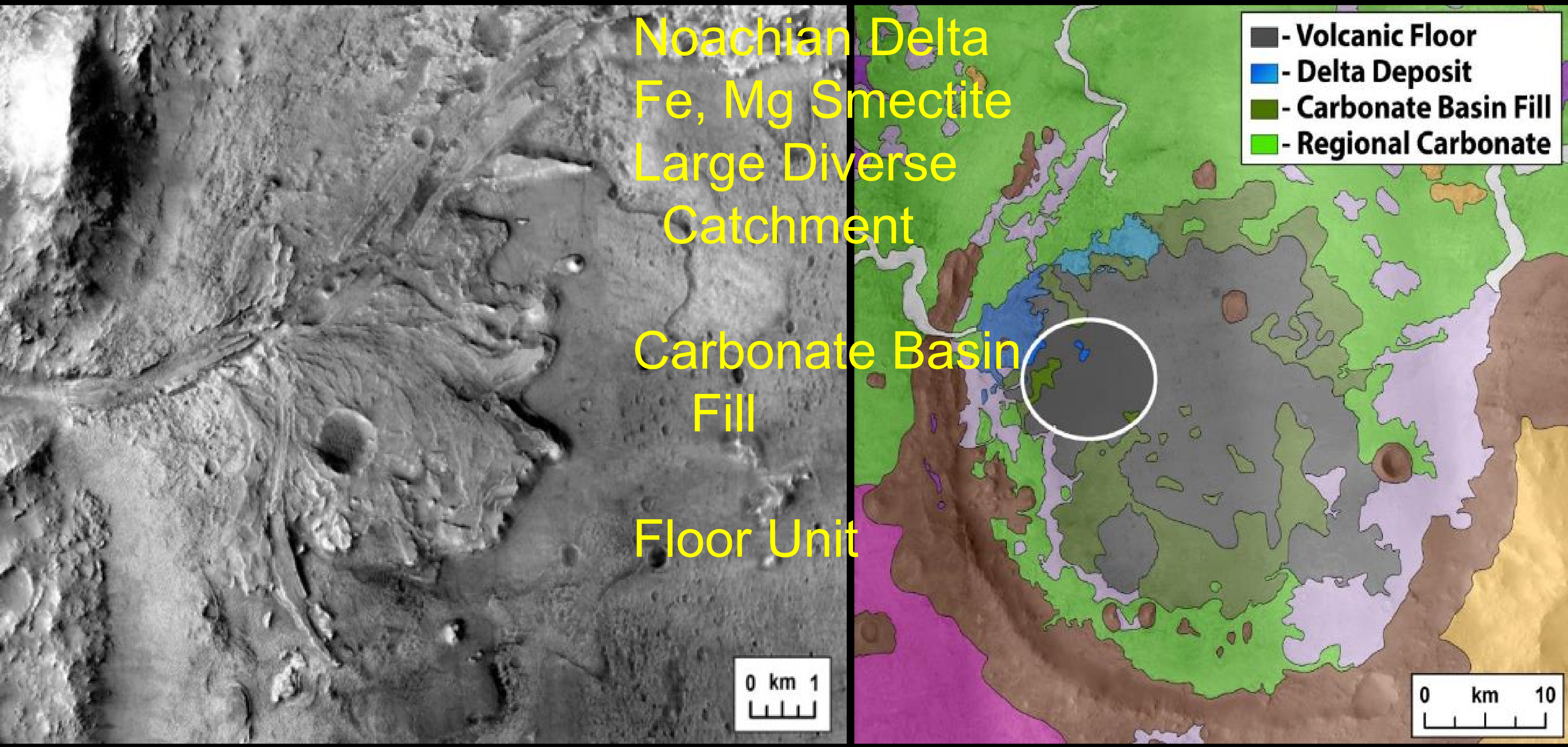
Candidate Sites after 3rd Workshop



4th Workshop – Project Selected Jezero Crater

Grant et al. 2018

Jezero Crater



Science - Landing Sites

- Increasingly sophisticated analysis of remote sensing data
- Thermal and Visible Near IR Spectra
- Identified mineralogy
  - Aqueous minerals
- Found Aqueous Environments – MER
- Found Potentially Habitable Environment – MSL
- M2020 – Seeking habitable environment that could preserve organics

Planetary Protection

- NASA Places Requirements on spacecraft cleanliness to prevent forward contamination to comply with COSPAR international agreements
- Without Life detection and Not bound for Special Region – Spacecraft designated Category IVa
- Spacecraft Cleanliness Compliance via documentation, test & analysis
- Interaction between project and NASA Planetary Protection Office on planetary protection requirements
- Planetary Protection Landing Site Review
  - Several briefings during downselection (InSight)

Golombek et al. 2017

Goal of Planetary Protection Review

- Demonstrate Compliance with PP Landing Site Requirements
  - "The InSight landing site shall not have ice within reach of the HP^3 instrument's mole."
  - No water or ice within 5 m of the surface
  - No Subsurface Discontinuities
  - "The InSight HP^3 mole operation at the InSight landing site shall not have the potential to release liquid that would create a thin liquid film (water/brine) that would mobilize a 50 nm particle" – Separate Analysis
  - Show that there are no high concentrations of water bearing soil or rocks at the landing site

Golombek et al. 2017

Landing Site Interaction with PPO

- InSight Landing Site Selection Process and Characteristics – Feb. 6, 2013
  - Intro to Landing Site, before 1st Workshop, Imaging Plan and Selection Process
  - Initial Characterization of Terrains, Surface Materials and Processes
    - First few CTX and HiRISE Images
- InSight Planetary Protection Plan - May 2013
  - Appendix D: InSight Landing Site Selection and PP Compliance, pp. 41-50
  - Description of Process and Imaging Plan
  - Description of Terrains, Surface Features
  - Literature Review – No Indication of Water, Ice or Concentrations of Aqueous Minerals
  - Images Acquired – Inspected to Understand Geological Processes
- Terrain Types and Landforms at the InSight Landing Site – Jan. 16, 2014
  - Description of Terrains in Extensive CTX and ~20 HiRISE Images
  - Four Preferred Ellipses in N – E5, E8, E9, E17
  - Eolian, Impact Processes – No Evidence Water or Ice
- Separate Analysis
  - Liquid water created by the mole that could mobilize a 50 nm particle

Golombek et al. 2017

Planetary Protection Landing Site Review

- "This review is to ascertain that the Project has a landing site that is in compliance with planetary protection requirements. The review shall address the adequacy of the documentation generated by the Insight Project to demonstrate that the proposed landing site is absent of ice or subsurface discontunities, and that the mole heating measurements and/or modeling are adequate. The landing site should be approved by the NASA PPO as a result of this review. After approval of the landing site the NASA PPO will inform the Science Mission Directorate Associate Administrator of the approval."

No Evidence for Water or Ice within 5 m of Surface

- No!!! This is Among the Driest Places on Mars
- Not Special region – Rummel et al. 2014
- No Ice within 5 m of Surface
- No Recurring Slope Lineae, No Gulleys
- No Polygonal terrain, No Glaciers
- No Lobate Debris Aprons, No Softened Ground
- No Lineated Valley Fill, No Pasted On Terrain
- No Ice Rich Mantles

Oct. 19, 2015
84 Page Review Package
Project Presented to PPO

PPO Office
Dec. 4, 2015
Summary of Review
"The InSight team has presented a well-substantiated package of information that demonstrates compliance with Planetary Protection requirements. They have met all of the Success Criteria"

HQ briefed Dec. 14, 2015
Landing Site Unchanged 2018

- No Rampart Craters with Diameters <10 km; water or ice > 1 km deep
- No New Impact Craters with Ice – 3 New Craters in Area
- No Subsurface Reflectors in Shallow Radar (SHARAD) – No Ice/Water Extensive Coverage
- If putative ocean – last underwater in Noachian (~200 m below surface)
- Erosion rates too slow for liquid water

Golombek et al. 2017

Selected Mars Landing Site References

- Golombek, M. P., et al., 1997, Selection of the Mars Pathfinder landing site: Journal of Geophysical Research, v. 102, p. 3967-3988.
- Golombek, M., and Rapp, D., 1997, Size-frequency distributions of rocks on Mars and Earth analog sites: Implications for future landed missions: Journal of Geophysical Research, v. 102, p. 4117-4129.
- Golombek, M. P., et al., 1997, Overview of the Mars Pathfinder mission and assessment of landing site predictions: Science, v. 278, p. 1743-1748.
- Golombek, M. P., Moore, H. J., Haldemann, A. F. C., Parker, T. J., and Schofield, J. T., 1999, Assessment of Mars Pathfinder landing site predictions: Journal of Geophysical Research, v. 104, p. 8585-8594.
- Golombek, M. P., Grant, J. A., Parker, T. J., et al., 2003, Selection of the Mars Exploration Rover landing sites: Journal of Geophysical Research, Planets, v. 108(E12), 8072, doi:10.1029/2003JE002074.
- Golombek, M. P., Haldemann, A. F. C., et al., 2003, Rock size-frequency distributions on Mars and implications for MER landing safety and operations: Journal of Geophysical Research, Planets, v. 108(E12), 8086, doi:10.1029/2002JE002035.
- Golombek, M., et al., 2005, Assessment of Mars Exploration Rover landing site predictions: Nature, v. 436, p. 44-48 (7 July 2005), doi: 10.1038/nature03600.
- Golombek, M. P., Haldemann, A. F. C., et al., 2008, Martian surface properties from joint analysis of orbital, Earth-based, and surface observations: Chapter 21 in, The Martian Surface: Composition, Mineralogy and Physical Properties, J. F. Bell III editor, Cambridge University Press, p. 468-497.
- Golombek, M. P., Huertas, A., et al., 2008, Size-frequency distributions of rocks on the northern plains of Mars with special reference to Phoenix landing surfaces: Journal of Geophysical Research, Planets, v. 113, E00A09, doi:10.1029/2007JE003065.
- Golombek, M., et al., 2012, Selection of the Mars Science Laboratory landing site: Space Science Reviews, v. 170, p. 641-737, DOI: 10.1007/s11214-012-9916-y.
- Golombek, M., Huertas, et al., 2012, Detection and characterization of rocks and rock size-frequency distributions at the final four Mars Science Laboratory landing sites: Mars, 7, 1-22, doi:10.1555/mars.2012.0001.
- Golombek, M., et al., 2017, Selection of the InSight landing site: Space Science Reviews, v. 211, p. 5-95, DOI 10.1007/s11214-016-0321-9.
- Golombek, M., Kass, D., Williams, N., Warner, N., Daubar, I., Piqueux, S., Charalambous, C., and Pike, W. T., 2020, Assessment of InSight landing site predictions: Journal of Geophysical Research, Planets, v. 125, e2020JE006502. https://dx.doi.org/10.1029/2020JE006502.
- Grant, J. A., Golombek, M. P., Wilson, S. A., Farley, K. A., Williford, K. H., and Chen, A., 2018, The science process for selecting the landing site for the 2020 Mars Rover: Planetary and Space Science, v. 164, p. 106–126, https://doi.org/10.1016/j.pss.2018.07.001.