Annotated for distribution

Subsurface Water Ice Mapping (SWIM) in the Northern Hemisphere of Mars

2018 Dec 12

Project Midterm Review & Pilot Study 1 Final Review

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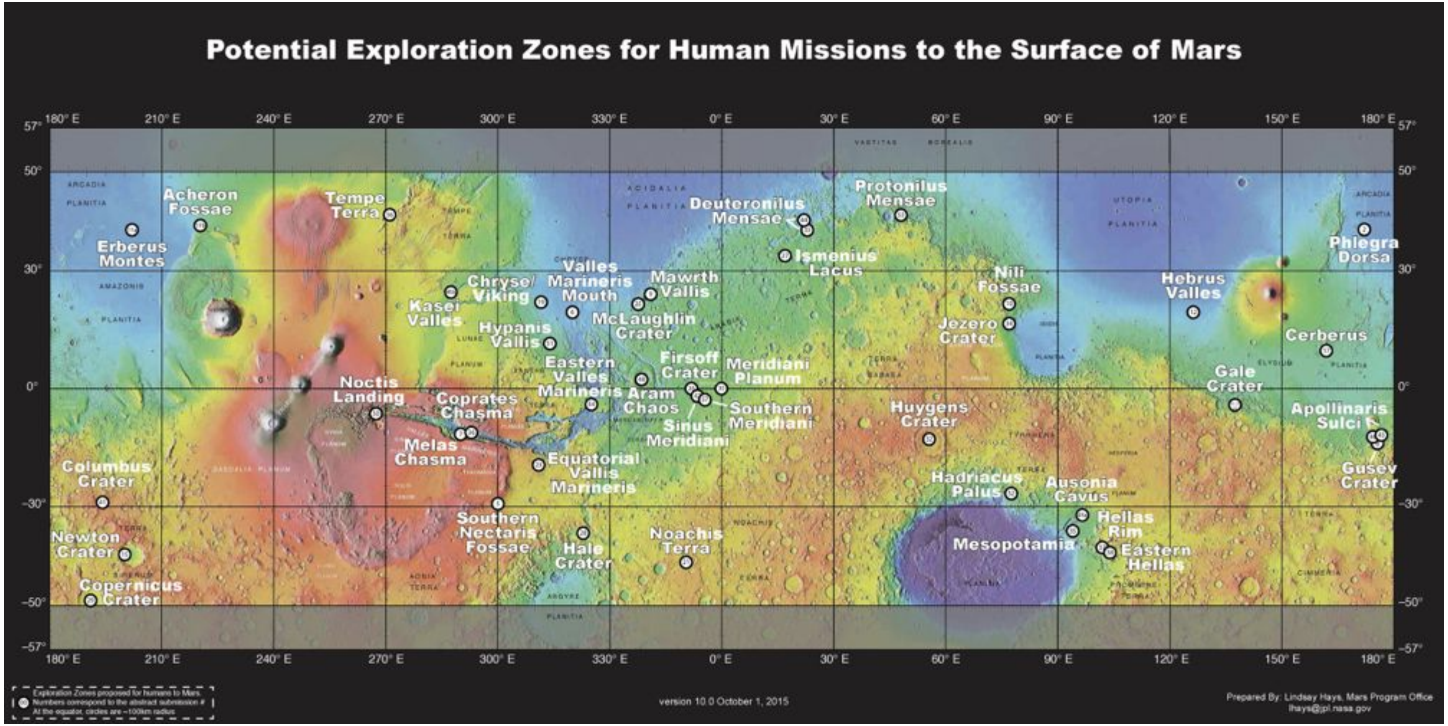
1 Pilot Study 1: “Mapping Buried Water Ice in Arcadia & Beyond with Radar & Thermal Data”

2 Pilot Study 2: “Local Subsurface Ice Mapping Through the Integration of SHARAD Derived Data Products with Other Datasets”

Outline

1. Prior State of Knowledge
2. SWIM Methods
3. Arcadia Planitia Results
4. SWIM Status
5. Deliverables
6. SWIM Extension



2015 Human Landing Site Selection Workshop

SWIM TEAM DISCLAIMER

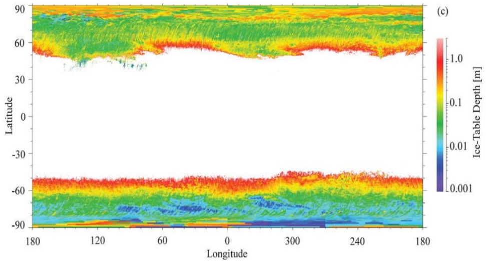
Mapping results presented herein are PRELIMINARY and could change substantially as work progresses toward the conclusion of the SWIM study.

Boxed annotations such as this one that appear in green text were added subsequent to the presentation on 2018 Dec 12.

Shallow (<1 m) water ice

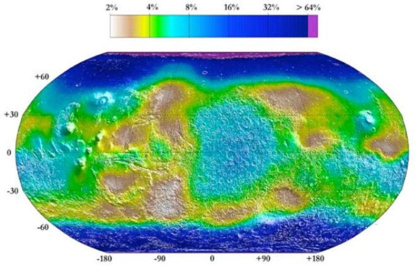
- Theory since the 1960s and thermal measures since the 1990s indicate that ice is likely present across high (>50°) latitudes of Mars.

TES derived depth of the ice table [Mellon et al., 2004].



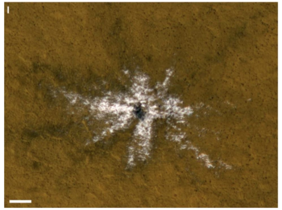
- In the early 2000s, the Mars Odyssey Neutron Spectrometer found clear indications of hydrogen in the form of water ice in these same regions.

Water-equivalent hydrogen content of the semi-infinite layer of water-bearing soils [Feldman et al., 2004].



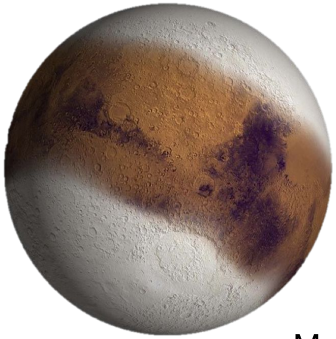
- Fresh ice-exposing small impact craters reveal high concentrations within the upper 1m, sometimes at lower latitudes.

HiRISE image of fresh crater with icy ejecta [Byrne et al., 2009; Dundas et al., 2013]

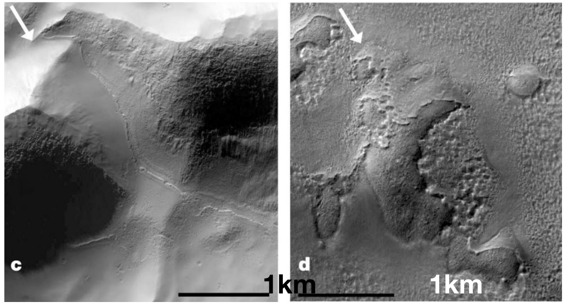


Geomorphology: Shallow & deep water ice

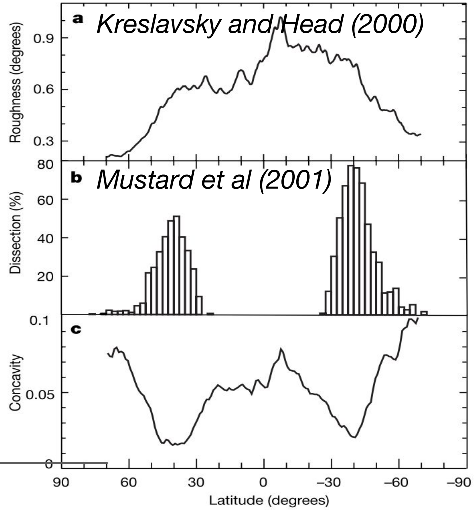
- Combination of high resolution image (MOC) and surface roughness studies (MOLA) led to the Mars Ice Age Hypothesis [Head et al., 2003].



Mars at high obliquity?



Dissected Mantle (1 - 10 m thick) at mid-latitudes

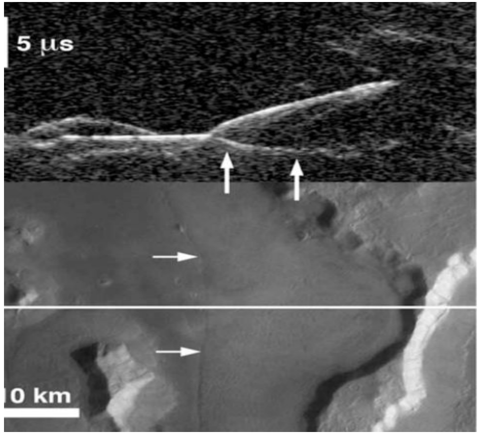


- Large scale (>100m thick) lobate features exhibiting evidence of flow within the mid latitudes and along the flacks of tropical volcanoes have been interpreted to be glacial in origin.

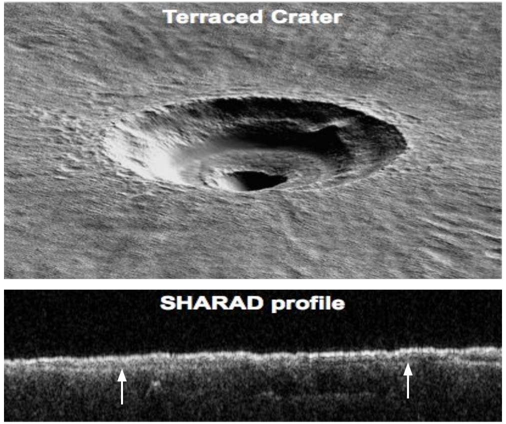
Promethei Terra region (HRSC Data)

Deep (>20 m) water ice

- Since 2008, MRO Shallow Radar (SHARAD) has shown that some of the glacial features contain large deposits of nearly pure water ice.
- Since 2014, SHARAD detection of mid-latitude non-glacial ices—at Phoenix and further south in Arcadia and Utopia Planitiae—have been reported.



SHARAD profile and HRSC image along radar ground track over debris-covered glacier in Deuteronilus [Plaut et al., 2009].



Terraced crater and SHARAD profile in Arcadia Planitia. Reflector at arrows in profile corresponds to lower crater terrace ~40 m depth. This yields subsurface material properties indicative of ground ice [Bramson et al., 2015].

Human Landing Sites

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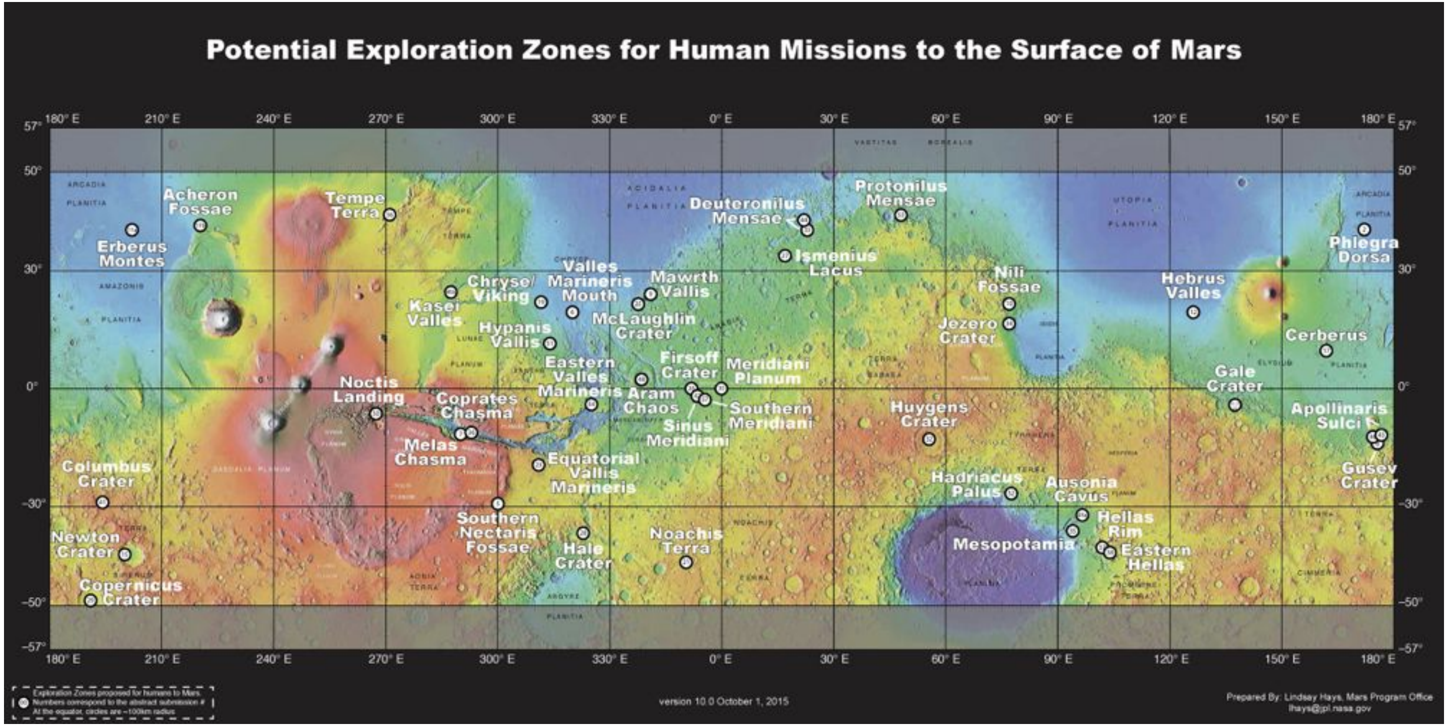

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Human Landing Sites
w/ ice stability, radar detections

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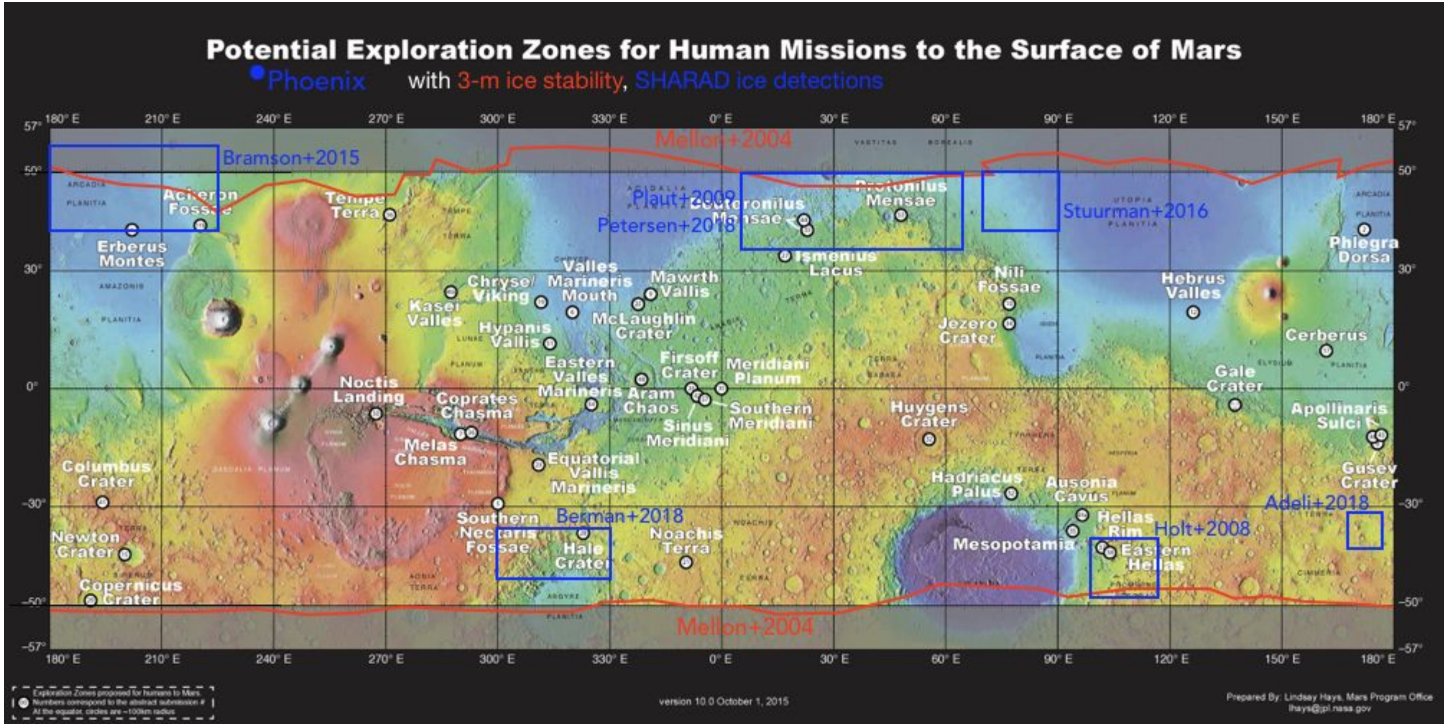

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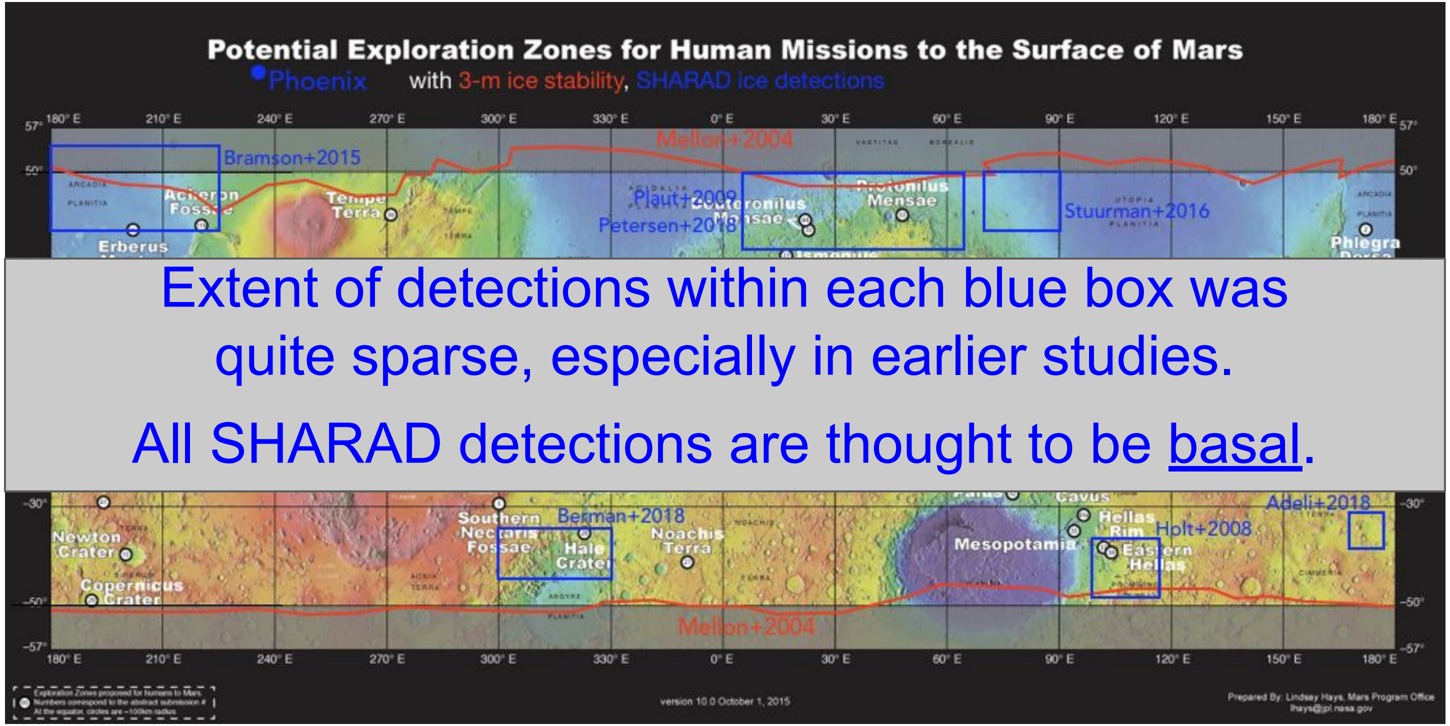

Extent of detections within each blue box was quite sparse, especially in earlier studies.

All SHARAD detections are thought to be basal.

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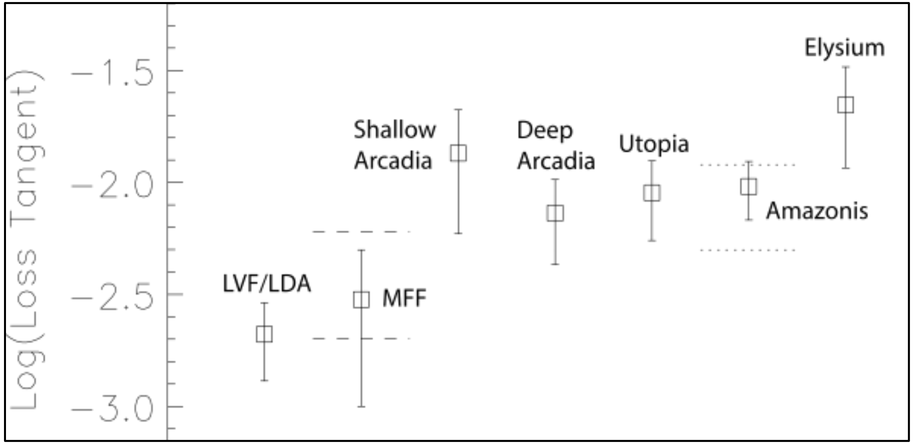
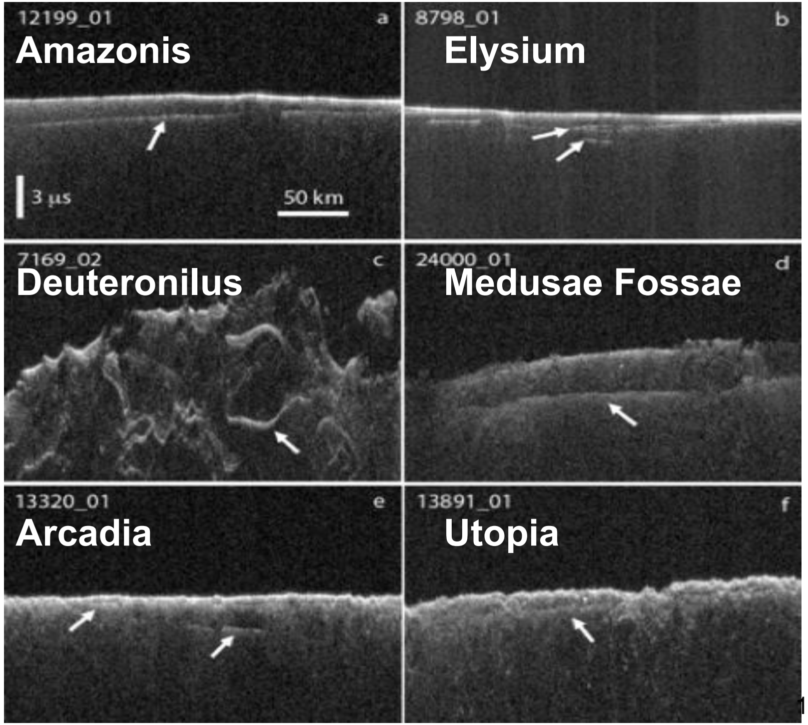
SHARAD losses in potentially ice-rich terrain

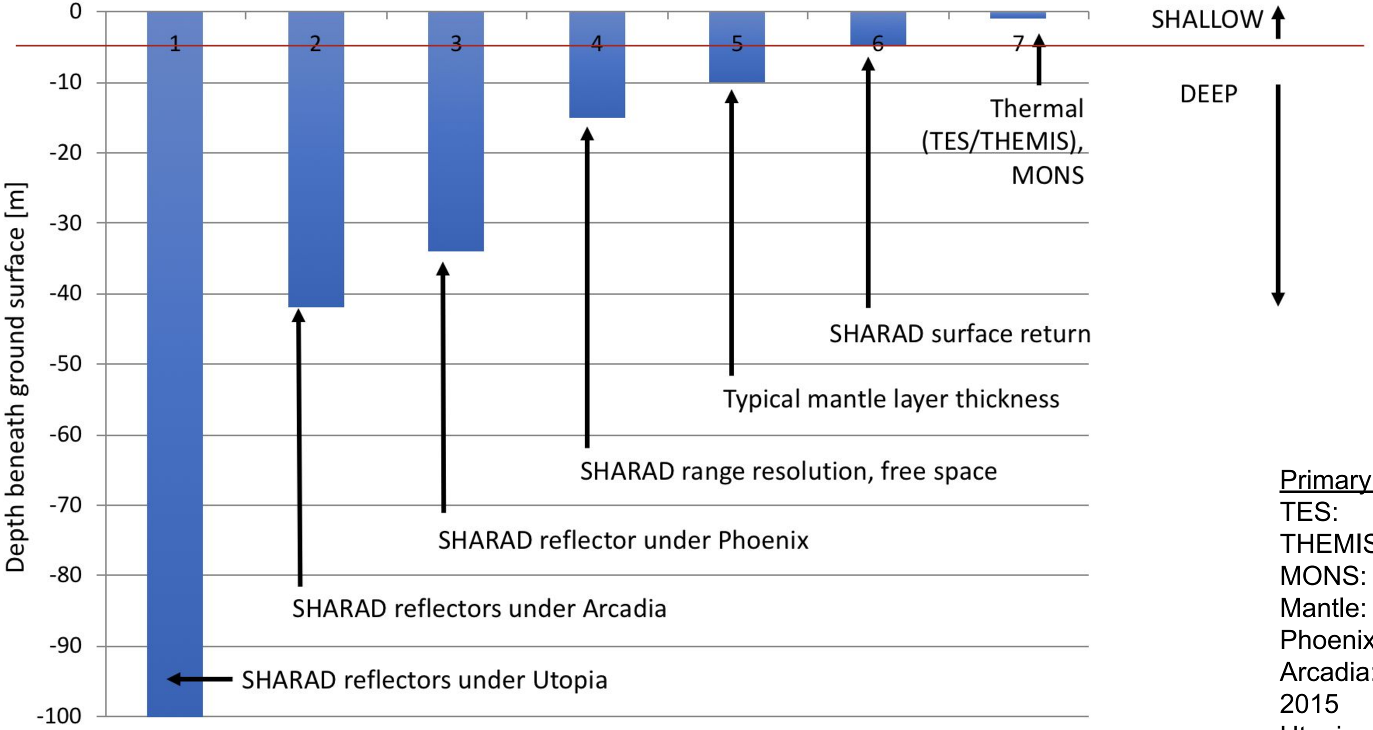
- Campbell & Morgan [2018] examined power vs. frequency to estimate radar loss tangent. **Sediments and rock have higher loss, water ice has lower loss.**
- Amazonis & Elysium results consistent w/ rock/dry sediments. LDA results indicate dominance by ice.
- Similar to LDAs, **Medusae Fossae may be ice-rich.** Similar to Amazonis, **Arcadia & Utopia may be devoid of <u>excess</u> ice.**





SWIM Approach to Mapping Ice

Our team is taking a multifaceted approach to assess the presence of buried ice:



<u>Primary method & data sources:</u>

TES:	Putzig and Mellon 2007
THEMIS:	Putzig et al. 2014a
MONS:	Pathare et al. 2018
Mantle:	Mustard et al., 2001
Phoenix:	Putzig et al. 2014b
Arcadia:	Bramson et al., 2015
Utopia:	Stuurman et al., 2016

SWIM Equation

We introduce **the SWIM Equation**, in the spirit of the famous Drake Equation.

$\mathbf{C_I} = (C_{IS} + C_{ID}) \div 2$ — Consistency of data with shallow & deep ice

$\mathbf{C_{IS}} = (C_N + C_T + C_{GS} + C_{RS}) \div 4$ — Consistency of data with shallow (< 5 m) ice

$\mathbf{C_{ID}} = (C_{GD} + C_{RD}) \div 2$ — Consistency of data with deep (> 5 m) ice

We establish **ice consistency values** for each data set:

C_N — Consistency of neutron-detected hydrogen with shallow (< 1 m) ice

C_T — Consistency of thermal behavior with (< 1 m) shallow ice

C_{GS} , C_{GD} — Consistency of geomorphology with shallow, deep ice (< , > 5 m)

C_{RS} , C_{RD} — Consistency of radar surface, subsurface returns w/ shallow, deep ice

Consistency values range between -1 and +1, where:

+1 means data is ***consistent*** with the presence of ice

0 means data is missing or gives no indications of ice presence or absence

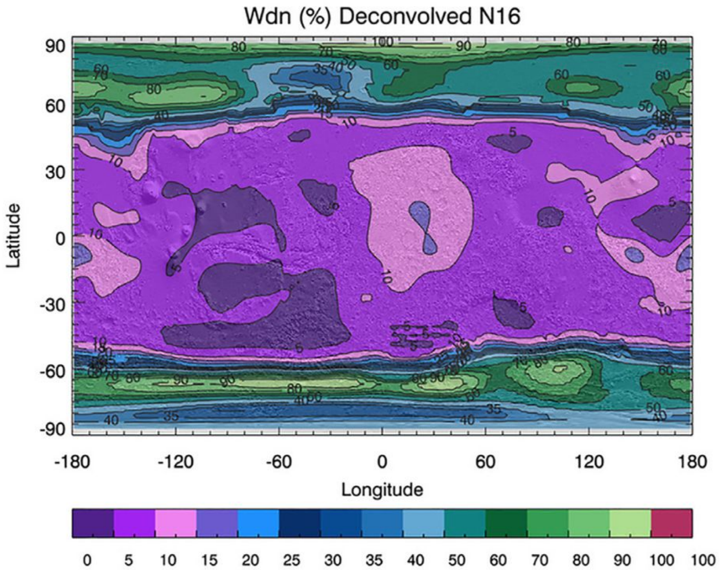
-1 means data is ***inconsistent*** with the presence of ice

C_N Neutron data

We use the latest mapping of water ice inferred from neutron-spectrometer data [Pathare et al., 2018].

Apart from converting to our consistency scale, we do not carry out any re-evaluation of this data set.

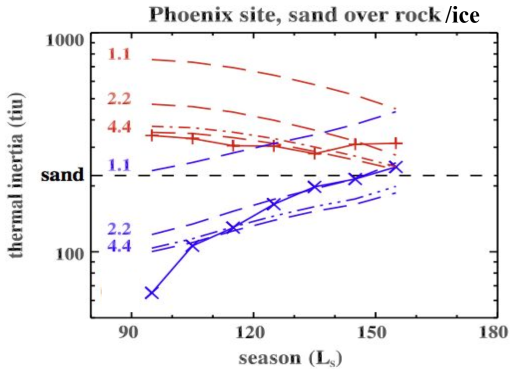
This data set provides one constraint on **the presence of shallow (< 1 m) water ice**, at latitudes ~ > 50°.



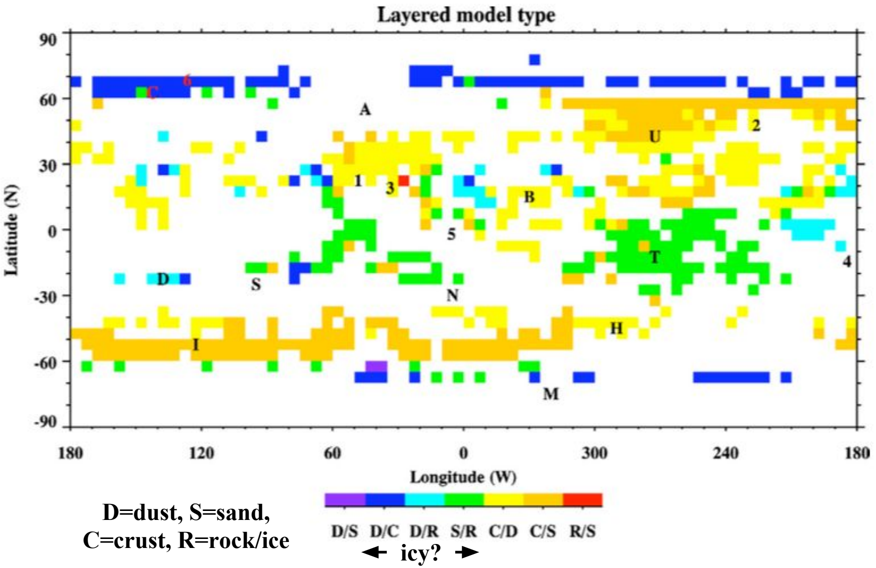
Global weight-percent concentration of water-equivalent hydrogen inferred from ODY MONS neutron spectrometer data [Pathare et al., 2018].

C_T Thermal Analysis

Seasonal variations in daytime & nighttime apparent thermal inertia (ATI) can be related to **layering of materials in the shallow (< 1 m) subsurface**. We use methods of Putzig and Mellon [2007], improving model coverage and resolution.



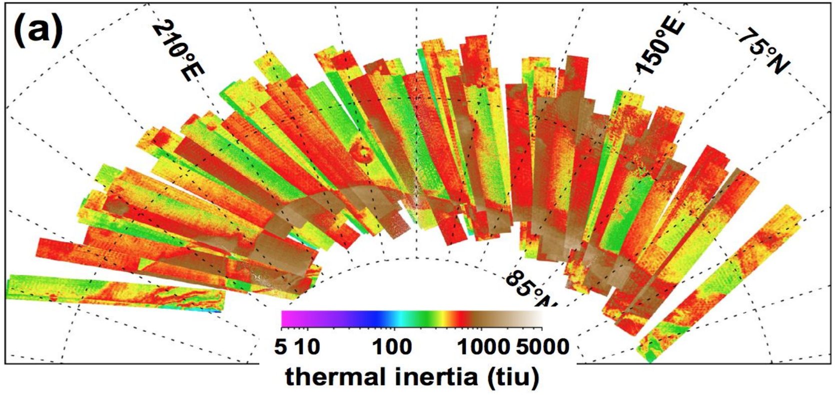
Above: *TES (×,+ symbols) and modeled seasonal thermal inertia for the Phoenix site at 2AM (blue) and 2PM (red). Labels give upper-layer thickness in cm. Seasons limited by CO_2 ice. Best fit (dash–dot curves) yield an upper-layer thickness of 4 cm of sand over 'rock' (thermally same as ground ice), matching that observed by the lander.*
Left: *Global map of best-fitting two-layer model types at 5° per pixel for TES apparent thermal inertia.*
Putzig and Mellon [2007].

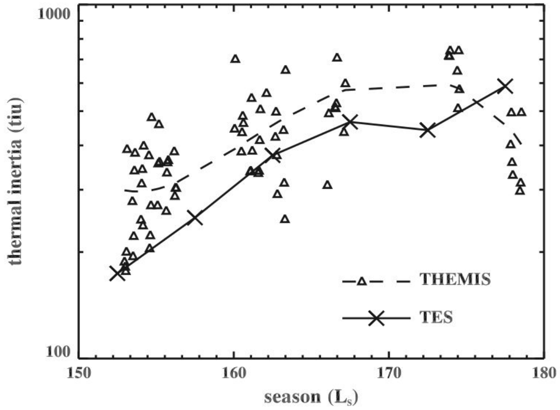


C_T Thermal Analysis

Following the methods of Putzig et al. [2014a] for the north polar erg, **we use mosaics of THEMIS images** to evaluate seasonal trends in nighttime ATI and compare against TES results.

- ATI can vary dramatically from one image to another, resulting in large seasonal scatter.
- This effect is not seasonal nor does it follow atmospheric opacity trends.
- Nevertheless, correspondences to TES trends help distinguish layering from other types of heterogeneity.





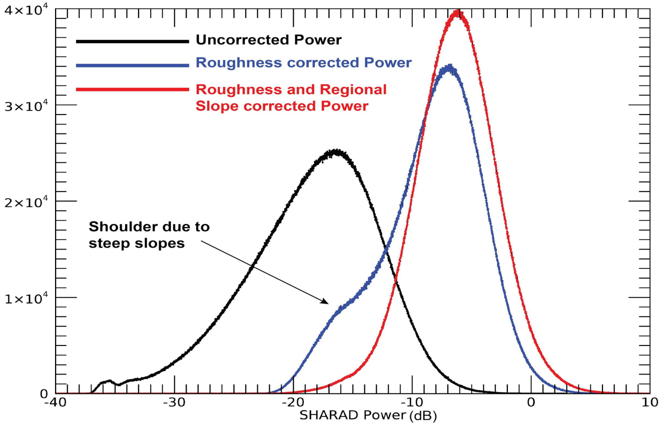
Above: *Mosaic of 77 THEMIS ATI images of Olympia Undae (north polar erg).*
Right: *Comparison of median values of THEMIS ATI images vs. season with that from TES data.*
Putzig et al [2014a].

C_{RS} Surface Reflections

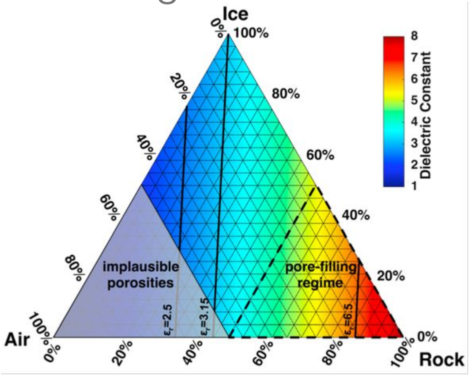
Fresnel reflectivity is related to dielectric properties and density of the shallow (< 5 m) subsurface.

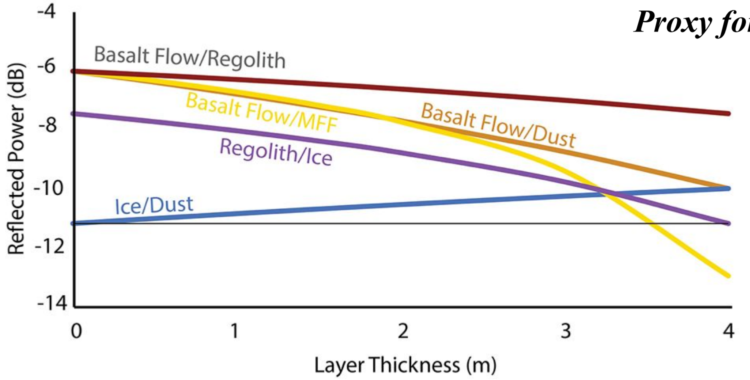
It is thus possible to isolate **the signature of ice in low power surface returns**, due to its low density.

However, ice mixed with other materials becomes indistinguishable from other dry mixtures.



Correcting Surface Power to Isolate a Proxy for Fresnel Reflectivity.



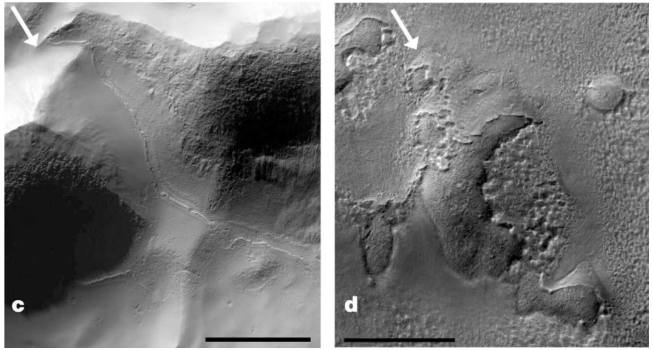


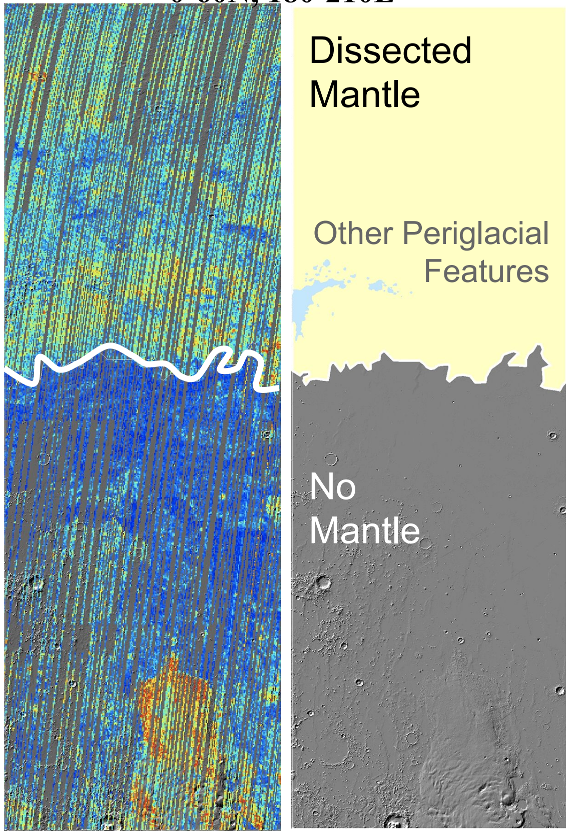
C_{GS} Shallow Geomorphology

First Order: We use the presence and nature (dissected/smooth) of the Latitude Dependent Mantle (LDM) to assess possible presence of ice.

We then use SHARAD Roughness Parameter [Campbell et al., 2013], which is sensitive to slopes over length scales 10 - 100 m, to define the boundary between dissected/no mantle.

Second Order: We incorporate additional high resolution image (HiRISE/CTX) data to identify other periglacial landforms.





We map large scale, distinctive landforms > 20 km in extent to determine the likelihood of ice >5 m.

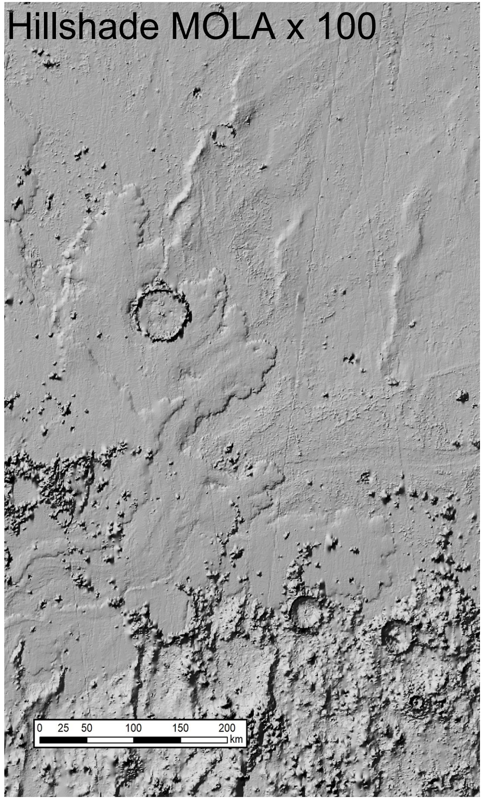
First Order:

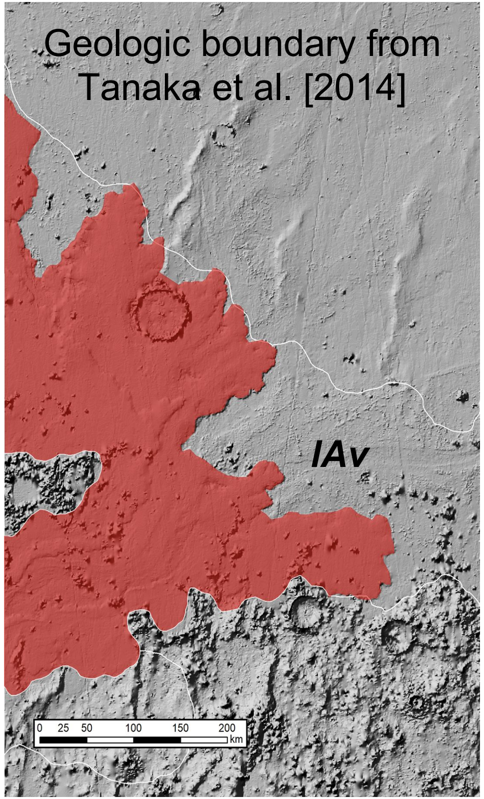
Lava Flows (Ice-Free)

Defining Properties: Found within volcanic terrains, as mapped by Tanaka et al (2014). Consist of elongated, flat topped features with well defined convex margins. 5 - 10s of meters thick.

Lobate Debris Aprons (Ice-Rich).

Lobate deposits extending from topographic high-stands (mesas and cliffs). 10s - 100s of meters thick.

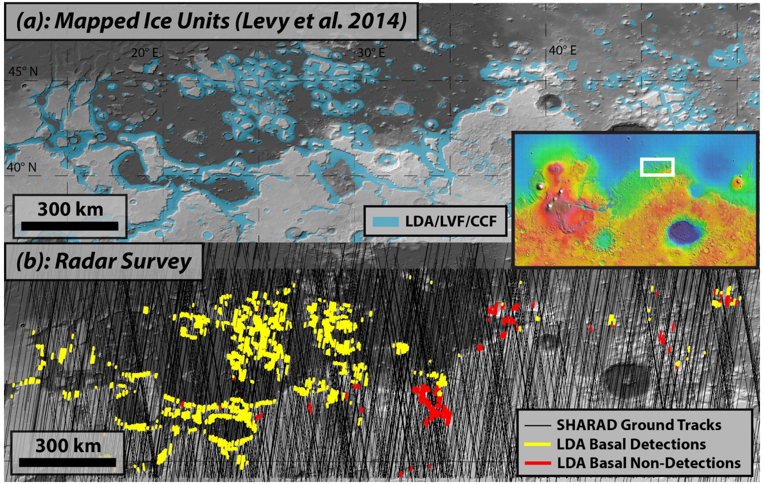




C_{RD} Subsurface Reflections

Following the methods of many prior studies [e.g., Putzig et al., 2014b; Bramson et al., 2015; Stuurman et al., 2016; Petersen et al., 2018], we use grids of SHARAD profiles (radargrams) to map out **subsurface interfaces that may be related to the base of buried ground ices and glaciers.**

We then **seek locations where elevation data allows a depth constraint** to be placed on the delay-time data, yielding values of dielectric permittivity, for which low values may indicate water ice.



Analysis of SHARAD reflectors for LDA and similar features in Deuteronilus Mensae by Petersen et al. [2018].

Pilot Study Swaths
+ice stability, detections

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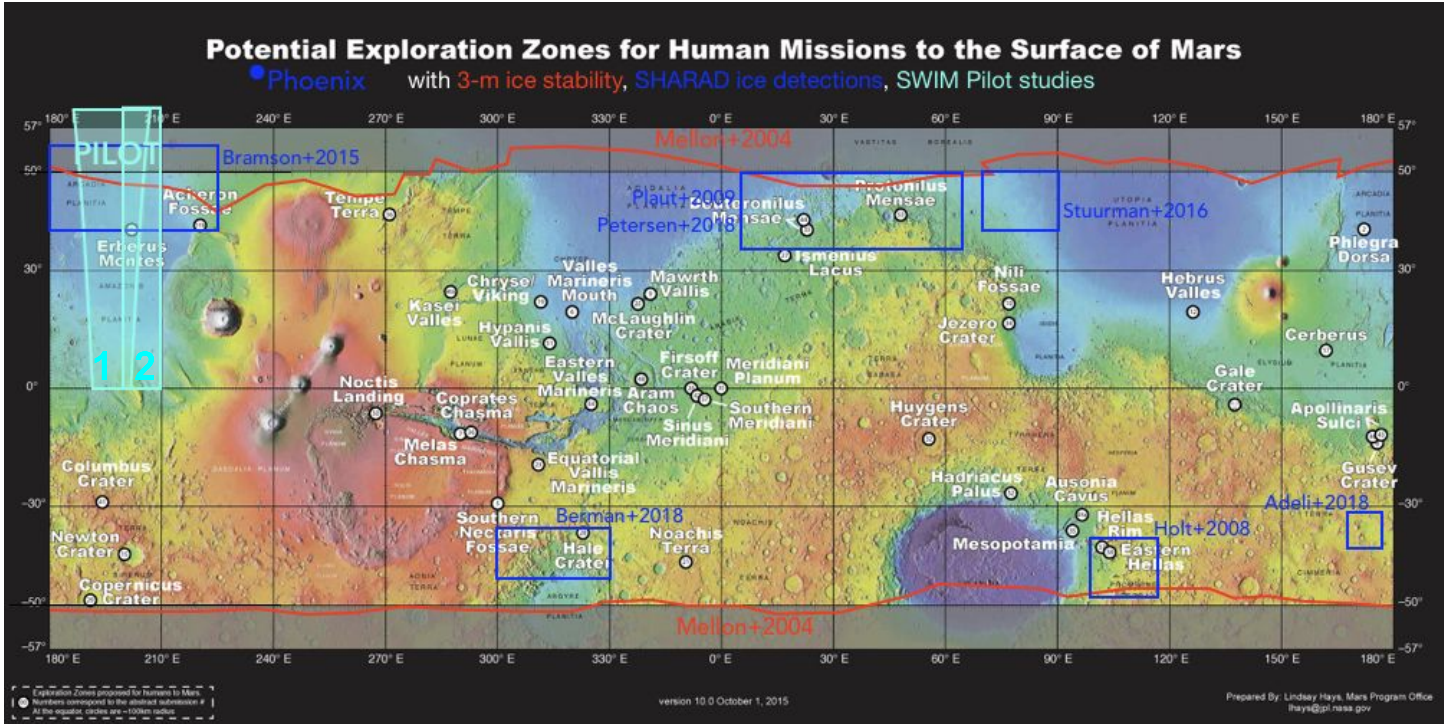

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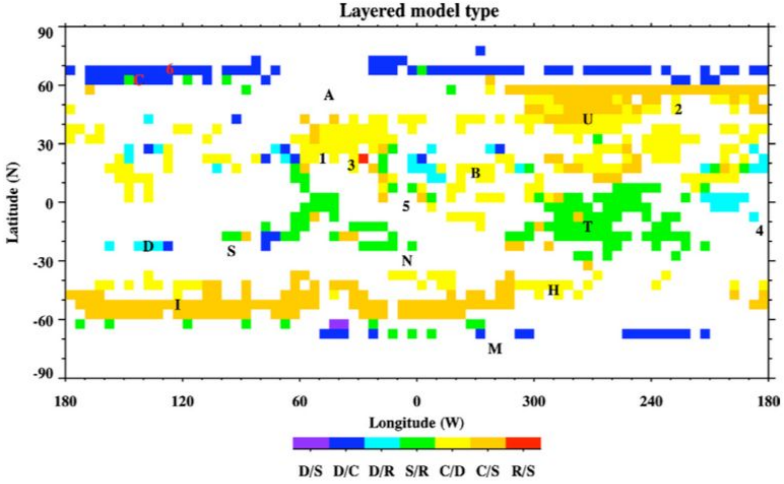
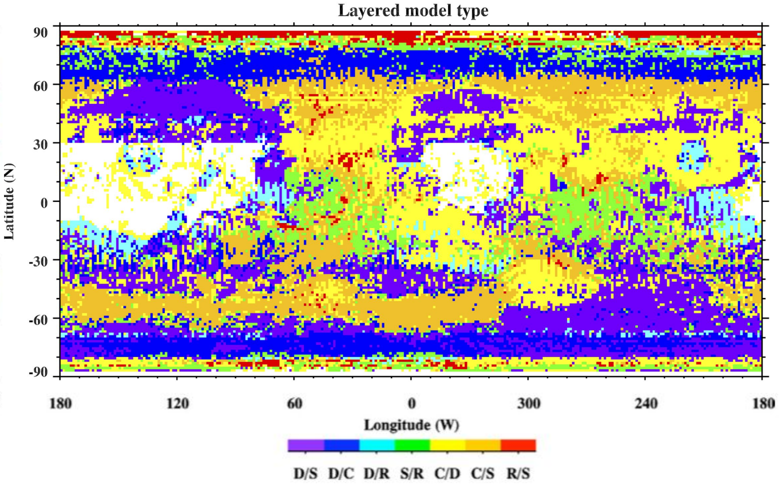
Thermal Analysis: TES Global

Putzig+Mellon [2007]



This work



Global maps at 5° per pixel (left) and 1.25° per pixel (right) for two-material layering, showing model types corresponding to TES seasonal and diurnal thermal-inertia results.

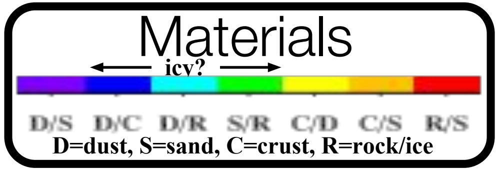
Model components are D: dust; S: sand; C: duricrust; and R: rock. Locations for landers, study sites by Putzig and Mellon [2007] are shown on their map as 1: Viking Lander 1; 2: Viking Lander 2; 3: Mars Pathfinder Lander; 4: MER-A (Gusev); 5: MER-B (Meridiani); 6: Phoenix Lander Box 1; A: Acidalia; B: Arabia Terra; C: Scandia Colles; D: Daedalia Planum; H: Hellas Planitia; I: Icaria; M: Melas Planum; N: Noachis Terra; S: Solis Planum; T: Tyrrhena Terra; and U: Utopia Rupes.

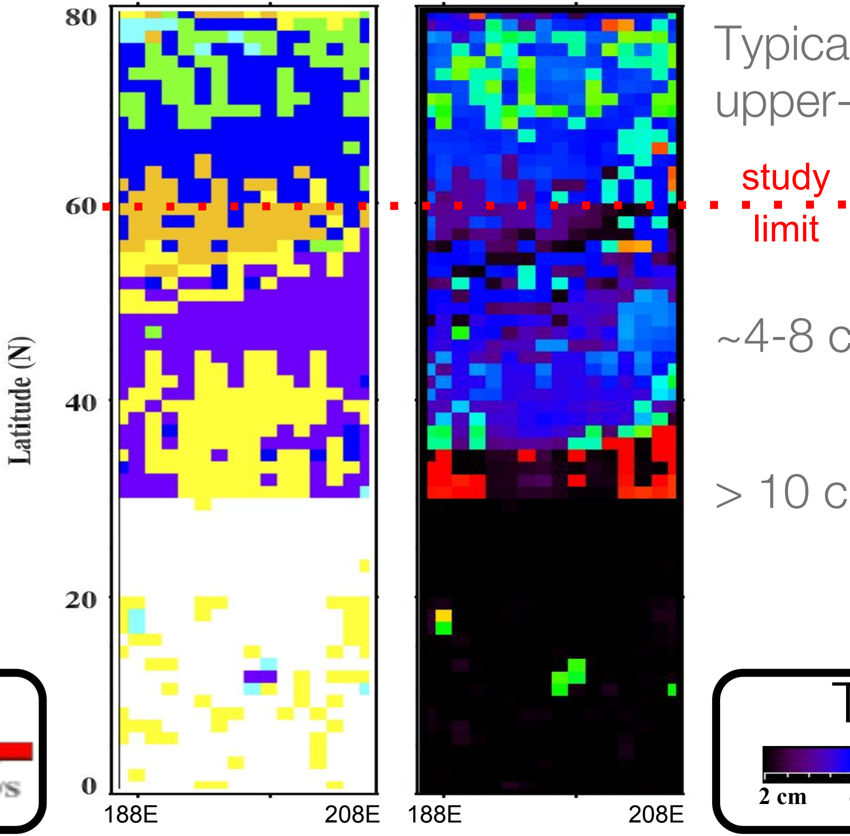
Thermal Analysis: TES

Poleward of 60°N, model fits consistent with buried ice (blues, green) are ubiquitous.

With new mapping, a few patches of ice model fits extend southward to ~30°N.

Purple areas have poor or ambiguous fits.

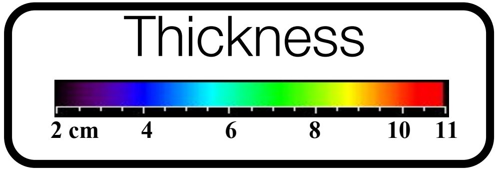




Typical modeled upper-layer thicknesses:

~4-8 cm in areas > 39°N

> 10 cm in areas < 39°N

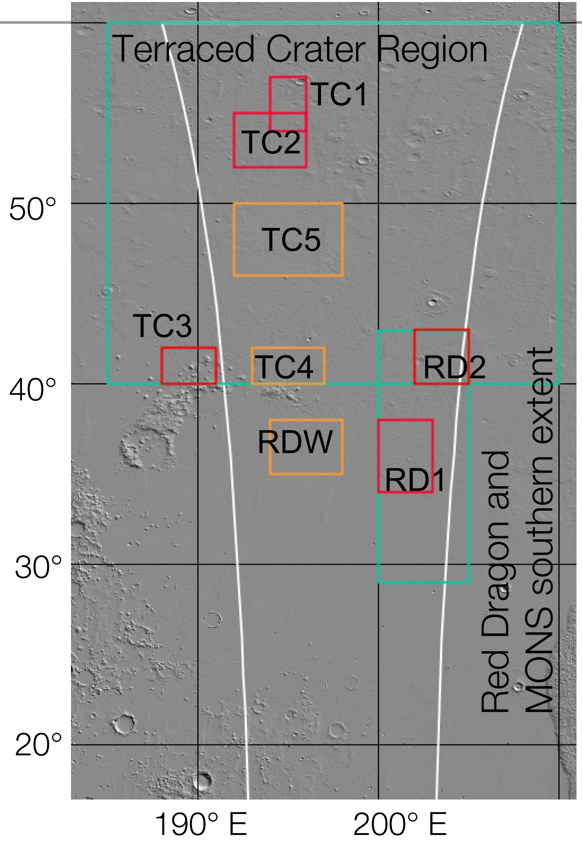


Thermal Analysis: THEMIS

Green boxes show **two primary study regions**

- Upper region contains many terraced craters from Bramson et al. [2015] and shallow ice per the Mars Orbiter Neutron Spectrometer (MONS).
- Lower region contains proposed Red Dragon landing site and the southernmost extent of ice within 1 m of the surface per MONS [Pathare et al., 2018].

We have carried out derivation of apparent thermal inertia from available THEMIS surface-temperature observations in these areas and have evaluated their **seasonal variations in 8 focus areas**.

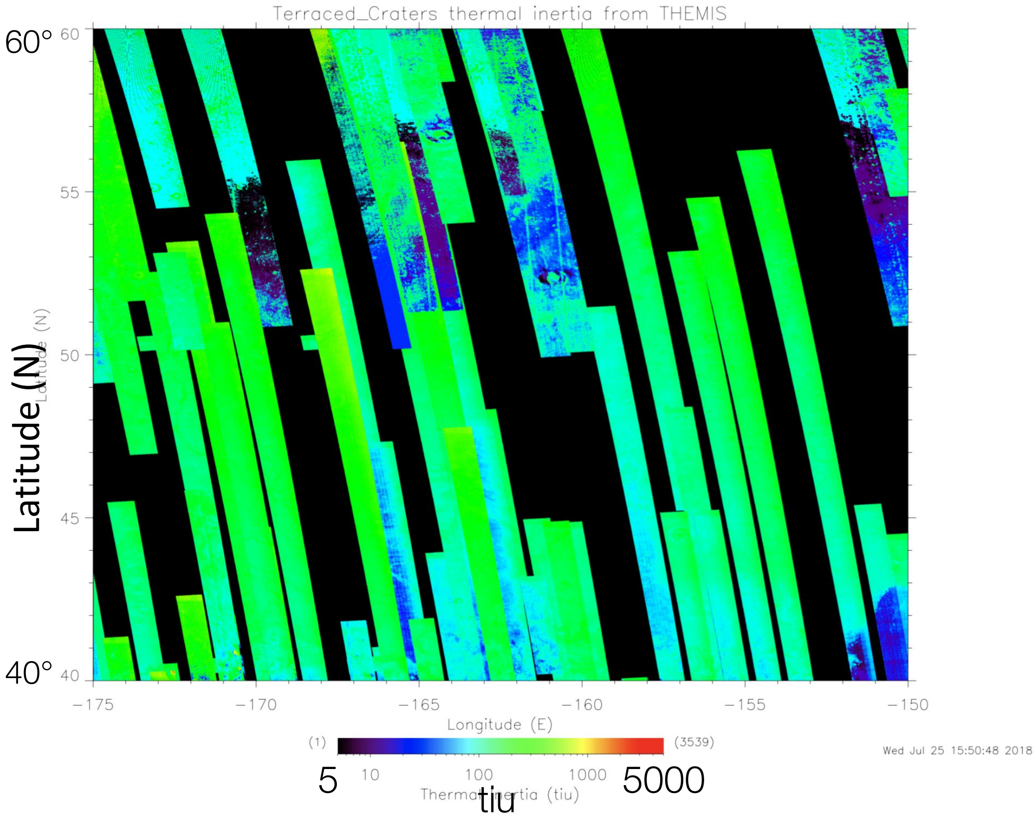


Analysis of focus areas in red was complete at mid-term review. Focus areas in orange were added subsequently.

THEMIS Terraced Crater Region

Uncalibrated THEMIS mosaic of Terraced Crater Region

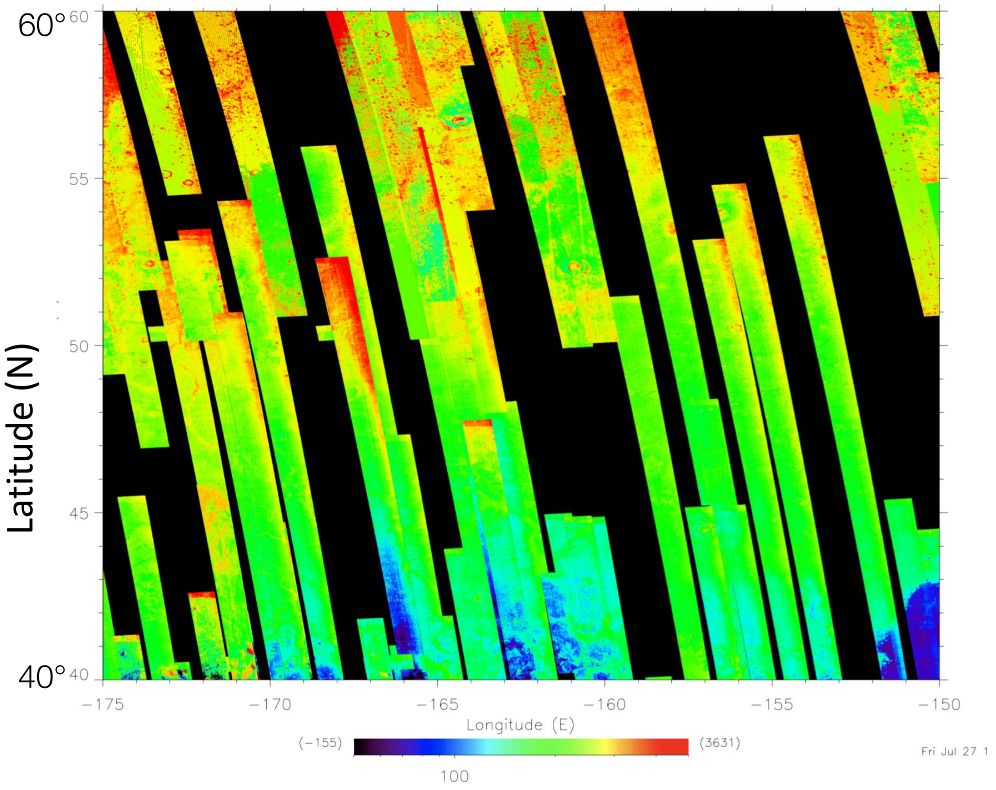
- As noted by previous authors, overall apparent thermal inertia can vary dramatically from one image to another.
- This effect does not appear to be a direct results of seasonal or opacity trends, resulting in large seasonal scatter.
- Coverage is relatively sparse in Arcadia Planitia.



Thermal Analysis: THEMIS

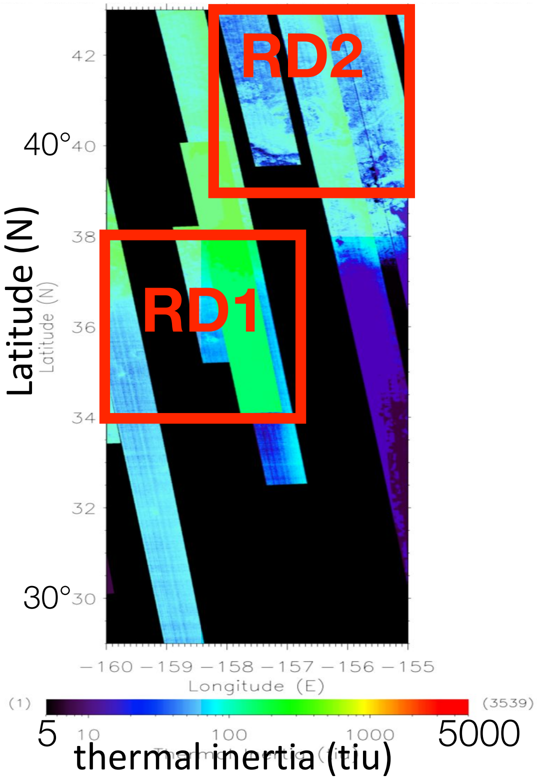
Calibrated THEMIS mosaic of Terraced Crater Region

- We created calibrated and uncalibrated mosaics of both study regions
- We created similar products for each focus area
- Focus areas were selected based on locations with maximum seasonal coverage and direct THEMIS image overlap

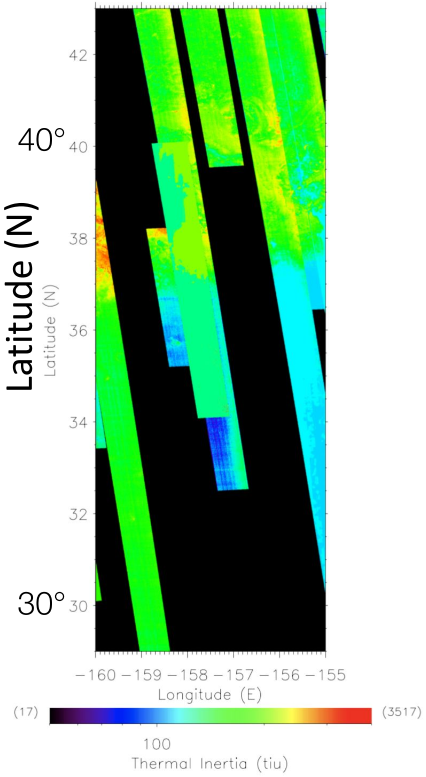


THEMIS MONS & Red Dragon areas

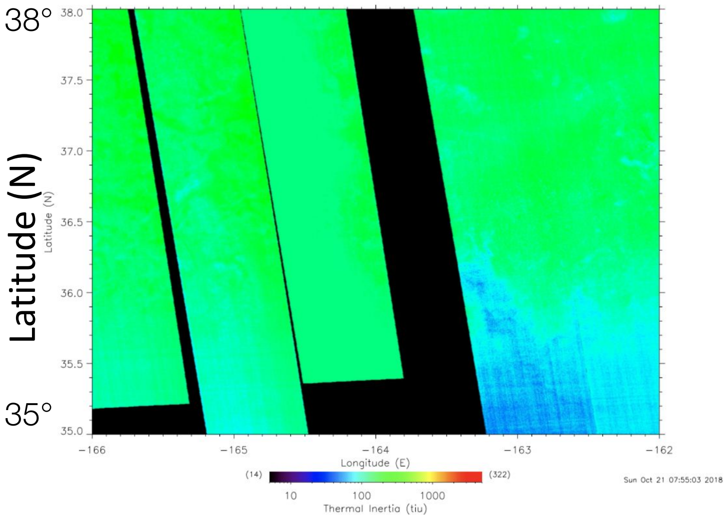
RD Uncalibrated



RD Calibrated, stretched



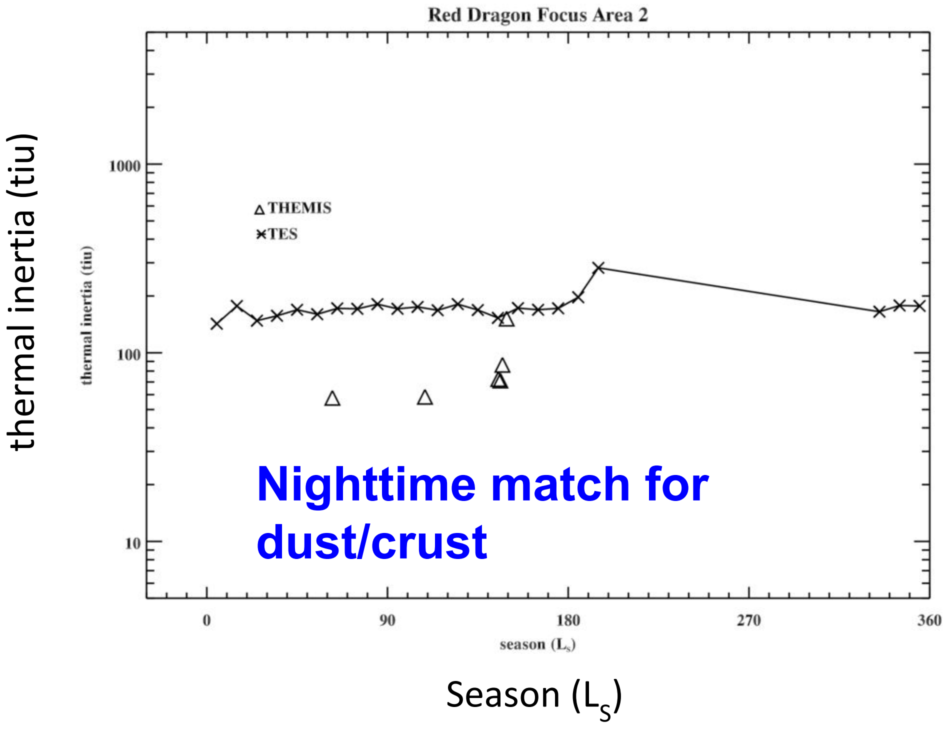
RD West, Uncalibrated

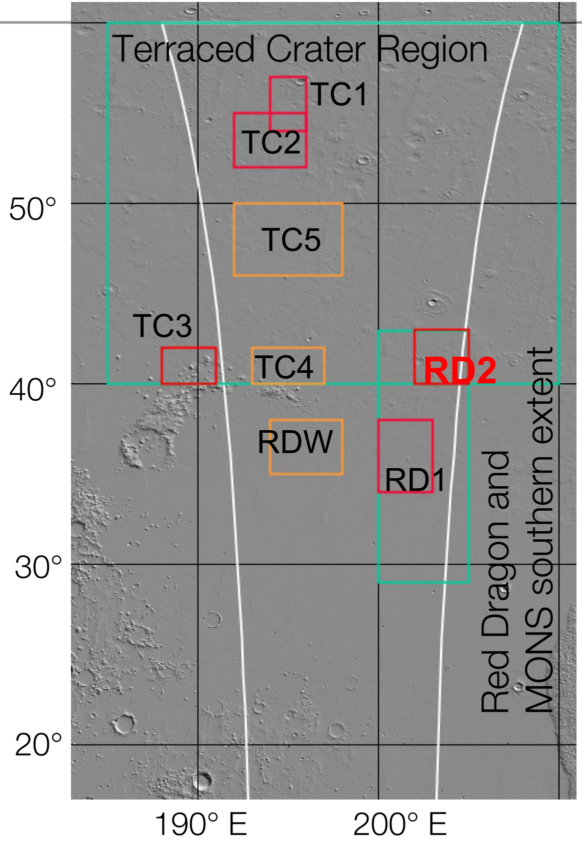


THEMIS mosaics covering the Red Dragon focus areas

THEMIS Focus Area Analysis

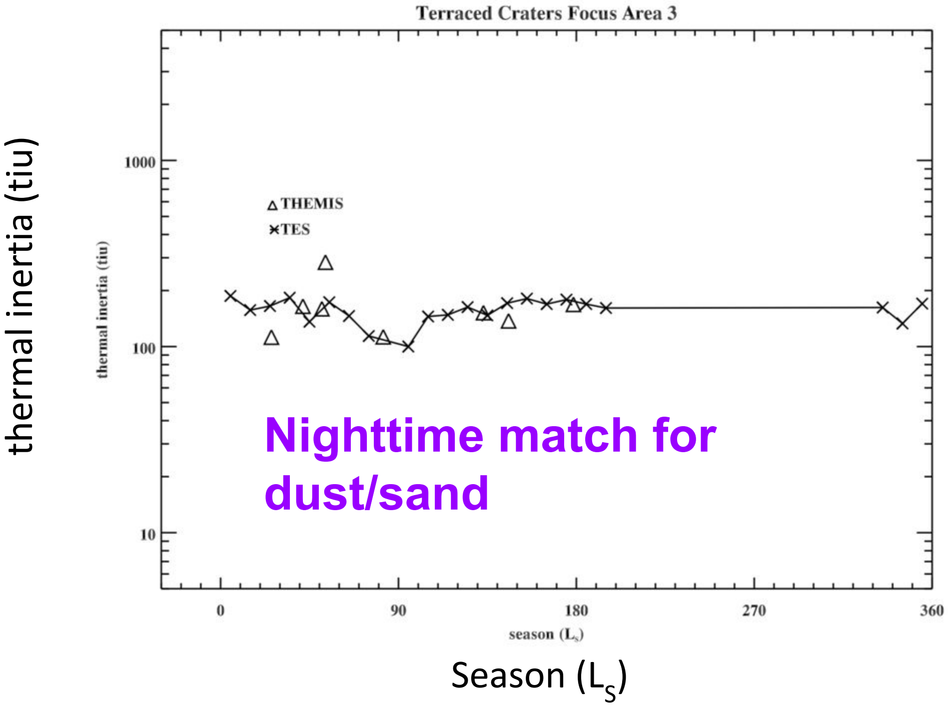
Red Dragon Area 2 : 202-205E, 40-43N

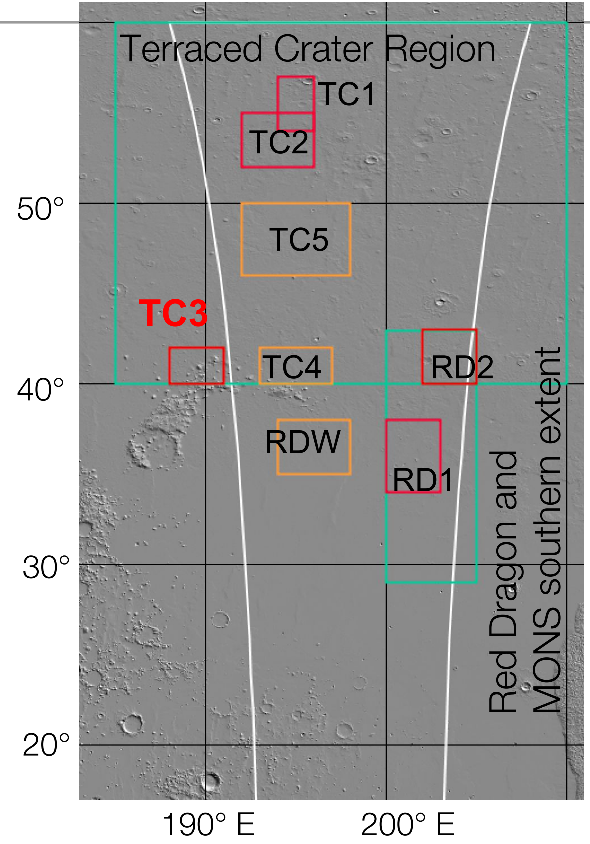




THEMIS Focus Area Analysis

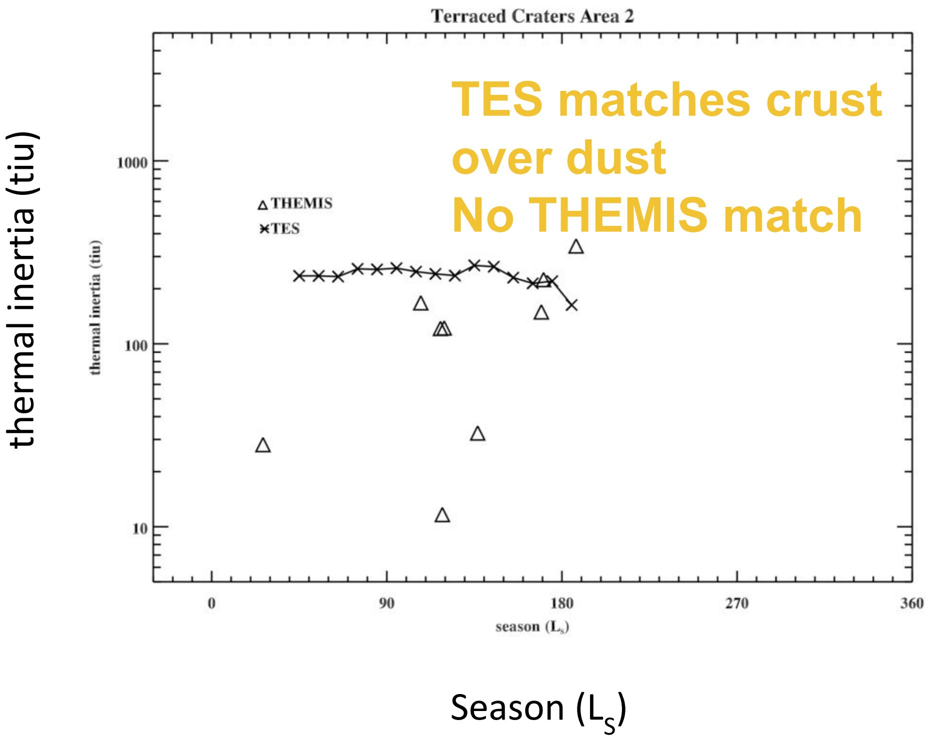
TC focus area 3: 188-191E, 40-42N

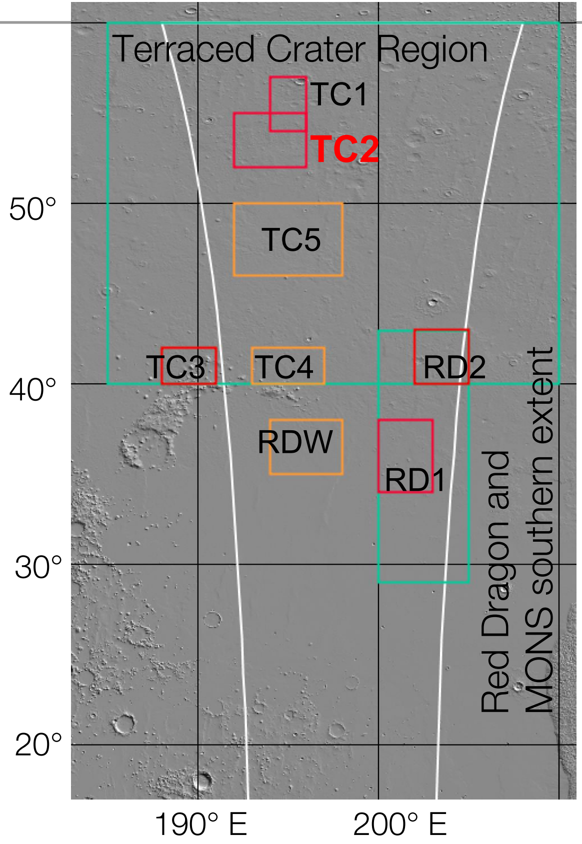




THEMIS Focus Area Analysis

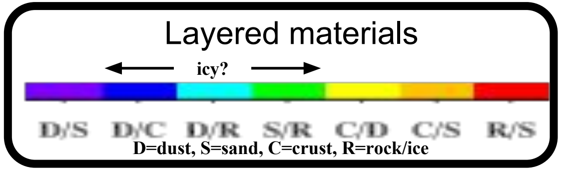
Terraced Craters Area 2 : 193-196E, 52-55N

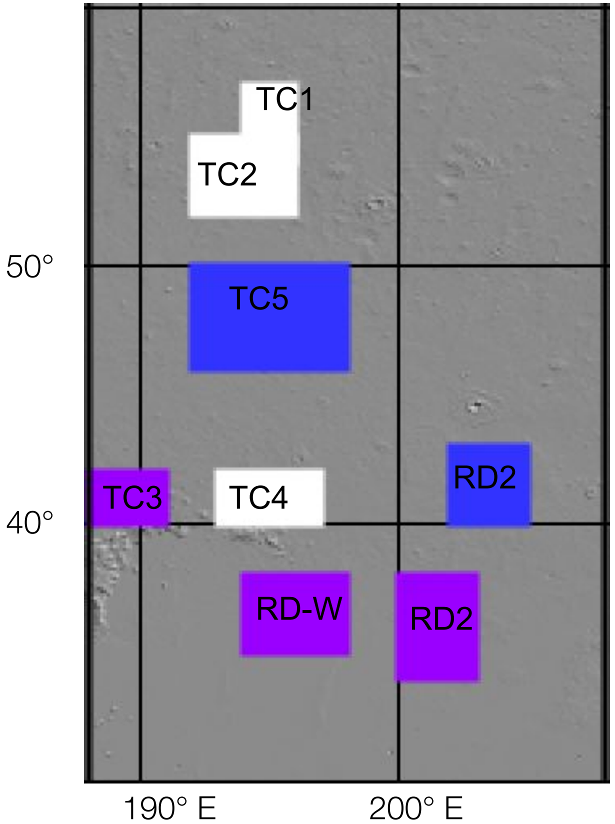




THEMIS materials map

- Colors indicate best heterogeneity match for THEMIS and TES, **nighttime data only**
- White areas indicate poor agreement between THEMIS and TES or no nighttime match found
- Only blue areas are consistent with ice





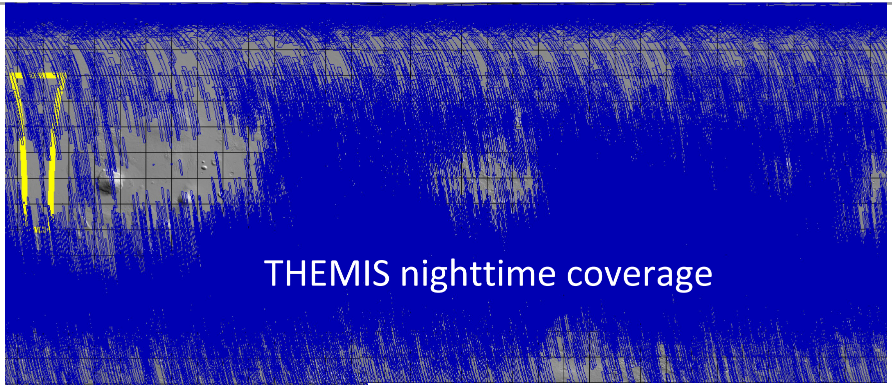
THEMIS Coverage

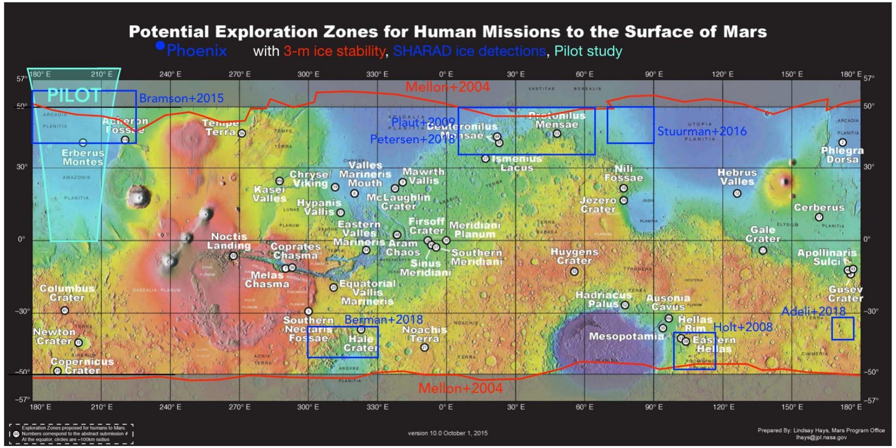
Sparse coverage was a challenge in Arcadia Swath:

- Between 60-75N
- Northern Tharsis
- Eastern Meridiani
-

Sparsity is predominantly in 10-30N zone where shallow ice is unlikely.

Ample coverage is available elsewhere.





Thermal Analysis
TES & THEMIS

Comparing observed and modeled seasonal ATI in Arcadia, we find isolated locations of subsurface layering consistent with shallow ice extending further south.

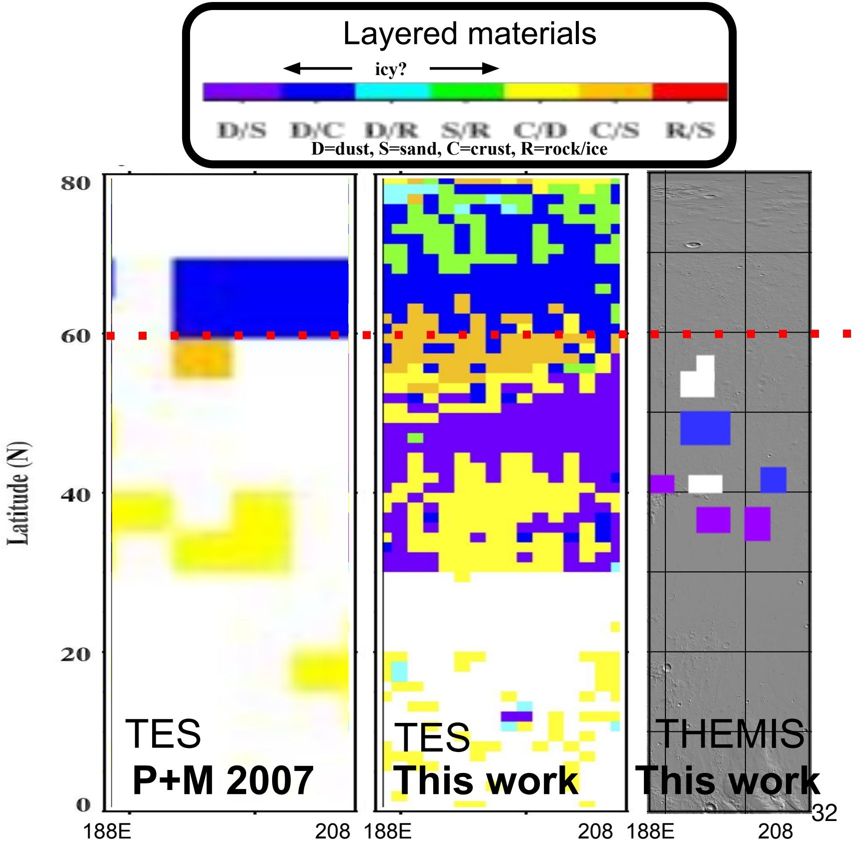
SWIM TES: improved resolution & infill of layer matches over full region

SWIM THEMIS: seasonal nighttime images, focused on areas of interest

TES/THEMIS differences:

THEMIS uses nighttime data only

TES uses day & night model match



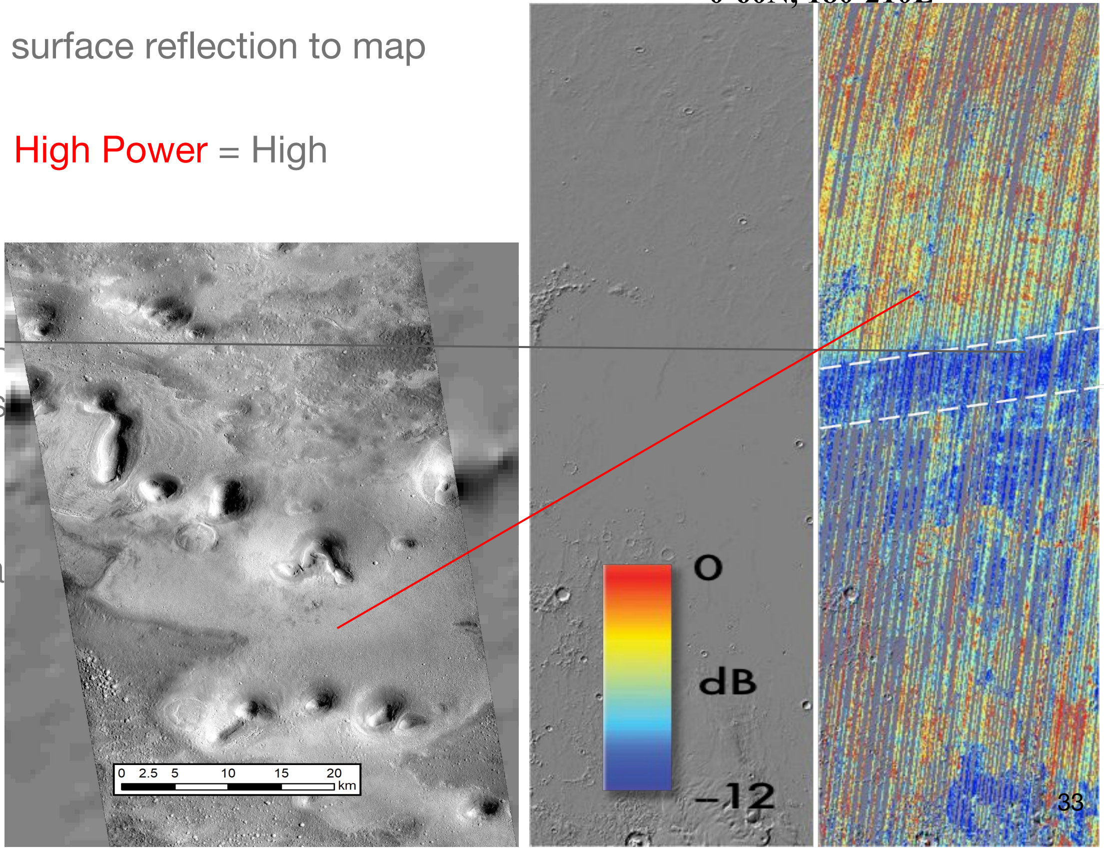
SHARAD Surface Reflections

New Technique corrects the SHARAD surface reflection to map density variations in the upper 5 m.

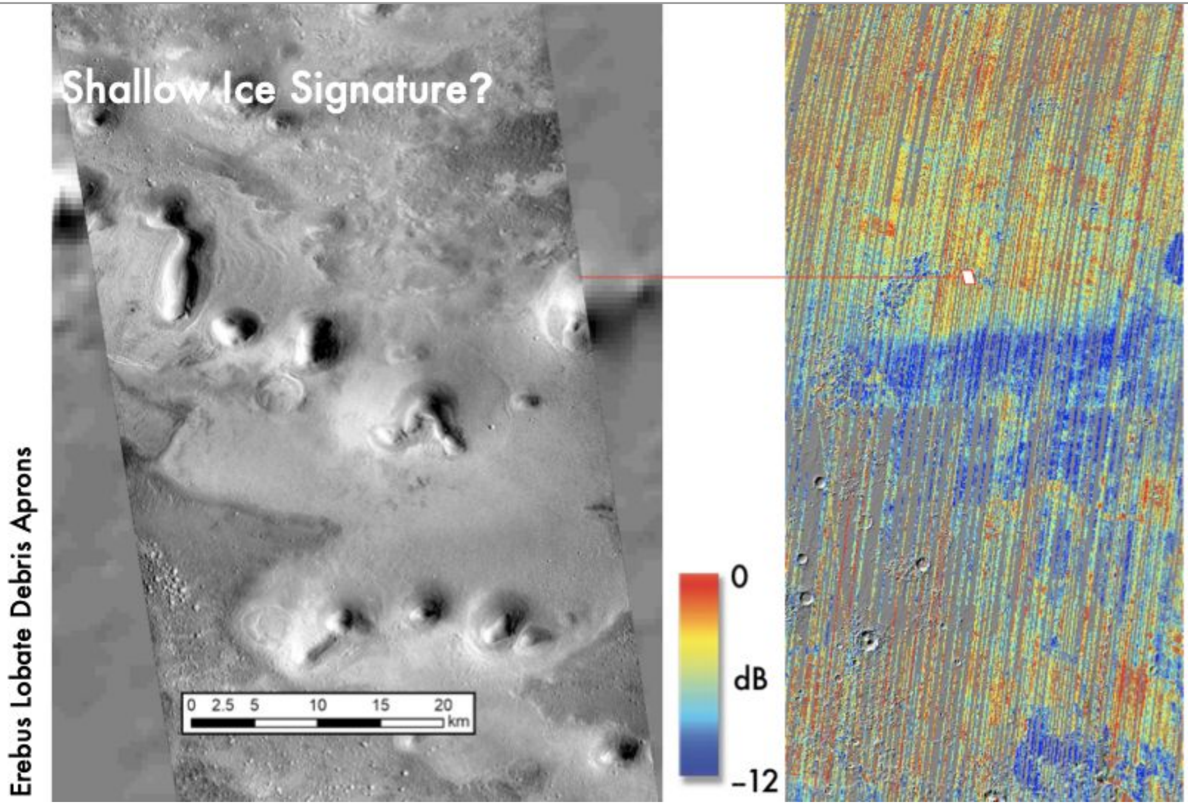
Low power = low density materials/ice. High Power = High density/rock

- Extensive low-power regions (indicator of low-density materials) are correlated with regions of known dust upwelling in northern Amazonis
- Further north in Arcadia, isolated low-power regions correlate with **periglacial** landforms, such as sma LDAs.
- We integrate **geomorphology** studies to aid the interpretation of the dataset.

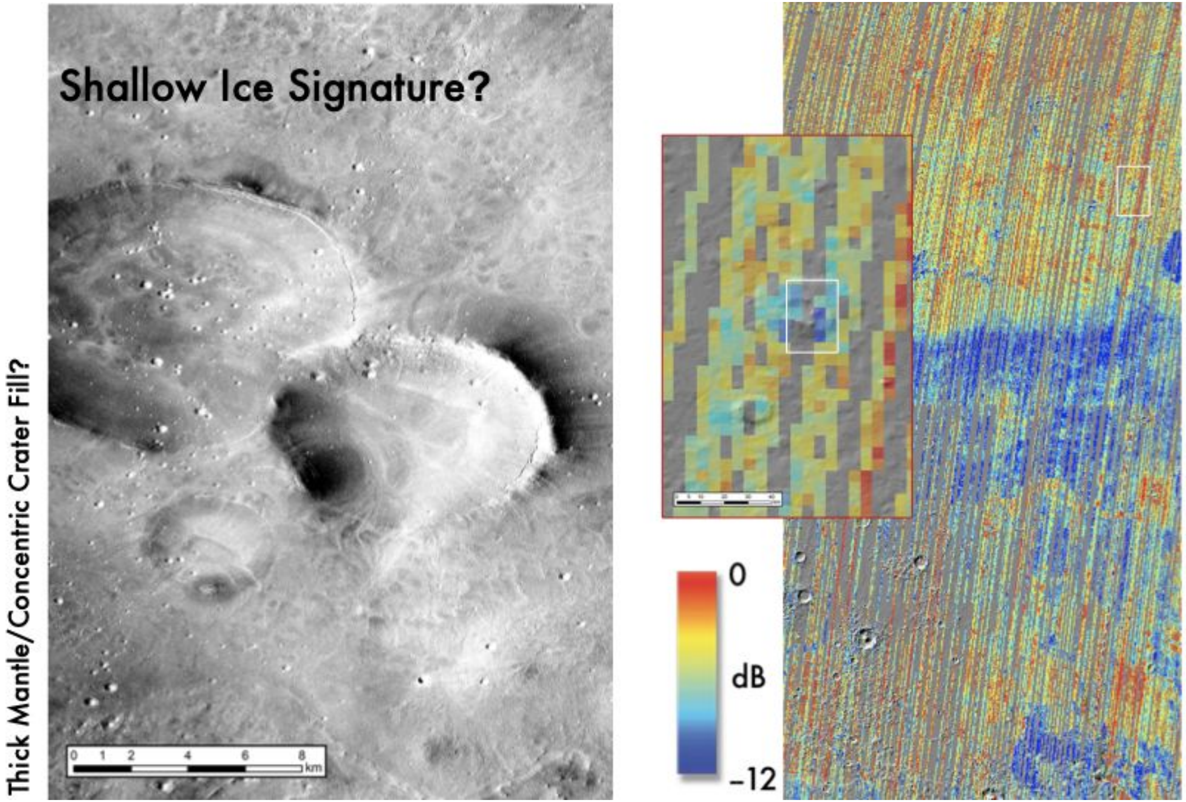
0-60N, 180-210E



SHARAD Surface Reflections

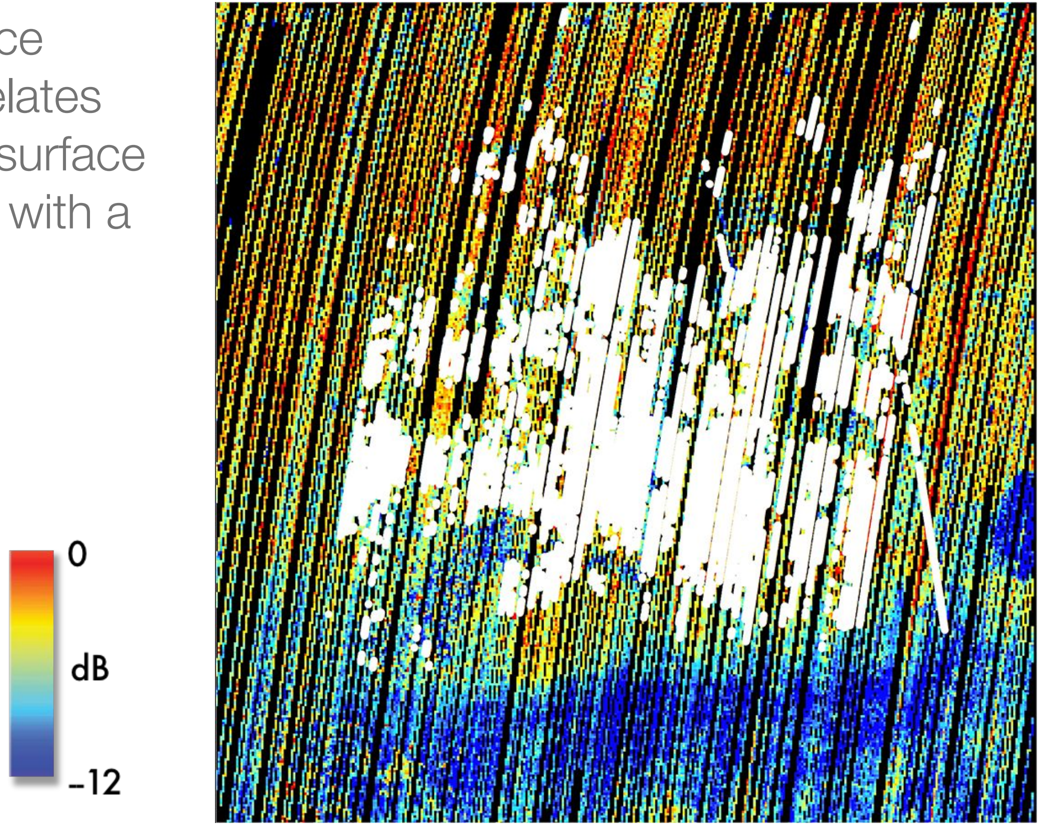


SHARAD Surface Reflections



SHARAD Surface Reflections

- SHARAD subsurface reflector map correlates with higher power surface returns, consistent with a dielectric > ice.



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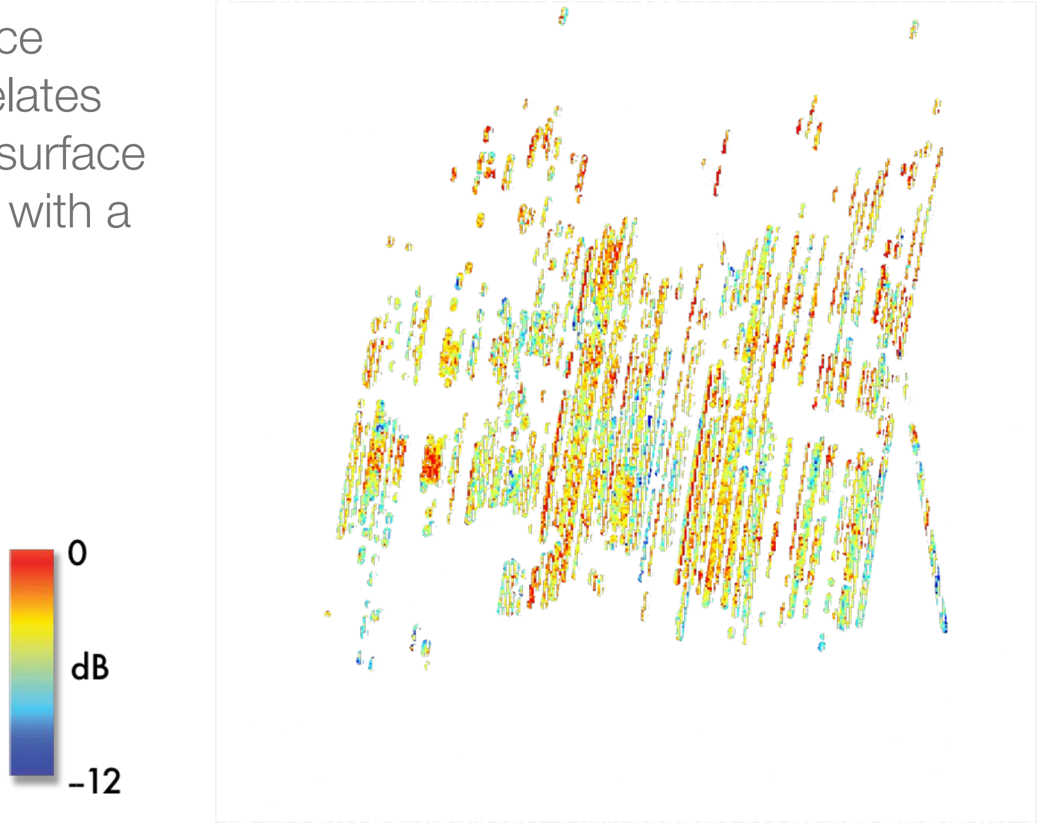
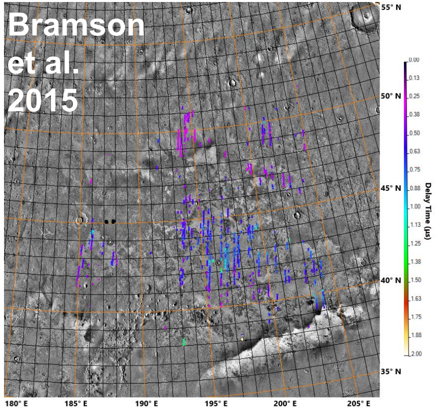
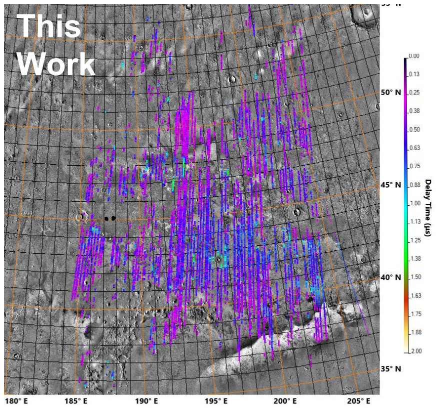


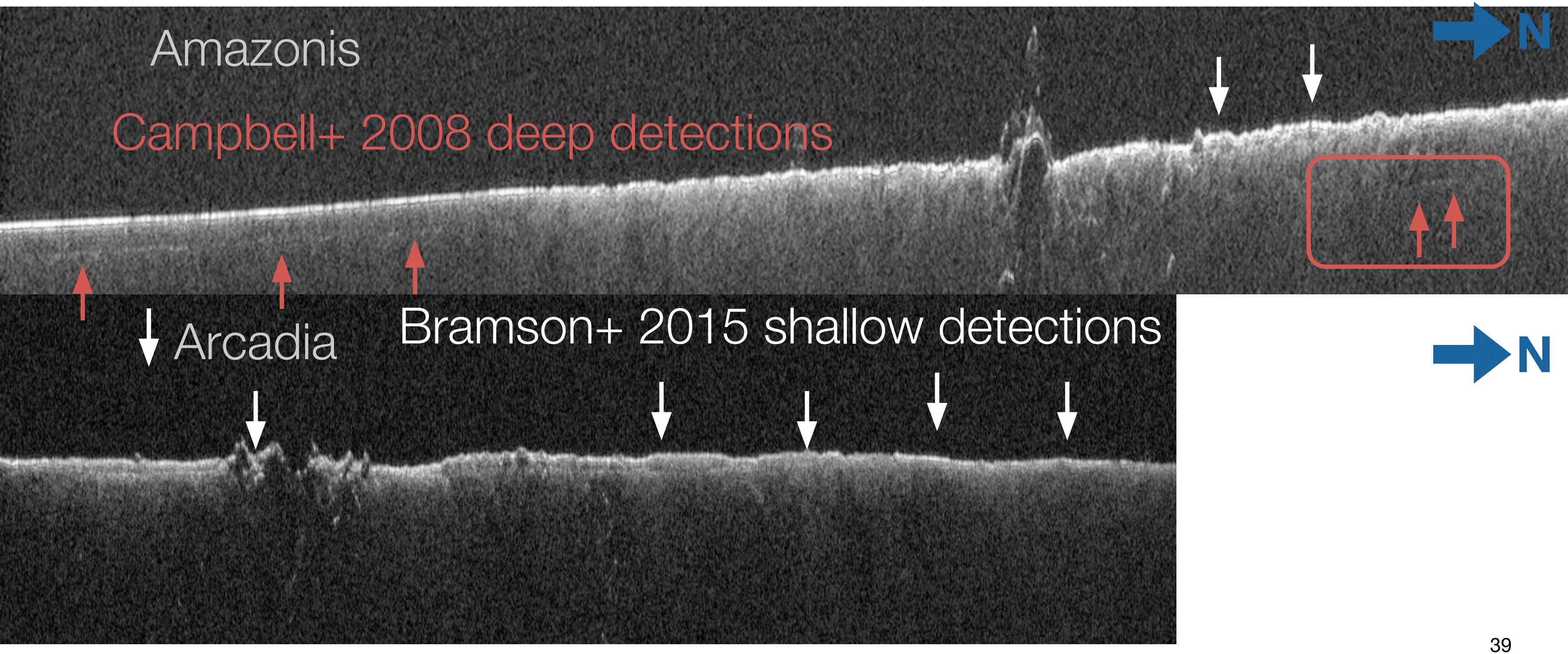
Subsurface Reflections

- We extended reflector mapping of Bramson et al. [2015], including southward extension to ~ 35.6°N.
- Using 19 more topographic features, we find real dielectric permittivity between 3 and 6, with a median of 5, above the shallow reflector.
- Revised permittivity value allows a large fraction of non-ice material* without ruling out ice presence.





* See also Campbell & Morgan [2018].



Amazonis
Campbell+ 2008 deep detections
N
Arcadia
Bramson+ 2015 shallow detections
N

Subsurface Reflections

- Map shows depth from surface to the shallow reflector using a dielectric value of 4.5±1.2, the average from 23 features.

- **Features used to calculate dielectric:**

Mesa

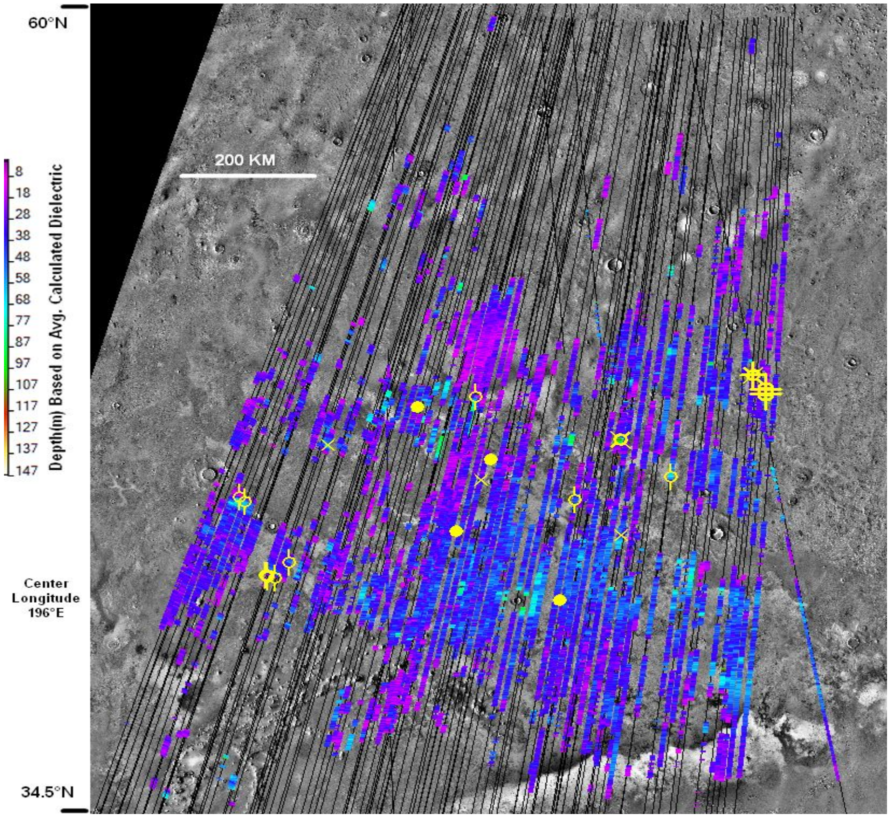
Terraced Crater [B+2015]

Hill

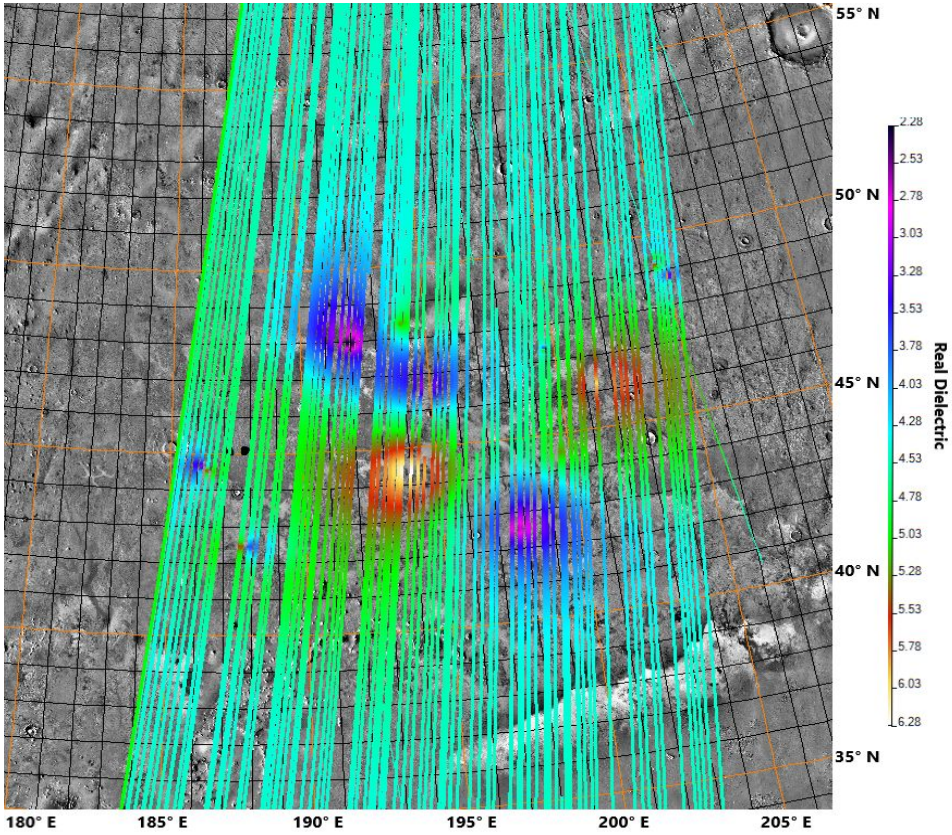
Valley

Dome

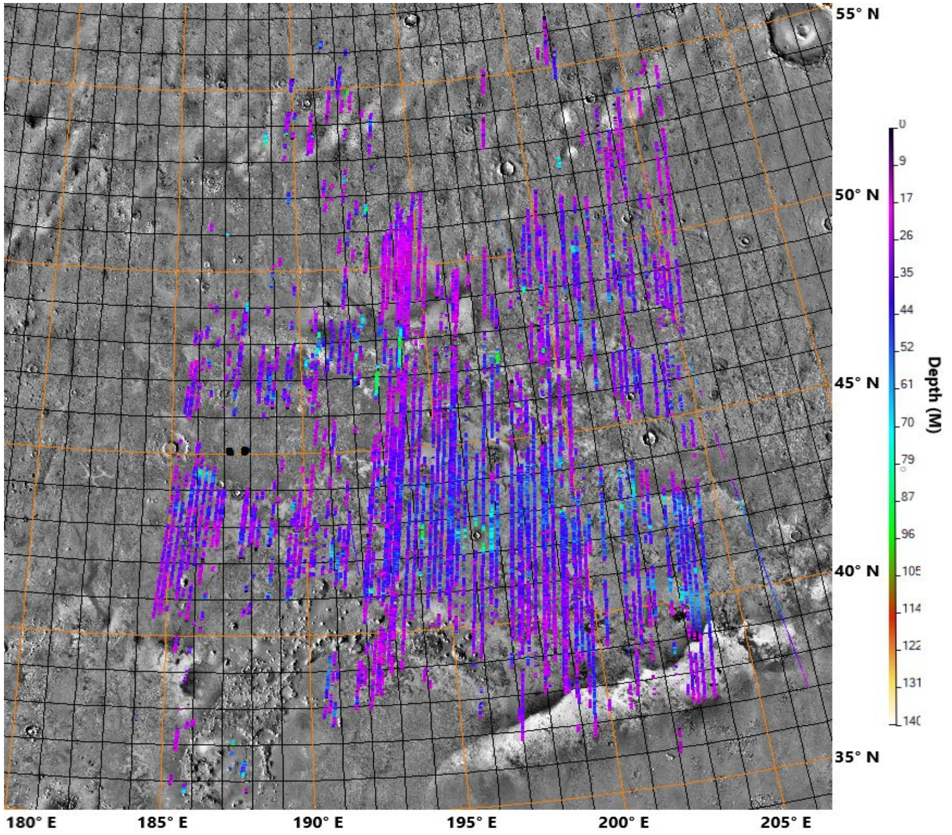
Pedestal Crater



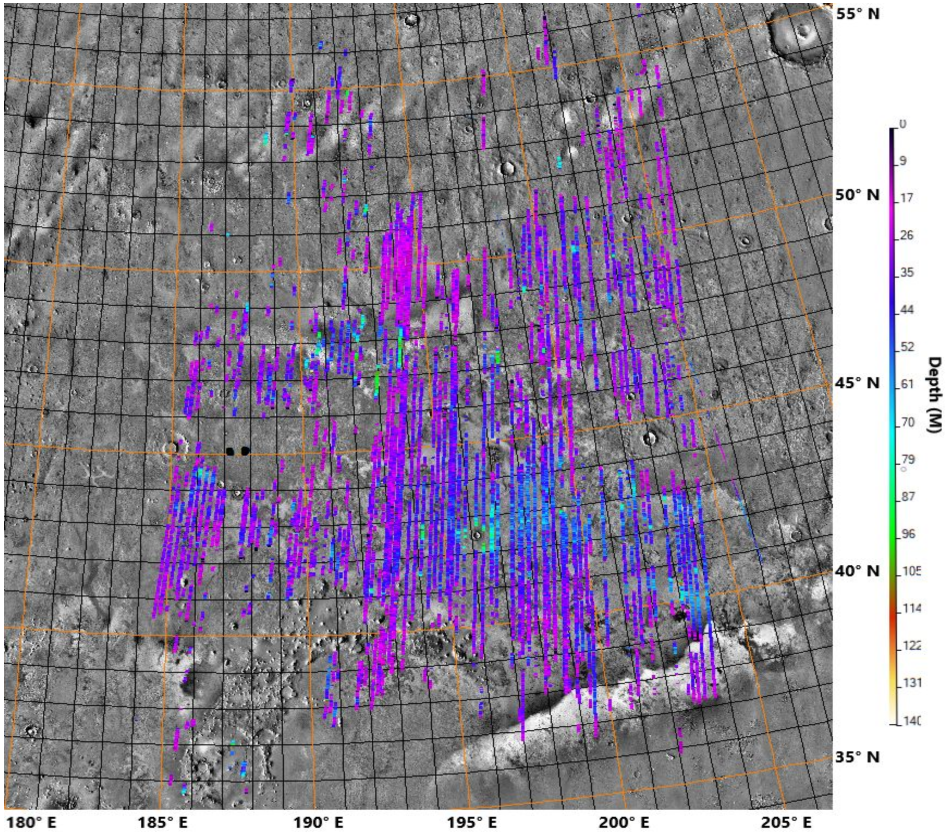
Interpolated & Extrapolated Real Dielectric

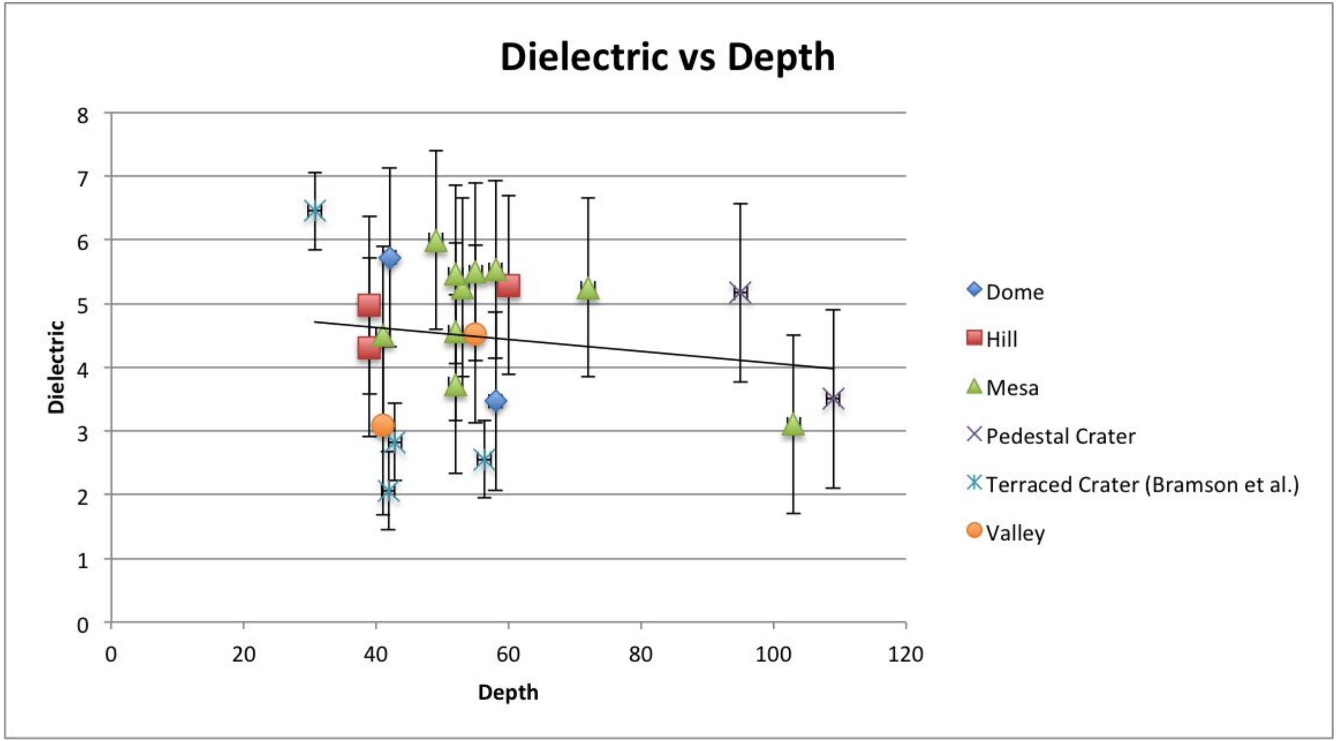


Depth Derived from Average Dielectric

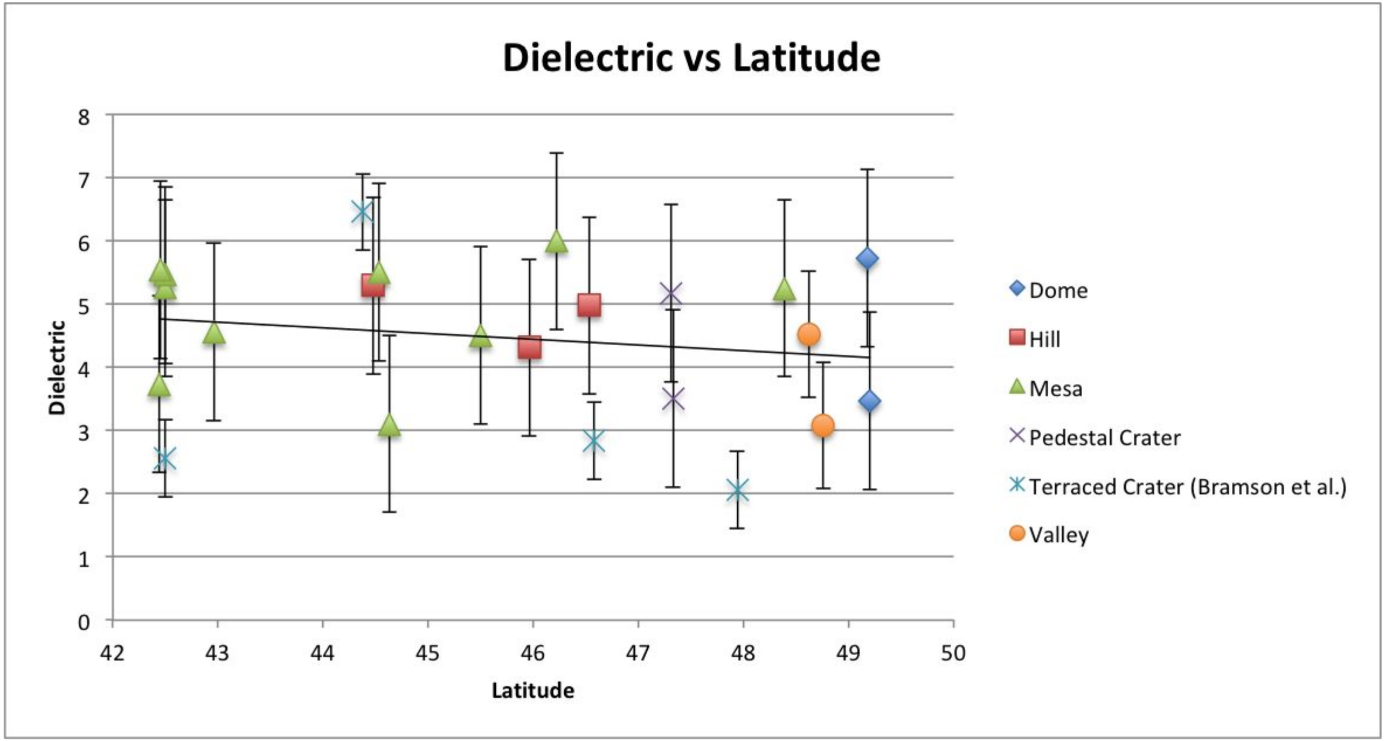


Depth Derived from Interpolated Dielectric





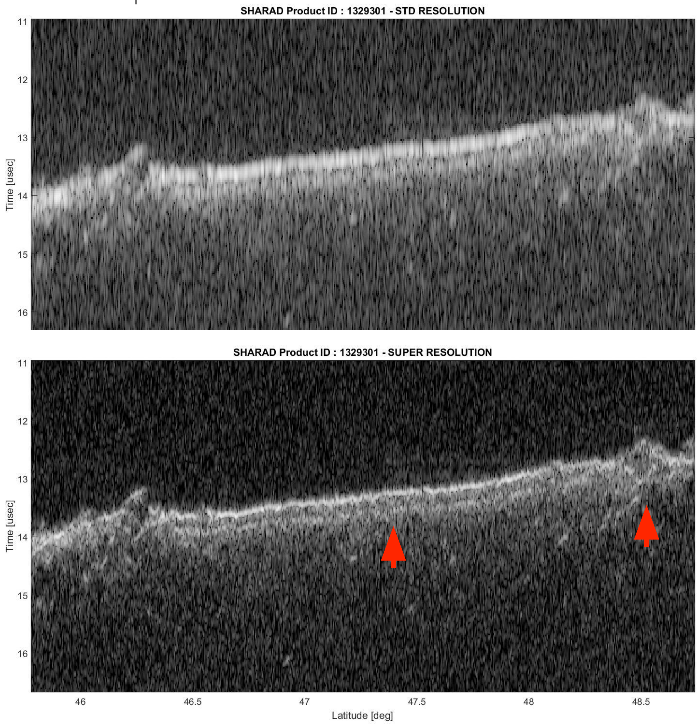
Dielectric vs Depth
Dielectric
Depth
0
1
2
3
4
5
6
7
8
0
20
40
60
80
100
120
Dome
Hill
Mesa
Pedestal Crater
Terraced Crater (Bramson et al.)
Valley



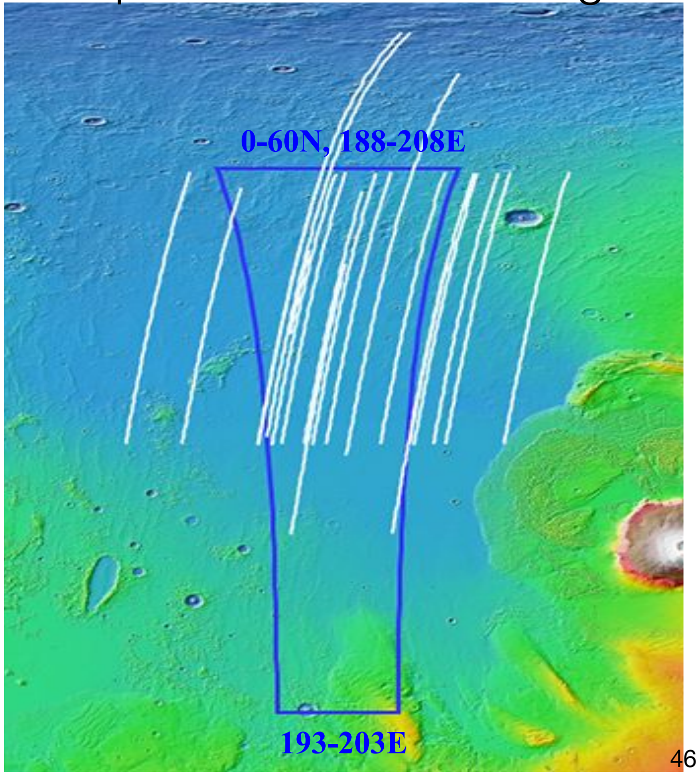
Dielectric vs Latitude
Dielectric
8
7
6
5
4
3
2
1
0
42
43
44
45
46
47
48
49
50
Latitude
Dome
Hill
Mesa
Pedestal Crater
Terraced Crater (Bramson et al.)
Valley

Subsurface Reflections

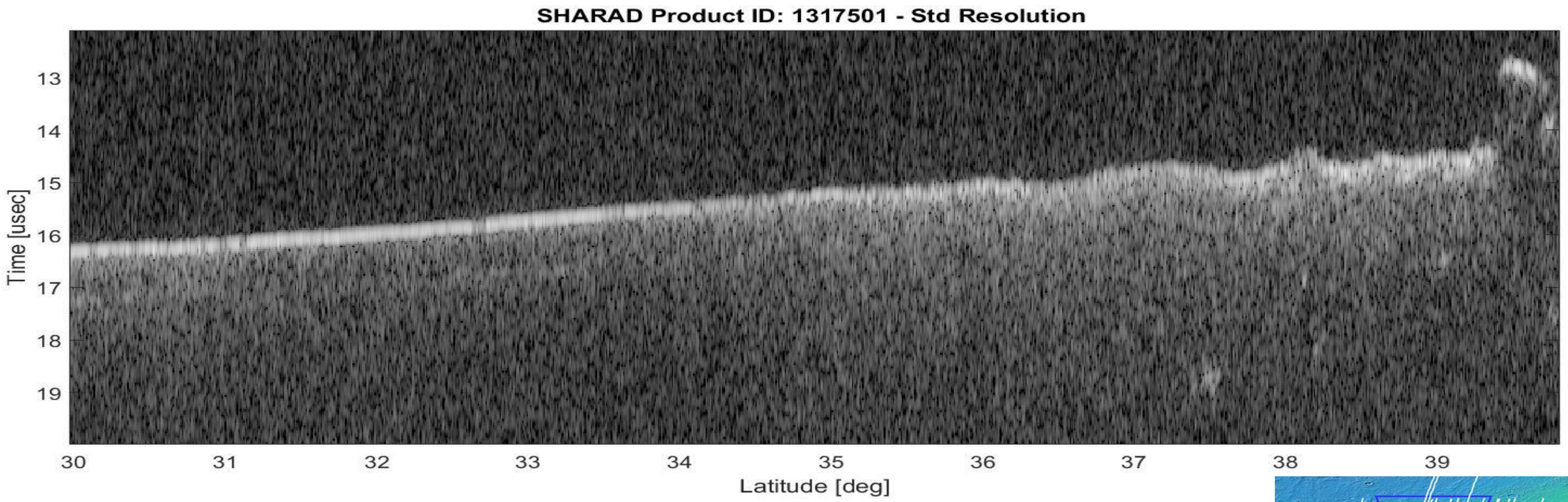
Super-resolution processing developed by Marco Mastrogiuseppe and others [Raguso et al., 2018] promises a 2-3 fold improvement in vertical resolution for SHARAD.

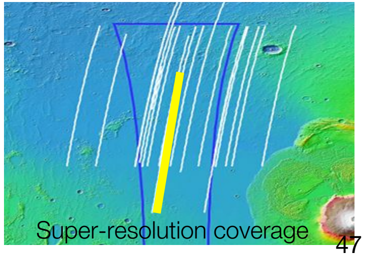


Super-resolution coverage



Subsurface Reflections





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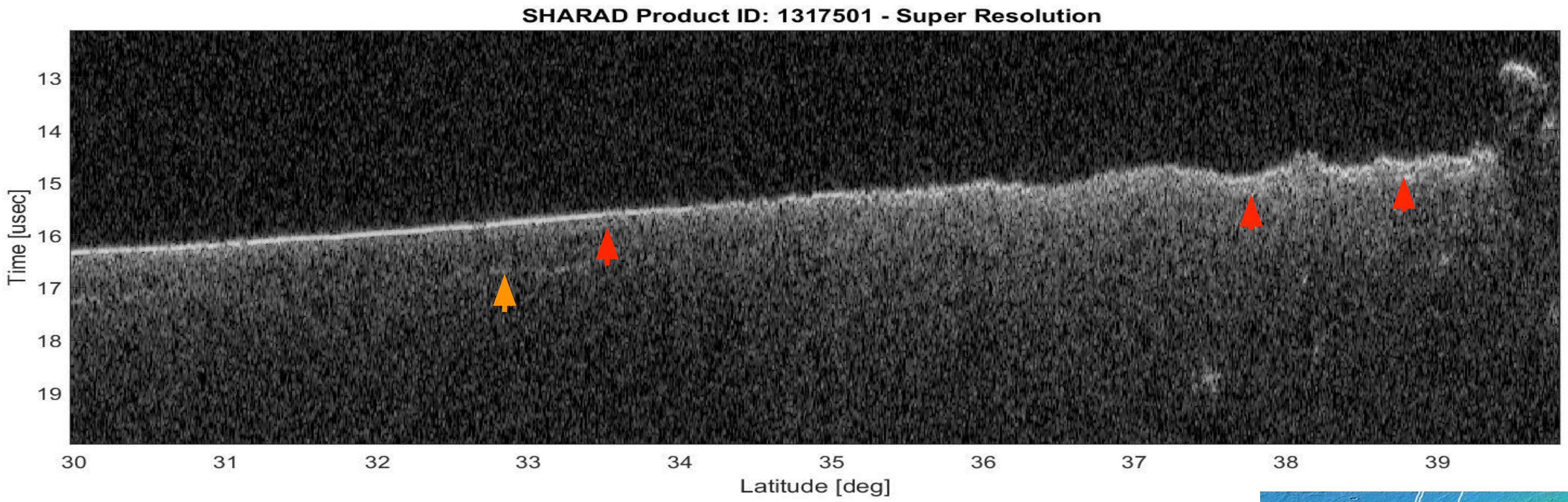
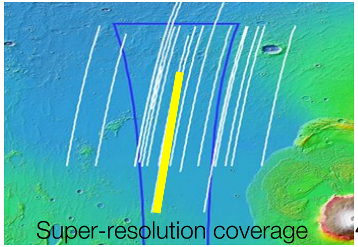
Subsurface Reflections



Substantial improvement in the clarity of reflectors is evident (e.g., at orange arrow, rightmost two red arrows) and newly evident shallow returns (leftmost red arrow) that may be associated with water ice.



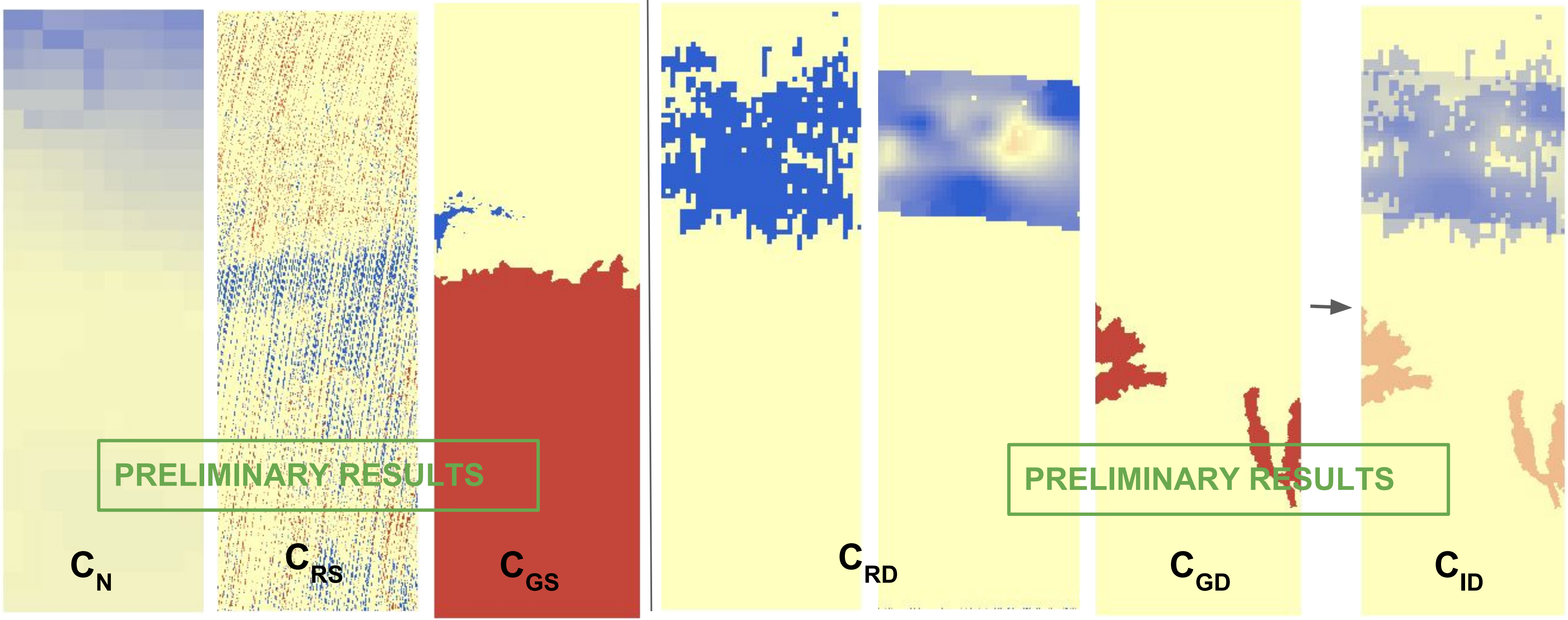
C* SWIM Maps of Consistency

Shallow Data

Wdn Deconvolved N16 | Surface Power | Shallow Geomorphology

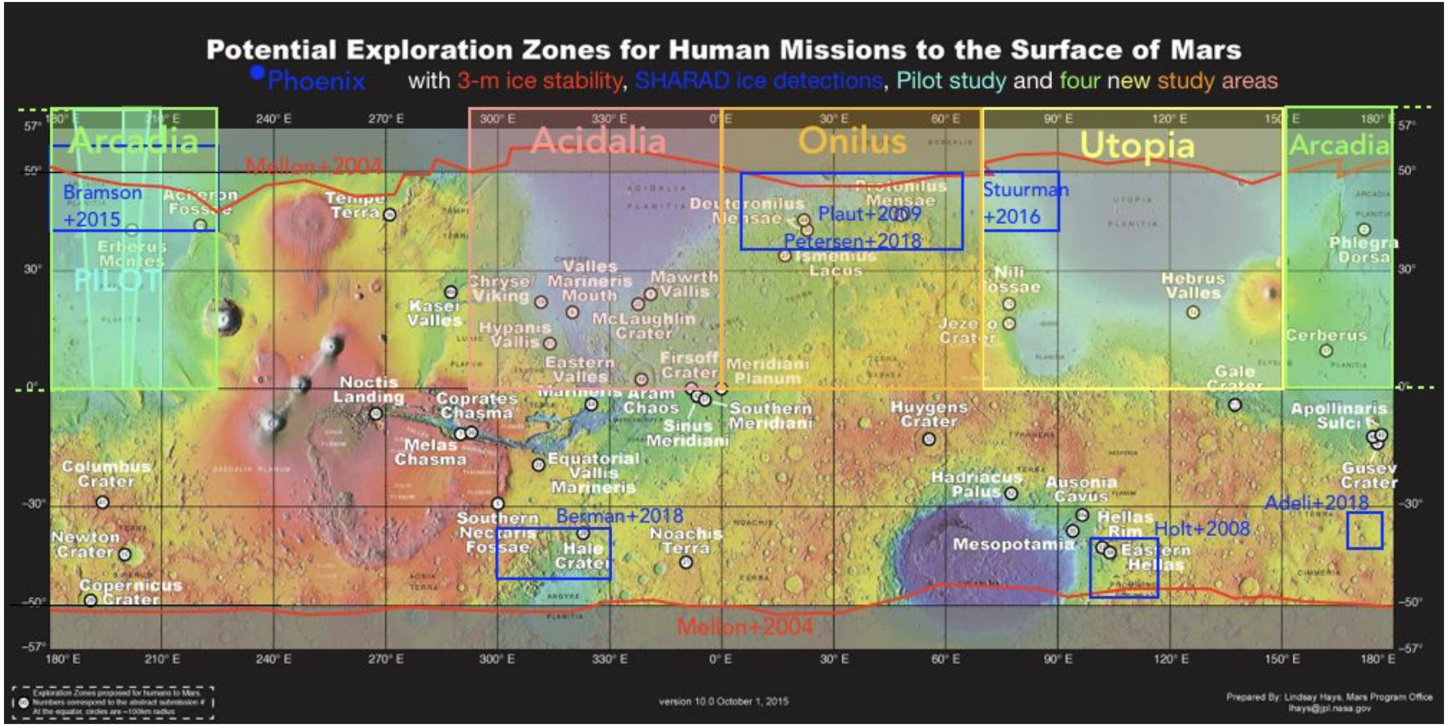
Deep Data

Shallow Reflector | Dielectric | Deep Geomorphology | Deep Consistency



Study Swaths
+ice stability, detections

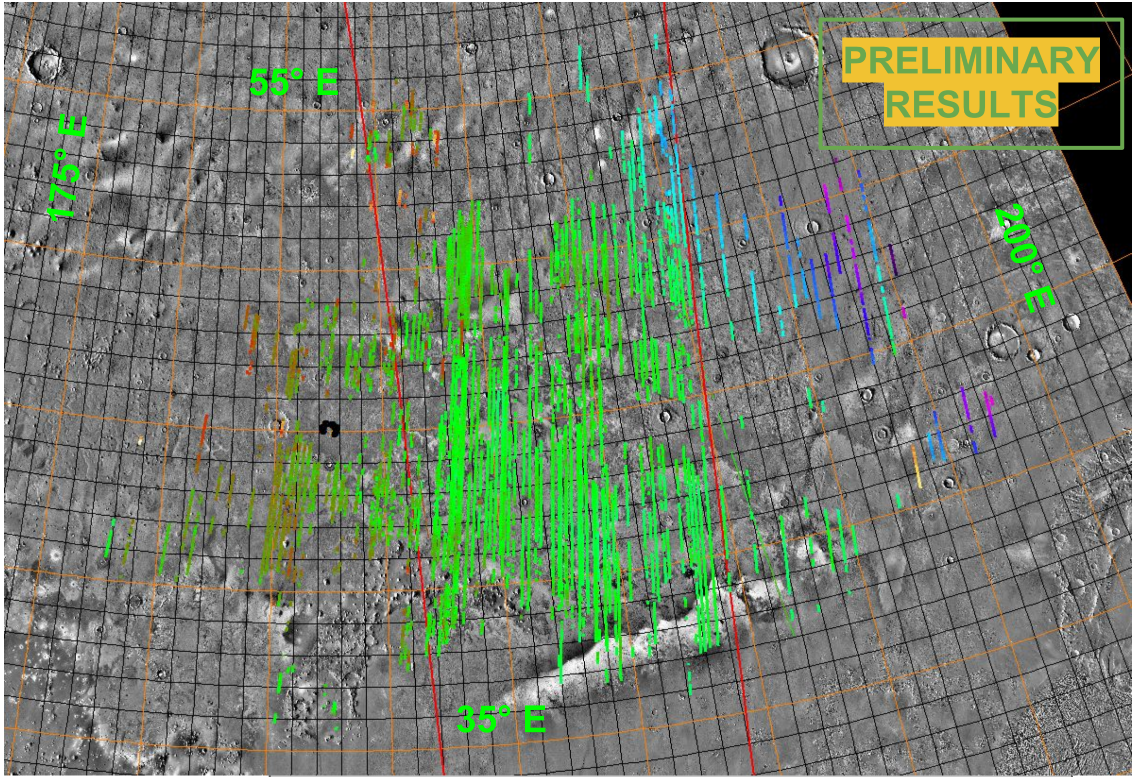
1. Prior State of Knowledge
2. SWIM Methods
3. Arcadia Planitia Results
4. SWIM Status
5. Deliverables
6. SWIM Extension



2015 Human Landing Site Selection Workshop

Arcadia Swath
(expanded)

Initial mapping in areas beyond the pilot-study region show that the northern reflector continues to the east and west, but reduces in latitudinal extent prior to disappearing.

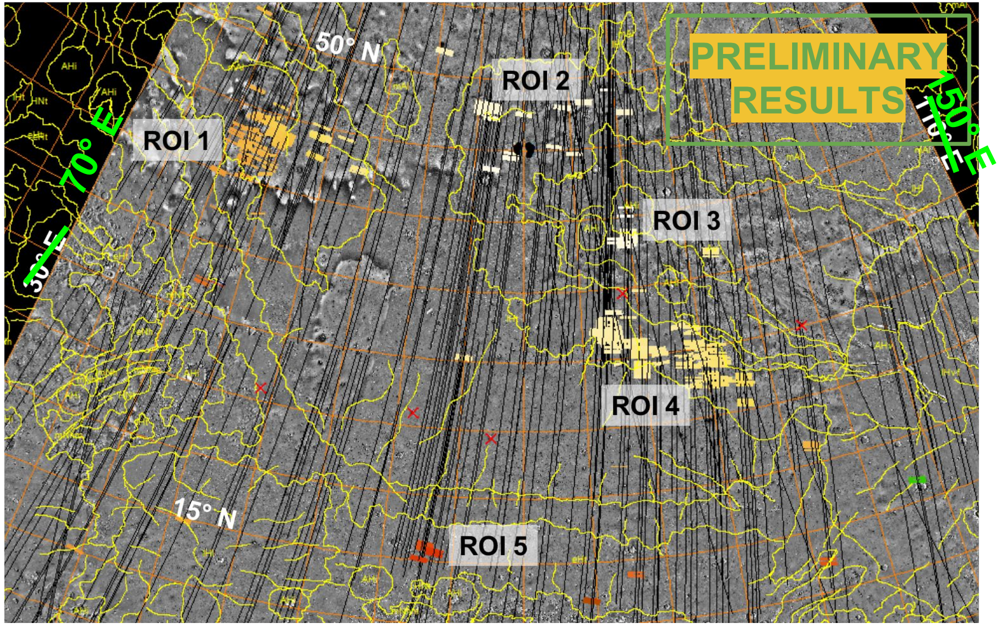


Utopia Swath

We have mapped 202 of 1402 SHARAD tracks across the region and identified at least 5 ROIs based on the presence of subsurface reflectors.

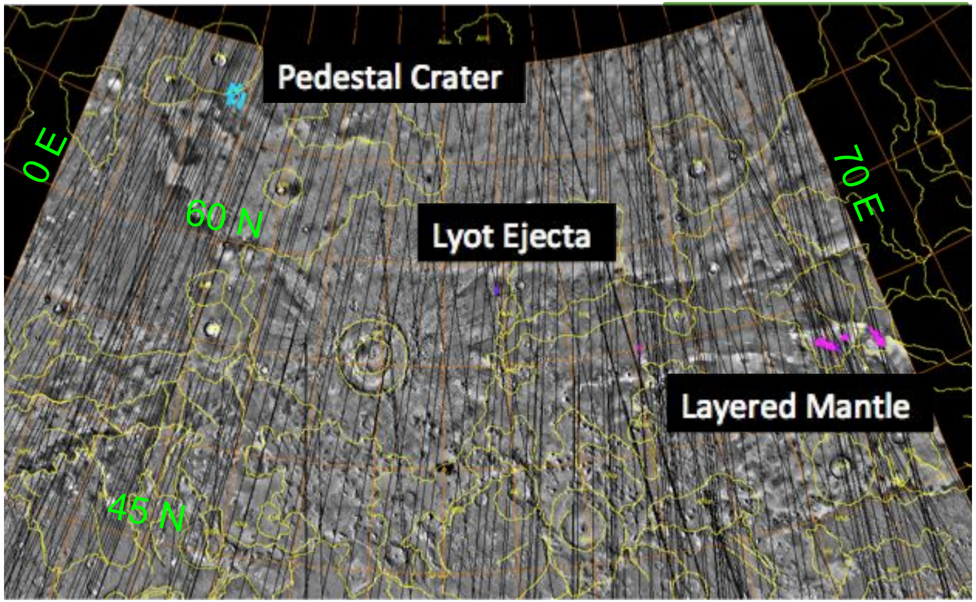
ROI 1 is updating the mapping of scalloped mesa terrain of Stuurman et al. [2016].

The low latitudes of ROI 4 and 5 suggest reflectors may be more likely due to lava flows, but we are inspecting for thin ice mantles in radar super-resolution and the other datasets.



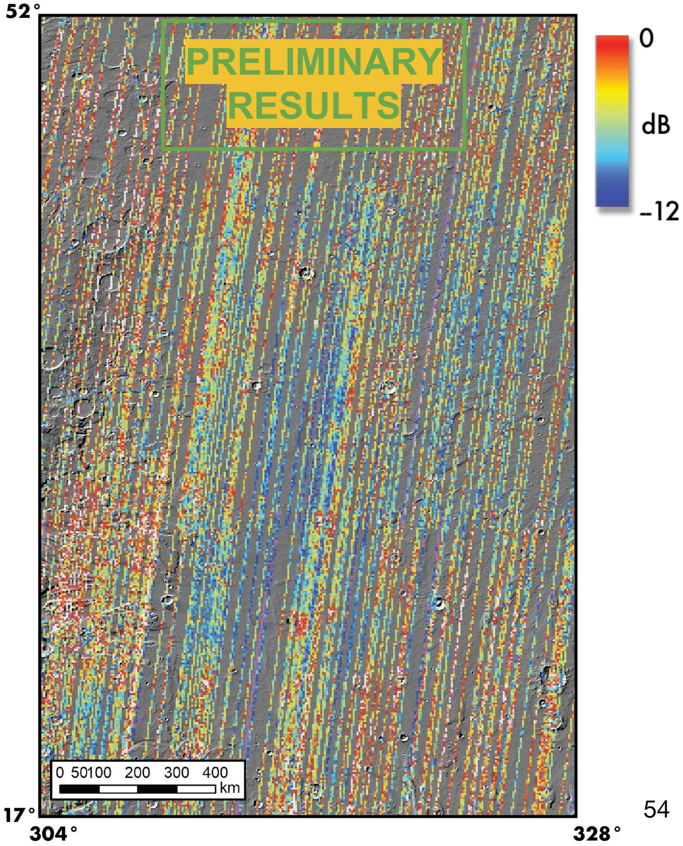
Onilus Swath

- We have examined 204 of 1938 SHARAD radargrams, and identified possible ice-rich features in 3 new ROIs across the region
- Expansion of mapping over debris-covered glaciers in Deuteronilus Mensae also under way.



Acidalia Swath

- SHARAD Data had been loaded, and initial cursory inspection had been completed, finding no obvious reflectors.
- Initial SHARAD surface return map has been generated (at right). Distinct power patterns are apparent across the plains units.

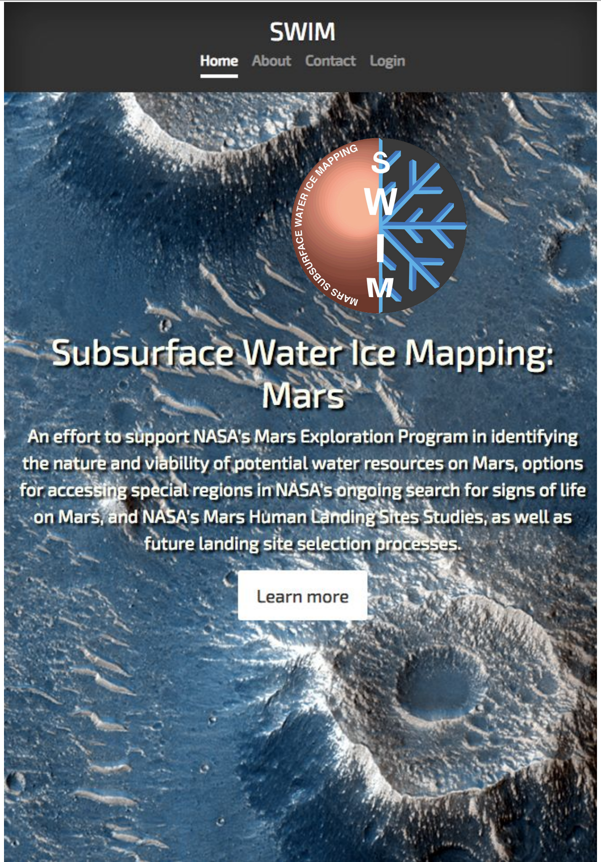


Study Products

Primary products by swath

- Ice consistency maps
  From neutron & thermal data, SHARAD surface and subsurface reflectors, morphology, and composites from all data sources
- Top of ice depth maps
  From thermal data & SHARAD surface returns
- Base of ice depth maps
  From SHARAD subsurface reflectors
- Ice concentration maps
  From SHARAD+DTM permittivity estimates

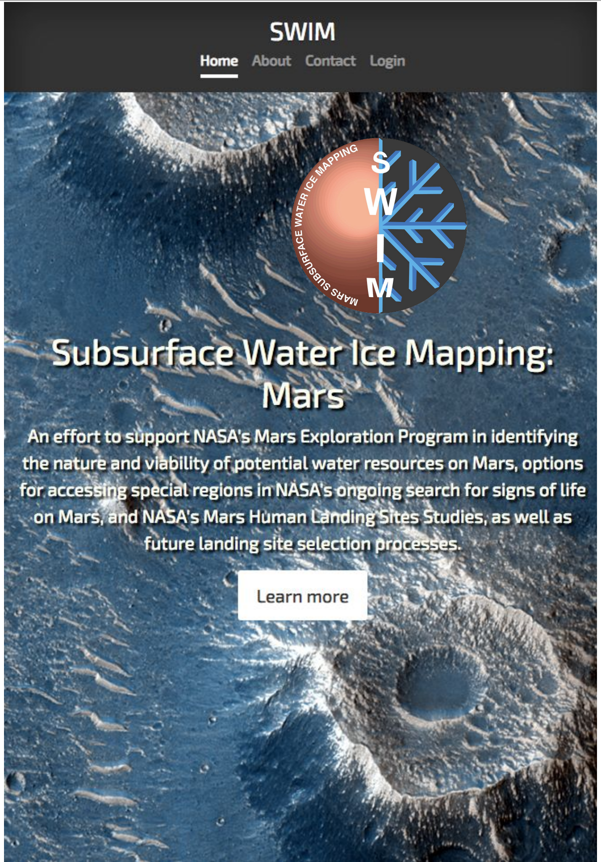
Maps will be provided as images and as GIS-compatible shape files.



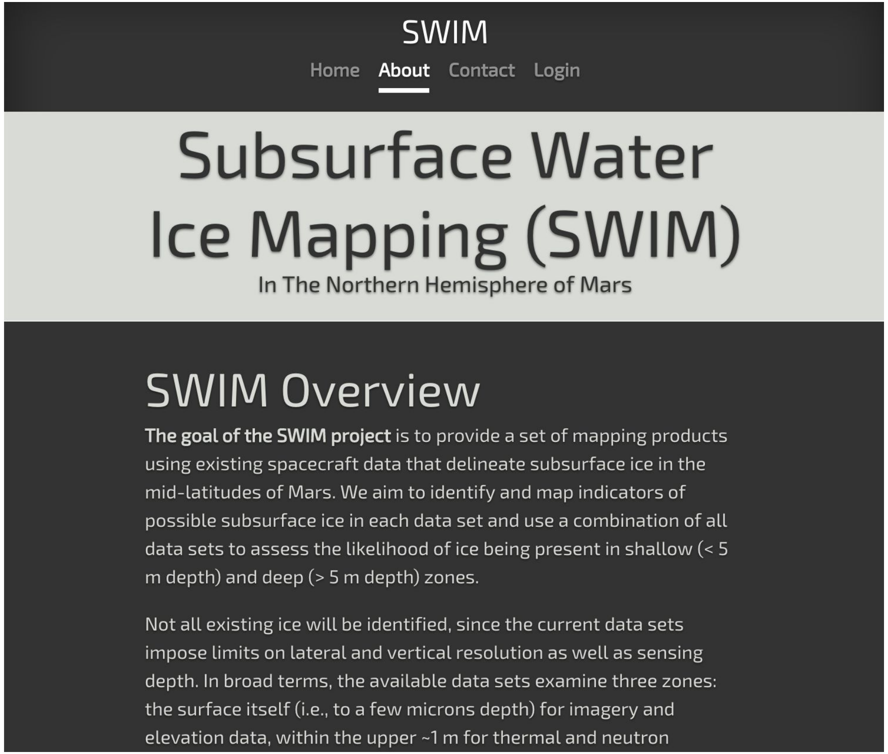
Study Products

Supplemental products for each swath

- TES heterogeneity maps
  Layered model type, RMS of differences
- THEMIS nighttime ATI image mosaics
  With and without calibration to TES map
- Geomorphological maps
  For regions of potential ice
- SHARAD surface-return corrected power maps
- Dielectric permittivity maps
  From SHARAD and DTM data
- Dielectric permittivity analyses
  Graphs vs. latitude and vs. depth of interface
- SHARAD subsurface-return delay-time maps
  Relative to surface returns



SWIM Website
Public access

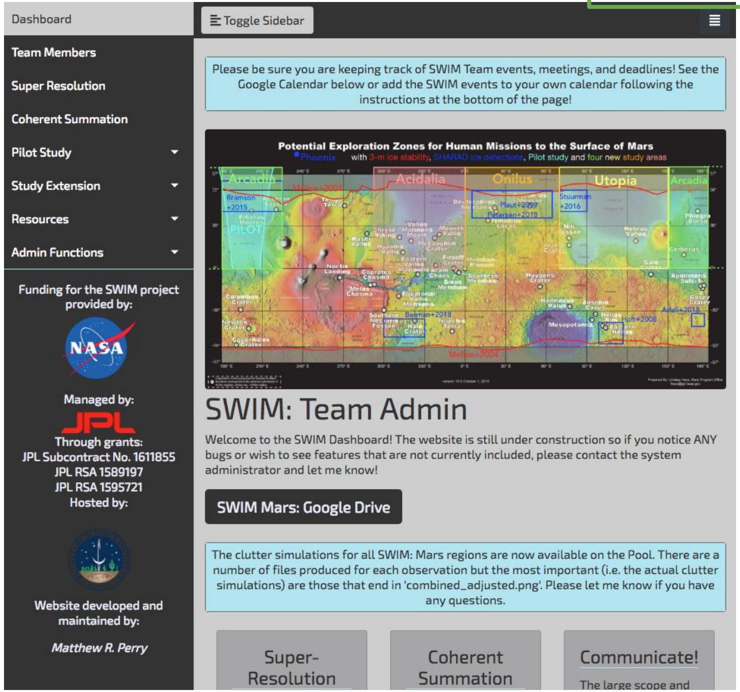


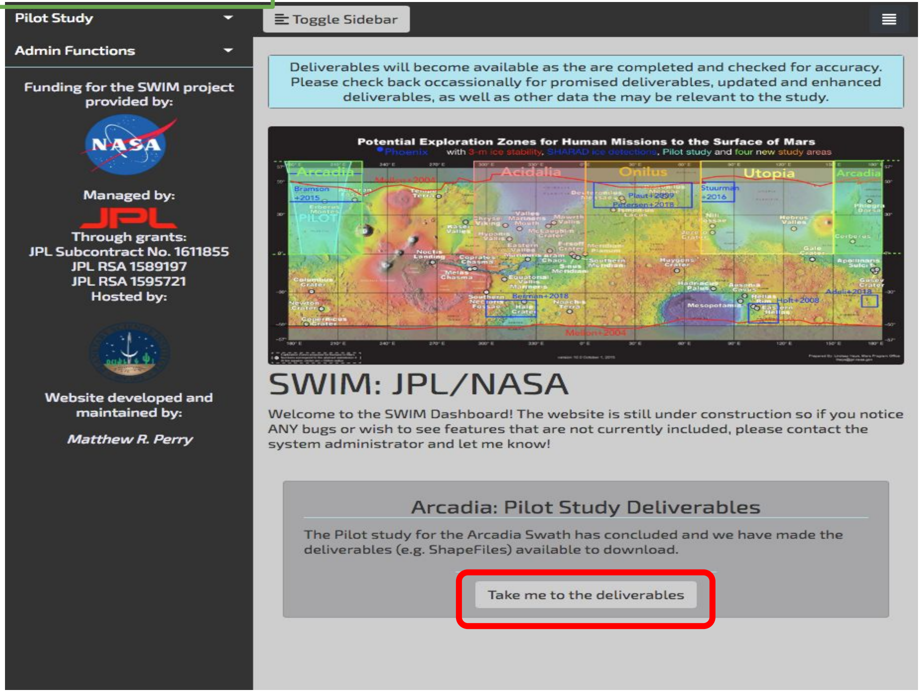
SWIM Website Team & JPL/NASA

Team Dashboard

https://swim.psi.edu

JPL/NASA Dashboard





Deliverables will be available on the public site once approved by NASA

SWIM Study Extension Options

1. Prior State of Knowledge
2. SWIM Methods
3. Arcadia Planitia Results
4. SWIM Status
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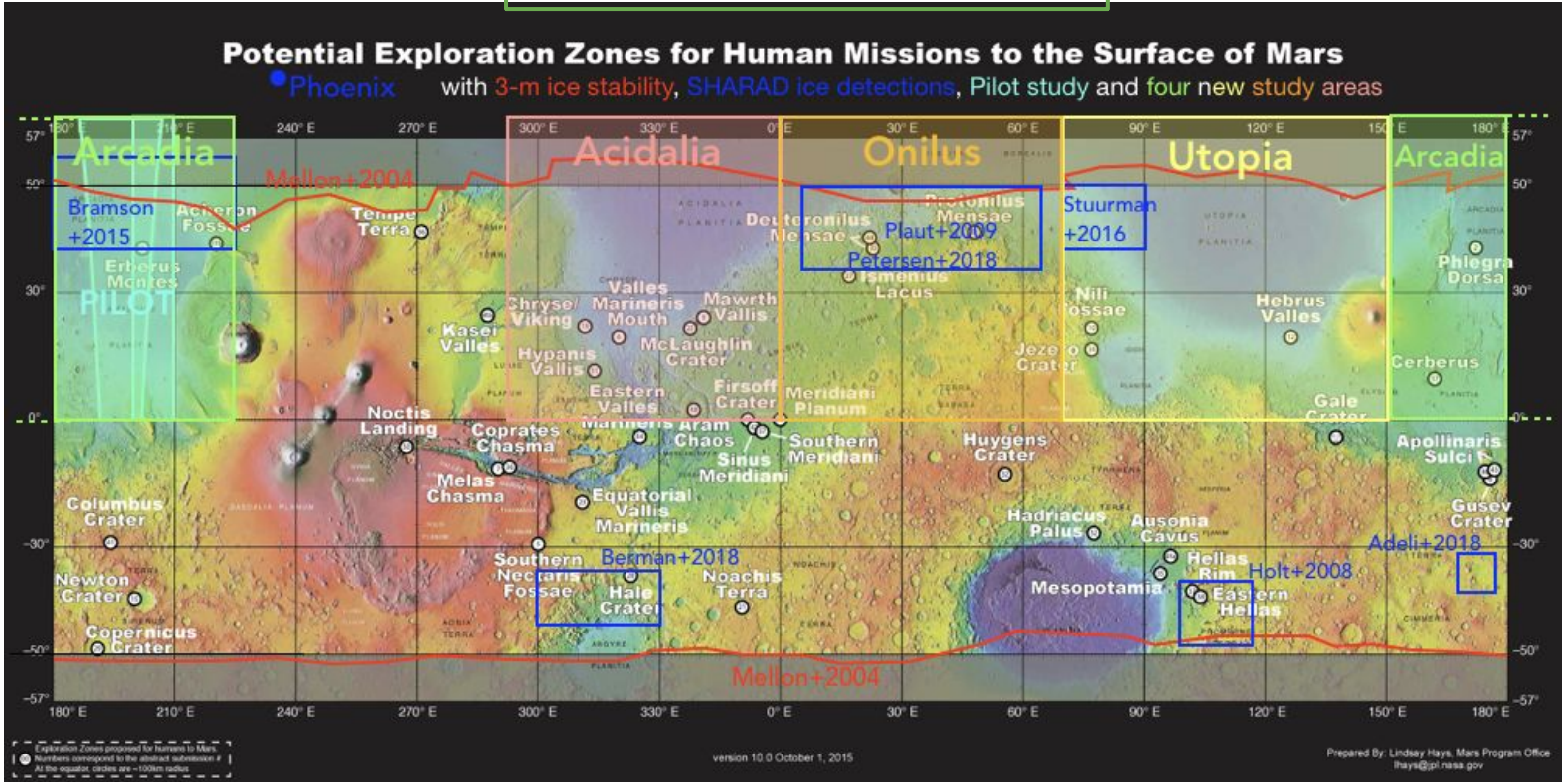
[1] WHERE NEXT?..... **Current study areas of ongoing work.**



SWIM Study Extension Options

1. Prior State of Knowledge
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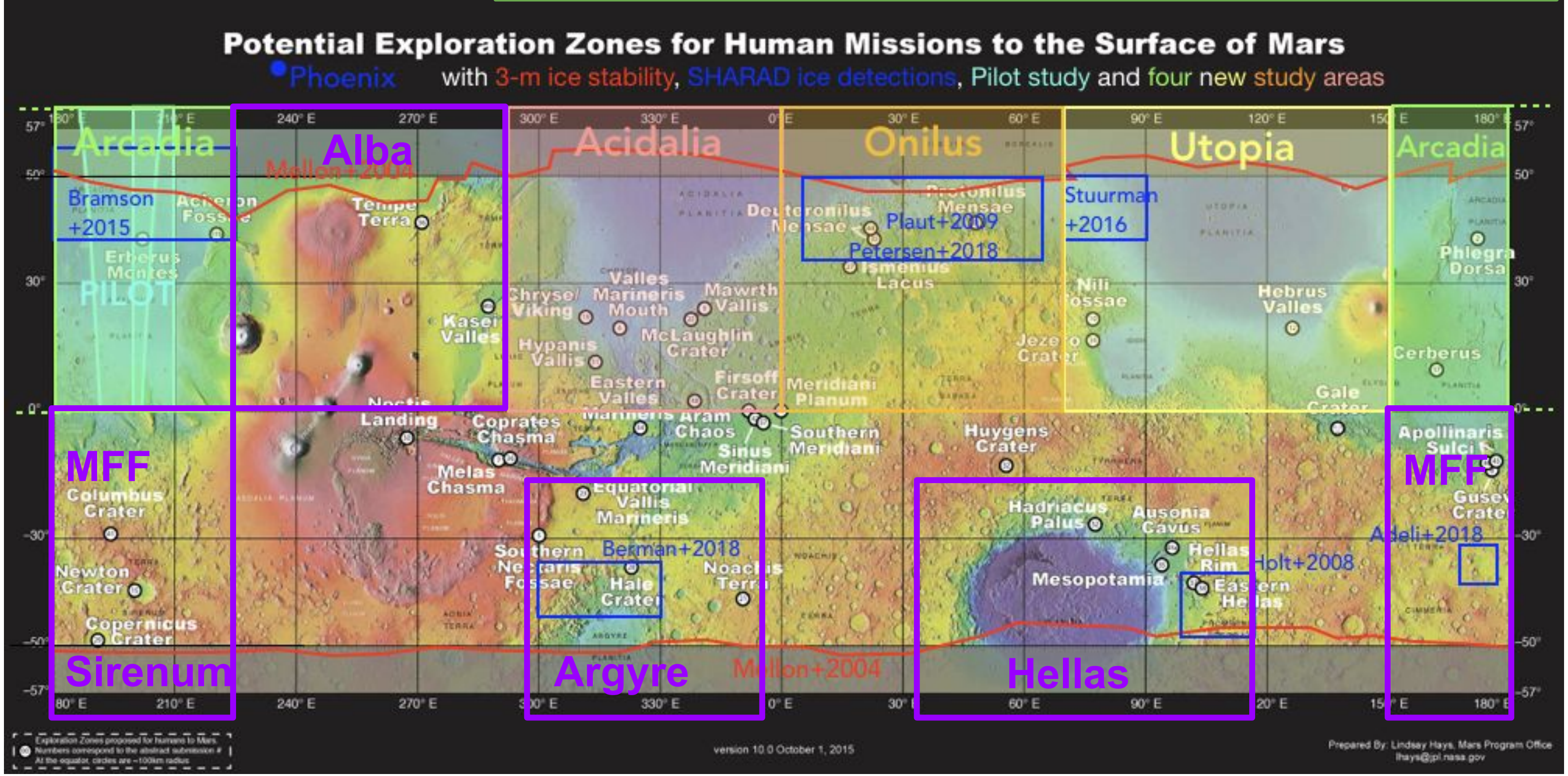
6. SWIM Extension

[1] WHERE NEXT?.....

Notional study expansion areas in purple have not been approved.



SWIM Study Extension Options

[2] PUSHING OUR TECHNIQUES FURTHER

A few ideas from the SWIM Team on how work could be expanded beyond the current study scope. These additions have not been approved, and they will require work beyond the existing study.

TES heterogeneity and THEMIS analysis

Multi-layer (3+) model & matching, improved fitting constraints

THEMIS nighttime ATI image mosaics

Better input to constrain albedo & dust/water-ice opacity

Geomorphological maps

Extend resolution and analysis coverage areas. Incorporate Grid-mapping technique.

SHARAD surface-return corrected power maps

Extract more info from roughness analysis, compensation of power vs. roll angle, solar array

SHARAD subsurface mapping and dielectric permittivity analyses

Increase use and coverage of super-resolution and coherent-summing processing of radaragrams

Add more techniques (split-chirp analysis, sloping reflector analysis) for dielectric estimation

Neutron spectroscopy

Add Asmin Pathare for extended analysis (multi-layer modeling)?

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