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SWIM Subsurface Water Ice Mapping in the Northern Hemisphere of Mars

Report to the 10th Joint Space Resource Roundtable and Planetary & Terrestrial Mining Sciences Symposium
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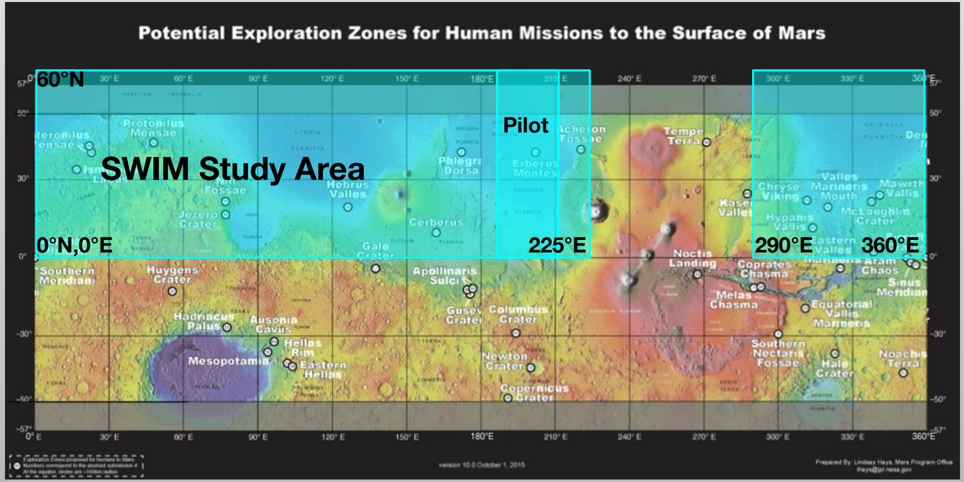
Motivation

After NASA's 2015 Mars Human Landing Site Selection Workshop, it became clear that **sources of water — in the form of either buried water ice or hydrated minerals — are critical for enabling human exploration missions.**

In June 2017, NASA put out a call for mapping water resources with available data. **NASA selected two pilot studies focused on mapping buried water ice in Arcadia Planitia.**

In August 2018, these studies were merged and extended across the northern hemisphere to create the SWIM Project.

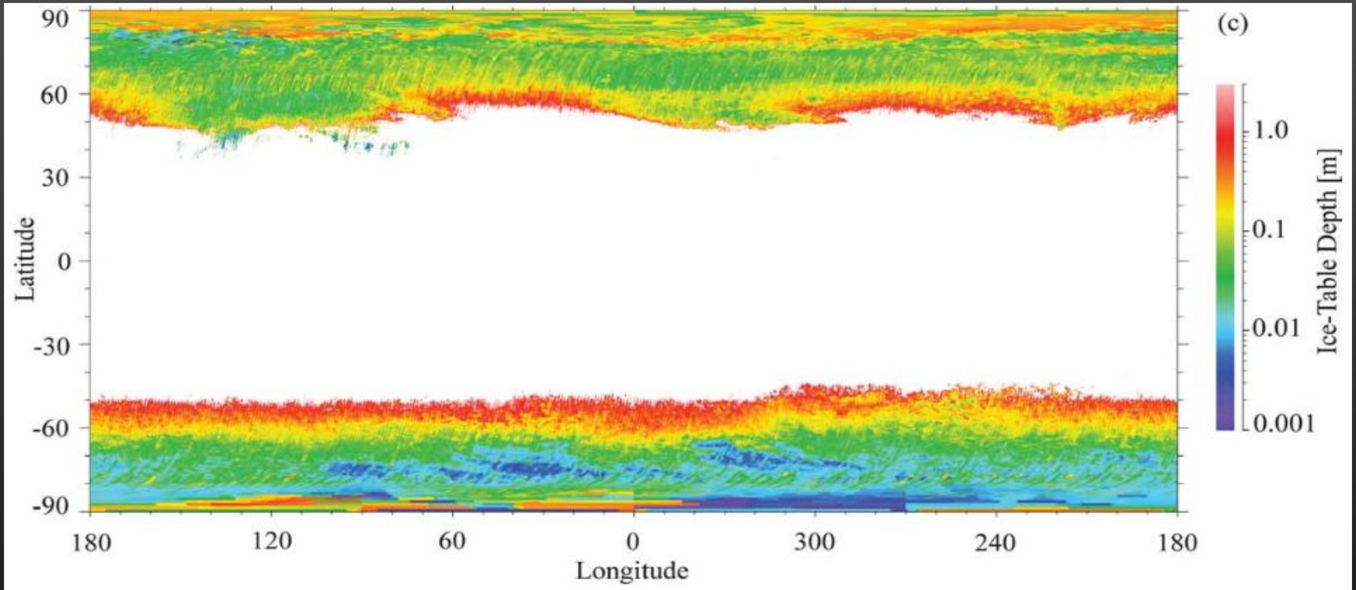
2015 Mars Human Landing Site Selection Workshop Map



Prior mapping of shallow (<1 m) water ice

By the early 2000s, thermal modeling and observations strongly suggest that **water ice is present all across the high (>50°) latitudes of Mars.**

Depth of the ice table derived from modeling and MGS TES data [Mellon et al., 2004]

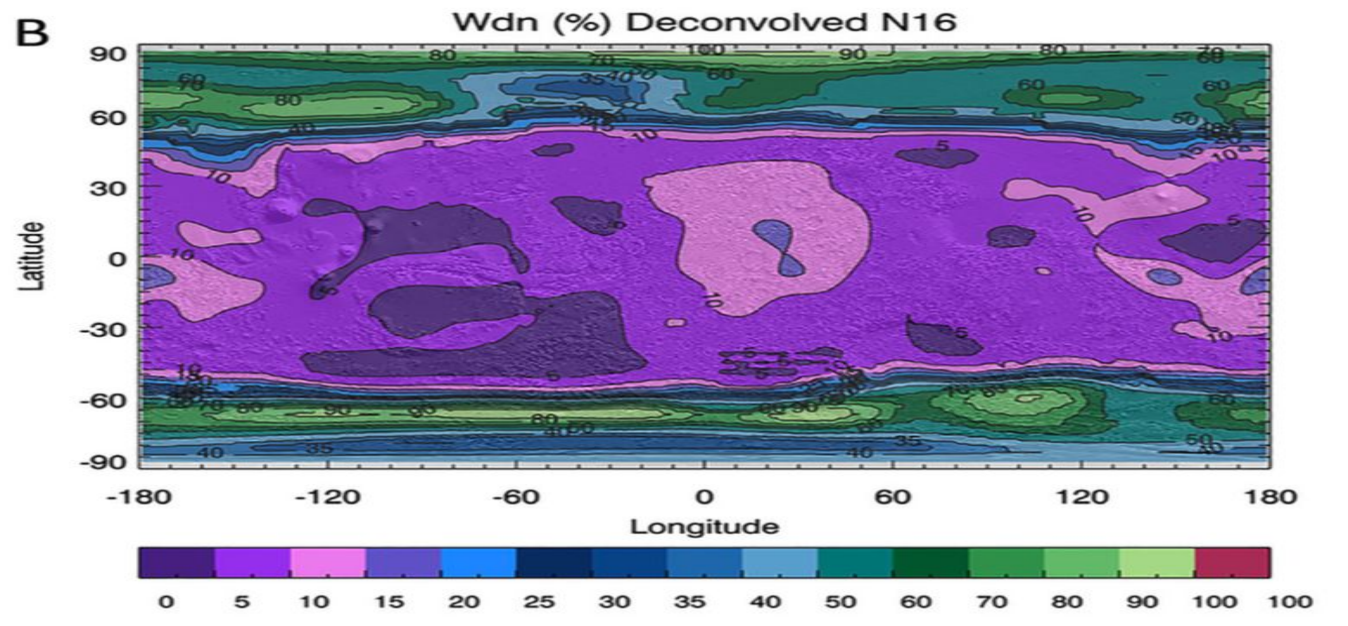


Prior mapping of shallow (<1 m) water ice

1. Prior Knowledge
2. Methods
3. Results
4. Conclusions

In the last two decades, Mars Odyssey Neutron Spectrometer has mapped **likely shallow water ice across these same high-latitude regions**.

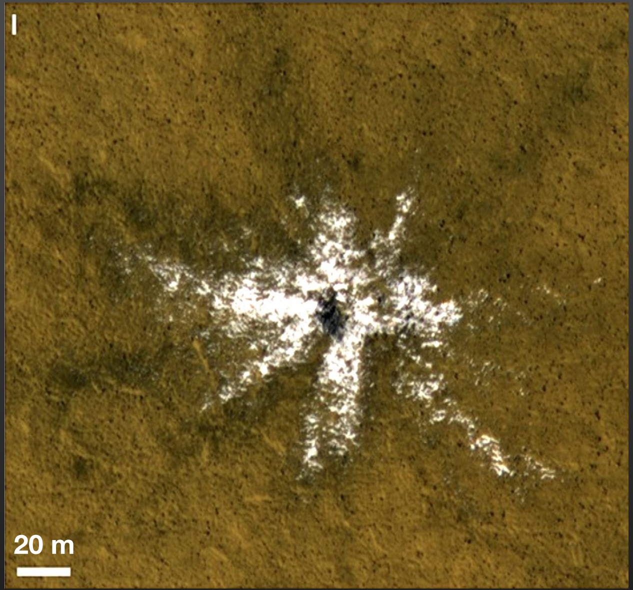
Concentration of water-equivalent hydrogen in lower layer [Pathare et al., 2018]

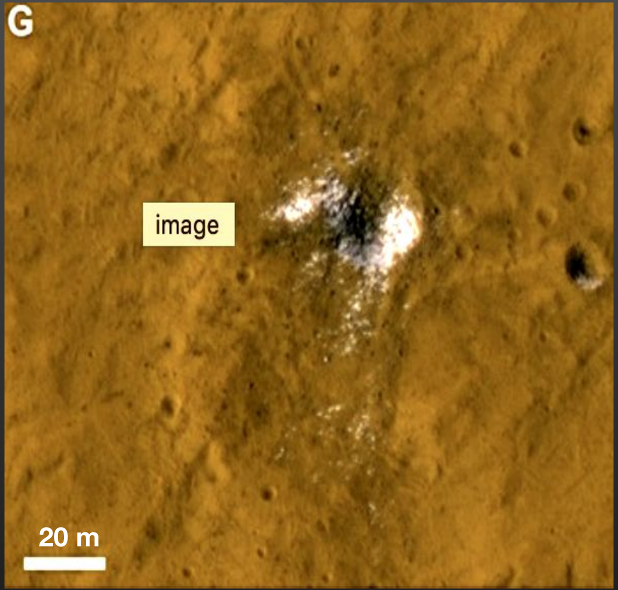


Prior **confirmation** of shallow (<1 m) water ice

More recently, MRO imagers have revealed fresh ice-exposing small impact craters — **direct evidence of shallow ice as far south as 39°N**

HiRISE images of newly exposed ice [Byrne et al., 2009; Dundas et al., 2014]



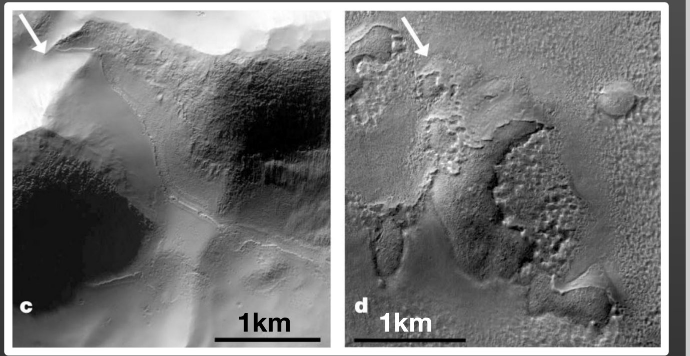


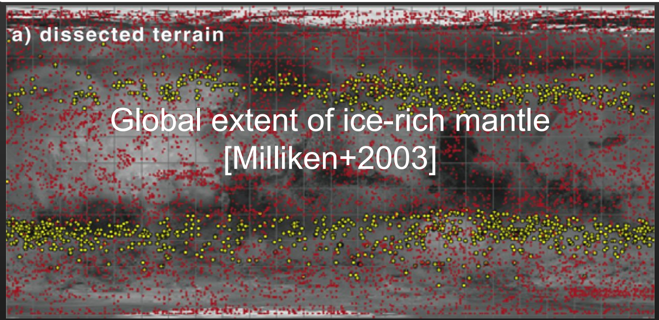
Prior mapping of water ice: Morphology Studies

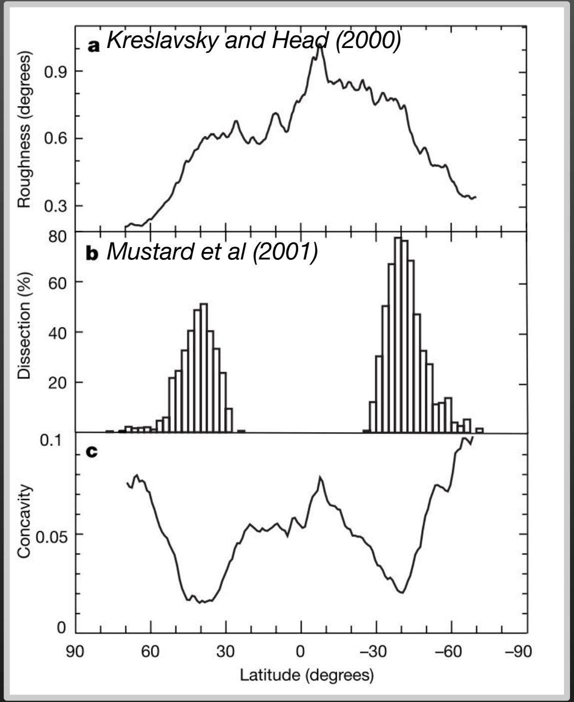
1. <u>Prior Knowledge</u>
2. Methods
3. Results
4. Conclusions

Early 2000s: High-resolution imaging (MGS MOC) of mantle deposits and surface roughness studies (MGS MOLA) led to the **Mars Ice Age Hypothesis**

Dissected Mantle at mid-latitudes







Prior mapping of water ice: Morphology Studies

1. Prior Knowledge
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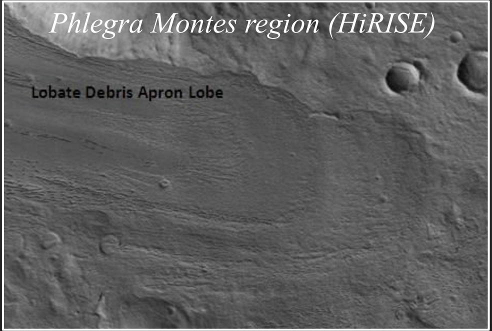
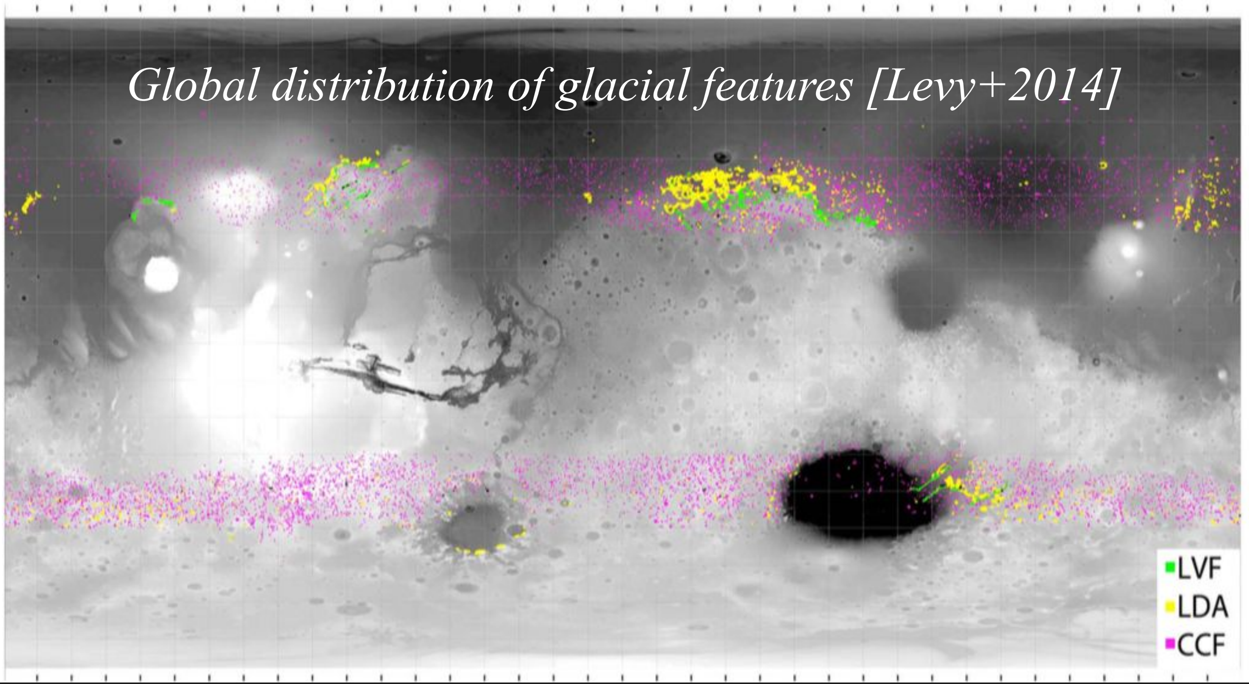
Imaging and mapping of glacial features that may contain buried water ice has been carried out across the Martian mid-latitudes for the last several decades,


Promethei Terra region (HRSC)



Phlegra Montes region (HiRISE)



Global distribution of glacial features [Levy+2014]

Prior mapping of deep (>20 m) water ice

1. Prior Knowledge
2. Methods
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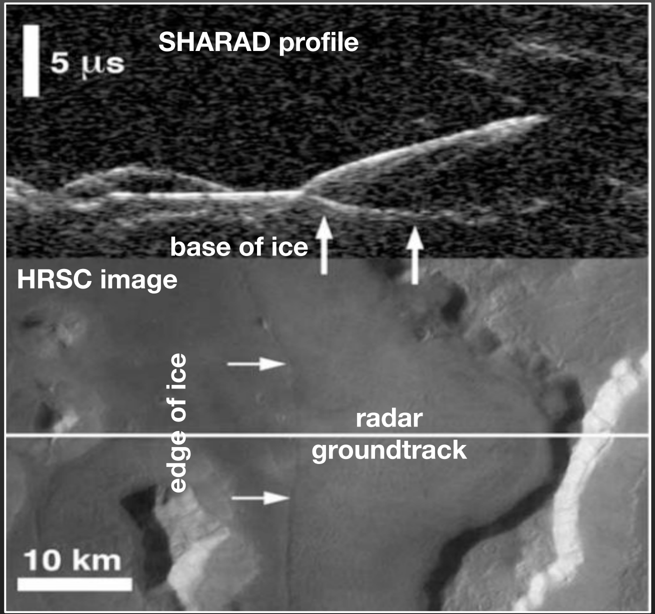
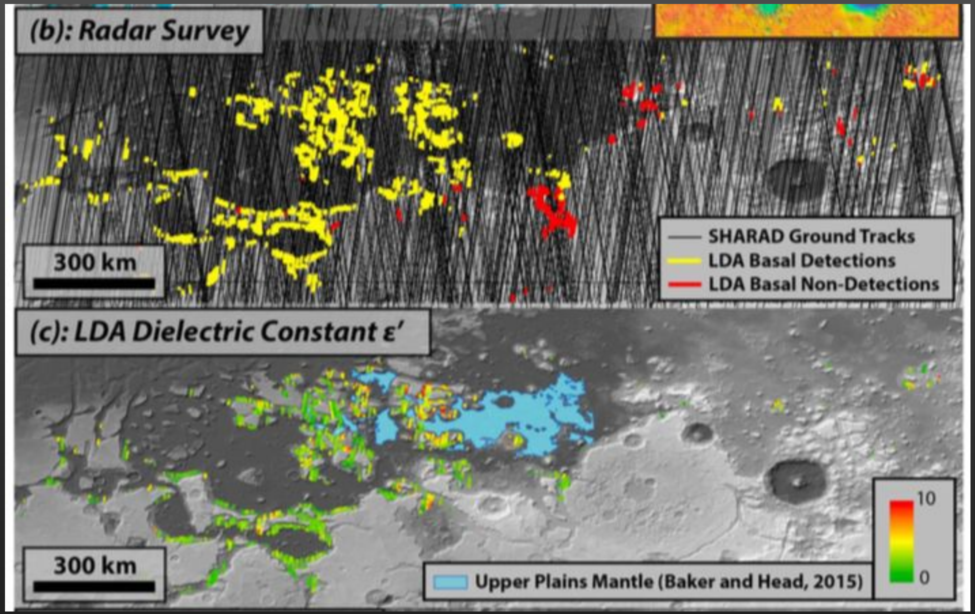
In the last decade, MRO's Shallow Radar (SHARAD) has shown that many **glacial features are nearly pure water ice** under a thin (< ~ 20 m) cover of debris.

Radar-revealed glacial ice [Plaut et al., 2009].



Deuteronilus glacier mapping [Petersen et al., 2018]



Prior mapping of deep (>20 m) water ice

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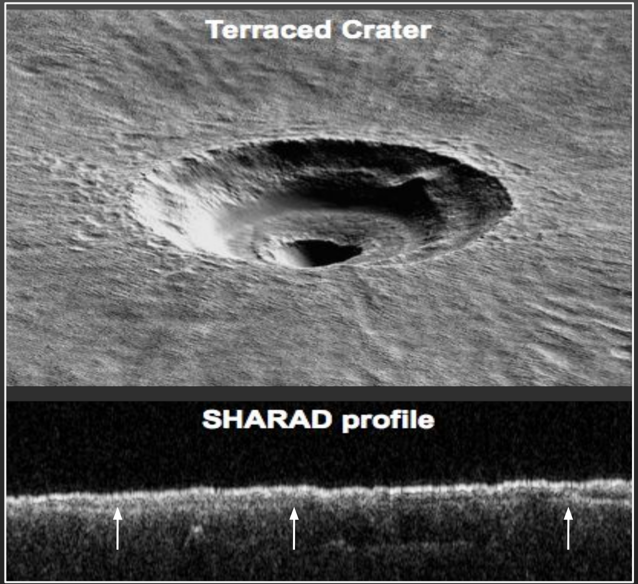
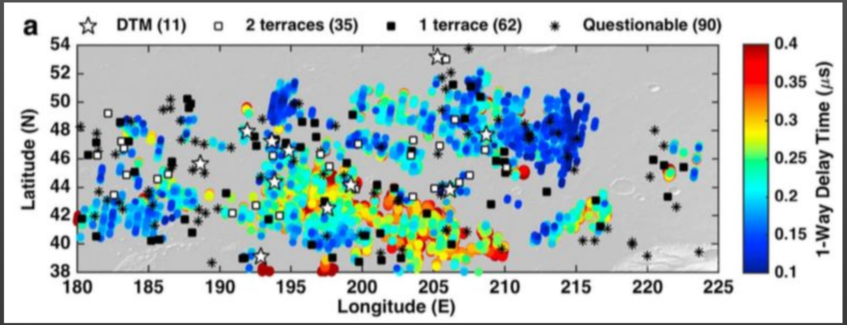
More recently, mid-latitude non-glacial ice detection by SHARAD has also been reported — including prior mapping in Arcadia & Utopia Planitiae

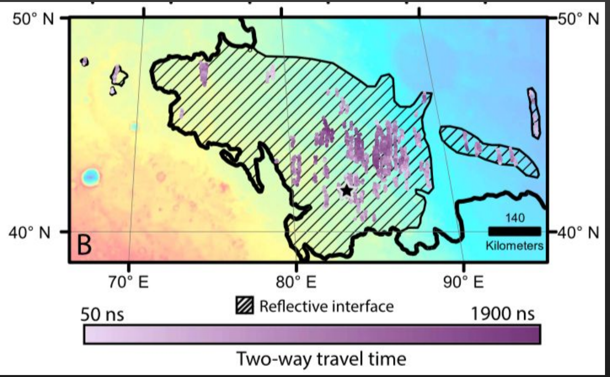
Radar-revealed ground ice [Bramson et al., 2015].



Arcadia Planitia ground ice [Bramson et al., 2015]



Utopia Planitia ground ice [Stuurman et al., 2016]



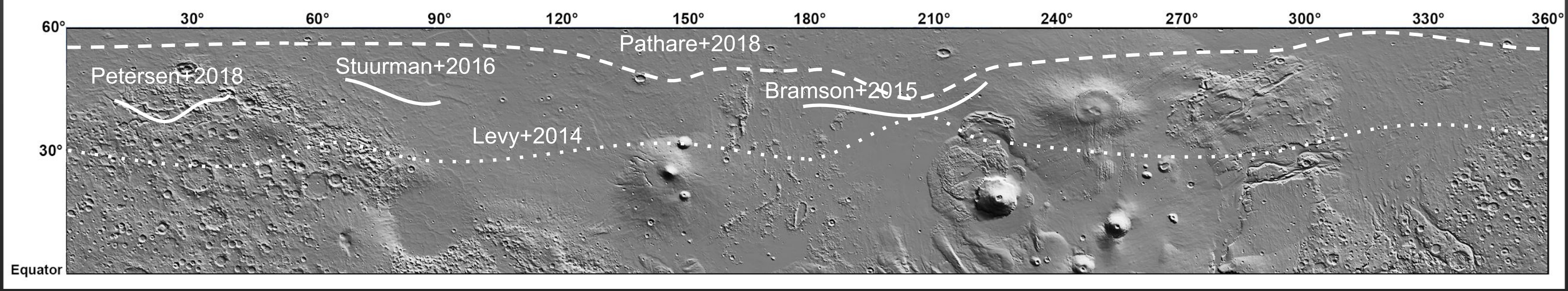
Prior southern limit of Northern Hemisphere ice

Southern boundaries are taken from maps on prior slides that were produced in earlier studies.

Prior shallow (<1 m) ice from neutrons

Prior deep (>15 m) ice from radar reflectors

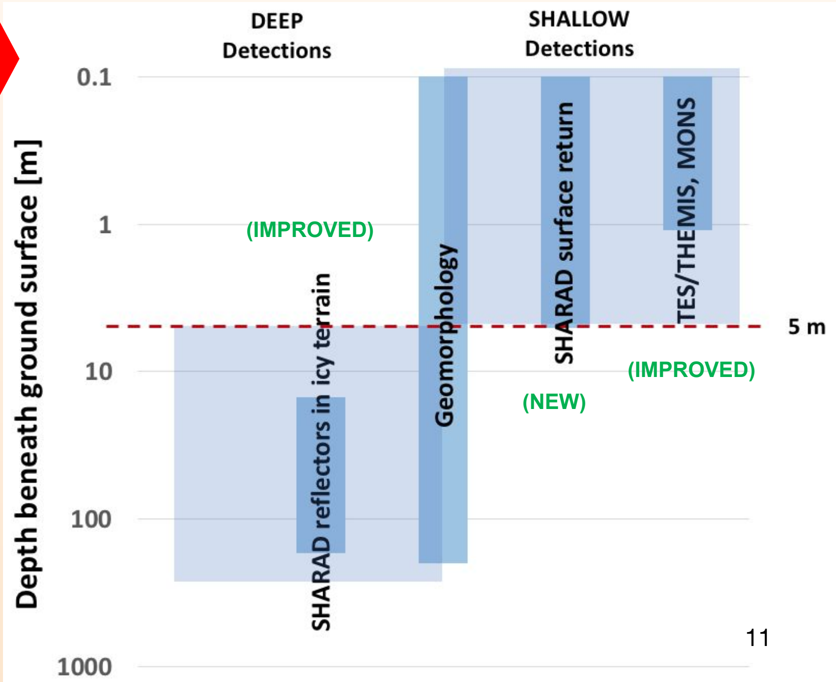
Glacial features from geomorphology



SWIM Approach to Mapping Ice

- **Previous Martian subsurface ice studies** used datasets in **isolation** or combined techniques in **limited geographical areas.**

- **For this study,** we extended previous methods and combined them with newly developed techniques:
  - ***Mapping potential ice in top 1 m*** using neutron and thermal spectrometer data.
  - ***Mapping potential ice in top 5 m*** using a new measure of radar surface-power returns.
  - ***Extensive mapping of potential base-of-ice depth (10s to 100s of m depth) and ice concentration*** with subsurface radar returns.
  - ***Mapping potential glacial & ground ices at all depths*** with imagery, elevation, and other geomorphic data.



Composite Ice Consistency

We introduced **the SWIM Equation**, in the spirit of the famous Drake Equation:

$$C_I = (C_N + C_T + C_{RS} + C_G + C_{RD}) \div 5$$ Consistency of data with the presence of buried ice

We map **consistency values** for each dataset:

C_N	Consistency of neutron-detected hydrogen with shallow (< 1 m) ice
C_T	Consistency of thermal behavior with shallow (< 1 m) ice
C_{RS}	Consistency of radar surface echoes with shallow (< 5 m) ice
C_G	Consistency of geomorphology with shallow and deep ice
C_{RD}	Consistency of radar dielectric properties with deep (> 5 m) ice

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

+1	Data are ***consistent*** with the presence of ice
0	Data are absent or gives no indication of ice presence or absence
-1	Data are ***inconsistent*** with the presence of ice

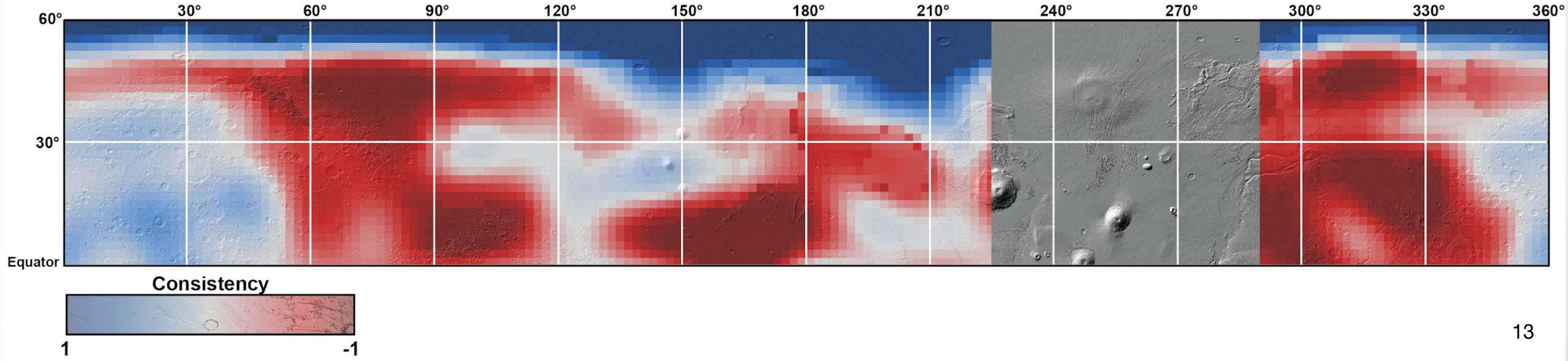
Neutron Ice Consistency

C_N, from MONS data

To compute **neutron ice consistency C_N**, we used the Pathare et al. [2018] map of lower-layer water-equivalent hydrogen (Wdn) as follows:

25% ≤ Wdn	-> 1
10% ≤ Wdn < 25%	-> scaled 0 to 1
5% ≤ Wdn < 10%	-> scaled -1 to 0
Wdn < 5%	-> -1

No additional analysis of neutron data was included in this study.

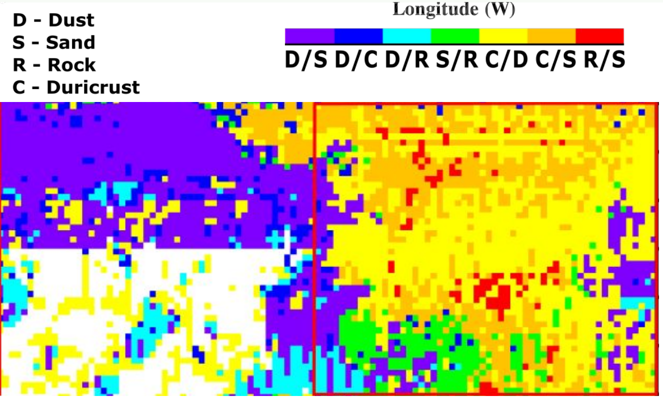


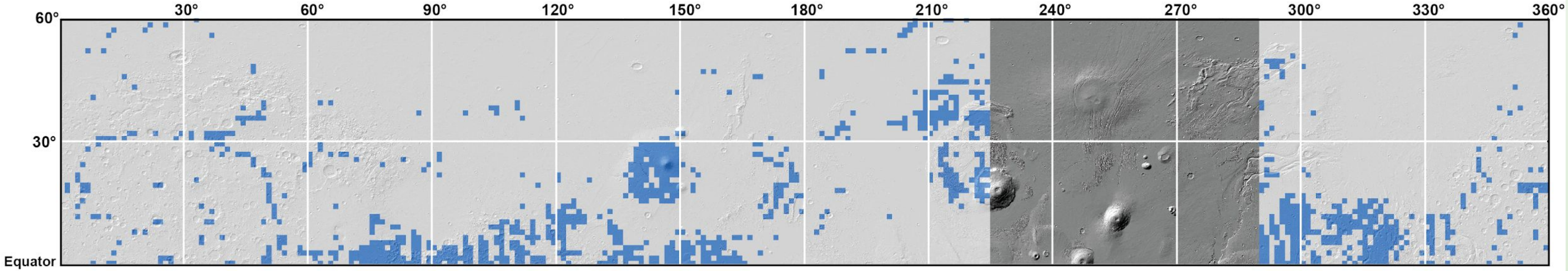
Thermal Ice Consistency

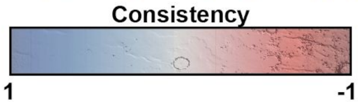
C_T, from TES & THEMIS data

TES heterogeneity map: Matches to two-layer models

blue+green layered models are consistent with buried water ice or rock







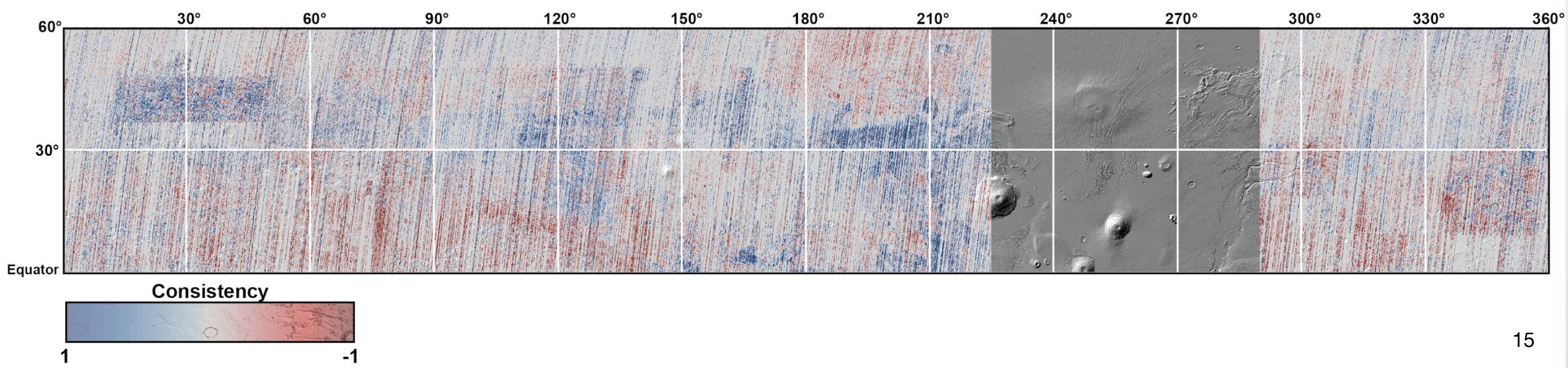
High thermal consistency with ice could also be explained by buried rock (more likely at lower latitudes). At higher latitudes, lack of consistency corresponding to that of neutron data is largely attributable to thermal masking by very thin layers of duricrust and dust.

Radar Surface Reflectivity Ice Consistency $\mathbf{C_{RS}}$

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

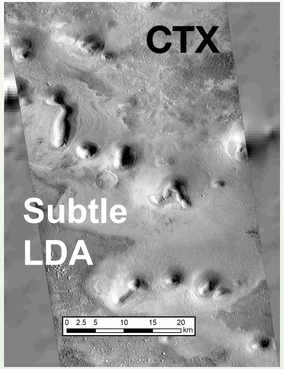
C_{RS} is scaled from the global power distribution ($< -1\sigma = 1$, $>1\sigma = -1$).

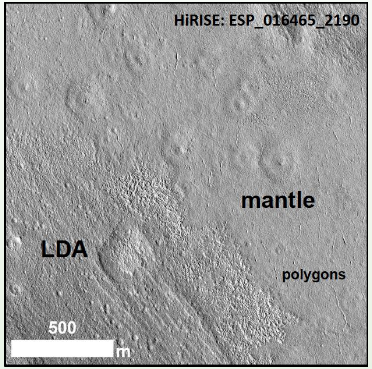
- Across the mid-latitudes, we find isolated, low-power areas, e.g., within the **debris-covered glacier features.**
- An broad belt in northern Amazonis of low-power returns at ~35°N, 200°E correlates with **known dust upwelling.**
- Equatorial **Medusae Fossae** also exhibits low power, consistent with prior interpretations of ice or low-density ash [Waters et al. 2007; Carter et al. 2009; Morgan et al. 2015].

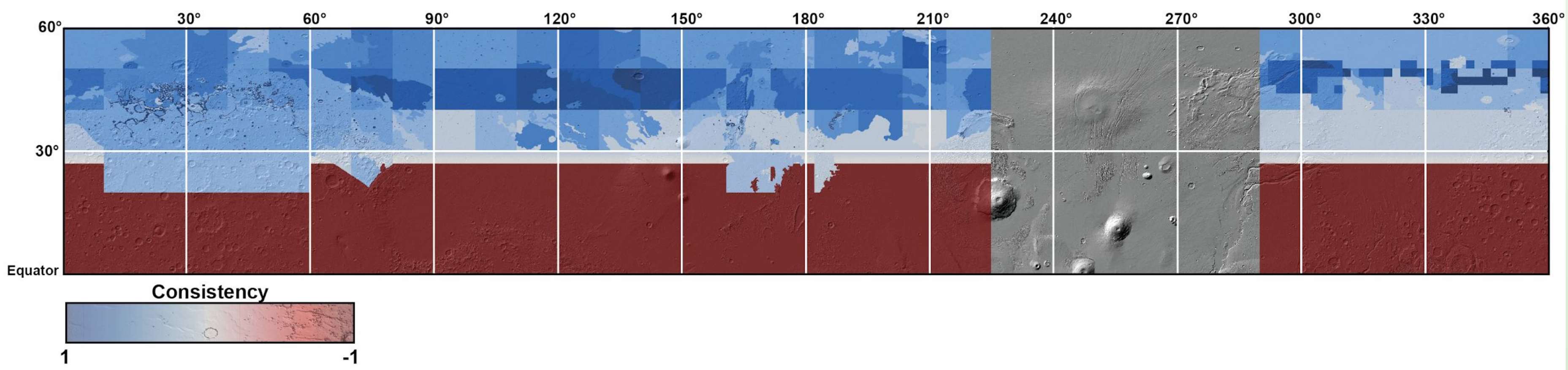


Geomorphology Ice Consistency $\mathbf{C_G}$

- Geomorphology bridges the gap between shallow and deep data sets.
- We investigate shallow ice by mapping landforms interpreted to be ice-rich such as **patterned ground**, **scalloped pits** and **mantling units**. Mapping is conducted using image data such as **CTX** and **HiRISE.**
- We also use **SHARAD roughness** (10-100 m horizontal baseline) to trace the boundary of dissected mantle and no mantle.





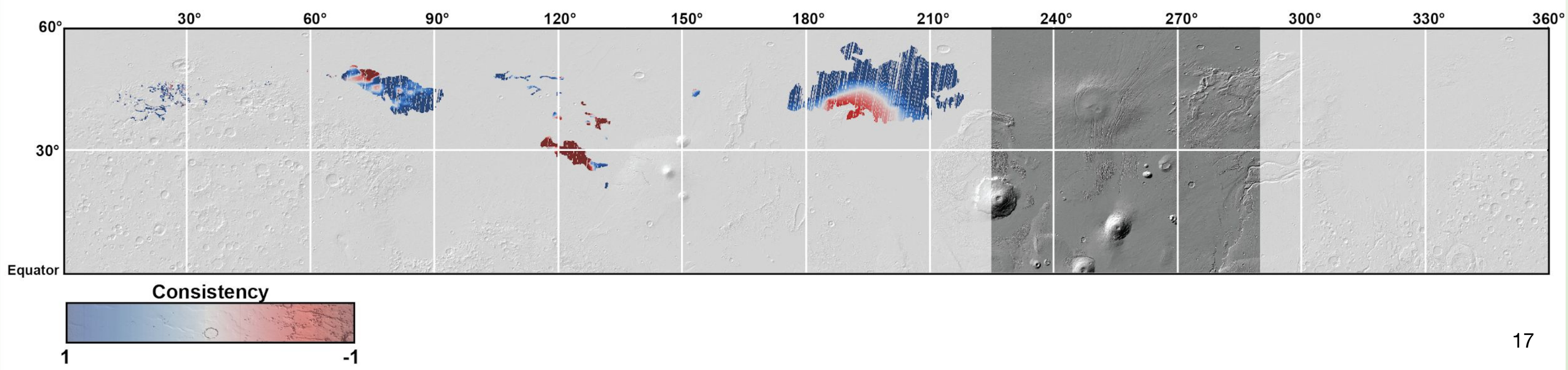


Radar Dielectric Ice Consistency C_{RD}

Radar dielectric ice consistency maps were made by tracing discrete subsurface reflectors in SHARAD radargrams, then estimating dielectric constant **ε'** in places with topographic constraints. We calculated consistency linearly to output:

$$C_{RD} = 1 \text{ where } \varepsilon' \leq 3$$
$$= 0 \text{ where } \varepsilon' = 5$$
$$= -1 \text{ where } \varepsilon' \geq 7$$

- For glacial ices (primarily Onilus), a flat-lying subsurface is assumed to extend from the plains, interpolating from two MOLA minima.
- For non-glacial ices (primarily Arcadia and Utopia), dielectric estimates are averaged for radar-track segments and interpolated across the whole region where the reflector is found.

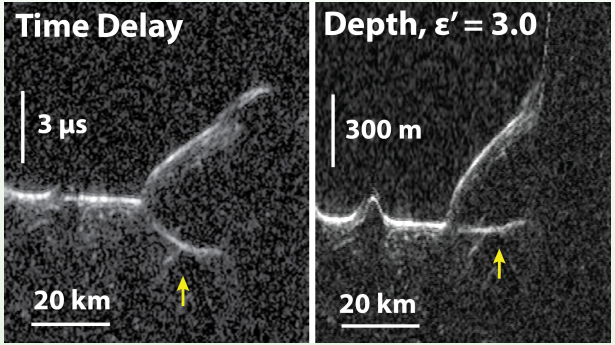


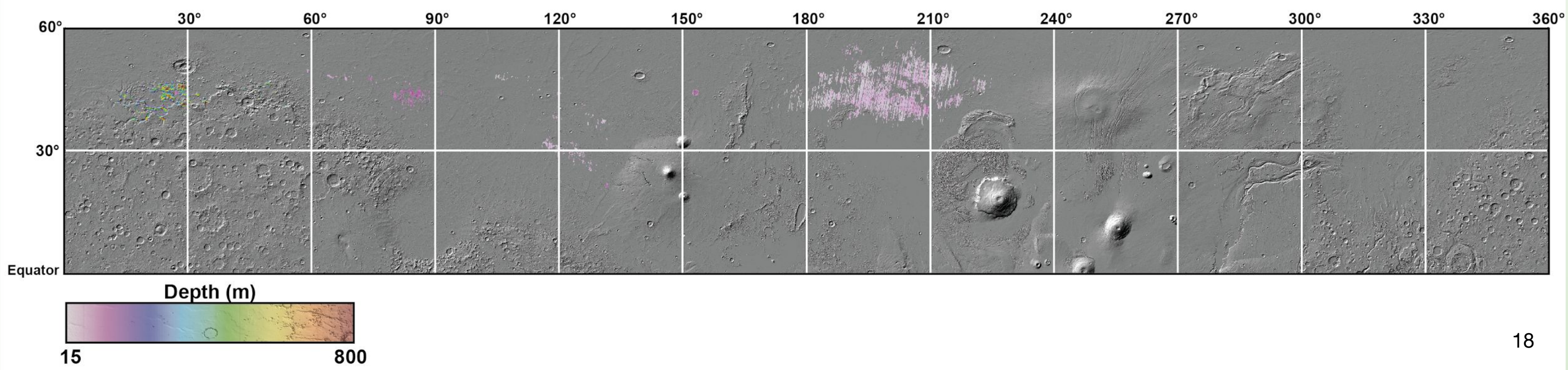
Depth to Base of Ice from Radar Reflections

The dielectric estimations allow us to convert radar delay times to depths below the surface.

While not incorporated directly into the SWIM equation, **the depth map is a valuable product for future planning of human exploration sites.**

Track 1736801: Debris-Covered Glacier





Composite Ice Consistency C_I

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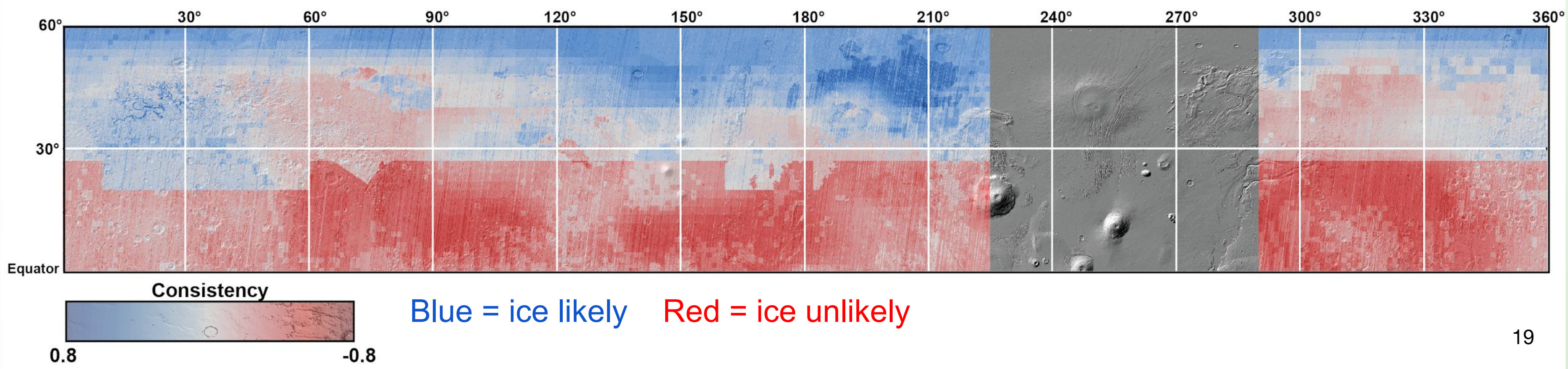
Our composite ice consistency map for the northern hemisphere of Mars is the product of combining mapping results from neutron and thermal spectrometers, radar surface returns, geomorphology, and subsurface radar data analysis using **the SWIM Equation:**

$$C_I = (C_N + C_T + C_{RS} + C_G + C_{RD}) \div 5$$

Consistency of data with the presence of buried ice



Blue = ice likely Red = ice unlikely

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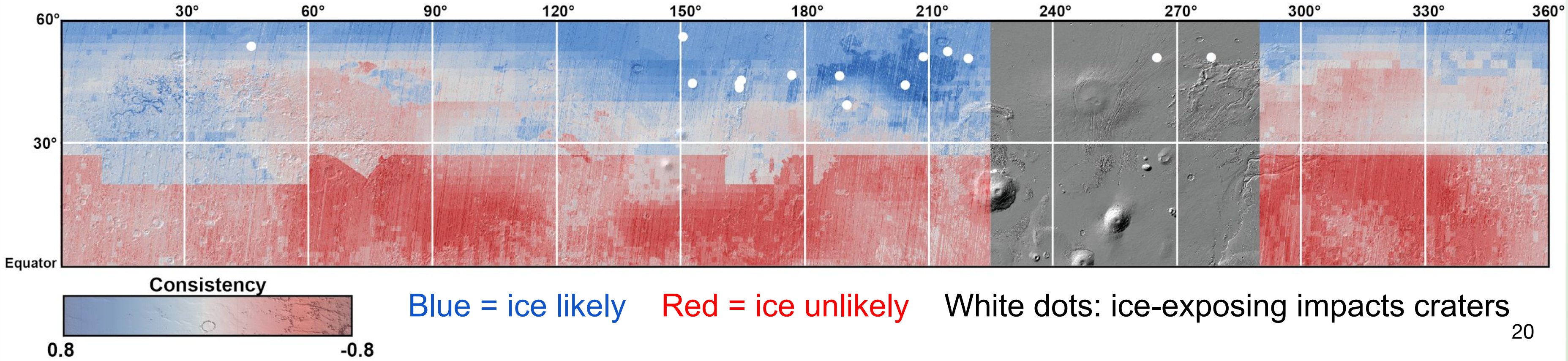
All fresh ice-exposing impacts occur in locations of positive (blue) ice consistency



Blue = ice likely   Red = ice unlikely   White dots: ice-exposing impacts craters

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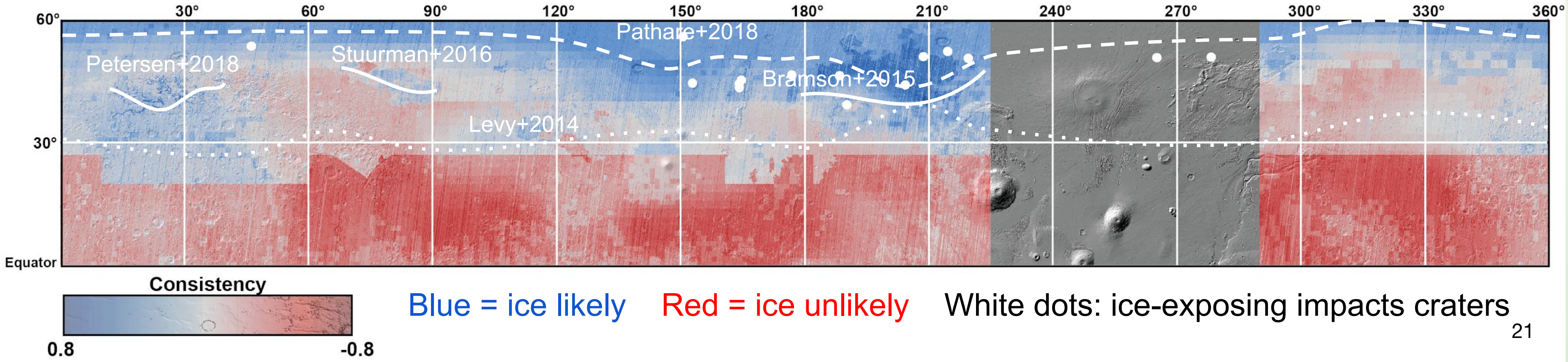

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SWIM Study Products

https://swim.psi.edu

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2. Methods
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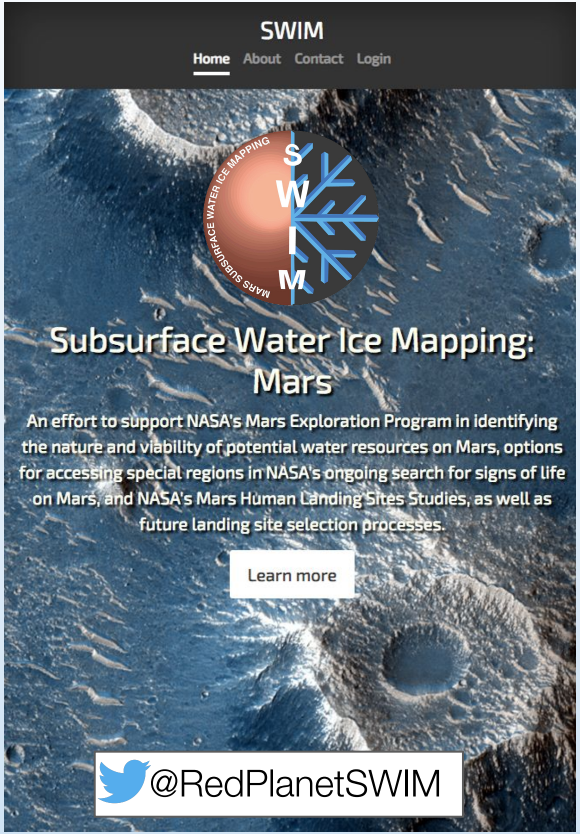
Primary products for entire NH study area:

- Ice consistency maps
  From neutron & thermal data, morphological features, radar surface reflectors, subsurface dielectric values, and a composite from all data
- Top of ice location and depth maps
  From thermal data & SHARAD surface returns
- Base of ice location and depth maps
  From SHARAD subsurface reflectors
- Ice concentration maps
  From SHARAD+DTM permittivity estimates

In addition, we are providing supplemental products associated with each study element

All NH products now available!

Spreading the Word & Results to the Community!



Final Remarks

Buried water ice in the mid-latitudes of Mars could serve as a **resource at future sites of human exploration** for life support and for fuel generation.

The SWIM Project has mapped buried ice using a broad array of datasets—radar observations, imagery and elevation data, and neutron and thermal spectrometry data. **Our composite map shows where the collection of datasets are or are not consistent with buried ice.**

Our results can be used directly for planning human exploration sites. They also inform **the choice of locations for more in-depth study** and **the limitations of current data sets that might be addressed by future robotic missions**.

This work was driven by the goal of mapping out and assessing buried ice for resource purposes. **However, the results also inform scientific investigations concerning the connections between buried ice and past climate on Mars.**