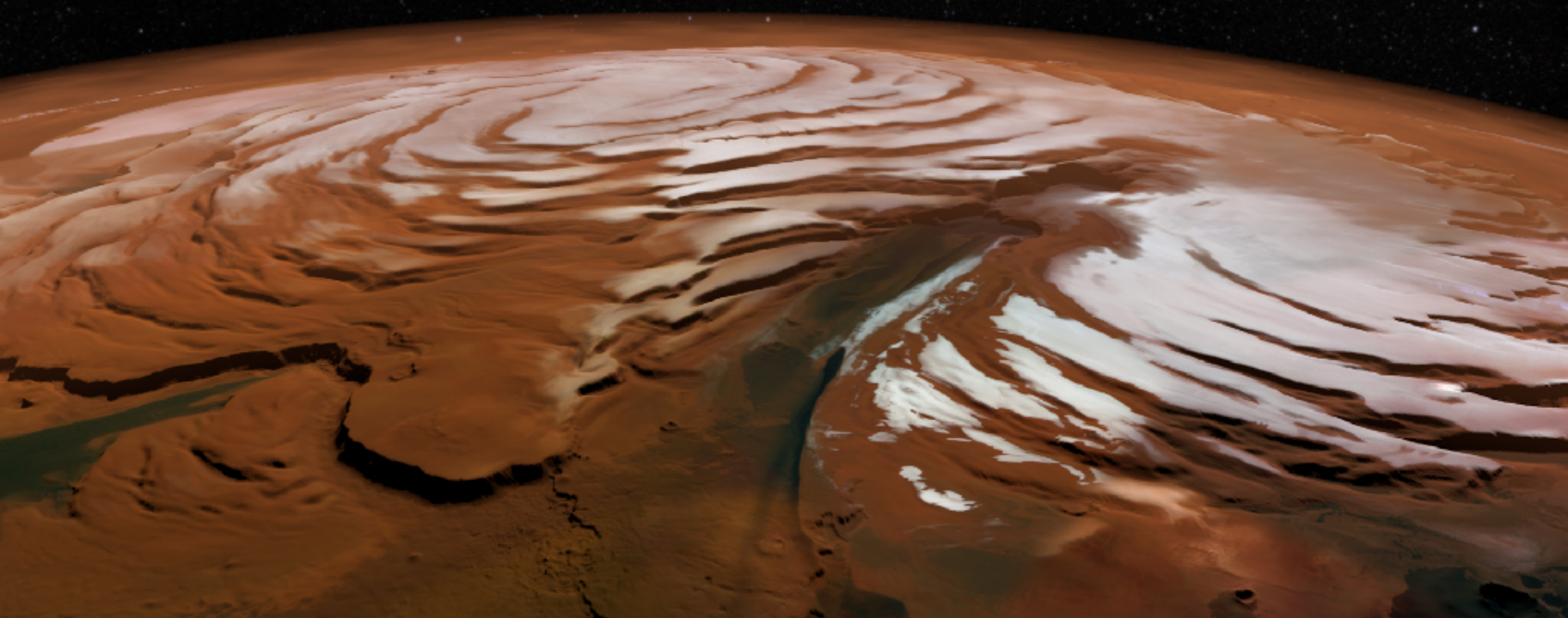
Exploring the subsurface of Mars with radar sounding

Jack Holt

February 26, 2024



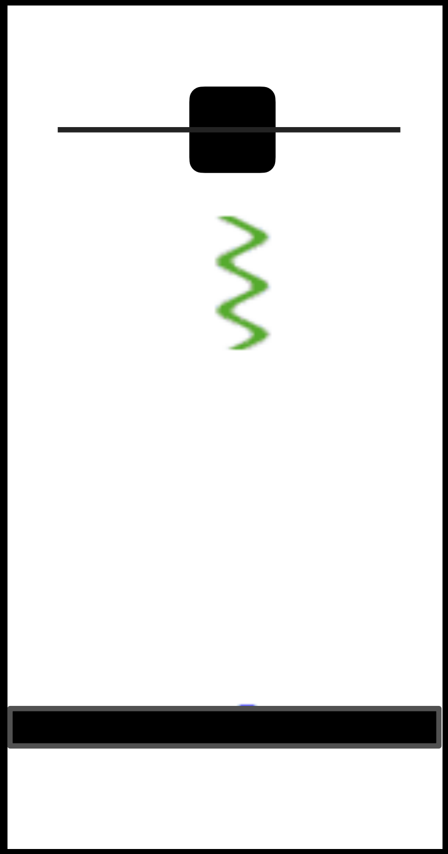
Radar sounders are subsurface profilers

Transmit a pulse of energy, when it hits an interface some reflects, some goes through...

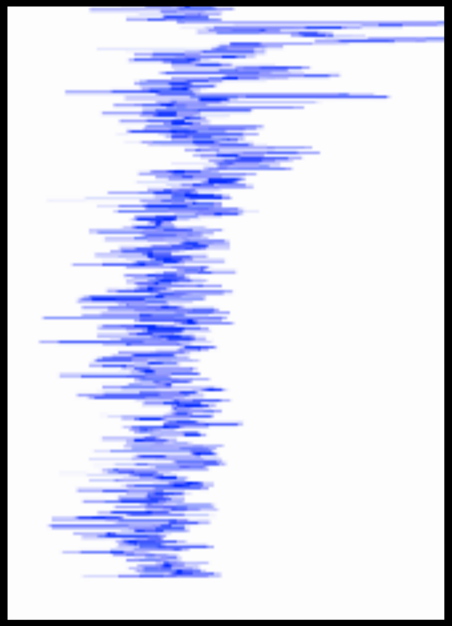
Record voltage vs. time, sum over multiple pulses to increase SNR.

Penetration dependent on electrical properties of the material and wavelength of the radar.

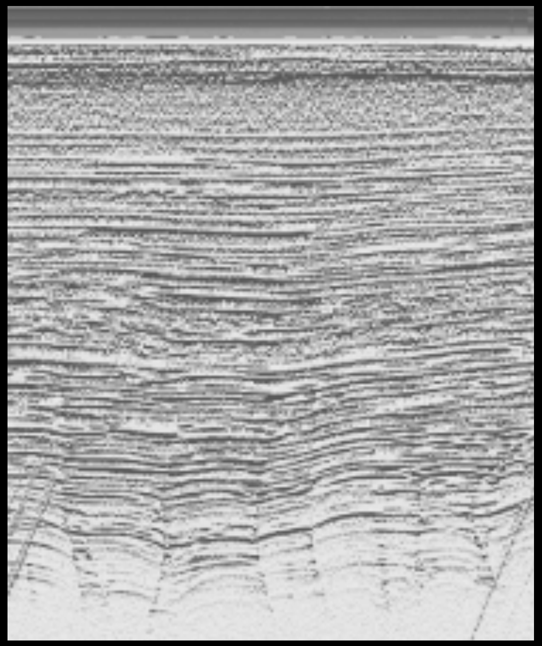
Vertical resolution is 1/BW (BW = bandwidth)



single return

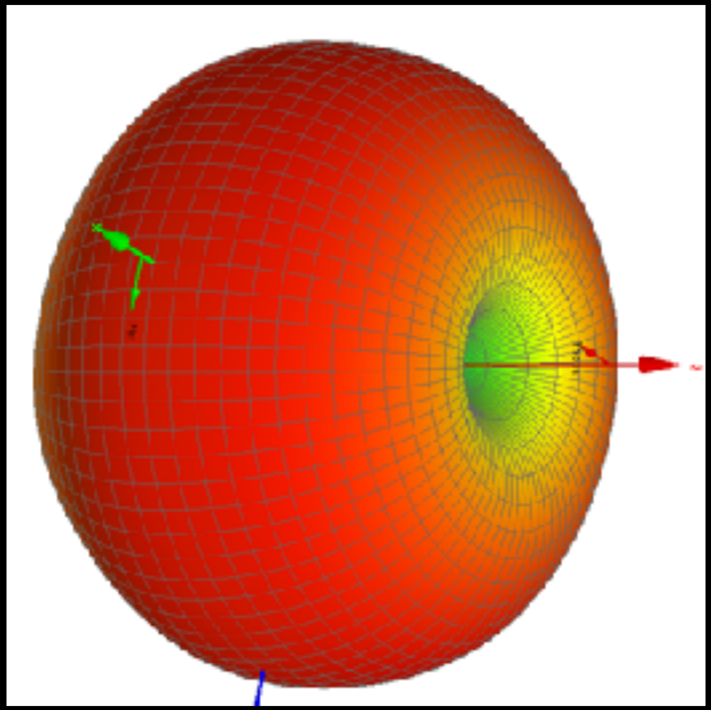


many returns



Wavelength considerations

- To penetrate into the subsurface, a long wavelength is required
  - Generally ~ 1 m or greater (300 MHz or lower)
  - Typically 2-60 m (150 MHz - 5 MHz)
- The longer the wavelength, the larger the antenna
- For airplanes and spacecraft, larger is a challenge - means something simple like a dipole (rod or wire)
- Simpler means broad pattern
  - Less power at the target
  - More reflections from the sides

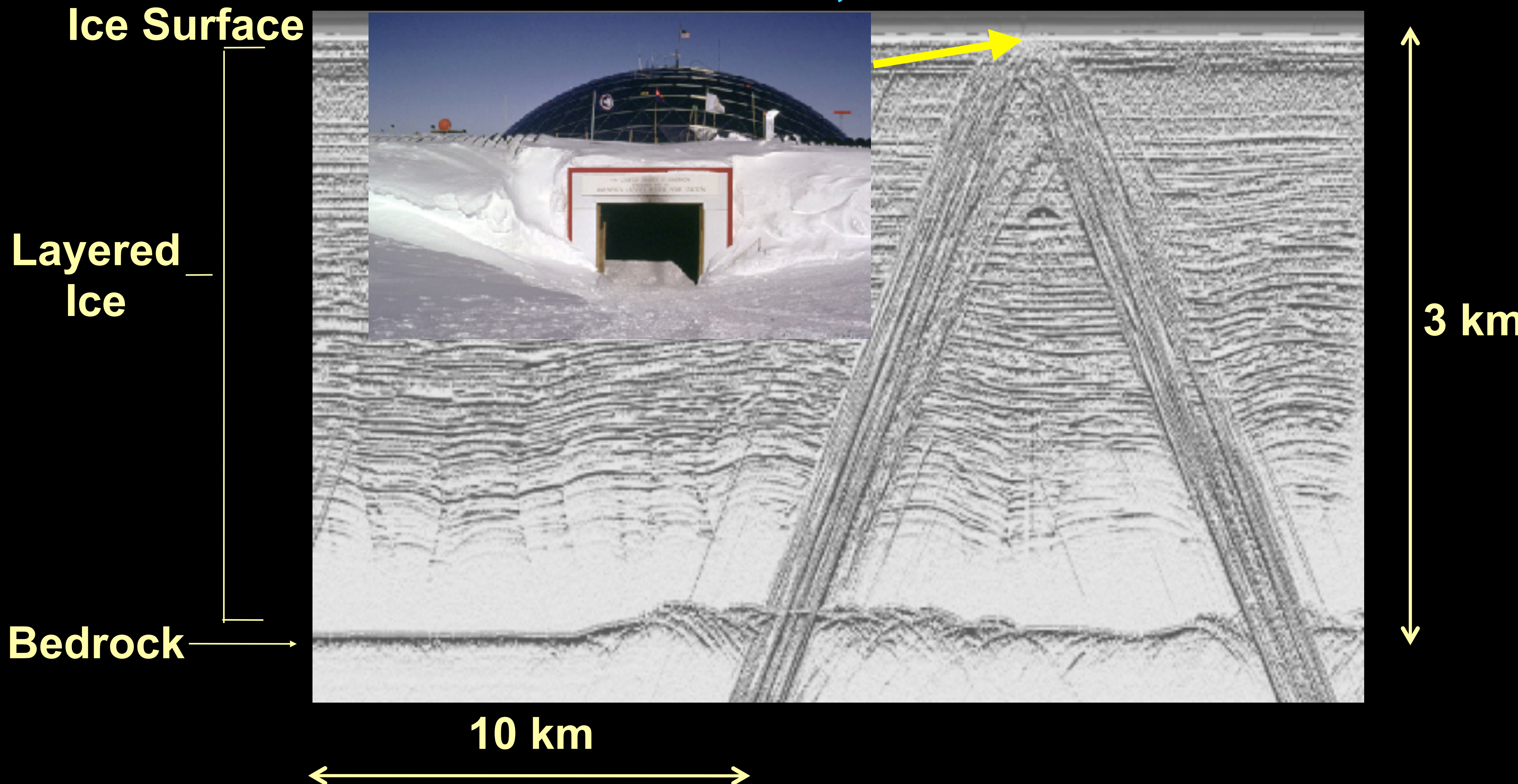


dipole antenna radiation pattern

Due to the electrical properties of freshwater ice, it is nearly radar transparent

(at wavelengths of a few meters or more)

Airborne radar data over the South Pole, Antarctica



RADAR PROPERTIES

A brief radar primer:

- Radar measurements rely on "dielectric permittivity" which is a complex quantity

$$\epsilon = \epsilon ' - i\epsilon ''$$

real part -> energy storage

imaginary part -> energy dissipation

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- Real part ("dielectric constant") primarily impacts **velocity** of radar wave

$$v = \frac{c}{\sqrt{\epsilon'}}$$

directly related to density

(more dense = slower velocity)

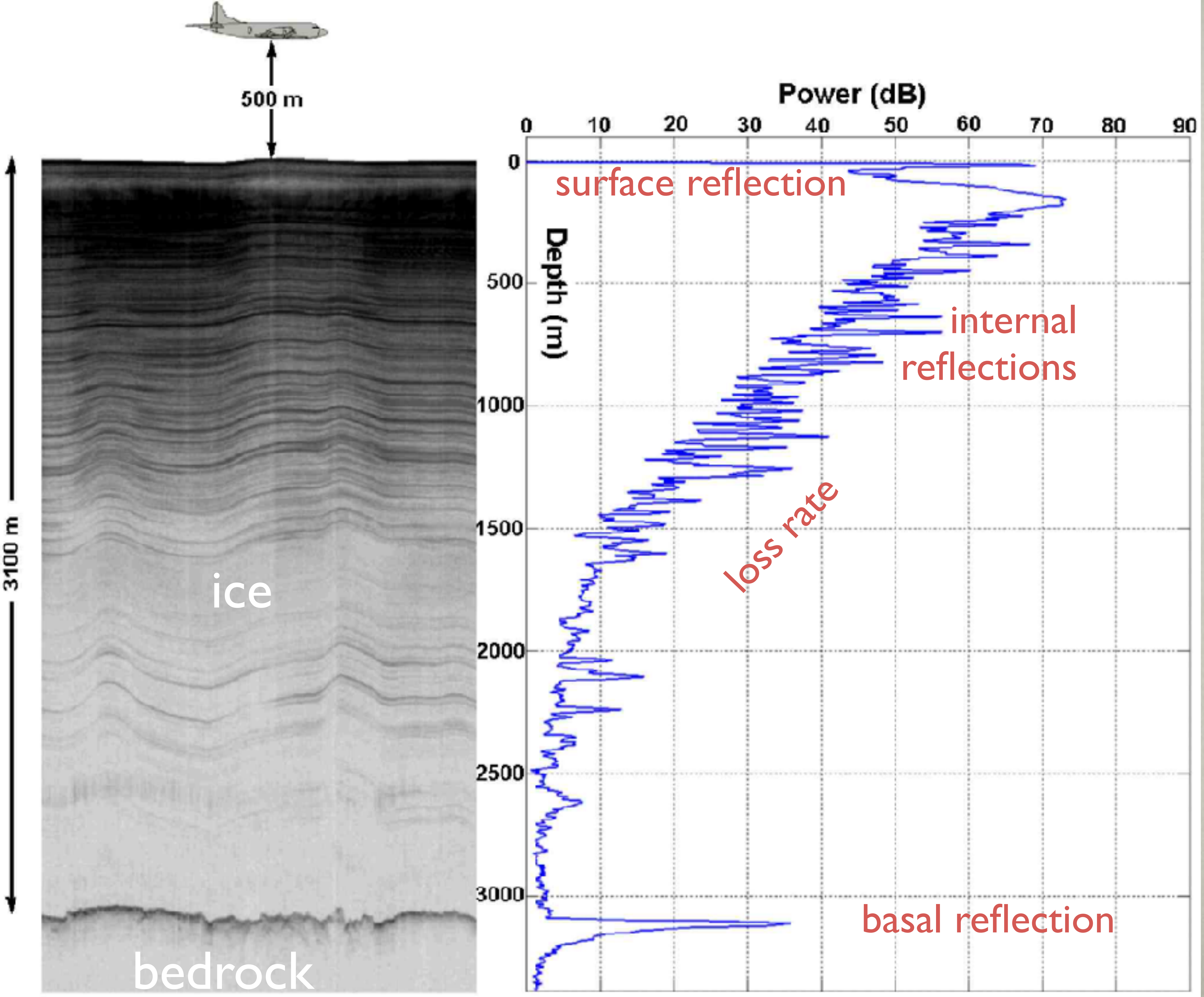
RADAR PROPERTIES

A brief radar primer:

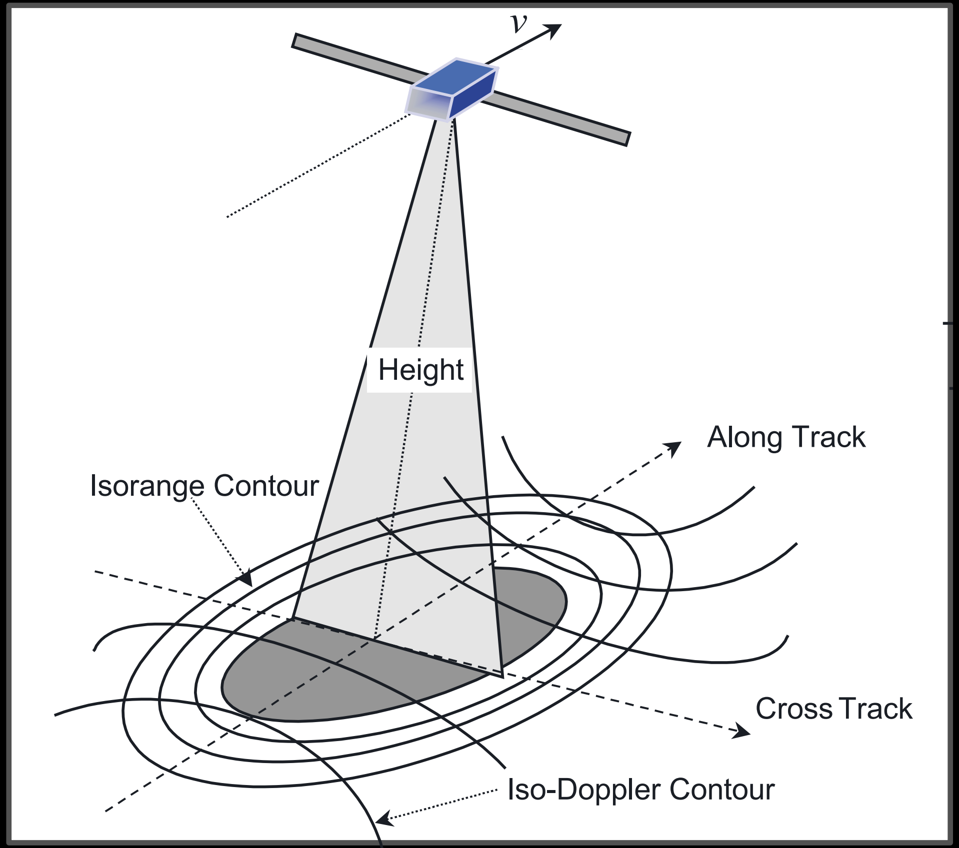
Radar measurements rely on "dielectric permittivity" which is a complex quantity	$\epsilon = \epsilon\,' - i\epsilon\,''$	real part -> energy storage imaginary part -> energy dissipation
Real part ("dielectric constant") primarily impacts **velocity** of radar wave	$v = \frac{c}{\sqrt{\epsilon\,'}}$	directly related to density (more dense = slower velocity)
Imaginary part primarily impacts **attenuation** of radar wave - "**Loss Tangent**" is the usual form.	$tan(\delta) = \frac{\epsilon\,''}{\epsilon\,'}$	directly related to conductivity (more conductive = more losses)

typically $\epsilon\,'' << \epsilon\,'$ (materials usually not very conductive)

- Therefore, if we can measure ***velocity*** and ***attenuation*** of the wave, we can constrain its material properties (i.e., density and conductivity).
- Water ice has distinctive (but nonunique) properties for each, so other information is often needed, such as context, structure, morphology, strength, etc.

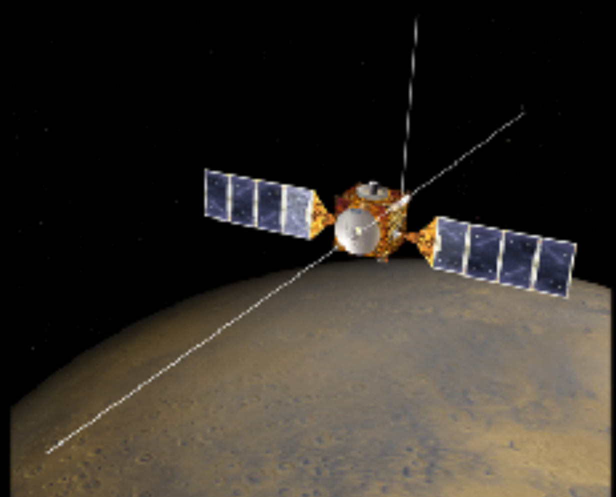

500 m
3100 m
ice
bedrock
Power (dB)
0
10
20
30
40
50
60
70
80
90
Depth (m)
0
500
1000
1500
2000
2500
3000
surface reflection
internal reflections
loss rate
basal reflection

SHARAD on Mars Reconnaissance Orbiter

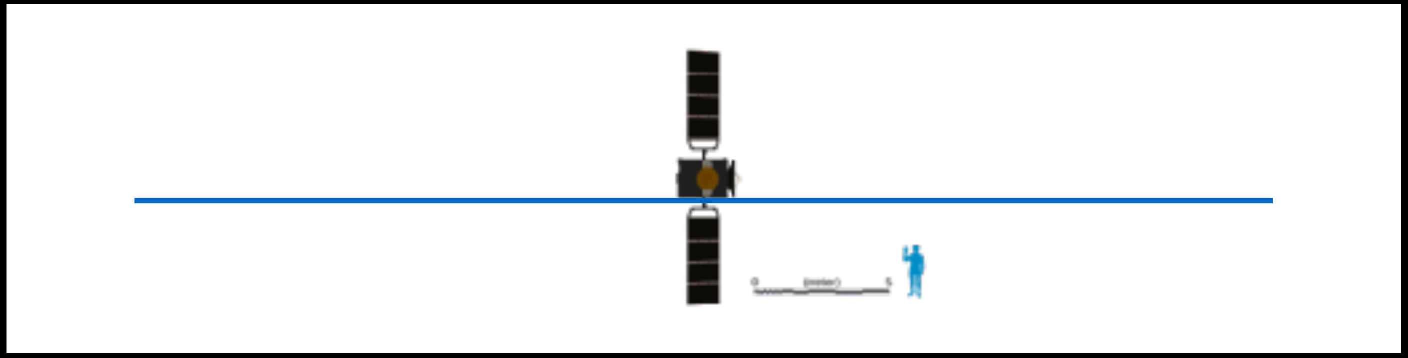


- **20 MHz with 10 MHz chirp (15 m wavelength)**
  - ***Vertical resolution of ~ 10 m***
- **Horizontal resolution: ~ 0.3 km along track, 3-6 km cross track.**
- **Designed to probe the top few hundreds of meters of Mars, and complement MARSIS**
- **In orbit since late 2006**

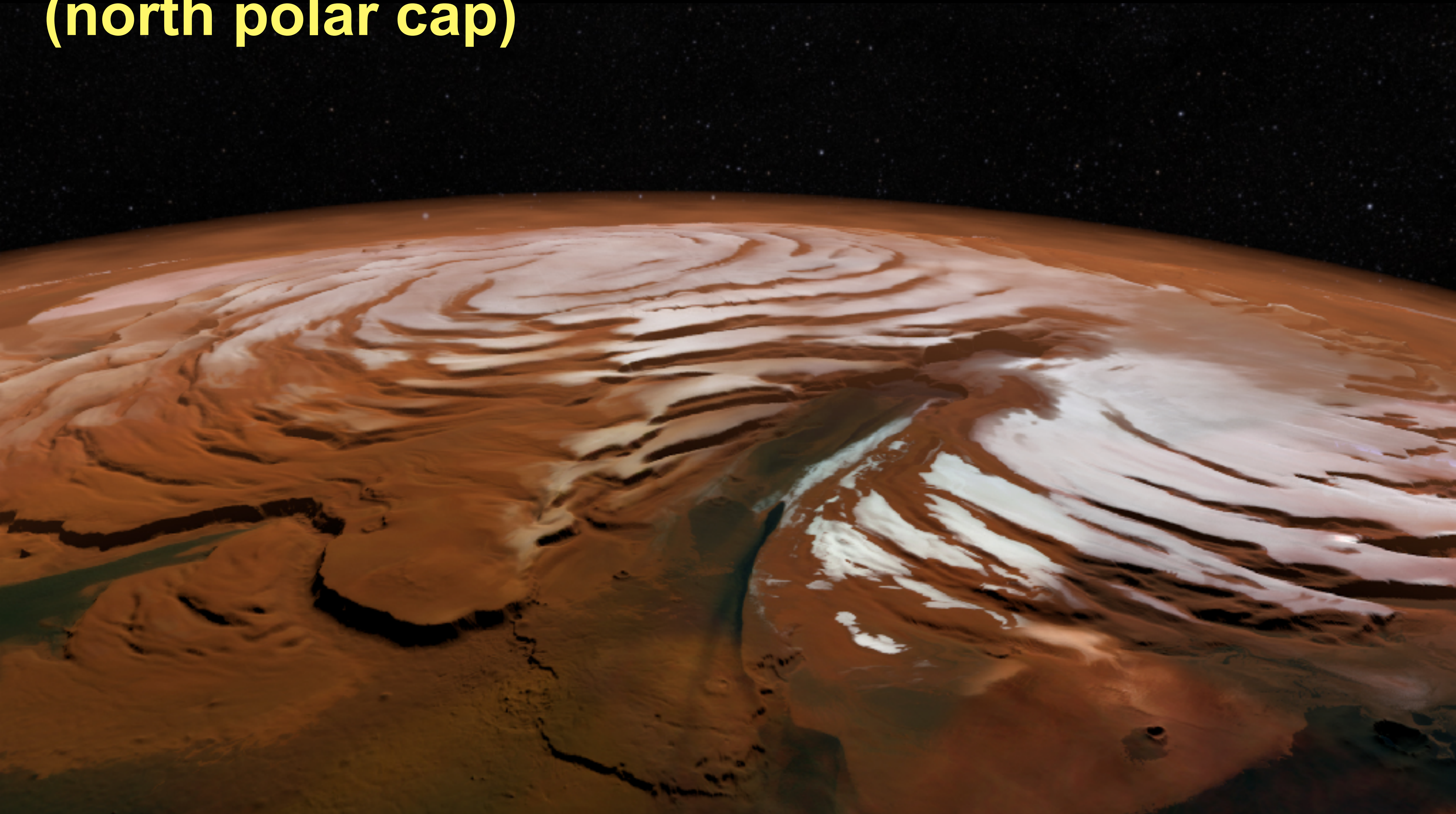
MARSIS on Mars Express



- 1 - 5 MHz in 4 discrete bands, each with 1 MHz bandwidth
- 60 - 300 m wavelength
- Vertical resolution of ~ 100 m
- Designed to probe deep (km's) to detect water table on Mars
- In orbit since 2005

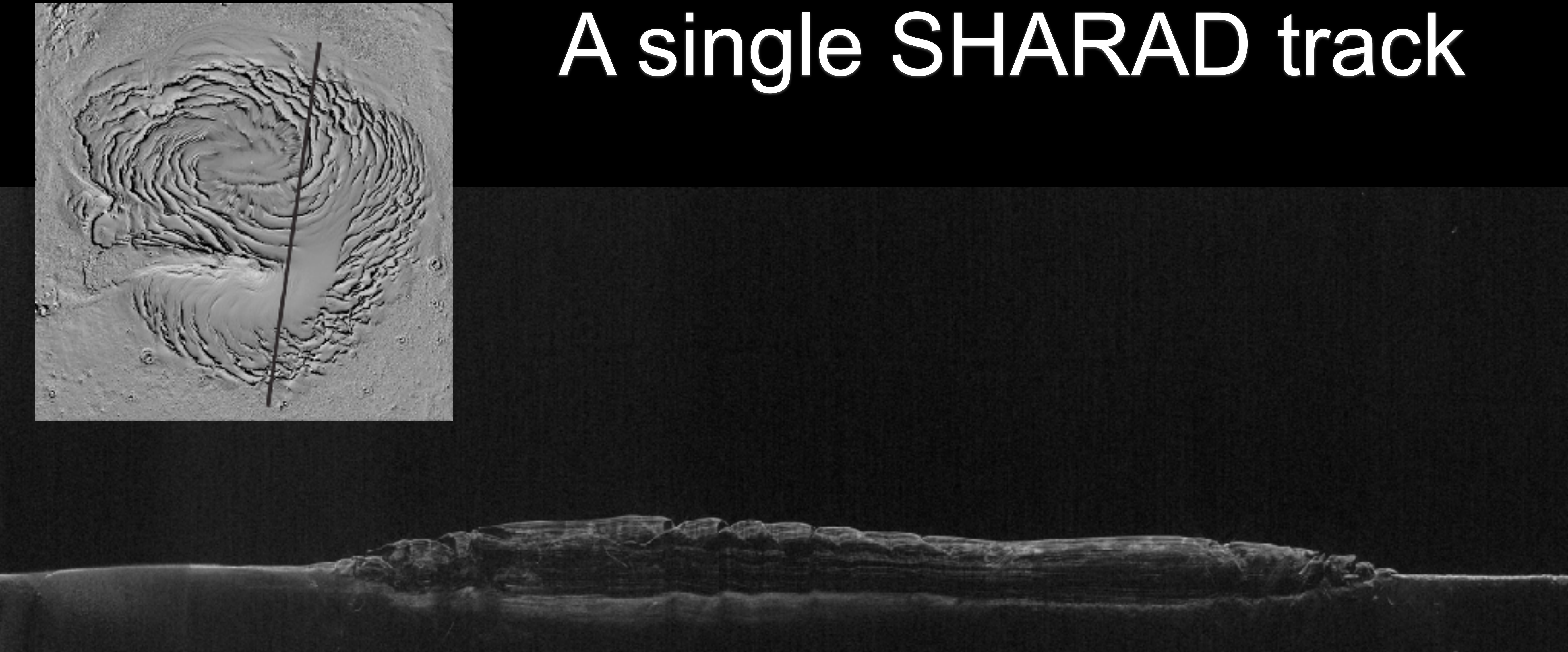


Planum Boreum (north polar cap)



HRSC on Mars Express

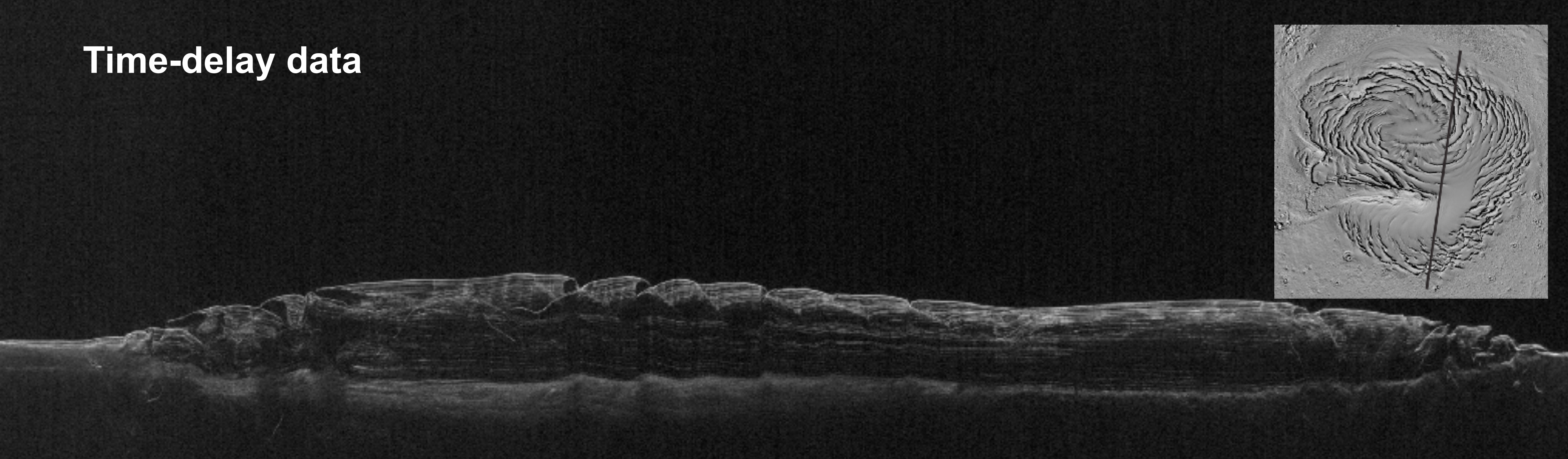
A single SHARAD track



Time-delay data

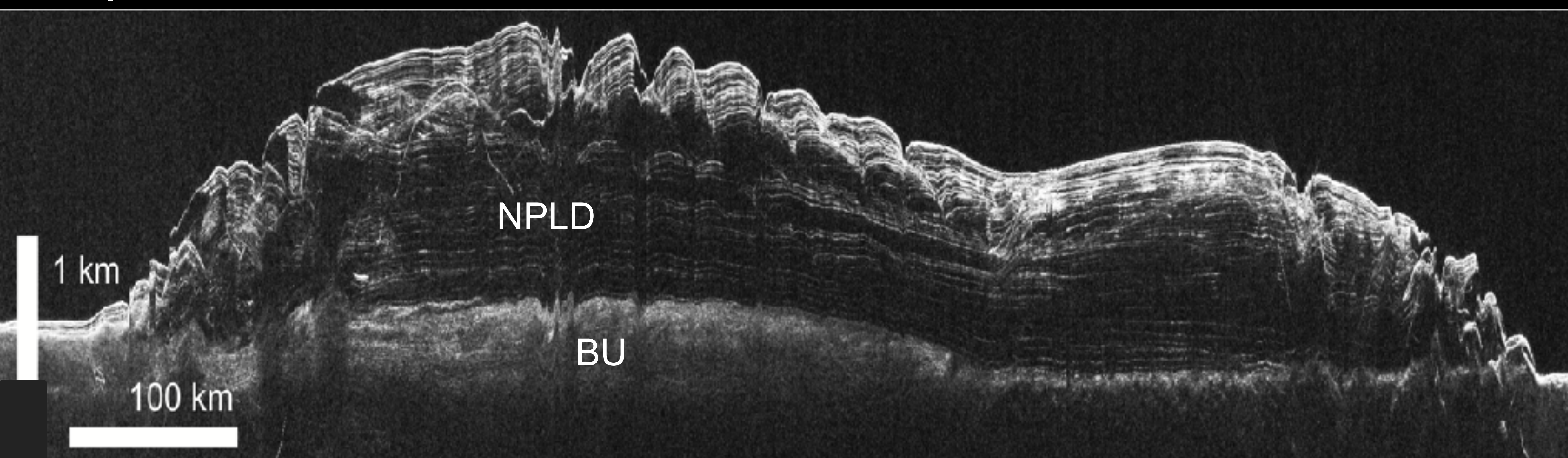
FPB_1294501_time

Time-delay data

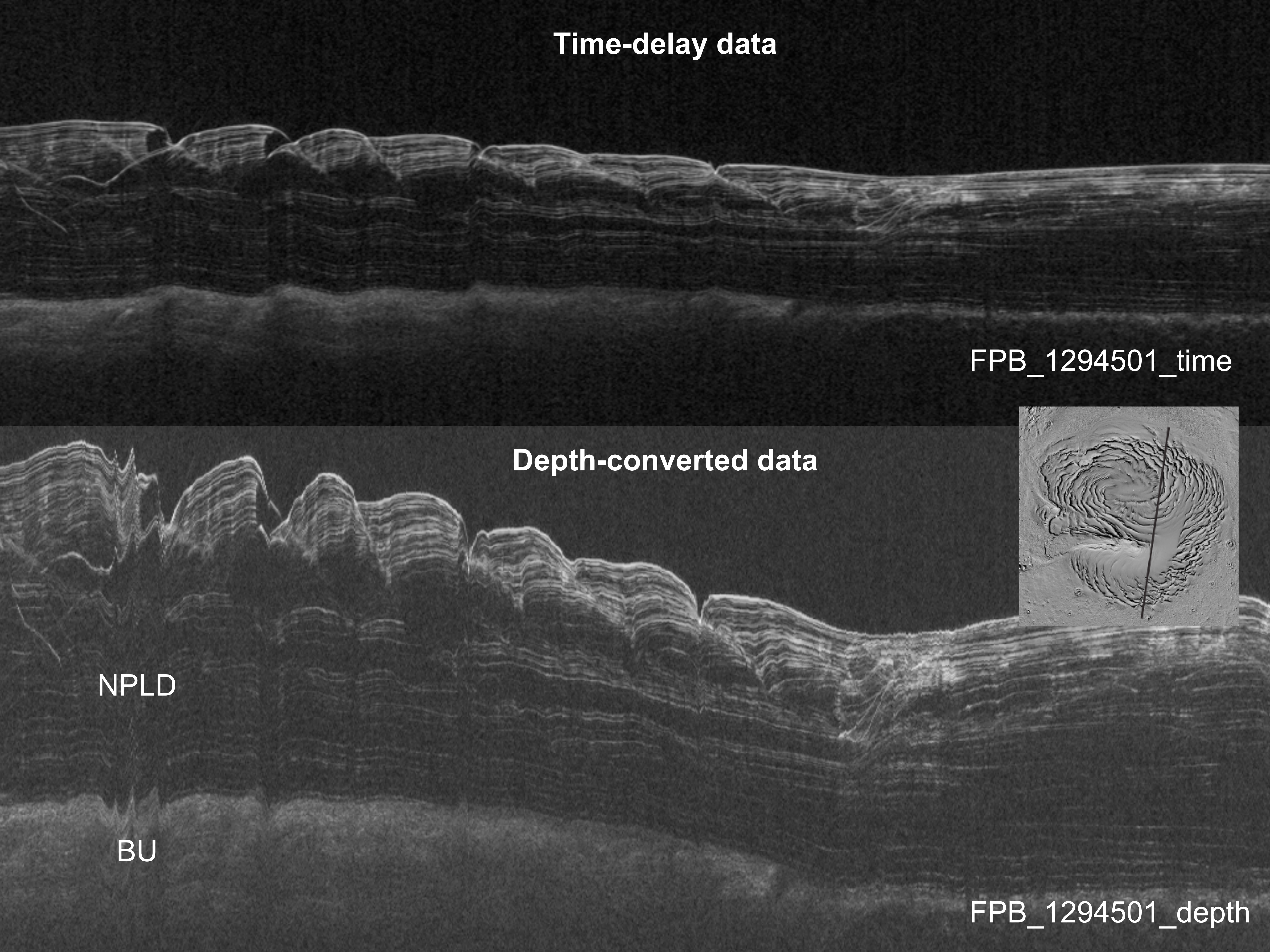


FPB_1294501_time

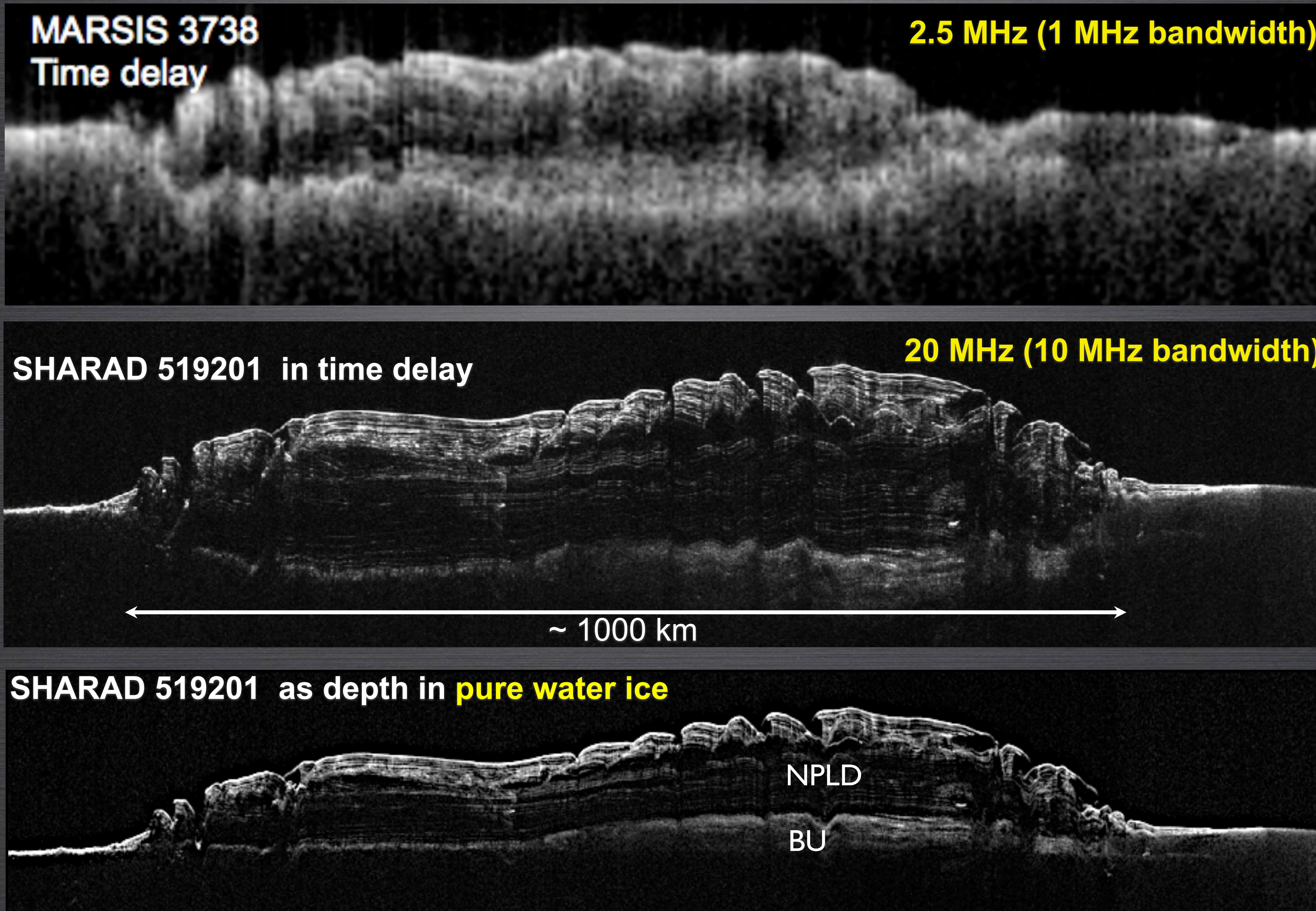
Depth-converted data



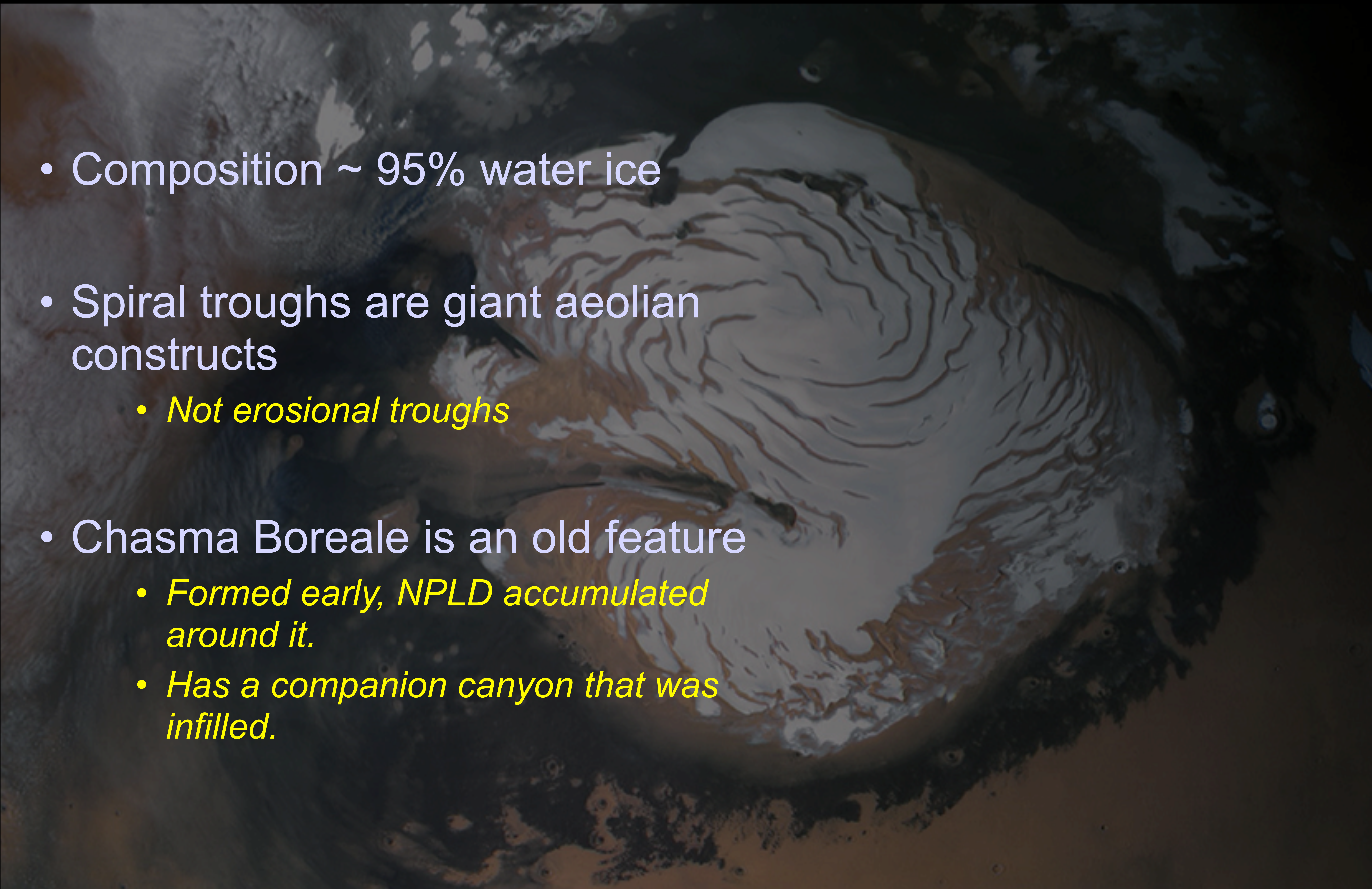
FPB_1294501_depth


Time-delay data
FPB_1294501_time
Depth-converted data
NPLD
BU
FPB_1294501_depth

Planum Boreum radar comparison

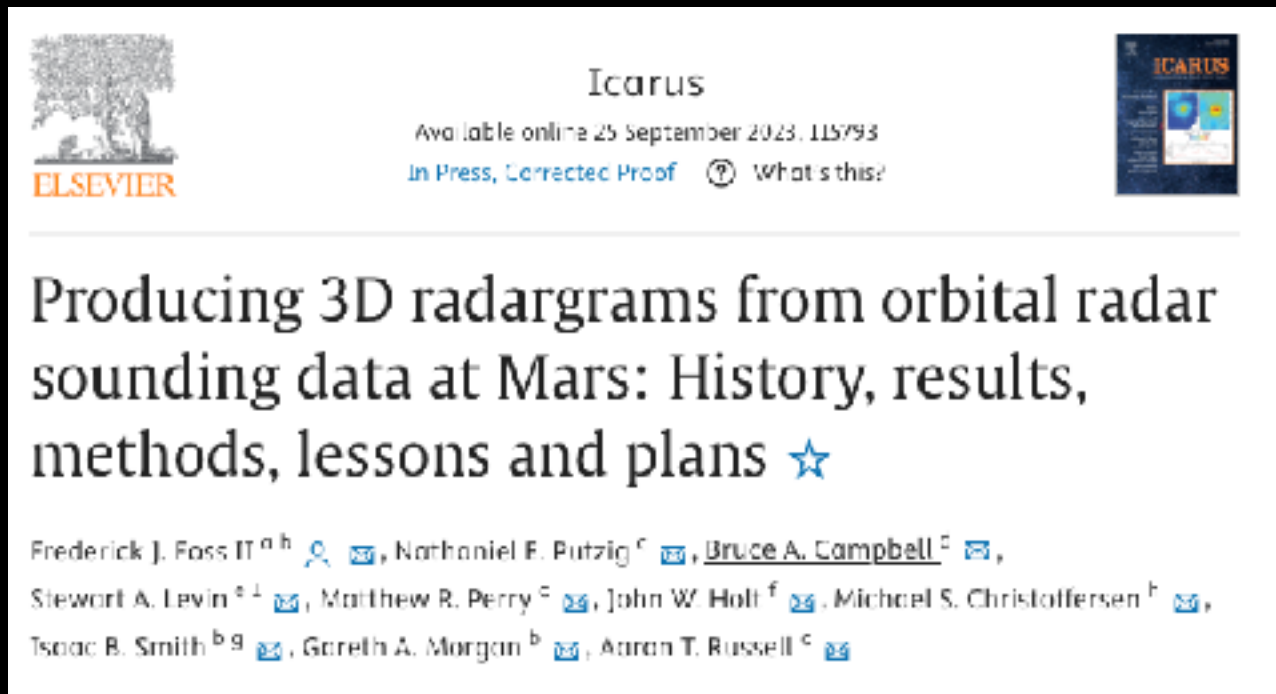


Some major NPLD findings from SHARAD



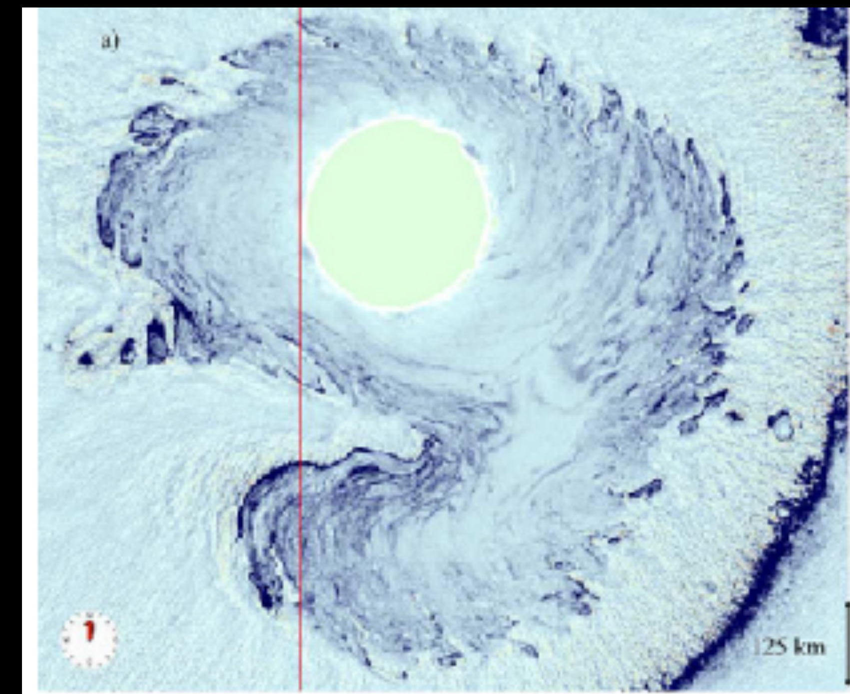
- Composition ~ 95% water ice
- Spiral troughs are giant aeolian constructs
  - *Not erosional troughs*
- Chasma Boreale is an old feature
  - *Formed early, NPLD accumulated around it.*
  - *Has a companion canyon that was infilled.*

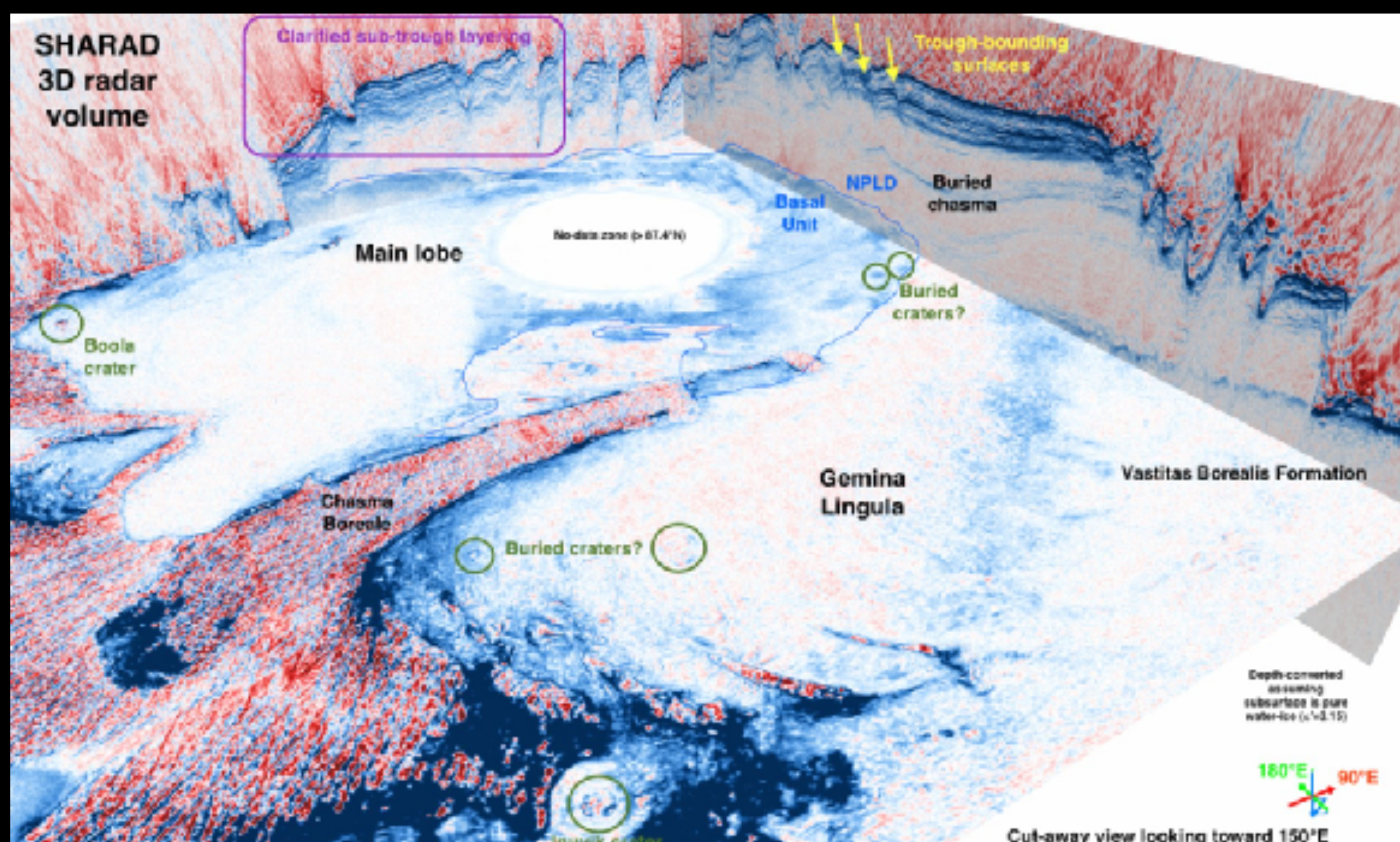
3D SHARAD data


Icarus
Available online 25 September 2023, 115793
In Press, Corrected Proof ⓘ What's this?

Producing 3D radargrams from orbital radar sounding data at Mars: History, results, methods, lessons and plans ☆

Frederick J. Foss II[a,h], Nathaniel E. Putzig[c], Bruce A. Campbell[c], Stewart A. Levin[a,i], Matthew R. Perry[c], John W. Holt[f], Michael S. Christoffersen[f], Isaac B. Smith[b,g], Gareth A. Morgan[b], Aaron T. Russell[c]





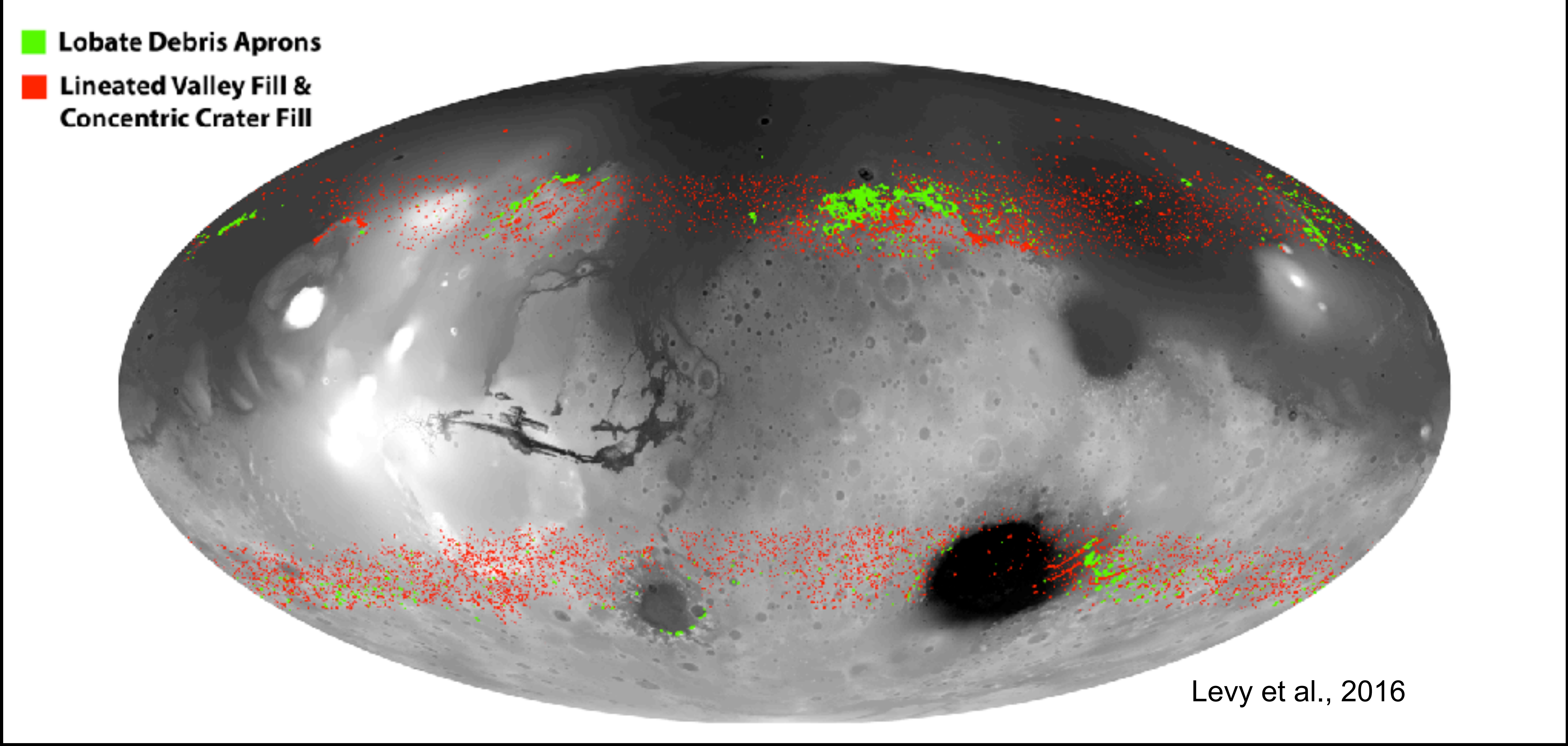
Mars Glaciers

Initially thought to be debris flows with some interstitial ice

“Lobate Debris Aprons” or LDA

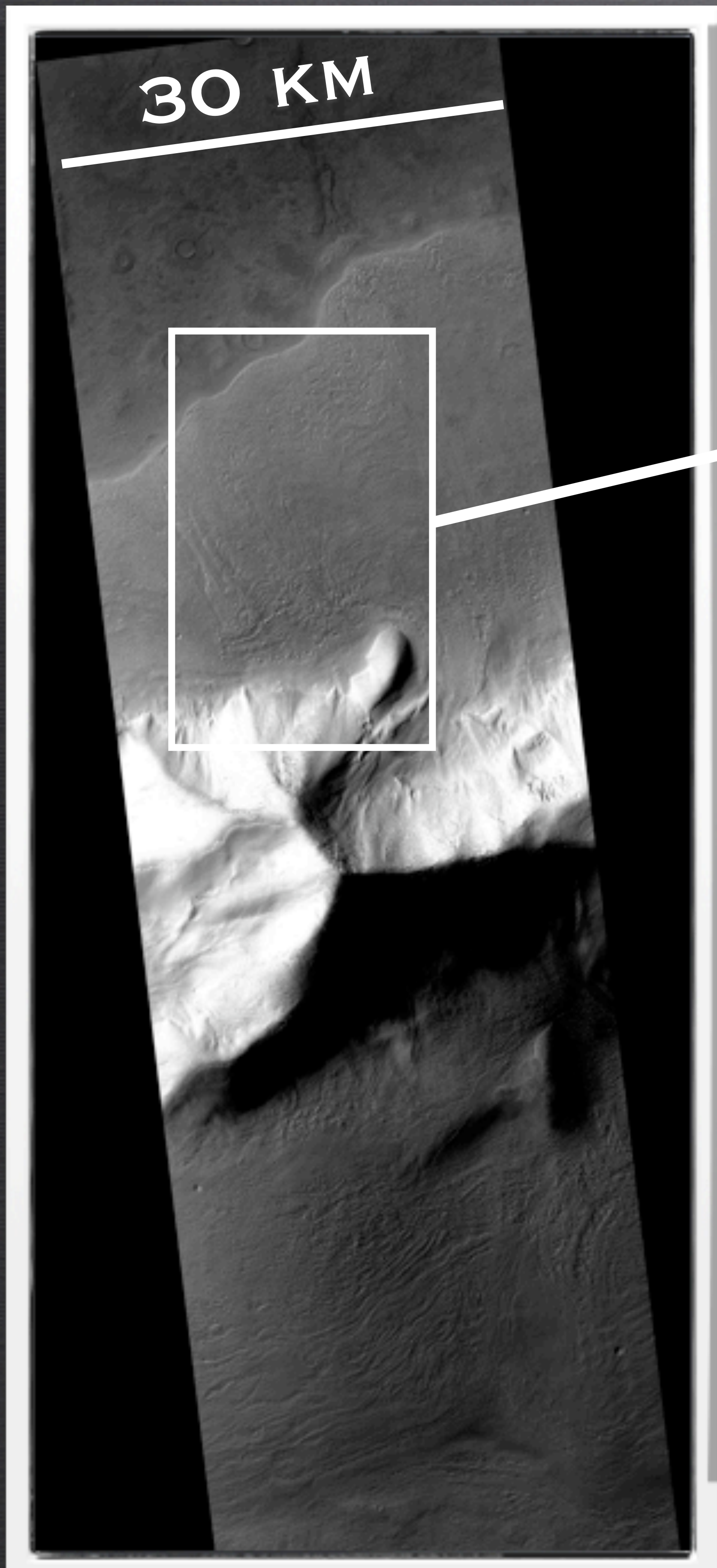
Mars Express (current ESA mission)
High Resolution Stereo Camera
perspective view

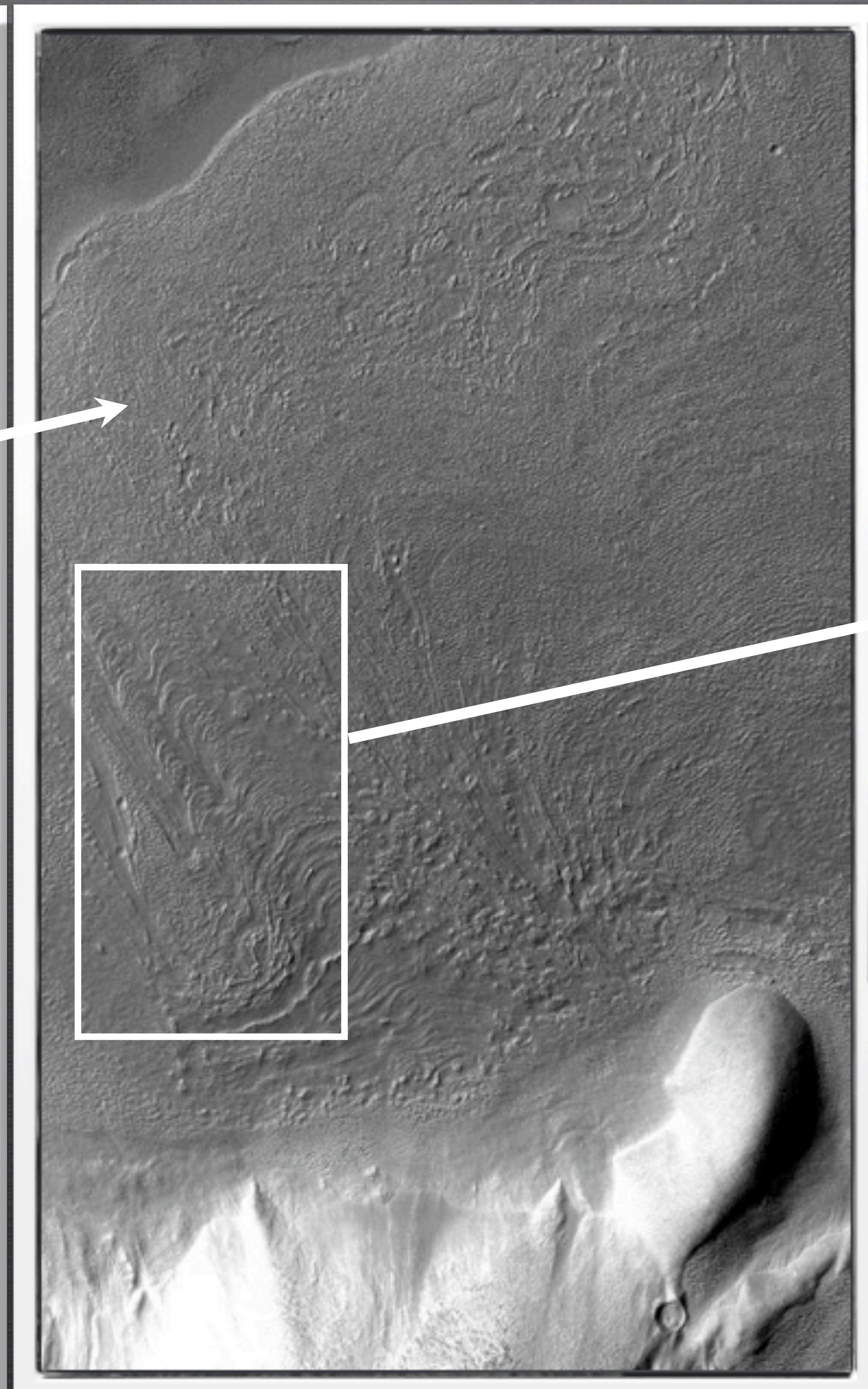
Global distribution

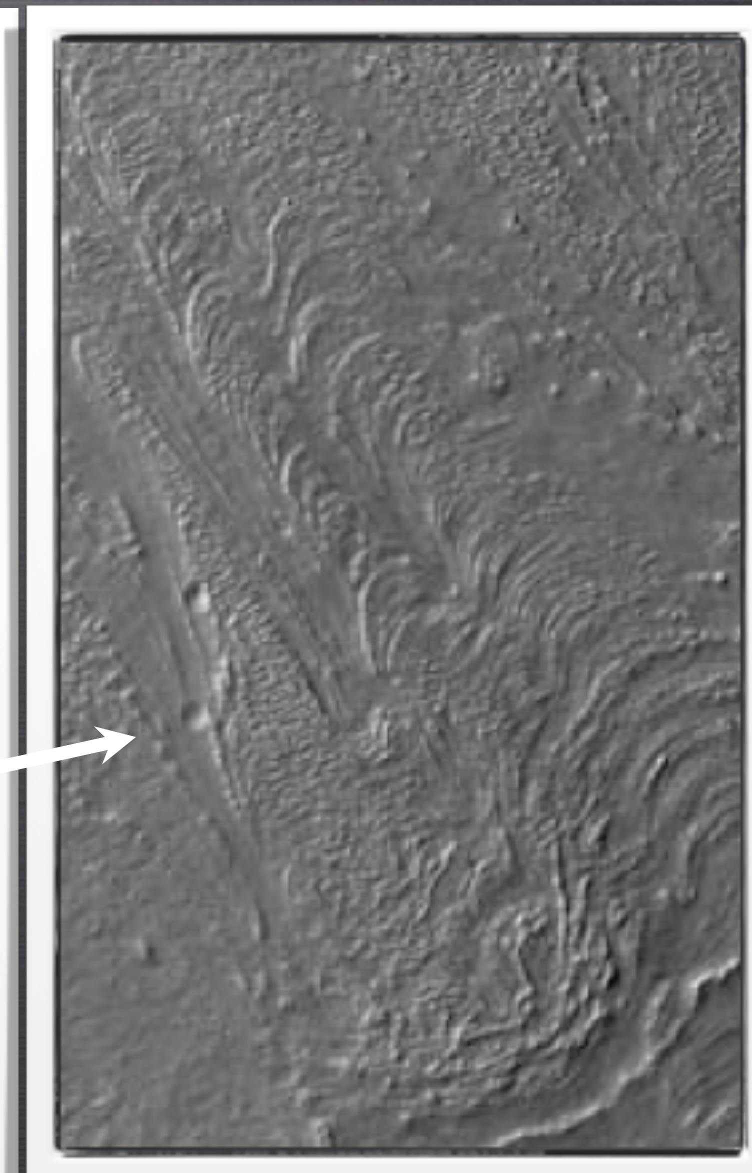


- ~ 30 - 60° latitude in both hemispheres
- Age: 100's of millions of years old, based on crater counting

Imagery from CTX on MRO



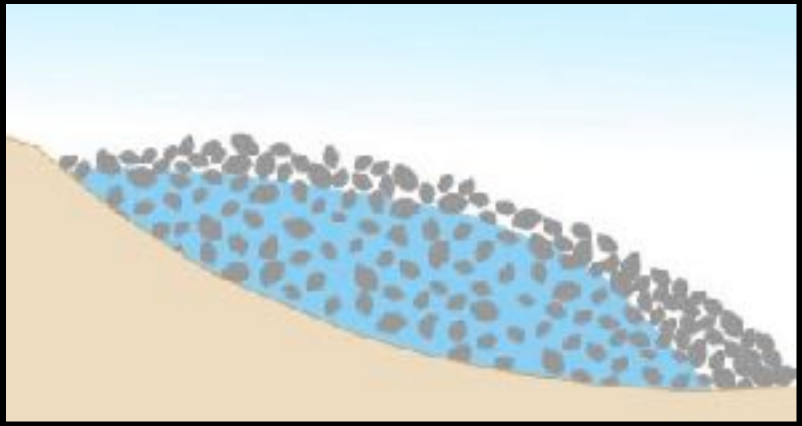




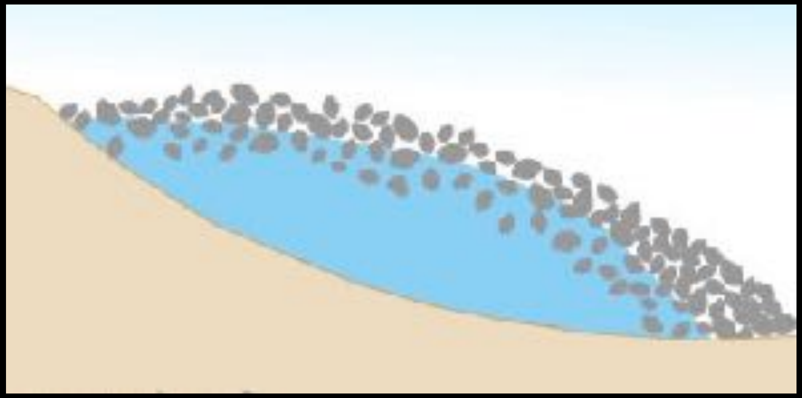
7 km across

Compressional ridges
Flow lineations
Lobate outer edge

What are they?



- Hypothesis 1: Debris flows
  - Just 10-30% ice
  - Source of water? Slow diffusion from ground or atmosphere.
  - Water ice could be long gone, just leaving behind evidence of flow.

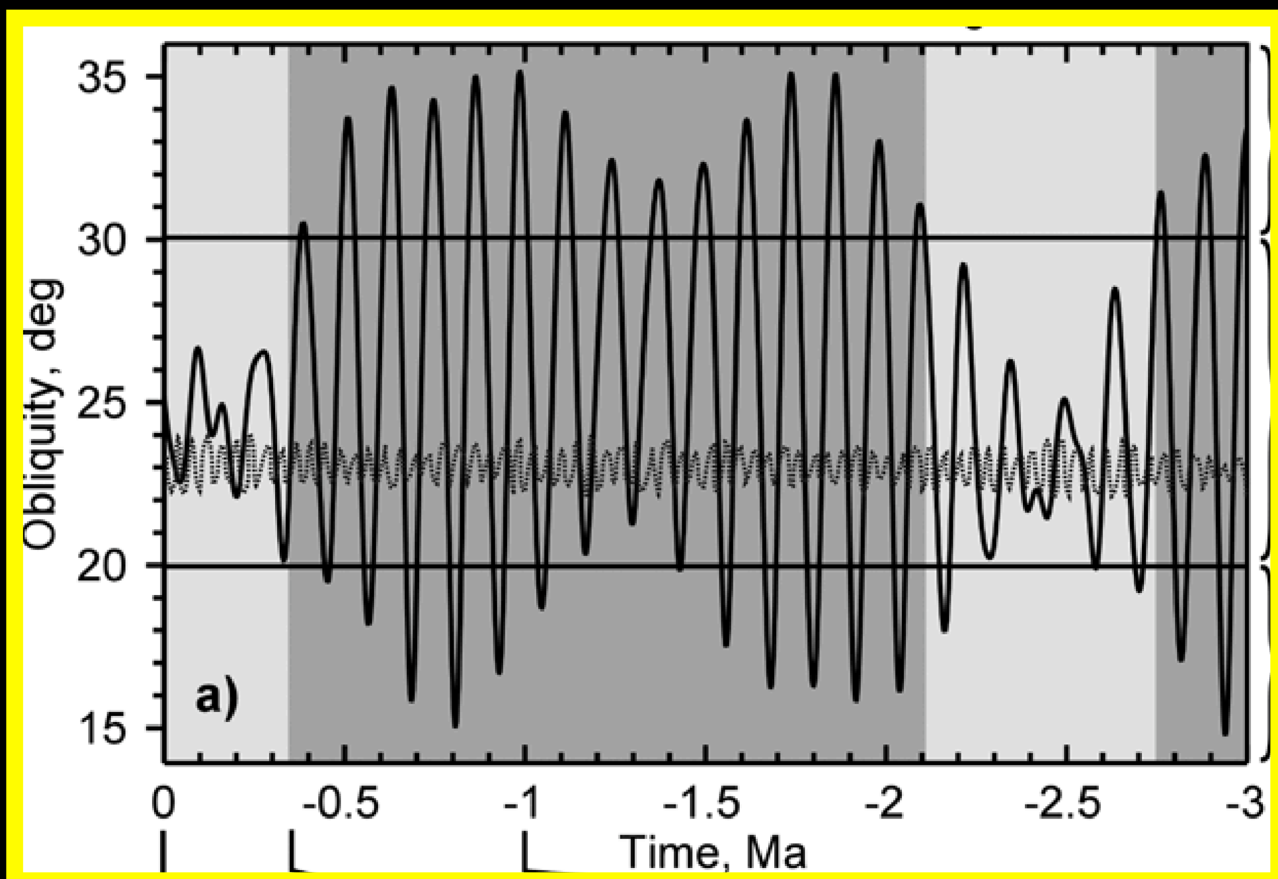


- Hypothesis 2: Debris covered glaciers
  - Would require large amounts of atmospheric deposition (snow!).
  - Would also require large amounts of ice to remain.
  - Can't reconcile with current climate, so didn't get much support.

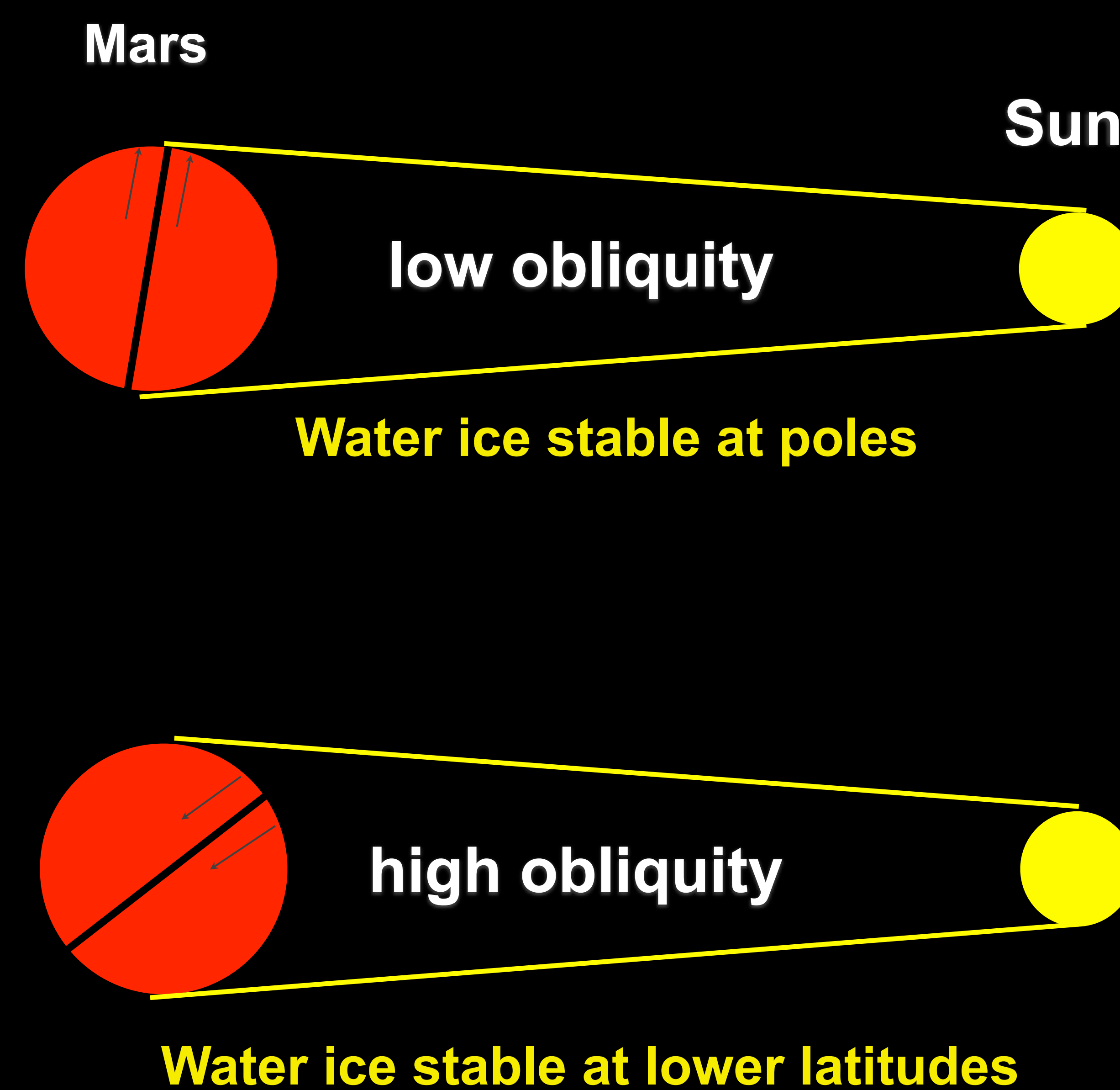
Why not glaciers?

- Water ice is only stable at the surface near the poles on Mars
- Surface temperatures -73° C at 40° latitude
    - *Much too cold for ice to flow*
    - *No liquid water to help it flow*

What about orbital forcing of climate?



Head et al., 3003
Laskar et al., 2002 primary source



Paleoclimate modeling supports glaciers

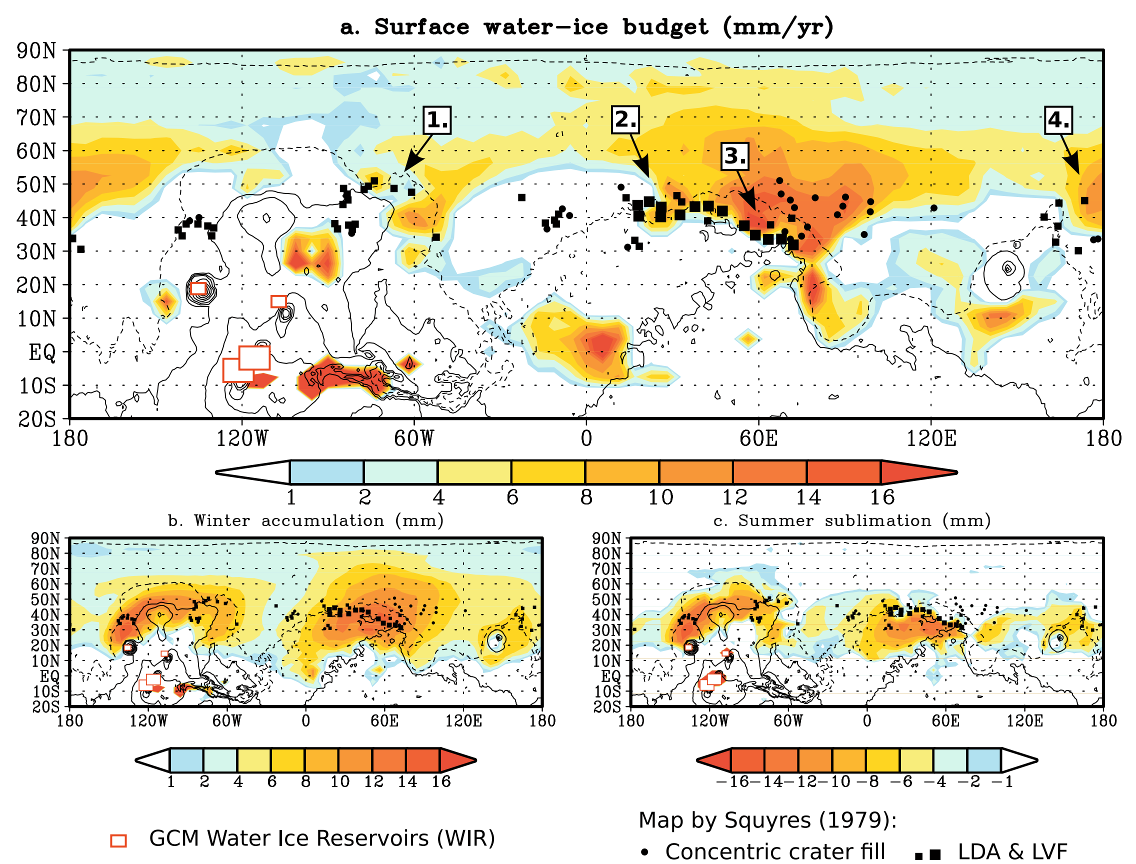


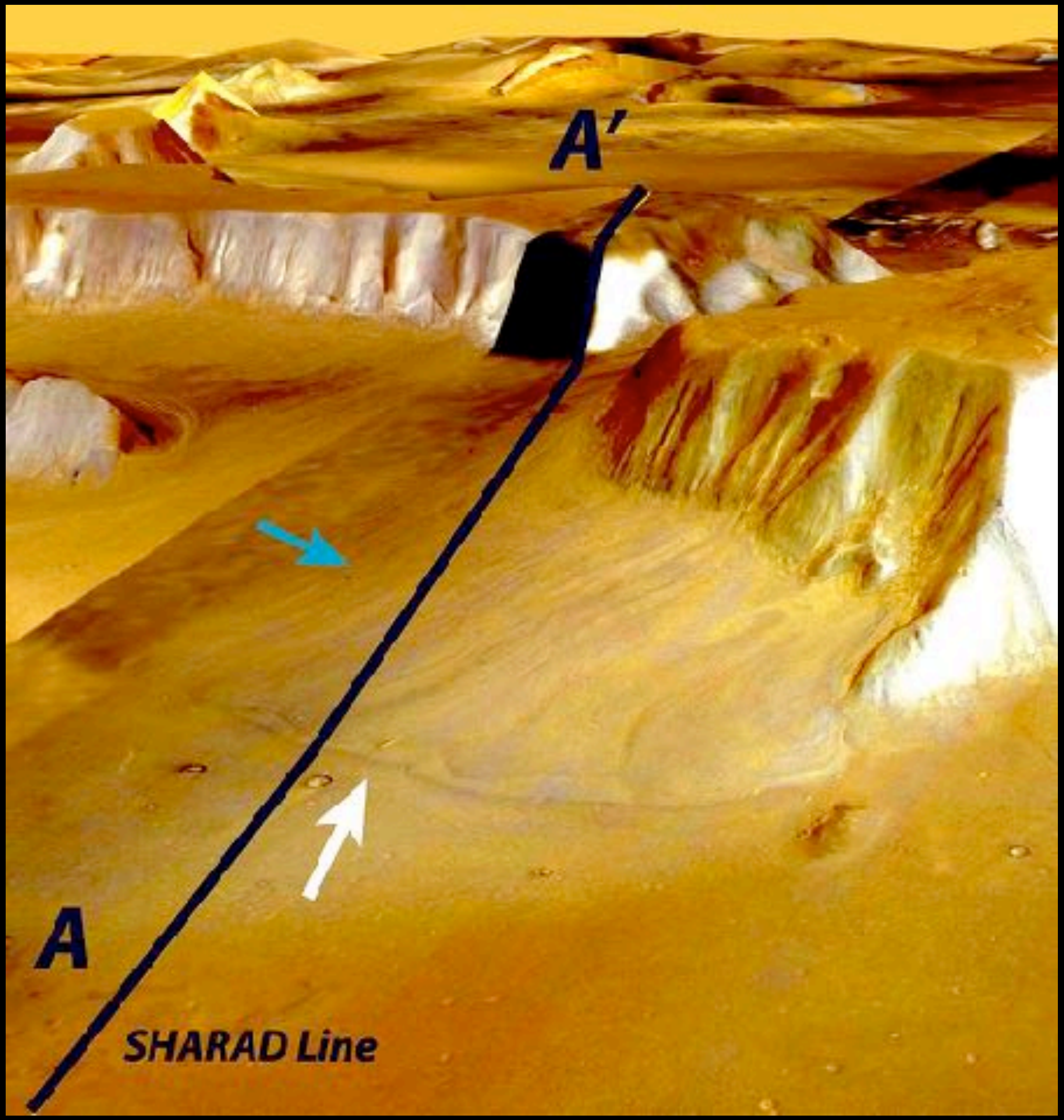
Fig. 7. (a) Net ice accumulation (mm yr^{-1}) predicted in simulation x_{ref} = (35°, 0.1, 270°, 2.5, TMG), superposed on the map by Squyres (1979), which shows the specific location of several different types of ice-related features. LDA and LVF stand for Lobate Debris Aprons and Lineated Valley Fill. See also Fig. 1, which shows the areas of widespread glaciation documented in Head and Marchant (2006). Indicated regions: 1. Tempe Terra, 2. Deuteronilus Mensae, 3. Nilosyrtis Mensae, 4. Phlegra Montes. (b) Water ice accumulation during the L_s = 180–360° period (mm). (c) Water ice sublimation during the L_s = 0–180° period (mm).

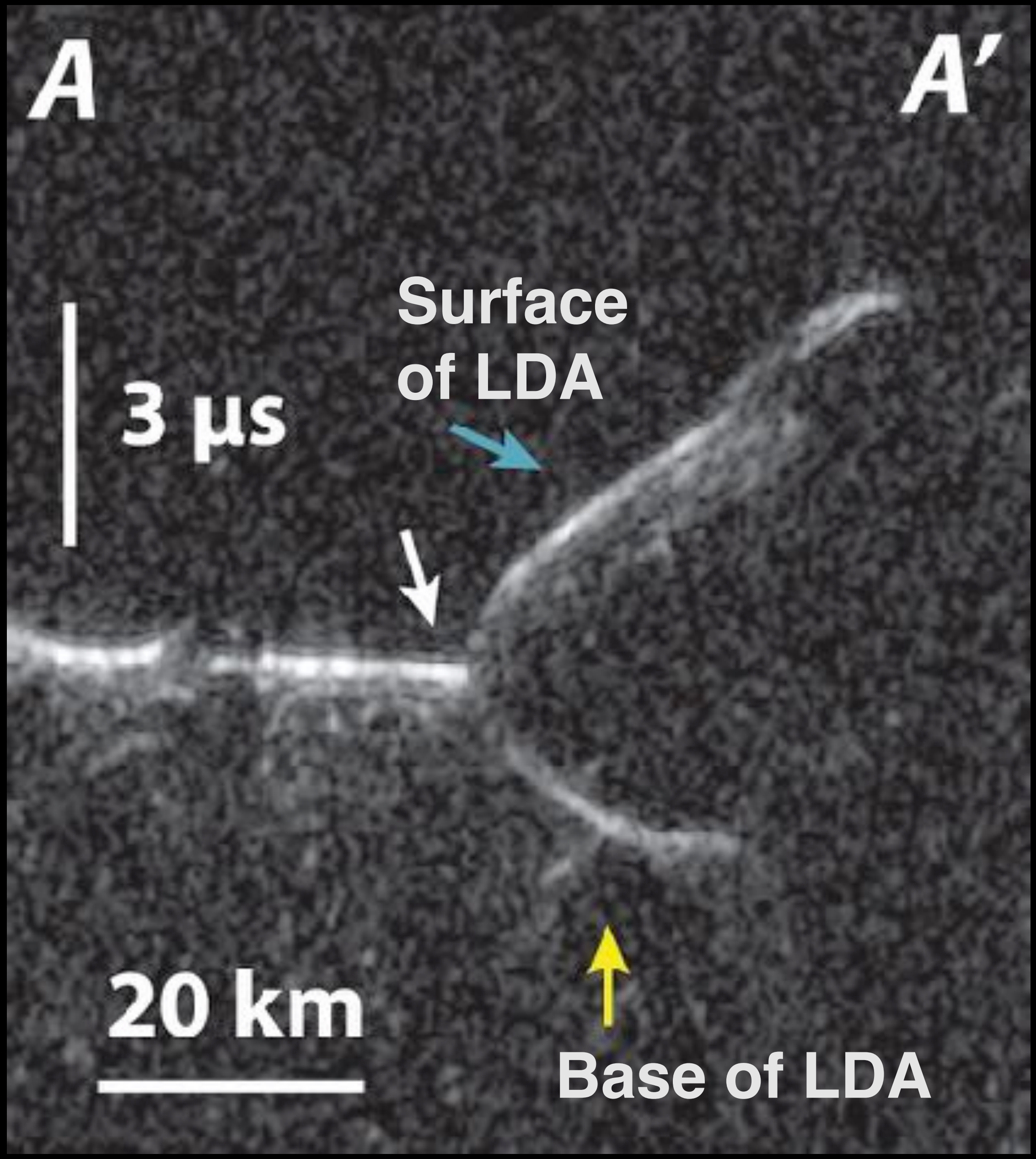
Madeleine et al., Icarus, 2009

- **Certain high-obliquity scenarios lead to accumulation of ice at mid-latitudes**
- **Over 15 mm/year in regions where LDA are observed today.**
- **That can easily produce 500 -1000 m thick ice in one obliquity cycle**
- **Ages of LDA imply episodic growth during many obliquity cycles is possible**

Radar provides a test

SHARAD data over LDA



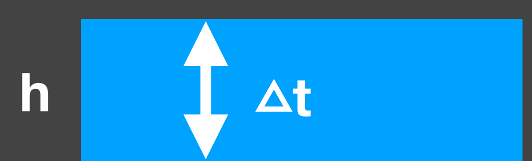


Sharp surface echo.
Sharp basal echo.
Nothing in between.

How do we know composition? - Part 1

Real part of permittivity determines *velocity* of radar waves (primarily a function of density)

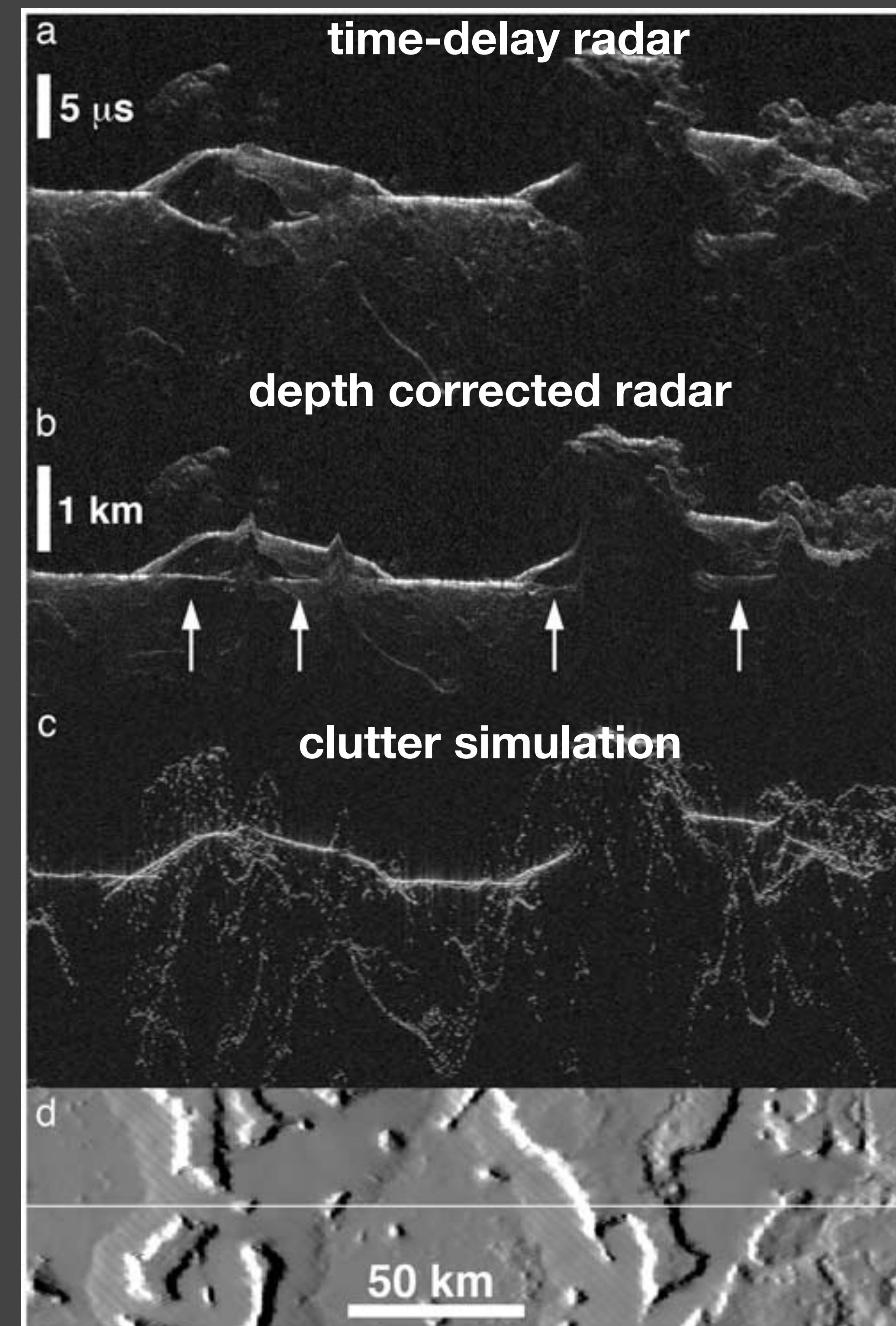
$$\varepsilon' = \left(\frac{c\Delta t}{2h}\right)^2$$



Power not used, only time delay

- Have time delay from radar
  - *roundtrip time in material*
- Need a constraint on thickness
  - *In this case, we can extrapolate surface surrounding apron, find value of dielectric constant that works.   = 3.15 (pure water ice)*

Plaut et al., 2009

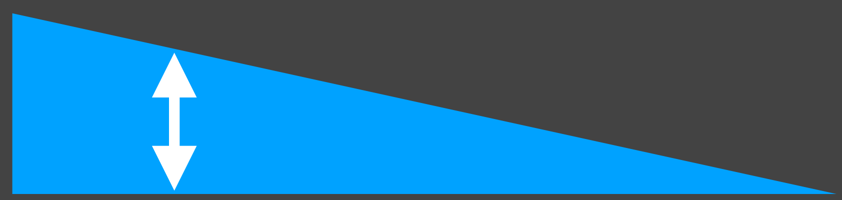


How do we know composition? - Part 2

Imaginary part of permittivity determines *losses*

(loss tangent is typically used)

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} = \sqrt{\left[2 * \left(\frac{\lambda}{4\pi c \Delta t}\ln(L)\right)^2 + 1\right]^2 - 1}$$

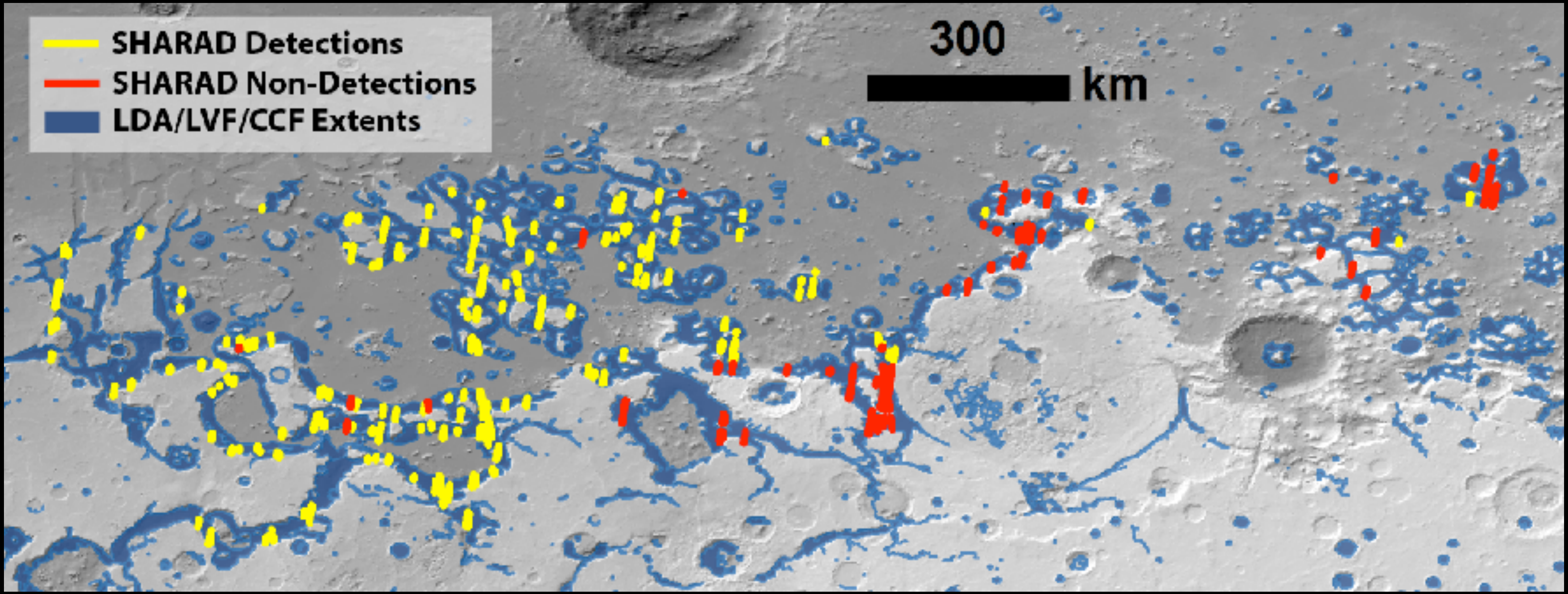


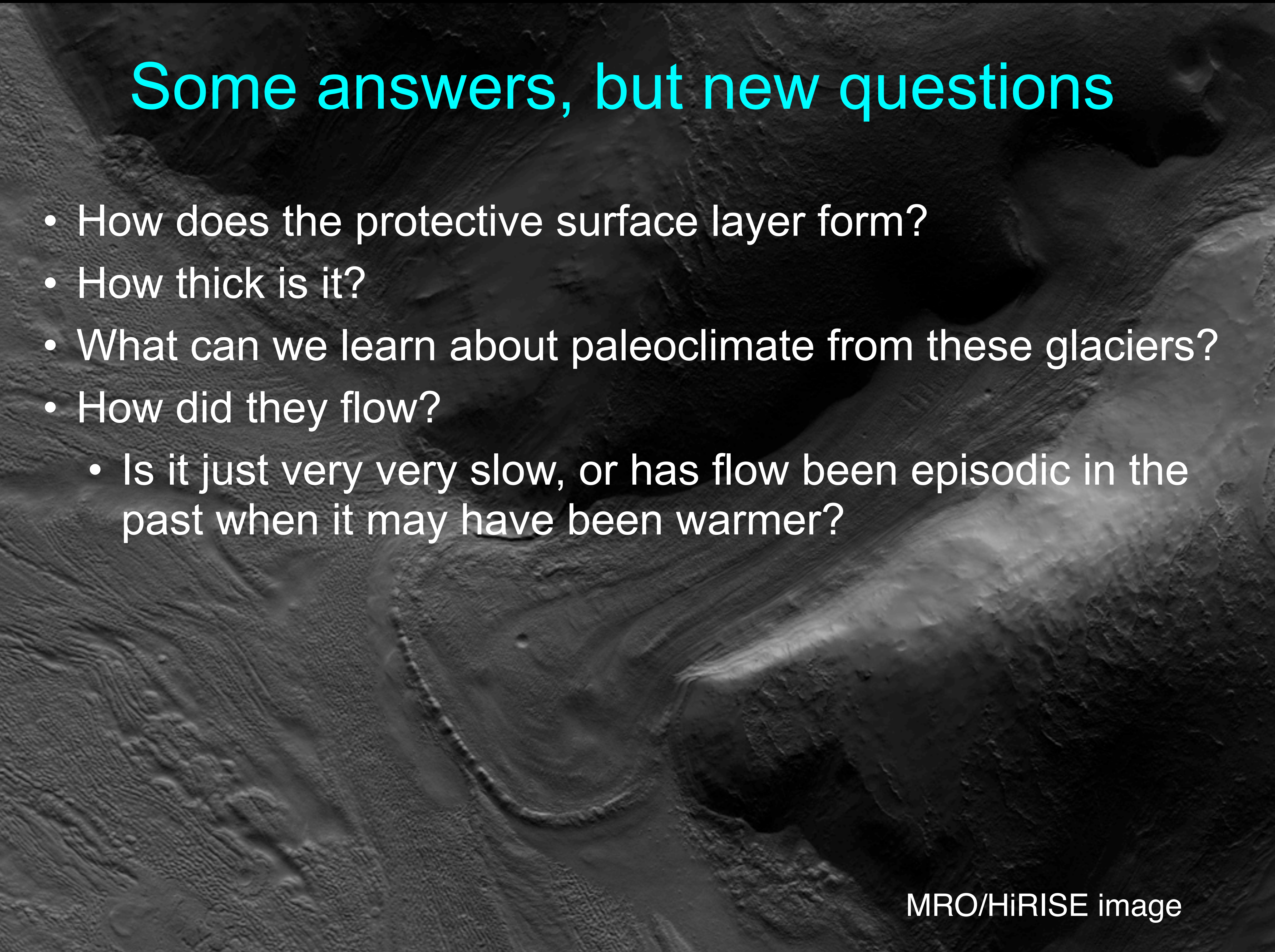
Power of echo used in addition to delay time

- Have time delay from radar
- L = power loss per unit time (through the material)
  - *Need a deposit with uniform properties and a range of thicknesses*

Variability of composition and debris layer thickness

- Petersen et al. (2018) showed that over hundreds of LDA, composition was highly uniform, with > 80% water ice. Variations in surface roughness impact SHARAD's ability to penetrate in some areas.
- Baker and Carter (2018) found no evidence for an echo from bottom of the surface debris layer in many hundreds of SHARAD tracks over LDA, implying debris layer is < 10 m thick or is always gradual in transition from rock to ice.
- Orbital radar cannot currently resolve this variability





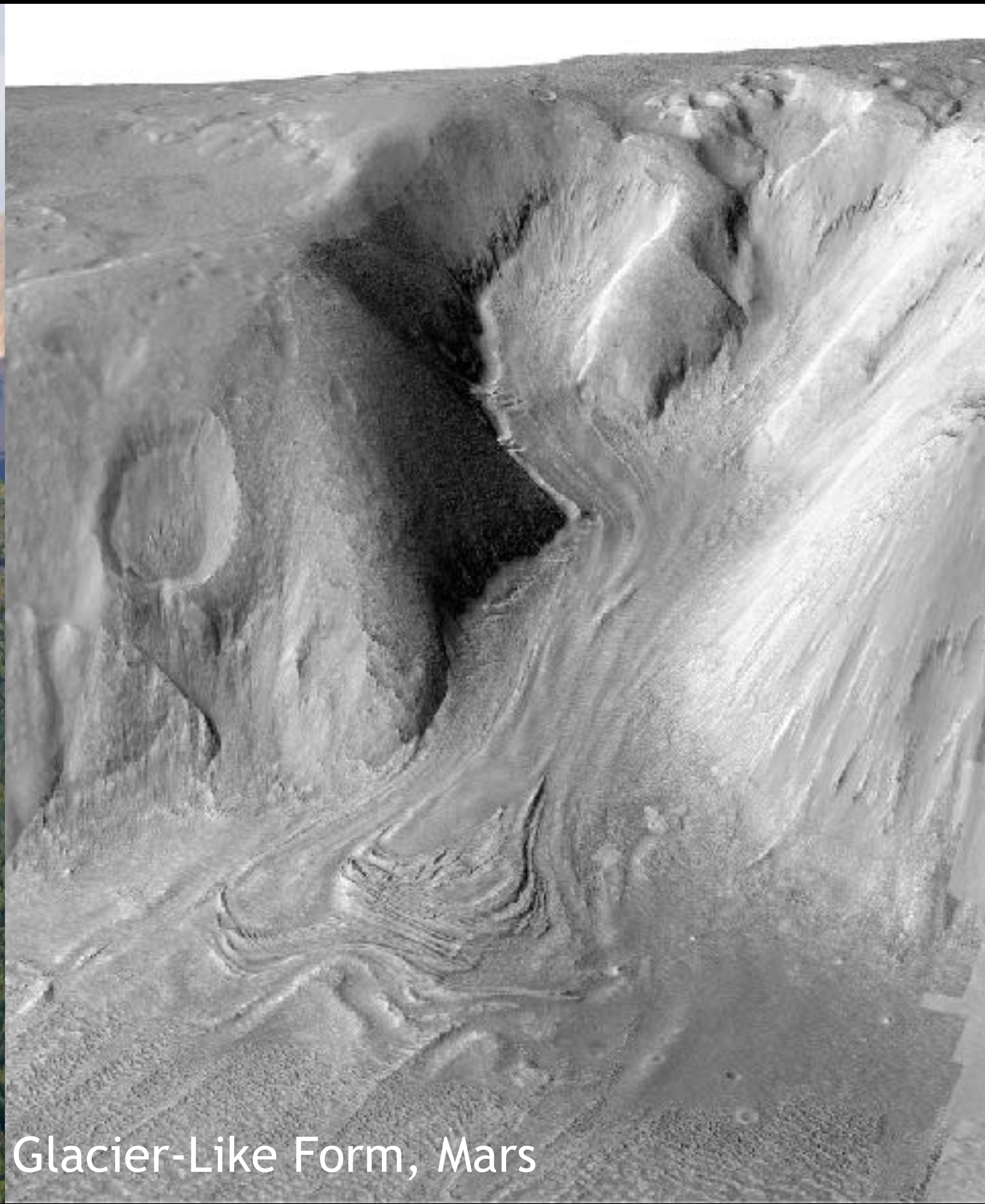
Some answers, but new questions

- How does the protective surface layer form?
- How thick is it?
- What can we learn about paleoclimate from these glaciers?
- How did they flow?
  - Is it just very very slow, or has flow been episodic in the past when it may have been warmer?

MRO/HiRISE image

Turning to Earth

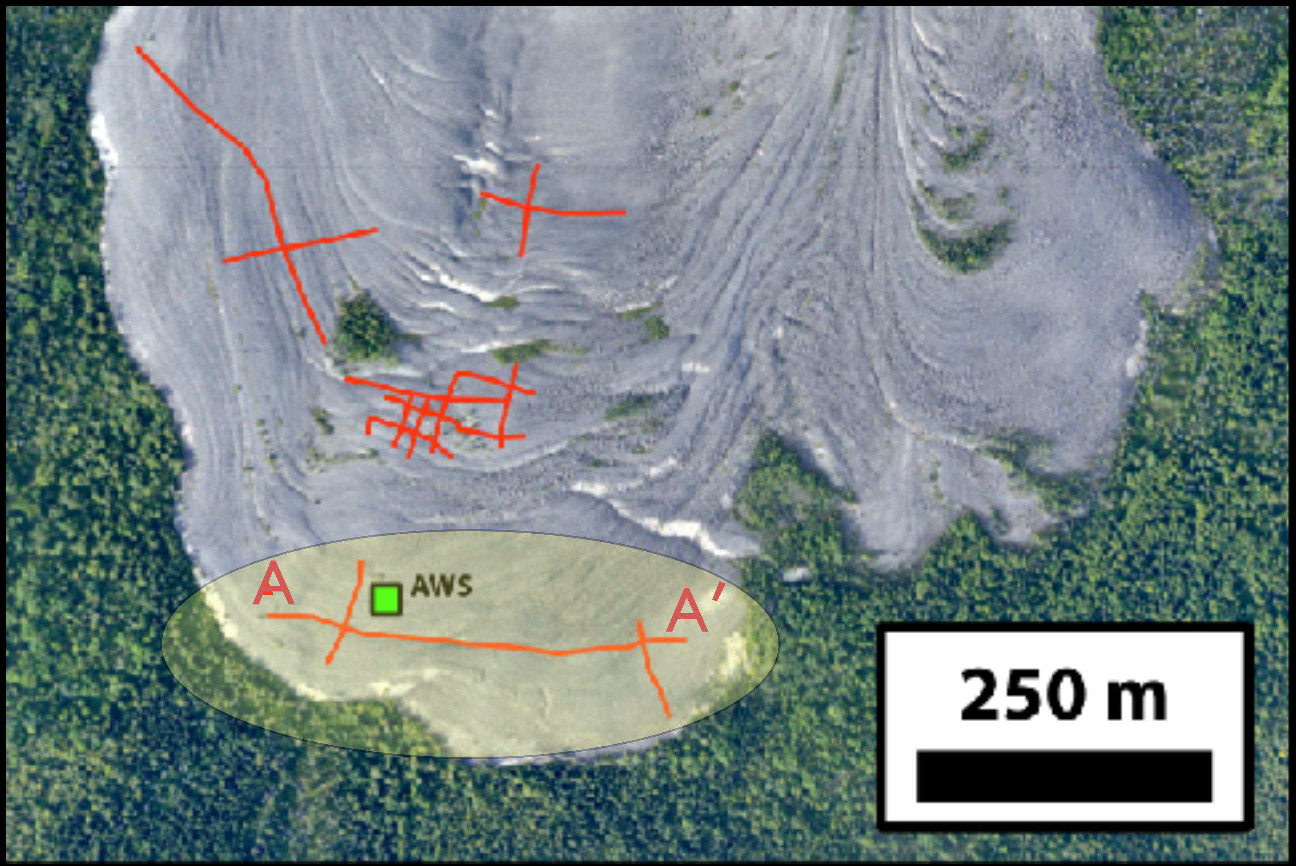
"Rock Glaciers" = Analogs to Martian Glacier-Like Forms

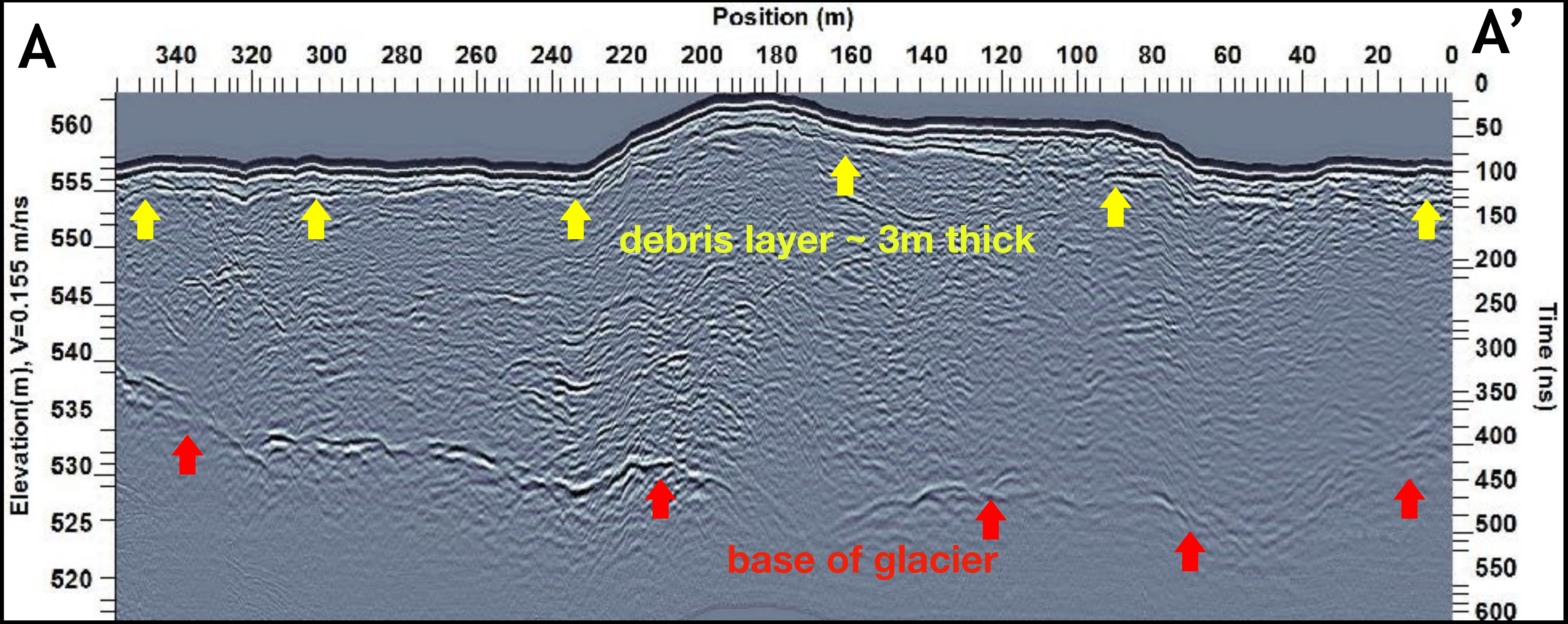


Stefano Nerozzi and Eric Petersen on Sourdough “rock glacier” in Alaska

Ground-penetrating radar measurements

GPR traverse near toe of glacier
100 MHz system

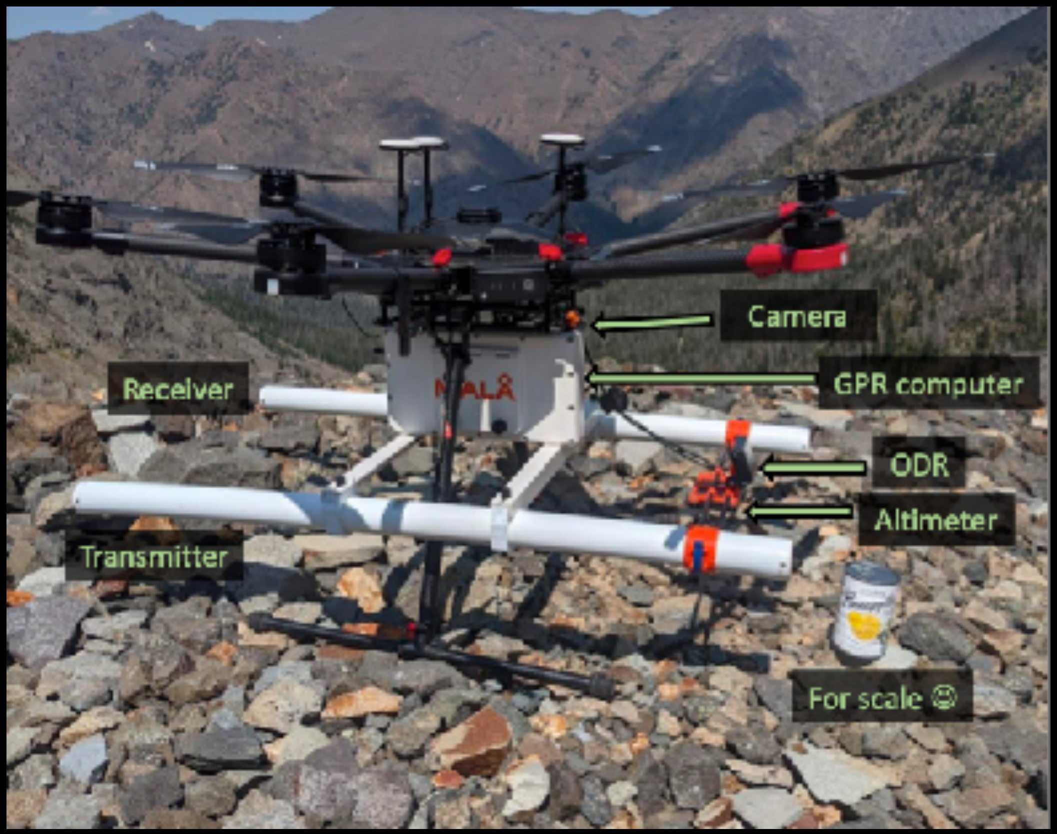




Drone-based GPR

potential planetary applications for near-surface mapping

Tyler Meng monitoring drone on rock glacier while it conducts automated terrain following



Roberto Aguilar leading this effort

Other massive ice deposits at low latitudes?

Geophysical Research Letters
RESEARCH LETTER
10.1029/2023GL105490

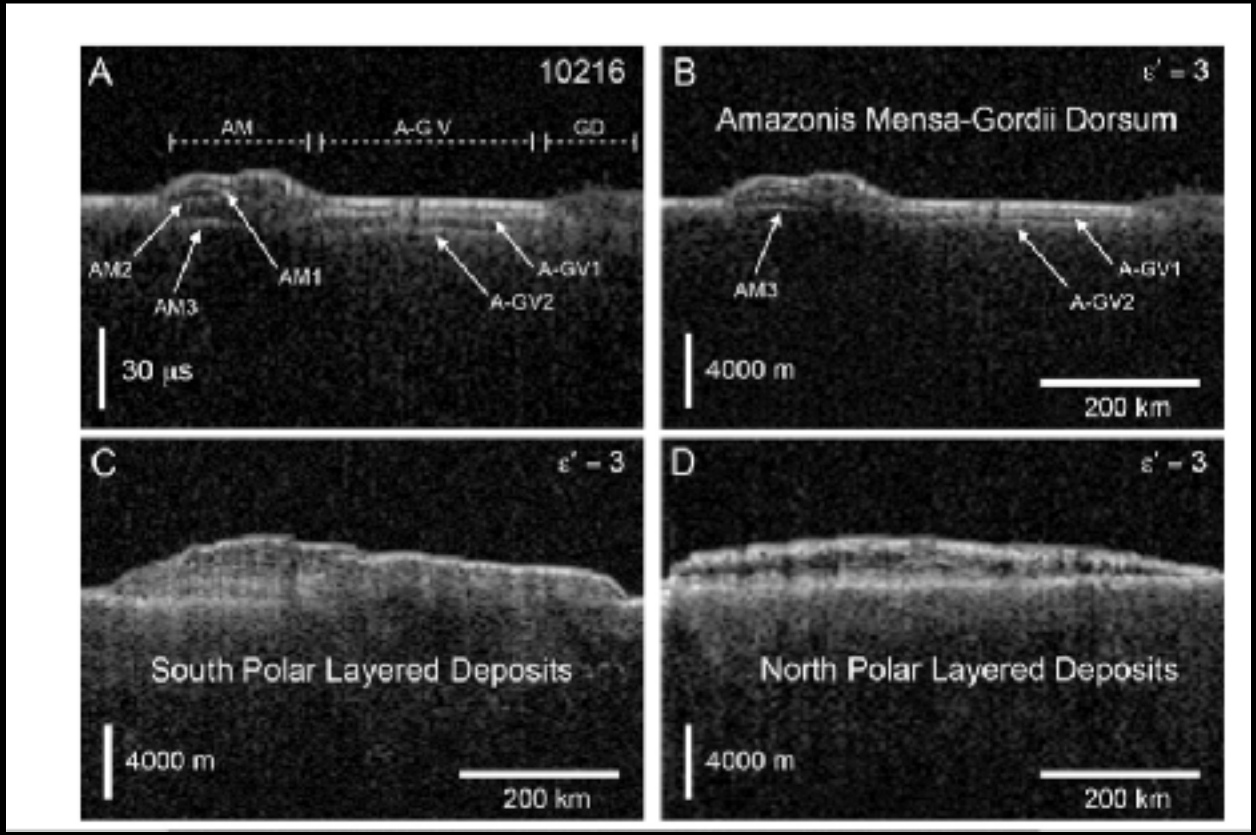
Evidence of Ice-Rich Layered Deposits in the Medusae Fossae Formation of Mars

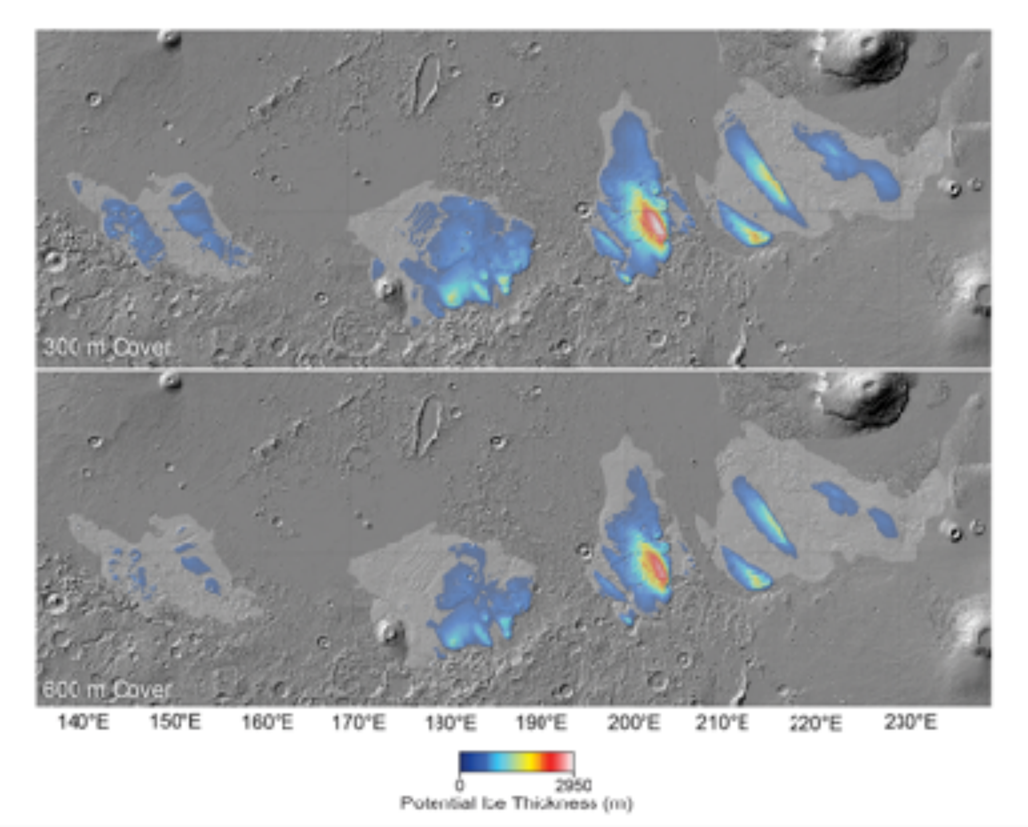
Thomas R. Watters[1], Bruce A. Campbell[1], Carl J. Leuschen[2], Gareth A. Morgan[3], Andrea Cicchetti[4], Roberto Orosei[5], and Jeffrey J. Plaut[6]

Key Points:
- Mars Advanced Radar for Subsurface and Ionospheric Sounding radar

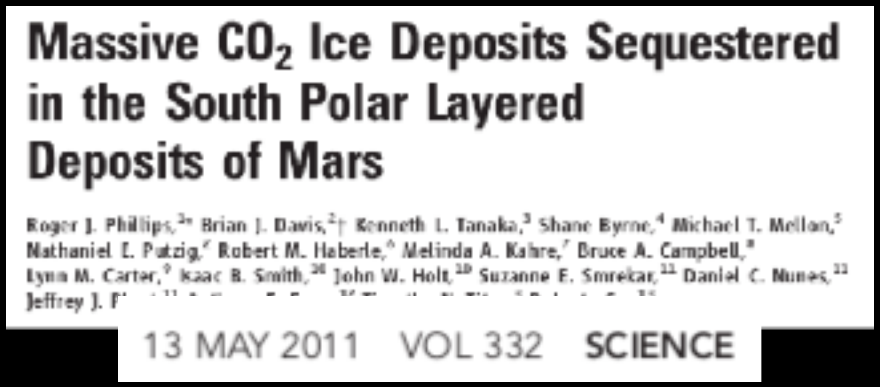
2023

- MFF is a very large deposit near the equator, up to 3 km thick and of debatable origin (volcanic - ash, pumice; aeolian - dust, etc)
- MARSIS data shows a two-layer system with a low dielectric constant consistent with a porous material or water ice in the lower portion
- They claim that it must be water ice because a porous sediment would compact under its own weight - so it is primarily a material strength argument





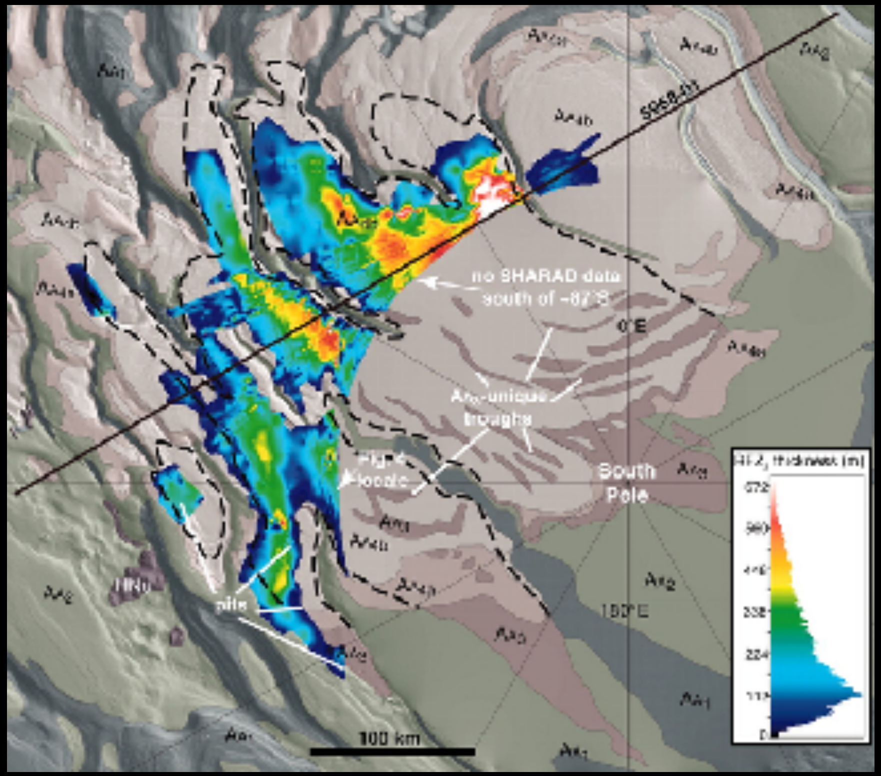
To the south pole - Sequestered CO2 ice

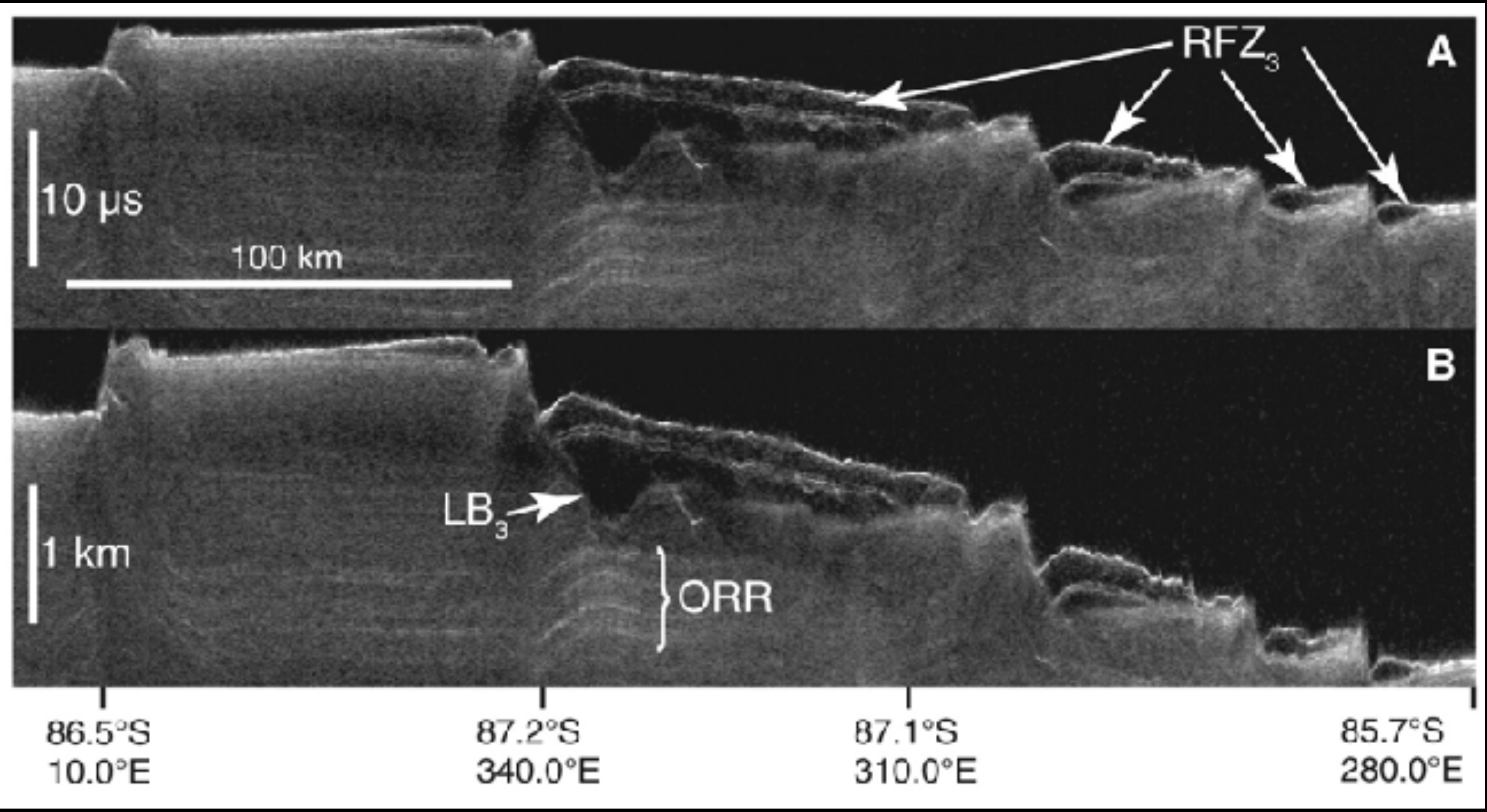


Massive CO_2 Ice Deposits Sequestered in the South Polar Layered Deposits of Mars

Roger J. Phillips,[1*] Brian J. Davis,[2†] Kenneth L. Tanaka,[3] Shane Byrne,[4] Michael T. Mellon,[5] Nathaniel E. Putzig,[6] Robert M. Haberle,[6] Melinda A. Kahre,[7] Bruce A. Campbell,[8] Lynn M. Carter,[9] Isaac B. Smith,[10] John W. Holt,[10] Suzanne E. Smrekar,[11] Daniel C. Nunes,[11] Jeffrey J. P...

13 MAY 2011 VOL 332 SCIENCE





- Enough CO2 to nearly double atmospheric mass of Mars

SOUTH POLE OF MARS – "LAKES" CONTROVERSY

- In 2018 a paper claimed there is liquid water below the south polar ice on Mars
- The press (not the authors) called it lakes.
- Much hoo-ha and debate ensued

RESEARCH

MARTIAN GEOLOGY

Radar evidence of subglacial liquid water on Mars

R. Orosei[1*], S. E. Lauro[2], E. Pettinelli[2], A. Cicchetti[3], M. Coradini[4], B. Cosciotti[2], F. Di Paolo[1], E. Flamini[4], E. Mattei[3], M. Pajola[5], F. Soldovieri[6], M. Cartacci[3], F. Cassenti[7], A. Frigeri[3], S. Giuppi[3], R. Martufi[7], A. Masdea[8], G. Mitri[9], C. Nenna[10] R. Noschese[3], M. Restano[11], R. Seu[7]

The presence of liquid water at the base of the martian polar caps has long been suspec but not observed. We surveyed the Planum Australe region using the MARSIS (Mars Advanced Radar for Subsurface and Ionosphere Sounding) instrument, a low-frequency radar on the Mars Express spacecraft. Radar profiles collected between May 2012 and December 2015 contain evidence of liquid water trapped below the ice of the South Polar Layered Deposits. Anomalously bright subsurface reflections are evident within a well-defined, 20-kilometer-wide zone centered at 193°E, 81°S, which is surrounded by much less reflective areas. Quantitative analysis of the radar signals shows that this bright feature has high relative dielectric permittivity (>15), matching that of water-bearing materials. We interpret this feature as a stable body of liquid water on Mars.

Orosei *et al.*, *Science* **361**, 490–493 (2018)   3 August 2018

There's water on Mars! Signs of buried lake tantalize scientists

The lake would be the first body of liquid water ever detected on the red plan observations by a European spacecraft are confirmed.

Mars has a giant hidden lake. Could there be life in it?

Science Updated on Jul 25, 2018 1:36 PM EST – Published on Jul 25, 2018 11:03 AM EST

WATER FOUND ON MARS: 20km wide subterranean lake discovered which could harbour life

SCIENTISTS have made a huge breakthrough in the search for life on Mars after they discovered what appears to be an existing lake of water.

More than 20 papers on this topic since 2018!

MATTERS ARISING — nature astronomy

Explaining Bright Radar Reflections Below The South Pole of Mars Without Liquid Water

D. E. Lalich, A. G. Hayes and V. Poggiali

Geophysical Research Letters — RESEARCH LETTER

The Basal Detectability of an Ice-Covered Mars by MARSIS

C. Grima, J. Mouginot, W. Kofman, A. Hérique, and P. Beck

JGR Planets — RESEARCH ARTICLE

Partially-Saturated Brines Within Basal Ice or Sediments Can Explain the Bright Basal Reflections in the South Polar Layered Deposits

D. E. Stillman, E. Pettinelli, S. E. Lauro, E. Mattei, G. Caprarelli, B. Cosciotti, K. M. Primm, and R. Orosei

Geophysical Research Letters — COMMENTARY

Alternatives to Liquid Water Beneath the South Polar Ice Cap of Mars

Dustin M. Schroeder and Gregor Steinbrügge

Geophysical Research Letters — RESEARCH LETTER

Characteristics of the Basal Interface of the Martian South Polar Layered Deposits

Aditya R. Khuller and Jeffrey J. Plaut

Thermophysical arguments against basal melting in the south polar region of Mars

Lujendra Ojha, Jacob Buffo, Baptiste Journaux

JGR Planets — RESEARCH ARTICLE

Modeled Subglacial Water Flow Routing Supports Localized Intrusive Heating as a Possible Cause of Basal Melting of Mars' South Polar Ice Cap

N. S. Arnold, S. J. Conway, F. E. G. Butcher, and M. R. Balme

Geophysical Research Letters — RESEARCH LETTER

Strong MARSIS Radar Reflections From the Base of Martian South Polar Cap May Be Due to Conductive Ice or Minerals

C. J. Bierson, S. Tulaczyk, S. W. Courville, and N. E. Putzig

LETTERS — nature astronomy

…urface topographic impact of subglacial water …eneath the south polar ice cap of Mars

…Arnold, F. E. G. Butcher, S. J. Conway, C. Gallagher and M. R. Balme

Geophysical Research Letters — RESEARCH LETTER

A Solid Interpretation of Bright Radar Reflectors Under the Mars South Polar Ice

I. B. Smith, D. E. Lalich, C. Rezza, B. H. N. Horgan, J. L. Whitten, S. Nerozzi, and J. W. Holt

nature astronomy — ARTICLES

Multiple subglacial water bodies below the south pole of Mars unveiled by new MARSIS data

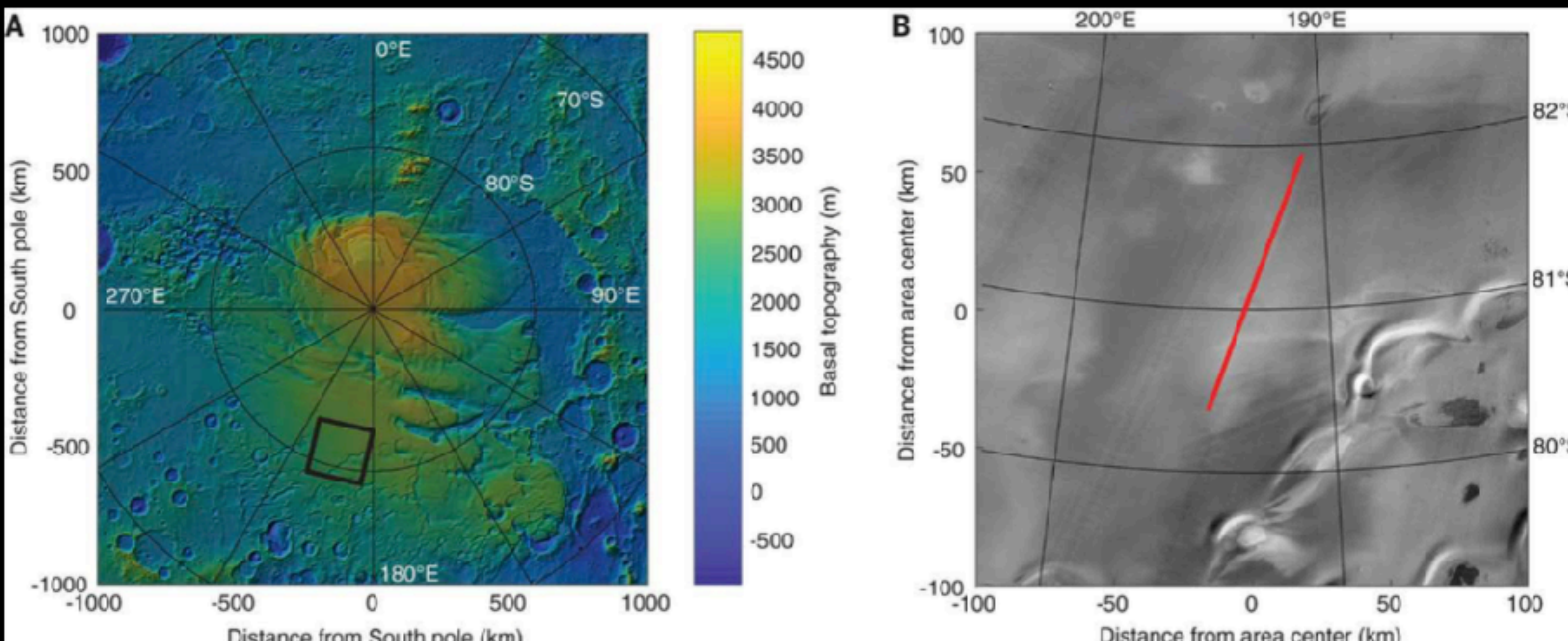
Sebastian Emanuel Lauro, Elena Pettinelli, Graziella Caprarelli, Luca Guallini, Angelo Pio Rossi, Elisabetta Mattei, Barbara Cosciotti, Andrea Cicchetti, Francesco Soldovieri, Marco Cartacci, Federico Di Paolo, Raffaella Noschese and Roberto Orosei

Assessing the role of clay and salts on the origin of MARSIS basal bright reflections

Elisabetta Mattei, Elena Pettinelli, Sebastian Emanuel Lauro, David E. Stillman, Barbara Cosciotti, Lucia Marinangeli, Anna Chiara Tangari, Francesco Soldovieri, Roberto Orosei, Graziella Caprarelli

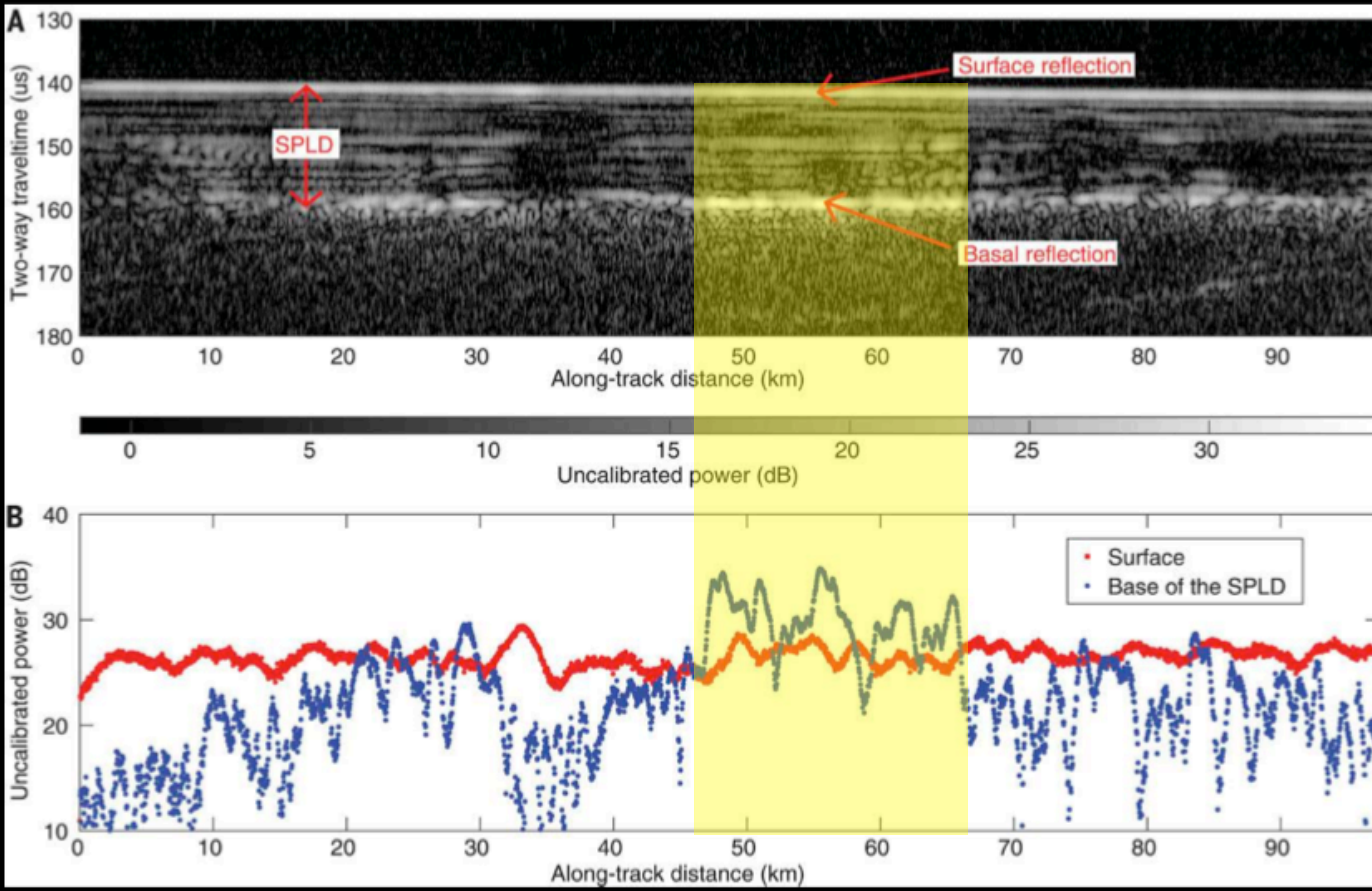
So, what's the deal?

South Polar MARSIS Track



Orosei et al., *Science*, 2018

Bright Basal Reflector



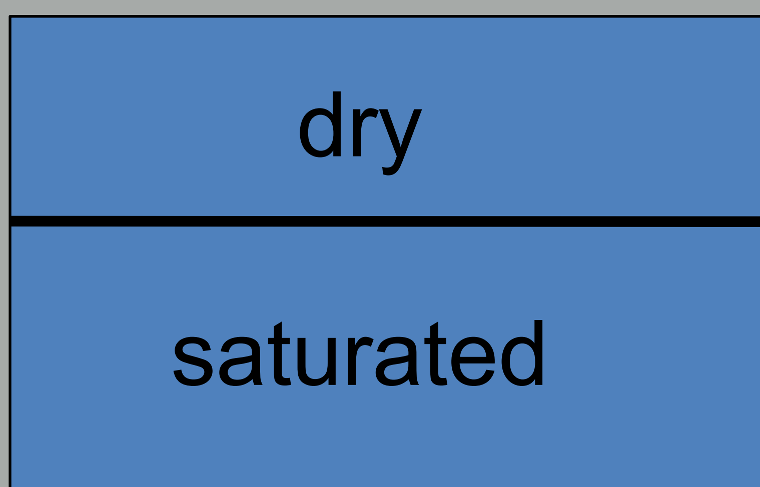
Orosei et al., *Science*, 2018

Solving for permittivity

- Ideally, one can use reflection amplitudes to constrain properties.

$$\epsilon = \epsilon' - i\epsilon''$$

Real part of permittivity is "dielectric constant"

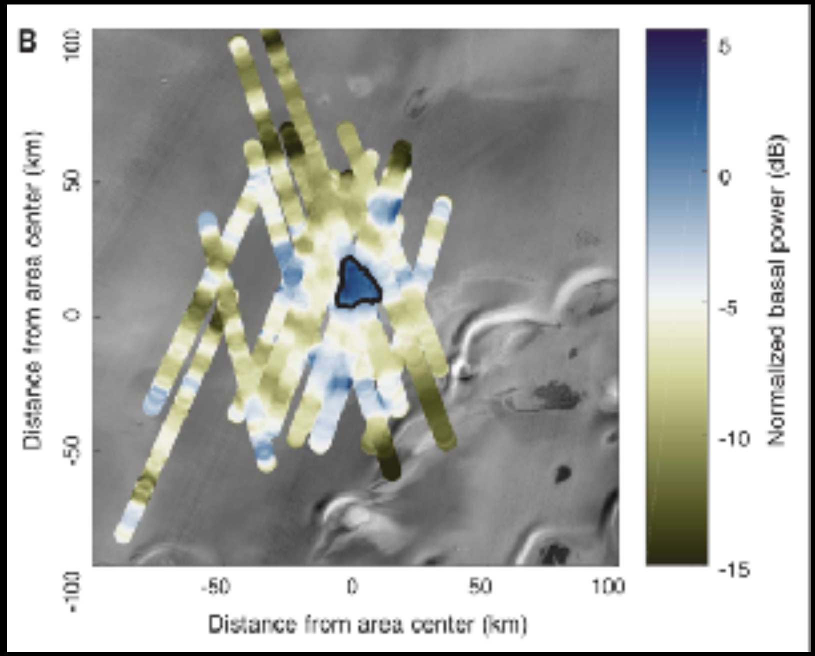


want to know reflection coefficient at this interface

$$\Gamma = \left(\frac{\sqrt{\varepsilon'_{dry}} - \sqrt{\varepsilon'_{sat}}}{\sqrt{\varepsilon'_{dry}} + \sqrt{\varepsilon'_{sat}}} \right)^2$$

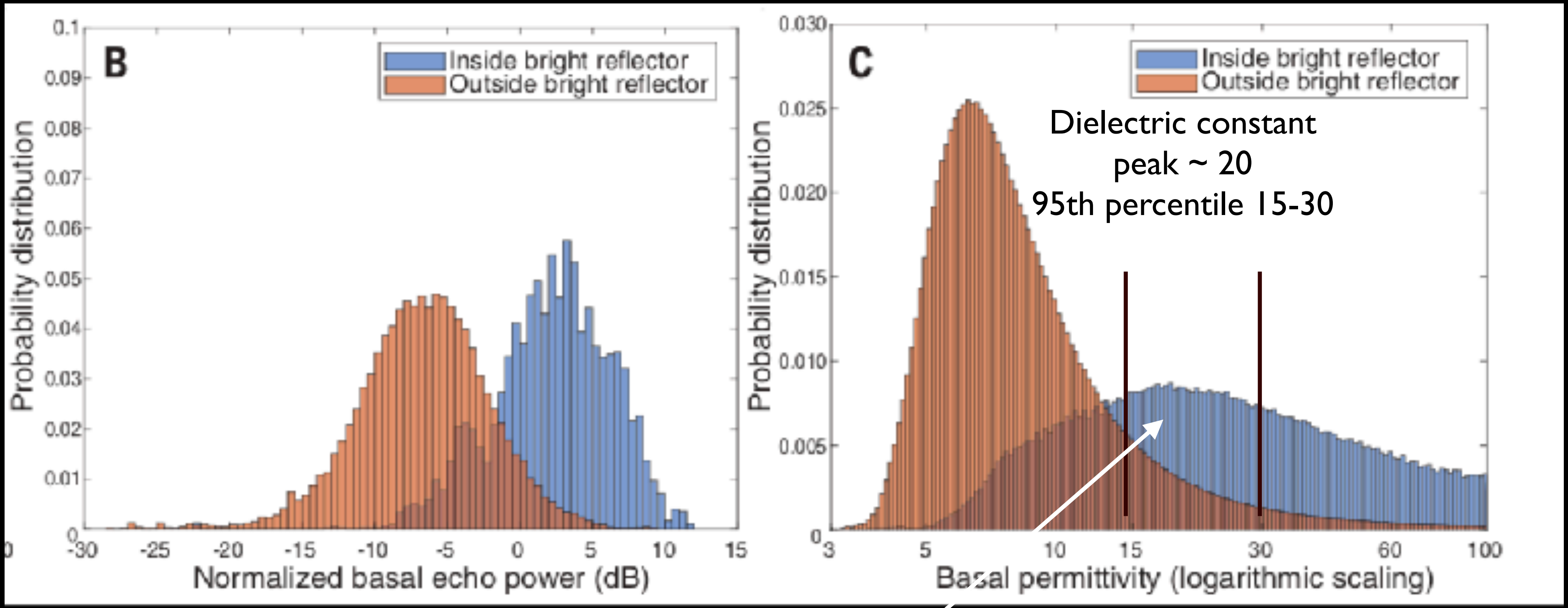
- If we measure the reflected energy at interface and know the dielectric constant of the top layer, we can solve for dielectric constant of the bottom layer
- *In practice, this is very hard to do (many assumptions)*

Estimates of basal permittivity under the south polar ice



NORMALIZED BASAL POWER

MODELED BASAL PERMITTIVITY (REAL PART)



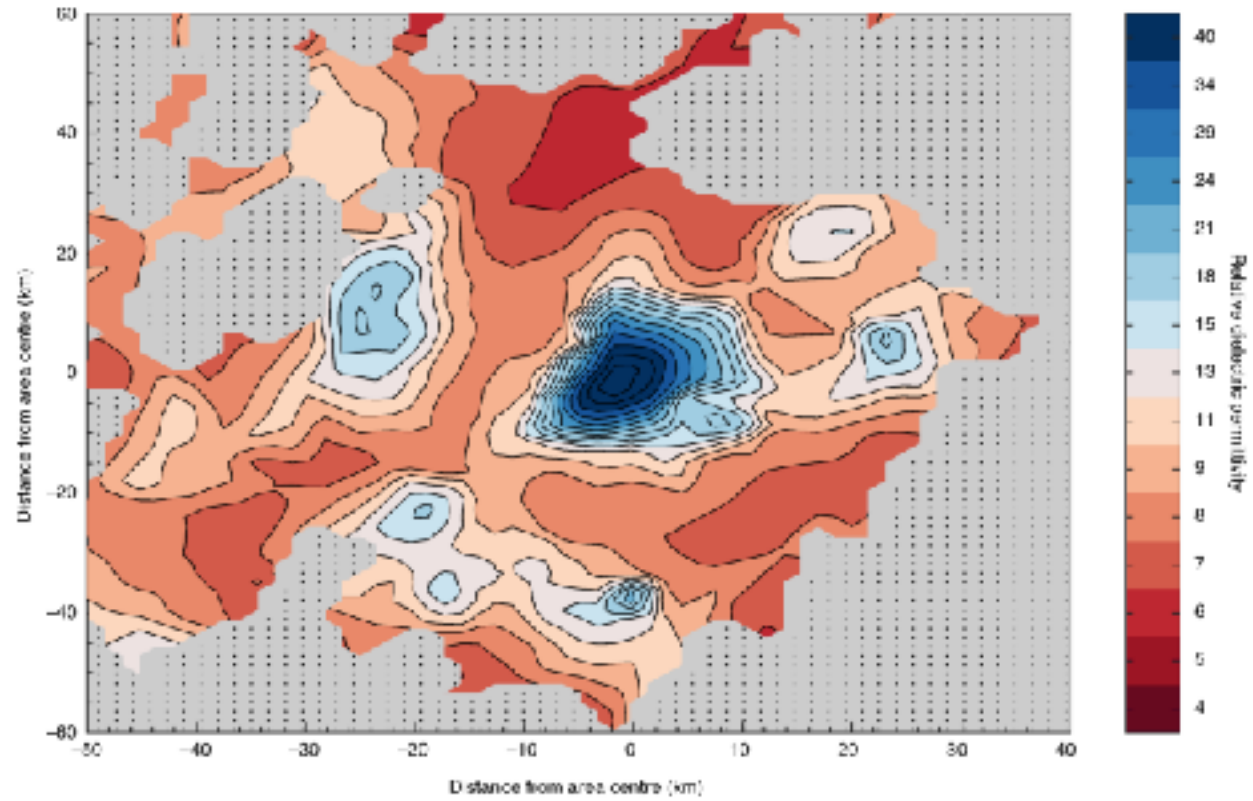
Orosei et al., *Science*, 2018

Their claim: a dielectric constant above 15 must be due to water

Their interpretation

- Assuming a single interface, bright reflections require a large permittivity contrast
- Achieving such large permittivities in natural materials usually requires the presence of liquid water
- To make water exist there it needs to have a very high salt content

Fig. 5: Relative dielectric permittivity map computed by inverting the radar data considering all regions where the number of samples is larger than 100.

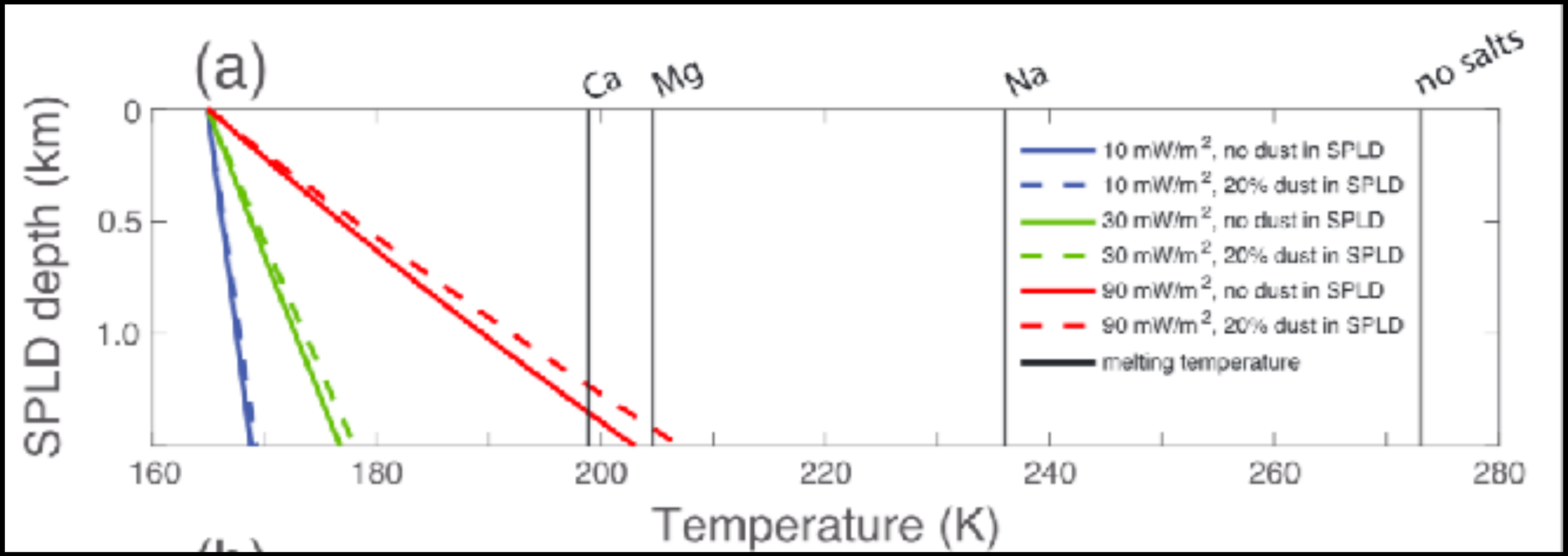


The map only shows the permittivity values retrieved from radar data having acuity values larger than 0.5 (Methods). This procedure has reduced the dimension of the study area to 90 × 120 km^2. Values larger than 15 suggest the presence of liquid water.

Lauro et al, *Nature Astronomy*, 2020

What are some problems with this scenario?

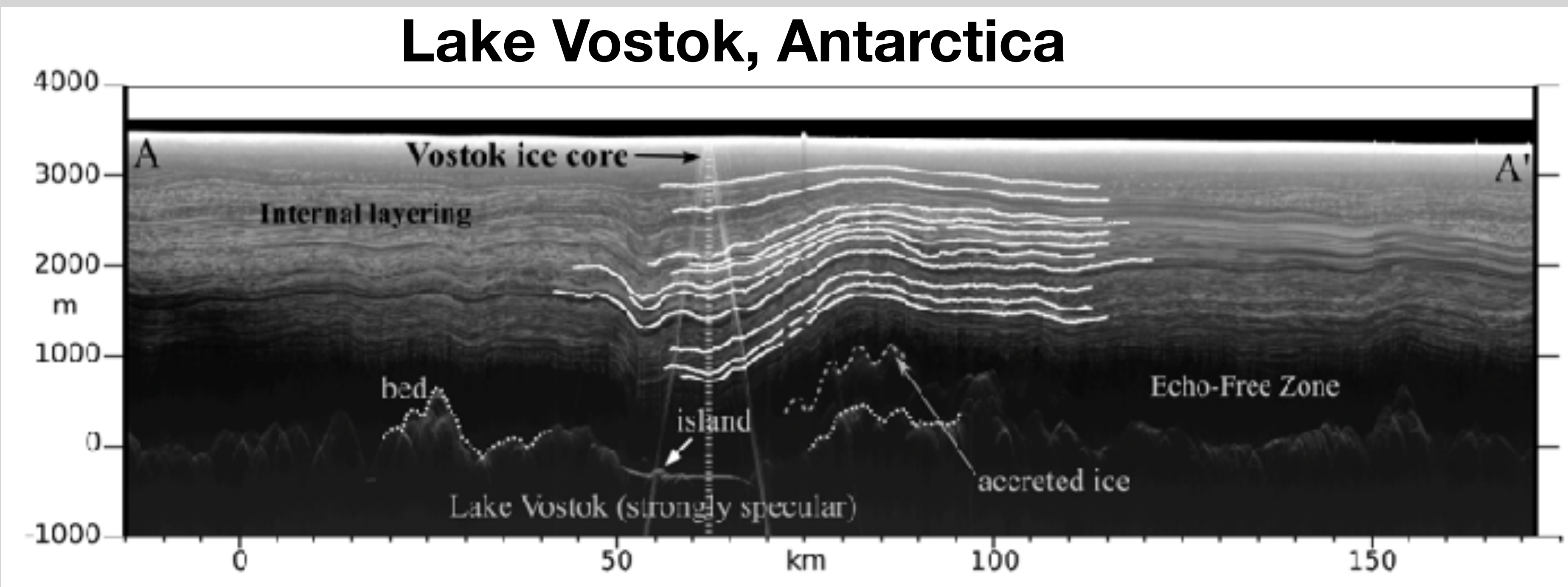
- Basal temperatures necessary to produce liquid, even as brines, are difficult to achieve
  - *Requires a highly localized thermal anomaly (Sori and Bramson, 2019)*
  - *Not consistent with very low regional heat flux based on crustal deflection beneath SPLD based on MARSIS data (Ojha et al, 2020)*
  - *Concentration of salt required is unreasonable (supersaturated, metastable state required)*



Sori and Bramson, 2019

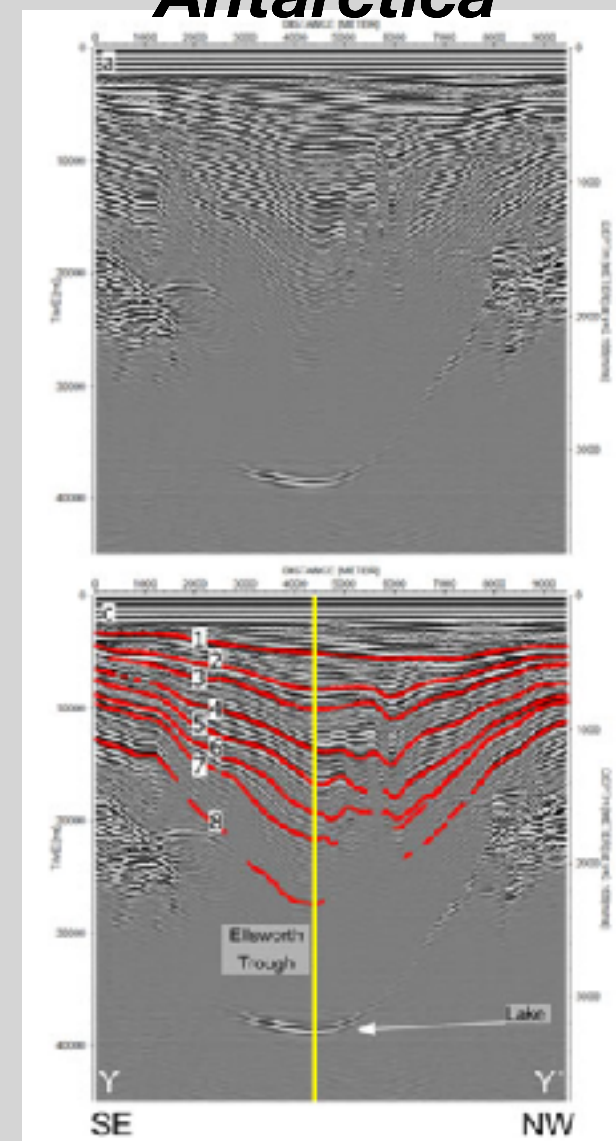
If there was basal melting, we would see drawdown of layers

As we see on Earth



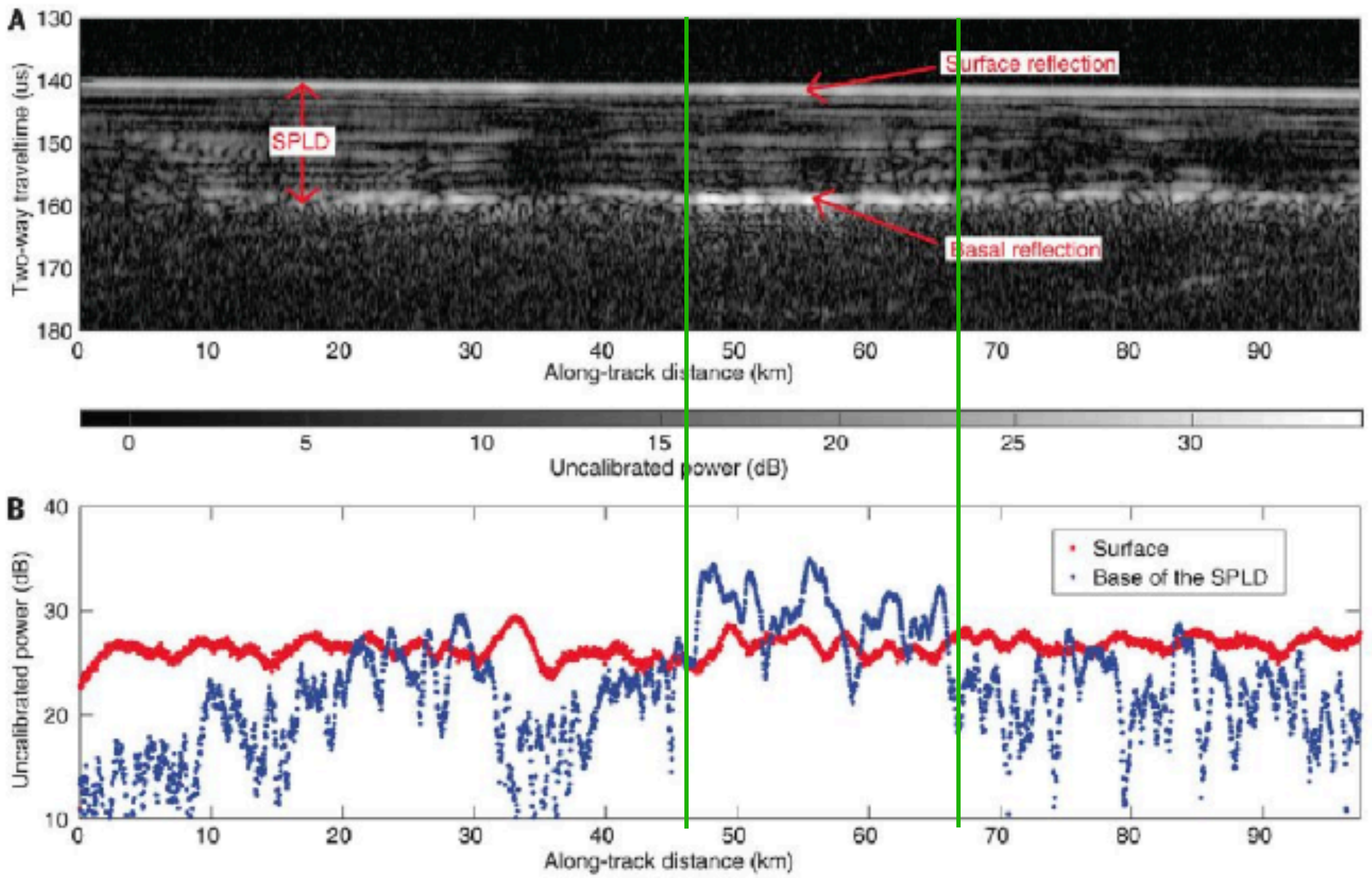
Cavitte et al., The Cryosphere, 2013

Lake Ellsworth Antarctica



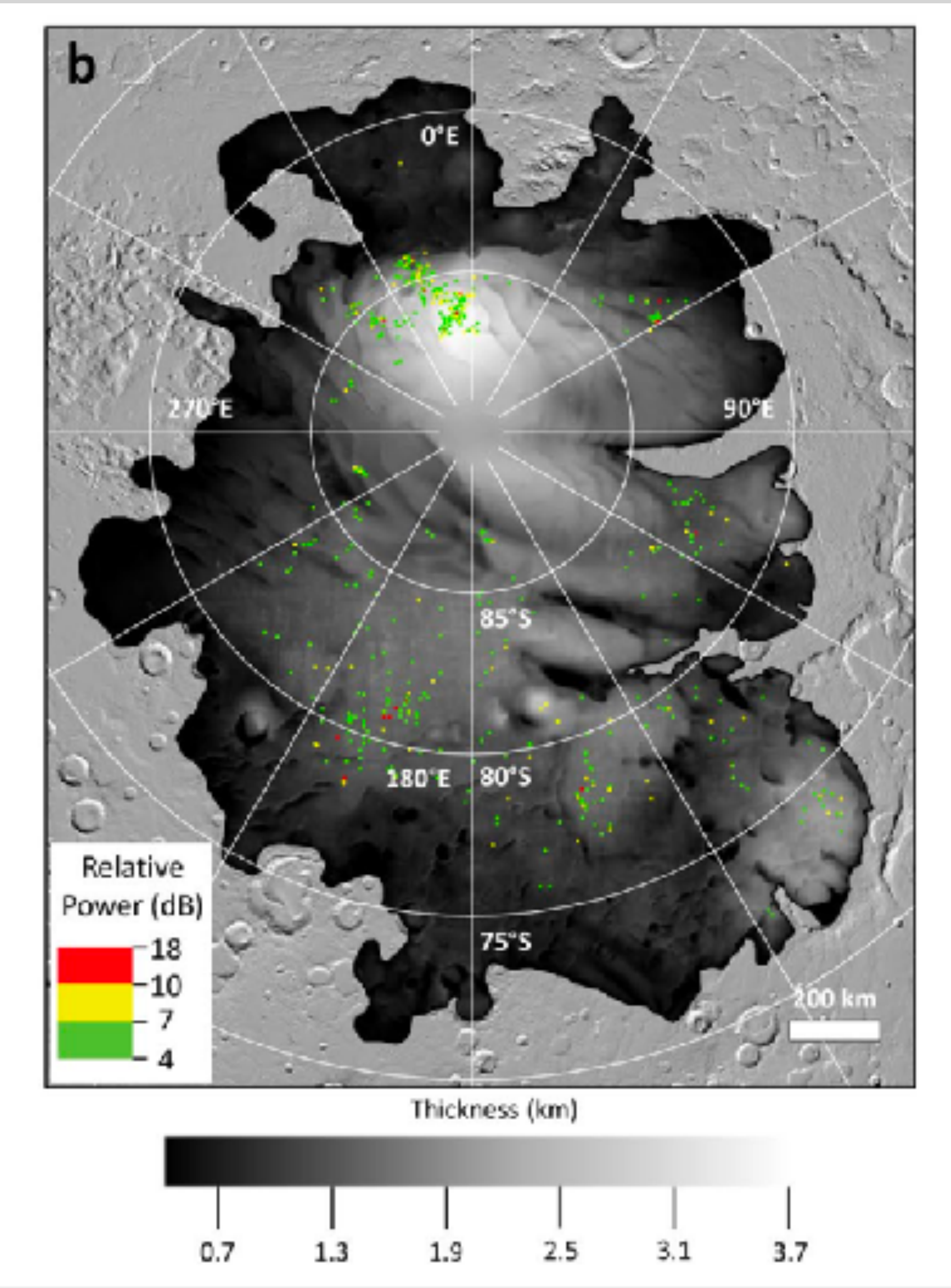
Ross and Siegert, Annals of Glac., 2020

No drawdown of layers over MARSIS bright spots

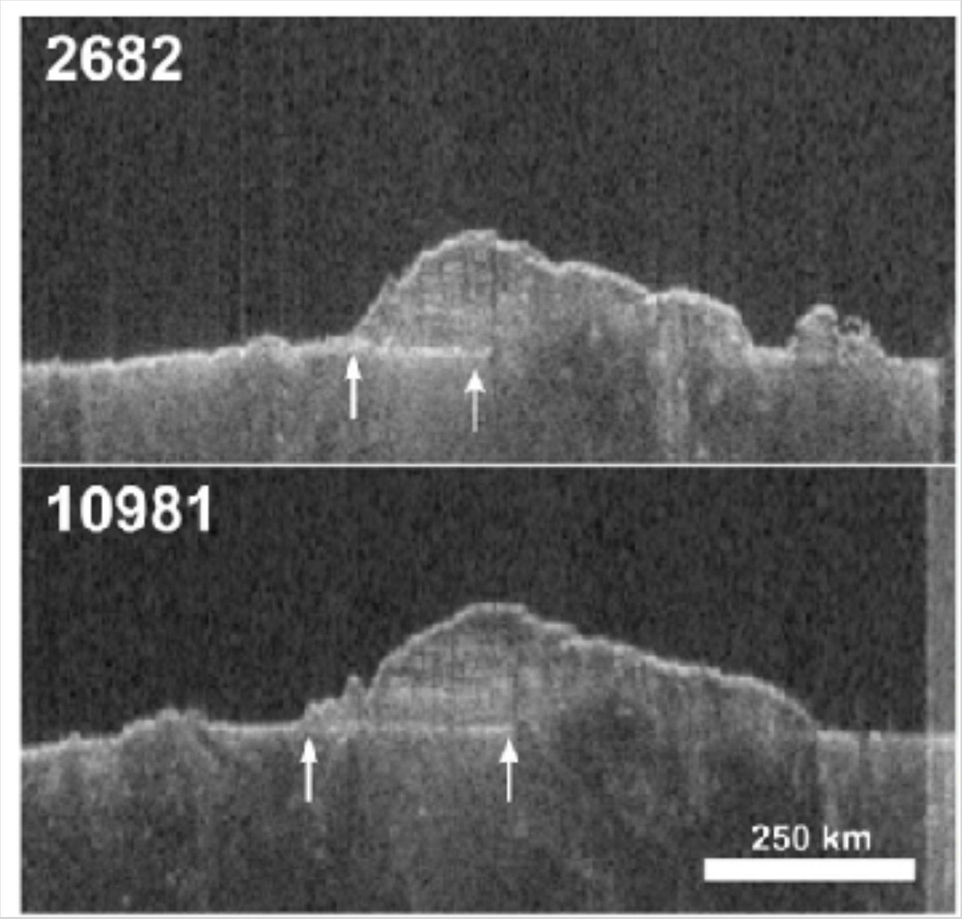


Orosei et al [2018]

There are other locations in the SPLD with bright basal echoes



Locations where the basal echo is brighter than surface echo
Khuller and Plaut, GRL, 2021



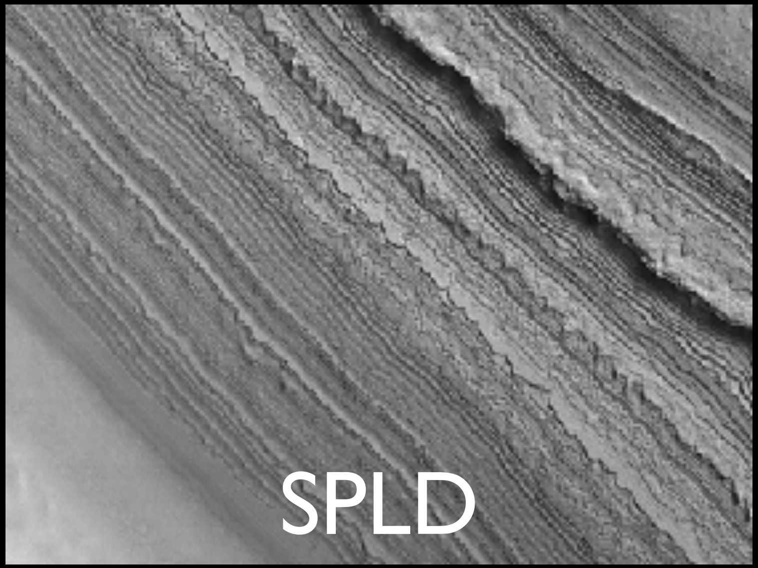
Smith et al., GRL, 2021

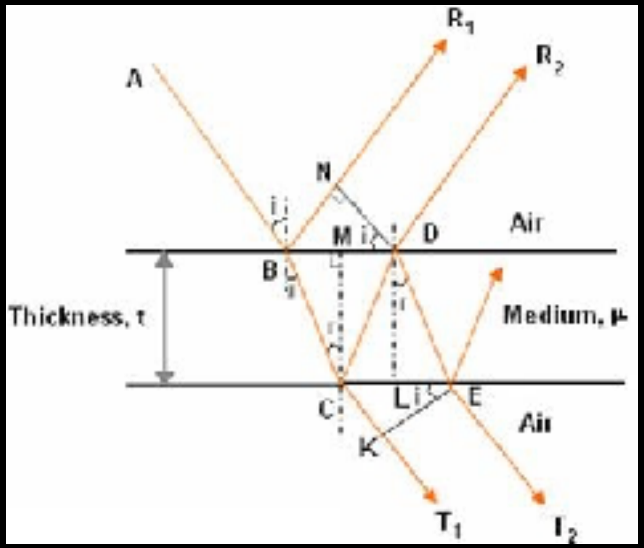
- Some are found at the edge of the SPLD, where it is far too cold for even a fully saturated brine to stay liquid
- There are no springs flowing from the edge of the polar cap.

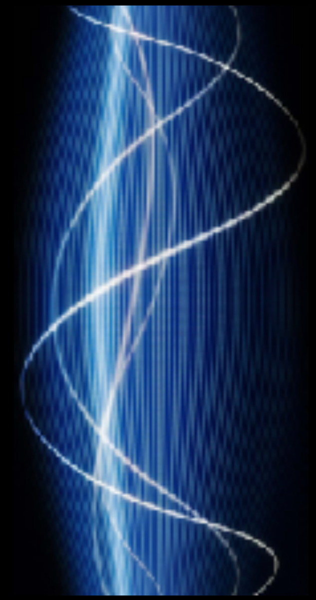
So, what else could explain the bright reflections?

A couple of ideas…

- 1 - Constructive interference (Lalich et al., 2022)

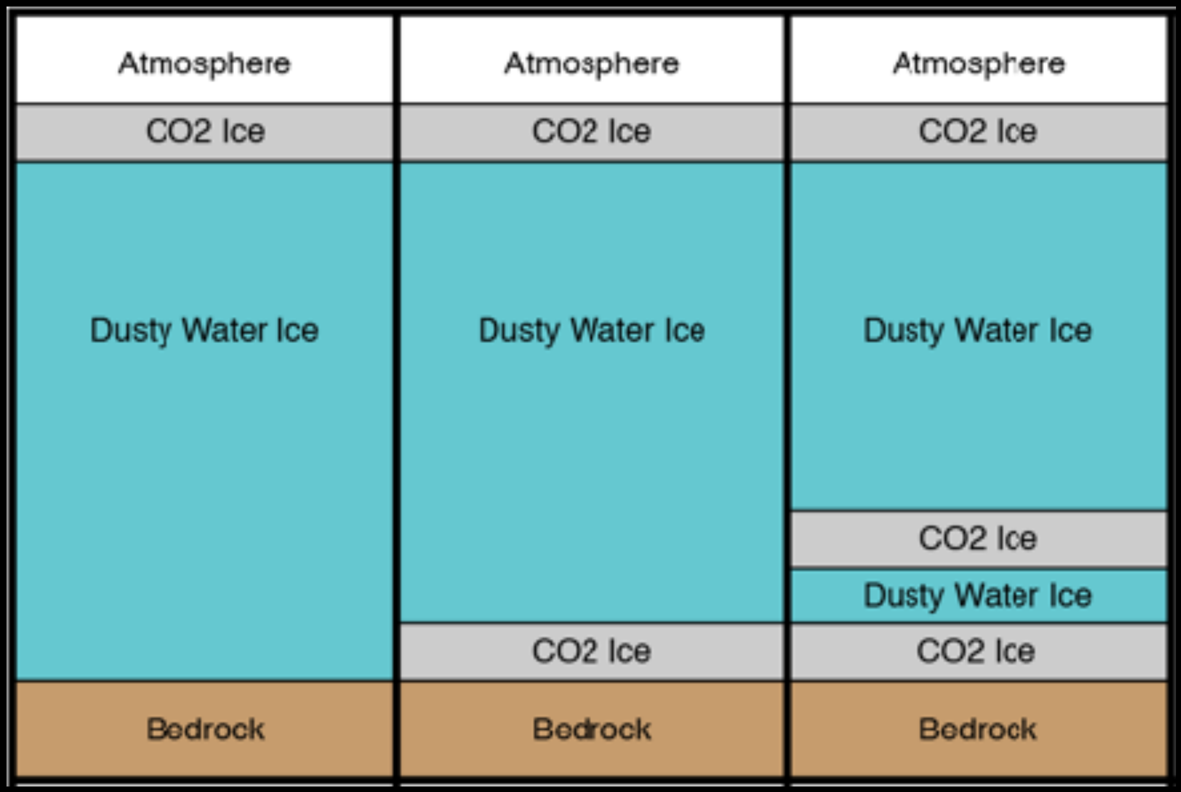




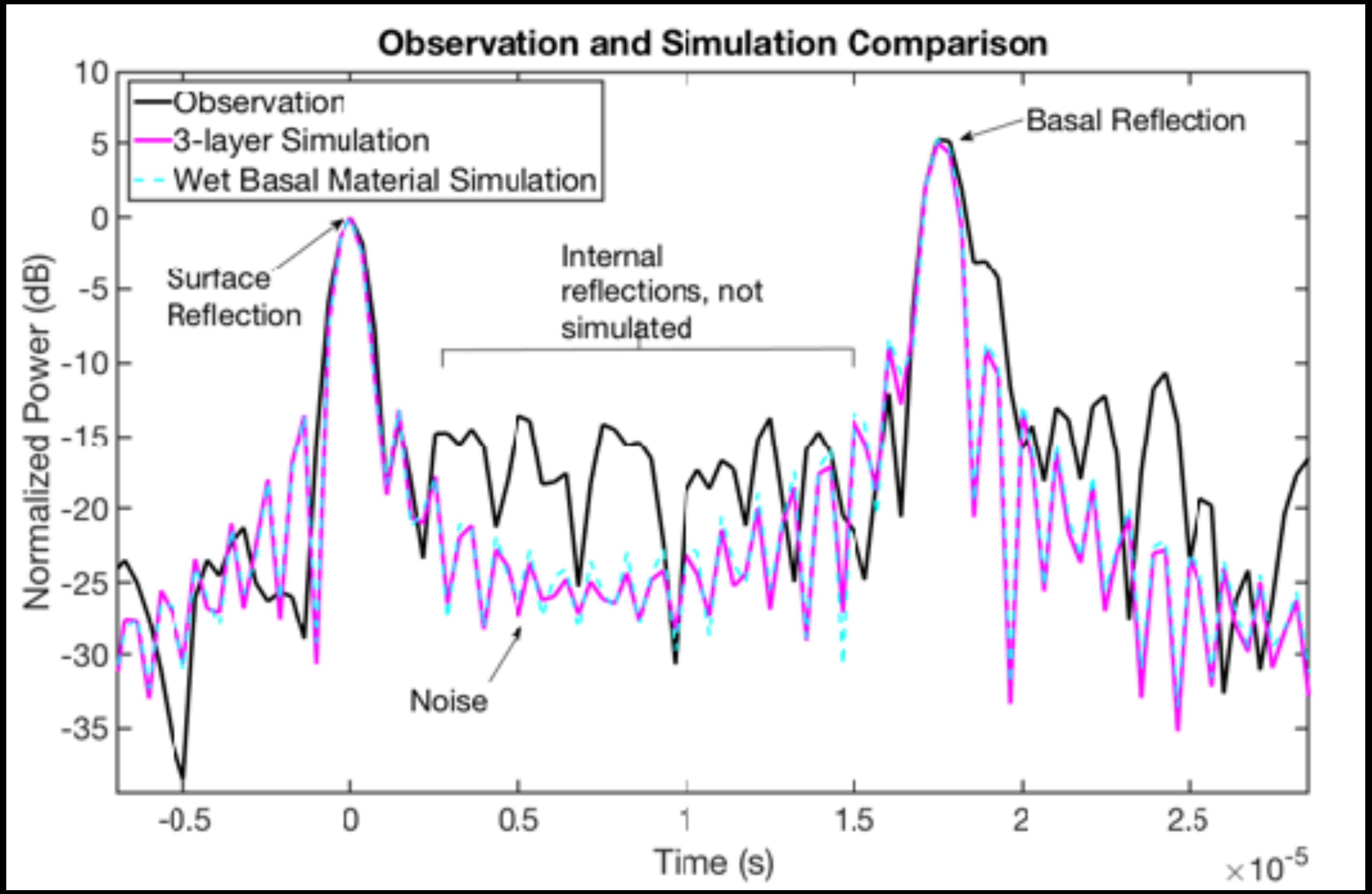


- 2 - Geologic materials with high reflectivity
  - clays (Smith et al., 2021)
  - volcanics with high Ti, Fe content (Bierson et al., 2021)

Constructive interference from multiple layers



Lalich et al., 2022

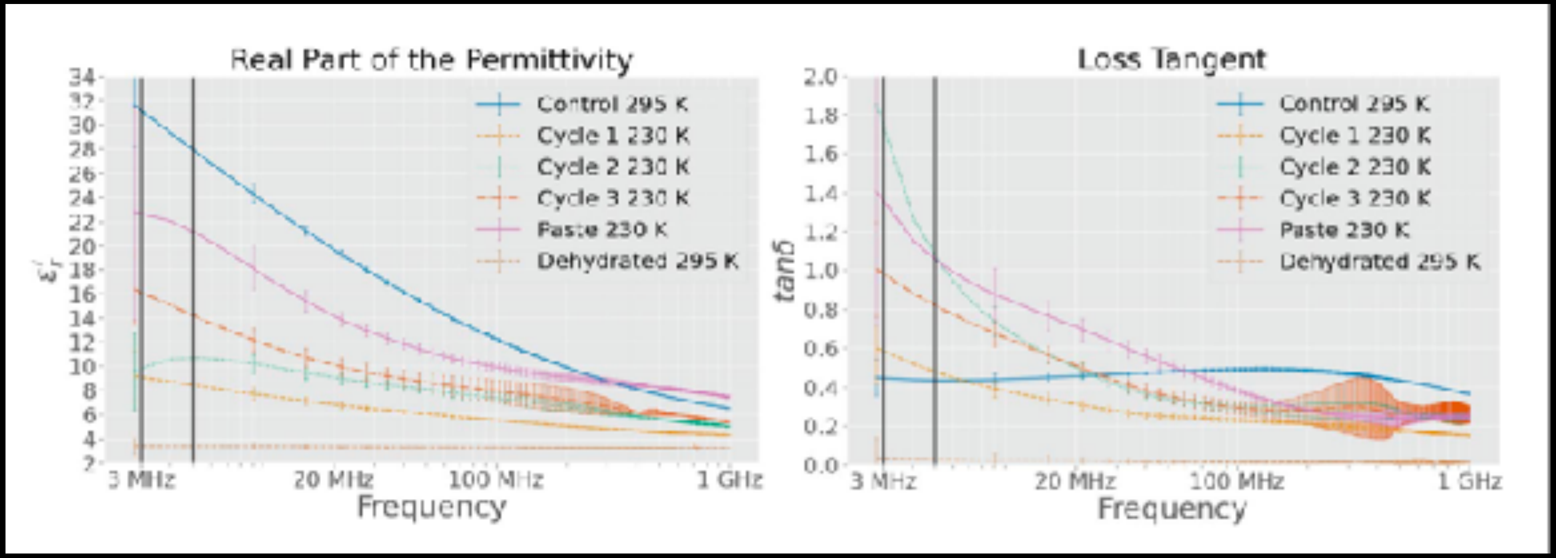


- Normalized power is the ratio of subsurface to surface reflection power (Pss/Ps)
- Simulations show that it could work
- Criticism - how likely is it?

(2) Other materials

Smectites (clays)

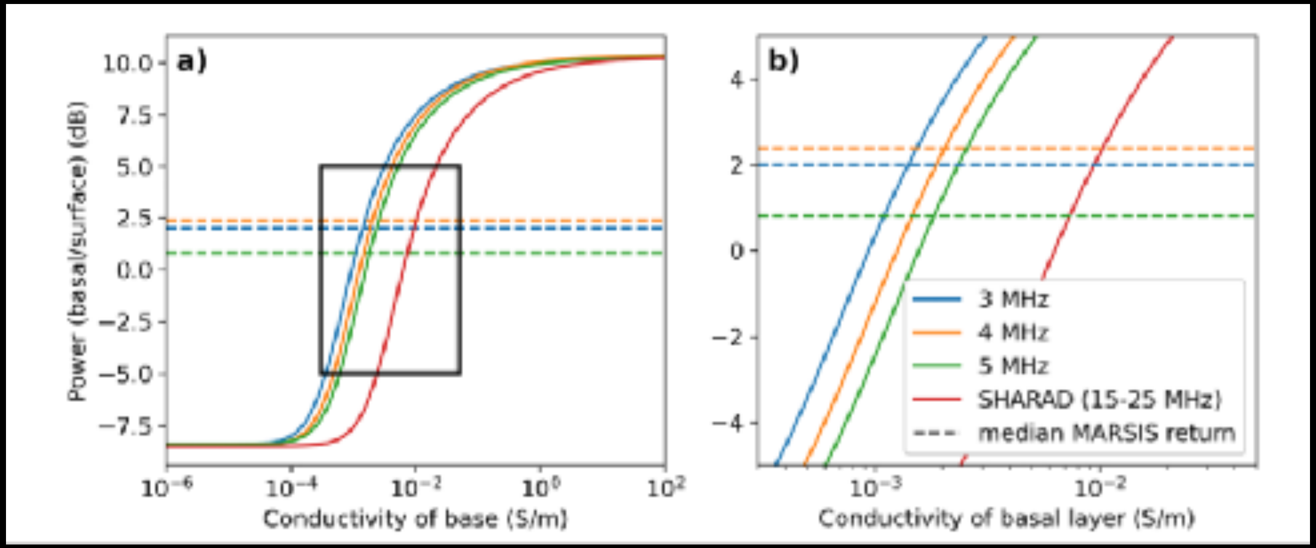
- Exhibit very high conductivities and are fairly common on Mars
- Conductivity (imaginary part of permittivity) was not included in the original analysis by Orosei et al. (2018)
- Criticism - lab experiments did not get to low enough temperatures



Smith et al,2021

Also clays, or maybe something else

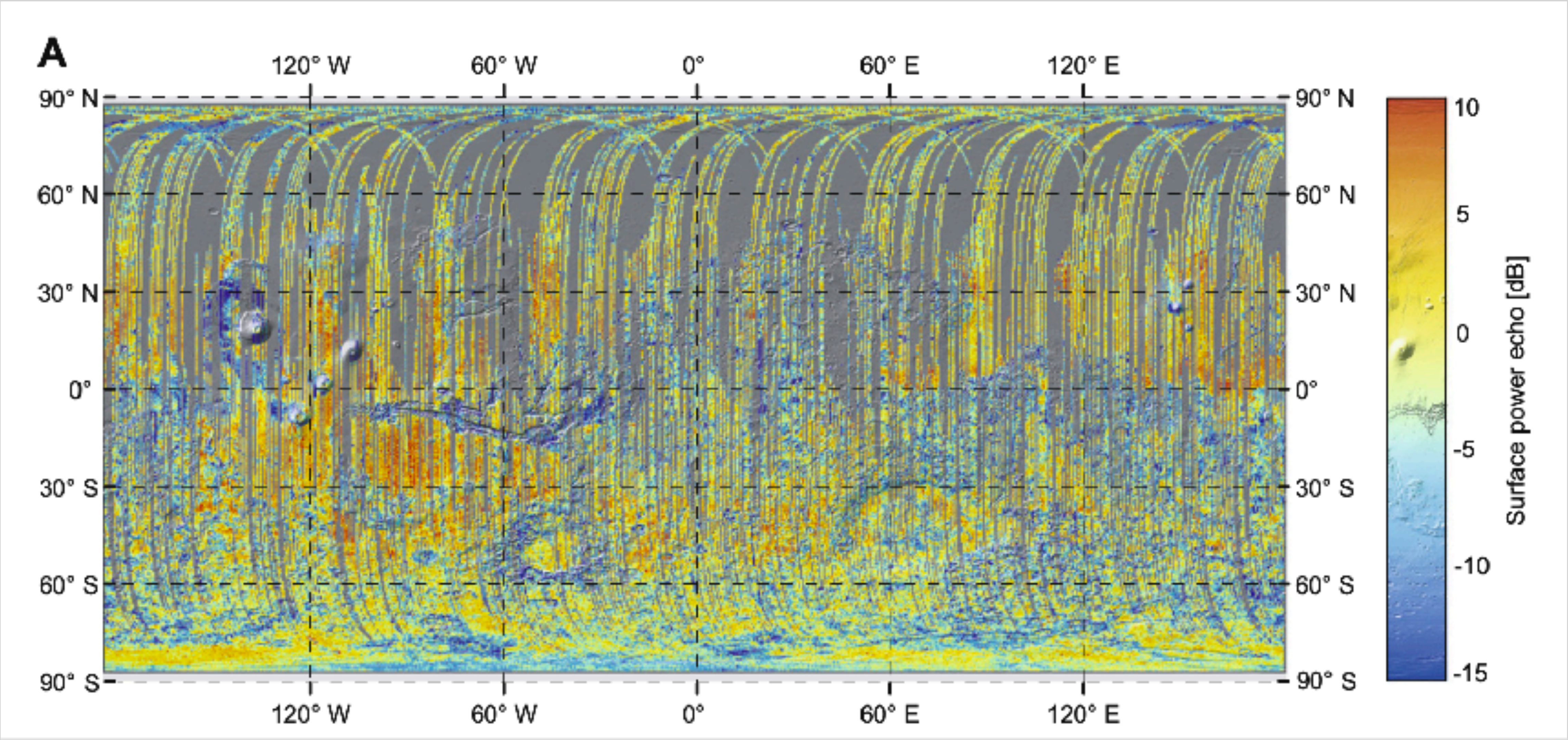
- Any hydrous mineral
- saline ice
- high-metal minerals (volcanics)
- Criticism - all theoretical, not definitive



Bierson et al., 2021

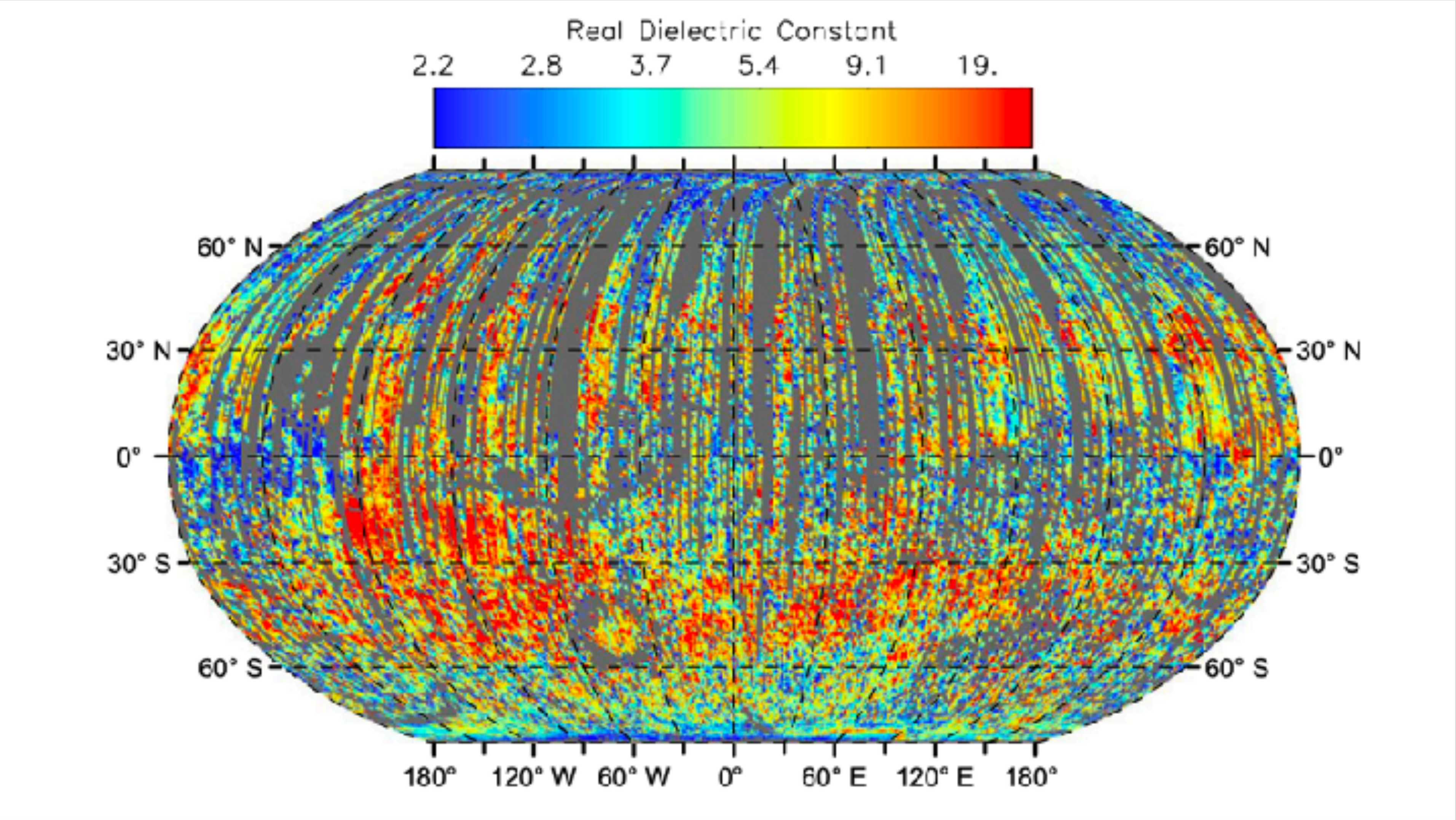
What about the rest of Mars?
Are there other radar-bright materials?

MARSIS surface power echo map



Mouginot et al., Icarus, 2010

Dielectric constant



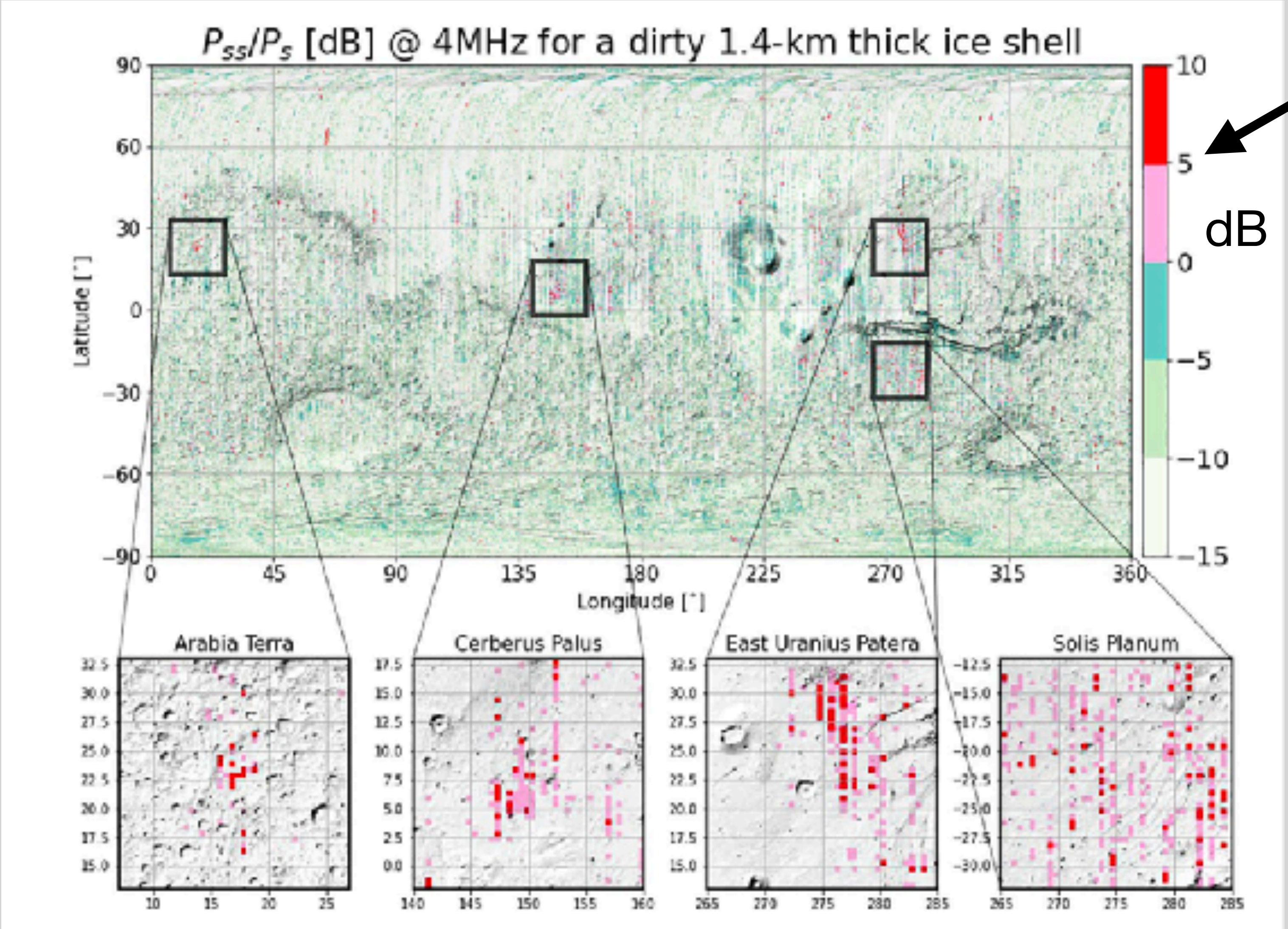
Mouginot et al., Icarus, 2010

- With roughness data from MOLA, surface echo power can be converted to dielectric constant

How strong would MARSIS echoes be if we covered Mars with SPLD?

Grima et al., GRL, 2022

Ratio of subsurface echo to surface echo power



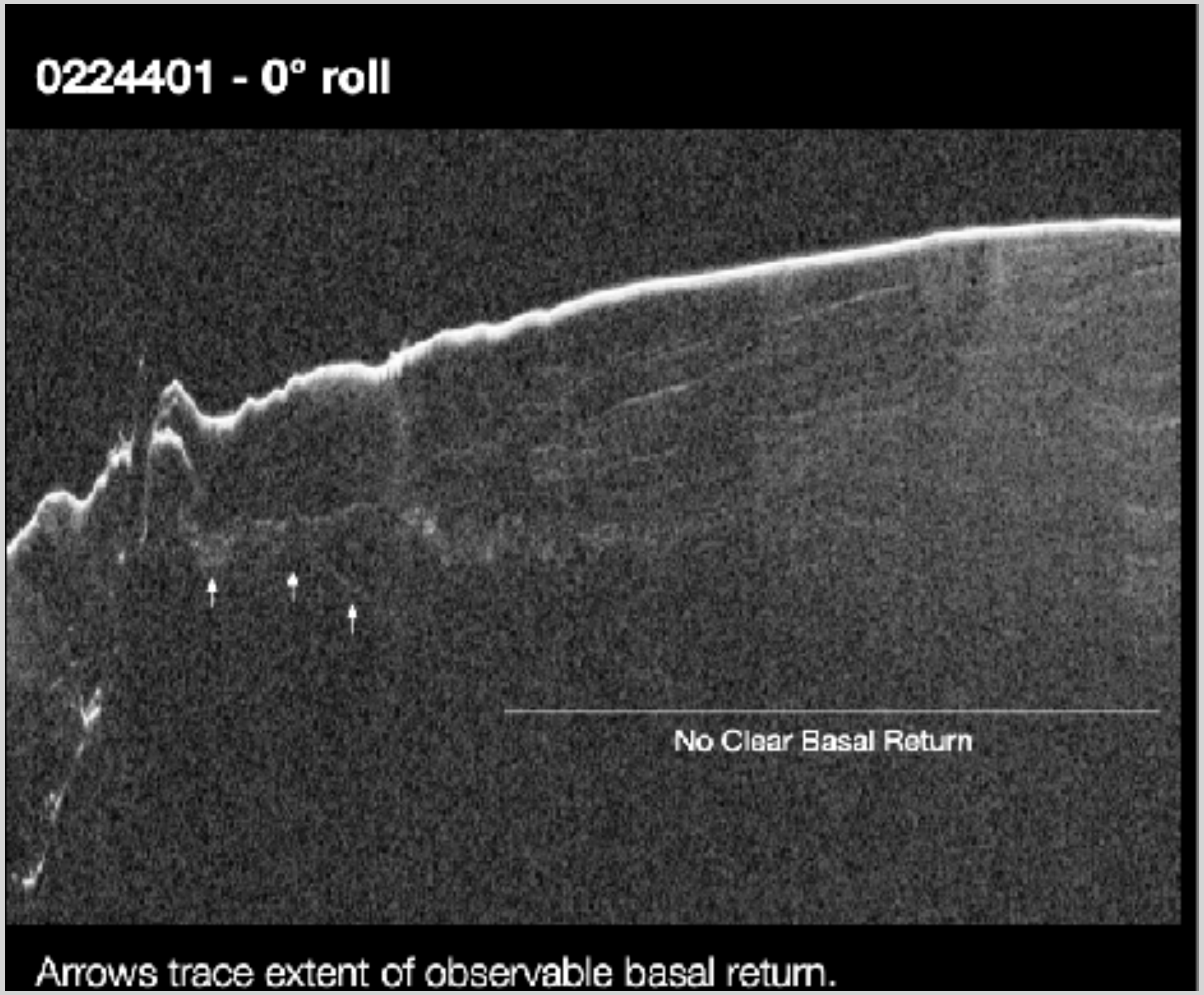
Threshold for SPLD "lakes"

- Assumes same impurities and loss tangent used by Orosei et al. (2018) for SPLD, and ice thickness at the site in question
- All of these regions of exposed, dry Mars **would produce basal echoes brighter than the surface** if covered by SPLD

Criticism - onboard processing by MARSIS may be a problem

SHARAD to the rescue?

- MARSIS is 3-5 MHz
- SHARAD on MRO is 15-25 MHz
- Analyzing frequency-dependent behaviors is useful to determine physical properties
- Until now, no basal detections in the area of interest have been available in SHARAD
- New data that increases SNR through a large spacecraft roll (120°) is promising



Morgan et al., in prep

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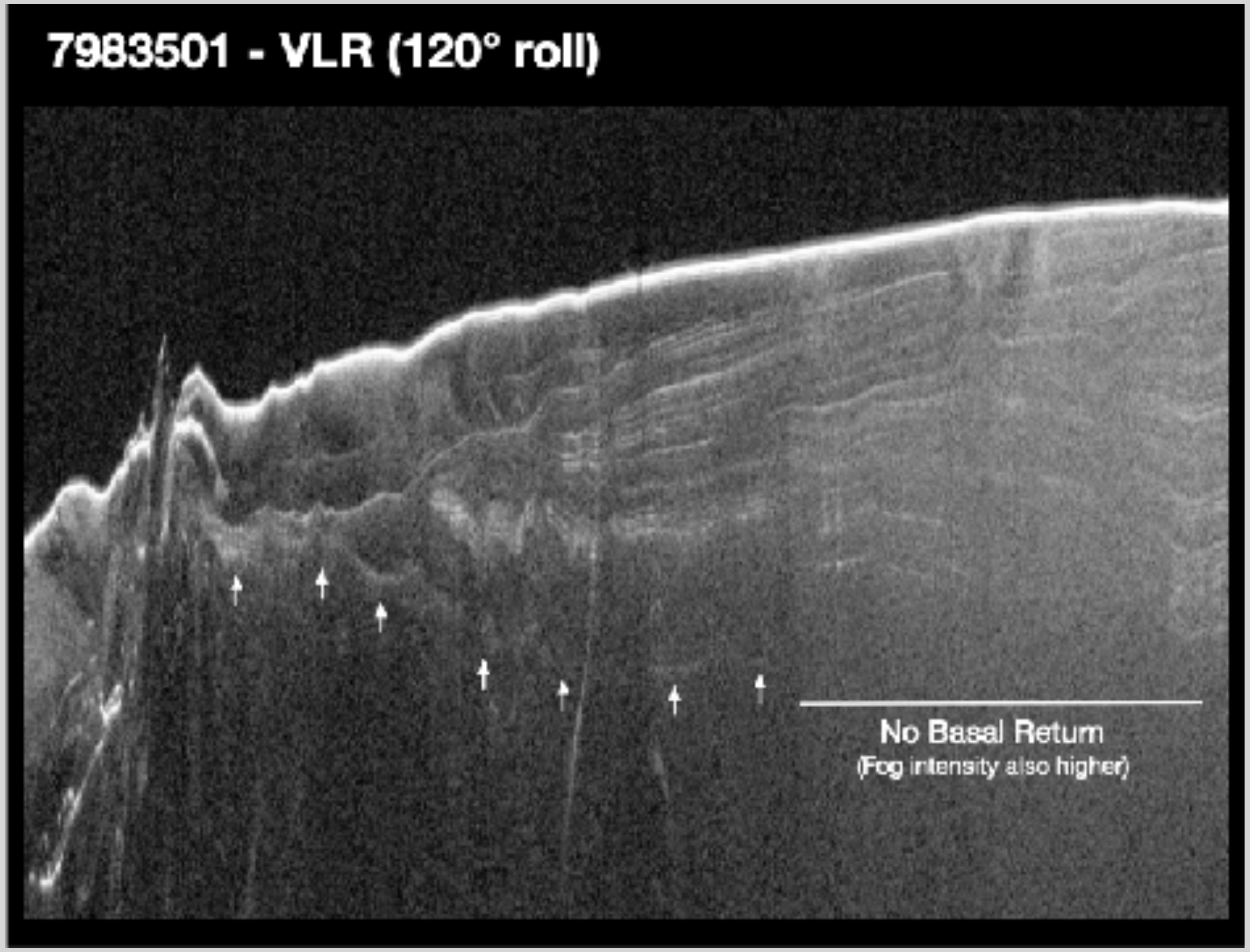
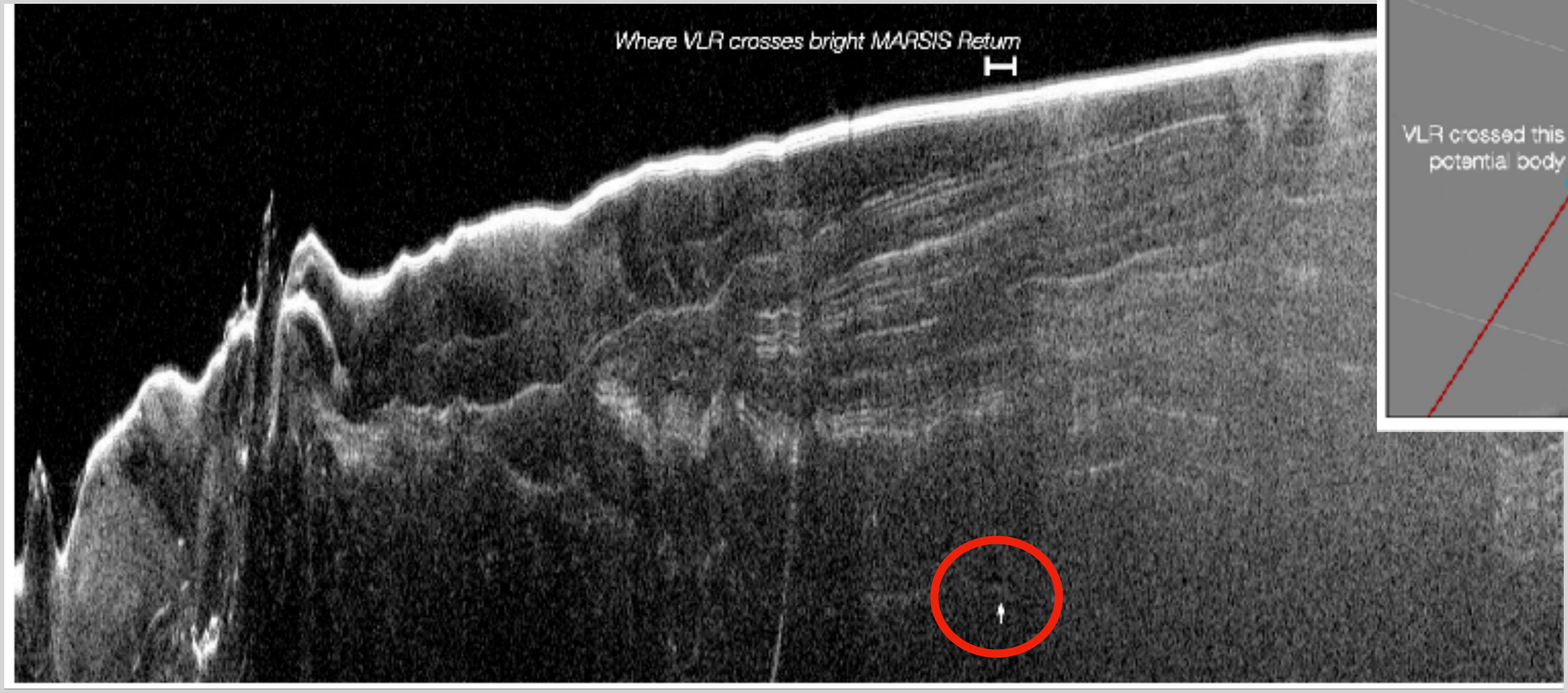
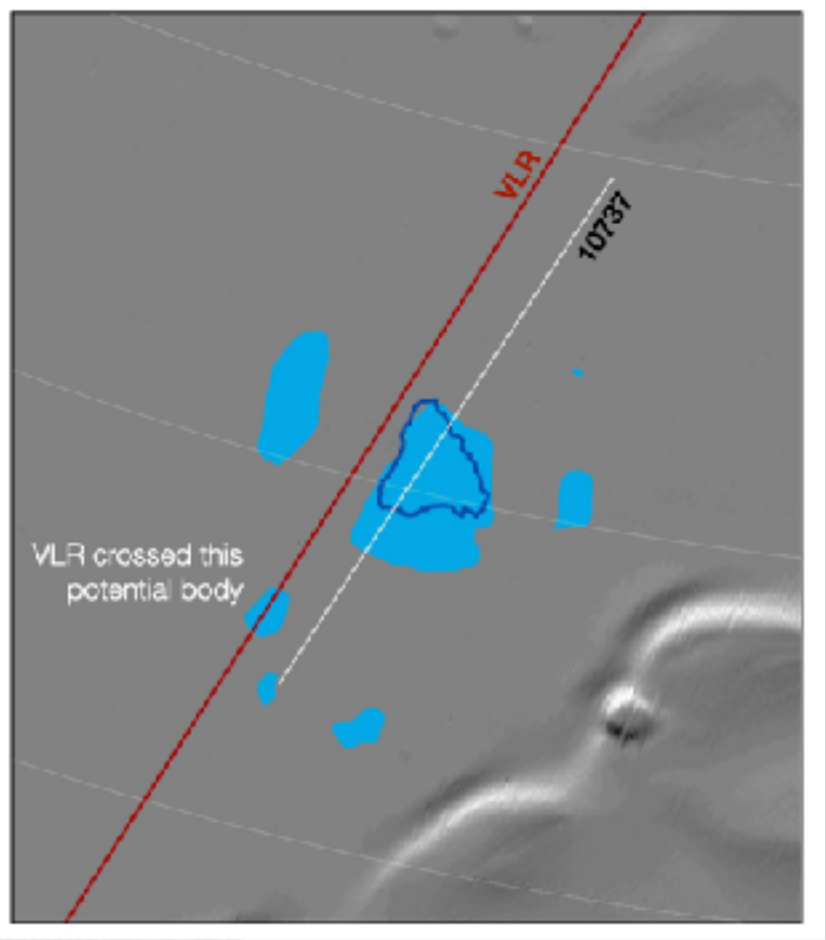


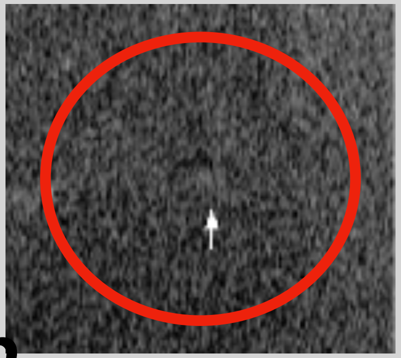
Morgan et al., in prep

SHARAD Very Large Roll

- Weak detection at one of the outlier sites of Lauro et al. (2021)







Morgan et al., in prep

In a nutshell

- Elevated geothermal flux is difficult to reconcile with the geology, and can't explain the broad distribution of bright returns
    - *No evidence for basal melting*
- Bright basal returns are seen in many places across the SPLD
    - *Khuller and Plaut, 2021*
- Geologic materials with higher reflectivity could be the answer
    - *Bierson et al., 2021*
    - *Smith et al., 2021*
    - *Stillman et al., 2022*
- Other places on Mars (dry) would yield similarly bright echoes if covered with SPLD
    - *Grima et al., 2022*
- Interference effects with closely spaced interfaces (either dust or CO2 layers) are also a possibility
    - *Lalich et al., 2022*
- SHARAD large rolls may provide new data to help constrain subsurface properties

SPLD water takeaways

- Studies claiming water were incomplete - their interpretation does not explain all the observations.
- Water is very difficult to explain in this environment given what we know.
- Alternative explanations are plausible.
- Yet the debate continues, due to the implications.
- Don’t believe everything you read in the news, *Science*, or *Nature*.

The End - Any Questions?

Major system tradeoffs

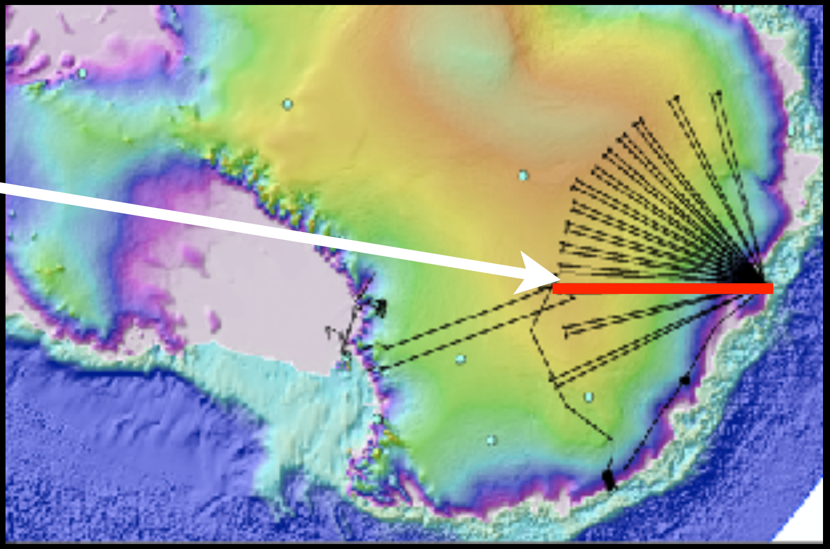
- Wavelength - penetration
- Bandwidth - resolution
- PRF - along-track sampling, SNR
- Power - usually limited by transmitter
- Sampling scheme
  - Rate - tied to bandwidth primarily
  - Dynamic range
    - *Noise floor*
    - *Maximum signal strength*
- Onboard summing (stacking)

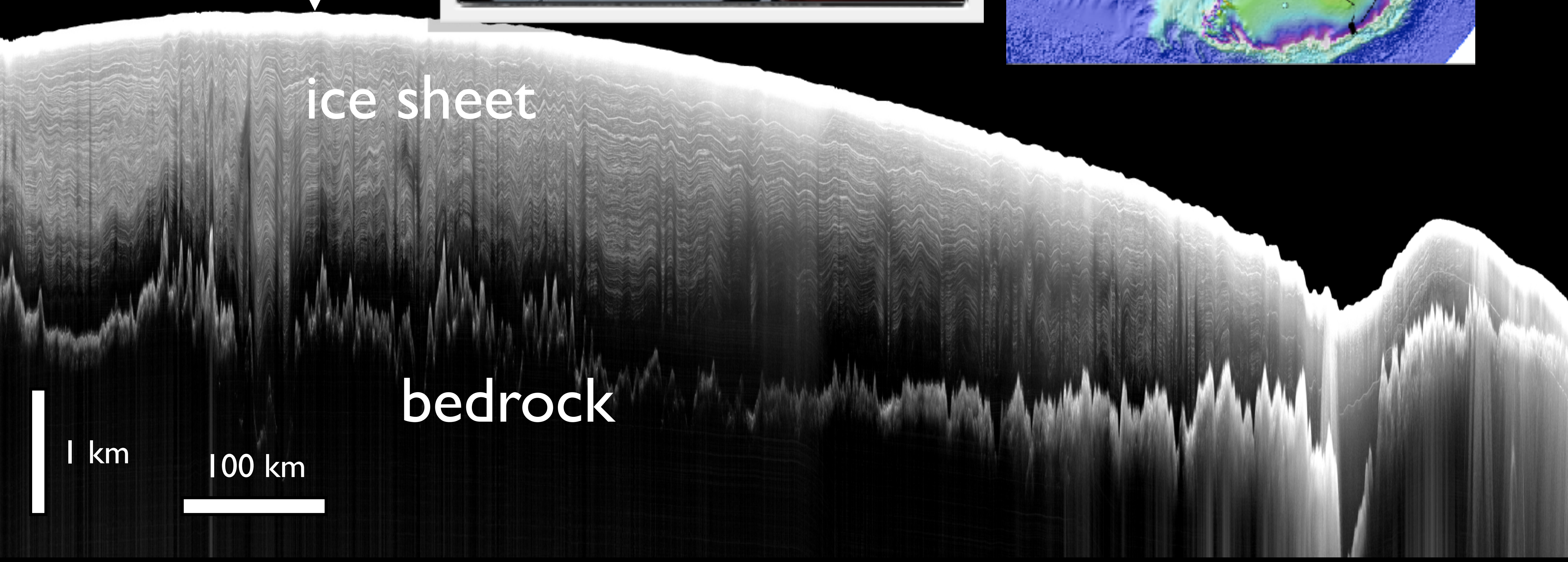
Table 1. Bulk dielectric constants (ϵ_r measured at 100 MHz) of common earth materials.

Material	from Davis and Annan, 1989	from Daniels, 1996
Air	1	1
Distilled water	80	
Fresh water	80	81
Sea water	80	
Fresh water ice	3-4	4
Sea water ice		4-8
Snow		8-12
Permafrost		4-8
Sand, dry	3-5	4-6
Sand, wet	20-30	10-30
Sandstone, dry		2-3
Sandstone, wet		5-10
Limestone	4-8	
Limestone, dry		7
Limestone wet		8
Shales	5-15	
Shale, wet		6-9
Silts	5-30	
Clays	5-40	

Basalt ~ 9-12
(and remember this is just the real part of permittivity)

A radar-sounding slice of Antarctica





Depth corrected. But note huge vertical exaggeration!