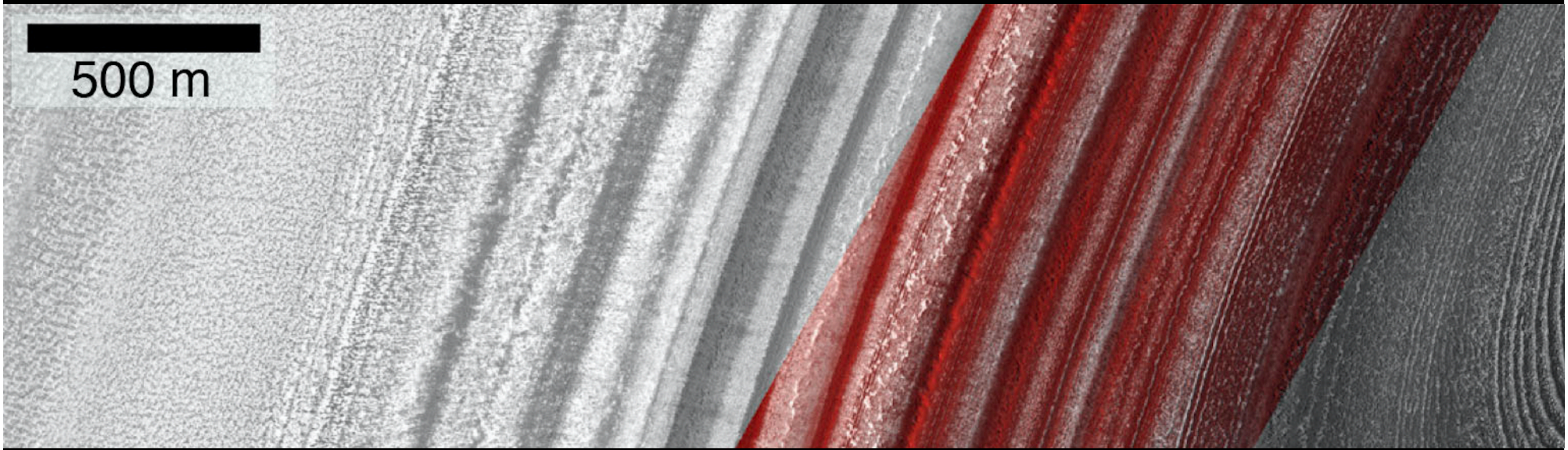
Polar Stratigraphy



UNIVERSITÄT BERN

Patricio Becerra
University of Bern
Pasadena, August, 2017

Planetary Imaging Group

Why study the stratigraphy of the PLD?

From 6th ICMPSE 2016:

*Question 2: What do the **characteristics of Martian polar ice** deposits reveal about their formation and evolution?*

*Question 3: How has the Martian climate evolved through geologic history, what are the **absolute ages of the observable climate records**, and how should we **interpret the records** of past states?*

We need:

- *Detailed knowledge of the layer properties and their arrangements in the geologic record*
- *Correlate to Mars' climate history influenced by the evolution of its astronomical parameters*

GOALS:

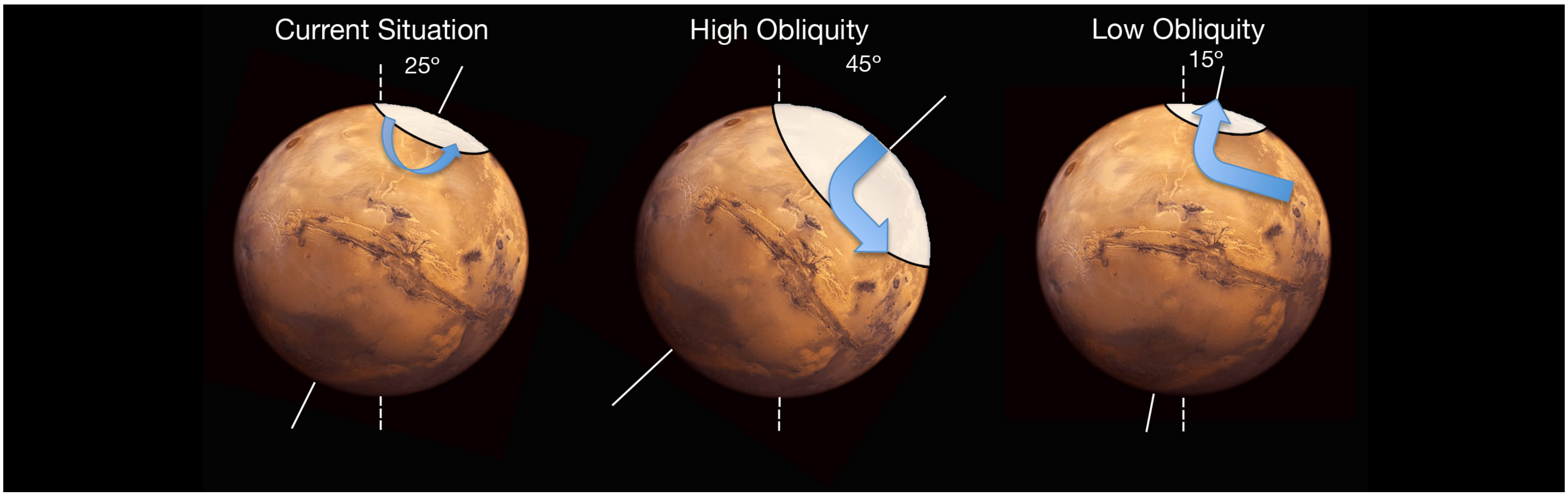
Determine the age of specific layers and the climatic state in which they were deposited

Detailed understanding of the geologically recent evolution of the Martian environment

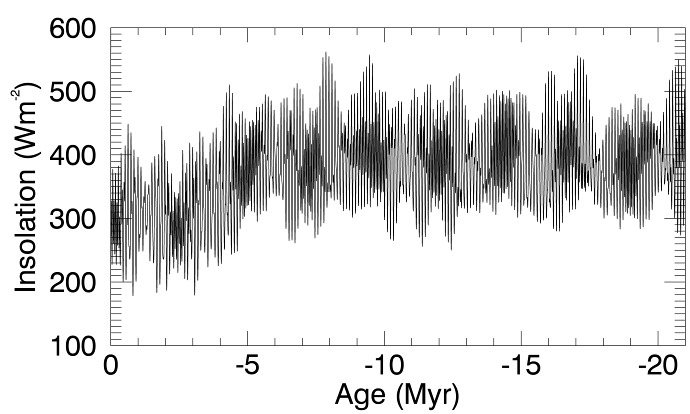
The connection of the PLD to climate

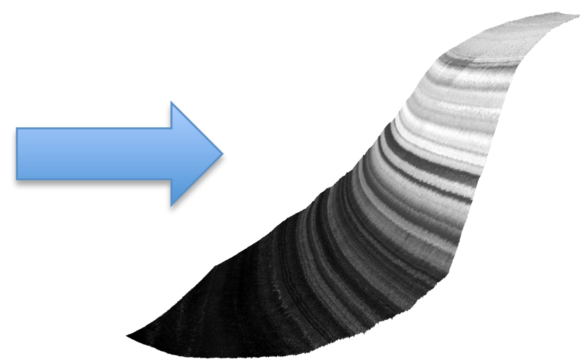
Orbital and axial oscillations = changes in the distribution of insolation on the surface

→ Changes in insolation drive changes in the distribution of ice and dust on the surface



Variations in the distribution of ice and dust result in varying episodes of accumulation and ablation of material in the PLD





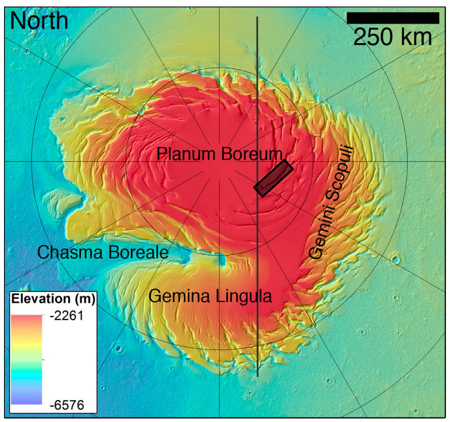
Solutions from *Laskar et al. 2004*

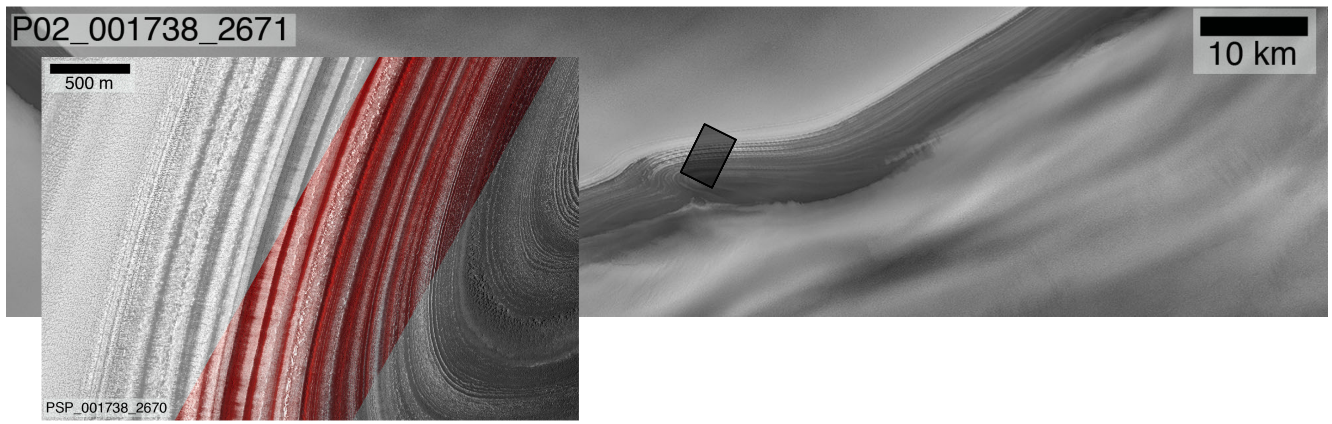
Observing the stratigraphic record

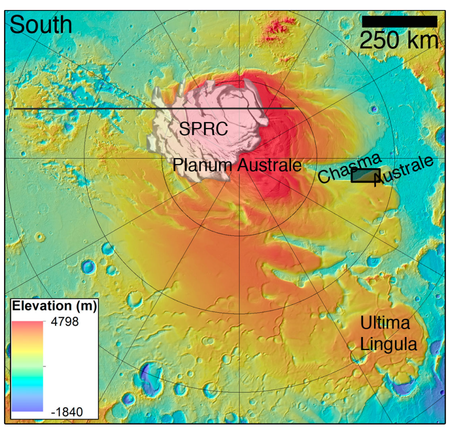
An **accurate characterization** of the internal layering is crucial to search for a record of climate → The best stratigraphic descriptors are those that most closely relate to the layer formation environments, e.g. dust/ice ratio, isotope variations.

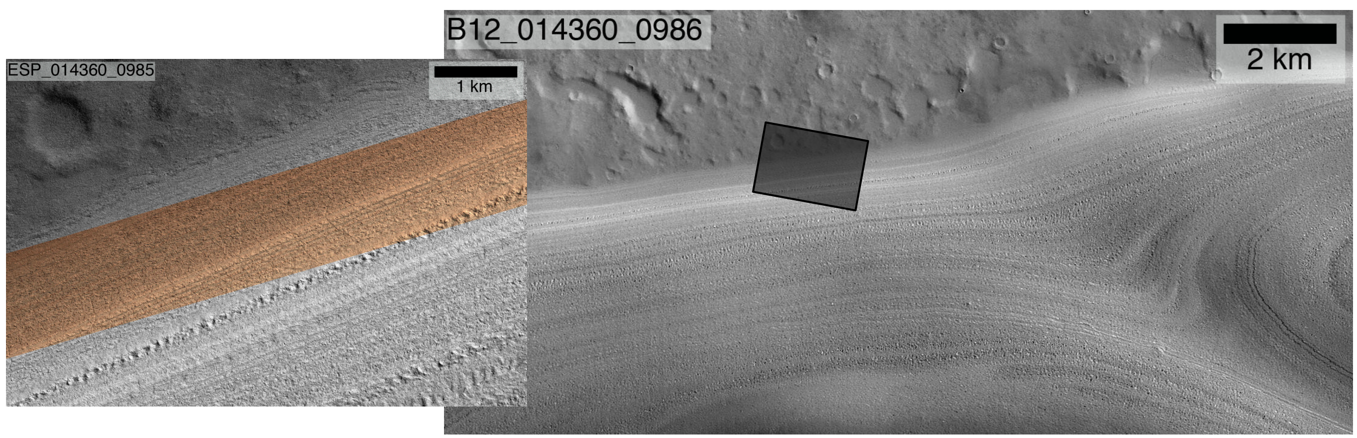
From orbit we have primarily two choices:

1. Imaging/Topography of **outcrops**: Complex relationship to intrinsic properties. Upper ~ 500 m.
2. Subsurface radar: Changes in dielectric properties. View deepest PLD layers. Relation to outcrops unclear.









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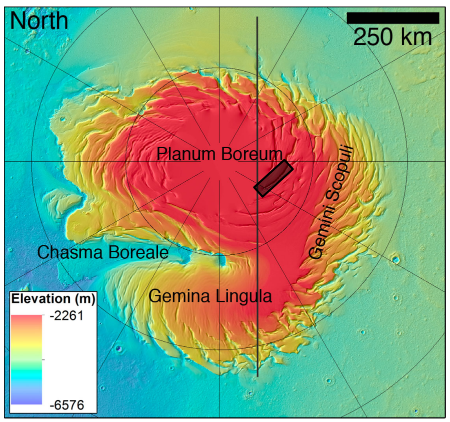
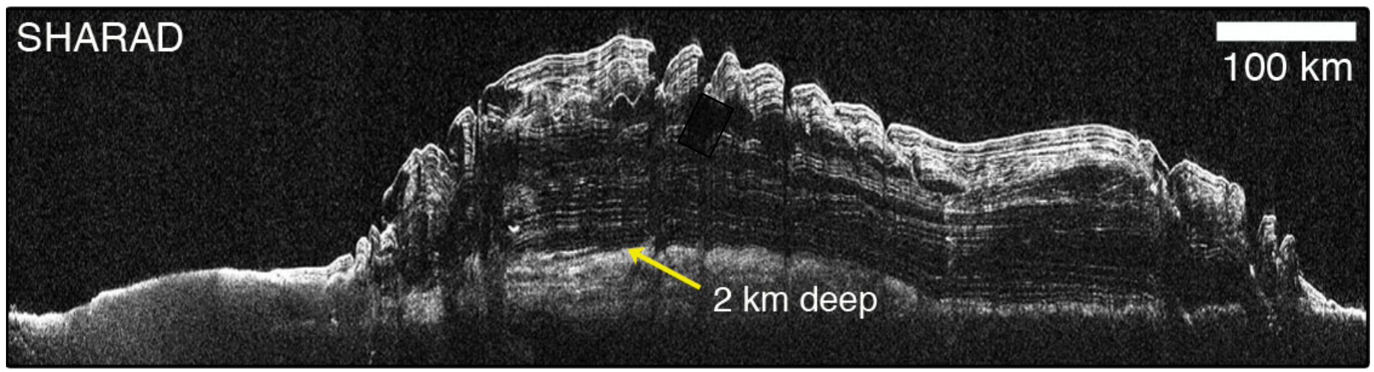
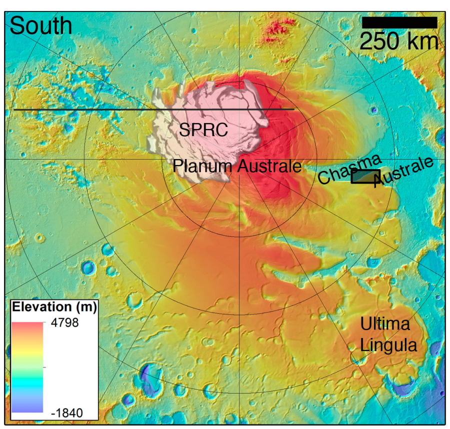
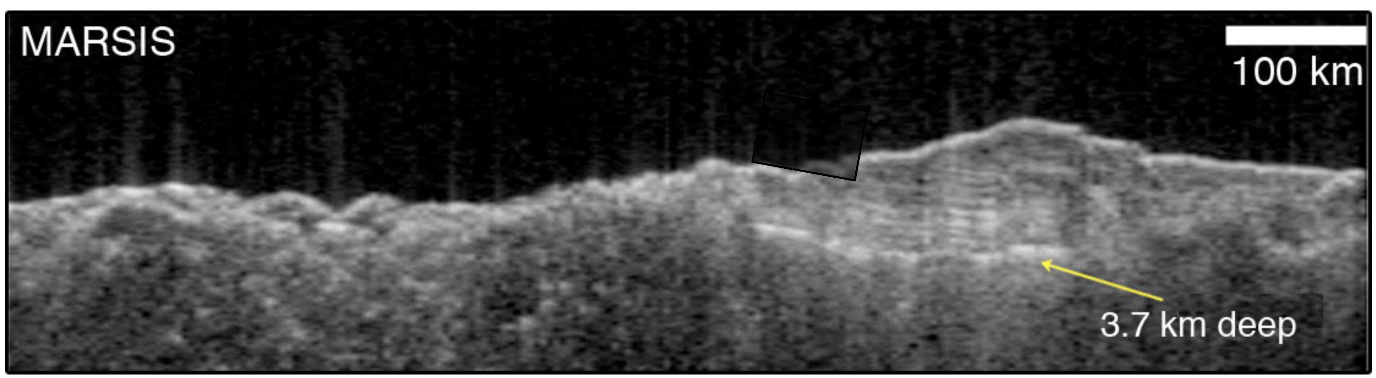




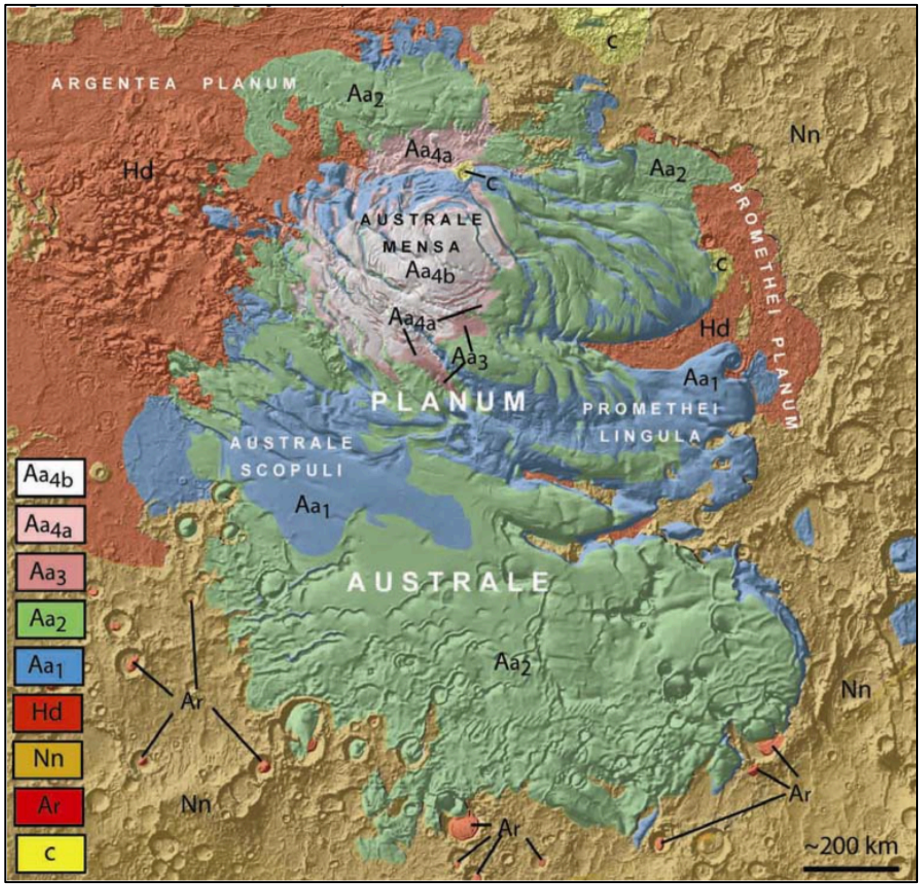




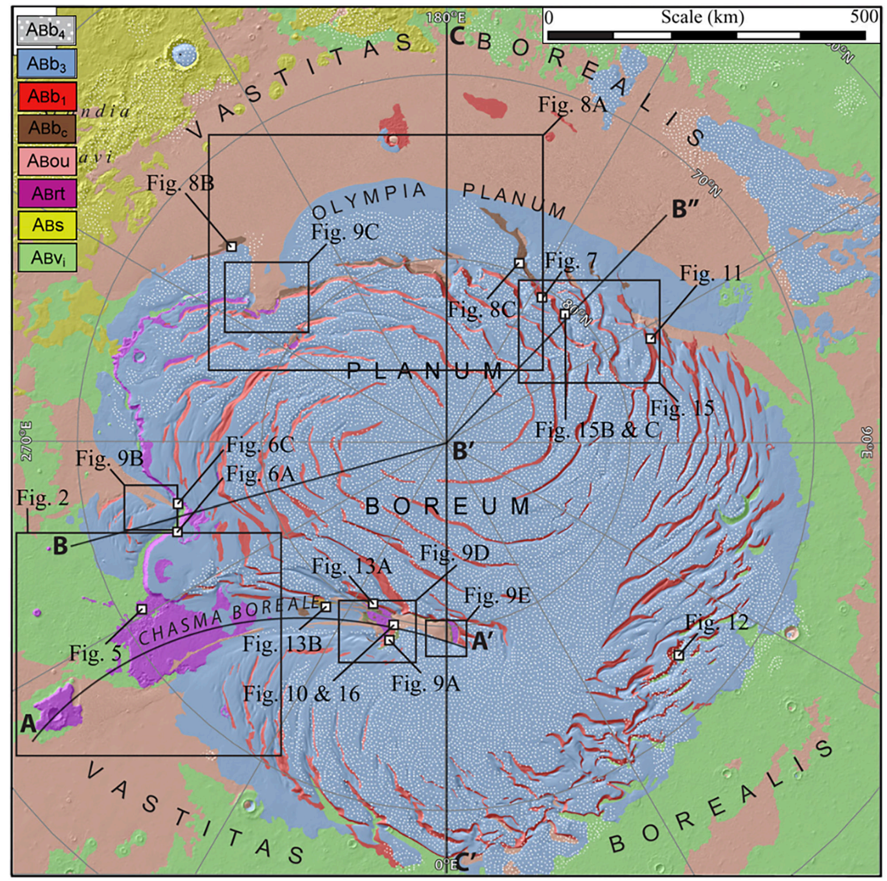
Mapping and Analysis Methods

Geologic Framework

- Widespread image coverage + topography → Visually identify broad stratigraphic units and unconformities
- Crater statistics = ~Age. Surface ages: 10 – 100 Myrs for the SPLD. < 5Myrs for the NPLD.



Tanaka et al. 2007



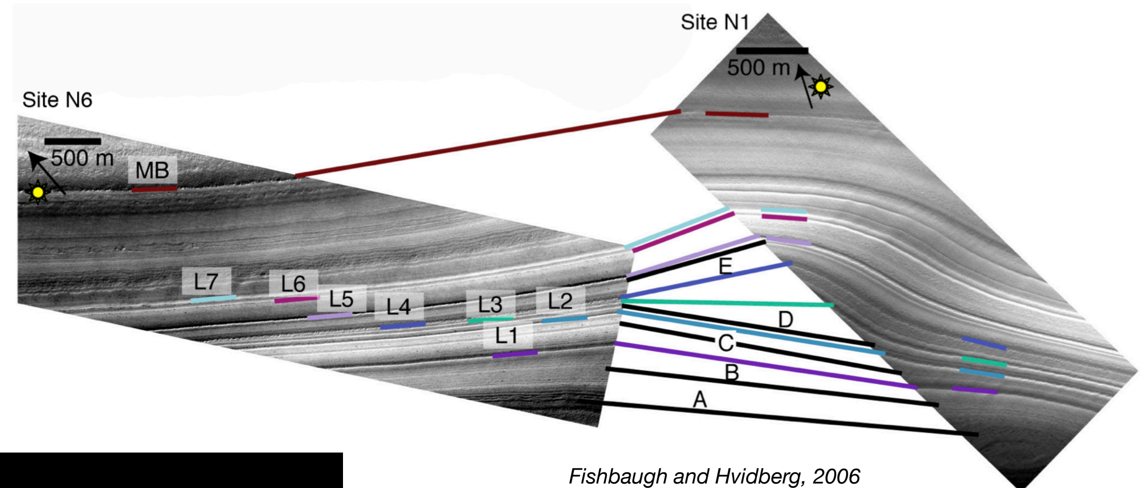
Tanaka et al. 2008

This work is expertly performed and published by Tanaka, Kolb, Fortezzo, et al., in a series of papers and geologic maps

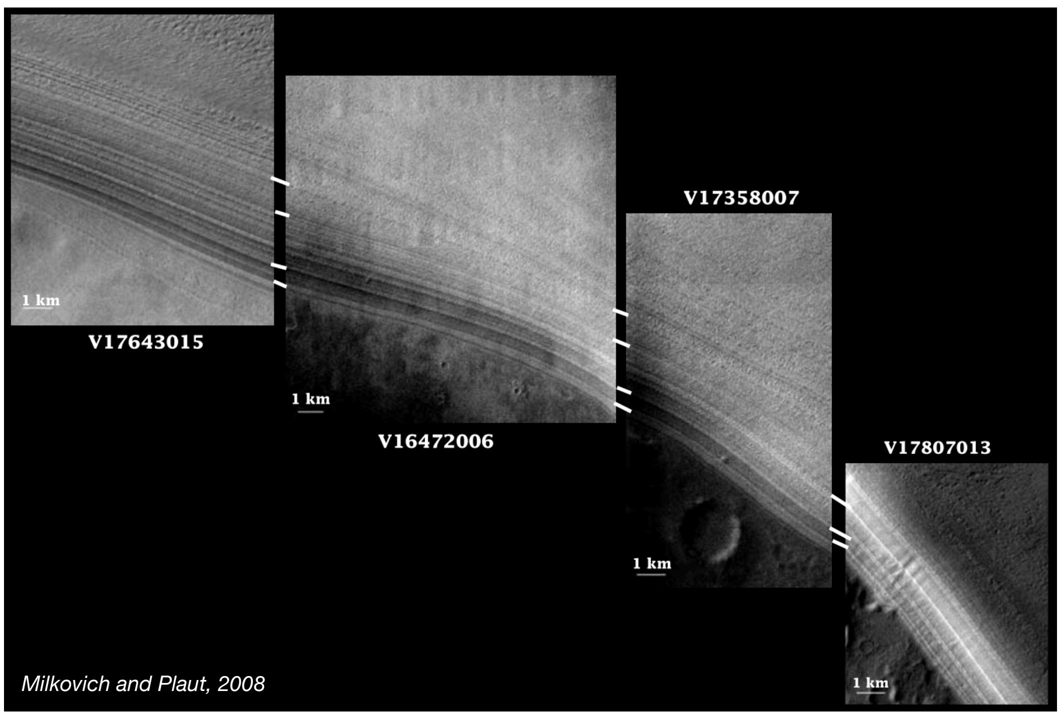
Layer Correlation in Images

Sequences of layers must be identified in separate locations for these to be considered correlated

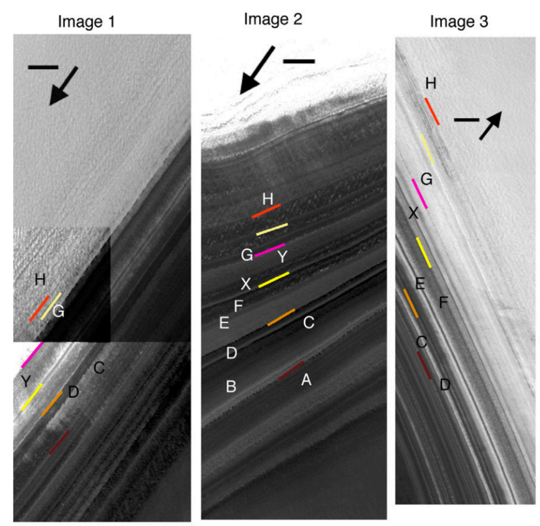
Identification is done through morphologic and/or topographic comparisons



Fishbaugh and Hvidberg, 2006



Milkovich and Plaut, 2008

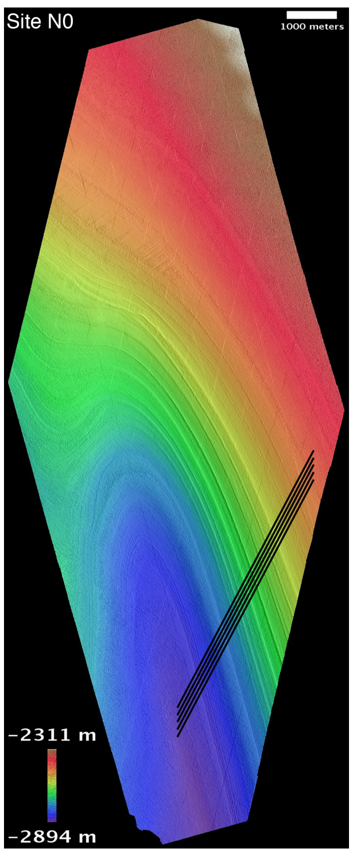


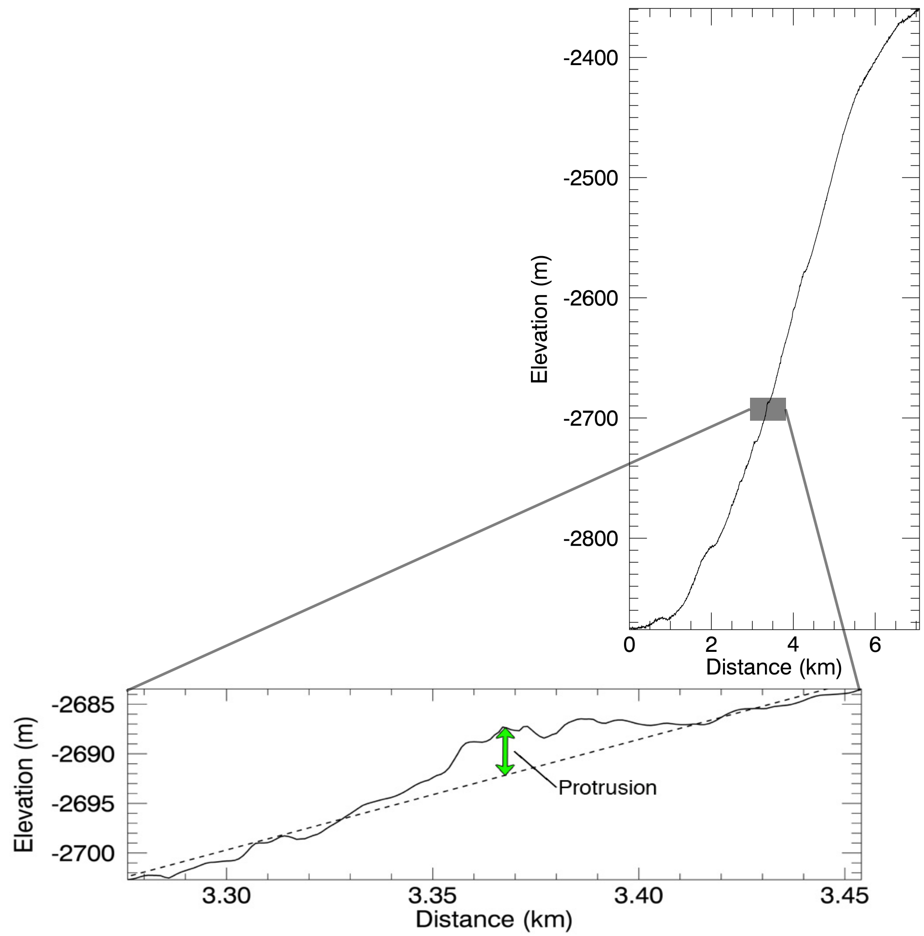
Because of the periodic nature of the PLD, this method can sometimes be unreliable

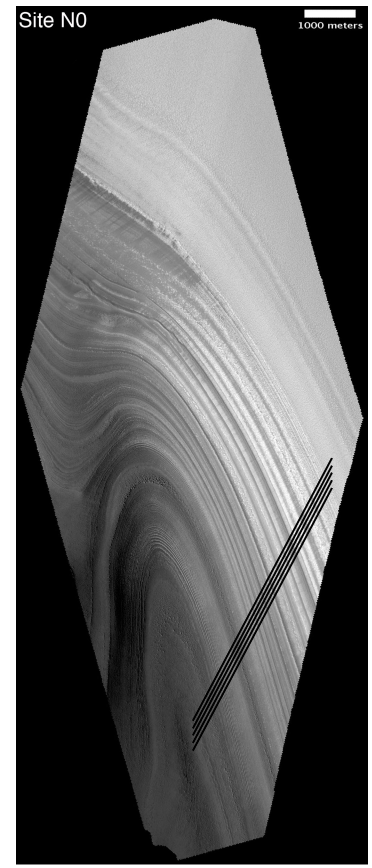
Correlation of continuous profiles

High resolution stereo allows a variety of measurements:

- Topographic expression at varying wavelengths (protrusion)
- Local slope
- Brightness from orthorectified images







Becerra et al. 2016, 2017

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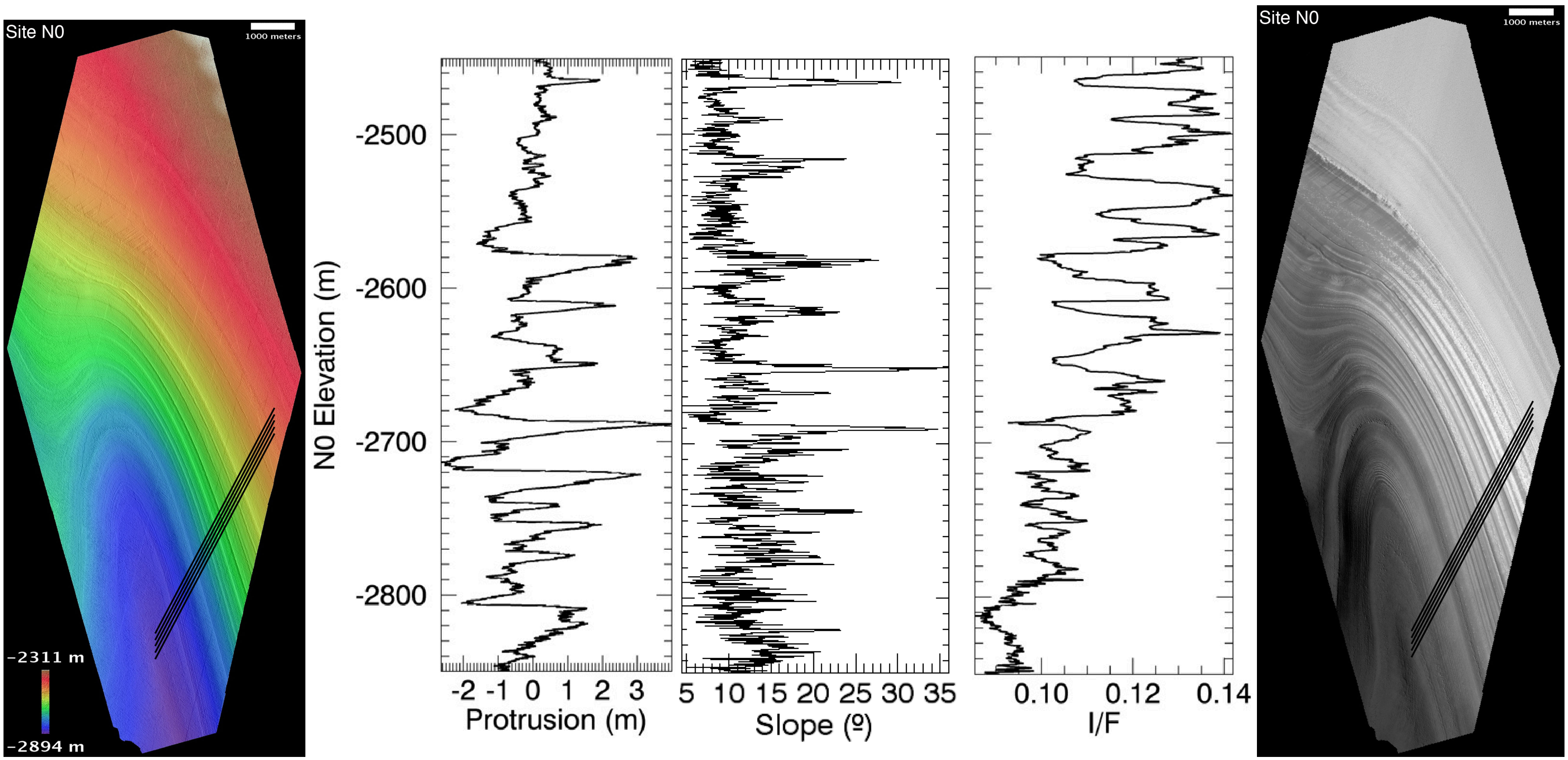
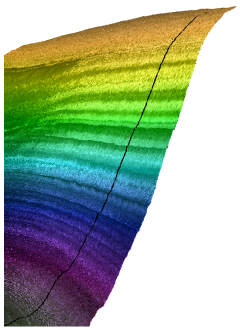


Becerra et al. 2016, 2017

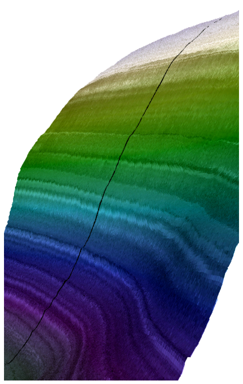
Signal matching techniques

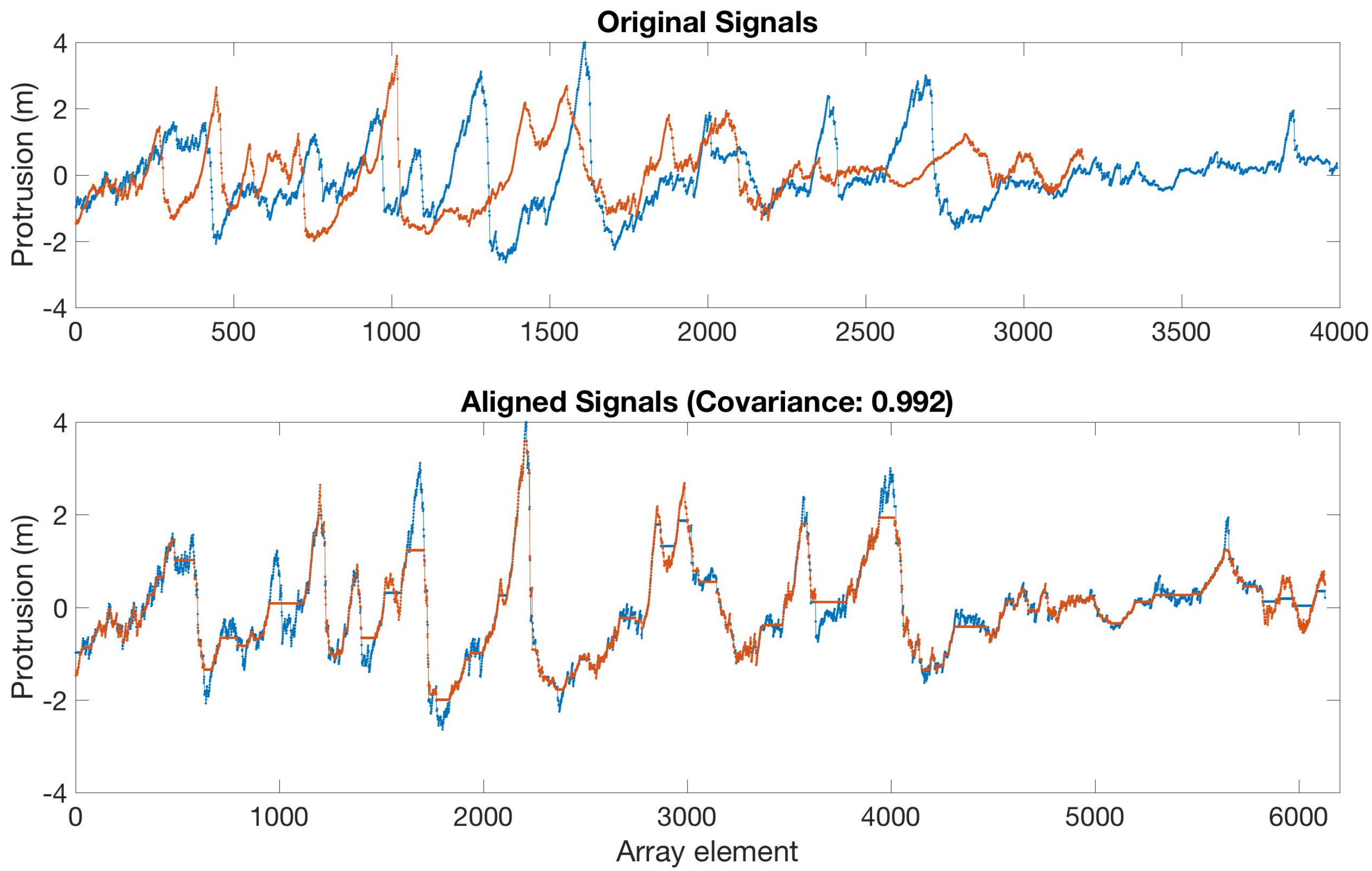
Continuous stratigraphic profiles allow for correlation through signal-matching techniques

Dynamic Time Warping (DTW): Tunes (stretches or contracts) a pair of signals to find the optimal match between them



10 x vertical exaggeration





Radar-based stratigraphy

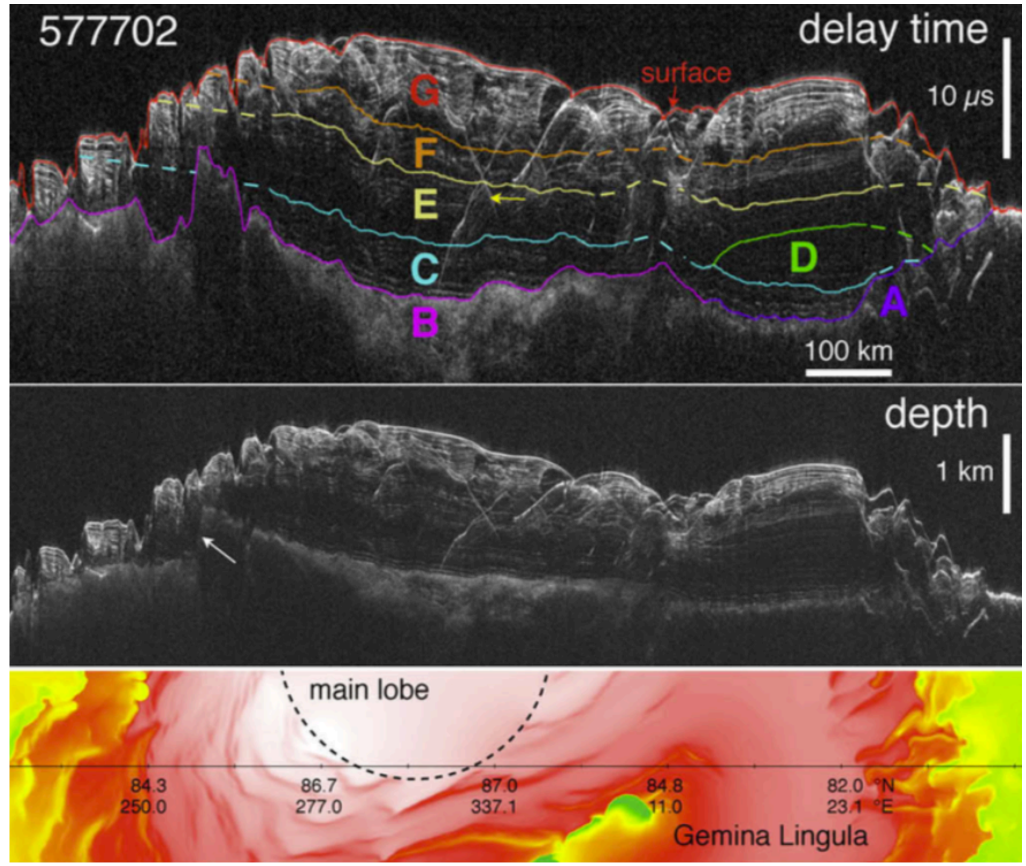
Radar enabled us to “see” the internal structure of the PLD

Radargrams = distance along track + power vs. delay time image:

- Geometric distortion from surface topography and change in signal speed through different media →

$$\Delta d = \sqrt{\frac{c\Delta t}{2\varepsilon}}$$

- Permittivity (ε) estimated from SHARAD + MOLA to be ~3.15 for the NPLD → typical of pure water ice under Martian conditions
- Good SHARAD data coverage allows mapping of radar units throughout the cap area
  → Radar-based stratigraphy



Putzig et al. 2009

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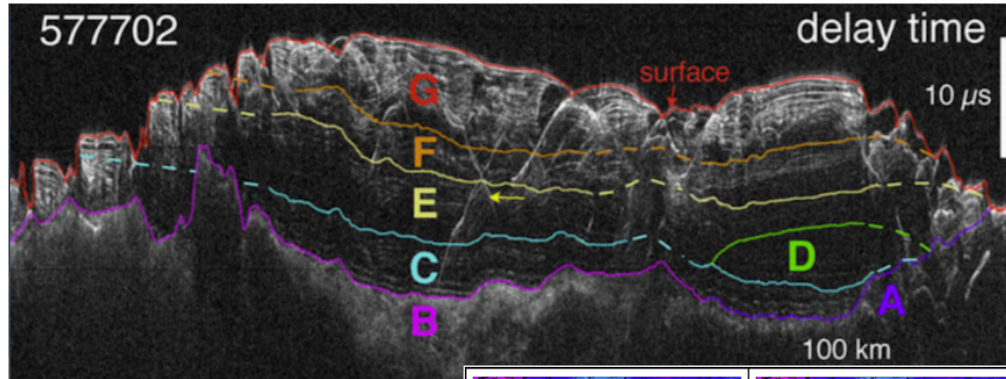
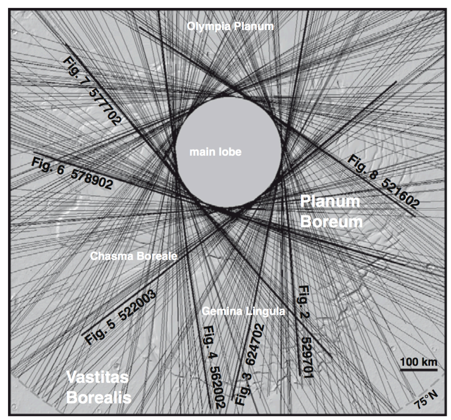
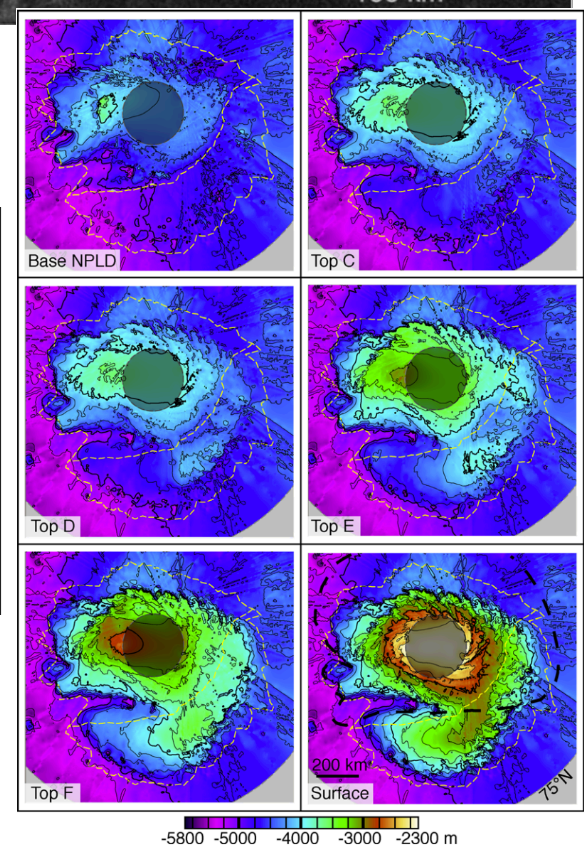






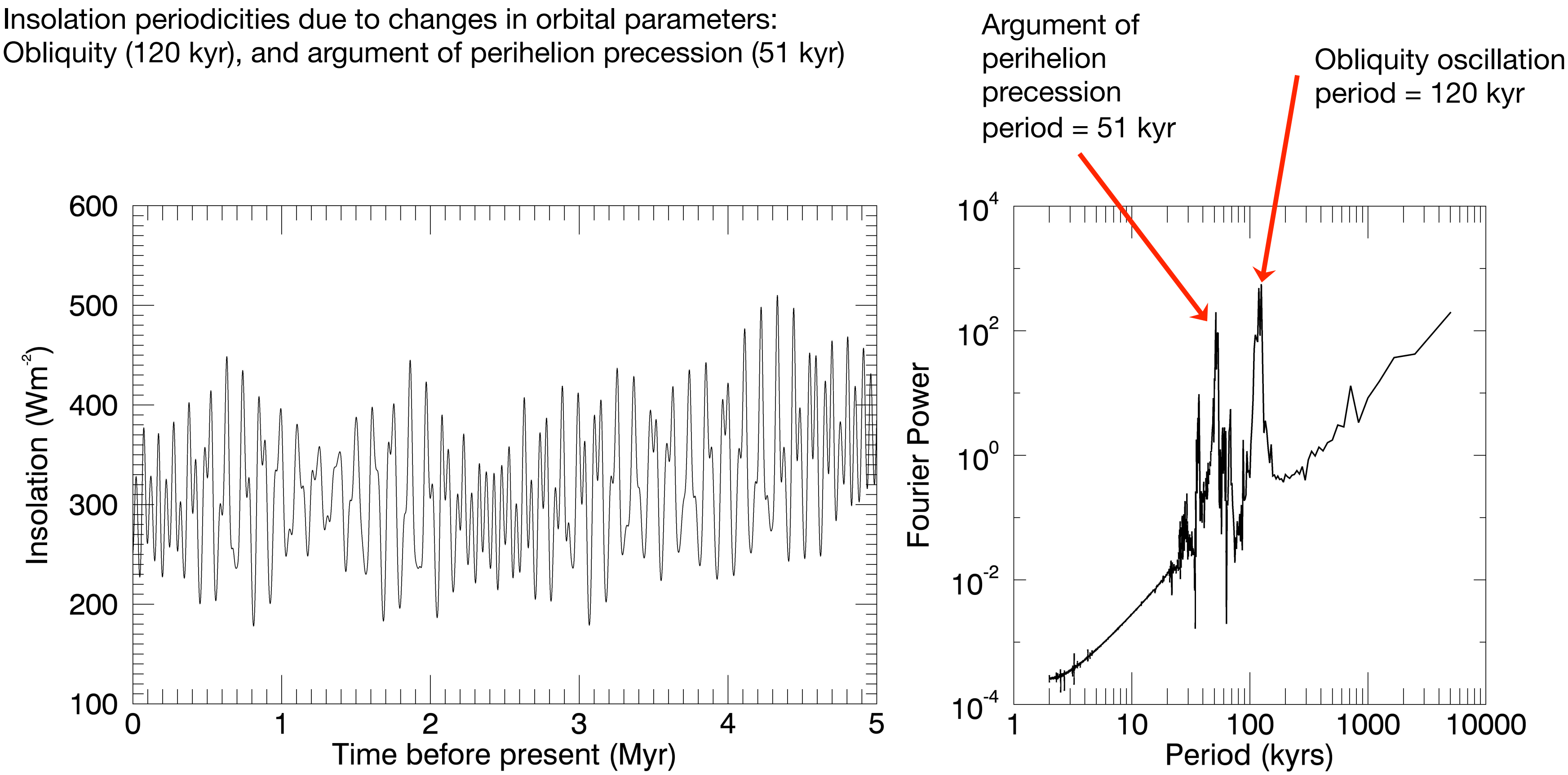
Putzig et al. 2009

Searching for periodicities

Time-Series Spectral Analysis:

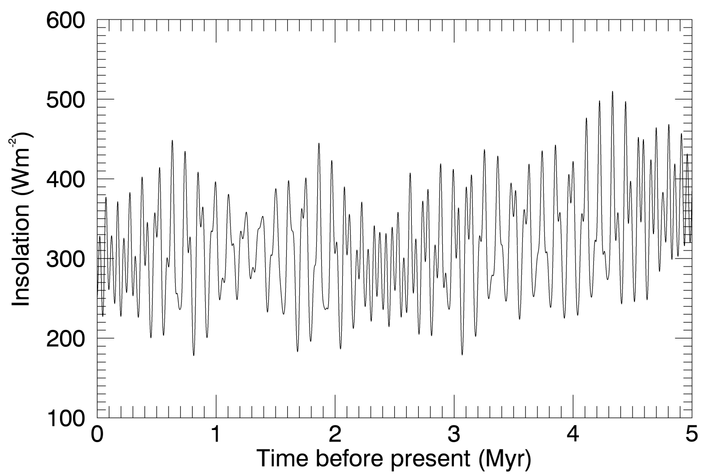
Decompose periodic-driven functions into their periodic components. E.g. FFT Analysis, Wavelet Analysis

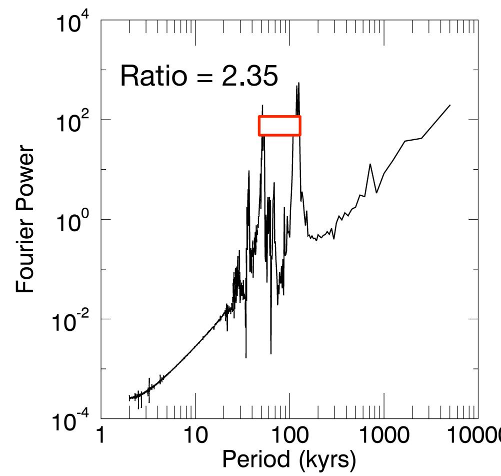
Insolation periodicities due to changes in orbital parameters:
Obliquity (120 kyr), and argument of perihelion precession (51 kyr)



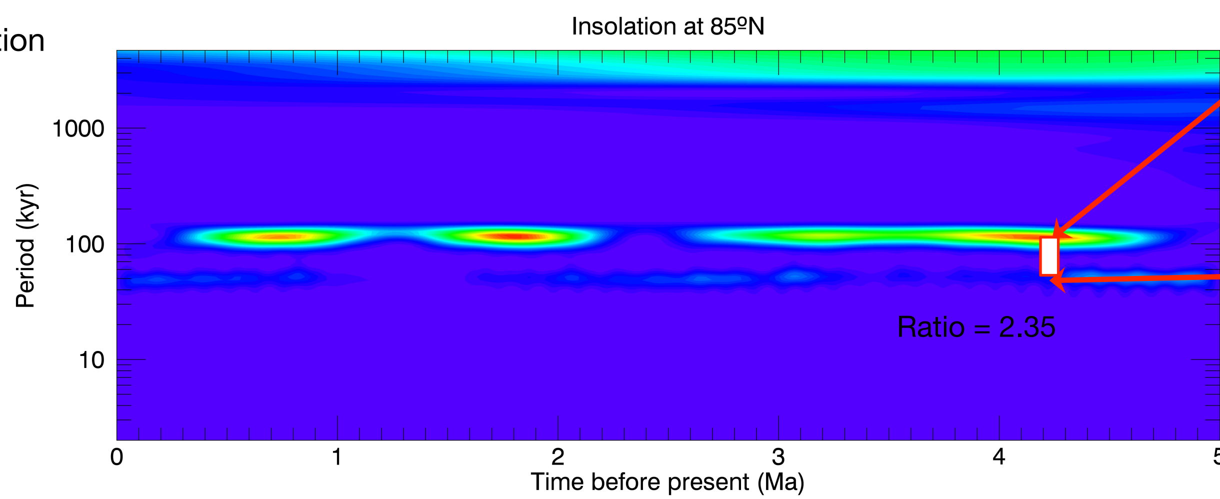
Searching for periodicities

Decomposes a 1D time/depth-varying function into a 2D depth-frequency/wavelength image of spectral power (WPS) → Reveals dominant wavelengths and their variation with depth



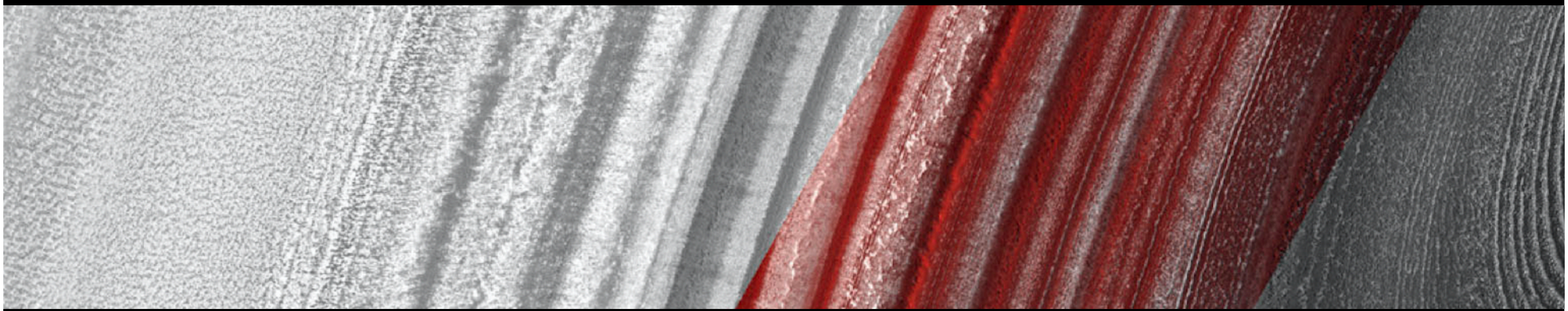


WPS of Insolation



Obliquity oscillation period = 120 kyr

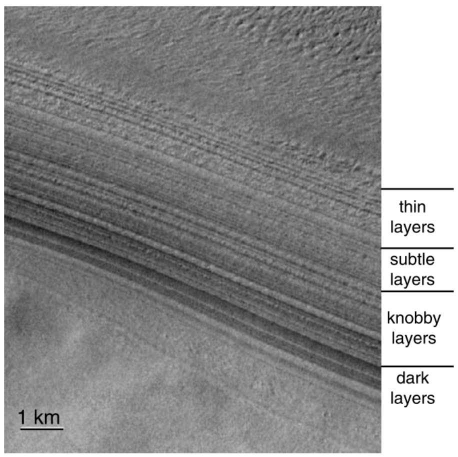
Argument of perihelion precession period = 51 kyr



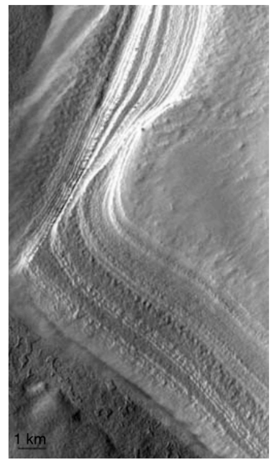
Stratigraphy of the SPLD

SPLD: Image-based stratigraphy

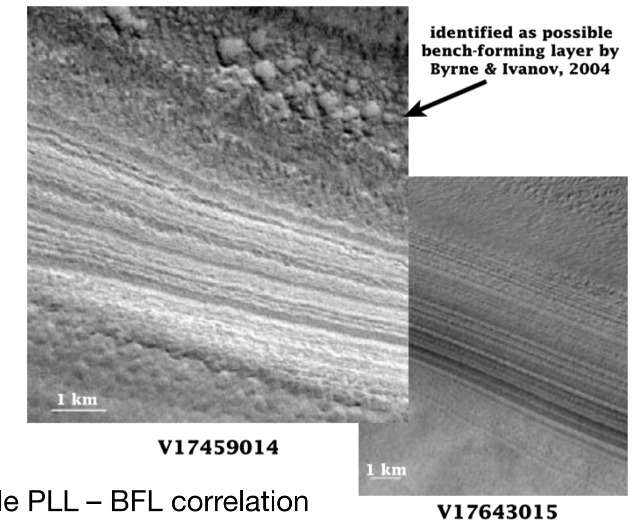
Milkovich and Plaut (2008) visibly correlated layer sequences by their morphology in THEMIS images (17 m/p) of exposures
→ Three large scale sequences of layers inferred, each with a different areal extent



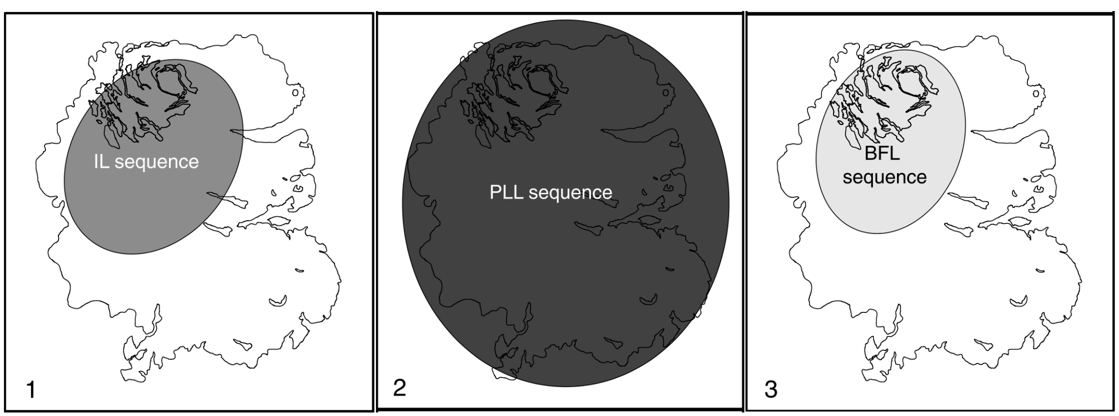
Promethei Lingula Layer Sequence (PLL)

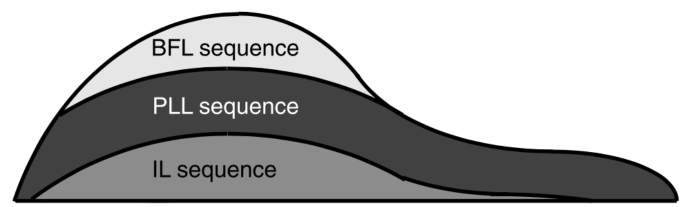


Bench Forming Layer Sequence (BFL)



Possible PLL – BFL correlation

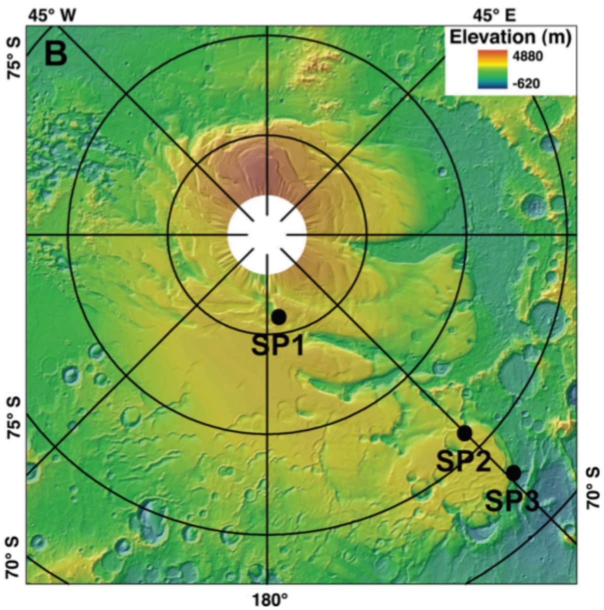


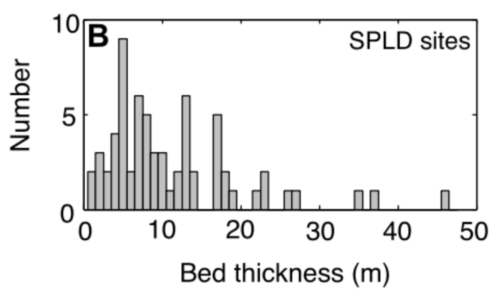


Inferred large-scale structure of the SPLD

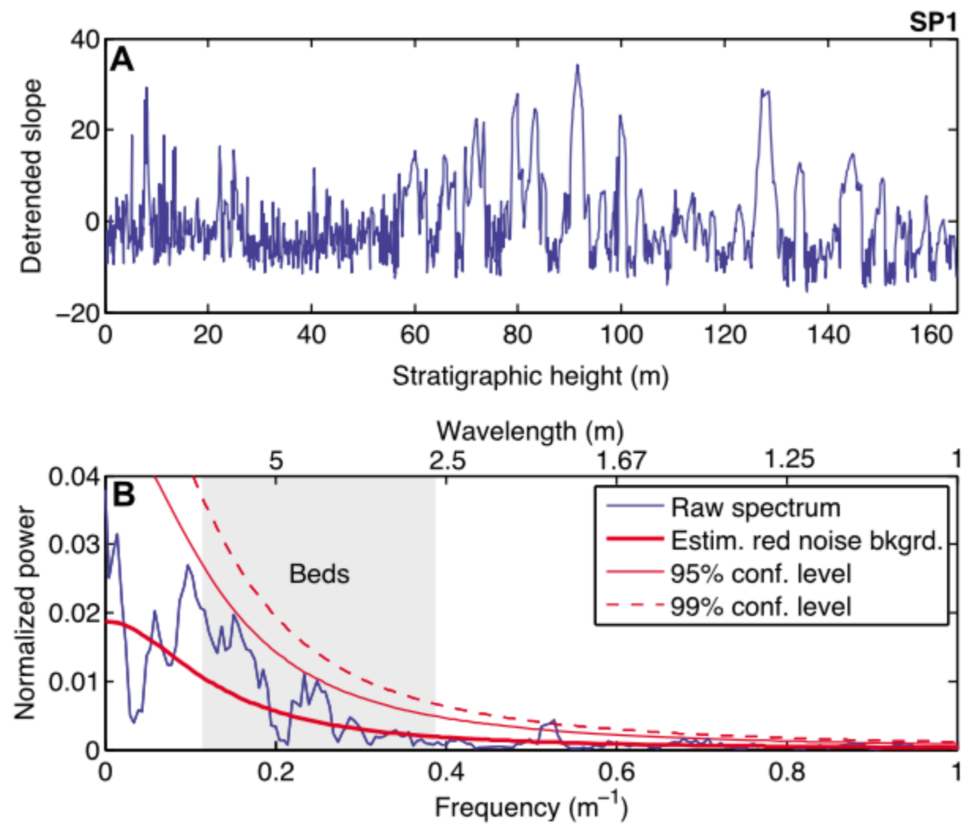
SPLD: Image-based periodicity analysis

Limaye et al. (2012) measured thicknesses of layers using HiRISE DTMs at three locations on the SPLD





High variability in bed thicknesses

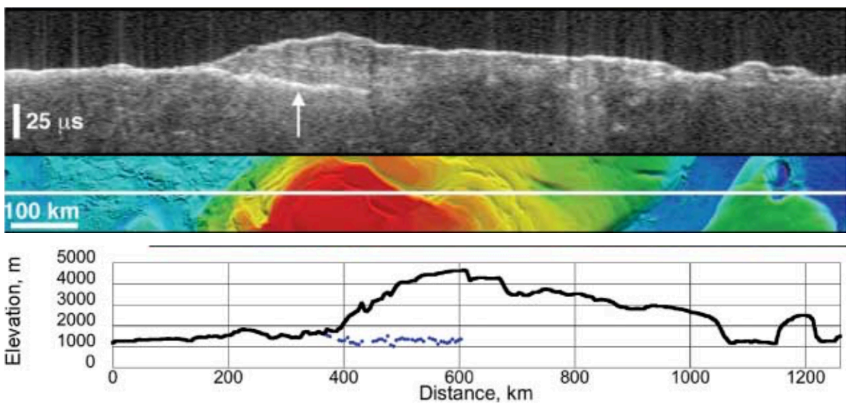


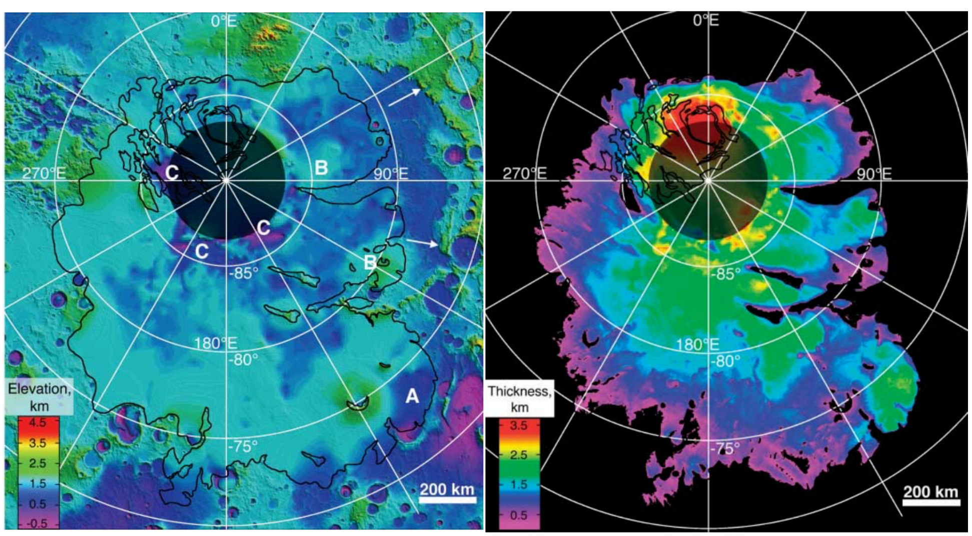
No statistically significant or consistent stratigraphic wavelength detected

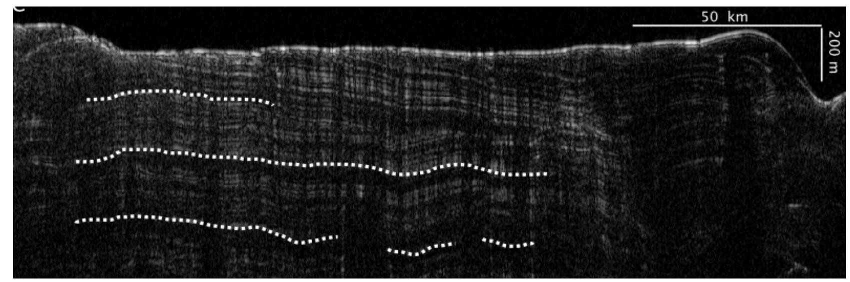
SPLD: Results from Radar

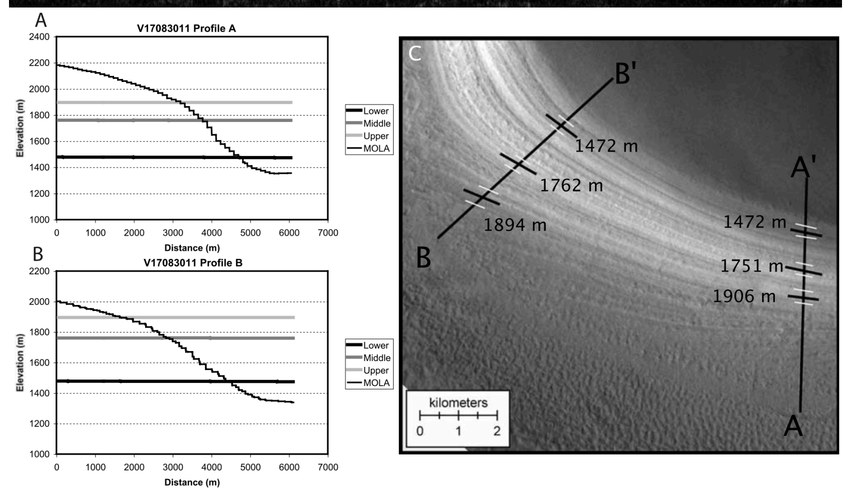
Plaut et al. (2007) used MARSIS to measure the thickness of the SPLD deposits

- Mapped base of SPLD (ε = 3)
- Calculated difference from MOLA topography









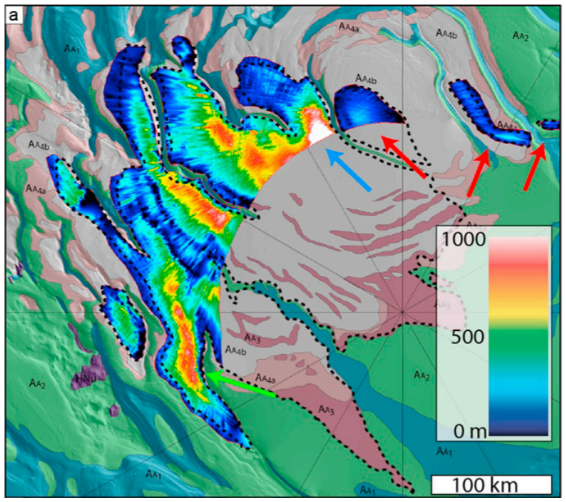
Milkovich et al. (2009) analysis of Promethei Lingula:

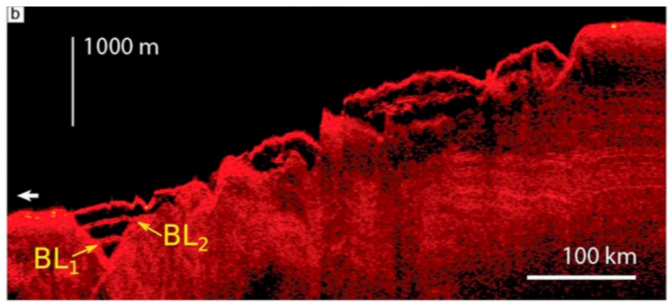
- Dark SHARAD bands correlate to MARSIS reflectors
  - High dusty to clean contrast?
- MARSIS reflectors correlate to groups of exposed layers in THEMIS

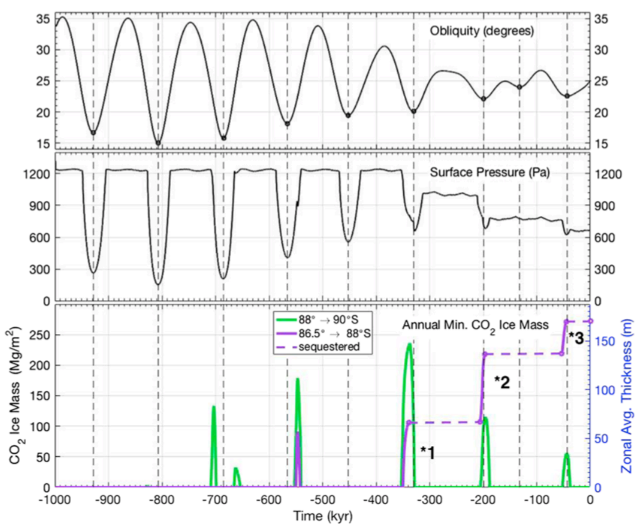
Evidence of a relationship between radar reflectors and exposed layers in the SPLD → dust/ice ratio?

SPLD: Radar detection of buried CO_2 units

Phillips et al. (2011) explored a SHARAD Reflection Free Zone (RFZ) under the SPRC → large deposits of buried CO_2 ice corresponding to unit AA_3 of Tanaka et al. (2007)

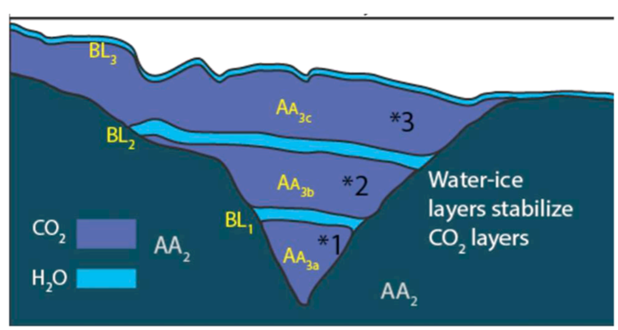


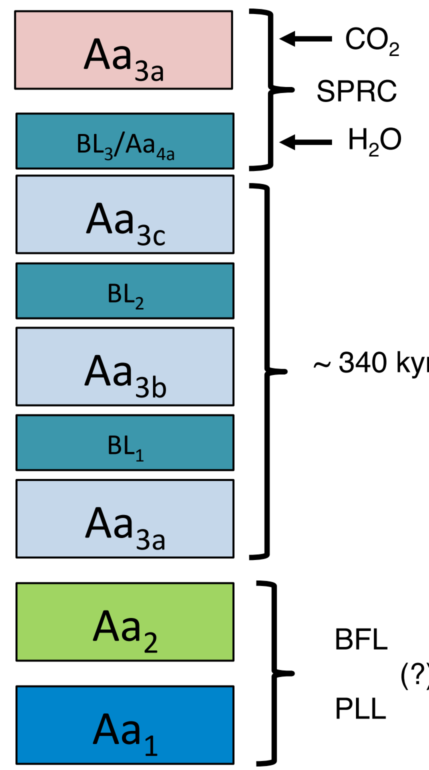


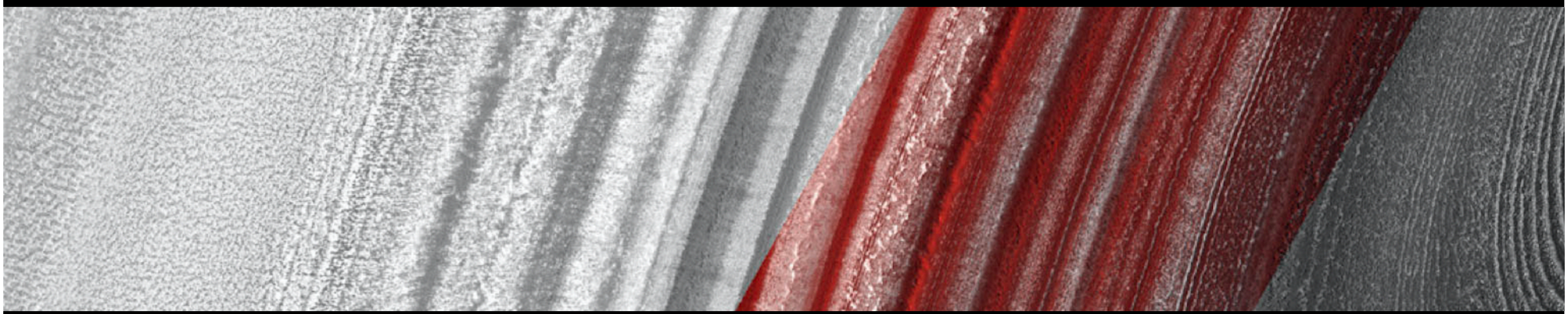


Further characterized by Bierson et al. (2016):

- 3 RFZ separated by water ice bounding layers (BL)
- Enough ice to double Mars' atmospheric pressure
- Modeling shows that CO2 ice can accumulate during low obliquity and that BL thickness is enough to sequester it



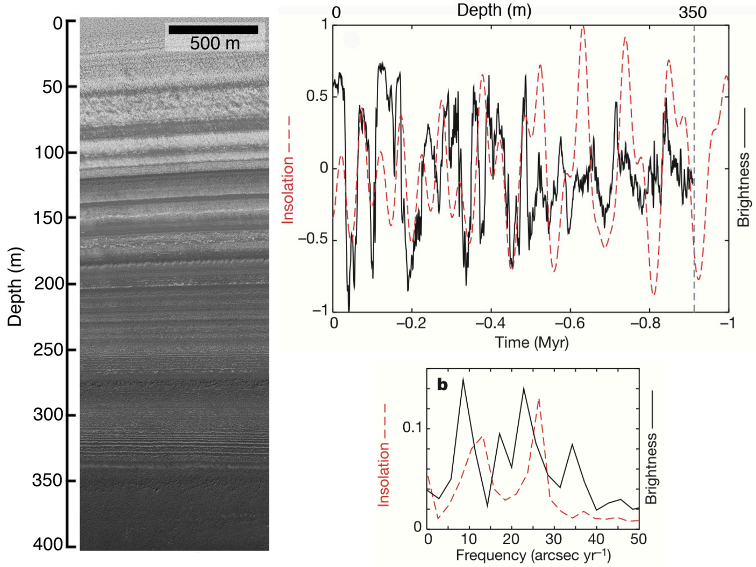




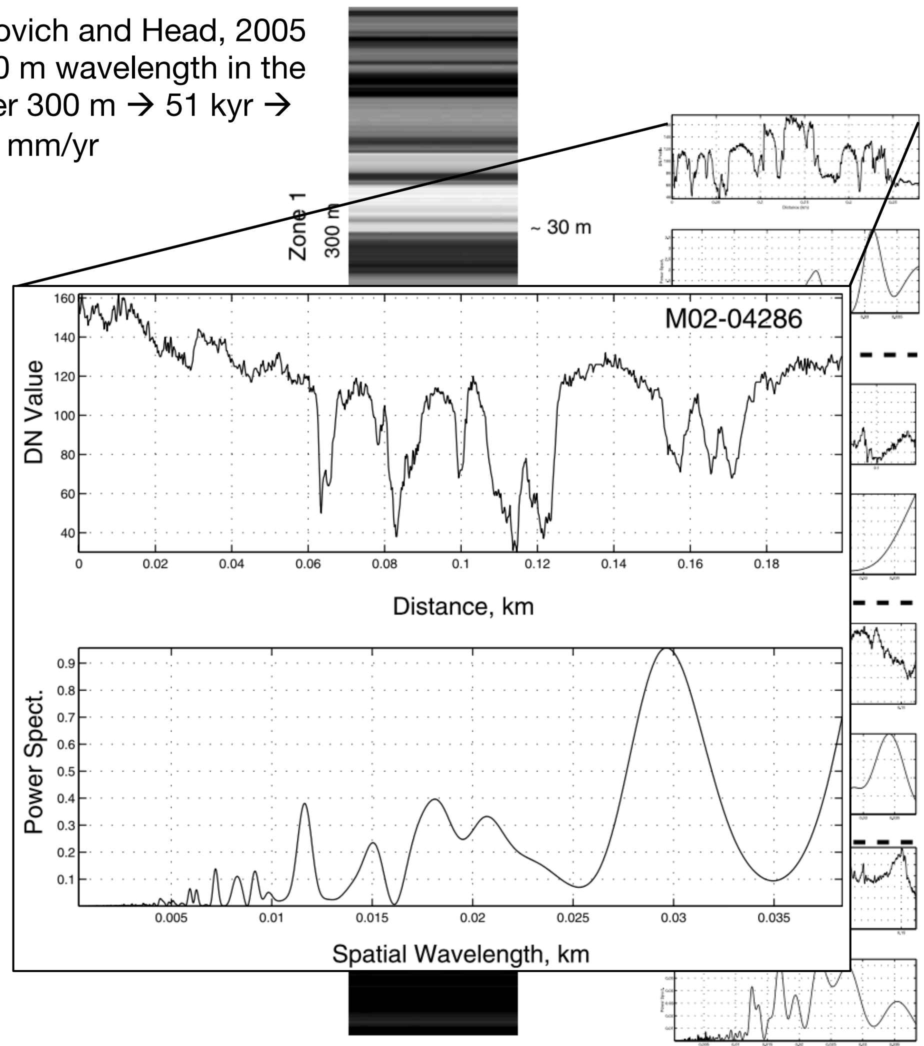
Stratigraphy of the NPLD

The search for an NPLD climate signal: Images

Laskar et al. (2002) compares 350 m of MOC brightness to insolation history → 51 kyr arg. of perihelion period → ~0.5 mm/yr



Milkovich and Head, 2005 → 30 m wavelength in the upper 300 m → 51 kyr → ~0.5 mm/yr



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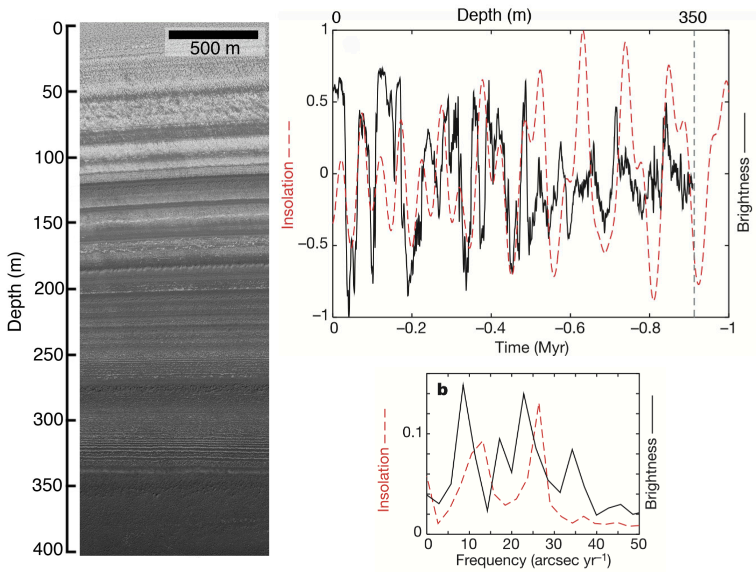
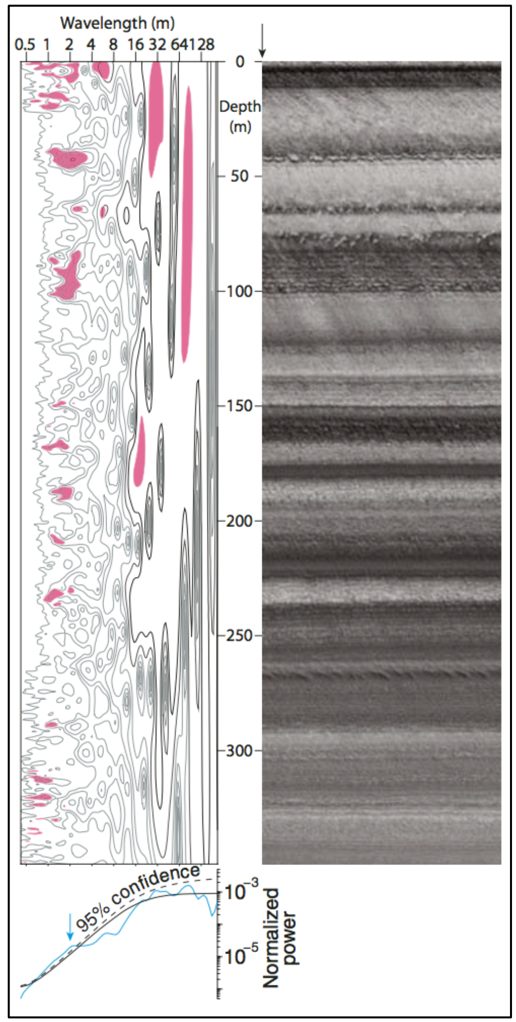
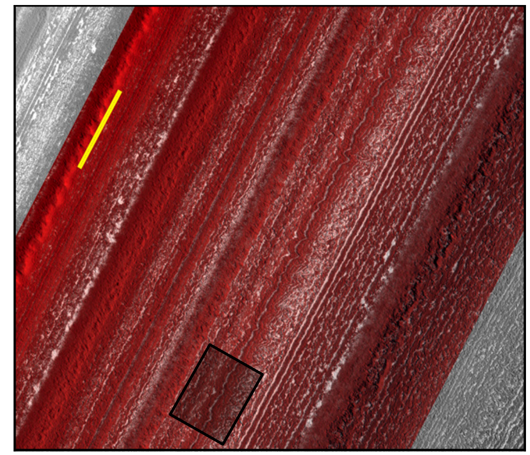


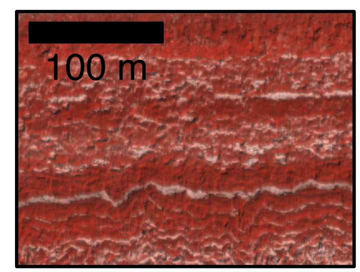
Perron and Huybers (2009) wavelet analysis on MOC → No 30 m periodicity but 1.6 m found

…but brightness is affected by slope, frost retention, surface texture, sublimation lag, etc. (Herkenhoff et al. 2007)

and w/out an absolute chronology, peak-to-peak correlations are suspect

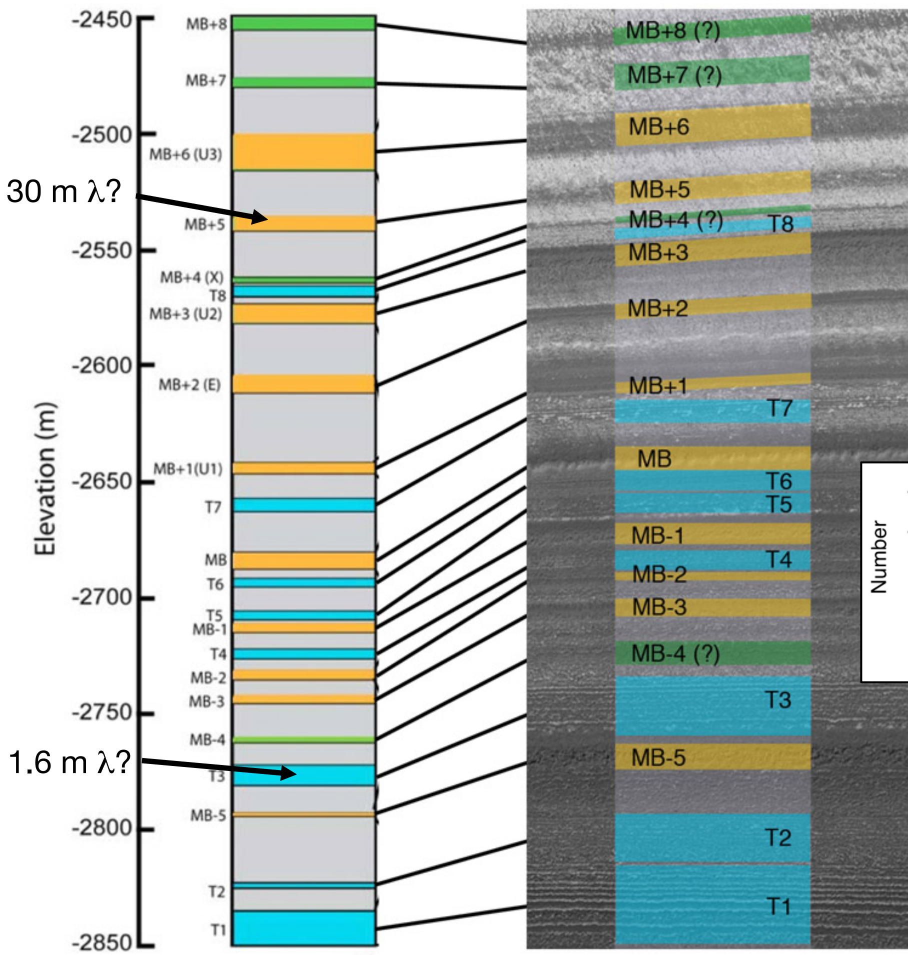


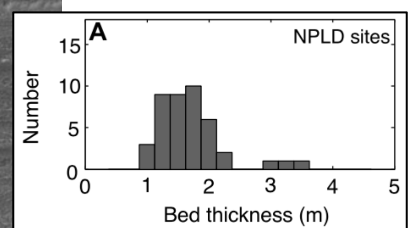


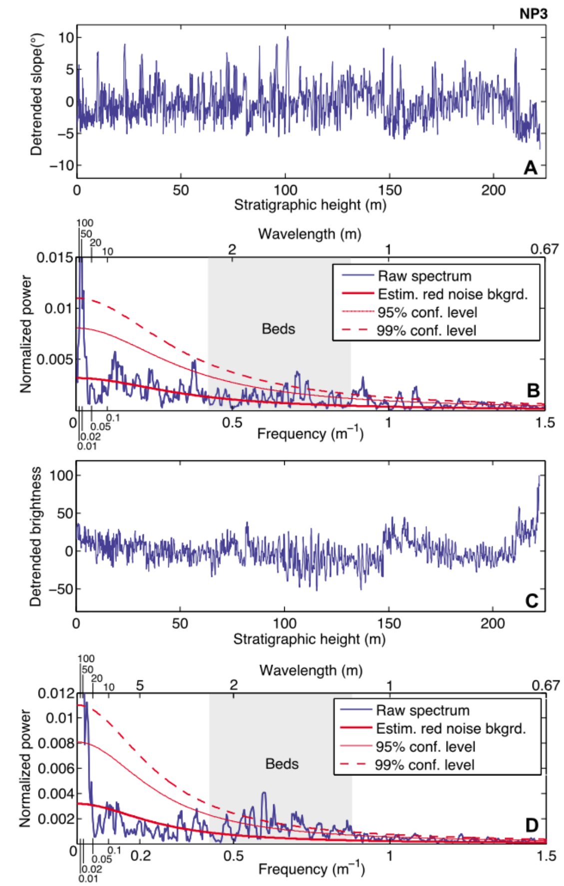


NPLD: Topography-based correlations

HiRISE Stereo allowed layer-scale topographic measurements → First layer-scale stratigraphic column of Fishbaugh et al. (2010)





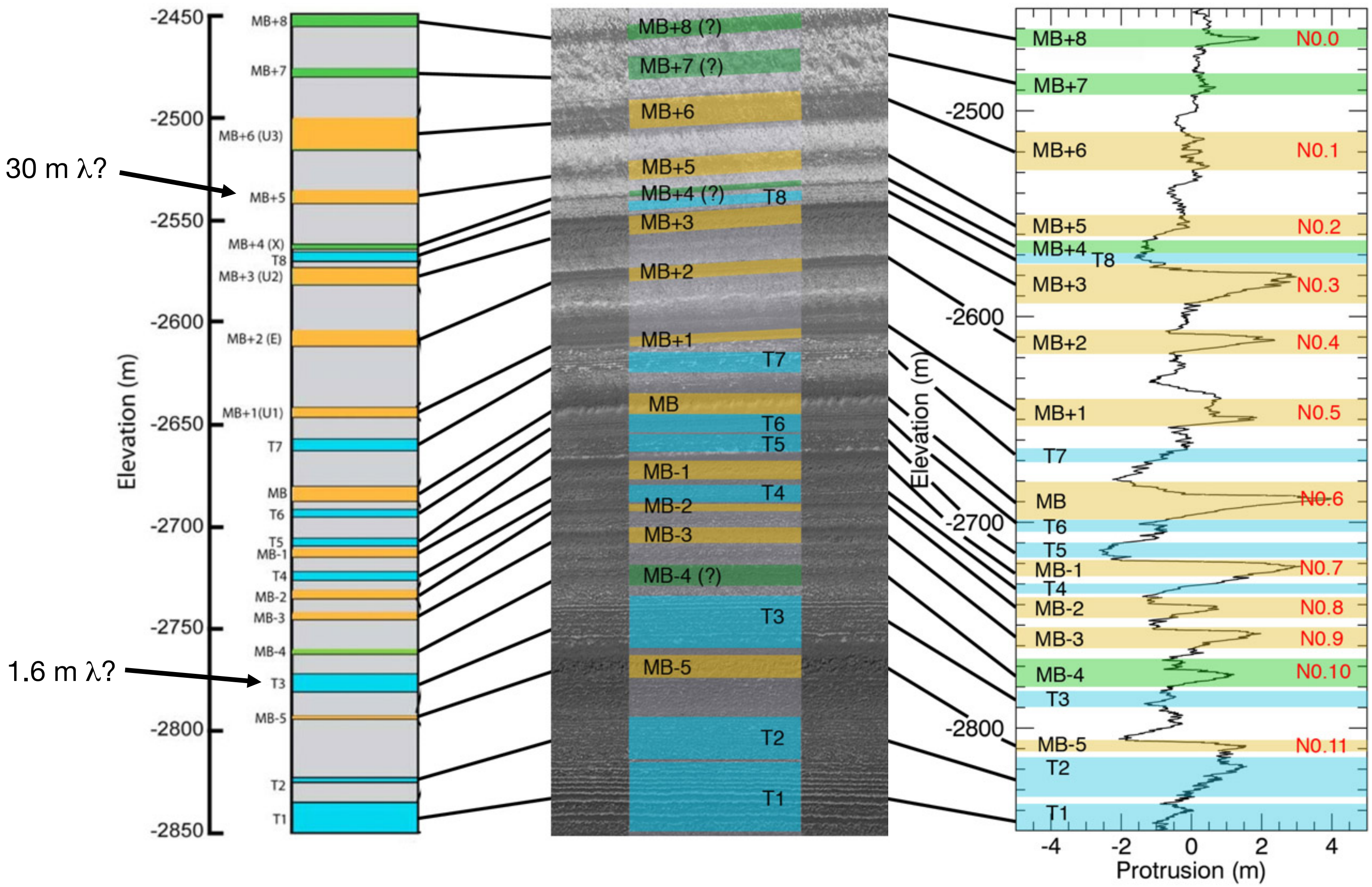


Limaye et al. (2012) confirms 1.6 m λ with thickness measurements and FFT

Observe relationship between thickness and brightness patterns

NPLD: Topography-based correlations

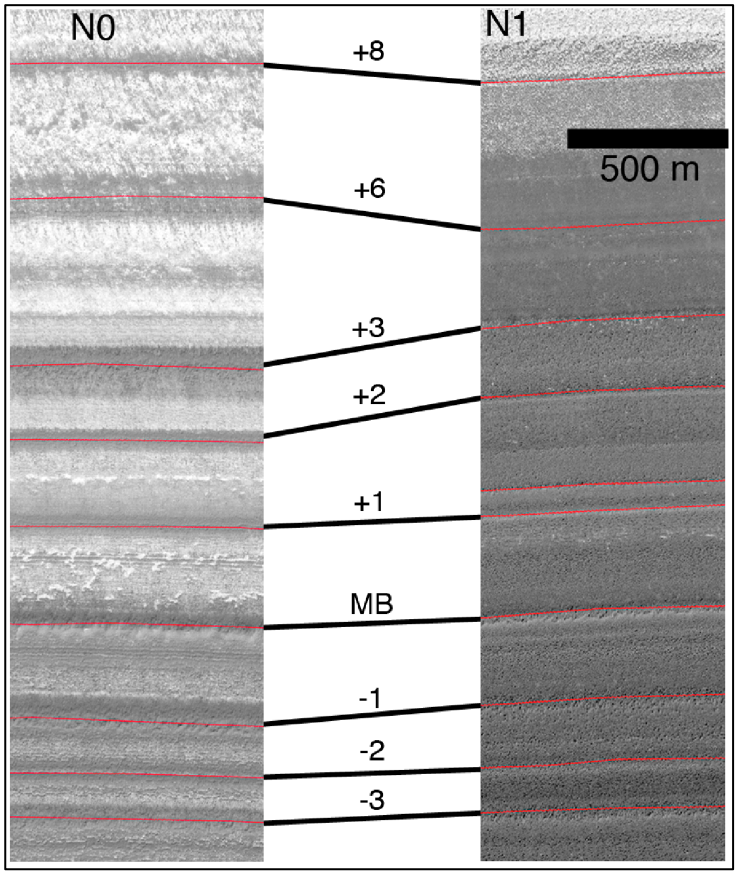
HiRISE Stereo allowed layer-scale topographic measurements →
First layer-scale stratigraphic column of Fishbaugh et al. (2010)

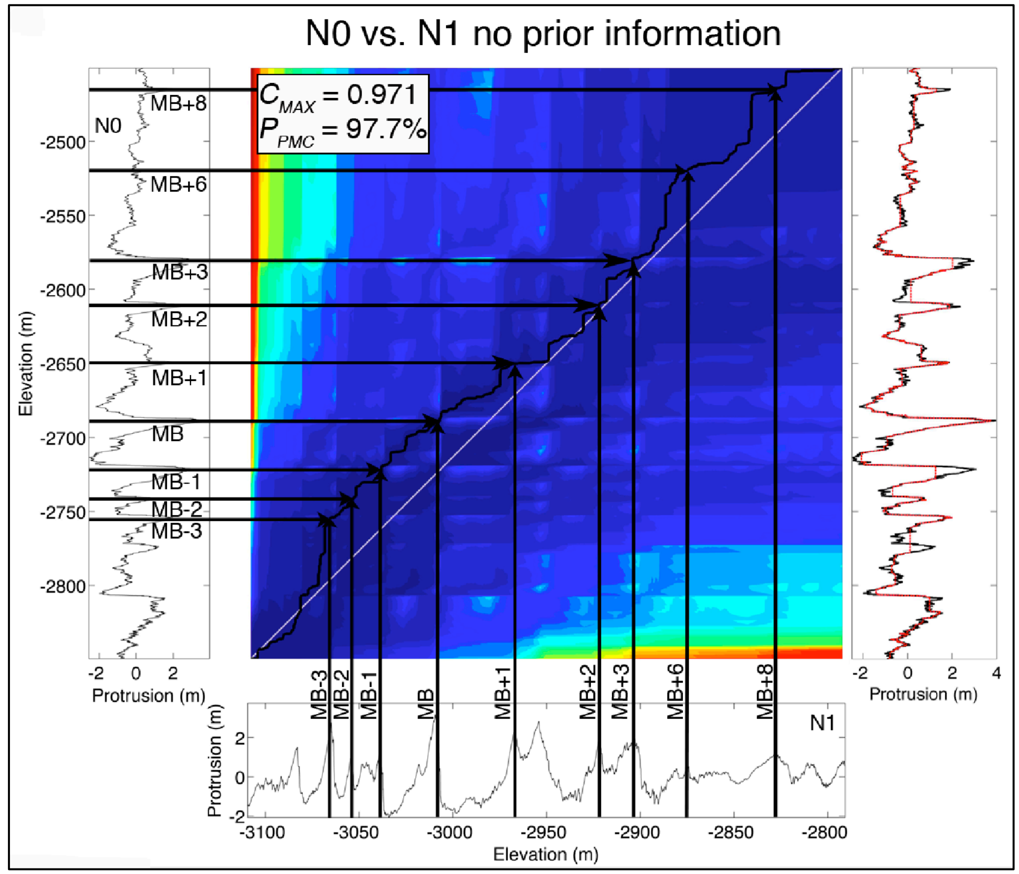


Becerra et al. (2016) correlate layer protrusion at this site to the Fishbaugh column…

NPLD: Topography-based correlations

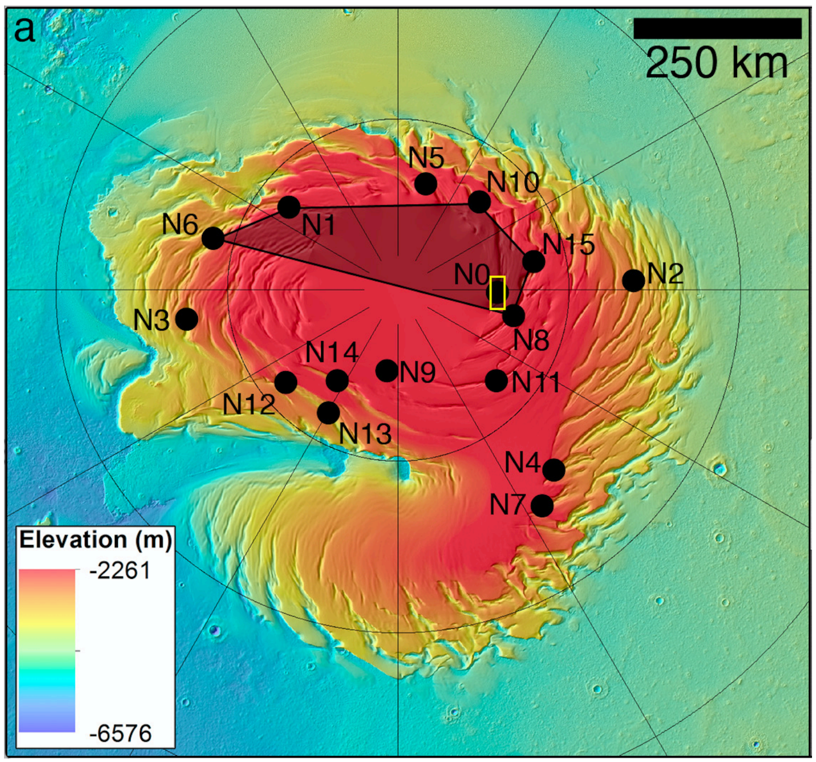
…and use DTW to correlate many sites to each other

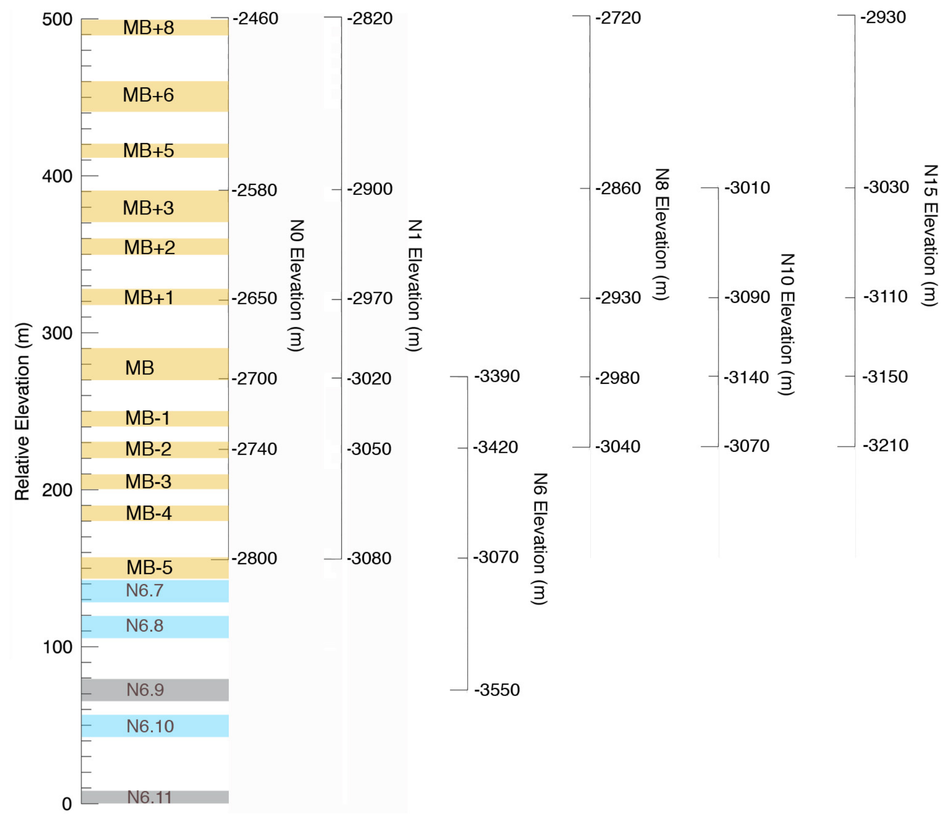




NPLD: Topography-based correlations

- Five sites were reliably correlated to site N0 of the Fishbaugh et al. (2010) column
- These sites share all or part of the Fishbaugh et al. sequence of layers that we call the Main Sequence
- Valid for at least 7% of the area of the NPLD

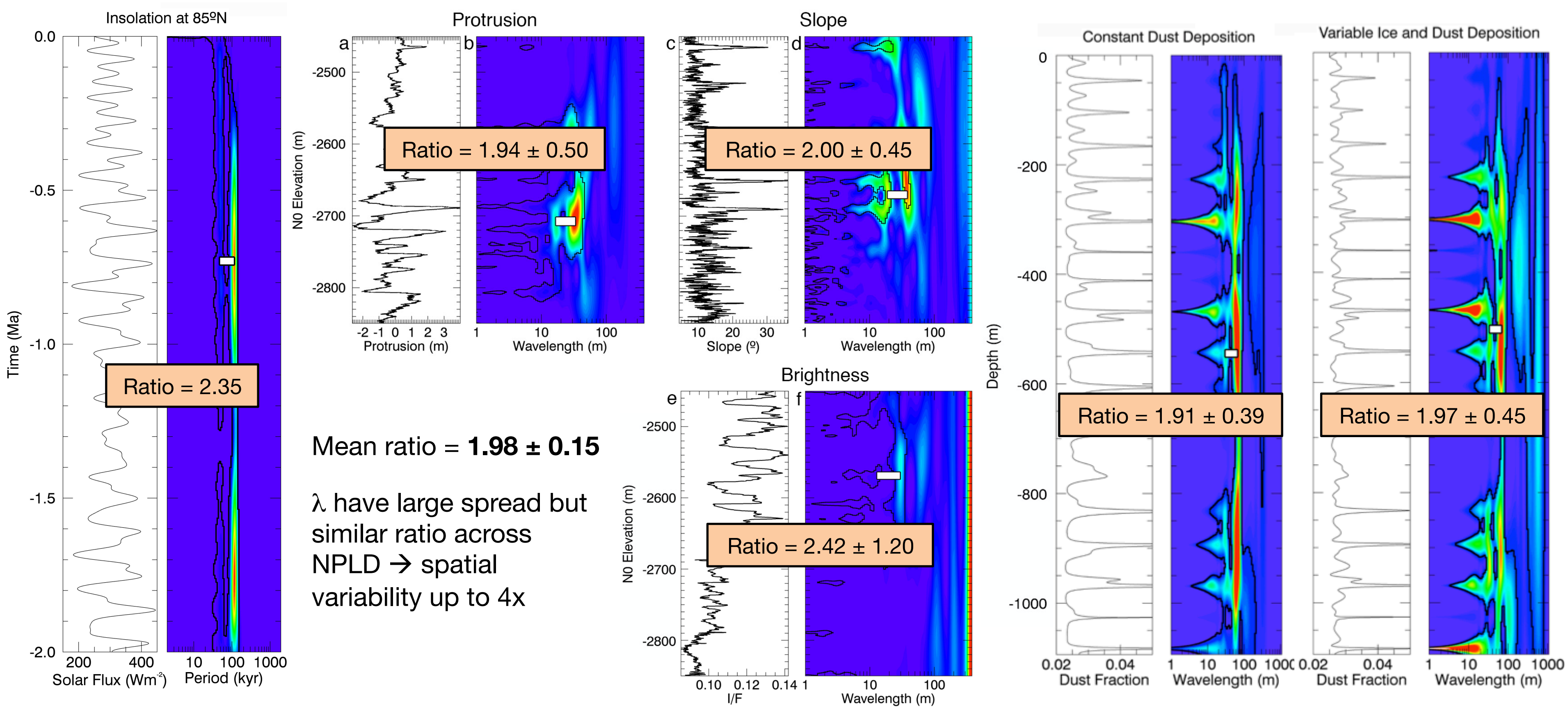




NPLD: Wavelet analysis of high-res imaging

No absolute chronology → Best to compare ratios of wavelengths diagnostic of known insolation periodicities

Becerra et al. (2017) finds a common ratio of wavelengths systematically lower than the characteristic wavelengths of insolation → Simulated stratigraphy with accumulation model of Hvidberg et al. (2012) results in a similar ratio



Mean ratio = **1.98 ± 0.15**

λ have large spread but similar ratio across NPLD → spatial variability up to 4x

Mean accum. rates 0.54 mm/yr → Assuming 0 yrs at the surface N0 ~ 215 ka – 960 ka

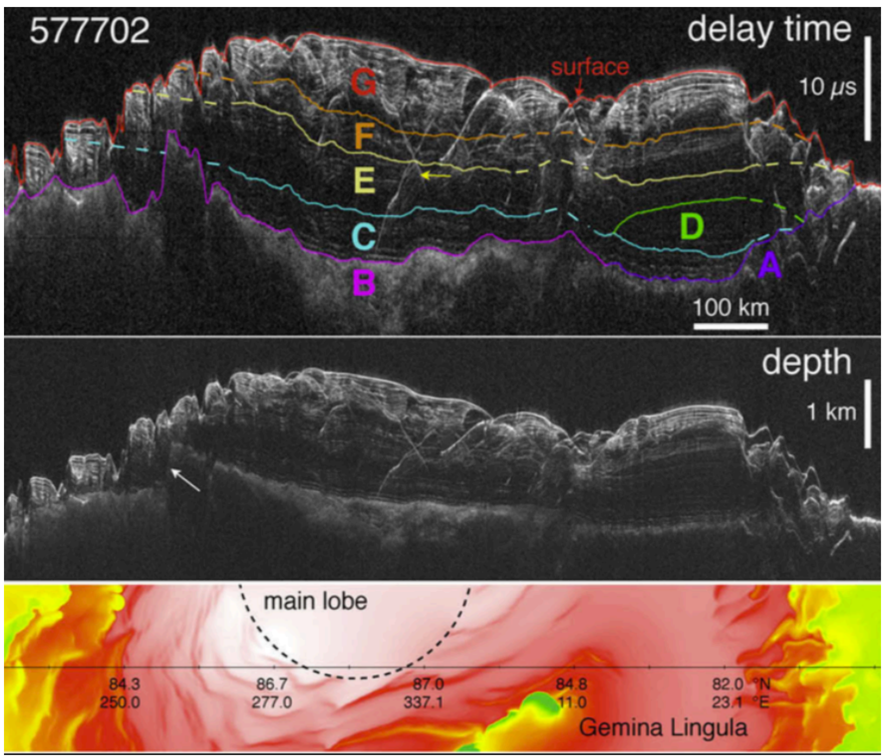
NPLD: Radar-based subsurface structure

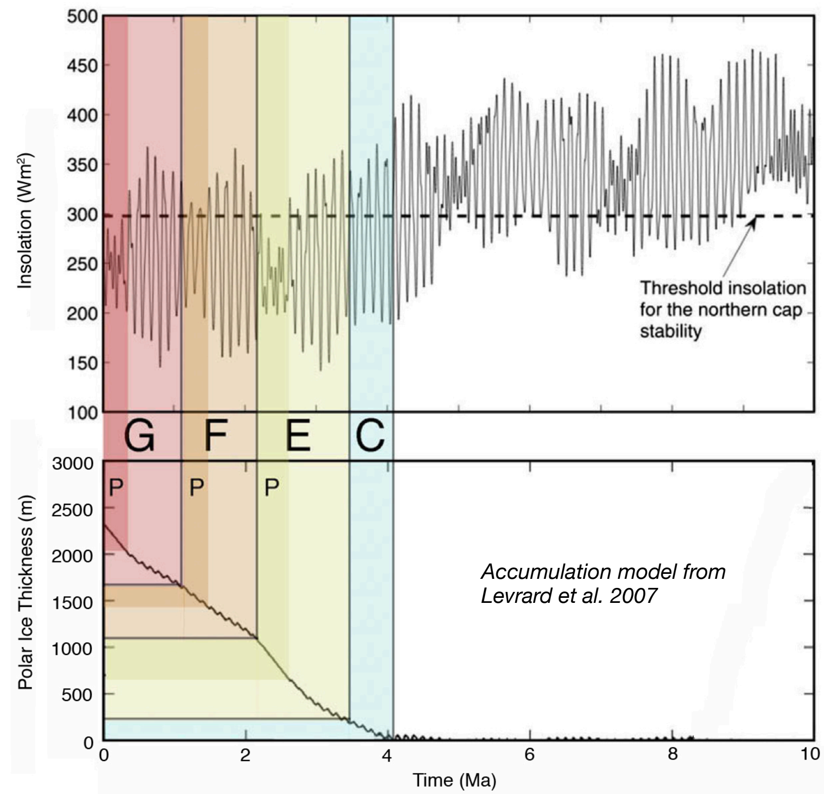
Putzig et al. (2009) mapped 5 units of packet-interpacket zones down to the base of the NPLD.

- Coverage and conformable geometry of units implies uniform accumulation
- Except for Unit D

- Interpacket = low amplitude insolation oscillation
- Packet = high amplitude variations

→ Packet reflectors are driven by dust content changes during periods of high ice accumulation



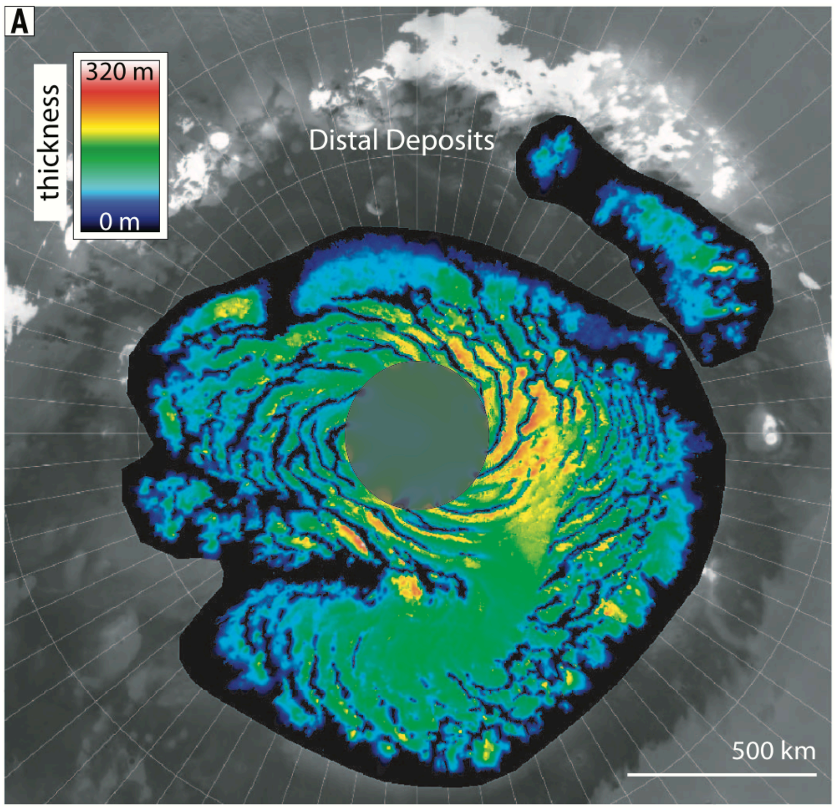


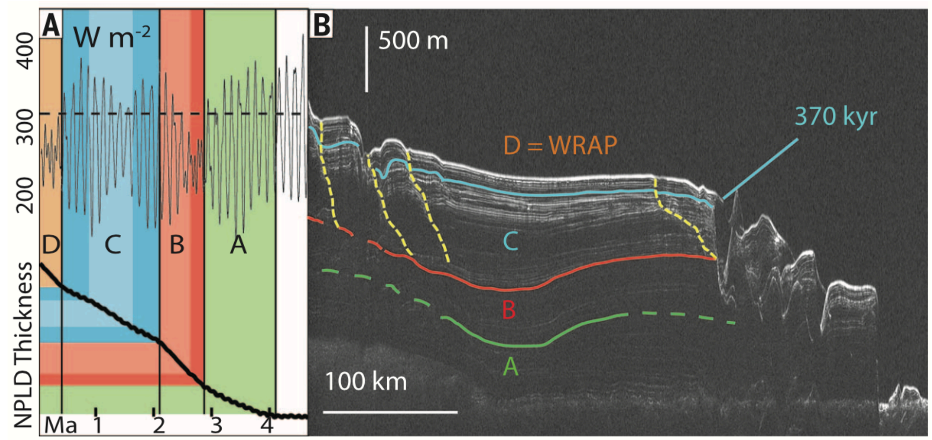
The detail shown by the SHARAD dataset was crucial to understanding the formation of Chasma Boreale and the spiral troughs (Holt et al. 2010, Smith and Holt, 2010. Previous talk)

NPLD: Recent Ice Age and the WRAP layer

Smith et al. (2016) mapped the Widespread Recent Accumulation Package (WRAP) based on changing SHARAD reflector properties throughout the extent of the NPLD

- Minimum thickness = 0 m (exposed unconformity). Maximum thickness = 320 m
- Matches end of last Martian ice age (~370 ka) → lots of ice would have been transferred to the poles from lower latitudes (rapid accumulation) after a period of the opposite (erosion → ice age)





Buried troughs, changing undulation patterns
→ period of erosion followed by increased accumulation
→ end of an ice age

Dataset correlation and Future Directions

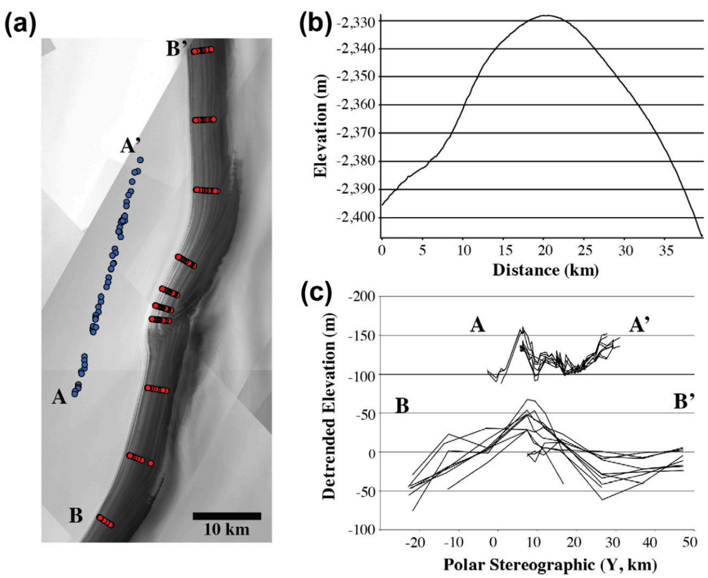
Potential correlation of datasets

Radar and visible often treated separately

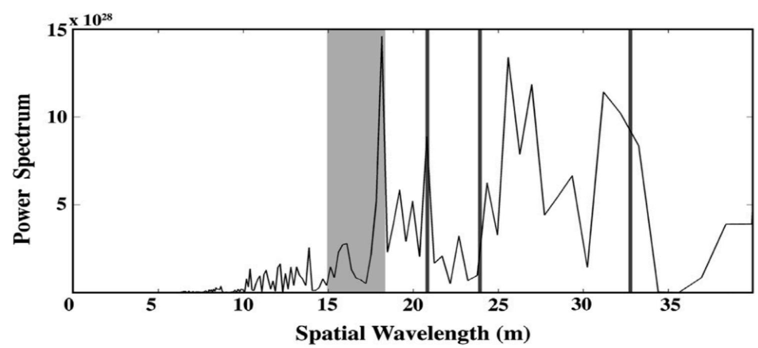
→ no complete picture of the relationship between NPLD and orbital forcing (let alone the SPLD)

Reminiscent of terrestrial climate science issues: orbital climate forcing ultimately confirmed by correlation of sedimentary, geochemical and paleomagnetic records

GOAL: Combination and correlation of optical data with radar data to inform modeling



Milkovich and Head, 2005 wavelengths



Christian et al. (2013): First quantitative attempt to correlate SHARAD reflectors to individual layer outcrops:

- Agreement between the topographic (similar long-wavelength topography) and spectral (30 m λ) properties of reflectors and exposed layers
- One-to-one reflector to layer/packet correlation not possible due to lack of coverage at the time and geometric issues

Potential correlation of datasets

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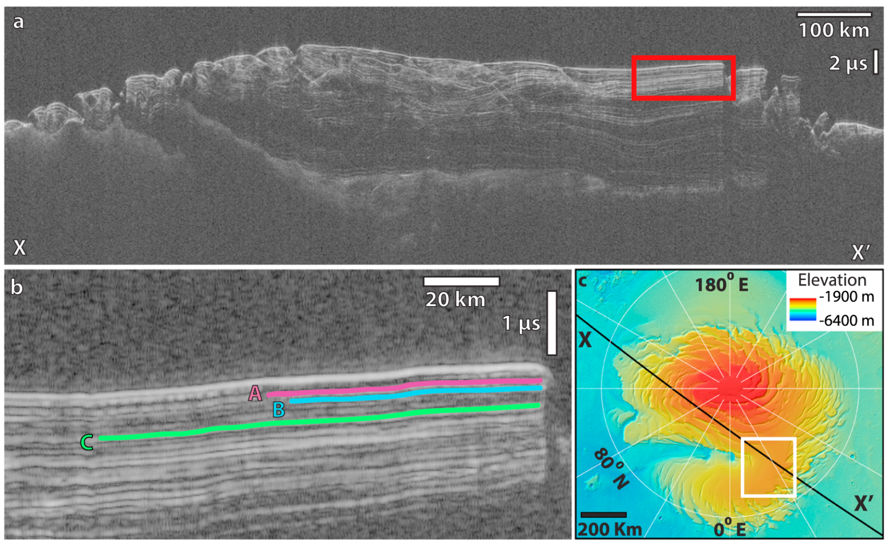
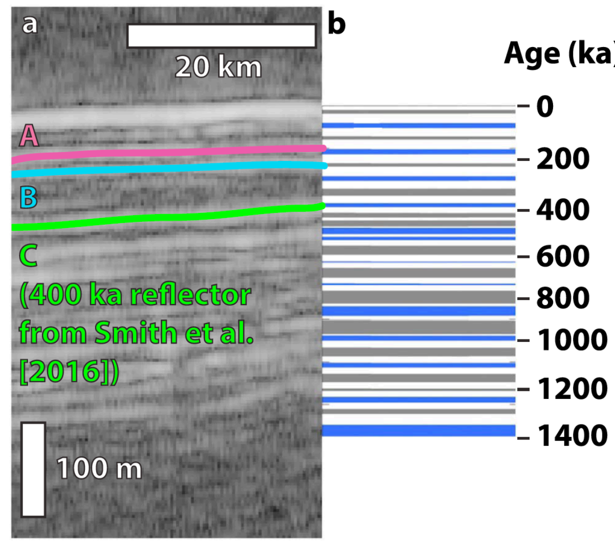


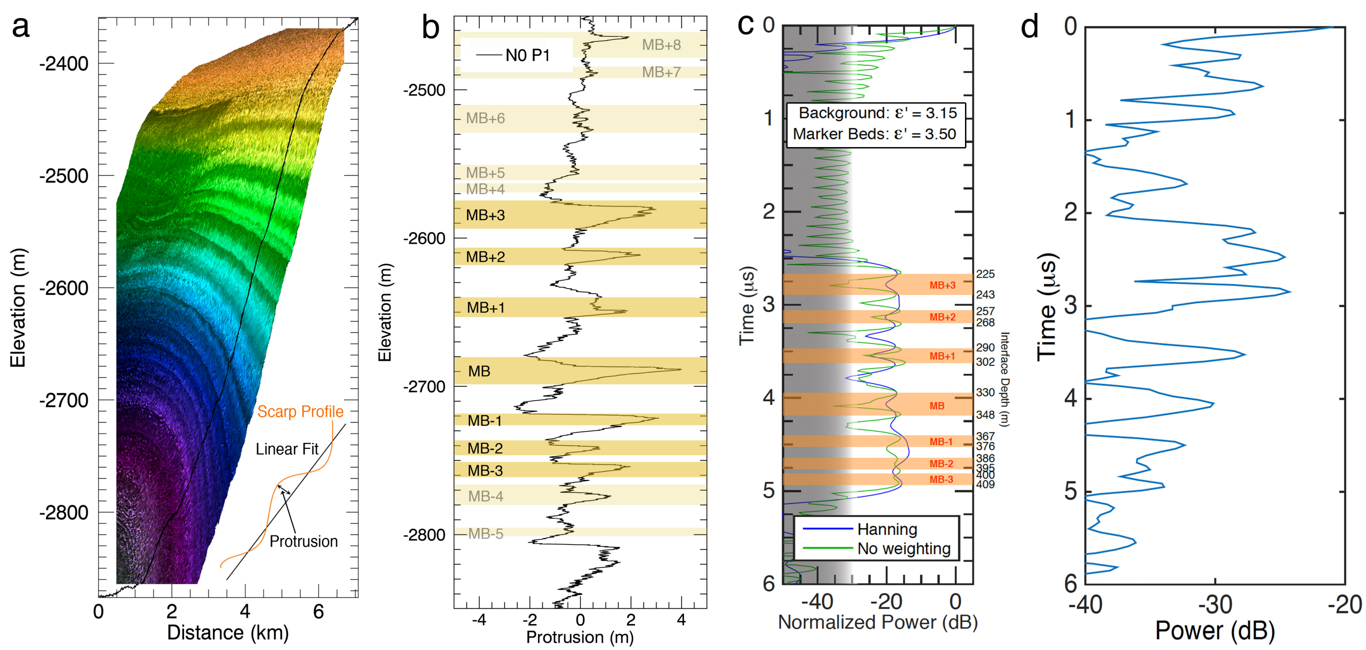


Lalich et al (2017): Tested hypothesis that reflectors are caused by erosionally resistant Marker beds

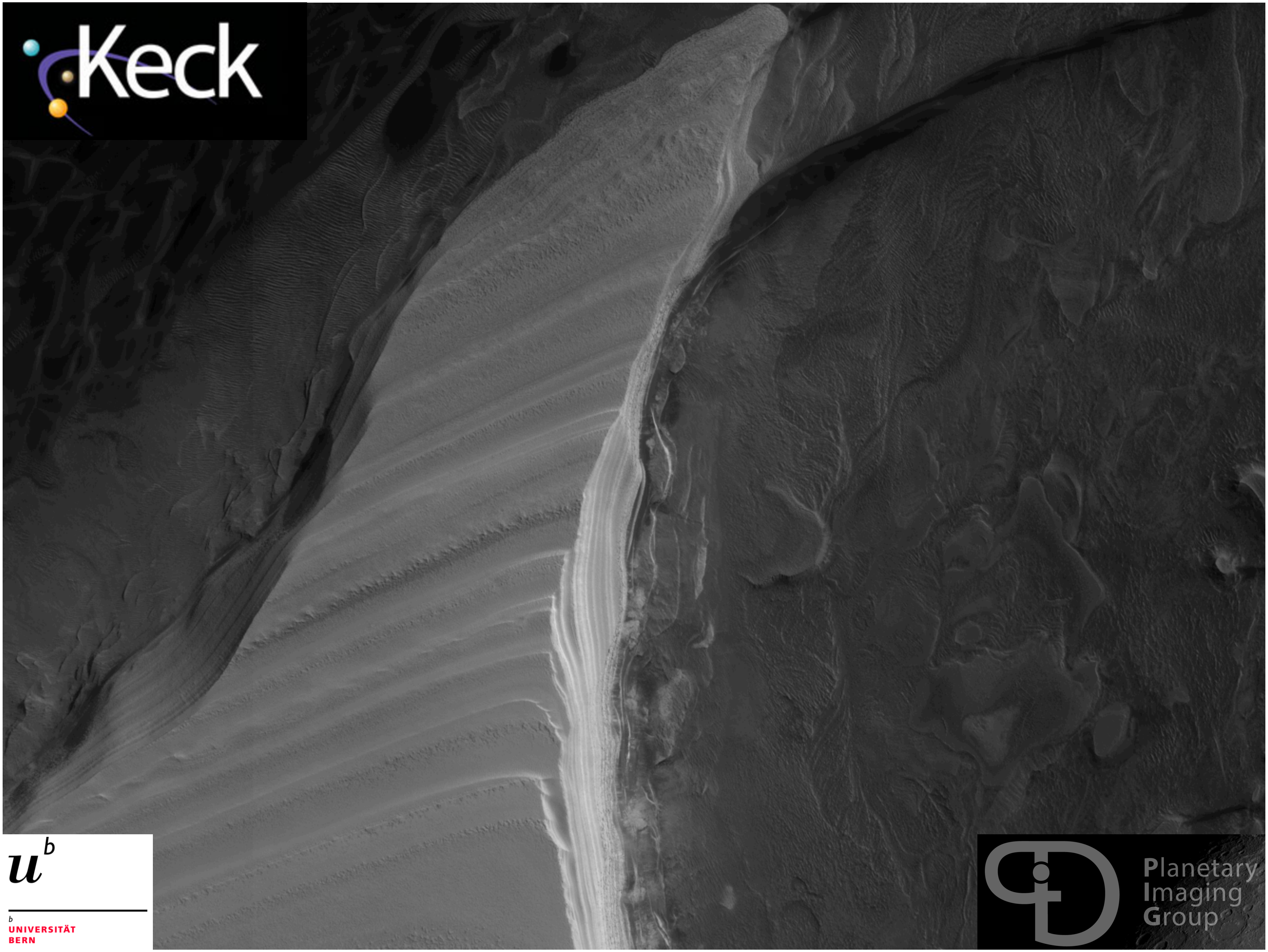
- Bed thickness more likely to cause variations in reflectivity
  → radargrams can inform on relative accumulation rates
- Correlation between reflectors and modeled Marker beds (Hvidberg et al. 2012), but dust content/accumulation rates probably underestimated

Future efforts

Use radar propagation modeling (Nunes and Phillips, 2006) to simulate radar signal through a permittivity profile constrained by HiRISE topography → compare to real radargram with spectral and signal-matching techniques



- Current goal is to obtain a dust/ice ratio stratigraphic column that describes the whole cap to input into orbital-based accumulation models
- In the future, samples would be ideal. Isotopic variation measurements, and we may learn about recent volcanic events or large ejecta blankets that intersect with our location
- Improve analysis on SPLD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