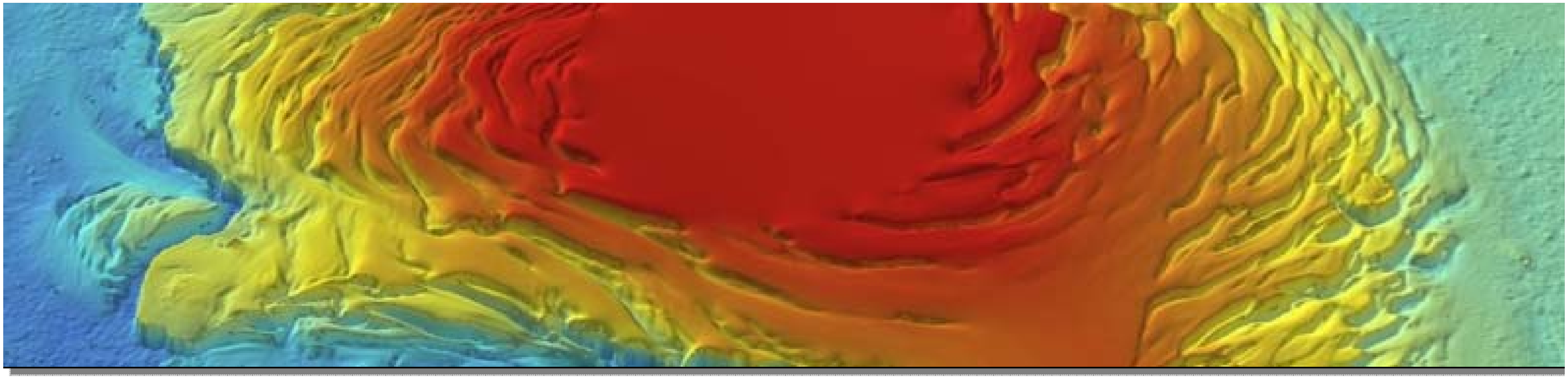
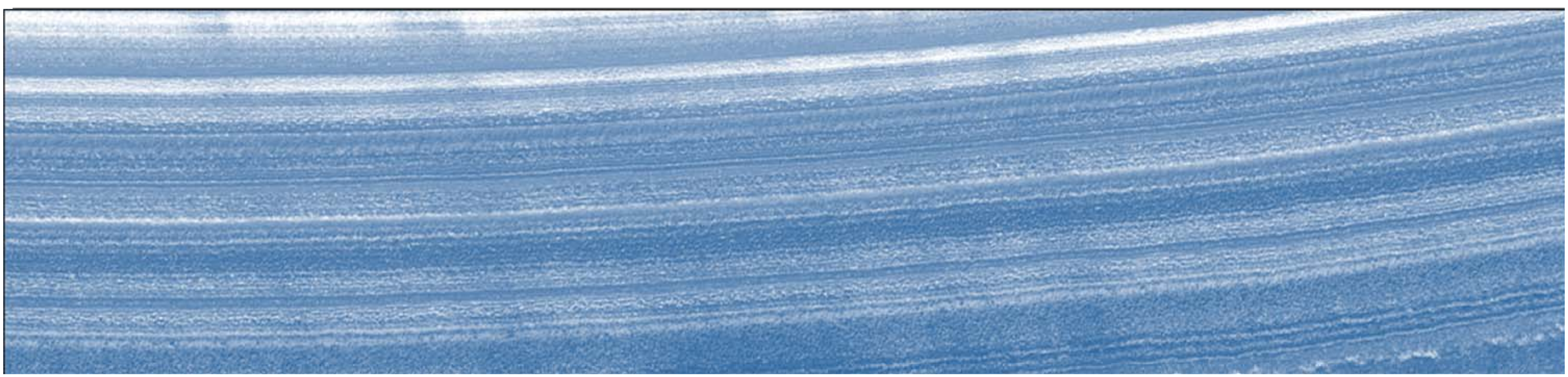


Overview of polar stratigraphy

Taylor Perron

MIT

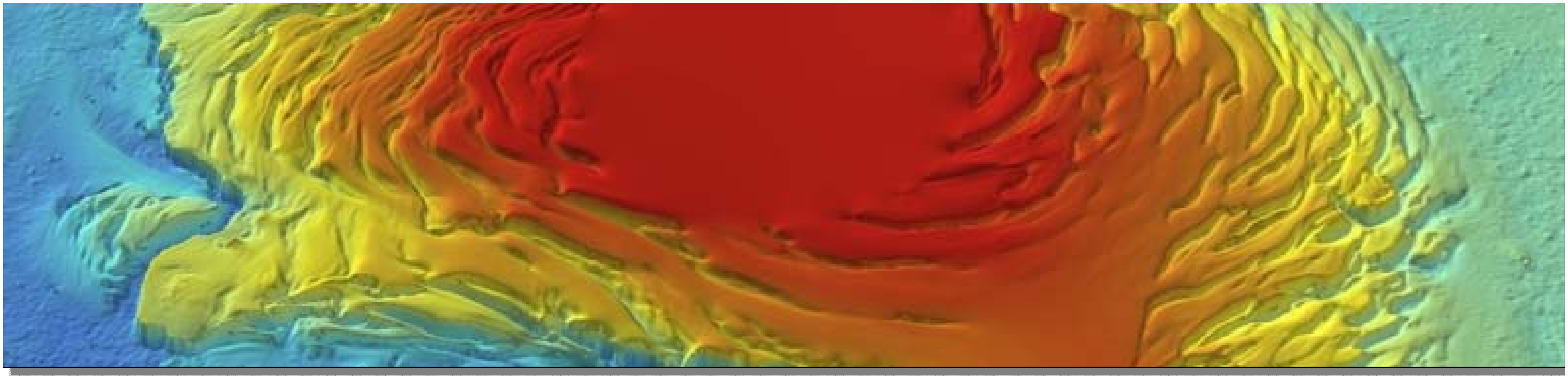


Summarize quantitative understanding of:

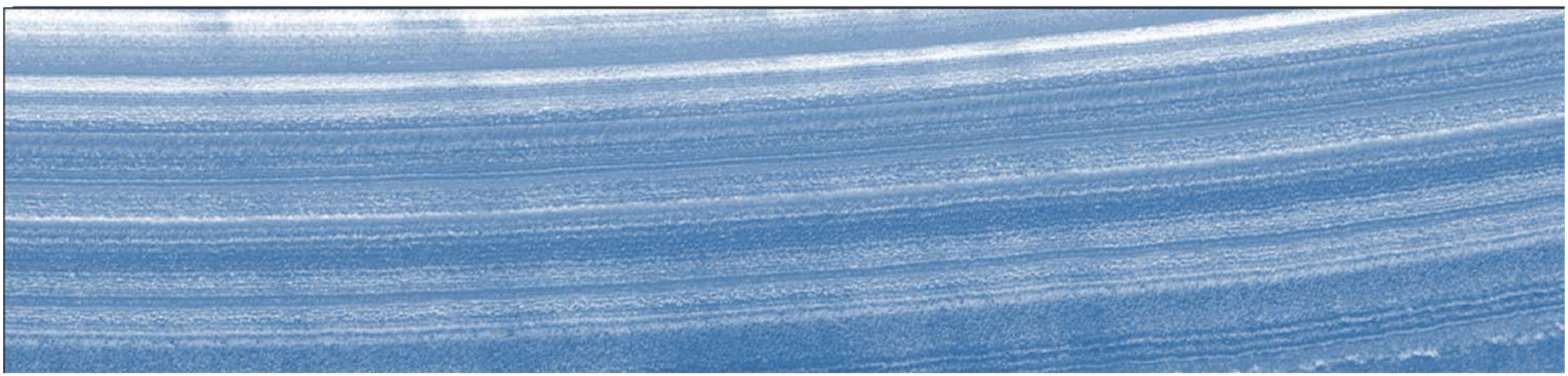
- Processes recorded by polar stratigraphy
- Rates of these processes
- Age of stratigraphic sequences

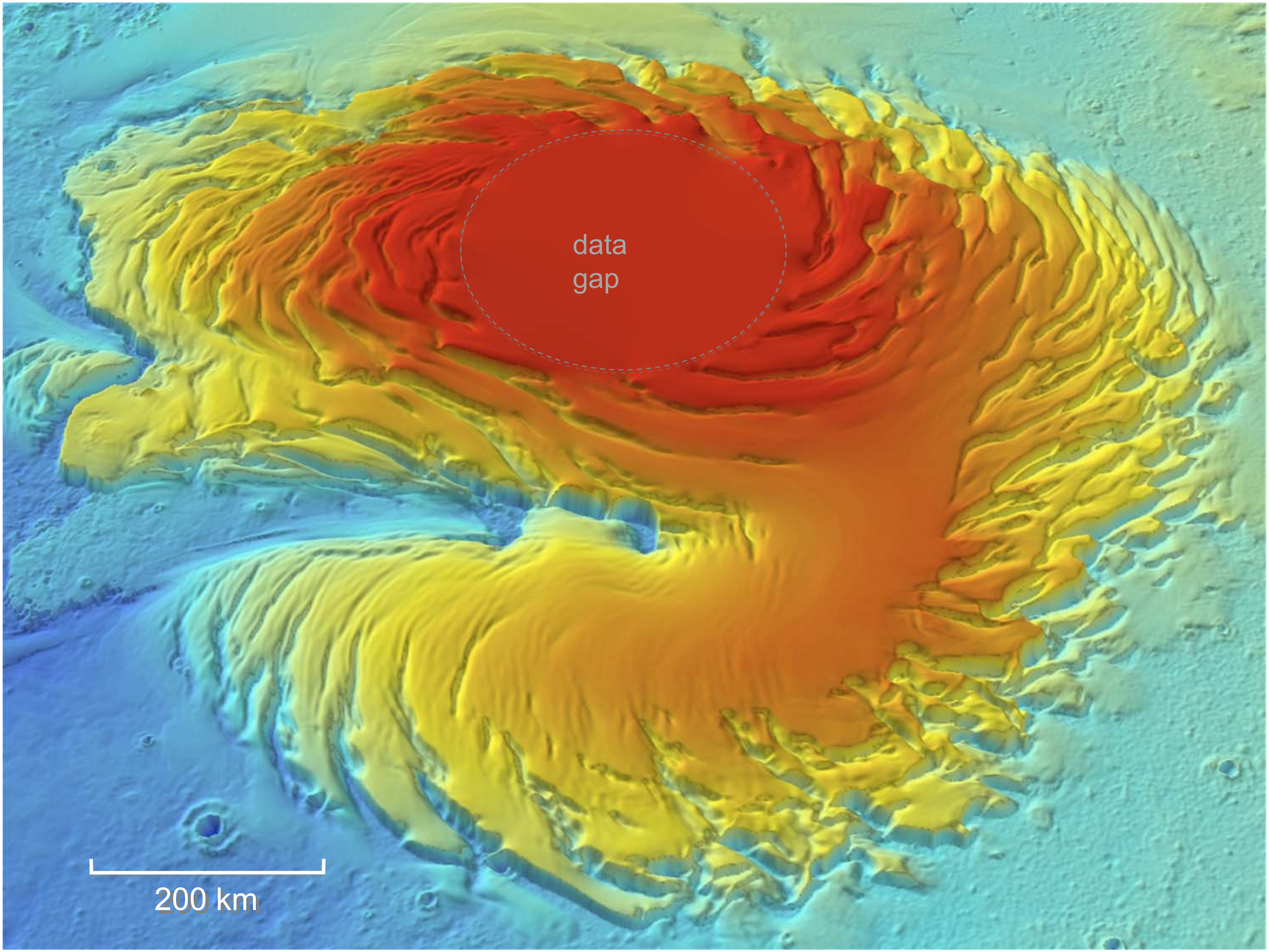
Outline

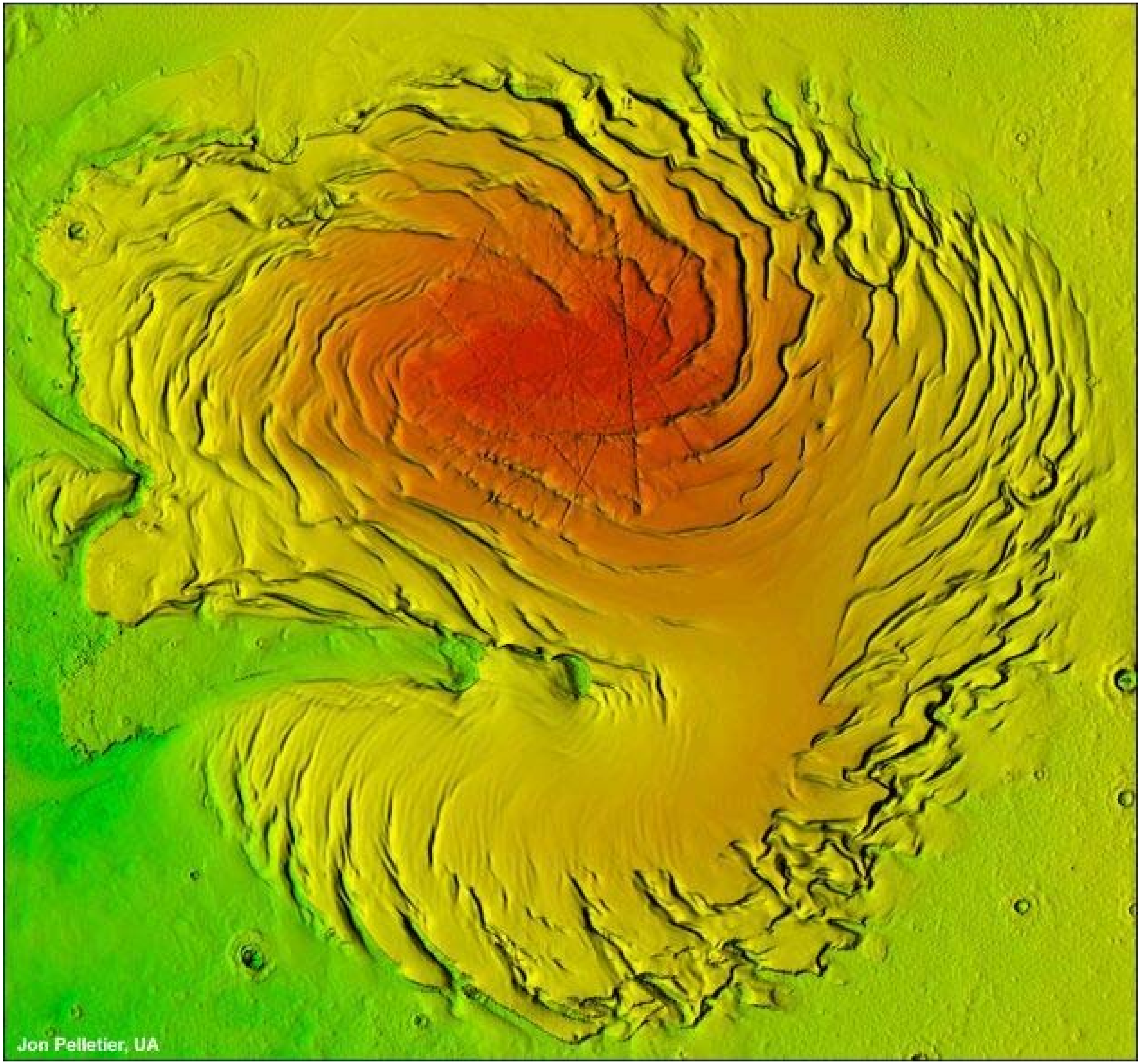
- Background
  - The basics
  - Recent discoveries
  - Ongoing debates
- Prospects for future missions
  - Key questions
  - Critical measurements
  - Biggest opportunities
  - Biggest challenges

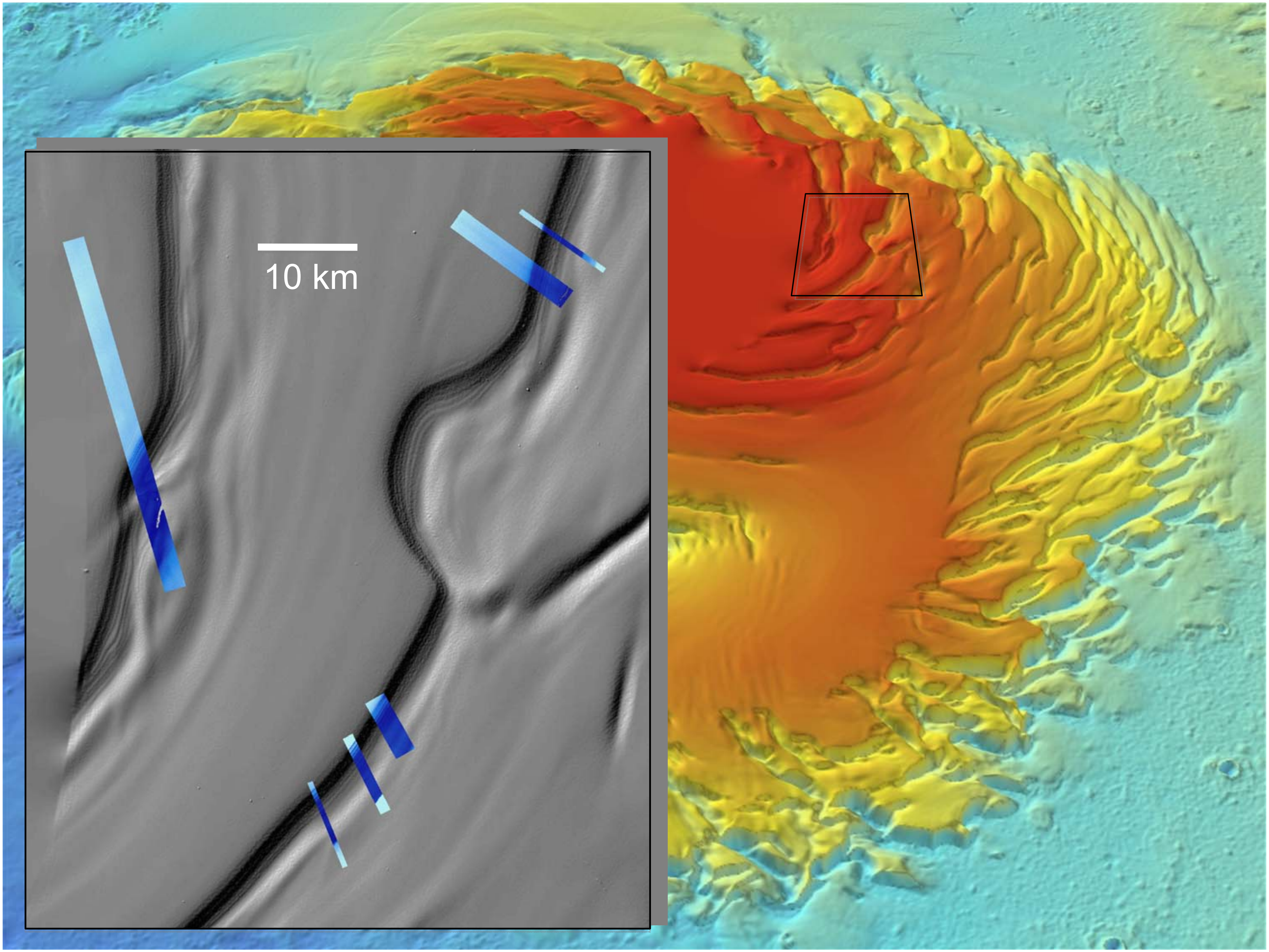


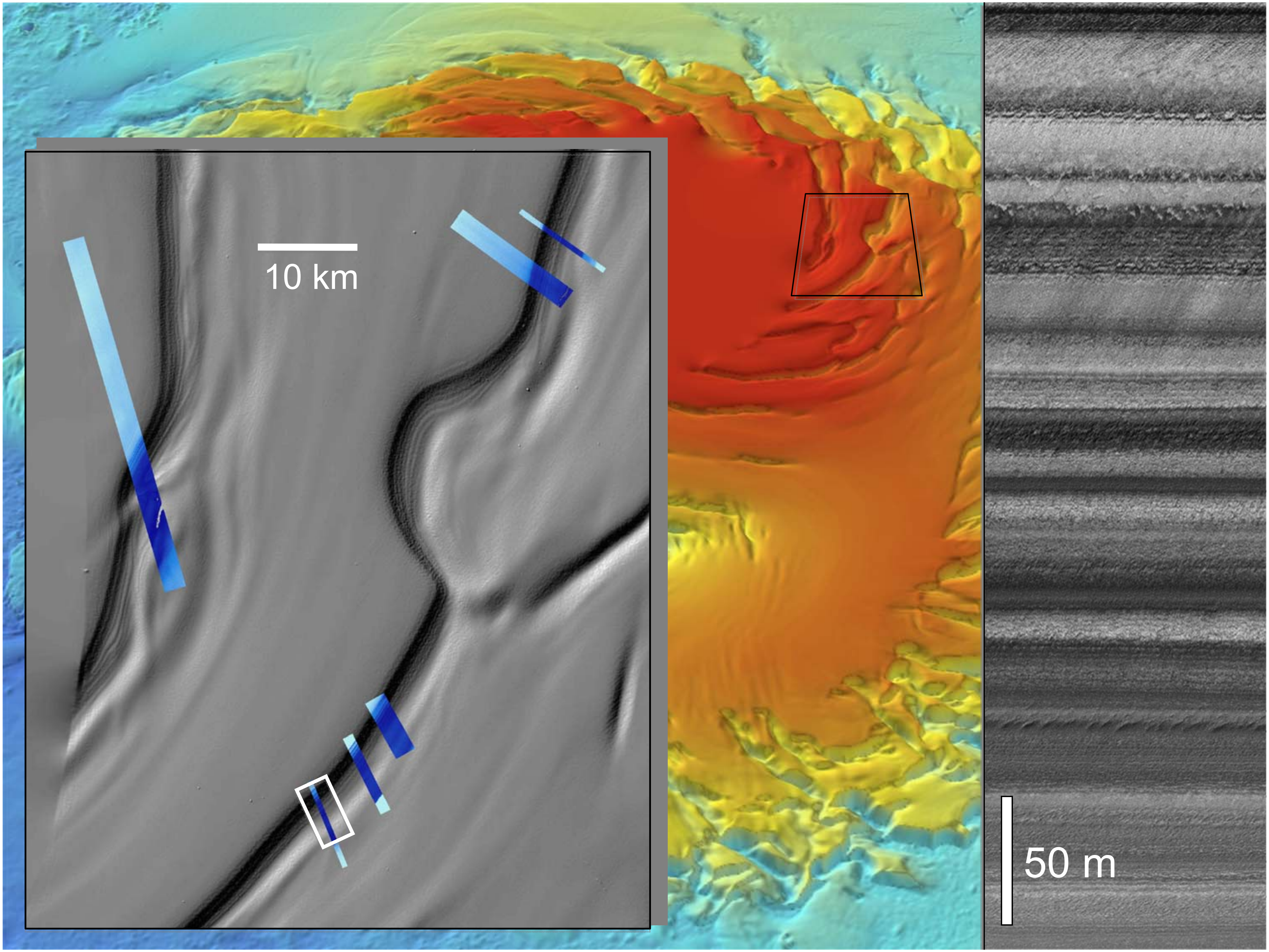
Basics




data
gap
200 km

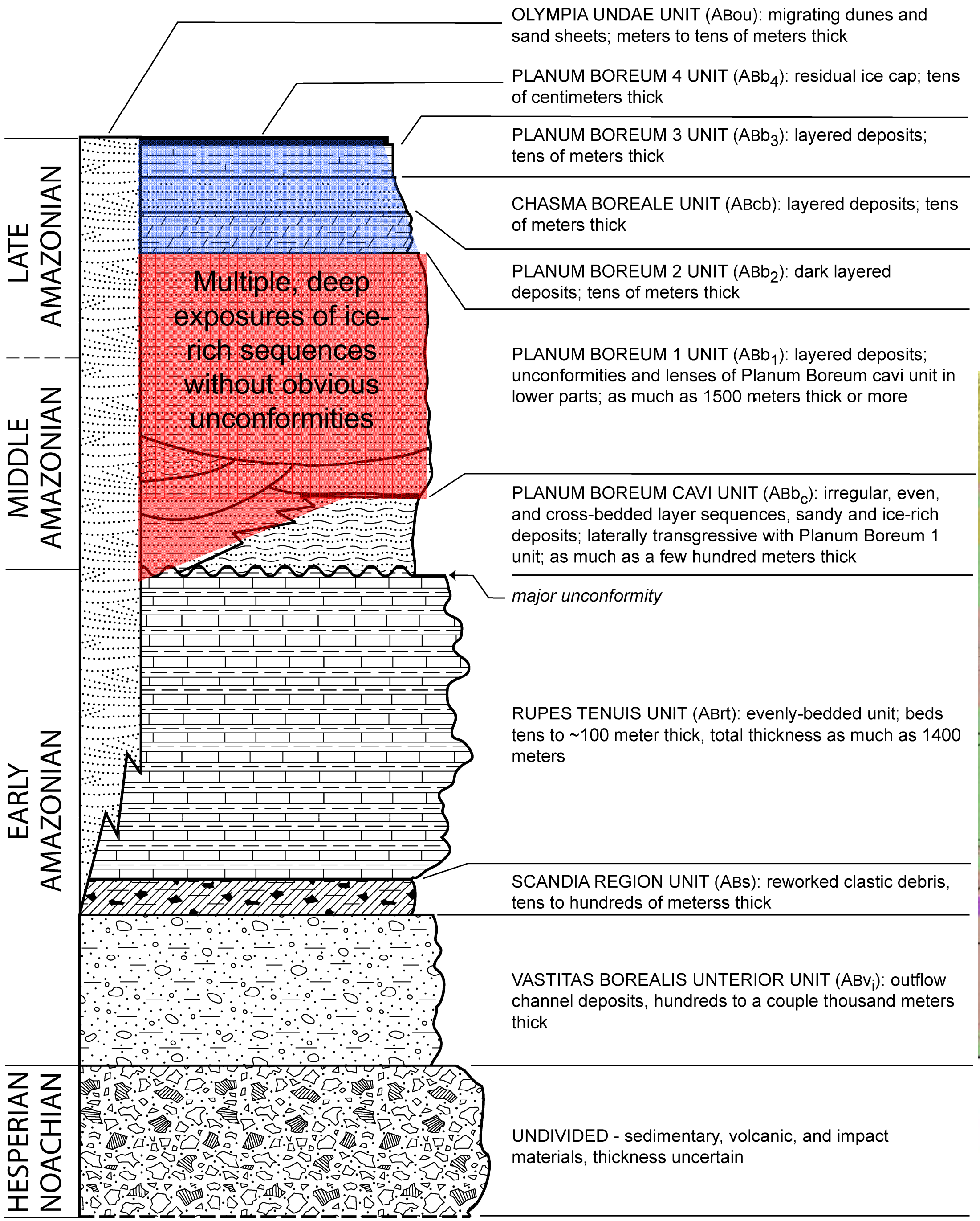

Jon Pelletier, UA

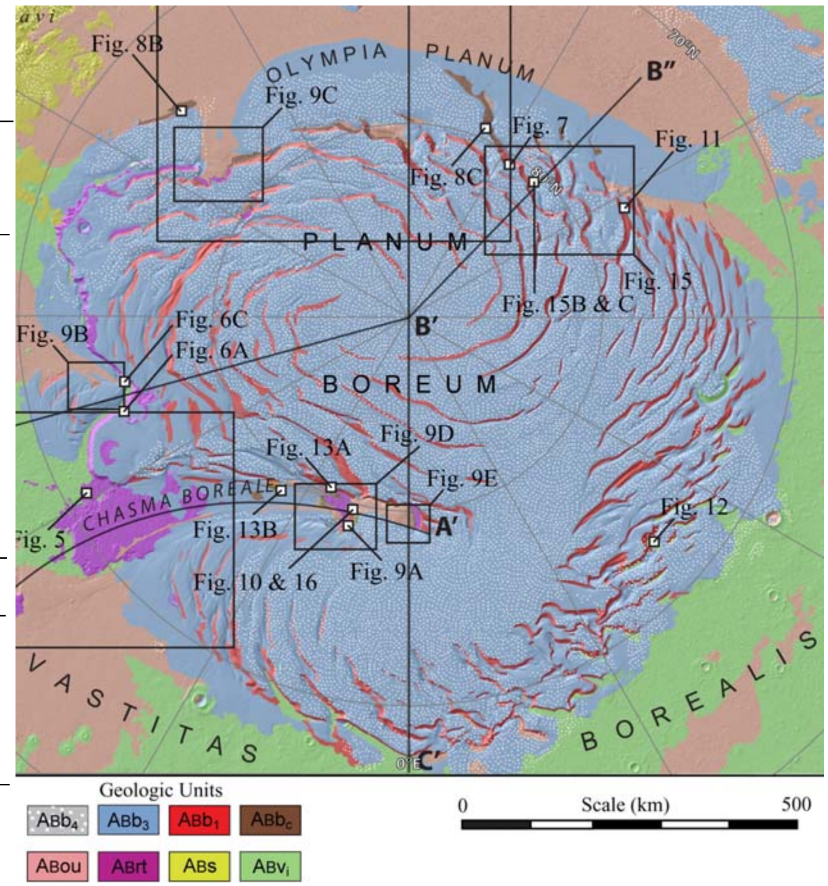

10 km


10 km
50 m

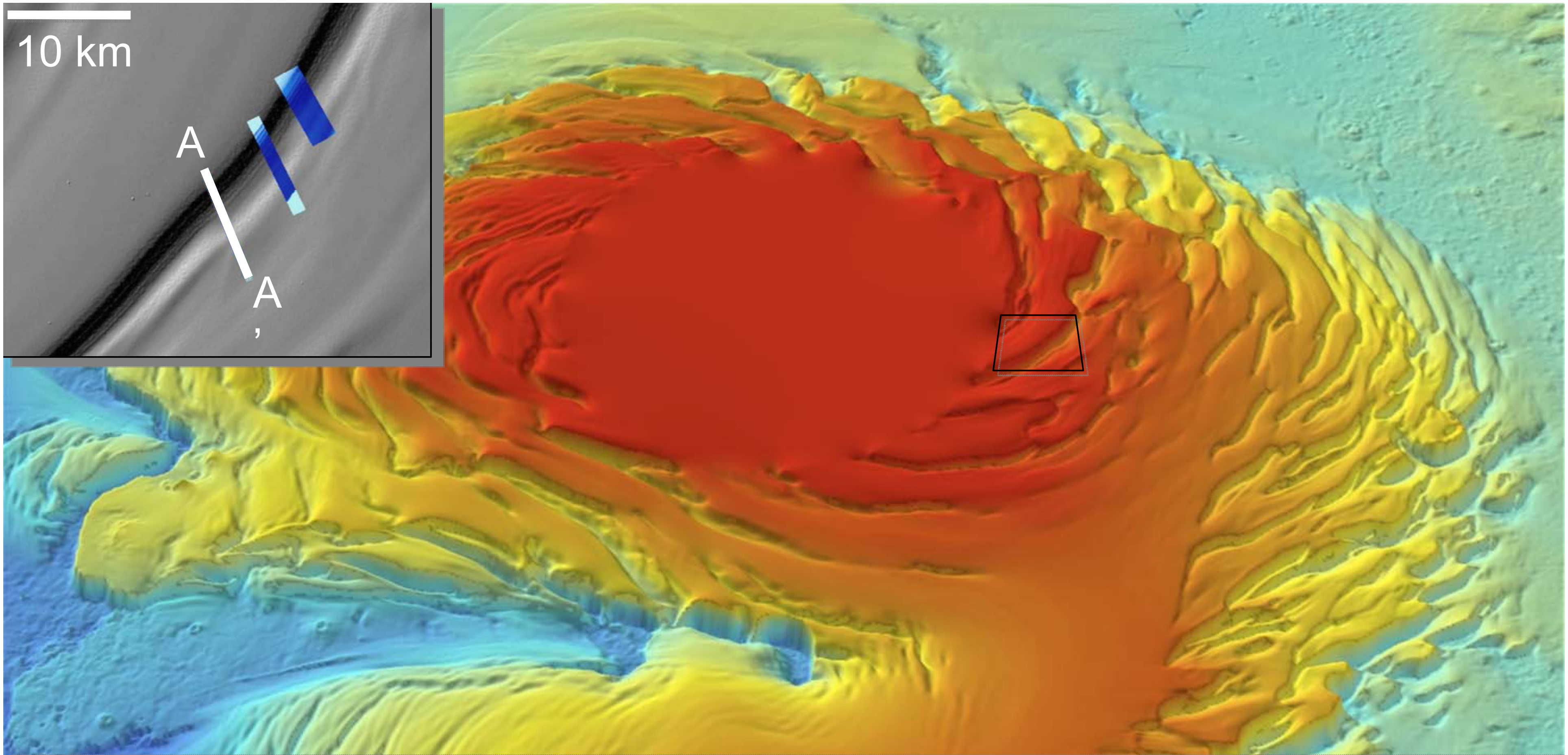
General polar stratigraphy has been mapped.

Upper north Polar Layered Deposits (PLD) are the most promising & best studied target.



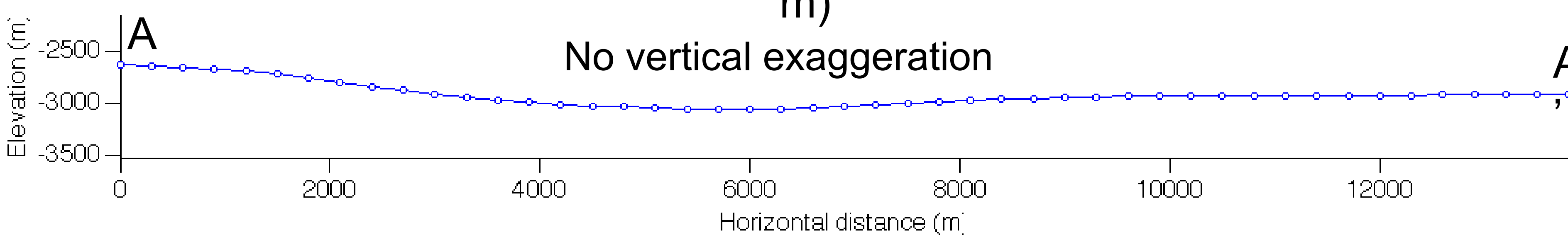


Tanaka et al. 2008



Trough walls have slopes of a few degrees.
Apparent thickness (kms) >> vertical thickness (100s of m)

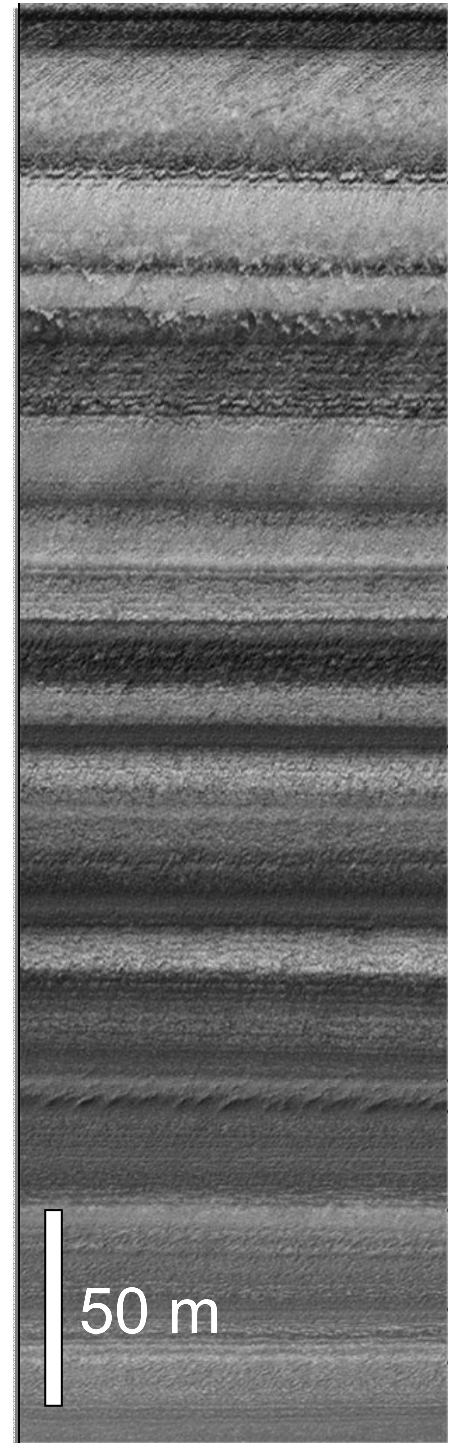
No vertical exaggeration



Layer formation mechanism

Net transport of water to poles	+	Variable ice deposition, sublimation	and/or	Variable dust deposition rate

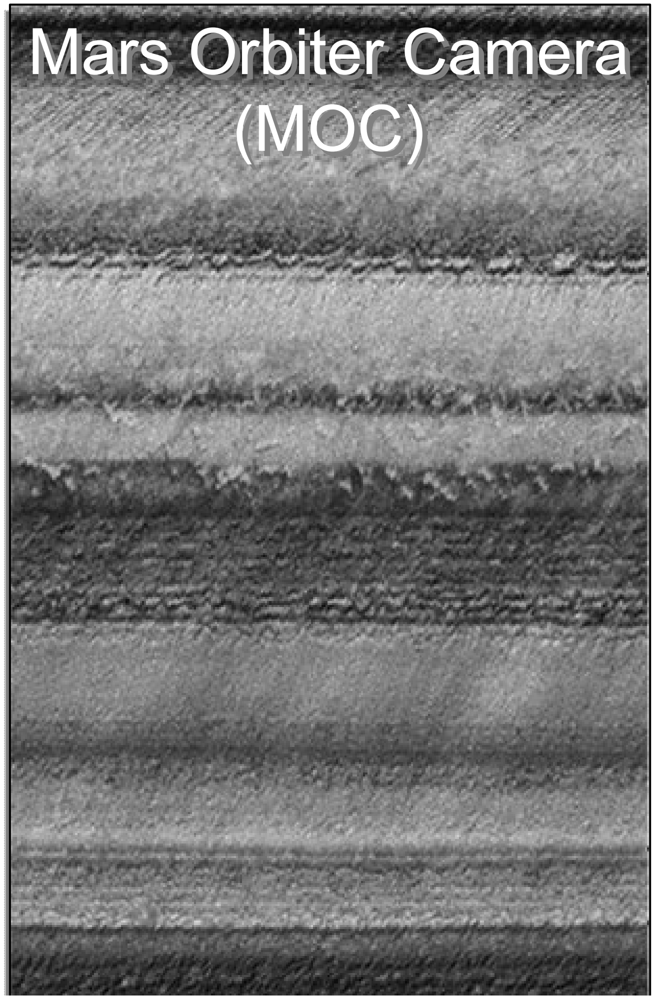
Relationship between layer composition and climate variables has been explored theoretically, and there are reasonable hypotheses, but ultimately it is empirically unconstrained



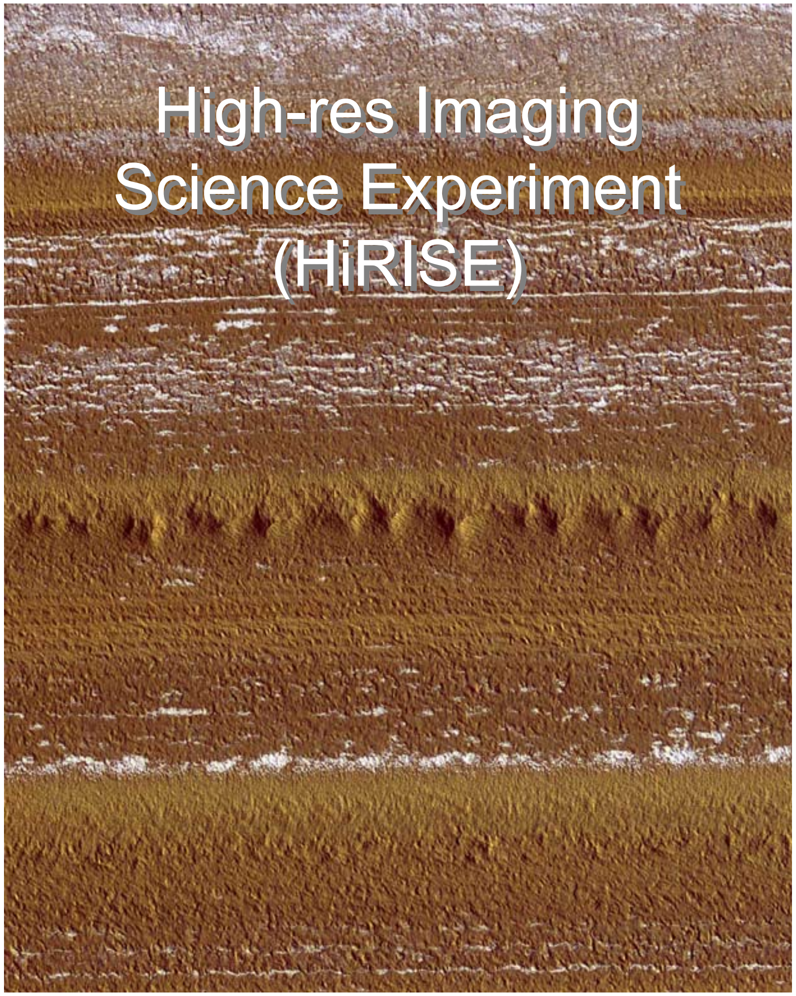

North polar
dust storms in
2002
MSSS/J
PL

Measurements we *do* have

Images: Lots, including some that offer high resolution and can be precisely co-registered with topography



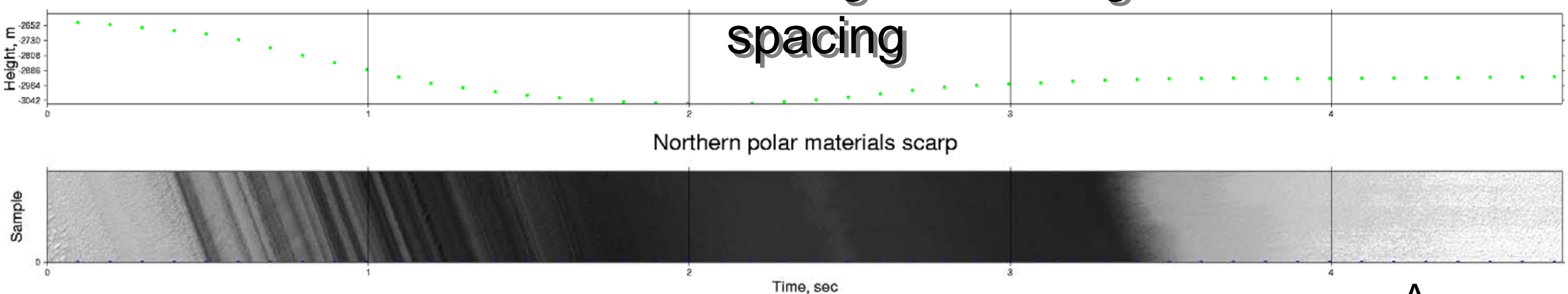
~50 m



Measurements we *do* have

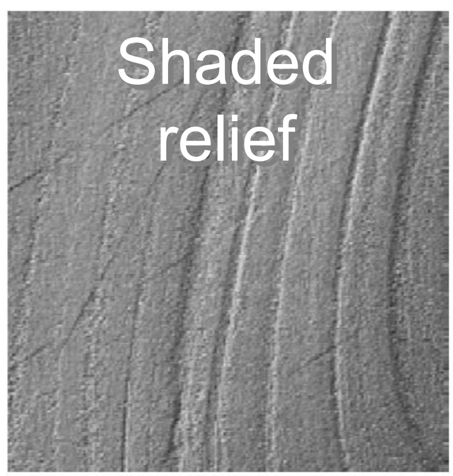
<u>Topography:</u> Global at sub-kilometer resolution (better at poles)

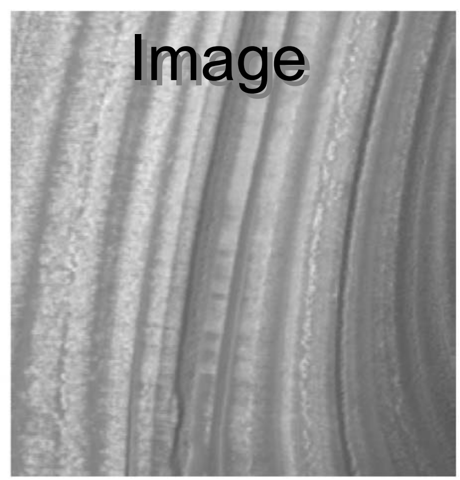
Laser altimeter shots along MOC images at 300m spacing



A. Ivanov/PDS

1m DEM from stereo HiRISE images

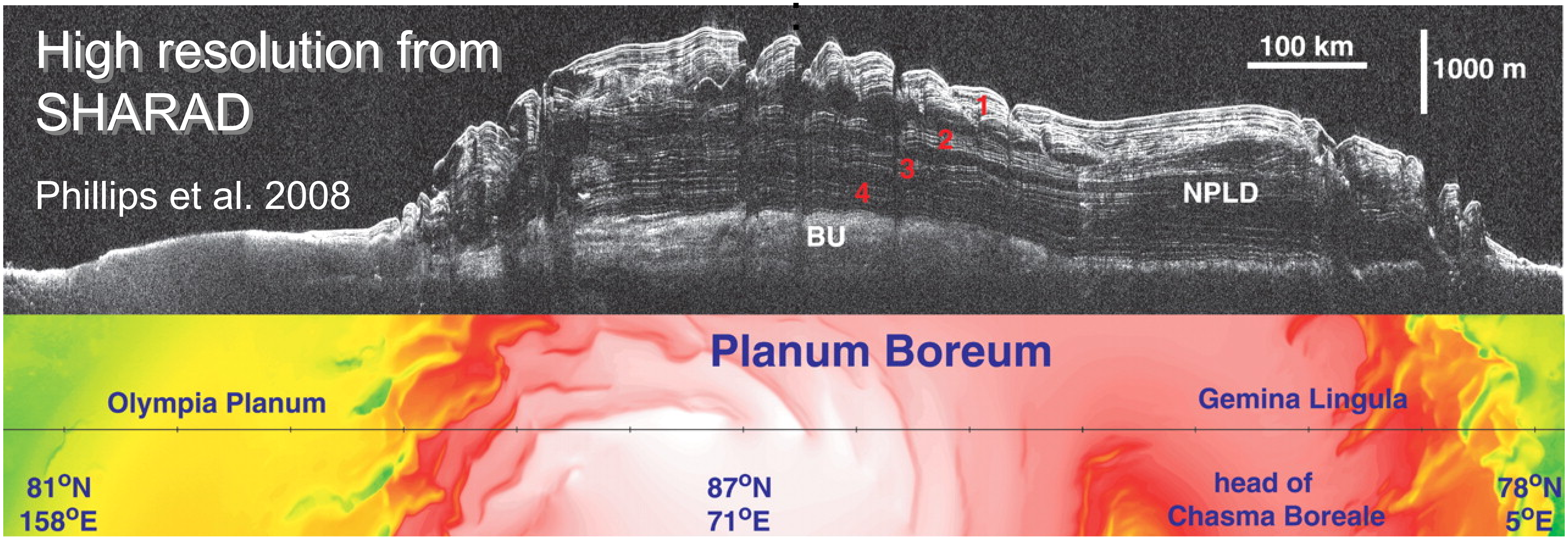


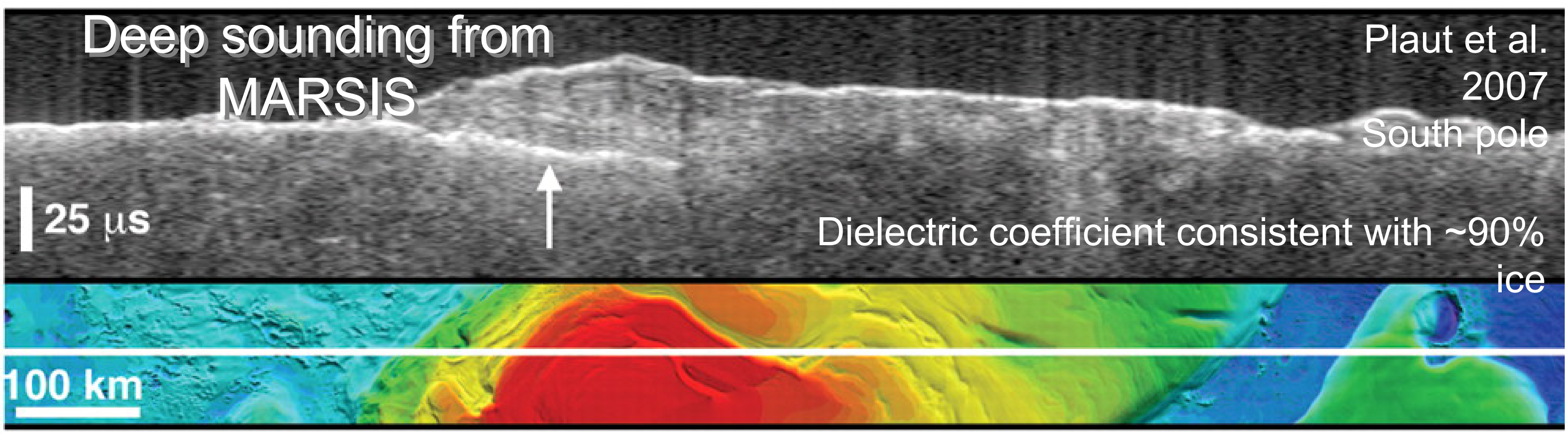


Fishbaugh et al.

Measurements we *do* have

Radar

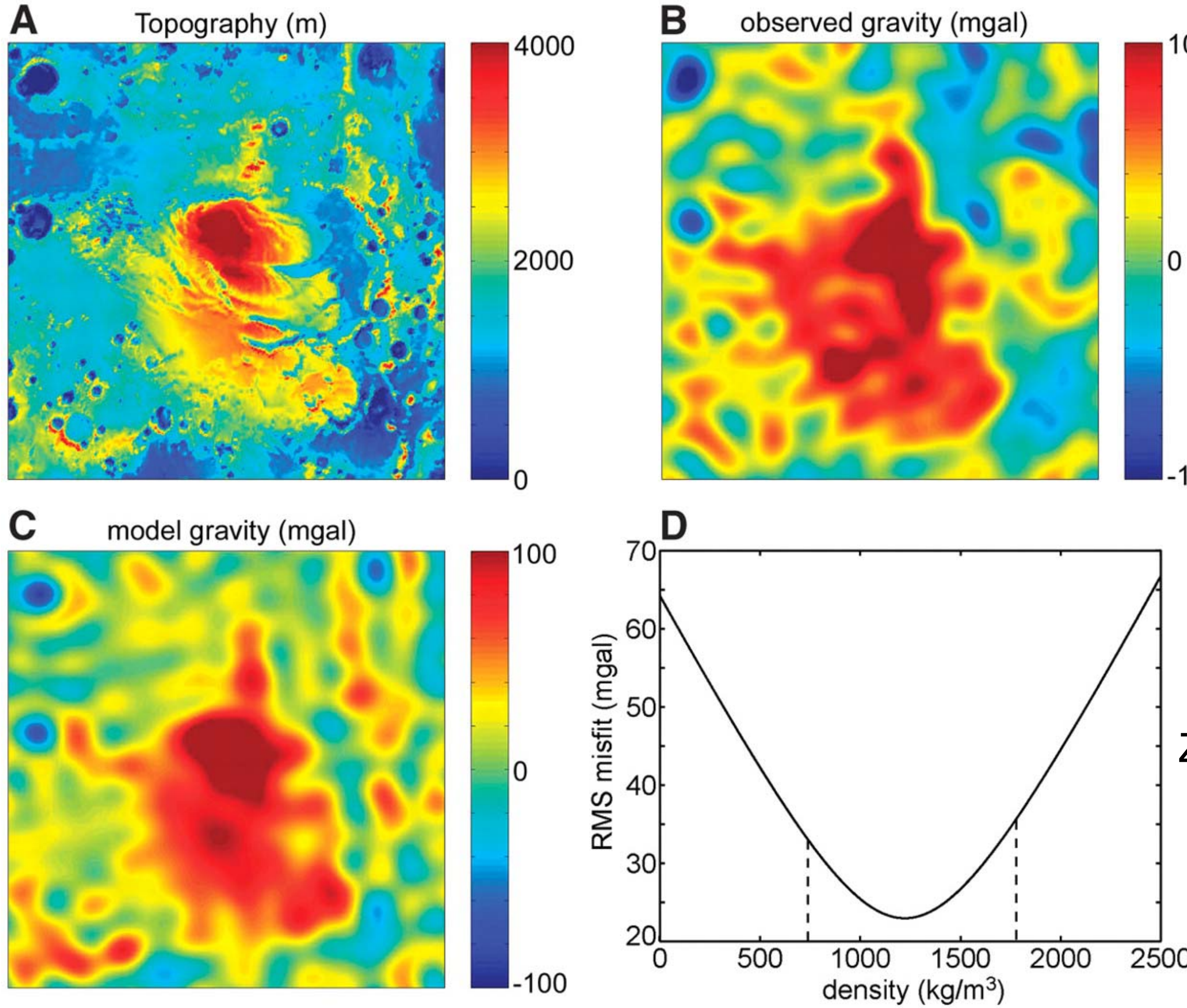




Measurements we *do* have

Gravity Inferred density of south polar deposits indicates 15%

:



Zuber et al. 2008

Measurements we *do* have

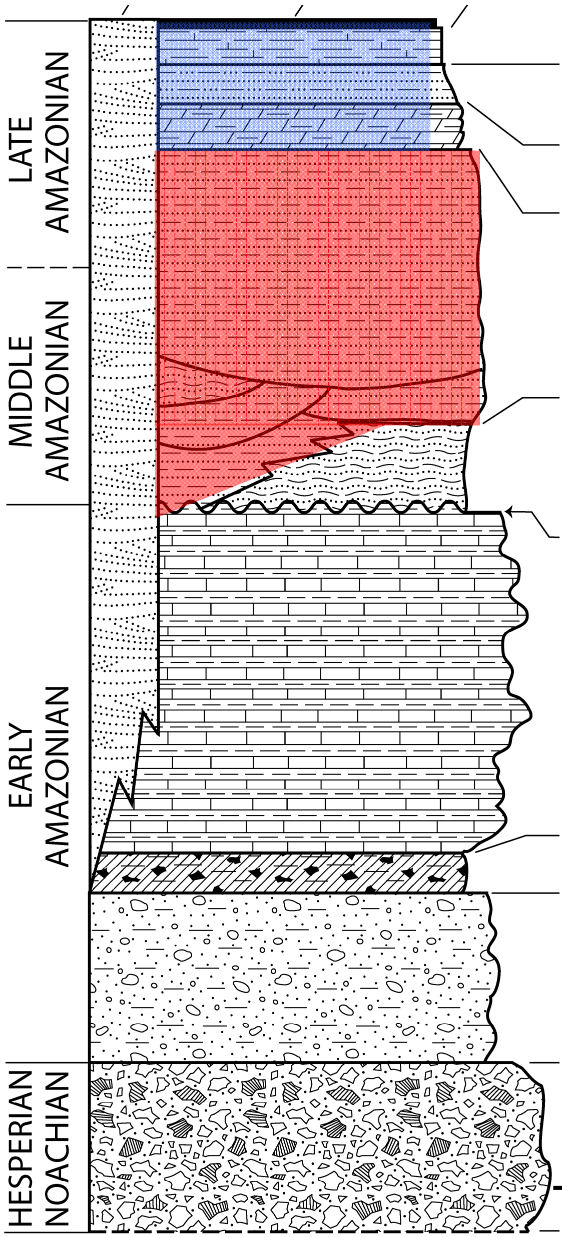
Spectra: Some information on composition and correlation to color

CRISM color composite

Strength of 1.5 μm H_2O

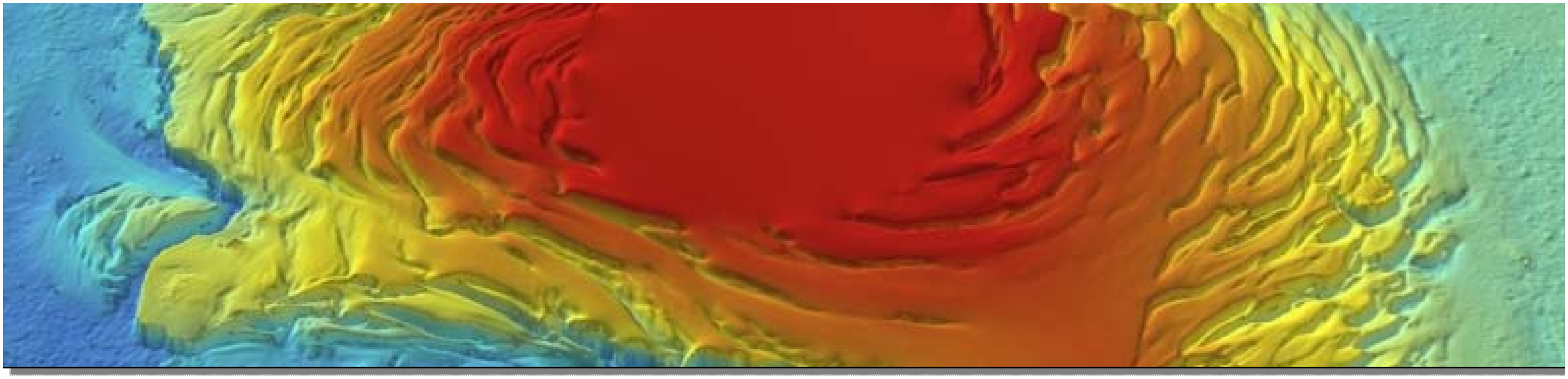
Calvin et al. 2008

Measurements we *don't* have

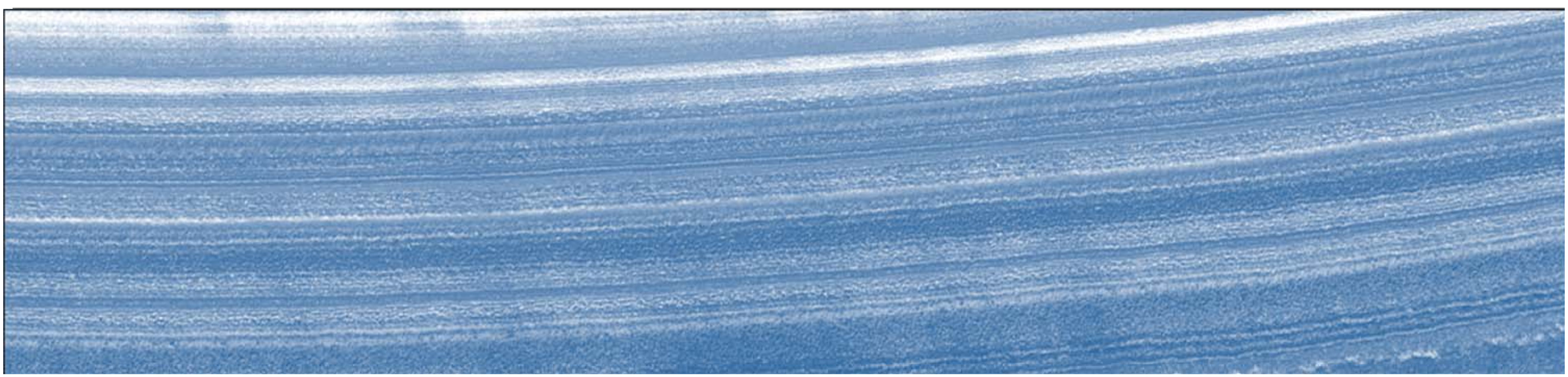


- Composition
  - At scale of layers (have bulk composition)
  - Direct, rather than using color, texture, topography as proxies
- Age
  - Upper bound of roughly 1 Gyr from cratering

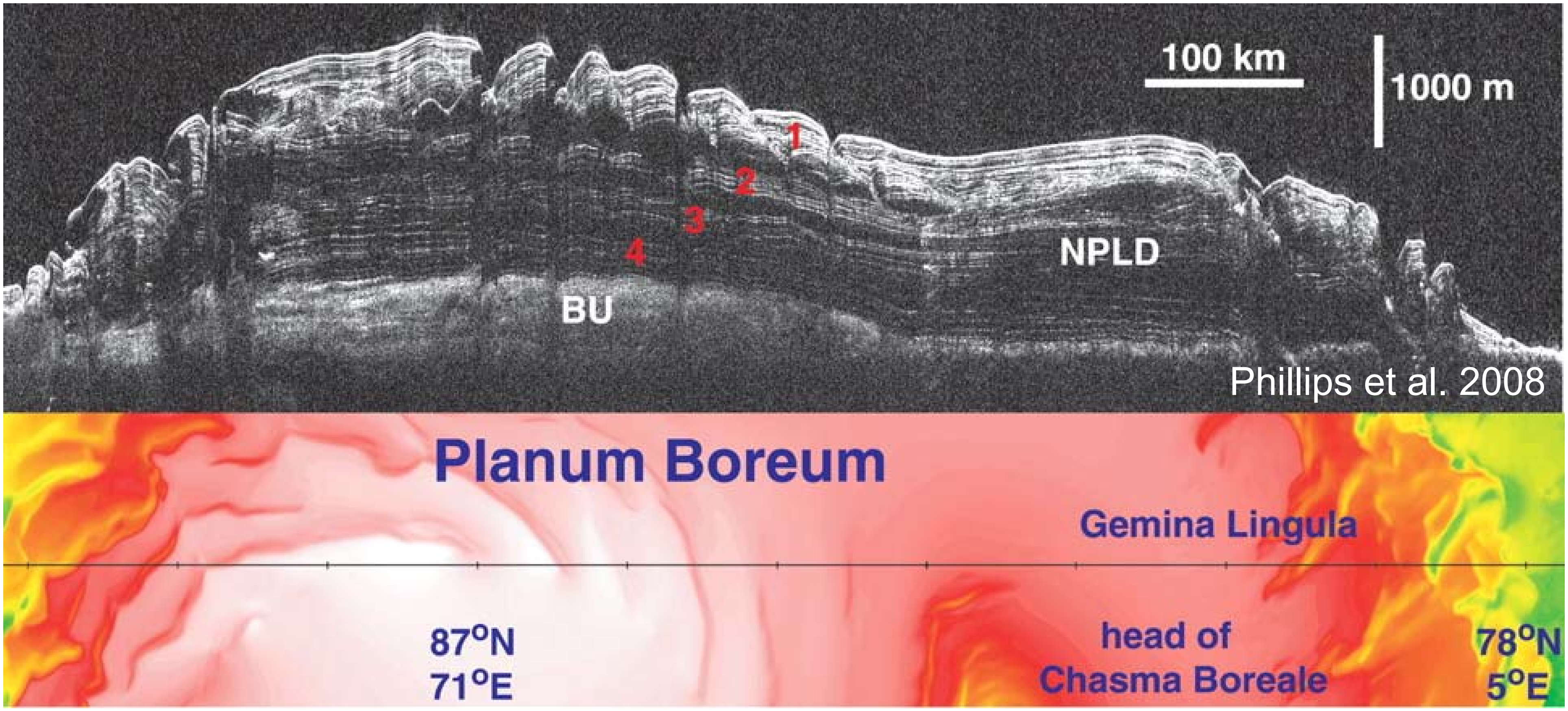
Tanaka et al. 2008



Recent discoveries



Polar strata record regional/global variability

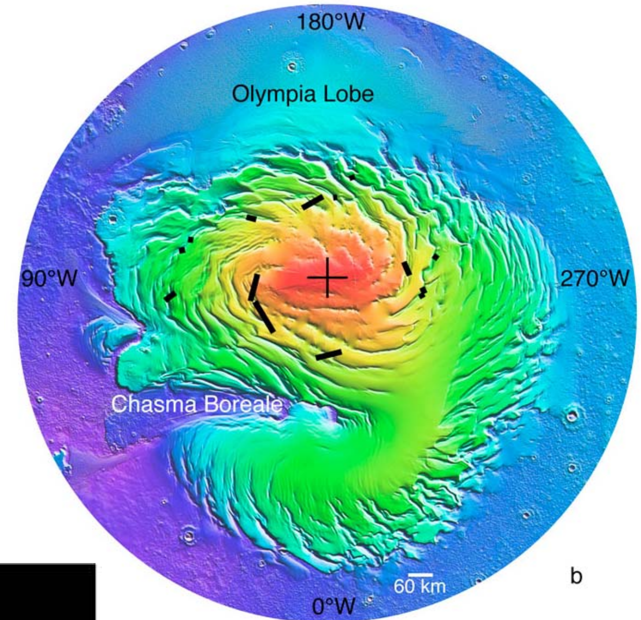


Radar shows that strata exposed in shallow troughs are continuous over 10s to 100s of km

Polar strata record regional/global variability

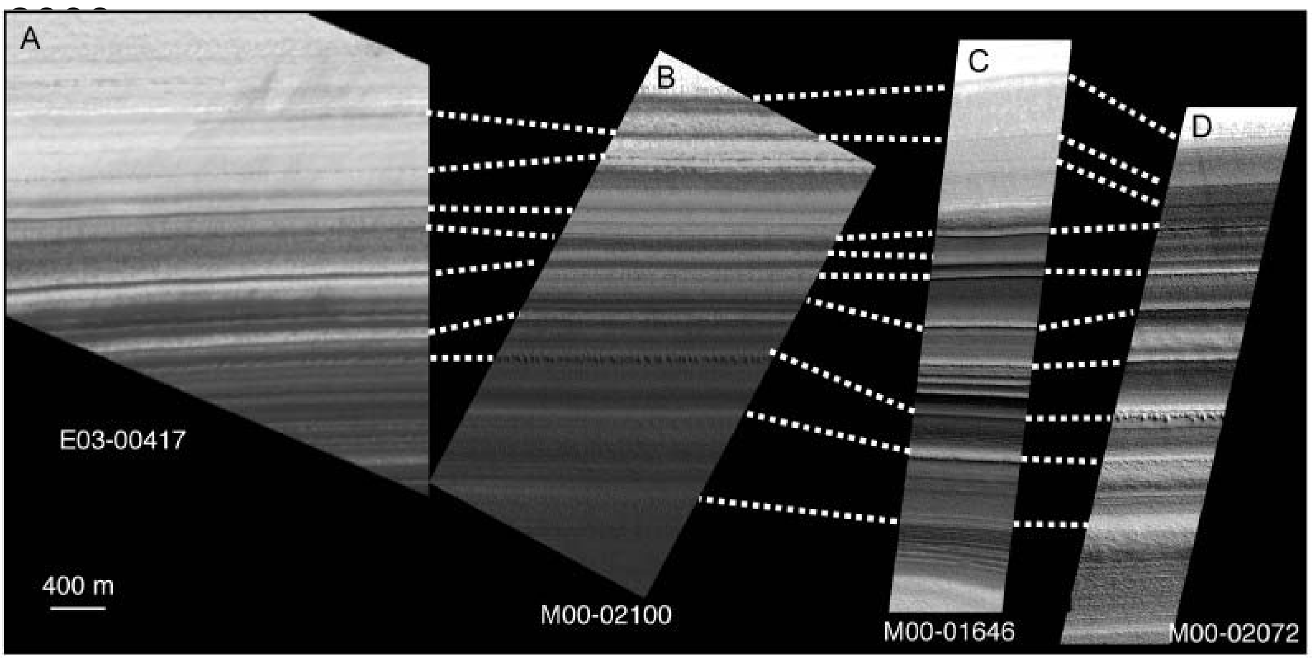
Fine-scale strata correlate across troughs, over 10s (100s?) of km

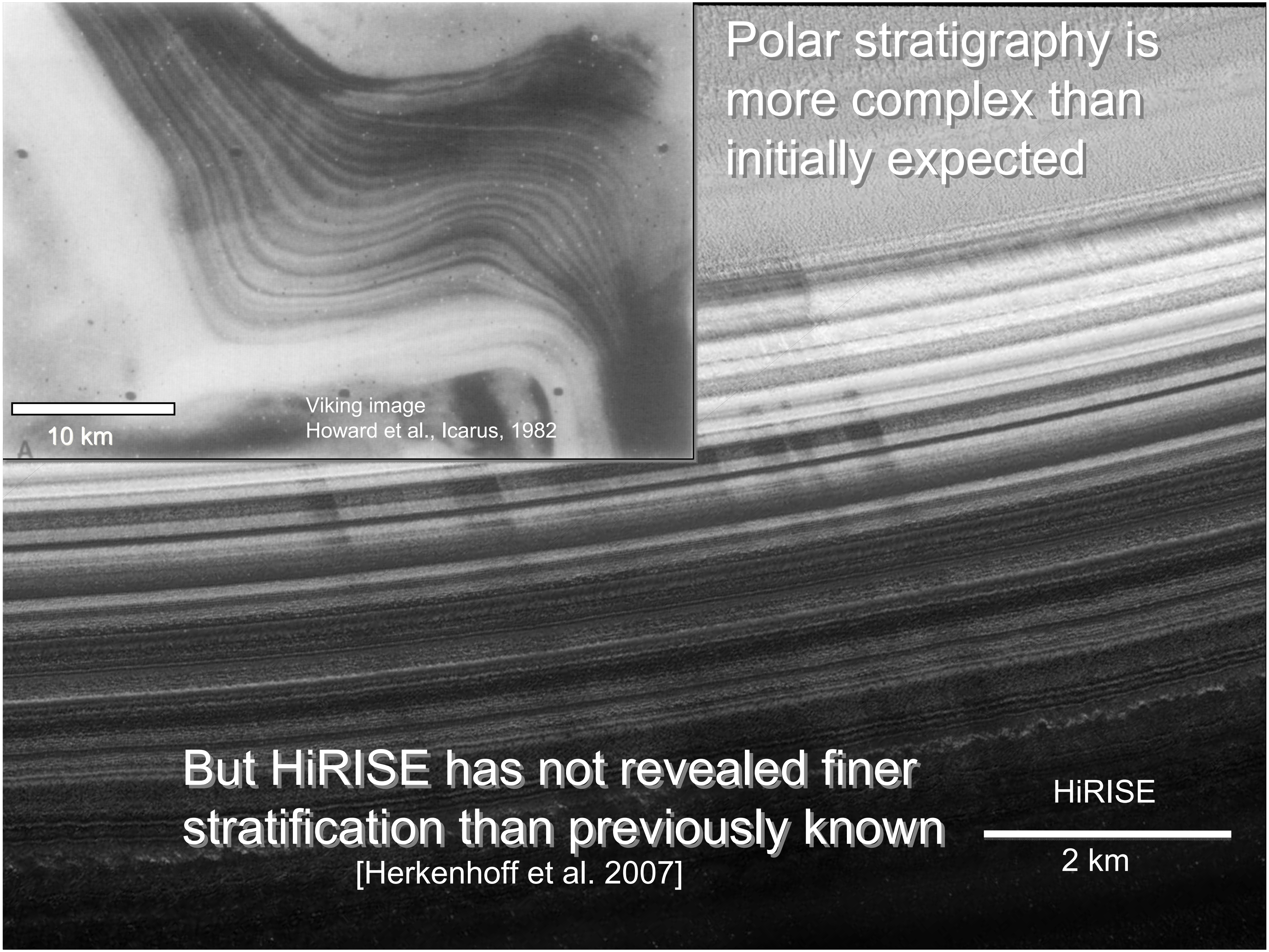
Trough migration has not significantly reworked the upper layered deposits

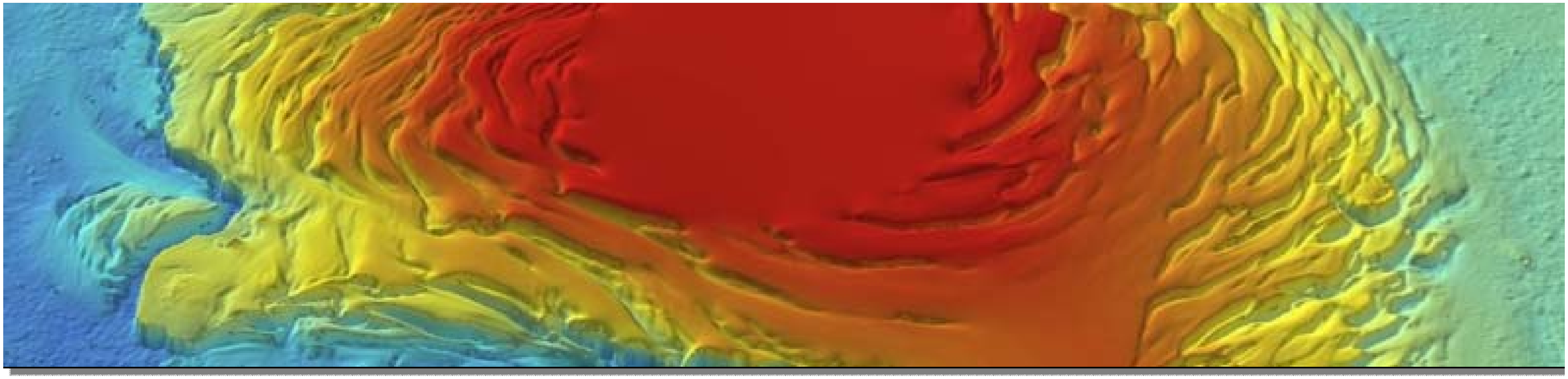


Fishbaugh & Hvidberg 2006

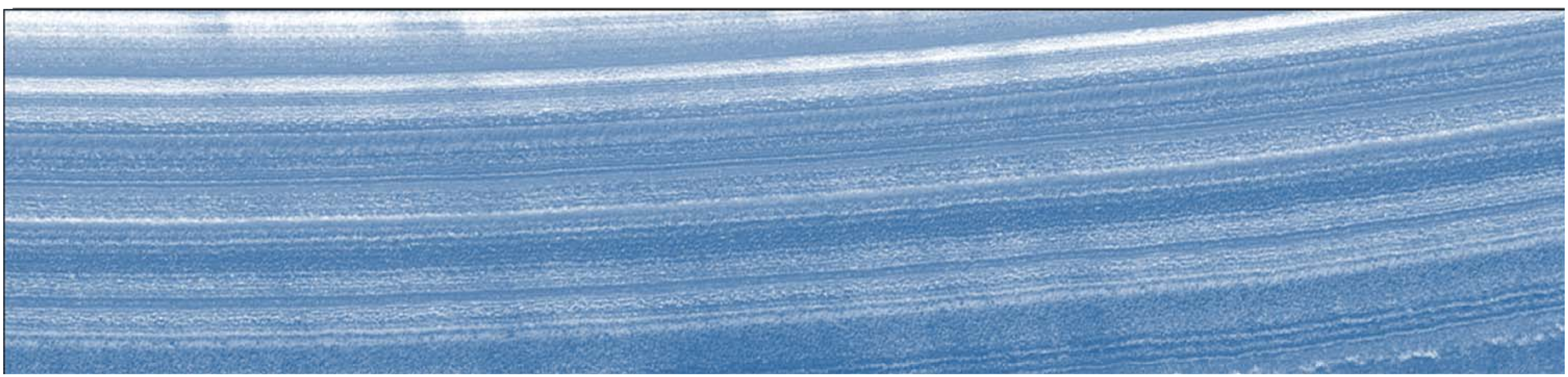
Milkovich & Head 2005,



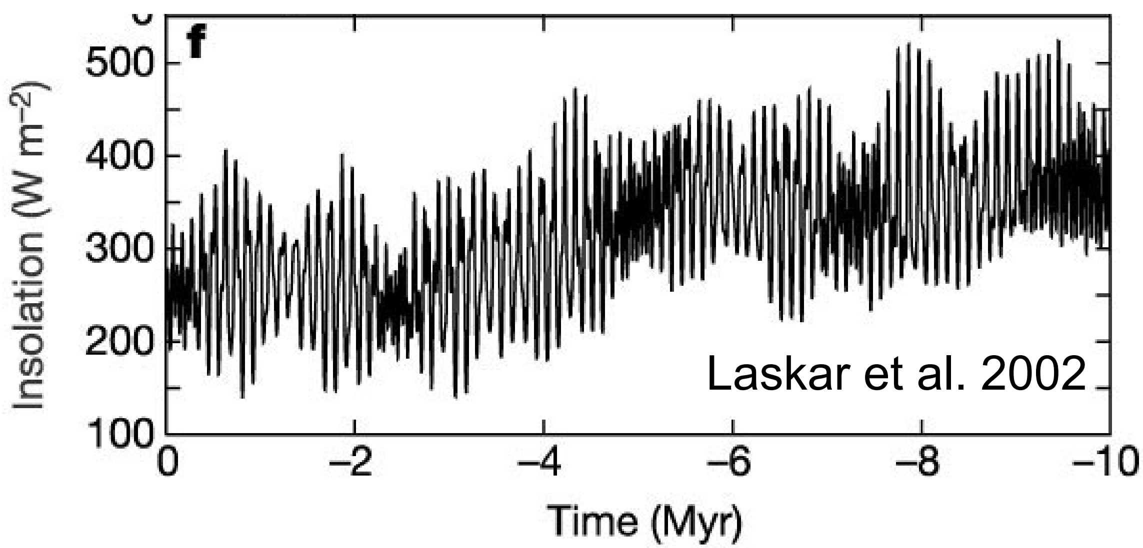

Polar stratigraphy is more complex than initially expected
10 km
Viking image
Howard et al., Icarus, 1982
But HiRISE has not revealed finer stratification than previously known
[Herkenhoff et al. 2007]
HiRISE
2 km



Controversies



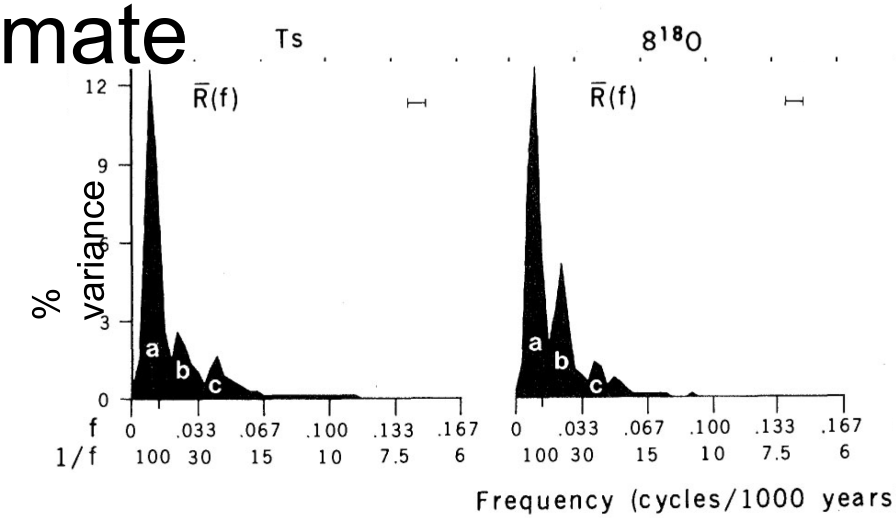
1. What time interval do polar strata span?
2. What is the nature of the polar climate record?
   - Quasi-periodic vs. stochastic variability
   - External (orbital) vs. internal forcing

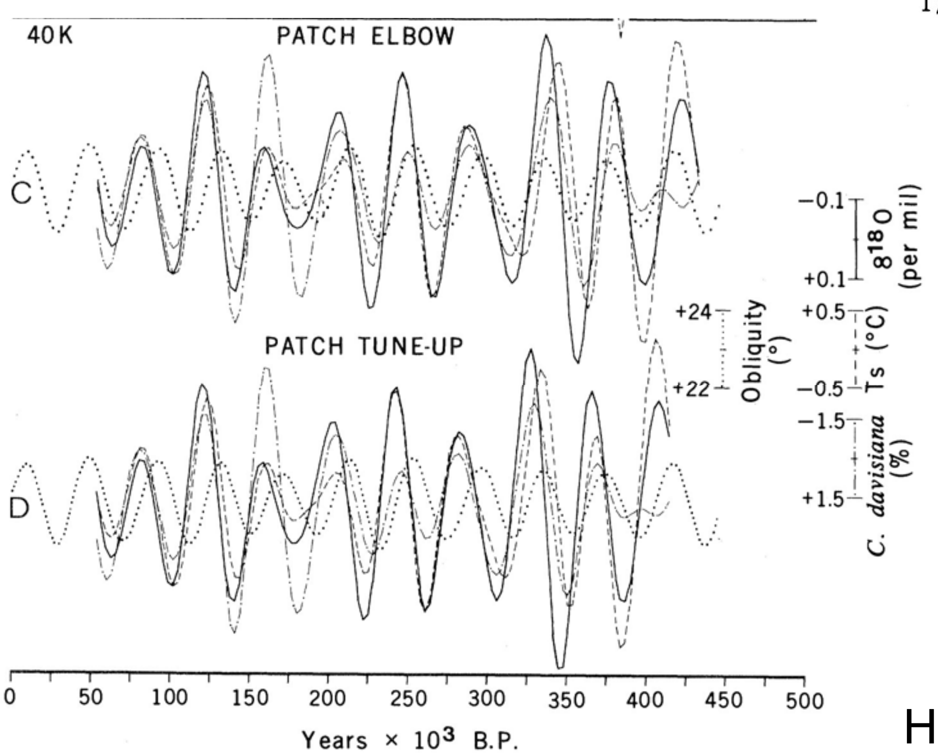


These are coupled questions:
In the absence of an absolute chronology, attempts have been made to connect polar stratigraphy to a forcing with known timescale

Precedent: Record of Earth's Pleistocene climate

Seafloor stratigraphy concentrates variability at same periods as orbital cycles





And there is phase coherence

Hays et al. 1976

But the degree to which Earth's paleoclimate reflects orbital forcing (as opposed to internal variability) is still debated

1970s

10 December 1976, Volume 194, Number 4270 **SCIENCE**

Variations in the Earth's Orbit: Pacemaker of the Ice Ages

For 500,000 years, major climatic changes have followed variations in obliquity and precession.

J. D. Hays, John Imbrie, N. J. Shackleton

SCIENCE, VOL. 204, 13 APRIL 1979

Pleistocene Climate: Deterministic or Stochastic?

MICHELLE A. KOMINZ
NICKLAS G. PISIAS

...although forcing by variations in the earth's orbital parameters of tilt and precession is real, it is small...

2000s

Quaternary Science Reviews 23 (2004) 1001–1012

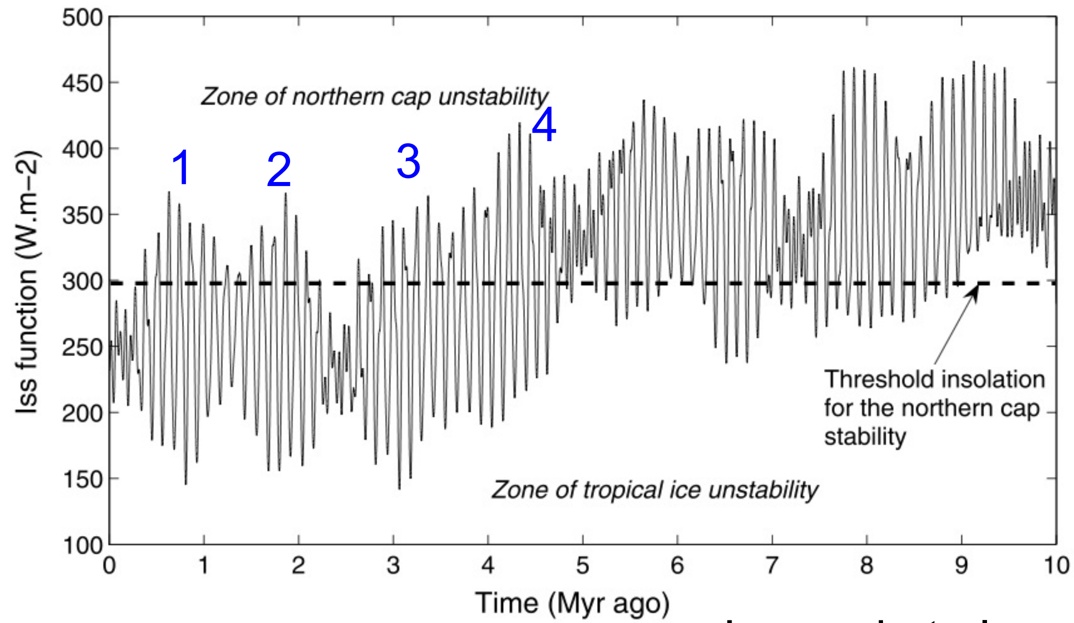
Quantitative estimate of the Milankovitch-forced contribution to observed Quaternary climate change

Carl Wunsch*

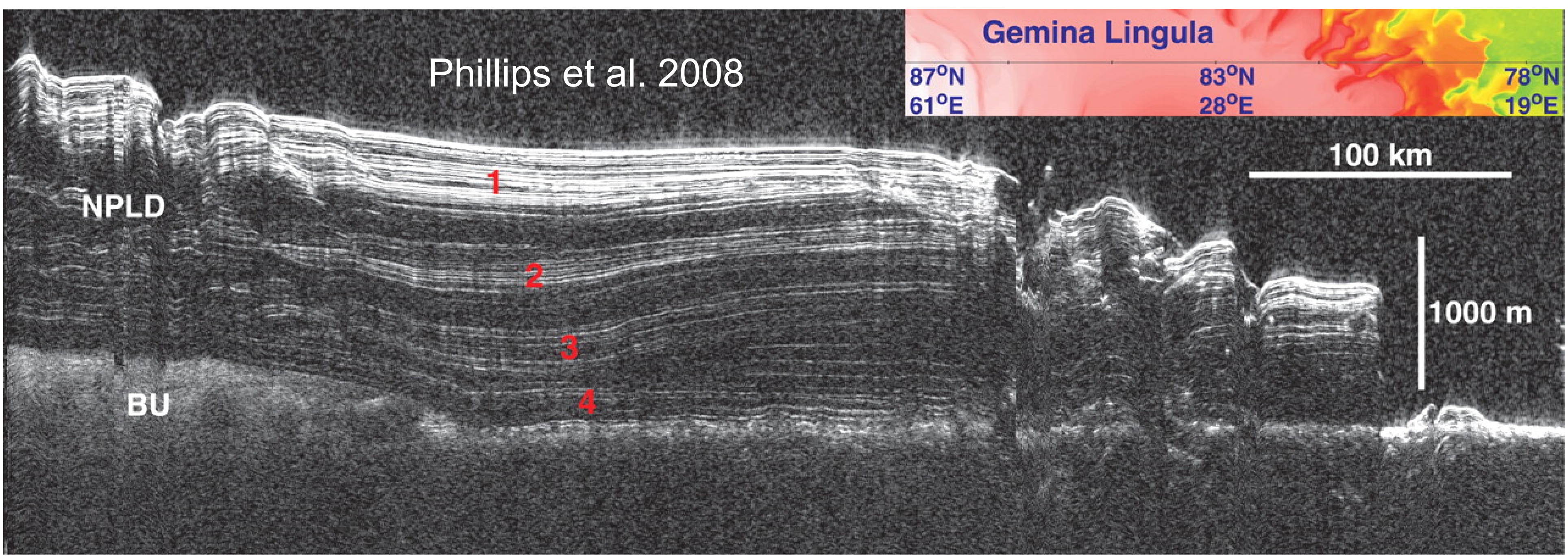
At zero order, all records are consistent with stochastic models of varying complexity with a small superimposed Milankovitch response, mainly in the obliquity band.

Phillips et al. 2008: NPLD formed during low mean obliquity of past 5 Myr

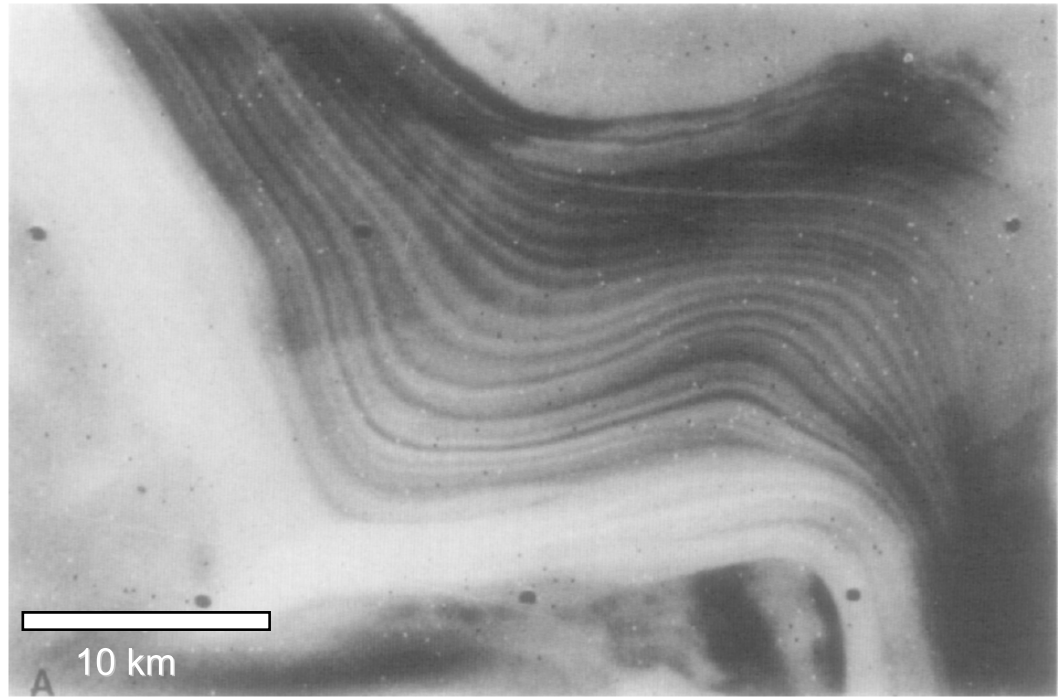
Dust-rich lags at tops of "packets" form during high-obliquity excursions



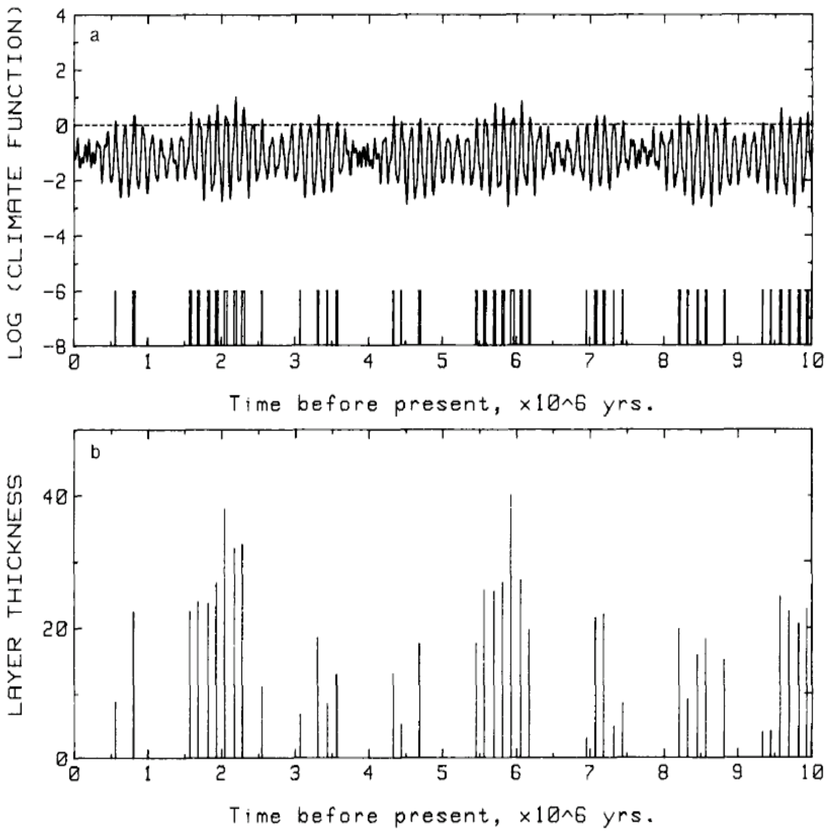
Levrard et al. 2007



Mariner, Viking resolved polar stratigraphy just enough to tantalize



Howard et al. 1982

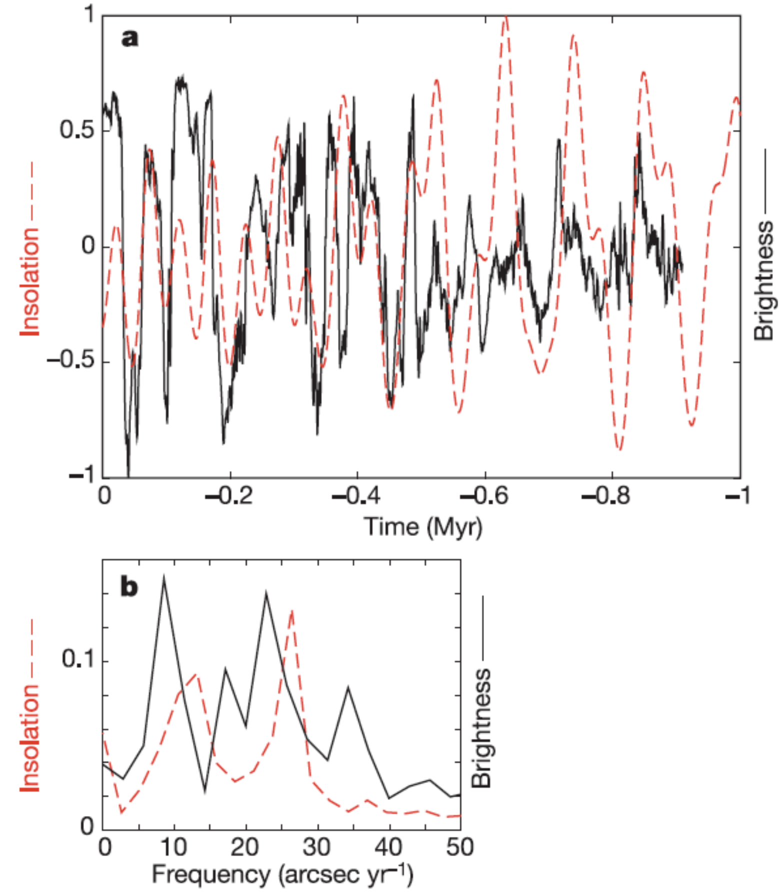


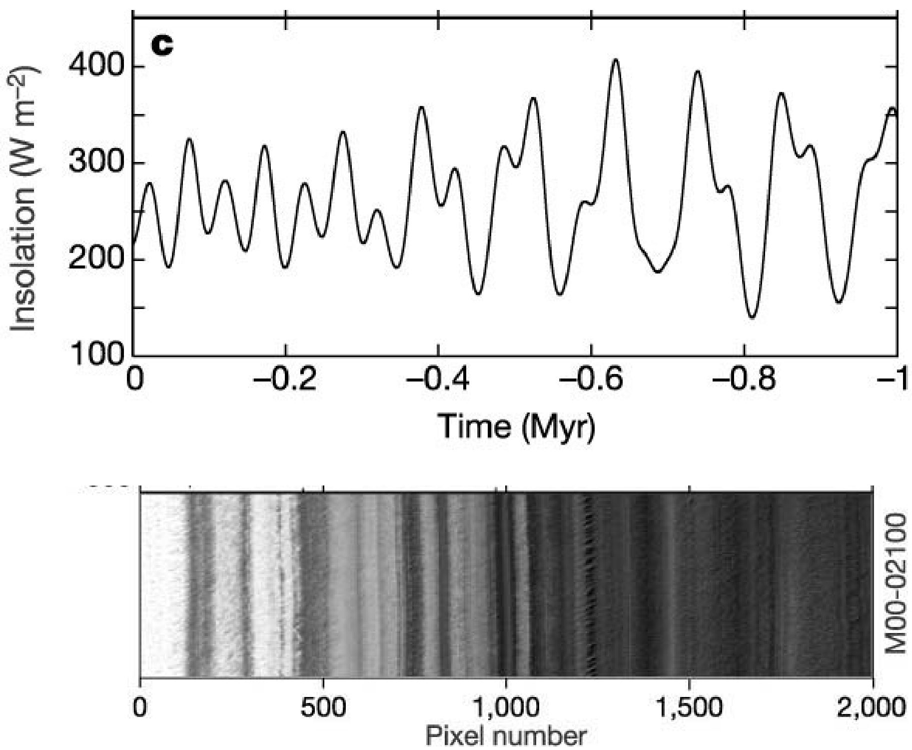
Cutts & Lewis 1982

This generated a rich theoretical literature exploring connection of insolation to ice + dust deposition

e.g., Murray et al. 1972, Toon et al. 1980, Cutts & Lewis 1982, Howard et al. 1982

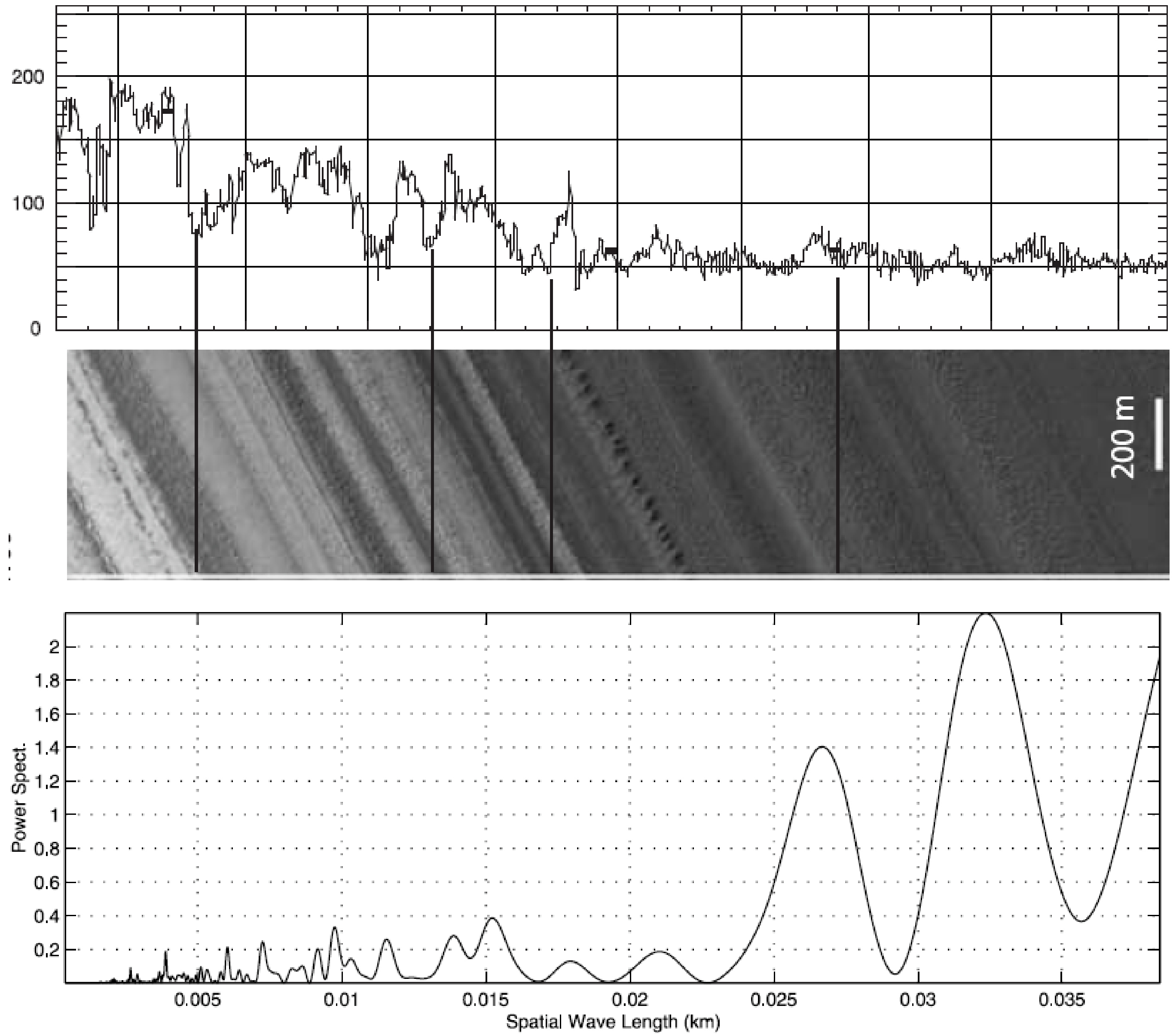
Tuning approach:
Laskar et al. (2002) estimated age of NPLD by tuning insolation record to match an image



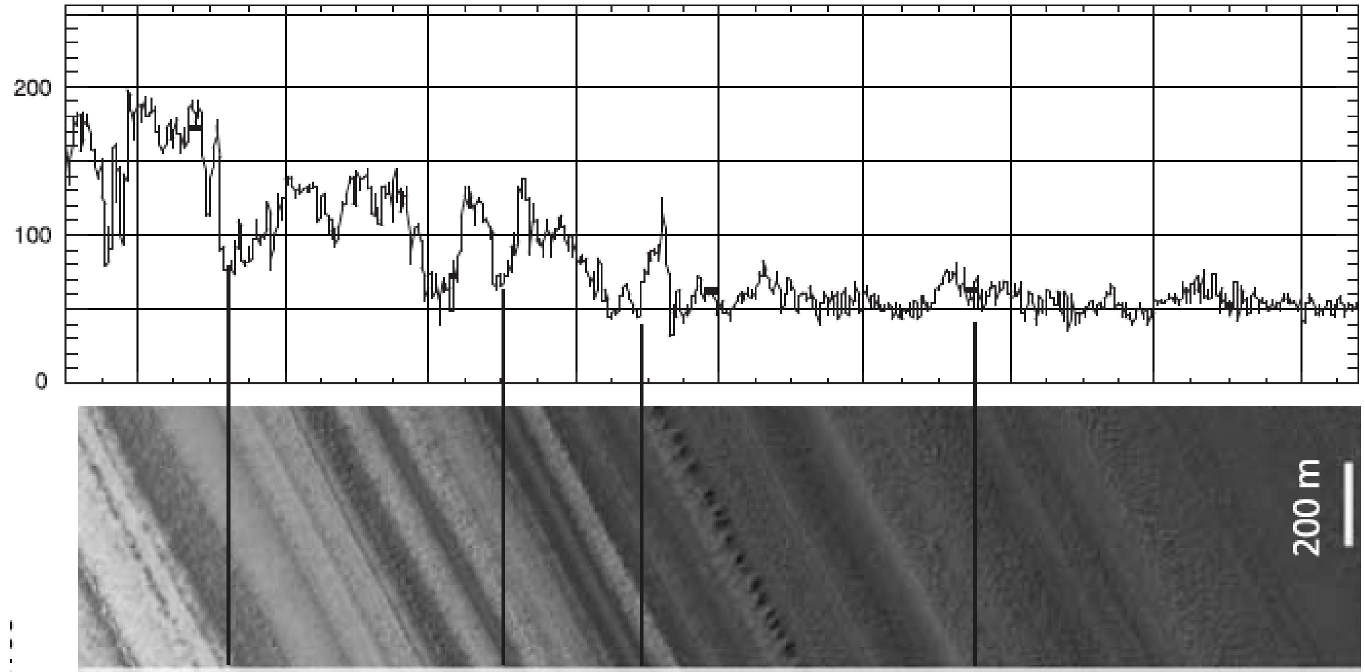


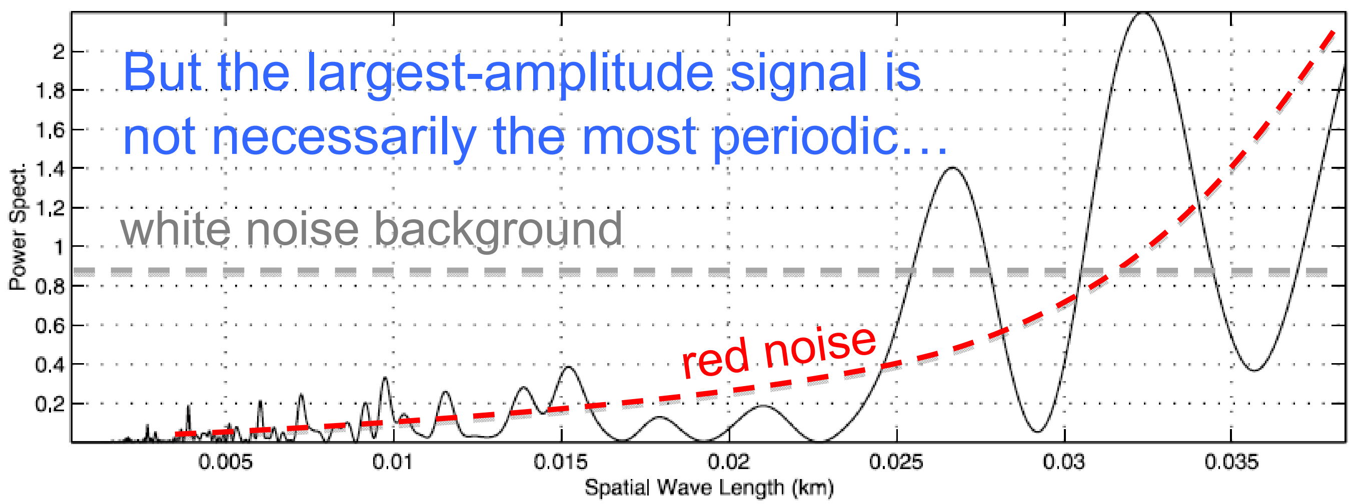
A phase match requires 2x change in deposition rate over half the image record

Milkovich & Head (2005, 2008) examine spectra for 30 images, and find strongest signals at ~30m wavelengths

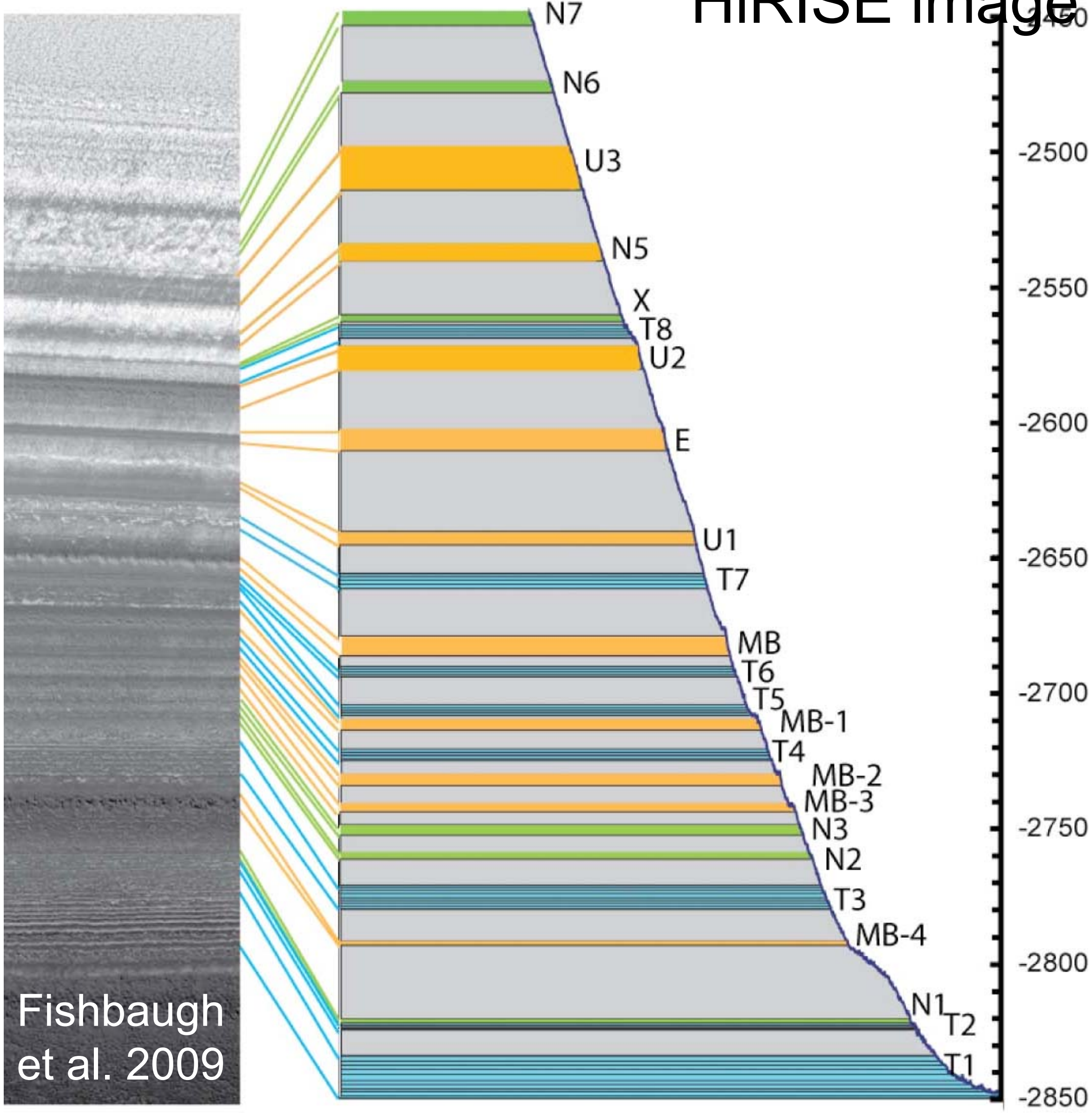


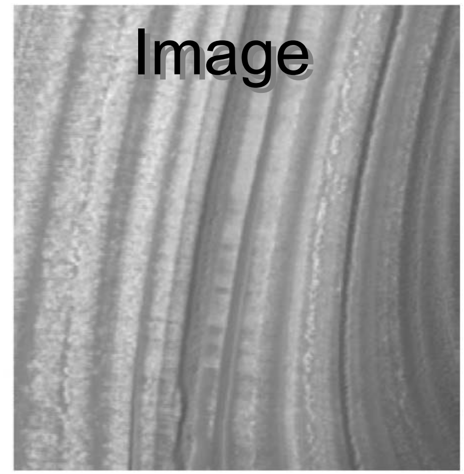
Milkovich & Head (2005, 2008) examine spectra for 30 images, and find strongest signals at ~30m wavelengths

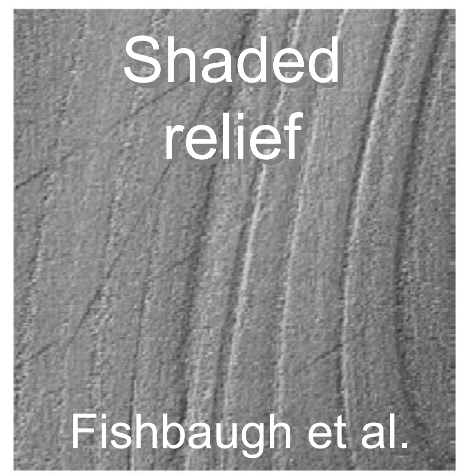




Fishbaugh et al. (2008, 2009, in press) find support for repeating beds 10s of m thick in topography from one stereo HiRISE image







Perron & Huybers, Geology, Feb. 2009

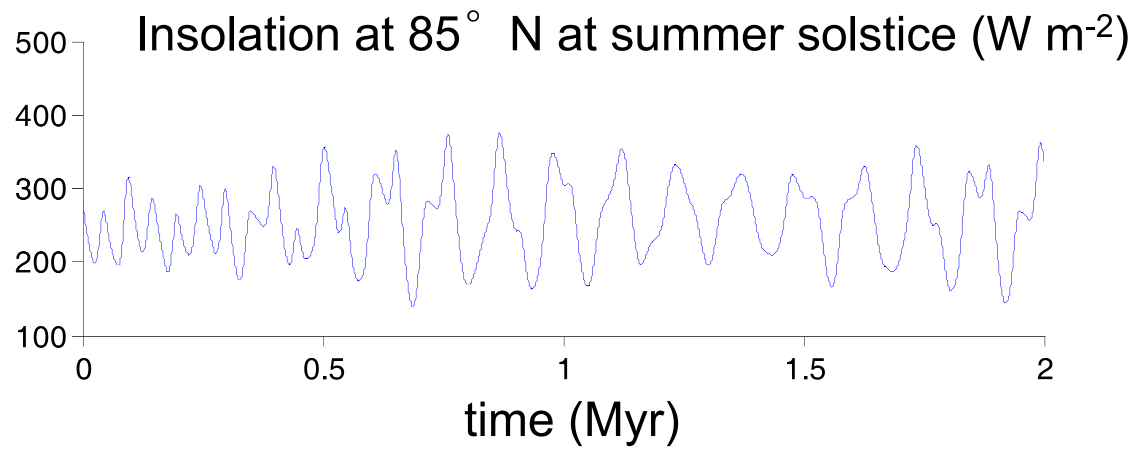
2 questions:

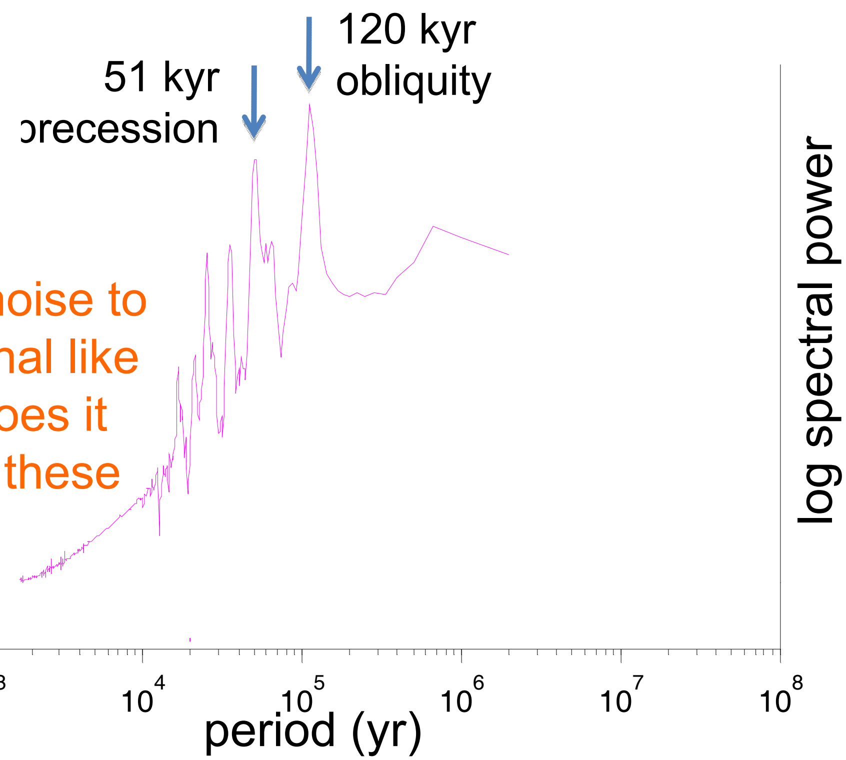
1. How do the uncertainties in a stratigraphic record reconstructed from spacecraft data affect our ability to detect an orbital signal?

2. Can we reject the null hypothesis that we are just seeing a record of stochastic internal variability of the Martian climate?

Criteria for detection of an orbital signal:

- Significantly more periodic than expected for a stochastic record
- No absolute chronology → need a diagnostic ratio of periods

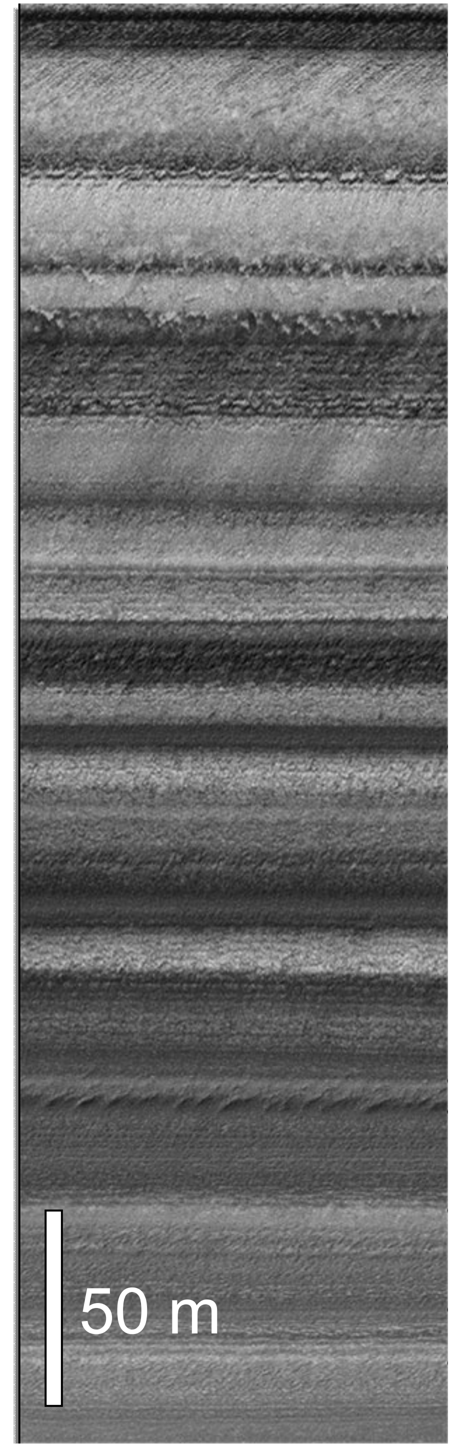




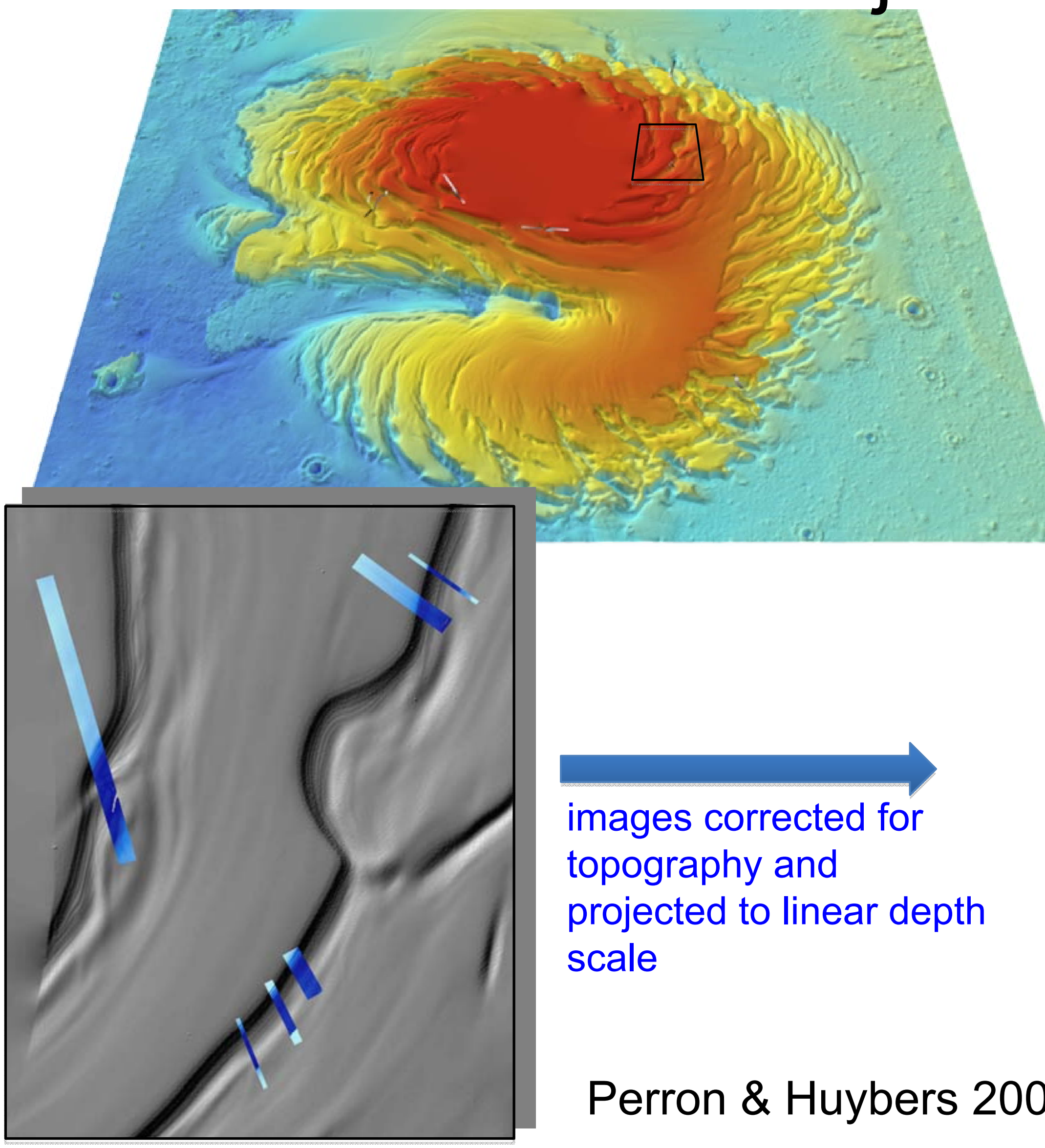
If we add noise to a clear signal like this one, does it still satisfy these criteria?

Uncertainties in signal amplitude (image pixels):

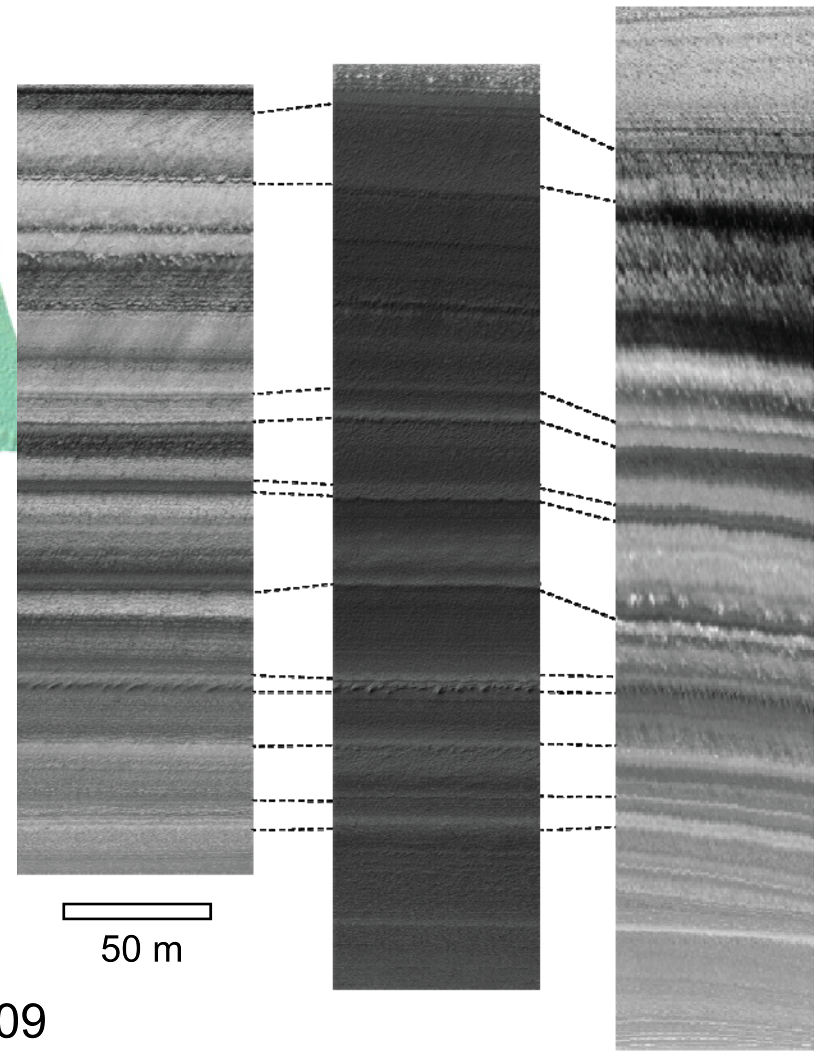
- Insolation $\leftrightarrow$ PLD formation?
  (but for this exercise we'll assume it's simple)
- Image artifacts
- Color $\neq$ composition [Tanaka 2005, Herkenhoff et al. 2007, Fishbaugh et al. 2008]
- Difficult to quantify this noise source, but we can explore its effects



Uncertainties in time (i.e., stratigraphy): "jitter"



images corrected for topography and projected to linear depth scale

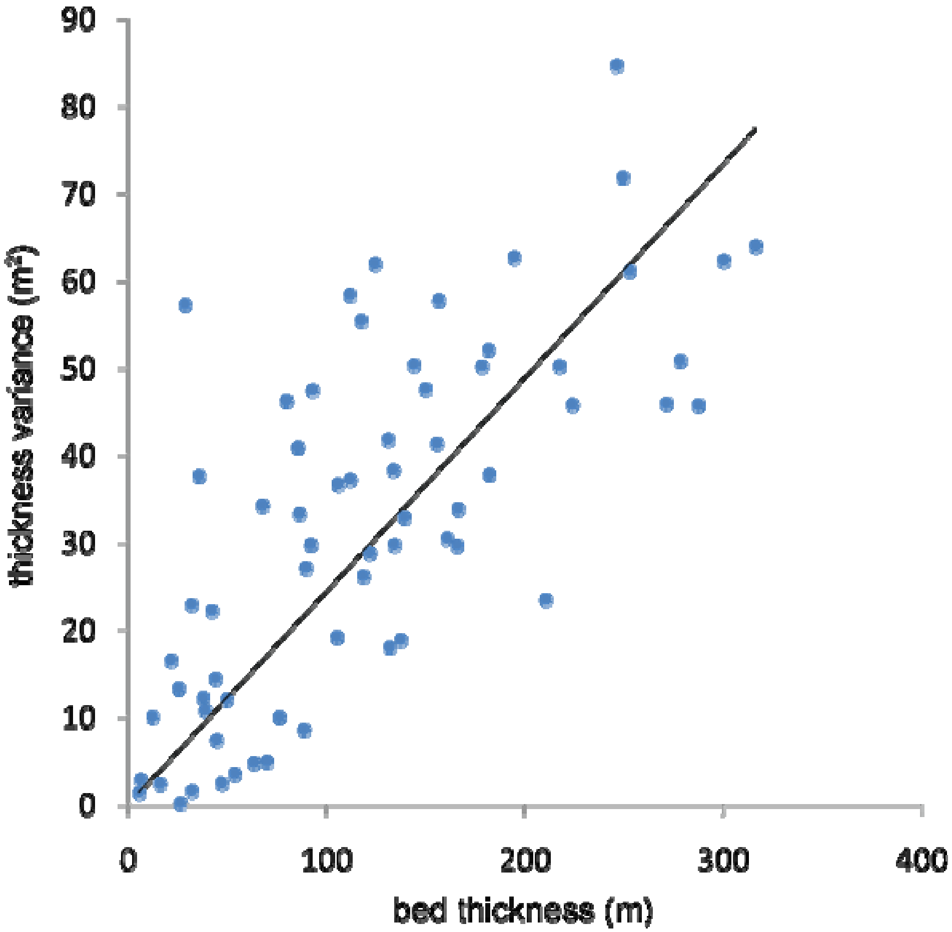


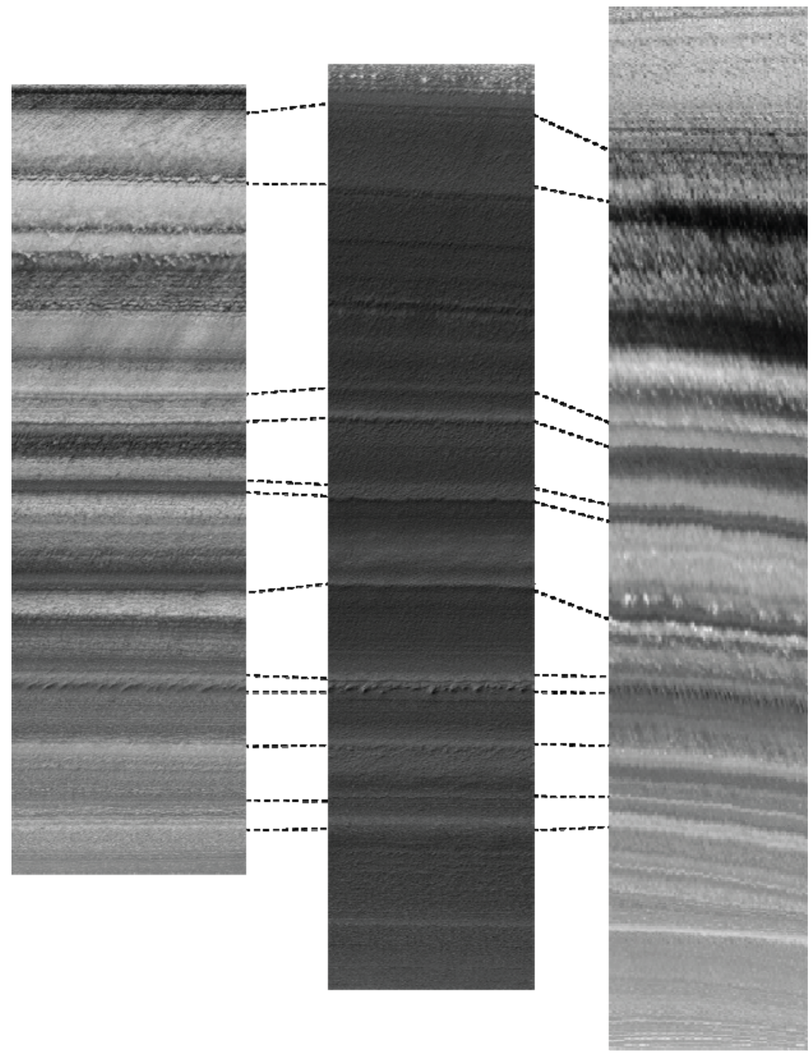
Perron & Huybers 2009

Uncertainties in time (i.e., stratigraphy): "jitter"

jitter = variance(thickness)/mean(thickness)

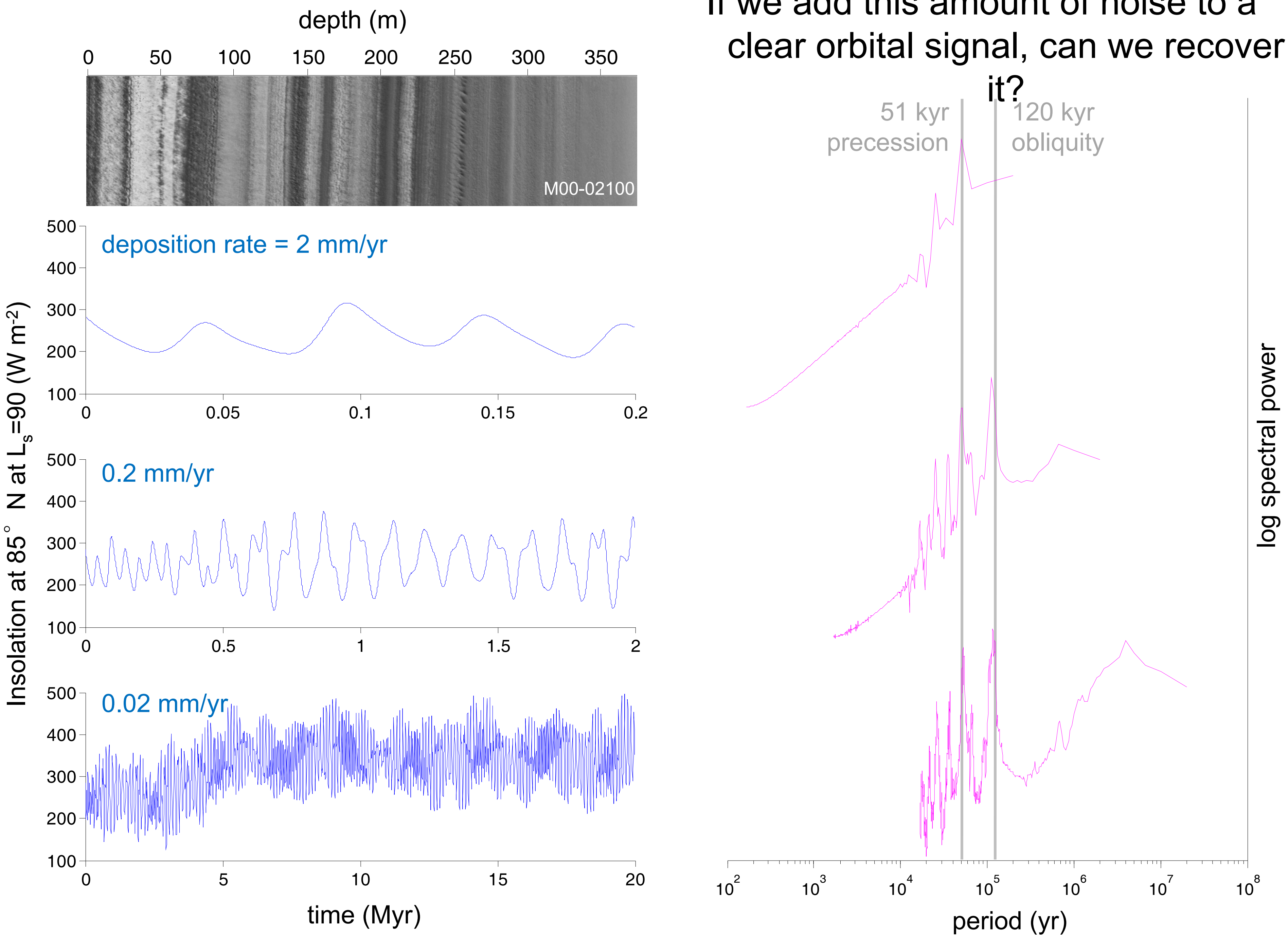
= 0.25 (a minimum)





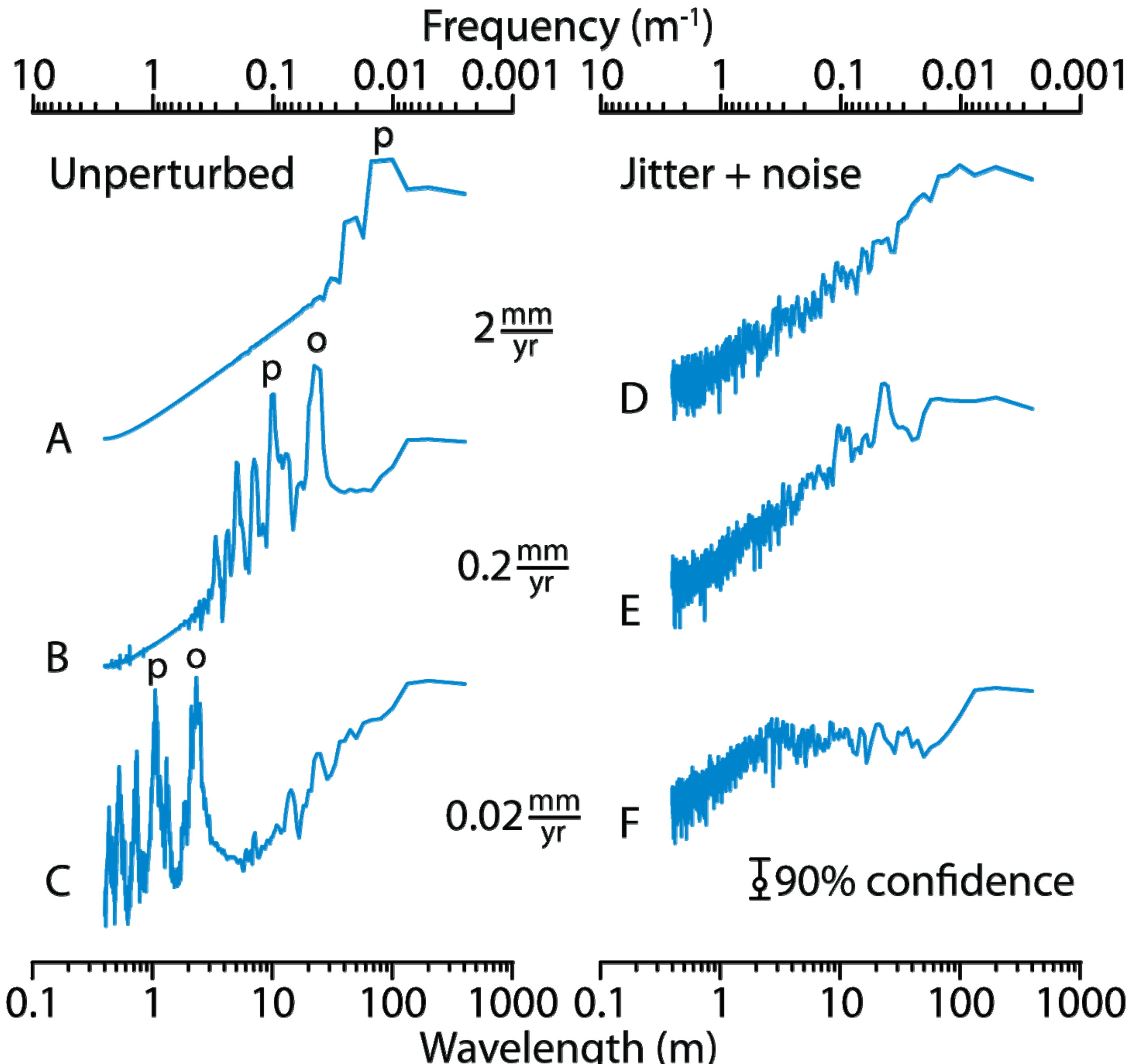
Perron & Huybers 2009

If we add this amount of noise to a clear orbital signal, can we recover it?



With jitter and noise, some orbital peaks cannot be distinguished from the background

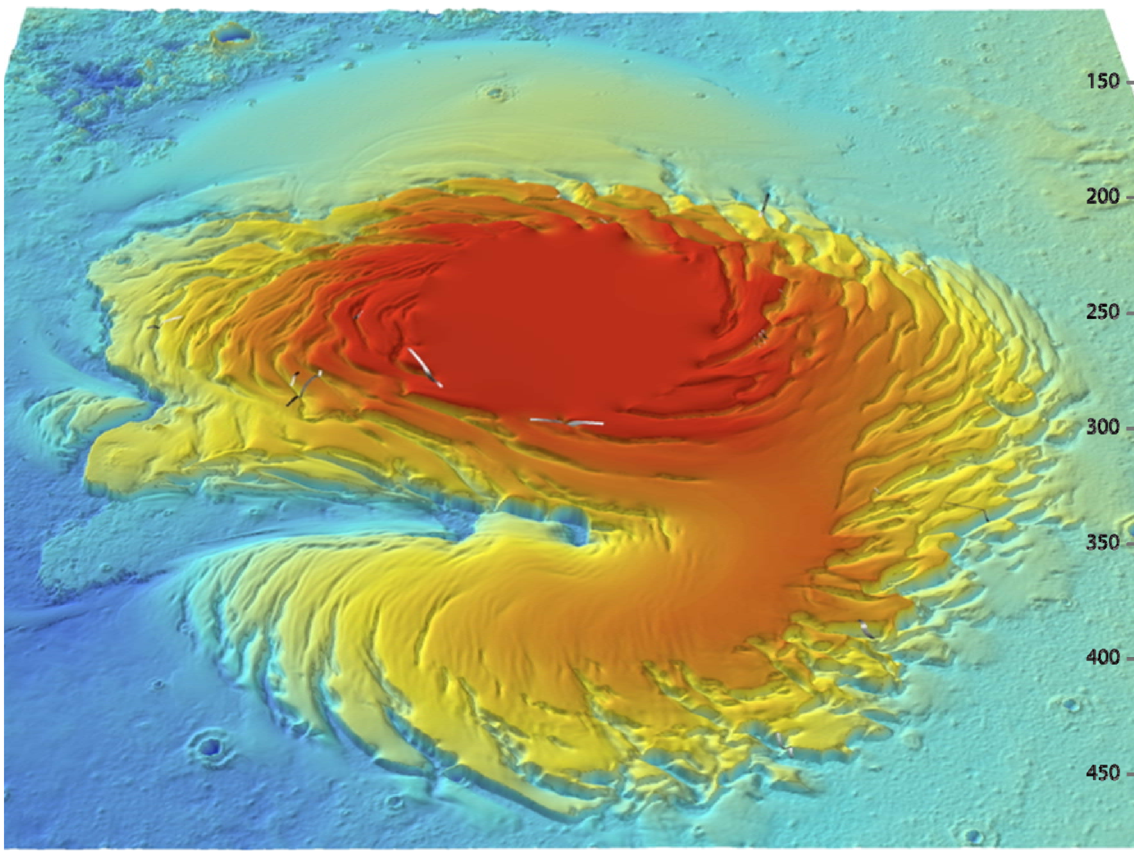
Our ability to resolve orbital signals with current data depends on accumulation rate

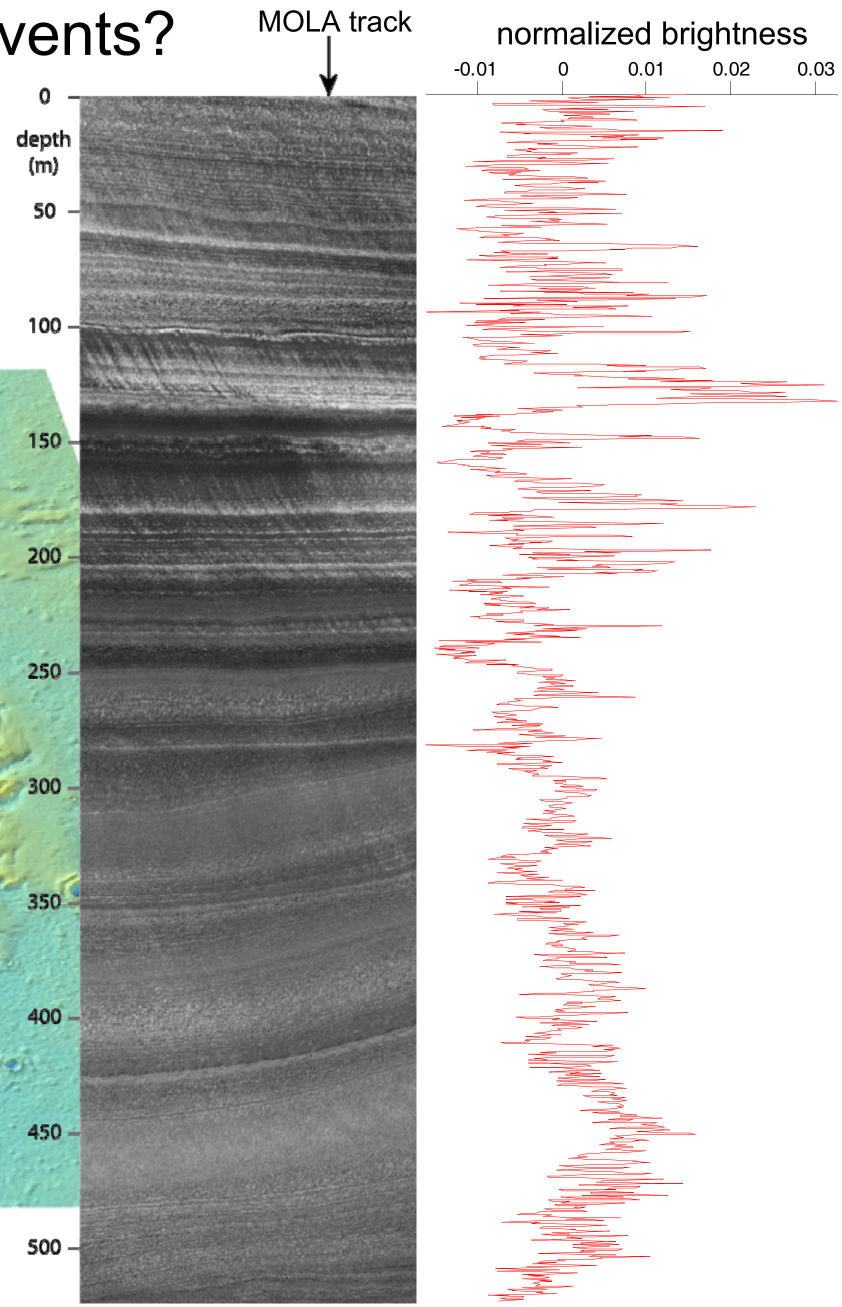


Perron & Huybers 2009

2. Can we reject the null hypothesis that the PLDs record stochastic climate events?

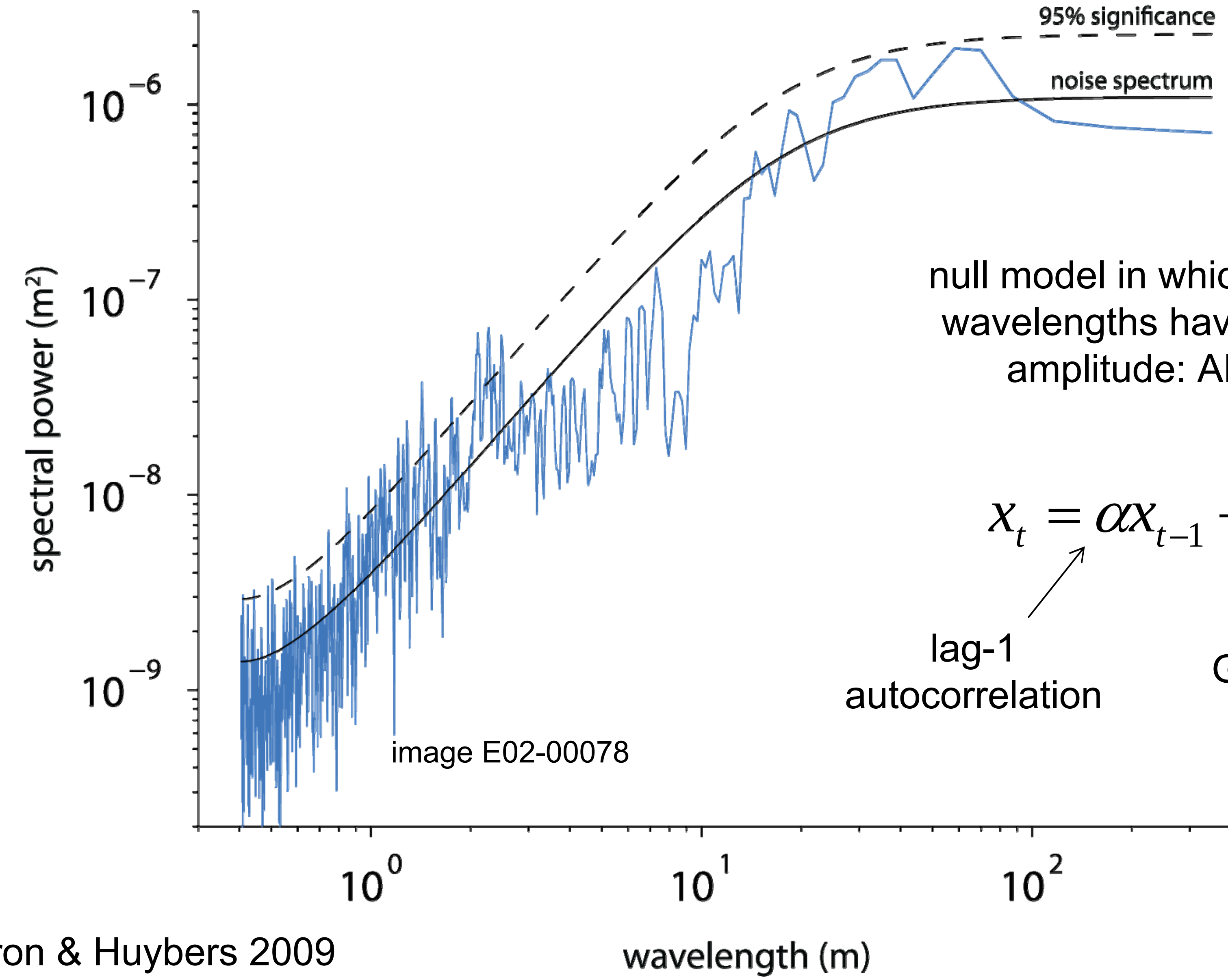
Constructed brightness vs. depth profiles for 30 images





E02-00078

Power spectra for the PLD stratigraphy are largely consistent with a red noise background



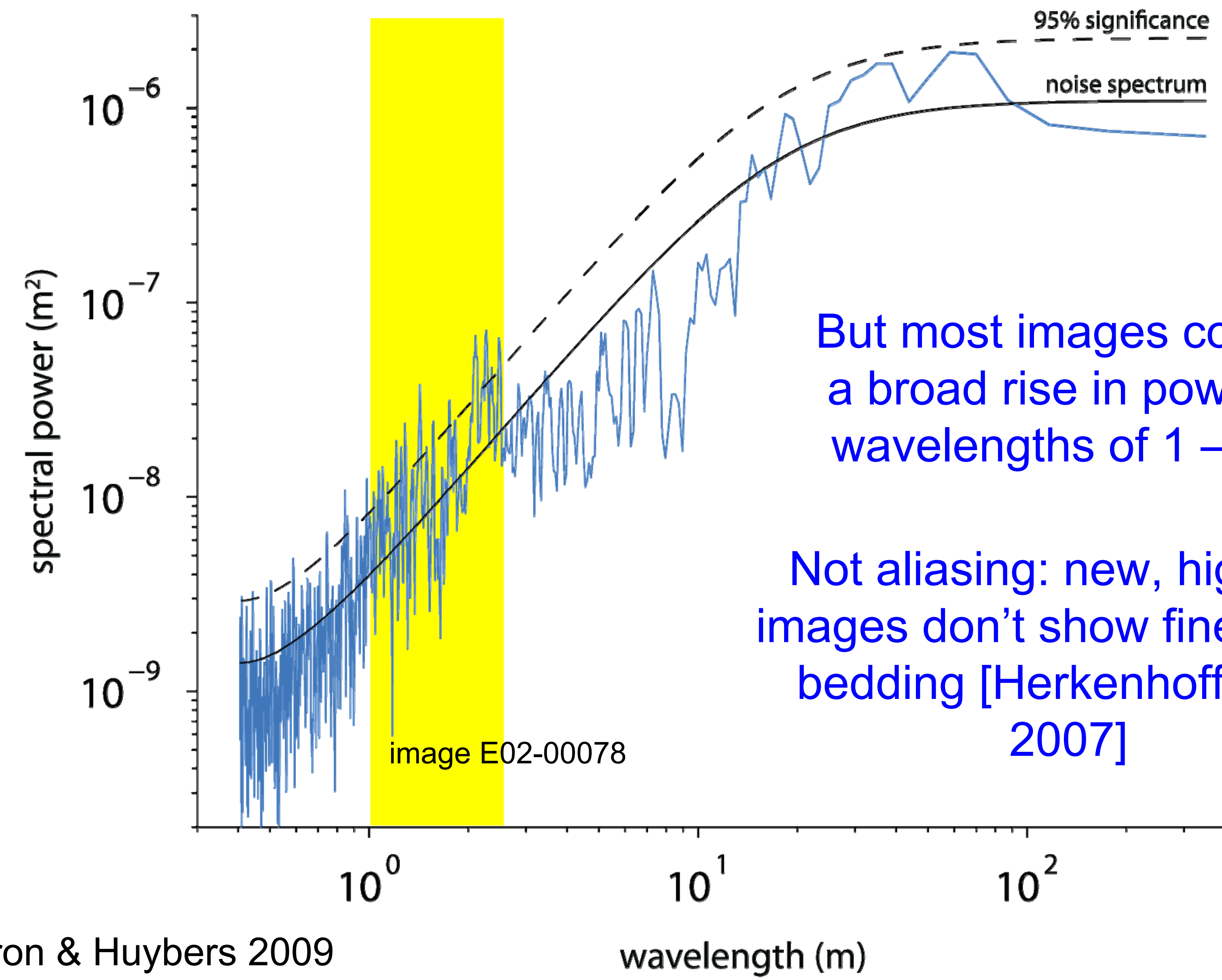
null model in which longer wavelengths have larger amplitude: AR(1)

$$x_t = \alpha x_{t-1} + x'_t$$

lag-1 autocorrelation

Gaussian noise

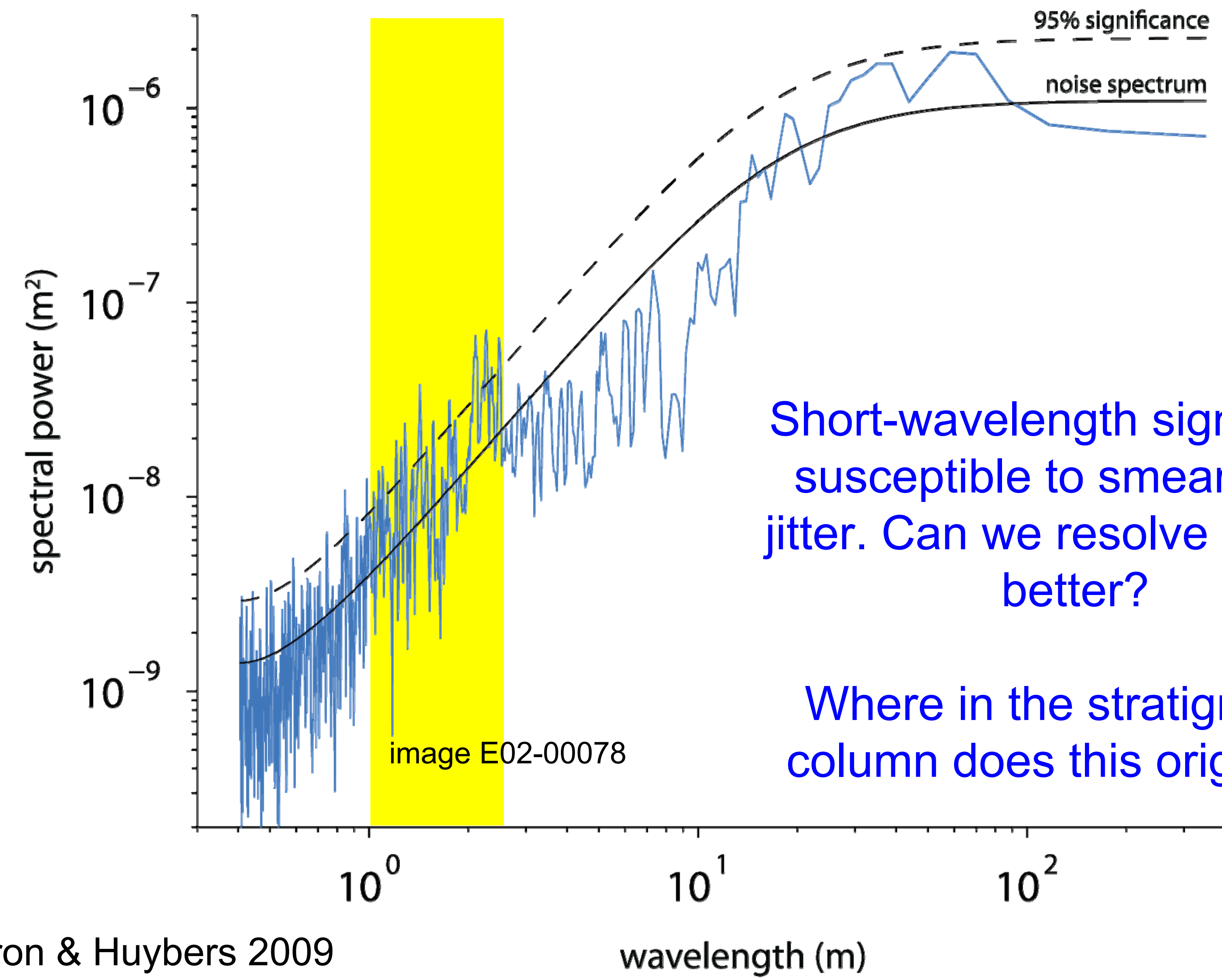
Perron & Huybers 2009



But most images contain a broad rise in power at wavelengths of 1 – 3 m

Not aliasing: new, high-res images don't show finer-scale bedding [Herkenhoff et al. 2007]

Perron & Huybers 2009

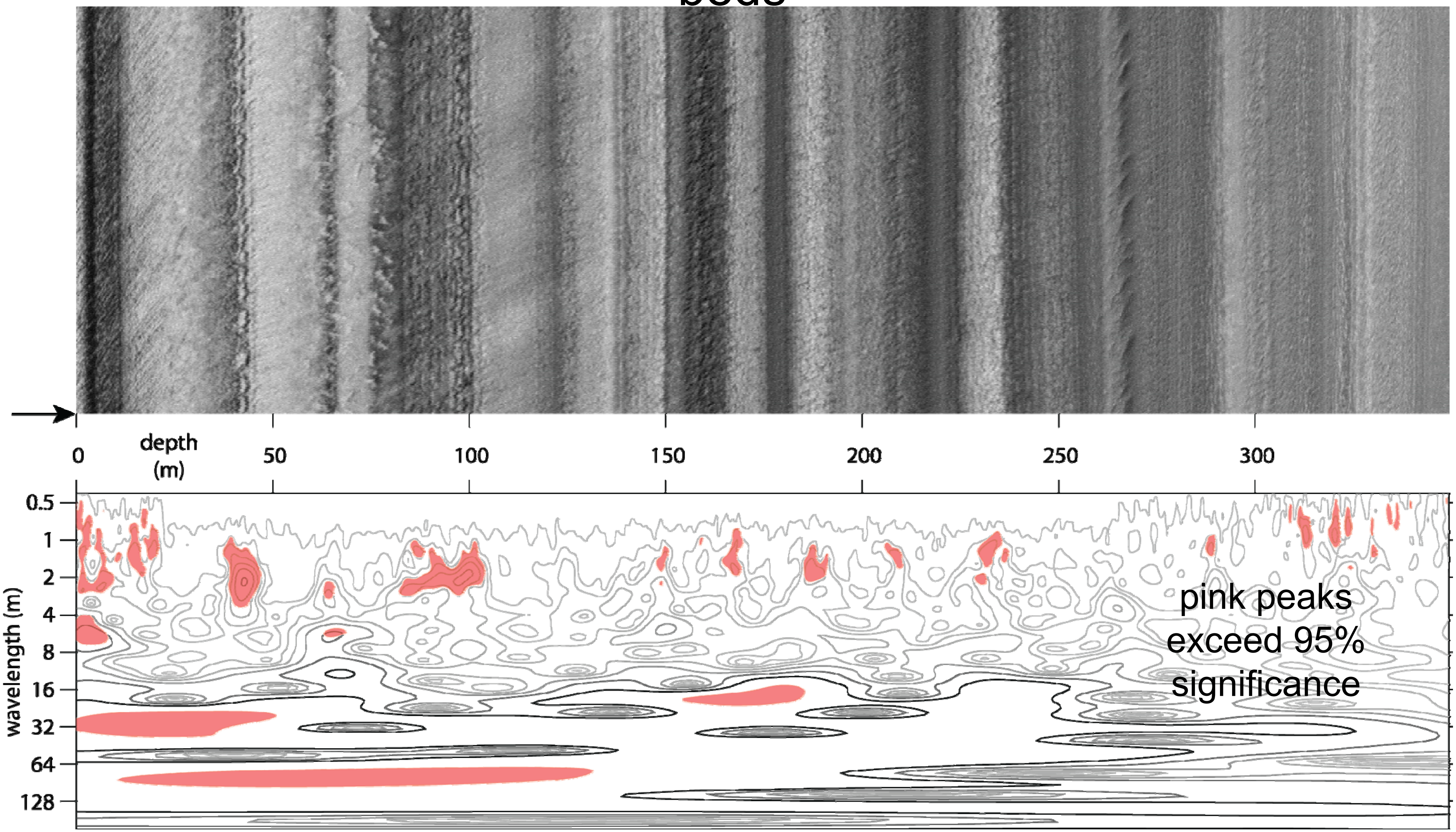


Short-wavelength signals are susceptible to smearing by jitter. Can we resolve this any better?

Where in the stratigraphic column does this originate?

Perron & Huybers 2009

Wavelet spectra reveal intermittent packages of 1.5 ± 0.1 m beds



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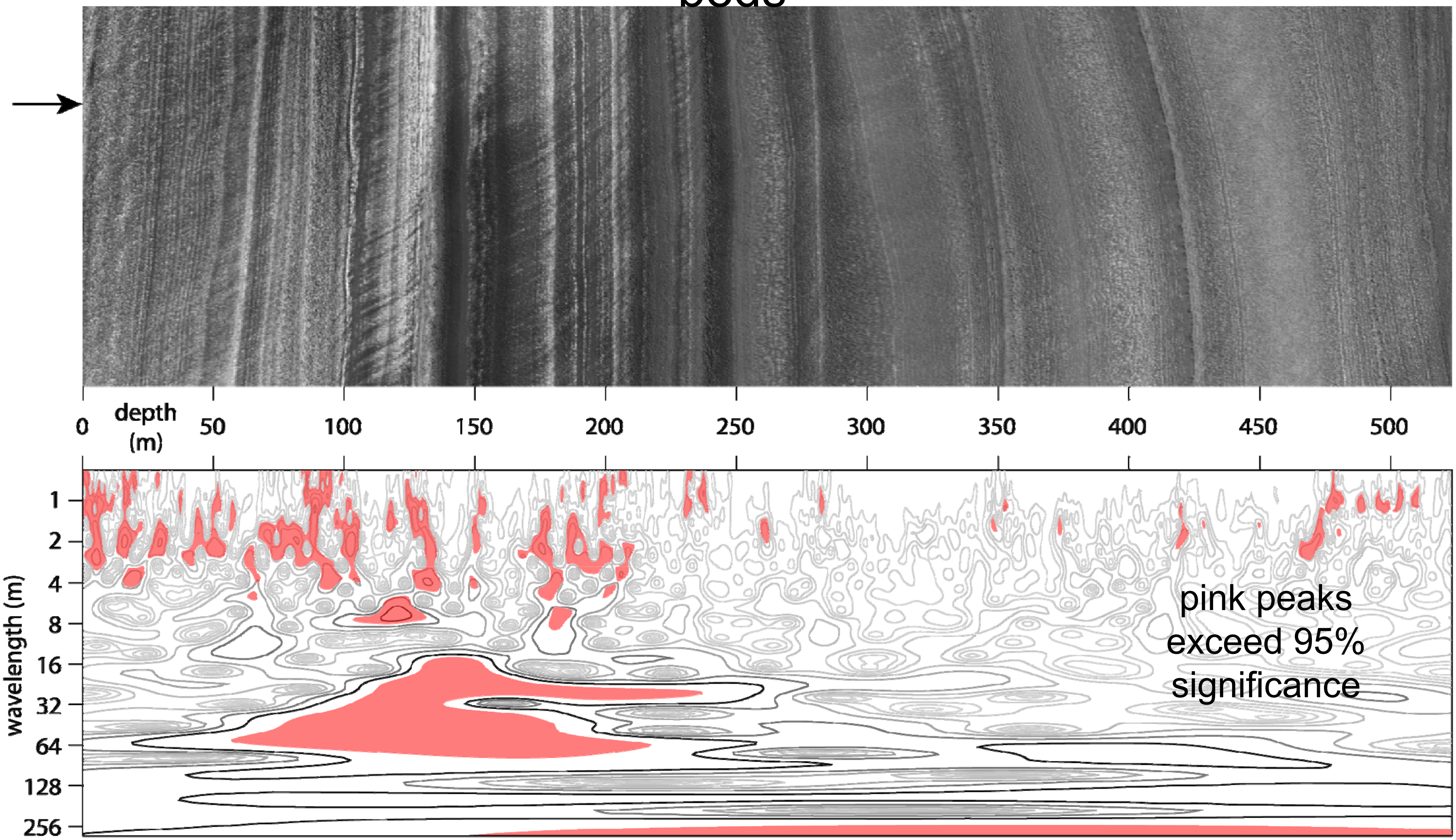
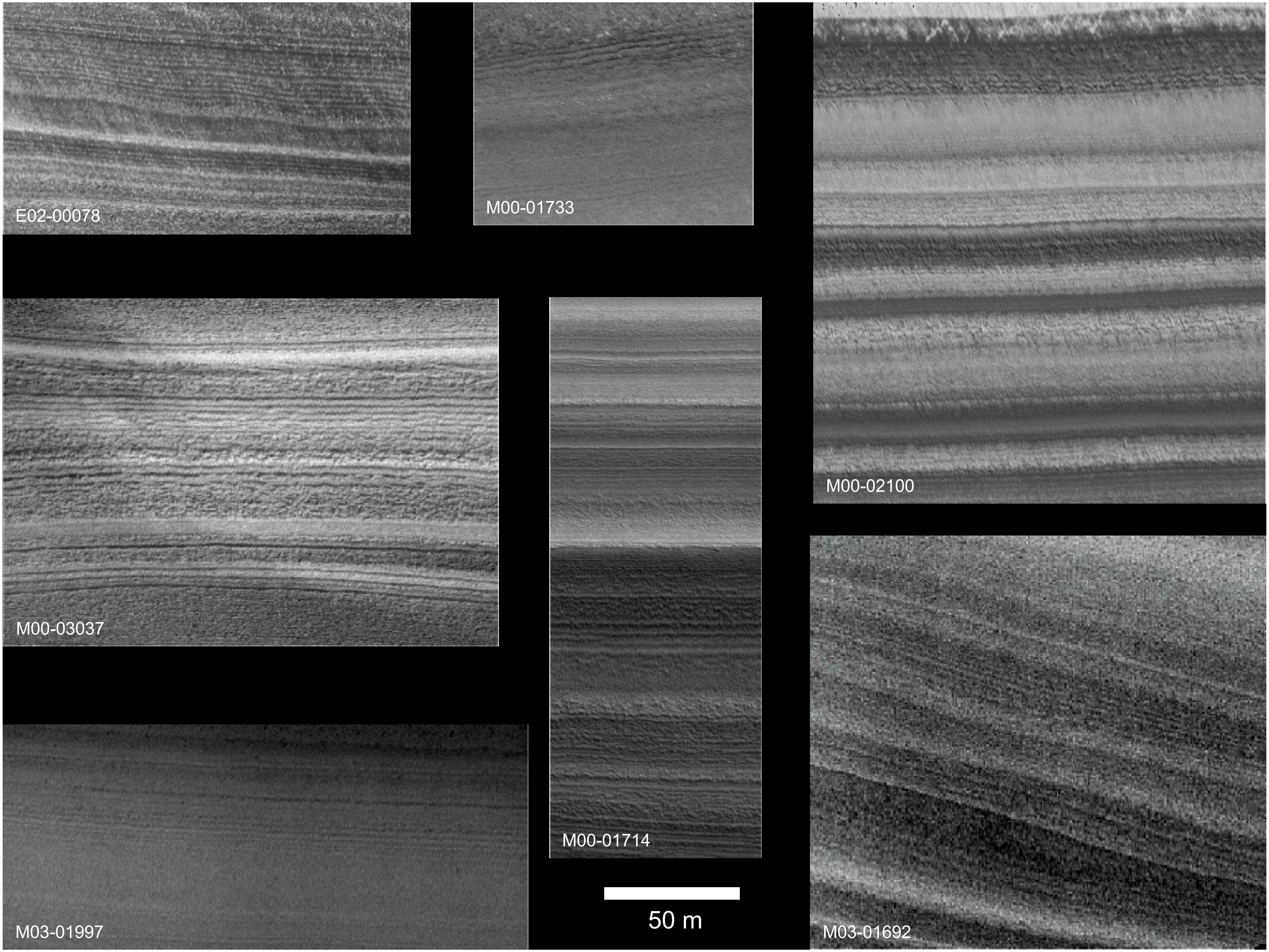
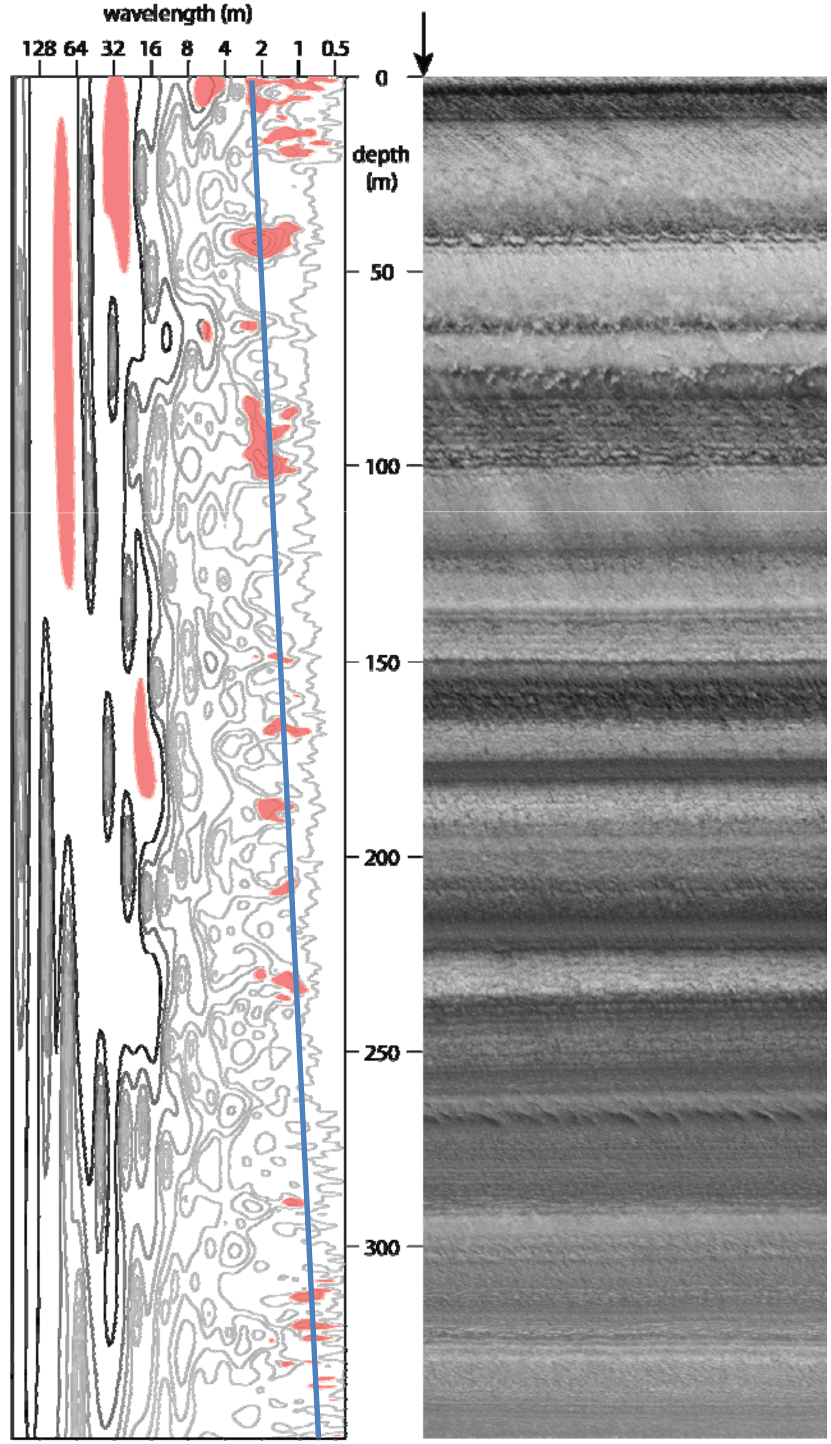


Perron & Huybers 2009

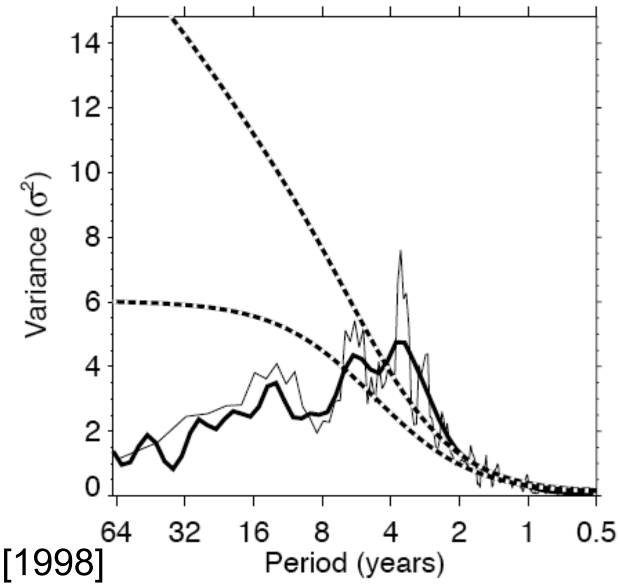

E02-00078
M00-01733
M00-02100
M00-03037
M00-01714
M03-01997
50 m
M03-01692

Thinning of beds with depth suggests compaction, shear, or systematic increase in deposition rate over time

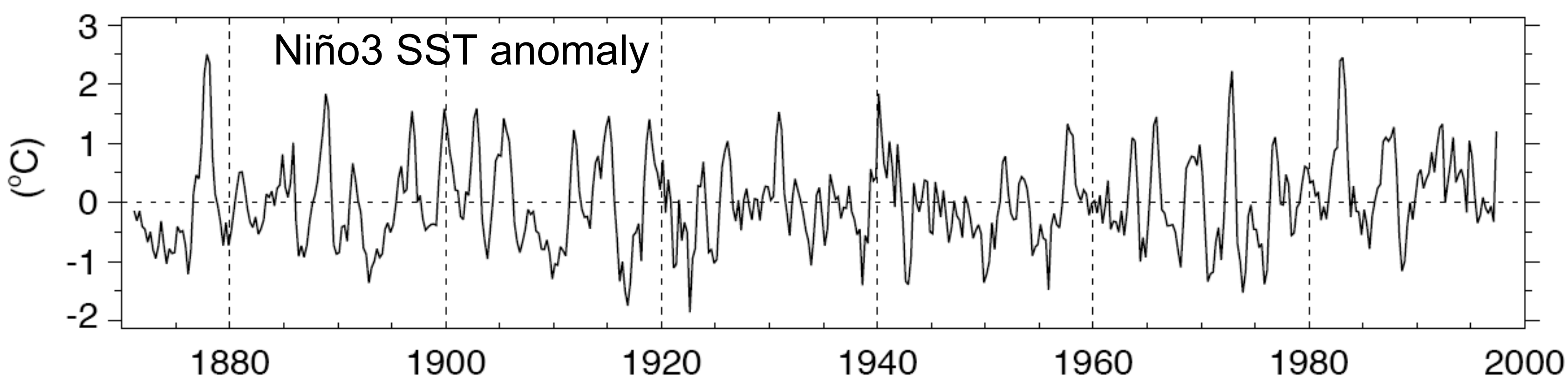


Possible interpretations of the fine-scale bedding:

- Formed in response to precession (51 kyr) or obliquity (120 kyr) forcing → PLD deposition rate 0.014 to 0.032 mm/yr, deposition time 30-70 Myr
- Results from internal climate processes that are not directly related to insolation
  - terrestrial examples: ENSO, Dansgaard/Oeschger events
  - Mars: dust storms



Torrence & Compo [1998]



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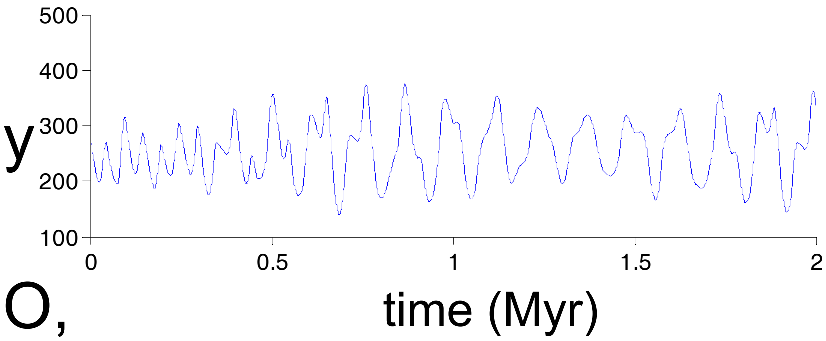
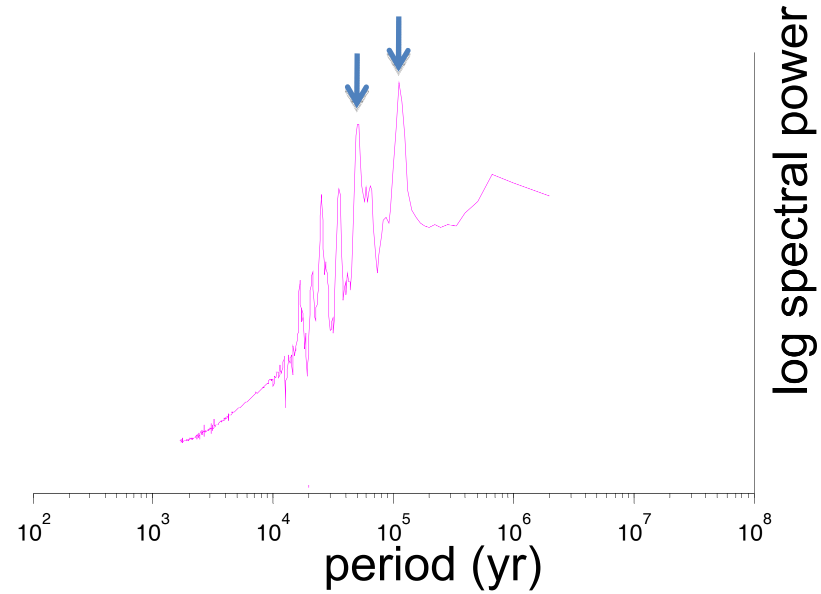
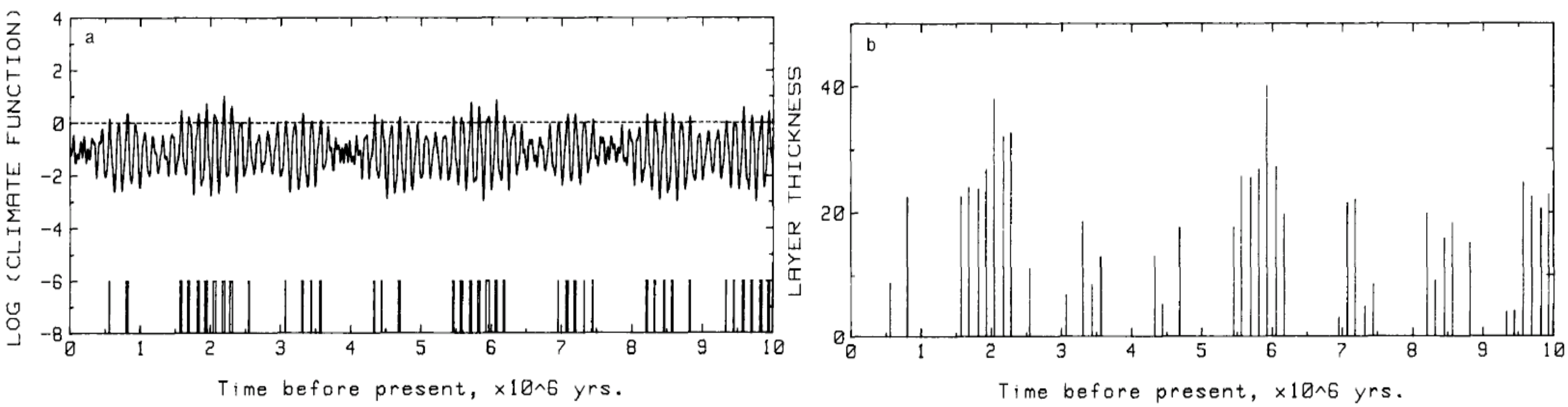


- Whatever its origin, it does not satisfy the criteria for detection of an orbital signal



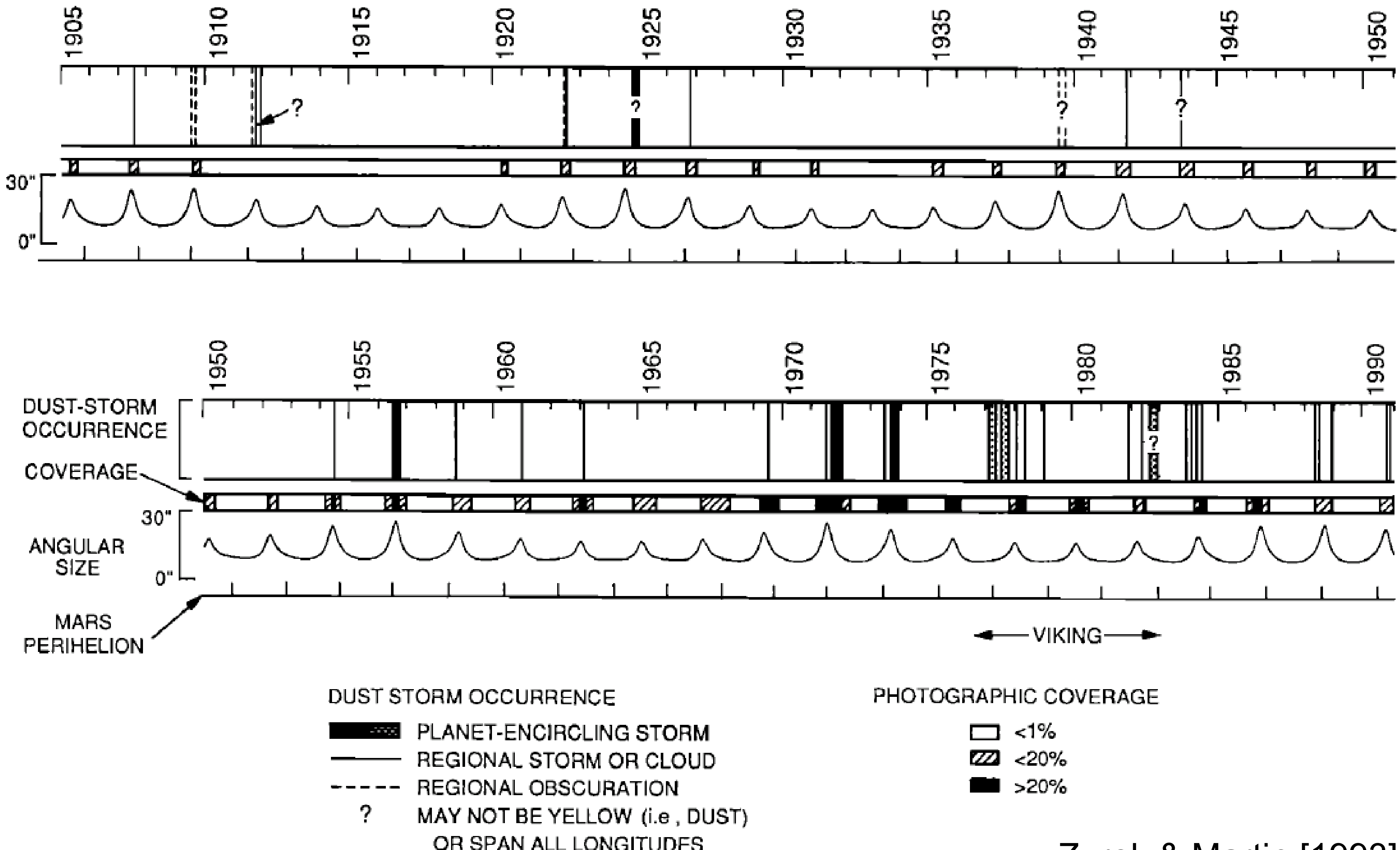
Why isn't there a clear orbital signal?

1. Orbital forcing is negligible
2. Stratigraphic record contains biases
   – Jitter and noise could be sufficient
3. Relationship between insolation and formation of PLD is nonlinear
   – Linearity requires constant ice deposition rate
   – GCMs: long-term dust dynamics are not simple
   – Cutts & Lewis [1982]: simple deposition rules (e.g. T threshold) create intermittently



Try as we might to simplify, nonlinear systems crop up when we're least expecting them…

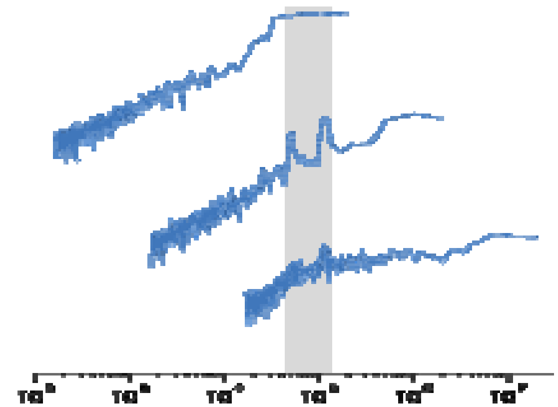
…and Mars' climate does seem to respond nonlinearly to insolation forcing



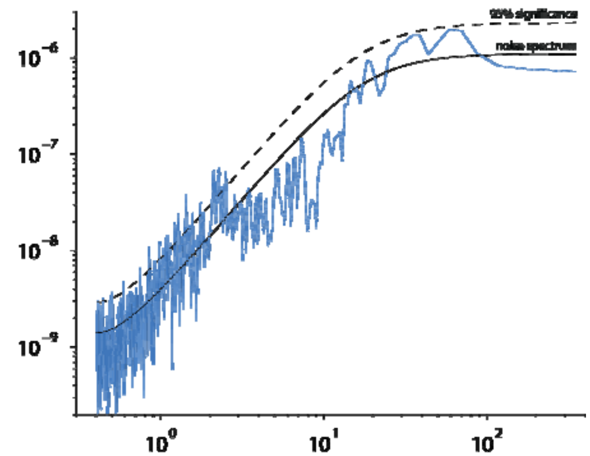
Zurek & Martin [1993]

Recent climate records: Conclusions

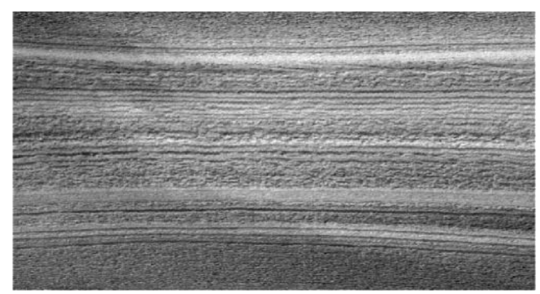
- Jitter, noise hamper detection of even simple orbital signals, especially if NPLD formed in >10 Myr or < 1 Myr

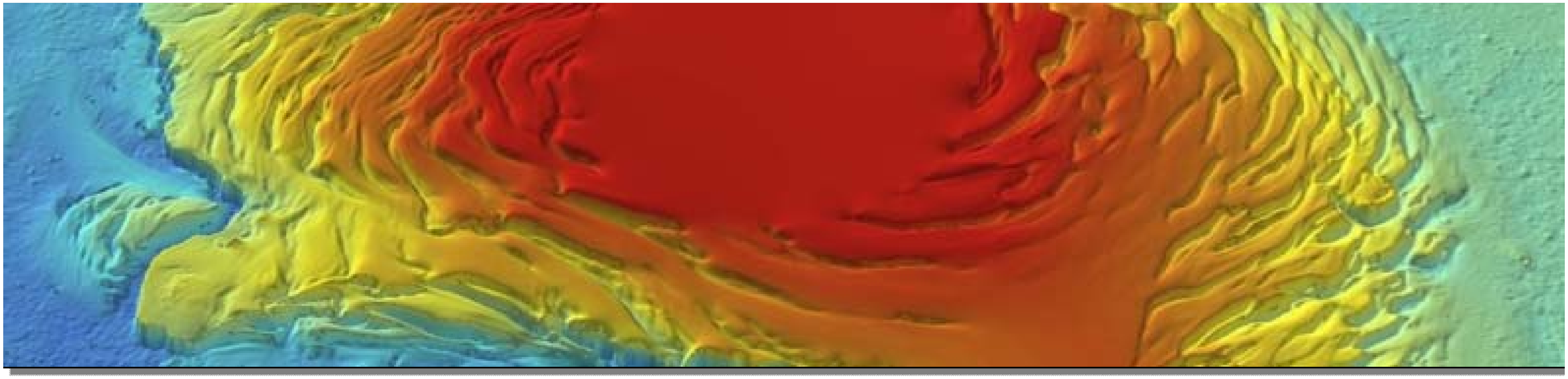


- NPLD stratigraphy is largely consistent with a stochastic formation process, with no diagnostic ratio of periods

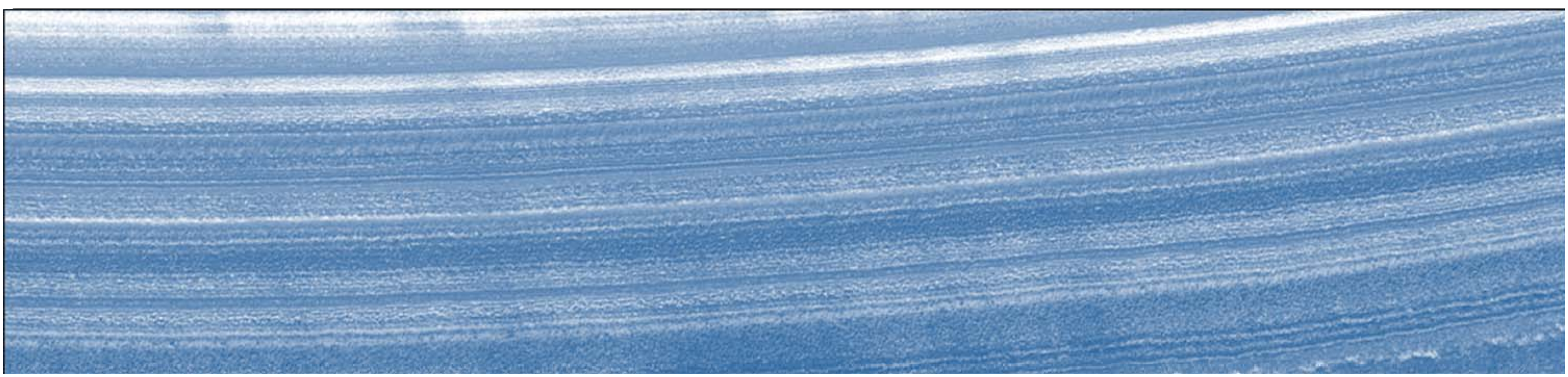


- Widespread, intermittent 1.6 m bedding deserves more investigation: high-res topography





Prospects for future missions



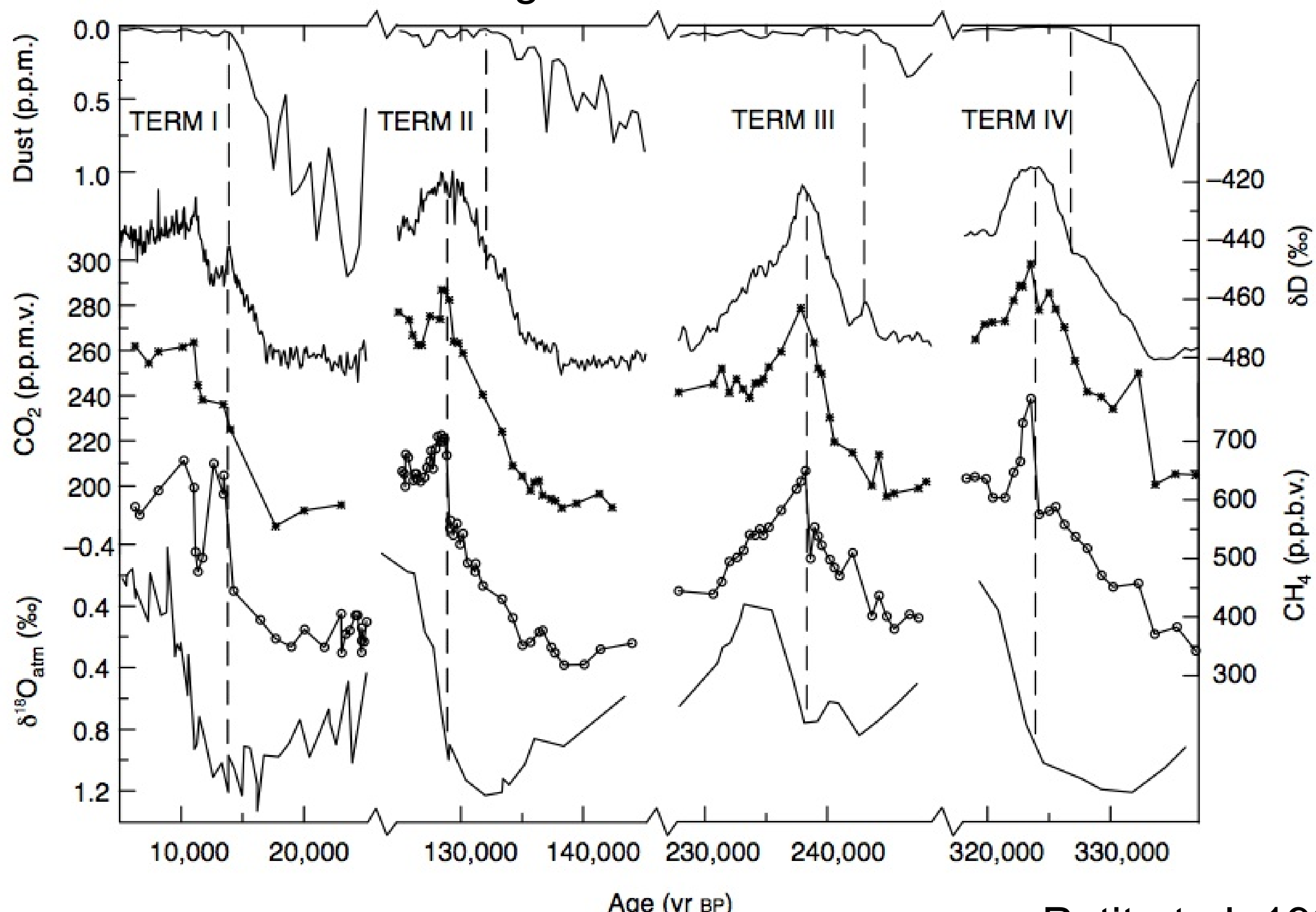
Key questions

- How is the polar stratigraphy related to global climate variables?
- Does this climate record reflect mainly:
  - External forcing, or internal variability?
  - Quasi-periodic or stochastic variability?
- What time span is covered, and how continuous is the record?

Key questions

- What sequence of events accompanies major changes in ice stability on Mars?

Pleistocene glacial terminations at Vostok



Petit et al. 1999

Critical measurements

- Composition
  - Dust
    - Mineralogy, ash/sulfur deposits
    - Concentration via magnetism, conductivity
    - Grain size as proxy for storm intensity
  - Ice
    - Stable isotopes: δD
    - Minor constituents (e.g. Na, Cl on Earth)
  - Atmosphere
    - Volcanic emissions
    - Greenhouse gases: CO_2, CH_4
- Physical properties
  - Ice grain size and fabric
  - Thermal properties
  - Magnetic signatures

Biggest opportunities

- Record of any duration is interesting
  - Slow accumulation → Long record that spans many orbital cycles
  - Fast accumulation → Record resolves timescales of orbital variability as well as short-term, internal variability
- Polar troughs provide access to 100s of meters of stratigraphy without deep drilling
- Clearest, most direct climate record on Mars
- Polar caps are largest known water reservoir

Biggest challenges

- Sustaining a mission in a high-latitude topographic depression
- Traversing stratigraphy: gentle slope on average, but steep over 1 to 10m
- Surface alteration of strata
- Establishing an absolute chronology
- Recent (Amazonian) climate record, not “deep time”

Major points

- Multiple datasets show that polar strata record regional/global events rather than local processes
- We lack direct information on composition of strata
- Stratigraphic variability likely related to temperature variations, but relationship is not well understood