Overview of polar stratigraphy
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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
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, 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
Measurements we *do* have

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

**Topography**
Global at sub-kilometer resolution (better at poles)

**Laser altimeter shots along MOC images at 300m spacing**

**1m DEM from stereo HiRISE images**

A. Ivanov/PDS

Fishbaugh et al. 2008
Measurements we do have

**Radar**

**High resolution from SHARAD**
Phillips et al. 2008

**Planum Boreum**

**Deep sounding from MARSIS**
Plaut et al. 2007
South pole

Dielectric coefficient consistent with ~90% ice
Measurements we do have

Gravity  Inferred density of south polar deposits indicates 15%

A  Topography (m)

B  observed gravity (mgal)

C  model gravity (mgal)

D  RMS misfit (mgal)

Zuber et al. 2008
Measurements we **do** have

**Spectr** Some information on composition and correlation to color

CRISM color composite

Strength of 1.5 μm H₂O absorption

Even dark layers are icy

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

Polar strata record regional/global variability

Planum Boreum

87°N 71°E

head of Chasma Boreale

Gemina Lingula

100 km

1000 m

Phillips et al. 2008
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

Milkovich & Head 2005,

Fishbaugh & Hvidberg 2006
Polar stratigraphy is more complex than initially expected.

But HiRISE has not revealed finer stratification than previously known. 

[Herkenhoff et al. 2007]
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

Laskar et al. 2002
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**

**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

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

Carl Wunsch*

Quaternary Science Reviews 23 (2004) 1001–1012

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

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 \(~30\)m wavelengths.
Milkovich & Head (2005, 2008) examine spectra for 30 images, and find strongest signals at ~30m wavelengths. But the largest-amplitude signal is not necessarily the most periodic...
Fishbaugh et al. (2008, 2009, in press) find support for repeating beds 10s of m thick in topography from one stereo HiRISE image.
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 ↔ PLD formation?
  (but for this exercise we’ll assume it’s simple)
- Image artifacts
- 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”

\[
\text{jitter} = \frac{\text{variance(thickness)}}{\text{mean(thickness)}} \leq 0.25 \quad \text{(a minimum)}
\]

Perron & Huybers 2009
If we add this amount of noise to a clear orbital signal, can we recover it?

deposition rate = 2 mm/yr

Insolation at 85° N at Ls=90 (W m⁻²)

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**
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

$95\%$ significance

noise spectrum

spectral power (m$^2$)

10$^{-6}$

10$^{-7}$

10$^{-8}$

10$^{-9}$

image E02-00078

Perron & Huybers 2009

wavelength (m)
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].
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 $1.5 \pm 0.1$ m beds

Perron & Huybers 2009
Wavelet spectra reveal intermittent packages of $1.5 \pm 0.1$ m beds.

Pink peaks exceed 95% significance.

Perron & Huybers 2009
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 nonlinearily 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: $\delta D$
    • 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