GEOS 28600

The science of landscapes: Earth & Planetary Surface Processes

Lecture 1

Monday 1 October 2018

Introduction.

Shape, geoid, true polar wander.

INTRODUCTION

SHAPE (HYDROSTATIC, $\rho = \rho(r)$)

GEOID (WHAT IS TOPOGRAPHY MEASURED RELATIVE TO?)

TRUE POLAR WANDER

Logistics

Class website:

http://geosci.uchicago.edu/~kite/geos28600_2018/

6 problem sets, 5 labs

Grading scheme: 60% homework, 30% final, 10% class participation. Final will be closed-book, but you will be allowed to take in 1 sheet of letter-sized paper with notes.

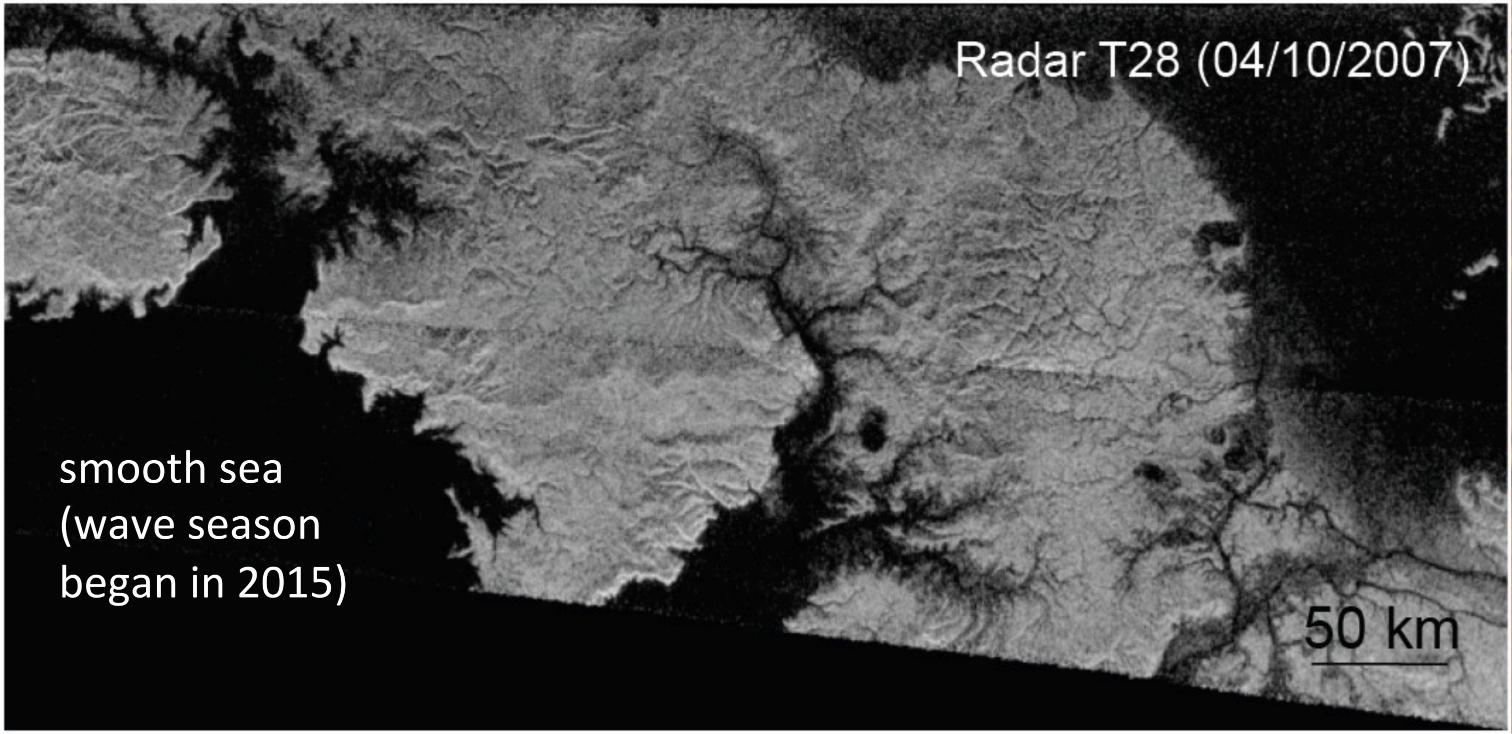
We study landscapes to gain a process understanding and to understand planetary history

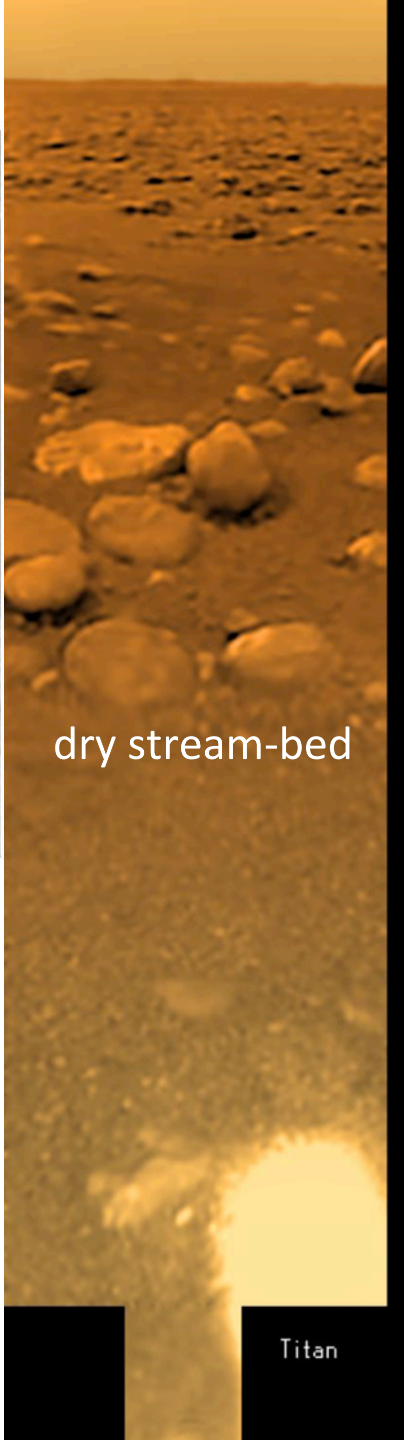
Earth's surface. Tectonics, aeolian processes, fluvial processes: H_2O, ~300K

Landscapes result from competition between geologic processes

- Know the processes, their rates, and the controls on those rates, and you have a scientific understanding of the landscape.

History: Fluid envelopes (atmosphere, ocean) permit life on Earth.
Planets with solid surfaces retain traces of the evolution of their fluid envelopes over geological time.

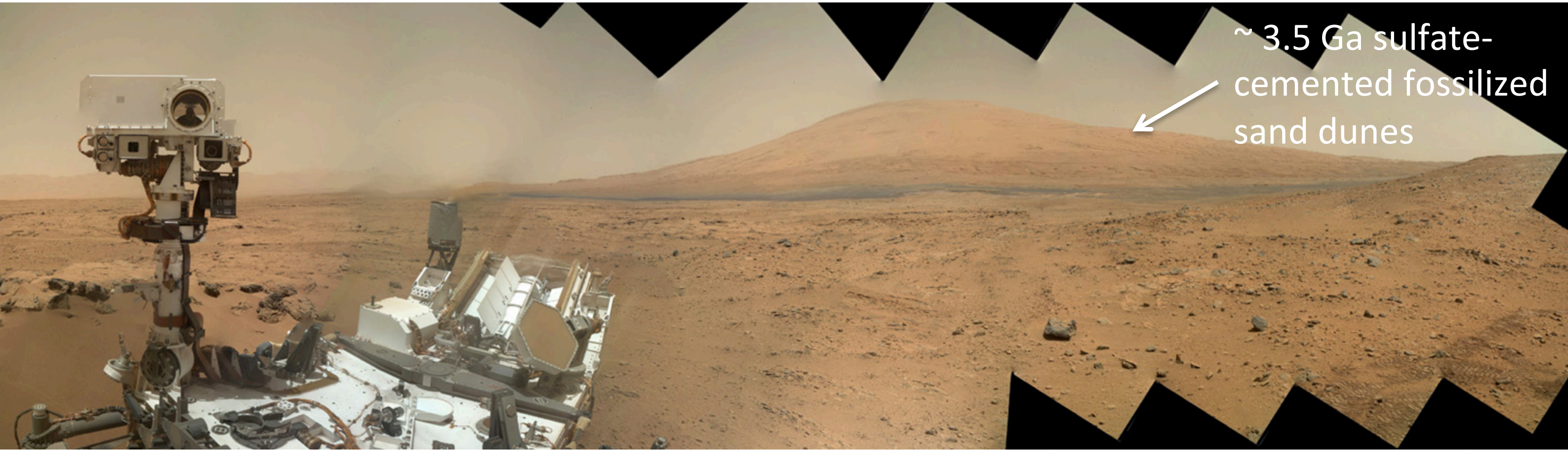




Titan’s surface. Fluvial processes: $CH_{4,}$ ~80K

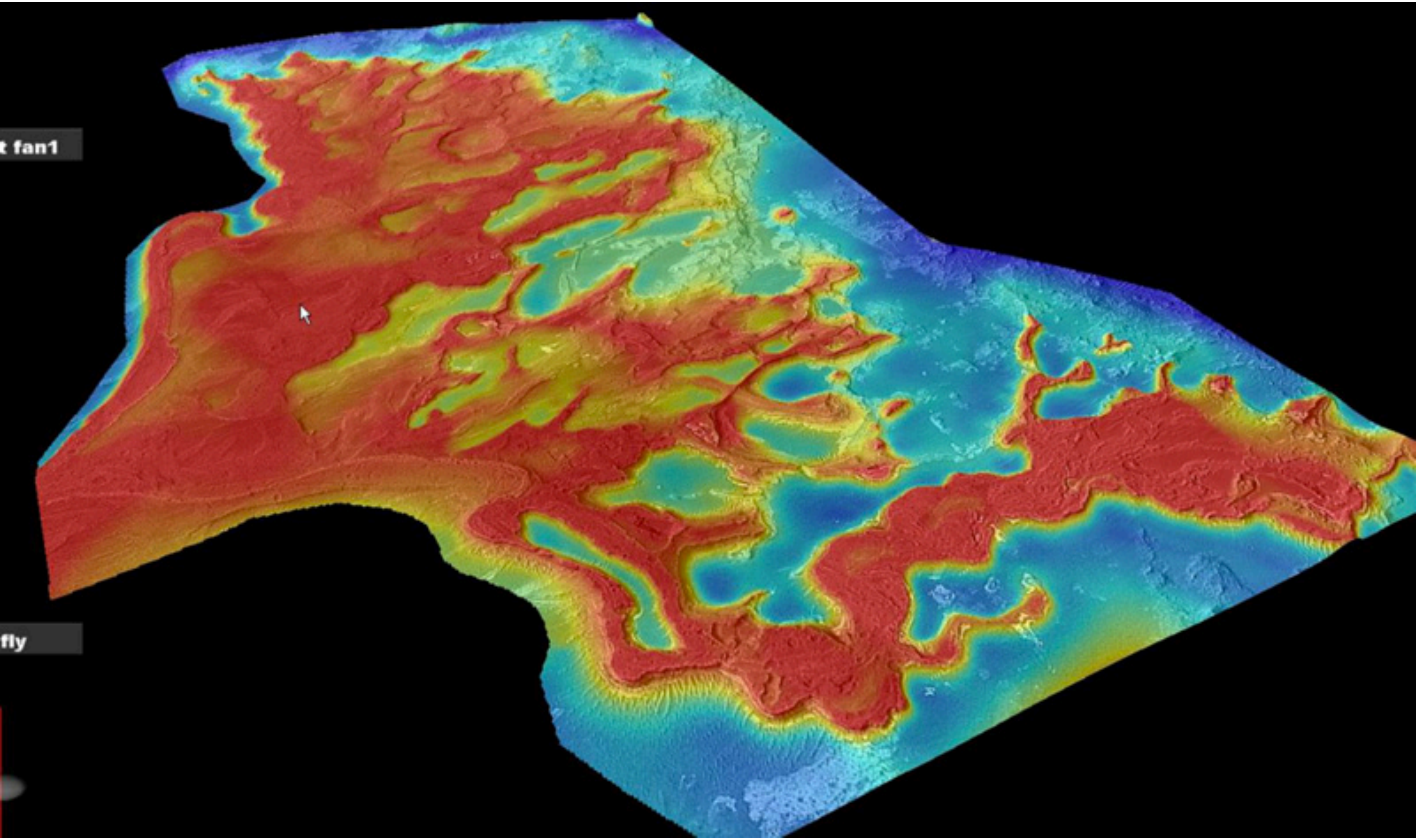
Apollo 15 Commander Dave Scott is picking up the Apollo Lunar Surface Drill at the ALSEP site. In the center is Mount Hadley and on the right, Lunar Module Falcon sits in front of the Swann Range

Moon’s surface. relatively simple: impact cratering + hillslope processes. Fundamentals



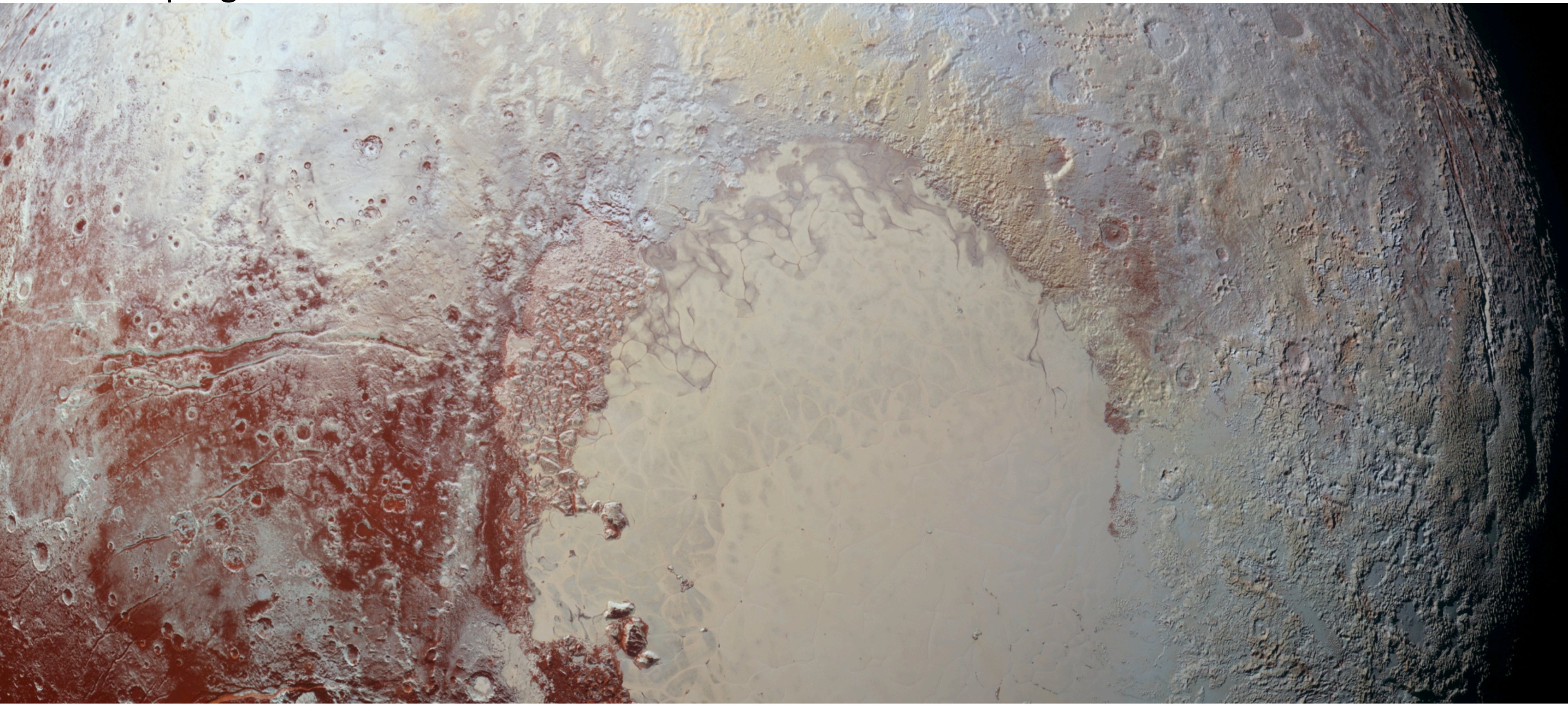
Mars surface. Weathering, soil formation, aeolian processes
intermediate complexity; history of fluvial processes

Ancient sediments on Mars




Sedimentary basins: time series of constraints on surface processes
Sedimentology, basin analysis

Course progression



FLYBY → ORBIT → LAND → ROVE

Pluto

Mercury

Titan

Mars, Earth

Lectures (plan: 2 per topic)

FLYBY

ORBIT

LAND

ROVE

a. Shape, gravity
b. Gravity, topography
c. Lithosphere (strength of)

examples mostly from Earth

d. Impact cratering
e. Hillslope processes
f. Lava
g. Ice
h. Aeolian processes

mix of Earth and Solar System examples

i. Rivers
j. Landscape evolution
   – Global
   – Local

examples mostly from Earth

Labs

- Sand dune formation (computer)
- Mars Exploration Rover analyst's notebook (Eagle crater)
- Landscape evolution modeling (computer)
- Mars landing site selection

Key points from today's lecture

- why planets are roughly spherical; relationship between internal mass distribution and rotational bulge.
- the definition of the geoid;
- principle of true polar wander;

evidence for true polar wander.

INTRODUCTION

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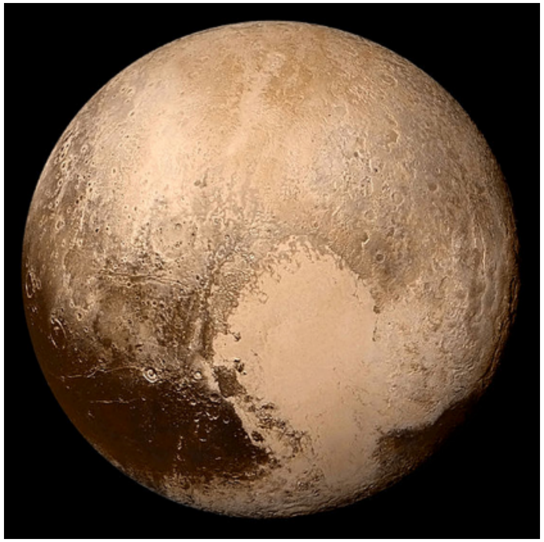
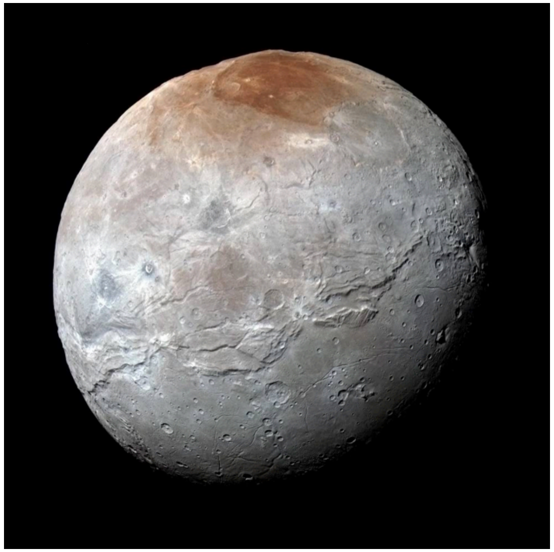
TRUE POLAR WANDER

Why do large worlds have round shapes?

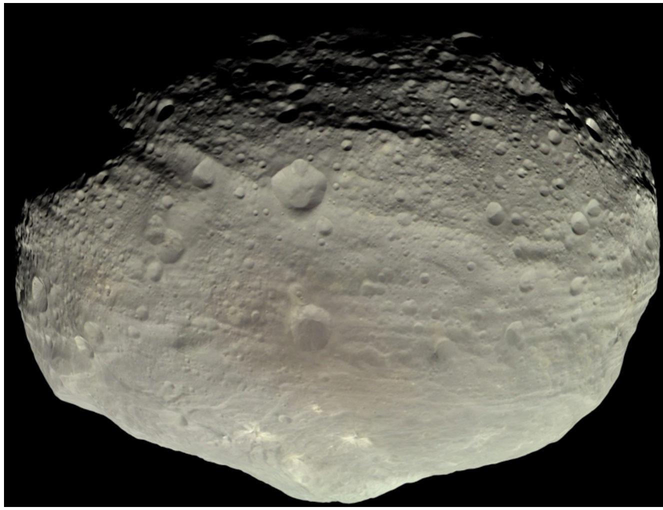
in this course: worlds = (planets + dwarf planets + moons + large KBOs)



Pluto, dwarf planet
2400 km diameter; ice



Charon, moon
1200 km diameter; ice



Vesta, asteroid
525 km diameter; rock

$$P_c = \frac{3GM^2}{8\pi \ R^4}$$

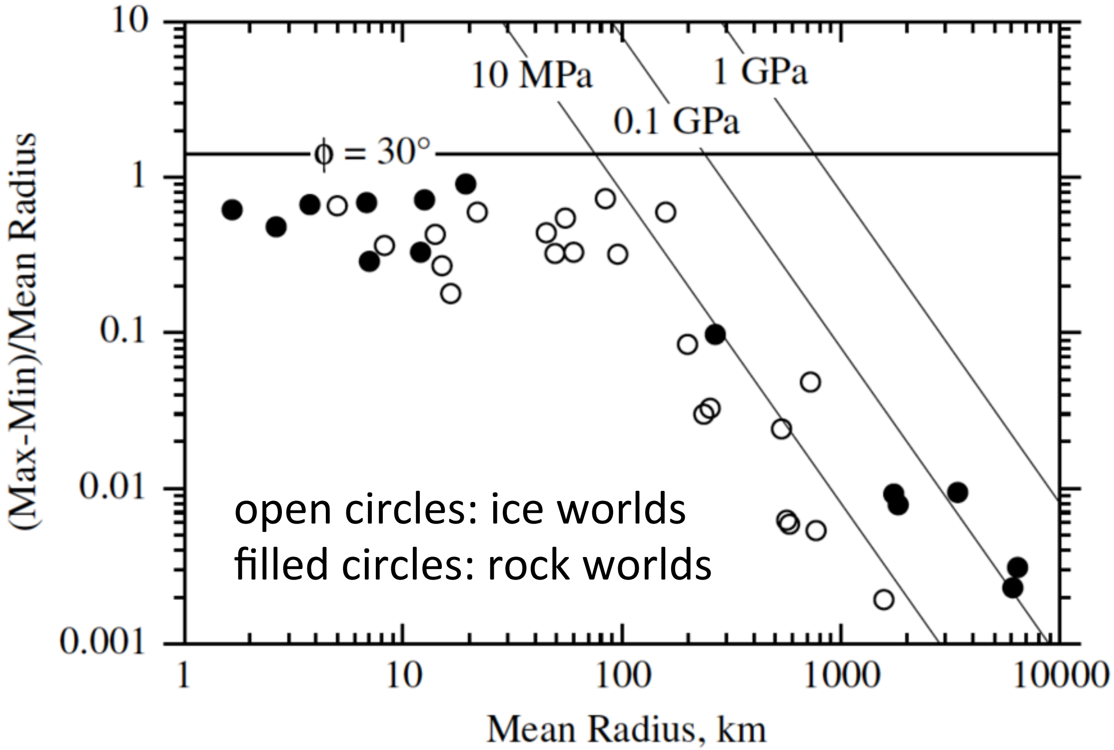
pressure or temperature?

do materials matter?

does time matter?

Why do large worlds have round shapes?

pressure or temperature?
do materials matter?



$$\frac{\left|\sigma_1 - \sigma_3\right|}{2} = Y$$

stress difference at failure/2

$$P_c = \frac{3GM^2}{8\pi\ R^4}$$

Why do large worlds have round shapes?

effect of temperature?

strain rate, s^{-1}

$$\dot{\varepsilon}_{\text{steady}} = A_c\, \sigma^n\, e^{-g\frac{T_m}{T}}$$

Planets are born hot and cool over time

Planetary materials deform geologically rapidly close to the melting point; worlds that are not relaxed either never got close to the melting point, or were modified after they cooled.

Material	A_c (MPa^{-n} s)	n	Q^* (kJ/mol)	T_m (K)	$g = Q/RT_m$
Olivine				2200	27
Dry	1.2×10^2	3.0	502		
Water ice, Ih,[d] $T > 258$ K $\sigma > 1$ MPa	6.3×10^{28}	4	181	273	80

Hydrostatic assumption: pressure is balanced by gravity

solid worlds behave like fluids

Strength also reduces on approach to melting point

sufficiently large

over geologic time & at large spatial scales

Does time matter? (Maxwell time)

Silly putty

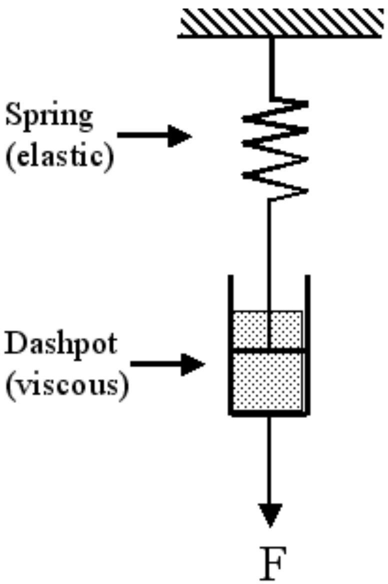
timescale over which solids behave like fluids?

$$\dot{\varepsilon}_{\text{total}} = \dot{\varepsilon}_{\text{elastic}} + \dot{\varepsilon}_{\text{viscous}}$$

$$\dot{\varepsilon}_{\text{total}} = \dot{\sigma}/2\mu + \sigma/2\eta$$

μ: elastic shear modulus

η: viscosity



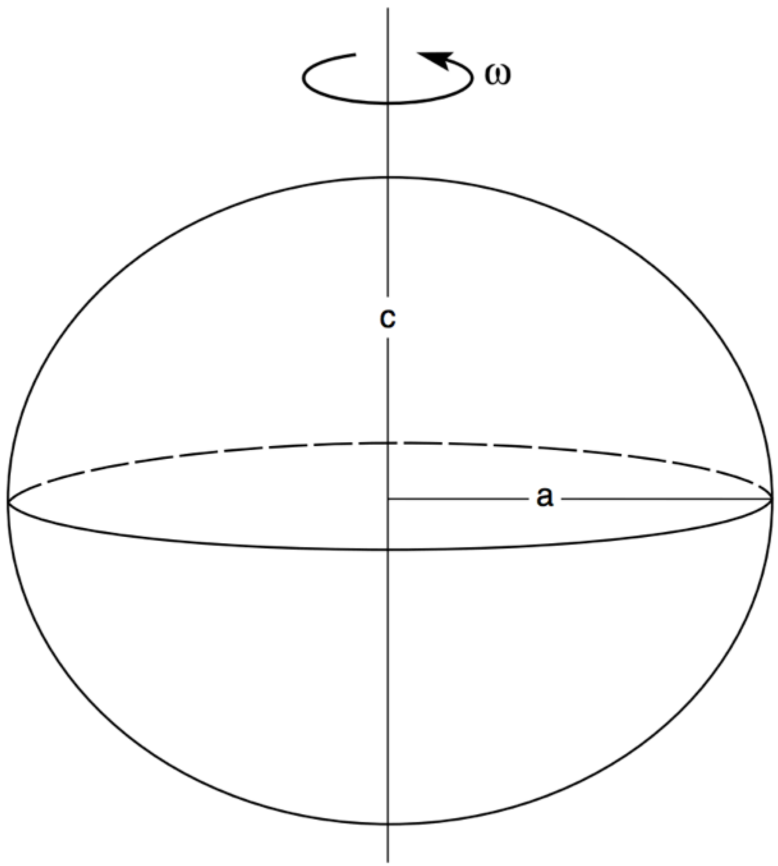
Maxwell Viscoelastic Model

$$\tau_M \equiv \frac{\eta}{\mu} \qquad \frac{\text{Pa}}{\text{Pa s}^{-1}}$$

Material	Shear modulus, μ (GPa)	Viscosity, η (Pa–s)	Maxwell time, τ_M
Soda-lime glass @ 250°C	25	4.3×10^{11}	17 s
Glacier ice @ 0°C	4	$\sim 10^{13}$	42 min
Halite @ 200°C	20	3×10^{16}	17 days
Earth mantle from glacial rebound	50	10^{20}	66 yr

as far as we know, all worlds in the solar system formed ~4.6 Gyr ago

Why do planets in hydrostatic equilibrium bulge at the equator?



$$m = \frac{\omega^2 a^3}{GM} \cong \frac{3}{4\pi} \frac{\omega^2}{G\bar{\rho}}$$

$$f = (a-c)/a = f(m) = ?$$

Assume: $m \ll 1$; no fluid circulation.
Basic criterion: no tangential forces at surface.

$$f \propto m$$

Hydrostatic equilibrium: pressure at the bottom of column-of-water (a) = pressure at the bottom of column-of -water (c)

"the appropriate theory [for the proportionality constant relating *f* and *m*] is quite nasty … and rather little insight emerges from wallowing in the nastiness."

How much do planets in hydrostatic equilibrium bulge at the equator?

Maclaurin spheroid:

$$f = \frac{\frac{5}{2}m}{1 + \frac{25}{4}\left[1 - \frac{3}{2}\left(\boxed{\frac{C}{Ma^2}}\right)\right]^2}$$

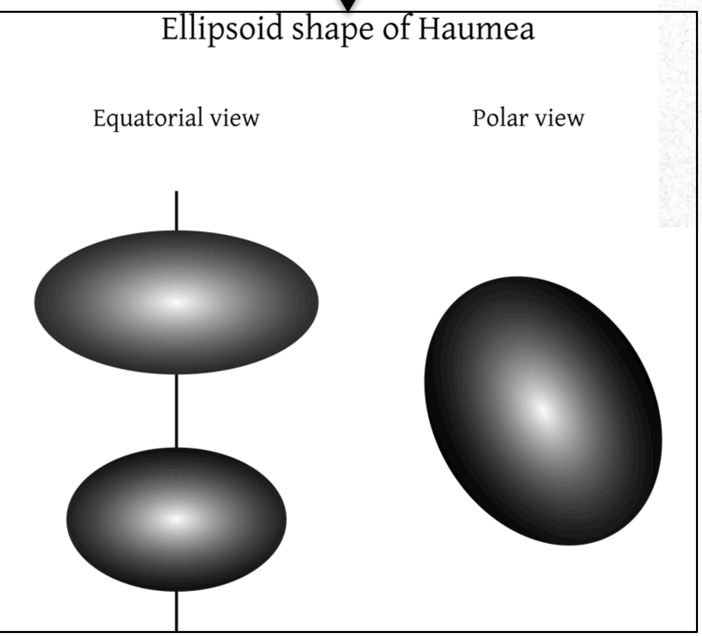
$$C = \int_o^M r^2 dm$$ where r is distance from the polar axis

0 for a point mass
0.4 for uniform density
1.0 for all mass in outer shell
0.331 for real Earth
(central concentration
of mass)

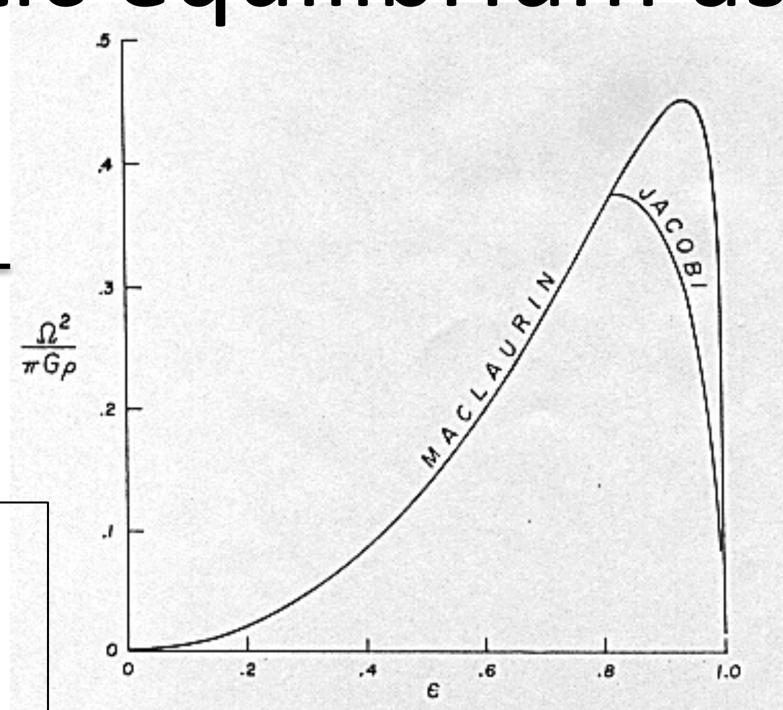
Assume: m<<1; no fluid circulation.

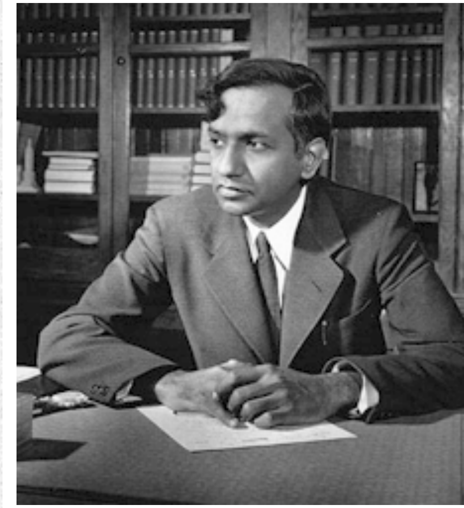
Hydrostatic equilibrium as $m \rightarrow 1$

$$m = \frac{\omega^2 a^3}{GM} \cong \frac{3}{4\pi} \frac{\omega^2}{G\bar{\rho}}$$

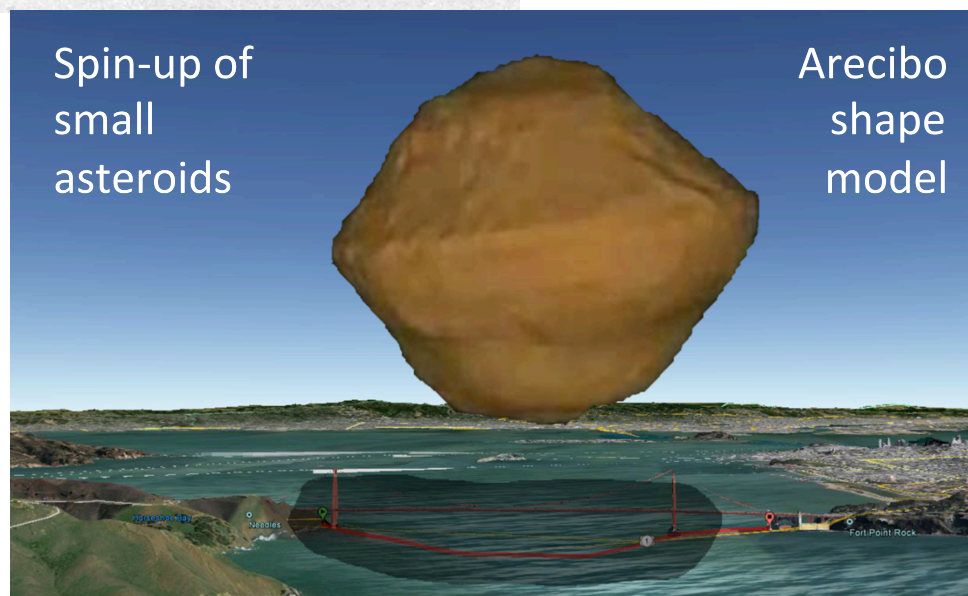


1,920 × 1,540 × 990 km





Chandrasekhar
(“Ellipsoidal figures,” 1960)



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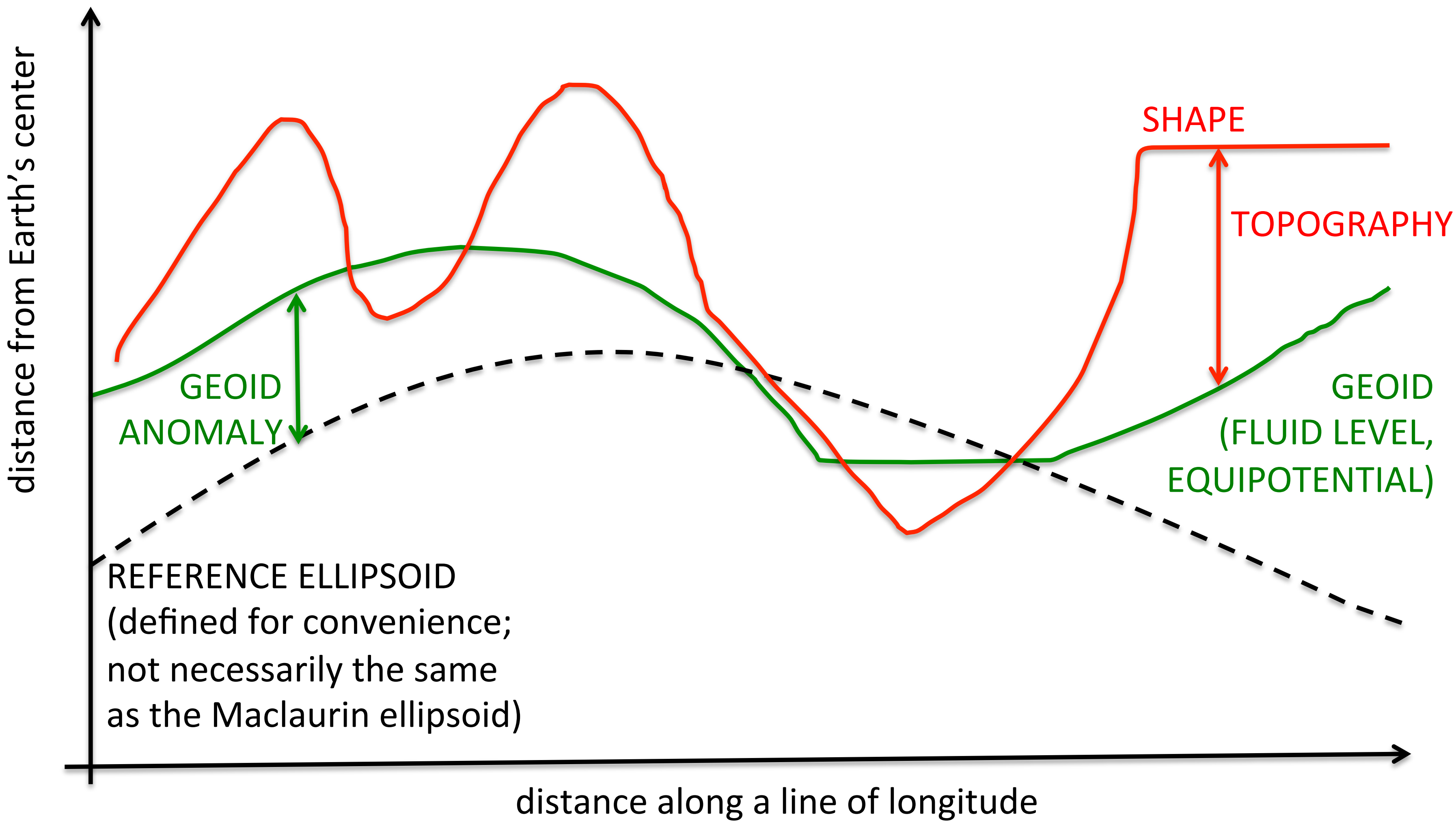
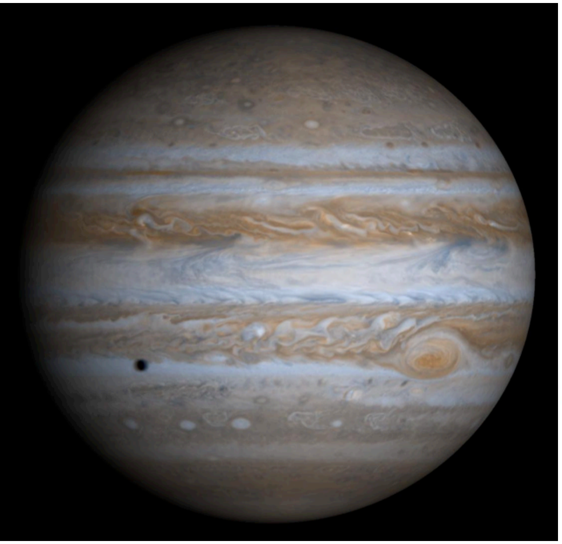
GEOID (WHAT IS TOPOGRAPHY MEASURED RELATIVE TO?)

TRUE POLAR WANDER

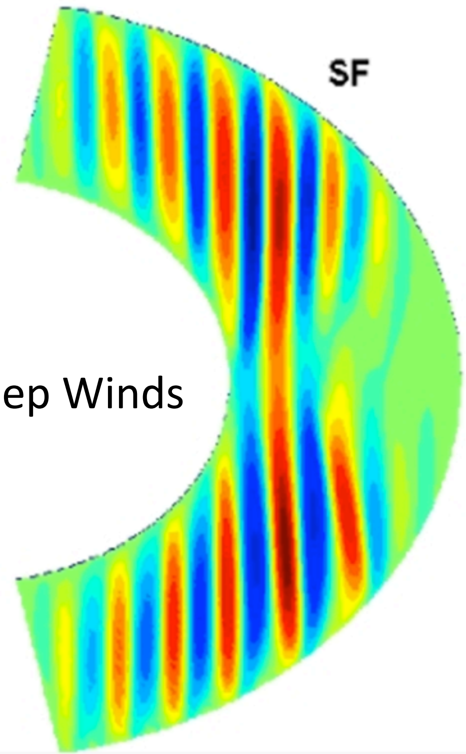
Reference ellipsoid, vs. geoid, vs. topography



Gravity of fluid planet = hydrostatic equilibrium + fluid circulation



$$\frac{2\pi}{\Omega} = 10hr$$



Deep Winds
ss

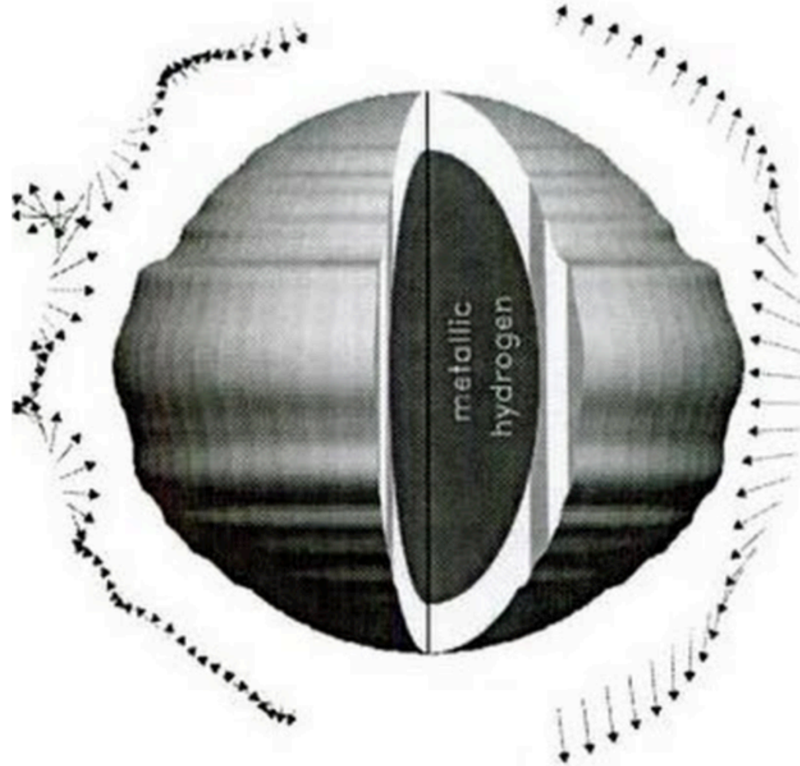


Figure 3.9. Schematic figure showing possible correlation between Jupiter "topography" produced by cylindrical zonal flows and gravity anomalies (arrows). The vectors to the right represent gravity anomalies calculated with respect to a planet rotating as a solid body. The vectors to the left represent gravity anomalies with respect to a "smooth" gravity field (calculated only from the first few gravitational moments) (see text).

Kaspi et al. GRL 2010
Hubbard Icarus 1999

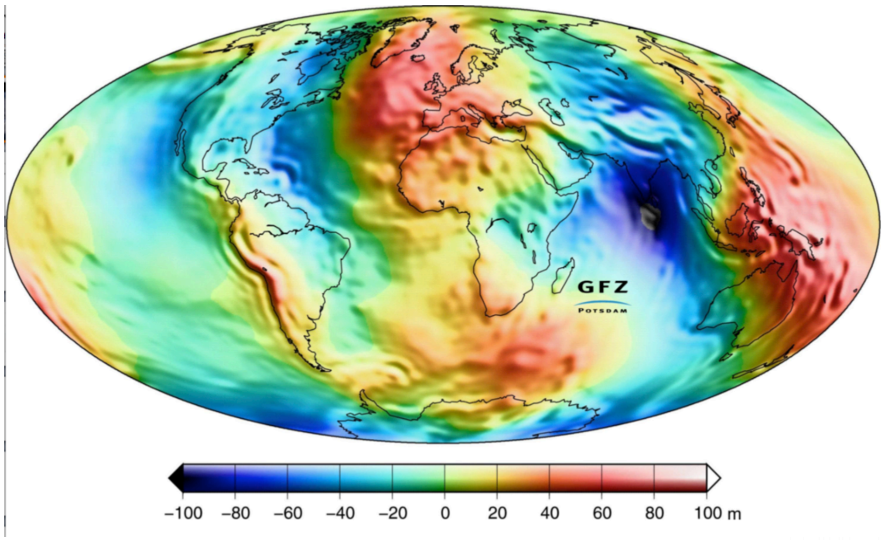
Analogous effects can be seen in Earth's gravity field due to ocean currents

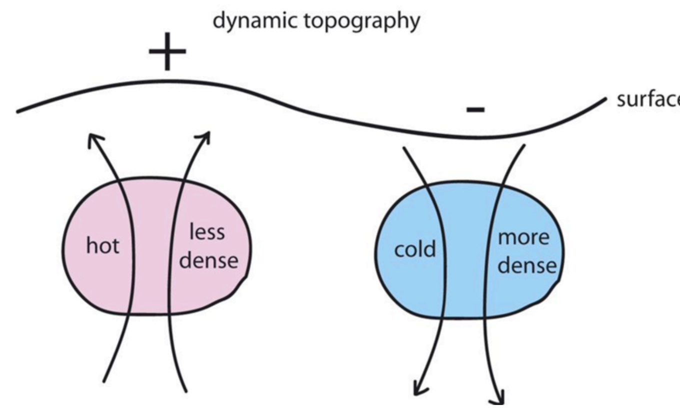
Earth's geoid: uncorrelated with topography

Not a record of surface processes (instead, mantle convection)

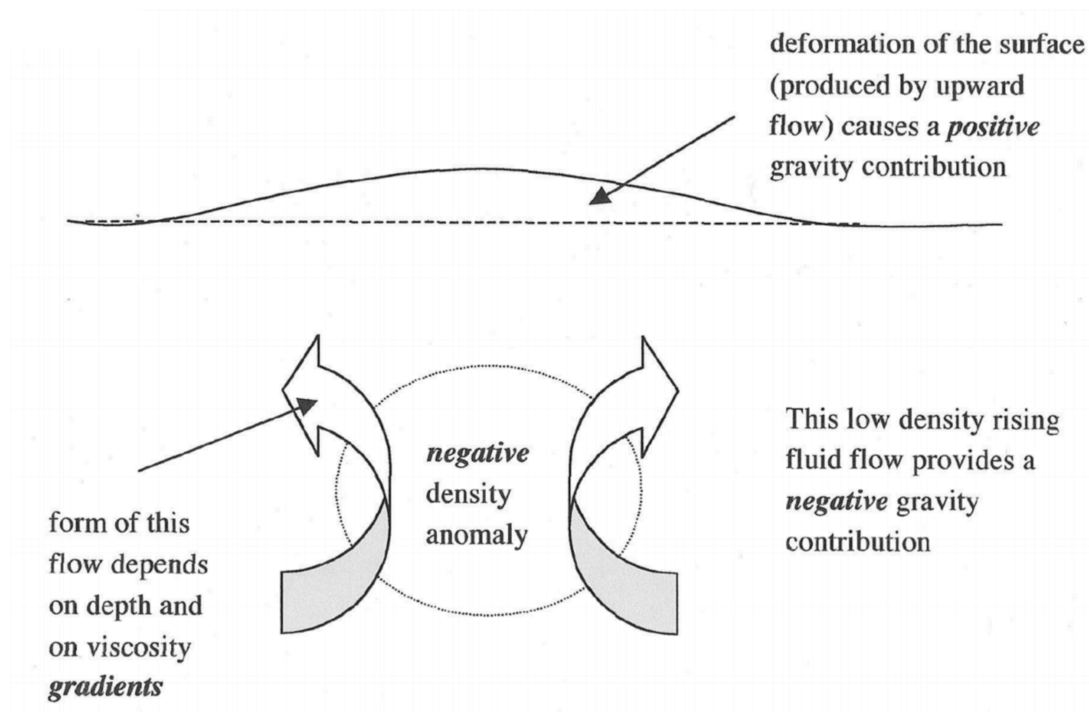
Can drive surface processes (e.g., Western Interior Seaway)

Steady, solid-state mantle convection





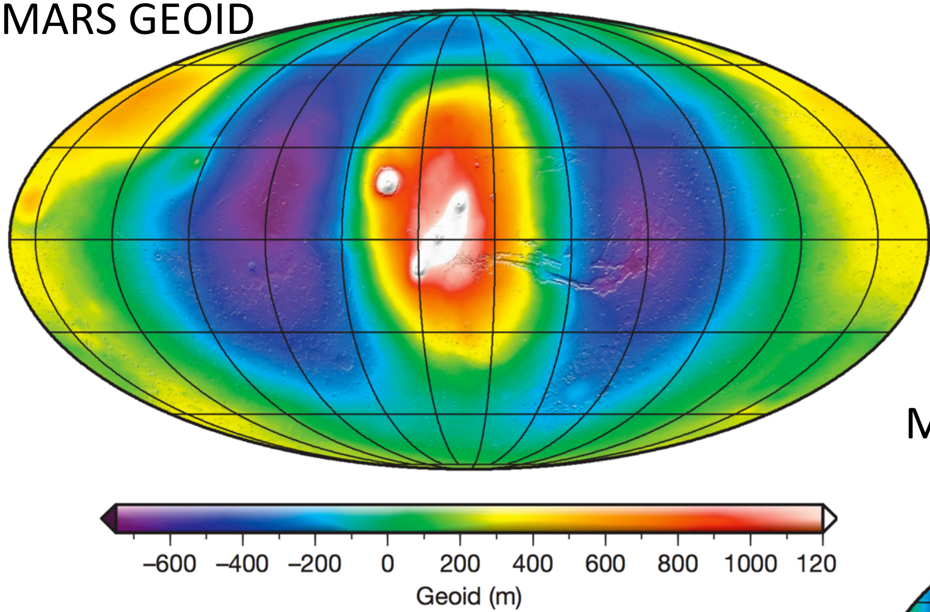
Earth dynamic topography: amplitude km



Richards & Hager, JGR 1988

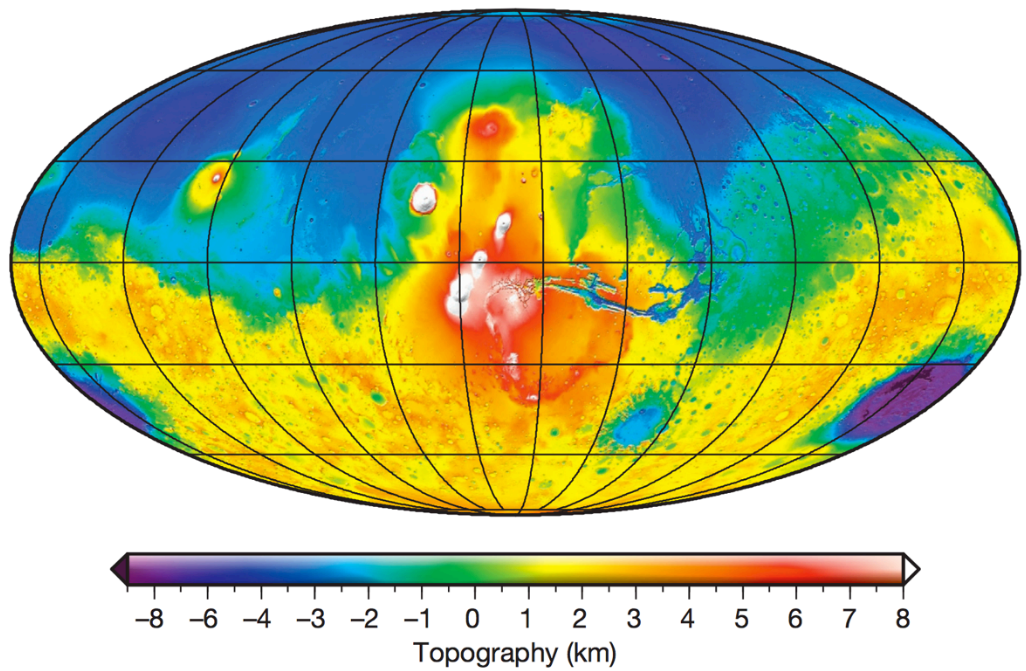
Mars' geoid: correlated with topography

MARS GEOID



- The large <4 Ga volcanoes are geoid highs
- The >4 Ga ancient dichotomy between southern highlands and northern lowlands leaves no trace in the geoid

MARS TOPOGRAPHY



Contrast between Earth & Mars geoid is mainly due to a difference in *strength of the lithosphere*

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True polar wander – migration of +ve (-ve) nonhydrostatic mass anomalies to equator (poles)

Over geologic time, energy dissipation within viscous interior will align the spin axis with the maximum moment of inertia.

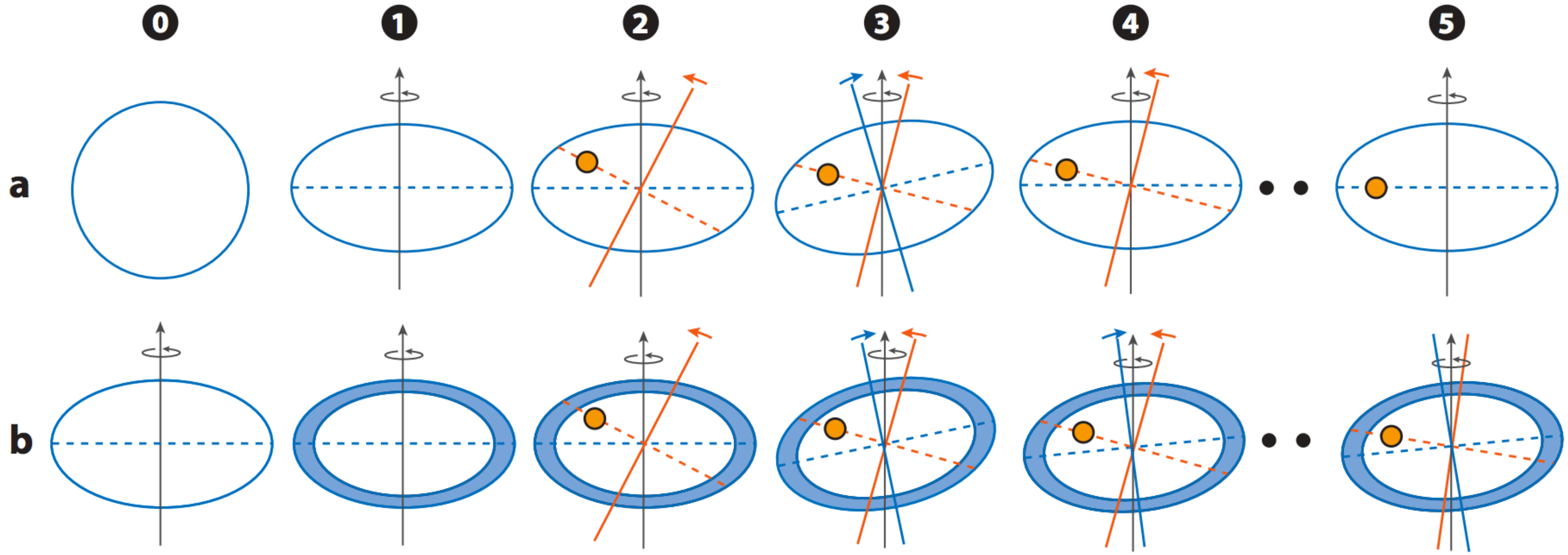


Figure 1

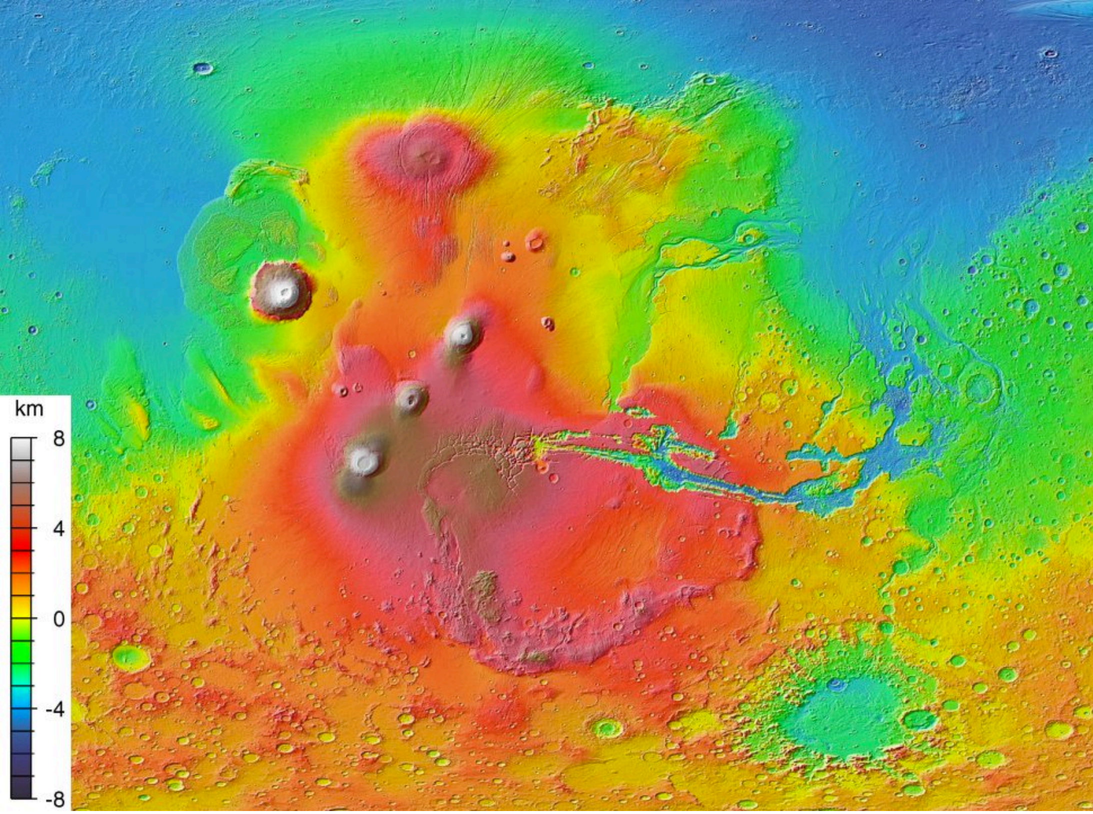
Schematic illustration of the physics of polar wander. The orange circle represents a positive load, the solid blue shell an elastic lithosphere, and the solid gray arrow the rotation vector. In each frame, the dashed blue and orange lines within the interior of the body denote the plane of the rotational bulge and the load, and the solid blue and orange lines denote the maximum principal axis of the rotational bulge and the load, respectively. Panel *a* treats the case in which the rotational bulge can ultimately relax perfectly to any reorientation. In this case, which is the scenario discussed by Gold (1955), an equilibrium theory predicts that the maximum principal axis of the load and the rotation axis will coincide (panel *a*, frame ❺). Panel *b* shows the case in which the initial state is hydrostatic but any readjustment of the bulge will introduce elastic stresses in the (initially unstressed) lithosphere. In this case, the rotational bulge cannot adjust perfectly to a reorientation (panel *b*, frame ❹), and the final maximum principal axis of the load and the rotation axis will not coincide (panel *b*, frame ❺). This final state is predicted by the equilibrium theory of Matsuyama et al. (2006) (see Equation 22), and it is governed by a balance between the load-induced forcing and the resistance provided by a remnant rotational bulge (Willemann 1984).

Matsuyama et al., Annual Reviews of Earth & Planetary Science, 2014

Significance of true polar wander

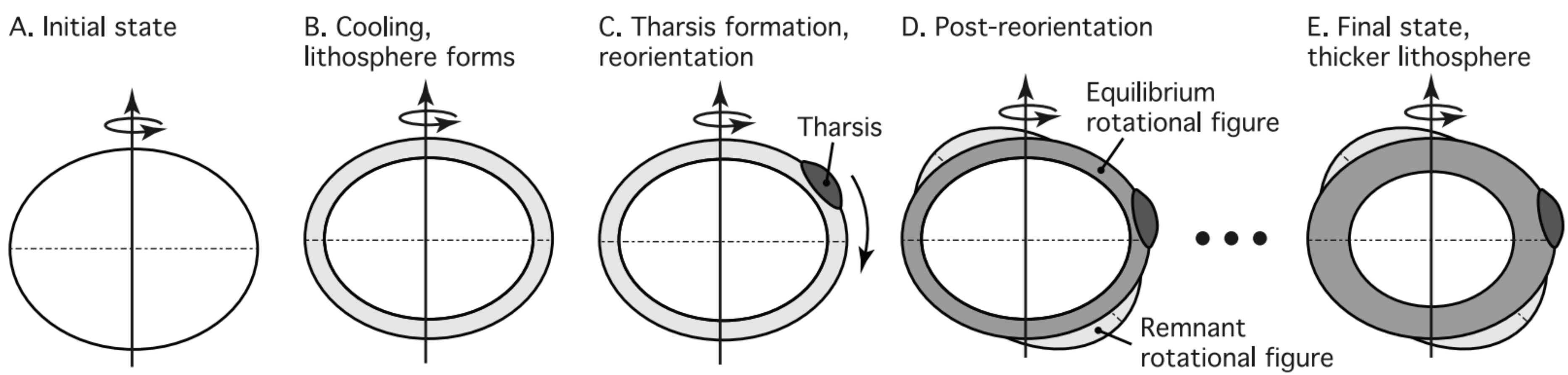
(Potentially rapid) shifts of (paleo)latitude

Complicate reconstruction of past climate



Tharsis bulge

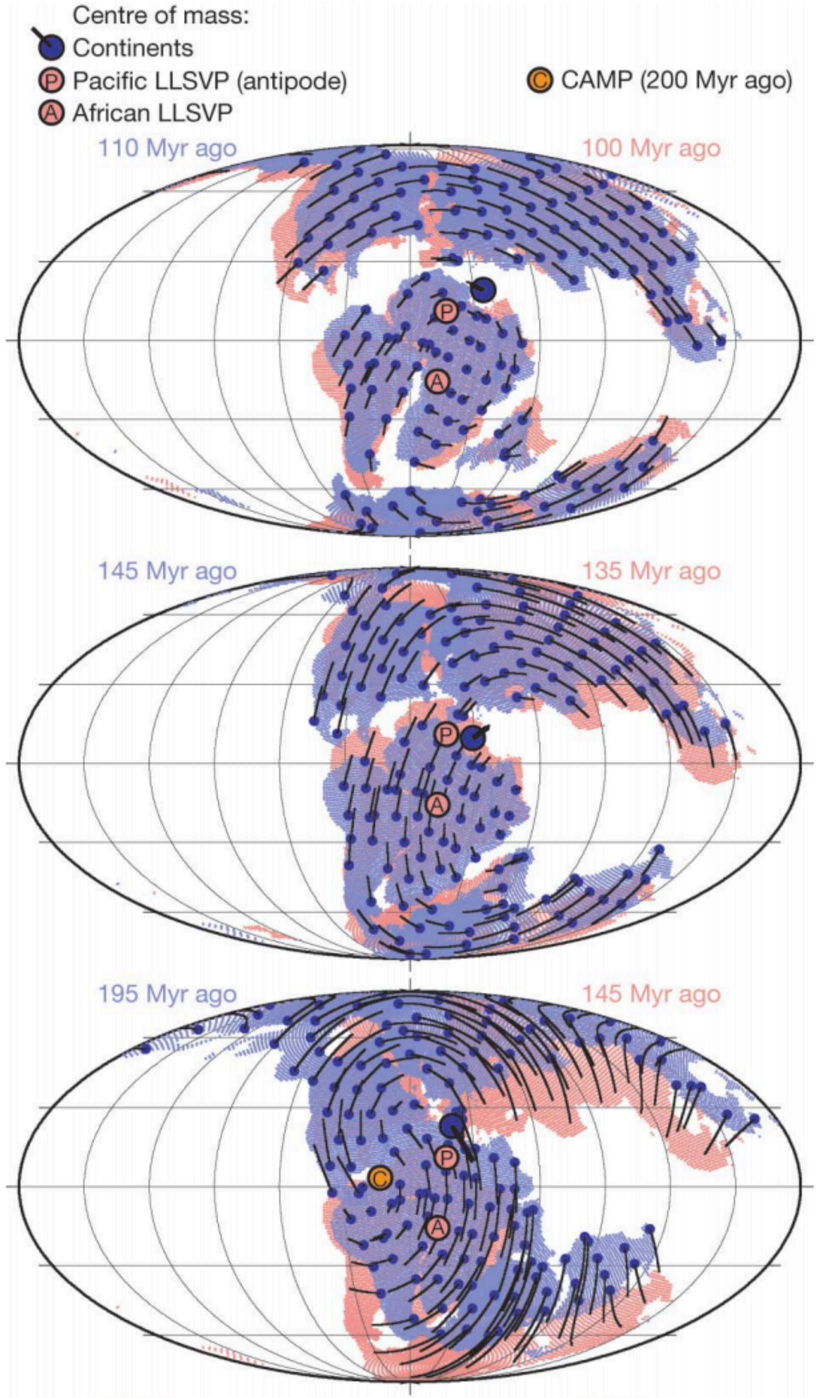
5,000 km across
up to 7 km high



Matsuyama & Manga, JGR, 2010

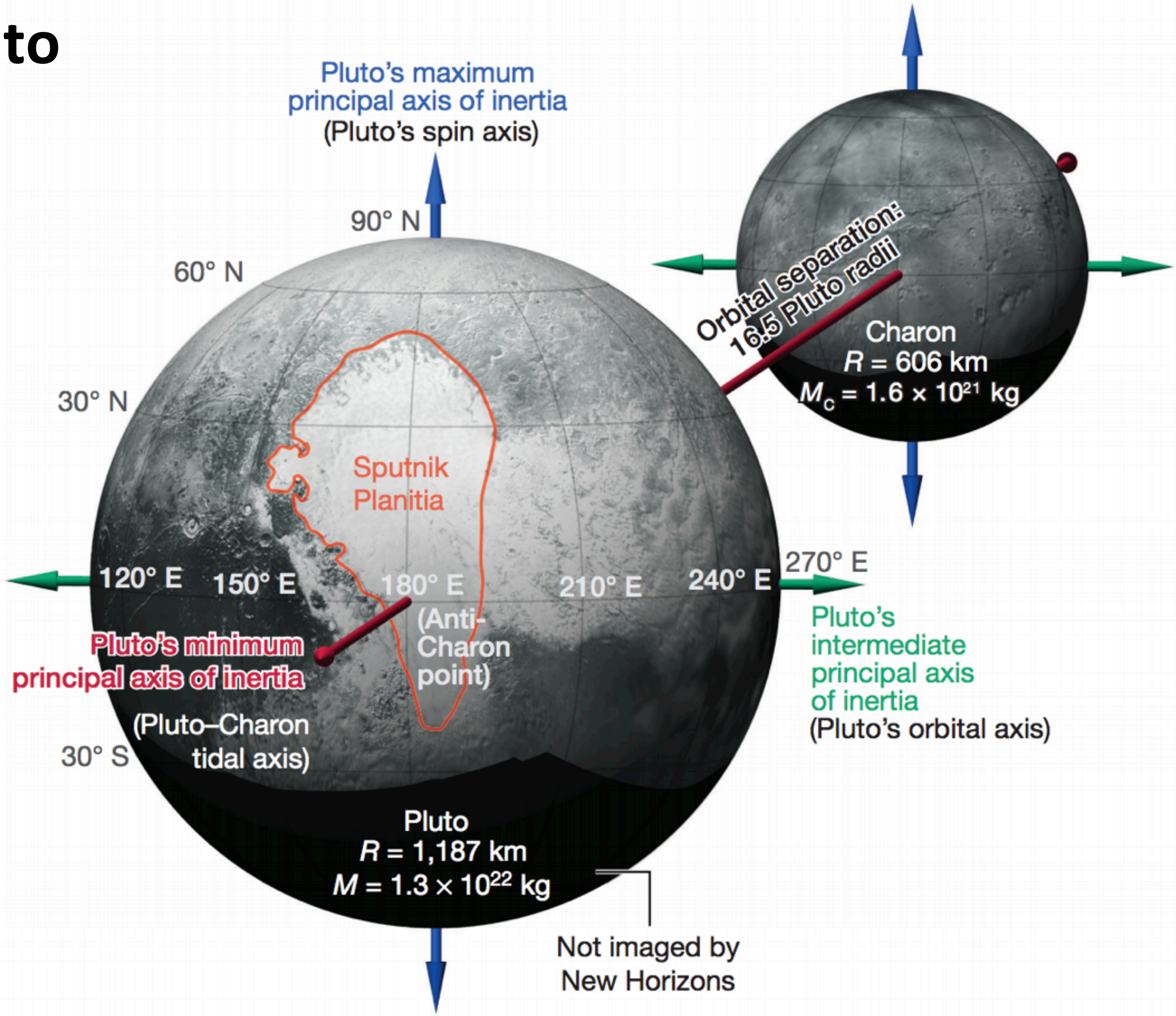
TPW on Earth

- less important (at least over the past 250 Myr) than plate tectonics
- suggests persistence of mantle superplumes



Steinberger & Torsvik, Nature, 2008

TPW on Pluto



Keane et al. Nature 2016

Key points from today

- why planets are roughly spherical;
  relationship between internal mass distribution and rotational bulge.
- the definition of the geoid;
- principle of true polar wander;
  evidence for true polar wander.

Next lecture

- How are mountains supported?