Thermal Convection and Plate Tectonics on Planetary Bodies

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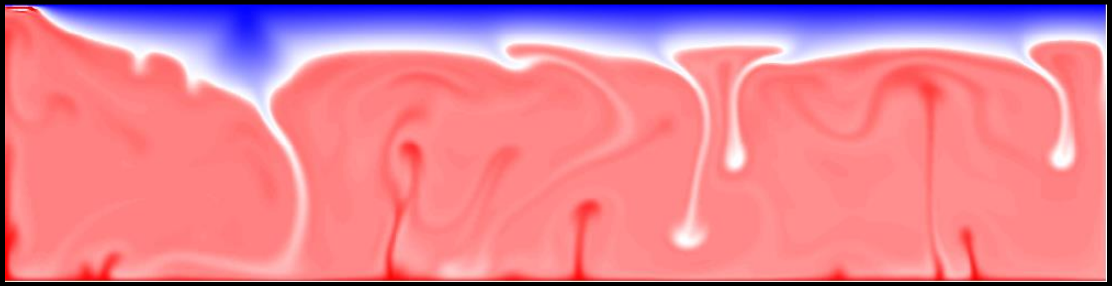
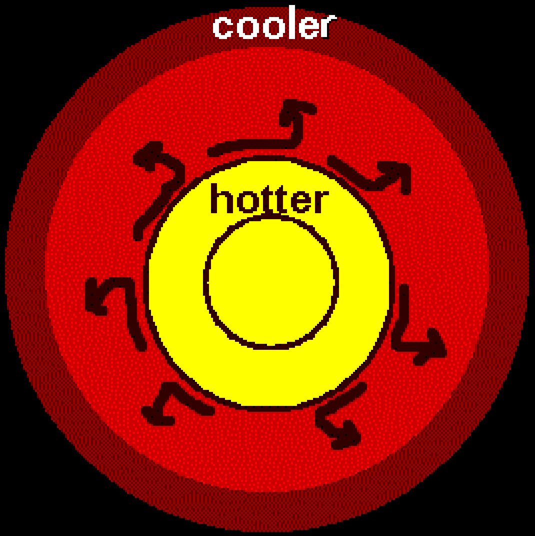


Northwestern University
2/10/2016

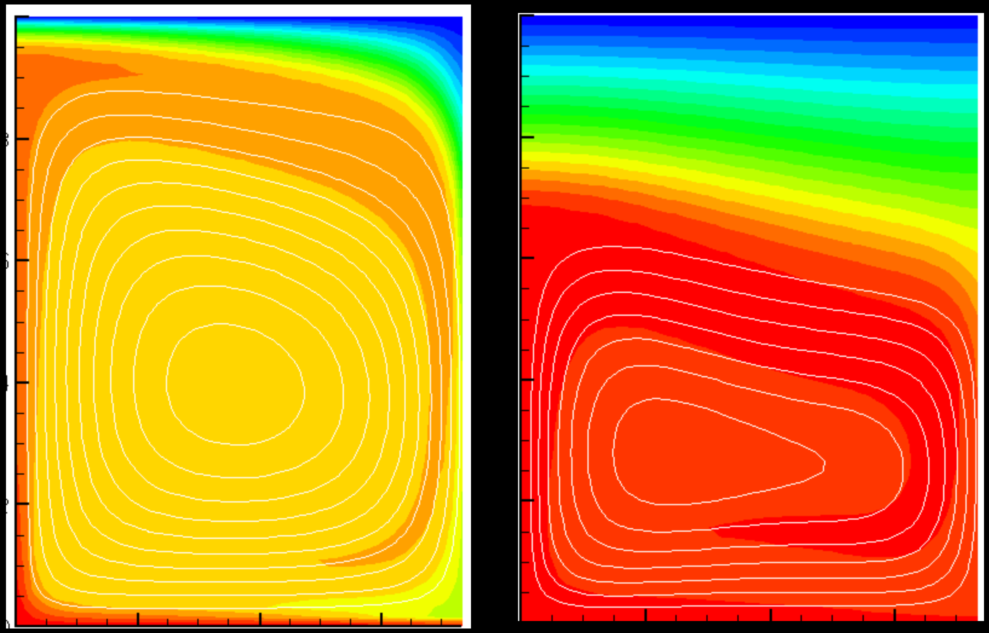
Mantle convection

- A mode of heat transfer (the others are conduction and radiation)
- Rocks can flow near solidus



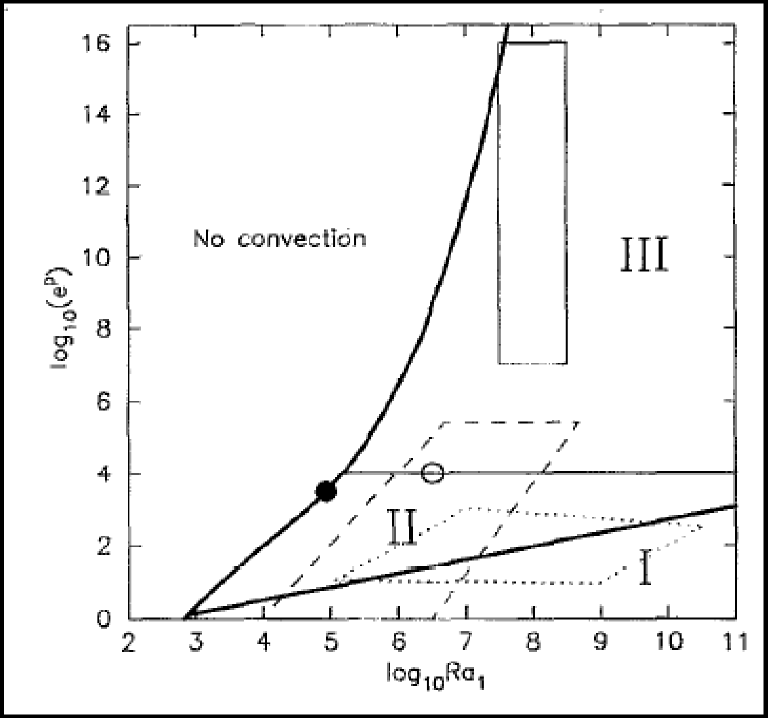
Convective regimes

- Small Δη - mobile lid
- Somewhat large Δη – transitional
- Very large Δη – stagnant lid



Temperature field

Convective regimes



Solomatov (1995)

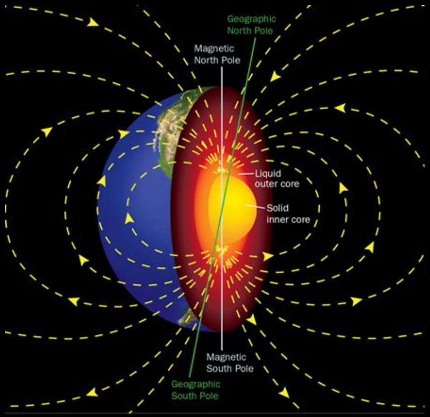
Plate tectonics

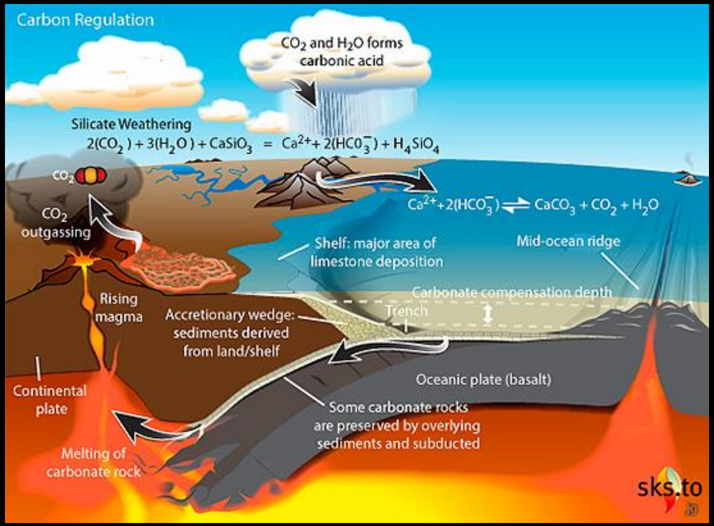
- “A model in which the outer shell of the Earth is divided into a number of thin, rigid plates that are in relative motion with respect to one another.”
  -- Turcotte D. and Schubert, G., Geodynamics, 2nd edition, Cambridge

- A style of mantle convection that involves the rigid lithosphere in the convective motions

Consequences of plate tectonics

- Cools planet more efficiently
- Existence of geodynamo
- Influences surface atmosphere
- Regulates surface temperature
- Diversity in minerals





Why does the Earth have plate tectonics?

How does the very first episode of lithospheric failure (subduction) occur on a one-plate planet?

What do we know about plate tectonics in the past?

- Paleomagnetic measurements
- Passive margins and transform faults
- Rock records
    - Ophiolites
    - Metamorphic rocks
    - Igneous rocks and isotopic evidence

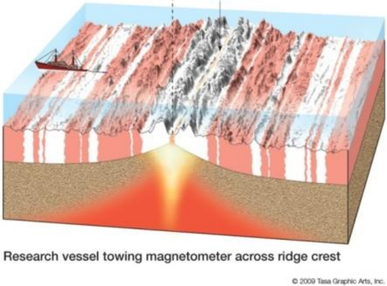
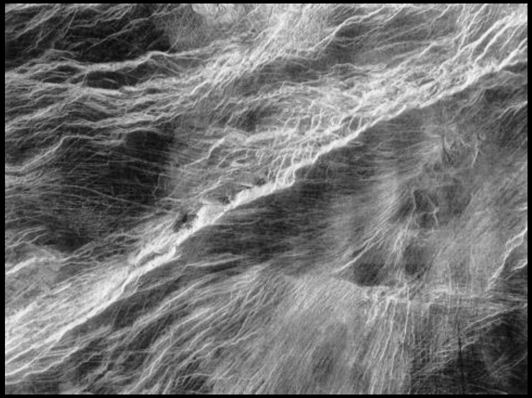


Plate tectonics on Venus?

- Currently not occurring
  - Random crater distribution
  - Widespread volcanism
- Catastrophic resurfacing (~1 Ga)
  - Tectonic or magmatic origin
- Localized subduction zones (Schubert and Sandwell 1995)

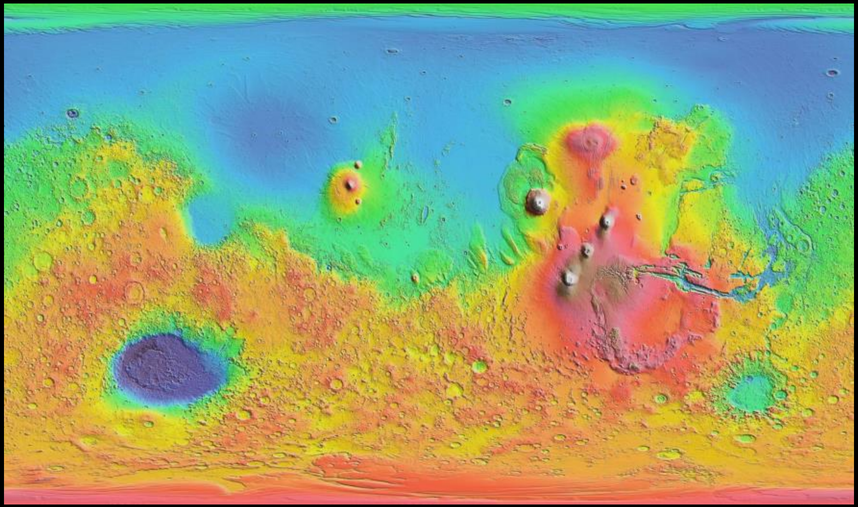


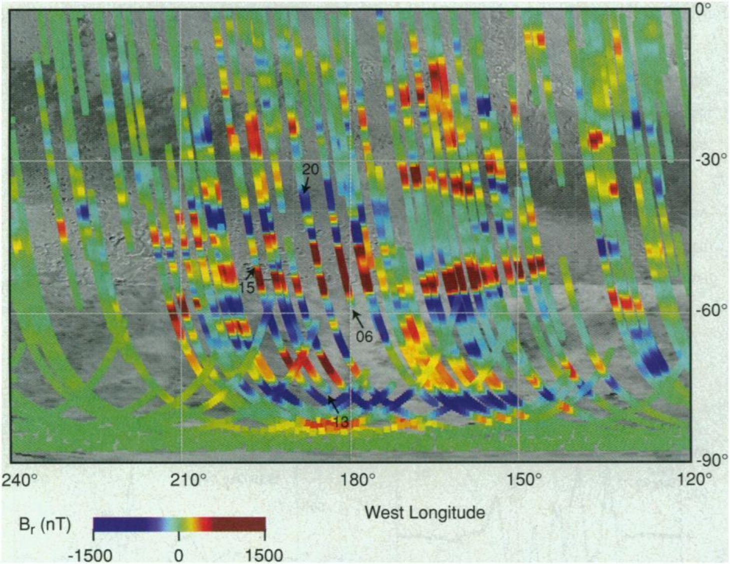
Hecate

Plate tectonics on Mars?

- Early plate tectonics on Mars (Sleep 1994)

- Late Hesperian and Amazonian – Valles Marineris (Yin 2012)





Extrasolar planets

The conditions for existence of plate tectonics on Earth-like exoplanets have been widely studied, but the problem remains unsolved

(e.g., O’Neill & Lenardic, 2007; Valencia & O’Connell, 2007, 2009; Foley et al., 2012; Stein et al., 2013; Stamenkovic & Breuer, 2014, Tachinami et al., 2014, Miyagoshi et al., 2014)

Plate tectonics initiation from stagnant lid convection

Can stresses from convection cause lithospheric failure?

What are the difficulties?

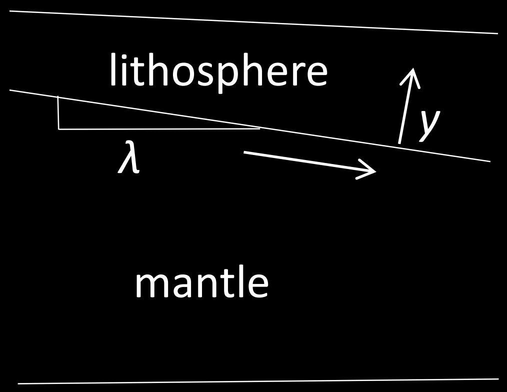
- Lack of robust constraints for the Earth
  - Active surface destroys evidence
  - Local vs global
  - Interpretation of rock records

- Theoretical difficulties
  - Strength of the lithosphere
    - Difficult to mobilize without existing plate motions
    - Rheology is not well-known
  - Buoyancy of crust

What controls plate tectonics initiation?

- Stresses in the lithosphere

Gravitational sliding model



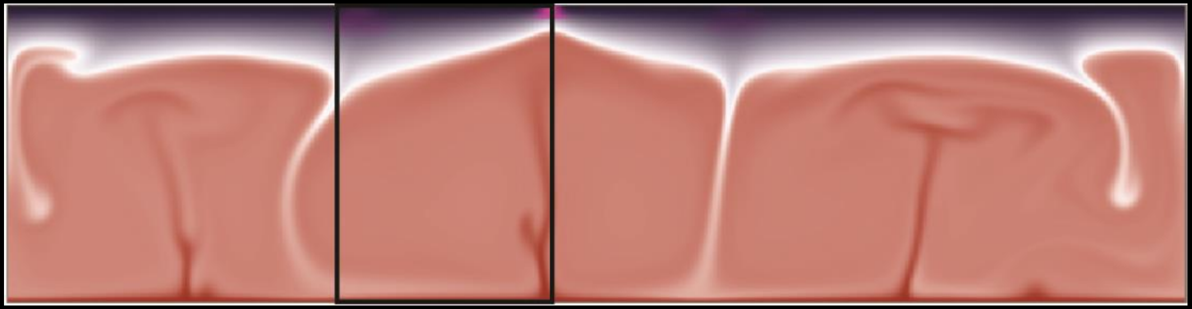
$$\tau = Ra \frac{dT}{dy} \frac{y^2}{2} \lambda$$

- Strength of the lithosphere expressed in terms of the yield stress

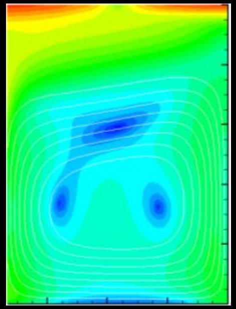
What controls subduction initiation?

To find out the conditions favorable for subduction initiation, *scaling laws* are derived to relate the yield stress and various parameters of mantle convection

(e.g., Solomatov 2004, O’Neill et al. 2007)



Temperature field



Stress field

What controls subduction initiation?

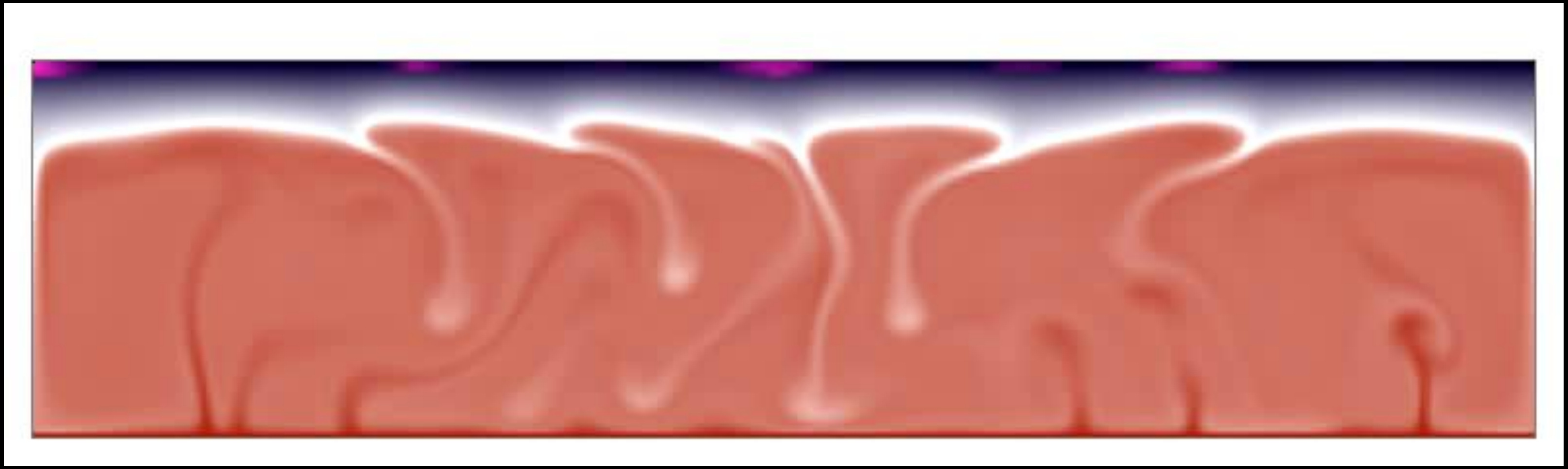
Scaling relation for critical yield stress in single-cell simulations (Wong and Solomatov, 2015)

$$\tau_{y,cr} \sim 2\alpha\rho g\Delta T d\left(\frac{E\Delta T}{RT_i^2}\right)^{-1}\left(\frac{\delta_0}{d}\right)^{-0.4}\boxed{a^{1.8}}$$

$$\mu_{cr} \sim 89\alpha\Delta T\left(\frac{E\Delta T}{RT_i^2}\right)^{-1.7}\left(\frac{\delta_0}{d}\right)^{-1.6}\boxed{a^{1.9}}$$

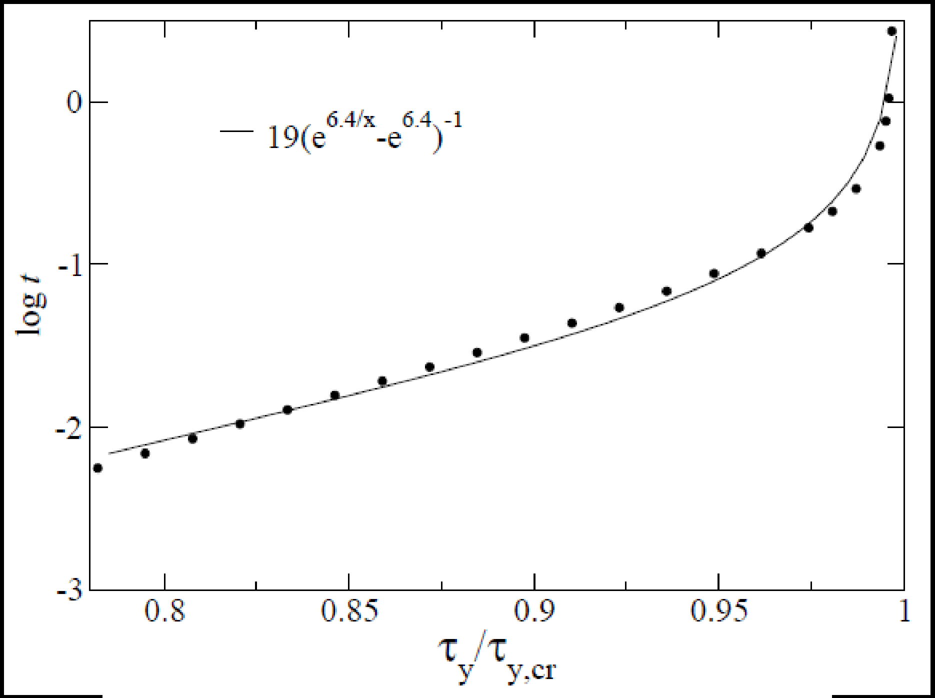
Chaotic time-dependent convection

Previous studies aimed to understand whether plate tectonics could happen, but they did not investigate the timing of plate tectonics initiation –

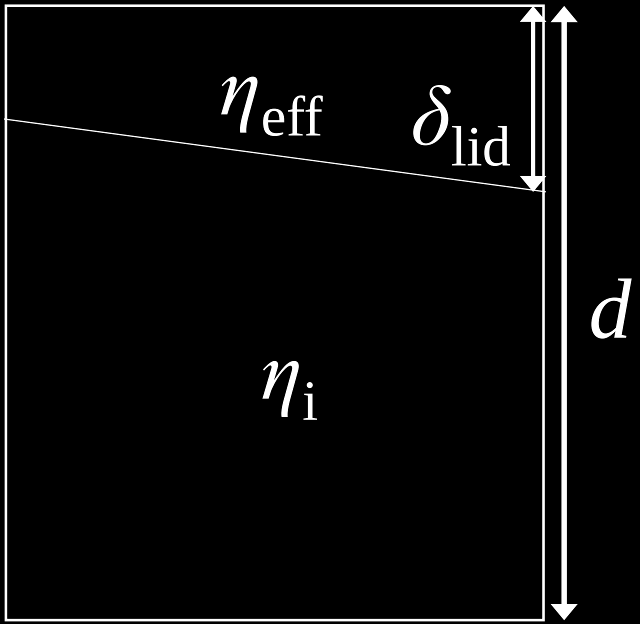


When does plate tectonics start under favorable conditions?

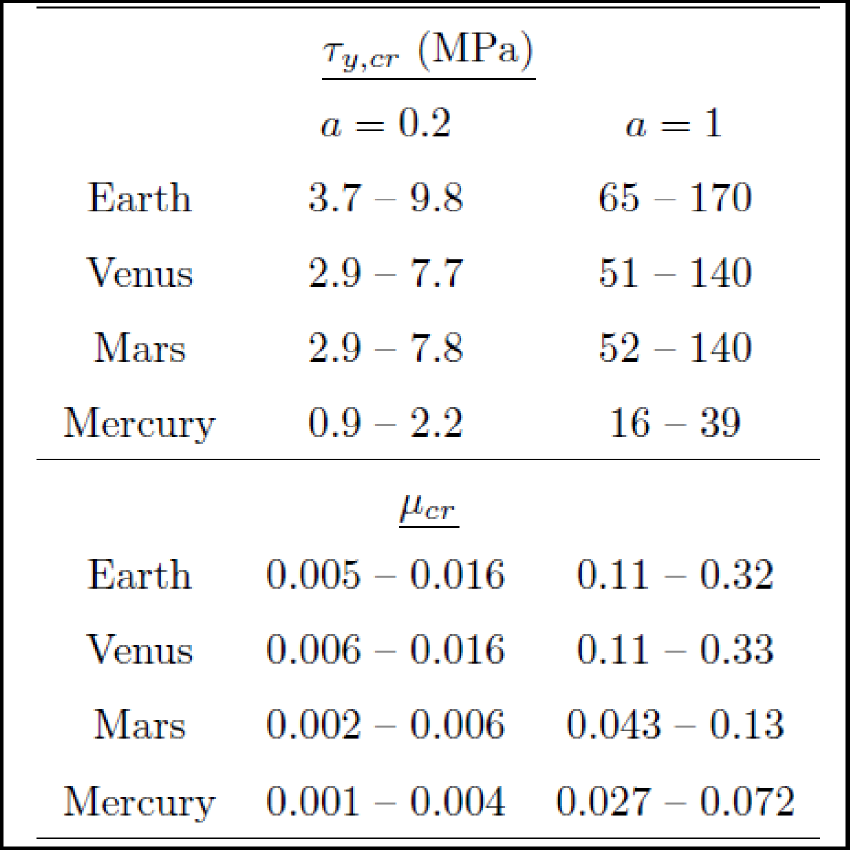
What controls the time of plate tectonics initiation?



$$t = \frac{1}{\tilde{s}\Delta\rho g \delta_{\mathrm{lid}}} \left(\frac{1}{\eta_{\mathrm{eff}}} - \frac{1}{\eta_{\mathrm{cr}}} \right)^{-1}$$



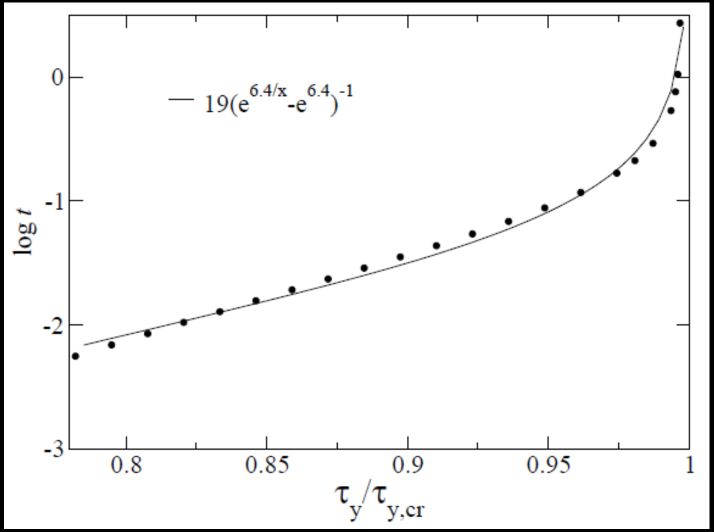
Critical yield stress for terrestrial planets



	$\tau_{y,cr}$ (MPa)	
	$a = 0.2$	$a = 1$
Earth	3.7 – 9.8	65 – 170
Venus	2.9 – 7.7	51 – 140
Mars	2.9 – 7.8	52 – 140
Mercury	0.9 – 2.2	16 – 39
	μ_{cr}	
Earth	0.005 – 0.016	0.11 – 0.32
Venus	0.006 – 0.016	0.11 – 0.33
Mars	0.002 – 0.006	0.043 – 0.13
Mercury	0.001 – 0.004	0.027 – 0.072

Wong and Solomatov (in review)

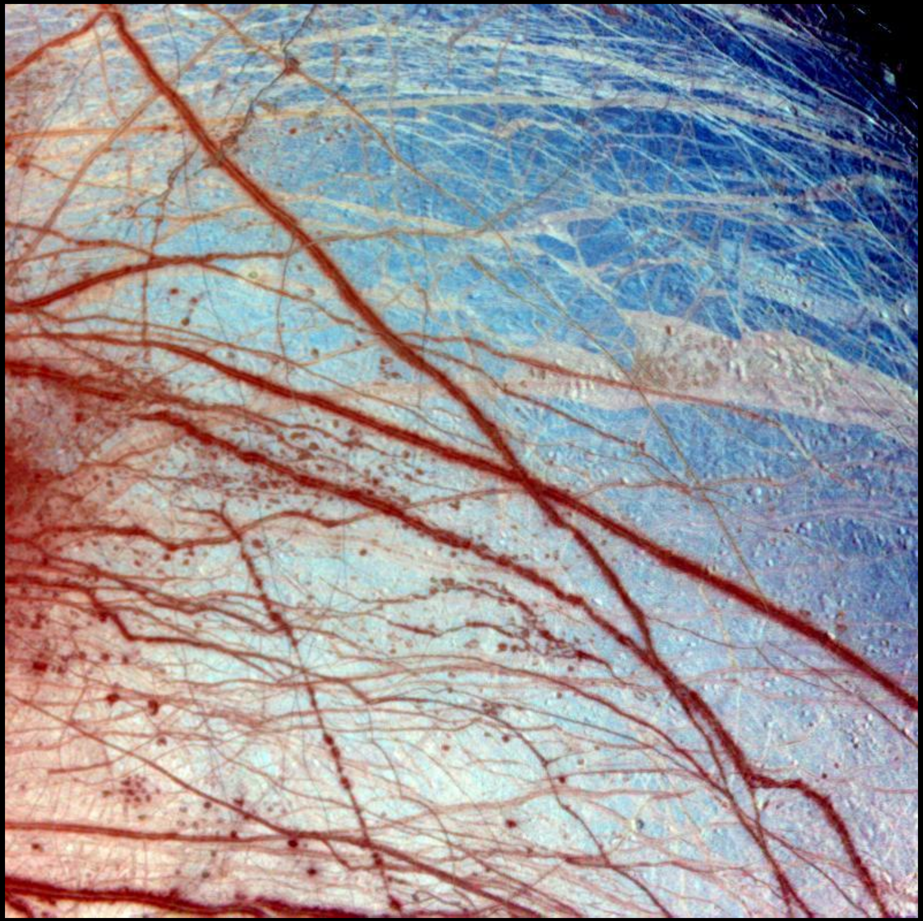
Time of plate tectonics initiation for terrestrial planets

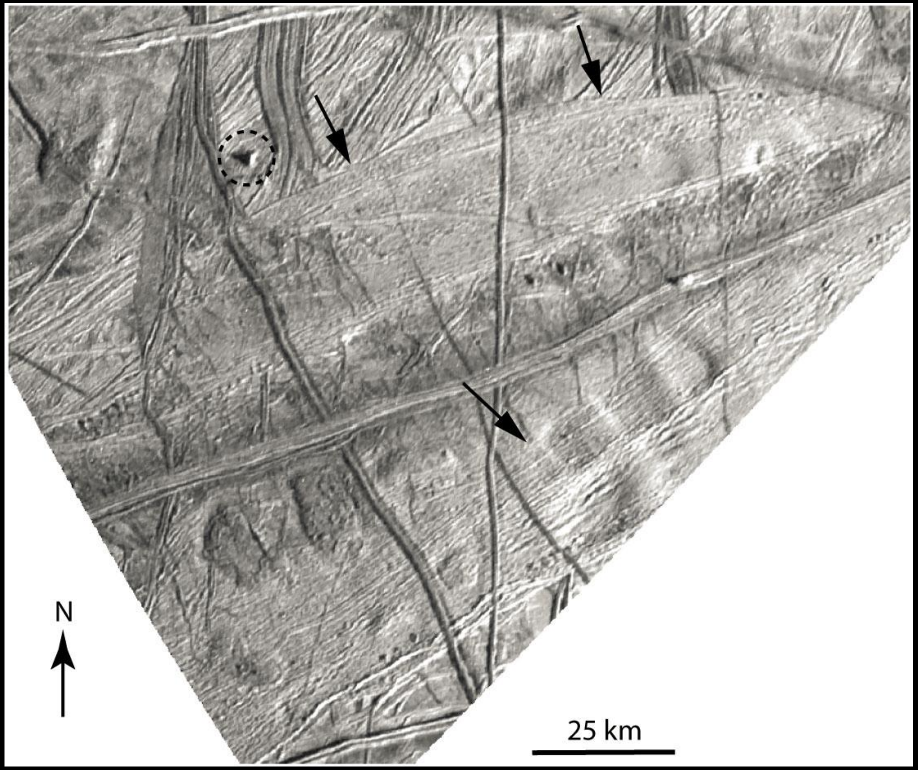


	d (km)	t ~ d^2/κ (Gyr)
Earth	350-700	3.9-16
Venus	350-700	4.8-19
Mars	850-1700	24-96
Mercury	350-660	3.9-14

For a range of dimensionless time 10^{-3}-$1(d^2/\kappa)$, if the yield stress of the lithosphere is below 0.97 $\tau_{y,cr}$, plate tectonics can initiate at any time during the lifetime of the planet.

Europa

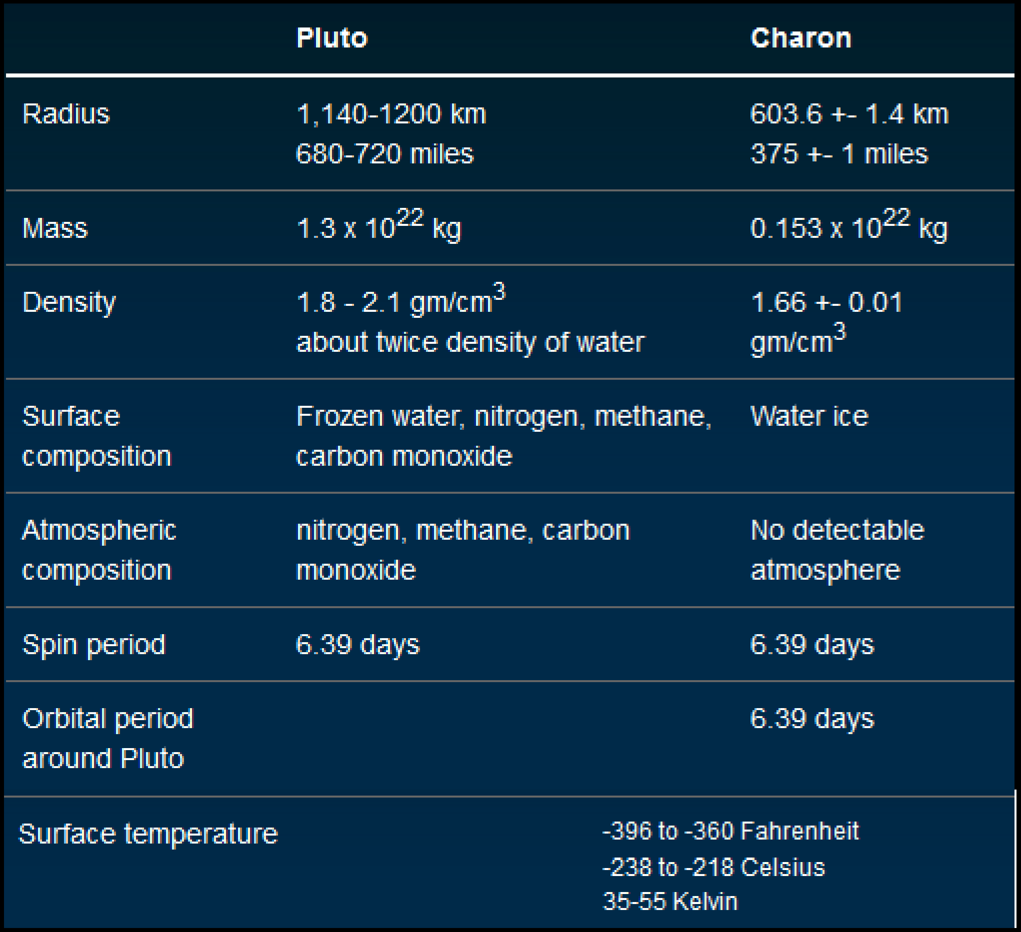




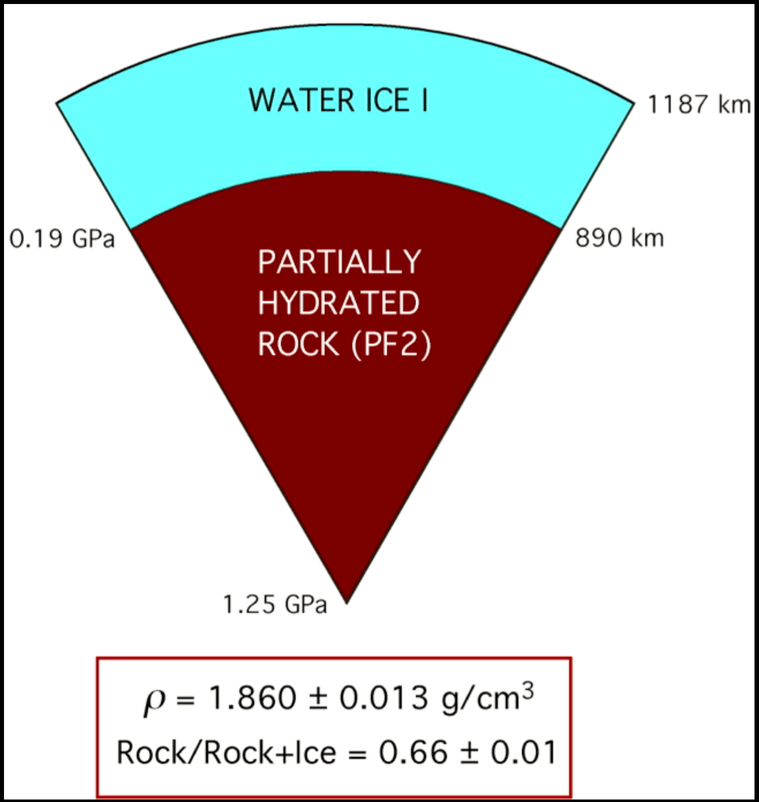
Kattenhorn and Prockter (2014)

Pluto Now

Pluto (and Charon) basics



	Pluto	**Charon**
Radius	1,140-1200 km 680-720 miles	603.6 +- 1.4 km 375 +- 1 miles
Mass	1.3 x 10^{22} kg	0.153 x 10^{22} kg
Density	1.8 - 2.1 gm/cm^3 about twice density of water	1.66 +- 0.01 gm/cm^3
Surface composition	Frozen water, nitrogen, methane, carbon monoxide	Water ice
Atmospheric composition	nitrogen, methane, carbon monoxide	No detectable atmosphere
Spin period	6.39 days	6.39 days
Orbital period around Pluto		6.39 days
Surface temperature	-396 to -360 Fahrenheit -238 to -218 Celsius 35-55 Kelvin	

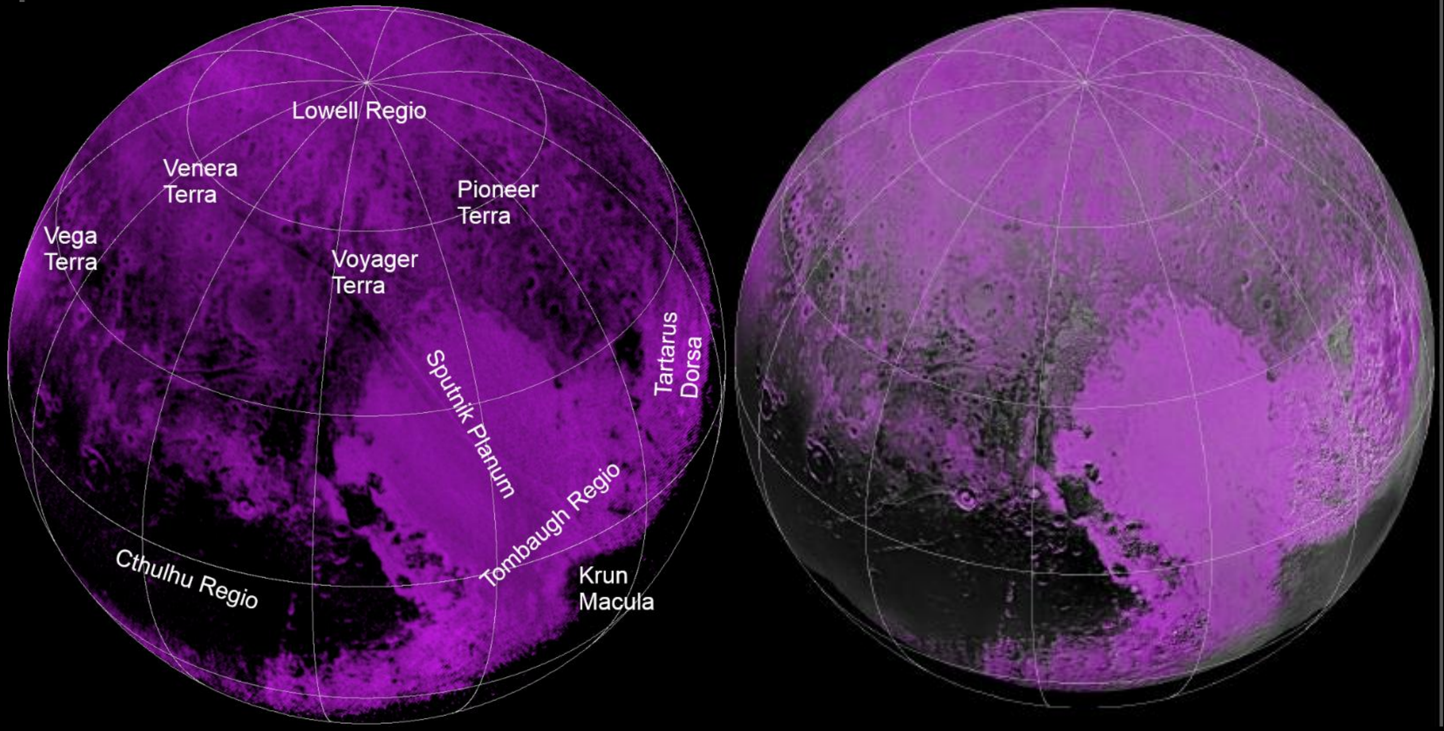


ρ = 1.860 ± 0.013 g/cm^3

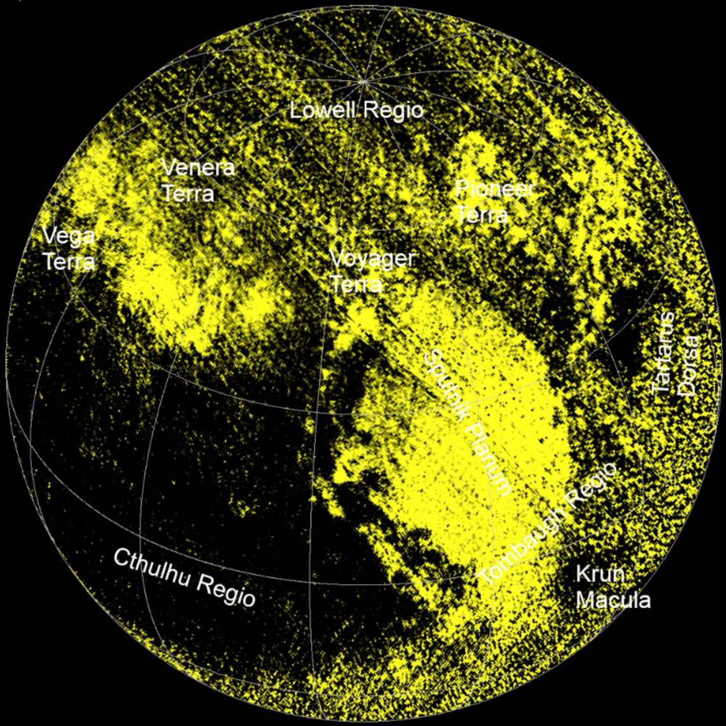
Rock/Rock+Ice = 0.66 ± 0.01

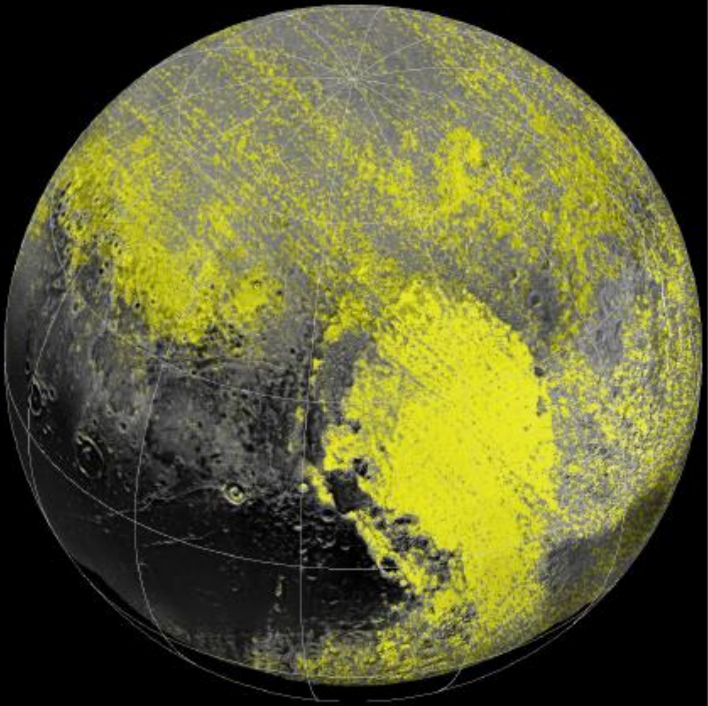
McKinnon et al. (2016) LPSC

CH_4 Ice Absorption

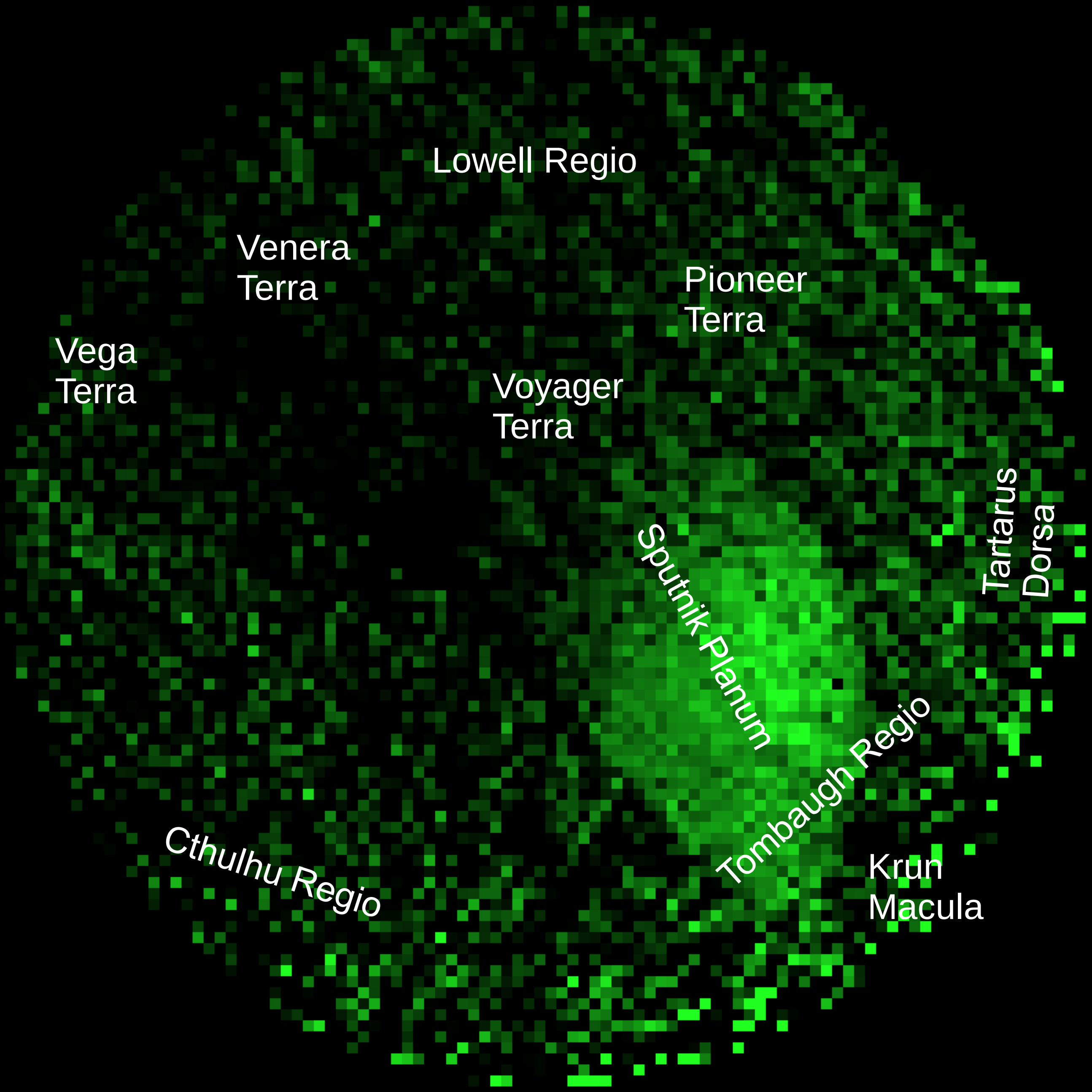


N_2 Ice Absorption

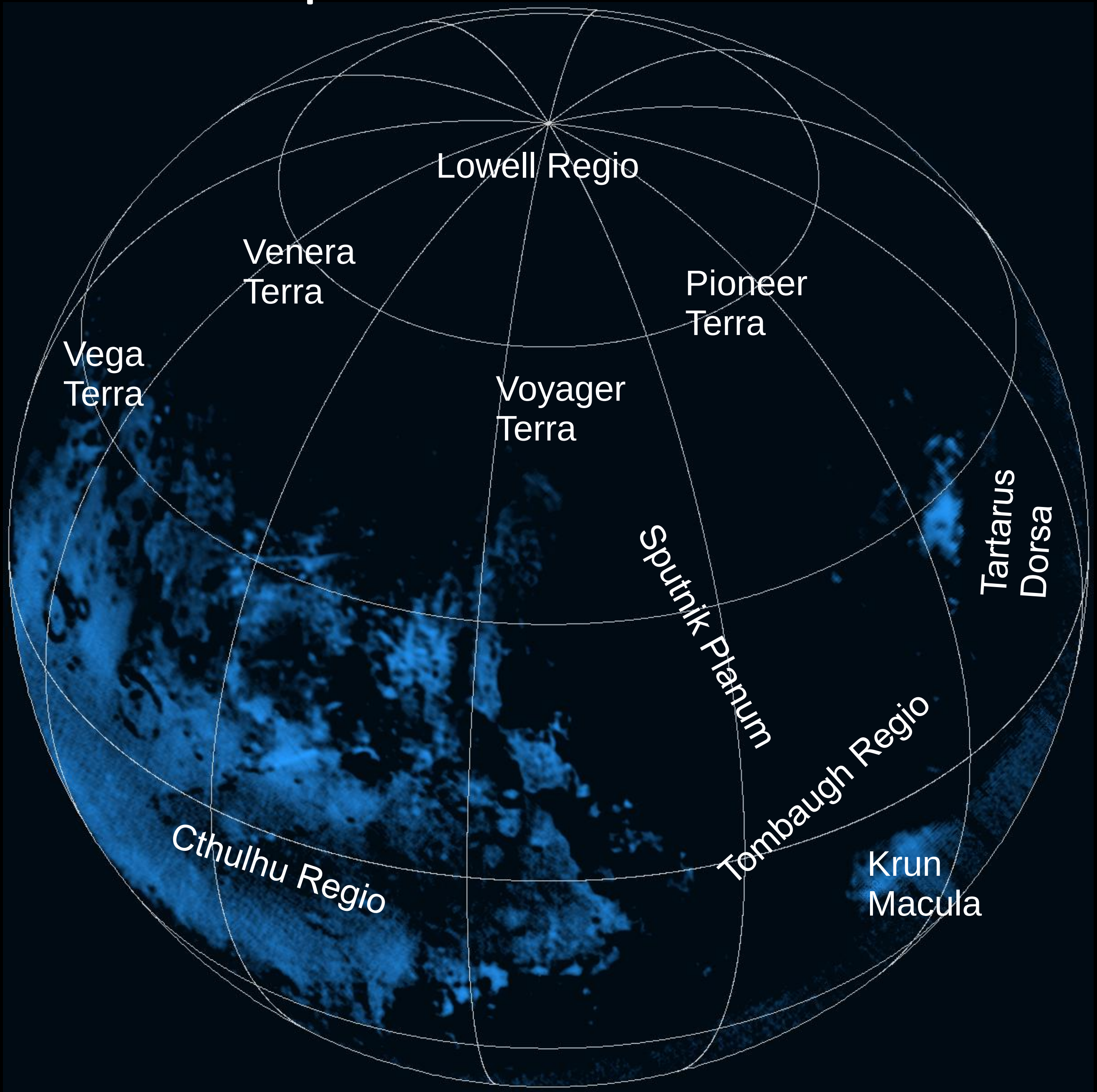




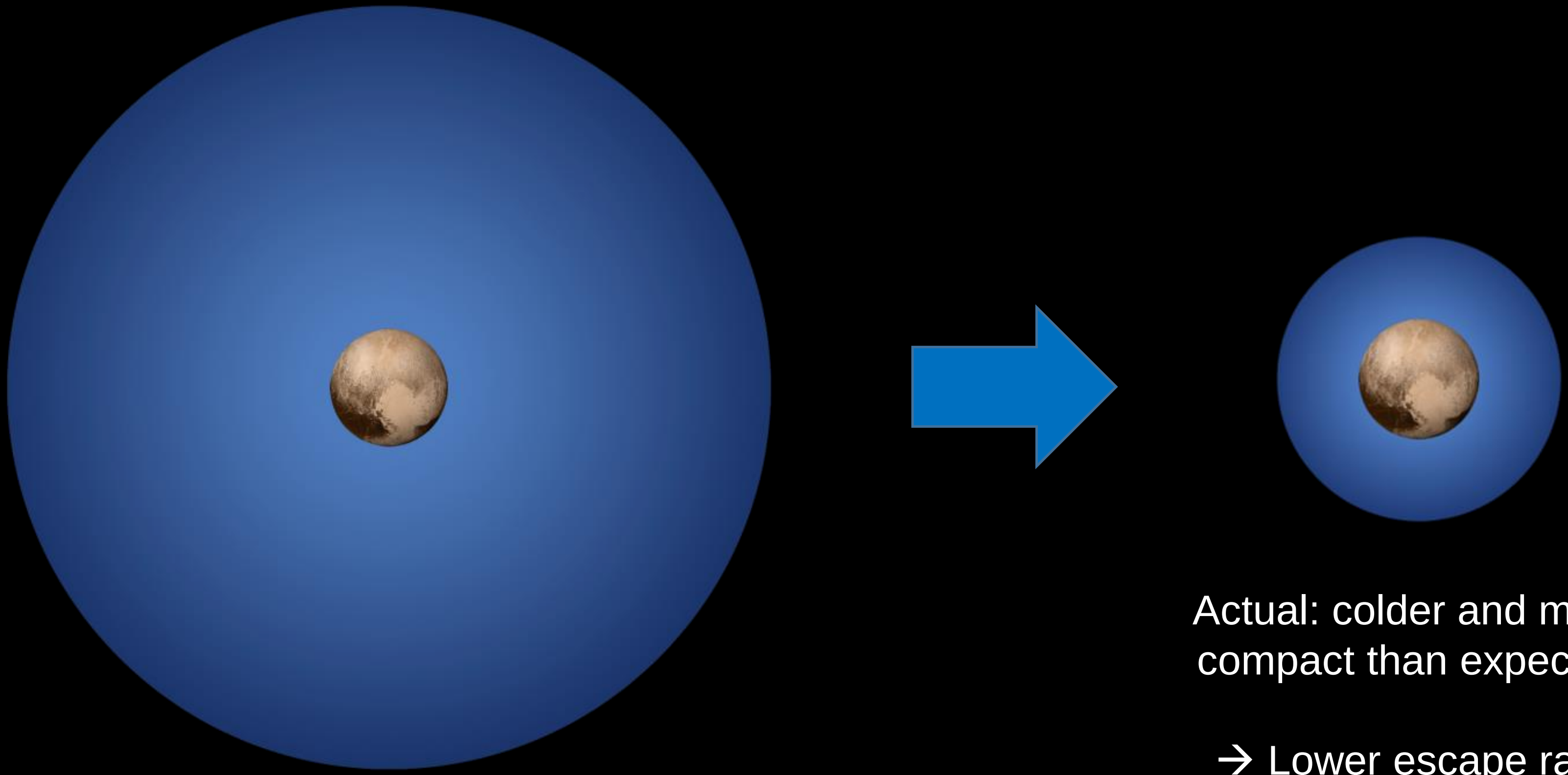
CO Ice Absorption



H_2O Ice Absorption



Atmospheres



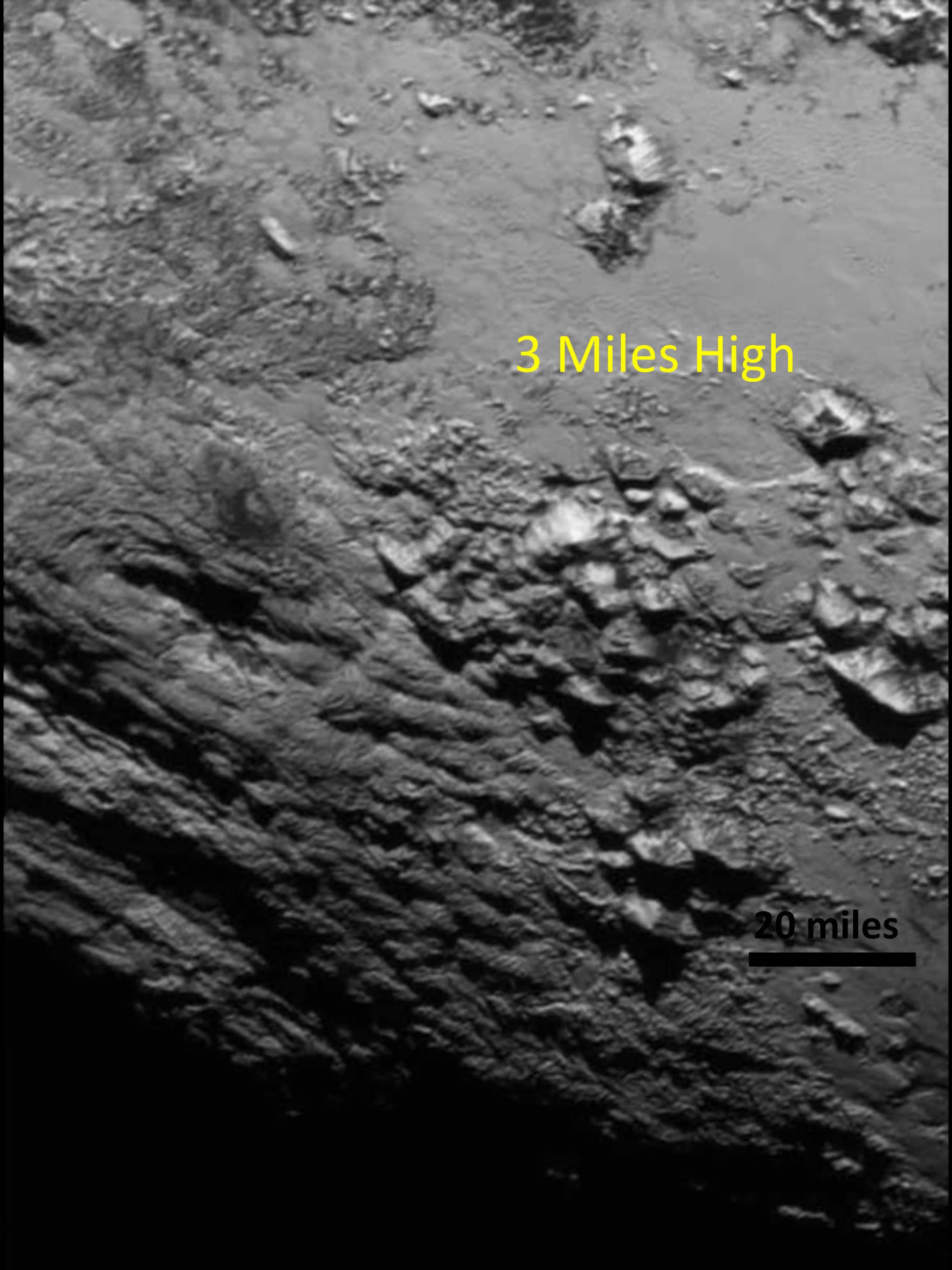
Models before New Horizons

Actual: colder and more compact than expected

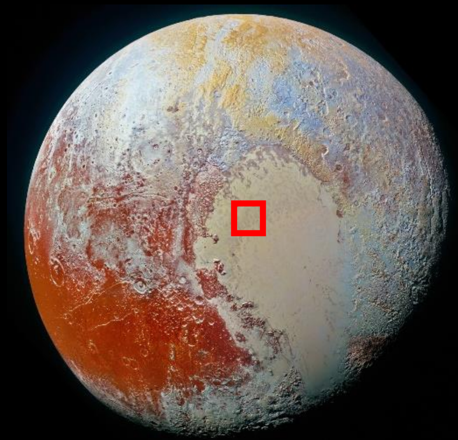
→ Lower escape rate

Mountains

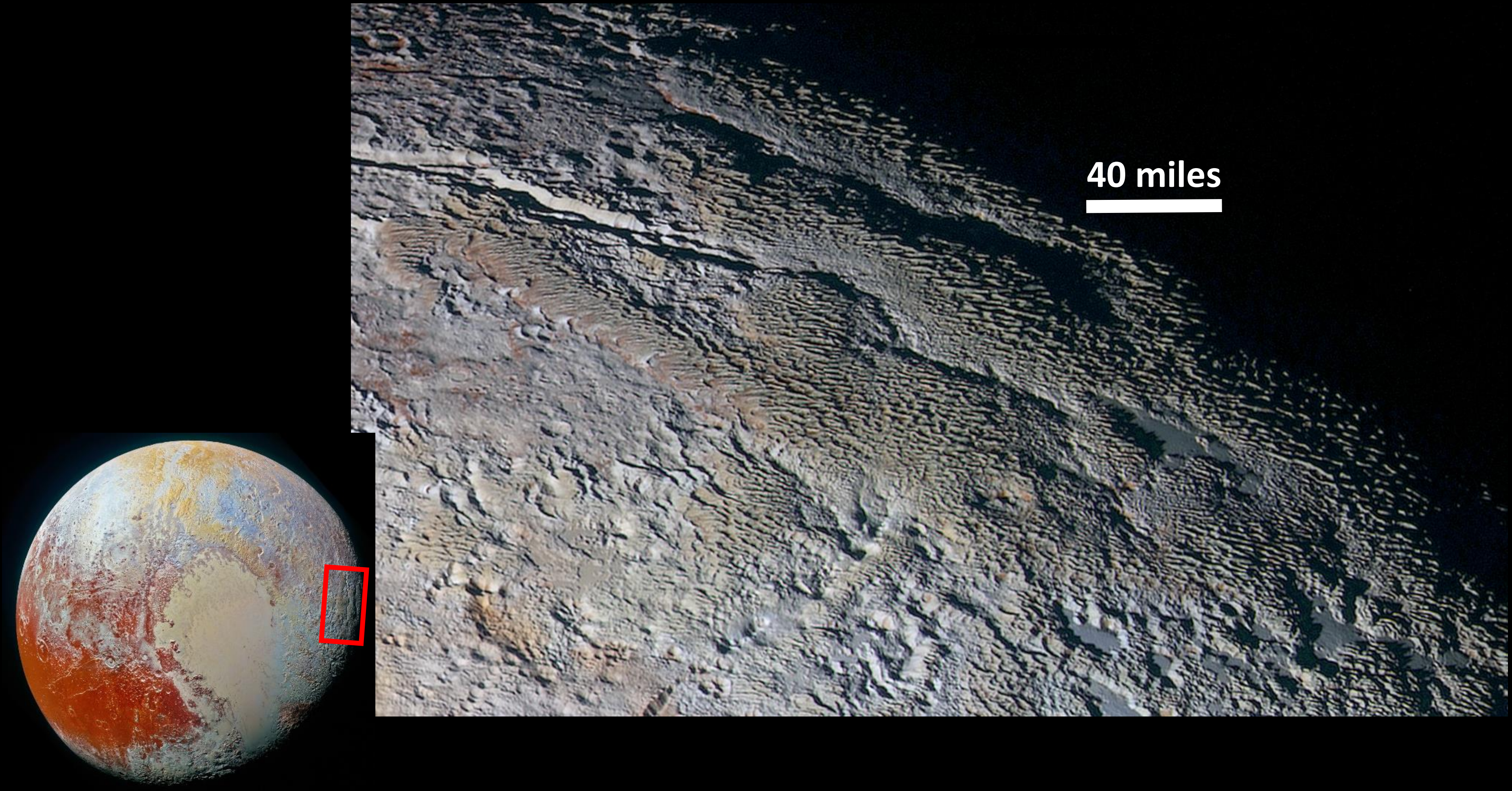
Similar to Mount Everest



Icy Plains



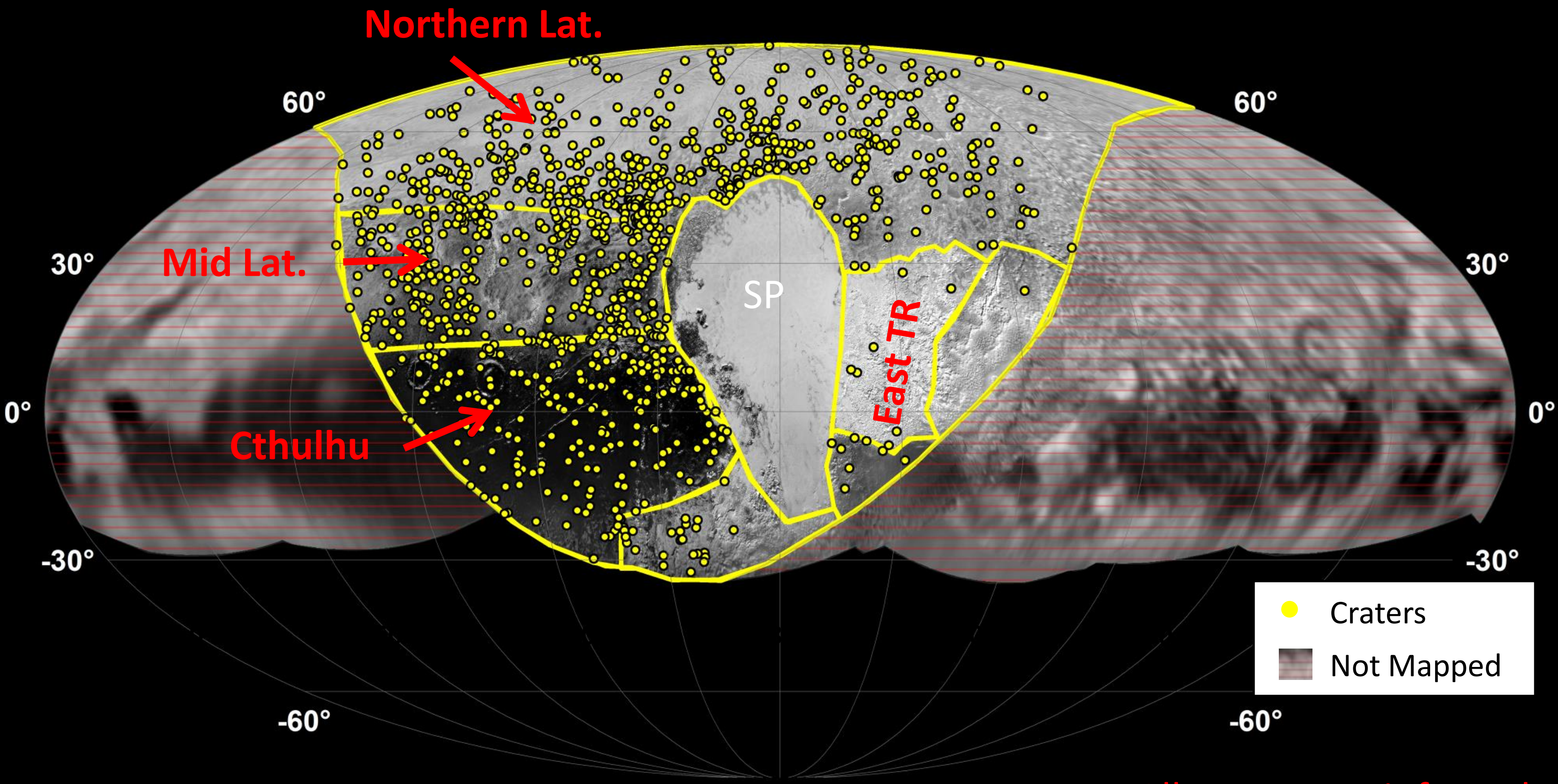
?? Bladed Terrain ??



Geologic processes

- Impact cratering
- (Cryo-)volcanism
- Tectonics
- Mass-wasting
- Glacial processes

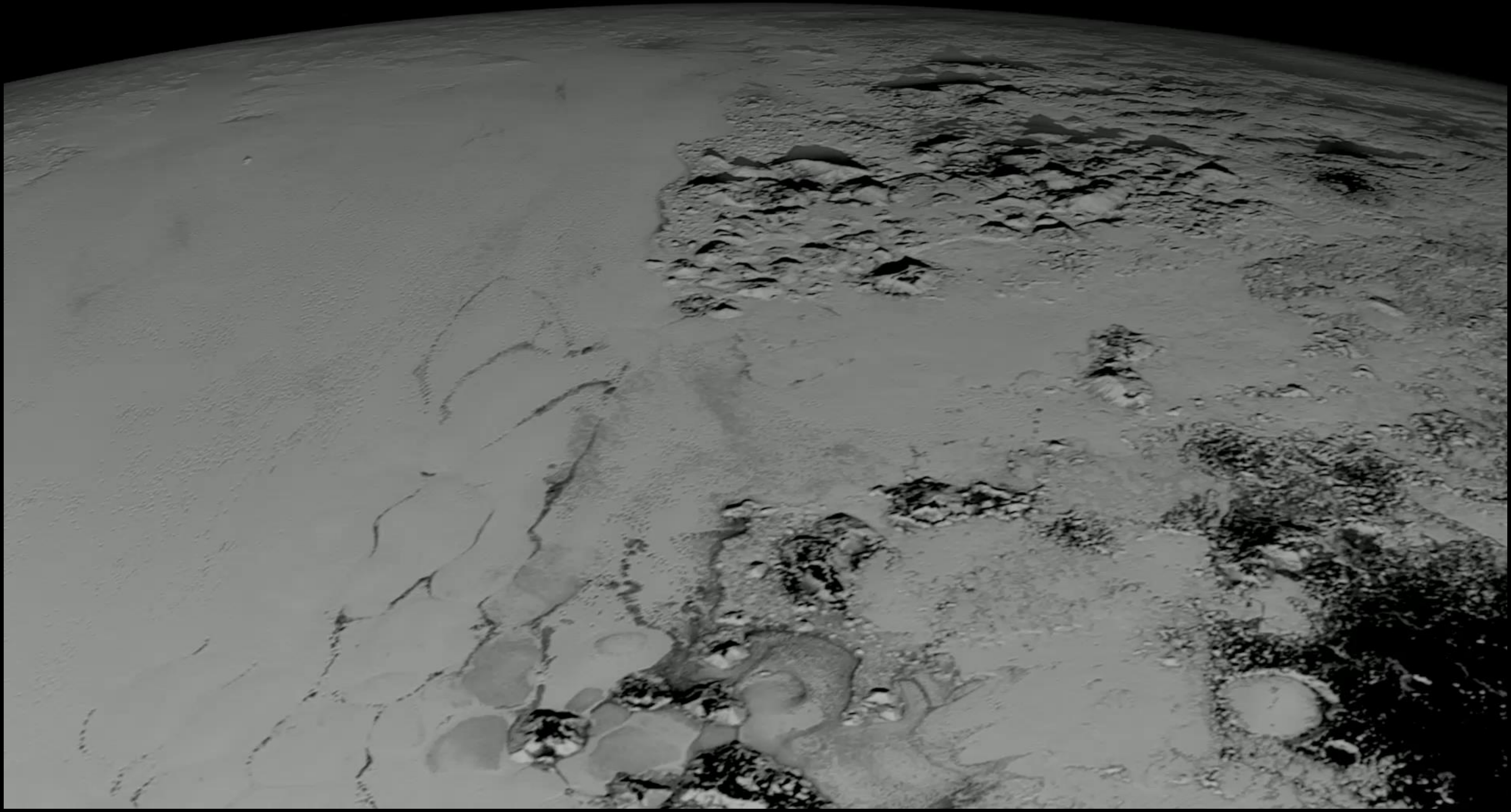
Pluto Crater Locations



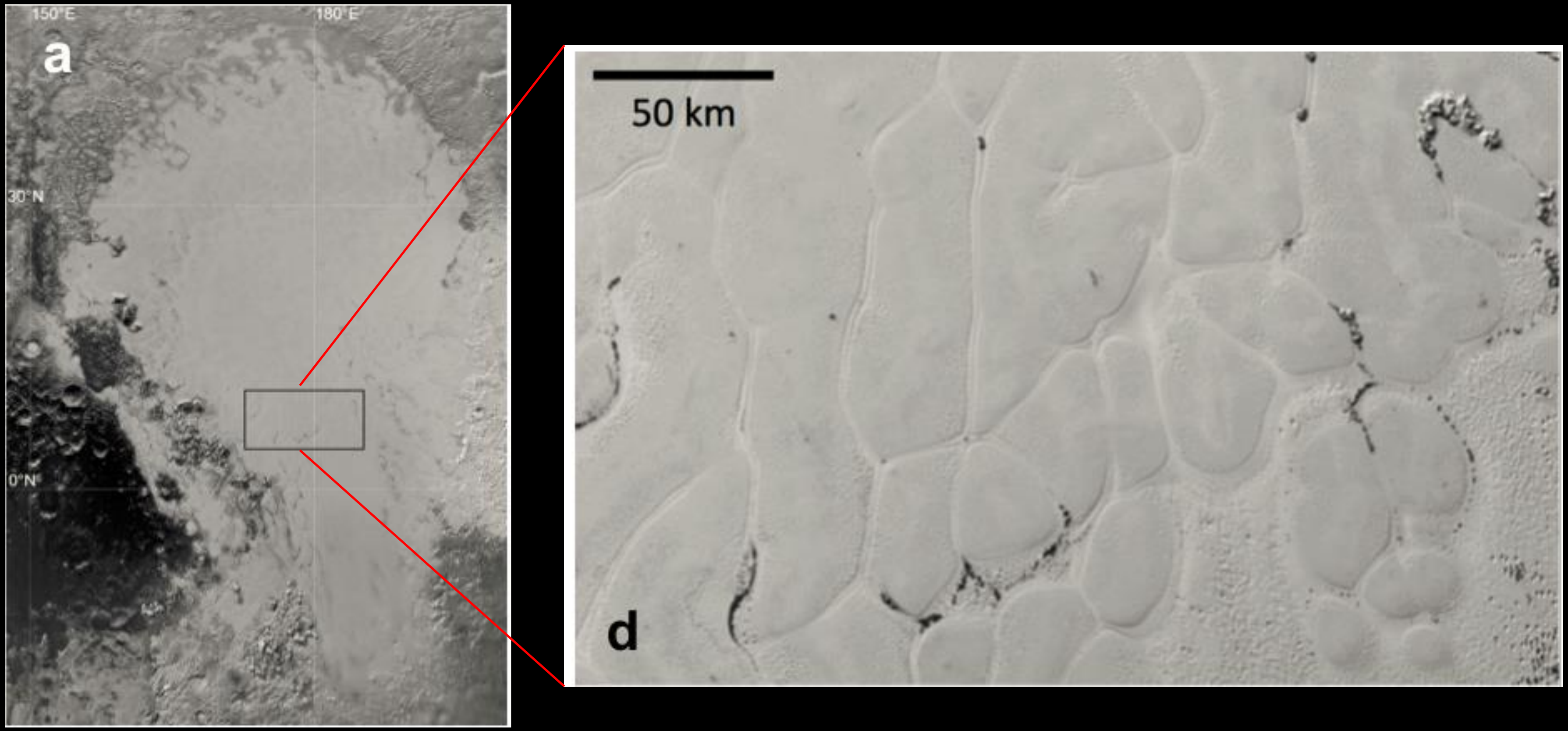
All names are informal.

- Mapped at a consistent resolution of ~900 m/px
- 1070 craters on encounter hemisphere

Sputnik Planum

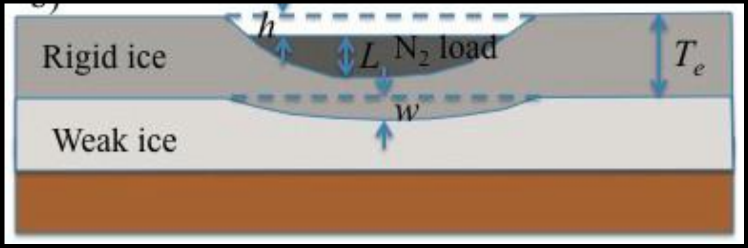


Sputnik Planum



Sputnik Planum

- Large extent (~900,000 km^2)
- Volatile ices
- No confirmed impact craters
- Renewal, burial, erosion of surface within 10 Myr



Nimmo et al. (2016) LPSC

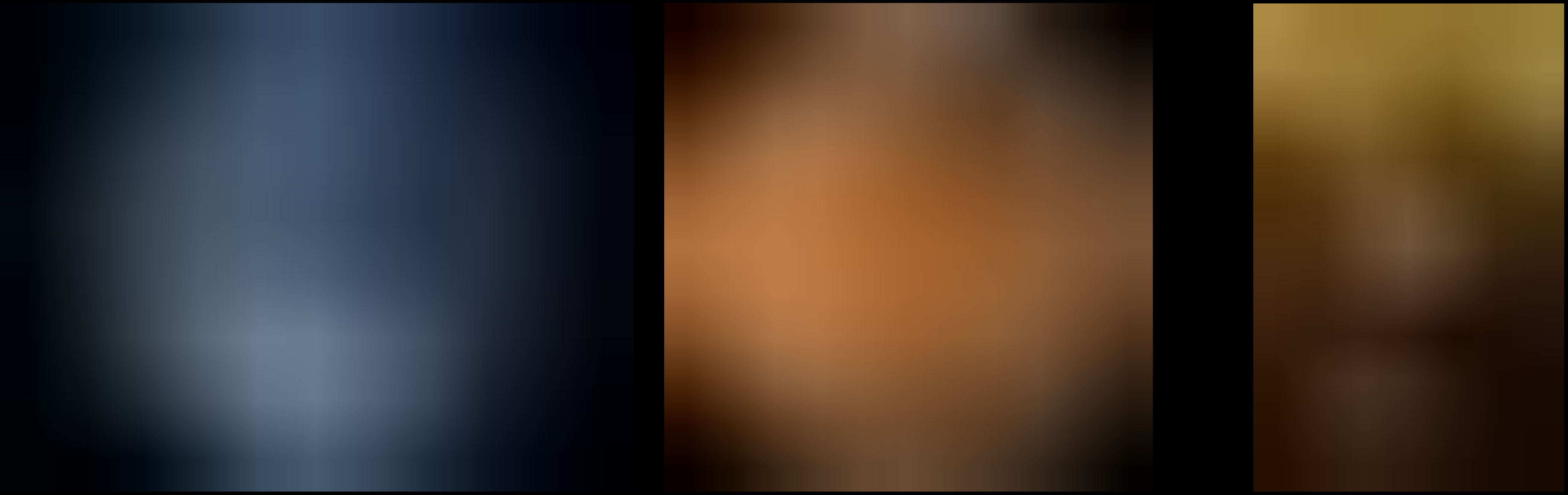
How did Sputnik Planum form?

Convection on Sputnik Planum?

If this is happening…

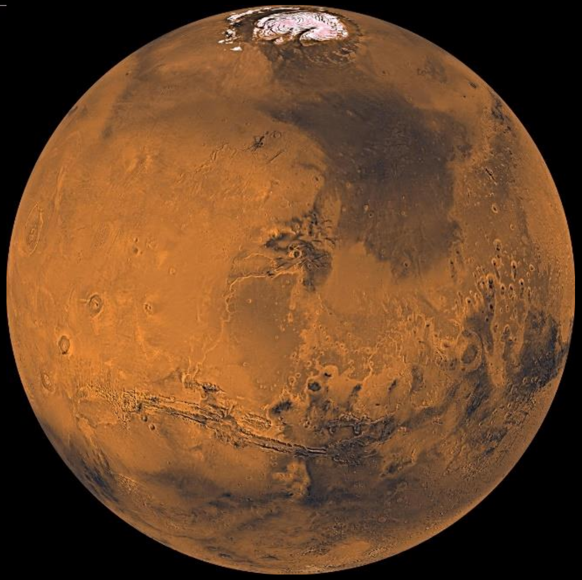
- Questions:
  - Does convection occur in the N_2 or the H_2O layer?
  - What drives convection?
  - Was it closer to the sun and warmer before?
  - What is the source of Pluto’s N_2?
- Derive constraints on
  - Depth of ice layer (N_2)
  - Present-day heat flow
  - Timescale of surface renewal

Pluto resolution



The Real Thing…

Earth From Space – Apollo 17
NASA Langley Research Center 12/7/1972 Image # EL–1996–00155



References and Acknowledgements

- Stern et al. (2015) Science, 350, 6258
- McKinnon et al. *Nature*. Submitted
- Moore et al. *Science*. Submitted
- McKinnon et al. (2016) LPSC abstract #1995
- Nimmo et al. (2016) LPSC abstract #2207
- Hammond et al. (2016) LPSC abstract #2234
- Slide courtesy of Kelsi Singer