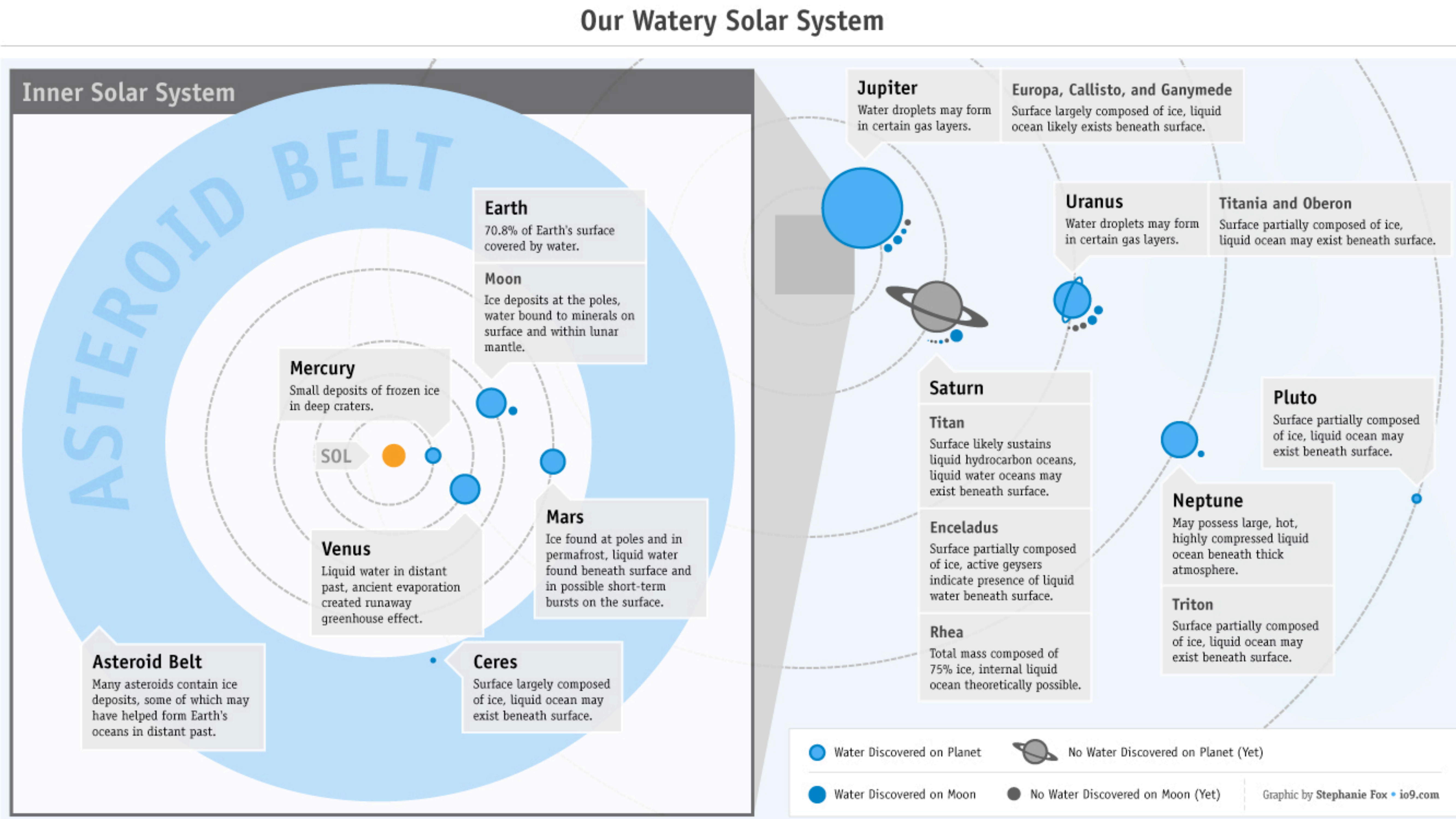
# Planetary Ices and their Rheology

# What is an “ice” anyway?

- Popular use: $H_2O$ solid phase
- Expansive use: solid phase of a volatile (something that would be a gas at room temperature)

# Where else is there water ice?



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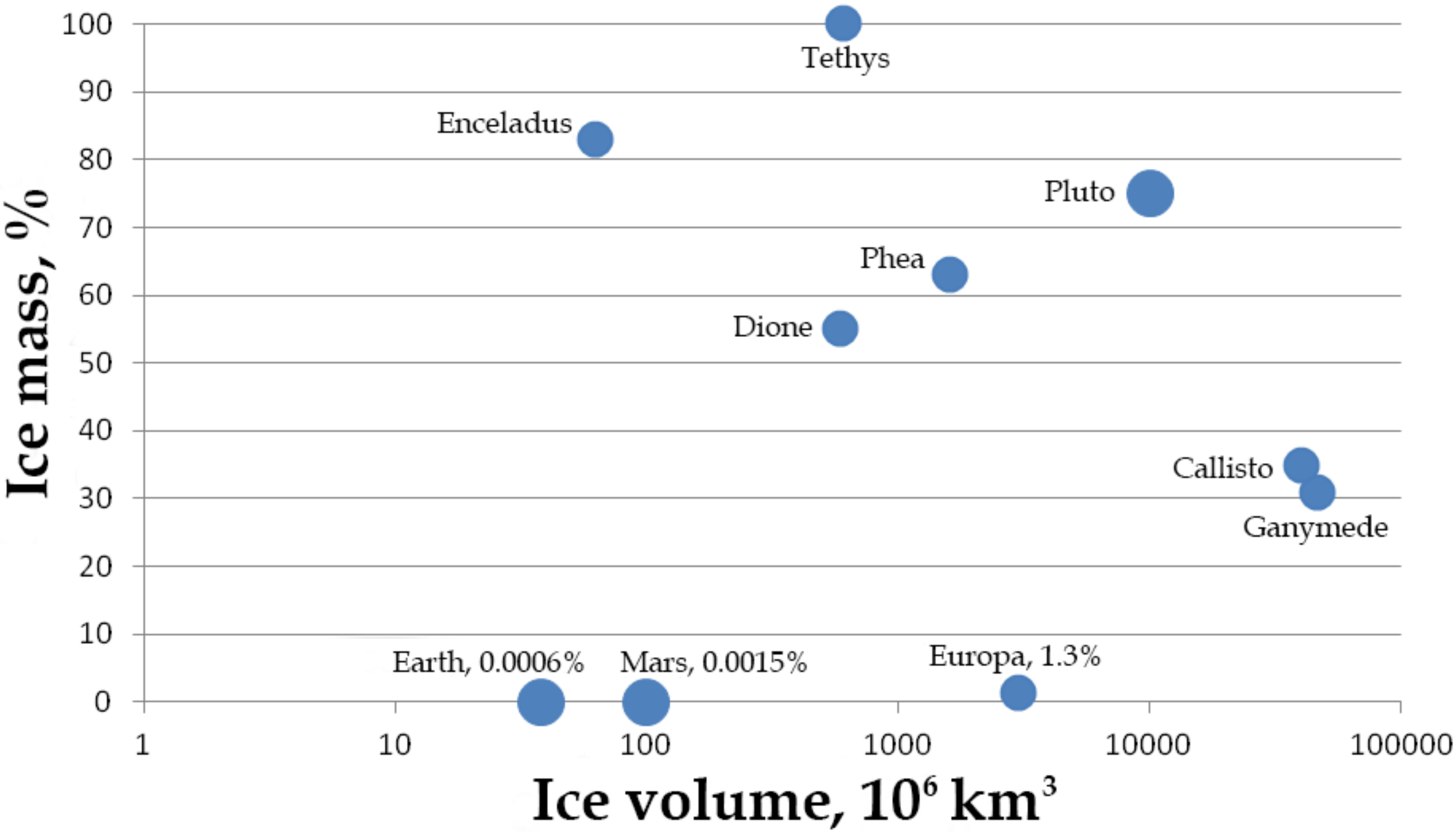
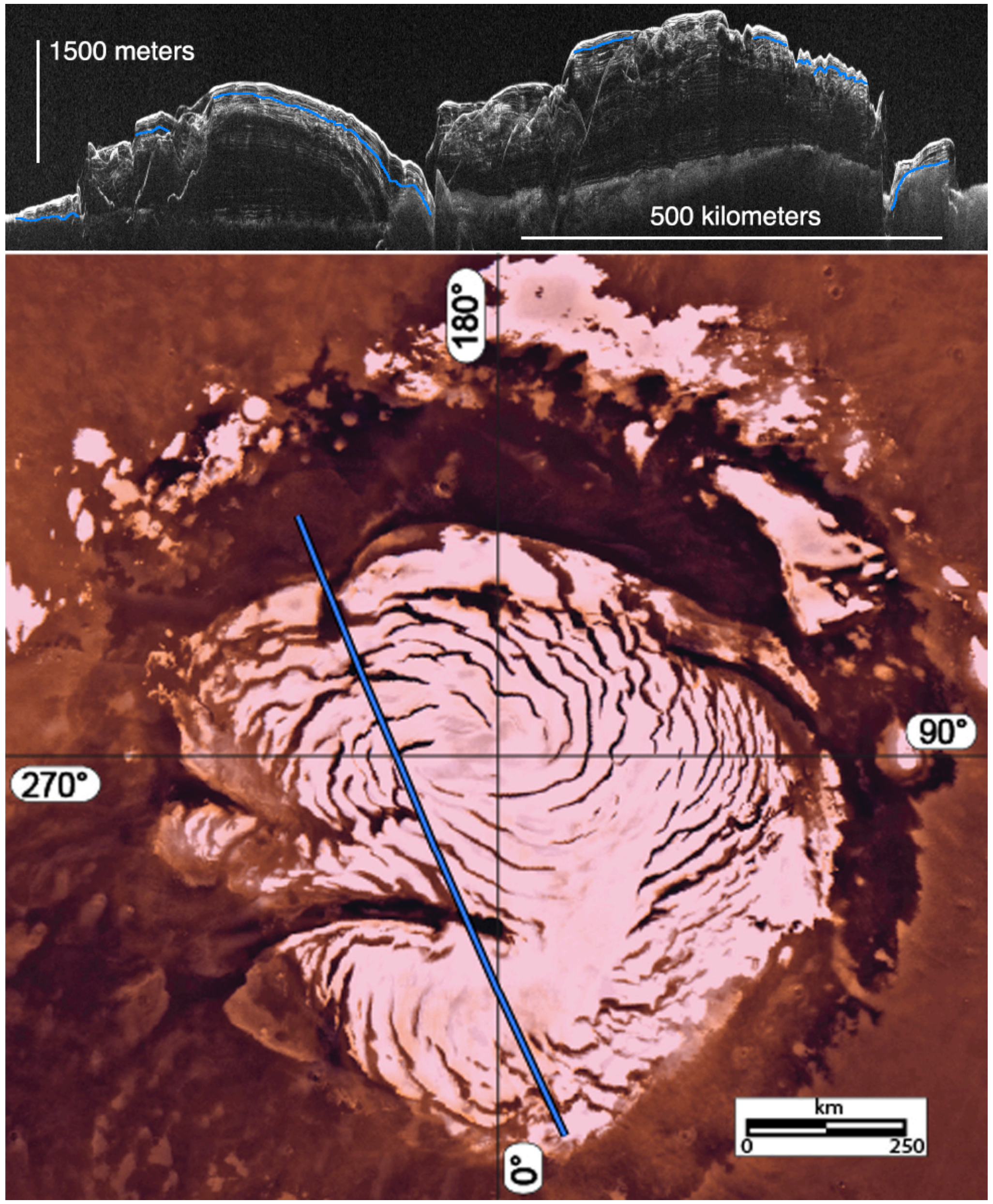



**Melnikov & Gennadinik 2018**

# Carbon dioxide ($CO_2$) ice

**Forms a seasonal deposit on top of Martian polar caps, which are composed primarily of water ice. Not much detail is known about $CO_2$ ice rheology (ignored in most martian ice cap modeling)**



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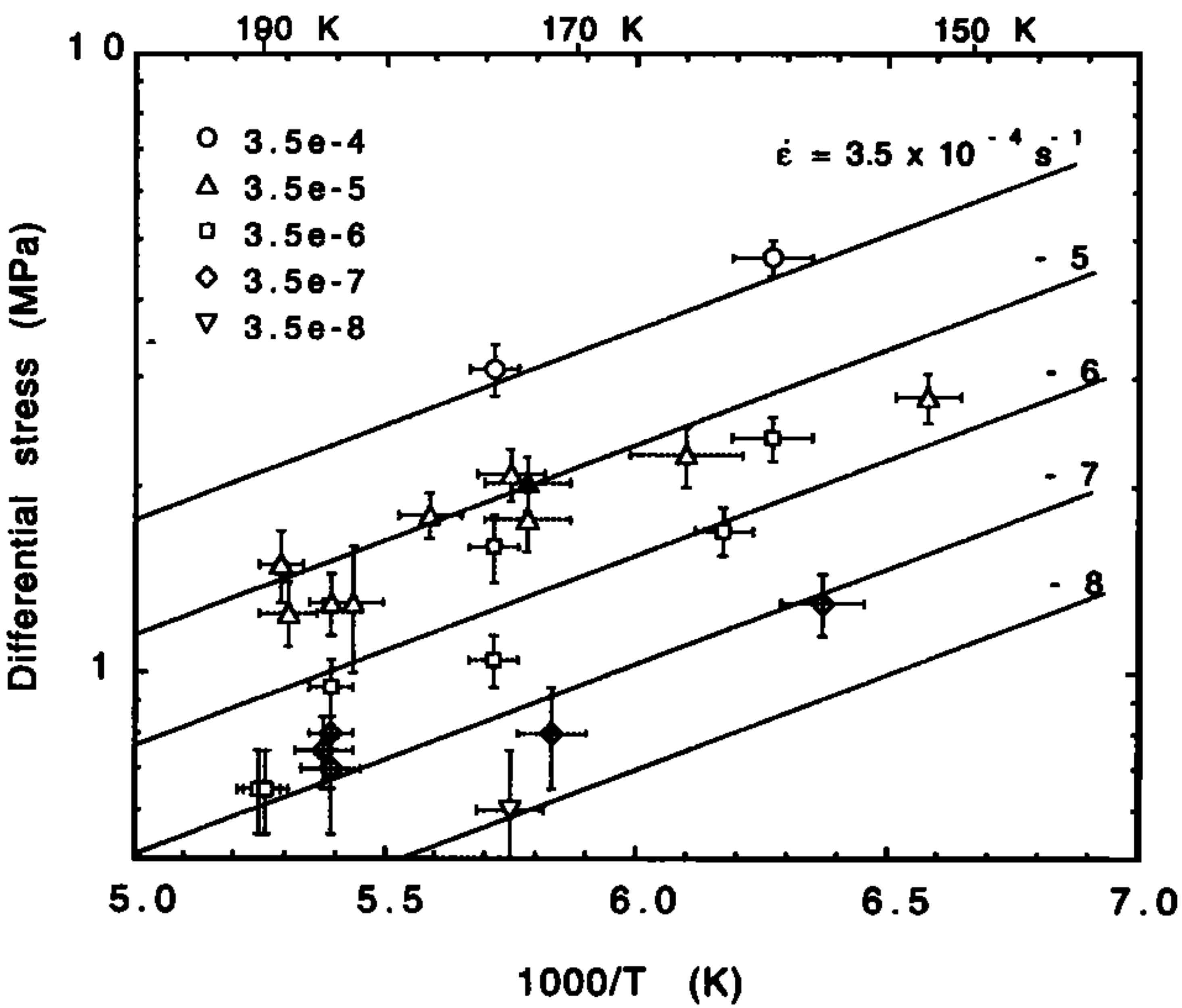


**(Durham et al. 1999)**

**$A = 10^{-27}$ $Pa^{-n}$ $s^{-1}$**
**n=5-7**

**Generally, CO2 ice has a low strength and should flow easily - the low of deformation of the Martian S. Pole Cap has been given as evidence that there isn't much CO2 there (Nye et al. 2000)**

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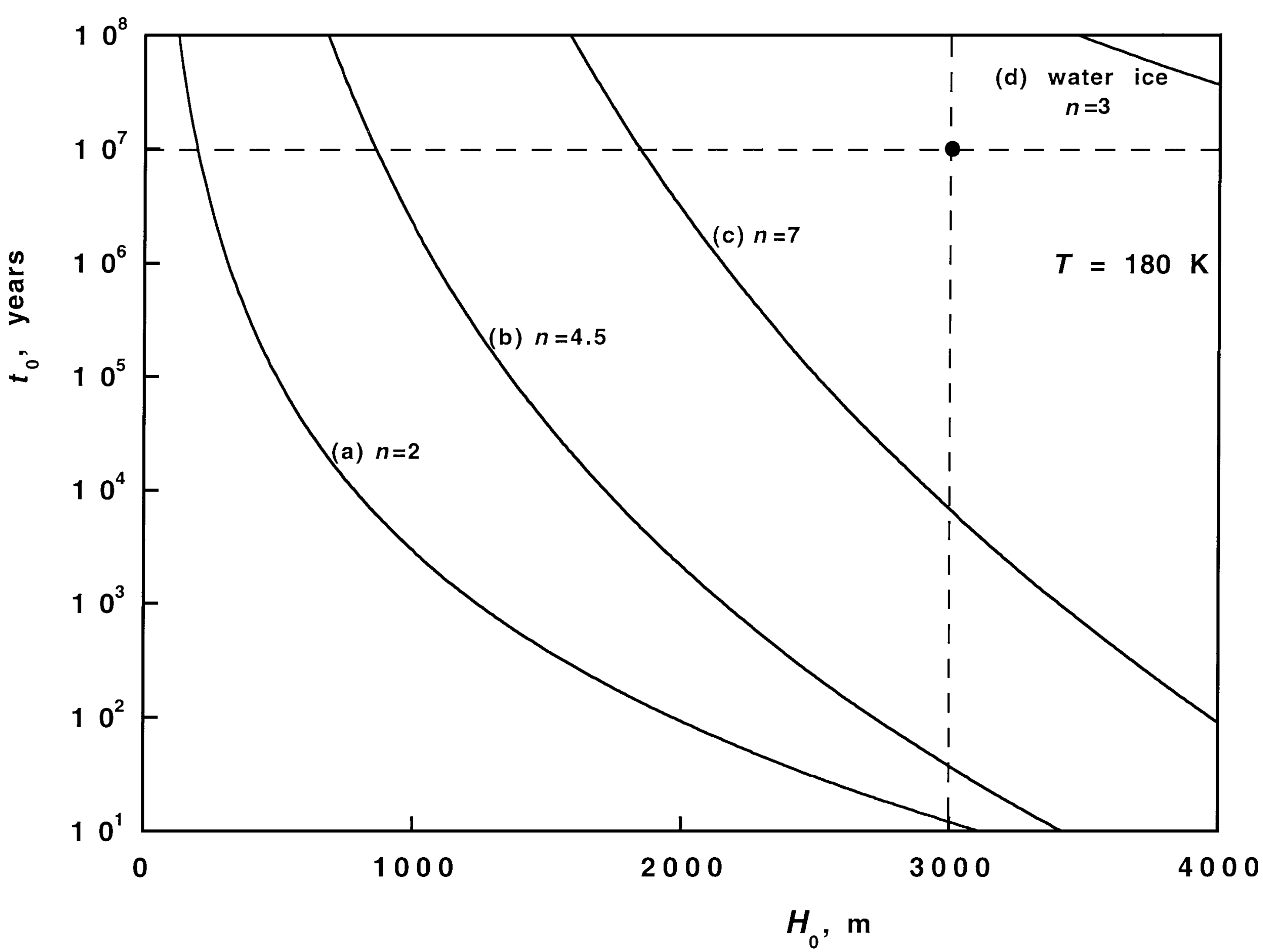


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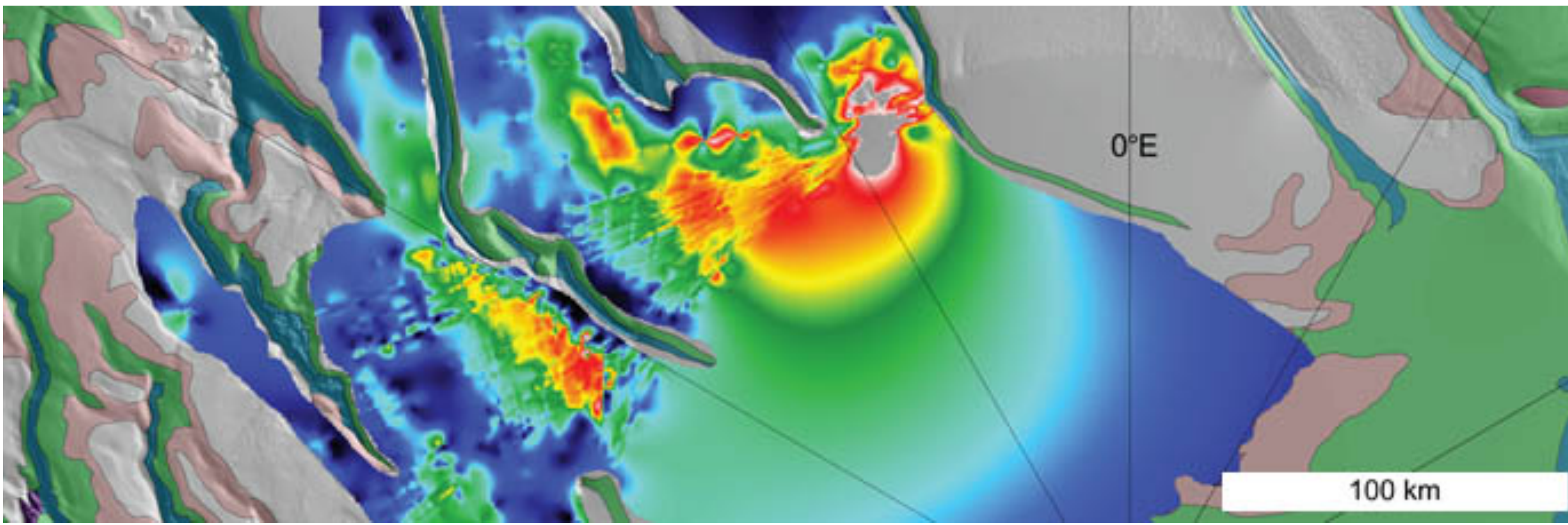
# Carbon dioxide ($CO_2$) ice

**There are large (100's m thick) deposits of buried/mixed $CO_2$ ice near the South Pole of Mars - its unclear whether they flow or not.**



# Sulfur dioxide ($SO_2$) ice

**Freezes at 200 K - no known rheological experiments - though has been suggested to be similar to CO2 ice, though molecular geometry is different**

**Moore et al. (2001) - SO2 ice present on Io - unclear whether deformation is evident**

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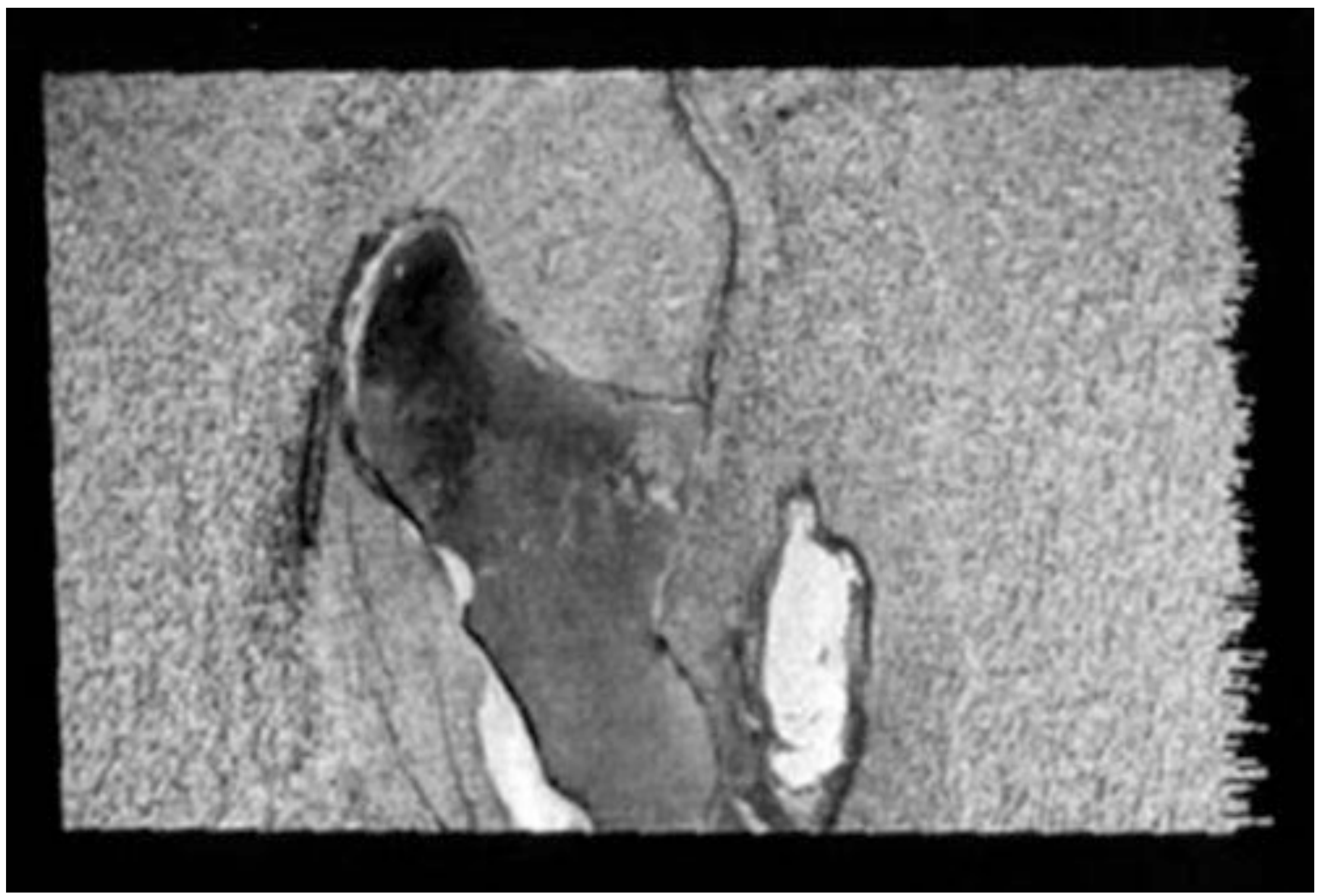
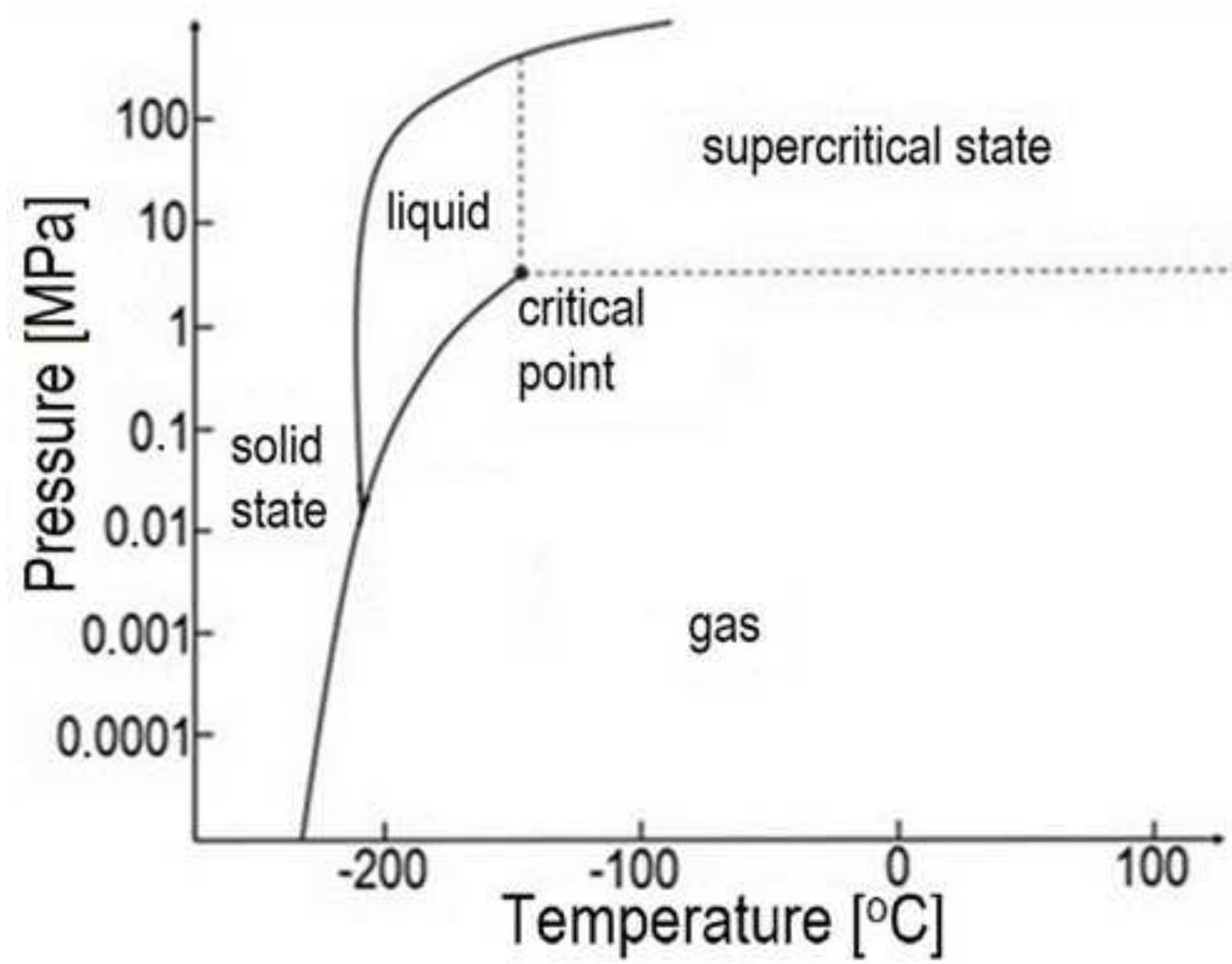


**The filling of calderas with SO2 ice may indicate some liquid or solid deformation? (rather than just condensation as a layer)**

**Clark et al. 2013**

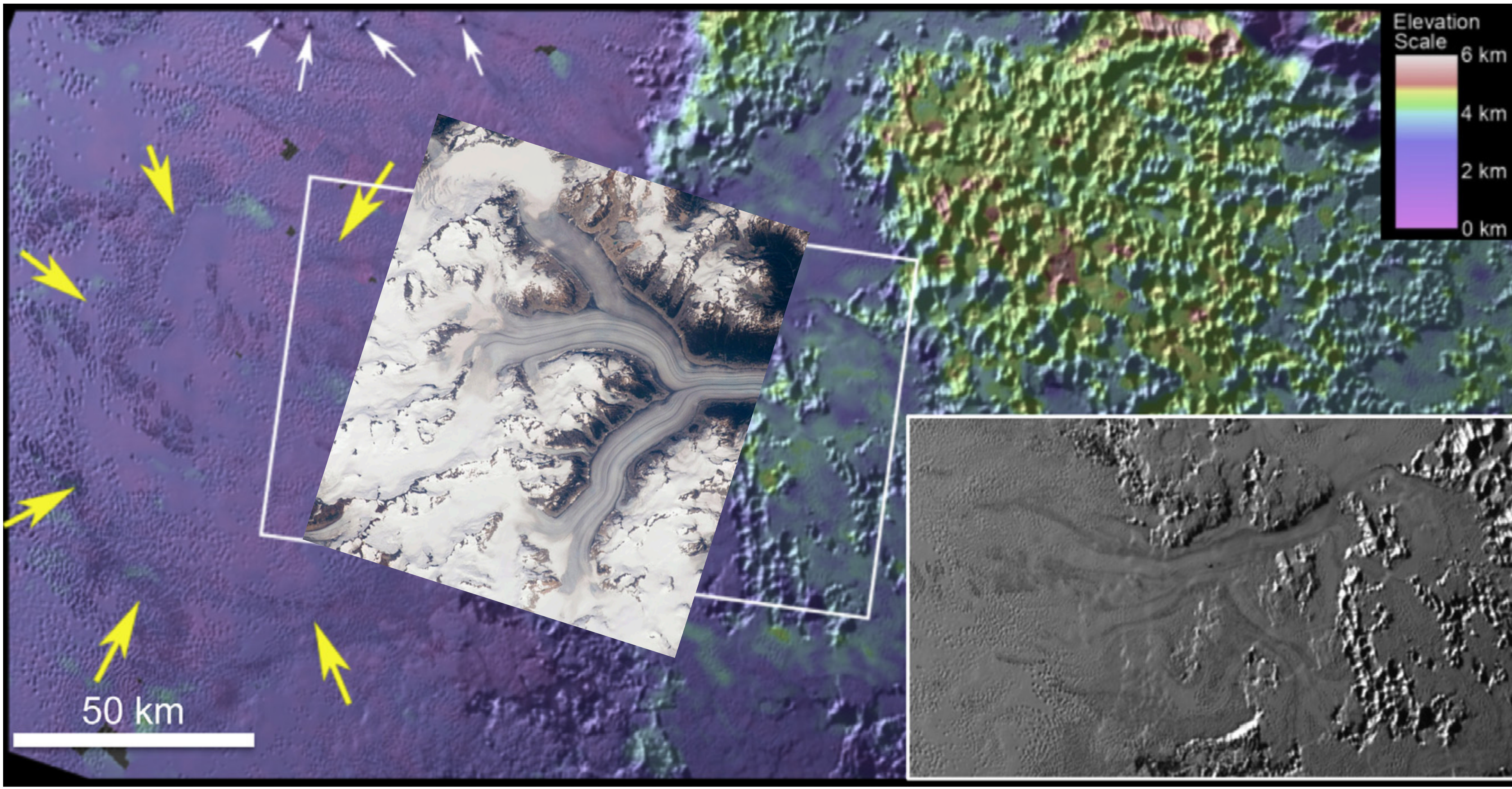
# Nitrogen ($N_2$) Ice

- Solid only at very low temperatures (~35 K)
- Pluto is cold enough!



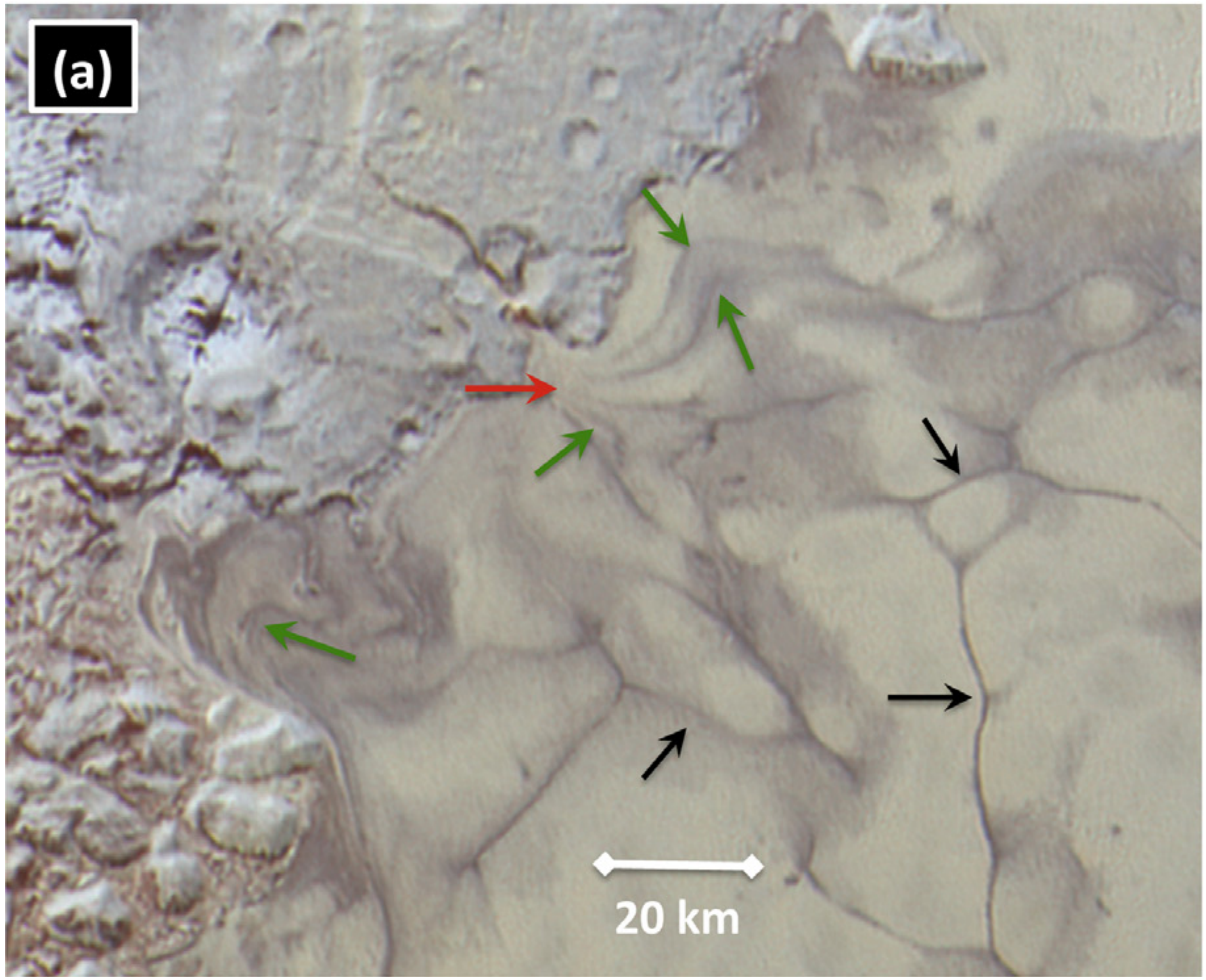
# Nitrogen ($N_2$) Ice

**Sputnik Planitia on Pluto**



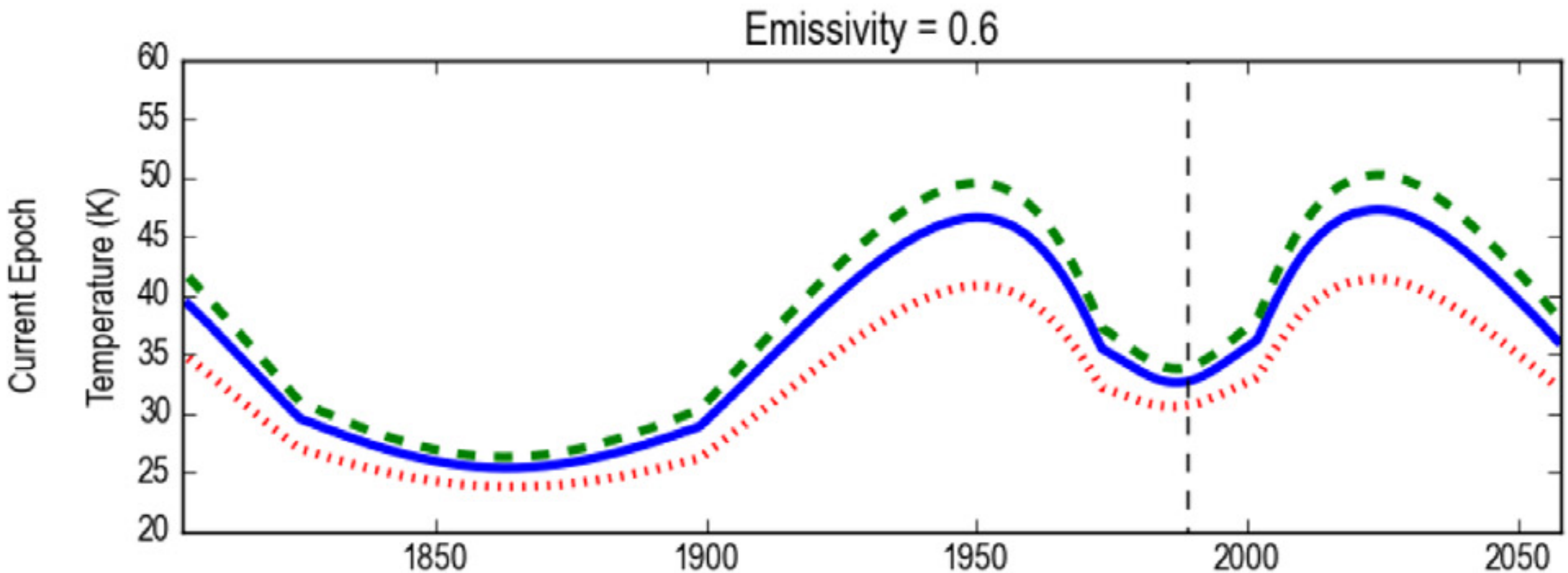

**N2 Glacier flow through a valley? (Thanks New Horizons!)**

# Nitrogen ($N_2$) Ice




**N2 convection cells?**

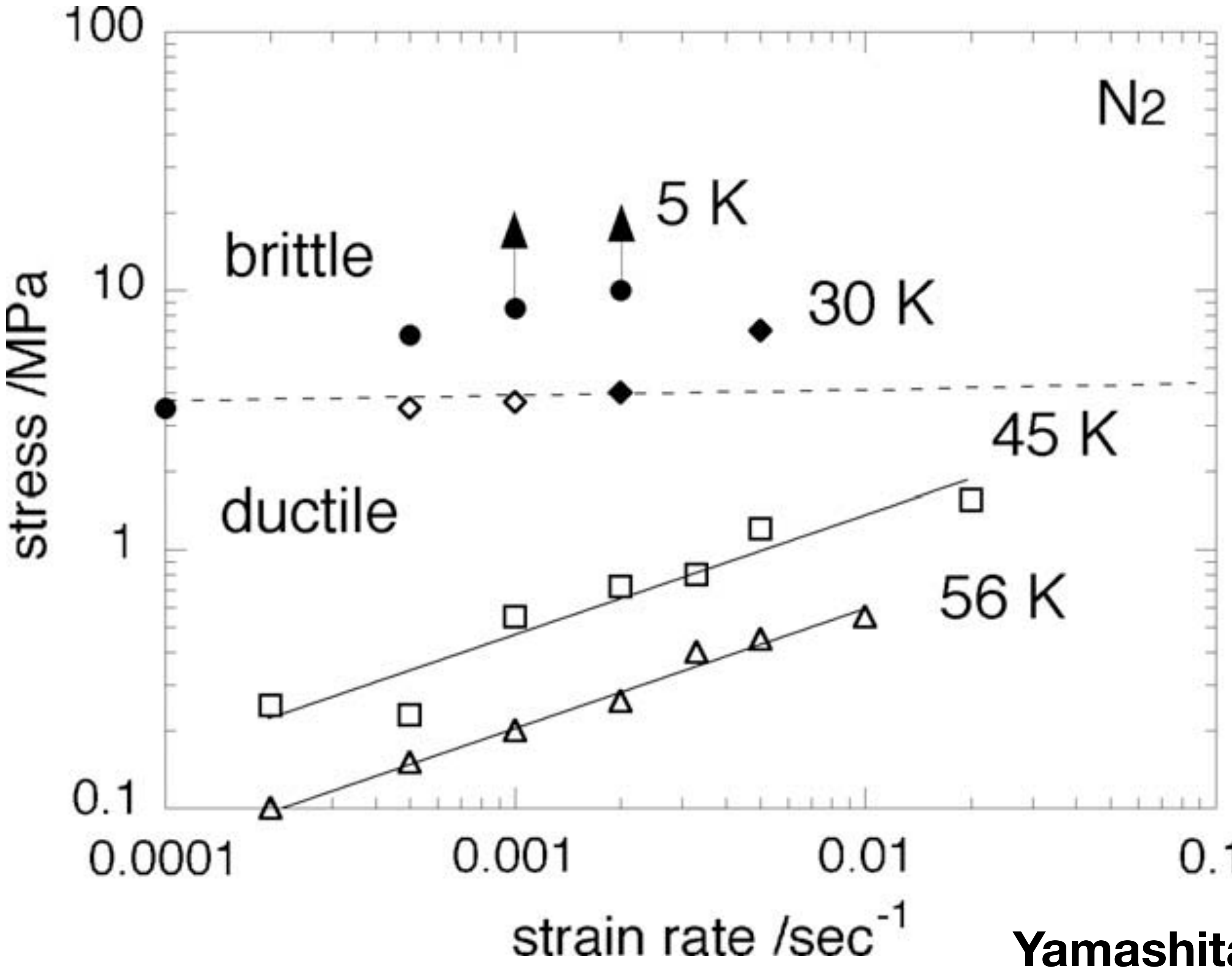
# Nitrogen ($N_2$) Ice




Umurhan et al. 2017

**Previous period of warmth during Pluto orbit may means N2 glacier are very recent features or that they have experience large (20 K) differences in temperature during their lifetime**

# Nitrogen ($N_2$) Ice




**Yamashita et al. 2010**

**N2 has had some stress-strain measurements done for low stresses**

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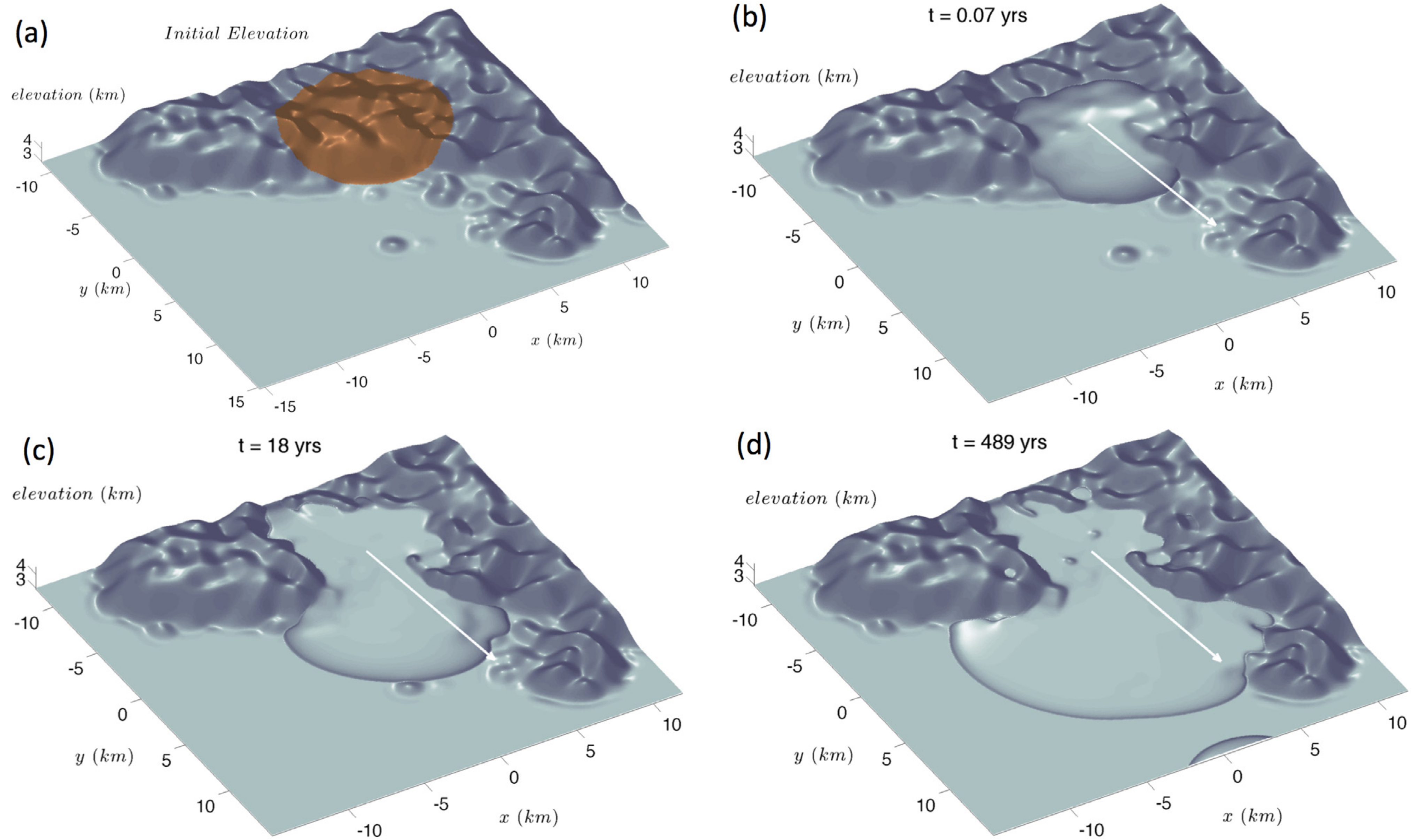
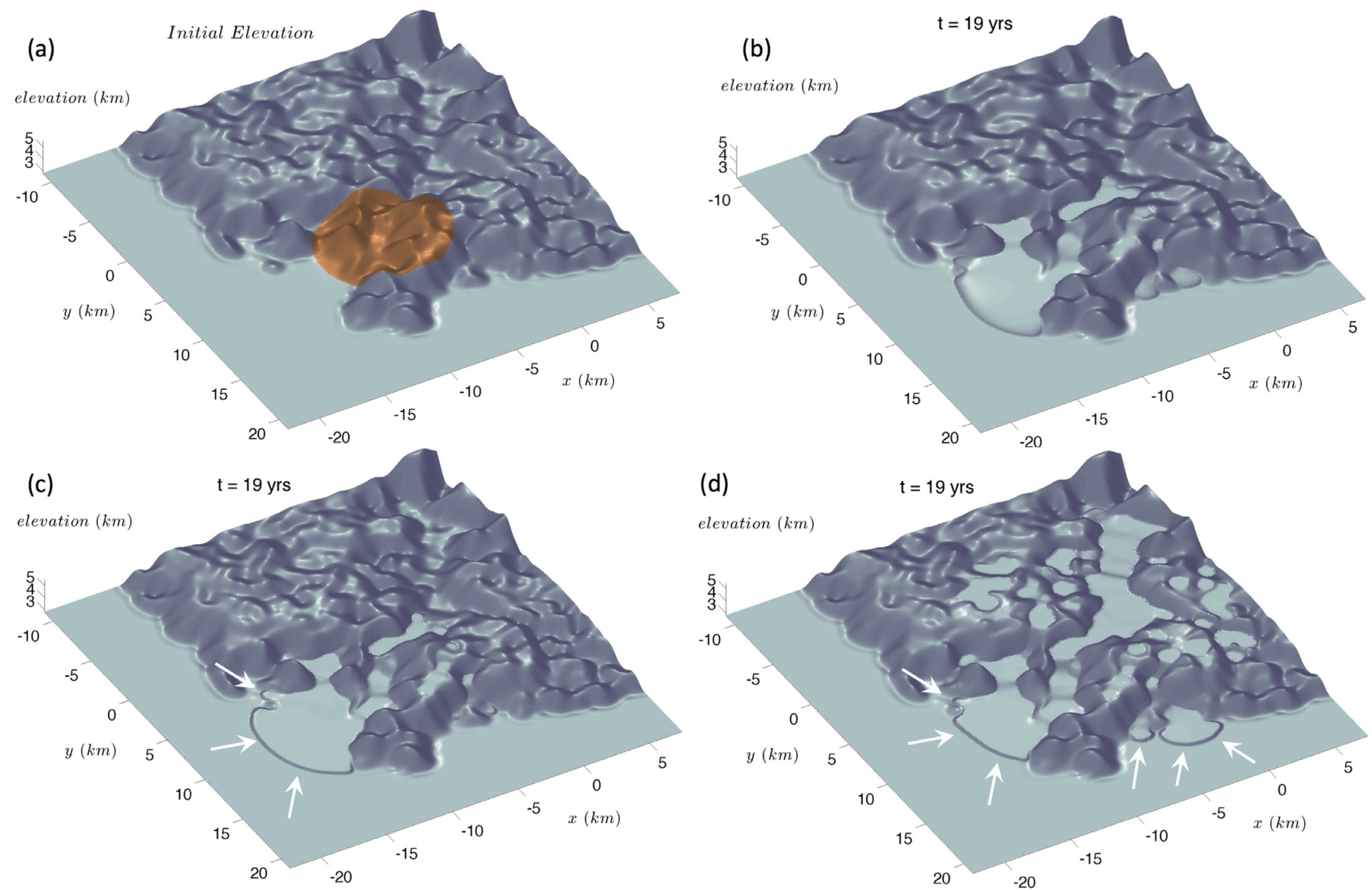



**Umurhan et al. 2017**

**Flow modeling of N2 glaciers on Pluto using SSA**

# Nitrogen ($N_2$) Ice



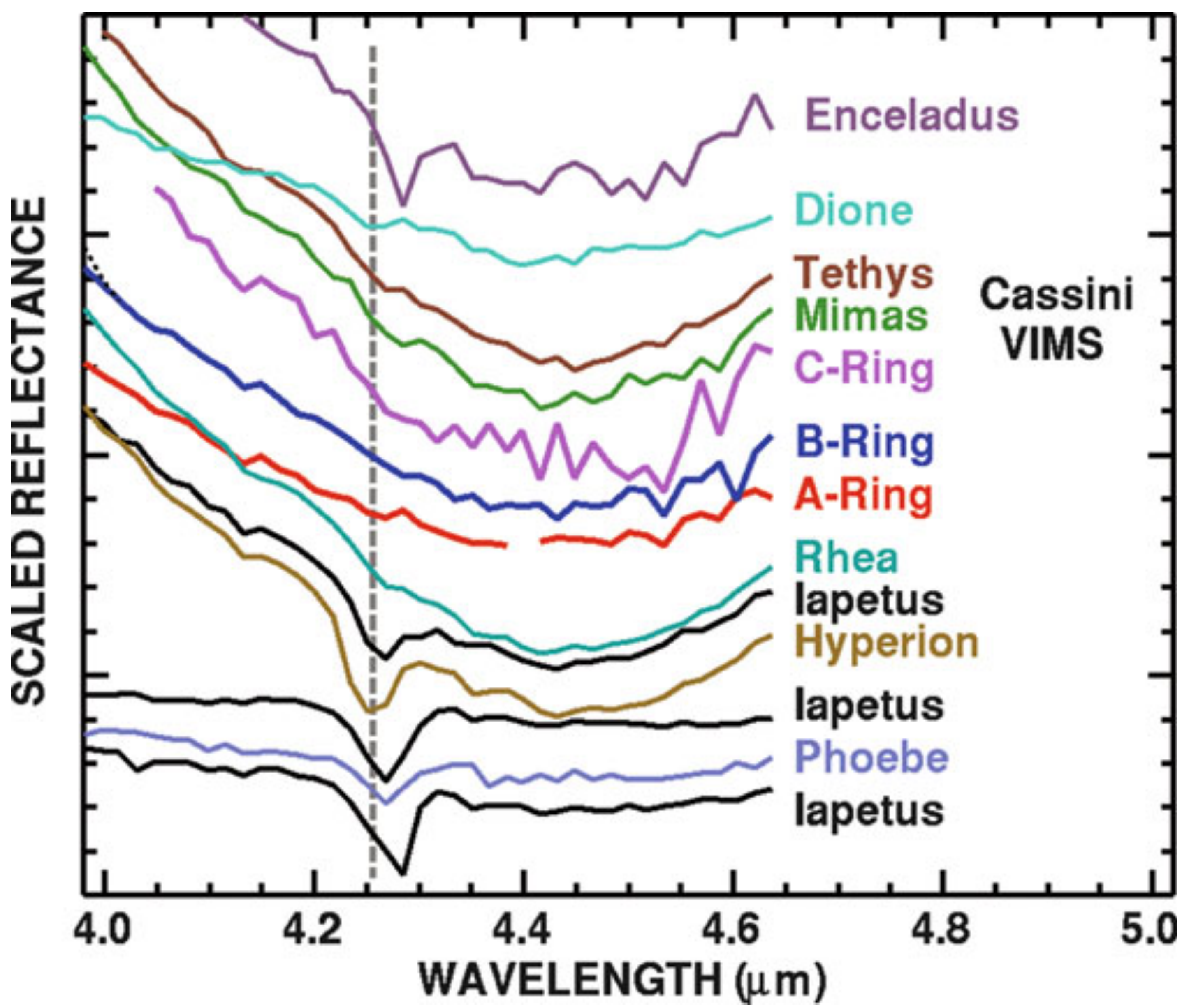

**Umurhan et al. 2017**

**N2 ice can flow pretty fast and also develop basal slipperiness due to liquid nitrogen**

# Triton

**N2 ice crust and extensive N2 and CH4 polar caps, along with a pitted “cantaloupe” terrain**

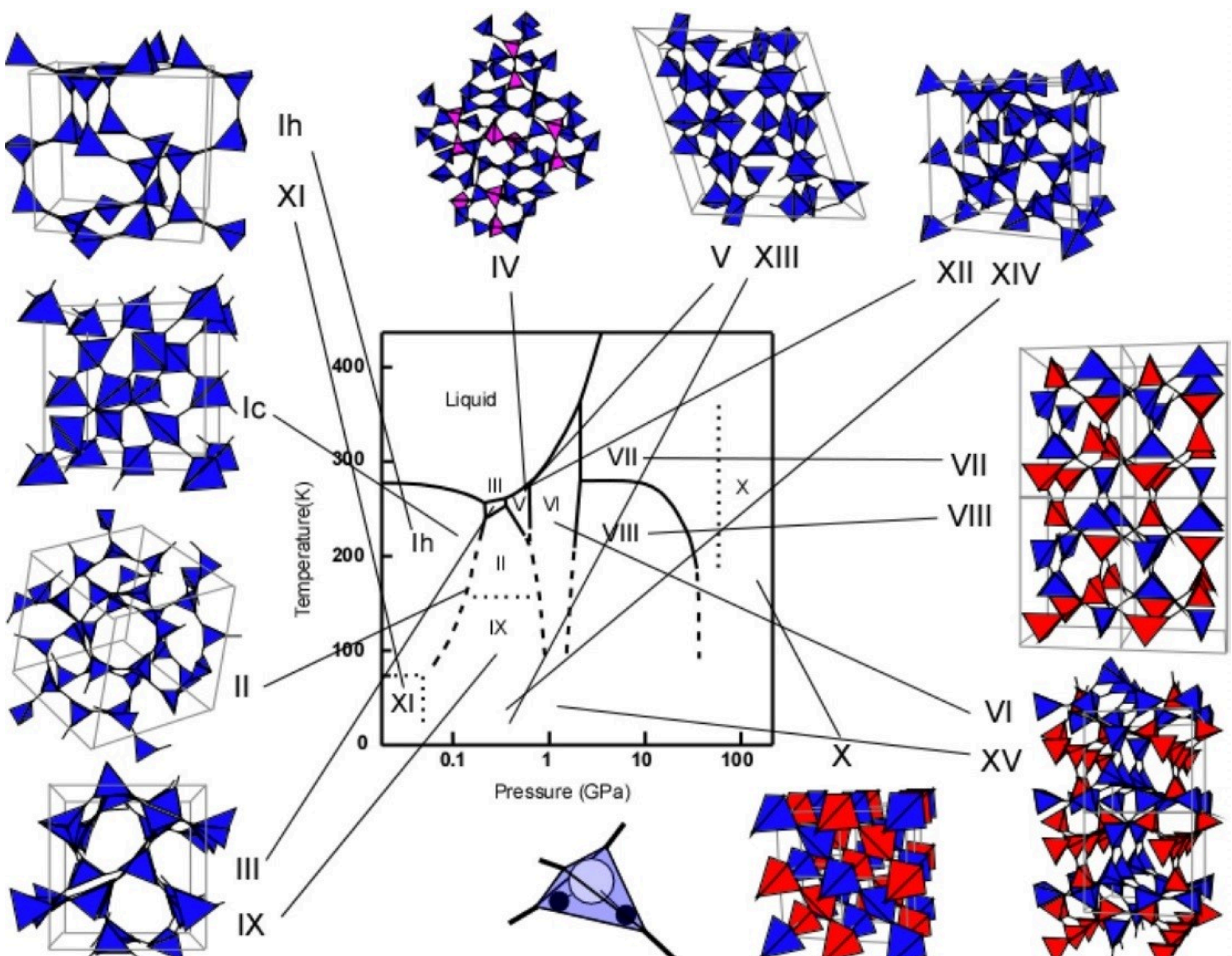
# Mixed ices




**Saturn's satellites mostly composed of pure water ice, with the exception of Iapetus and Phoebe which indicate mixture of other components into the water ice**

**Cuzzi et al. 2010**

# Water ice phase diagram



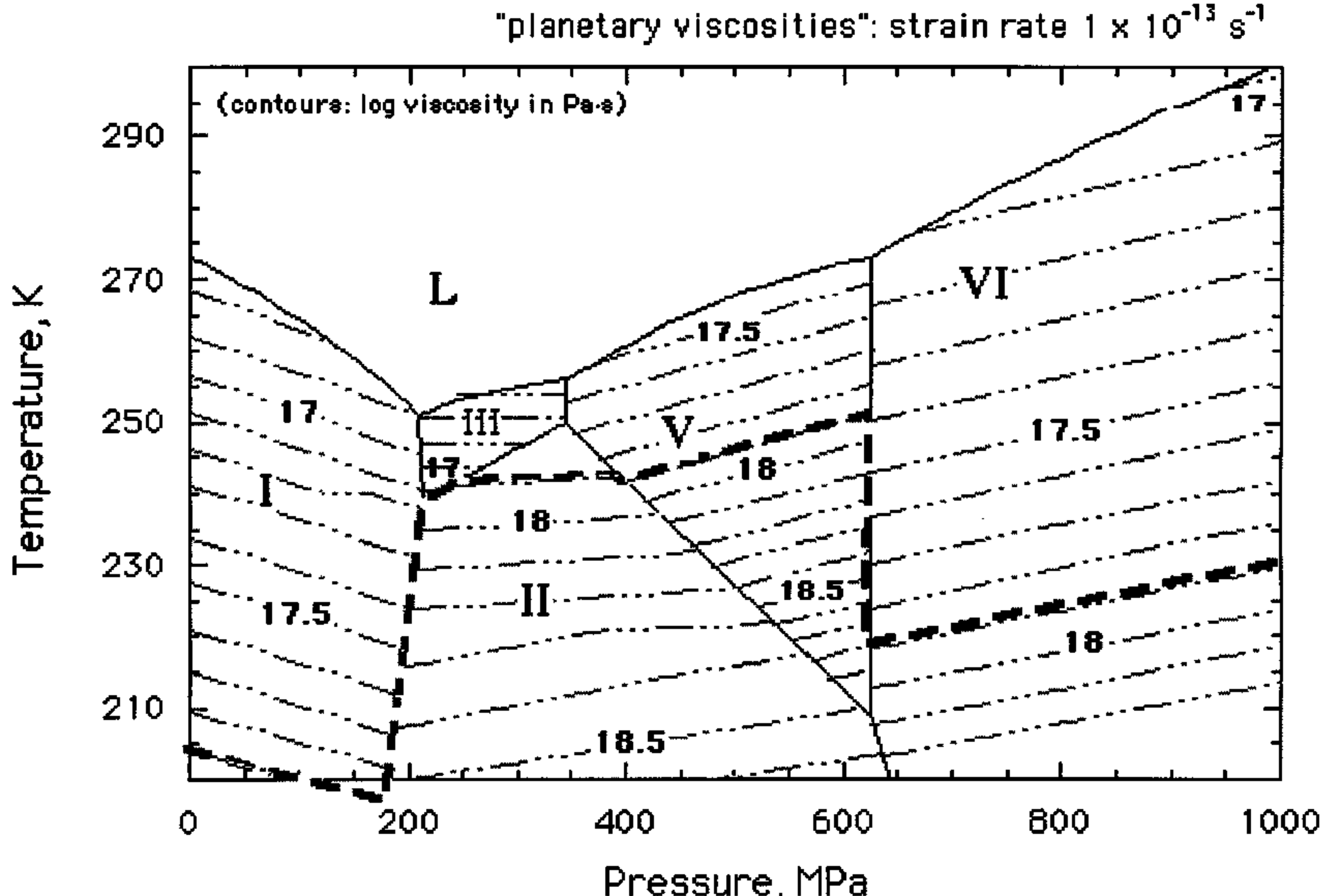
# Ice rheologies

$$\dot{\epsilon}_{ij} = A(T, d)\tau_E^{n-1}\tau_{ij}$$

**For most ices, non-Newtonian viscous deformation is typically found to be a good empirical model for ductile flow**

**…but lithostatic stress, temperature and grain size can become much more important to the viscosity, and different deformation mechanisms might play a role in setting *n***

# Water Ice rheology under planetary conditions




Durham & Stern 2001

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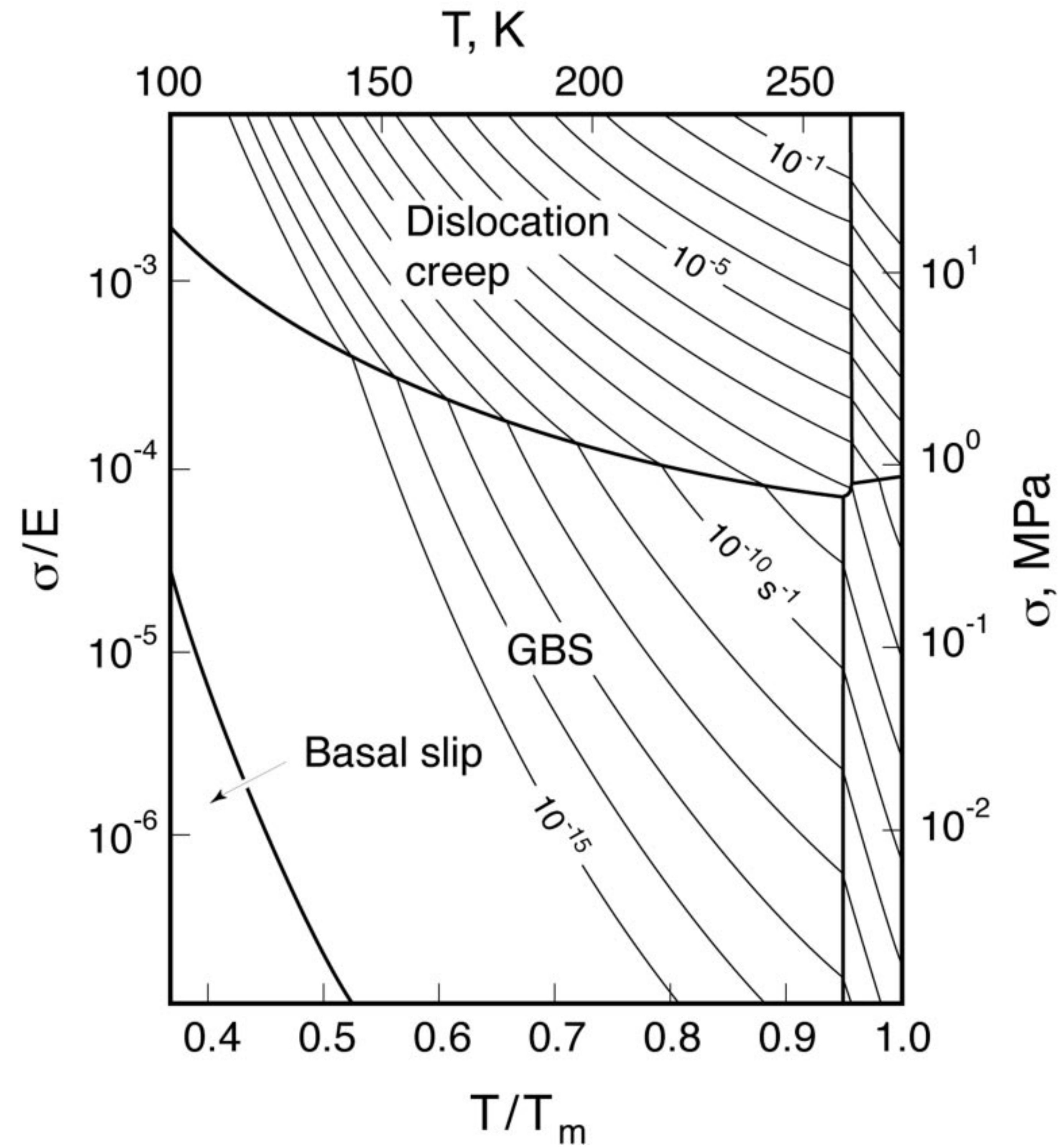
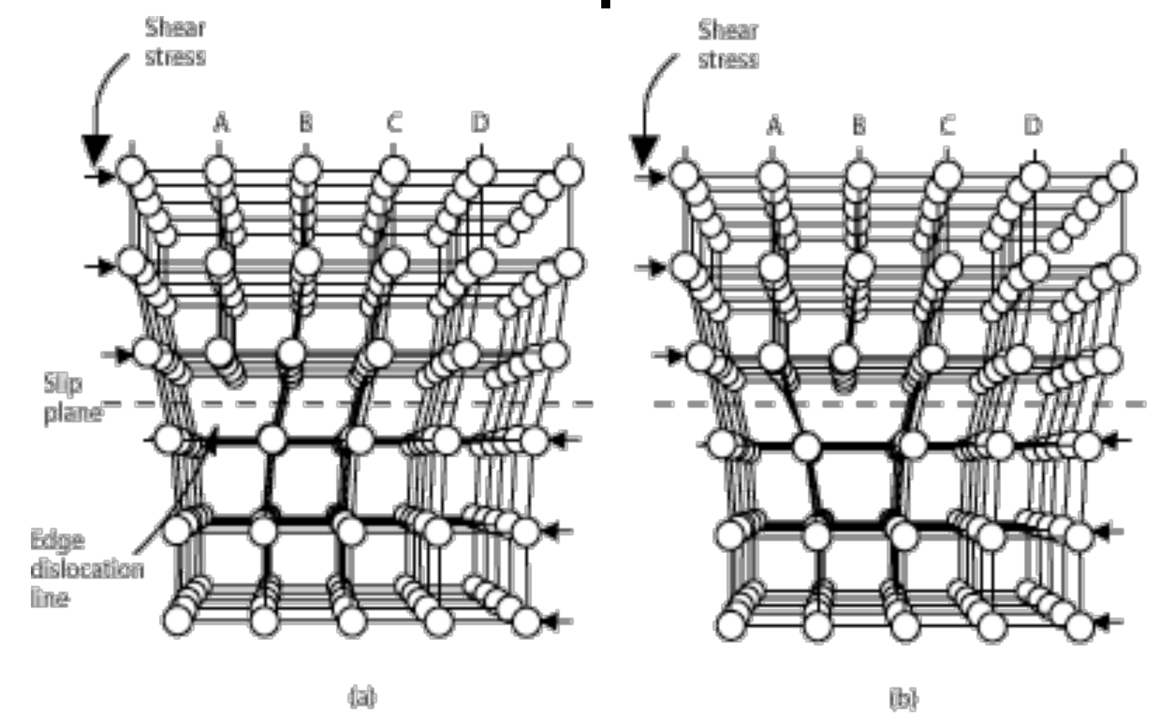
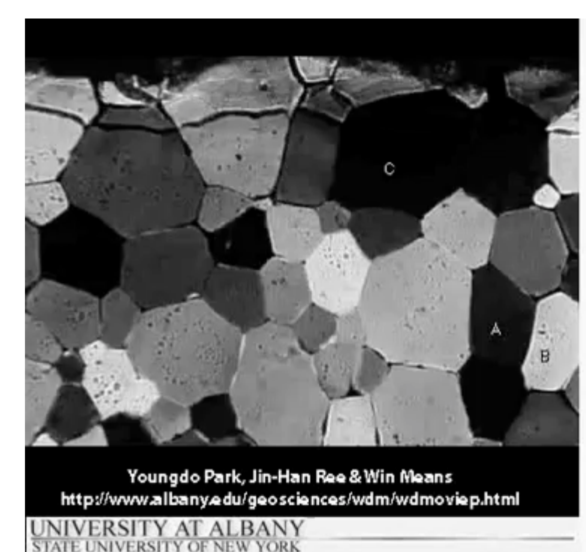



Durham & Stern 2001

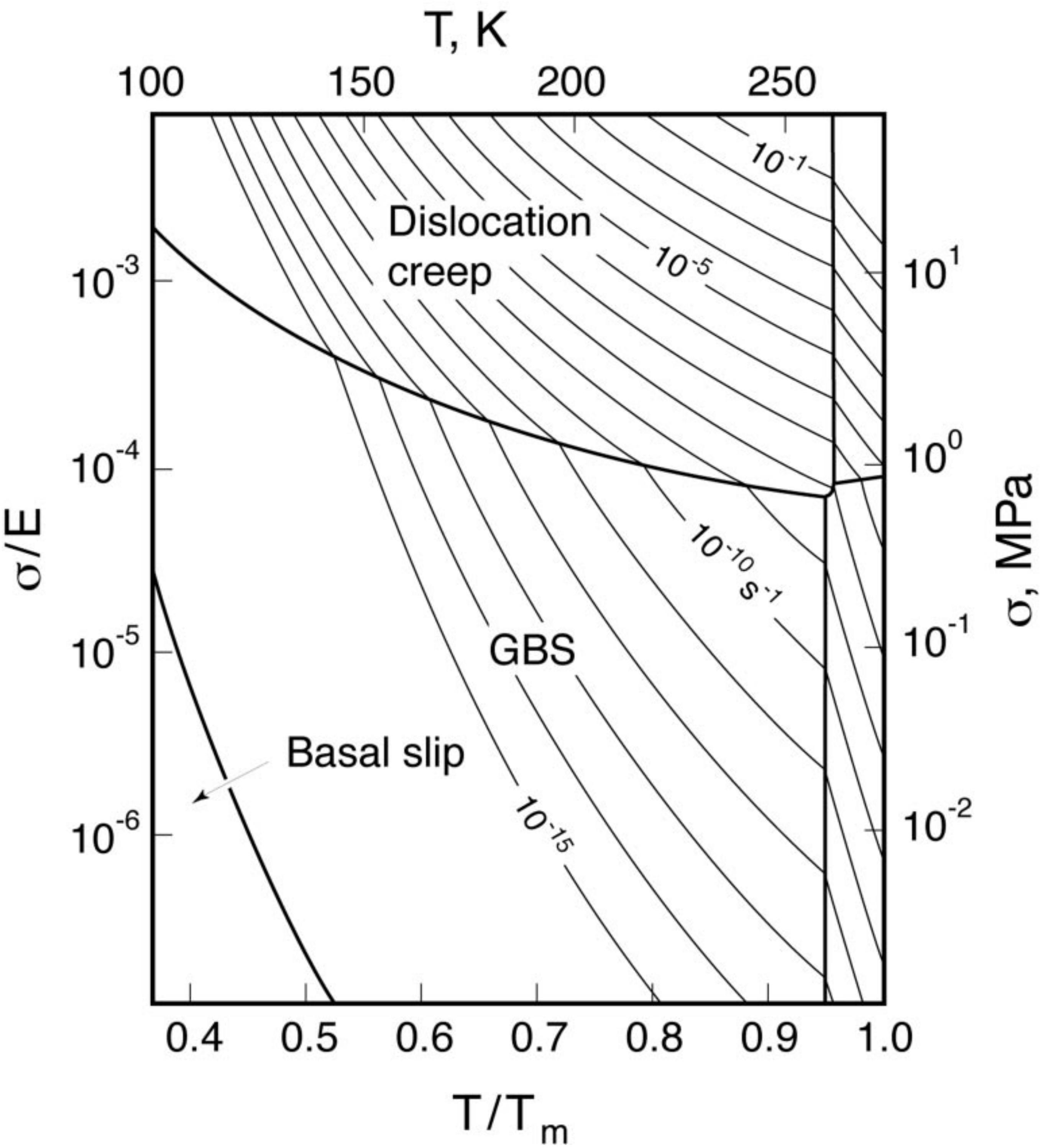
## Dislocation Creep




## Grain Boundary Sliding



# Water Ice rheology under planetary conditions




Durham & Stern 2001

**Under most planetary circumstances, Grain Boundary Sliding is the dominant mechanism by which ice deforms - which is very sensitive to grain size. So, models of grain size/growth/ reduction are very important to determining the rheology of planetary ices**

# Grain growth

$$d^2 - d_0^2 = Kt$$

$$K = K_0 e^{-Q/RT},$$

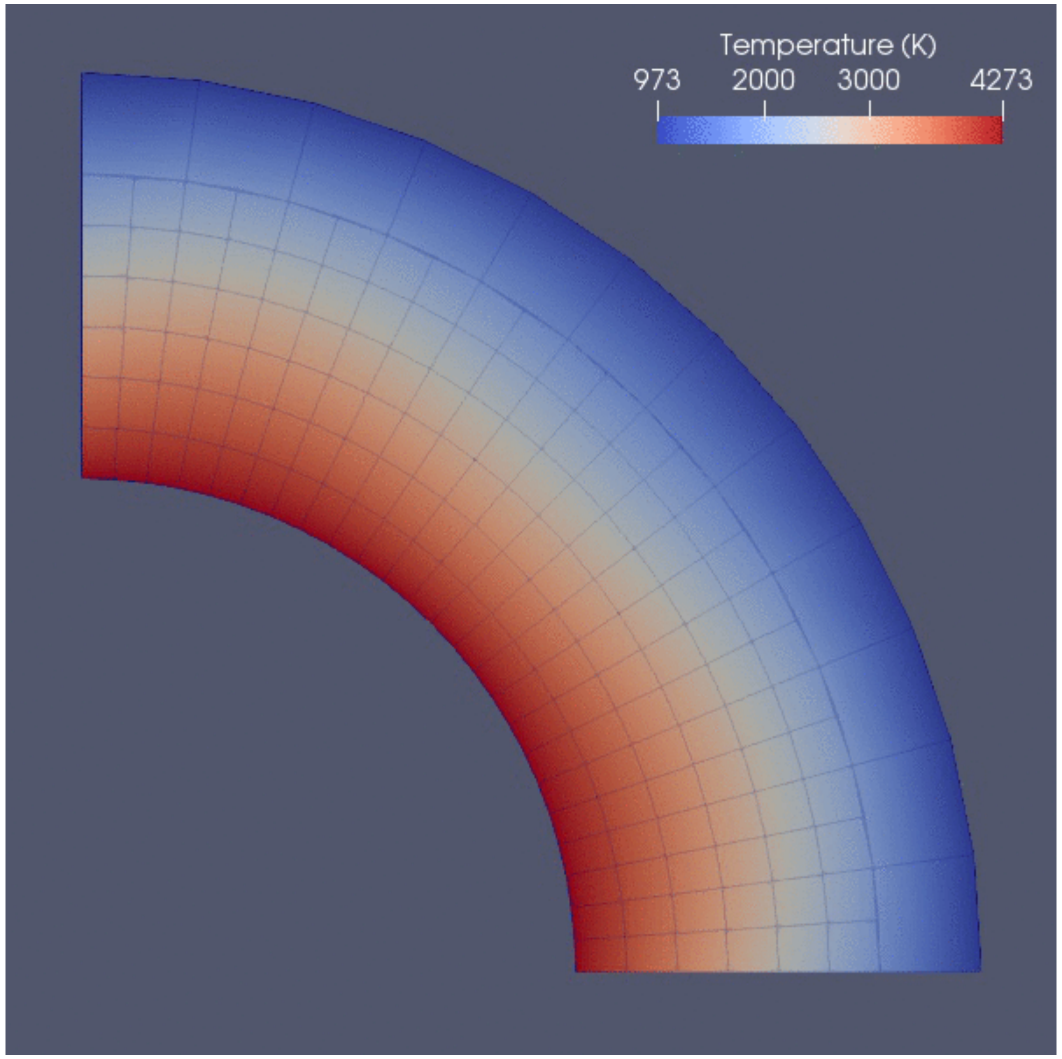
**Grain size, *d*, grows over time at a rate, K, that depends on temperature**

**If dislocation creep occurs, grain size will shrink**

# Why Planetary Ice Rheology is important

$$Ra = \frac{g\alpha\rho D^3 \Delta T}{\kappa \eta_{eff}}$$

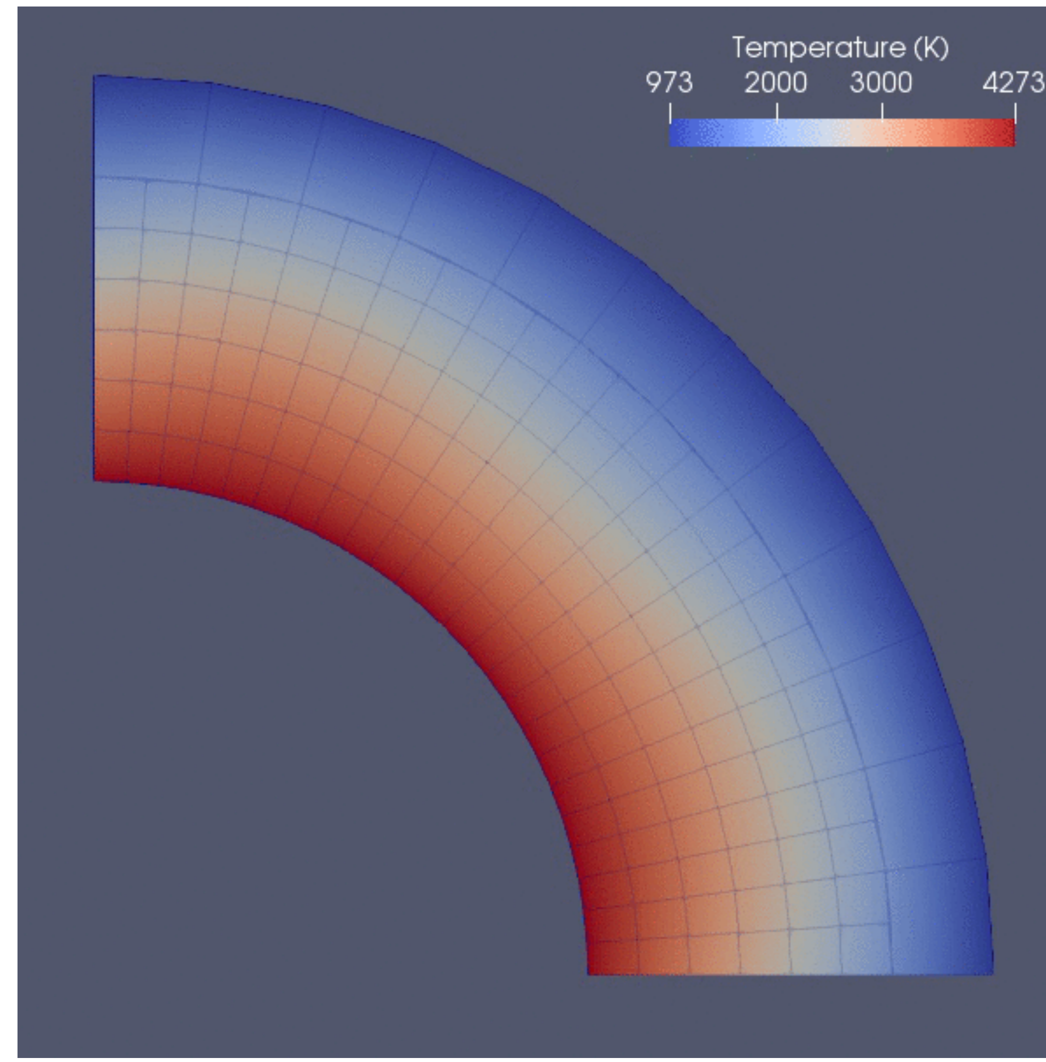
If $Ra > Ra_{crit}$ than a material will convect




**If ice has low viscosity, convection may occur, preventing differentiation and melting within an icy body by bringing cold material from the surface down to depth**

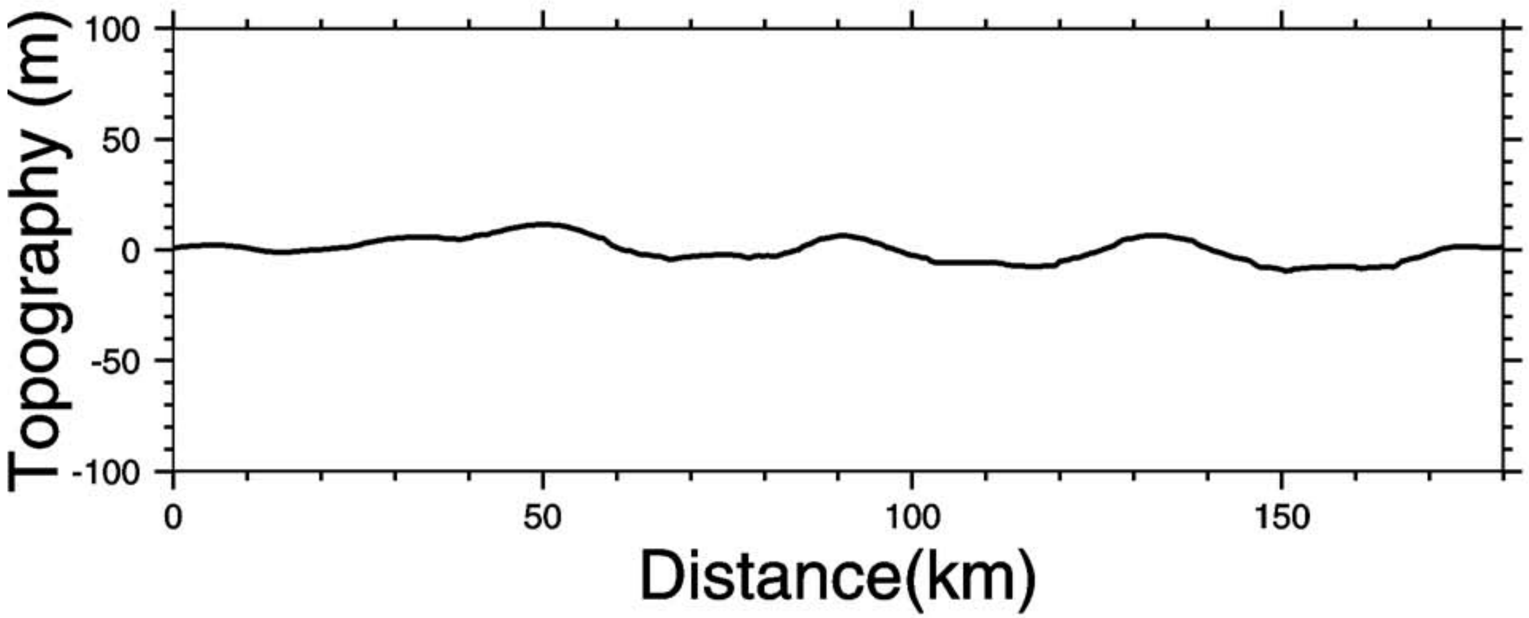
# Why Planetary Ice Rheology is important

Planetary self-regulation: convection causes temperatures to reach the level required to achieve a viscosity (depending on temperature) which balances internal heat production and suppresses further convection.
(Durham & Stern 2001)
“

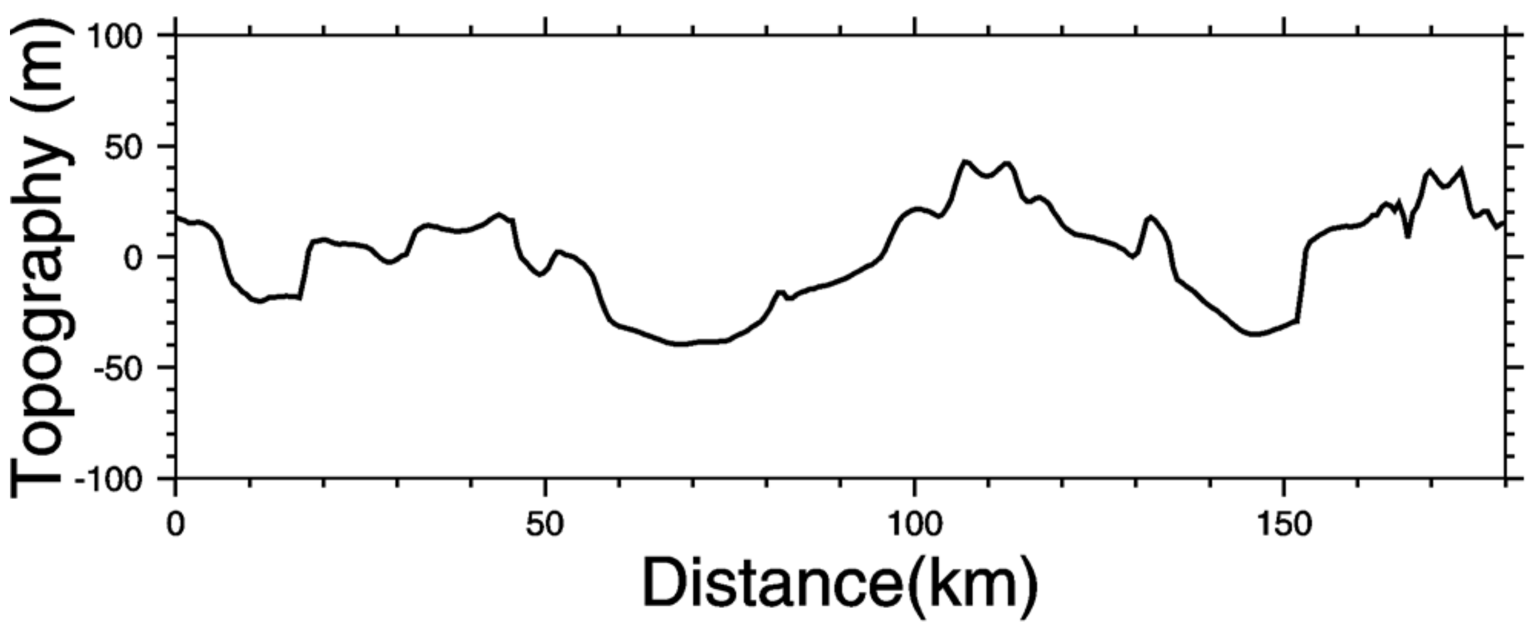


# Ice rheology determines how surface features on Europa are produced

**Visco-plastic rheology with convection (Showman & Han 2005)**

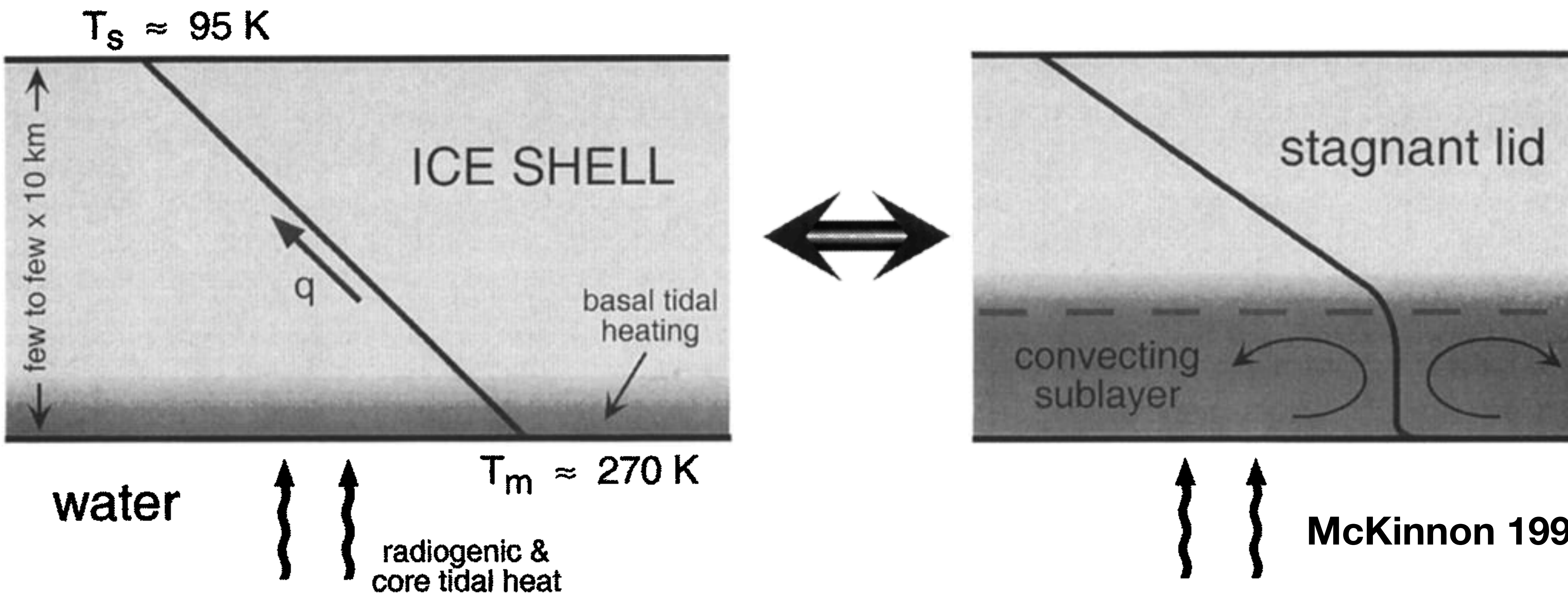



**High yield stress (no yielding)**




**Intermediate yield stress (some yielding)**

# Ice rheology determines ice shell thickness on Europa




McKinnon 1999

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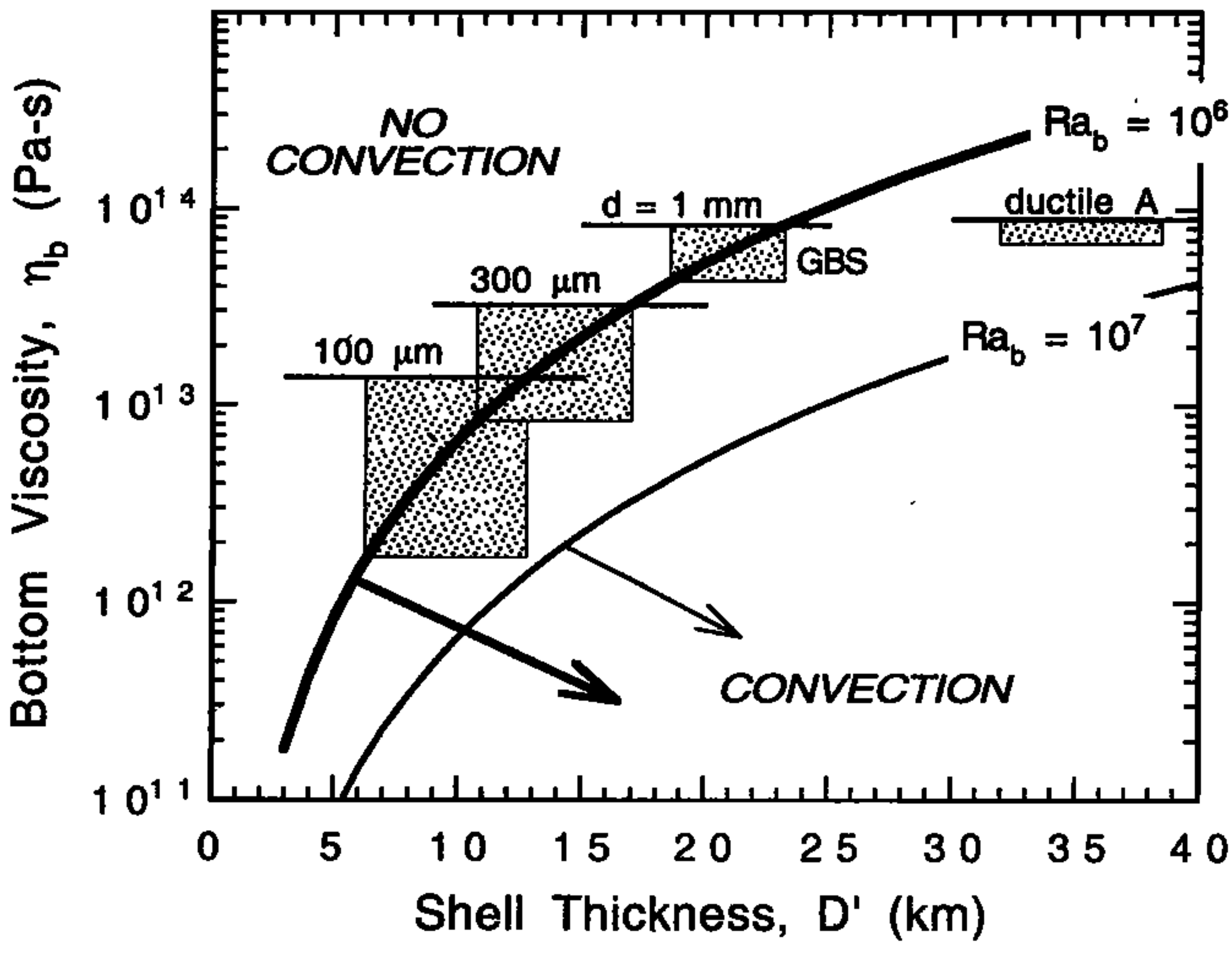
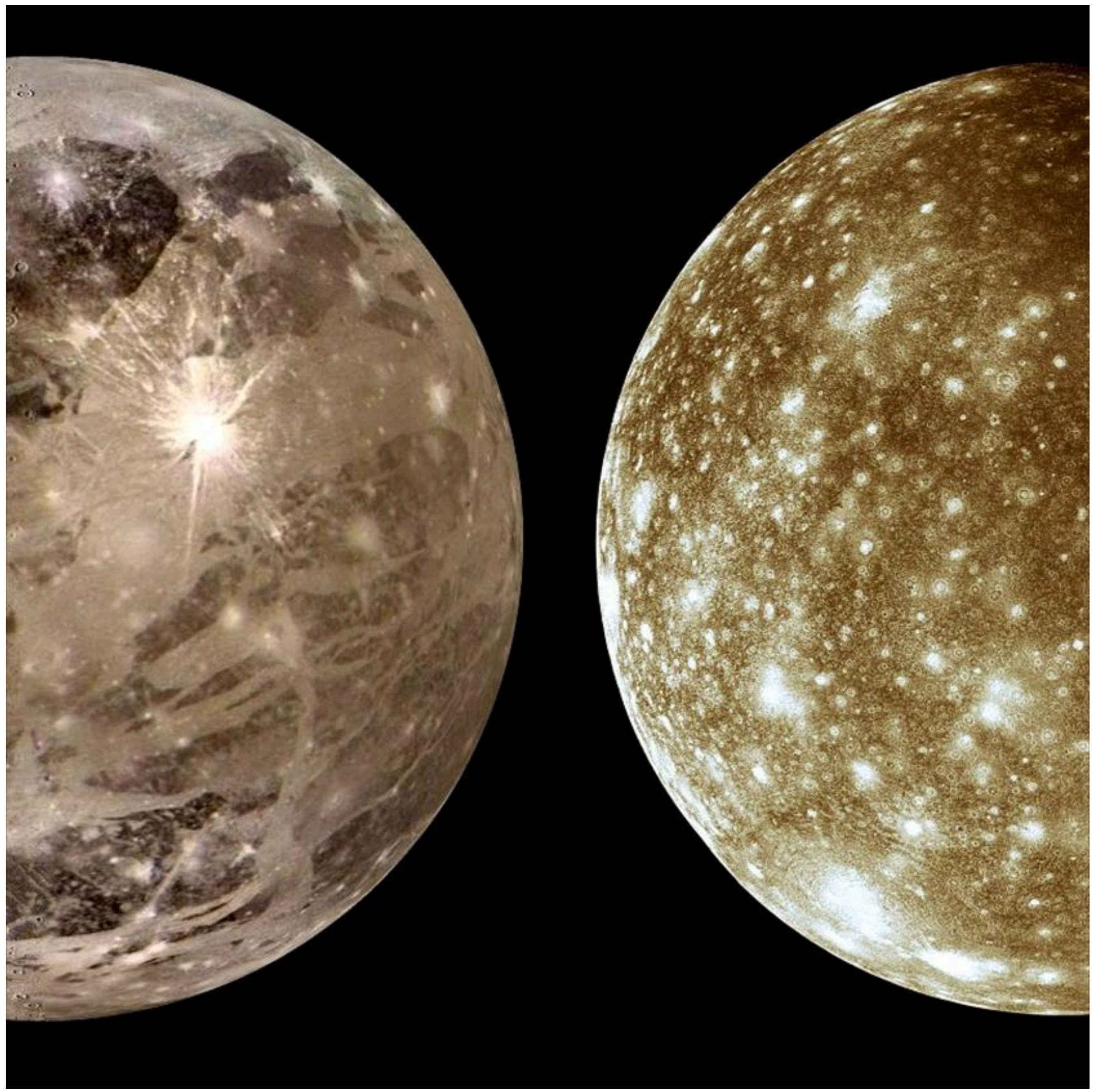



McKinnon 1999

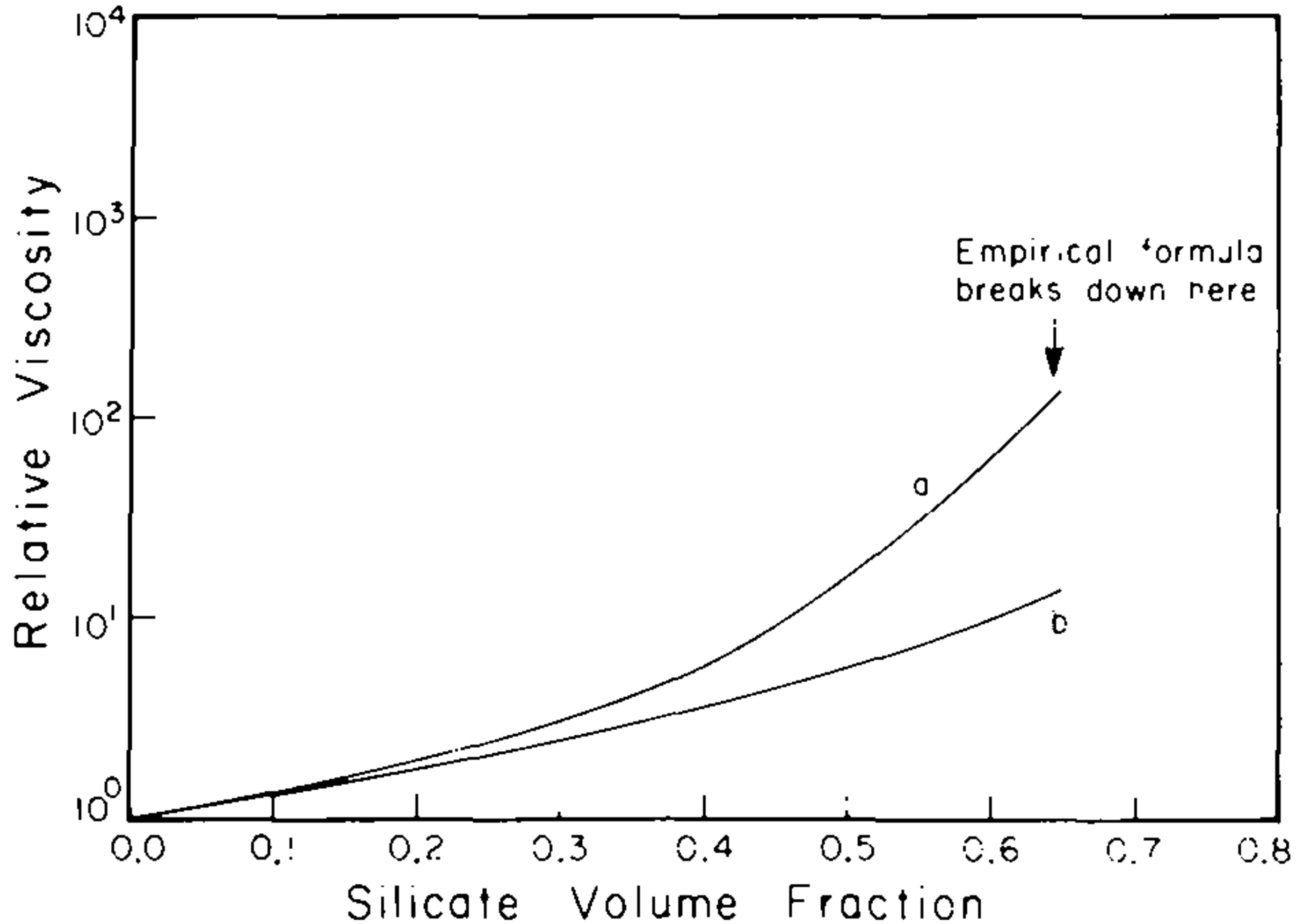
# Ganymede-Callisto dichotomy

**Ganymede: resurfaced and a differentiated interior**



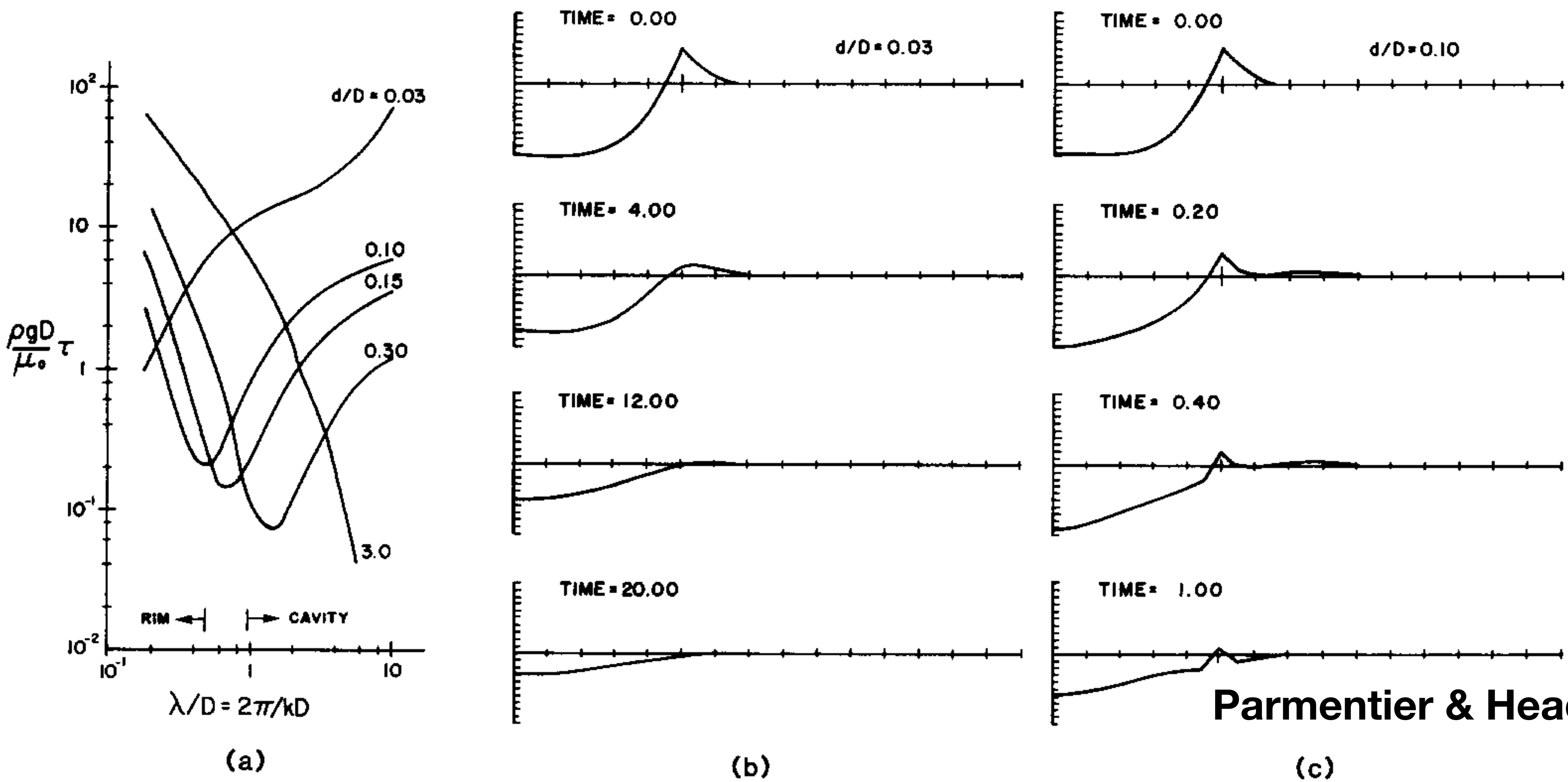
**Callisto: only partially differentiated interior**

# Ganymede-Callisto dichotomy




**Friedson & Stevenson 1983: small difference in rock content can cause large differences in viscosity and controls likelihood of convection**

# Crater relaxation




Parmentier & Head 1981

**The age of planetary surfaces is often determined through examination of craters. Since craters in ice relax over time, this determination is highly dependent on the rheology of planetary ices**

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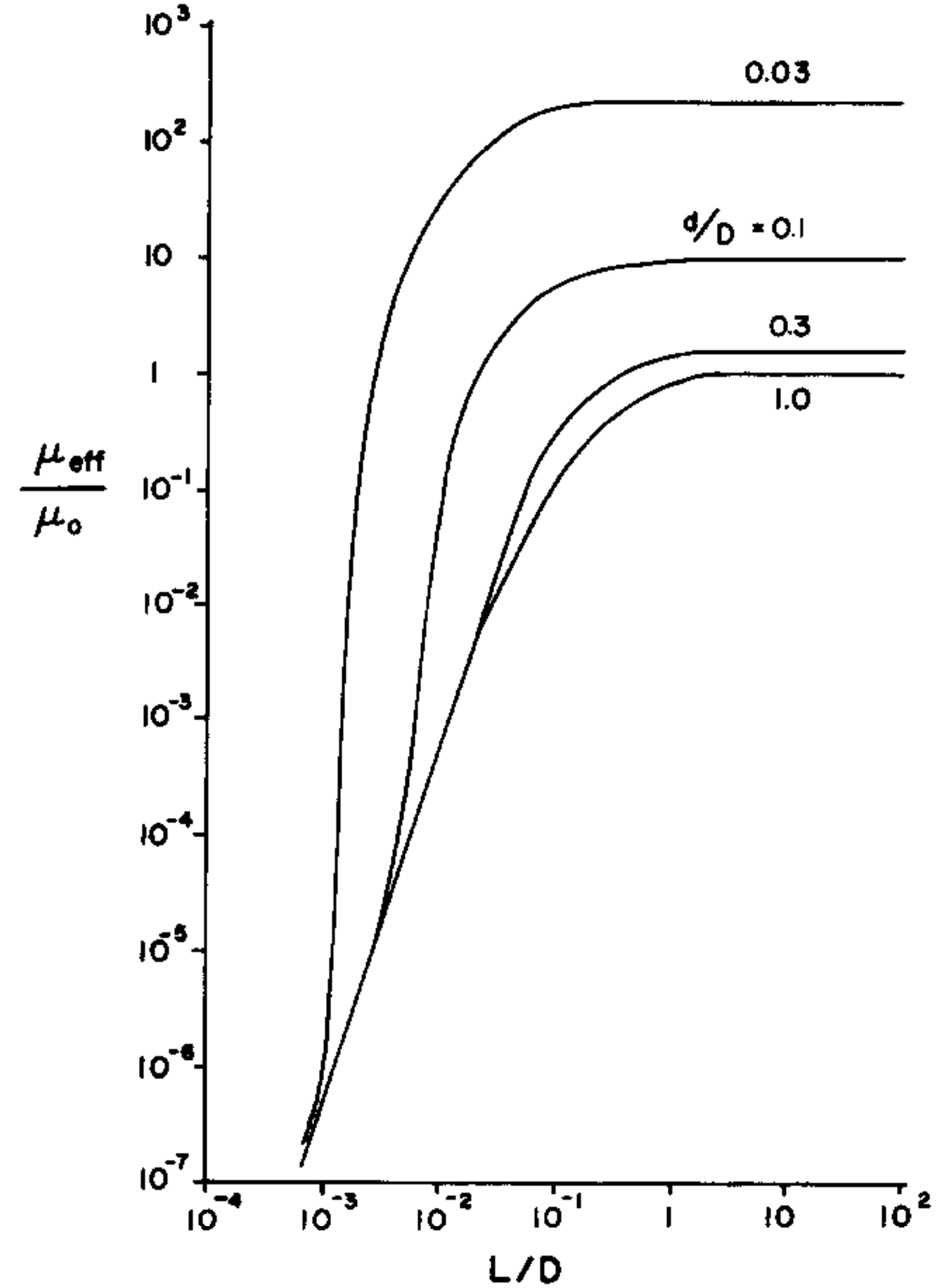


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