Ice shell convection in Europa

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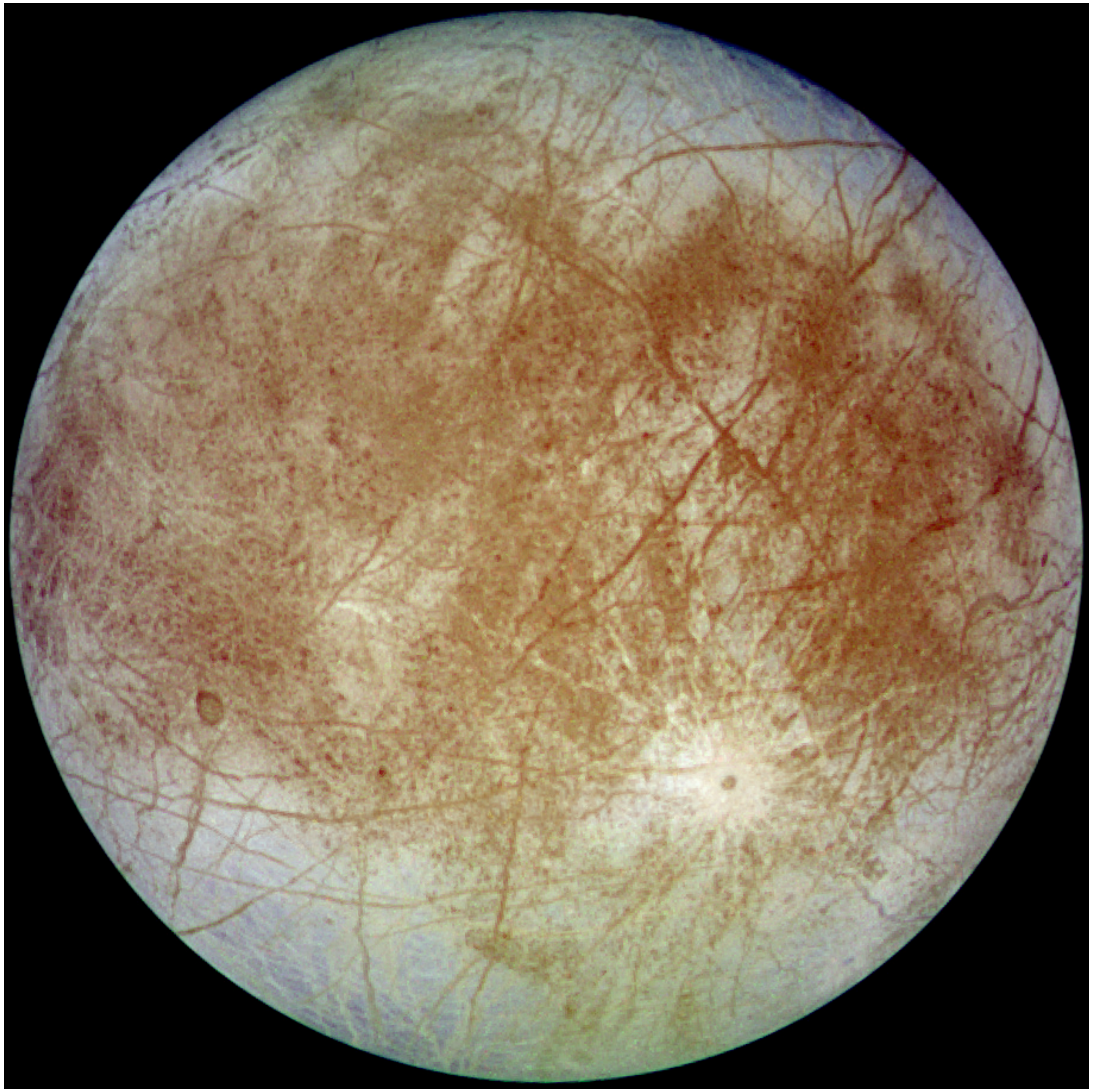
Western Washington University, Bellingham WA, Jan 30th 2015

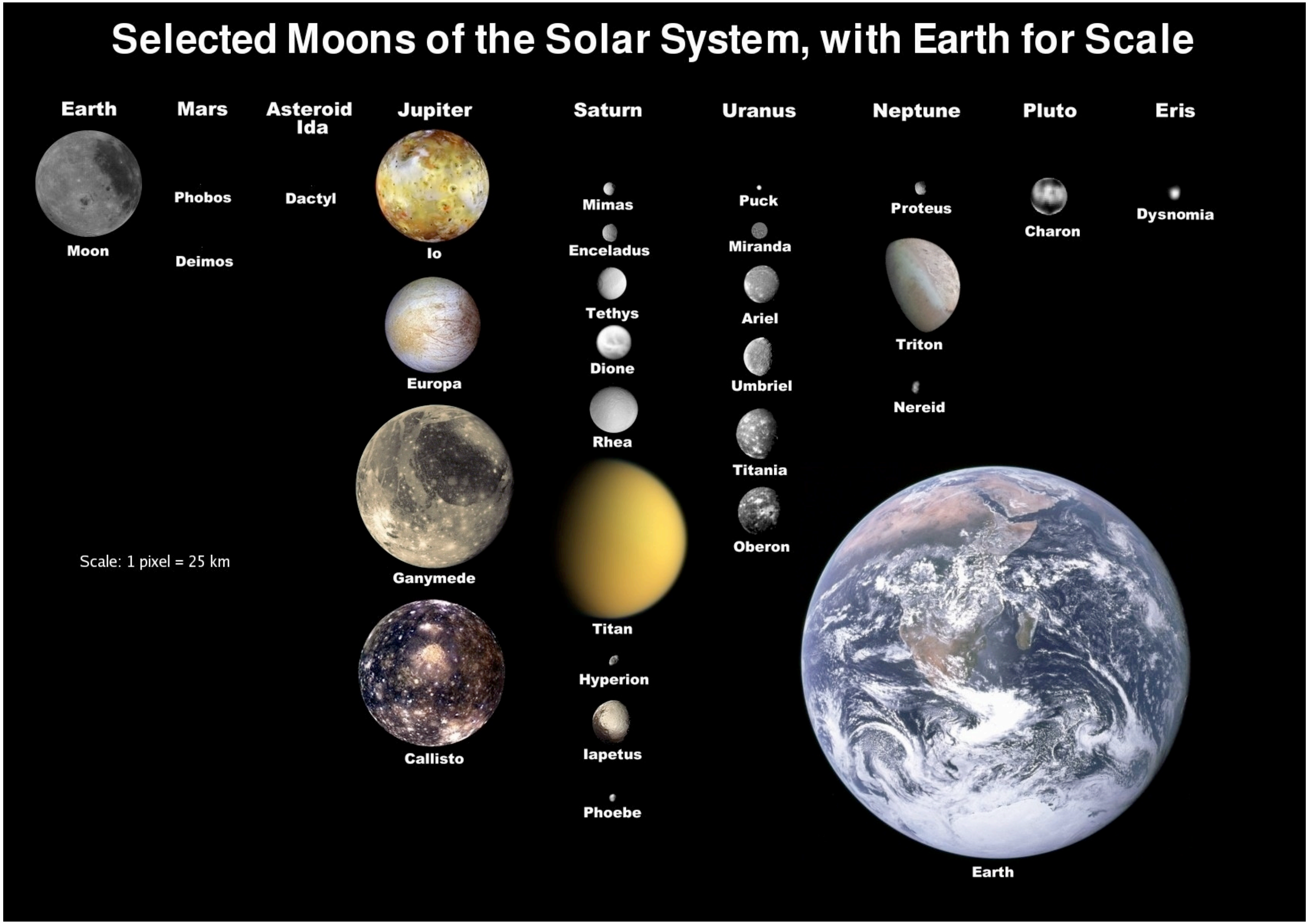
Europa



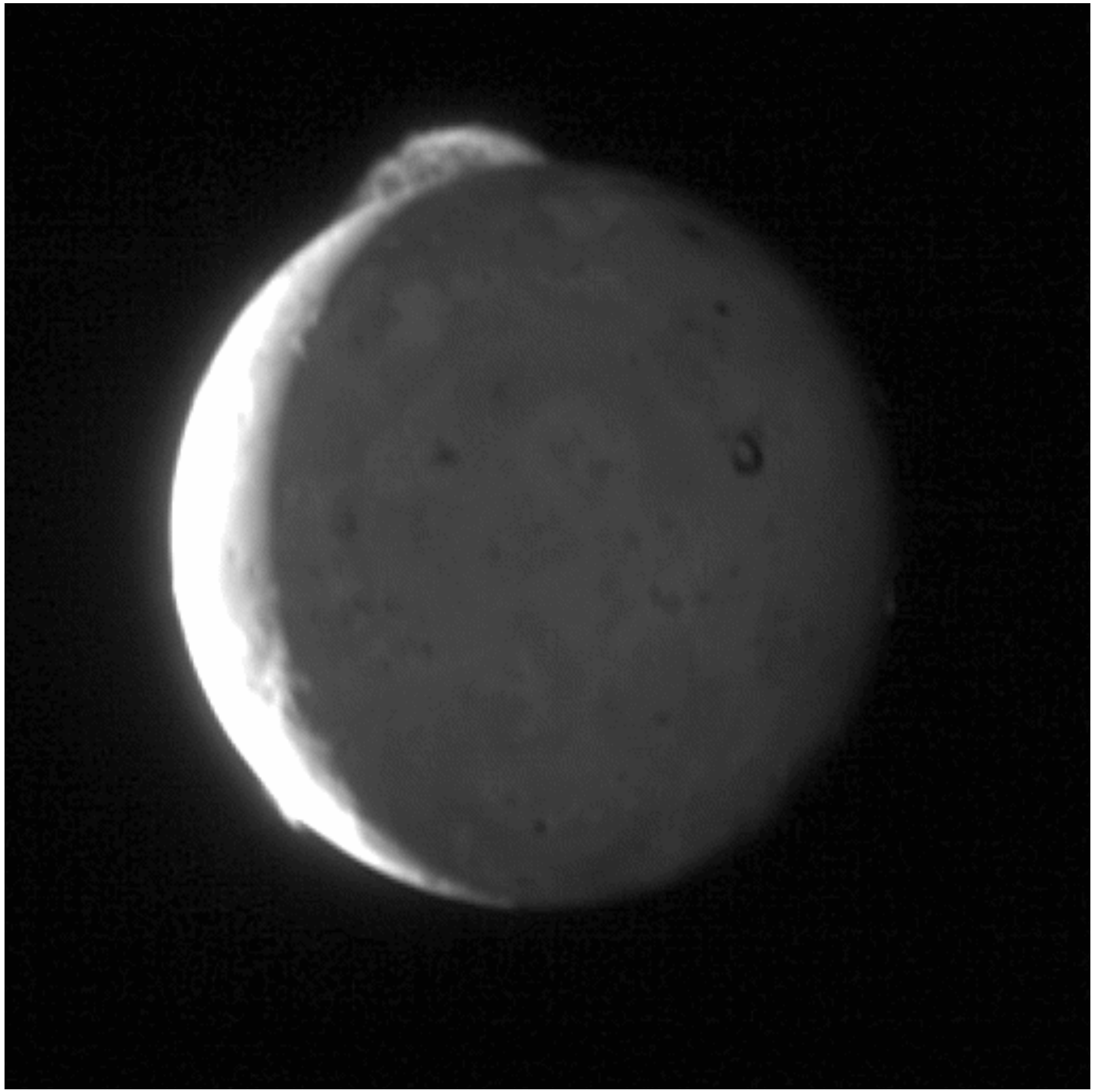
Jupiter's family portrait

Io Europa Ganymede Callisto

Moons of the Solar System

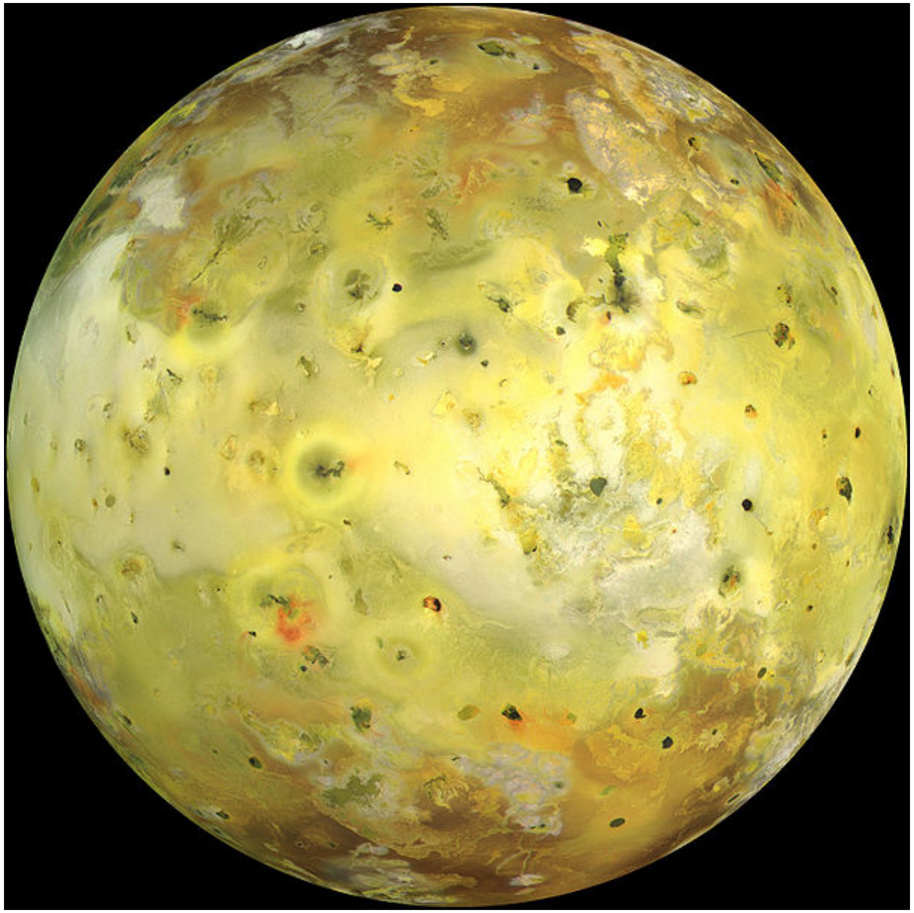


Io in action



Io – Jupiter's Volcanic Moon

Nowhere else in the Solar System
do **volcanic processes**
so **dominate** everything we see as on **Io**



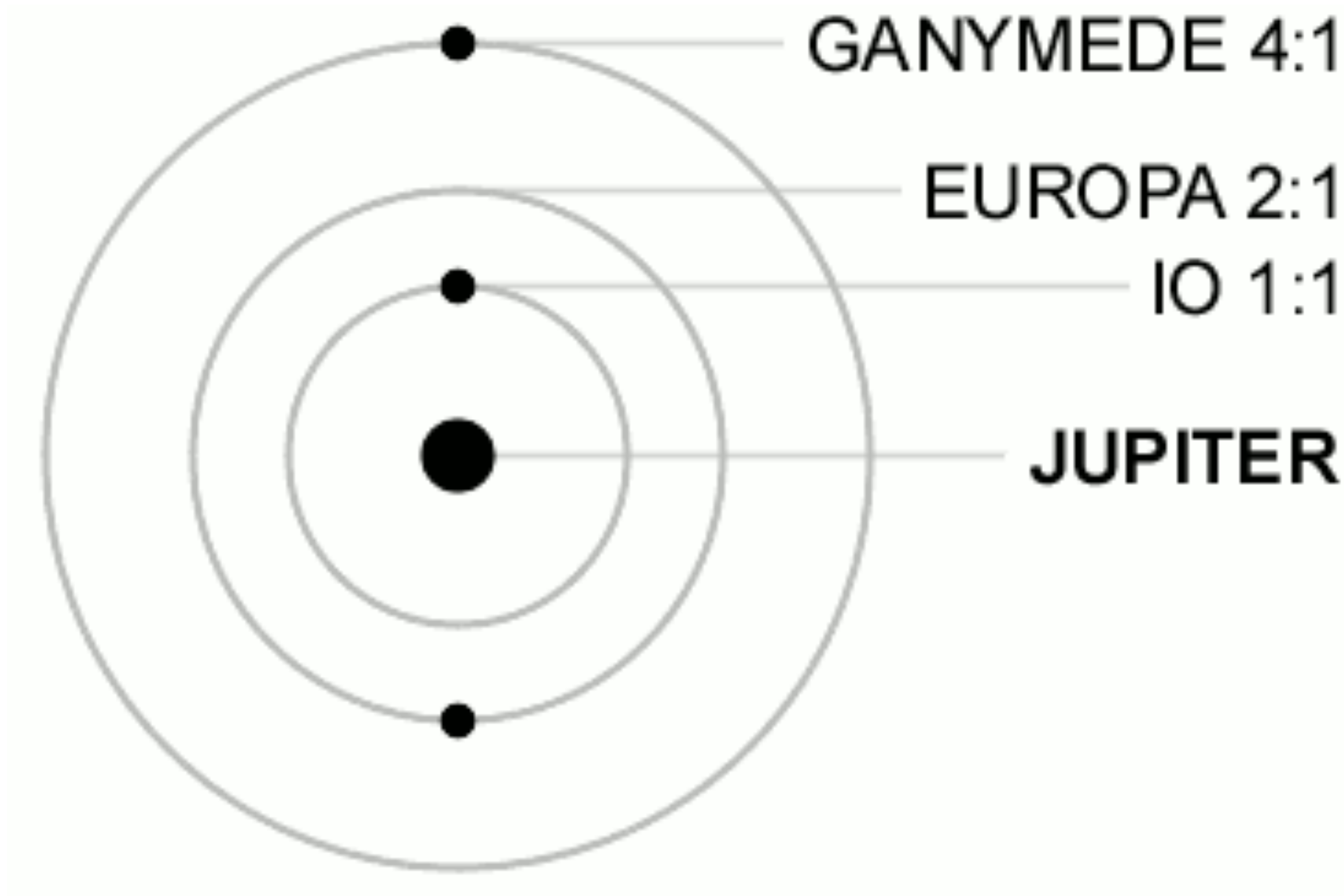
100 times more volcanic than Earth!!

Ground temperature: 110K

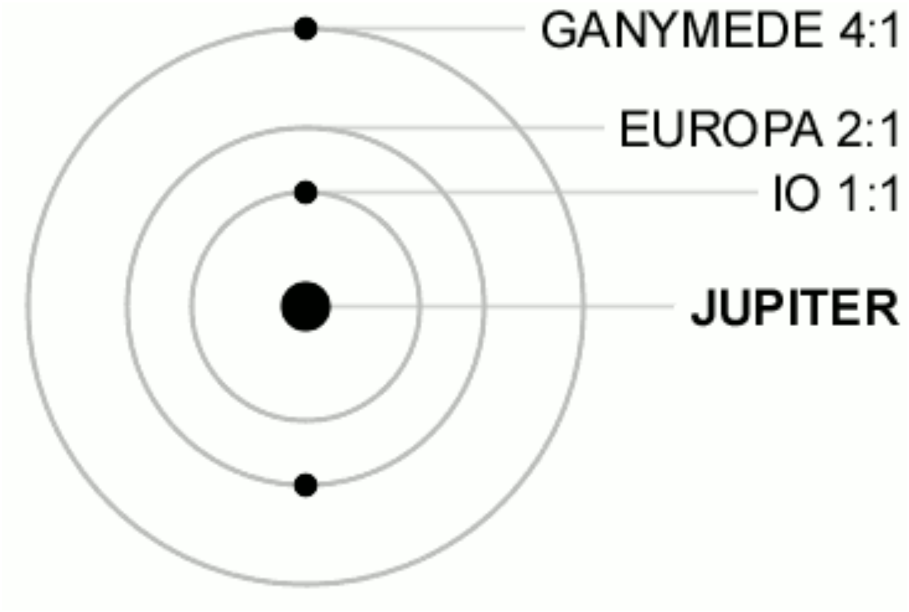
Bright areas: Fresh sulfur frost

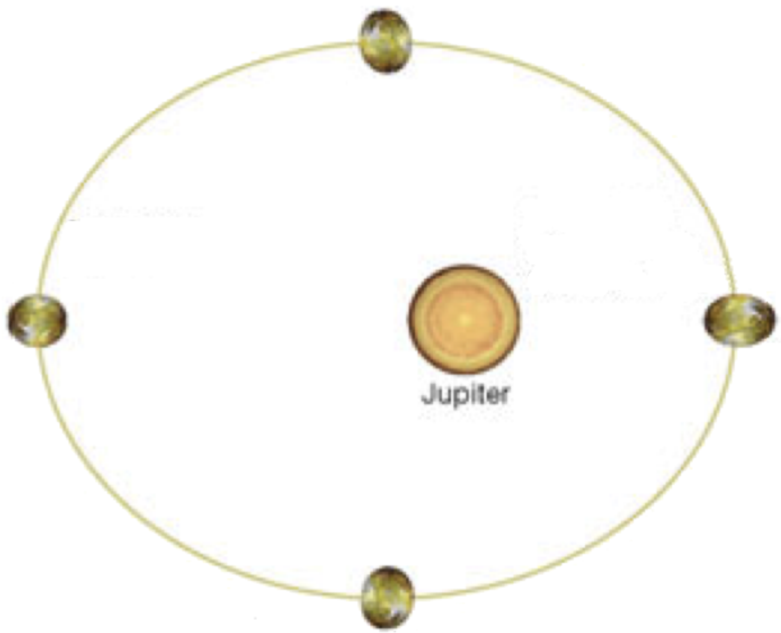
Yellow-Brown areas: older sulfur compounds

Orbital Clockwork



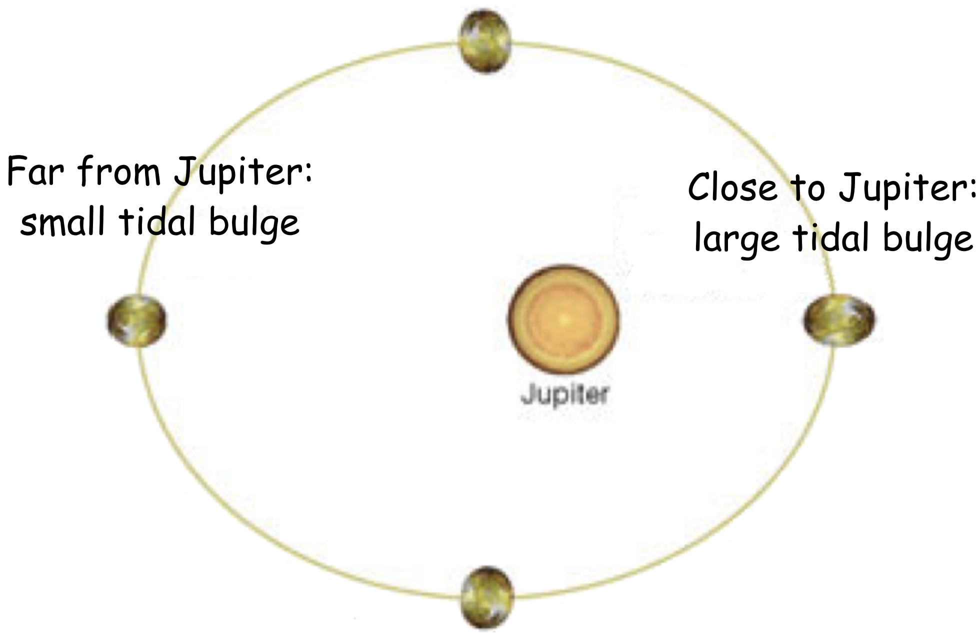
Swinging Moons





Periodic tug of Europa makes
Io's orbit slightly elliptic
(e ~ 0.004)

Tidal Heating



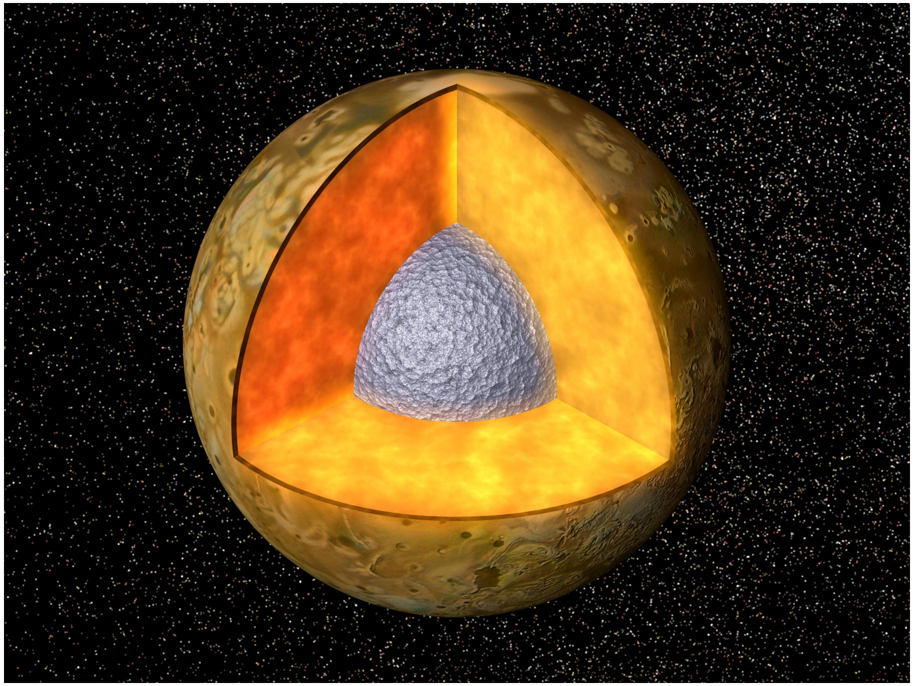
Difference in tidal bulge

from closest to farthest from Jupiter:

100 m (~300 ft)

MASSIVE FRICTION!!!

Tidal heating
keeps Io's interior molten

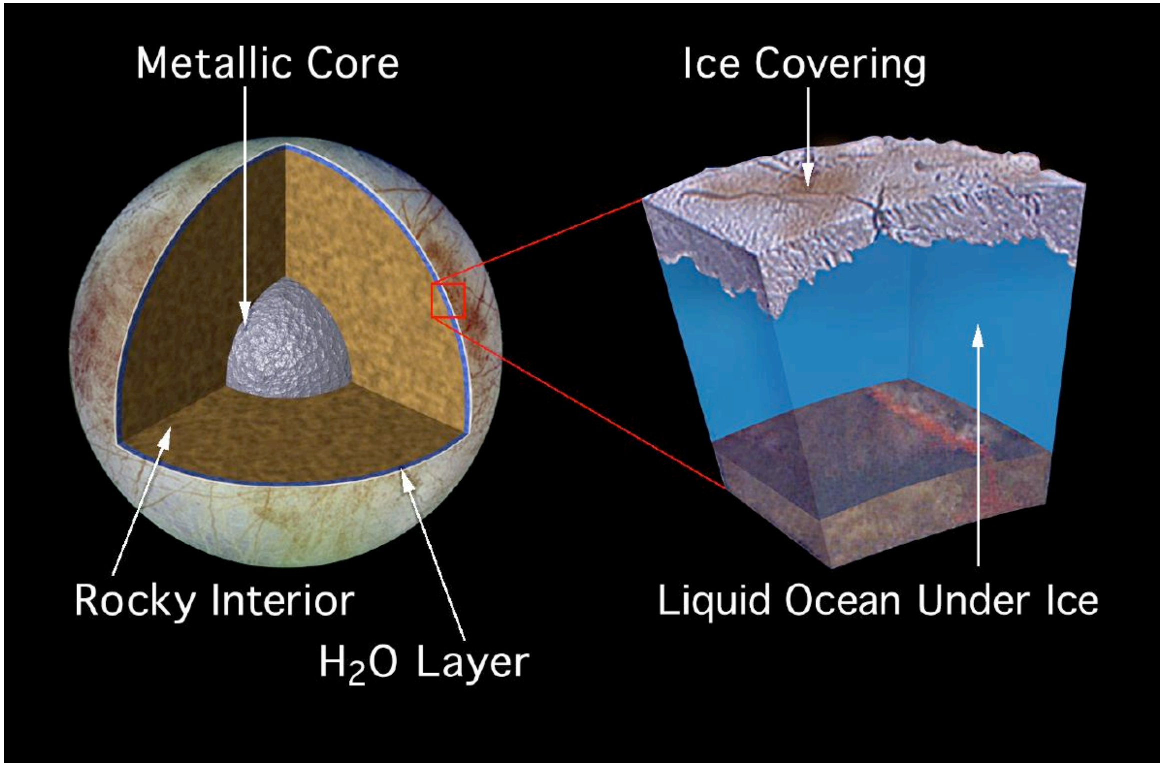


Thin silicate crust

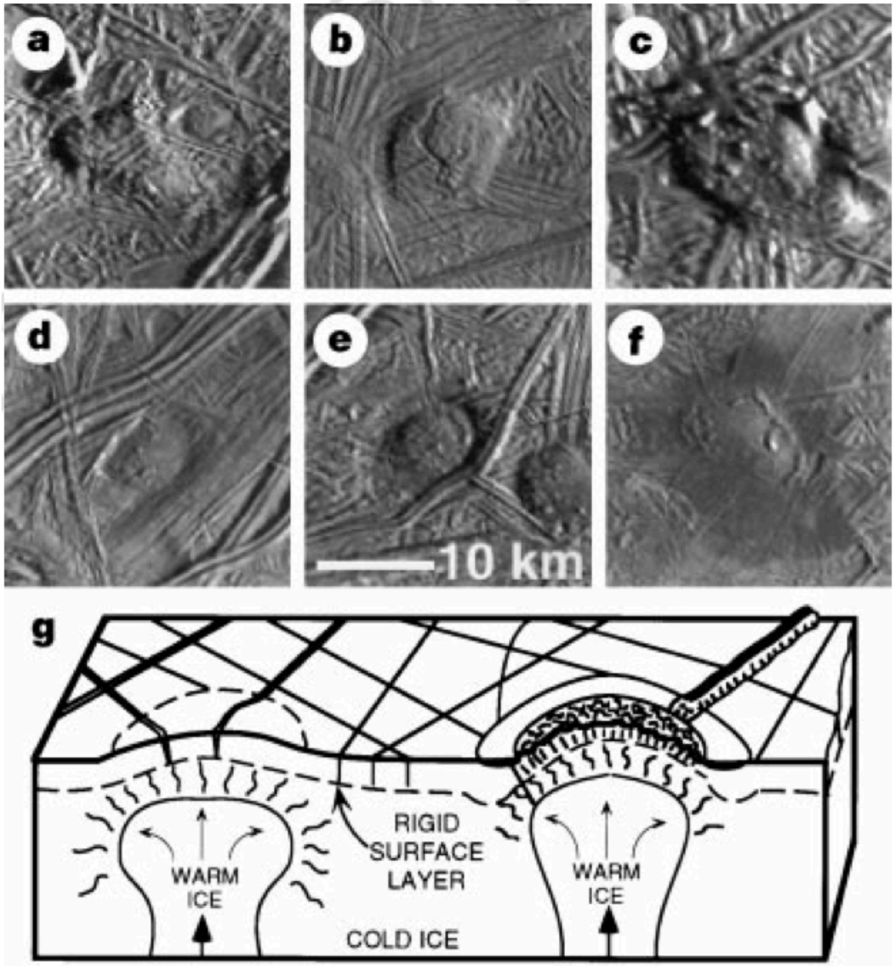
Molten silicate interior

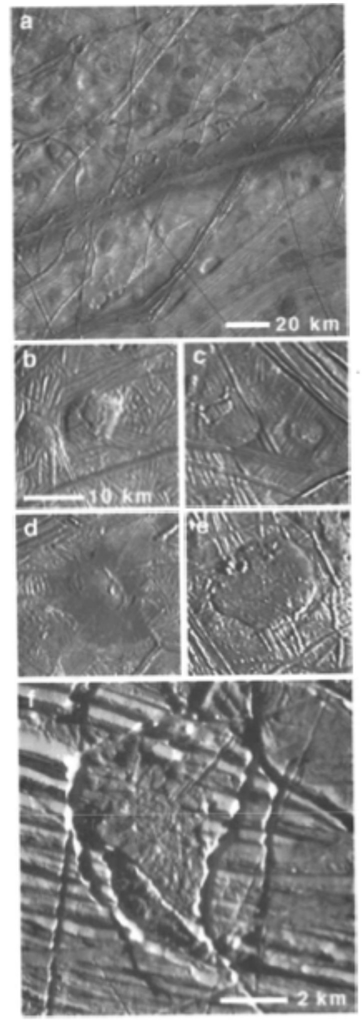
Iron rich core

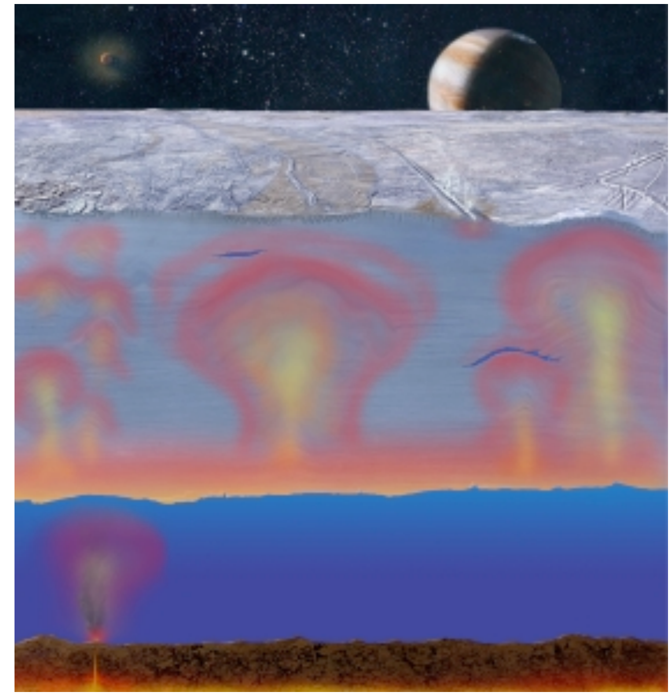
Europa has less tidal heating



Evidence for Convection





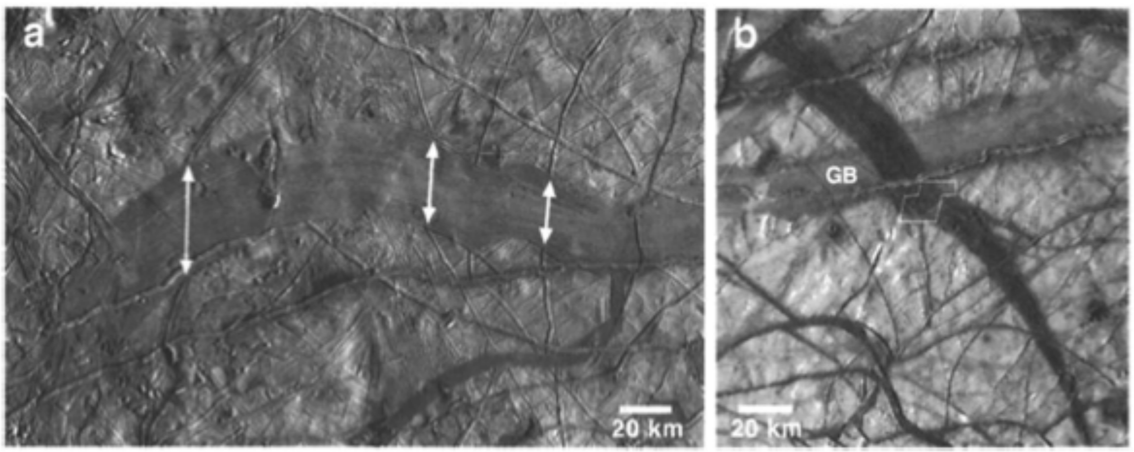


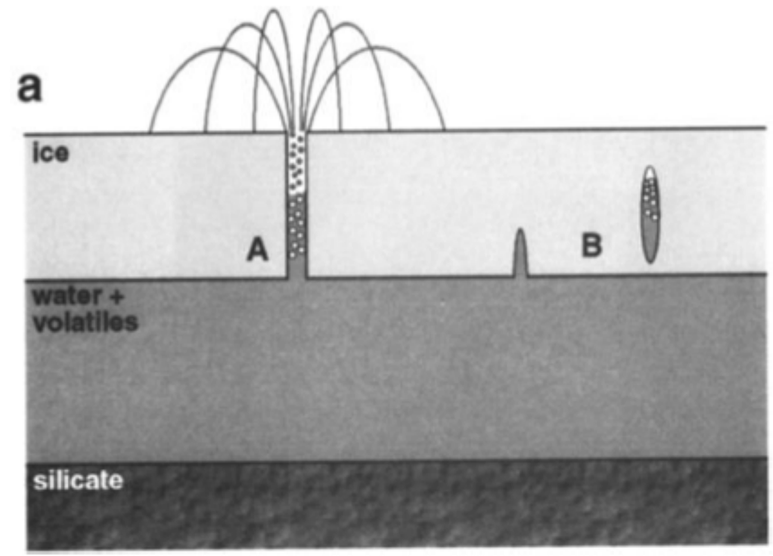
Ice diapirism

(Pappalardo et al. 1998, Nature, 391, 22

Pappalardo et al. Journal of Geophysical Research, 1999, 104, 24015)

Evidence for Convection

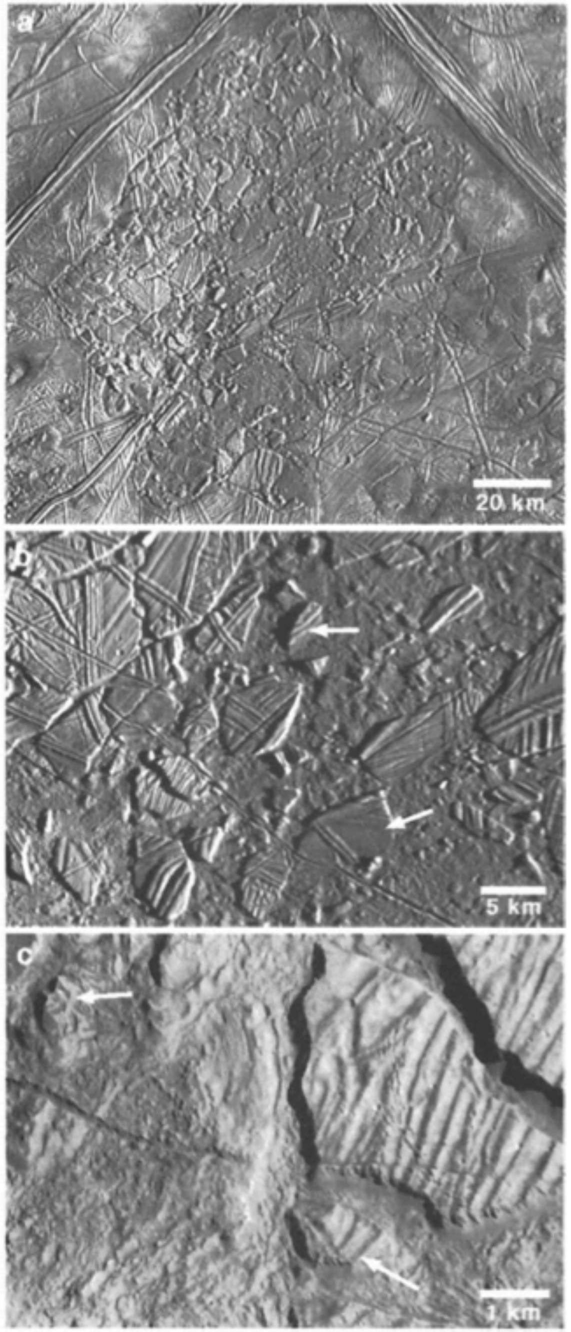


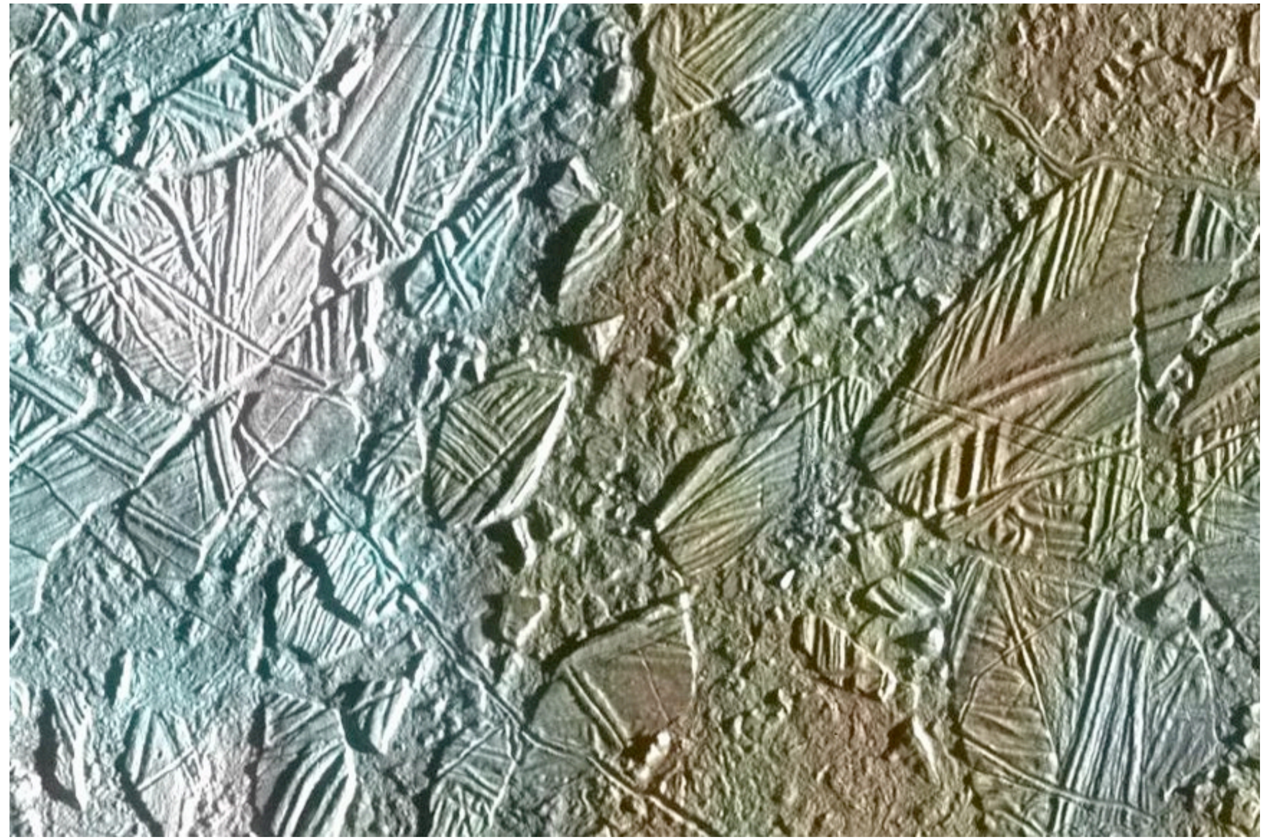


“Pull-apart” bands

(Tectonic faults, like mid-ocean ridges)

Evidence for Convection



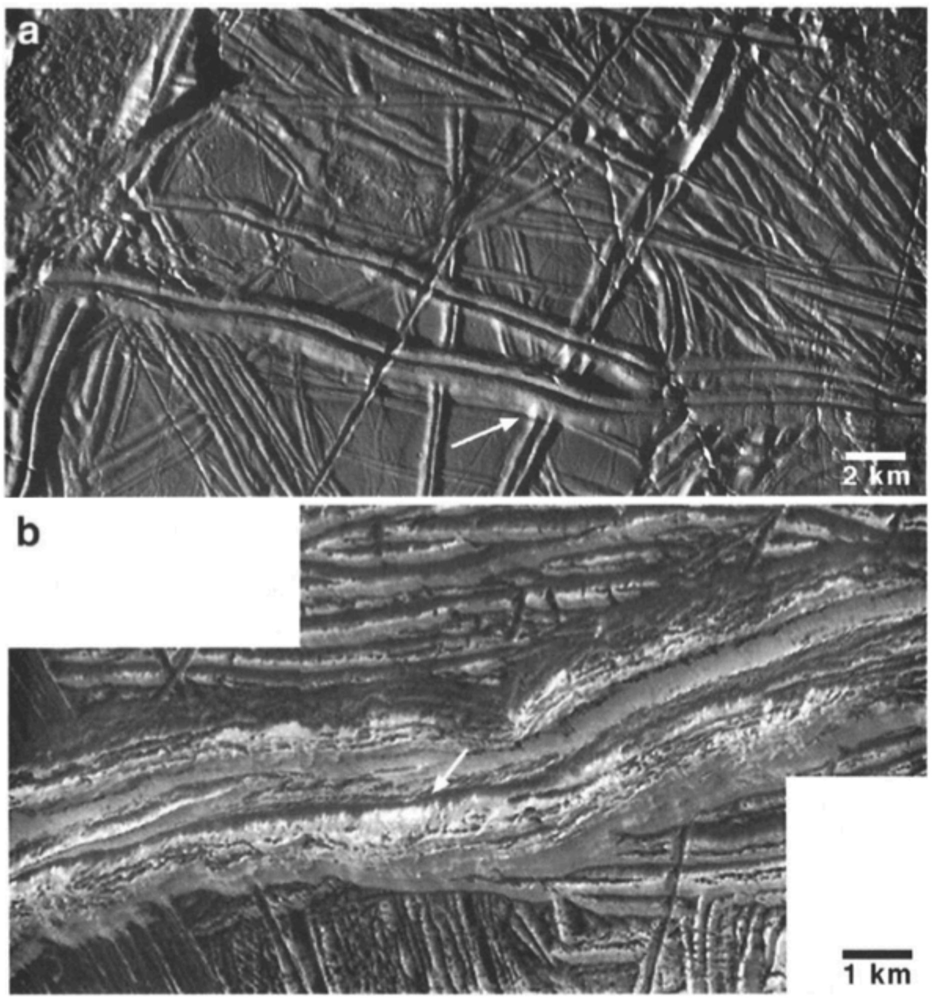


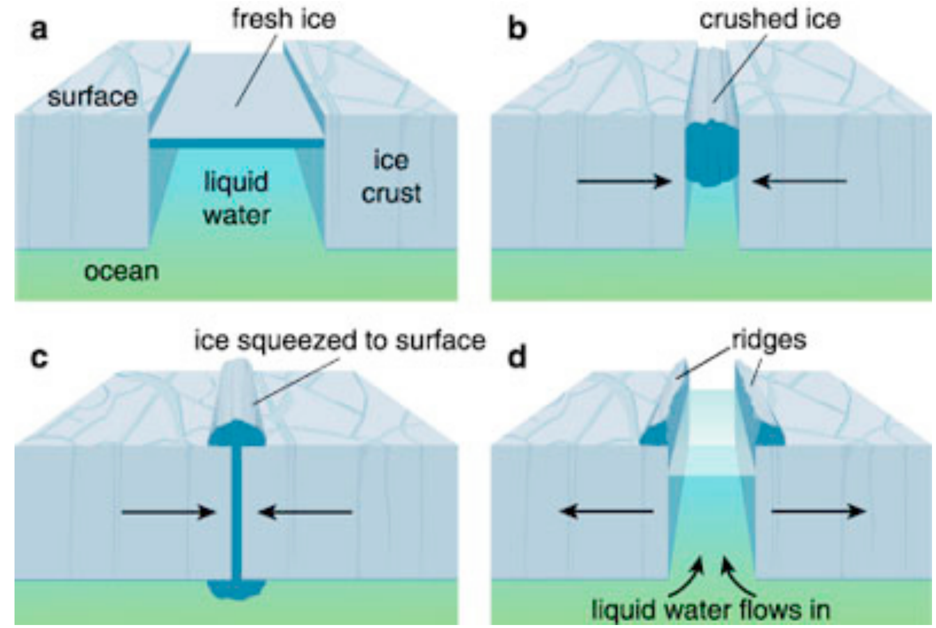
Chaos regions

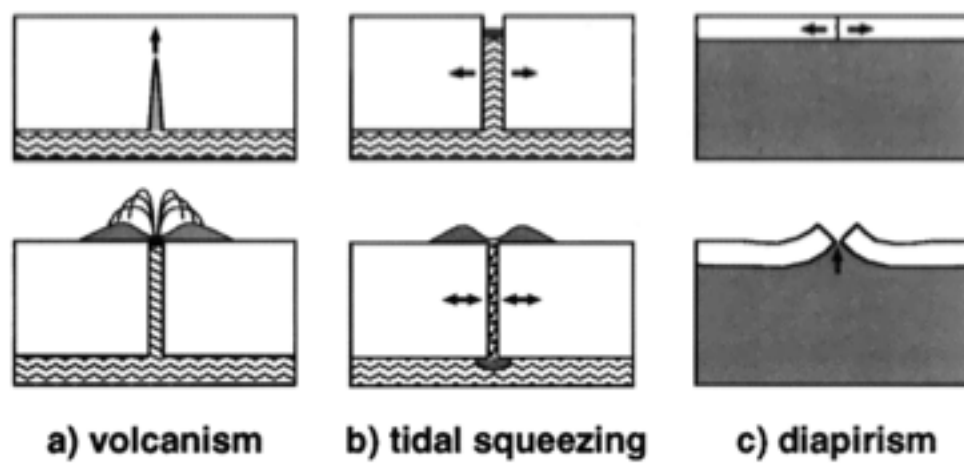
(large areas of melt that refroze)

Evidence for Convection

Ridges







Evaporites

PAPPALARDO ET AL.: DOES EUROPA HAVE AN OCEAN?

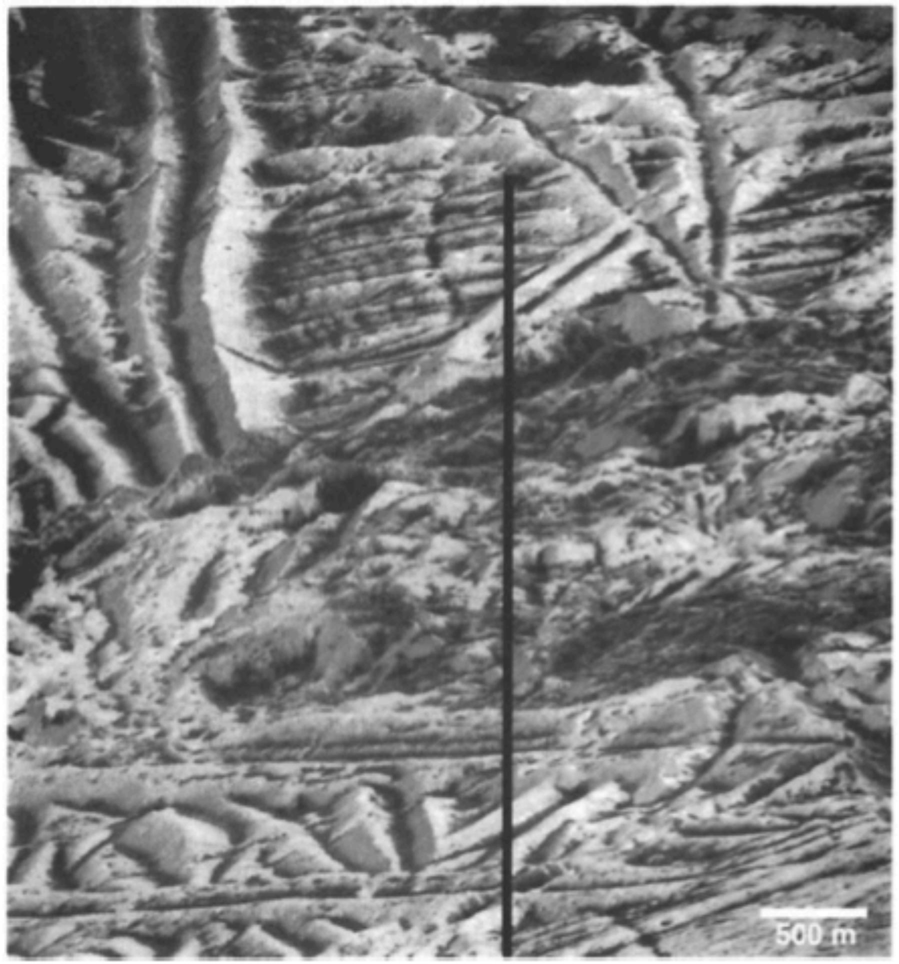


Figure 14. Bright and dark materials seen at the highest Galileo resolution. This oblique-looking view is the highest resolution image of Galileo's orbital tour, with ~6 m/pxl horizontal scale. Topography is the chief control on the albedo patterns. Bright material generally correlates with higher topography, and dark material occupies topographic lows. Segregation of surface materials into bright (icy) and dark (non-ice) patches is suggestive of sublimation-driven thermal segregation, which acts on very short timescales and can dominate over sputtering in Europa's equatorial region [*Spencer*, 1987]. Warmer temperatures there and downslope movement of non-ice materials may initially act to concentrate dark materials in topographic lows. There is no direct evidence seen for venting of bright frosts from ridges or cracks. North is to the right, and the scene is illuminated from the east-northeast (lower right). Galileo observation 12ESMOTTLE01.

Non-synchronous rotation

Geissler et al. 1998

Evidence for non-synchronous rotation of Europa

P. E. Geissler*, R. Greenberg*, G. Hoppa*, P. Helfenstein†, A. McEwen*, R. Pappalardo‡, R. Tufts*, M. Ockert-Bell†, R. Sullivan‖, R. Greeley‖, M. J. S. Belton§, T. Denk¶, B. Clark†, J. Burns†, J. Veverka† & the Galileo Imaging Team

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Non-synchronous rotation of Europa was predicted on theoretical grounds[1], by considering the orbitally averaged torque exerted by Jupiter on the satellite's tidal bulges. If Europa's orbit were circular, or the satellite were comprised of a frictionless fluid without tidal dissipation, this torque would average to zero. However, Europa has a small forced eccentricity $e \approx 0.01$ (ref. 2), generated by its dynamical interaction with Io and Ganymede, which should cause the equilibrium spin rate of the satellite to be slightly faster than synchronous. Recent gravity data[3] suggest that there may be a permanent asymmetry in Europa's interior mass distribution which is large enough to offset the tidal torque; hence, if non-synchronous rotation is observed, the surface is probably decoupled from the interior by a subsurface layer of liquid[4] or ductile ice[1]. Non-synchronous rotation was invoked to explain Europa's global system of lineaments and an equatorial region of rifting seen in Voyager images[5,6]. Here we report an analysis of the orientation and distribution of these surface features, based on initial observations made by the Galileo spacecraft. We find evidence that Europa spins faster than the synchronous rate (or did so in the past), consistent with the possibility of a global subsurface ocean.

hemisphere, centred at 45° N, 221° W. False-colour composites made up from these images show at least three distinct classes of linear features on Europa's surface (Fig. 1). These features may represent different stages of development of tectonic lineaments on Europa. Their distributions are shown in Fig. 2, derived from photogeological and spectral mapping (supervised classification) of the photometrically corrected four-colour data. Bands with spectral reflectance similar to the bright wedge (Fig. 2a) make up the stratigraphically oldest lineaments and generally have south-west–northeast trends. The intermediate-aged triple-bands (Fig. 2b) trend roughly east–west, with the younger of the two

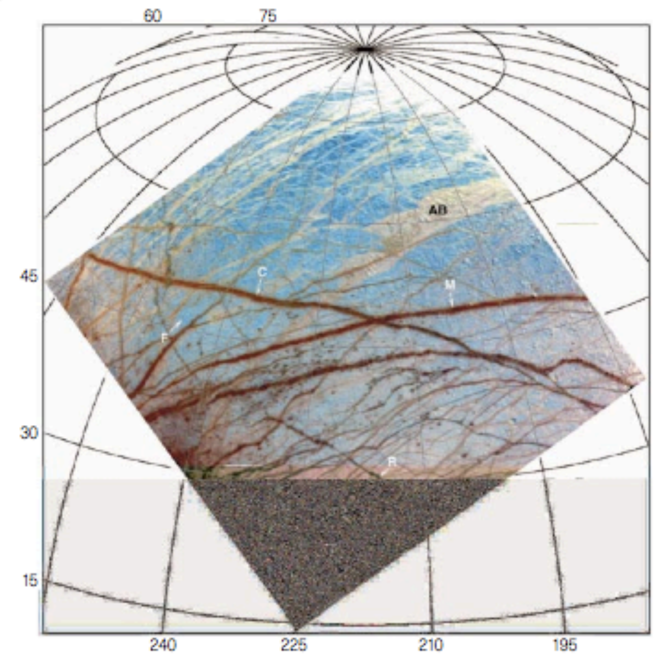

Figure 1 False-colour composite of northern high-latitude region of Europa, produced from images images taken through the 968-nm, 756-nm and green filters. Overlaid is a grid showing location in degrees North latitude and West longitude. The most prominent linear features are the dark triple-bands such as Cadmus Linea and Minos Linea. The triple-bands overprint many older lineaments which are intermediate in colour between the triple-bands and the

Induced magnetic field

Induced magnetic fields as evidence for subsurface oceans in Europa and Callisto

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** Institute of Geophysics and Planetary Physics, † Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA*
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The Galileo spacecraft has been orbiting Jupiter since 7 December 1995, and encounters one of the four galilean satellites—Io, Europa, Ganymede and Callisto—on each orbit. Initial results from the spacecraft's magnetometer[1,2] have indicated that neither Europa nor Callisto have an appreciable internal magnetic field, in contrast to Ganymede[3] and possibly Io[4]. Here we report perturbations of the external magnetic fields (associated with Jupiter's inner magnetosphere) in the vicinity of both Europa and Callisto. We interpret these perturbations as arising from induced magnetic fields, generated by the moons in response to the periodically varying plasma environment. Electromagnetic induction requires eddy currents to flow within the moons, and our calculations show that the most probable explanation is that there are layers of significant electrical conductivity just beneath the surfaces of both moons. We argue that these conducting layers may best be explained by the presence of salty liquid-water oceans, for which there is already indirect geological evidence[5,6] in the case of Europa.

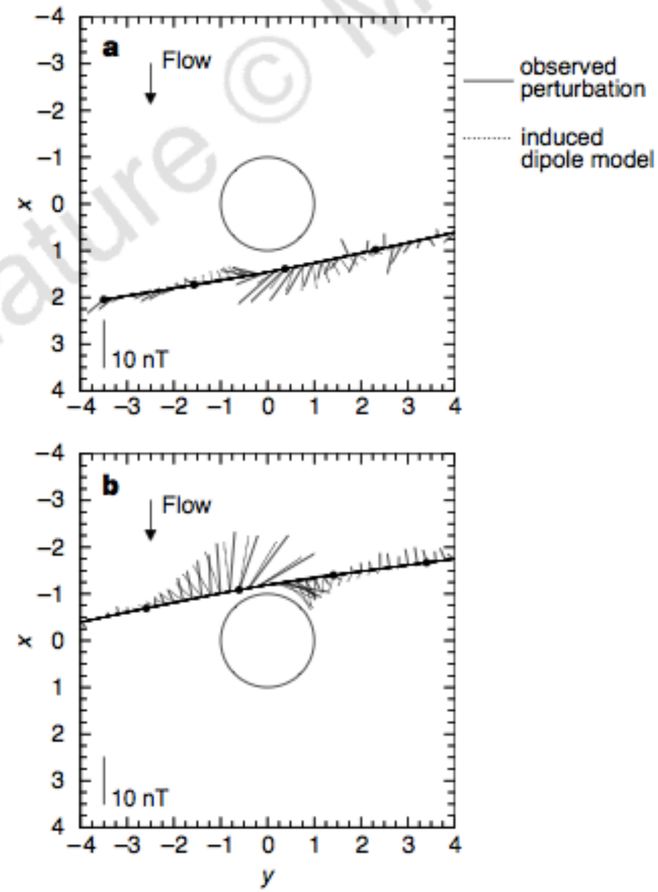
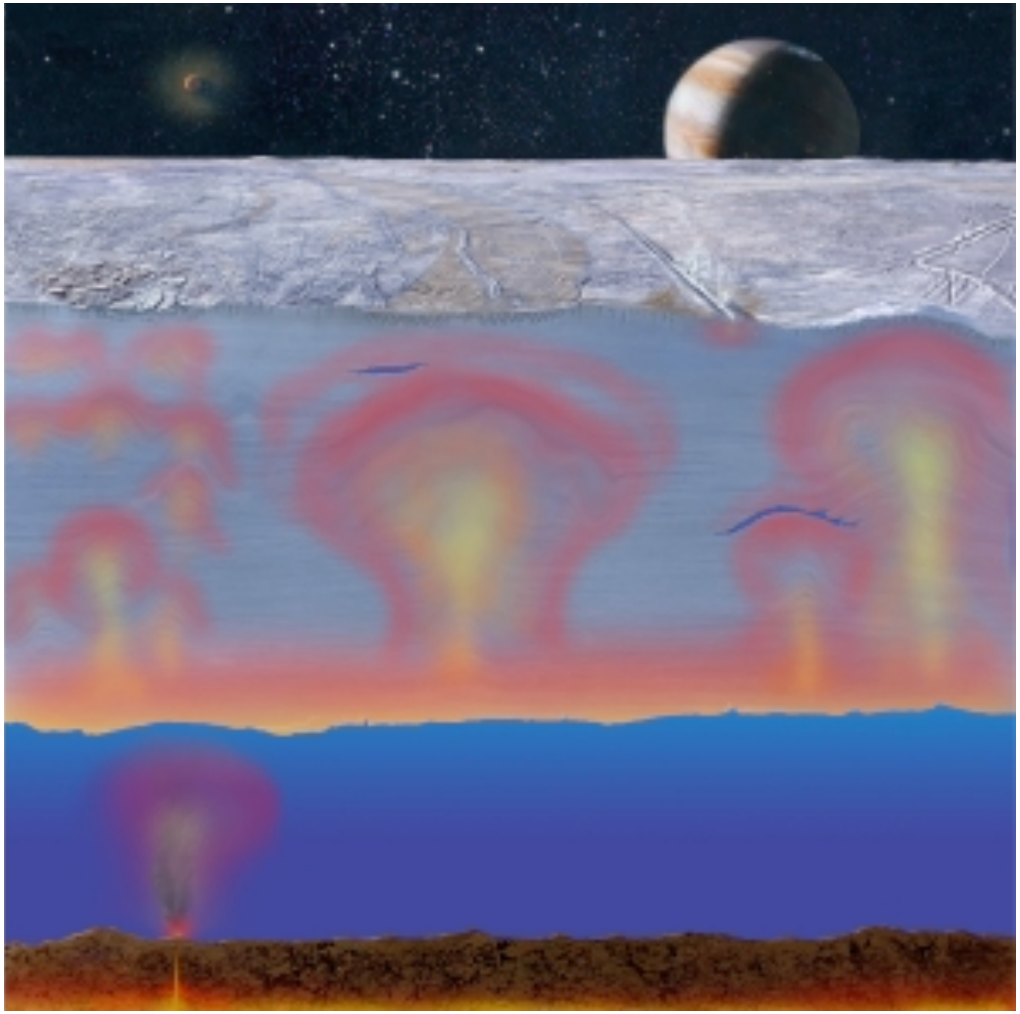
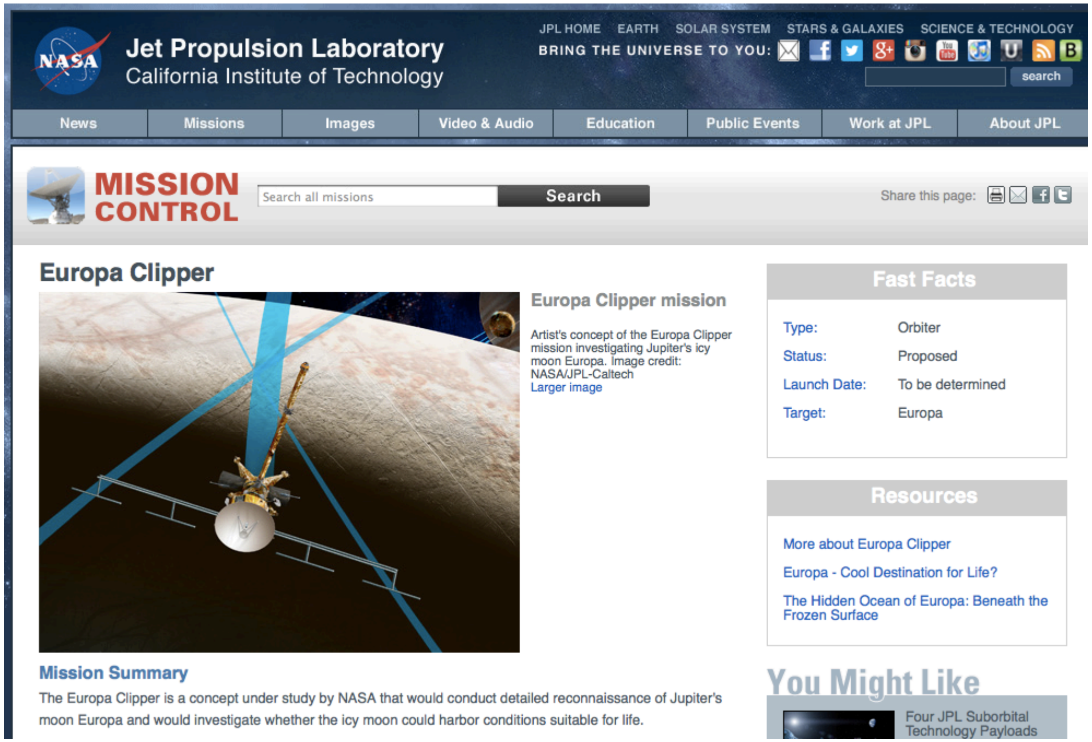


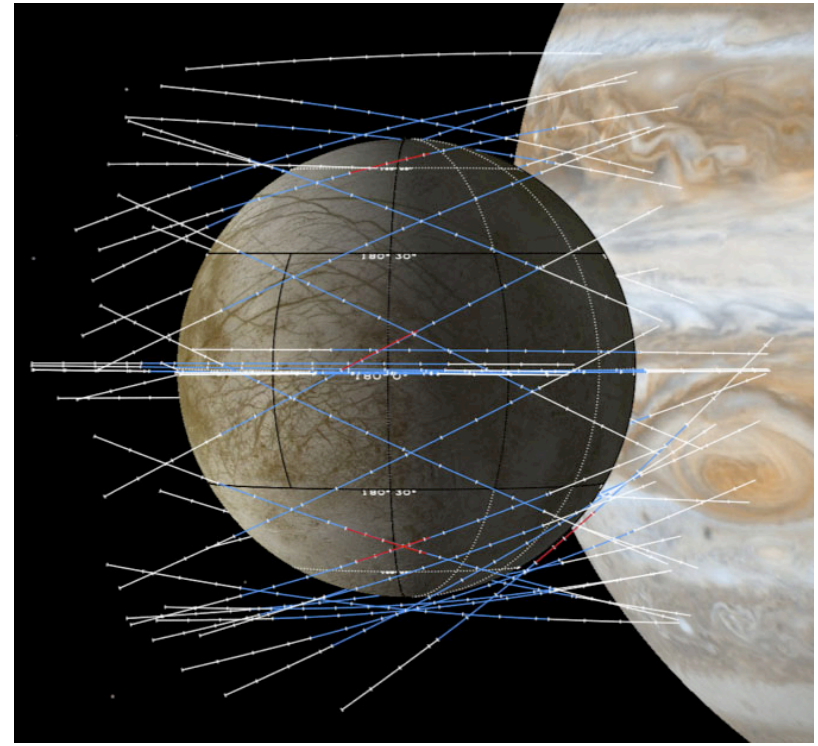
Figure 3 Magnetic field observations from the C3 and C9 passes. **a**, The magnetic field perturbations (vectors drawn with solid lines) and the modelled induction field (vectors shown dotted) along the trajectory of the C3 encounter in the *x*–*y* plane. **b**, The magnetic field perturbations and the modelled induction field for the C9 encounter. The distance scale is in units of R_C ($1R_C$ = radius of Callisto = 2,409 km).

Ice Convection



Europa Clipper





Reconnaissance: 45 flybys, as low as 25km

Radar to determine ice's thickness

High resolution camera

Identify future landing sites

Ice Convection: Statement of the Problem

Dynamical equations

$$\frac{\partial}{\partial x_j}\sigma_{\mathbf{ij}} - \nabla p + (RaT)\mathbf{z} = 0,$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \nabla^2 T + q',$$

$$\nabla \cdot \mathbf{u} = 0.$$

Ice Rheology

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right).$$

$$\dot{\varepsilon}_{ij} = A^{-1}\sigma^{n-1}\sigma_{ij} \quad \text{or} \quad \sigma_{ij} = A^{1/n}\dot{\varepsilon}^{(1-n)/n}\dot{\varepsilon}_{ij},$$

$$\eta = \frac{\sigma_{ij}}{2\dot{\varepsilon}_{ij}} = \frac{1}{2}\sigma^{1-n} = \frac{1}{2}\dot{\varepsilon}^{(1-n)/n}.$$

Parameters

$$Ra = \frac{\rho g \alpha \Delta T d^3}{\kappa \eta_0},$$ *Rayleigh number*

$$q = \frac{\epsilon_0^2 \omega^2 \eta}{2\left[1 + \frac{\omega^2\eta^2}{\mu^2}\right]}.$$ *Tidal heating*

Inputs

Physical Parameter	Symbol	Values
Gravity	g	$1.3\ m\ s^{-1}$
Density	ρ	$917\ kg\ m^{-3}$
Thermal expansivity	α	$1.65 \times 10^{-4} K^{-1}$
Thermal diffusivity	κ	$1 \times 10^{-6} m^2 s^{-1}$
Specific heat	c_p	$2000\ J\ kg^{-1} K^{-1}$
Surface temperature	T_t	$100\ K$
Bottom temperature	T_b	$270\ K$
Melting-temp. viscosity	η_0	$10^{13} - 10^{14}\ Pa\ s$
Rigidity of ice	μ	$4 \times 10^9\ Pa$
Amplitude of tidal flexing	ϵ_0	2.1×10^{-5}
Thickness of ice shell	d	$15 - 20\ km$

Ice Convection: Statement of the Problem

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Ice Convection: Statement of the Problem

Dynamical equations

$$\frac{\partial}{\partial x_j}\sigma_{\mathbf{ij}} - \nabla p + (RaT)\mathbf{z} = 0,$$

$$\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T = \nabla^2 T + q',$$

$$\nabla \cdot \mathbf{u} = 0,$$

Ice (Newtonian) Rheology

$$\eta(T) = \eta_0 exp\left\{A\left(\frac{T_m}{T} - 1\right)\right\},$$

Parameters

$$Ra = \frac{\rho g \alpha \Delta T d^3}{\kappa \eta_0},$$

Rayleigh number

$$q = \frac{\epsilon_0^2 \omega^2 \eta}{2\left[1 + \frac{\omega^2\eta^2}{\mu^2}\right]}.$$

Tidal heating

Streamfunction Approach

$$\sigma_{ij} = 2\eta\dot{\varepsilon} = \eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right),$$

$$u_x = \frac{\partial \Psi}{\partial z},\ u_z = -\frac{\partial \Psi}{\partial x},$$

$$\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2}\right)\eta\left(\frac{\partial^2 \Psi}{\partial z^2} - \frac{\partial^2 \Psi}{\partial x^2}\right) + 4\frac{\partial^2}{\partial x \partial z}\eta\frac{\partial^2 \Psi}{\partial x \partial z} = -Ra\frac{\partial T}{\partial x},$$

$$\frac{\partial T}{\partial t} + \frac{\partial \Psi}{\partial z}\frac{\partial T}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} + q'.$$

Solution Method

Method:
- SOR – Successive Over-Relaxation

Boundary Conditions:
- Periodic in *x*
- Free-slip in *z*

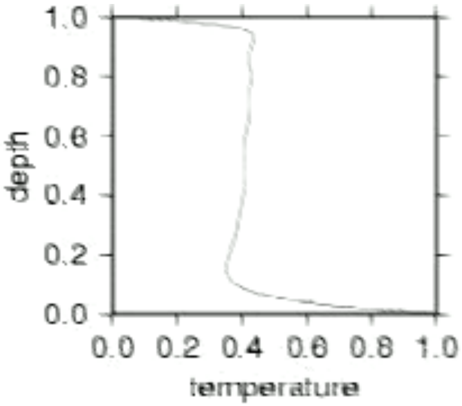
1. Calculate Ψ
2. Update T
3. Recalculate Ψ

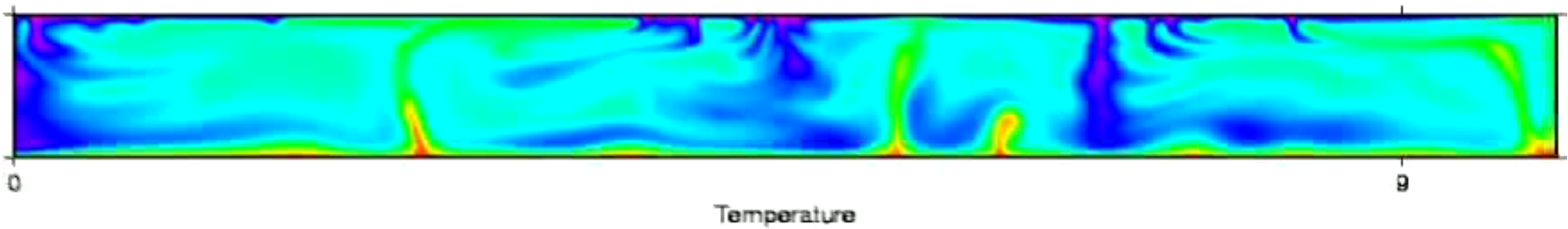
$$\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2}\right) \eta \left(\frac{\partial^2 \Psi}{\partial z^2} - \frac{\partial^2 \Psi}{\partial x^2}\right) + 4\frac{\partial^2}{\partial x \partial z} \eta \frac{\partial^2 \Psi}{\partial x \partial z} = -Ra\frac{\partial T}{\partial x},$$

$$\frac{\partial T}{\partial t} + \frac{\partial \Psi}{\partial z}\frac{\partial T}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial T}{\partial z} = \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2} + q'.$$

State of the art

McNamara et al. – 2D Earth Mantle Convection





State of the art

3. Coupled thermal convection with tidal dissipation

Next, we perform fully coupled numerical simulations of thermal convection and tidal heating that we self-consistently calculate from the time-evolving temperature structure. We again adopt 2D cartesian (rectangular) geometry, with the dimensions in this case representing horizontal position *x* and height *z*. Cartesian geometry is appropriate for regional studies of Europa's ice shell because Europa's ice-shell thickness is much smaller than its radius. We neglect inertia and adopt the Boussinesq approximation. We use the finite-element code ConMan (King et al., 1990) to solve the dimensionless equations of momentum, continuity, and energy, respectively given by

$$\frac{\partial \sigma_{ij}}{\partial x_j} + Ra\,\theta k_i = 0 \tag{3}$$

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{4}$$

$$\frac{\partial \theta}{\partial t} + u_i \frac{\partial \theta}{\partial x_i} = \frac{\partial^2 \theta}{\partial x_i^2} + q' \tag{5}$$

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Coupled convection and tidal dissipation in Europa's ice shell

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ABSTRACT

We performed 2D numerical simulations of oscillatory tidal flexing to study the interrelationship between tidal dissipation (calculated using the Maxwell model) and a heterogeneous temperature structure in Europa's ice shell. Our 2D simulations show that, if the temperature is spatially uniform, the tidal dissipation rate peaks when the Maxwell time is close to the tidal period, consistent with previous stud-

Han and Showman (2010)

2D, Resolution 100x100

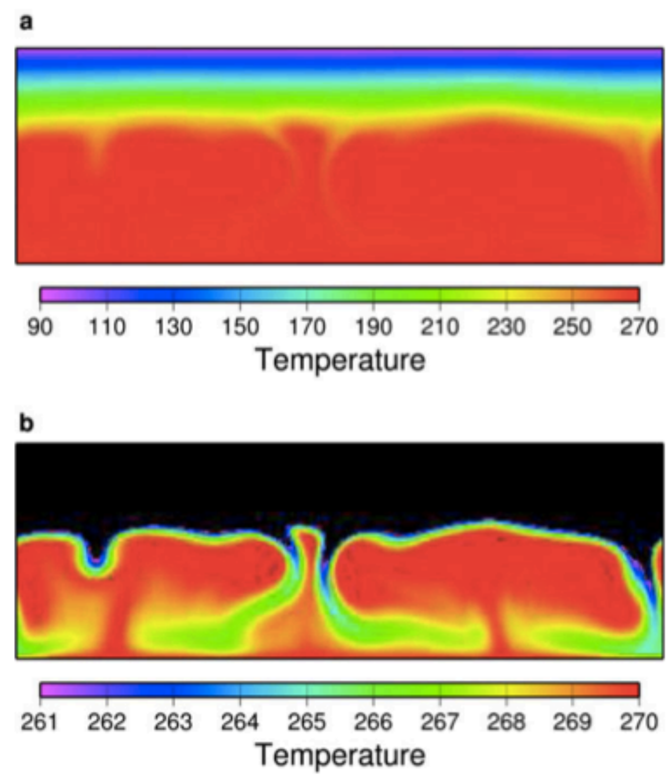
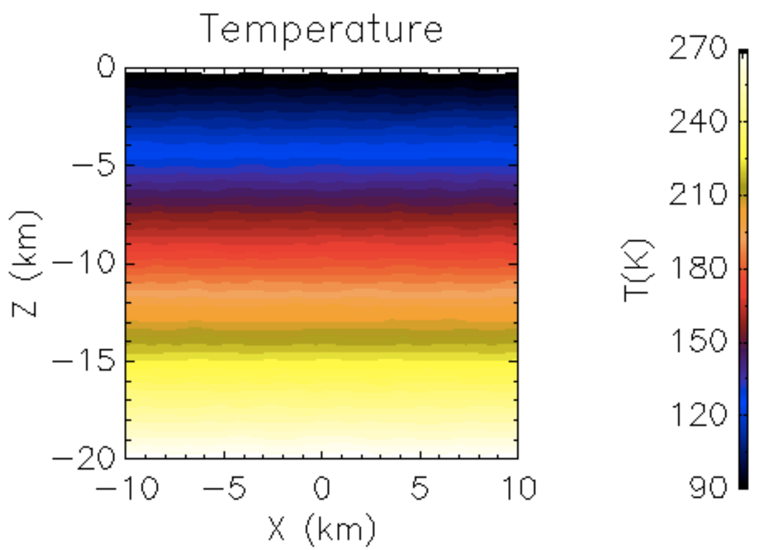


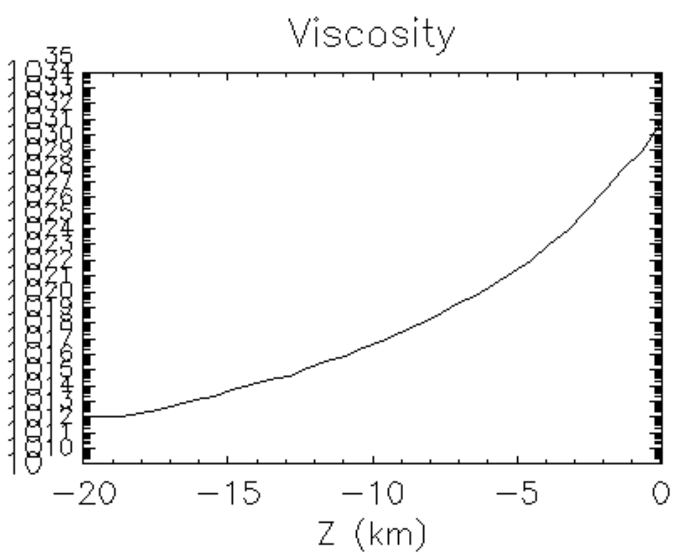
Fig. 5. Temperature distribution from a fully coupled ConMan/Tekton model of thermal convection and oscillatory tidal flexing. The model implements a domain-averaged tidal-flexing amplitude of 1.25×10^{-5} and tidal period of 3.5 days. The thickness of the ice shell is 15 km, and the Rayleigh number is 1.81×10^7. Top: temperature range of 90–270 K. Bottom: temperature range of 260–270 K.

Local Box model

~ 20x20 km
(Resolution: 20m for 1024^2)

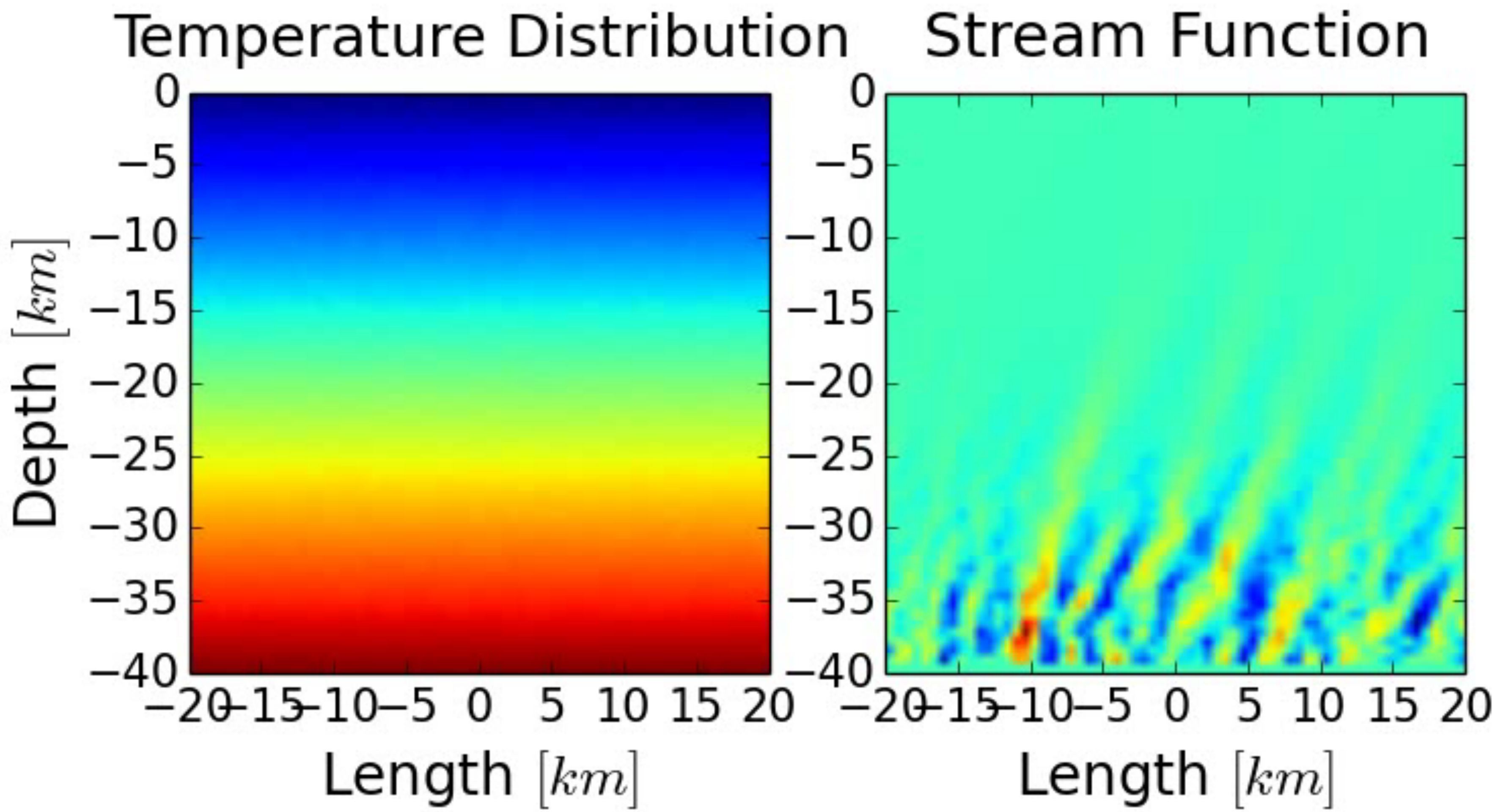


Viscosity changes over
10^{20}
in 20 km!!!

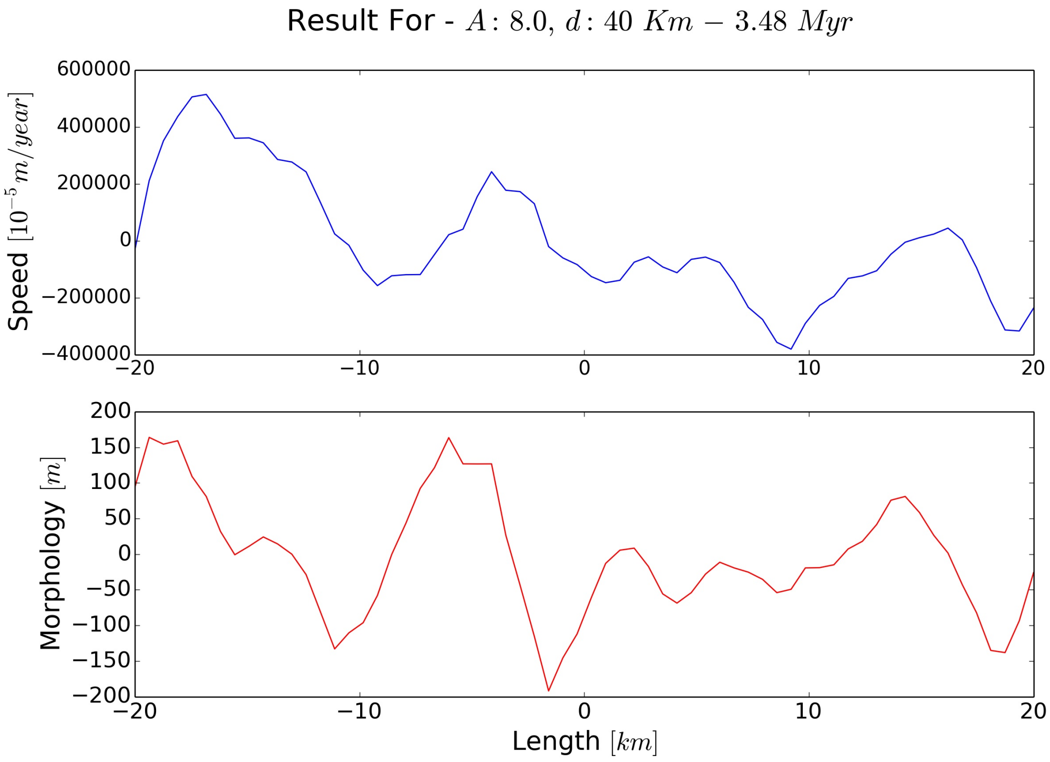


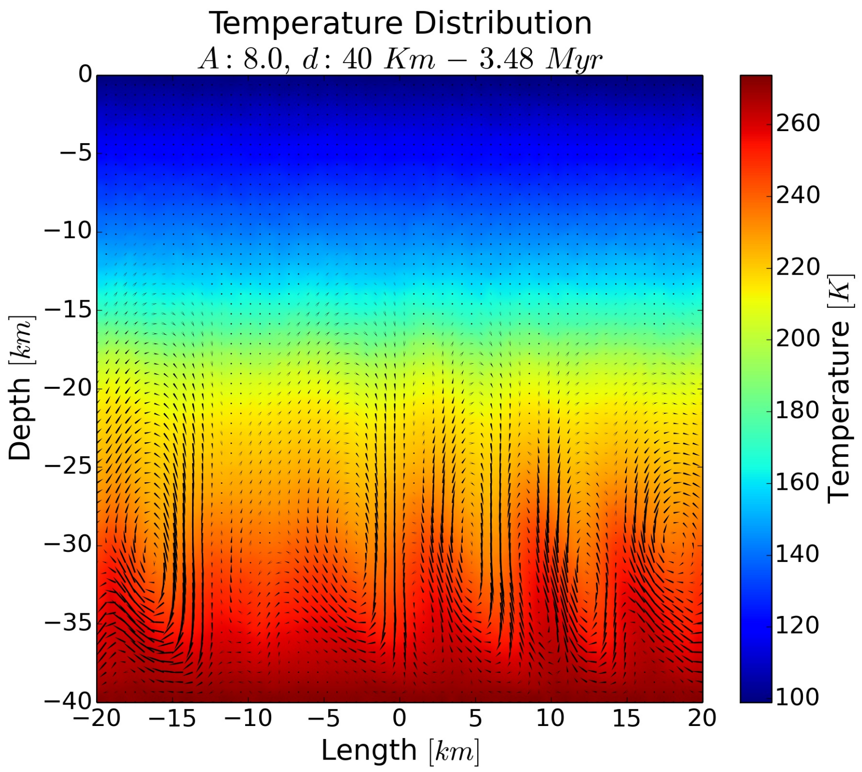
$$\eta(T) = \eta_0 \exp\left\{A\left(\frac{T_m}{T} - 1\right)\right\}$$

Evolution for - A: 8.0, d: 40Km

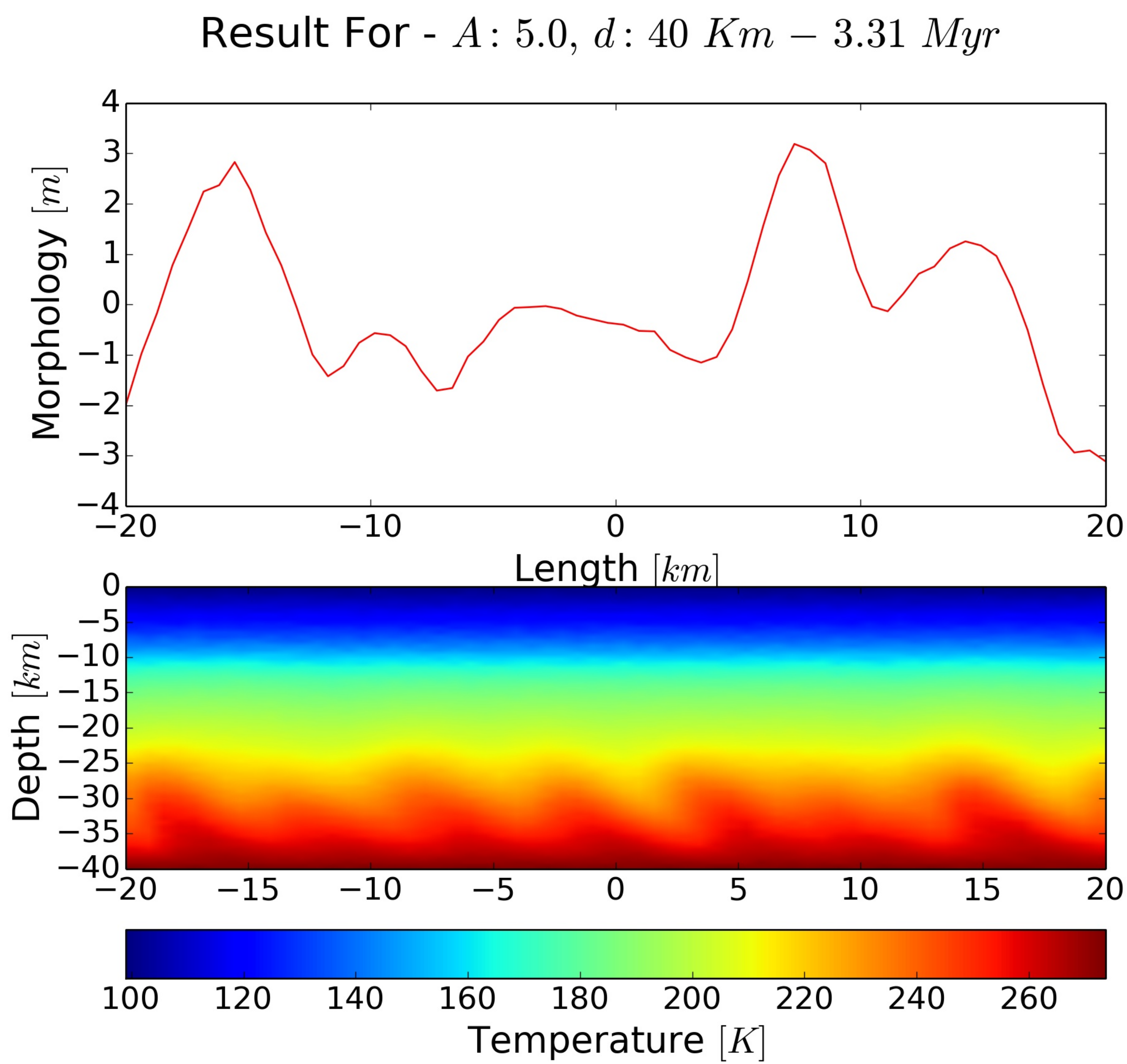


Temperature structure and terrain morphology

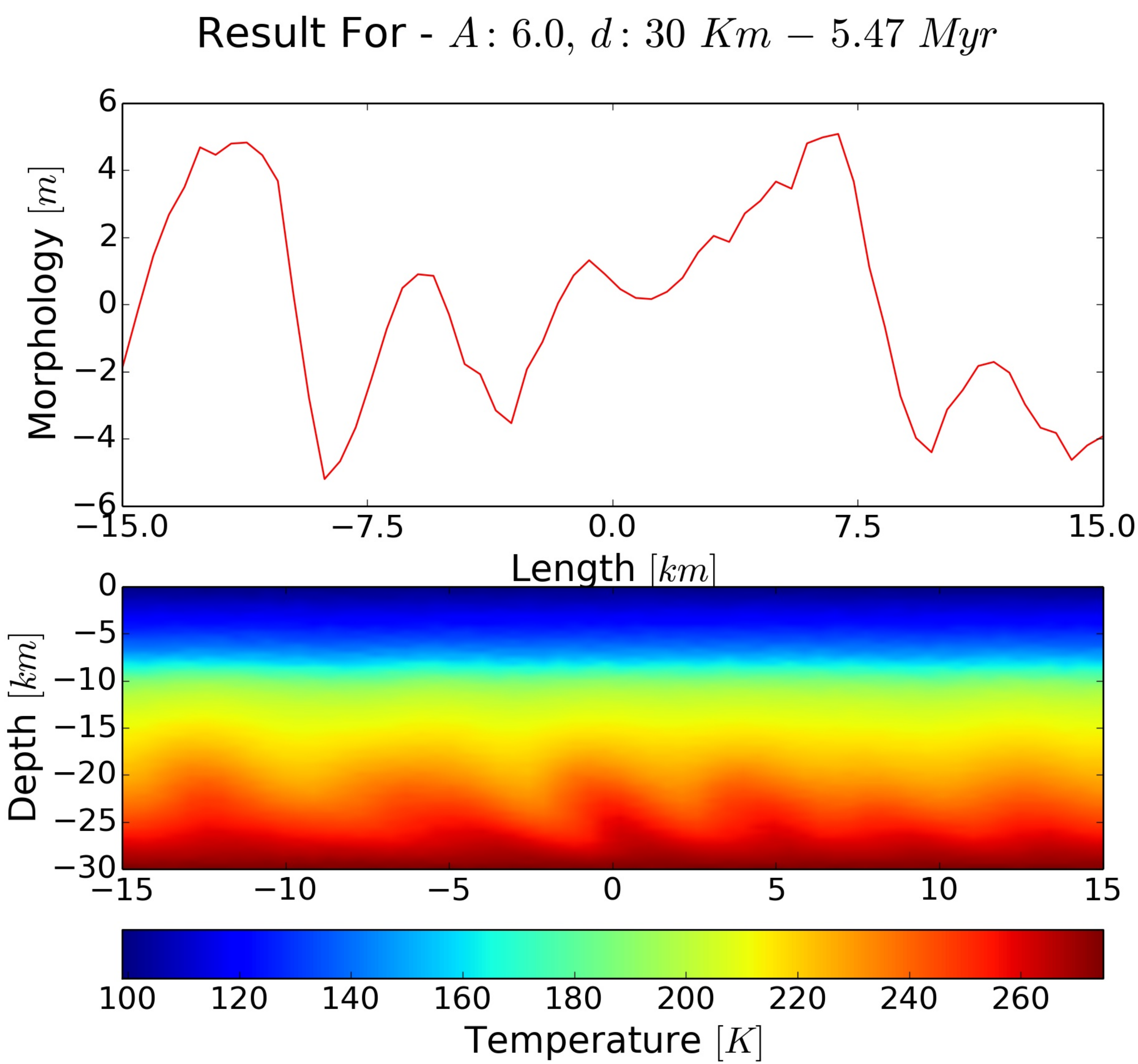




Parameter space



Parameter space



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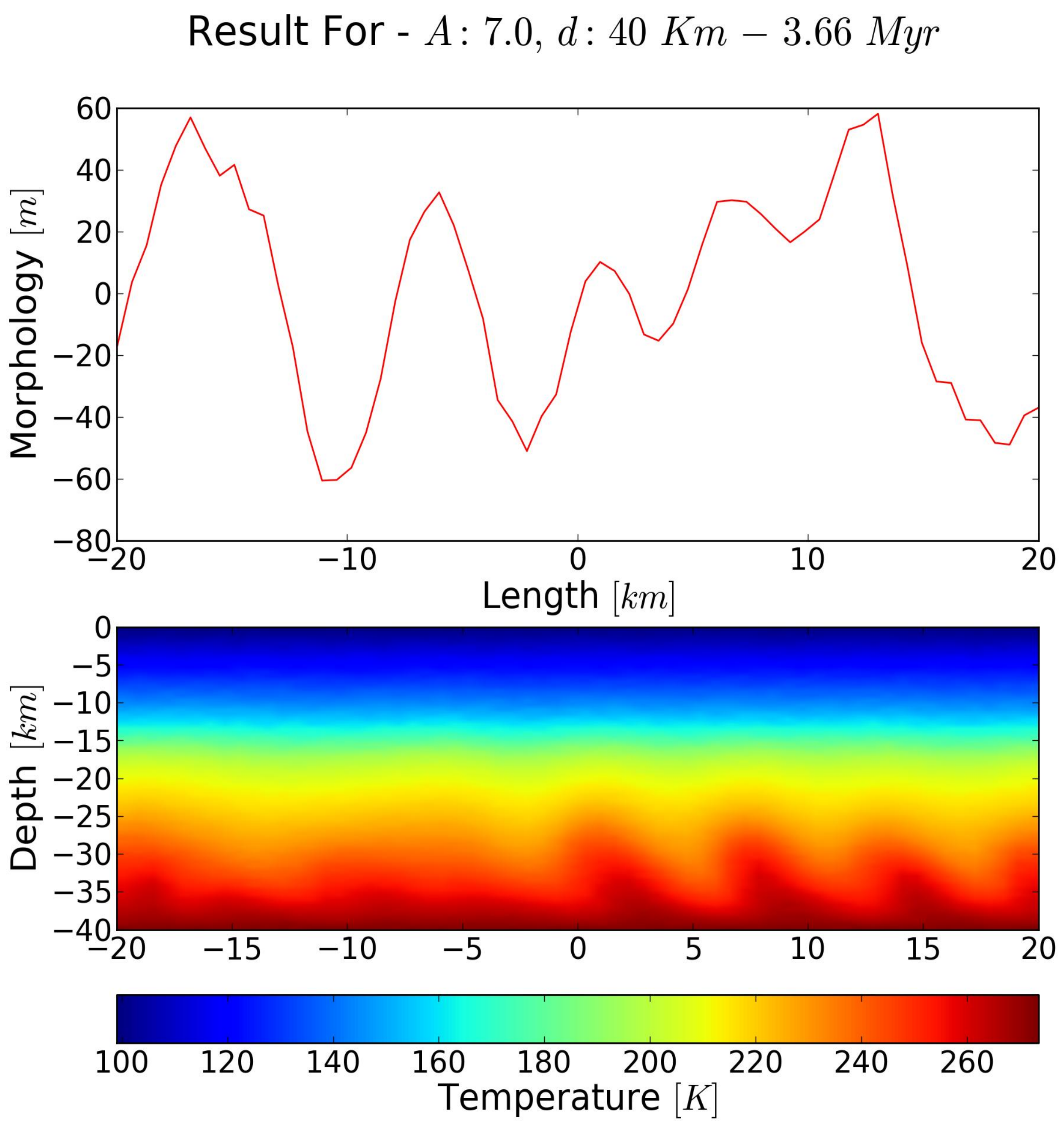

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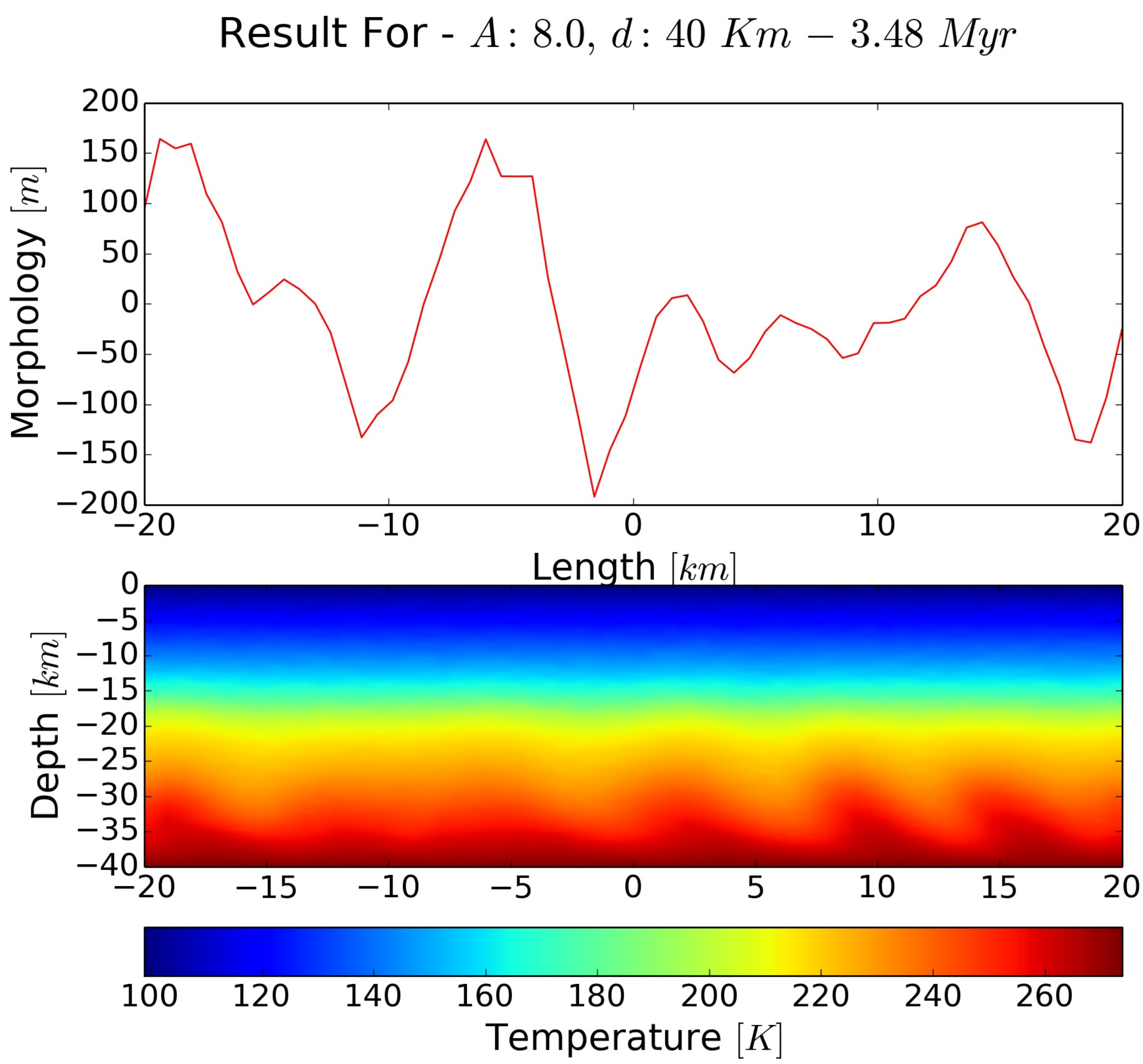

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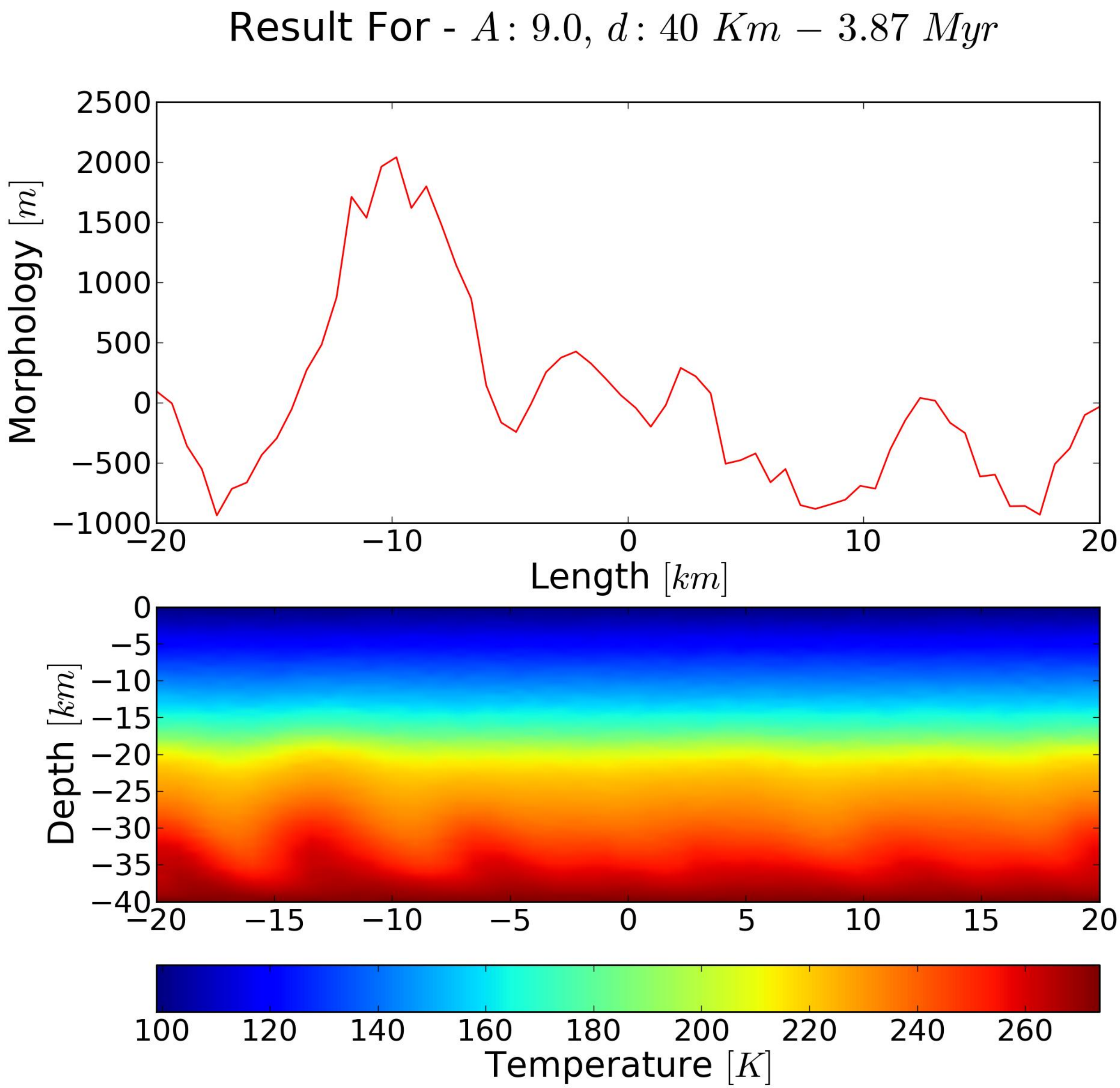

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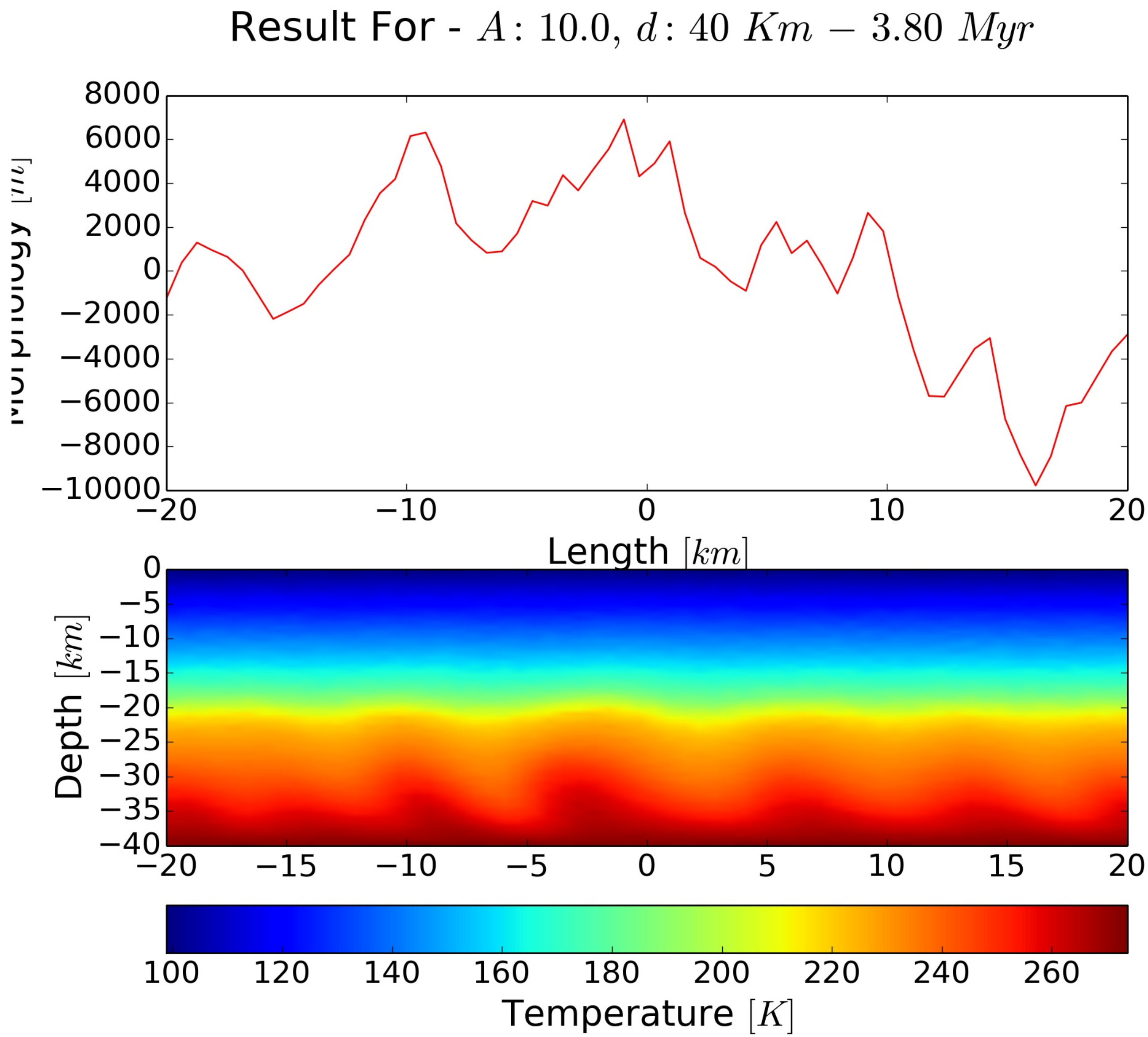

To be done:

- Consider more realistic equation of state for the ice.
- Include melting and different grain size.
- Code 3D model.

Thanks!