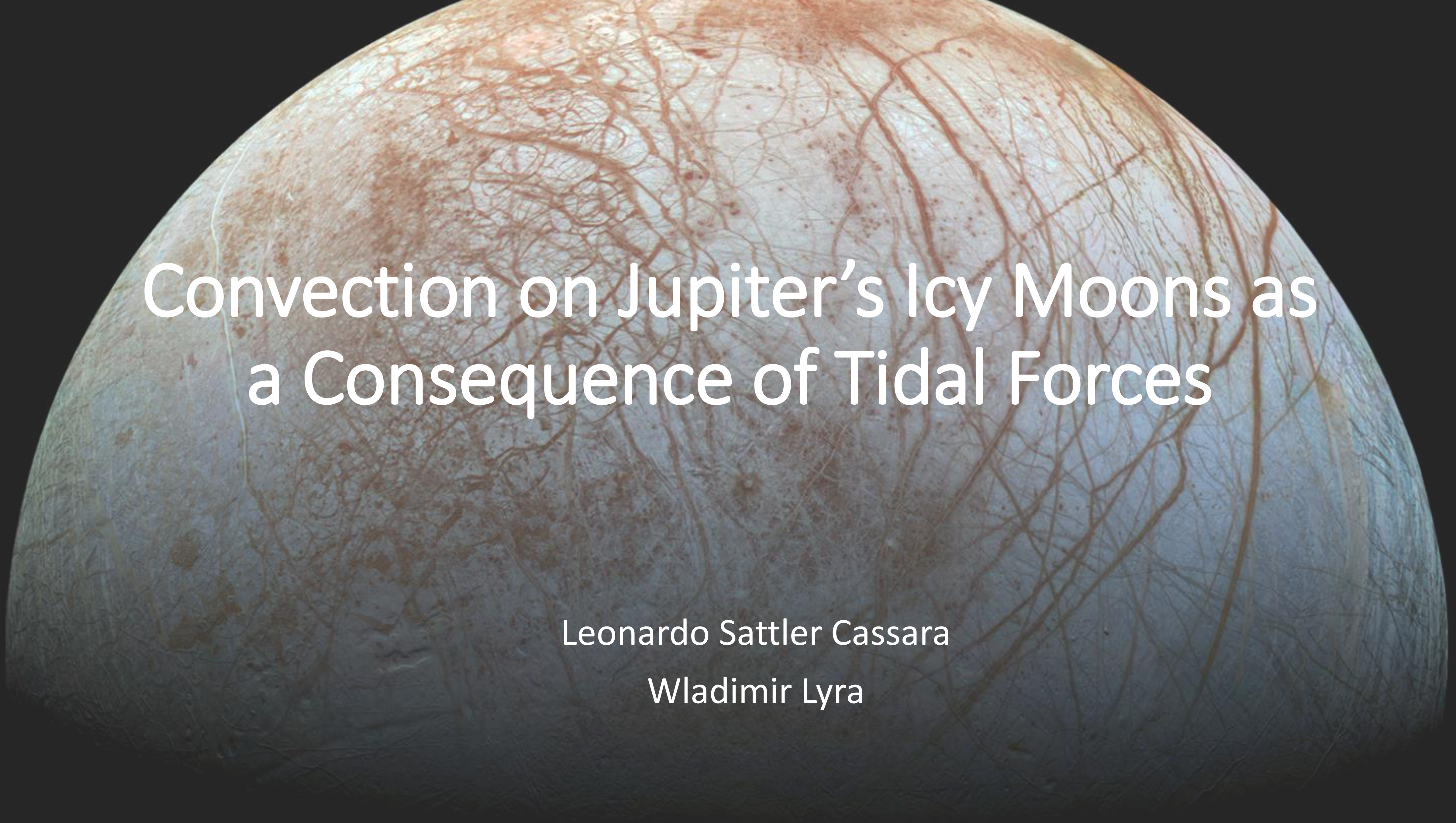
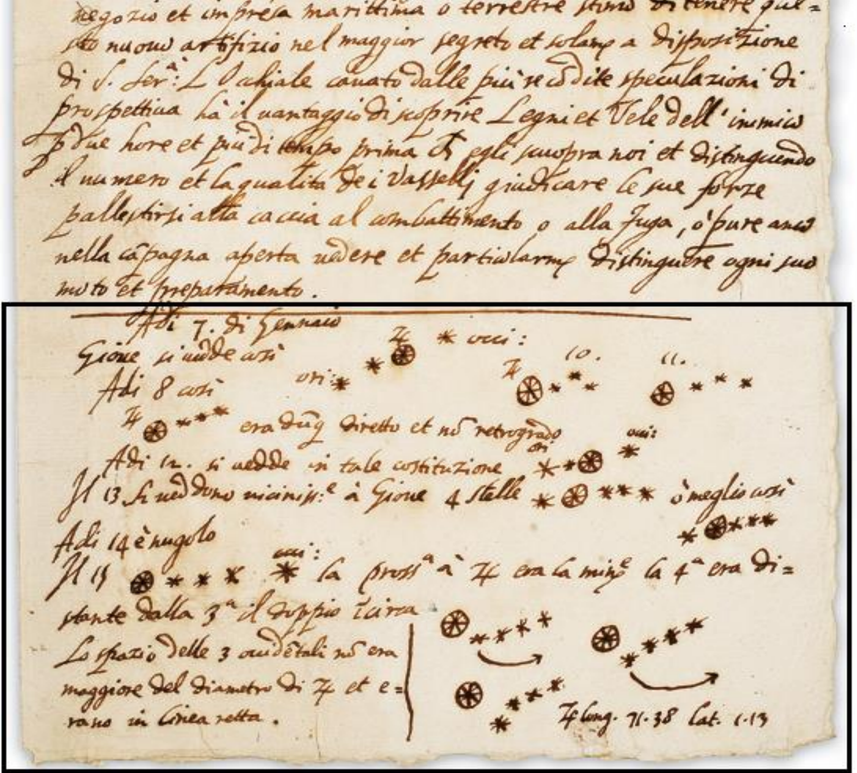


Convection on Jupiter’s Icy Moons as a Consequence of Tidal Forces

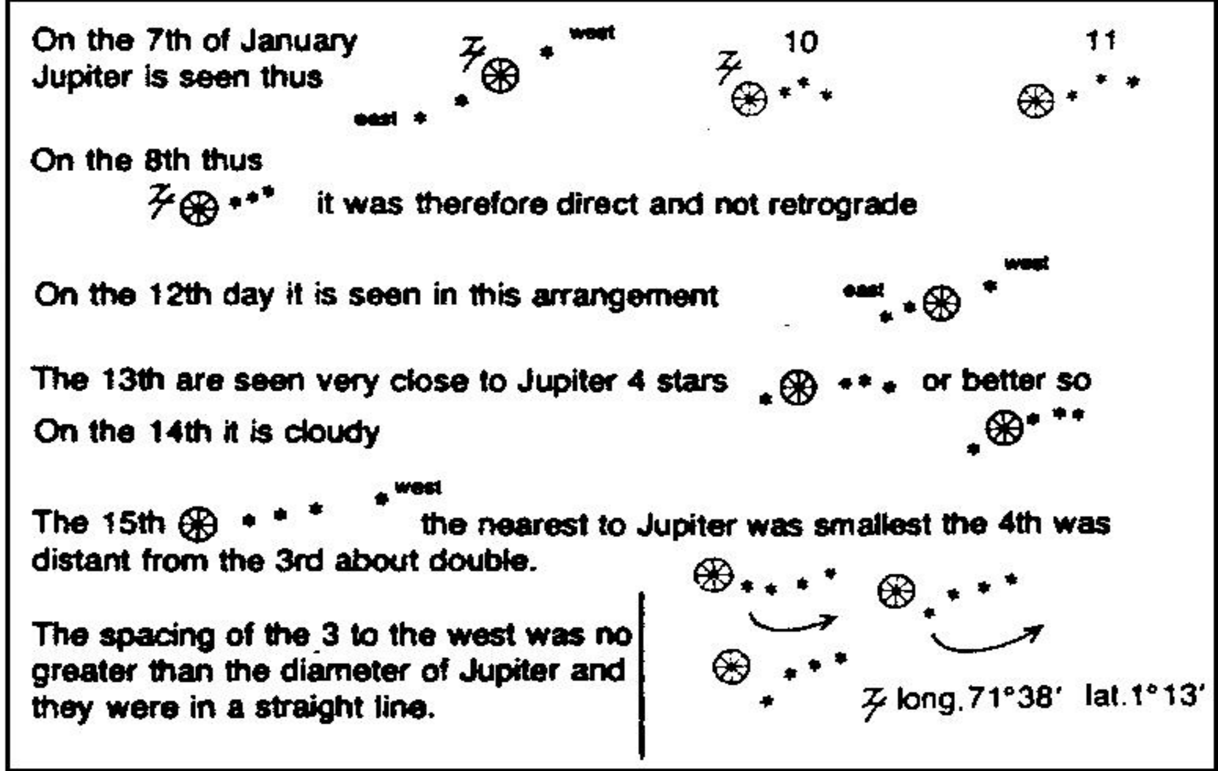
Leonardo Sattler Cassara

Wladimir Lyra



negozio et impresa marittima o terrestre stimo di tenere questo nuovo artifizio nel maggior segreto et solam.te a disposizione di S. Ser.tà L'Occhiale cavato dalle più recondite speculazioni di prospettiva ha il vantaggio di scoprire Legni et Vele dell'inimico per due hore et più di tempo prima che egli scuopra noi et distinguendo il numero et la qualità dei Vasselli giudicare le sue forze pallestirsi alla caccia al combattimento o alla fuga, o pure anco nella campagna aperta vedere et particolarm.te distinguere ogni suo moto et preparamento.

Adi 7. di Gennaio
Giove si vedde così ♃ * occ: 10. 11.
Adi 8 così or:
♃ era dunq diretto et no retrogrado
Adi 12. si vedde in tale costituzione or: occ:
Il 13 si veddono vicinis.e à Giove 4 stelle ò meglio così
Adi 14 è nugolo
Il 15 occ: la pross.a à ♃ era la min.e la 4.a era distante dalla 3.a il doppio incirca
Lo spatio delle 3 occidentali no era maggiore del diametro di ♃ et erano in linea retta.
♃ long. 71.38 lat. 1.13



On the 7th of January
Jupiter is seen thus

On the 8th thus

it was therefore direct and not retrograde

On the 12th day it is seen in this arrangement

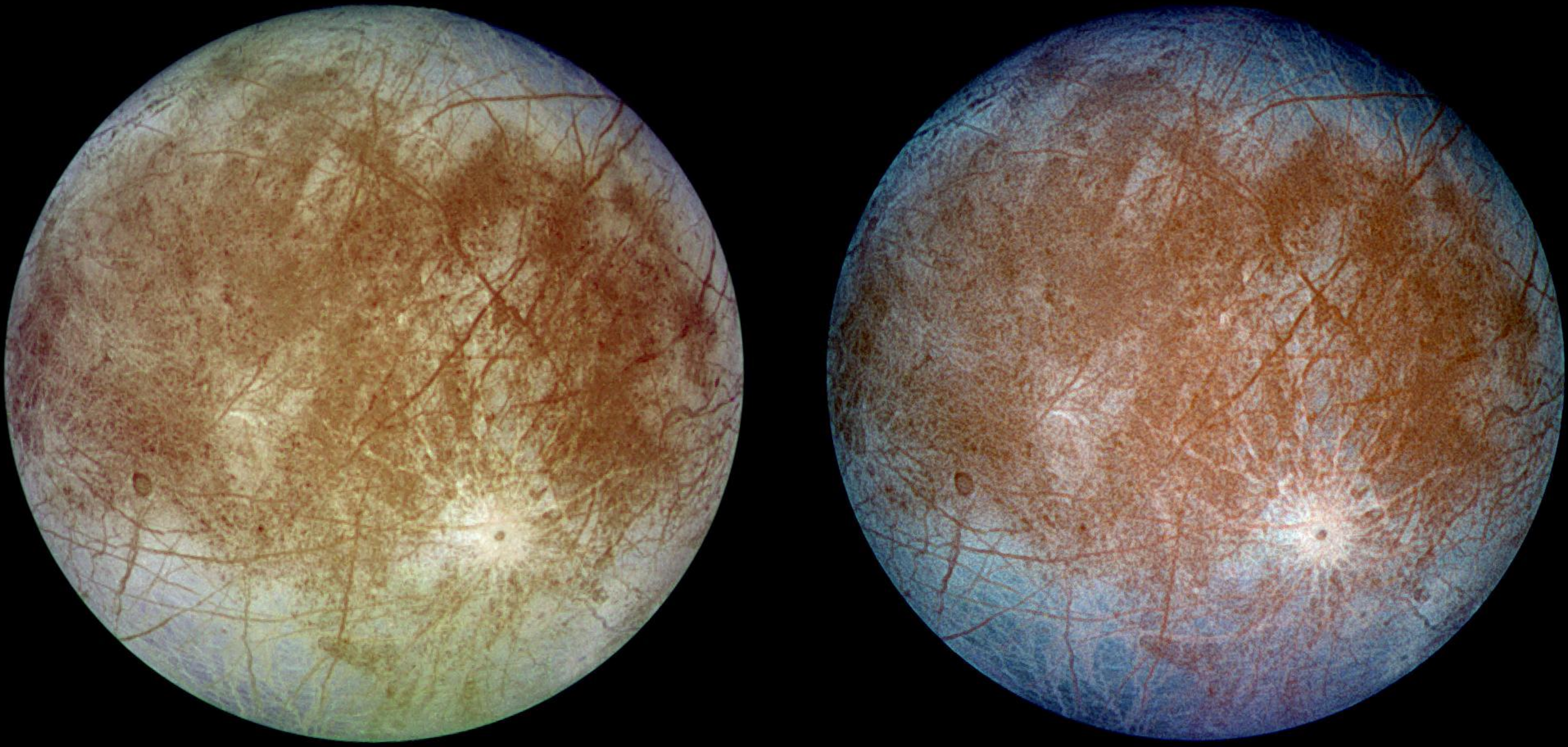
The 13th are seen very close to Jupiter 4 stars or better so

On the 14th it is cloudy

The 15th the nearest to Jupiter was smallest the 4th was distant from the 3rd about double.

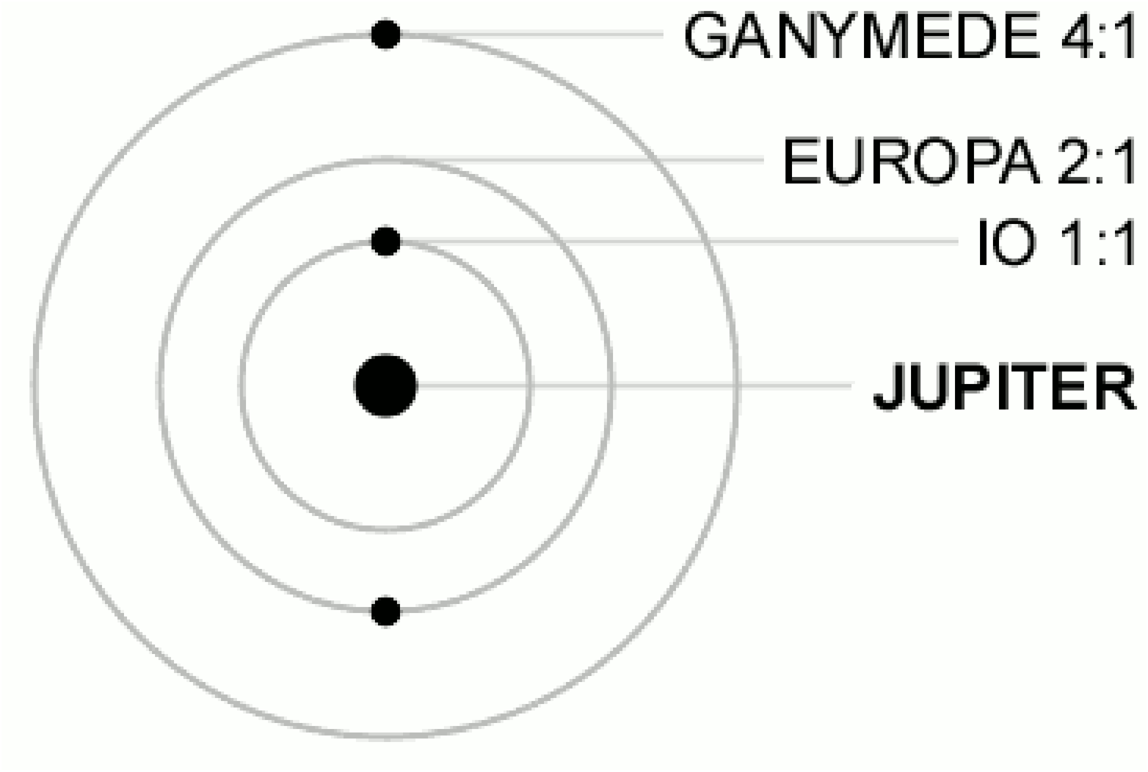
The spacing of the 3 to the west was no greater than the diameter of Jupiter and they were in a straight line.

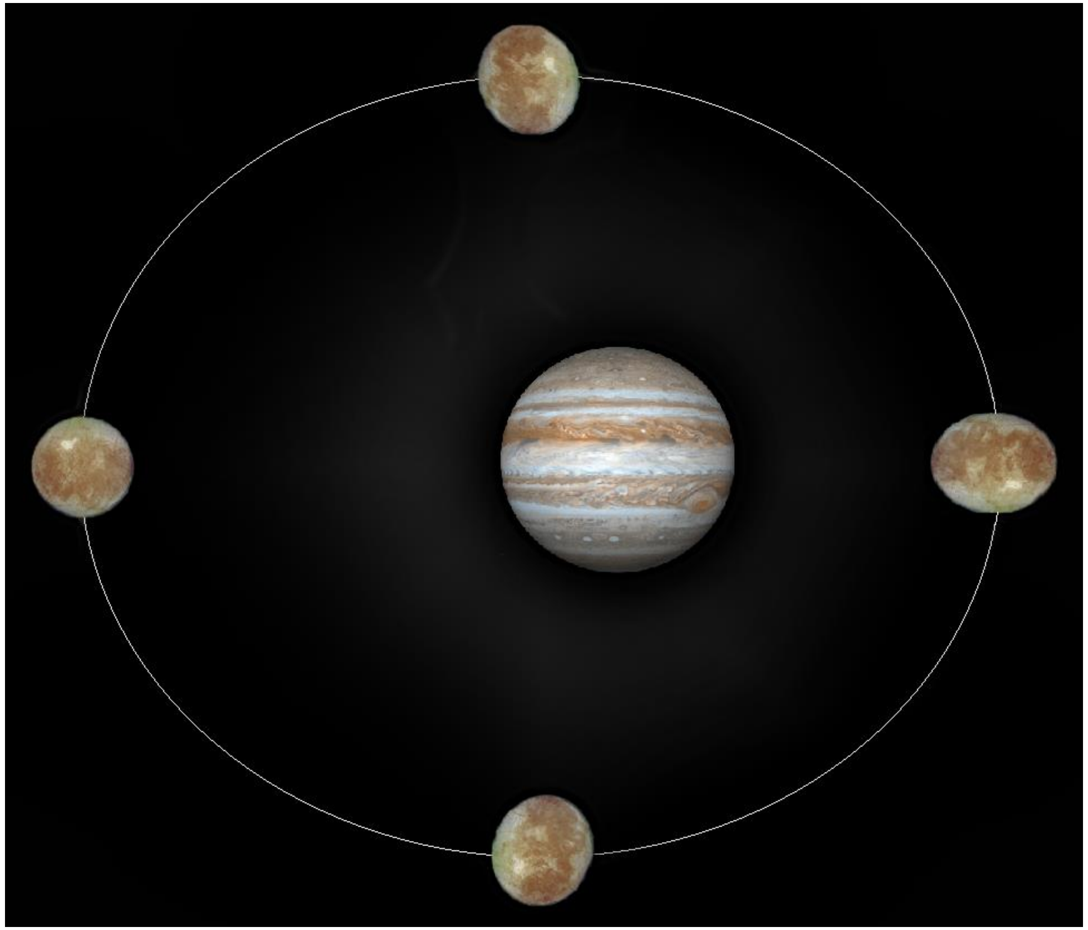
♃ long. 71°38′ lat. 1°13′



Source: Greenberg (2005)

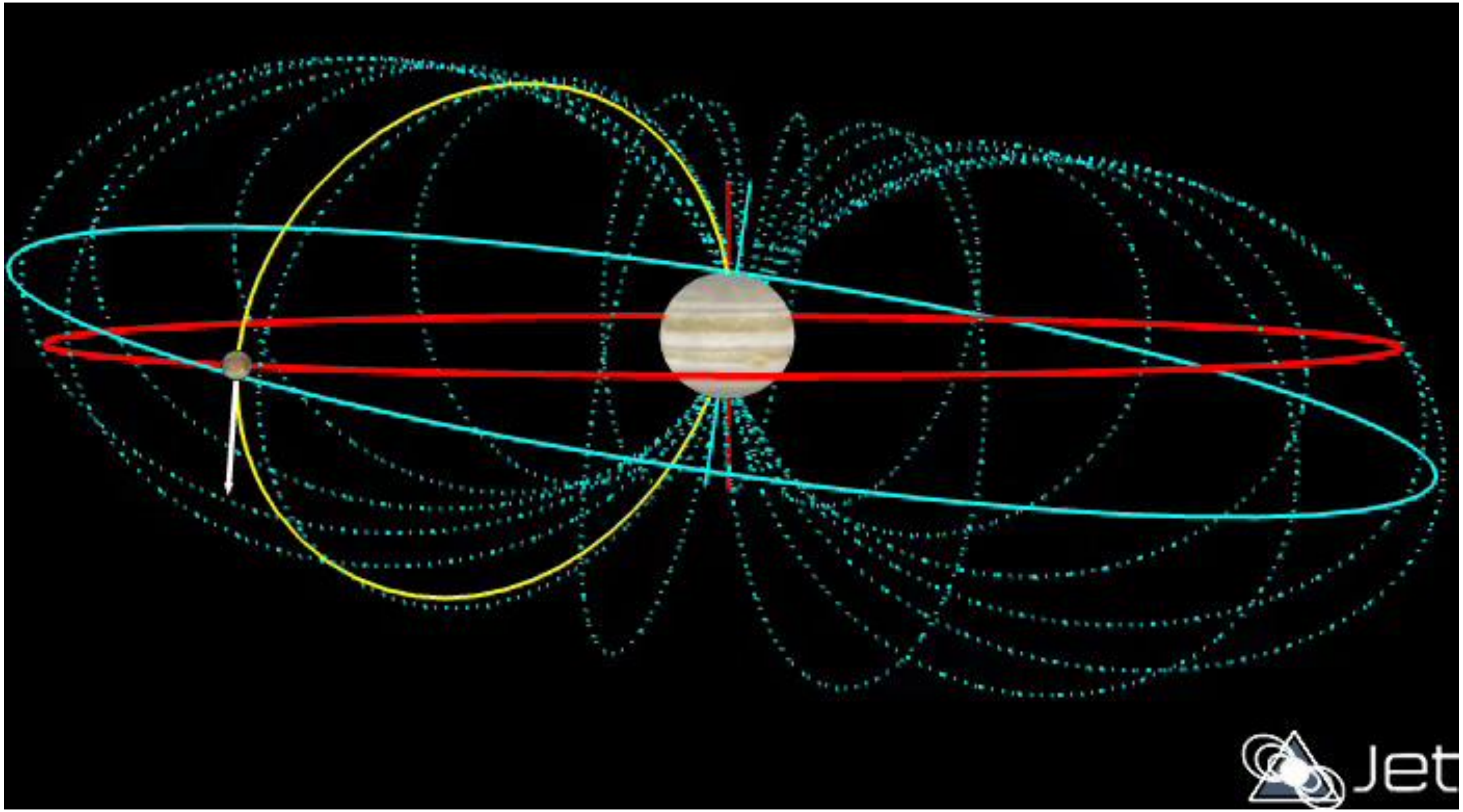
Orbital Configuration

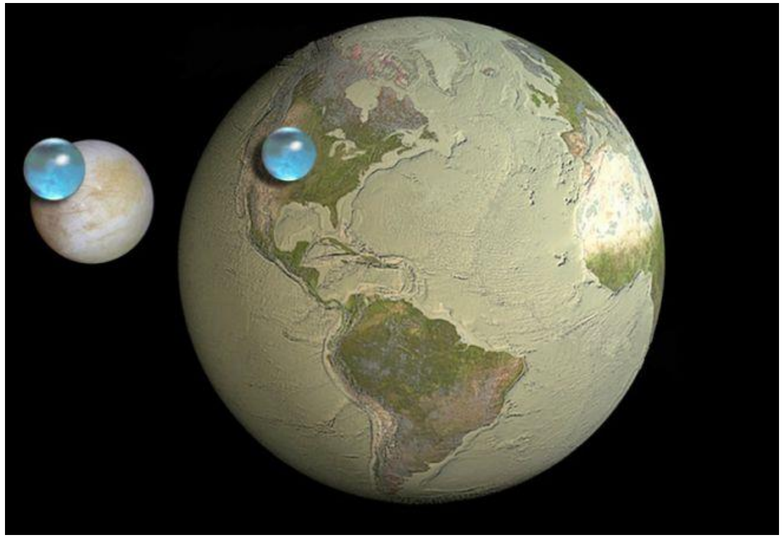




Orbital period: 3.5 days -
Resonance

Arguments for Liquid Ocean





Type I ice + high pressure

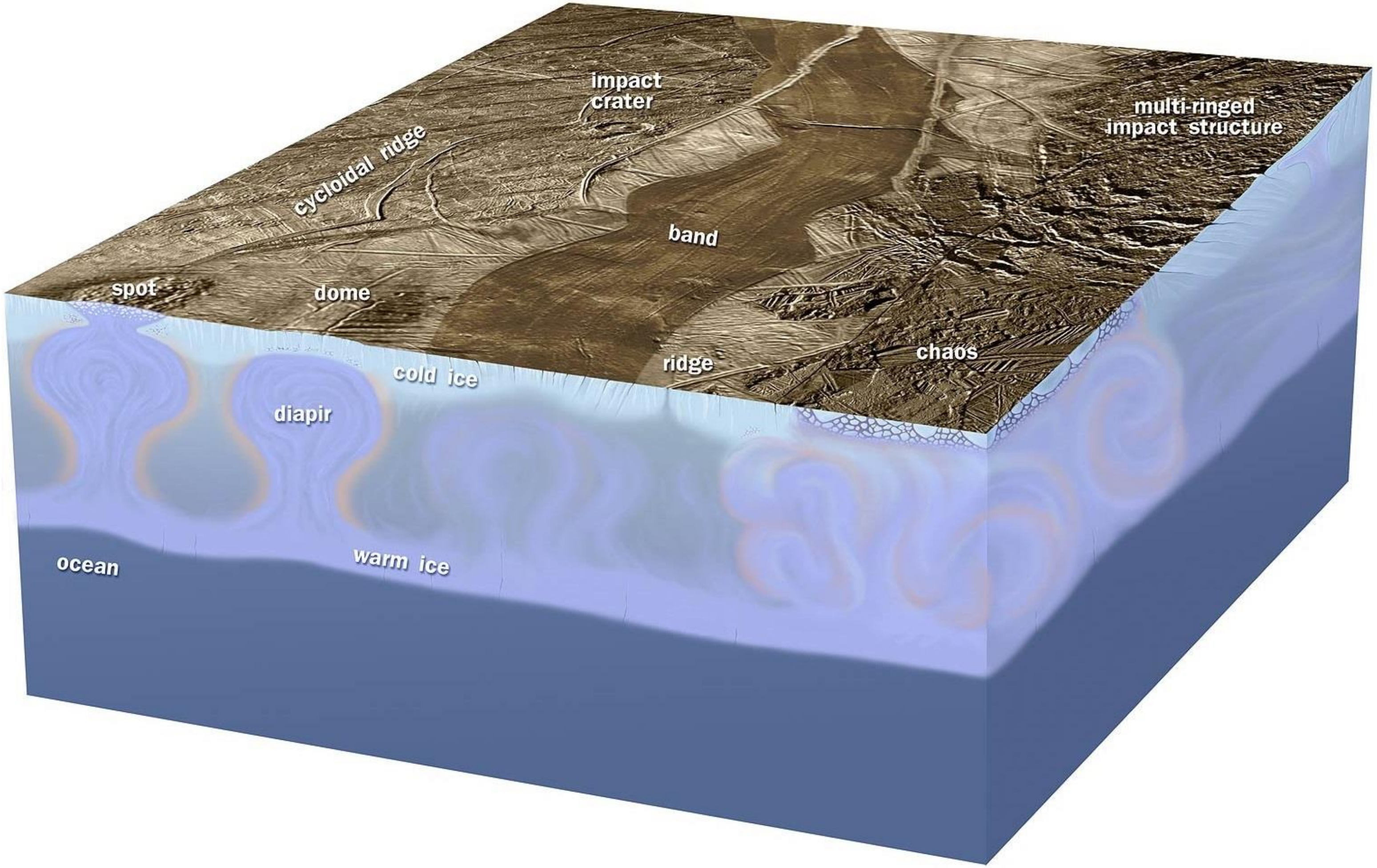
Kivelson et al. (2000)

Arguments for Convection

- Tidal Heating → Thermal Evolution
- Few Number of Craters → Resurfacing
- Viscosity strongly depends on Temperature

$$P_r = \frac{\eta}{\rho\kappa} >> 1$$

- Thermal Eq. + Temp. Gradient =
  Convective Layer



Pappalardo et al. (1998)
Nimmo et al. (2003)
Sotin et al. (2004)
Barr and Showman (2009)

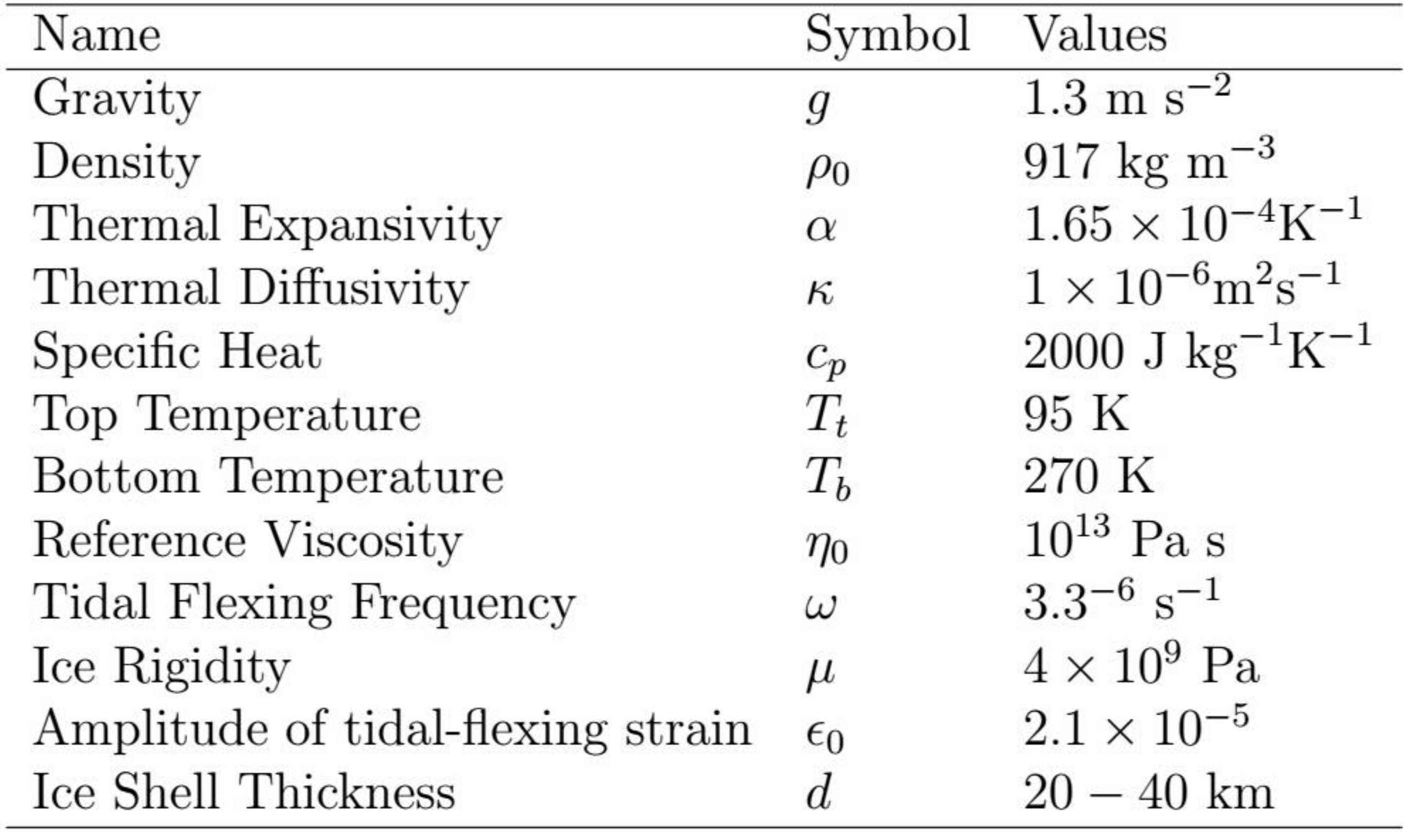
The Model

Rheology and **Internal Heating:**

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

$$Ra = \frac{\rho_0 g \alpha \Delta T d^3}{\kappa \eta_0}$$

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



Name	Symbol	Values
Gravity	g	1.3 m s^{-2}
Density	ρ_0	917 kg m^{-3}
Thermal Expansivity	α	1.65×10^{-4}K^{-1}
Thermal Diffusivity	κ	1×10^{-6}m^{2}s^{-1}
Specific Heat	c_p	2000 J kg^{-1}K^{-1}
Top Temperature	T_t	95 K
Bottom Temperature	T_b	270 K
Reference Viscosity	η_0	10^{13} Pa s
Tidal Flexing Frequency	ω	3.3^{-6} s^{-1}
Ice Rigidity	μ	4×10^9 Pa
Amplitude of tidal-flexing strain	ϵ_0	2.1×10^{-5}
Ice Shell Thickness	d	$20 - 40$ km

The Model

Incompressible Fluid:

$$\frac{D\rho}{Dt} = \frac{\partial\rho}{\partial t} + \vec{v}\,\mathrm{grad}\,(\rho) = 0$$

$$\mathrm{div}(\vec{v}) = 0$$

Boussinesq approximation:

$$(\rho - \rho_0)g_i = -\rho_0 g_i \alpha (T - T_0)$$

The Model

Governing Equations:

$$\frac{\partial}{\partial z}\sigma'_{\mathbf{xz}} - \nabla p - (Ra\theta)\mathbf{z} = 0$$

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

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

The Model

Stream function approach: $\nabla \cdot \mathbf{u} = \nabla \cdot (\nabla \times \Psi) = 0$

$$\frac{\partial}{\partial z}\sigma'_{\mathbf{xz}} - \nabla p - (Ra\theta)\mathbf{z} = 0$$

$$\sigma'_{xz} = 2\eta\dot{\varepsilon} = \eta\left(\frac{\partial u_x}{\partial z} + \frac{\partial u_z}{\partial x}\right)$$

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

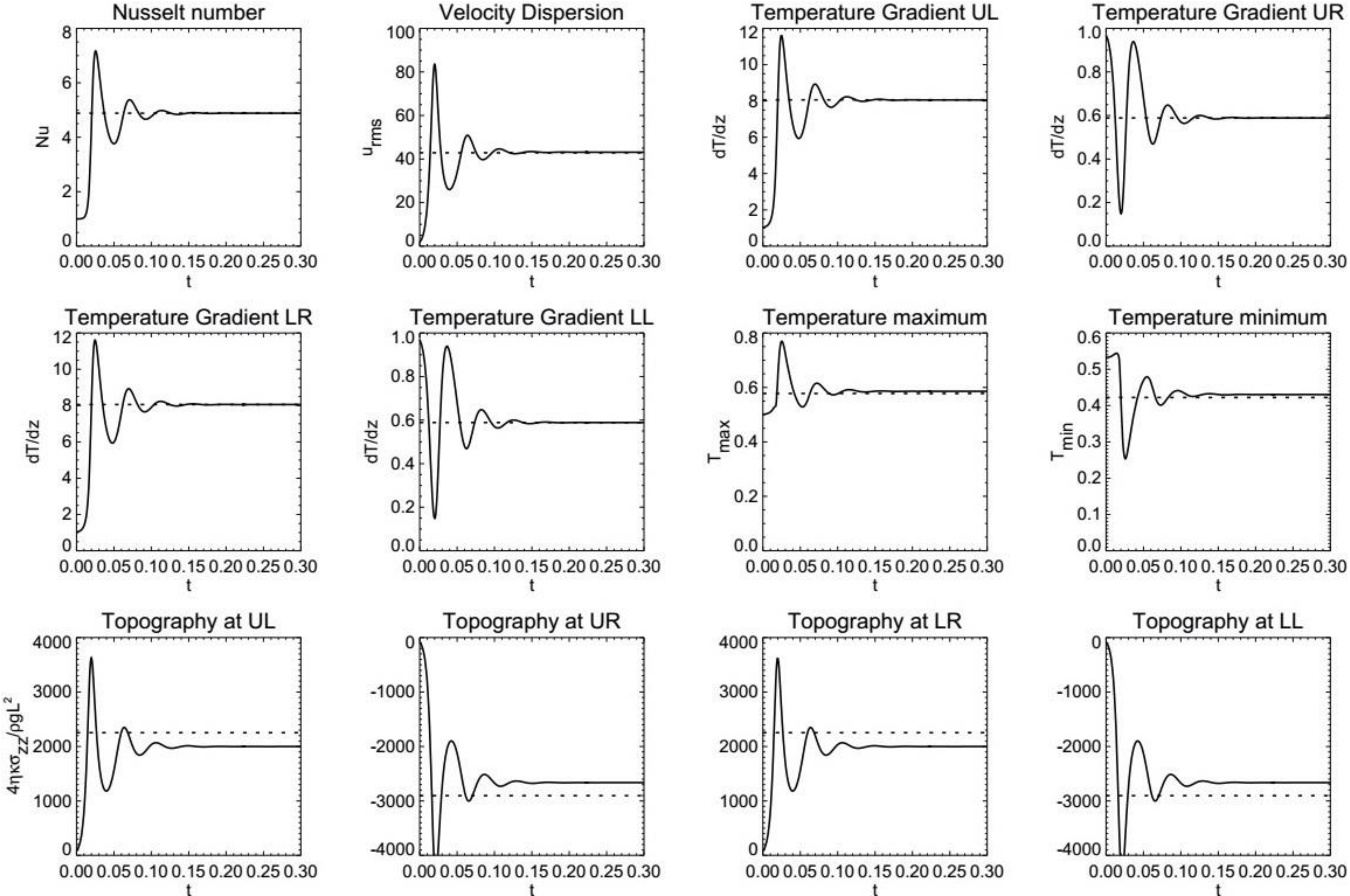
$$\left(\frac{\partial^2}{\partial z^2} - \frac{\partial^2}{\partial x^2}\right)\eta\left(\frac{\partial^2 \Psi}{\partial z^2} - \frac{\partial^2 \Psi}{\partial x^2}\right) + 4\frac{\partial^2}{\partial x \partial z}\eta\frac{\partial^2 \Psi}{\partial x \partial z} = -Ra\frac{\partial \theta}{\partial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

The Model

Stream function approach: $\nabla \cdot \mathbf{u} = \nabla \cdot (\nabla \times \Psi) = 0$

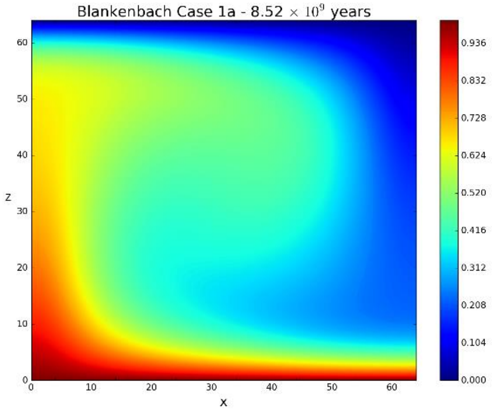
$$\frac{\partial \theta}{\partial t} + \mathbf{u} \cdot \nabla \theta = \nabla^2 \theta + q'$$

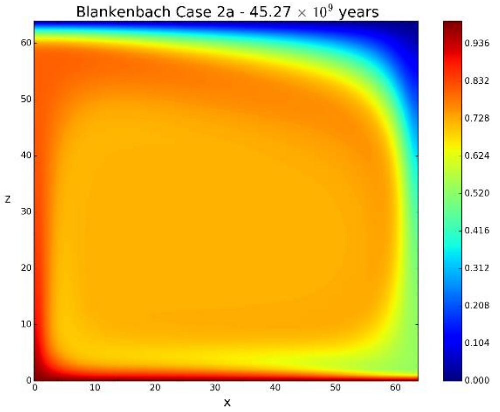
$$\frac{\partial \theta}{\partial t} + \frac{\partial \Psi}{\partial z}\frac{\partial \theta}{\partial x} - \frac{\partial \Psi}{\partial x}\frac{\partial \theta}{\partial z} = \frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial z^2} + q'$$

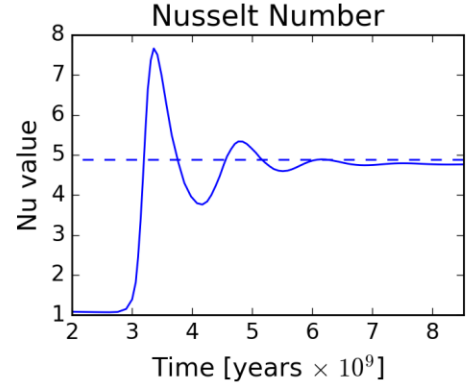

Nusselt number
Nu
Velocity Dispersion
u_{rms}
Temperature Gradient UL
Temperature Gradient UR
Temperature Gradient LR
Temperature Gradient LL
dT/dz
Temperature maximum
T_{max}
Temperature minimum
T_{min}
Topography at UL
Topography at UR
Topography at LR
Topography at LL
$4\eta\kappa\sigma_{zz}/\rho g L^2$
t
0.00 0.05 0.10 0.15 0.20 0.25 0.30

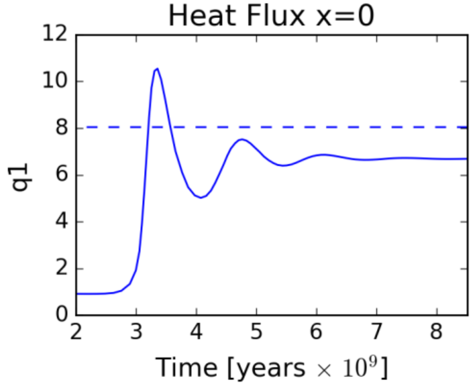
CitcomS

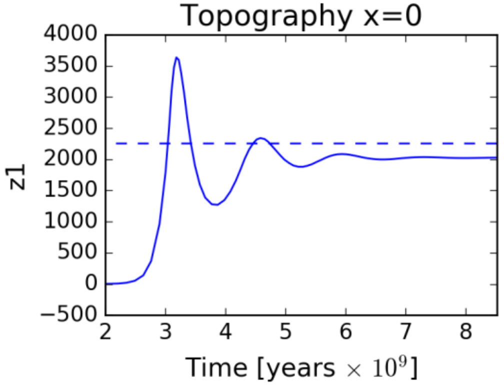
California **I**nstitute of **T**echnology **C**onvection in the **M**antle - Spherical

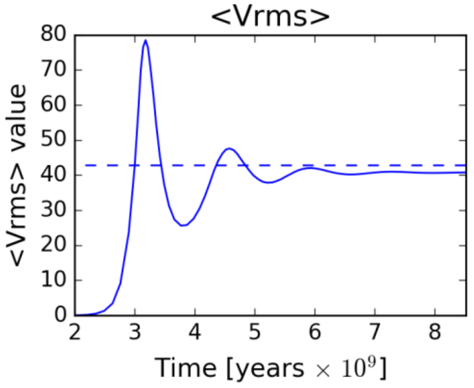

Blankenbach Case 1a - 8.52 $\times 10^9$ years

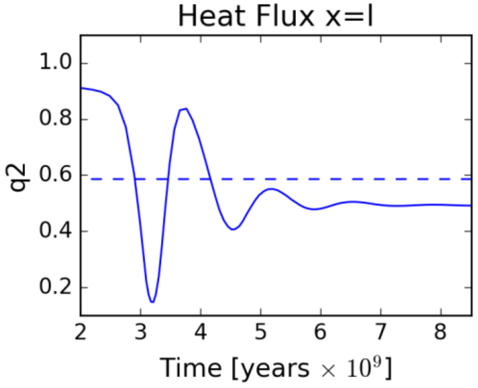

Blankenbach Case 2a - 45.27 $\times 10^9$ years

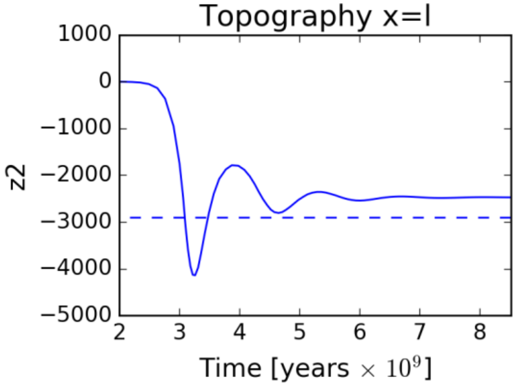

Nusselt Number

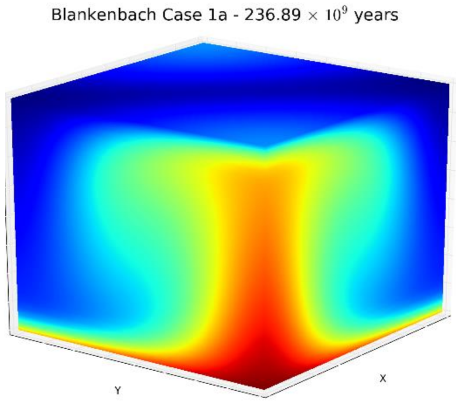

Heat Flux x=0

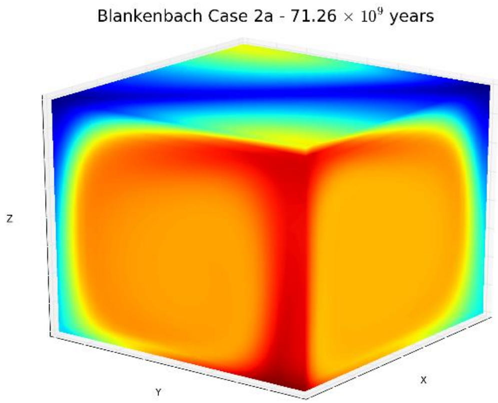

Topography x=0


<Vrms>


Heat Flux x=l

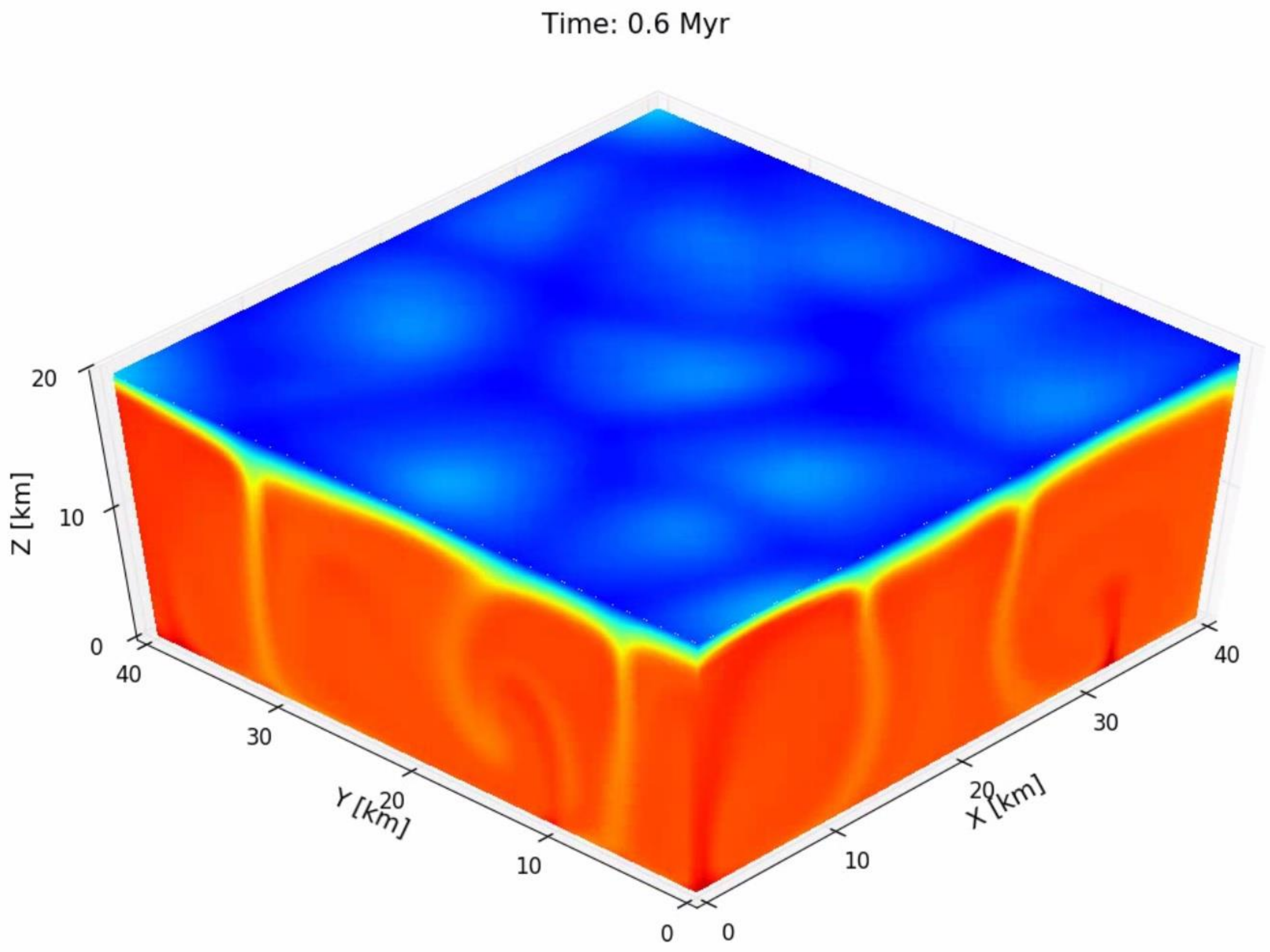

Topography x=l


Blankenbach Case 1a - 236.89 $\times 10^9$ years


Blankenbach Case 2a - 71.26 $\times 10^9$ years

Blankenbach et al (1989)

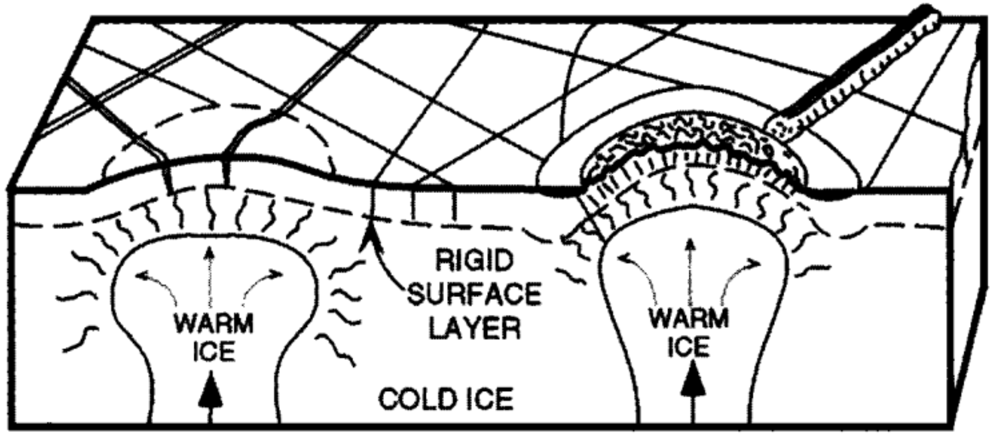
Results



External Features

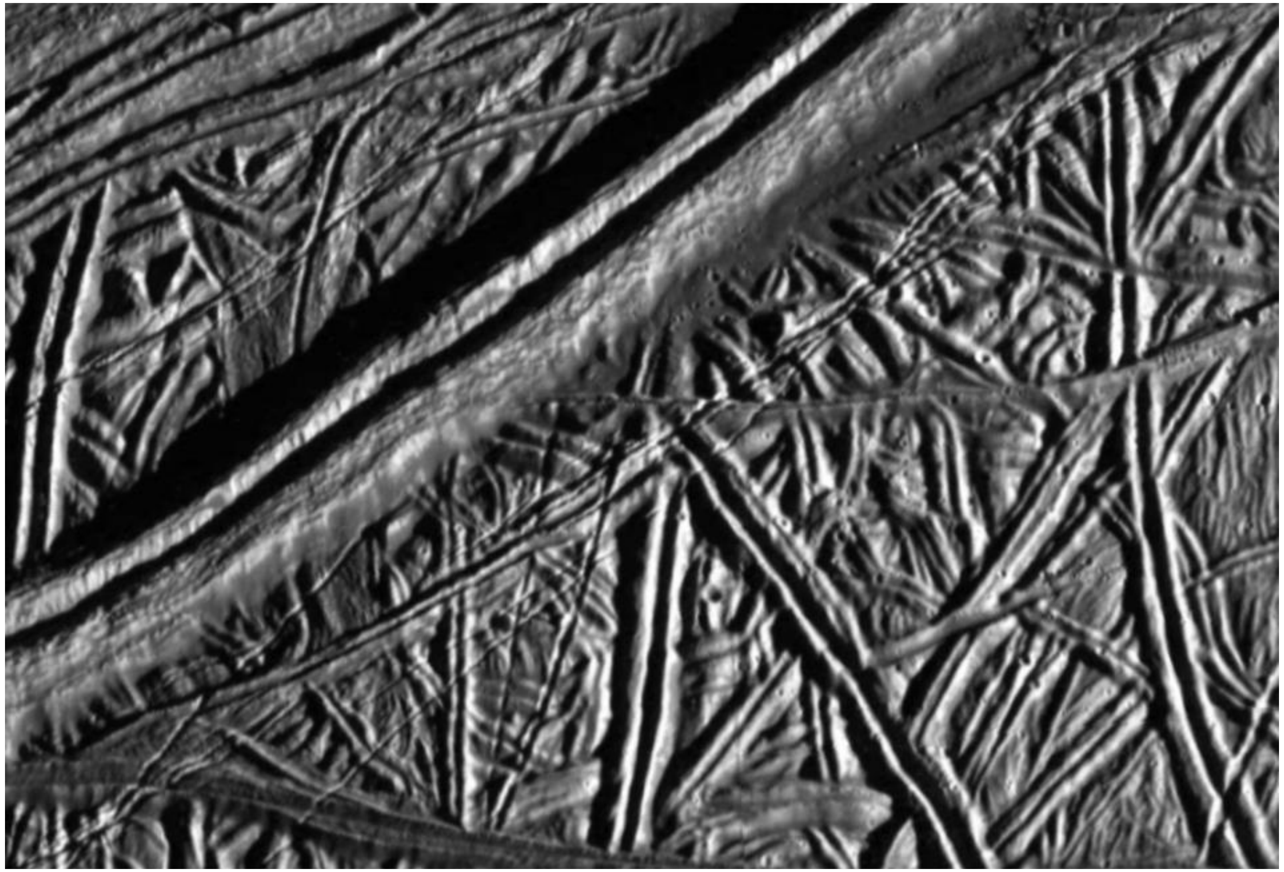
Pits and Domes

Chaotic Region

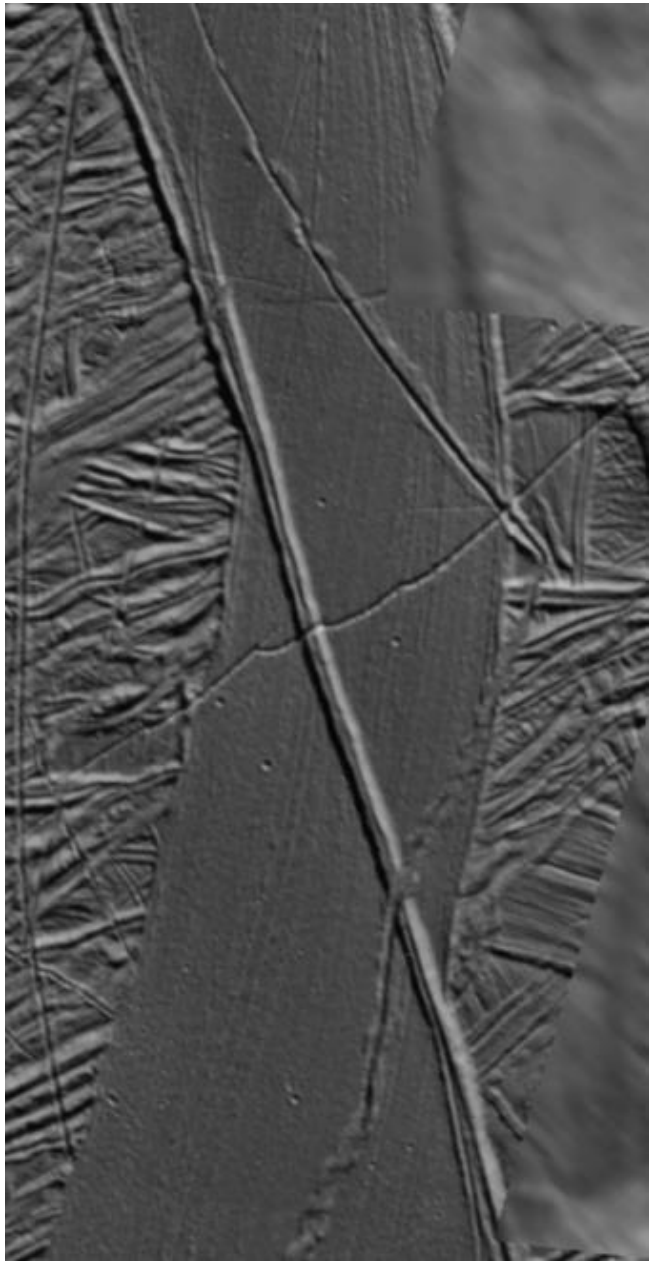


Diapirism

External Features



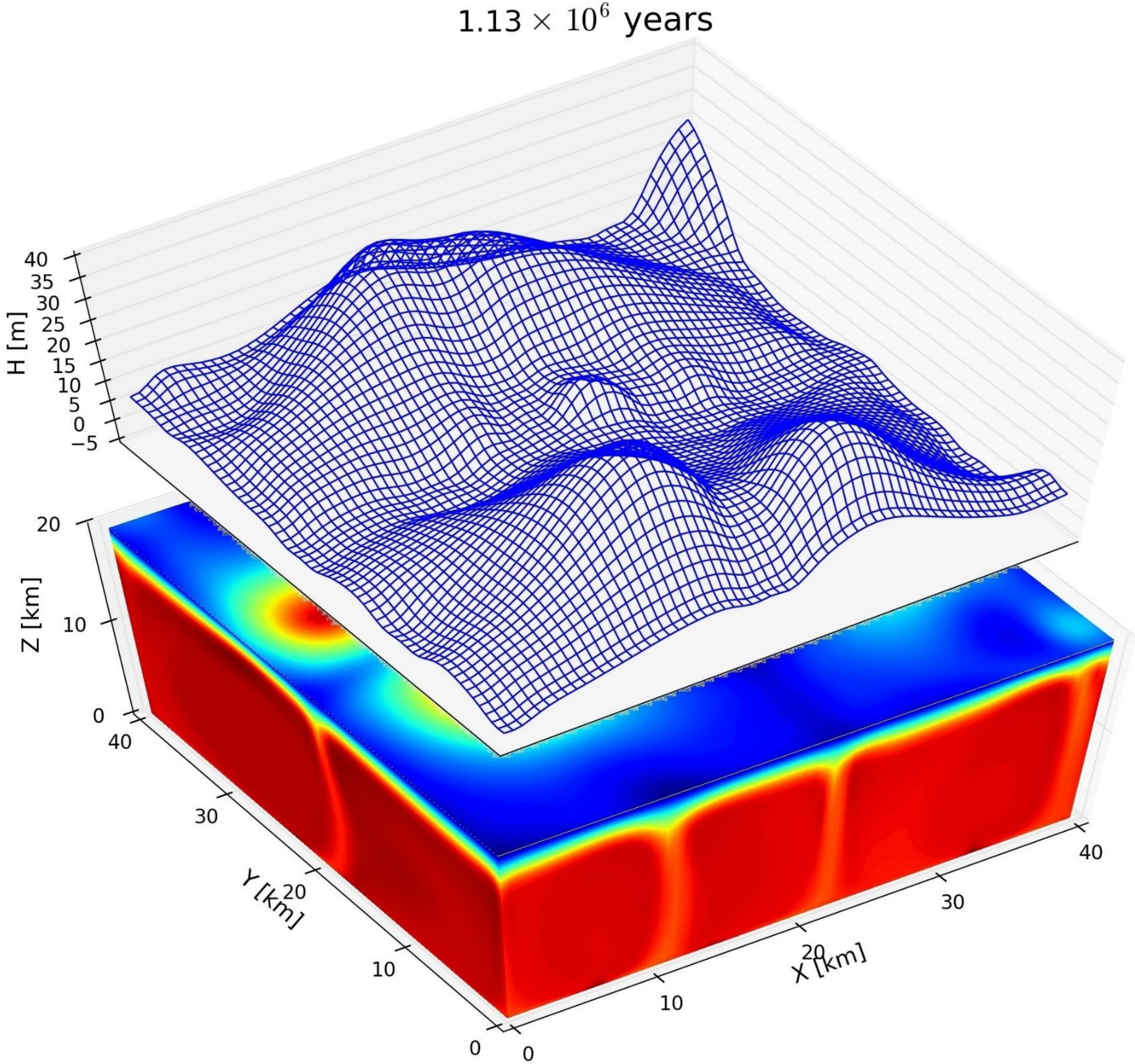
Ridges



Pull apart bands

Results –
Dynamical Topography

$$h = \frac{\sigma'_{zz}}{\rho g}$$



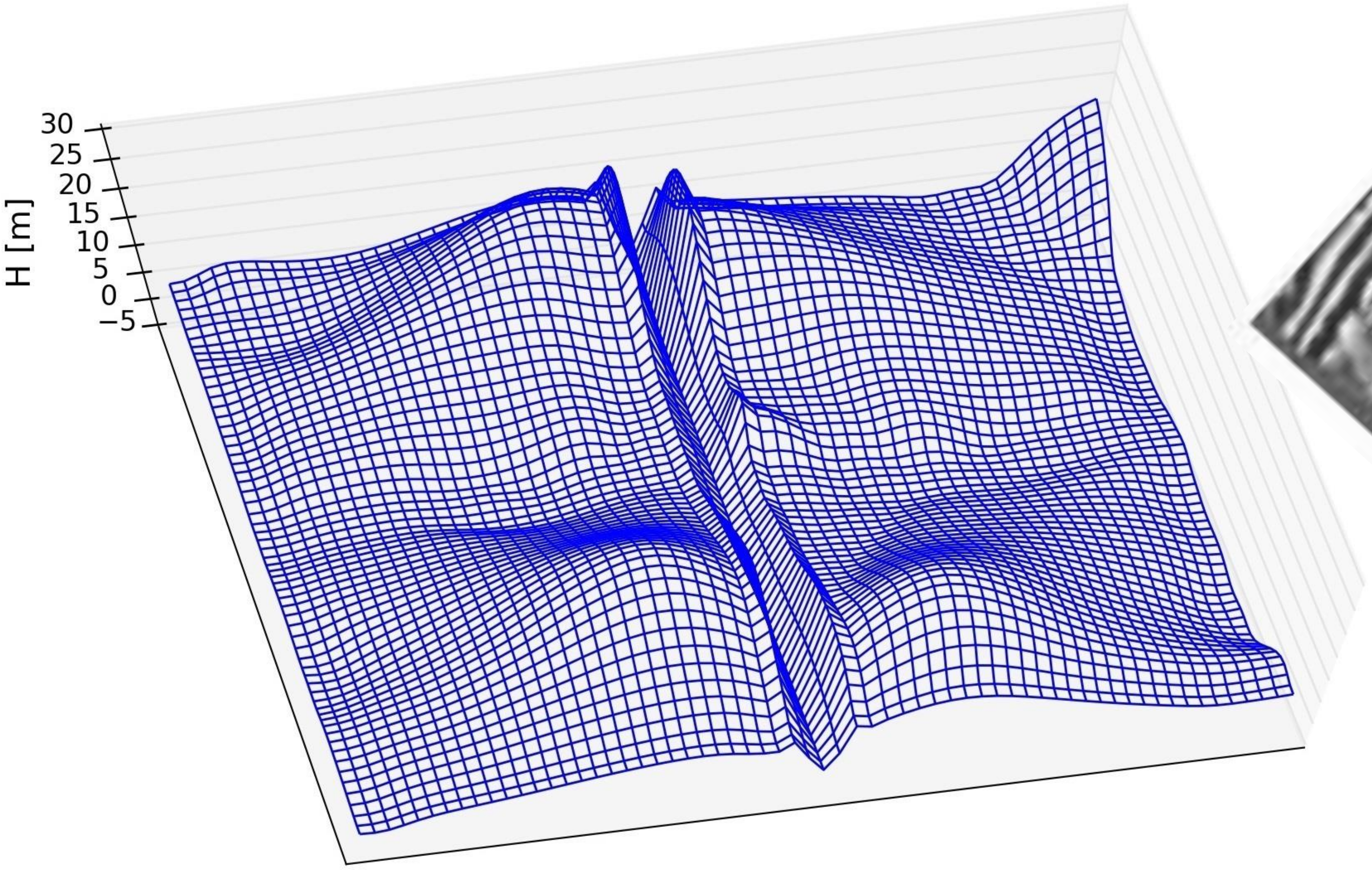
Surface Weakening and Resistance

- *Lee et al. (2005):* underestimated fracture depth for Europa (> 100m)

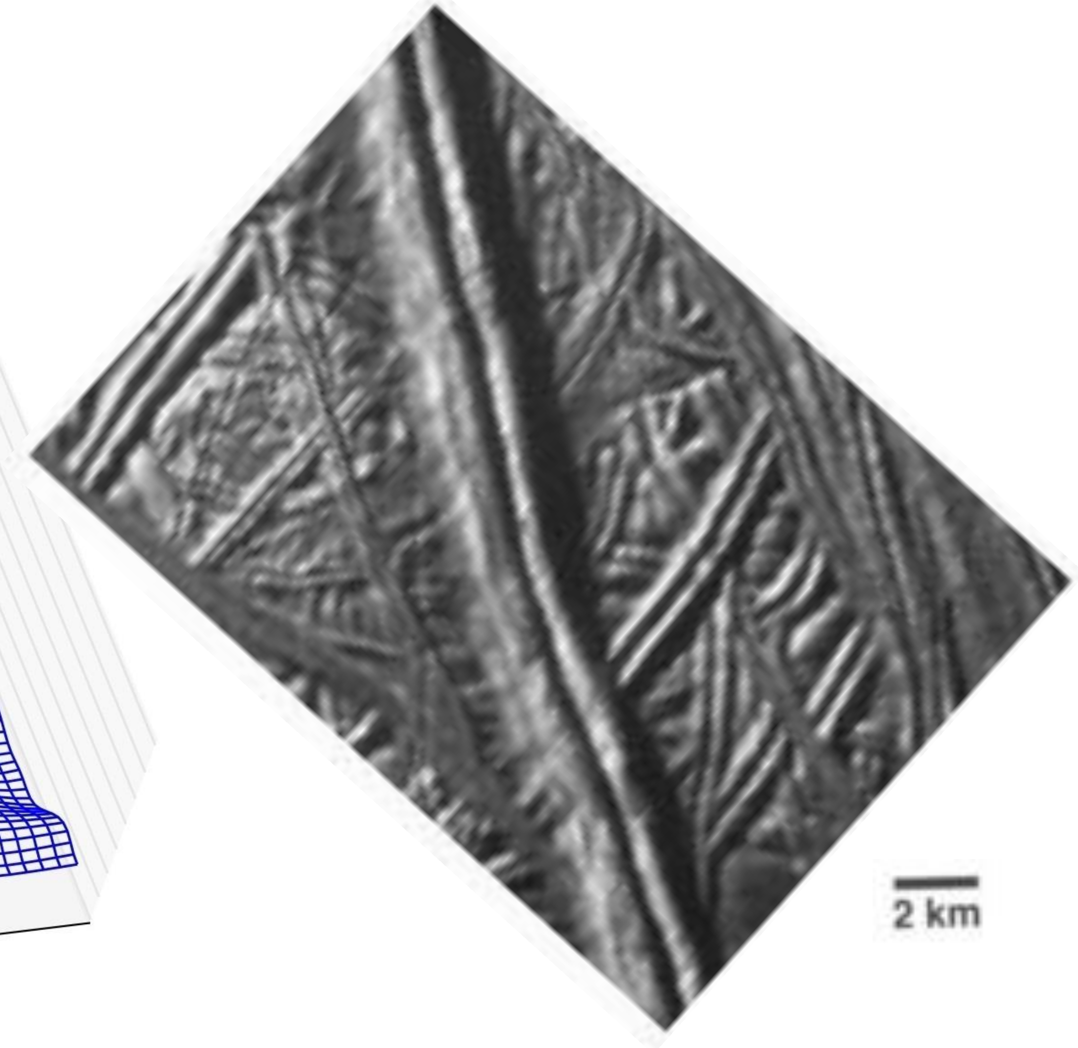
- *Han and Showman (2008)*: included surface weakening (as Zhong et al., 1998)

- *Wahr et al. (2009)*: NSR + viscoelastic body

Results: double ridges



1.13×10^6 years



Future Work

- More Modelling: different parameters
- Improve Stress: SatStress
- Global Model
- Model for Cycloidal Ridges

Thanks!