Feasibility of Earth-like plate tectonics on Europa: Implications for ocean-surface interaction

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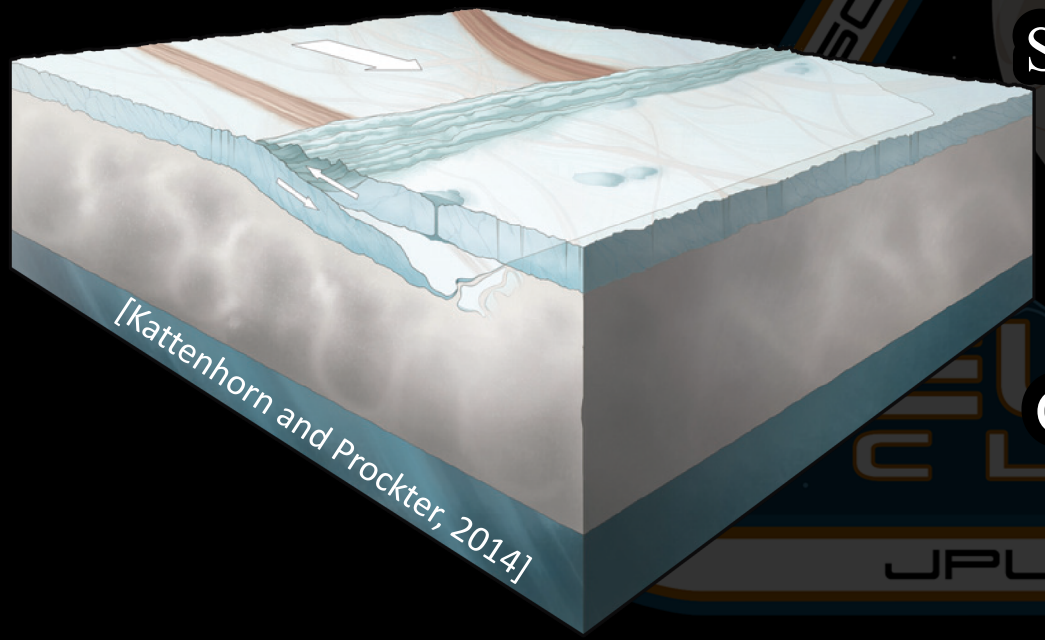
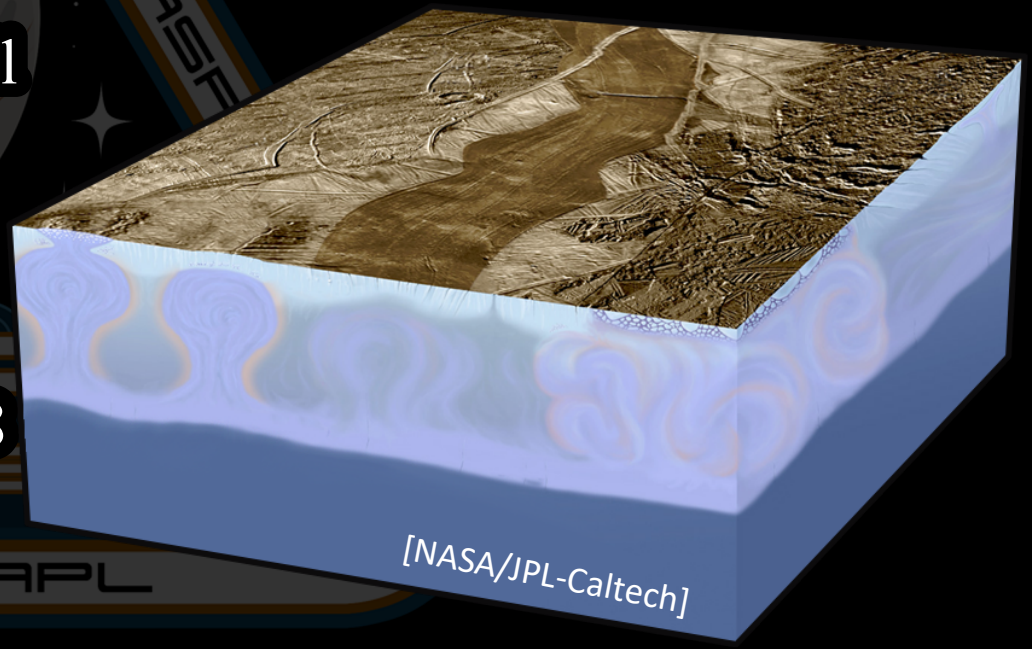
+Bob Pappalardo
+Erin Leonard

October 5th, 2018





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Outline

What is Plate Tectonics?

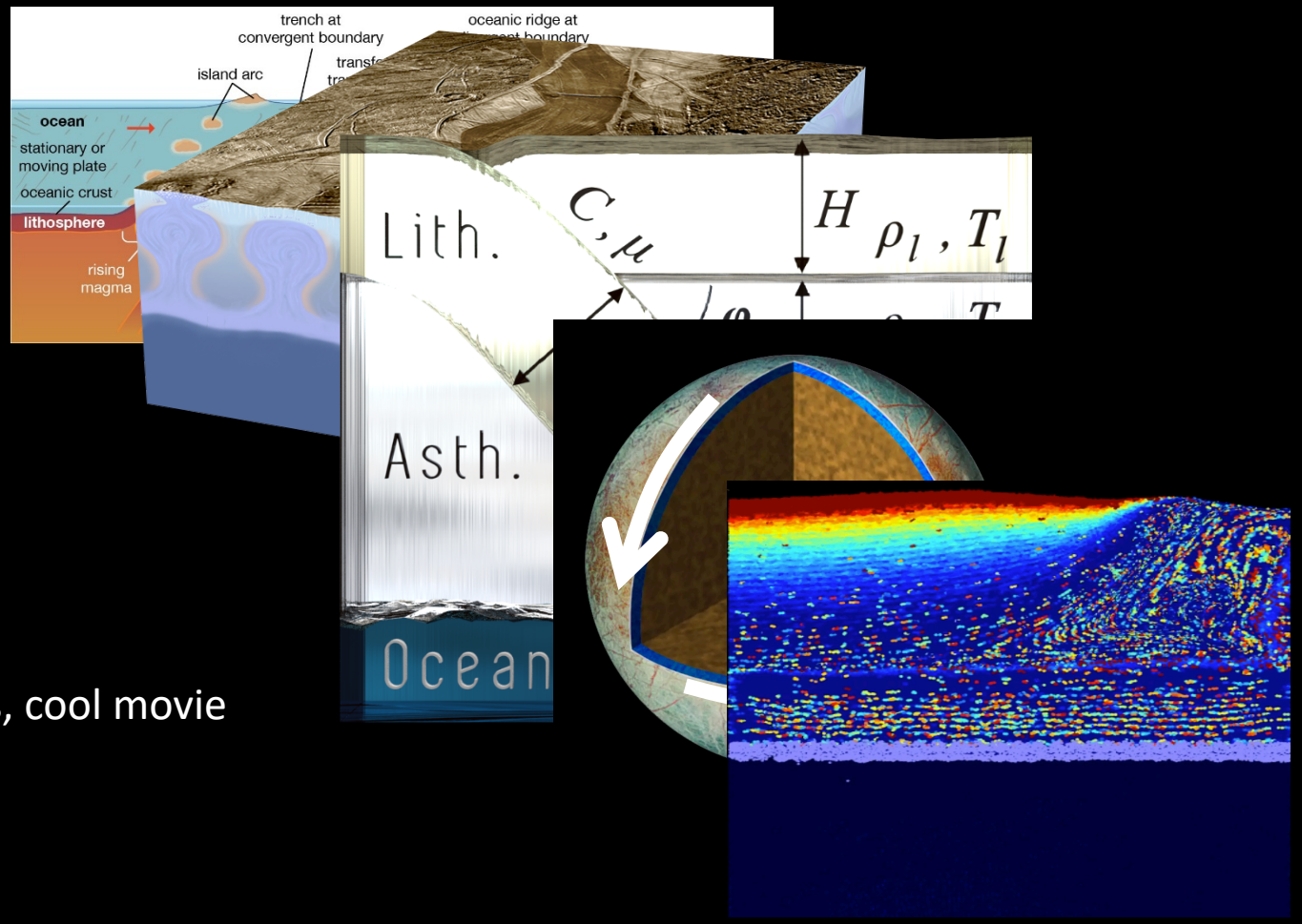
Evidence for Plate Tectonics on Europa

The force balance problem

What else might drive tectonics?

Surface-ocean interaction – Processes, timescales, cool movie

Implications for Clipper



Continental Drift

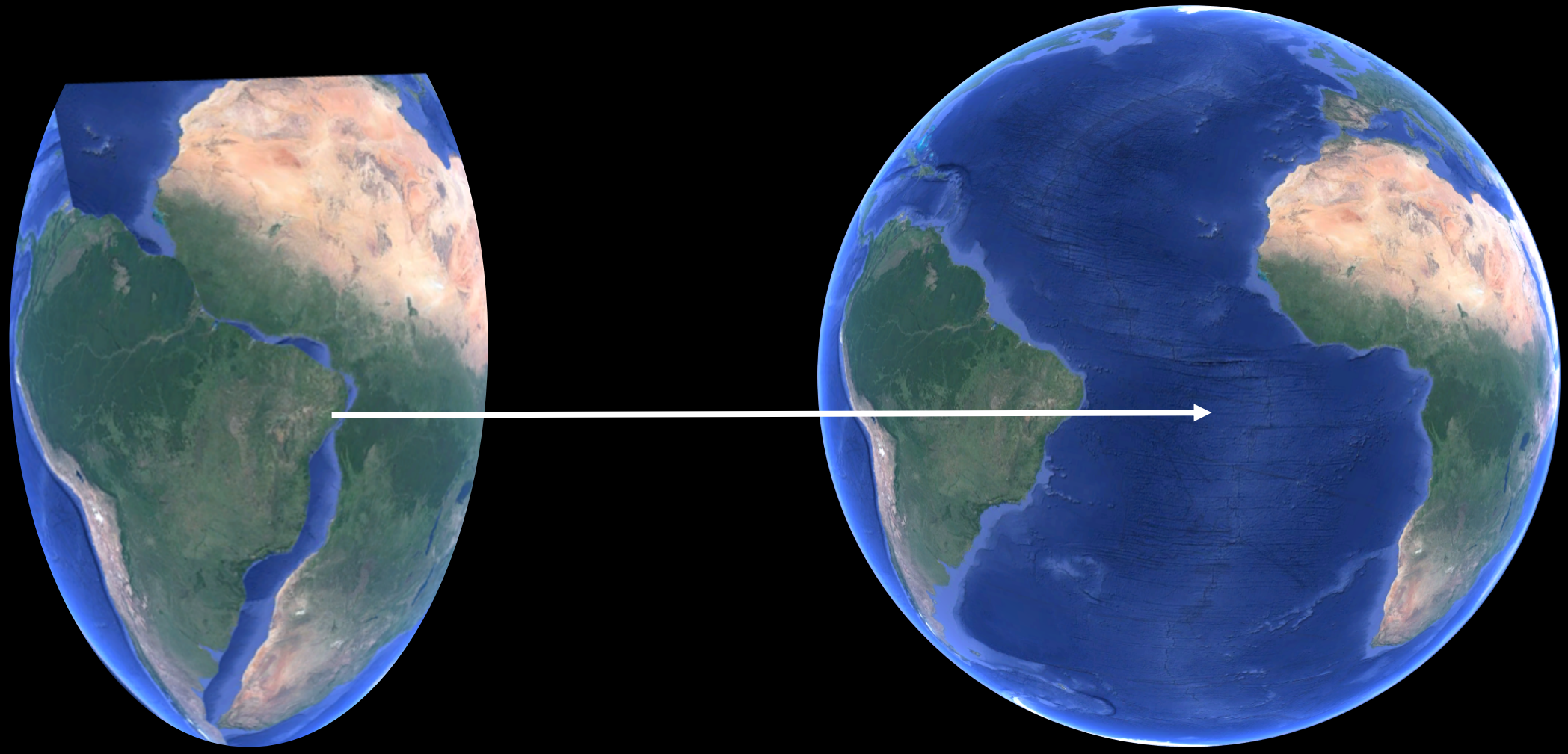
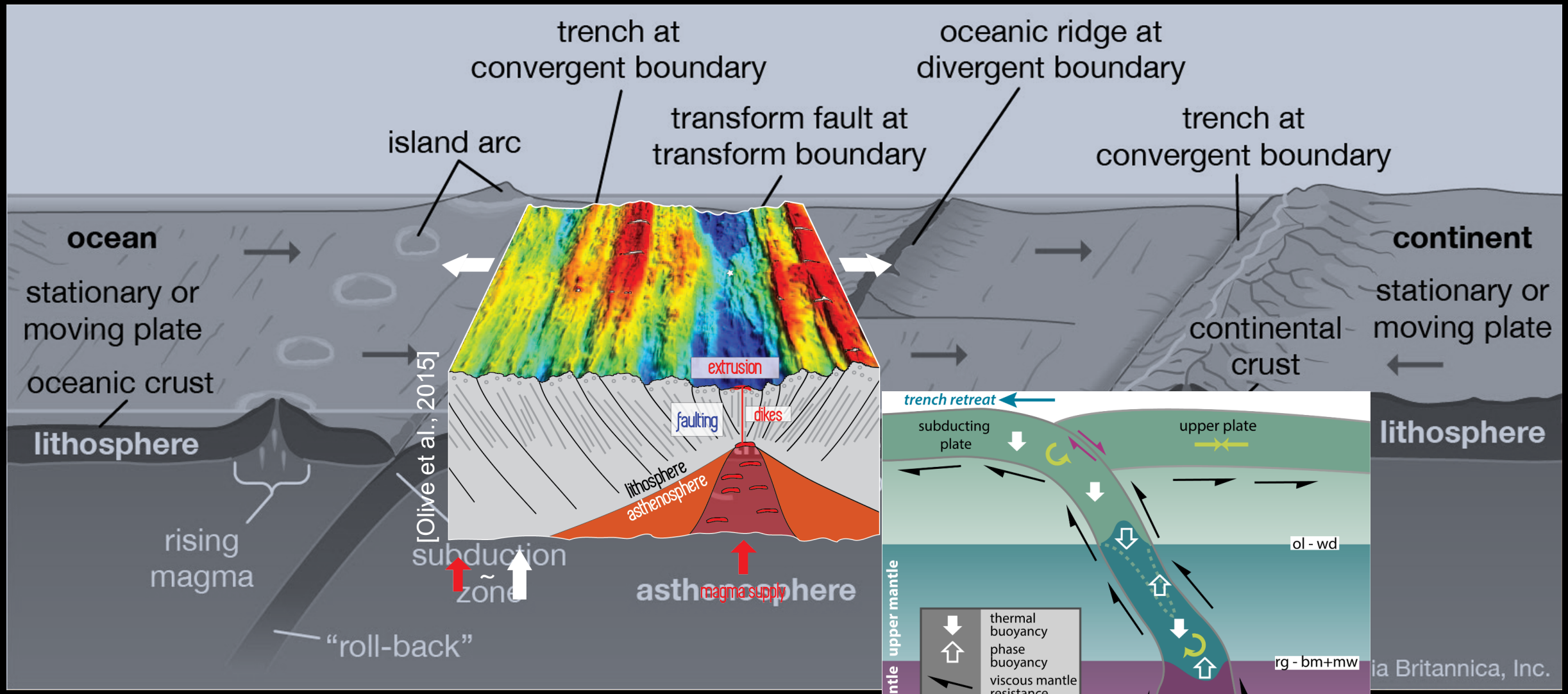
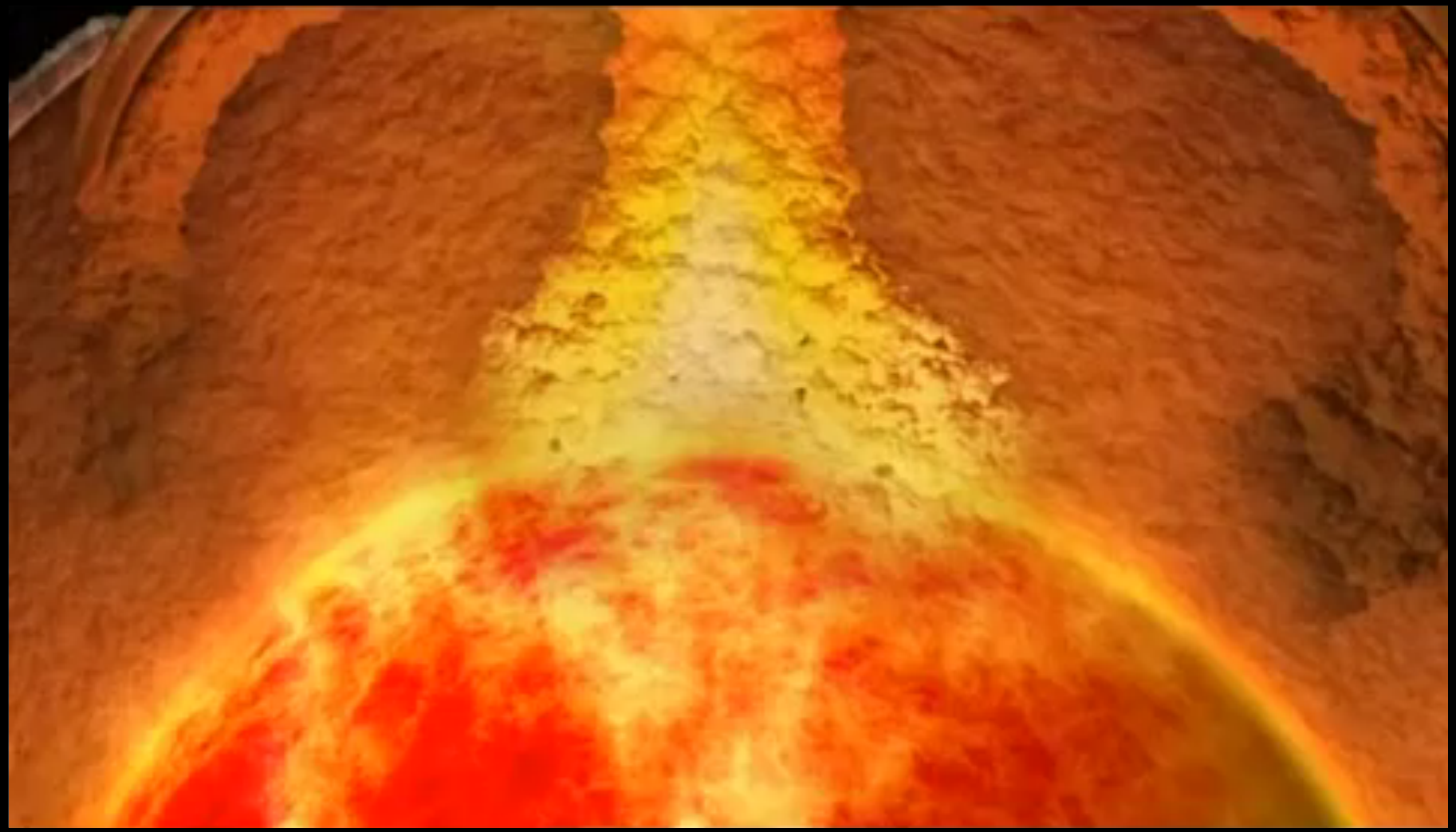


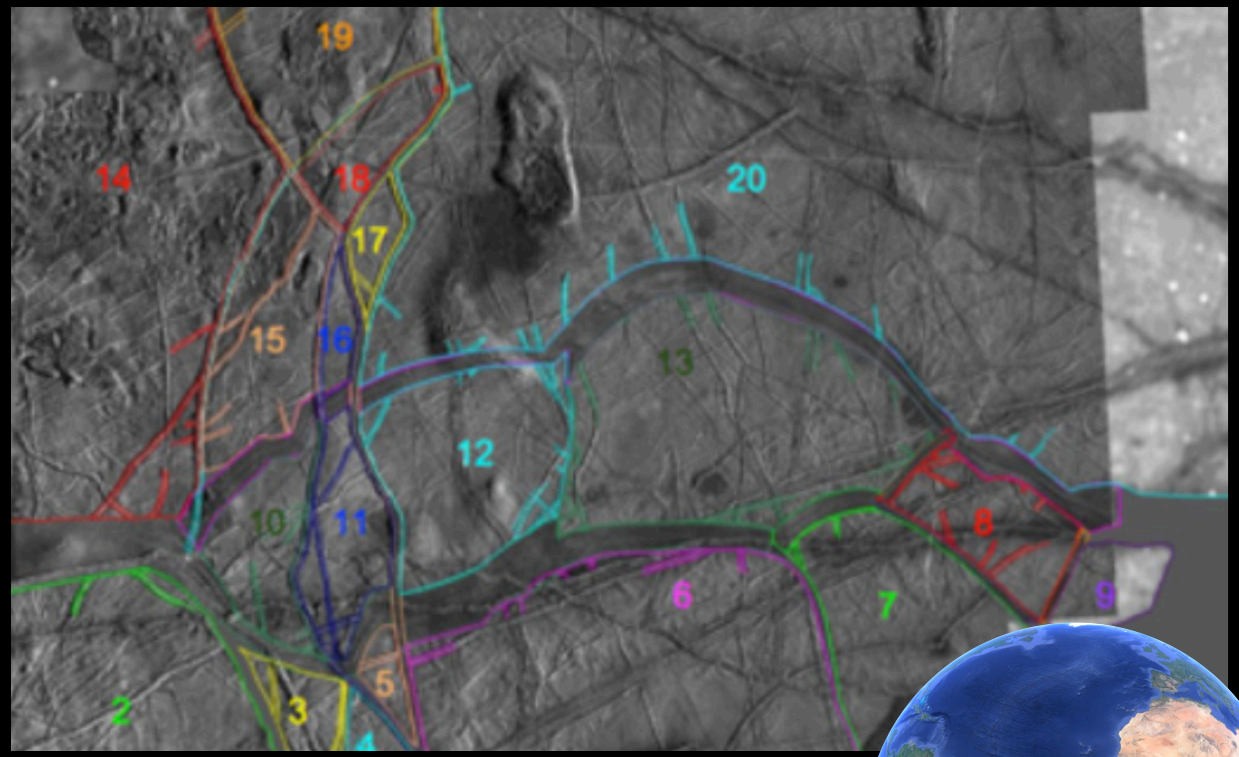
Plate Tectonics

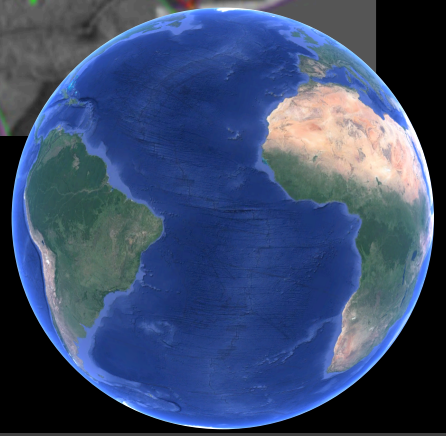


Europa’s Plate Tectonics?



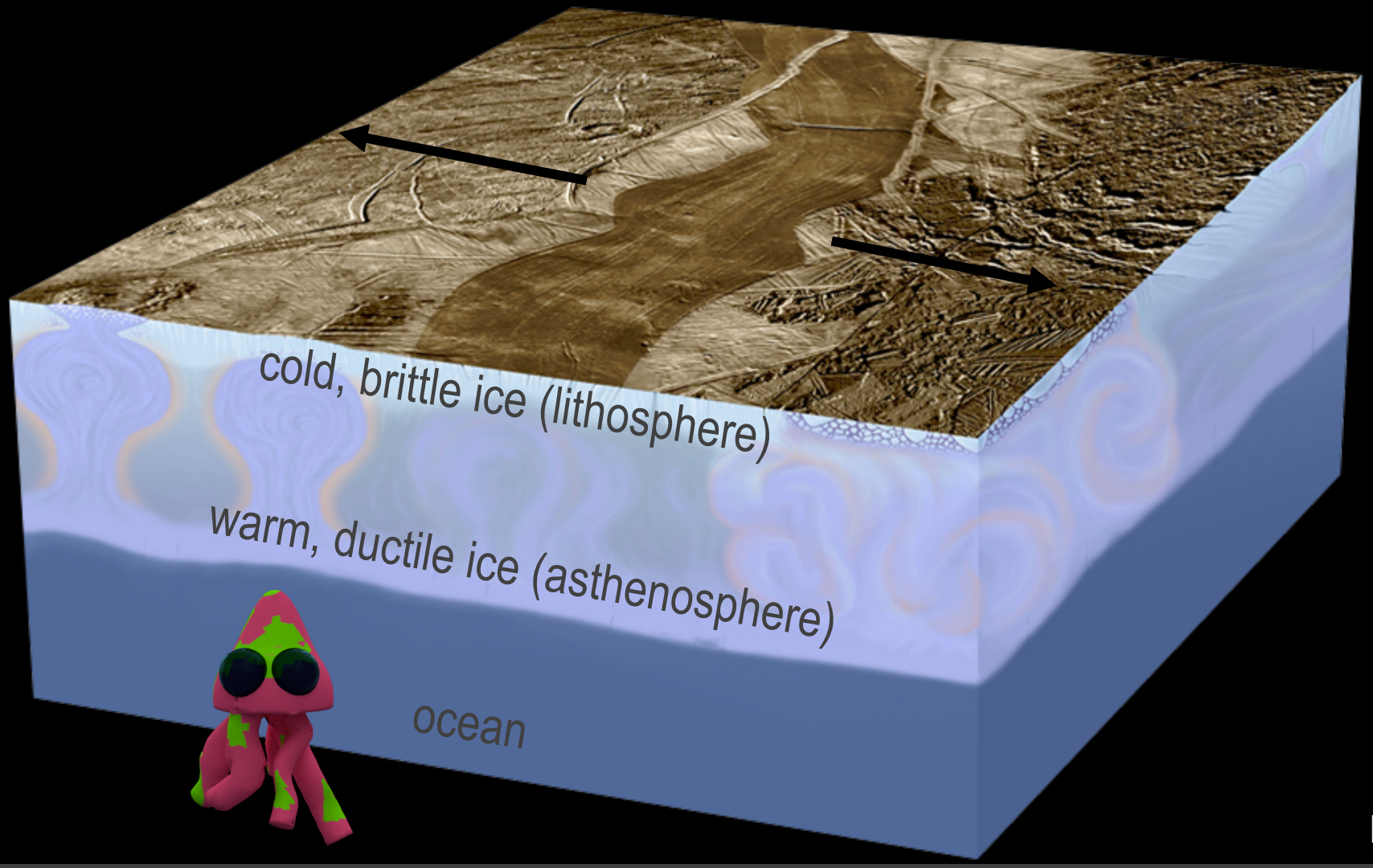
Organized Plates





[Collins et al., 2016]

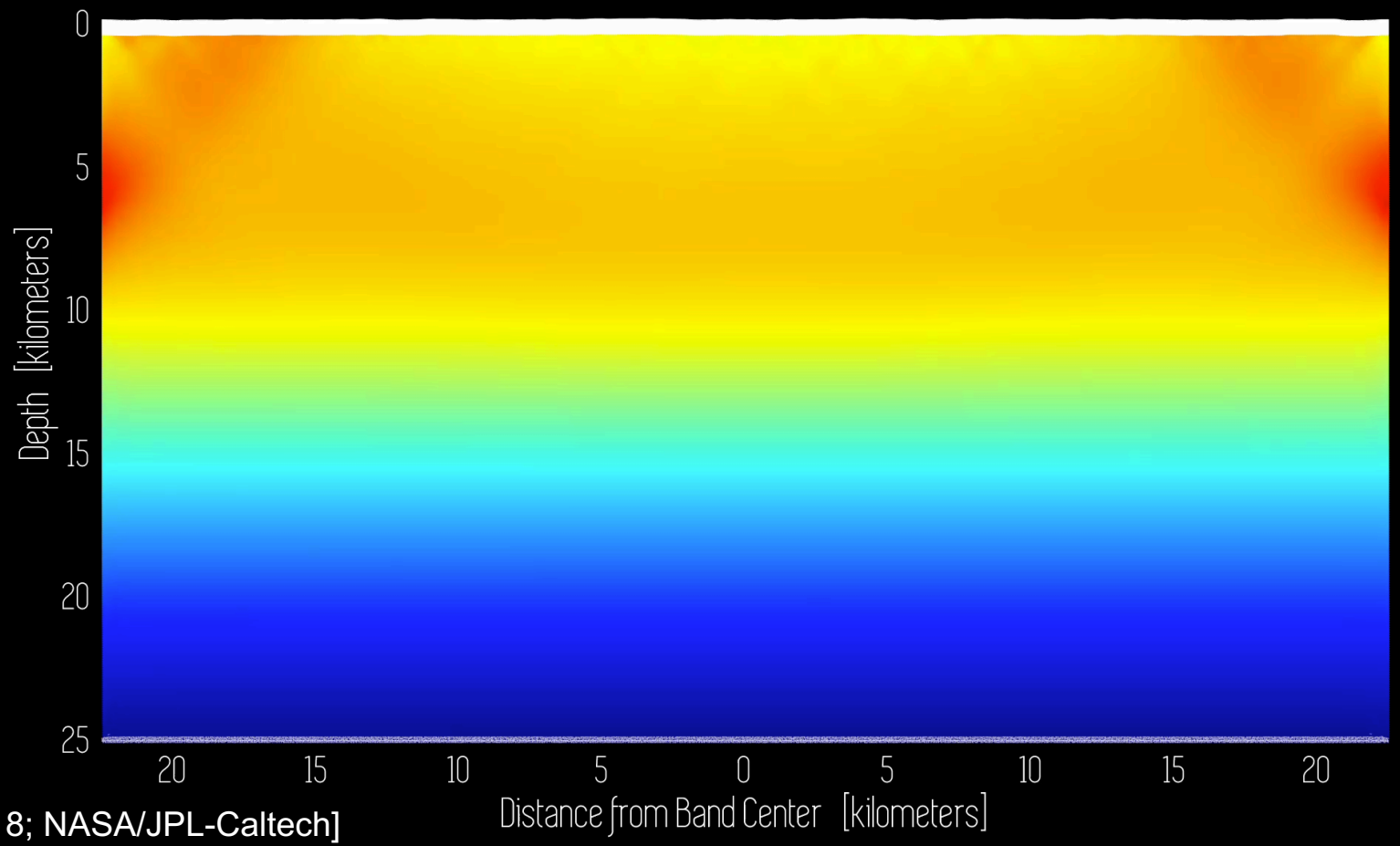
Extension



[NASA/JPL-Caltech]

Extension

6 Thousand Years

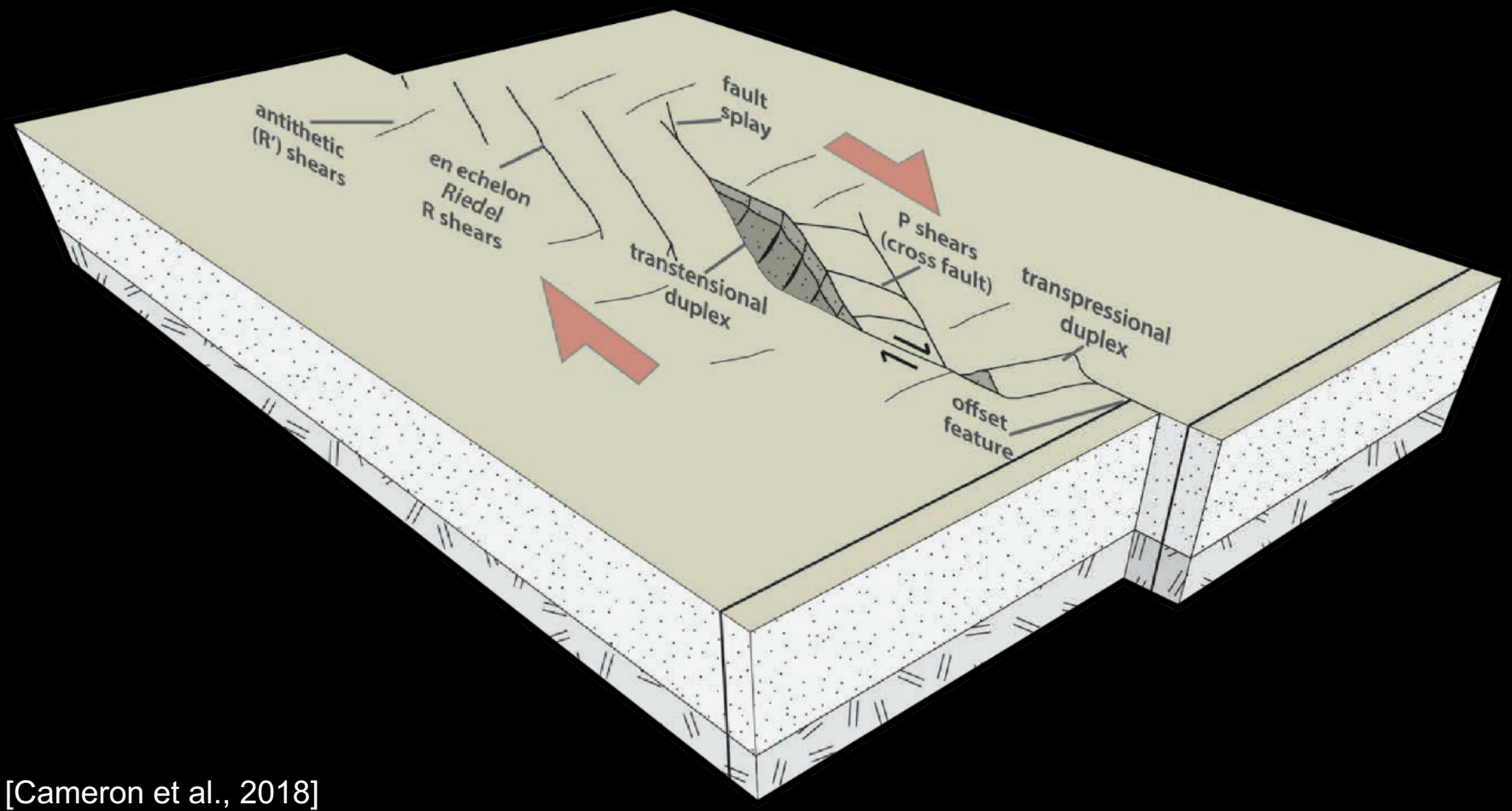


More rigid ice

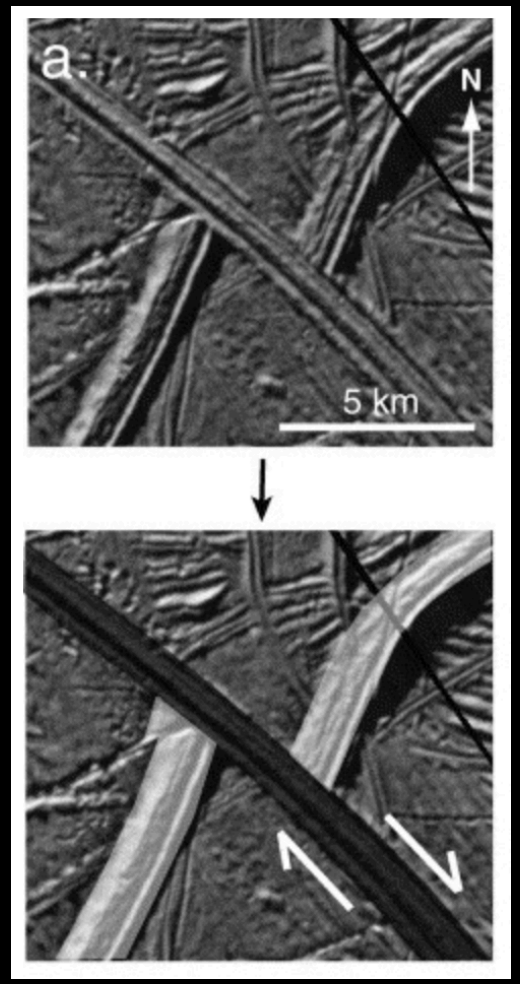
Less rigid ice

[Howell and Pappalardo, 2018; NASA/JPL-Caltech]

Strike-Slip

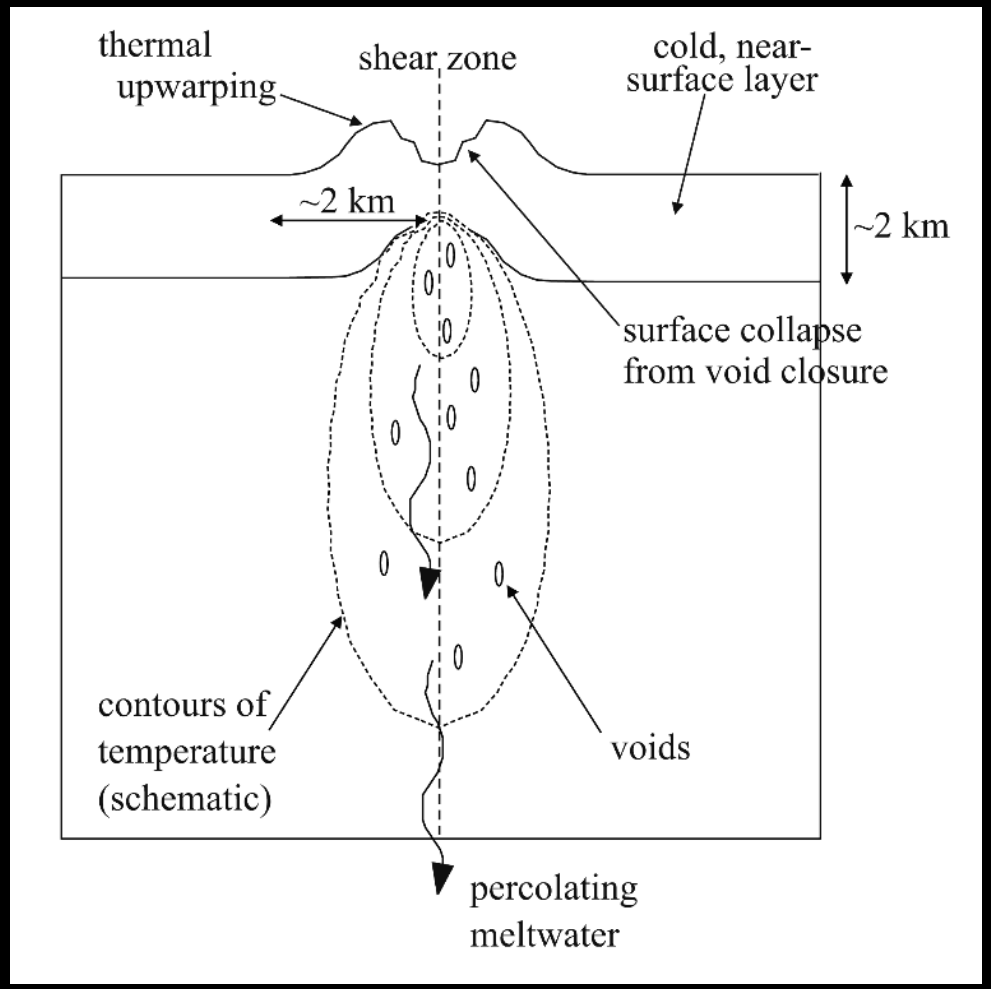


[Cameron et al., 2018]

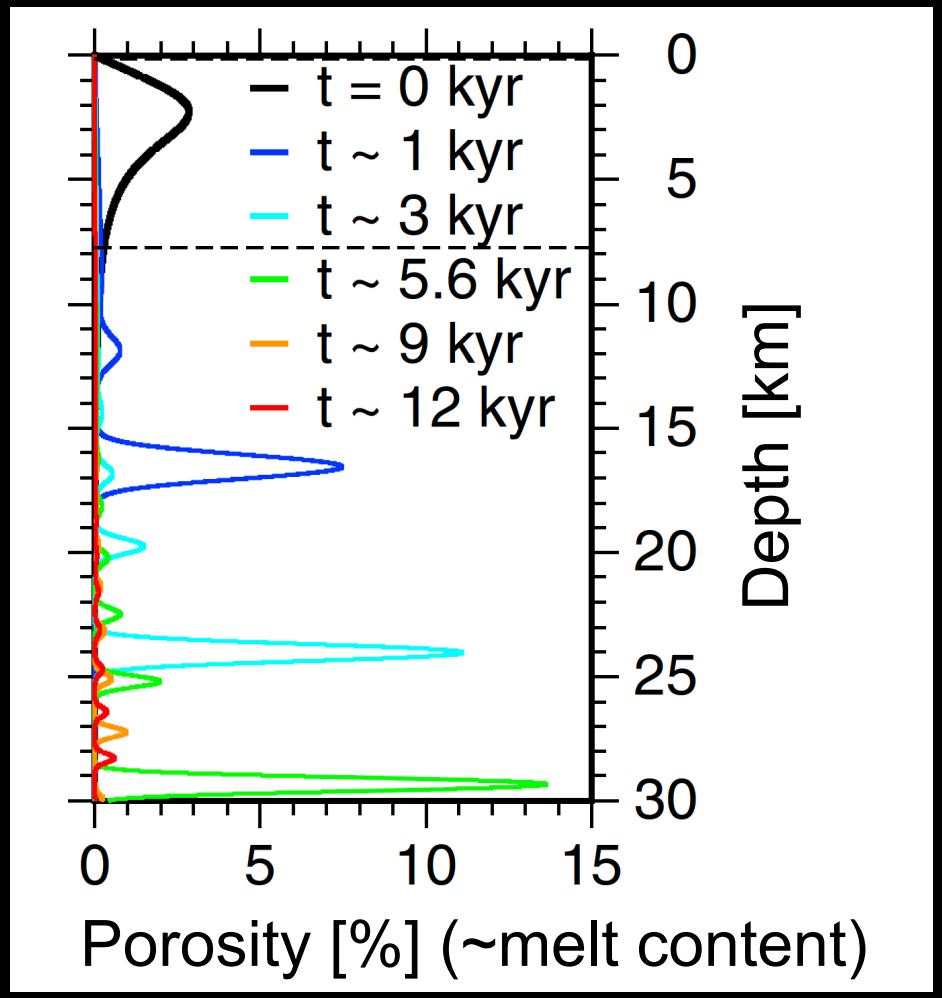


[Kattenhorn, 2004]

Strike-Slip

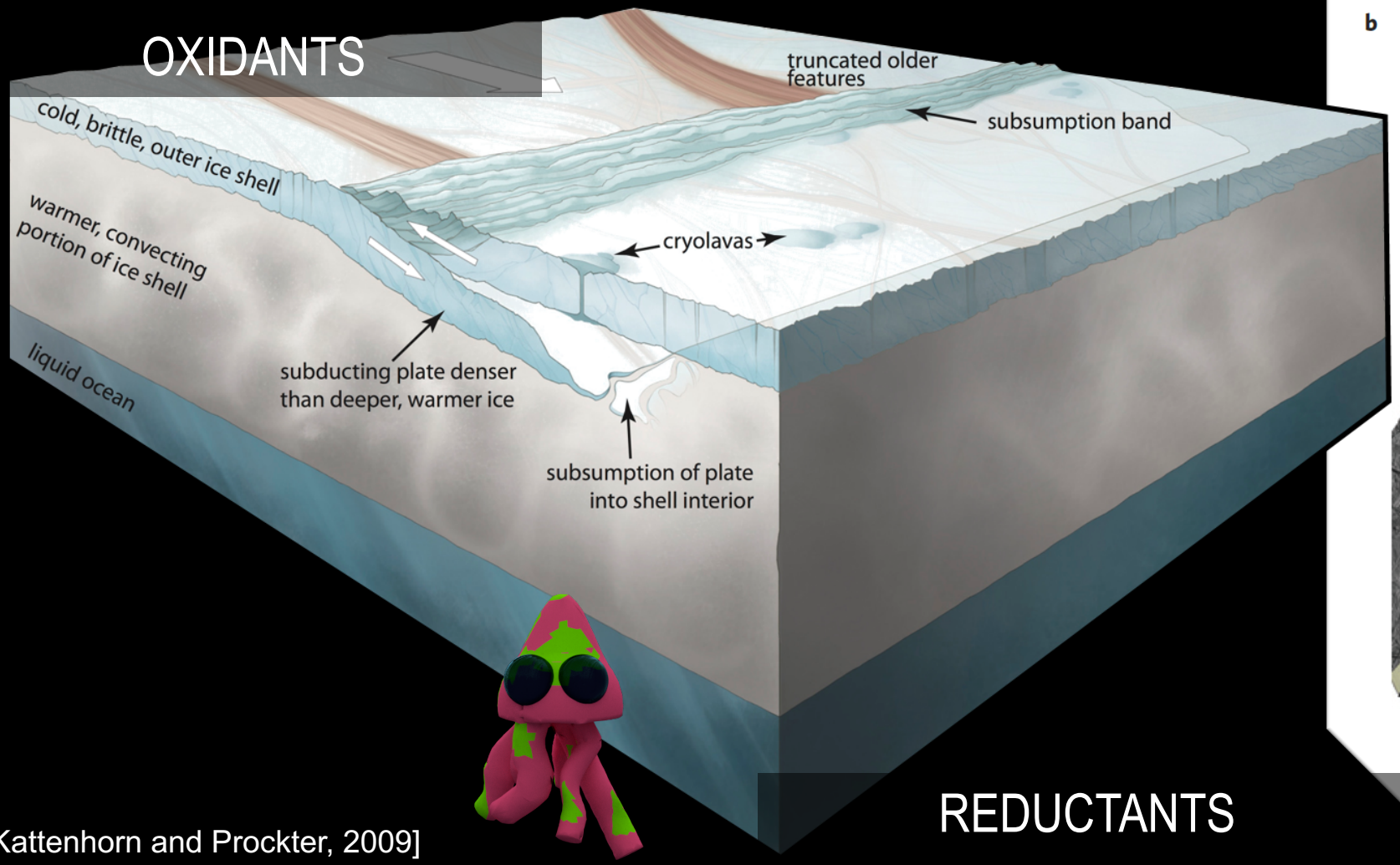


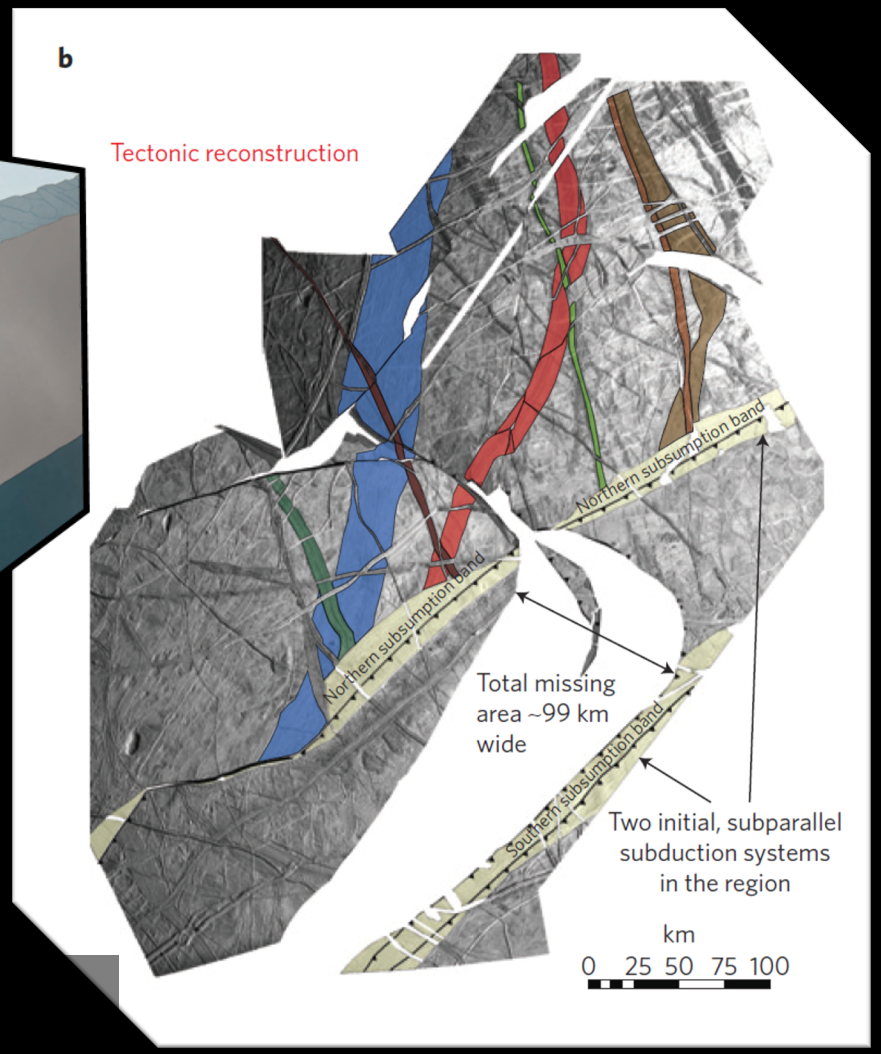
[Nimmo and Gaidos, 2002]



[Kalousová et al., 2014]

Subduction?

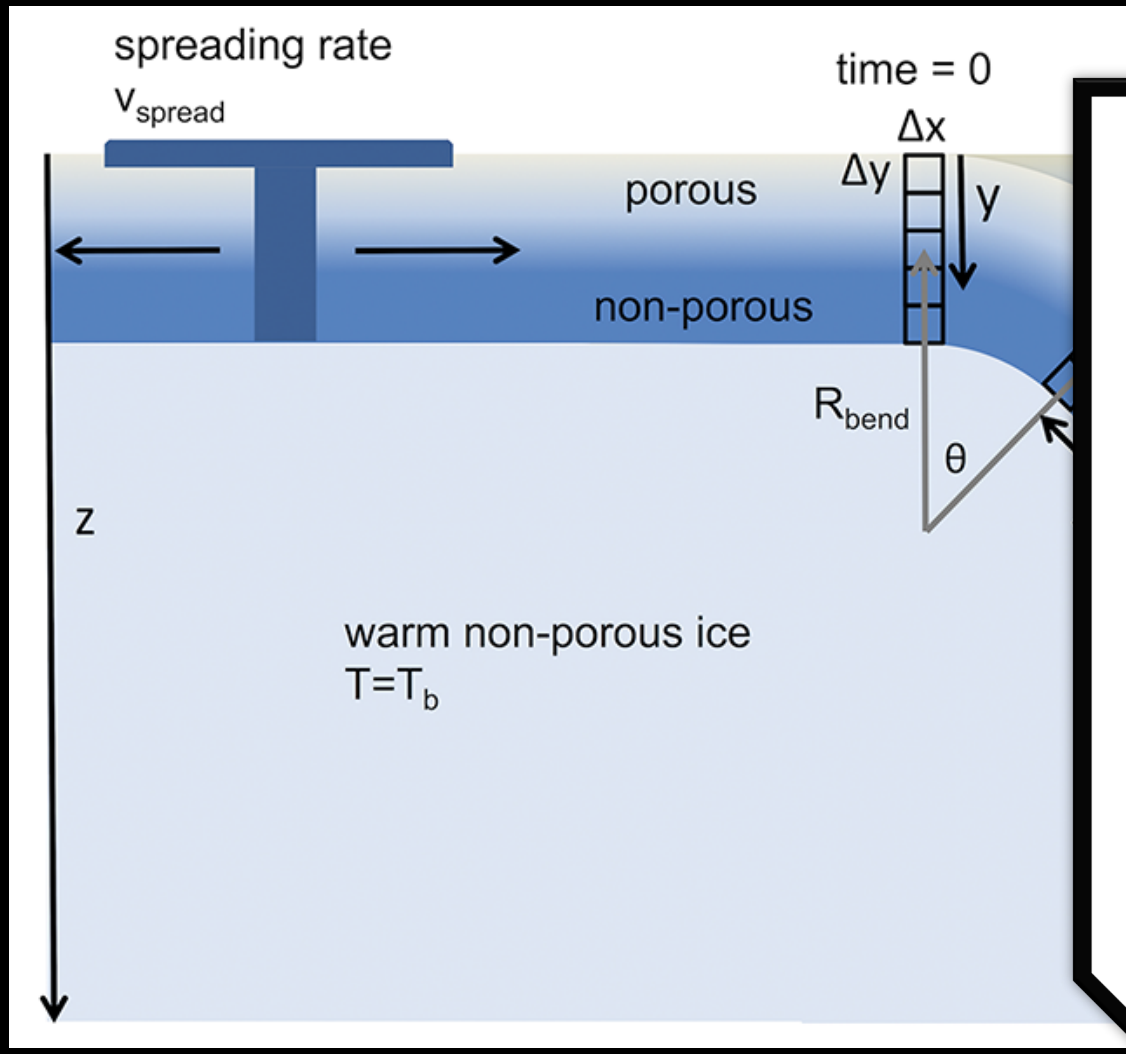




[Kattenhorn and Prockter, 2009]

Subduction

[Johnson et al., 2017]



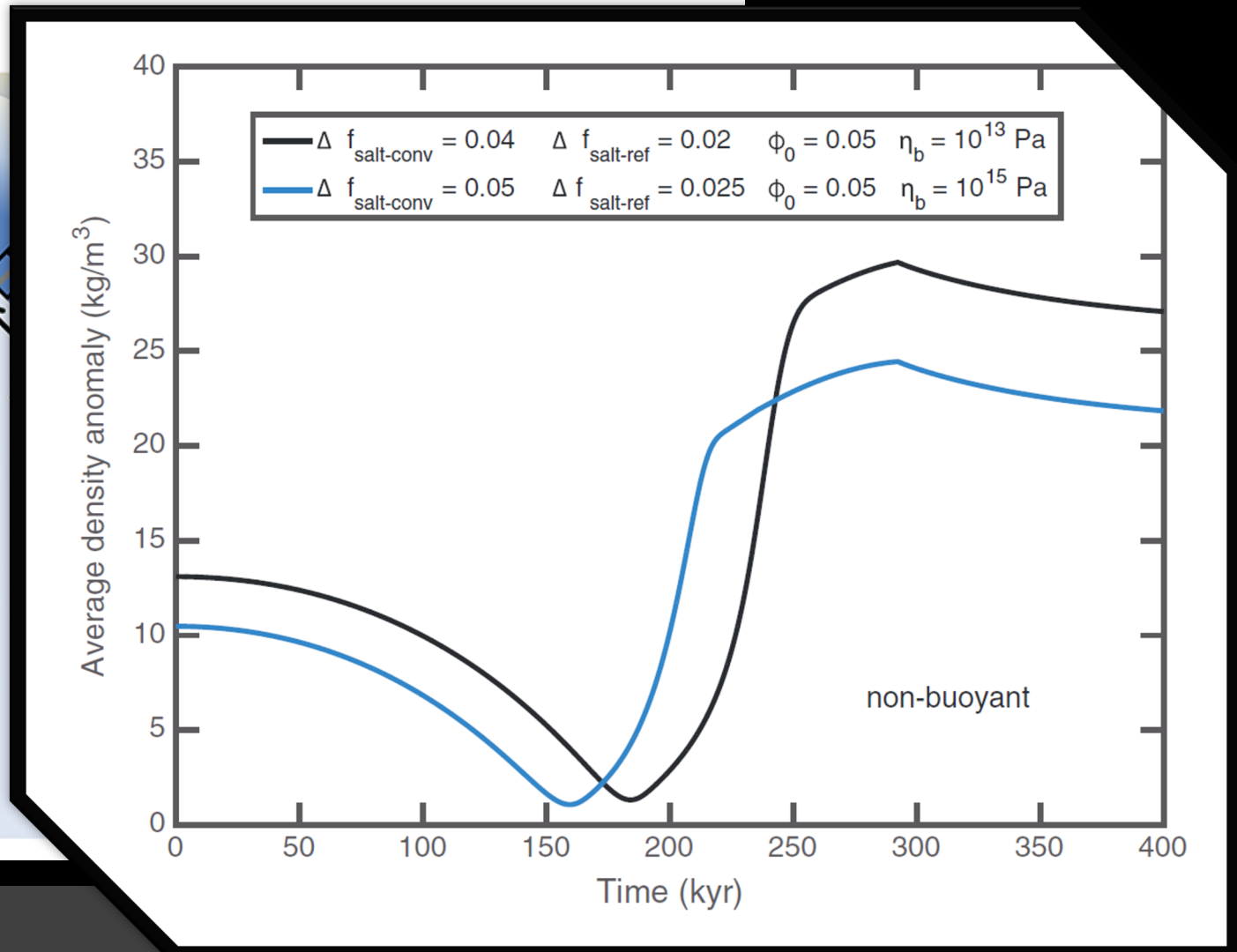
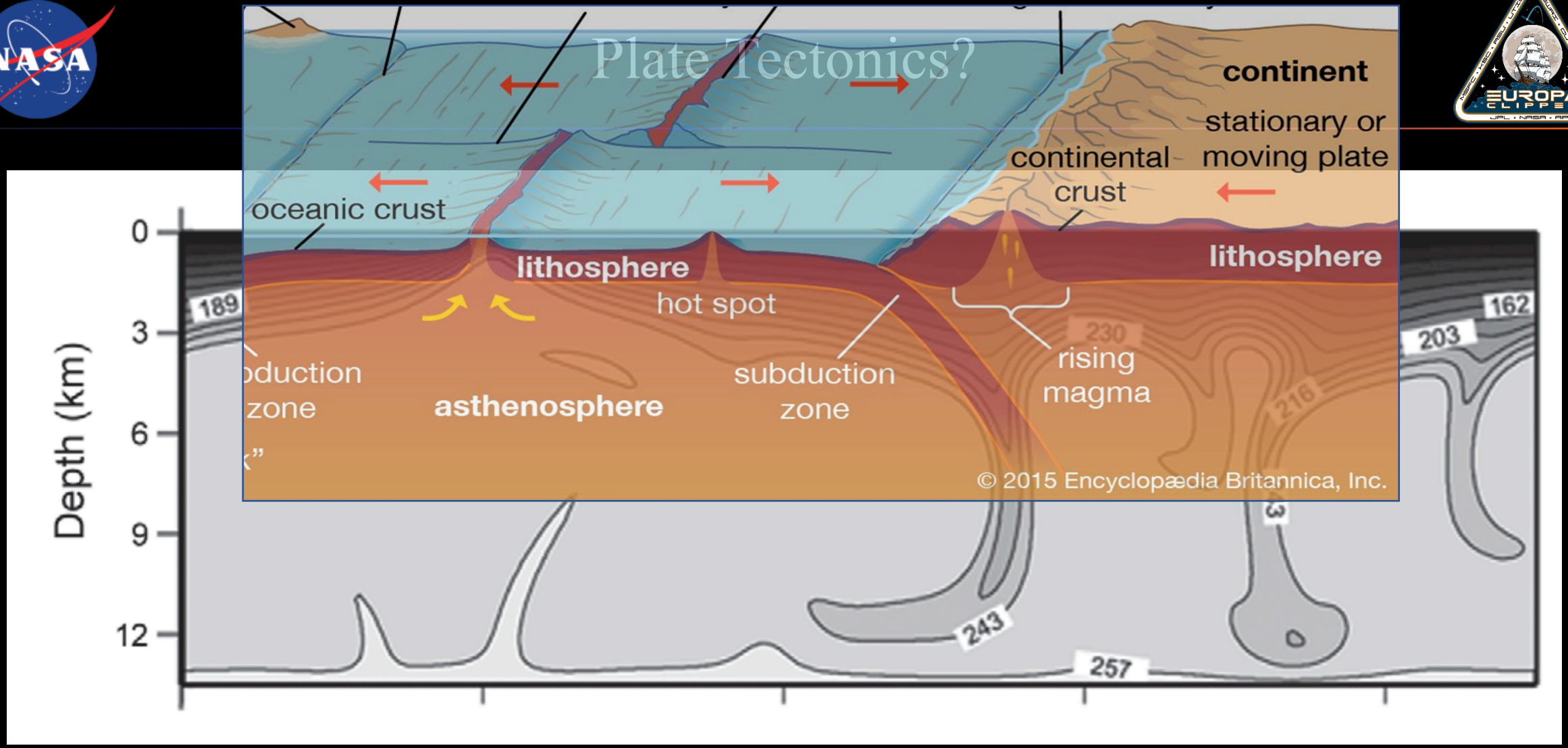


Plate Tectonics?



[Barr and Showman, *Europa*]

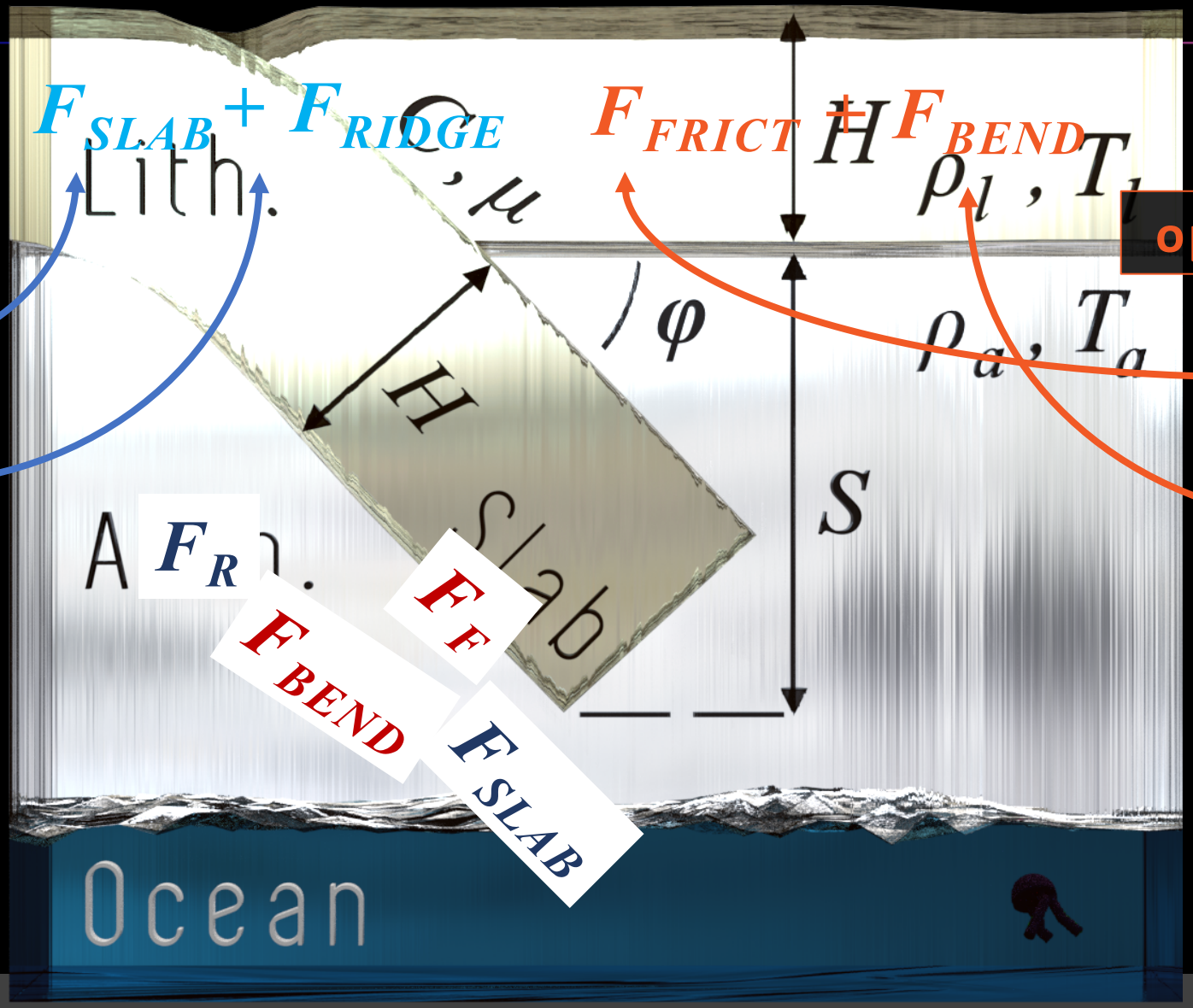
Materials Can Resist Subduction

Why doesn't the hammer subduct through the air inside the bottle?

7 lbf hammer with 3 cm² contact area ~100 kPa
(~ diurnal tidal stress on Europa)xa
(~3 km of subducting slab @ 40 kg/m³)

Yield Strength of HPDE is 15 MPa
(~ 10 km thick Europa lithosphere)
(~400 km of subducting slab @ 40 kg/m³)

Requirement for Subduction



driving forces

slab pull

ridge push?

opposing forces

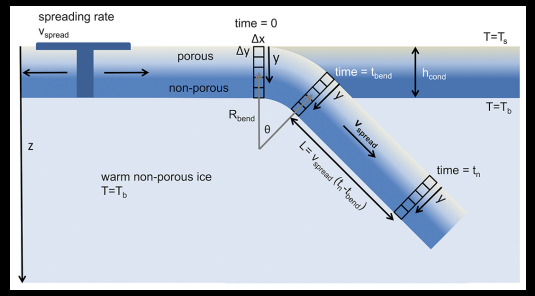
yield strength of the lithosphere

Viscous bending

Requirement for Subduction

$$F_{SLAB} = \Delta\rho g L H$$

L = length of subducted slab (along-slab)
H = slab/lithosphere thickness



$$\rho = \left\{\alpha\Delta T\left[(1-f_{SALT})\rho_0 + f_{SALT}\rho_{SALT}\right]\right\}(1-\phi)$$

Φ = Porosity

$$F_{BAND} = g\Delta\rho\frac{H^2}{2}$$

C = cohesion μ = coefficient of friction

$$F_{FRICT} = \frac{CH + \tfrac{1}{2}\mu\rho_l g H^3}{\sin\theta\cos\theta - \mu\sin^2\theta}$$

θ = subduction zone dip

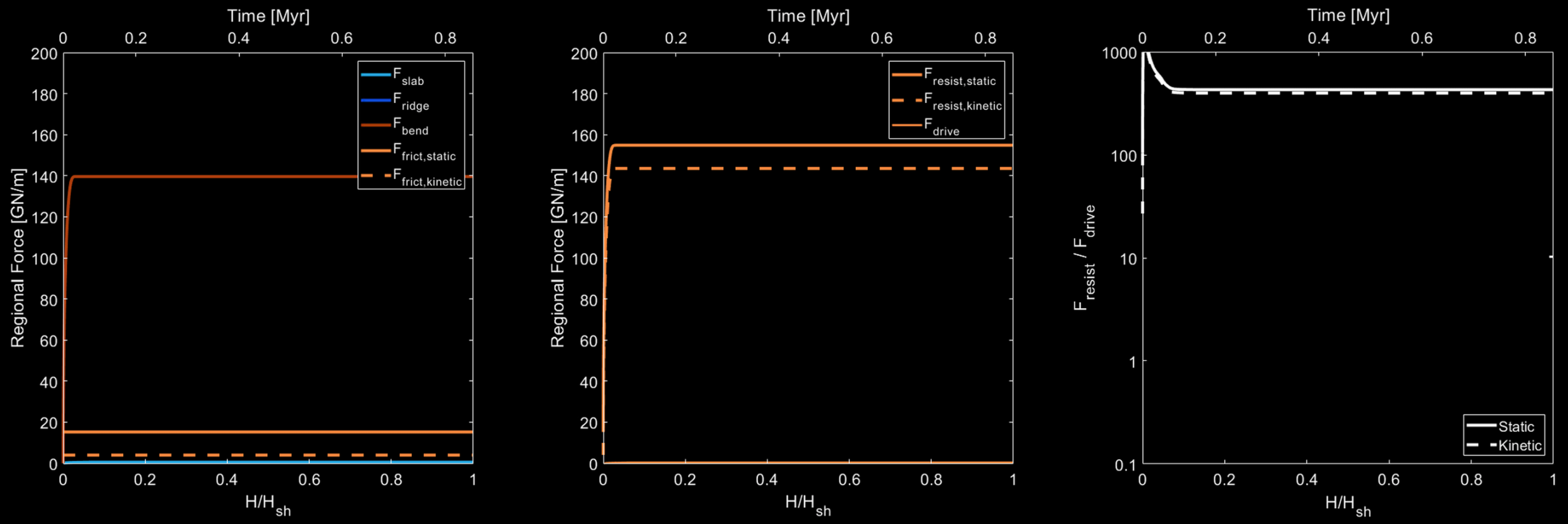
η = viscosity

$$F_{BEND} = \frac{2}{3}\left(\frac{H}{r}\right)^3 \eta u$$

r = radius of bending

Force Balance Results

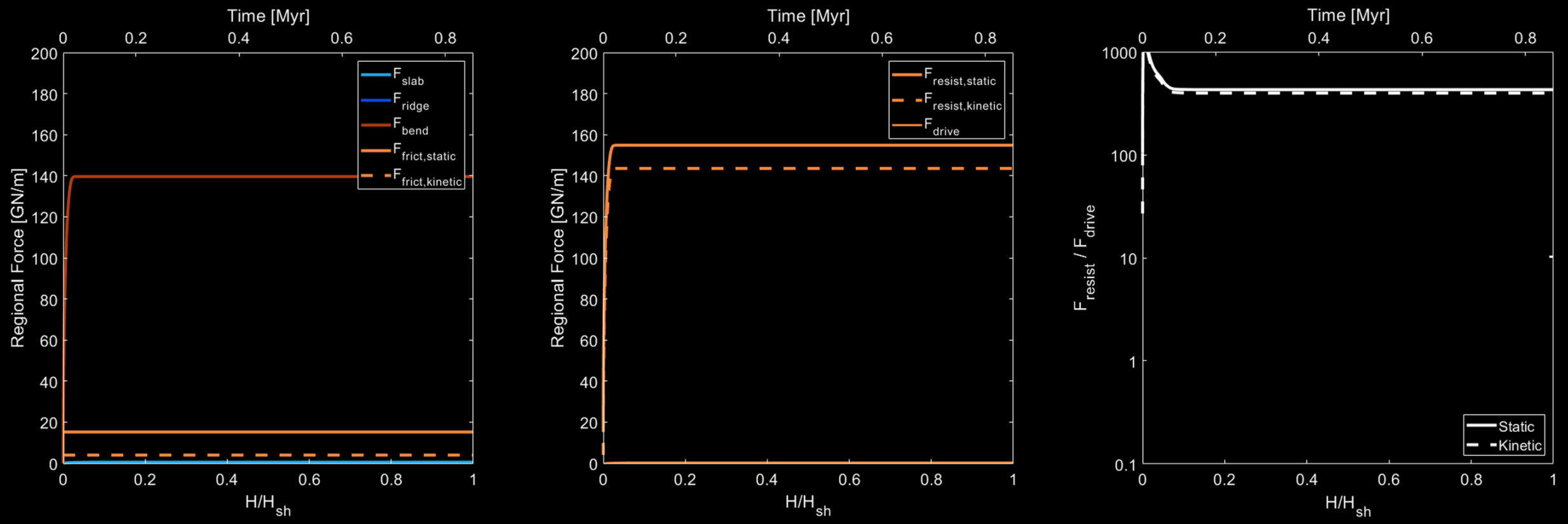
Europa: ϕ_0 = 0.10, f_{salt} = 0.00, u = 40 km/Myr, H = 2.5 km, $\eta_0 = 10^{13}$ Pa s



[Howell and Pappalardo, *in revision*]

Force Balance Results

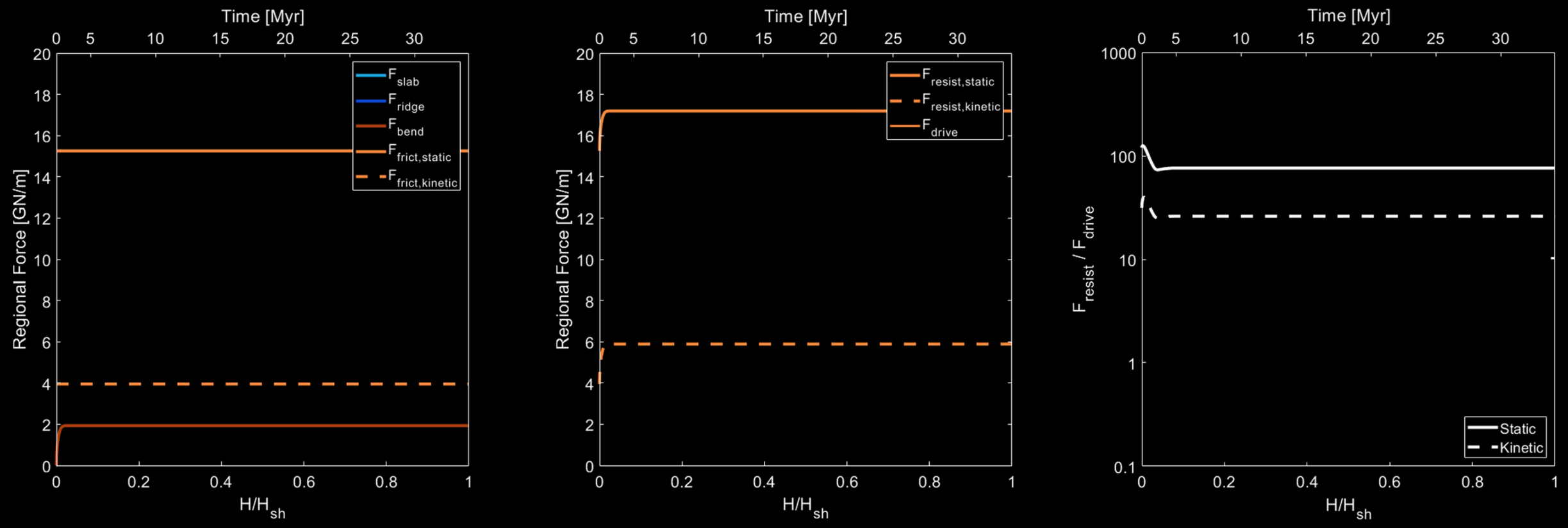
Europa: ϕ_0 = 0.10, f_{salt} = 0.00, u = 40 km/Myr, H = 2.5 km, $\eta_0 = 10^{13}$ Pa s



[Howell and Pappalardo, *in revision*]

Force Balance Results

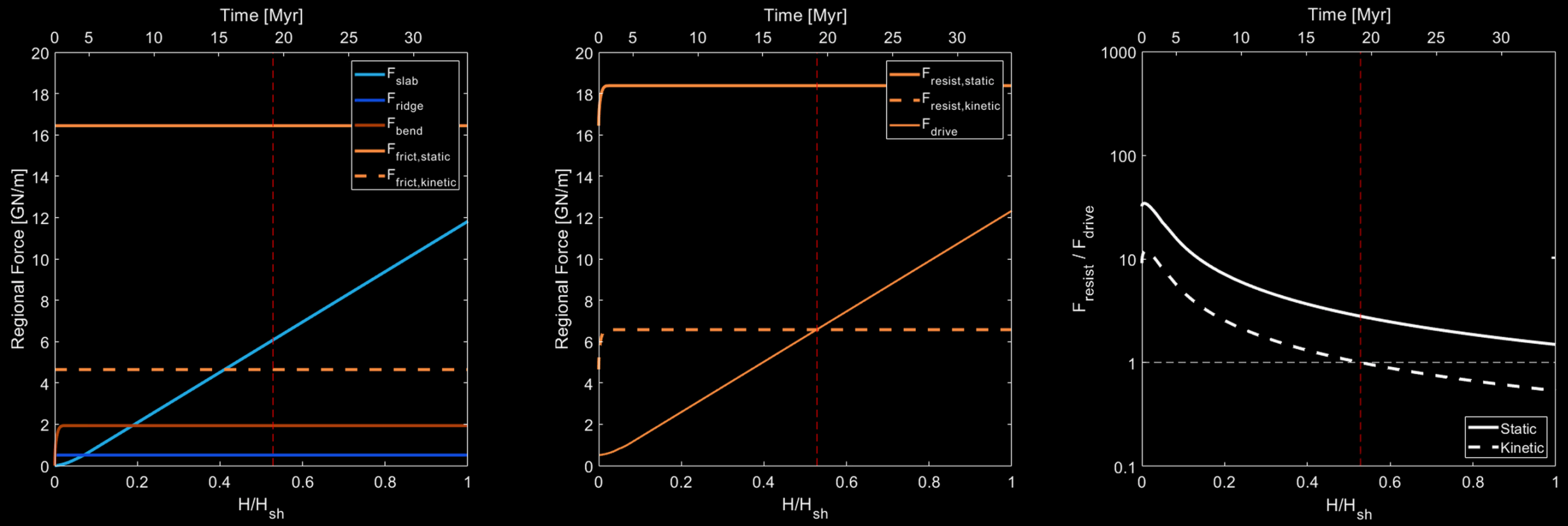
Europa: ϕ_0 = 0.10, f_{salt} = 0.00, u = 1 km/Myr, H = 2.5 km, $\eta_0 = 10^{13}$ Pa s



[Howell and Pappalardo, *in revision*]

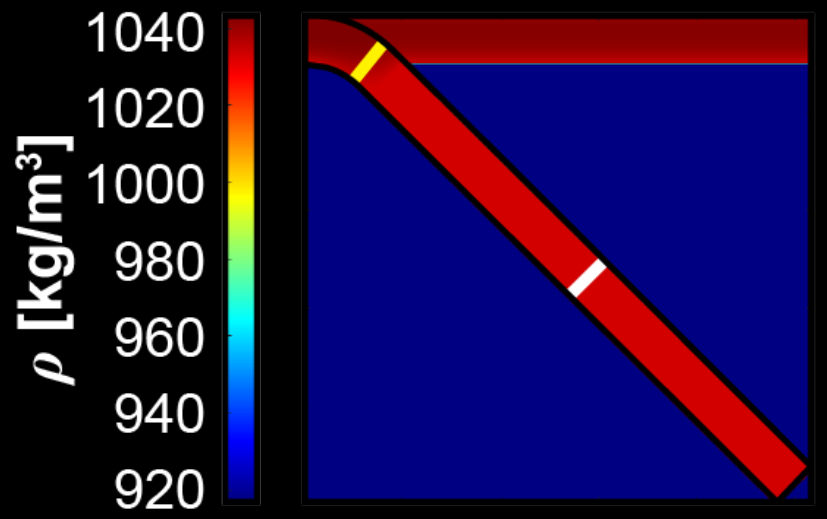
Force Balance Results

Europa: ϕ_0 = 0.00, f_{salt} = 0.22, u = 1 km/Myr, H = 2.5 km, $\eta_0 = 10^{13}$ Pa s

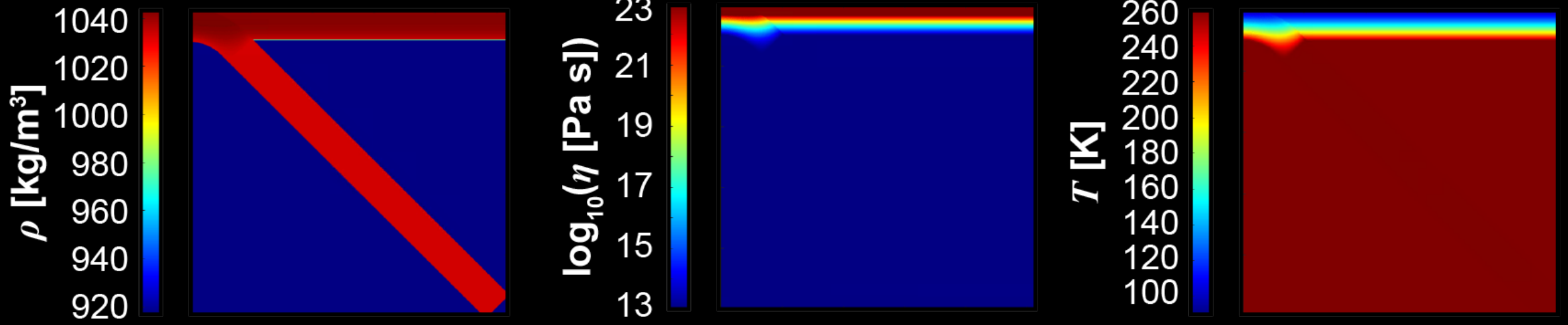


[Howell and Pappalardo, *in revision*]

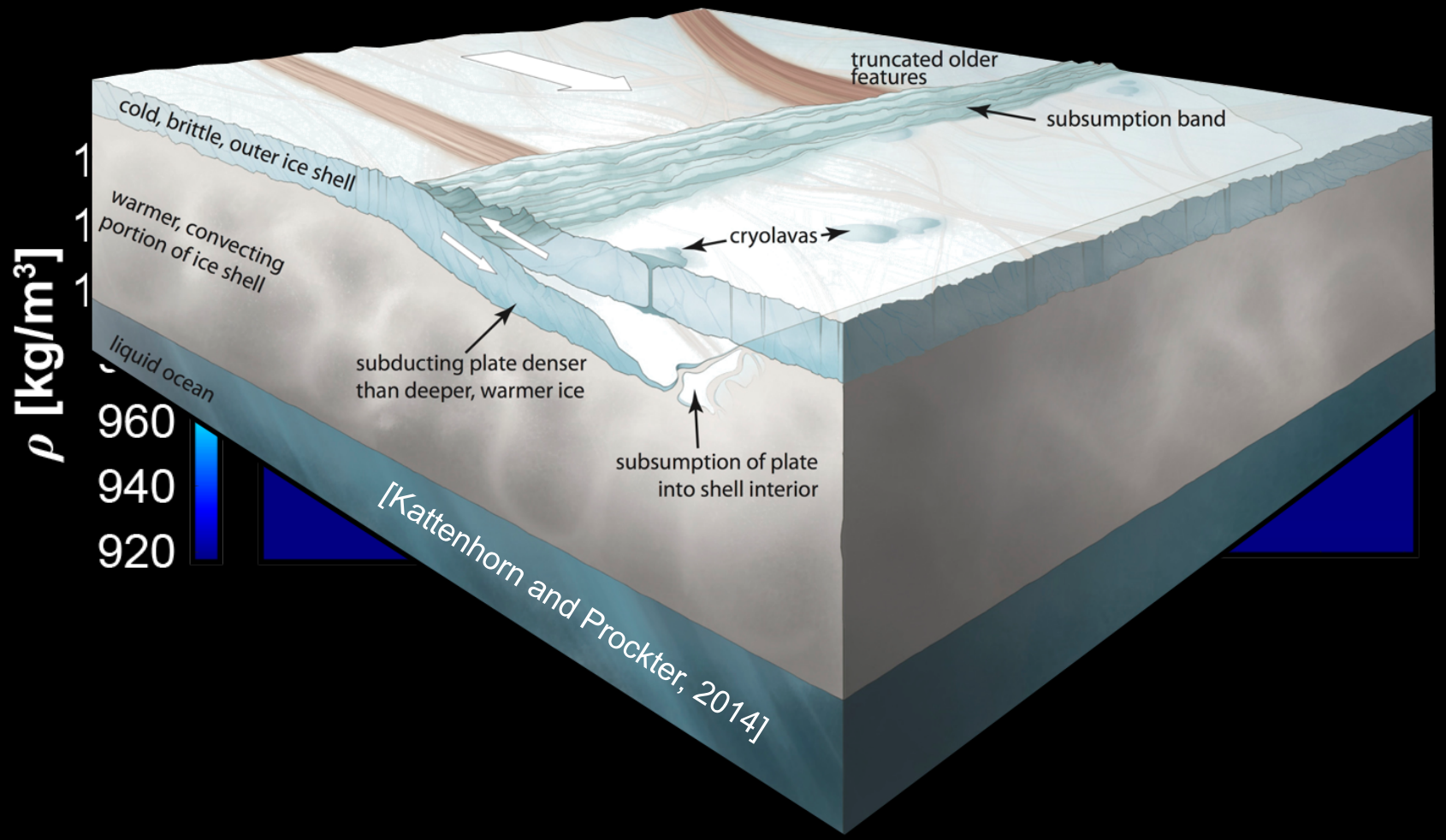
Slab Evolution

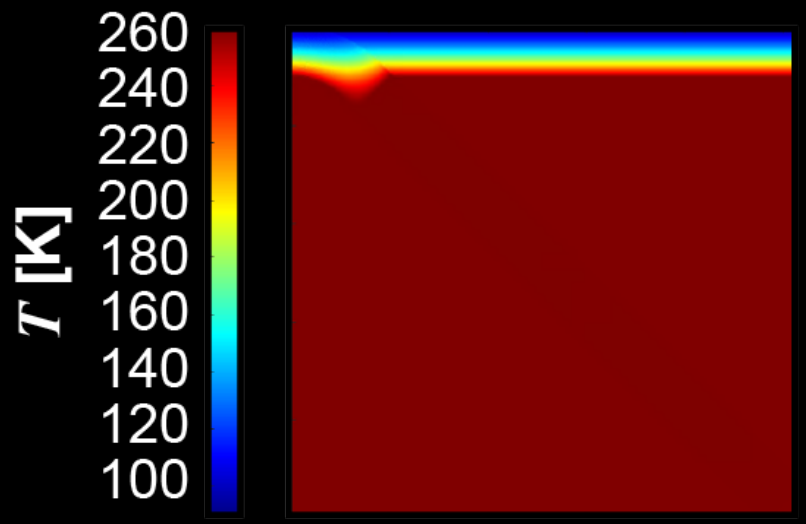


Slab Evolution

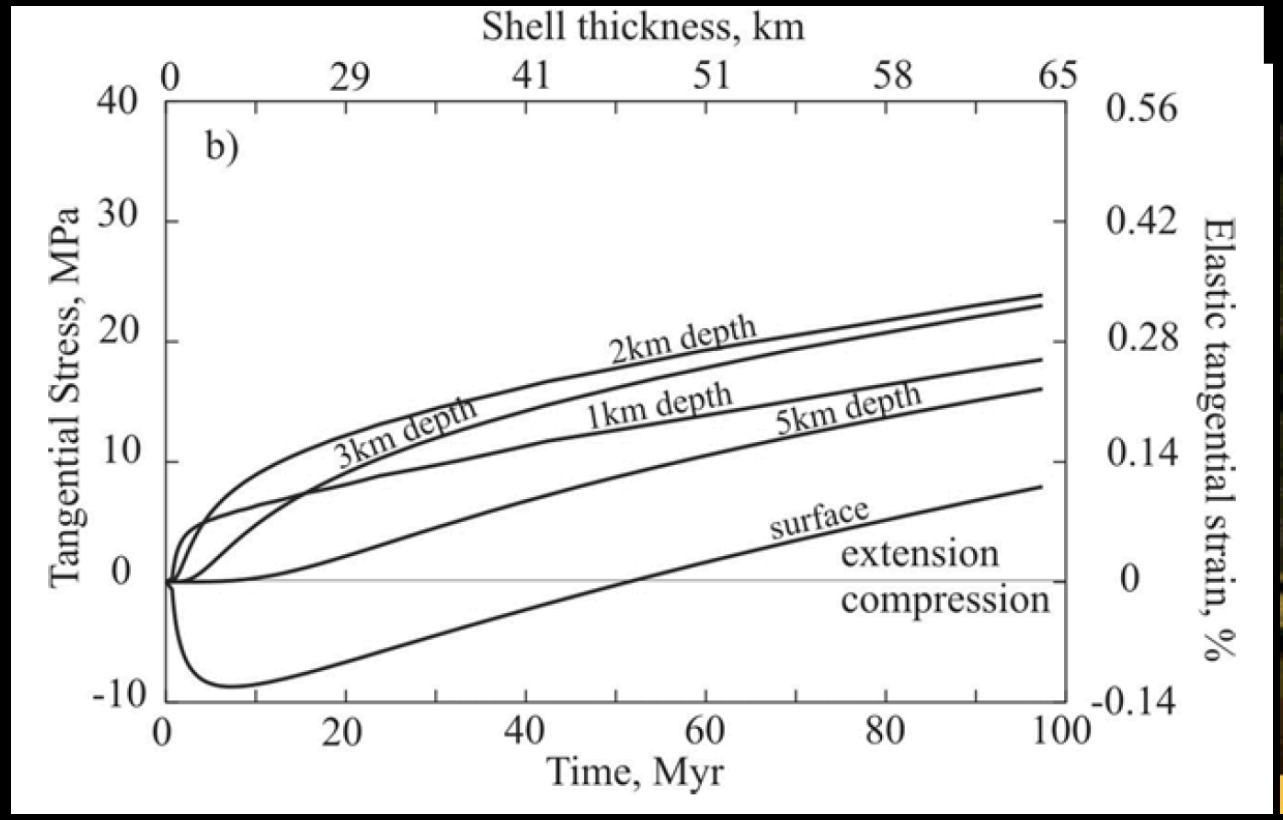


Slab Evolution

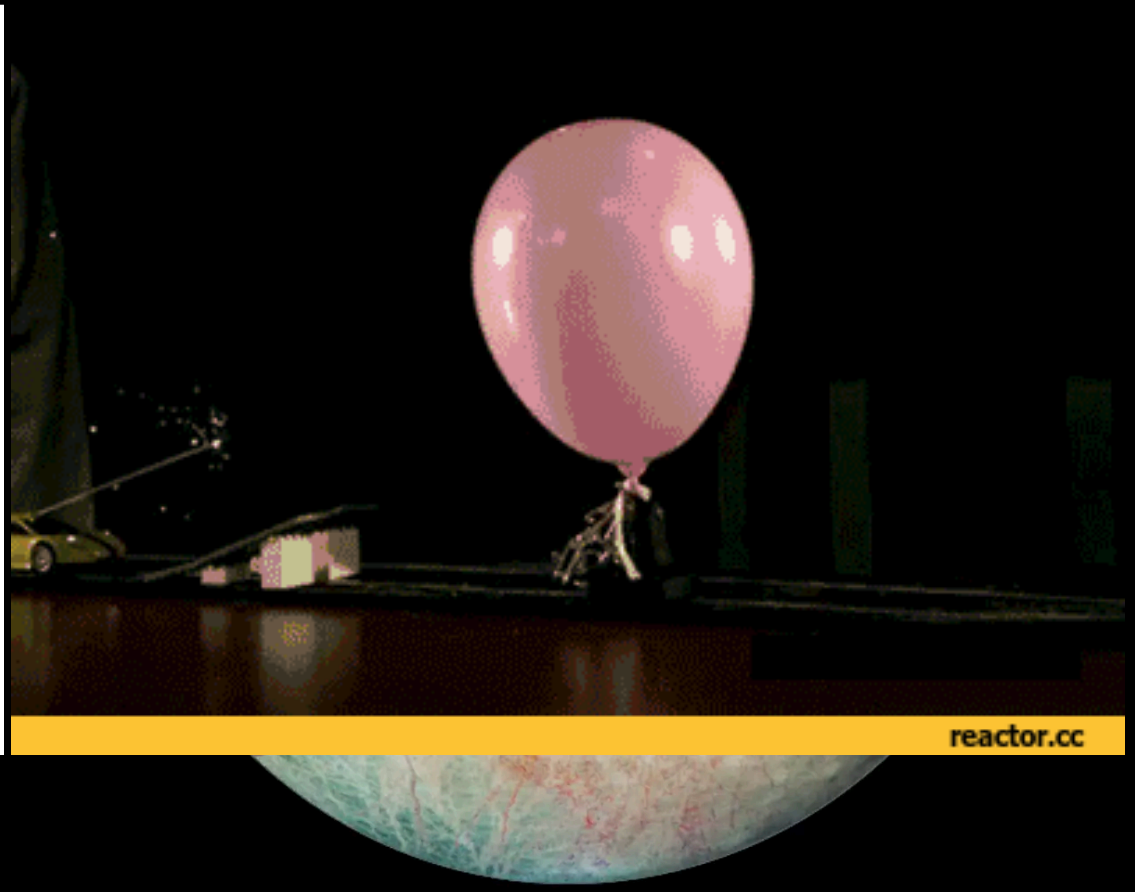




If not subduction, then what?



[Nimmo, 2004b]



SiStER of Theseus

Conservation of Mass

Conservation of Momentum

Conservation of Energy (temperature and heat flow)

Full ice I viscous rheology (1 Newtonian and 3 non-Newtonian deformation mechanisms)

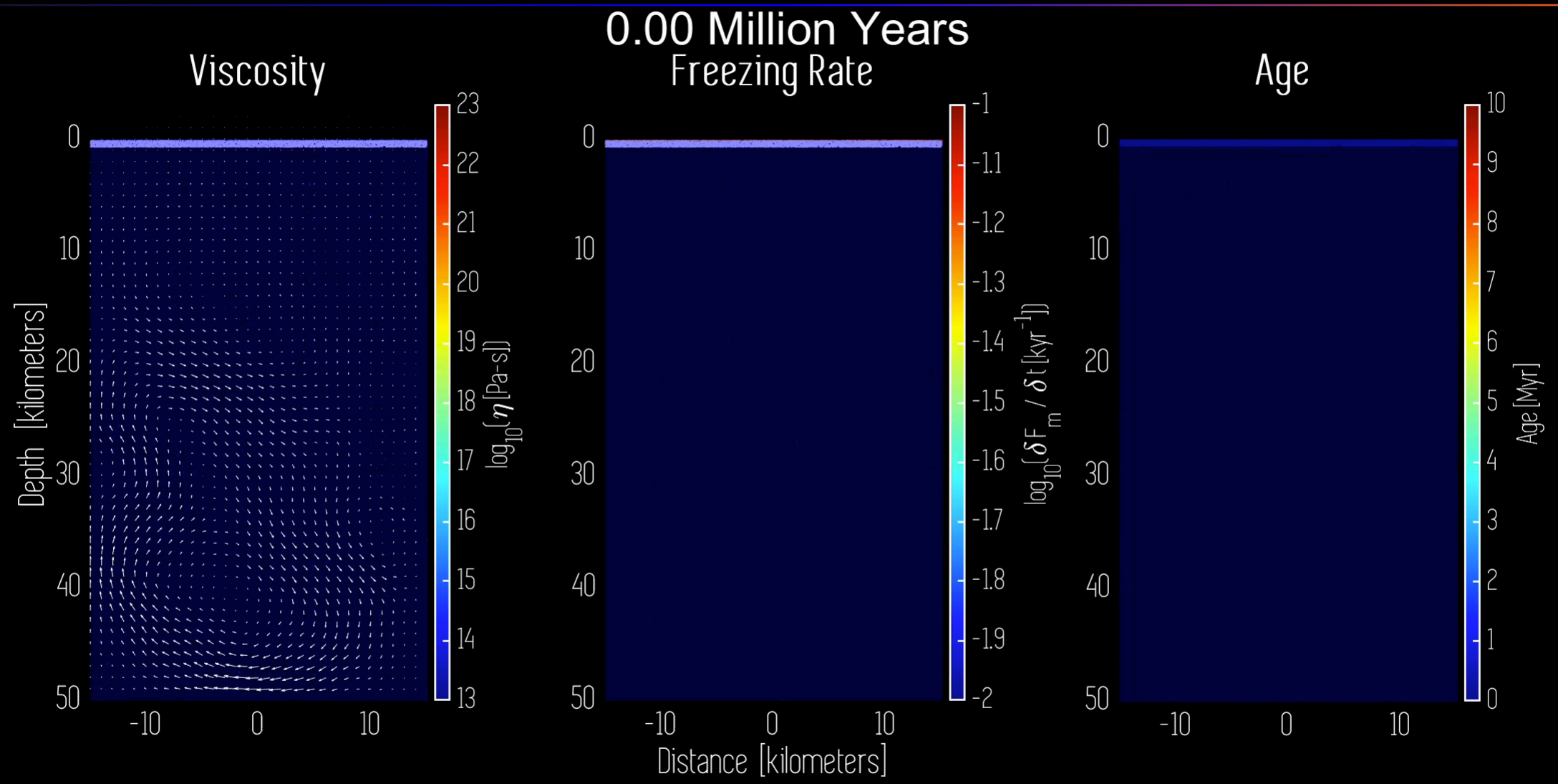
Elastic bending, ductile plastic flow, brittle failure

Melting/freezing with latent heating of recrystallized ice
NOTE: Melt is assumed to be trapped in the parent ice, regardless of porosity

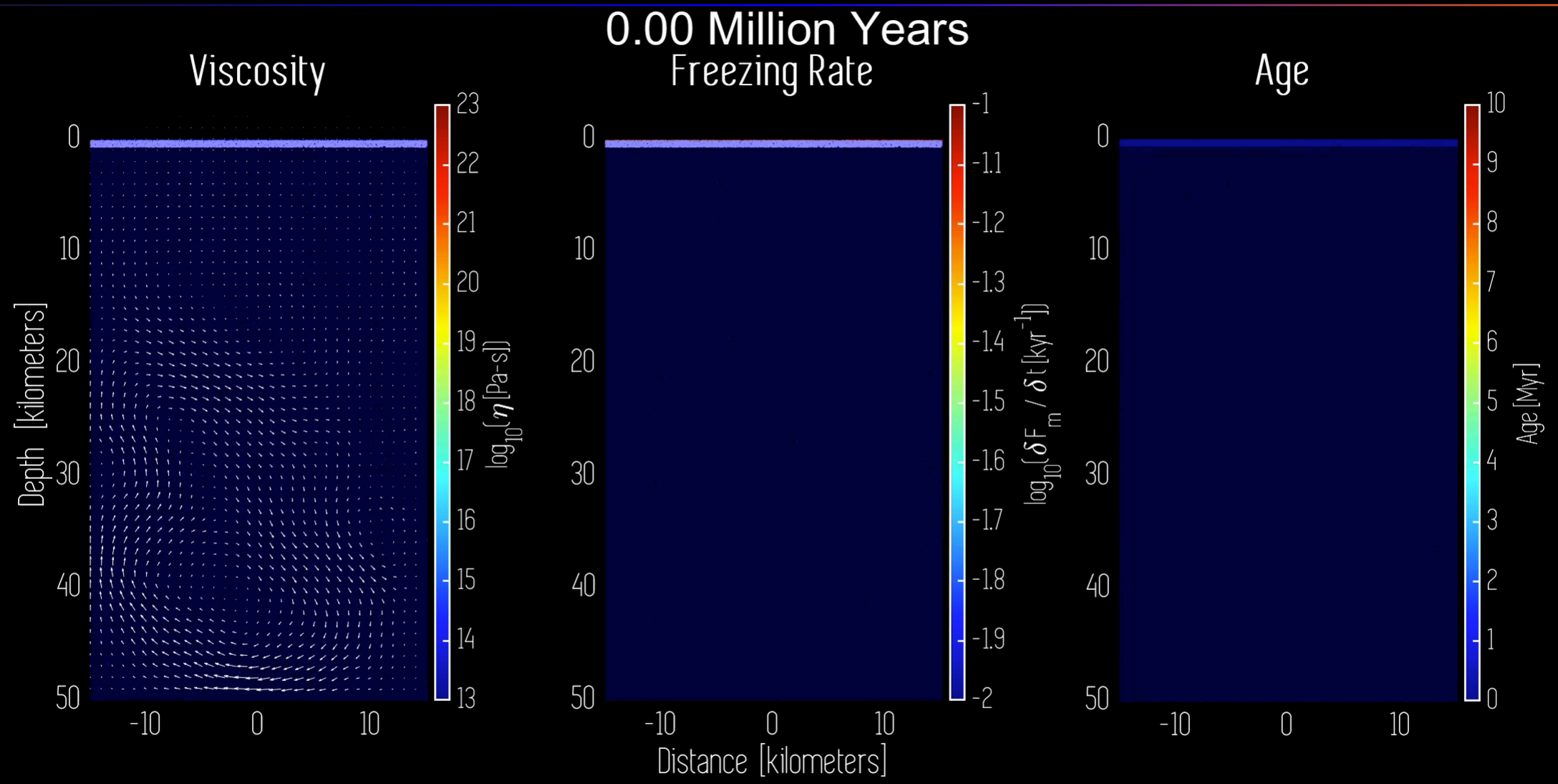
Material tracking on markers (including melt fraction)

Age and freezing rate tracking

Freeze it!

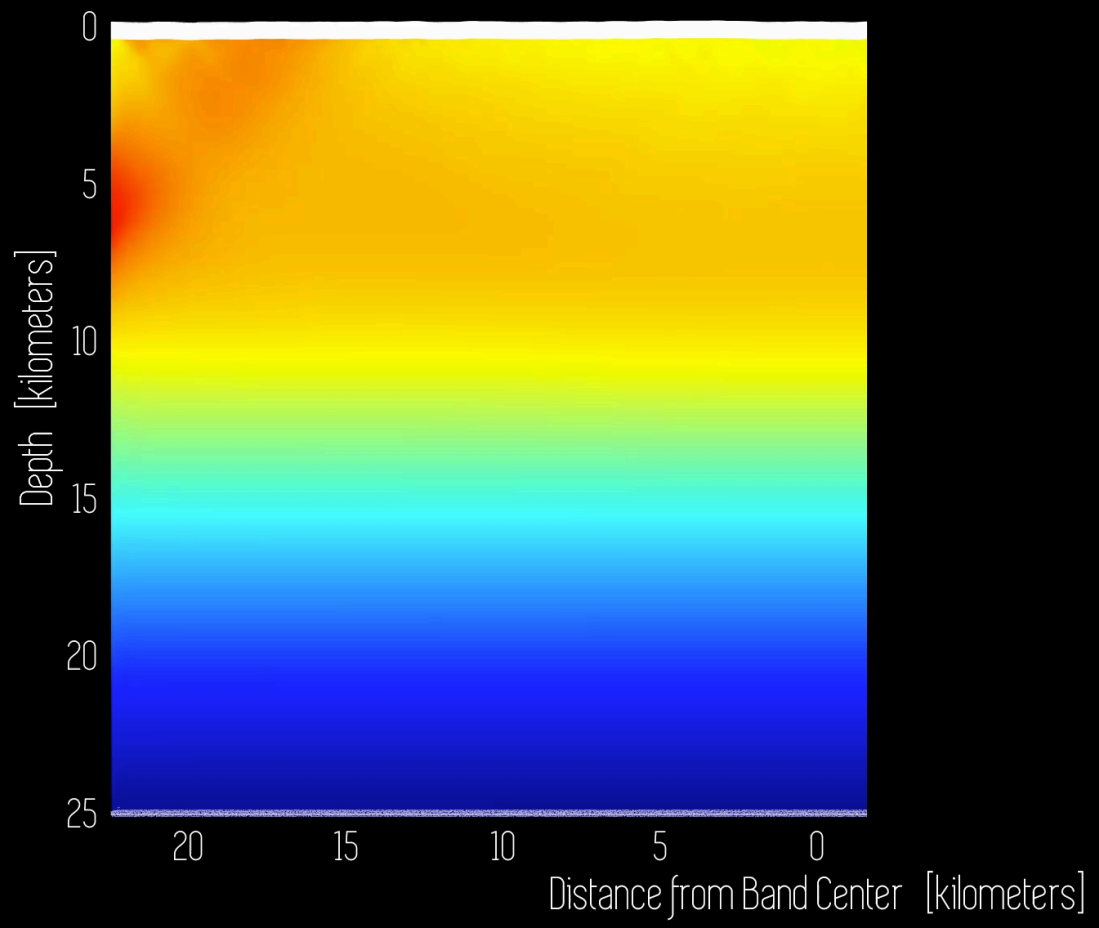

0.00 Million Years
Viscosity
Freezing Rate
Age
Depth [kilometers]
Distance [kilometers]
0
10
20
30
40
50
-10
0
10
23
22
21
20
19
18
17
16
15
14
13
$\log_{10}(\eta$ [Pa-s])
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
$\log_{10}(\delta F_m / \delta t$ [kyr^{-1}])
10
9
8
7
6
5
4
3
2
1
0
Age [Myr]

Freeze it!

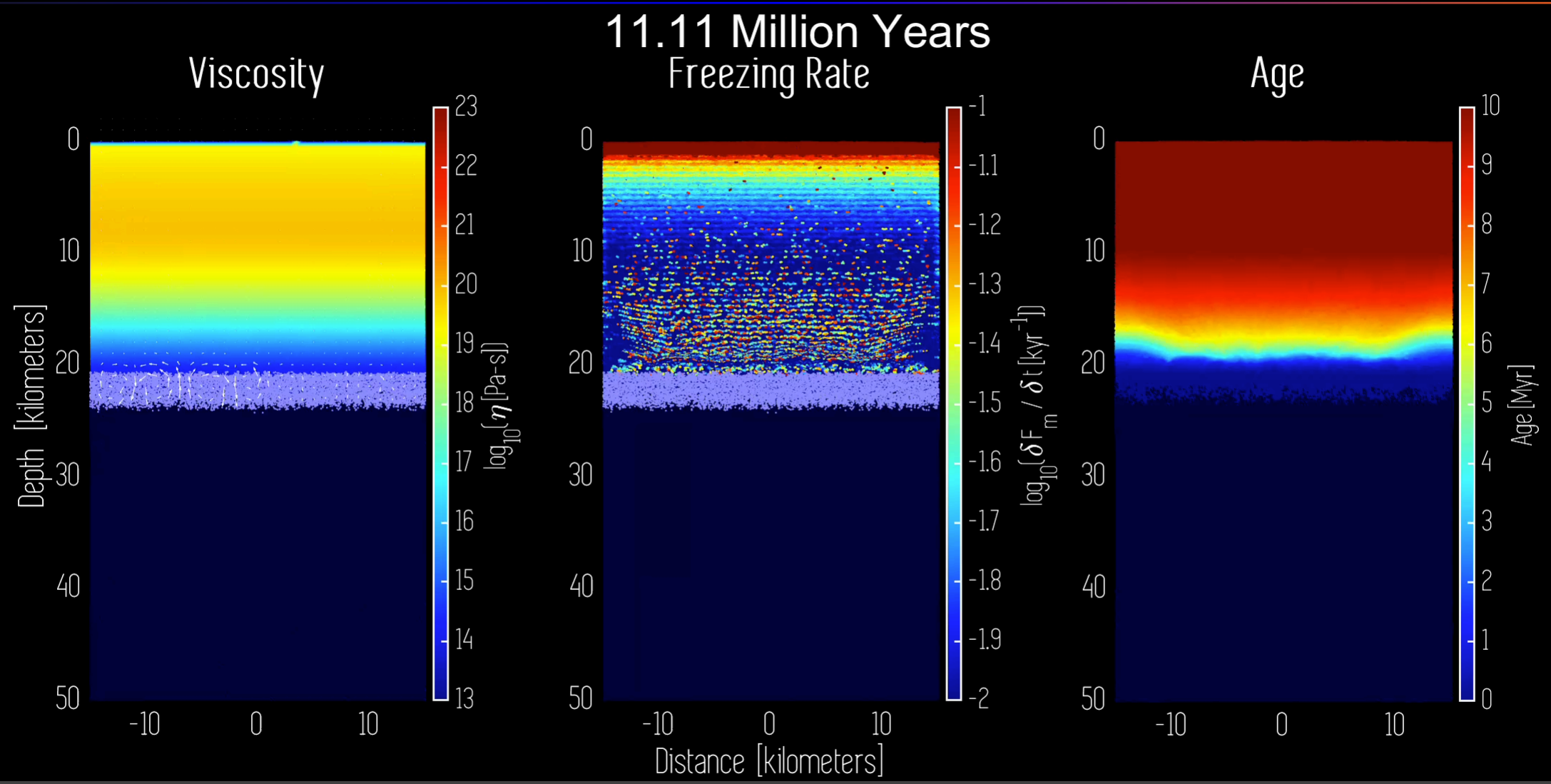

0.00 Million Years
Viscosity
Freezing Rate
Age
Depth [kilometers]
Distance [kilometers]
0
10
20
30
40
50
-10
0
10
23
22
21
20
19
18
17
16
15
14
13
$\log_{10}(\eta$ [Pa-s])
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
$\log_{10}(\delta F_m / \delta t$ [kyr^{-1}])
10
9
8
7
6
5
4
3
2
1
0
Age [Myr]

Pull it!

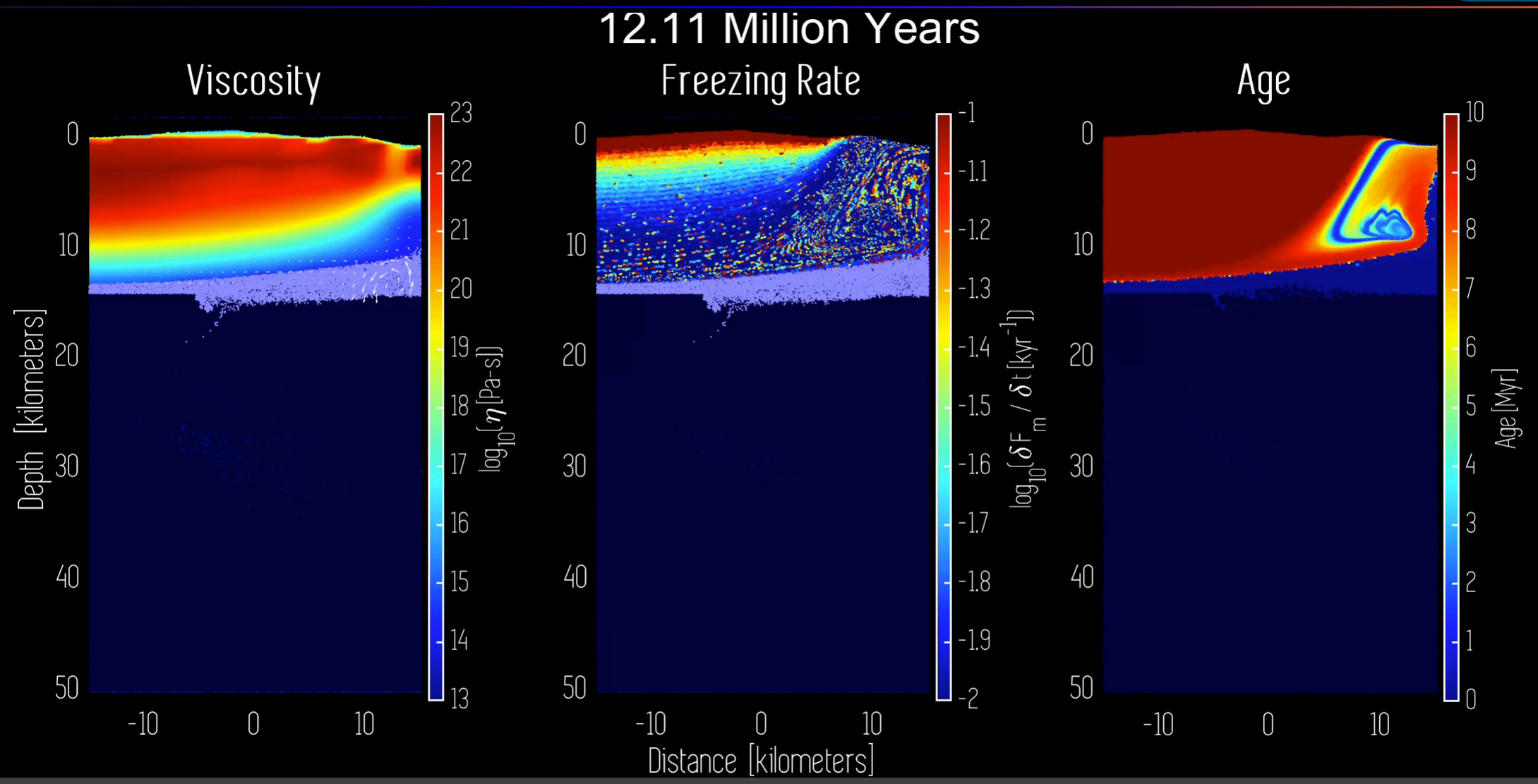
6 Thousand



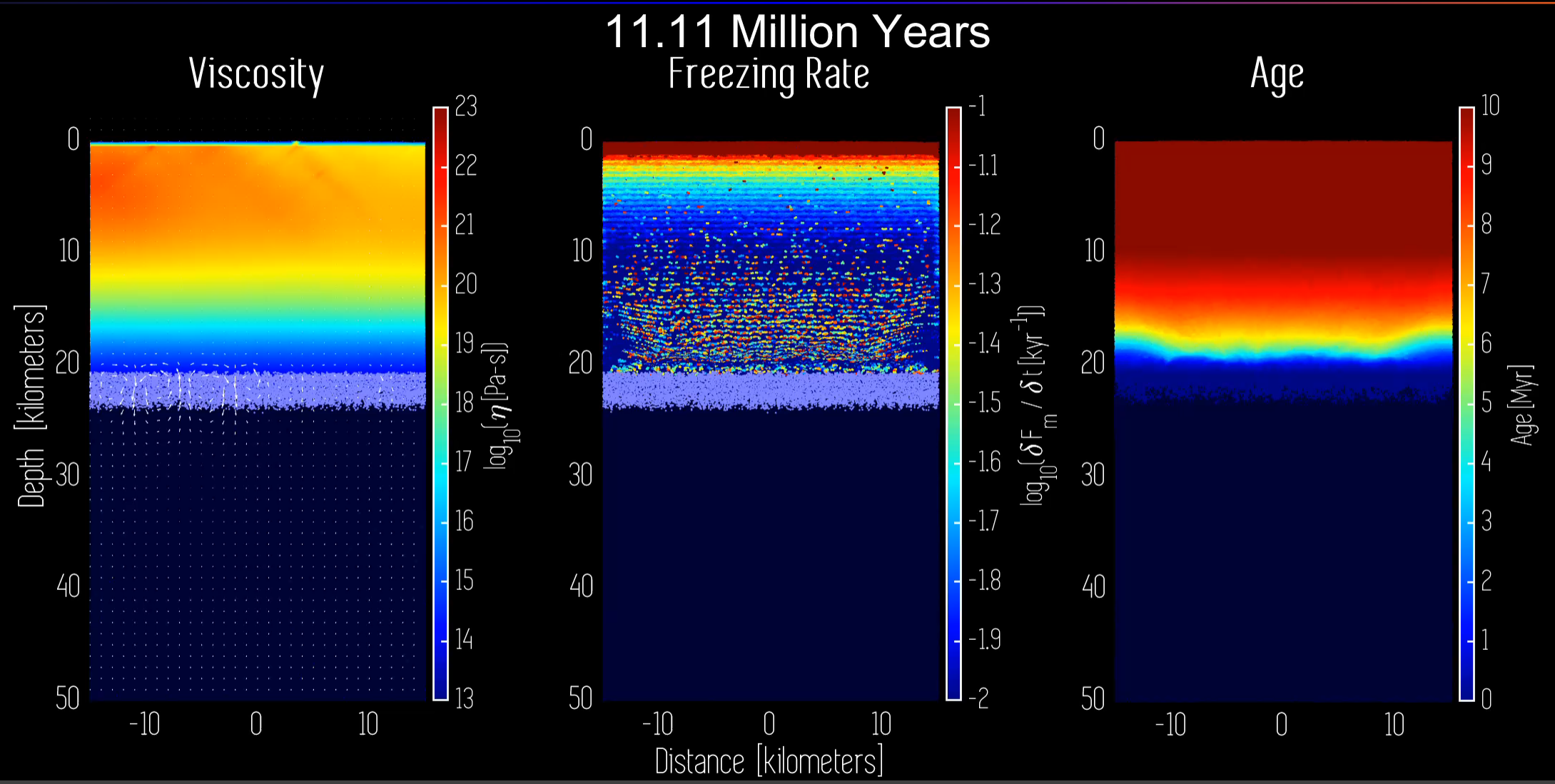
Pull it!


11.11 Million Years
Viscosity
Freezing Rate
Age
Depth [kilometers]
Distance [kilometers]
$\log_{10}(\eta\,[\mathrm{Pa\text{-}s}])$
$\log_{10}(\delta F_m / \delta t\,[\mathrm{kyr}^{-1}])$
Age [Myr]
0
10
20
30
40
50
-10
0
10
23
22
21
20
19
18
17
16
15
14
13
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
10
9
8
7
6
5
4
3
2
1
0

Freeze it!

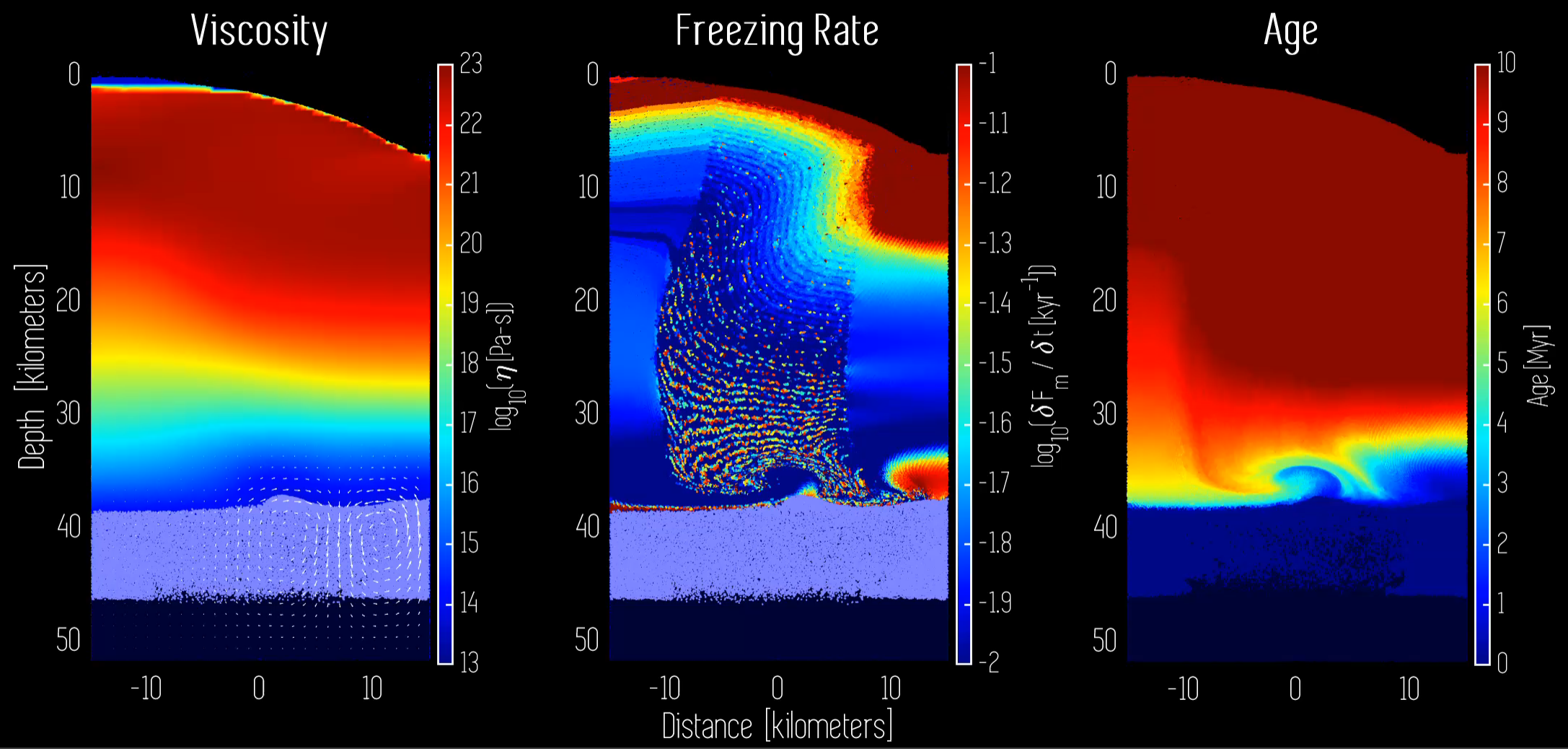

12.11 Million Years
Viscosity
Freezing Rate
Age
Depth [kilometers]
Distance [kilometers]
$\log_{10}(\eta$ [Pa-s])
$\log_{10}(\delta F_m / \delta t$ [kyr^{-1}])
Age [Myr]
0
10
20
30
40
50
-10
0
10
23
22
21
20
19
18
17
16
15
14
13
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
10
9
8
7
6
5
4
3
2
1
0

Push it!


11.11 Million Years
Viscosity
Freezing Rate
Age
Depth [kilometers]
Distance [kilometers]
$\log_{10}(\eta\,[\mathrm{Pa\text{-}s}])$
$\log_{10}(\delta F_m / \delta t\,[\mathrm{kyr}^{-1}])$
Age [Myr]
0
10
20
30
40
50
-10
0
10
23
22
21
20
19
18
17
16
15
14
13
-1
-1.1
-1.2
-1.3
-1.4
-1.5
-1.6
-1.7
-1.8
-1.9
-2
10
9
8
7
6
5
4
3
2
1
0

Freeze it!

12.01 Million Years

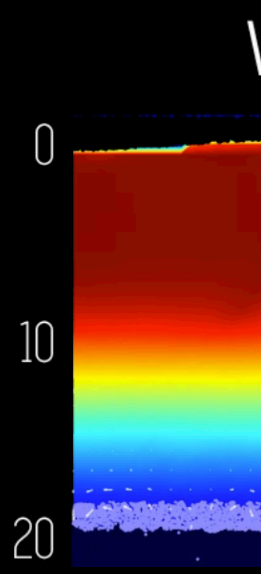


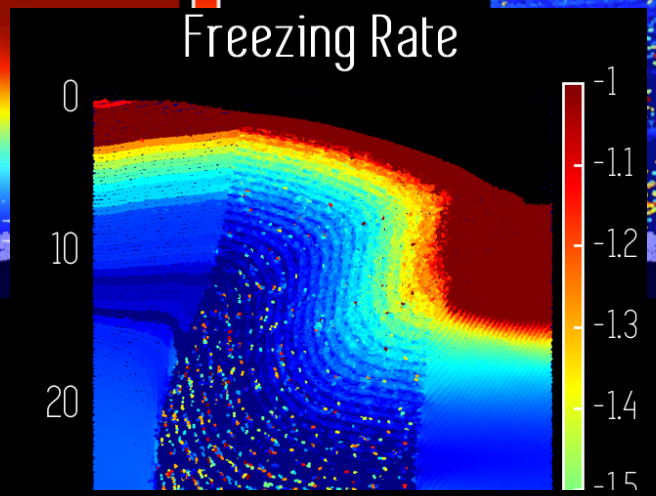
Detectable Interior Structures?

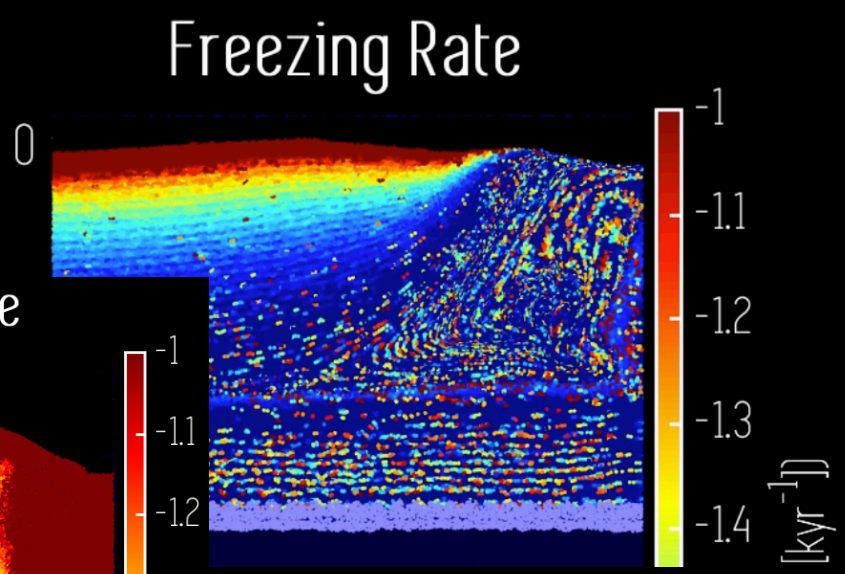
Are the tectonic structures still there at depth?

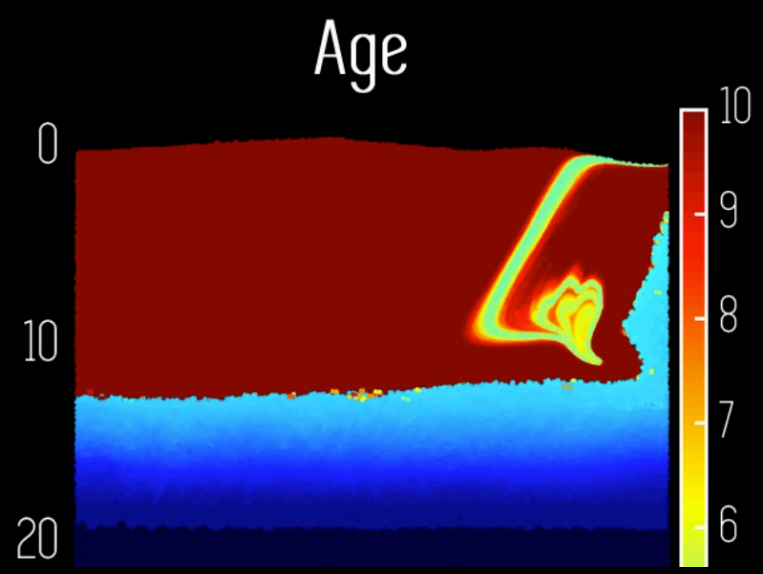
Do brine-ice thicknesses change in space or with depth?

What are surface ice ages?

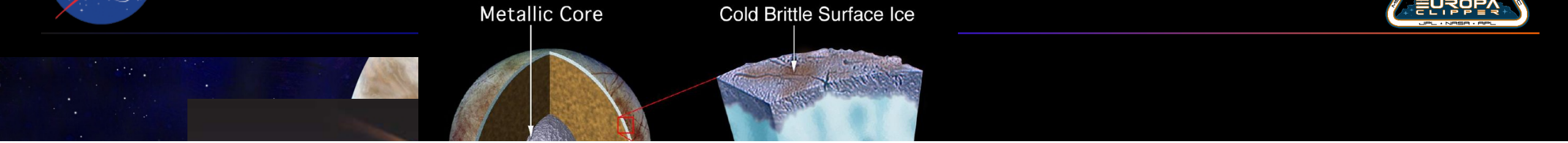


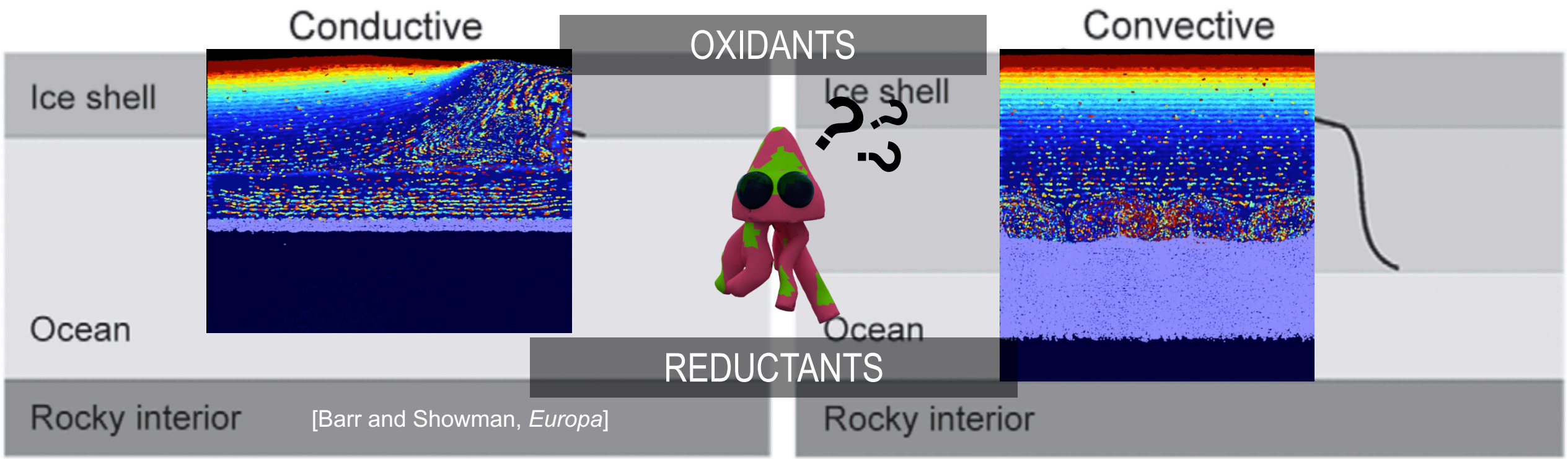




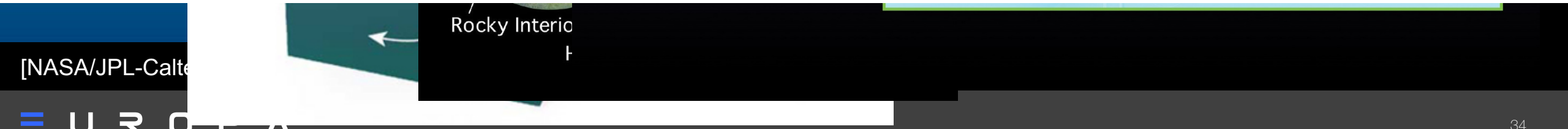


The Ice Shell May be Weird





[Barr and Showman, *Europa*]



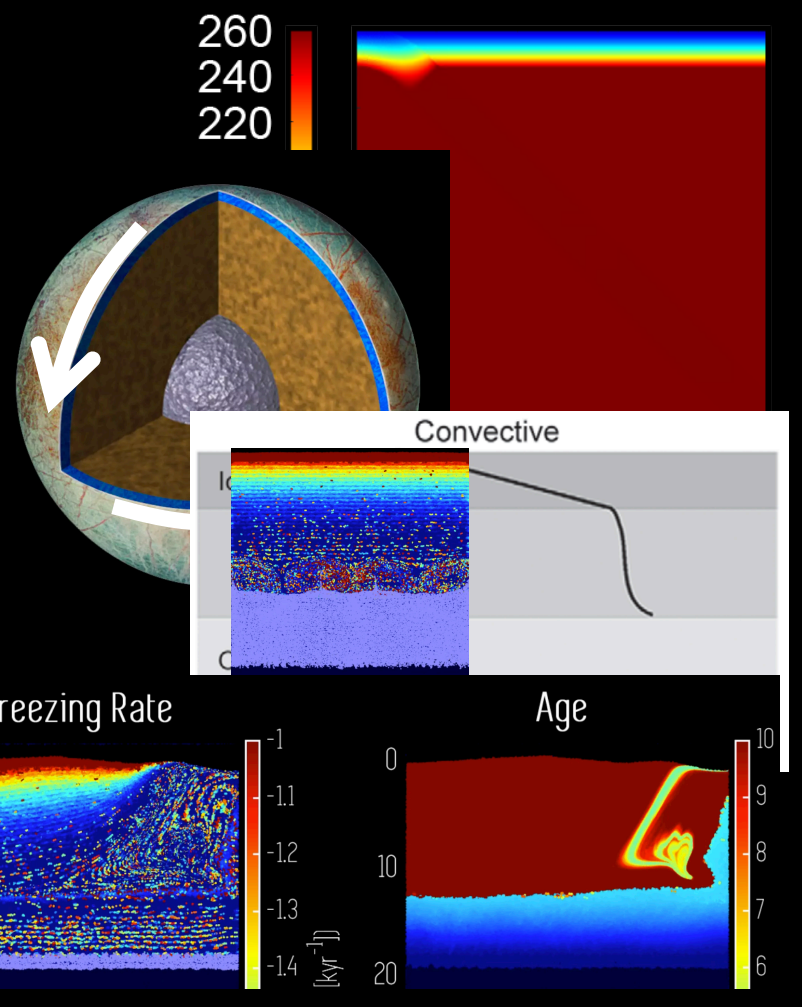
[NASA/JPL-Calte

Final Thoughts and Future Directions

Material recycling and resurfacing is unlikely to be driven by rapid, steady state thermo-chemical convection (including plate tectonics forces), because slabs would subsume

The timescale and periodicity of surface-ocean interaction may be that of ice shell thickness changes or decoupled rotation

The thermal and compositional state of Europa might not be straightforward

Compositional horizons within the ice shell and lateral variations provide insight into the geologic history

Next up: Impurity partitioning and thermo-mechanical changes