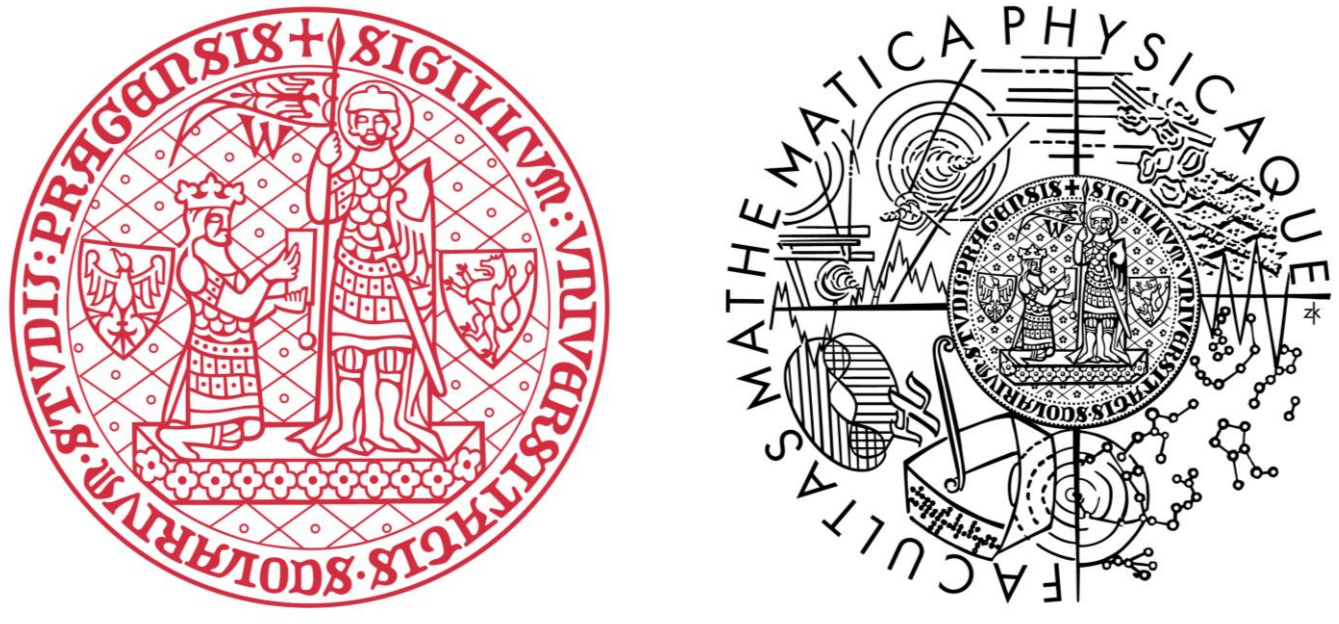


Plume-induced initiation of subduction: insights from global visco-elasto-plastic models with a free surface



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Motivation and perspectives:

The onset of plate tectonics on Earth is not well understood. For how long has the Earth's surface been covered by mutually colliding and subducting plates is unknown - the geochemical and geological data provide only limited constraint, with most estimates ranging from cca. 600 My to about 3.5 Gy (e.g. Dhuime et al., 2015). Various mechanisms have been proposed to weaken the existing plate boundaries and thus to allow for subductions to proceed, but only a few of these can act to form a new lithospheric-scale shear zone inside an unbroken plate. One such plausible candidate that may have triggered plate tectonics on Earth is plume-induced subduction (e.g. Gerya et al., 2015). The mechanism is recently gaining attention also because some observations indicate that it is occurring on Venus at present time (e.g. Davaille et al., 2017).

When the strength of lithospheric rocks is derived from laboratory measurements, one needs relatively strong plumes in order to break a stagnant lid. The relative buoyancy of mantle plumes depends on the amount of internal heating. We plan to investigate the role of internal heating in the plume-induced subduction scenario, because estimates of the amount of radioactive heat in primordial mantle range broadly.

This work (in progress):

We perform models of mantle convection in which strong plumes self-consistently develop and analyze the interaction between plume heads and the lithosphere. The models incorporate realistic parameter values descriptive of the planet Earth and thus include compressibility, phase transitions, shear heating, diffusion creep with pressure and temperature dependent viscosity, and are heated both internally and from the bottom. We employ visco-elasto-plastic (VEP) rheology and a free surface, and test the influence of 1) elasticity, 2) yield stress, and 3) free surface on the dynamic features of the observed subductions.

Numerical model

Truncated anelastic Boussinesq approximation

$$\nabla \cdot (\rho \mathbf{v}) = 0; \quad -\nabla p + \nabla \cdot \boldsymbol{\sigma} + \rho \mathbf{g} = 0$$

$$\rho C_p \frac{DT}{Dt} = -\alpha T \rho |g| v_z + \nabla \cdot (k \nabla T) + \rho H + \boldsymbol{\sigma} : \mathbb{D}_{\text{vis}}$$

Visco-elasto-plastic rheology with Jaumann objective stress rate

$$\frac{\boldsymbol{\sigma}}{2\eta} + \frac{\dot{\boldsymbol{\sigma}}}{2G} + \lambda \frac{\boldsymbol{\sigma}}{|\boldsymbol{\sigma}|} = \mathbb{D}_{\text{vis}} + \mathbb{D}_{\text{el}} + \mathbb{D}_{\text{pl}} = \mathbb{D}$$

$$\dot{\boldsymbol{\sigma}} := \frac{\partial \boldsymbol{\sigma}}{\partial t} + \vec{v} \cdot \nabla \boldsymbol{\sigma} + (\boldsymbol{\sigma} \mathbb{W} - \mathbb{W} \boldsymbol{\sigma})$$

$\boldsymbol{\sigma}$... Cauchy stress; η ... viscosity;

G ... shear modulus; $\mathbb{D}$... Strain rate

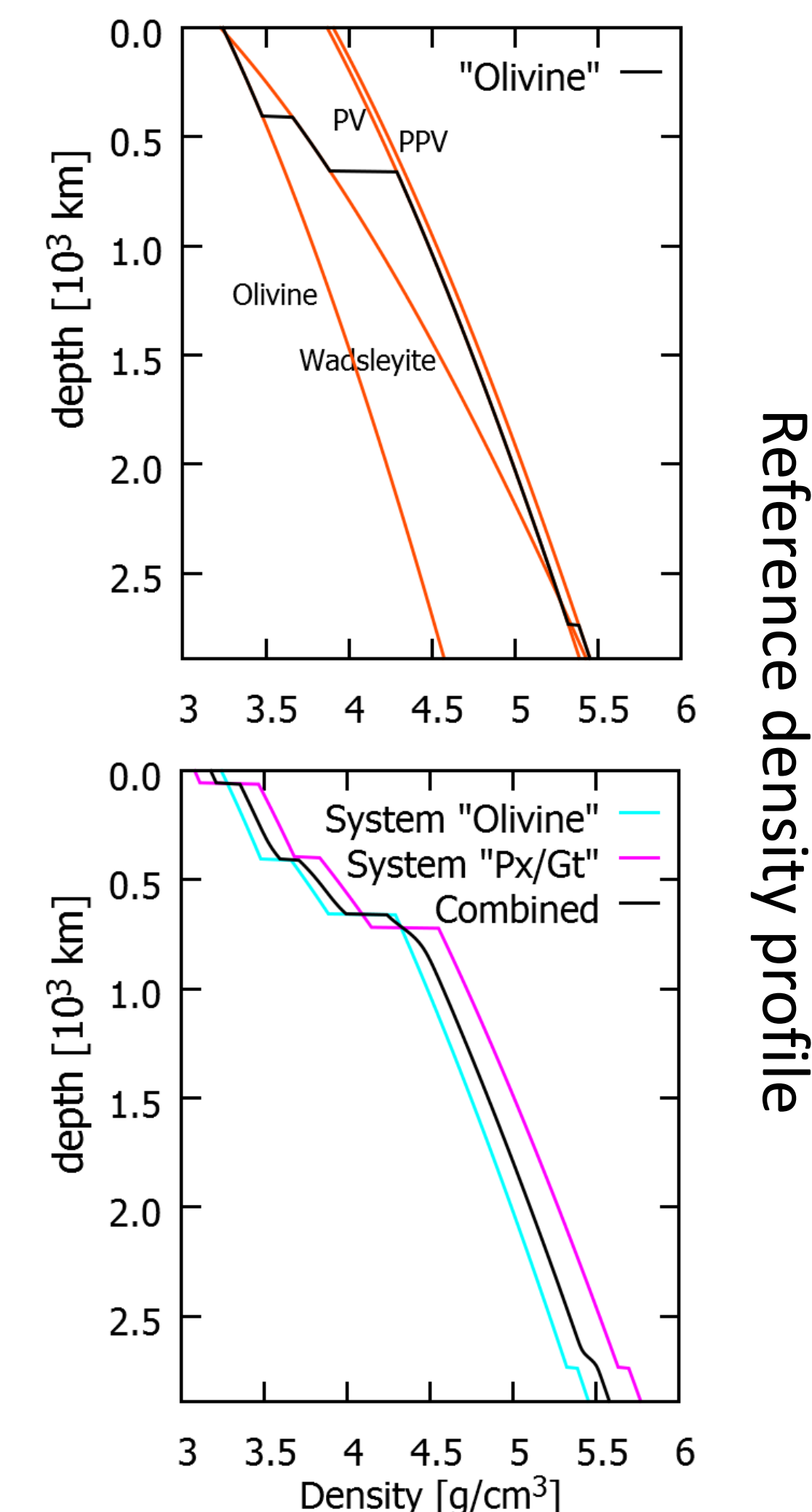
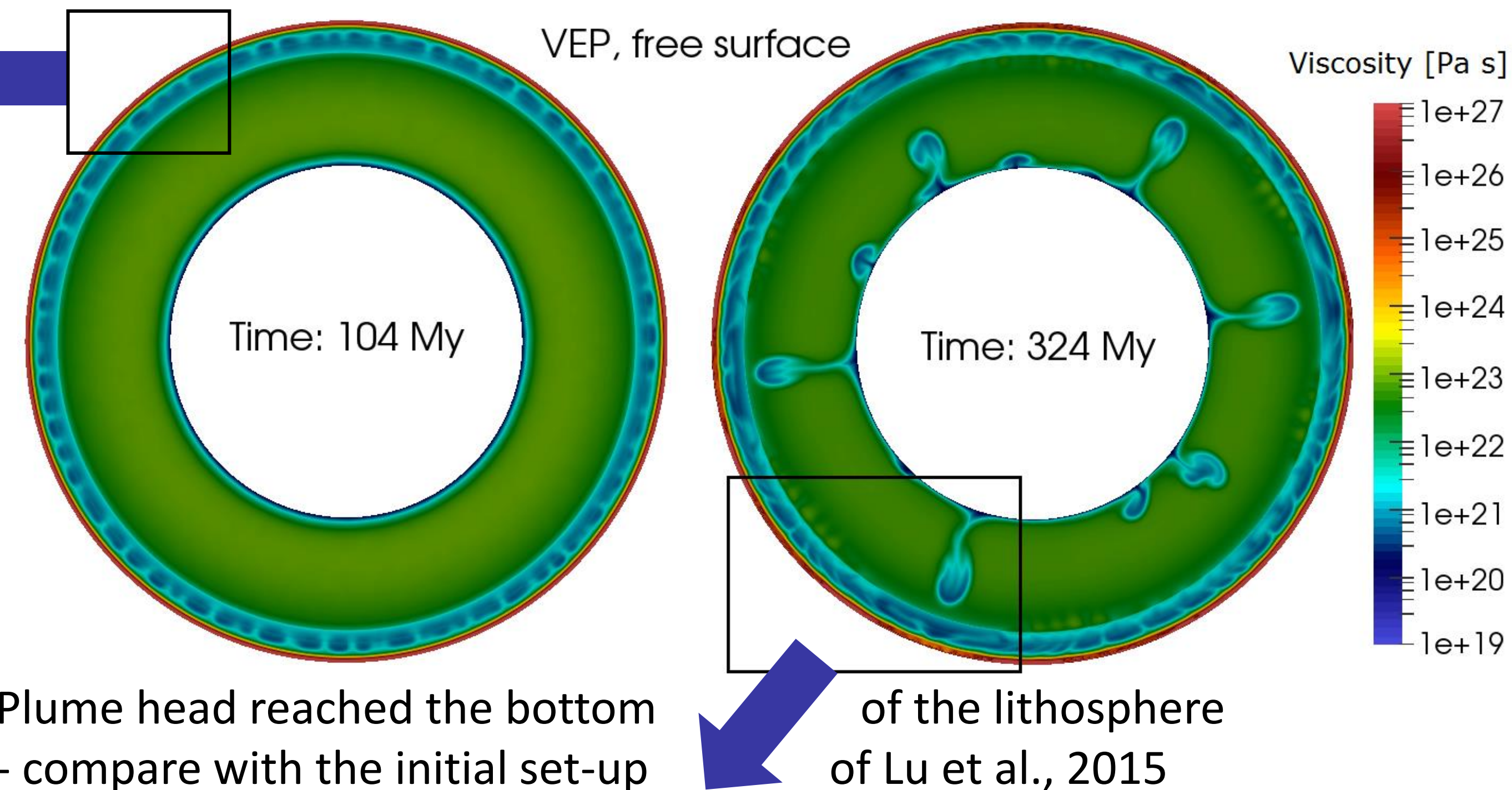
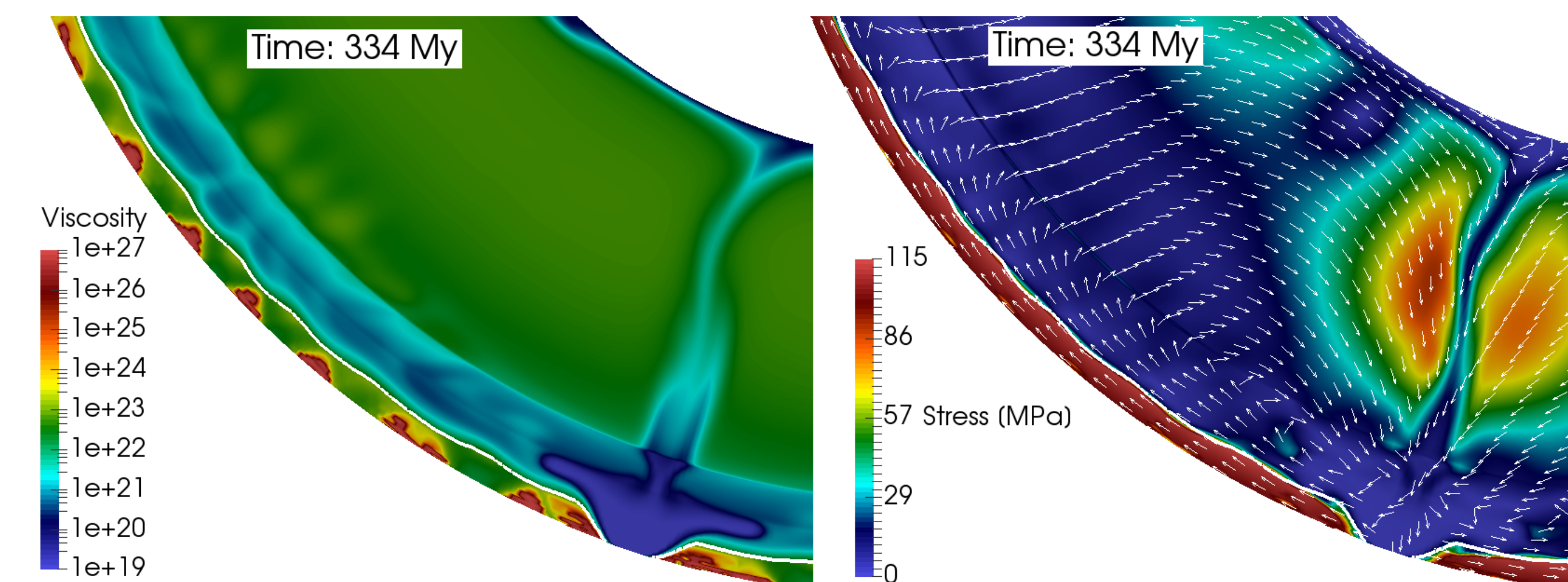
λ ... parameter determined iteratively so that

$$|\boldsymbol{\sigma}| \leq \sigma_{\text{yld}} + \mu p_0$$

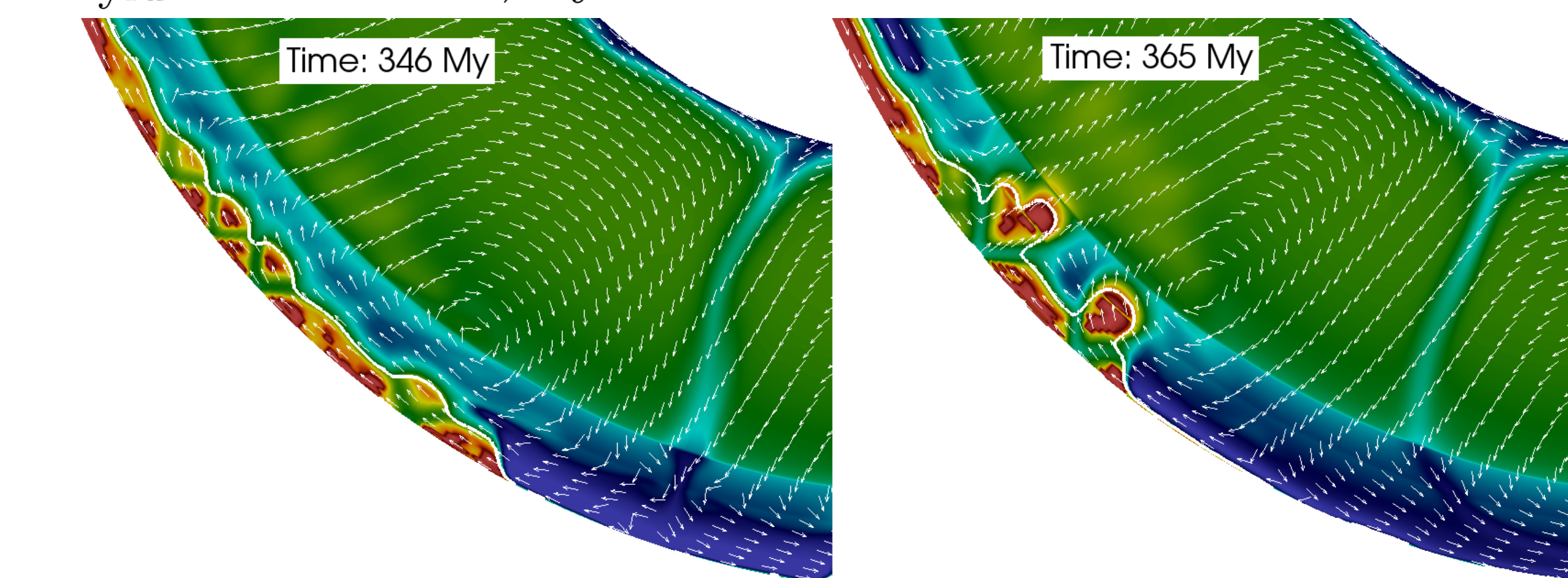
Model parameters

UM = upper mantle (dry olivine); PV = Perovskite; PPV = Post-Perovskite

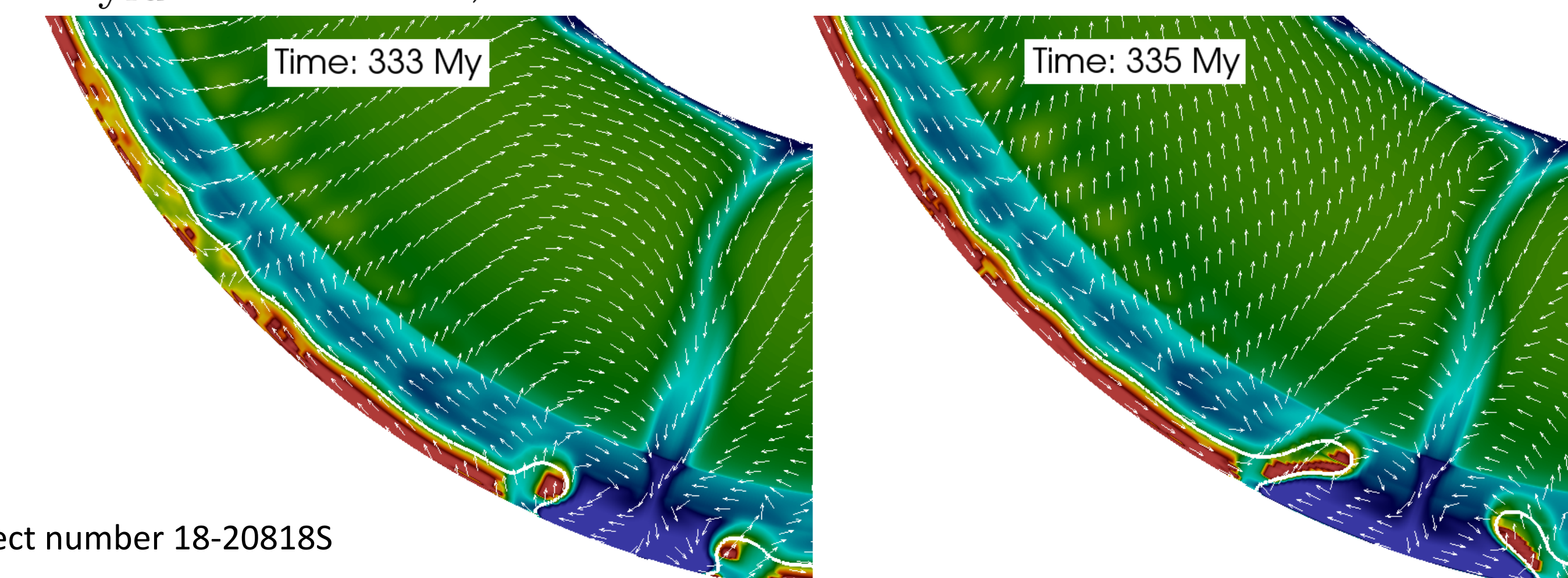
Parameter	Symbol	Value	Units
Mantle depth	D	2890	km
Gravitational acceleration	g	9.81	m/s ²
Reference density	ρ_0	3300	kg/m ³
Surface temperature	T_{surf}	300	K
Super-adiabatic temp. diff.	ΔT	2500	K
Reference viscosity	η_{ref}	10^{21}	Pa s
Upper viscosity cut-off	η_{max}	10^{27}	Pa s
Thermal diffusivity	κ	7.6×10^{-7}	m ² /s
Thermal expansivity	α	3×10^{-5}	K ⁻¹
Heat capacity	C_p	1200	J/kg/K
Gas constant	R	8.3145	J/K/mol
Internal heating rate	H	5.2×10^{-12}	W/kg
Half-life	t_{half}	∞	Ga
Activation energy - UM	E_{ol}	300	kJ/mol
Activation volume - UM	V_{ol}	5.00	cm ³ /mol
p_{decay} - UM	$p_{\text{decay,ol}}$	∞	GPa
Activation energy - PV	E_{pv}	370	kJ/mol
Activation volume - PV	V_{pv}	3.65	cm ³ /mol
p_{decay} - PV	$p_{\text{decay,pv}}$	200	GPa
Activation energy - PPV	E_{ppv}	162	kJ/mol
Activation volume - PPV	V_{ppv}	1.40	cm ³ /mol
p_{decay} - PPV	$p_{\text{decay,ppv}}$	1610	GPa
Shear modulus	G	7×10^{10}	Pa



$\sigma_{\text{yld}} = 100$ MPa, Symmetrical subduction



$\sigma_{\text{yld}} = 80$ MPa, Venus-like subduction



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