The influence of overriding-plate velocity on surface topography in subduction zones

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Subduction dynamics and upper plate topography

- **Subduction dynamics generates the deflection of the overriding plate (OP)**, that we can refer to as a dynamically-induced flexural topography :
  - Consistently shown in elastic [*Davies,* 1981; *Hassani et al.*, 1997], visco-elastic [*Hampel* & *Pfiffner*, 2006] and viscous [*Crameri et al.*, 2017; *Chen et al.*, 2017] subduction models.
  - **Wavelength : 100s of kms**

- **Plate kinematics and strength of the plates** influence the dynamically-induced OP flexural topography [e.g. *Hampel* & *Pfiffner*, 2006; *Crameri et al.*, 2017].

- **Changes in OP velocity** (driven by external forces) have been shown to affect subduction dynamics [*Guillaume et al.*, 2018; *Cerpa et al.*, 2018]. Its impact on OP surface elevation has not yet been addressed.

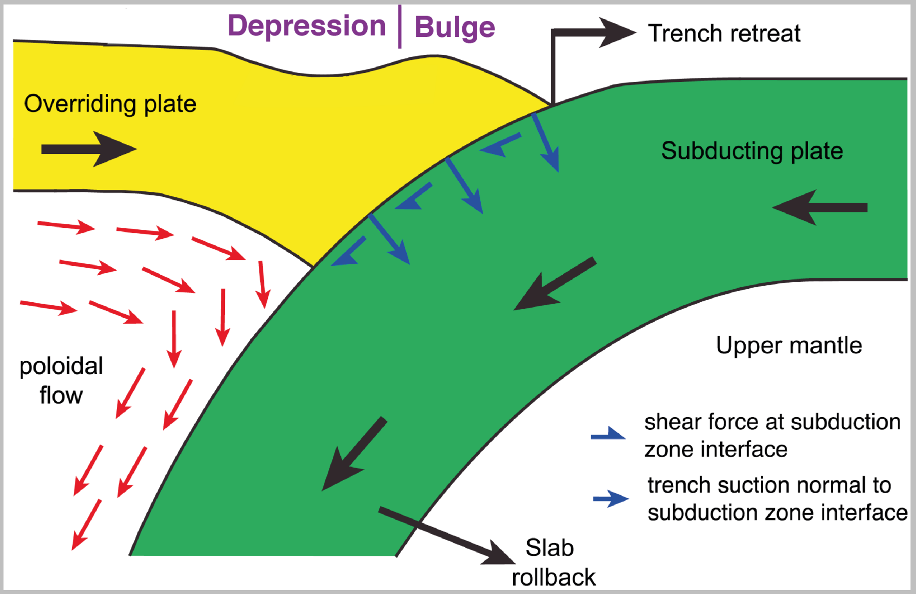


Fig. 1 : Sketch of flexural topography (Depression and Bulge) that forms at the surface of the overriding plate due to the dynamics of the system (Modified after Chen et al., [2017]).

In this study we investigate :

1. **How OP velocity and the plates and the subduction interface strengths control OP topography in models that reach steady-steate ?**
2. **What is the impact of sudden changes in overriding plate velocity on OP topography?**

Model set-up

- We use **cartesian 2-d mechanical models** of subduction zones which consists of two solid **viscoelastic plates** and an **isoviscous Newtonian upper mantle**. The two solvers are coupled via a fictitious domain method [*Cerpa et al.*, 2014].
- The two plates have **free-surfaces**. A **planar contact surface defines the subduction interface**, with a constant friction coefficient μ.
- We **impose the far-field OP velocity v_{op} (SP-free models)**, while the **subducting plate (SP) is free** (initially pushed by a piston until the self-sustained downgoing SP motion starts). In a few models, the OP is also free (free models).

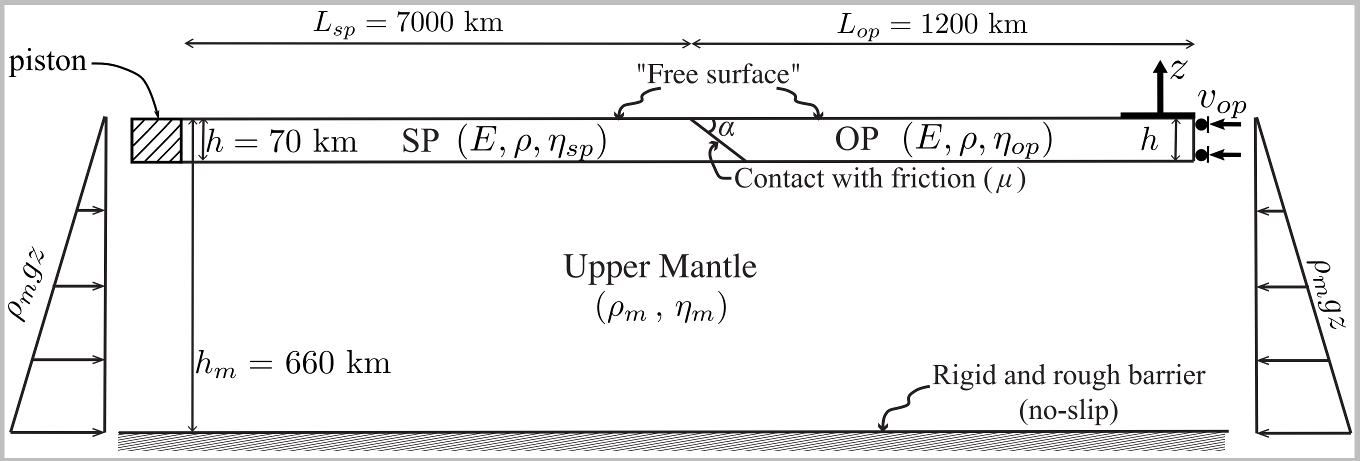


Fig. 2 : Sketch of initial geometry and boundary conditions.

- We evaluate the effect of
  - OP viscosity
  - SP viscosity
  - Friction at subduction interface
  - OP velocity

Model parameters		
E	Young modulus	10^{11} Pa
η_{op}	OP viscosity	10^{24} Pa s
η_{sp}	SP viscosity	10^{24} Pa s
η_m	Upper mantle viscosity	10^{20} Pa s
h	Plates' thickness	70 km
$\Delta\rho$	Plates-mantle density contrast	50 kg/m^3
μ	Interplate friction coefficient	0.01

Values in reference models

- We evaluate a free and a SP-free model (with v_{op}= 4 cm/yr) in the cases $\mu = 0.01$ and $\mu = 0.04$
- All models exhibit 4 distinct phases including a last quasi-steady state phase where relatively little changes are observed.
- **During the quasi-steady state phase** :
  - Low-μ case : the **OP** in the SP-free model moves slower than in the equivalent free-model thus the OP is in **extension**
  - High-μ case : the **OP** in the SP-free model moves faster than in the equivalent free-model thus the OP is in **compression**

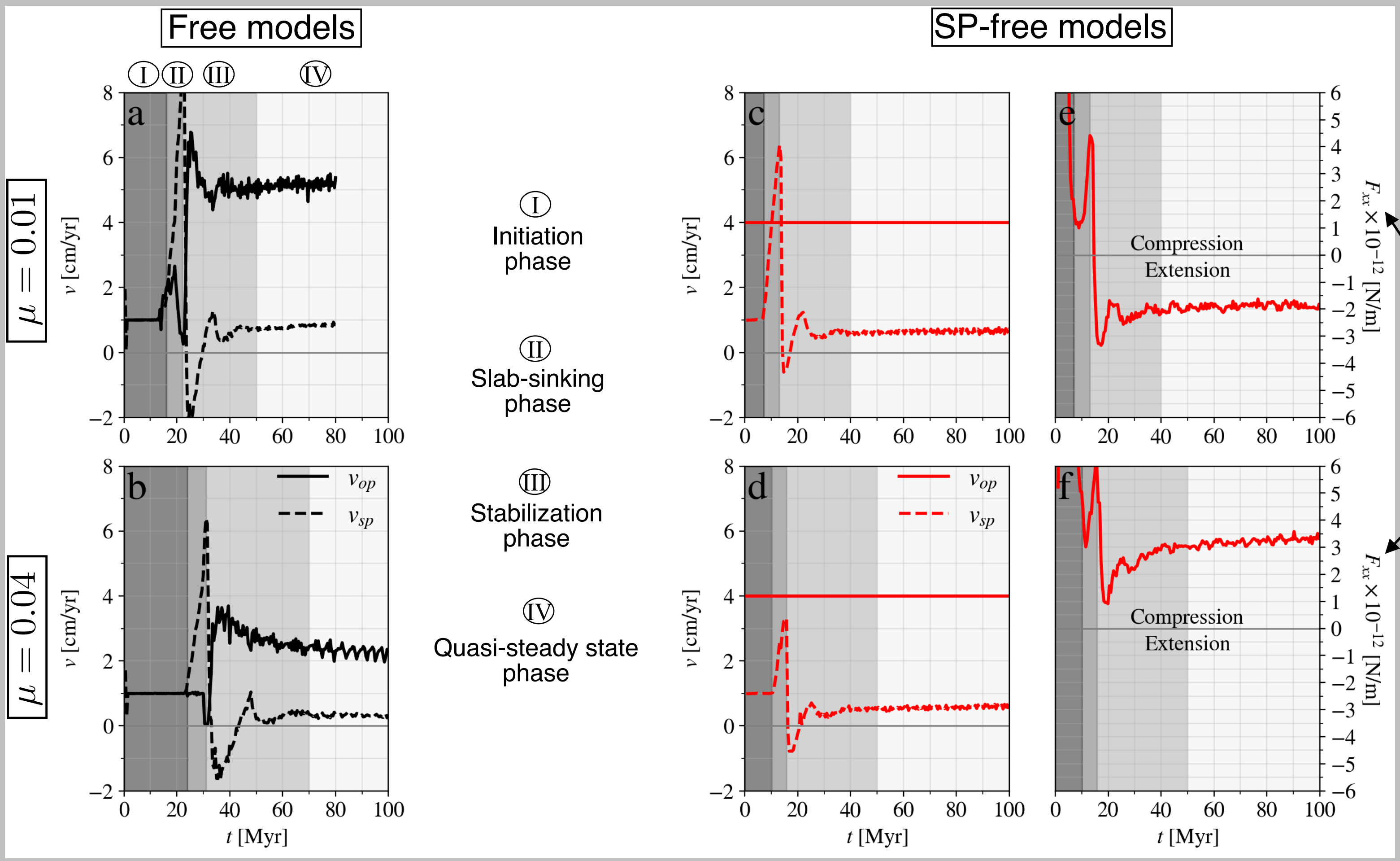


Fig. 3 : Kinematic evolution of free models (a, b) and SP-free models (c, d) with reference constant OP velocity (4 cm/yr), for an interplate friction coefficient of 0.01 (top row) and 0.04 (bottom row). The far-field horizontal force calculated at the trailing edge of the overriding plate is displayed for the SP-free models (e, f).

Overriding plate flexural topography

- The topography in the SP-free model with $v_{op} = 4$ cm/yr and $\mu = 0.01$ is represented below
  - Development of a prominent **forebulge**, a **depression** and a 2nd bulge of very small amplitude
  - The estimation of the **arc position lies near the surface depression**
  - **During the quasi-steady state, the topography evolves little**.

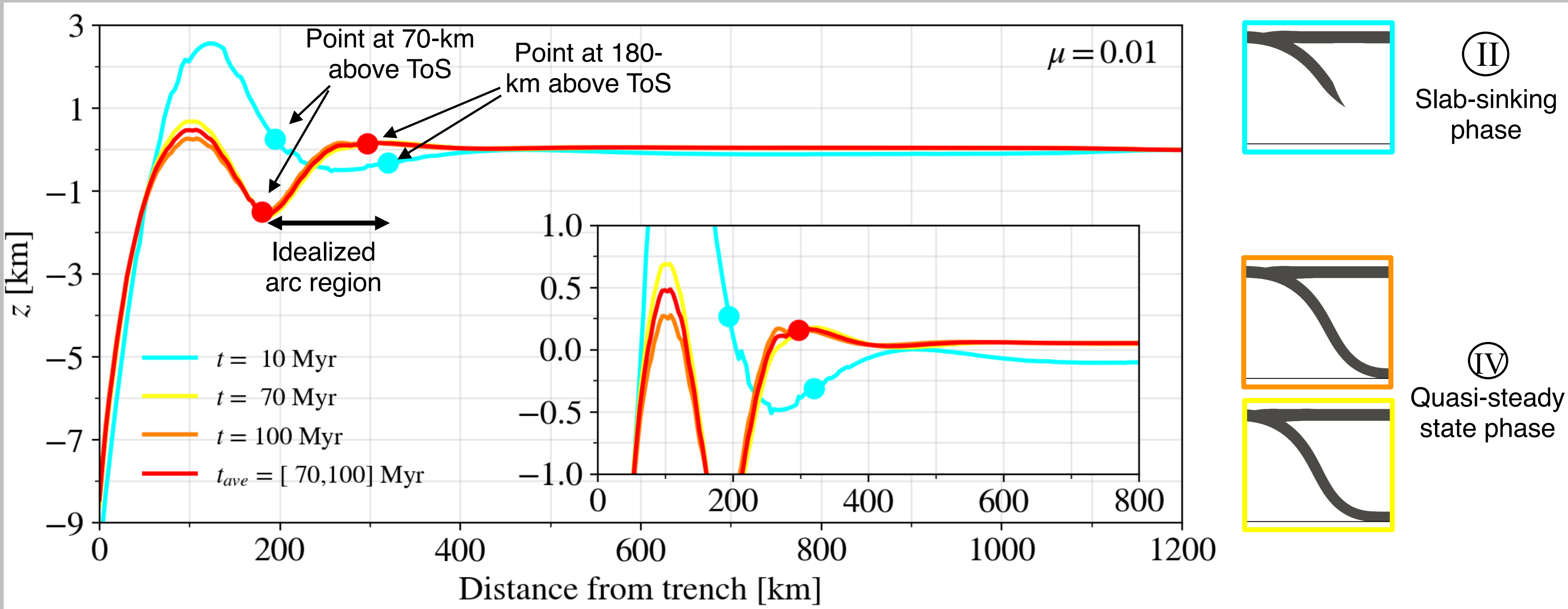
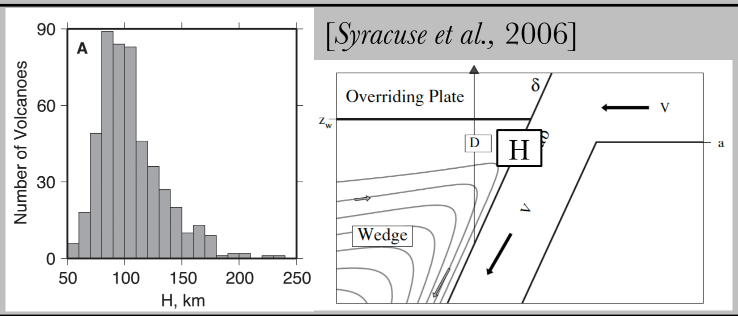


Fig. 4 : *Topographic profiles during the slab-sinking phase (cyan lines) and the quasi steady state phase (yellow and orange lines) for the models with the reference constant overriding plate velocity of 4 cm/yr and reference rheological parameters. Time-averaged profiles during the quasi steady state is also displayed (red lines). The circles represent the predicted arc location.*

Note: We define (geometrically) the idealized arc location as the region at the OP surface lying between 70 and 180 km above the top of the slab (ToS), consistent with observations for present-day subduction zones.



Effect of kinematics and OP tectonic regime on topography

- We evaluate the influence of v_{op} on OP topography (holding all the other rheological parameters fixed)
- **OP topography in the SP-free models varies according to the tectonic regime of the OP** (Fig. 5):
    - In the **neutral regime** (regime where far-field Fxx is close to zero because the imposed OP motion is close to its "free" velocity) the OP topography is close to that in the equivalent free-model. The peak-to-peak height between the forearc bulge crest and the bottom of the depression is the lowest among all the models, i.e. the **OP topography is the flattest**.
    - In the **extensive regime** (OP moves slower than its "free" motion), the **depression grows** with $|F_{xx}|$ whereas the height of the forearc-bulge crest changes little.
    - In the **compressive regime** (OP moves faster than its "free" motion), the **forearc bulge grows** with $|F_{xx}|$, while the depression remains stable regardless of Fxx.
    - OP **topography correlates with the shape of the subduction interface**, also controlled by the OP tectonic regime (Fig. 6)

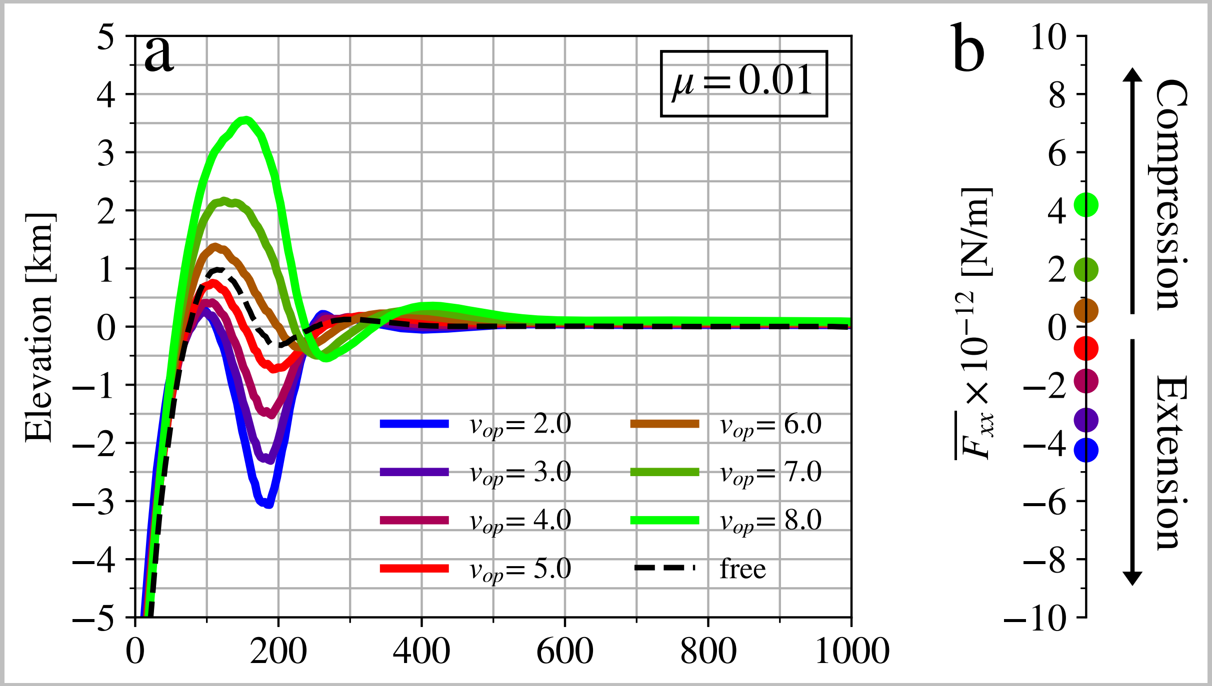


Fig. 5 : Time-averaged topographic profiles for SP-free model with μ=0.01 and various constant OP velocities. For comparison, we have also plotted the profiles obtained in the free models with identical rheological parameters. Right columns: time-averaged far-field horizontal force Fxx within the overriding plate.

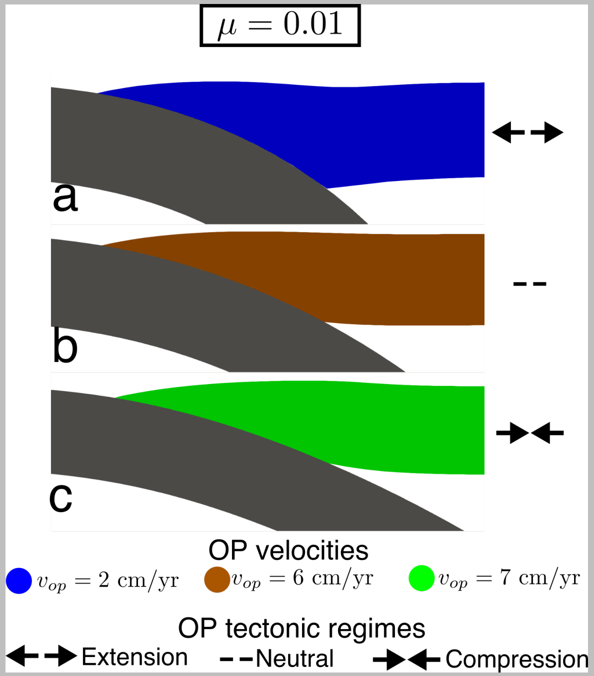


Fig. 6 : Geometry of the plate interface and average OP tectonic regime during the quasi-steady state phase.

Effect of interplate friction on OP topography

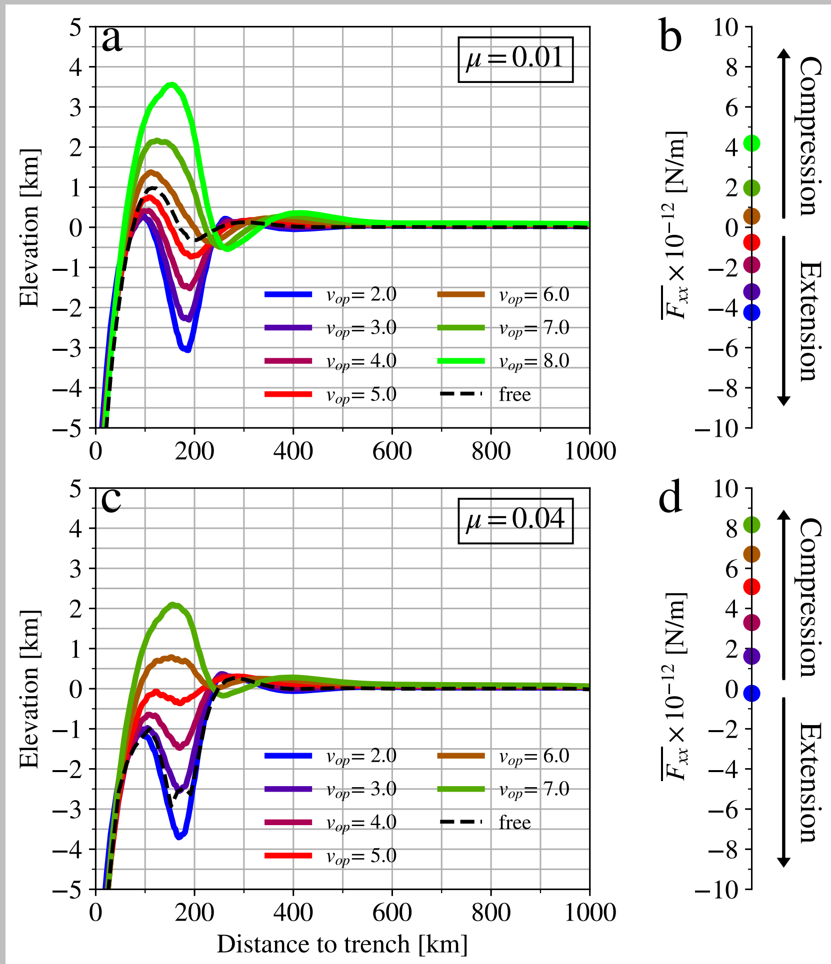


Fig. 7 : Time-averaged topographic profiles and time-averaged horizontal force F_{xx} for SP-free model with μ=0.01 (a,b) and μ=0.04 (c,d). See legend Fig. 4 for additional details.

We now compare the OP topography in models with different values of friction/shear at the subduction interface.

- **In high-μ models, the forearc region tends to be dragged down** by the shear at the plates interface.
- High values of **μ affects the relationship between OP topography and tectonic regime** :
  - In the neutral regime, the depression has a relatively high amplitude (also seen in the equivalent free model).
  - The flattest topography is observed when the OP is in moderate compression.

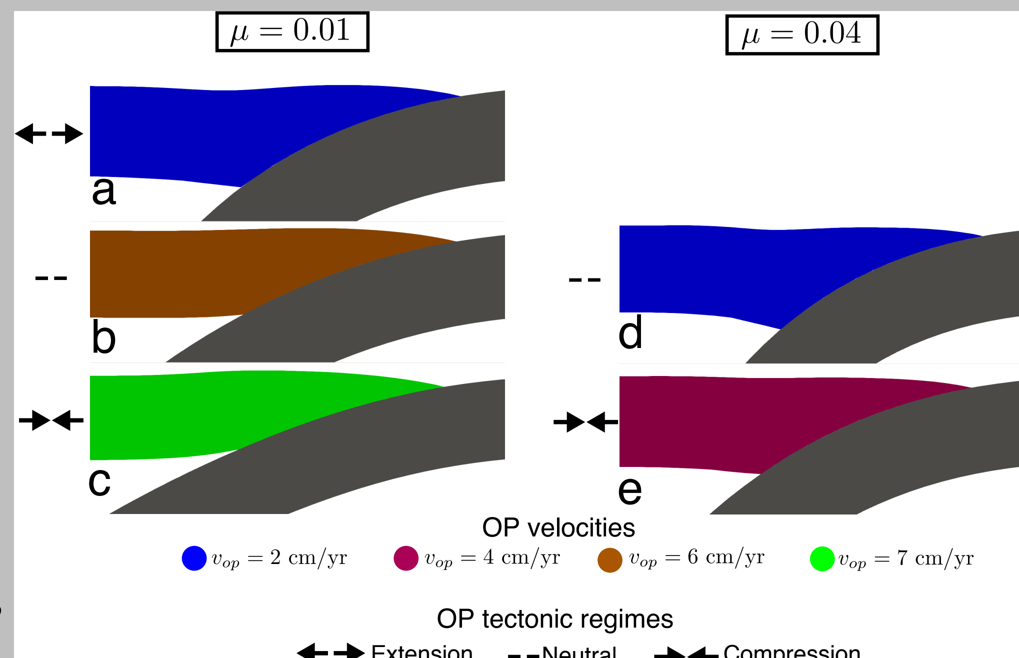


Fig. 8 : Geometry of the plate interface in models with constant OP velocity during the quasi-steady state phase. The average OP tectonic regime is also reported on the left side of the sub-panels.

Main take-home messages

- **The OP tectonic regime is modulated by the differential between the OP far-field velocity and its equivalent free-motion** (which depends on internal parameters such as the rheology).
- **The OP tectonic regime and the friction at the subduction interface are prime controls on the OP (flexural) topography**.

- **We have further studied the impact of changes in OP velocity** and showed that :
  - Following OP-velocity changes, a **transient episode of strong vertical motions (order of 0.1 mm/yr)** are predicted from the trench up to a distance of 600-800 km from the trench.
  - The transient episode is followed by a slower (rates of motions << 0.1 mm/yr) steady-state accommodation of topography to the new boundary condition.

⟹ To learn more about this check our recent paper [Cerpa & Arcay, G^3, 2020]

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Key Points:
- The topography amplitude and position on top of the overriding plate are controlled by its kinematics and the plate and interface strengths
- Changes in overriding plate velocity yield transient strong (rates ~0.1 mm/yr) surface vertical motions from the trench to the arc region
- The strength of the subducting plate has the strongest impact on the topographic response after a change in overriding plate kinematics

Supporting Information:
- Supporting Information S1
- Movie S1
- Movie S2

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Overriding Plate Velocity Control on Surface Topography in 2-D Models of Subduction Zones

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Abstract We study the dynamically induced flexural topography in subduction numerical mechanical models. We focus on the topographic changes at the overriding plate (OP) surface induced by variations in OP kinematics, particularly when the subducting plate (SP) has a stationary motion after having reached the rigid base of the upper mantle. Our models consist of two viscoelastic plates with free surfaces and an isoviscous mantle. Friction is imposed along the planar subduction interface. We first characterize the main topographic features at a constant OP velocity, using spatial definitions based on geometrical estimations of the volcanic arc position. The models exhibit the formation of a bulge in the forearc area followed landwards by a depression and a smaller second bulge, both bracketing the arc region. The steady-state distance to the trench of these features increases with OP velocity. Their amplitude is affected by the far-field OP tectonic regime that depends on kinematics, and plates and subduction interface strength. We next test the effect of sudden changes in OP velocity. An OP acceleration yields a transient topographic tilt, during which the outer forearc quickly subsides whereas the arc region uplifts, and that is followed by reverse slower motions. An OP slowdown induces opposite motions. The rates of elevation change during the tilt are approximately proportional to velocity variations and mainly sensitive to the SP strength. The rates are higher than 0.1 mm/yr for velocity changes higher than 1 cm/yr. We suggest that topographic accommodations of OP velocity changes should be considered when quantifying nonisostatic topography.

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