Overriding plate thickness as a controlling factor for trench retreat rates in narrow subduction zones

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Key Points:

- Three-dimensional numerical models of narrow subduction zones including all plates are performed to study trench kinematics
- Overriding plate thickness is the main factor affecting trench retreat velocities in narrow subduction zones
- The overriding plate has an important role in modulating trench geometries

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Abstract

Slab width plays a major role in controlling subduction dynamics and trench motion. However, observations on natural narrow subduction zones do not show any correlation between slab width and trench velocities, indicating that other factors may have a greater impact. Here, we use 3D numerical subduction models to evaluate the effect of slab width, strength of slab coupling to the lateral plate and overriding plate thickness on trench kinematics. Model results show that slab width has little influence on trench migration rates for narrow subduction zones, but that the thickness of the overriding plate plays a major role, with trench velocities decreasing as the thickness increases. These results explain trench velocities observed in natural narrow subduction zones showing no relation with slab width but an inverse dependence on overriding plate thickness. Finally, we find that the overriding plate thickness also significantly affects the trench shape.

Plain Language Summary

Subduction zones are the main drivers of plate tectonics and control much of the seismic and volcanic activity on Earth. For that reason, subduction processes have been widely studied in the last few decades. Because of the limited amount of available data, one of the key techniques has been numerical modelling. Some earlier models have shown that the velocity of the trench (long region marking where subduction starts) is affected by the width of the subduction zone, but this is not observed for narrow subduction zones in nature. In this work, we model 3D narrow subduction systems and find that the thickness of the unsubducted overriding plate affects trench velocities much more than the width of the subduction zone: the thicker the plate, the slower the trench motion. Moreover, the thickness of the overriding plate affects the shape that the trench develops. Our models explain some key observations in Earth's narrow subduction zones and help to better understand these processes.

1 Introduction

Subducting slabs are the main drivers of plate motion and flow in Earth's mantle. Thus, much effort has been put in the last few decades into understanding the main factors controlling slab dynamics and subduction-induced mantle flow (e.g., Billen, 2008; Funiciello et al., 2003; Gerya, 2022; Schellart, 2004; Stegman et al., 2010; van Hunen & Allen, 2011). Previous geodynamic modelling studies have shown the wide variety of physical parameters that influence subduction processes, such as the slab thickness (Bellahsen et al., 2005; Capitanio & Morra, 2012; F. Chen et al., 2022; Funiciello et al., 2008; Stegman et al., 2010) and length (A. F. Holt & Becker, 2016; Xue et al., 2020), the mantle rheology (A. F. Holt & Becker, 2016; Pusok et al., 2018), the strength and thickness of the overriding plate (OP) (Butterworth et al., 2012; Hertgen et al., 2020; A. Holt et al., 2015; Meyer & Schellart, 2013; Rodríguez-González et al., 2014; Sharples et al., 2014), the slab-mantle viscosity contrast (Funiciello et al., 2008; Schellart, 2008; Stegman et al., 2010), the coupling at the subduction-interface (Čížková & Bina, 2013, 2019; Behr et al., 2022) or the mechanical boundary conditions (Z. Chen et al., 2015; Funiciello et al., 2004). All these studies highlight the complexity of subduction, which makes these processes still incompletely understood in their key aspects (Gerya, 2022).

Among the factors controlling subduction dynamics, the slab width (W) has been shown to be of major importance (Bellahsen et al., 2005; F. Chen et al., 2022; Di Giuseppe et al., 2008; Guillaume et al., 2010, 2021; Royden & Husson, 2006; Schellart et al., 2007; Stegman et al., 2006, 2010; Strak & Schellart, 2016). Earlier geodynamic studies have distinguished three types of trench curvature depending on slab width: concave for narrow slabs (W $\leq$ 1500 km), "w"-shaped (also referred to as sublinear) for intermediate width slabs (W $\sim$ 2000-3000 km) and convex for wide slabs (W $\geq$ 4000 km) (Schellart et al., 2007; Stegman et al., 2010; Strak & Schellart, 2016), although the exact values differentiating these regimes depend somewhat on the specific conditions. In addition, the slab dip seems to be controlled by W, increasing (producing steeper slabs) with wider subducting plates (Schellart, 2004; Strak & Schellart, 2016). W also controls the subduction-induced mantle flow (Piromallo et al., 2006; Stegman et al., 2006), causing faster and more localized mantle upwellings near the lateral slab edges for wider slabs (Strak & Schellart, 2016). Regarding the slab kinematics, previous studies have shown that the trench retreat velocity (V_T) decreases as the slab becomes wider (F. Chen et al., 2022; Schellart, 2004; Schellart et al., 2007; Stegman et al., 2006). All these studies provide useful insights that help to understand the effect of W on subduction processes. However, most of these model setups that specifically focused on slab width had no OP, which is known to affect subduction dynamics significantly (e.g., Hertgen et al., 2020; Magni et al., 2014; Yamato et al., 2009). Additionally, the inverse depencence of V_T on W predicted by some models is not observed in natural narrow subduction zones (e.g., Calabria, Gibraltar, Scotia), which do not show any correlation between W and V_T, suggesting that other factors may play a more relevant role on trench retreat velocities. Incorporating an OP can help to better understand the effect of W on V_T and the dominant factors controlling trench retreat rates in narrow subduction zones.

In this study, we have conducted self-consistent 3D numerical subduction models to systematically evaluate in narrow subduction zones the effect of slab width, overriding plate thickness and coupling of the slab with the lateral plate on trench motion. In order to model realistic subduction processes, we have included the subducting and surrounding plates (lateral and overriding). Based on our geodynamic models and a comparison with observations in nature, this work explores the factors dominating trench retreat velocities in narrow subduction zones and provides new insights on the role of the OP in trench motion.

2 Methods

The simulations have been performed with version 2.4.0 of the finite-element code ASPECT (Advanced Solver for Problems in Earth's ConvecTion) (Kronbichler et al., 2012; Heister et al., 2017; Gassmöller et al., 2018; Bangerth et al., 2021a, 2021b). We have used the Boussinesq approximation to solve the coupled conservation equations for mass, momentum and energy, which assumes that the density is constant in all equations except in the buoyancy term of the momentum equation (Text S1 in the supporting information).

The initial 3-D model setup is shown in Figure 1. The initial geometry has been built using the Geodynamic World Builder (GWB) version 0.4.0 (Fraters et al., 2019, 2021) and it measures 2000x800x660 km in the x, y and z directions. Because the XZ plane at y = 0 is a plane of symmetry (Figure 1), we only model one half of the subduction zone. The initial geometry consists of an ongoing subduction system with a 220 km-long slab and a dip angle of 40°. In this way, the model is self-driven by buoyancy and the rest of internal forces. The subducting plate (SP) is comprised of weak crust 10 km thick and lithospheric mantle 85 km thick. The weak crust allows for the decoupling of the slab from the top surface and from the OP to facilitate subduction. The SP width is varied between models in the range of 400-1200 km. The OP has an initial thickness of 70 km, consisting of a 30 km crust and a 40 km lithospheric mantle, although its thickness also varies between models. The lateral plate (LP) is completely made of lithosphere 95 km thick, without any compositional stratification. We use a zone 20 km wide (transform fault) as a mechanical coupling of the lateral plate with the other plates. The trench is initially located at x = 1000 km, and we use particles placed along its length to track its movement over the time. The inclusion of the OP and LP provides a reasonable model setup and avoids unrealistic behaviour since the presence of these plates strongly affects the subduction dynamics (e.g., Yamato et al., 2009). For example, previous studies have shown that the presence of an OP results in a slowdown of the trench retreat velocities, highlighting that the poloidal flow is affected by the coupling of the subducting and overriding plate (e.g., Capitanio et al., 2010; Yamato et al., 2009). Regarding the role of the LP, its inclusion in subduction models prevents lateral shortening (Yamato et al., 2009).

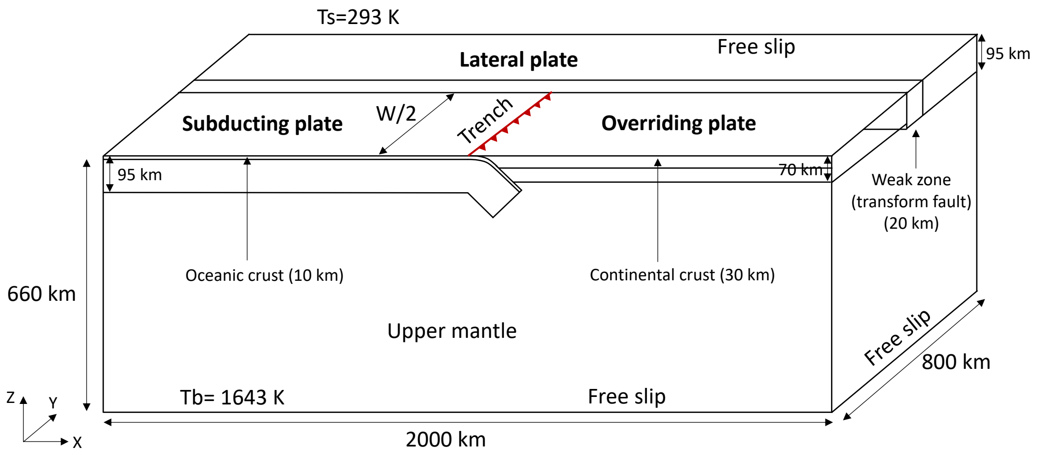

Figure 1. Three-dimensional model setup and boundary conditions. The setup includes a subducting plate (SP), an overriding plate (OP) and a lateral plate (LP). W indicates slab width and the red line with triangles marks the initial trench position at x = 1000 km. The trench is plotted for the whole subduction zone in Figures 2 and 3. The temperature is fixed to 293 K at the top boundary and 1643 K at the bottom boundary. All boundaries are free slip. Note that only half of the subduction zone is modelled due to the symmetry of the problem.

The initial temperature profile increases linearly from 293 K at the surface to 1643 K at the lithosphere-asthenosphere boundary (LAB). For the top and bottom boundaries we use Dirichlet temperature conditions. All boundaries are free slip, which means that the velocity perpendicular to the boundaries is prescribed to 0 (Dirichlet boundary condition) and that there are no stresses parallel to the boundary (Neumann boundary condition). In terms of rheology, we use a temperature-dependent viscosity (Text S2 and Table S1 in the supporting information) except for the subducting plate crust and weak zone where we impose constant viscosities of 10^{20} Pa s. With this rheology, we obtain a viscosity of $1.57 \cdot 10^{20}$ Pa s at a depth of 150 km. Finally, we impose cutoffs of $1 \cdot 10^{19}$ and $1.57 \cdot 10^{23}$ Pa s (1000 times the upper mantle viscosity at a depth of 150 km) to avoid large viscosity jumps. All model parameters are listed in Table S1 in the supporting information.

3 Results

3.1 Effect of slab width and coupling at the lateral slab edge

In order to study narrow subduction zones, we performed experiments varying W in the range of 400 to 1200 km. For each experiment, we have tested different amounts of mechanical coupling of the slab with the lateral plate by changing the viscosity of the transform fault (μ_{TF}) (experiments 1-15, Table S2 in the supporting information).

The subduction dynamics is similar in all the experiments. Initially, the slab freely sinks into the upper mantle due to the density contrast and the trench retreat velocities quickly increase (Figure 2d), accompanied by slab rollback and inducing toroidal flow around the slab edges (Figure S1 in the supporting information). All models show the maximum V_T when the slab tip reaches ~400 km depth. Thereafter, trench velocities slightly decrease due to the interaction of the slab tip with the deep viscous upper mantle, and approach a roughly constant value (Figure 2d).

Figures 2a-2d show the trench kinematics for a weak slab coupling to the lateral plate ($\mu_{TF} = 10^{20}$ Pa s). Models develop two types of trench geometries in the center of the subduction zone depending on W. The trench in models with W $\leq$ 1000 km shows a concave geometry toward the overriding plate, with the trench in the center of the subduction zone retreating faster than its edges (Figures 2a and 2b). This characteristic geometry is attained earlier in models with smaller W. For example, the concave geometry for W = 400 km is almost achieved in 2 Myr, while for W = 600 km it is not attained until 10 Myr. For the model with W = 1200 km, the trench geometry is rectilinear in its center up to 10 Myr, and thereafter adopts a "w"-shape, with retreat velocities being higher in between the lateral slab edge and the center of the subduction zone (Figure 2c). The highest V_T is found for W = 600 km and decreases for wider slabs (Figure 2d and blue line in Figure 2e).

Concerning the mechanical coupling of the slab with the lateral plate, we find that the maximum V_T correlates positively with W for W $\leq$ 600 km when the viscosity of the transform fault is $\mu_{TF} = 10^{20}$ Pa s, but for W $\leq$ 800 km when $\mu_{TF} = 10^{21}$ or $\mu_{TF} = 10^{22}$ Pa s (Figure 2e). The maximum V_T decreases as the viscous coupling increases for W $\leq$ 800 km, but does not change significantly for W > 800 km. The fact that the three curves in Figure 2e tend to converge with W approaching 1200 km indicates that effect of the strength of lateral coupling on V_T is only significant for very narrow subduction zones, and give maximum V_T differences about 1.8 cm/yr for W = 400 km. Finally, increasing the viscous coupling to the lateral plate also results in more concave trench geometries. For a W of 1200 km, we obtain "w"-shapes for $\mu_{TF} = 10^{20}$ and $\mu_{TF} = 10^{21}$ Pa s and concave geometries for $\mu_{TF} = 10^{22}$ Pa s (Figure S2 in the supporting information).

3.2 Effect of overriding plate thickness

We have varied the overriding plate thickness in the range of 40 to 100 km to study its effect on trench motion (experiments 2 and 16-21, Table S2 in the supporting information). In our models, the trench develops a concave geometry in all cases (Figures 3a, 3c and 3d) except for an OP thickness of 100 km, where a "w"-shape develops after about 10 Myr of evolution (Figure 3b), showing that thick overriding plates facilitates the formation of such geometries. Significant trench lateral shortening is also observed as the OP thickness increases (Figures 3b and 3d). Regarding the kinematics, V_T significantly decreases with thicker overriding plates (Figure 3e). For example, the maximum V_T is $\sim$ 6.8 cm/yr with an OP 40 km thick and decreases to $\sim$ 5.4 cm/yr with an OP 60 km thick. Short periods of small trench advance at the beginning of the simulation occur for OP thicknesses greater than 70 km (Figure 3e).

4 Discussion

4.1 Comparison with previous studies

Our geodynamic models provide new insights into the effect of W, OP thickness and strength of slab coupling to the lateral plate on trench kinematics. We find two out of the three types of trench geometries identified by Schellart et al. (2007), Stegman et al. (2010) and Strak and Schellart (2016) but for a different range of W values. The numerical models of Schellart et al. (2007) and Stegman et al. (2010) suggest values of W $\leq$ 1500 km, W $\sim$ 2000-3000 km and W $\geq$ 4000 km leading to concave, "w"-shaped and convex trenches, while the analog models of Strak and Schellart (2016) indicate values of W = 2000-2500 km and W $\geq$ 3000 km for "w"-shaped and convex geometries respectively. The analog modelling of Guillaume et al. (2021) predicts concave and "w"-shaped geometries even for wider slabs (W = 2000 and W = 4000 km respectively). Similarly, the recent 3-D spherical shell numerical models of F. Chen et al. (2022) place the transition from concave trenches to "w"-shaped geometries at a W of 2400 km for their reference case. Our results do not show convex geometries, which is expected as we focus only on narrow subduction zones and these geometries are found for very wide slabs (Schellart et al., 2007; Strak & Schellart, 2016). However, our models show a "w"-shaped geometry for a much narrower slab (W = 1200 km, Figure 2c) than in previous studies (W $\geq$ 2000). Following our results, a likely factor

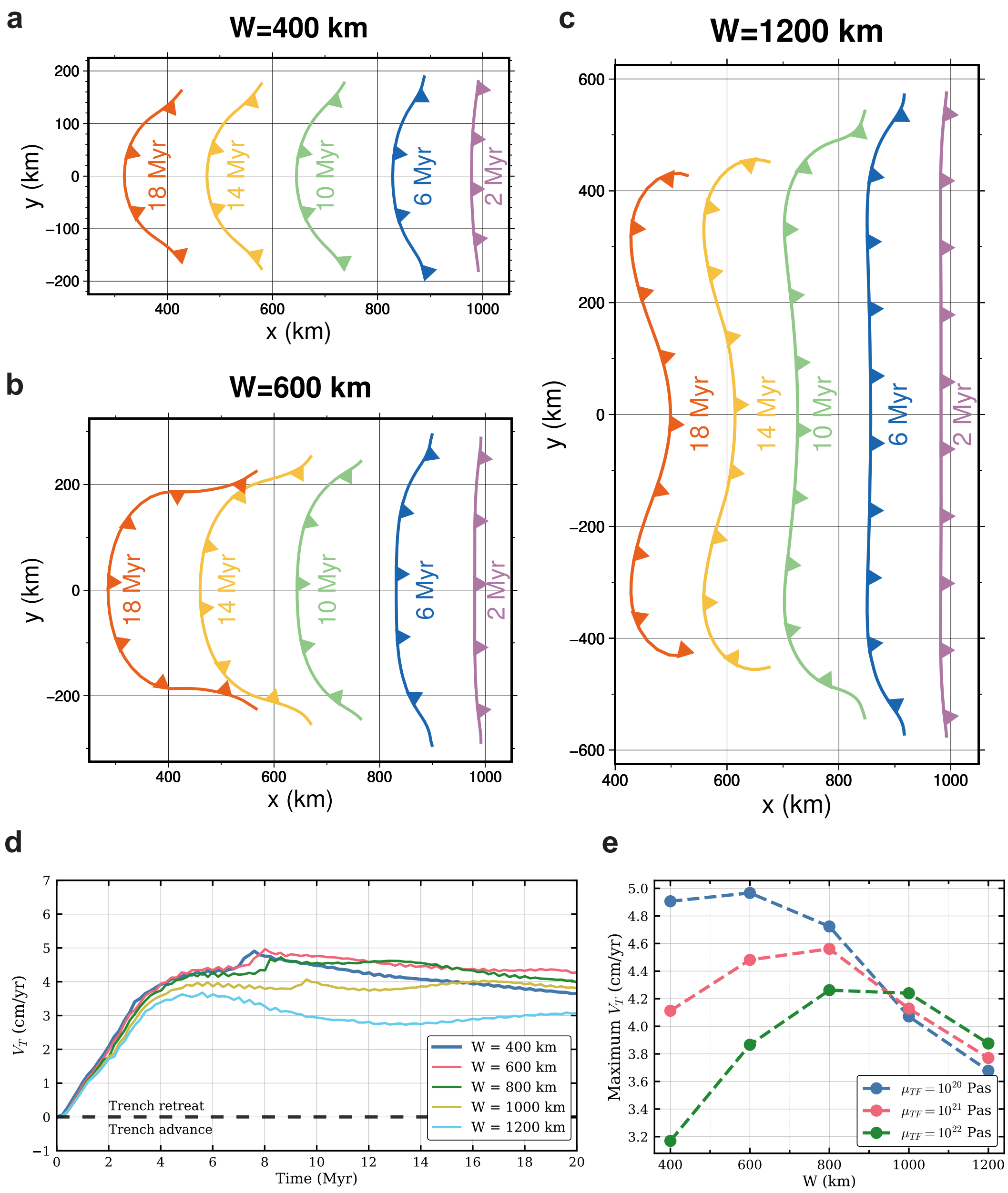

Figure 2. (a-c) Evolution of the subduction trench for three simulations with (a) W = 400 km, (b) W = 600 km and (c) W = 1200 km. Note that the entire trench is plotted but we only model half of the subduction zone. (d) V_T over time (measured in the center of the subduction zone) for simulations with different W. Panels (a-d) show the results for a $\mu_{TF} = 10^{20}$ Pa s. (e) Maximum V_T at the center of the subduction zone for diferrent W and different viscous coupling at the lateral slab edge.

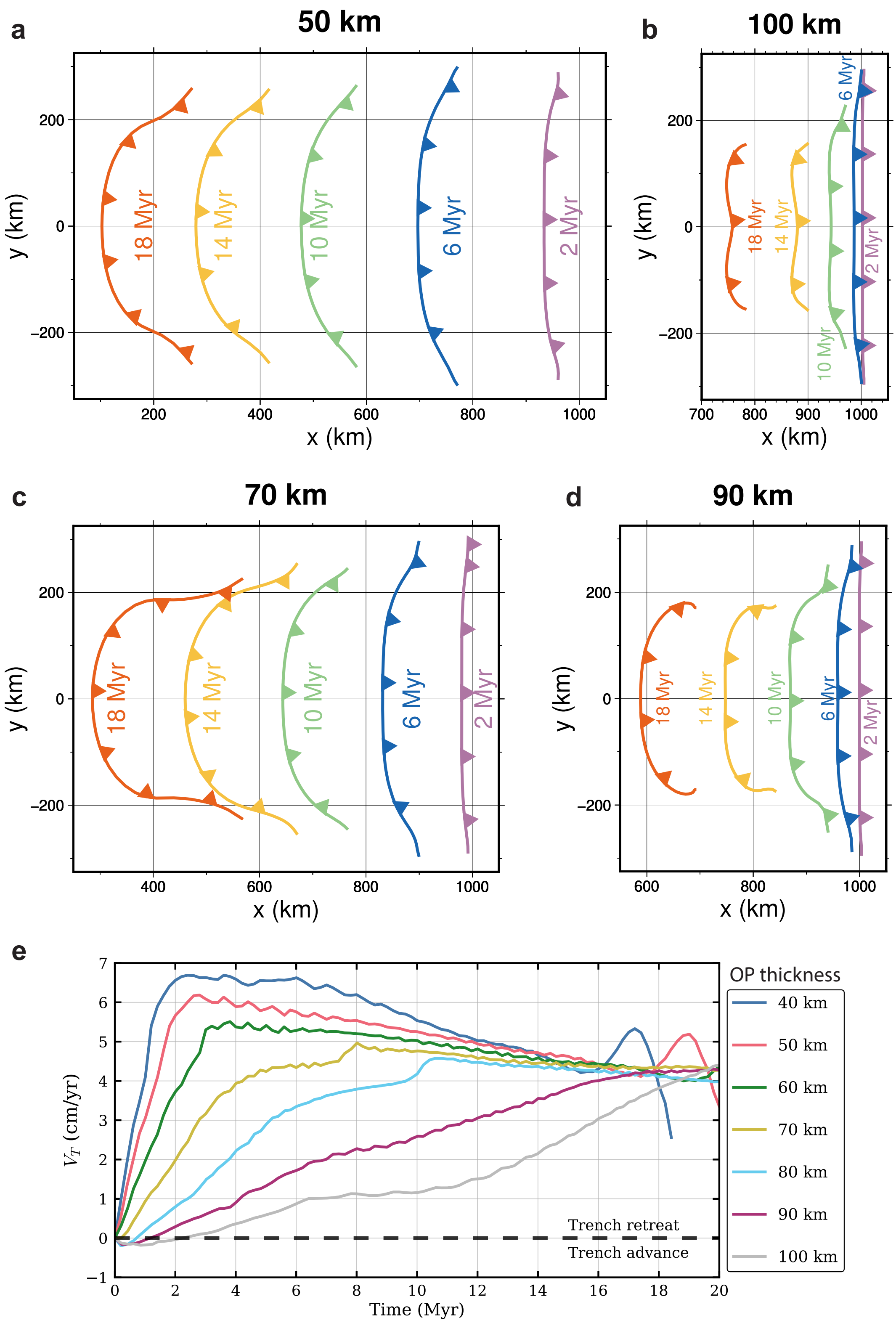

Figure 3. (a-d) Evolution of the subduction trench for four simulations with OP thicknesses of (a) 50 km, (b) 100 km, (c) 70 km and (d) 90 km. Note that the entire trench is plotted but we only model half of the subduction zone. (e) V_T over time (measured in the center of the subduction zone) for simulations with different OP thicknesses.

that could explain these discrepancies is the influence of the OP, which was not included in such previous studies. In fact, our results show that increasing the OP thickness in models with the same W leads to "w"-shaped trenches (Figure 3b).

Regarding trench migration velocities, previous modelling studies have found that V_T decreases with increasing W (e.g., F. Chen et al., 2022; Schellart et al., 2007; Stegman et al., 2006). However, this behaviour is not always maintained for narrow subduction zones. Our results show a direct dependence of V_T on W for W $\leq$ 600 km when the mechanical coupling of the slab with the lateral plate is weak ($\mu_{TF} = 10^{20}$ Pa s) and for W $\leq$ 800 km when the coupling is stronger ($\mu_{TF} = 10^{21}$ and $\mu_{TF} = 10^{22}$ Pa s) (Figure 2e). This positive correlation between V_T and W has also been suggested in previous works for W $\leq$ 500-600 km (Schellart, 2004; Stegman et al., 2006) and for W $\leq\sim$ 1000 km (Strak & Schellart, 2016). Our models using a weak coupling are in agreement with the results of Stegman et al. (2006) finding a maximum retreat velocity for W = 600 km. The difference between the present work and previous studies on which slab width exhibits the highest V_T suggests a dependence on different model parameters and setup. For example, our models show that the W for which V_T peaks increases as the viscous coupling at the transform fault becomes stronger (Figure 2e). More research is needed to clarify the dynamics and factors affecting this phenomenon. Here we propose that a peak V_T is observed in Figure 2e due to an energy balance (Magni et al., 2014) between the available gravitational potential energy of the slab E_{pot} and the energy required for frictional dissipation in the mantle $E_{diss,m}$ and at the transform fault $E_{diss,TF}$. For relatively wide slabs, $E_{diss,TF}$ is relatively unimportant, E_{pot} linearly increases with slab width, while $E_{diss,m}$ increases faster than that. So trench retreat is slower for wider slabs. For narrow slabs, E_{pot} and $E_{diss,m}$ are both small, and $E_{diss,TF}$ becomes more important. Since E_{pot} decreases for narrowing slabs, while $E_{diss,TF}$ is independent of slab width, narrow slabs retreat slower than wider slabs. Finally, our models demonstrate the strong impact of the OP thickness on trench retreat velocities, with V_T decreasing significantly with increasing OP thickness (Figure 3e). This result is in agreement with the recent 3D numerical modelling including a SP and OP by Hertgen et al. (2020), who found that thin/weak OP favours faster trench velocities and rollback compared to a thick/strong OP. The 2D self-consistent subduction models of Gea et al. (2023) and A. Holt et al. (2015) also show that a thicker OP leads to a reduction in V_T. Increasing the thickness of the OP limits the space for the induced mantle to flow beneath it, thus reducing the interaction between the slab and the poloidal flow and resulting in lower trench retreat.

4.2 Comparison with nature

Natural subduction zones on Earth are influenced by a large number of factors that are not included in our models, such as slabs of non-uniform age, complex slab morphologies or plate velocities. Thus, comparing our results with observations on Earth should be approached with caution, being aware of the inherent limitations. Nevertheless, our geodynamic model predictions are useful to explain some observations on natural narrow subduction zones.

The concave trench geometries predicted by our geodynamic models are widely observed on Earth for narrow subduction zones. The Gibraltar slab is the clear example of this geometry (Figure 4a). Our results have demonstrated that including an OP facilitates the formation of "w"-shaped geometries. For example, our model with W = 1200 km and $\mu_{TF} = 10^{20}$ Pa s develops a "w"-shape (Figure 2c) for much smaller W than any of the previous studies not using an OP (e.g., F. Chen et al., 2022; Schellart et al., 2007; Stegman et al., 2010; Strak & Schellart, 2016). Increasing the thickness of the OP has also been shown to affect the geometry of the trench, with a OP 100 km thick leading to a "w"-shaped geometry (Figure 3b). This effect of the OP could explain why some natural subduction zones of narrow to intermediate widths develop "w"-shapes. For example, the Manila trench (W = 1000 km) has a geometry between concave and "w"-shaped (Figure

4c) and the Hellenic Arc (W = 1700 km) shows a clear "w"-shape (Figure 4b), with a much narrower W than those predicted by previous studies not including an OP.

The decrease in V_T with increasing W observed in the present work for W $\geq$ 800 km (Figures 2d and 2e) and in previous works (e.g., F. Chen et al., 2022; Royden & Husson, 2006; Schellart et al., 2007; Stegman et al., 2006) is in general agreement with observations in narrow and wide subduction zones. This result explains why narrow subduction zones (e.g. Calabria, South Shetland, Halmahera) exhibit relatively high V_T, while wide subduction zones (e.g. Melanesia, South America) are essentially stationary (Schellart et al., 2007). However, when this comparison is restricted to narrow subduction zones, no such correlation is observed (Figure 4d). For the same slab width ($\sim$ 900 km), the Makran subduction zone has a V_T of 0.2 cm/yr while the Trobriand system has a V_T of 7.6 cm/yr. Our results showing that W has little effect on V_T for narrow subduction zones, with variations in $V_T \leq 1$ cm/yr (Figure 2e), are in agreement with the lack of correlation between W and V_T observed in nature and provide an explanation for these observations. In contrast, our models reveal that the effect of OP thickness is much stronger, showing an inverse dependence of V_T on OP thickness (Figure 3e). This tendency is also observed in nature for narrow subduction zones (Figure 4e) and brings an explanation of why two subduction zones with the same W (such as Makran and Trobriand) show such different V_T.

5 Conclusions

The 3-D numerical subduction models presented in this work shed light on some factors (slab width, overriding plate thickness and coupling of the slab with the lateral plate) controlling trench kinematics in narrow subduction zones, and help to explain some observations of natural subduction processes. As opposed to what happens in wide subduction zones, our models show that the slab width has little effect on trench retreat velocities for narrow subduction zones, which is consistent with the lack of correlation between these parameters observed in nature. In contrast, from our models and observations in nature we conclude that the thickness of the overriding plate is the main controlling factor on trench retreat velocities for narrow subduction zones, with velocities decreasing as the thickness increases. The strength of slab coupling to the lateral plate is only significant for very narrow subduction zones. Finally, the inclusion of an overriding plate plays an important role in modulating trench geometries, facilitating the formation of "w"-shaped geometries, which are predicted for smaller slab widths than in previous studies.

6 Open Research

The version 2.4.0 of ASPECT used in this study is available at `https://zenodo.org/record/6903424`. All the information and parameters of the models of this work can be found in the Methods section, in Text S1 and S2 in the supporting information and in Table S1 in the supporting information. The files required to reproduce our simulations are available on `https://github.com/Pedrogea08/Gea_et_al_2023GRL`.

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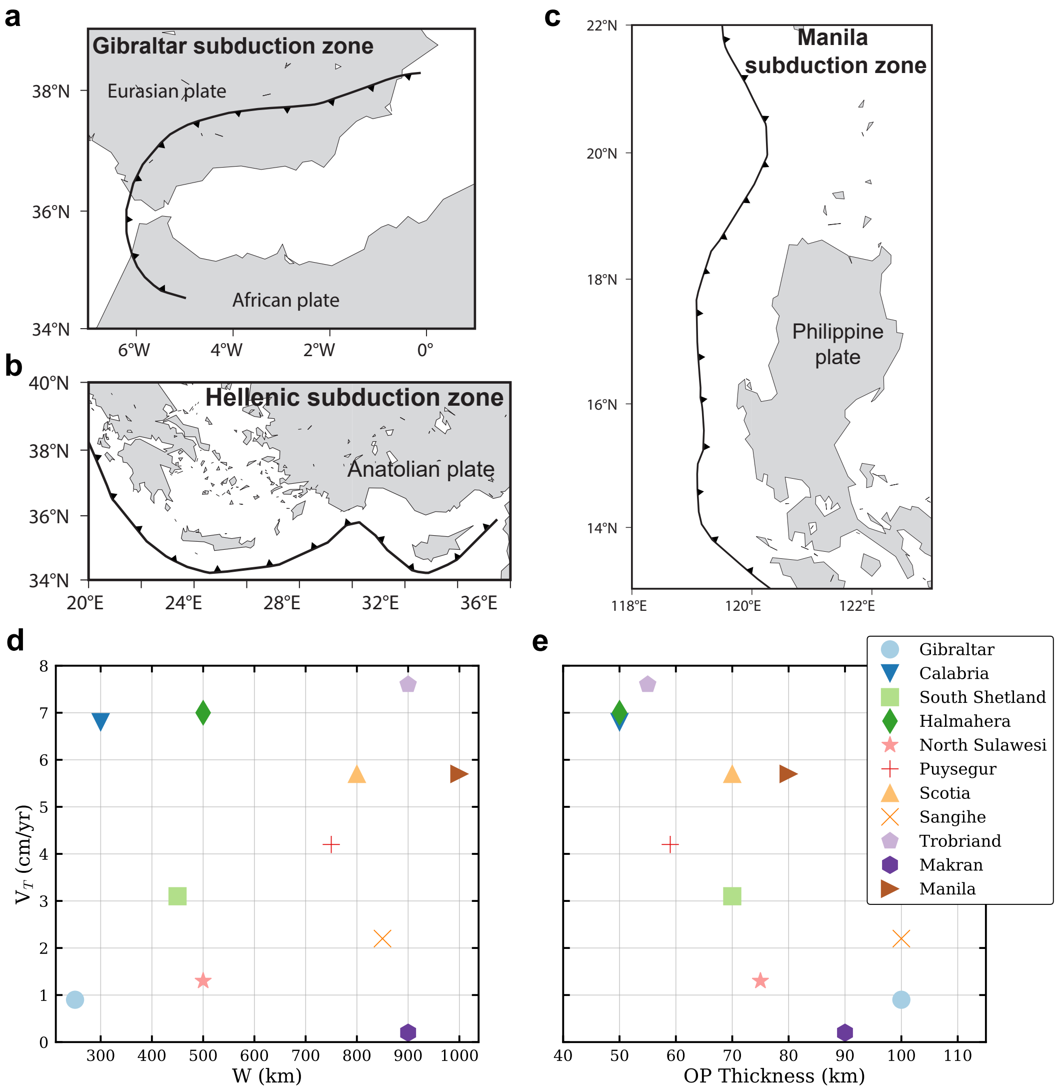

Figure 4. (a-c) Subduction fronts at present-day for the (a) Gibraltar subduction system (from Gutscher et al. (2012), (b) Hellenic subduction zone (from Lemenkova (2021)) and (c) Manila subduction zone (from Qiu et al. (2019)). (c) V_T against W for all subduction zones in Earth with W $\leq$ 1000 km (data from Schellart et al. (2007)). (e) V_T against OP thickness for all subduction zones in Earth with W $\leq$ 1000 km (data can be found in table S3 in the supporting information).

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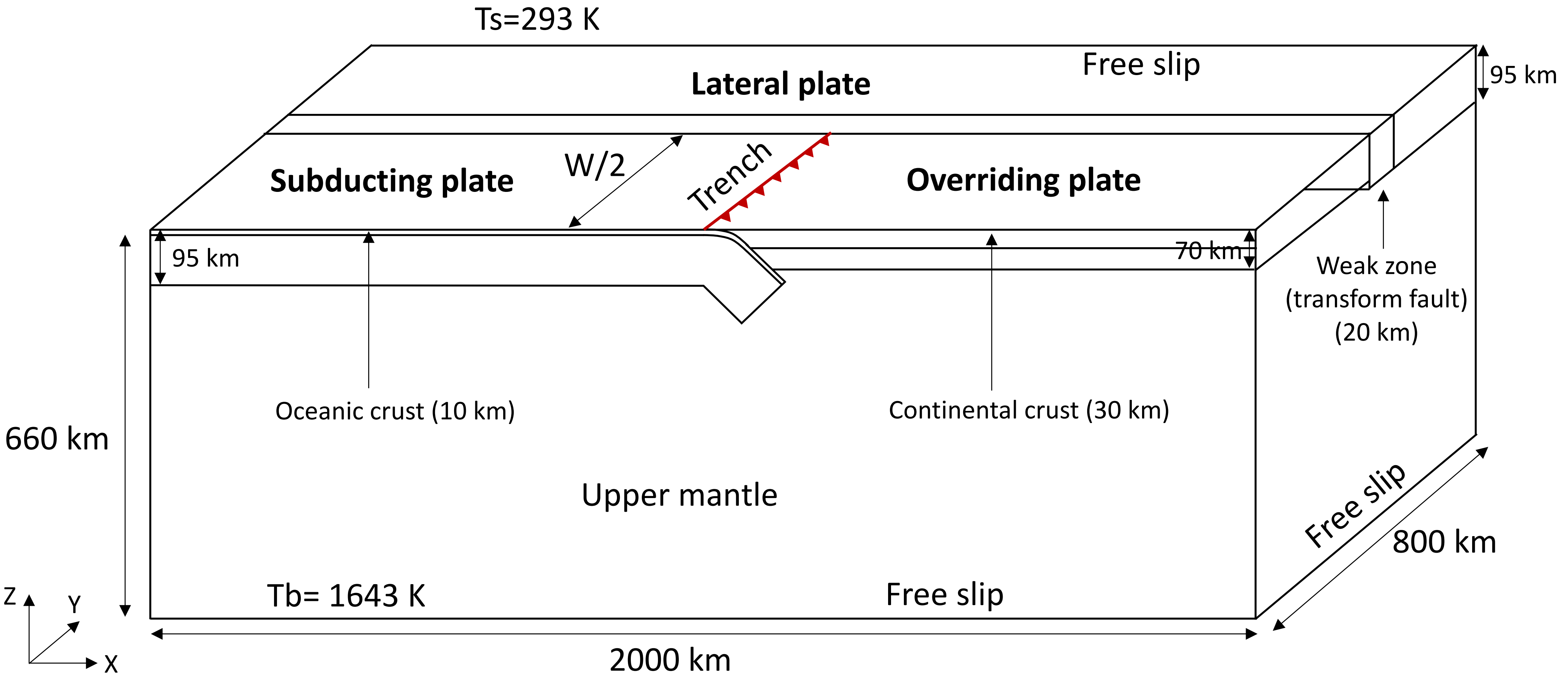
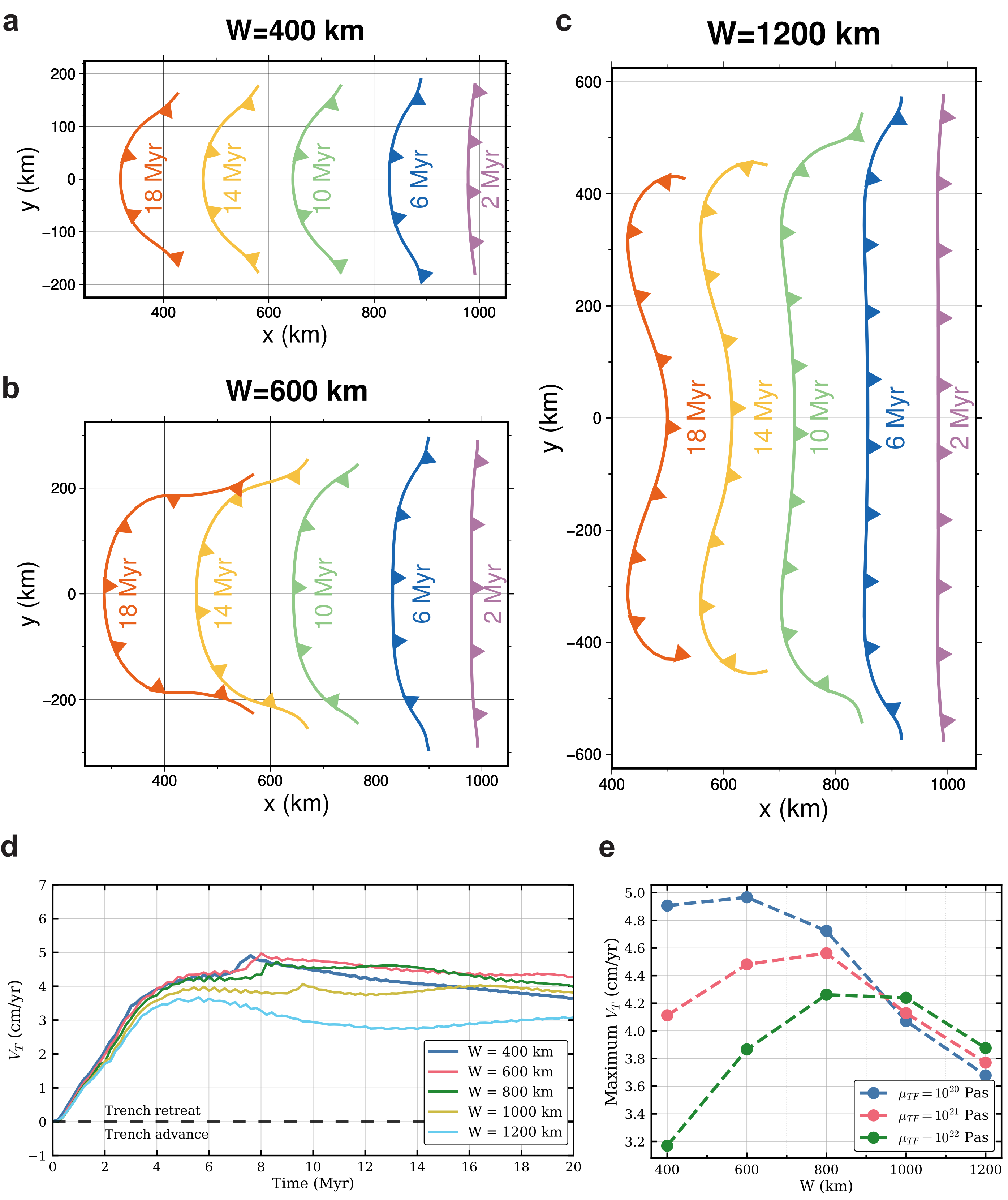
Figure 1.



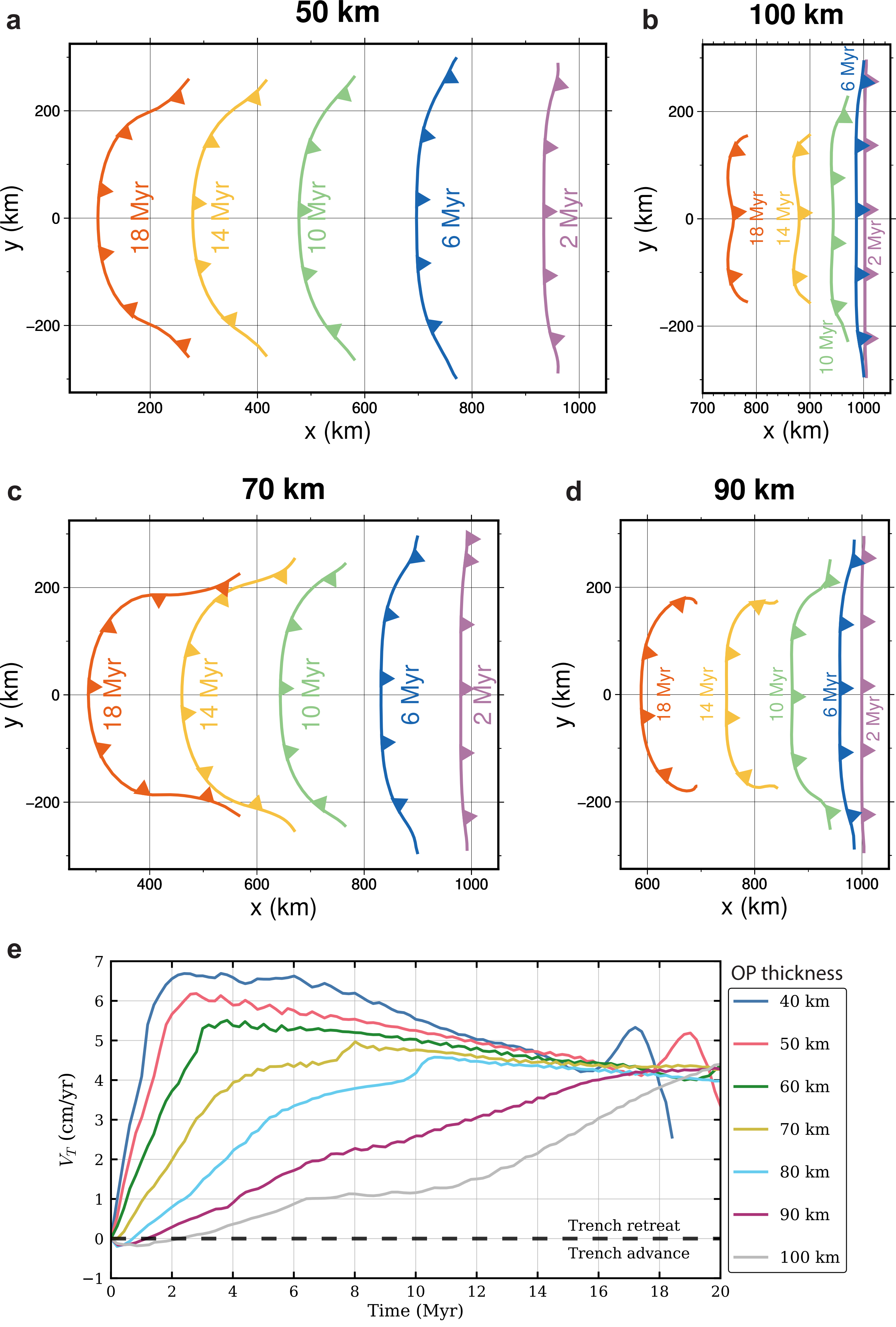
Ts=293 K
Free slip
95 km
Lateral plate
Subducting plate
W/2
Trench
Overriding plate
95 km
70 km
Weak zone
(transform fault)
(20 km)
660 km
Oceanic crust (10 km)
Continental crust (30 km)
Upper mantle
Free slip
800 km
Tb= 1643 K
Free slip
Z
Y
X
2000 km

Figure 2.



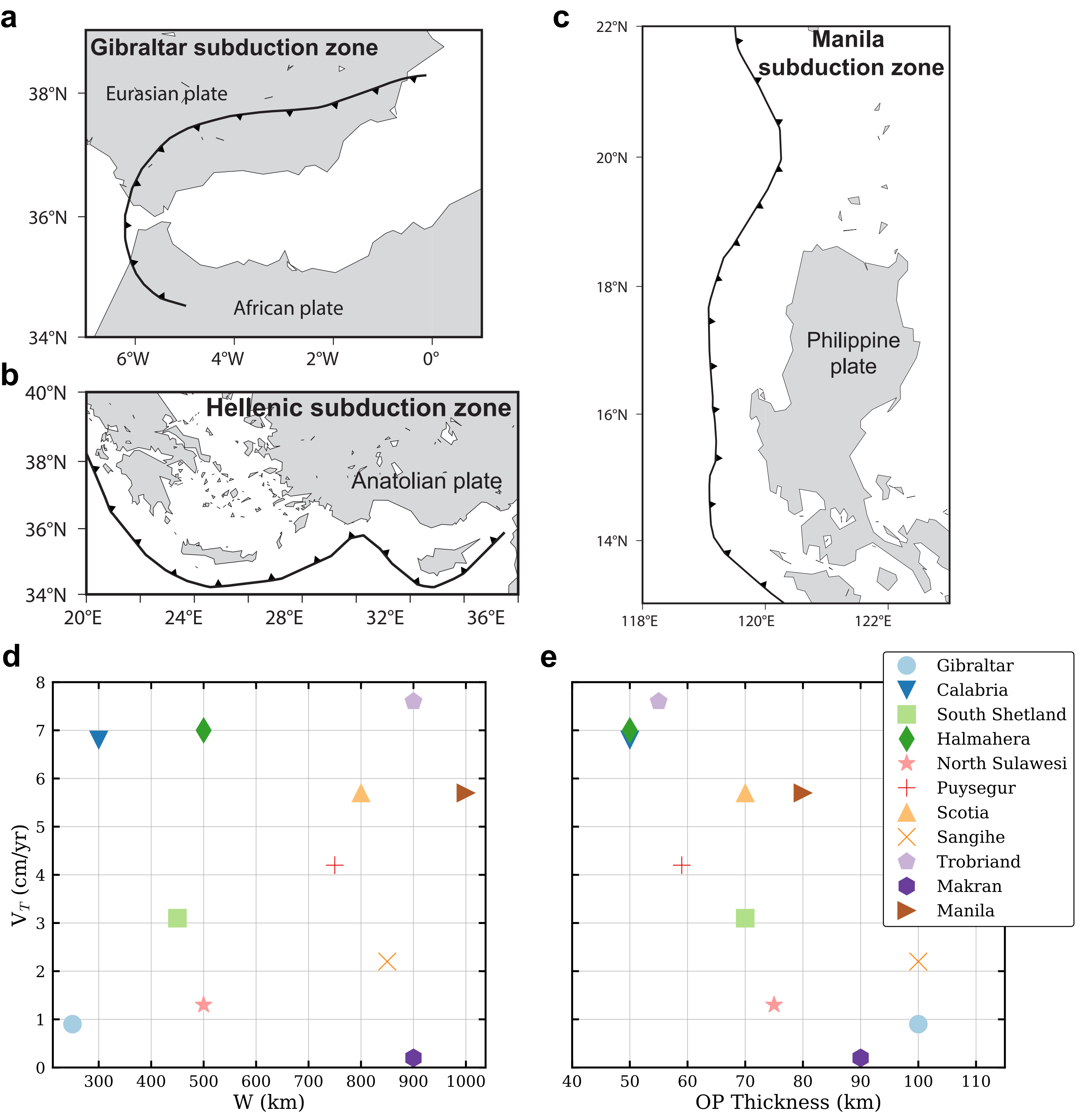
a
W=400 km
18 Myr
14 Myr
10 Myr
6 Myr
2 Myr
y (km)
x (km)
b
W=600 km
c
W=1200 km
d
Trench retreat
Trench advance
W = 400 km
W = 600 km
W = 800 km
W = 1000 km
W = 1200 km
V_T (cm/yr)
Time (Myr)
e
Maximum V_T (cm/yr)
W (km)
$\mu_{TF} = 10^{20}$ Pas
$\mu_{TF} = 10^{21}$ Pas
$\mu_{TF} = 10^{22}$ Pas

Figure 3.



a
50 km
b
100 km
c
70 km
d
90 km
18 Myr
14 Myr
10 Myr
6 Myr
2 Myr
y (km)
x (km)
e
OP thickness
40 km
50 km
60 km
70 km
80 km
90 km
100 km
Trench retreat
Trench advance
V_T (cm/yr)
Time (Myr)

Figure 4.


a
Gibraltar subduction zone
Eurasian plate
African plate
38°N
36°N
34°N
6°W
4°W
2°W
0°
b
Hellenic subduction zone
Anatolian plate
40°N
38°N
36°N
34°N
20°E
24°E
28°E
32°E
36°E
c
Manila subduction zone
Philippine plate
22°N
20°N
18°N
16°N
14°N
118°E
120°E
122°E
d
V_T (cm/yr)
W (km)
e
OP Thickness (km)
Gibraltar
Calabria
South Shetland
Halmahera
North Sulawesi
Puysegur
Scotia
Sangihe
Trobriand
Makran
Manila