The impact of a very weak and thin upper asthenosphere on subduction motions

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Key Points:

• Numerical models show that a very weak and thin upper asthenosphere layer can alone reduce trench retreat and enhance plate motion
• The impact of this effect depends on the relative contrast between the effective stiffness of the lithosphere and the underlying mantle
• This regional mechanism explains the high convergence and low trench migrations rates observed globally at natural subduction zones

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Abstract
Recent geophysical observations report the presence of a very weak and thin upper asthenosphere underneath subducting oceanic plates at convergent margins. Along these margins, trench migrations are significantly slower than plate convergence rates. We use numerical models to assess the role of a weak upper asthenospheric layer on plate and trench motions. We show that the presence of this layer alone can enhance an advancing trend for the motion of the plate and hamper trench retreat. This mechanism provides a novel and alternative explanation for the slow rates of trench migration and fast-moving plates observed globally at natural subduction zones.

Plain Language Summary
Plate tectonics relies on the concept of a rigid surface layer (the lithosphere) fragmented in a series of major and minor tectonic plates moving over a weaker and buoyant layer of asthenospheric material. The motion and deformation of the lithosphere are primarily driven by the sinking of the colder and denser oceanic lithosphere through time into the Earth’s interior at subduction zones. A range of geophysical regional studies has recently brought considerable attention to the detailed structure of the asthenosphere at these zones. These studies report the presence of a thin and even weaker asthenospheric layer at the base of the subducting lithosphere. We investigate the role of this layer on subduction dynamics using geodynamics numerical models. Our models apply knowledge of physics, chemistry, mathematics and geology, and study the dynamics of the Earth’s deep interior and their feedback on surface deformation. Our numerical results demonstrate that a very weak and thin upper asthenosphere affects the dynamics of sinking plates. It acts as a slippery base for the motion of the plate significantly increasing its speed and deformation. Our research provides a novel explanation to interpret some of
the subduction phenomena at the regional scale observed on Earth, which have proven numerical difficulties until now.

1 Introduction

The boundary between the Earth’s tectonic plates and the underlying mantle, the lithosphere-asthenosphere boundary (LAB), is a fundamental element of plate tectonics as it critically controls the mechanical coupling between the motion of the tectonic plates and the flow in the underlying mantle (Anderson, 1995). The motions and deformation of the solid plates are primarily driven by the downward pull of slabs (Harper, 1975; Forsyth et al., 1975; Chapple & Tullis, 1977; Conrad & Lithgow-Bertelloni, 2002) and by the coupling with the viscous mantle flow surrounding them (Lithgow-Bertelloni & Richards, 1995, 1998; Conrad & Hager, 1999; Becker & O’Connell, 2001). Forces associated with the sinking of slabs into the mantle propagate to the surface controlling plate motions towards the trench zone and mantle flow around subducting slabs. Therefore, a very weak and thin upper asthenosphere (WL) may contribute to the drag exerted at the base of subducting plates having an impact on the force balance around the oceanic lithosphere. This could play an important role in decoupling the motion of tectonic plates from the flow in the underlying mantle, promoting or opposing subduction motions with respect to the mantle underneath.

The subduction of an oceanic plate into the mantle occurs concurrently with the motion of trenches at the surface. These are mobile and can either retreat, advance, or have a mixed type of motion in time with respect to a specific reference frame. We refer to the percentage ratio between the horizontal plate ($V_P$) and trench migration ($V_T$) velocities as the subduction partitioning ($\frac{V_T}{V_P}$). The subduction partitioning, as well as the subduction dip angle and the morphology assumed by the subducting slab while interacting with the 660km transition zone are considered diagnostic elements to iden-
ify the subduction style (e.g., Christensen, 1996; Zhong & Gurnis, 1997; Bellahsen et al., 2005; F. Capitanio et al., 2007; Faccenna et al., 2007; Di Giuseppe et al., 2008; Funiciello et al., 2008; F. A. Capitanio et al., 2009; Stegman et al., 2010; Goes et al., 2011; Gérald et al., 2012). Most of the Earth’s slab and trench motions occur in conjunction with roll-back and retreat (-VT), however advancing plate and trench motion (+VT) towards the upper plate can also be found in some trench zones, e.g. at some of the edges of the Pacific plate (Schellart et al., 2008). Furthermore, the average absolute trench velocity observed globally is one third or less of the total convergence at the present, consistently across the majority of plate motions reference frames (e.g., Elssasser, 1971; Jarrard, 1986; Schellart et al., 2008; Becker & Faccenna, 2009; A. F. Holt & Becker, 2016; Goes et al., 2011). Numerical and analogous subduction models have previously helped explain the fundamental force balance of plate motions, yet the observed slow retreat with fast advance does not emerge as a general feature (A. F. Holt & Becker, 2016; Coltice et al., 2017). Geoid observations (Moresi & Gurnis, 1996; Mitrovica & Forte, 1997; Zhong & Davies, 1999), and numerical and geophysical studies (e.g., Schellart, 2004; Bellahsen et al., 2005; Di Giuseppe et al., 2008; Funiciello et al., 2008; Schellart et al., 2008; Wu et al., 2008; F. A. Capitanio et al., 2009) constrain the viscosity contrast between the subducting oceanic plates and the mantle to be within a range of 100-500. These show significant slab roll back and trench retreat (i.e. VT/VP < -0.3). In most of these models, trench advance occurs for stiff, slowly migrating plates such as those with a viscosity contrast between the subducting lithosphere and the mantle greater than 1000. However, this is not easily reconciled with what is generally observed in nature and might apply to regional cases only (e.g., Jarrard, 1986; Garfunkel et al., 1986; Lallemand et al., 2005; Bellahsen et al., 2005; Sdrolias & Müller, 2006; Faccenna et al., 2007; Funiciello et al., 2008; Schellart et al., 2008; Di Giuseppe et al., 2008; Stegman et al., 2010; Goes et al., 2017). This still presents the difficult task of explaining the low apparent strength of tectonic plates relative to the
underlying mantle and the efficient slab pull propagation needed in subduction models to match plate velocities. Some solutions to explain such a slow retreating motion have been proposed, such as the role of slab rheology (e.g., F. Capitanio et al., 2007; Billen & Hirth, 2007; F. A. Capitanio et al., 2009) or a complex mantle rheology (e.g., A. F. Holt & Becker, 2016), the effect of slab and trench widths (e.g., Schellart et al., 2007, 2010), the presence of an overriding plate (e.g., Rodríguez-González et al., 2012; A. F. Holt et al., 2015), multiple plates (e.g., Yamato et al., 2009) or slabs (e.g., Faccenna et al., 2017; A. Holt et al., 2017), the effect of the interaction between the slab and the upper/lower mantle discontinuity (e.g., Goes et al., 2008; Garel et al., 2014; Yang et al., 2017; Billen & Arredondo, 2018) and the effect of ridge push and a low viscosity asthenosphere (e.g., F. Capitanio et al., 2007; Stegman et al., 2010).

Some of these studies (i.e., F. Capitanio et al., 2007; A. F. Holt & Becker, 2016; Billen & Arredondo, 2018) have also provided insights into how an asthenosphere of diverse origin could diminish trench retreat rates. However, the globally observed trend in trench and plate motions and their partitioning at subduction zones is yet to be investigated, especially in light of the recent geophysical observations of a very weak and thin upper asthenosphere (Kawakatsu et al., 2009; Schmerr, 2012; Naif et al., 2013; Stern et al., 2015; Hawley et al., 2016). Common to all these observations is the evidence of a seismic velocity drop (5 to 10%) across a sharp boundary, no more than 30km thick, at base of the subducting lithosphere at different locations in the Pacific plate. The presence of this layer, which may support the theory of a plume-fed asthenosphere (e.g., Morgan, 1971, 1972; Phipps Morgan et al., 1995), is attributed to a significant number of volatiles and/or hydrated mantle phases. These are thought to have lowered density and viscosity, increasing the partial melt fraction, and resulting in partial melt "ponded" in lenses or channels at the base of the oceanic lithosphere (e.g., Schmerr, 2012; Sakamaki et al., 2013; Haw-
ley et al., 2016). Furthermore, at these localities, we generally observe $|V_T/V_P| < \frac{1}{3}$, which applies in the majority the reference frames (Schellart et al., 2008; Goes et al., 2017; Coltice et al., 2017). A thin layer with a high fraction of partial melt is expected to have significantly reduced mechanical strength that could potentially decouple plate motions from mantle tractions and strongly influence the force balance between slabs, plate and the mantle.

Previous global numerical models (i.e. Lithgow-Bertelloni & Richards, 1995; Bercovici, 1996; Zhong et al., 1998; Tackley, 2000; F. Capitanio et al., 2007; F. A. Capitanio et al., 2009; Stegman et al., 2010; Höink et al., 2011, 2012; Gérald et al., 2012; Goes et al., 2017; Becker, 2017) analyzed the role of a low viscosity asthenosphere (LVZ) but only a few have accounted for an LVZ of a limited thickness within the range of 100-200 km (Becker, 2017; Richards & Lenardic, 2018; Semple & Lenardic, 2018). Generally, an asthenosphere seems to better characterize plate-like behaviour improving our ability to match with observed surface velocities (Tackley, 2000; Gérald et al., 2012). Interestingly, a thinner LVZ with a stronger viscosity contrast shows to further promote plate motions leading to a stress magnification at the base of the lithosphere and helping overcome the viscous resistance at the base of the lithosphere (Richards & Lenardic, 2018). However, this has also shown to have a smaller effect on the global net rotation and observed global seismic anisotropy, as well as on global plate and subduction velocities, where large-scale plate dynamics seem most likely governed by broad continent-ocean asthenospheric viscosity and buoyancy contrasts (e.g., F. Capitanio et al., 2007; Goes et al., 2017; Becker, 2017).

On the other hand, if an LVZ seems to have a negligible effect on the large-scale subduction dynamics or represents a global feature, a very thin and weak top asthenosphere could still play a fundamental role for deciphering some of the observations of subduction partitioning at the regional scale, and provide relevant insights on global subduction zones on Earth. Such as those
dominated by fast-moving plates and slow migrating trenches, which have proven numerically difficult until now. Yet, the role of a very thin ($h_{WL} \sim 10-100$ km) and weak ($\eta_{WL}/\eta_{WL} \sim 10-1000$) WL on the subduction partitioning ($V_T/V_P$) has remained unexplored to date. Here we aim to address the impact of a WL on trench and plate velocities and their partitioning at subduction zones. Additionally, our work builds upon the recent geophysical inferences of a very weak and thin upper asthenosphere at convergent margins in the Pacific plate. We use a series of numerical experiments carried out in 2D to investigate the impact of a WL on the velocity and morphology of subducting slabs, adopting the geological and geophysical constraints described above. We then discuss the inferences these models yield on subduction dynamics.

2 Method

To investigate the role of a WL on subduction dynamics, we use the numerical code Underworld, described in detail by Moresi et al. (2007) and Stegman et al. (2006). The code follows a continuum mechanics approximation, which is widely used to describe geological and geophysical processes, and solve the conservation equations of mass, momentum and energy. We assume incompressibility and neglect temperature diffusion.

The initial model setup follows the approach of Schmeling et al. (2008); Yamato et al. (2009); Enns et al. (2005) and is adapted to solve the problem under investigation. We model subduction dynamics and mantle flow in a Cartesian box that extends 4000 km in the horizontal (X) direction and 660 km in depth (Y). Our models are made of 4 layers. There is an oceanic crust, an oceanic plate, a weak upper asthenospheric layer and an underlying mantle, as shown in figure 1b. Although similar, this setup differs from previous studies (e.g., Schellart et al., 2007; Stegman et al., 2006) because the oceanic plate is made of one single layer and the WL is characterized by a lower viscosity value than in the underlying asthenosphere or deeper mantle. The initial condition for
the subducting plate includes an initial trench position 1000km away from the wall and a slab tip already penetrating the mantle, 257km deep with a dip angle of 34° to the horizontal. The modelled WL is located at the base of the oceanic plate and extends underneath the whole length of the oceanic plate, and has a thickness of 30km. We use a model domain of 256*128 elements with a uniform grid spacing in each coordinate direction. This ensures sufficient numerical resolution to promote and properly-resolve the development of a weak hinge zone. Our 2-D experiments use a pseudo-plastic (PP) constitutive law with visco-plastic rheology near the surface and a Newtonian formulation deeper into the lithosphere and mantle. The visco-plastic rheology of the crust promotes the development of a weak hinge zone, which simulates the free surface and enables the oceanic lithosphere to detach from the top surface of the model and subduct freely into the mantle (Schmeling et al., 2008; Crameri et al., 2012). Plasticity is implemented through a depth-dependent yield criterion (Moresi & Solomatov, 1998). We use a cohesion of a 20MPa, a friction angle of 30 degrees and a density contrast between the oceanic lithosphere and the underlying mantle of 80kg/m³. The visco-plastic crustal layer controls the kinematics (Enns et al., 2005; Royden & Husson, 2006); however, the description of this phenomena is outside the scope of this study. The velocity boundary conditions are free-slip everywhere to minimize the influence of the box sidewalls (a free-slip condition means no tangential stress and zero normal velocity). We do not apply any kinematic boundary and subduction is thus dynamically initiated. The reliability of the model has been tested against previous work as shown in section 3. The assigned values result in subduction velocities of 10-2 cm/yr in line with the average values predicted on Earth (figure 1c, 2 and 3).

We aim to identify end-member cases that support the description of the mechanical effect of a WL at the LAB on a subduction zone. For this goal, we use a simplified rheological and geometrical model. This very setup is nec-
necessary to constrain only the impact of a WL and to prove that subduction motions can be the result of a simple force balance around subducting plates, while no external forces are needed. In our study, we vary the properties of the WL at the base of the oceanic lithosphere, i.e. its viscosity, density and thickness. Additionally, we also explore the effects of different viscosity and thickness contrast between the plate and the mantle, and the effect of the crustal friction angle. A small number of more complicated models explores the extent to which these simplifications may influence our conclusions, such as the use of a more realistic visco-elastic-plastic temperature (T)-dependent rheology (VEP) with and without a WL. Finally, we omit the study of the mechanical effects given by variation in buoyancy of plates, as these are well documented in the literature (e.g., Christensen, 1996; Bellahsen et al., 2005; Faccenna et al., 2007; F. Capitanio et al., 2007; Funiciello et al., 2008; Di Giuseppe et al., 2008; F. A. Capitanio et al., 2009; Stegman et al., 2010; Goes et al., 2011; Gérault et al., 2012).

The type of flow in the asthenosphere can promote or resist plate motions with respect to the underlying mantle. This flow can be driven by the plates themselves (Couette flow), pressure driven by the flow within the mantle (Poiseuille flow) or a combination of the two (combined Couette-Poiseuille flow). Several authors (e.g., Conrad & Hager, 1999; N. M. Ribe, 1992; N. Ribe, 2001; N. M. Ribe, 2010; Buffett & Becker, 2012; Stegman et al., 2010; Gerardi & Ribe, 2018; Semple & Lenardic, 2018; Gerardi et al., 2019) hat the force balance of the oceanic lithosphere is controlled by the balance of both bending-stretching momentum and boundary and internal stresses (flow in the boundary layer).

Among these authors (i.e., N. M. Ribe, 1992; N. Ribe, 2001; Gerardi & Ribe, 2018; Richards & Lenardic, 2018; Gerardi et al., 2019) show that the motion of a mantle fluid in an interface layer, can be approximated with the motion of a Stokes fluid in the lubrication limit. This procedure is valid when
the thickness of the layer is much thinner than the horizontal length, if $l_{WL}/h_{WL} \ll 1$. An approximation of the tangential forces representing the motion of a Stokes’s fluid in a thin layer in the lubrication limit led to the definition of the dimensionless stiffness of a surface shell (N. M. Ribe, 1992; N. Ribe, 2001) and an interface layer (Gerardi & Ribe, 2018; Gerardi et al., 2019). In our study, we are interested in describing the deformation in the effective lithosphere relative to the underlying mantle, which may or may not contain a WL on the partitioning of trench and plate motions. Based on our numerical experiments, we represent a first order approximation of the deformation occurring in the system (with and without a WL) using a series of parameters related to the dimensionless stiffness of the effective lithosphere.

We empirically find that the effective relative strength, $S'$, and thickness, $h'$, of the lithosphere relative to the underlying mantle (figure 3a and b, and figure 7SI in the supporting information) can be taken into account as:

$$S' = \frac{\eta_P \eta_{WL}}{\eta_M}, \quad h' = \frac{h_P}{h_M} \left(1 + \frac{h_{WL}}{h_M}\right)$$

where $\eta_P$, $\eta_{WL}$ and $\eta_M$ indicate the viscosity of the plate, weak layer and mantle, and with $h_P$, $h_{WL}$ and $h_M$ being thicknesses of the plate, the WL and the mantle respectively. Note that when a WL is not included $\eta_{WL} = \eta_M$ and $h_{WL} = 0$, allowing us to characterise all the experiments with and without a WL.

We also find that the combined effect of the relative contrast in strength and thickness between the effective lithosphere and the underlying mantle can be expressed by the effective relative stiffness of the lithosphere, $D'$, as:

$$D' = \log(S')h'$$
D' represents an approximation of the tangential forces acting on a subducting lithosphere (with and without a WL) and help to explain the decoupling effect of a WL at the base of the lithosphere. Our study represents a balance of forces problem where the subduction dynamics with a WL are governed by the balance of bending-stretching moment and internal and boundary stresses (flow in the lithosphere and asthenosphere), which controls dip and curvature of slabs, figure 3c, providing new insights on the partitioning of subduction surface motions.

Further in the text, these parameters are used to describe the deformation occurring in the system. Finally, in our simulations we refer to $V_{OP}$ as the magnitude of the horizontal plate velocity and $V_T$ as the trench migration velocity. The results obtained in our numerical simulations were systematically analysed, particularly through the analysis of the morphological and velocity fields through time evolution of the models. More information about the methodology adopted and the parameters used and varied in this study is available in the supporting information.

3 Results

Here, we firstly present the evolution and general aspects of the reference model (RM), which satisfy a range of geophysical and geological observations, then summarize the results obtained for all the subduction experiments in comparison to the RM case. Also, all the PP models presented here share three common subduction temporal evolution stages. These evolution stages are: (i) an initial period where subduction is dynamically initiated and the slab progressively accelerates while is sinking into the mantle; (ii) a transitional stage where the slab decelerates while interacting with the bottom of the model; and (iii) a final steady-state configuration at the mid-mantle boundary. These are shown in figure 1C and 2, and are in agreement with pre-
previous studies (e.g., Bellahsen et al., 2005; Yamato et al., 2009; Stegman et al., 2010).

### 3.1 Reference model evolution

The reference model has the same characteristic of the model setup presented above, but it does not contain a WL (figure 1Aa). The temporal evolution of this model is shown in figure 1Ca, b, and c. As the model progresses in time, we distinguish three stages of evolution given by the sinking of the oceanic plate into the mantle. In the first stage, the initiation of subduction follows the initial buoyancy configuration, with a slab tip immersed in the mantle. During this stage, the slab reaches a dipping angle of 60-70° and the magnitude of the plate velocity increases progressively. This stage is associated with trench retreat at the surface, while at depth, the progressive sinking drives a displacement of the mantle from beneath the slab (figure 1Ca). In the second phase, the slab tip interacts with the bottom of the model box. This phase is reached in 9.23 million years and is characterized by a general velocity drop (figure 1Cb). The final stage is defined by the sliding of the slab at the bottom of the model and the system reaches an approximate steady-state configuration (figure 1Cc). During this stage, the plate velocity increases toward an intermediate value between the two previous time phases and the slab continues to roll back while the trench retreats (figure 2a, b). Since the reliability and the evolution of this model are well known and in agreement with the literature (e.g., Bellahsen et al., 2005; Funiciello et al., 2008), it was chosen as a reference for comparison with the models having a WL.

### 3.2 An advancing trend for plate and trench motions.

The primary effect of introducing a weak upper asthenospheric layer is to increase the subduction speed, particularly increasing plate convergence velocity and reducing trench retreat motion. In some models, it also increases
the subduction dip angle and influences the shape assumed by the subducting slab, while interacting with the 660km discontinuity (figure 1C and 3).

A comparison between the RM and a WL model having a viscosity contrast between the mantle and the WL of 2 order of magnitude ($\eta_M/\eta_W=10^2$) shows these effects in figure 1Ca, b, c and 1Cd, e, f, respectively.

The impact of these effects depends mainly on the viscosity between the mantle and the WL and on the thickness of the WL, and less on the density of the WL. In our PP models, we find that for moderate viscosity contrasts mantle-WL ($10^1<\eta_M/\eta_W<10^2$) and a layer thickness between 10-20km, $V_P$ increases and trench retreat rate decreases, while the overall shape of the slab is not substantially affected. However, for larger viscosity contrasts ($\eta_M/\eta_W \geq 10^2$) and thickness of the weak layer (>20km), a significant change in velocity and trench migration mechanism develops and, the morphology of the subducting slab may also change (figure 2). For thinner ($h_W<10$km), more buoyant ($\Delta \rho h_W$) and stronger layers ($\eta_M/\eta_W \leq 10$), the overall effect is reduced. However, thinner layers are sensitive to numerical resolution and, it is plausible that thinner layers may also play a relevant role on the $V_T/V_P$. It is also important to note that a WL has not a significant impact on the time necessary for the slab tip to reach the bottom of the model (figure 2c and f), which shows that a WL has a smaller influence on the vertical slab motion than it has on the horizontal plate motion.

All models with a WL show a significantly steeper velocity transition at the base of the lithosphere compared with models with no WL (figure 1C). This suggests that a weak and thin upper asthenosphere has the potential to effectively decouple the motion of the lithosphere from the flow into the underlying mantle. This process results in a more efficient asthenosphere drag, which decreases the resistance to shearing in the underlying mantle, lubricates the base of a plate and in turn contributes to increasing the plate speed (figure 1C and figure 2a,b,d and e). The WL acts as a slippery base for the mo-
tion of the oceanic plate while sinking into the mantle. Since a WL is lighter than the above lithosphere (Kawakatsu et al., 2009; Hawley et al., 2016), also the rising of lighter material contributes to the gravitational sliding of the plate (figure 1C). Furthermore, the deep entertainment of a WL on one side of the subducting slab also reduces the viscous drag and thus, facilitates the sinking of the slab into the mantle. Such vanishing drag on one of the slab’s sides justifies the increase in sinking velocities up to a factor of $\approx 2$ we observe in our models, (figure 1C and 2a and d).

In our models, we also observe a correlation between the value of the subduction partitioning and the effective relative strength, $S'$, and the inverse of the thickness, $1/h'$, of the lithosphere, as shown in figure 3a and b. Three important features are worth noting. First, this trend can be described by an inverse-tangent function for both $S'$ and $1/h'$. Second, for low and high values of $S'$ and $1/h'$, the subduction partitioning doesn’t change significantly and the function trend is asymptotic. Hence a WL can increase plate velocities value up to a maximum of a factor of $\approx 2$ and oppose trench motions. This shows that the effect of a WL on subduction motions is limited by the sinking dynamics. Third, this asymptotic trend is further constrained by the fact that areas having $S' > 5 \times 10^2$ and $S' < 10^{-2}$ are excluded from the graph (figure 3a). Such values of $S'$ would correspond to plate-mantle and mantle-WL viscosity contrasts above 500 and 1000, respectively. These are not found in nature and therefore not considered. For intermediate $S'$ and $1/h'$ values, the subduction partitioning follows a co-tangential trend.

In this study, we perform simulations with varied parameters over a range that is Earth-like (figure 1b and supporting table T1. Our full set of experiments include cases where the initial viscosity of the plate and the mantle, the plate thickness and the crustal friction angle are varied to reproduce previous work (e.g., Bellahsen et al., 2005; Funiciello et al., 2008; Di Giuseppe et al., 2008), and expand upon these through the incorporation of a WL. On
the basis of all our experiments we propose a regime diagram, which defines three distinctive subduction styles as a function of $D'$, subduction motions ($V_T/V_P$%) and slab morphologies and dips, figure 3c. These subduction regimes are characterized by (i) a very steep slabs buckled at the mid-mantle discontinuity with advancing to quasi-stationary trenches; (ii) a relatively steep slab (but < 90°) with quasi-stationary to moderately-retreating trenches, which continue flat at the 660km discontinuity; and (iii) a shallower slabs with usually fast-retreating trenches, which buoyantly tend to stagnate at the mid-mantle boundary (figure 3c). $D'$ allows us to capture and constrain these three subduction styles, which characterise the deformation in the system with and without a WL, as well as most of the variety of shapes and subduction partitioning mechanisms we observe in nature. These observations support a mechanism whereby the subduction style and motions are controlled by the amount of asthenospheric drag exerted at the base of the plate.

Finally, in most of our experiments we observe a correlation between $V_P$ and $V_T$, which shows $V_T \pm 1/3 V_P$ (figure 3d). To test the validity of our models with relation to subduction zones on Earth, we use the estimate on $V_P$ and $V_T$ from Goes et al. (2008) for subduction zones in the Pacific plate and plot this versus our numerical experiments (figure 3d). Goes et al. (2008) uses the database of Sdrolias and Müller (2006), which is built on the Indo-Atlantic hot spots reference frame from O’Neill et al. (2005). The values of $V_P$ and $V_T$ emerging from our models mostly positively align with observed natural plate and trench migration rates. There are, however, zones that show poor correlation with our models, such as, the Tonga and Marianas trenches, which show $V_T > \pm 1/3 V_P$. At these localities, it is plausible that other mechanisms may be of major regional importance or coexist with the presence of a WL, and indeed further contribute to the complexity we observe in natural systems, e.g. double subduction systems, arcuate arcs and so on. Nonetheless, at the global scale, it appears that a regional WL mechanism may play a key
role in dictating the partitioning of plate and trench motions and offers a better match to the average $V_T/V_P$% values we presently observe on Earth.

4 Discussion and conclusion

Previous global numerical models, observations and laboratory-derived creep laws suggest a moderate bulk viscosity contrast of 1-2 orders of magnitude between the asthenosphere beneath the oceanic lithosphere and the underlying mantle (Becker, 2017; Richards & Lenardic, 2018) and asthenosphere viscosity between $\sim 0.5 \times 10^{18}$ - $10^{21}$ Pa.s in $\sim 200$km thickness (Mitrovica, 1996; Hu et al., 2016; Freed et al., 2017). Such inferred large scale asthenosphere weaknesses are generally explained by invoking the role of temperature or pressure; however, uncertainties on the true values remain, e.g. choice of appropriate rheologies and parameters. Also, the non-uniqueness relating to viscosity and thickness of an LVZ can confound the ability to distinguish between a thin layer of very low viscosity and a thick layer of greater viscosity (Cathles III, 1975; Richards & Lenardic, 2018). Moreover, the trade-off between the resolving power and lateral extent of seismic studies may hinder the ability to distinguish narrow channels at the base of the lithosphere, such as that of a WL. Kawakatsu et al. (2009); Schmerr (2012); Naif et al. (2013); Stern et al. (2015) and Hawley et al. (2016) show that asthenospheric local and regional configurations may lead to up to a $\approx 4$ orders of magnitude melt-induced viscosity reduction into one or multiple thin and more buoyant layers at the base of the lithosphere; e.g. Hawley et al. suggests that the enhanced melt content and/or presence of hydrated phases would have significantly lubricated the base of the subducting lithosphere of the Farallon slab with potential implications for subduction motions. These asthenospheric configurations seem to be compatible with global plates and seismic anisotropy models as long as their lateral extent remains limited compared to the rest of the plate (Becker, 2017).
In our study, we show that the presence of a thin WL at the base of the oceanic lithosphere critically affects subduction dynamics, particularly influencing the subduction speed, reducing trench migration rates and, in some cases, controlling the morphology assumed by a subducting slab. Our results show that for large viscosity contrasts ($\eta_{\text{M}} / \eta_{\text{WL}} \geq 10^2$) and a WL thickness greater than 20 km, the morphology of the subducting slab can be affected. In such cases, the subduction system may likely develop a quasi-stationary to an advancing moving trench with a moderate to fast convergence rate for the plate. For moderate viscosity contrasts between the mantle and the WL ($10^1 < \eta_{\text{M}} / \eta_{\text{WL}} < 10^2$), the subduction velocity increases and trench retreat rate decreases without significantly changing the overall shape of the slab. The overall effect is reduced where thinner and more buoyant layers exist (figure 2c, d and e, and 3b). This effect is constrained within end-member cases, and a description of the full range of slab behaviours is captured by the regime diagram in figure 3c. We also find that all the simulations with a WL are confined by velocity variations of a factor of $\approx 2$ maximum, and all show a low absolute subduction partitioning component, i.e. $|V_T / V_P| < 40\%$ (figure 3a and b).

The overall impact of a WL on subduction dynamics depends on the relative contrast between the effective properties of the lithosphere and the mantle. We have proposed the effective relative stiffness of the lithosphere ($D'$), as a diagnostic parameter for this effect. $D'$ not only describes the results found in this study and thus the effect of a WL but also includes plate strength values, which have previously been examined in a broad range of published numerical and analogical studies (e.g., Bellahsen et al., 2005; Funiciello et al., 2008; Di Giuseppe et al., 2008). All our experiments create a comprehensive subduction regime diagram that allows one to distinguish three subduction styles as a function of the relationship between $D'$, subduction motions ($V_T / V_P\%$), and slab morphologies and dips. This characterises and constrains the deformed...
mation in the system, as well as most of the variety of shapes, velocities and
trench migration mechanisms we observe in nature (figure 3c). Although our
study does not exclude the potential for alternative mechanisms, the role of
the effective relative stiffness of the lithosphere seems to be of significance con-
sistently with previous studies (F. Capitanio et al., 2007; Stegman et al., 2010)
and due to lithosphere-mantle decoupling processes, thus affecting trench and
plate motions at subduction zones.

The setup chosen has allowed us to demonstrate that low trench retreat
and fast plate speed can be the result of a simpler force balance around the
subducting plate alone, whilst no extra forces or factors are needed (e.g. an
overriding plate and an upper-lower mantle discontinuity); however we do not
exclude that other factors which have already shown to reduce trench motions
may additionally affect or coexist with the mechanism illustrated here. Nonethe-
less, we also employed a small number of more complicated models to explore
the extent to which our simplifications may influence our conclusions (sup-
porting figure S3-S6.). We tested the role of a VEP T-dependent rheology,
which would naturally lead to weakening at the base of the lithosphere, the
inclusion of the upper/lower mantle transition zone and the effect of an ex-
tended modelled box. While rheology and choice of parameters can be dif-
ferent, the effect of a WL shows a consistent signature.

In the literature, many models have been made to describe subduction
dynamics. While these models have provided useful insights toward the mod-
elling of natural subduction systems and mantle convection processes, the mod-
elling of subduction zones has not yet resolved clear trends for the subduc-
tion style, convergence velocity, trench motion, and slab dip, especially in the
case of slow retreating or advancing trenches in natural settings (e.g., Jarrard,
1986; Garfunkel et al., 1986; Lallemand et al., 2005; Heuret & Lallemand, 2005;
Sdrolias & Müller, 2006; King, 2001; F. Capitanio et al., 2007). Some more
recent studies have also brought considerable attention to the effect of an as-
thenosphere of some origin in reducing trench retreat (e.g., A. F. Holt & Becker, 2016; Billen & Arredondo, 2018) and also enhancing plate motion when a ridge push condition is applied (e.g., F. Capitanio et al., 2007). This, along with the addition of an overriding plate to the system seems to be relevant for reducing $|V_T/V_P|$ observed in numerical modelling (Rodríguez-González et al., 2012; A. F. Holt et al., 2015; A. Holt et al., 2015; A. F. Holt & Becker, 2016).

Here, we suggest that the presence of a weak upper asthenosphere underneath subducting plates in a free subduction model is already alone of importance in decreasing the high absolute values of the subduction partitioning observed in many precedent analogues and numerical models and to level more in line with the average values presently seen on Earth. Specifically, in our models the average absolute trench velocity is approximately 30 per cent or lower of the total convergence plate velocity (figure 3d), as found in many plate motion reference frames, e.g. (Schellart et al., 2008; Goscombe & Gray, 2008; Becker & Facenna, 2009). Furthermore, while a maximum increase in convergence velocity of a factor of $\approx 2$ due to the weak layer is likely negligible in global models, its role becomes relevant at a regional scale influencing subduction motions and mantle flow dynamics. Thus, the regional mechanism proposed here provides a novel and explanation to interpret the apparent dichotomy in subduction partitioning values and slab dip angles globally observed along the edges of the Pacific Plate (Lallemand et al., 2005; Bellahsen et al., 2005; Coltice et al., 2017), such as the localities where the presence of a WL is confirmed by geophysical studies (e.g., Kawakatsu et al., 2009; Schmerr, 2012; Naif et al., 2013; Stern et al., 2015; Hawley et al., 2016).

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Figure 1. A shows a schematic representation of the geometrical setup for the reference model (RM) and the models with a weak layer (WL) in a and b, respectively. B shows the material field in a, the initial rheological setup for the pseudo-plastic (PP) with different viscosity contrast mantle and WL in b and WL thickness in c. C shows the subduction time evolution in a comparison between the RM and a model with a WL ($M_2, \eta_M/\eta_{WL} = 100$).
Figure 2. Evolution of plate velocities ($V_P$), trench and slab tip migrations through time, for a progressive increase in $\eta_{M}/\eta_{WL}$ and $\Delta\rho_{(M-WL)}$, and in $h_{WL}$, as seen in a, b, c and d, e, f, respectively.
Figure 3. shows in a and b the subduction partitioning ($V_T/V_P\%$) as a function of the effective relative strength ($S'$) and thickness ($h'$) of the lithosphere for a progressively weaker or thinner WL, respectively. The values for each simulation are plotted using a scatter plot function of $S'$ and $h'$ in a and b, respectively. Figure c shows variations in $V_T/V_P\%$ with respect to the effective relative stiffness of the lithosphere ($D'$) for all the simulations performed in this study. The different coloured fields define the three areas having different subduction styles. d shows the relationship between $V_P$ and trench velocity $V_T$, as found in our experiments and in natural cases (Goes et al., 2011). The majority of the points lies between the dotted lines ($V_T=mV_P$) having $m$ equal to $\pm1/3$. 

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**A**

- **Reference Model - RM**
  - Initial Geometrical Setup
  - Free slip
  - Initial Geometrical Setup

**B**

- **Rheological Approximation of the Oceanic Lithosphere**
  - Oceanic Crust
  - Oceanic Lithosphere
  - Asthenospheric Sub-Layer
  - Asthenosphere
  - Upper Mantle

**C**

- **Time evolution of the models**
  - RM
  - M2
  - 3.54 Myrs
  - 4.02 Myrs
  - 9.23 Myrs
  - 7.33 Myrs
  - 16.6 Myrs
  - 15.9 Myrs
  - Velocity Magnitude [cm/yr]
  - Temperature [°C]
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