A regime diagram for subduction styles from 3-D numerical models of free subduction

D.R. Stegman a,b,⁎, R. Farrington b, F.A. Capitanio b,c, W.P. Schellart c

a School of Earth Sciences, The University of Melbourne, Carlton, Victoria 3010, Australia
b School of Mathematical Sciences, Monash University, Clayton, Victoria 3800, Australia
c School of Geosciences, Monash University, Clayton, Victoria 3800, Australia

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A B S T R A C T
Previous models of subduction (both analogue and numerical) have observed a number of distinct styles of subduction, each with particular subduction motions (partitioned between slab rollback and forward plate advance) and associated slab morphologies. We use 3-D numerical models to investigate subduction dynamics by varying the strength of slabs as well as the buoyancy, and propose a new classification based on these parameters. The slab strength is specified both through the ratio of viscosities between the subducting plate and upper mantle (ηplate/ηum) as well as the plate thickness, hplate. Only a very restrictive range of plates (“strong” plates with smaller buoyancy) tend to favor modes of subduction which are exclusively advancing. Plates which have greater negative buoyancy will eventually transition into a retreating style. We find that the flexural strength and the buoyancy determine the subduction style (as distinguished by a characteristic slab morphology), and control several subduction characteristics including the partitioning between slab rollback and plate advance, the trench curvature, and the slab’s radius of curvature. Plates that are 80–100 km thick with ηplate/ηum ~ 100–300 are classified here as “weak” and are the only plates to exhibit slab geometry with several recumbent folds atop the more viscous lower mantle. This regime of weak plates with their associated slab morphologies (predominant folding) is argued to be most similar to slabs on Earth based on the presence of folded slab piles in Earth’s upper mantle (as interpreted from seismic tomography). © 2009 Elsevier B.V. All rights reserved.

1. Introduction
Subduction is the process of recycling negatively-buoyant oceanic lithosphere into the mantle and strongly influences the dynamic evolution of the planet. Negative buoyancy of the plate provides the main driving force and it is resisted by viscous bending at the subduction hinge (Conrad and Hager, 1999) and viscous drag provided by the upper mantle (Forsyth and Uyeda, 1975). The absolute and relative magnitude of these forces helps determine how subduction of the plate is accommodated. The total subduction velocity is normally partitioned between two modes: forward plate motion and slab rollback (Elsasser, 1971), the latter of which is accompanied by a retreating motion of the trench (opposite to the direction of plate motion) and a backwards component in the slab sinking velocity. These motions are shown in Fig. 1.

The resultant trench motion can initiate and sustain back-arc spreading/extension during trench retreat (Garfunkel et al., 1986). An important component of slab rollback is that of toroidal flow, consisting of a circulation of mantle material in a horizontal plane around slab edges from behind the slab to in front of the slab as seen in Fig. 1. Toroidal flow can only exist in a 3-D domain (Dvorkin, 1993; Zhong and Gurnis, 1995) and is generated from poloidal sources of buoyancy (such as sinking slabs) through lateral variations of viscosity. More generally, the trench location determines the surface position for where slab material is deposited into the upper mantle (and thereby influences the slab geometry at depth) (van der Hilst and Seno, 1993; Fukao et al., 2001; Wortel and Spakman, 2000). To better understand this process, a number of numerical and analogue models using a 3-D geometry have been studied in which a single, isolated plate subducts into a vertically confined upper mantle with linear viscosity (Facenna et al., 2001; Faccenna et al., 2003; Schellart, 2004; Faccenna et al., 2004; Bellahsen et al., 2005; Martinod et al., 2005; Morra et al., 2006; Royden and Husson, 2006; Faccenna et al., 2006; Stegman et al., 2006; Schellart et al., 2007; Capitanio et al., 2007b; Schellart, 2008; Goes et al., 2008; Di Giuseppe et al., 2008; Ozbench et al., 2008). Common to all experiments are three distinct stages of subduction with an initial sinking slab tip, followed by a transient period characterized by the slab tip interacting with the 660 km depth boundary, and finally a period of long-term subduction in which a particular mode of subduction emerges. The last stage of long-term subduction can be identified into one of several distinct subduction styles that have been observed and are illustrated in Fig. 2. Each style has an associated trench motion and resultant slab morphology: (i) a 2-D continuously retreating trench accompanied by predominantly slab rollback resulting in a flat-lying slab, (ii) an initially advancing trench accompanied by forward plate motion which then switches into a retreating style, resulting in a flat-lying slab with a single, long recumbent fold (hereafter referred to as the Advance-Fold-Retreat

⁎ Corresponding author. Now at Scripps Institution of Oceanography, Univ. of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92037-0225, USA. Tel.: +1 (858) 822 0767.
E-mail address: dstegman@ucsd.edu (D.R. Stegman).

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mode), III] a continuously advancing trench accompanied by predominately forward plate motion resulting in an overturned, flat-lying slab, IV) a 3-D continuously retreating trench accompanied by predominantly slab rollback resulting in a flat-lying slab, and V) a nearly-stationary trench accompanied by a forward moving plate resulting in a slab pile made up of multiple recumbent folds. The earliest two stages of subduction establish the slab tip trajectory and provide some indication which mode of subduction may develop, but it is not robust enough to predict with confidence which mode will eventually emerge. Although long-term subduction does not necessarily correspond to a steady-state behavior, in the cases of styles I and IV in particular, the trench retreat during long-term subduction is approximately constant. Considerable attention has also been given to the strength of the subducting lithosphere, which has typically been modeled using viscous plates. The strength of the viscous plate is typically reported using both the absolute viscosity of the plate as well as relative to the upper mantle ($\eta_{\text{plate}}/\eta_{\text{hum}}$). Plate strength is described qualitatively as “strong” or “weak” and in practice, a value of $\eta_{\text{plate}}/\eta_{\text{hum}} \sim 1000$ usually discriminates between the two. Although, Enns et al. (2005) found slabs only need to be as strong as $\eta_{\text{plate}}/\eta_{\text{hum}} \sim 500$ to display different transition zone morphology than weaker slabs. The strength of the slab can also be described by an elastic core, which becomes thicker (and stronger) with increasing age of the lithosphere (Morra et al., 2006). This elastic strength can be modeled as a thin elastic sheet (Royden and Husson, 2006) or with a viscoelastic lithosphere (Morra et al., 2006; Capitanio et al., 2007a). In the case of having a viscoelastic core, this can be made into an equivalent viscous core if the Maxwell relaxation timescale is comparable to the background strain rate (see Ozbench et al. (2008) and Appendix B in Schmeling et al. (2008) for additional details). In the case of the elastic plate, it has been found that the elastic plate thickness has no significant influence on the subduction dynamics as long as it is smaller than 30 km (Royden and Husson, 2006) which is comparable to estimates of observed elastic thicknesses. This is similar to the effect of low viscosity plates, which if they are sufficiently weak, will also not express an appreciable difference in the dynamical evolution.

It seems reasonable that models with plates that have similar buoyancies can be compared to one another. However, the absolute subduction velocity can vary between experiments. Using semi-analytic elastic models (Royden and Husson, 2006) found that trench retreat occurs in all cases, but very strong slabs ($\eta_{\text{plate}}/\eta_{\text{hum}} \sim 10^3$) subduct significantly more slowly than weaker slabs ($\eta_{\text{plate}}/\eta_{\text{hum}} \sim 10^2$). Using purely viscous analogue models in a similar experimental setup although not including an overriding plate, Funiciello et al. (2008) found just the opposite, that stronger slabs retreat significantly faster. Furthermore, numerical models which used a layered plate rheology but included lateral variations in lithospheric age (and therefore $\eta_{\text{plate}}$) generate corresponding variations in slab strength and produce variations in subduction velocities and dip angle (Morra et al., 2006).

Previous studies that performed experiments that have similar buoyancy and viscosity contrasts reported varying amounts of dependence on plate width (signifying the importance of 3-D effects). Similarly, there is noticeable disagreement between such experiments as to how the same subduction velocity is partitioned between subduction modes of trench retreat and plate advance. Analogue experiments that use “strong” plates (e.g. Funiciello et al., 2004; Bellahsen et al., 2005) find that subduction dynamics tend to favor plate advance as well as an accompanied advancing trench (e.g. Modes II and III in (Bellahsen et al., 2005)). Similar behavior is observed in the numerical models of Di Giuseppe et al. (2008). Equivalent models with weaker plates (Schellart, 2004; Stegman et al., 2006; Morra et al., 2006; Schellart et al., 2007; Capitanio et al., 2007a; Schellart, 2008) predominantly subduct via trench retreat and slab rollback. In particular, the mode III observed in (Bellahsen et al., 2005) is only achieved with weak plates when the models are “pushed” by an applied velocity boundary condition to the plate’s trailing edge (Schellart, 2005; Stegman et al., 2010-this issue). A significant dependence on plate width is observed to influence subduction dynamics in some experiments (Schellart, 2004; Stegman et al., 2006; Schellart et al., 2007) but Bellahsen et al. (2005) report no dependence on plate width. Additionally, Di Giuseppe et al. (2008) report that different modes occur for different width plates with the widest plates (2300 km) retreating, narrow plates (660 km) advancing and intermediate plates in the Advance-Fold-Retreat mode, which is essentially the opposite behavior observed by Schellart et al. (2007).

A goal of this study is to not only make an attempt to reconcile these diverse observations, but also to provide a more useful parameter space map of subduction which has some predictive capability. We will show that indeed the strength of the lithosphere has a major controlling influence on the observed mode of subduction and attempt to provide some explanation as to how these distinct modes emerge.

2. Slab buoyancy

Models of free subduction are driven only by the negative buoyancy of the slab, which interacts with the strength of the plate through an applied bending moment, $M$, as defined by:

$$M = \int_0^l x \Delta \rho g h_{\text{plate}} dx$$  (1)
where the negative buoyancy of the slab acts as an applied load, \( F \), per unit length, \( dx \), and is applied at some distance, \( x \). When this expression is integrated over the length of the slab, \( l \), the total bending moment that acts on the plate's subduction hinge scales like \( M = -2 \Delta \rho g h_{\text{plate}} l^2 \). This illustrates that the bending moment is simply the weight of the slab, \( \Delta \rho g h_{\text{plate}} \), acting on a lever arm of length, \( l \).

We define a related quantity, the Stokes buoyancy, \( B_S \) (with units of \( s^{-1} \)), as the ratio of volumetric potential energy (\( \Delta \rho g h_{\text{plate}} \)) to the upper mantle viscosity:

\[
B_S = \frac{\Delta \rho g h_{\text{plate}}}{\eta_{\text{um}}} \tag{2}
\]

where gravity, \( g \), is assigned to be 9.8 m/s. Another related and useful quantity to define is the Stokes velocity, \( v_s \), which is a characteristic velocity defined as \( v_s = B_S H \) where \( H \) is the depth of the upper mantle, i.e. for when a length of slab extends from the surface to the bottom of the upper mantle.

3. Definition of plate stiffness

The stiffness of a plate (and therefore its associated slab) has previously been simply described as the viscosity ratio, \( \eta_{\text{plate}}/\eta_{\text{um}} \). (Funiciello et al., 2008; Di Giuseppe et al., 2008). However, the thickness of the plate also plays a role (Capitanio et al., 2007b; Schellart, 2008) and also needs to be taken into consideration for the mechanical strength of the plate (in regards to both bending and stretching). The mechanical strength of viscous sheets can be decomposed (Ribe, 2001, 2003) into a resistance to bending (here called the flexural stiffness, \( D_{\text{vis}} \)), and a resistance to stretching (here called the tensile stiffness, \( k_T \)). Thus, a more appropriate description for the mechanical strength of the plate (i.e. viscous sheet) would be to use these quantities.

The flexural stiffness, \( D_{\text{vis}} \) (with units of N m s) for a plate of thickness, \( h_{\text{plate}} \), sensitively depends on the cube of the plate thickness:

\[
D_{\text{vis}} = \frac{\eta_{\text{plate}} h_{\text{plate}}^3}{3} \tag{3}
\]

Flexural stiffness is similar to the elastic equivalent (flexural rigidity) in that it supports an applied bending moment. However, rather than the amount of bending described as displacement (as in solid mechanics), it relates the rate of bending (with units of \( m^{-1} s^{-1} \)) (Turcotte and Schubert, 1982; Karato et al., 2001; Ribe, 2001):

\[
M = D_{\text{vis}} \frac{\dot{v}}{h} \tag{4}
\]

The bending rate has been shown to be equivalent to the rate at which plate material goes through the subduction hinge (Karato et al., 2001; Ribe, 2001; Buffett, 2006), which can be approximated as:

\[
\frac{\dot{v}}{h} = \frac{u_{\text{sub}}}{R^2} \tag{5}
\]

For the purposes of this study, we define an effective flexural stiffness, \( D_{\text{vis}}^* \) (non-dimensional), that has been normalized by a large number using values appropriate for the upper mantle:

\[
D_{\text{vis}}^* = \frac{D_{\text{vis}}}{\frac{4}{3} \eta_{\text{um}} H^2} = \frac{\eta_{\text{plate}}}{\eta_{\text{um}}} \left( \frac{h_{\text{plate}}}{H} \right)^3 \tag{6}
\]

where \( H \) is the depth of the upper mantle. In general, \( D_{\text{vis}}^* \) is a more useful quantity because it better describes the mechanical properties, than that given by \( h_{\text{plate}} \) and \( \eta_{\text{plate}} \) alone.

The tensile stiffness for a viscous sheet is defined as \( k_T = 4 \eta h \) (Ribe, 2001) where the quantity \( 4h \) is referred to as a material’s Trouton viscosity. Capitanio et al. (2007b) demonstrate that it is through specifying the magnitude of these quantities (which they refer to as \( B_i \) and \( S_i \), respectively, although they define \( S_i = 2h \)) that the subduction dynamics can be sensitively controlled. This is essentially the internal strength of a viscous sheet in resisting a stress resultant (stretching moment), \( N \), which is the integrated amount of fiber stresses arising from stretching or contraction over the thickness of the viscous sheet (Ribe, 2001). The flexural stiffness is typically the dominant control on the system (Capitanio et al., 2007b; 2009b), but in cases when the flexural stiffness is small, the tensile stiffness is also important (Ribe, 2001). There is feedback coupling between the two in the case of weak sheets, where the resistances to bending and stretching are both low, the sheet will stretch more easily, which reduces the thickness, \( h \), and results in a greatly reduced flexural stiffness (Ribe, 2001; Capitanio et al., 2009b).

4. Numerical model

4.1. Geometrical setup

We model the subduction of a negatively-buoyant plate into a completely passive upper mantle within a 3-D Cartesian geometry using an experimental setup similar to Ozbench et al. (2008). This conceptual (and greatly simplified) model focuses the investigation on how the lithosphere influences the plate tectonics system through slab–mantle coupling. The mantle has a Newtonian viscosity, with a 660 km deep upper mantle overlying a lower mantle which is 100X more viscous and fills the remaining amount of the 1000 km deep box as seen in Fig. 3a. The full domain is always 4000 km long and either 4000 km or 6000 km wide depending on the width of the plate (the ratio of plate width to plate thickness, \( W/h \), is always 12). All experiments have a 2200 km long plate with a free trailing edge that is initially placed 600 km from the back wall boundary and the domain’s boundary conditions are free-slip everywhere. Model parameters are given in Table 1.

Here we do not consider the issue of subduction initiation (for a treatment of this problem see e.g. (Regenauer-Lieb et al., 2001; Hall et al., 2003; Gurnis et al., 2004), but rather the evolution of previously established, self-sustaining subduction zones. Rather, a perturbation is applied by bending the front 100 km of the plate (i.e. slab tip) at a shallow (30°) angle, which is sufficient to begin the process of subduction. Thus, these models are applicable to previously established subduction zones which are self-sustaining and predominantly driven by negative buoyancy of the slabs. The amount of mantle stratification (\( \eta_{\text{um}}/\eta_{\text{um}} = 100 \)) is a simplistic parameterization of the barrier to flow between the upper and lower mantle. The viscosity increase is somewhat larger than what is normally considered for the mantle because viscosity alone is used to represent both the normal amount of mantle viscosity increasing with depth as well as the endothermic phase transitions at 660 km depth which are not included in the model. Neither overriding plates or adjacent plates to the side are not included in these models.

4.2. Plate description

For this study we use a similar plate description as Ozbench et al. (2008), which is a composite material with a 50 km thick, strong viscous core embedded between two 25 km thick (upper and lower) visco-plastic layers (see Fig. 3b). The visco-plastic layers use a Von Mises failure criteria such that the pre-yielded viscosity (200\( \eta_{\text{um}} \)) is replaced by an effective viscosity which is reduced through an iterative procedure. The low value of yield stress adopted (48 MPa) ensures that the entire visco-plastic portion of the hinge has yielded which allows us to approximate the total strength of the hinge as
simply dependent on properties of the strong core. Thus, only the thickness of the strong viscous core is used when estimating the flexural stiffness of the plate. The plate strength in the experiments is controlled only by the viscosity of the core, and thus, core thickness is held constant at 50 km inside a 100 km thick plate. However, models with very high-viscosity cores became too computationally expensive so a few larger core thickness (75 and 100 km) are used within correspondingly thicker plates (125 and 150 km) to achieve higher values of flexural stiffness. Although the brittle crust overlying a strong lithospheric core may be smaller than 25 km, currently this is the minimum resolvable layer for numerical grid resolutions used for these models.

4.3. Numerical methods

Subduction velocities (advection of the plate into the mantle) are much faster than the timescale for thermal diffusion (scaled model evolutions are <50 Ma), and consequently, the energy equation is not included in these models. Due to this assumption, the thickness of the plate is constant over the duration of the experiments. All the layers within the subducting plate, and the upper and lower mantle are assumed to have uniform material properties. Each material in the numerical model is distinct and is represented using Lagrangian particles that are embedded in a standard Eulerian finite element mesh. The number of elements used in the model provides a resolution of approximately 21 km in the vertical direction and 42 km in horizontal directions (96×48×48 or 96×48×64 for the half-domain) and there are ~20 particles per element in the initial particle layout.

We use the geodynamics modeling framework Underworld to discretize the problem domain and solve the governing equations. The weak form of the problem is formulated via the standard Galerkin method. The flow variables velocity and pressure are represented with mixed tri-linear and constant shape functions respectively. To enforce incompressibility, we employ a preconditioned conjugate gradient-based Uzawa scheme for computing the pressure correction with the aim of driving \( u \) towards 0. Within the mesh are embedded Lagrangian particles which carry material properties. Coupling between the Eulerian finite element problem and the Lagrangian particles is achieved by using the particles as the integration points for evaluating the element stiffness matrices. The formation of the finite element problem requires the evaluation of the integrals arising from the discretized weak form of the

### Table 1

Model parameters which are common to all experiments.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain height</td>
<td>( H_{\text{box}} )</td>
<td>1000 km</td>
</tr>
<tr>
<td>Domain width</td>
<td>( W_{\text{box}} )</td>
<td>4000 or 6000 km</td>
</tr>
<tr>
<td>Characteristic length scale (depth of upper mantle)</td>
<td>( H )</td>
<td>660 km</td>
</tr>
<tr>
<td>Gravitational acceleration</td>
<td>( g )</td>
<td>10 m/s²</td>
</tr>
<tr>
<td>Initial plate length</td>
<td>( L_{\text{plate}(0)} )</td>
<td>2200 km</td>
</tr>
<tr>
<td>Reference viscosity (upper mantle value)</td>
<td>( \eta_{\text{um}} )</td>
<td>1.4 × 10^{19} Pas</td>
</tr>
<tr>
<td>Viscosity of lower mantle</td>
<td>( \eta_{\text{lm}} )</td>
<td>100 ( \eta_{\text{um}} ) Pas</td>
</tr>
<tr>
<td>Initial viscosity of visco-plastic layers</td>
<td>( \eta_{\text{plate}} )</td>
<td>200 ( \eta_{\text{um}} ) Pas</td>
</tr>
<tr>
<td>Dimensional reference velocity</td>
<td>( V )</td>
<td>( \Delta \rho g H_{\text{box}} / \eta_{\text{um}} ) m/s</td>
</tr>
<tr>
<td>Dimensional velocity</td>
<td>( v )</td>
<td>( V / \Delta \rho g H_{\text{box}} ) m/s</td>
</tr>
<tr>
<td>Dimensional reference stress</td>
<td>( \Delta \rho g H_{\text{box}} )</td>
<td>800 MPa</td>
</tr>
<tr>
<td>Dimensional yield stress</td>
<td>( \tau_0 )</td>
<td>48 MPa</td>
</tr>
</tbody>
</table>
Stokes equation with the incompressibility constraint. Whilst the integrands are typically polynomials, for ease of implementation they are approximated numerically via a suitable quadrature scheme. By using the particles as the integration points we can only adjust the integration weights to minimize the error as the particle positions are dictated by the fluid velocity. For further details of the numerical method, software implementation and numerical benchmarks please refer to Moresi et al. (2003).

5. Model results

We investigate subduction dynamics with a suite of 29 3-D numerical experiments in total (see Table 2). Values for Stokes buoyancy and effective flexural stiffness are systematically varied through material parameters of the plate ($\Delta \rho$, $\rho_{\text{plate}}$, $\eta_{\text{core}}$, and $\eta_{\text{core}}/\rho_{\text{plate}}$).

We provide quantitative measurements for a subset of the subduction models presented in Table 3 including the radius of curvature, the sinking velocity, the subduction velocity, the trench and plate velocities. All velocities are normalized by an appropriate velocity of the system. In the case of the sinking velocity, it is normalized by a characteristic velocity such as the Stokes velocity, $v_S$. In the case of the sinking velocity, it is normalized by the plate velocity, $v_p$.

The plate is embedded with passive tracers that move with the plate and allow us to calculate the subduction motions, which are measured along the symmetric mid-plane. The velocities are averaged over a steady-state period between when the slab tip reaches a mid-mantle depth and just before it reaches the lower mantle. Additionally, tracers provide snapshots of the slab morphology and these are used to derive the radius of curvature for a snapshot corresponding to just before the slab tip reaches the lower mantle. A cubic spline is fit to a continuous line of tracers from the slab through the trench and back into plate, which provides the derivatives needed to calculate the curvature with the osculating circle method as in Capitanio et al. (2009b). This method is an analytical one to detect the maximum curvature of the surface which corresponds to the minimum in the radius of curvature, $R_{\text{min}}$. However, previous studies using analogue models cannot measure the curvature to the same level of precision as analytical or numerical models, and report values for $R$ using the convention that the estimated value of $R/H \sim 0.5$ corresponds to when a slab is curved into a semi-circle that fills the depth of the upper mantle. Thus, values for $R_{\text{min}}$ as measured here need to be converted to this convention in order to be compared to previous work. This is done by multiplying by a factor of 2 (i.e. $R_{\text{meas}} = 2R_{\text{min}}$), and the converted values are then given in Table 3. The measured values of the two largest and two smallest $R_{\text{meas}}$ models 15 and 24 and models 2 and 5, respectively, qualitatively agree to a visual inspection of those models having the correspondingly largest and smallest $R_{\text{meas}}$ value.

5.1. Classification of subduction styles

Subduction is observed to occur via several different styles (as illustrated in Fig. 2), primarily in accordance to the two controlling factors of flexural stiffness and slab buoyancy. Each style is characterized by a distinct type of slab geometry generated by the associated subduction kinematics which have been previously described (Bellahsen et al., 2005; Schillart, 2008; Di Giuseppe et al., 2008). Using these free subduction experiments we map out the approximate regions in which particular styles of subduction are favored to occur. Following this, we

### Table 2

| Exp | Width (km) | $\Delta \rho$ (kg m$^{-3}$) | $\rho_{\text{plate}}$ (km) | $\eta_{\text{core}}$ (km) | $\eta_{\text{core}}/\rho_{\text{plate}}$ | $B_S$ | $D_{\text{core}}$ | $k_f$ | Observed mode$^a$
|-----|------------|-----------------|-----------------|-----------------|-----------------|-------|-----------------|-------|-------------------
| 1   | 1200       | 26.7            | 100             | 50              | 20              | 1.9 $\times 10^{-12}$ | 0.0087 | 4.0 $\times 10^4$ | F     |
| 2   | 1200       | 80              | 100             | 50              | 20              | 5.7 $\times 10^{-12}$ | 0.0087 | 4.0 $\times 10^4$ | IV    |
| 3   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | F     |
| 4   | 1200       | 26.7            | 100             | 50              | 20              | 5.7 $\times 10^{-12}$ | 0.0087 | 4.0 $\times 10^4$ | IV/V  |
| 5   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV    |
| 6   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 7   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 8   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 9   | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 10  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 11  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 12  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 13  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 14  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 15  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 16  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 17  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 18  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 19  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 20  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 21  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 22  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 23  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 24  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |
| 25  | 1200       | 1200            | 50              | 20              | 1.7 $\times 10^{-11}$ | 0.0087 | 4.0 $\times 10^3$ | IV/V  |

$^a$ Mode F denotes when subduction failed to occur. Refer to Fig. 2 for illustration of other modes.

$^b$ There is strong indication from Experiments 7–7a and 8–8a that the mode of subduction is not sensitive to the shape factor, through which $W/h$ can influence the sinking kinematics.

$^c$ This model has a dual-core plate. Values given are for both cores.

$^d$ To save computational expense, the width of these models is not increased in accordance to the thickness (reducing the $W/h$ ratio from 12 to 8) and the experiments are performed in a domain that is 4000 km wide.

$^e$ There were insufficient computational resources available to allow the model's evolution to reach the phase of long-term subduction.
and appears more similar to a bending beam mode. We have classified this Experiment 24 begins with a slab tip having a very slight forward sinking trajectory, indicating possibly an Advance-Fold-Retreat mode but quickly becomes dominated by a retreating trench and plate configuration, analogous to an initially horizontal viscous beam clamped at one end and bending under its own weight (Ribe, 2001). Subduction begins with an initially vertical sinking trajectory of the slab tip while the trench is continuously retreating. This produces the slab geometry of a slightly bent beam, which lands bottom-side down, seen in Fig. 4a. The slab tip becomes anchored during interaction with the lower mantle, resulting in a highly bent slab that eventually lands upside down as seen in Fig. 4a. After interaction with the high-viscosity lower mantle, the trench and plate begin to experience any 3-D effects (Fig. 4c). All subduction is accommodated by the high-viscosity lower mantle, analogous to an initially horizontal viscous beam clamped at one end and bending under its own weight (Ribe, 2001). Subduction begins with an initially vertical sinking trajectory of the slab tip while the trench is continuously retreating. This produces the slab geometry of a slightly bent beam, which lands bottom-side down, seen in Fig. 4a. The slab tip becomes anchored during interaction with the lower mantle, resulting in a highly bent slab that eventually lands upside down as seen in Fig. 4a. After interaction with the high-viscosity lower mantle, the trench and plate begin to explore larger values of \( \phi_{\text{pred}} \) for some models subsequent to the time of measurement.

### Table 3 Measurements of sinking kinematics and subduction motions for all experiments which successfully subducted.

<table>
<thead>
<tr>
<th>Exp</th>
<th>( V_{\text{sink}} \text{(cm/yr)} )</th>
<th>( V_{\text{sub}} \text{(cm/yr)} )</th>
<th>( V_{\text{vis}} \text{(cm/yr)} )</th>
<th>( \frac{V_{\text{sub}}}{V_{\text{vis}}} )</th>
<th>( \frac{V_{\text{sink}}}{V_{\text{vis}}} )</th>
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<td>2</td>
<td>14.3</td>
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<td>0.3475</td>
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<tr>
<td>5</td>
<td>6.15</td>
<td>0.8868</td>
<td>0.5120</td>
<td>0.1114</td>
<td>0.2418</td>
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<tr>
<td>6</td>
<td>118.8</td>
<td>0.9506</td>
<td>0.4186</td>
<td>0.5108</td>
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</tr>
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<td>7</td>
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<td>1.1039</td>
<td>0.5662</td>
<td>0.4340</td>
<td>0.1929</td>
</tr>
<tr>
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<td>0.5898</td>
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<td>0.4075</td>
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</tr>
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<td>0.9711</td>
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<tr>
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</tr>
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</tr>
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<td>2.0342</td>
<td>0.4801</td>
<td>1.3747</td>
<td>1.1181</td>
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</table>

The measurements for the radius of curvature are taken just prior to the slab tip reaching the lower mantle. The sinking velocity, the subduction velocity, the trench and plate velocities are measured during a steady period while the slab tip is sinking through the upper mantle. We note that trench advance does not occur in any models prior to the slab tip reaching the lower mantle, so \( V_{\text{sub}} \) cannot exceed a value of 1, but is likely greater than 1 for some models subsequent to the time of measurement.

5.1.2. Regime II: advance-fold-retreat mode (heavy, strong slabs)

This mode is observed in Experiment 15 that has a plate with a very large flexural stiffness (\( D^\text{vis}_{\text{eff}} = 35 \)) and also a large Stokes buoyancy (\( B_T \sim 1.1 \times 10^{-11} \text{ s}^{-1} \)). The slab morphology shown in Fig. 2a illustrates this shallow subduction angle and flat-lying slab atop the lower mantle, analogous to an initially horizontal viscous beam clamped at one end and bending under its own weight (Ribe, 2001). Subduction begins with an initially vertical sinking trajectory of the slab tip while the trench is continuously retreating. This produces the slab geometry of a slightly bent beam, which lands bottom-side down, seen in Fig. 4a. The slab tip becomes anchored during interaction with the lower mantle, resulting in a straightening slab with shallower dip angle as trench retreat continues (Fig. 4b). Although the plate is not laterally confined, the slab and trench remain sheet-like and rectilinear without exhibiting any 3-D effects (Fig. 4c). All subduction is accommodated by trench retreat and slab rollback. Due to the extremely large viscosity ratios between the strong viscous core and upper mantle (\( \sim 10^5 \)), these models are the most computationally expensive and we are unable to explore larger values of flexural stiffness within this regime. We note that Experiment 24 begins with a slab tip having a very slight forward sinking trajectory, indicating possibly an Advance-Fold-Retreat mode but quickly becomes dominated by a retreating trench and appears more similar to a bending beam mode. We have classified this Experiment as II–I indicating that it has some characteristics of both modes, however based on the slab geometry it is possibly better described as being in the Viscous Beam Regime.

5.1.3. Regime III: advancing mode (very strong slabs)

This mode is observed in several Experiments (8, 11, 14, 19, 21, and 22) that have values of \( D^\text{vis}_{\text{eff}} > 0.3 \) and \( B_T < 6 \times 10^{-12} \text{ s}^{-1} \). Fig. 6 documents a quintessential model (Experiment 22) for this regime, typified by an advancing trench and plate with slab rollover geometry (variations of this mode are described in Appendix A). There is a significant initial curvature in the sinking trajectory of the slab tip (bending the slab into the rollover geometry) until it lands atop the lower mantle with the bottom-side up (prone) as shown in Fig. 6a. Nearly simultaneous with the slab tip reaching the lower mantle, the nearly-stagnant underlying flow field gradually increases in magnitude as the trench and plate begin advancing. Curvature attained near the trench due to bending of the plate is preserved as the slab descends through the mantle, making the slab develop into the well-documented

### Fig. 4 Evolution of subduction in Experiment 15 showing second invariant of the strain rate during (a) slab–tip interaction with the lower mantle, (b) steepening slab producing the bending beam slab geometry, and (c) top view showing a rectilinear trench and no influence of 3-D effects.

5.1.3. Regime III: advancing mode (very strong slabs)

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Nearly simultaneous with the slab tip reaching the lower mantle, the nearly-stagnant underlying flow field gradually increases in magnitude as the trench and plate begin advancing. Curvature attained near the trench due to bending of the plate is preserved as the slab descends through the mantle, making the slab develop into the well-documented
rollover geometry as seen in Fig. 6b, (also sometimes referred to as the “umbrella handle” or “candy cane” morphology). After the slab–tip interaction with the lower mantle, both the direction and magnitude of the underlying flow field evolve as plate and trench continuously advance (Fig. 6c,d). This morphology corresponds to $R/H$ ratios of ~0.5. There is little discernible lateral trench curvature.

5.1.4. Regime IV: retreating mode (heavy, weak slabs) 

This mode is observed in 4 experiments (2, 5, 6, and 18) within the range of $D^{*}_{vis} < 0.3$ and $B_s > 5 \times 10^{-12} \text{s}^{-1}$. Experiment 6, shown in Fig. 7, is an archetypical example for this regime which is characterized by pure trench retreat and slab rollback producing flat-lying, backwards-draping slab morphology atop the lower mantle. The sinking trajectory of the slab tip is subvertical and lands bottom-side down atop the lower mantle (Fig. 7a) and subsequent to that, the slab continues to remain subvertical. The slab is deposited entirely in the backwards-draping manner under a retreating trench, producing a flat-lying slab (Fig. 7b). The slab tends to be steeply dipping (with correspondingly smaller radius of curvature and $R/H$) but the dip angle becomes shallower for plates with larger Stokes buoyancy. As the slab sinks, its edges curl upwards and this provides evidence for a large influence of 3-D effects on subducting plates as seen in Fig. 7bc. This slab deformation is expressed on the surface as a highly curved trench (concave towards the mantle wedge/overriding plate) as seen in Fig. 7c.

5.1.5. Regime V: folding mode (weak slabs)

This behavior is most clearly displayed by Experiment 17 (Fig. 7) which is in the same range of flexural stiffness as Regime IV ($D^{*}_{vis} < 0.8$) but has $B_s < 6 \times 10^{-12}$. The sinking trajectory of the slab tip is relatively subvertical, landing nose-first and then immediately folding twice (first forwards and then backwards) as seen in Fig. 7ab. After some period of trench retreat and slab rollback, the trench and plate motion again switch to advancing with accompanying forwards slab draping,
generating an accumulation of recumbent folds of various lengths into a slab pile atop the lower mantle as seen in Fig. 8c. The slab, in any case, remains subvertical, with a steeply-dipping angle of subduction and correspondingly small values of $R/H$. Experiment 17 also displays noticeable trench curvature (concave towards the mantle wedge/overriding plate) in addition to slight lateral bending of the slab at depth as seen in Fig. 8d.

6. Discussion

6.1. Description of regime diagram

These numerical results are compiled by observed subduction mode and shown in Fig. 9. The regime boundaries (dashed lines) are admittedly somewhat arbitrary as they are only constrained by factors of 2 in Stokes buoyancy and $10^{-1}$ order of magnitude in flexural stiffness. Both the exact location and shape of the regime boundary are not known, as is the area to which these regimes extend outwards (this uncertainty is indicated by "?"s on Fig. 9).

In instances where a model failed to subduct, recycling of the lithosphere still occurs but this behavior does not meet the traditional definition of subduction (although the definition itself may be somewhat of a subjective issue). Based on Experiment 10 we propose that for small values of $B_s$ and large values of $D_{vis}$, subduction is inhibited. The plate is quite strong and easily resists the amount of bending moment applied by the initial slab perturbation. Thus, rather than bending the slab and initiating subduction, the plate does not bend at the hinge and the perturbation drips away leaving the plate at the surface.

We propose that in the isoviscous limit ($\eta_{core}/\eta_{um} = 1$), recycling of the lithosphere will occur through the Rayleigh–Taylor drip-like mode rather than traditional single-sided subduction of a viscous sheet. Both Experiments 1 and 3 show that the competence of the viscous sheet is vastly reduced and is subjected to the growth of large-scale instabilities which are dominant over the normal subduction modes of plate advance and slab rollback. We use Eq. (6) as a guide to find this theoretical lower limit to subduction by setting $\eta_{core}/\eta_{um} = 1$ and
assuming thickness of a plate’s strong core ranges between 10–80 km. We derive that this lower limit should be between $D_{\text{vis}} = 10^{-3}$ and 0.0018, and plot the corresponding area in grey at the bottom of Fig. 9.

Regime V, but in practice this mode has a variety of expressions in the slab geometry. As described in Section 5.1.4, Experiment 5 is in a retreating mode and exhibits pronounced curvature of the slab and trench. However, Experiment 5 (plate width = 1200 km) has the same parameters as models in Schellart et al. (2007) who observed that for plate widths in excess of 2000 km, plates are observed to subduct via the folding mode. Further review of Experiment 5 shows that the trench retreat is not steady, but undergoes a slight decrease (pause) leading towards a pulsation in subducted slab material. This is taken as a subtle, yet important distinction of Experiment 5 from the other slabs which exhibit uninterrupted trench retreat. For these reasons, Experiment 5 is represented by both a circle and a triangle and Regime V (folding) is understood to encompass a broader range of behavior than just slab piles.

6.2. Analysis of regime diagram

We propose that a variety of subduction regimes are generated primarily as a product of two mechanisms. The first mechanism is that of the competition between the weight of the slab and the strength of the plate, which can be understood in terms of the applied bending moment, and this competition results in a particular radius of curvature. The second mechanism is that of the interaction between the slab and the more viscous lower mantle, and this results in producing distinct slab morphologies for each regime. The sinking velocity of the slab is important for the second mechanism, as it determines the time which the slab tip interacts with the lower mantle, which in turn defines the slab-mantle interaction through the radius of curvature and slab morphology at that instant.

The buoyancy of the slab enters the problem through both the bending moment (i.e. Eq. (1)) as well as the bending rate (Eqs. (4) and (5)). Using the expression that results from Eq. (1), $M \sim \frac{1}{2} \Delta \rho g h_{\text{plate}} R^2$, we make the assumption that the effective length of slab acting to bend a plate of a strength $D_{\text{vis}}$ into a radius of curvature $R$ is approximately equal to $R$. Thus,

$$M \sim \frac{1}{2} \Delta \rho g h_{\text{plate}} R^2 \tag{7}$$

Now it is possible to quantitatively relate the weight of the slab to the strength of the plate by using the two expressions for the bending moment and setting Eq. (7) equal to Eq. (4) (and substituting in Eq. (5)):

$$\frac{1}{2} \Delta \rho g h_{\text{plate}} R^2 = D_{\text{vis}} \frac{u_{\text{sub}}}{R} \tag{8}$$

Both sides of this new expression are then normalized by the same factor that was used in Eq. (6):

$$\frac{1}{2} \Delta \rho g h_{\text{plate}} R^2 = \frac{D_{\text{vis}}}{1 \text{ km} H^3} \frac{u_{\text{sub}}}{\frac{1}{3} \text{ km} H^2} \tag{9}$$

Finally, rearranging and using the definitions for $D_{\text{vis}}$ and $B_{\text{s}}$, the expression simply becomes:

$$\left( \frac{R}{H} \right)^3 = \frac{2 u_{\text{sub}} D_{\text{vis}}}{3 \frac{1}{3} B_{\text{s}}} \tag{10}$$

We note that the quantity $B_{\text{s}} R$ is similar to a characteristic velocity such as the Stokes velocity (we defined $v_S = B_{\text{s}} H$). Also, given our initial assumption the length of slab, $l$, that is loading the bending plate is approximately a length equivalent to $R$, the expression could be rewritten as a ratio of the two velocities, $u_{\text{sub}}$ and $B_s$:

$$\left( \frac{R}{H} \right)^3 = \frac{2 u_{\text{sub}} D_{\text{vis}}}{3 B_{\text{s}} l} \tag{11}$$

Fig. 9. Observed subduction mode for the 25 numerical experiments that have unique combinations of $D_{\text{vis}}$ and $B_{\text{s}}$, Regime boundary lines are approximate. Experiment 5 is represented by both a circle and a triangle. It has the same parameters as models in Schellart et al. (2007) and is observed to subduct via the folding mode for plate widths in excess of 2000 km.
In this form, the expression appears to depend most strongly upon $D_{\text{vis}}$ with probably only a slight correction factor coming from the buoyancy as it is contained in the velocity ratio.

Eq. (10) quantitatively describes how the competition between slab weight and plate strength produce a particular radius of curvature. One issue with the scaling law is that the subduction velocity is only available a posteriori, so the equation does not allow for a full prediction of $R$. In Fig. 10, we show the radius of curvature that is predicted for each model plotted against the measured value. In order to obtain a reasonable fit, the same factor of 2 has been applied to the predicted radius of curvature to follow the same convention that was used in the measured radius of curvature (as discussed in Section 5).

This figure shows the fit is good for a range of values for $R/H$ between 0.05 and 0.7, but the predicted value is systematically underestimated for values larger than 0.7. This underestimation could result from the approximation that $I - R$, which is expected to be a better approximation for small values of $R$.

The radius of curvature is one of the most important characteristics of the subduction system, and is a primary control on the development of slab morphology because the upper mantle has a finite depth. In particular, several aspects of the subduction regimes occur only because of this finite depth of the upper mantle such as the flat-lying slabs of Regimes I and IV, the recumbent folding of slabs as in Regimes II and V, and the advancing trench motion of Regime III. Over most of the range of $B_\text{f}$, plates in Regime IV and V usually have $(R/H) < 0.3$ resulting in steeply-dipping slabs that are subvertical upon reaching the lower mantle. For plates in Regime III, $(R/H) \sim 0.5$ which is a special value because when the slab tip reaches the lower mantle, the slab in the upper mantle has obtained a half-circle shape. At that point, the interaction with the bottom of the upper mantle produces forward rolling of a stiff, circular slab and results in trench advance.

6.3. Influence of flexural stiffness on subduction dynamics

These results demonstrate the flexural stiffness is a quantity that has a profound effect on the behavior of a subducting plate, in agreement with previous work (Capitanio et al., 2007b). Some insight can be gained by considering the simple relationship between flexural stiffness and buoyancy in the context of subduction. The good fit in Fig. 10 suggests that the competition between the weight of the slab and strength of the plate self-consistently produces an appropriate value of $R$, and thus validates our approximation that the length of slab that is important in the system is of order $R$.

It is seen that plates with small flexural stiffness (Regimes IV and V) bend more easily and thus, the smaller lengths of slab are required to produce correspondingly smaller $R/H$ values (0.1–0.3). Plates with a larger flexural stiffness (Regimes II and III) have a greater resistance to the same applied bending moment and require larger lengths of slabs to bend the plate. In this case, the plates are also bent to a lesser degree and the corresponding values of $R/H$ increases to ~0.5. For even larger flexural stiffness (Regime I), plates resist bending to an even greater extent and subduct in the viscous beam mode leading to situations where $R/H \sim 0.8–1$.

However, because the length of the subducted slab is continuously increasing, the magnitude of the applied bending moment is also increasing until it reaches the point of saturation. A good example of this is models in Regime II, which undergo a mode transition from initially advancing plates into retreating trenches. Such plates have a single flexural stiffness and a single buoyancy, but as the length of the slab increases from the beginning of the experiment, the bending moment being applied through the increasing weight of the slab also slowly increases. When the slab extent into the upper mantle reaches an appropriate length ($\sim R$), the applied moment becomes large enough to eventually dominate the flexural stiffness and triggers the mode transition into a retreating trench. Within Regime II, plates with larger buoyancy undergo this transition at an earlier stage into the long-term subduction (less of the length of the plate has been subducted). This is confirmed by the shorter length of recumbent fold seen in Experiments 9 (larger $B_\text{f}$) than in Experiment 20.

Slightly more complicated is to consider the general role of buoyancy while keeping the flexural stiffness constant. Larger buoyancies require faster subduction velocities (which must be partitioned between trench retreat and plate advance), and such fast velocities become increasingly difficult to be achieved by plate advance. However, faster subduction velocities imply faster bending rates which naturally leads to less deformation being achieved through bending. The result of this is shallower dip angles and correspondingly larger $R/H$ as seen in Regimes I, II and IV. Smaller buoyancies with smaller subduction velocities (and smaller bending rates) favor viscous deformation at the trench bend as seen in Regimes III, IIIa and V. This control on the slab dip and the bending radius by the buoyancy of plates as observed in these models is in good agreement with previous studies (Royden and Husson, 2006; Capitanio et al., 2007a, 2009b) who provide some additional analysis on the subject.

Finally, consider the case of two plates with the same flexural stiffness but one plate has greater negative buoyancy than the other. The plate with a larger buoyancy has both a faster bending rate (due to faster sinking and subduction velocities) and a greater bending moment. These two effects trade off against each other as the greater bending moment leads to increased bending, but the faster bending rate acts to decrease deformation through bending. Once the buoyancy becomes large enough, the bending rate becomes dominant and trench retreat is favored over plate advance. This is most clearly evident for the transition from Regime V (folding mode) to Regime IV (retreating mode), however the same applies for the mode transition between Regime III (advancing) and Regime II (Advance-Fold-Retreat). An interesting case may arise if the buoyancy is variable along the length of the subducting plate, for example density gradients or zones of compositionally buoyant material, and this is shown to cause a response in the system expressed as a time-dependent slab morphology and associated oscillations in trench motions (Royden and Husson, 2006).

6.4. Importance of the tensile stiffness for allowing subduction

Because most of the experimental suite had a single, strong core, the tensile stiffness is varied over as many orders of magnitude as the flexural stiffness. The very weak plates in Experiments 1–3 with small flexural stiffness ($D_{\text{vis}} \sim 0.01$) have difficulty achieving subduction.

![Fig. 10. Comparison between the measured and predicted values for $(R/H)$, using the scaling analysis in Eq. (10).](image-url)
One of the most salient features of the strong core is to provide a stress guide which allows the weight of the slab to be transmitted to the trailing plate (i.e. slab pull force). It is through this mechanism that the viscous drag along the base of the plate can be overcome and forward plate motion can be achieved. For cases in which the magnitude of tensile stiffness is very small \( (k_t = 4 \times 10^3 \text{kg s}^{-1}) \), the competence of the stress guide may not be enough to overcoming the basal drag. Perhaps a more appropriate model for very weak slabs \( (\text{D}^\text{ex} = 0.1) \) is a very thin strong core \( (< 10 \text{km}) \) which offers sufficiently large tensile stiffness and a very good stress guide for transmitting the slab pull force while providing relatively little flexural stiffness. Then depending upon the exact buoyancy and length of the trailing plate, the viscous drag on the base of the trailing plate can be overcome and subduction can be achieved.

There is another aspect of the low tensile stiffness in the very weak plates in Experiments 1–3 which is the observed horizontal contraction that leads to slab thickening. The thickened plates subsequently have greater flexural stiffness than initially, but only after subduction failed to begin. Another important effect of having a larger tensile stiffness is increasing the plate’s ability to avoid this horizontal contraction. Larger values such as \( k_t = 10^5 \text{kg s}^{-1} \) allow the response to horizontal fiber stresses in the plate to take sufficiently long that the overall contraction is negligible over the period of subduction.

The four-layer model described in Section A-3 is exactly the type of model setup that allows one to specify the exact values for both flexural stiffness and tensile stiffness independently. Many of the models were run prior to realizing how important the tensile stiffness is, particularly for the cases with very low tensile stiffness. New models with greater tensile stiffness may help improve the regime diagram in the region of very weak slabs and it is presumed that plates with such small flexural stiffness can subduct successfully. Additionally, one could construct the regime diagram such that the tensile stiffness is held constant for all values of flexural stiffness.

6.5. Importance of 3-D geometry

Provided the sinking slab is sufficiently weak \( (\text{D}^\text{ex} < 0.1) \), the induced toroidal flow that impinges across the face of the slab is strong enough to deform the slab. This slab–mantle interaction results in the slab edges curling up as the slab sinks, and this lateral curvature of the slab at depth is expressed on the surface as trench curvature. For a given Stokes Buoyancy, the induced toroidal flow (and the effective lateral bending moment) will be approximately equivalent for slabs of different flexural stiffness, which leads to a more pronounced lateral curvature in weaker slabs. Weaker plates are more susceptible to lateral deformation and trench curvature arising from this slab–mantle feedback and display a pronounced variation in trench retreat rates depending on plate width \( \text{(Schellart, 2004; Stegman et al., 2006)} \). Conversely, if a retreating slab is sufficiently strong (Regimes I and II), this effect is not apparent and trenches remain rectilinear or exhibit only slight curvature and there is no dependence upon plate width \( \text{(Bellahsen et al., 2005)} \).

On Earth, some highly curved trenches are observed (concave towards the mantle wedge/overriding plate for retreating trenches) and is comparable to the curvature expressed by weak slabs in subduction models \( \text{(Schellart et al., 2007)} \). Subject to the condition that trenches are not modified by anything else such as an overriding plate \( \text{(Clark et al., 2008; Bonnardot et al., 2008)} \), lateral variation in plate age and strength \( \text{(Morra et al., 2006)} \), or subducting plateau or ridge \( \text{(Martinod et al., 2005)} \), the trench curvature on the surface reflects the amount of lateral slab bending. If indeed the origin of trench curvature on Earth arises from the slab–mantle interaction bending slabs, this is further evidence for slabs on Earth being “weak” \( \text{(Schellart, 2008)} \).

For the models presented here, an induced toroidal flow around the edges of slabs exists for all the regimes, which is merely a consequence of lateral variations in viscosity. This induced flow is not present in 2-D models, and certainly effects the subduction kinematics if all flow is confined to a 2-D plane (implying an infinitely wide plate).

6.6. Comparison with previous 3-D model results

Our experiments are in broad agreement with both analogue and numerical experiments of several previous studies. The viscous beam mode has been observed by laboratory models of \( \text{Funiciello et al. (2006)} \) of which Experiment 4 is an excellent example, but it is also well-documented by \( \text{Bellahsen et al. (2005)} \) (of their Experiments 3, 4, 22–24, and 30). Models presented in \( \text{Funiciello et al. (2006)} \) show plan view toroidal flow patterns but a straight trench (see for example Fig. 7 in \( \text{Funiciello et al., 2006)} \). This is a good indication that the effective flexural stiffness is large enough that the slab and trench do not deform in the trench-parallel direction. Our model setup is slightly different than previous laboratory models by virtue of a lower mantle with a finite viscosity contrast \( (100 \times \text{H_m}) \) as opposed to an infinite viscosity contrast (rigid bottom), and this may account for differences in the motion of the slab tips. Nonetheless, the basic characteristics of this mode that were previously documented are reproduced by Experiment 15. This results in a very shallow dip angle and correspondingly large ratio of radius of curvature to mantle depth, \( R/H, (~0.9) \) \( \text{(Bellahsen et al., 2005; Funiciello et al., 2006, 2008)} \).

Both the Advance-Fold-Retreat mode (Regime II) and the advancing modes (Regime III) have been observed in several previous studies \( \text{(Bellahsen et al., 2005; Schellart, 2008; Di Giuseppe et al., 2008)} \). \( \text{Bellahsen et al. (2005)} \) refer to these modes as Mode II and Mode III, respectively. Many of the models of \( \text{Bellahsen et al. (2005)} \) typically have a large flexural stiffness \( (1/\eta_{\text{plate}}/\eta_{\text{hum}} > 1000) \), and do not exhibit much plate lateral curvature or dependence of subduction kinematics on plate width. Most of the subduction observed in \( \text{Schellart (2004)} \) is similar in its retreating mode characteristics as experiments presented here that are classified as Regime IV (retreating). This includes significant lateral trench curvature and a dependence on plate width for retreat rate. Slab folding and piling (Regime V) is less commonly observed, having been found with pushed trailing edge boundary conditions \( \text{(Schellart, 2005) \} \) which show 3–5 recumbent folds. Both the studies of \( \text{Schellart (2004) and Schellart (2005) use plates with smaller flexural stiffness (1/\eta_{\text{plate}}/\eta_{\text{hum}} < 200).} \)

6.7. Implications for subduction dynamics in Earth

Several geophysical observations are consistent with a viscosity \( 1/\eta_{\text{plate}}/\eta_{\text{hum}} \sim 100 \). Models of the Earth’s geoid provide one of the most important constraints on mantle structure which repeatedly find best fit models when slabs are about \( ~100 \) more viscous than the upper mantle \( \text{(Hager, 1984; 1991; Moresi and Gurnis, 1996; Zhong and Davies, 1999)} \). In particular, 3-D numerical modeling of the Tonga-Kermadec subduction zone \( \text{(Billen et al., 2003)} \) very carefully estimated the viscosity structure required to match several geophysical
observations including the geoid, the magnitude of the strain rate release in the slab, as well as the depth-dependent strain rate and stress orientations within the slab inferred from seismicity and moment tensor solutions. Billen et al. (2003) concluded that only models with $\eta_{\text{plate}}/\eta_{\text{mantle}} \sim 100$ could simultaneously satisfy all these constraints, and further that models with $\eta_{\text{plate}}/\eta_{\text{mantle}} > 1000$ failed to satisfy the strongest constraint of the slab strain rate. Those findings are in agreement with previous models of stress orientation and distribution of earthquakes with depth (Vassiliou et al., 1984; Tao and O’Connell, 1993).

The direction of the plate motion has also been used to constrain the strength of plates and their associated slabs by using a variational description of mantle convection which accounts for dissipation by bending of the lithosphere (Buffett and Rowley, 2006). Using this method, Buffett and Rowley (2006) found an absolute value of plate strength of $6 \times 10^{13}$ Pa s which is not more than a few hundred times most estimates of the upper mantle viscosity. Using plate motions and geophysical observations such as radius of curvature, Wu et al. (2008) estimate that slabs must be no more than 300 times more viscous than the upper mantle. Bending at subduction zones works to resist plate motion and the observed plate velocities are not able to be matched unless slabs are sufficiently weak (Wu et al., 2008).

The interaction of weak slabs with the mantle viscosity stratification produces either slab piles atop the lower mantle from recumbent folding of nearly vertically deposited slab material underlying a nearly-stationary trench, or backwards draping of the slab following a retreating trench. Based on the experiments of this study, the region of parameter space occupied by Regime V (folding and slab piling) is relatively confined to a combination of weak slabs and modest Stokes buoyancy (such as Experiment 17), but nonetheless this is the buoyancy range expected for slabs on Earth. Experiment 17 exhibits 4 consecutive recumbent folds and a similar number of folds was observed in experiments of Schellart et al. (2007) for plate widths in excess of 2000 km (most subduction zones on Earth are also at least this wide). Based on interpretations of seismic tomographic images, Ribe et al. (2007) describe a few locations on Earth (beneath Java and Central America) in which slab piling behavior may have occurred and produced seismically fast wedge-shaped features 500–700 km in extent. Similar piles have been reported previously underneath the Mariana subduction zone (van der Hilst and Seno, 1993) as well as possibly underneath Tonga and Kuril–Kamchatka (Fischer et al., 1988, 1991; Schellart et al., 2006). These wedge-shaped envelopes are interpreted to be the result of periodic buckling instabilities of the slab due to oblique injection of slab material (at some dip angle) into the transition zone, where slab folding increases the thickness by up to a factor of 5 (Ribe et al., 2007). Weak slabs are easily bent in either direction upon reaching the more viscous lower mantle, and thus the observation of slab piles can be considered a strong indication of weak slabs and that slabs on Earth are in Regime V (the folding regime).

The recumbent folding of weak slabs is expressed on the surface in four dimensions as oscillations of the plate boundary between periods of trench retreat and advance. Sinking kinematics of the slab and corresponding trench migration of Experiment 17 are shown in Fig. 11. The vectors show sinking motion between two times during a period of backwards-draping slab motion atop the lower mantle viscosity increase which corresponds to a net trench retreat (Fig. 11a) while a net trench advance is seen during a period of forwards-draping slab motion (Fig. 11b).

Such trench oscillations translate into episodicity of active back-arc spreading with periods of quiescence (Clark et al., 2008; Guillaume et al., 2009; Capitanio et al., 2010–this issue) and provide a geological observable within the age distribution of oceanic lithosphere which may be addressed by future modeling. Furthermore, the resultant slab piles are larger density anomalies that can sink faster through the mid-mantle, and slab piles can also influence observed sinking rates of upper mantle slabs (Goes et al., 2008) as well as possibly trigger regional tectonic reorganizations (Pysklywec et al., 2003; Capitanio et al., 2009a).

The experiments presented in this study cover a wide range of parameter space and it is presumed that the conditions appropriate for Earth are contained within this coverage. We can infer from several other lines of available evidence, including the observed slab morphology from seismic tomography, that the estimated value for Earth is $D_{\text{elas}} \sim 0.1$. If the effective flexural stiffness is averaging over the entire thickness of mature oceanic lithosphere (100 km), it corresponds to an average lithosphere viscosity that suggests $\eta_{\text{plate}}/\eta_{\text{mantle}} \sim 288$. This value is in excellent agreement with the estimate of bending viscosity provided by Wu et al. (2008). For laboratory experiments that model a 100 km thick subducting plate which is entirely viscous, this implies such models should adopt a value of $\eta_{\text{plate}}/\eta_{\text{mantle}} < 0.1$. In numerical experiments which can allow for strong core, this amount of strength can be partitioned into a smaller core with a higher viscosity. However, we note this estimate is also on the upper end of the expected range, with more likely values of $D_{\text{elas}} < 0.1$ and correspondingly smaller and less viscous cores.

7. Conclusions

These numerical models of free subduction support the view that the lithosphere is the primary factor in describing key elements of the
plate tectonics system such as subduction kinematics, slab geometries, and mantle flow due to slab–mantle coupling. We identify the two essential controlling factors for the dynamics in these models which are the Stokes buoyancy and flexural stiffness, and demonstrate that all previously described subduction regimes can be reproduced with just these two parameters. The buoyancy is important for determining both the bending rate as well as the bending moment, which are balanced through the flexural stiffness. Similarly, in order to successfully model subduction with plates that have a small flexural stiffness, it is important to consider the tensile stiffness as well. The tensile stiffness must necessarily be large enough to provide a competent stress guide for slab pull to be transmitted and must be sufficiently large enough to prevent horizontal contraction (and slab thickening). Depending upon the value of the two parameters (\(D_{\text{vis}}^*\) and \(B_\text{g}\)), a total of 5 regimes for subduction dynamics are observed to occur as well as regions where subduction is inhibited (possibly even prohibited). Each of the regimes can be explained, from a conceptual level, with respect to these quantities and this allows us to successfully explain the observed mode transition in Regime II (Advance-Fold-Retreat) as well as understand the origin of regime boundaries. If plates are sufficiently strong (\(D_{\text{vis}}^* > 1\)), the observed mode of subduction is not sensitive to the influence of 3-D geometry, although 3-D flow fields are present. These models as well as those of Schellart et al. (2007) demonstrate that weak slabs are sensitive to the induced 3-D toroidal flow, and that plate width is an important factor for understanding subduction dynamics in Earth.

The results presented here are the first to characterize the strength of plates in an absolute sense, and indicate the transition between strong slabs (Regimes I–III) and weak slabs (Regimes IV–V) is \(D_{\text{vis}}^* \approx 0.5\). The models in the weak slab regimes exhibit features such as highly curved trench geometry that have previously been recognized as features indicative of modern subduction systems. The models in certain strong slab regimes exhibit advancing features (as seen in Regime III) and the distinct lack of advancing trenches on Earth at the present time (Schellart et al., 2008) would not favor Regime III as representative of Earth. Moreover, we conclude based on the results of Ribe et al. (2007) that slab piles occur in Earth as a result of weak slabs interacting with a partially stratified mantle. This is an indication that many plates on Earth (and their associated slabs) are in Regime V (folding mode) and should exhibit steeply-dipping slabs except in cases where trench retreat rates are fast. Based on this, we advocate that 3-D geometry is essential for faithfully reproducing subduction dynamics (and resultant subduction kinematics) that are appropriate for Earth. Slabs that are weak can be easily perturbed by a number of processes that occur in the Earth, including the subduction of buoyant plateaus and ridges, the induced mantle flow from nearby slabs or piles entering the lower mantle, or possibly interact if plume heads directly impinge upon them from underneath.

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Appendix A

A-1. Evidence for variations of subduction in Mode III

There are some slight variations in the slab morphology for this Advancing Regime which are a product of the initial sinking trajectory, the amount of bend preservation at the point of slab–tip interaction, and overall subduction velocity. The evolution of slab geometry for Experiment 8 is subtly different to Experiment 22, having developed an “elephant trunk” slab morphology as shown in Fig. A-1. Experiment 8 has the same Stokes buoyancy as Experiment 22 but slightly more than a factor of 3 times smaller flexural stiffness \(D_{\text{vis}}^* = 0.87\). Consequently, less of the slab’s bend is preserved as it sinks sub-vertically through the upper mantle and this is true for whether it is just the initial length of slab (Fig. A-1a) or later after some amount of forward slab draping has occurred (Fig. A-1b).

Another variation is observed in Experiment 19, which has both less bending resistance (factor of 3) and less buoyancy (factor of 2) than Experiment 22. In this case, the rollover slab geometry preserves very little of the initial bend and the backwards-sinking slab tip trajectory produces an apparent dip angle of more than 90° (Fig. A-2a). The slab bends easily, and this backwards-dipping slab geometry is translated in the forward direction as the plate and trench advance (Fig. A-2b).

There is also a subset of the advancing mode in which the slab initially begins landing bottom-side down atop the lower mantle, which is opposite to all the other experiments in this regime. Eventually, the plate and trench begin advancing and produce rollover slab geometry similar to the rest of the advancing mode experiments. This mode is observed in two Experiments (7 and 16) that have the smallest values of \(D_{\text{vis}}^*\) and \(B_\text{g}\). A nice example of this is Experiment 16 (shown in Fig. A-3) in which the backwards-sinking slab tip has reached the lower mantle and subsequent backwards-sinking (and accompanying trench retreat) produces a short length of backwards slab draping (Fig. A-3a). There is also considerable plate advance during this period, which continues when the trench suddenly starts advancing (Fig. A-3b) and the rest of the long-term subduction is in the advancing mode.

A-2. Parameter space for non-subduction based on failed models

Subduction is inhibited for Experiment 10, which has a factor of 1.5× less Stokes buoyancy than Experiment 16 but has more than a factor of 30× more bending resistance. At the lower range of flexural stiffness, plates with the same buoyancy as Experiment 10 seem to have enough buoyancy to overcome bending at the subduction hinge

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Fig. A-1. Evolution of subduction in Experiment 8 showing second invariant of the strain rate during (a) slab–tip interaction with the lower mantle, and (b) development of slab rollover geometry.
and the slab again sinks in a backwards-sinking trajectory as shown in Fig. A-4a. In this case it is likely that the flexural stiffness is too large to be overcome by the available buoyancy, leaving the completely rigid plate stationary and dormant atop the upper mantle. The slab tip becomes anchored in the lower mantle and bending (and folding) of the slab at depth is inhibited. After some time, the strong slab contracts in both horizontal directions and thickens significantly (which further prevents any future bending), and the dormant plate at the surface begins to collapse driven by instabilities on the plate corner (Fig. A-4b). Thus, subduction, as normally defined, does not occur in this region of the parameter space.

At the lowest value of flexural stiffness investigated ($D_{vis} = 0.0087$), plates typically have difficulty subducting. The perturbation is able to induce some amount of sinking (which is always subvertical), but the accompanying amount of trench retreat depends on the Stokes buoyancy. The trench retreat is minimal in Experiment 1 and the resultant slab is subvertical (Fig. A-5a). The lack of subduction leads instead to the plate contracting in both horizontal directions and

![Fig. A-2. Evolution of subduction in Experiment 19 showing second invariant of the strain rate during (a) slab–tip interaction with the lower mantle, and (b) development of slab rollover geometry.](image)

![Fig. A-3. Evolution of subduction in Experiment 16 showing second invariant of the strain rate during (a) slab–tip interaction with the lower mantle, and (b) development of slab rollover geometry.](image)

![Fig. A-4. Evolution of subduction in Experiment 10 showing second invariant of the strain rate during (a) backwards-sinking slab tip through the mantle, and (b) subduction having become inhibited.](image)

![Fig. A-5. Evolution of subduction in Experiment 1 showing second invariant of the strain rate during (a) backwards-sinking slab tip through the mantle, and (b) subduction having become inhibited.](image)
thickening. The stagnant (unstable) plate develops instabilities at the corners of the plate’s tail (Fig. A-5a) and begins to collapse inwards, analogous to a Rayleigh–Taylor instability (Fig. A-5b).

In the case of Experiment 3, the sinking kinematics of the heavier slab produce faster trench retreat which result in a shallower dip angle (Fig. A-6a). However, here again the plate has horizontal contraction, resulting in plate thickening, growth of instability near the tail’s corner, and eventual collapse (Fig. A-6b).

Subduction is achieved for a length of time in Experiment 2, with an initial slab tip sinking sub-vertically through the mantle (Fig. A-7a) followed by trench retreat and slab rollback (Fig. A-7b). However, shortly after the slab tip reaches the lower mantle, an instability at the corner of the plate grows and subduction initiates from the tail of the plate as well (Fig. A-7c). Thus, the plate is technically subducting but not really in any classical definition of the term.

A-3. Mechanical equivalence

In order to reduce the computational expense of models with large flexural stiffness (corresponding to large viscosity ratios \(10^5\)), models were run with an equivalent flexural stiffness achieved through a thicker core (factor of 2) which allows for a smaller viscosity ratio (factor of 8). Given two plates with different thicknesses and viscosities for the core or plate, mechanical equivalence is only achieved when both the tensile and flexural stiffnesses of one plate match the other plate. The estimates we have provided for flexural and tensile stiffnesses are those calculated using expressions that are actually derived from expressions for integrating the strength over the thickness of a plate with respect to the neutral line of stress. Therefore, there is some inexactness to the estimates provided but the estimates are still useful indication of flexural stiffness given the experiments covered 5 orders of magnitude in parameter space. Given the limitations to the numerical resolution for the models, only discrete thicknesses of layers are available (25 km) and in practice an exact mechanical equivalence was difficult to achieve. A suite of experiments with 100 km thick cores were performed (7a, 8a, and 9a) in which the aim was to qualitatively reproduce the observed subduction mode of corresponding models with 50 km thick cores (7, 8, and 9). Experiments 7a and 8a ostensibly matched Experiments 7 and 8, however, Experiment 9a clearly exhibited a mode I behavior instead of the previously observed mode II of Experiment 9 (as seen in Fig. A-8a,b).

In the case of Experiment 9a, the smaller viscosity of the thicker core \((\eta_{\text{core}}/\eta_{\text{um}} = 250)\) also substantially reduces the tensile stiffness (factor of 4), undermining the ability of the strong core to act as a stress guide between the weight of the slab and the trailing plate. In order to match both the flexural stiffness and tensile stiffness, a 4-layer plate can be used to allow an additional set of parameters that can be varied to reproduce the 100 km thick plate. Experiment 9b adopts this 4-layer (dual-core) plate and successfully reproduces the mode II behavior from Experiment 9 (Fig. A-8c) thereby achieving better dynamic similarity between the two experiments. Experiment 9b is also 1800 km wide (rather than 1200 km) such that the shape of the subducting slab is similar between Experiments as the shape factor can influence the sinking kinematics of viscous bodies. This demonstrates a successful way to ensure that a mechanical equivalence is achieved is to have a thick, strong core that provides the resistance to bending, and a thin, stronger core that provides additional resistance to stretching. The computational expense of these models presently limits the thinnest layer that can reasonably be resolved to about 25 km, however, this is sufficiently thin for decomposing the two mechanical resistances. In this case, the dual-core model has most of the flexural stiffness (85%) concentrated in the thicker core (75 km) while the thin core (25 km) provides the majority of the tensile stiffness (62.5%).
Upon further scrutiny, Experiments 7a and 8a were observed to be subtly different than, and may not qualitatively reproduce, Experiments 7 and 8 (which have a factor of 4 larger tensile stiffness). Experiment 7a begins very similar to Experiment 7 but does not have a period of backwards slab draping and instead contracts, thickens, and undergoes an instability. Experiment 8a is solidly in an advancing mode but later in the evolution has some characteristics of Mode II. We conclude that full integrations of the plate strengths (rather than crude estimates) are required to achieve greater fidelity in the mechanical equivalence between the 100 km and 150 km thick plates.

References


