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Dynamic models of downgoing plate-buoyancy driven subduction: Subduction motions and energy dissipation

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Abstract

It is much debated whether the forces associated with the downgoing plate, the overriding plate, passive or active mantle flow are dominant in controlling the paths of plates into the mantle. We investigate the dynamics and energetics for a free subduction system, driven solely by downgoing plate buoyancy, using a finite-element model of a viscoelastic plate with a free surface, sinking into a passive unbounded mantle represented by drag forces. Parameters are varied to study effects of an asthenosphere, ridge push, and a passive overriding plate, for a range of subducting plate viscosities and densities. Such a single, free plate achieves subduction mainly through trench retreat. Most of the energy dissipation occurs in driving the passive mantle response. As a result, the slab's sinking velocity is its Stokes velocity, determined by lithospheric buoyancy and mantle viscosity. The total subduction velocity and dip adjust to minimize bending dissipation in the lithosphere, and are affected by slab rheology as well as buoyancy. A low viscosity asthenosphere and ridge push facilitate plate advance, increasing plate dips and lowering subduction velocity, while suction and buoyancy of a work-free passive overriding plate decreases plate dips, thus increasing subduction and rollback velocities. However, the geometrical relation between the different parameters is the same in all model cases, because the slabs sink according to their Stokes velocity. The free subduction models thus provide a reference that can be used to distinguish the signature of downgoing plate buoyancy from that of other driving forces in global compilations of subduction parameters.

Keywords: subduction; trench motion; plate advance; lithosphere buoyancy; mantle drag; finite-element modeling

1. Introduction

It is commonly assumed that the balance between the driving forces associated with downgoing plate buoyancy (i.e., slab pull and ridge push), and viscous mantle resistance exerts the main control on subduction (e.g., Forsyth and Uyeda, 1975; Vlaar and Wortel, 1976; Chapple and Tullis, 1977; Davies, 1988). Conrad and Lithgow-Bertelloni (2002) inferred, by matching global plate motions, that upper-mantle slab pull is indeed a significant driving force, but drag by the overall whole-mantle flow pattern driven by subduction globally is as least as important. Becker and O'Connell (2001), using similar methods, concluded that whole-mantle

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subduction drag is probably dominant. Several authors (Becker et al., 1999; Conrad and Hager, 1999, 2001; Buffet and Rowley, 2006) have argued that the plate's resistance to bending at the trench significantly modulates plate velocities. On the other hand, compilations of global subduction parameters favor an important influence of the overriding plate (Lallemand et al., 2005), because of the clear correlation between overriding plate deformation mode and subduction parameters (Jarrard, 1986; Lallemand et al., 2005). The subduction data resolve no clear trends of convergence velocities, trench motion, and slab dip with thermal age of the downgoing lithosphere, which exerts the main control on slab buoyancy and an important influence on slab rheology (Jarrard, 1986; Garfunkel et al., 1986; King, 2001; Lallemand et al., 2005; Heuret and Lallemand, 2005; Sdrolias and Müller, 2006). But, Carlson et al. (1983) did find a correlation between age and absolute velocity of the downgoing plate. Thus the question of what controls the dynamics of subduction is still open, and slab pull, ridge push, viscous mantle resistance, active mantle drag, lithospheric bending resistance and forces exerted by the overriding plate may all be important.

Many subduction models have been made, but most (had to) impose kinematic constraints on one or both plates, the trench and/or the mantle. In such models, the system's response can be influenced or even controlled by the implied forces required to maintain the imposed kinematics, and it is difficult to ensure that the models are energetically consistent (King et al., 1992; Han and Gurnis, 1999). Therefore, although such models have led to many insights, they are generally not appropriate for studying dynamics.

Here we study the most basic kind of subduction, free subduction. Free subduction is driven solely by downgoing plate buoyancy while encountering passive mantle and overriding plate resistance. It can thus be regarded as a "null-hypothesis" for subduction dynamics. Our aim here is to characterize the response of free subduction in terms of plate and trench motions and plate dip, in a fully dynamic set up, and understand the underlying energetics. This will provide a better insight in the most basic type of subduction, as well as a baseline to evaluate subduction data against to test to what extent natural subduction is slab pull–ridge push driven and where other driving forces are important (Capitanio et al., this volume).

Some other studies investigated aspects of the free subduction system (Kincaid and Olson, 1987; Gurnis and Hager, 1988; Zhong and Gurnis, 1995; Ita and King, 1998; Funiciello et al., 2003a; Schellart, 2004a; Funiciello et al., 2004; Bellahsen et al., 2005; Enns et al., 2005; Stegman et al., 2006; Royden and Husson, 2006). These models display similar characteristics as ours, where subduction conditions are the same. The forces and energetics of free subduction have been investigated before in analogue set-ups (Schellart, 2004b; Bellahsen et al., 2005), where quantification is more difficult. Numerical models have been used to either study overall behavior over larger space and time scales that include penetration into the lower mantle (Gurnis and Hager, 1988; Zhong and Gurnis, 1995; Ita and King, 1998), or to perform a characterization of subduction parameters for relatively weak slabs that yield during bending (Enns et al., 2005; Stegman et al., 2006), or in a system that includes a more complex interaction with the mantle wedge and overriding plate than we do here (Royden and Husson, 2006).

Our models comprise a single plate interacting with an unbounded passive mantle, and in some models a passive overriding plate. The downgoing plate is a solid viscoelastic body of finite width, but with no variations in properties or strain along strike, represented by a two-dimensional plane-strain finite-element model. The response of the fluid mantle is implemented as a set of dissipative drag forces, proportional to the local velocity at the plate's borders, and (non-dissipative) isostatic restoring forces. The local drag tensors are calculated from the three-dimensional solution of Stokes drag for a 1000 km wide plate. We solve the mechanical energy conservation equations using the implicit Arbitrary Lagrangian–Eulerian FE package ABAQUS (Hibbit et al., 1999). This approach (which is based on Funiciello et al., 2003a; Morra and Regenauer-Lieb, 2006a,b) fully captures the energetics of the three-dimensional system, including the influence of lateral (i.e. toroidal) flow, without needing to explicitly calculate the pattern of induced mantle flow. Strengths of this model are that (a) it is fully dynamic, and (b) it allows investigating the role of the subducting plate, which is difficult to isolate from convection models, numerical or analogue, where the slab is treated as an integral part of the mantle, and where mantle flow is often affected by box boundaries, (c) the numerical approach allows a good quantification of energy and stress.

2. Modelling approach

Our approach distinguishes itself in its detailed treatment of the plate, while the effects of the mantle are imposed through dynamic boundary conditions, whereas many other models simplify the implementation of the plate(s) and solve for mantle flow. The set-up is similar to the one used by Houseman and Gubbins