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Flexural modeling of the elastic lithosphere at an ocean trench: A parameter sensitivity analysis using analytical solutions

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ABSTRACT

The outer rise is a topographic bulge seaward of the trench at a subduction zone that is caused by bending and flexure of the oceanic lithosphere as subduction commences. The classic model of the flexure of oceanic lithosphere $w(x)$ is a hydrostatic restoring force acting upon an elastic plate at the trench axis. The governing parameters are elastic thickness T_e, shear force V_0, and bending moment M_0. V_0 and M_0 are unknown variables that are typically replaced by other quantities such as the height of the fore-bulge, w_b, and the half-width of the fore-bulge, $(x_b - x_o)$. However, this method is difficult to implement with the presence of excessive topographic noise around the bulge of the outer rise. Here, we present an alternative method to the classic model, in which lithospheric flexure $w(x)$ is a function of the flexure at the trench axis w_0, the initial dip angle of subduction β_0, and the elastic thickness T_e. In this investigation, we apply a sensitivity analysis to both methods in order to determine the impact of the differing parameters on the solution, $w(x)$. The parametric sensitivity analysis suggests that stable solutions for the alternative approach requires relatively low β_0 values ($< 15°$), which are consistent with the initial dip angles observed in seismic velocity-depth models across convergent margins worldwide. The predicted flexure for both methods are compared with observed bathymetric profiles across the Izu-Mariana trench, where the old and cold Pacific plate is characterized by a pronounced outer rise bulge. The alternative method is a more suitable approach, assuming that accurate geometric information at the trench axis (i.e., w_0 and β_0) is available.

1. Introduction

Slab pull is one of the most important forces driving plate tectonics and continental drift (e.g., Forsyth and Uyeda, 1975; Conrad and Lithgow-Bertelloni, 2002). It is associated with the negative buoyancy of the dense, cold rocks of the sinking oceanic lithosphere. Due to the stiffness of the lithosphere and its elastic behavior at long wavelengths (several hundred kilometers), it can transmit stresses efficiently to the surface and is able to pull the lower plate toward the ocean trench. A consequence of this process is the bending of the oceanic plate prior to subduction, which is characterized by the formation of a prominent fore-bulge (the outer rise). Modeling the flexural bending of the oceanic lithosphere provides important constraints on trench tectonic loading and on the long term strength of the lithosphere (e.g., Bodine et al., 1981; Mueller and Phillips, 1995; Capitanio et al., 2009). Additionally, as the flexural curvature becomes significant, bending stresses could exceed the yield strength of the lithosphere (e.g., McNutt and Menard, 1982), causing pervasive faulting and tensional earthquakes in the upper part of the oceanic plate (Christensen and Ruff, 1988; Masson, 1991; Ruiz and Contreras-Reyes, 2015), as well as local plate weakening (e.g., Turcotte et al., 1978; Bodine and Watts, 1979; McAdoo et al., 1985; Judge and McNutt, 1991; Levitt and Sandwell, 1995; Watts, 2001; Billen and Gurnis, 2005; Contreras-Reyes and Osses, 2010; Zhang et al., 2014).

The flexural wavelength and amplitude of the outer rise has been modeled using an elastic lithosphere overlying a weak astenosphere. In this model, the lithosphere is loaded on the arcward side of the trench axis by a shear force V_0 and bending moment M_0 (Fig. 1A; Watts and Talwani, 1974; Parsons and Molnar, 1978; Levitt and Sandwell, 1995; Bry and White, 2007; Contreras-Reyes and Osses, 2010; Zhang et al., 2014; Hunter and Watts, 2016). The third independent parameter is the elastic thickness T_e, which in turn is related to the flexural rigidity $D = \frac{ET_e^3}{12(1-\nu^2)}$; a measure of the flexural resistance to loading. The Young's modulus, E, and Poisson's ratio, ν, are material properties commonly treated as constants. With this assumption, strong plates have large elastic thickness T_e, while weak plates have small elastic thickness T_e. Thereby, the independent three parameters V_0, M_0 and T_e have been classically used to model the flexure of the oceanic

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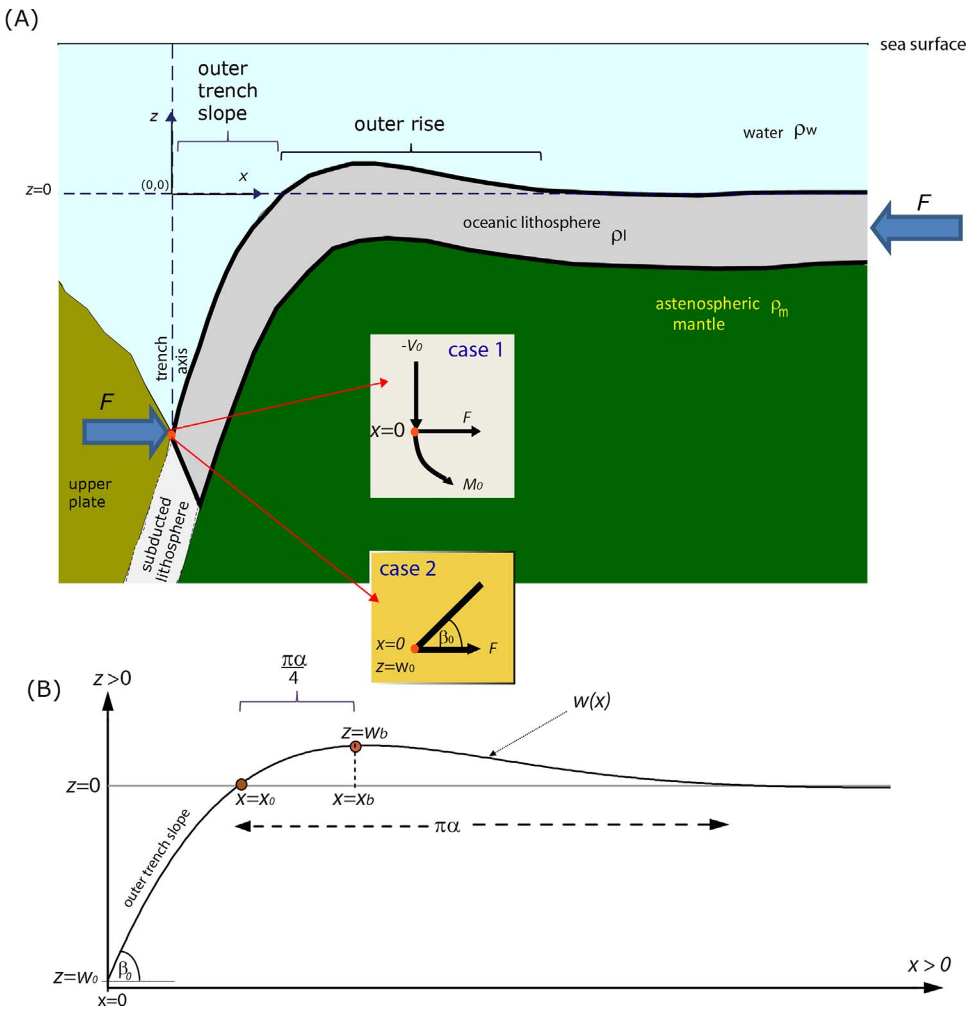

Fig. 1. (A) Bending of the lithosphere at an ocean trench due to the applied vertical shear force V_0, horizontal force F and bending moment M_o. ρ_m, ρ_l, and ρ_w are the astenospheric mantle, lithosphere and water density, respectively. (B) Schematic representation of topography (x_o, x_b, w_b, α) defining the deflection curve $w(x)$. The point (x_b, w_b) corresponds to the position of the maximum positive amplitude of $w(x)$ or peak of the outer rise while (0, w_0) corresponds to the position of the maximum negative amplitude of $w(x)$ at the trench axis. β_0 is the initial angle of subduction at the trench axis and it is related to $w(x)$ as $\tan\beta_0 = dw/dx|_{x=0}$.

lithosphere using an elastic rheology. However, V_0 and M_0 cannot be determined directly, whereas other quantities can be measured from bathymetric profiles, such as the amplitude of the fore-bulge w_b and the half-width of the fore-bulge $x_b - x_o$ (Fig. 1B), and are typically used in the classic approach to model the shape of the outer rise (Caldwell et al., 1976; Turcotte and Schubert, 2002). In practice, however, these morphological quantities present considerable uncertainties associated with bathymetric noise and are hardly recognizable along some profiles inhibiting the constraint of lithospheric parameters. In this paper, we present an alternative approach to analytically model the flexure of the oceanic lithosphere using, as independent parameters, the flexure at the trench axis w_0 (depth of the trench axis), the initial dip angle of subduction at the trench axis β_0, and the elastic thickness T_e. w_0 and β_0 are quantities that can be directly measured from bathymetric profiles across poorly sediment-loaded trenches, which occur in more than 50% of the convergent margins (von Huene and Scholl, 1991). A comparison between the classical method and the new approach is presented in two steps. First, we present a parametric sensitivity analysis using the analytical solutions for the predicted lithospheric flexure associated with each approach. Second, we model the shape of the outer rise across the Izu-Marianas trench where the outer rise of the older oceanic Pacific plate is well developed. Advantages and disadvantages, as well as tectonic implications, of both methods are discussed in the following.

2. Flexural modelling

The flexure of the oceanic lithosphere at trenches is modeled as a hydrostatic restoring force $g(\rho_m - \rho_w)w$ acting upon an elastic plate, where w is plate flexure, g is average gravity, and ρ_m and ρ_w are mantle and water density, respectively (Fig. 1; Caldwell et al., 1976; Levitt and Sandwell, 1995; Turcotte and Schubert, 2002; Bry and White, 2007; Contreras-Reyes and Osses, 2010; Hunter and Watts, 2016). If the applied load implements a horizontal force F, and a bending moment M, the deflection w of the plate is governed by the following differential equation:

$$-\frac{d^2M}{dx^2} + \frac{d}{dx}\left(F\frac{dw}{dx}\right) + \Delta\rho g = q(x) \quad (1)$$

where $q(x)$ is the vertical load acting on the plate, and $\Delta\rho = \rho_m - \rho_w$ is the density contrast between the asthenospheric mantle ρ_m and sea water ρ_w (Fig. 1). The bending moment M and the shear force V are related to the negative curvature of the plate $\kappa = -d^2w/dx^2$, by the flexural rigidity D:

$$M(x) = -D\frac{d^2w}{dx^2} \quad (2)$$

and

$$V(x) = \frac{dM}{dx} - F\frac{dw}{dx} \quad (3)$$

Combining these three equations, and assuming F = cte and $q = 0$ we have:

$$D\frac{d^4w}{dx^4} + F\frac{d^2w}{dx^2} + \Delta\rho g = 0 \quad (4)$$

The general solution of (4) which considers the boundary condition