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Sediment loading at the southern Chilean trench and its tectonic implications

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ABSTRACT

Non erosive margins are characterized by heavily sedimented trenches which obscure the morphological expression of the outer rise; a forebulge formed by the bending of the subducting oceanic lithosphere seaward of the trench. Depending on the flexural rigidity (D) of the oceanic lithosphere and the thickness of the trench sedimentary fill, sediment loading can affect the lithospheric downward deflection in the vicinity of the trench and hence the amount of sediment subducted. We used seismic and bathymetric data acquired off south central Chile, from which representative flexural rigidities are estimated and the downward deflection of the oceanic Nazca plate is studied. By flexural modeling we found that efficient sediment subduction preferentially occurs in weak oceanic lithosphere (low D), whereas wide accretionary prisms are usually formed in rigid oceanic lithosphere (high D). In addition, well developed forebulges in strong oceanic plates behaves as barrier to seaward transportation of turbidites, whereas the absence of a forebulge in weak oceanic plates facilitates seaward turbidite transportation for distances >200 km.

1. Introduction

The thermal subsidence model has successfully predicted the increase in seafloor depth as the oceanic lithosphere cools and contracts as it spreads away from the mid ocean ridge axis (Parsons and Sclater, 1977; Stein and Stein, 1992; Gouturbe and Hillier, 2013). Eventually the oceanic lithosphere becomes so dense that it should founder at a subduction zone (e.g., Stern, 2002). This model, however, does not predict the seafloor depth near subduction zones, where the lithosphere bends into the trench, producing a prominent bathymetric bulge, the outer rise and deep trench. The wavelength and amplitude of the outer rise depend on the rheology and stress state of the oceanic plate (e.g., Caldwell et al., 1976; McNutt and Menard, 1982; Levit and Sandwell, 1995).

Non erosive margins are usually characterized by thick trench fill sediment which obscures the morphologic expression of the outer rise in the vicinity of the trench or deformation front. In addition, thick trench fill sediment represents an additional load on the oceanic lithosphere. The local response of the lithosphere upon sediment loading depends on the sediment thickness, flexural rigidity $D = (ET_e^3/12(1-\nu^2))$, and regional stresses. D is a measure of the resistance of the lithosphere to flexure in response to loading. The Young's modulus, E, and Poisson's ratio, ν are material properties commonly treated as constant. Sensitive analysis shows that D is much more sensitive to T_e than E and ν (see discussion of Contreras-Reyes and Osses, 2010). In the case of a weak lithosphere (low D), thick sediment may considerably increase the local flexure of the lithosphere near the trench, affecting the amount of sediment subducted. In order to test this hypothesis, we predict the top of the oceanic lithosphere using a flexural elastic model which is constrained with high resolution seismic reflection and bathymetric data along the southern central Chile margin. We choose this study region because of the existence of a large amount of available geophysical data (e.g., Flueh and Grevemeyer, 2005; Scherwath et al., 2009; Contreras-Reyes et al., 2010; Moscoso et al., 2011) sampling the uppermost part of the oceanic Nazca plate at different thermal ages (Voelker et al., 2011a).

Since sedimentation at the trench varies over time, the flexure in the vicinity of the trench is not a steady-state process but time-dependent. The southern central Chile trench started to be considerably sedimented as a response to a rapid increase of glacial age sediment supply to the trench during the middle Pliocene (Melnick and Echtler, 2006). The high average sedimentation rate since the Pliocene linked to fast denudation of the Andes

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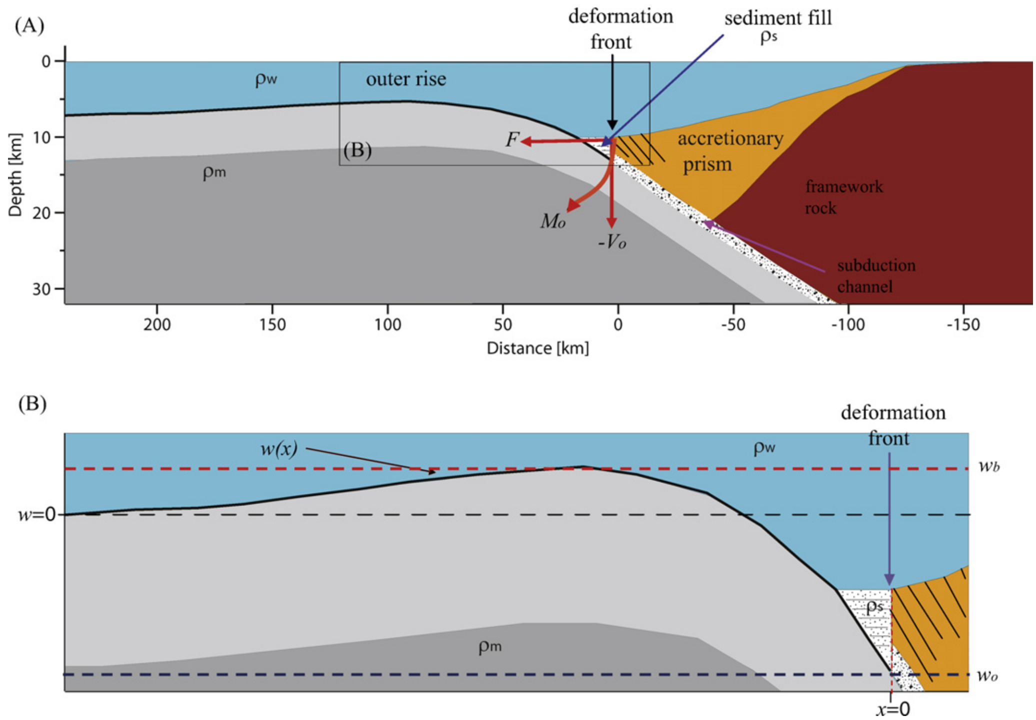

Fig. 1. (A) Bending of the lithosphere at an ocean trench due to the applied vertical shear force V_o, horizontal force F and bending moment M_o. ρ_m, ρ_s and ρ_w are the mantle, trench-sediment and water density, respectively. (B) Schematic representation of topography defining the deflection curve $w(x)$. w_o and w_b are the minimum and maximum flexure, respectively.

Cordillera and that the steady decrease of the subduction rate of the incoming oceanic Nazca plate had shifted the margin from erosive to accretionary during the Pliocene (Melnick and Echtler, 2006). This process has facilitated the formation of a frontal accretionary prism (FAP) ~7–50 km wide (Contreras-Reyes et al., 2010). Seismic data show that both the subduction channel thickness and FAP size largely vary along the southern central Chile margin (e.g., Contreras-Reyes et al., 2010; Geersen et al., 2011). In order to predict qualitatively these differences in terms of lithospheric downdeflection at the trench, we model the lithospheric flexure in the vicinity of the deformation front as a function of the sediment thickness, which in turn varies over time. These results provide insights in how the subduction channel and accretionary prism form. In addition, the predicted temporal evolution of the deflected top of the oceanic lithosphere has direct implications for sediment transportation seaward of the trench.

2. Flexural modeling

The flexure of the oceanic lithosphere at trenches has been modelled by many authors as an elastic plate acted upon by a hydrostatic restoring force $g(\rho_m - \rho_w)w$, where w is the plate flexure, g is average gravity, and ρ_m and ρ_w are mantle and water density, respectively (Fig. 1A) (e.g., Caldwell et al., 1976; Turcotte and Schubert, 1982; Levitt and Sandwell, 1995; Contreras-Reyes and Osses, 2010). If the applied load consists of a bending moment M, the deflection w of the plate is governed by the following ordinary differential equation:

$$-\frac{d^2M}{dx^2} + (\rho_m - \rho_w)wg = q(x) \quad (1)$$

where $q(x)$ is the load acting on the plate and the bending moment and shear force V are related to the negative curvature of the plate $\kappa = (-d^2w/dx^2)$ by the flexural rigidity D by:

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

and

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

In order to include the effect of sediment loading at the trench basin in our flexural model, we incorporate the sediment loading $q(x) = (\rho_s - \rho_w)gh_s(x)$, where ρ_s and $h_s(x)$ are the sediment density and thickness, respectively (Fig. 1B). Thus, we solve (1) using the method of finite differences (Contreras-Reyes and Osses, 2010). It is worth noting that effect of forces and moments acting arcward of the trench are concentrated to the vertical shear force V_o and bending moment M_o at the trench (Turcotte and Schubert, 1982). V_o and M_o cannot be independently measured, and they are modeled jointly with T_e (Contreras-Reyes and Osses, 2010).

Because the sedimented trench fill or trench basin is located seaward of the trench axis (Fig. 1), we modeled explicitly this load in our approach. To show the effect of sediment loading on the downward deflection of the lithosphere, we calculated $w(x)$ for a trench basin with three different sedimentary thickness distributions ($h_s(x)$) which are shown in Fig. 2A. We computed $w(x)$ for an elastic plate with T_e of 10 km, and 35 km and sediment densities of 2100 kg/m^3 and 2700 kg/m^3 (Bray and Karig, 1985). Results are plotted in Fig. 2B–E. Fig. 2B and D shows representative weak oceanic plate with little elastic strength (T_e = 10 km), resulting in a small forebulge (w_b in Fig. 1B). This morphology is typical of hot and young oceanic plate (<25 Ma) observed in the southeastern Gulf of Alaska (Harris and Chapman, 1994) and south Chile (Contreras-Reyes and Osses, 2010). Fig. 2C and E shows representative rigid oceanic plate with greater elastic strength (T_e = 35 km) with a well developed outer rise (high w_b of ~700 m). The effect of episodic trench sedimentation is studied for these two end members models when $h_s(x)$ increase from $h_s^1(x)$ to $h_s^2(x)$, and then successively from $h_s^2(x)$ to $h_s^3(x)$. The amplitude and wavelength of the downdeflection is larger for the weaker plate (Fig. 2B and D). This process allows the seaward accommodation of sediment and locally the