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Three-dimensional numerical models of the influence of a buoyant oceanic plateau on subduction zones

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ABSTRACT

We have investigated potential effects on a subduction zone during oceanic plateau–trench collision, using three-dimensional numerical models. An oceanic plateau of varied density was embedded in the slab, which was pinned at one end. The plateaus strongly influenced the shape of the trench. For a plateau with a higher density, the trench retreat rate was reduced in the region surrounding the plateau, and the plateau subducted along with the slab. For lower density plateaus, the trench in the region of the plateau advanced, and the plateau compressed and resisted subduction, spreading laterally along the trench. With a weaker slab rheology, the arcuate shape of the trench towards the free end of the trench was enhanced. Beneath the most buoyant plateaus, a tear formed in the subducted portion of the slab, soon after the slab tip reached the top of the lower mantle. We compare the model results with a region in the northwest Pacific, where the Ogasawara Plateau meets the trench of the Izu–Bonin–Mariana subduction zone.

1. Introduction

The collision of elevated regions on the seafloor with the trench of subduction zones has been linked to arcuate plate boundary/trench development and tearing of the subducted portion of the slab. Examples of these bathymetric highs include oceanic plateaus, seamounts and seamount chains, and oceanic ridges (Vogt, 1973). Oceanic plateaus are igneous expressions which, along with oceanic flood basalts and volcanic passive margins, are classified as oceanic large igneous provinces (Coffin and Eldholm, 1993, 1994; Eldholm and Coffin, 2000; Coffin and Eldholm, 2001).

There is an observed correlation between regions with arcuate plate boundaries, and collisions with bathymetric highs located on the subducting plate (e.g. Vogt et al., 1976; Scholz and Small, 1997; Miller et al., 2004; Schellart and Lister, 2004; Miller et al., 2005; Rosenbaum et al., 2005). Analogue models of a bathymetric high colliding with a subduction zone have been used to demonstrate flat subduction (Martinod et al., 2005), regional uplift of the overriding plate (Dominguez et al., 1998, 2000) and indentation of the trench (Dominguez et al., 1998, 2000; Schellart and Lister, 2004; Martinod et al., 2005). Numerical modelling in one dimension shows a correlation between the subduction of bathymetric highs and mineralisation in the overriding plate (Rosenbaum et al., 2005); in two dimensions with associated uplift in the overriding plate (Litchfield et al., 2007; Gerya et al., 2009), reduction in the angle of slab dip (van Hunen et al., 2002, 2004; Trubitsyn et al., 2007), as well as increased subduction erosion and a decrease in magma production (Gerya et al., 2009); and in three dimensions with rotation in the overriding plate (Wallace et al., 2009).

Sharp discontinuities in trench shape are also evident in some regions where slab tearing may have occurred. One example lies at the juncture of the Izu–Bonin and Mariana arcs in the northwest Pacific, where the Ogasawara Plateau meets the trench, below which an anomalous region in bulk sound, shear wave speed and P-wave models has been detected within the subducted portion of the slab below the Izu–Bonin arc, which may represent a gap or tear (Miller et al., 2004, 2005). Slab windows, gaps or tears are regions within a subducted portion of a tectonic plate, where an absence of lithospheric material has been inferred. Possible orientations of a slab tear include sub-vertical, as in the case of sharp discontinuities in slab dip or slab segmentation (e.g. Rosenbaum et al., 2008), and sub-horizontal, which may extend across an entire slab as a detachment or slab break-off (Sacks and Secor, 1990; Davies and von Blanckenburg, 1995; Govers and Wortel, 2005).

In this study we have used a three-dimensional numerical subduction model to investigate the influence of the density contrast of an oceanic plateau, when colliding with the trench of a subduction zone, on trench shape and rollback rates, and on the occurrence and timing of slab tears.

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Table 1
Common dimensional model parameters.

Parameter	Units	Material	Symbol	Value
Height, depth or thickness (y)	km	Domain	D_{box}	1000
		Upper mantle	D_{um}	650
		Lower mantle	D_{lm}	From 650 to 1000
		Slab	D_{slab}	100
		Plateau	D_{plat}	50
Length (x, normal to trench)	km	Domain	L_{box}	4000
		Slab	L_{slab}	2200
		Plateau	L_{plat}	900
Width (z, parallel to trench)	km	Domain	W_{box}	4000
		Slab	W_{slab}	2750
		Plateau	W_{plat}	200
Gravitational acceleration	m/s^2	Domain	g	10
Density	kg/m^3	Upper mantle	ρ_{um}	3300
		Lower mantle	ρ_{lm}	3300
		Slab	ρ_{slab}	3380
		Contrast	$\Delta\rho=\rho_{slab}-\rho_{um}$	80
Viscosity	Pa s	Upper mantle	η_{um}	10^{20}
		Lower mantle	η_{lm}	100 η_{um}
Reference stress	MPa	Domain	$\tau_{ref}=\Delta\rho g D_{box}$	800

Table 2
Varied dimensional model parameters.

Model name	Plateau density ρ_{plat} (kg/m^3)	Slab and plateau viscosity η_{slab} (Pa s)	Slab and plateau cohesion μ_0 (MPa)	Slab and plateau depth coefficient μ_1 (MPa/km)
No plateau	N/A	200 η_{um}	32	0.2
3300	3300	200 η_{um}	32	0.2
3200	3200	200 η_{um}	32	0.2
3100	3100	200 η_{um}	32	0.2
3000	3000	200 η_{um}	32	0.2
2900	2900	200 η_{um}	32	0.2
2800	2800	200 η_{um}	32	0.2
2700	2700	200 η_{um}	32	0.2
2700_1000	2700	1000 η_{um}	32	0.2
2700_Strong	2700	200 η_{um}	64	0.4
2700_1000_Strong	2700	1000 η_{um}	64	0.4

2. Methodology

In this study we modified the Underworld (Moresi et al., 2007) viscoplastic numerical reference subduction rollback model of Stegman et al. (2006), which has also been adapted in other subduction modelling studies (Schellart et al., 2007; Clark et al., 2008; OzBench et al., 2008). We based the slab rheology on that used by Stegman et al. (2006). As there is some debate regarding suitable choice of rheological parameters for plate-like behaviour (e.g. Tackley, 2000; Di Giuseppe et al., 2008), we also repeated one model using selected alternative rheologies for comparison.

2.1. Foundation

The models solve the Stokes Equation for creeping flow, excluding any explicit dependence on temperature:

$$\frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial p}{\partial x_i} = \rho g_i \quad (1)$$

where $\boldsymbol{\tau}$ is the deviatoric stress tensor, p is dynamic pressure, ρ is a prescribed density and $\mathbf{g}$ is gravitational acceleration. An incompressibility constraint is applied:

$$\frac{\partial v_i}{\partial x_i} = 0 \quad (2)$$

where v is velocity. The constitutive model is a non-linear viscous flow:

$$\tau_{ij} = 2\eta(\tau)\dot{\varepsilon}_{ij} \quad (3)$$

$$\dot{\varepsilon}_{ij} = \frac{1}{2}\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right) \quad (4)$$

$$|\dot{\varepsilon}| = \sqrt{\frac{1}{2}\dot{\varepsilon}_{ij}\dot{\varepsilon}_{ij}} \quad (5)$$

where η is dynamic viscosity and $\dot{\varepsilon}$ is strain rate. The viscosity is chosen such that a yield criterion can be satisfied. A depth-dependent yield criterion consistent with Byerlee's observations of the lithosphere (Byerlee, 1968, 1978) is applied to the subducting slab:

$$\tau_{yield} = \mu_0 + \mu_1 D \quad (6)$$

where τ_{yield} is yield stress, μ_0 is cohesion, μ_1 is a depth coefficient and D is depth. Thus the material yields when the stress applied to the material reaches the yield stress ($|\tau|=\tau_{yield}$). Because the yield stress increases with depth, a higher applied stress will be required to cause the material to yield as depth increases. For materials to which a yielding criterion is applied, the dynamic viscosity of the material ($\eta_{material}$) will equal the viscosity initially set for the material ($\eta_{material}=\eta_0$) so long as the applied stress is less than the yield stress of the material:

$$\eta = \eta_{material} \quad \text{for} |\tau| < \tau_{yield}$$
$$|\tau| = \sqrt{\frac{1}{2}\tau_{ij}\tau_{ij}} \quad (7)$$

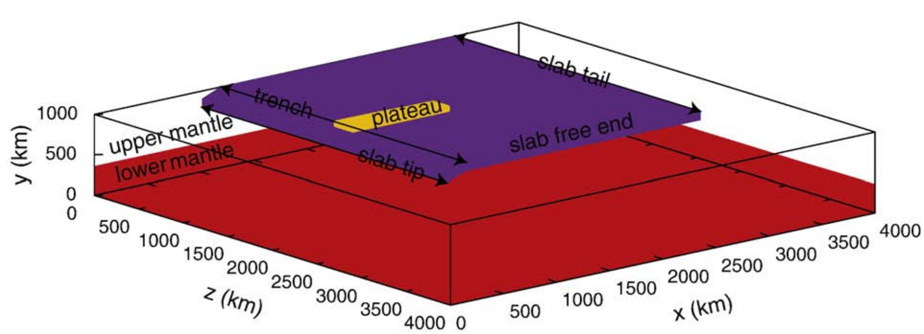

Fig. 1. Initial setup of numerical model domain, including slab perturbation and plateau embedded in the slab. Initial locations of the trench, slab tip, slab tail and free end of slab are illustrated. Dimensional model parameters are listed in Tables 1 and 2.