GEOPHYSICAL RESEARCH LETTERS, VOL. 24, NO.13, PAGES 1563-1566, JULY 1, 1997

Quantification of interplate coupling in subduction zones and forearc topography

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Abstract. The effect of long term coupling in subduction zones on forearc topography is studied using a 2-dimensional finite element model. A curved fault, representing the interface between subducting slab and overriding plate, has been incorporated into a model with an elastic crustal layer, a viscoelastic upper mantle, an initial topography and an effective coefficient of friction on the fault. We assume that traction arising from friction is one of the stresses acting on topography. For various friction coefficients, the change of topography after some equilibration time is computed with specific geometry and kinematic boundary conditions for three subduction zones: northern Chile, northern Japan and Tonga. While the intrinsic coefficient of friction for small rock samples is high ($\mu \sim 0.6-0.8$), the observed topography of forearc regions are inconsistent with an effective friction coefficient larger than 0.2.

Introduction

The friction coefficient value is relatively well known at laboratory scale and quite independant of rock type ($\mu \sim 0.6-0.8$) [*Byerlee,* 1978; *Scholz,* 1990]. At large scale, this coefficient has been quantified for the San Andreas fault [*Lachenbruch and Sass,* 1992; *Zoback and Healy,* 1992] where both the stress and heat flow measurements from Cajon Pass can only be satisfied if the friction coefficient is low ($\mu \leq 0.2$). Futhermore, surface heat flow and geochronological data constrain the friction coefficient on the basal decollement fault beneath Taiwan to be $\mu = 0.5 \pm 0.2$ [*Barr and Dahlen,* 1990]. In subduction zone (interplate contact or base of accretionary wedge), where the fluids play a prominent role, this parameter is rarely quantified ($0.05 \leq \mu \leq 0.25$) [*Kao and Chen,* 1991; *Lallemand et al.,* 1994]. Thus a large uncertainty exists on the magnitude of friction at the contact between the downgoing plate and the overriding plate. However, knowledge of friction is essential to understand the physics of occurence of earthquakes [e.g. *Dmowska et al.,* 1988].

Paper number 97GL01550.
0094-8534/97/97GL-01550$05.00

In this paper, a mechanical approach is used to study the average long-term steady state coefficient of friction in subduction zones. We assume that the topography in the forearc region is in equilibrium which results from a balance of stresses acting on an elastic crustal layer and a viscoelastic upper mantle. One of these stresses is the traction arising from friction on the boundary of the overriding plate. We study the effect of the average coefficient of friction on the long term topography to constrain this parameter. We apply this approach to three subduction zones (northern Chile, northern Japan and Tonga), representing various geometry and kinematic boundary conditions.

Model

The finite element code used in this study, is designed to study quasi-static strain of elasto-visco-plastic media [*Hassani,* 1994]. This code uses an explicit finite difference scheme coupled with a dynamic relaxation method to solve two-dimensional steady state thermomechanical problems. Space is meshed with 9000 triangular elements and time step ranges from 20 to 200 years.

The Coulomb criterion governs slip on the curved fault representing the interface between the subducting slab and the overriding plate (Fig. 1). Along the upper surface of the model (Earth's surface), we impose a traction free boundary, providing the upper surface to develop topography. Along the lower surface of the continental lithosphere, we impose an hydrostatic pressure, simulating isotropic stresses due to inviscid mantle below.

The subduction component of the convergence velocity (V_{slab}) is imposed along the bottom surface of the subducting slab. In other words the bottom nodes of the slab are fixed in the normal direction and are only allowed to move in the tangential direction. The slab radius of curvature is constant. The horizontal location of the trench is stationary and we impose a constant horizontal relative convergence velocity (V_{over}) on the overriding plate along its rigtht side boundary. For northern Japan and Tonga the right side boundary is chosen at the place where back-arc opening starts and V_{over} is the opening velocity of back-arc. The velocity

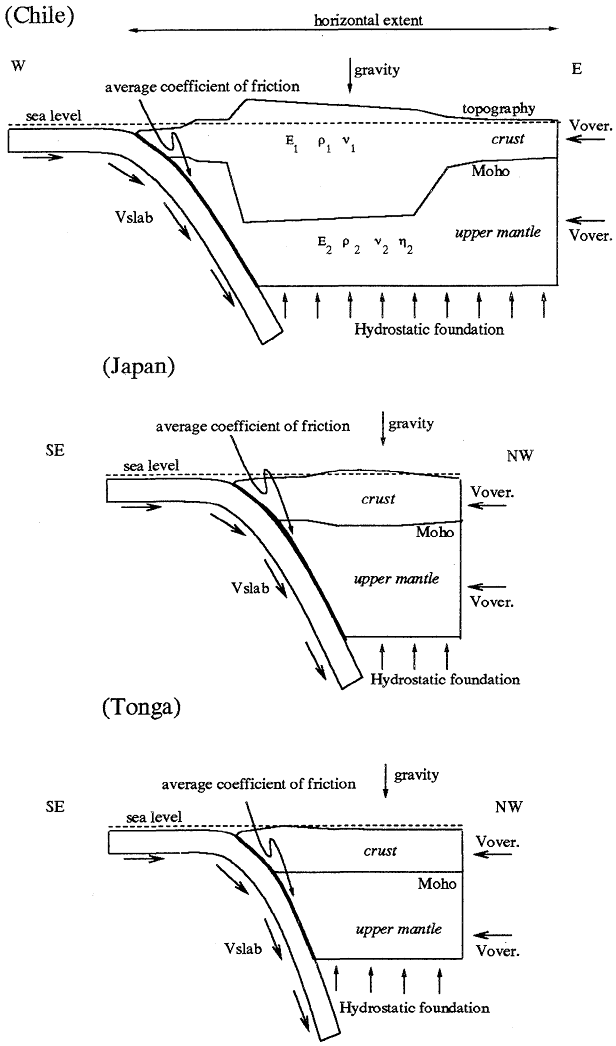

Figure 1. Geometrical configuration of models, mechanical boundary conditions used for northern Chile, northern Japan and Tonga. E_i, ρ_i, ν_i and η_i are respectively the Young's modulus, the density, the Poisson's ratio and the viscosity of the body "i".

boundary condition behind the back-arc basin has no effect on the state of stress in the forearc region [*Hassani et al.*, 1997].

We assume that the observed topography is in equilibrium. The initial topography of the overriding plate is isostatically compensated. The depth of the boundary between the crustal root and the upper mantle is calculated assuming constant densities for the crust (ρ_1) and the upper mantle (ρ_2). This hypothesis is consistent with gravity data at the scale of this study, although this may not be true at shorter wavelengths.

In this study, we neglect the effect of weathering, tectonic erosion and addition of mantle material to the crust (underplating) on the topography.

We study three subduction zones: northern Chile, northern Japan and Tonga, with specific geometries and boundary conditions (Tab. 1) and assume that all three regions have the same average rheology. The continental lithosphere is composed of an elastic crust (Young's modulus, $E_1 = 0.9\ 10^{11} Pa$; Poisson's ratio, $\nu_1 = 0.25$; density , $\rho_1 = 2.9\ 10^3 kgm^{-3}$), and a viscoelastic mantle ($E_2 = 1.75\ 10^{11} Pa$, $\nu_2 = 0.25$, $\rho_2 = 3.3\ 10^3 kgm^{-3}$). The time scale of our study is between 400000 and 1 My. For such period of time a viscoelastic crust with a viscosity of $10^{25} Pas$ will have an elastic behaviour. Thus in these models, the upper part of the lithosphere is elastic and the lower part is viscoelastic with an assigned viscosity of 10^{23} Pa.s [e.g. *Bott et al.*, 1989]. The assumption of an homogeneous crust is valid here because we are not studying back-arc deformation which may require zones of crustal weaknesses, we only study the variations of topography in the forearc region.

Table 1. Parameters used in the finite element model [*Jarrard* (1986)[a]; *Hasegawa et al.* (1994)[b]; *Schmitz* (1994)[c]; *Burov and Diament* (1995)[d]; *Comte and Suárez* (1995)[e]].

	Chile	Japan	Tonga
Horizontal extent (km)	1060	522	600
Slab radius of curvature (km)	1100[d,e]	670[b]	500[a]
V_{over} (cm/yr)	-1[c]	-0.5[a]	-2[a]
V_{slab} (cm/yr)	9[a]	8.6[b]	8[a]

Table 1 reports geometrical parameters used in the computation for each subduction zone. One of the most important geometrical feature is the slab radius of curvature because this parameter governs the wavelength of the topographic perturbation [*Wdowinski*, 1992].

Results

The model assumes an equilibrium between tectonic and buoyancy forces. An increase of tectonic forces, due to an increase of interplate coupling, is balanced by a higher magnitude buoyancy force, induced by a higher-magnitude near trench topography. In other words no change in the topography implies that the initial assumption of density distribution, topography, kinematic boundary conditions and friction coefficient is in equilibrium. We search the range of values of μ enabling to preserve initial topography with the specified boundary conditions. A time of 400.000 years (corresponding to the smallest time when the steady state is achieved for all subduction zones and for all friction coefficients) is taken to present the results on the long term behaviour (Fig. 2). We assume that for each subduction zone dynamic equilibrium is achieved when the stresses relax in the viscoelastic region and are concentrated in the upper elastic layer.

For northern Chile, northern Japan and Tonga, a similar pattern is observed. The distance between the maximum of topographic variation and the trench is independent of the magnitude of the friction coefficient but is correlated with the slab radius of curvature. In the three cases, the initial topography is stable only for an average coefficient of friction at interface ranging from ~ 0.1 to ~ 0.2 (curve with no cumulated vertical elevation in Fig. 2). If the interplate average friction coefficient is high ($\mu > 0.2$) the continental lithosphere is dragged along by the oceanic lithosphere creating a deepening of the trench. If the interplate average friction coefficient is low ($\mu < 0.1$), the model predicts an unrealistic uplift. This is also observed by *Wdowinski and Bock* (1994) when the forearc crust is strong. In this case changes in the near trench topography are an outcome of a force balance change as the strength of the crust varies without changing the forces that deform it.

In this study the force acting on the slab is not really the slab pull force because the slab radius of curvature is fixed and consequently the geometry of the oceanic lithosphere is constant. Thus the variation of topography is not due to variation of the slab geometry. Accounting for slab pull in our model, would make it possible to create a trench and a stable forearc topography with a very low friction coefficient ($\mu < 0.1$) [*Hassani et al.*,1997]. For example, for an interface without friction ($\mu = 0$), the slab radius of curvature can decrease and

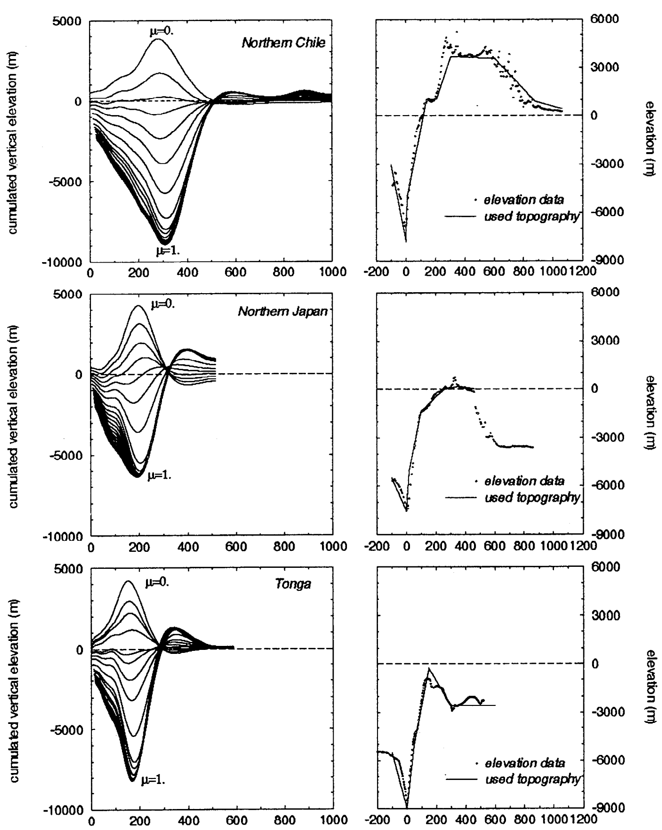

Figure 2. *On the left*: Evolution of initial topography for northern Chile, northern Japan and Tonga cases, after 400.000 years with an average coefficient of friction,μ, ranging from 0.0 to 1.0 with a step of 0.05. *On the right*: Initial topography used in the computation for the same subduction zones.

thus creates a depression near the trench. In any case, allowing for slab pull would only lower the upper limit on μ (0.2) found here.

This result is almost independent of the upper mantle viscosity and of the density contrast between crust and upper mantle. The relative effect of friction coefficient on topography decreases with increasing upper mantle viscosity or decreasing density contrast. For the same friction coefficient, the magnitude of cumulated vertical elevation decreases with increasing viscosity or decreasing density contrast. Nevertheless, for various viscosity (ranging from 10^{21} Pa.s to 10^{25} Pa.s) and various density contrast ($\Delta\rho$ ranging from 0.3 to 0.6 kgm^{-3}), the stability of topography is obtained for the same friction coefficient.

Another important feature of the induced topography is the relative role played by the slab-continental crust and slab-continental mantle interface. If we assume that the slab-crust interface plays a predominant role on the trench depth and the slab-mantle interface governs the topography far in land, it would be possible to study the depth of the uncoupled-coupled boundary [e.g. *Dmowska et al.*, 1988]. So, the depth of the uncoupled-coupled boundary is equal to the depth of crust-mantle boundary if the trench depth is constant and the topography evolved. The depth of uncoupled-coupled boundary decreases when the trench depth increases.

Discussion and conclusion

We have argued in this paper that the variation of topography enables to constrain the long term effective friction coefficient in subduction zones. Our mechanical model indicates that friction is an essential parameter to produce and maintain forearc topography. With the same kinematic boundary conditions, the maximum deviation from initial topography ranges from +4000 m to -8000 m when friction coefficient is equal to 0. and 1. respectively.

For each of the three subduction zones examined which represent a wide spectrum of type of subduction, a friction coefficient of 0.1 to 0.2 is required to match the observed topography. Futher more, heat flow data have been used to constrain the magnitude of average friction coefficient in subduction zones [e.g. *Molnar and England*, 1990; *Kao and Chen*, 1991; *Tichelaar and Ruff*, 1993]. All these thermal approaches bound the friction coefficient between 0.03 to 0.15.

Shear stress levels inferred from our mechanical approaches and from thermal approaches are about a factor of 5 lower than those observed for laboratory samples [*Byerlee*, 1978]. This indicates that dry friction cannot be used to mimic plate coupling in subduction zone, probably because the effect of water and gouge are neglected.

Indeed, the dry coefficient of friction μ_{dry}, corresponds to solid-solid interface with no fluid pressure. Water due to presence of sediment or to dehydratation process of subducting oceanic crust, may play an important role, increasing the pore pressure and consequently reducing the interplate frictional stress [e.g. *Lachenbruch and Sass,* 1992].

A second problem is that Coulomb criterion does not really apply to gouge materials which are mixtures of rocks fragments and clays in various proportion. In this case, the faults frictional behaviour is likely controlled by gouge properties (clays and granular material) rather than by solid-solid interface [*Morrow et al.,* 1982]. It is well known that at room conditions, clays have structural layers of molecular water which give lubricating properties. Nevertheless, these lubricating properties of clay are lost at high pressure and temperature due to deshydratation of clays [e.g. *Wang and Mao,* 1980; *Scholz,* 1990]. Thus, in gouge, clays do not play an important role in reducing interplate frictional stress, and the frictional behaviour may mostly be controlled by the behaviour of granular material. In these materials, wear tends to roughen smooth surface and to decrease the friction coefficient.

Acknowledgments. We are grateful to Riad Hassani, Steve Tait and François Cornet for fruitful discussions. We would also like to thank Philip England and two anonymous reviewers for helpful comments on the initial version of the manuscript.

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(Received November 26, 1996; revised April 2, 1997; accepted May 7, 1997.)