

# The impact of the South-American plate motion and the Nazca Ridge subduction on the flat subduction below South Peru

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[1] Flat subduction near Peru occurs only where the thickened crust of the Nazca Ridge subducts. Furthermore, the South-America continent shows a westward absolute plate motion. Both the overriding motion of South-America and the subduction of the Nazca Ridge have been proposed to explain the flat slab segment below South Peru. We have conducted a series of numerical model experiments to investigate the relative importance of both mechanisms. Results suggest that the average upper mantle viscosity should be about  $3.5 \times 10^{20}$  Pa s or less and basaltic crust should be able to survive 600 to 800°C ambient temperature before transforming into eclogite to explain the slab geometry below Peru. The effect of the overriding plate is estimated to be as large or twice as large as that of the plateau subduction. *INDEX TERMS*: 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8155 Tectonophysics: Evolution of the Earth: Plate motions—general; 8162 Tectonophysics: Evolution of the Earth: Rheology—mantle; 8159 Tectonophysics: Evolution of the Earth: Rheology—crust and lithosphere; 8147 Tectonophysics: Evolution of the Earth: Planetary interiors (5430, 5724)

## 1. Introduction

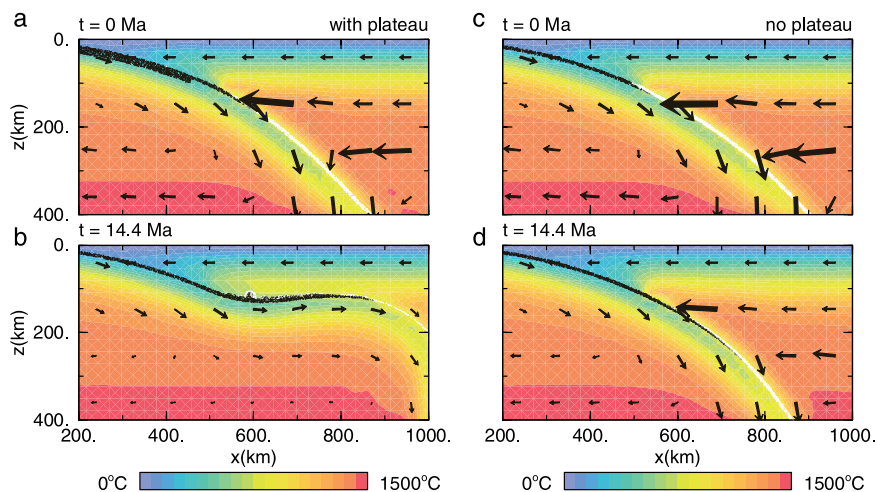
[2] It is widely believed that the gravitational instability of a subducting slab forms the main driving force in the process of plate tectonics [Forsyth and Uyeda, 1975]. However, the presence of shallow horizontal subduction does not fit into such model. Modern flat subduction is observed at several locations around the Pacific [Gutscher *et al.*, 2000], but the largest occurrences are below Peru and Central Chile [Jarraud, 1986], where a flat slab segment is present as far as 700 km inland. Several mechanisms have been proposed to explain the presence of flat subduction. A westward motion of South America has been suggested to lead to shallow flat subduction [Cross and Pilger, 1978; Vlaar, 1983; van Hunen *et al.*, 2000; van Hunen *et al.*, 2002]. Alternatively, buoyant subducting lithosphere has been proposed to explain flat subduction [Cross and Pilger, 1978; McGeary *et al.*, 1985; Gutscher *et al.*, 2000]. Young oceanic lithosphere may be buoyant during a period of 30–40 Ma after formation, while oceanic plateaus, aseismic ridges and seamount chains all contain a thickened basaltic crust and underlying harzburgite layer, which provide compositional buoyancy for older slabs. The Nazca Ridge below South Peru and the Juan Fernandez seamount chain below Central Chile are proposed

as the cause for flat subduction below South-America, but also other regions of low-angle subduction, such as the Nankai Trough in Japan, can be spatially correlated to subducting thickened crust [Gutscher *et al.*, 2000]. Other mechanisms have been proposed as well, such as a non-hydrostatic pressure force [Jischke, 1975] or a slab suction force [Tovish *et al.*, 1978]. In principle, these last mechanisms apply to any subduction zone, but their contribution might be most relevant to areas of low-angle subduction. Here, we study the relative importance of the 3-cm/yr trenchward motion of the South-American continent [Olbertz, 1997; Olbertz *et al.*, 1997] and the subduction of the Nazca Ridge (with a 2.5 times thicker-than-average crust and harzburgite layer [McGeary *et al.*, 1985]) on the development of approximately 400 km of flat slab below Peru.

## 2. Model Setup and Numerical Methods

[3] We performed the numerical model simulations with a two-dimensional finite element model. Using the extended Boussinesq approximations and an infinite Prandtl number fluid, we solve for the conservation of mass, momentum, energy and composition [van Hunen *et al.*, 2000]. The oceanic lithosphere is compositionally layered with a crust and depleted mantle layer (harzburgite) on top of undepleted mantle material. We use a composite rheology of temperature and pressure dependent diffusion and dislocation creep [van den Berg *et al.*, 1993; Karato and Wu, 1993] for crust and mantle material separately, and a uniform stress limiter of 300 MPa. Hydrous weakening in the mantle wedge [Mei and Kohlstedt, 2000a, 2000b; Karato, 2001] is included by means of a simple parameterization. Further elaboration of the effects of the yield strength in the slab and the effect of hydrous mantle wedge weakening on the development of a flat slab segment due to plateau subduction is given in [van Hunen *et al.*, 2002]. Mantle phase transitions, including latent heat effects [van Hunen *et al.*, 2001], are incorporated in the model. Basalt-to-eclogite phase change kinetics are included in the model, using a parameterization from [Giunchi and Ricard, 1999], in which the kinetics are assumed to be purely determined by the ambient temperature and the Gibbs free energy values of the two phases. In this approach, the reaction rate increases approximately exponentially with increasing temperature using a kinetic activation energy  $E_{kin}^*$ . Values for  $E_{kin}^*$  are chosen such, that the eclogitisation takes place within 20 Ma if the temperature equals a given transition temperature  $T_{tr}$ . Values for  $T_{tr}$  vary between 400 and 800°C in the presented model calculations. Calculations are performed in a 5200 km wide and 2000 km deep Cartesian model domain. For numerical convenience, the model reference

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**Figure 1.** Temperature plot (colors) of the subduction zone for model time  $t = 0$  Ma and 14.4 Ma. Panels a and b show the development of a flat slab segment as a result of the subduction of an oceanic plateau. In panels c and d, the absence of a subducting plateau results in continuing steep subduction. Arrows give the flow direction and velocity with respect to the deep mantle. Black and white areas show the basaltic and eclogitic parts of the crust, respectively.

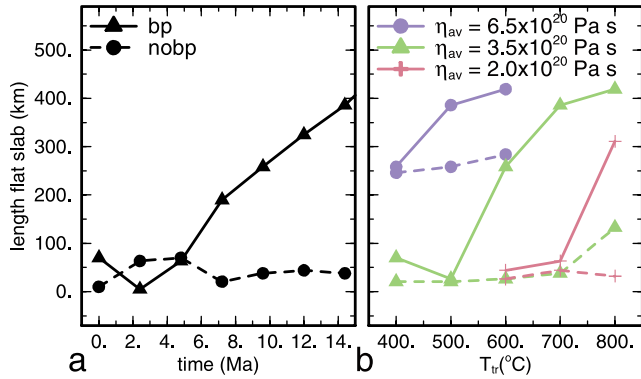
frame is chosen fixed to the overriding continent. A 400-km-long region with an 18-km-thick crust and 45-km-thick harzburgitic layer defines the oceanic plateau. At model time  $t = 0$ , the leading edge of the plateau just enters the subduction zone. The vertical temperature distribution of the plateau is similar to the surrounding normal oceanic lithosphere, which has an age of 45 Ma at the trench. We assume, that the plateau buoyancy does not influence the convergence rate at the trench. Therefore, a constant convergence rate is imposed as a surface boundary condition on the subducting slab. A free-slip fault ensures total decoupling of the upper part of the converging plates, while for larger depth, the weak oceanic crust partly decouples the plates. More detailed descriptions of the model setup, rheology, initial conditions, fault implementation, as well as applied physical model parameters and numerical solution methods are given in [van Hunen *et al.*, 2000, 2001].

### 3. Obtaining Sets of Suitable Model Parameters

[4] Before determining the relative contributions of the plateau subduction and the absolute South-American plate motion to the development of flat subduction, we first need to define sets of model parameters that show shallow flat subduction in the presence of plateau subduction, and, equally important, steeper subduction in the absence of a plateau (which is consistent with observations below Peru). To reduce the amount of model calculations, we fixed most of the model parameters to a reasonable value. Absolute overriding plate motion (3.1 cm/yr) and convergence rate (6.7 cm/yr) are taken from [Olbertz, 1997; Olbertz *et al.*, 1997]. Data from [Jarrard, 1986] are used to fix the slab age (44 Ma) and intermediate dip angle ( $23^\circ$  as an average value for all subduction zones). A free-slip fault extending to 100 km depth meets the requirement of weak plate margins [Zhong and Gurnis, 1996; Zhong *et al.*, 1998]. The thickness of the plateau crust was taken 18 km [McGeary *et al.*, 1985], and the underlying harzburgite layer is taken proportionally thickened with respect to normal oceanic lithosphere. The mantle viscosity is an

important parameter in the mechanism of flat subduction below a trenchward moving overlying plate [van Hunen *et al.*, 2001], and a realistic range of viscosity prefactors are chosen such that the average upper mantle viscosity  $\eta_{av}$  extends from  $2.0$  to  $6.5 \times 10^{20}$  Pa s, which roughly satisfies results from post-glacial rebound studies [Lambeck *et al.*, 1998]. The extent of the kinetic delay of the basalt-to-eclogite transition strongly influences the capacity of a buoyant plateau to flatten a slab; in this study, we examine a range of possible transition temperatures  $T_{tr}$  from 400 to  $800^\circ\text{C}$ , as suggested by geological observations [Hacker, 1996; Austrheim, 1998]. Figure 1 shows the temperature distribution for one set of model calculations ( $\eta_{av} = 3.5 \times 10^{20}$  Pa s and  $T_{tr} = 700^\circ\text{C}$ ) that satisfies the observations for the Peru subduction area. Panels a and b show the slab geometry before and after the subduction of the plateau. The compositional buoyancy of the basalt is large enough to gradually change the slab geometry and to create a flat slab segment of a few hundred km. Panels c and d show the same time snapshots for a model without a subducting plateau, where the normal crust is not buoyant enough to create a flat slab segment. Figure 2a shows the development of the slab geometry in time for the models with (bp) and without (nobp) a plateau from Figure 1. The length of the flat slab segment is defined as the horizontal position where the (rheological core of the) slab exceeds the depth of 200 km with respect to the situation in Figure 1c: a flat slab segment develops during the plateau subduction.

[5] Figure 2b combines model results for varying mantle strength and extent of the basalt-metastability depicted by the resulting flat slab length at model time  $t = 14.4$  Ma. The tendency to develop a flat slab segment is enlarged by both an increased basalt metastability (by increasing  $T_{tr}$ ) and a stronger mantle (by increasing  $\eta_{av}$ ). These effects operate differently: an increased mantle viscosity affects the slab dip angle in all models, regardless of the presence of a plateau, while in increased basalt metastability has a larger impact on a plateau than on normal oceanic lithosphere. Models with  $\eta_{av} = 6.5 \times 10^{20}$  Pa s, therefore, all show flat subduction, even without a plateau and for any basalt



**Figure 2.** (a) Development of the flat slab segment in time for the models with (bp) and without (nobp) an oceanic plateau in Figure 1. (b) Length of the flat slab segment at model time  $t = 14.4$  Ma for varying transition temperature  $T_{tr}$  and effective upper mantle viscosity  $\eta_{av}$ .

metastability. Since this type of model cannot explain the observed style of subduction below Peru, we excluded this set of models from further investigation. Models with  $\eta_{av} = 3.5 \times 10^{20}$  Pa s and  $T_{tr} = 600$  or  $700^\circ\text{C}$  (hereafter referred to as models A and B, respectively), and the model with  $\eta_{av} = 2 \times 10^{20}$  Pa s and  $T_{tr} = 800^\circ\text{C}$  (hereafter model C), however, give slab geometries that are consistent with observations, i.e., only subduction of a plateau, and not of normal oceanic lithosphere causes flat subduction.

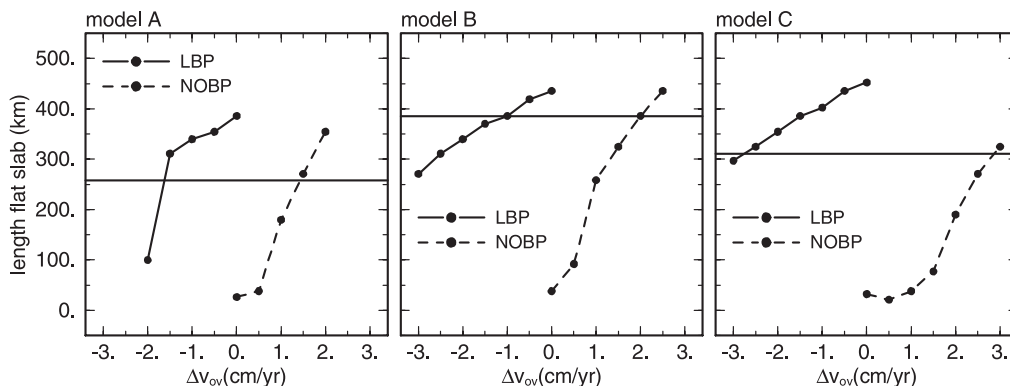
#### 4. The Relative Importance of Both Mechanisms

[6] We use these models A, B, and C to further investigate the relative importance of the two flattening mechanisms. For each model, we proceed by varying the plateau thickness of the plateau in each model with  $\pm 11$  km, which results in a plateau thickness of 7 km (i.e., normal oceanic crustal thickness and not a plateau anymore, model NOBP) or 29 km (model LBP). The trenchward motion of the overriding plate is then adapted from the reference value (3.1 cm/yr) in steps of 0.5 cm/yr until approximately the same (flat) slab geometry is again obtained. Results are

shown in Figure 3. For model A, the increased plateau thickness (LBP) and removal (NOBP) of the plateau are best compensated by a  $\Delta v_{ov} = 1.5$ -cm/yr decrease and increase, respectively, of the overriding plate velocity  $v_{ov}$ . In case of model B, removal of the plateau (NOBP) requires an increase of the overriding plate velocity  $\Delta v_{ov} = 2$  cm/yr to obtain the same flat slab segment. Comparison with the  $\Delta v_{ov} = 1.5$  cm/yr in model A reflects the larger impact of a plateau in case of more extensive basalt-metastability. The increased plateau thickness (LBP), however, is best compensated by  $\Delta v_{ov} = -1$  cm/yr only: the flat slab segment is already large for a normal plateau (almost 400 km), and a further increase of the plateau thickness has only a limited effect. Comparison of models A and B with model C shows the effect of the decreased mantle strength in the latter: the overriding plate motion is less effective in flattening the slab, and the plateau effect is compensated by a change in the overriding plate motion of 2.5 to 3 cm/yr. To summarize, the effect on flat subduction of the thickened crust and harzburgite in the oceanic plateau is roughly equal to the effect of a 1.5 to 3.0 cm/yr increase of the overriding plate velocity, which is about 50 to 100% of the observed absolute plate velocity. This implies that the South-American westward absolute plate motion is approximately equally or twice as important as the effect of the subducting Nazca Ridge for the creation of the Peru flat slab region.

#### 5. Discussion and Concluding Remarks

[7] We investigated the relative importance of the westward absolute plate motion of the South-American continent, and the subduction of the Nazca Ridge, an oceanic plateau with thickened crust and harzburgite layer, on the development of the Peru flat slab region. With a simple model setup, we are able to model the essential features for such study: a 40–50 Ma old slab, which converges with about 6.7 cm/yr with a 3 cm/yr-overriding continent, shows flat subduction only when an oceanic plateau like the Nazca ridge subducts. Variation of the plateau thickness and overriding plate motion in the numerical model allows for a comparison of the effects of the two mechanisms, and suggests that the South-American absolute plate motion



**Figure 3.** Display of the relative importance of the overriding plate motion and the plateau subduction of models A, B, and C (see text) at time  $t = 14.4$  Ma. Horizontal lines represent the flat slab lengths from Figure 2b. The LBP- and NOBP-models in model A show that an overriding velocity change  $\Delta v_{ov} \approx \pm 1.5$  cm/yr compensates the effect of a plateau. For model B, a doubled plateau thickness is compensated by a  $\Delta v_{ov} = -1$  cm/yr, while removal of the plateau is compensated by a  $\Delta v_{ov} = +2$  cm/yr. In model C, the plateau is compensated by a  $\Delta v_{ov}$  of plus or minus 2.5 to 3 cm/yr.

contributes to the flat slab development roughly one to two times more than the plateau subduction does.

[8] The contribution of the South-American motion to the flat subduction is controlled by the (continuous) lithospheric displacement relative to the underlying mantle, and measuring the actual displacement is not straightforward. Here, we assumed that the absolute plate motion with respect to the hotspot reference frame describes this motion reasonably well, but we have to be aware of the uncertainties of this method, and the results derived from it. First, the validity of of this reference frame is widely debated, and the westward component of the South-American motion varies somewhat between the different models [Meijer and Wortel, 1992]. Second, relative motion between the probably deep source location of the hotspots and the shallow mantle is basically unknown and is therefore ignored, although a recently proposed deep-mantle return flow model [Wang and Wang, 2001] may provide a viable alternative approach.

[9] Very few model results show a decreasing flat slab segment after full plateau subduction. One would expect such 're-steepening' to occur, since flat subduction occurs at only about 10% of the trenches Gutscher et al. [2000]. Possible explanations are a slab suction force that is somewhat too effective, or the two-dimensional model used. Slab suction Stevenson and Turner [1977]; Tovish et al. [1978] is implicitly incorporated in a viscous flow subduction model and is likely to be partly responsible for the flat slab development. This mechanism is proposed to explain the absence of observed subduction dip angles between 10 and 20 degrees. Indeed, such dip angles are also rare in the numerical calculations. Also the implicit absence of along-trench mantle flow in a 2-D model could reduce the ability of the flat slab segment to separate from the overlying continental lithosphere: such separation requires inflow of mantle material to form a new mantle wedge, that accompanies steep subduction. Lateral mantle flow might facilitate this process.

[10] Figure 2b shows that the transition temperature  $T_T$  also affects the dip angle in models without a subducting plateau. The eclogitisation of the normal oceanic crust and the thickened plateau crust are controlled by the same function, in which only the Gibbs free energy difference between basalt and eclogite and the ambient temperature plays a role. However, also the presence of water and deformation is suggested to enhance eclogitisation significantly Rubie [1990]; Austrheim [1998]. Extension of the kinetic function with a hydration dependence could result in a larger metastability in the deeper parts of the plateau, while 'normal' oceanic lithosphere could be more hydrated and show faster eclogitisation. The influence of water on eclogitisation and even the (de)hydration of the slab, however, are poorly constrained.

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