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Numerical analysis of subduction initiation risk along the Atlantic American passive margins

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ABSTRACT

As the oceanic lithosphere ages and cools, its density increases and at some stage exceeds the density of the underlying asthenosphere, so that the plate can sink spontaneously under its own weight. However, despite the fact that some seafloors are ~170 m.y. old, an undeniable Cenozoic example of a passive continental margin transforming into an active margin by subduction initiation is not yet known. Several workers have indicated the sources of difficulty of such a transformation; however, no evaluations of existing passive margins from the viewpoint of their future stability have been provided. As suggested by recent numerical experiments with generalized passive margin structures, spontaneous subduction initiation may have a hidden initial phase that is not expressed in diagnostic features such as trench and magmatic arc. Here we analyze numerically the probability of subduction initiation along the Atlantic American passive margins based on their topography and lithospheric and crustal structure. According to our experimental results, proper subduction will likely start during the next 10–20 m.y. along the southern part of the Brazilian margin, while other Atlantic margins of North and South America are stable under the present geodynamic conditions.

INTRODUCTION

The main reason for an oceanic plate to subduct is its negative buoyancy, which is achieved in 20–50 m.y. after the oceanic plate forms at the mid-ocean ridge (Cloos, 1993). However, the negative buoyancy is not enough to overcome frictional resistance along the continent-ocean boundary and the coherence of the joint oceanic-continental plate (McKenzie, 1977). In addition to the negative buoyancy of the oceanic lithosphere, passive margins are usually characterized by at least two additional factors favoring subduction initiation: (1) lateral density difference between relatively thick (25–35 km) continental crust and adjacent significantly denser oceanic lithosphere (Mart et al., 2005; Goren et al., 2008), and (2) a chemical density contrast between the continental and oceanic lithospheric mantle (Mart et al., 2005; Carlson et al., 2005). Both forces generated by these density differences weaken the contact zone and may trigger break-off of the joint plate (Carlson et al., 2005; Niu et al., 2003). Moreover, additional topography-related forces may come into play at passive margins, e.g., sedimentary loading at the margin (Erickson, 1993), horizontal push exerted by the topographic loads located within the continent, or forces coming from another oceanic ridge on the other side of the continent, as happens in North or South America.

It has been shown numerically (Nikolaeva et al., 2010) that during spontaneous subduction nucleation at a passive margin, the weaker continental lithosphere is internally deformed rather than the stronger oceanic one (Steckler and Brink, 1986), which is only subjected to gentle viscoelastoplastic bending (Faccenda et al., 2009). It has also been shown (Nikolaeva et al., 2010) that the strength of the continental lithosphere actually defines the lower stress limit needed to be overcome to initiate subduction. The strength of rocks is strongly influenced by temperature; therefore, the thermal structure of the continent is the key parameter for the stability of the passive margin. Temperature at the continental Moho is particularly important as it controls the strength of the lower crust and the upper lithospheric mantle, where initial plate separation, leading to subduction, is initiated (Nikolaeva et al., 2010).

Atlantic margins of North and South America are ideal for analyzing the probability of subduction initiation because they are characterized by great variations in continental lithospheric thickness (from 75 to 150 km) and hence Moho temperature, in addition to the presence of both the old oceanic lithosphere and the topography, all of which induce forces favoring subduction (Husson et al., 2008). In particular, topography-related forces come from the mass excesses in the Andes and North American Cordillera, as well as from the Appalachian Mountains and Brazilian Plateau. Both continental margins are affected from the east by the push of the Mid-Atlantic Ridge and from the west by forces coming from the Pacific ridges. Of particular interest is the Brazilian coast, where igneous activity as well as considerable seismic activity was recognized. This observation was attributed to possible subduction initiation by Fyfe and Leonardos (1977), who argued that the material deflected downward due to sedimentary load or by oceanic floor underthrusting the continent or thickened oceanic crust may in fact undergo the basalt-eclogite transition, which would lead to low-velocity subduction.

METHODS

Numerical Model

The numerical experiments were performed with the I2ELVIS code (Gerya and Yuen, 2007). The applied numerical technique is a combination of a finite difference method used on a staggered grid with non-uniform grid spacing and a marker-in-cell method. The computational domain depends on the actual profiles we model and varies from 6000 × 300 km to 7980 × 300 km. The maximum vertical resolution was 1 km for the region from depths of 6–30 km, and was 2 km everywhere else in the domain. The horizontal resolution was maximal around the margin (2 km for 500 km at each side of the continent-ocean boundary) and increased gradually to 30 km at the boundaries of the model. The mechanical boundary conditions of the model are free slip at all boundaries. The temperature structure of the continental part of the plate is controlled by its thickness and is defined by a linear profile from 0 ºC at the surface to prescribed temperature at the base of the lithosphere (T_{base}), which is calculated as:

$$T_{base} = 0.5 \times d_{lit} + 1250, \qquad (1)$$

where d_{lit} is the thickness of the continental lithosphere. The initial temperature gradient in the asthenospheric mantle is 0.5 ºC/km. The temperature profile of the oceanic lithosphere is computed from the age of the ocean according to the cooling of a semi-infinite half-space equation (Turcotte and Schubert, 2002). The age of the Atlantic Ocean was maximal (170 Ma for North American margin and 110 Ma for South American margin) at 300 km offshore and decreases linearly toward the right boundary corresponding to the Mid-Atlantic Ridge (0 Ma). The oceanic plate is thus not attached to the right model boundary and can move. We emphasize that the velocity field in the model arises spontaneously due to gravitational

TABLE 1. MATERIAL PROPERTIES USED IN THE TWO-DIMENSIONAL NUMERICAL EXPERIMENTS

Rock type	Density ($kg\ m^{-3}$)	Thermal conductivity ($Wm\ K^{-1}$)	Flow law*	Cohesion (MPa)	Friction angle (sinφ)
Mafic crust	3200	1.18 + 474 / (*T* + 77)	plagioclase An_{75}	3	0.1
Felsic crust	3000	0.64 + 807 / (*T* + 77)	wet quartzite	3	0.1
Oceanic lithospheric mantle and asthenosphere	3300	0.73 + 1293 / (*T* + 77)	dry olivine	3	0.6
Continental lithospheric mantle	3225–3250†	0.73 + 1293 / (*T* + 77)	dry olivine	3	0.6

Note: *T* is temperature.
*Flow laws are taken from Ranalli (1995).
†Density of the continental lithospheric mantle was variable in our experiments; see Table 2.

and topographic forces. (For details of the numerical model set up, see the GSA Data Repository[1] and Nikolaeva et al. [2010].)

Model Design

Our two-dimensional (2-D) numerical models simulate the lithosphere–upper asthenosphere sections (Table 1) of North and South American plates along different sections as shown in Figure 1A. Models of both plates start at mountains at the eastern edge of the continents and end at the Mid-Atlantic Ridge to include the main topographic forces. To construct the continental lithosphere of North America, we used data from Artemieva and Mooney (2001) for the lithosphere thickness and data on crustal thickness from Hasterok and Chapman (2007). The crustal structure of the South American continent is based on data of Feng et al. (2007). The deep Moho of southeastern Brazil, unusual for a rifted margin, reported by Feng et al. (2007), was also suggested by Cobbold et al. (2001, and references therein) and Assumpção et al. (1997). The model lithosphere thickness of South America is based on estimations of Artemieva and Mooney (2001) (Fig. 2).

RESULTS AND DISCUSSION

The continental lithosphere of North America is rather thick (>100 km) along most of its eastern margin (Artemieva and Mooney, 2001), which implies <500 °C Moho temperatures at the base of 35–40-km-thick continental crust (Hasterok and Chapman, 2007). We performed several numerical experiments to test the stability of the margin at different latitudes (Fig. 1A; Table 2). The results show that the Atlantic margin of North America will remain stable (passive; Fig. 3) over the next tens of millions of years, if the compositional and temperature structure is not affected by other processes such as rifting or rising mantle plumes. The latter scenario was proposed for the passive North American margin due to water addition from the subducted Farallon plate (van der Lee et al., 2008). According to this hypothesis, aqueous fluids released from the slab may affect the eastern part of the American continental lithosphere and form an elongated zone characterized by reduced strength and density parallel to the Appalachians. This could cause subduction initiation, as argued by van der Lee et al. (2008).

The Atlantic margin of South America is characterized by a rather thin lithosphere, especially for the southern part of the Brazilian margin, as suggested by terrestrial gravity (Pérez-Gussinyé et al., 2007; Tassara et al., 2007) and heat flow data (Artemieva and Mooney, 2001). To evaluate the likelihood of future subduction initiation along the margin, we constrained five representative profiles across South America, where the continental thermal structure is reasonably well defined (Artemieva and Mooney, 2001) (Fig. 1A). Results of the numerical experiments are different for the northern and southern part of the studied area. The northern part of the margin, which is characterized by thick continental lithosphere (125–150 km, T_{Moho} = 317–418 °C; points B and J in Fig. 1A), is stable for the duration of the experiment (>50 m.y.). In contrast, the southern part of the margin has a thin lithosphere (75 km; point C in Fig. 1A), and high estimated continental Moho temperature (~735 °C), which implies notably reduced strength of the continental lithosphere. Under these conditions, the weak lower continental crust in experiments

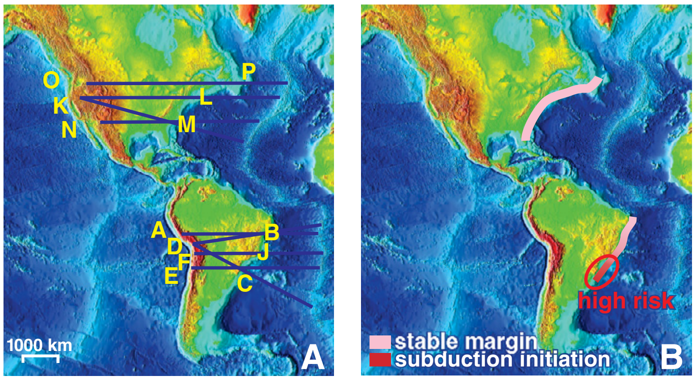

Figure 1. A: Locations of analyzed cross sections for Atlantic margins of North and South America. B: Risk evaluation map. Dark solid lines in A denote cross sections analyzed with two-dimensional numerical models. As suggested by results of numerical experiments, southern part of Brazilian margin is under likelihood of subduction initiation (Fig. 4), while other modeled margins are stable (Fig. 3).

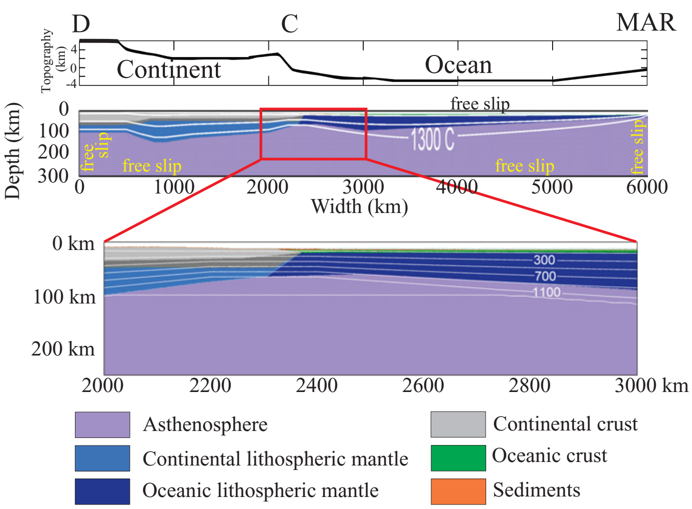

Figure 2. Model setup for cross-section D-C. White lines indicate temperature (in °C). All mechanical boundary conditions are free slip. Oceanic and continental crusts consist of two layers of different densities. MAR—Mid-Atlantic Ridge.

[1]GSA Data Repository item 2011149, detailed description of the numerical model, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 2. PARAMETERS AND RESULTS OF CONDUCTED EXPERIMENTS

Experiment	Cross section	H_{crust} (km)	H_{lith} (km)	T_{Moho} (°C)	$\rho_{cont.m}$ (kg m^3)	Geodynamic regime
1	O-P	37	110	496	3250	stable margin
2	O-P	37	110	496	3225	stable margin
3	K-L	40	125	325	3250	stable margin
4	K-L	40	125	325	3240	stable margin
5	K-L	40	125	325	3230	stable margin
6	K-M	35	130	376	3250	stable margin
7	K-M	35	130	376	3225	stable margin
8	N-M	35	130	376	3250	stable margin
9	N-M	35	130	376	3225	stable margin
10	A-B	35	150	317	3250	stable margin
11	A-B	35	150	317	3225	stable margin
12	D-B	35	150	317	3250	stable margin
13	D-B	35	150	317	3225	stable margin
14	F-J	35	125	418	3250	stable margin
15	F-J	35	125	418	3225	stable margin
16	D-C	38	75	736	3250	subduction
17	D-C	38	75	736	3225	subduction
18	E-C	38	75	736	3250	subduction
19	E-C	38	75	736	3225	subduction

Note: H_{crust} and H_{lith} are thicknesses of the continental crust and continental lithosphere at the margin, respectively; T_{Moho} is the continental Moho temperature at the margin; $\rho_{cont.m}$ is the density of the continental lithospheric mantle.

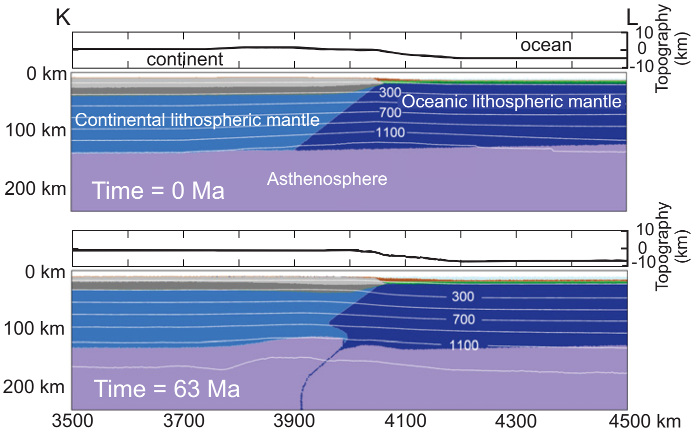

Figure 3. Two-dimensional evolution of lithological and temperature fields obtained from experiment on cross-section K-L (Fig. 1; enlarged areas from 7050 × 300 km model). Each snapshot is accompanied by topographic profile; isotherms are shown as white lines for each 200 °C; time is shown starting from beginning of experiment (i.e., from present). At 42 m.y., relief is smoother and small delamination of oceanic lithospheric mantle occurs at base of lithosphere. Oceanic and continental lithospheres remain connected to each other.

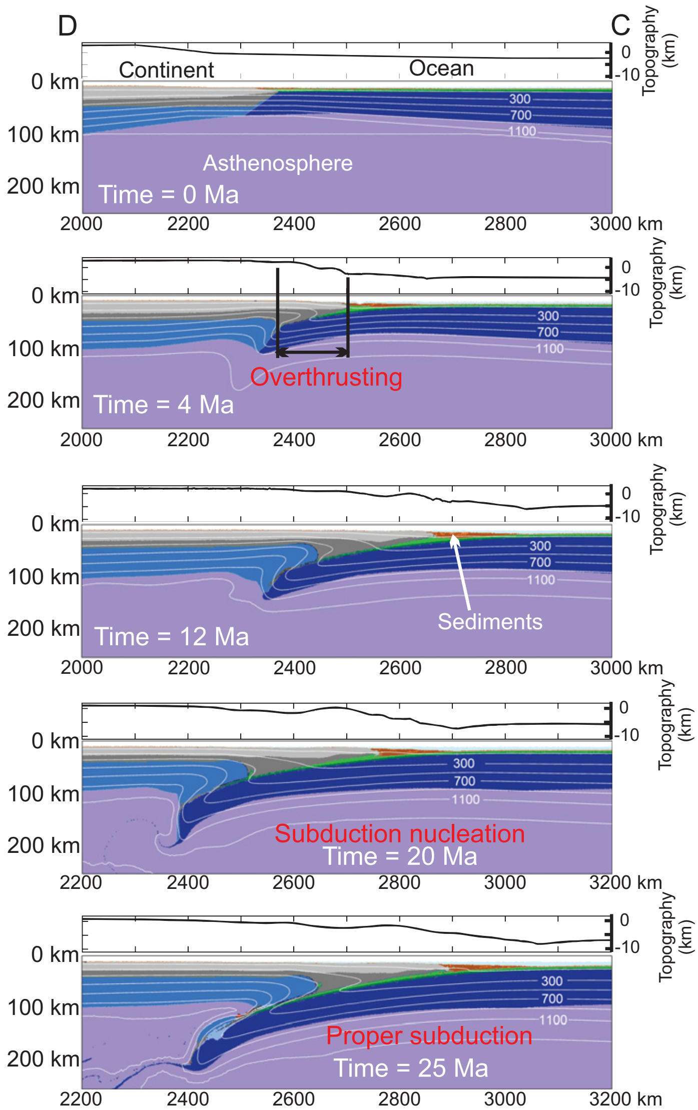

Figure 4. Two-dimensional evolution of lithological and temperature fields obtained from experiment on cross-section D-C (Fig. 1; enlarged areas from 6000 × 300 km model). After starting the experiment, lateral density contrasts at margin promote thrusting of continental crust over oceanic crust (time = 4 m.y. and 12 m.y.). At that early stage, stresses are not enough to break lithosphere. At later stage, stresses concentrated at deflected continent-ocean mantle boundary overcome ductile strength of continental mantle, which become sheared along boundary while oceanic plate starts to sink under continental lithosphere (time = 20 m.y.). At final modeled stage of 25 m.y., two plates are fully separated and proper retreating self-sustaining subduction continues.

thrusts over the oceanic crust due to the lateral density contrast, and deflects the oceanic lithosphere downward (Fig. 4; time = 4 m.y. and 12 m.y.). At a later stage, proper retreating subduction initiates by ductile shearing of oceanic-continental mantle boundary and becomes self-sustained at ~25 m.y. (oceanic crust becoming overridden by the mantle wedge asthenosphere in Fig. 4 at 25 m.y.). This predicted scenario appears to be robust and does not crucially depend on the model profile (Fig. 1A; Table 2), although the beginning of subduction may vary by ±10 m.y. In particular, we tested the influence of geometry of transition from the continent to the ocean by varying the width of the thinned continental crust from 50 to 110 km. Test experiments indicate that subduction initiation time varies within the specified limits of ±10 m.y.

Another important controlling parameter for subduction nucleation at a passive margin is the density difference between continental and oceanic lithospheric mantles (Nikolaeva et al., 2010; Mart et al., 2005). Although the lithospheric mantle beneath continents is known to be more compositionally depleted, and thus less dense than the oceanic lithospheric mantle (Carlson et al., 2005), the exact value of the mantle rock density at lithospheric conditions is unknown. In our experiments, the compositional density difference between subcontinental and suboceanic mantle is chosen to be 50 kg/m^3 (Table 2). For the Brazilian margin this value appears to be realistic because the continental lithosphere is believed to be cratonic there (Pérez-Gussinyé et al., 2007). For margins of South and

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North America, which showed no sign of subduction initiation, we performed additional experiments with higher density contrast between oceanic and continental lithospheric mantles (to 75 kg/m^3; Table 2). Results are irrespective of density difference and show that these margins should remain stable. Lower density contrast would lead to higher margin stability (Nikolaeva et al., 2010) and, thus, to lower probability for subduction initiation at these settings.

The model gives an interesting prediction of the future tectonic evolution of the passive Brazilian margin, which could be in the process of conversion to an active margin. This prediction does not disagree with natural data indicating present-day reverse faulting offshore southeastern Brazil (e.g., Assumpção 1992). Such initiation should be in the very early stage, evidenced by the absence of a noticeable oceanic trench along the margin (Nikolaeva et al., 2010).

CONCLUSIONS

Based on the numerical experiments conducted, we propose that the southern part of the Brazilian margin is under the likelihood of subduction initiation within the next 20 m.y., while other Atlantic margins of North and South America should remain rather stable within the next few tens of millions of years (Fig. 1B; Table 2). Also, according to our data the lower thickness of the continental lithosphere underneath southeastern Brazil, implying a higher Moho temperature, is the main factor favoring future subduction initiation in this region. A thicker, colder, and hence stronger lithosphere under the rest of the studied American passive margins should prevent subduction initiation, unless some additional geodynamic forces, such as rifting and/or thermal-chemical plume ascent (Burov and Cloetingh, 2010), occur in the future.

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