Journal of Geodynamics 93 (2016) 1–16

Contents lists available at ScienceDirect

Journal of Geodynamics

journal homepage: http://www.elsevier.com/locate/jog

Speculations on the impact of catastrophic subduction initiation on the Earth System

F.O. Marques [a,b,*], B.J.P. Kaus [b]

[a] Universidade de Lisboa, 1749-016 Lisboa, Portugal
[b] Institute of Geosciences, Johannes Gutenberg-University, Mainz, Germany

ARTICLE INFO

Article history:
Received 5 March 2015
Received in revised form 18 September 2015
Accepted 18 September 2015
Available online 12 November 2015

Keywords:
Subduction initiation
Passive margin
Geodynamic setting
Global changes
Biotic crisis
Earth System
Numerical modelling

ABSTRACT

The physics of subduction initiation can be studied with numerical models of lithosphere dynamics, to the extent where we can now test the potential consequences of a catastrophic subduction initiation event on the Earth System. The South American Atlantic passive margin is here used to show that, once subduction has catastrophically initiated there, a major geodynamic reconfiguration of the South American plate (SAm) is likely to take place: (1) compression in the east will be inverted to extension, because ridge push will be replaced by subduction rollback and trench retreat; (2) compression in the west will be inverted to extension due to absolute rollback; and (3) without buttressing from the east and west, the Andes will collapse. Extension at both margins of continental SAm will produce two new volcanic arcs, several thousands of kilometres long each, bounded by trenches and two new back-arc basins. The spreading rate of the Mid-Atlantic Rift will significantly increase, because of the cumulative effect of ridge-push and slab-pull in the same direction. The substantially increased volcanism all around SAm and in the MAR will most likely release massive amounts of greenhouse and (toxic) gases into the atmosphere and oceans, which might lead to major oceanic and atmospheric circulation changes. We present new numerical modelling that supports the proposed evolution of the SAm after subduction has catastrophically initiated at its eastern passive margin.

1. Introduction

When discussing global changes and impact on life on Earth, one has to consider the time scale of the process: it must be large-scale and catastrophic (occur in a short period of time), such that the biosphere does not have the time to adapt to the new conditions, particularly in the atmosphere and hydrosphere. One way to look at this problem is to consider the time scale during which the process occurs and divide it by the characteristic timescale of observation, which gives a non-dimensional number similar to the Deborah number (Reiner, 1964, Physics Today). When considering subduction initiation, this would be the time during which subduction initiation occurs divided by the characteristic time that living beings need to adapt to new conditions. If $De < 1$, then catastrophic subduction initiation at a passive margin (<1 Ma) is a process capable of producing a biotic crisis. Otherwise, there is time for adaptation, because environmental changes take place over a long period of time ($\gg$1 Ma).

In this work, we concentrate on the fast end-member of subduction initiation, the catastrophic initiation, because this is the one capable of producing sudden global changes in the Earth System and impact on life on Earth, which previous studies have shown to exist. We use well-known constitutive equations and experimentally determined parameters (e.g. Weertman, 1968; Hirth and Kohlstedt, 2003; Korenaga and Karato, 2008), and show numerically that subduction can initiate in less than 1 Ma, which seems insufficient time for a great part of the biosphere to adapt to new conditions (Wignall and Twitchett, 1996; Wignall, 2001). We therefore speculate that catastrophic subduction initiation at a passive margin can be responsible for mass extinctions.

At the surface, subduction is responsible for catastrophic events like explosive volcanism, large earthquakes and major tsunamis, which obviously impact human societies. Although omnipresent, mature subduction does not seem capable of triggering fast global changes that would impact the whole Earth System. In contrast, subduction initiation at a passive margin can be a catastrophic process, both in terms of the time over which it occurs as well as on the modifications it makes to the lithosphere.

McKenzie (1977) mathematically analysed the problem of subduction initiation at a passive margin, and concluded that the

* Corresponding author at: Universidade de Lisboa, 1749-016 Lisboa, Portugal.
E-mail address: fomarques@fc.ul.pt (F.O. Marques).

http://dx.doi.org/10.1016/j.jog.2015.09.003
0264-3707/

development of a new trench and sinking slab occurs through a finite amplitude instability, because elastic and frictional forces prevent trenches from arising spontaneously. This means that an external force is needed to initiate subduction. The compressive stress required is about 80 MPa, and the rate of approach must be greater than about l.3 cm/yr. Two immediate sources of compressive stress in a passive margin are ridge-push and topography push from the passive margin. The difference in mean density between continental and oceanic crusts produces a horizontal force (e.g. Niu et al., 2003; Marques et al., 2014a) similar to the push caused by elevated mid-oceanic ridges (ridge-push). If the difference in elevation between a continent and adjacent ocean is 7 km, with 2 km above sea level and 5 km below (as at the Brazilian margin), it can maintain a compressive stress of 85 MPa. If to these stresses we add the stresses due to Andean topography and deep roots, which can amount to 100 MPa if the estimated value of 10^{13} N/m (e.g. Artyushkov, 1987; Husson et al., 2008) is integrated over a 100 km thick lithosphere, then the South American plate (SAm) seems the best place for subduction to initiate at a passive margin. The probability of subduction to initiate along the eastern American Atlantic margins has been numerically evaluated by Nikolaeva et al. (2011) and Marques et al. (2013), who concluded that the SE Brazilian margin has the highest probability for subduction initiation to occur there. According to Marques et al. (2013), subduction could likely be initiating at the Brazilian passive margin, because of additional forcing by the current massive Andean Plateau and its very deep crustal roots (which are hot and of low-density). Given the favourable geodynamic setting for subduction initiation, we here concentrate on SAm's possible future evolution.

If the current theoretical analyses and the physics governing subduction initiation are accepted, then a major question arises: what is the impact of subduction initiation on the Earth System? The answer to this question is the aim of this article. We use current knowledge about the SAm and numerical models to predict what will happen to the SAm in the future, and evaluate the impact these changes can have on the Earth System if subduction initiates catastrophically at a passive margin.

The main premises of this work relate to (1) catastrophic subduction initiation at a passive margin, (2) the role that rheology of the sub-lithospheric mantle plays in this process, (3) the support of mountain belts (buttressing), and (4) the motion of the subduction hinge:

(1) Catastrophic subduction initiation – Hall et al. (2003) and Nikolaeva et al. (2010) have analysed numerically subduction initiation at a passive margin, and both have concluded that self-sustained subduction can take off in about 1 Ma (which was also observed in more recent models of Lu et al., 2015). Nikolaeva et al. (2010) carried out a parametric study that shows that the thickness of the continental lithosphere can lead to catastrophic (<1 Ma) subduction initiation at a passive margin (cf. their Fig. 6). Using the current geological and geophysical knowledge of the SAm, we further tested the effects of rheology (diffusion and dislocation creeps) and activation volume on the velocity of subduction initiation.

(2) Rheology of the sub-lithospheric mantle – the rheological properties of the mantle are critical to its dynamics; however, fundamental issues such as the dominant flow mechanisms or the parameters (such as the activation volume of the mantle) are still not consensual. Laboratory studies and geophysical and geological data indicate that both diffusion and dislocation creep can occur in the mantle (Karato and Wu, 1993). However, according to Bürgmann and Dresen (2008), broadly distributed deformation in the asthenosphere probably occurs by dislocation creep, with a stress-dependent power-law rheology. Therefore, we used dislocation creep (power-law creep) as the rheology of the sub-lithospheric mantle in our models. However, we tested the influence of rheological law (diffusion or dislocation creep), and of activation volume on subduction initiation (see also Billen and Hirth, 2005, 2007).

(3) Buttressing – it is long known that mountains like the Himalaya or the Andes are supported by the surrounding lithosphere; if this support vanishes, the mountain belt collapses. This is what has happened to all orogens worldwide and through the Earth's history; when convergence and compressive forces cease, the mountain belt collapses and the deep continental roots isostatically rebound, denudation removes the topographic relief, and the Moho returns to its normal position at 30–40 km depth.

(4) Motion of the trench – It is now well established that the large majority of N-S trenches and their associated subduction zones are found at, or very near, the margins of the Pacific Ocean. Exceptions are the much smaller Indonesian, Caribbean, and Scotia trenches. Along the N-S portions of the Pacific trenches, all slabs go down so as to slope away from the Pacific margins. Given that the Atlantic and the Indian oceans have been opening in an approximately E-W direction since the Mesozoic, it follows that the Pacific plate must have shrunk by a corresponding length during the same period of time, which means that the trenches have retreated (e.g. Elsasser, 1971; McKenzie, 1977). Fig. 1 illustrates how this can happen: after subduction is initiated and is self-sustained, the sinking of the oceanic slab is dominated by its negative buoyancy. Under the pull of gravity, the slab tends to rotate vertically and oceanwards, which is the concept of slab rollback. Slab rollback induces trench retreat oceanwards, and, in order to fill the gap, the overriding plate either drifts or stretches and opens a back-arc basin. The force resulting from trench retreat was called trench suction by Forsyth and Uyeda (1975). Trench retreat has even been suggested to be responsible for the break-up of supercontinents (e.g. Bercovici and Long, 2014), and might currently be responsible for the shrinking of the Pacific. However, the scheme in Fig. 1 is valid only if the oceanic plate has no horizontal displacement (fixed at the right end in Fig. 1). This might not be the case if the oceanic plate could move, e.g. by having a mid-ocean rift. Therefore, we analysed this possibility by running simulations with and without a mid-ocean rift.

Natural examples (e.g. Gvirtzman and Nur, 1999; Rosenbaum and Lister, 2004; Schellart et al., 2006; Spakman and Hall, 2010) and theoretical analysis of subduction initiation at a passive margin (e.g. Faccenna et al., 1999; Nikolaeva et al., 2010, 2011; Marques et al., 2013, 2014a) have shown that rollback is a natural consequence immediately following subduction initiation (e.g. Kincaid and Olson, 1987; Hall et al., 2003; Kincaid and Griffiths, 2003; Funiciello et al., 2003a,b, 2006, 2008; Gurnis et al., 2004; Schellart,

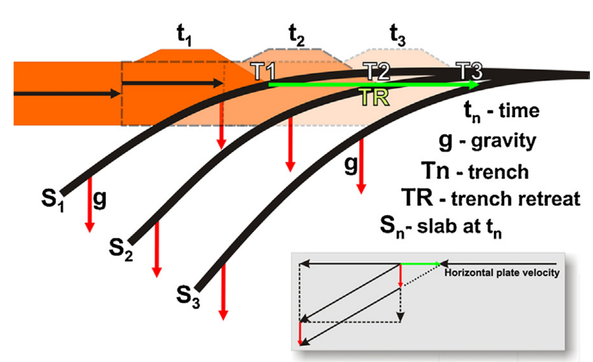

Fig. 1. Sketch illustrating slab rollback and consequent trench retreat. The overriding continent may either drift or rift, in the latter case to form a back-arc basin.