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Long-term stratigraphic evolution of Atlantic-type passive margins: A numerical approach of interactions between surface processes, flexural isostasy and 3D thermal subsidence

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ABSTRACT

The thermal and flexural evolution of passive margins is impacted by the (un)loading effects of erosion/sedimentation processes, which, in turn, affect their relief and sediment accumulation. These complex couplings are recorded by the stratigraphic trend of the associated sedimentary basins, which is controlled by the balance between sediment accumulation, subsidence and eustasy.

Our objective is to constrain the relative contribution of the factors controlling the mechanical response of the lithosphere and the efficiency of the surface processes on parameters such as the denudation/accumulation and uplift/subsidence history and long-term stratigraphic trends. The novel aspect of our approach is to integrate the evolution of both domains in erosion and in sedimentation, using state of the art modeling of the flexure of the lithosphere including the surface processes (erosion/sedimentation) and the thermal evolution, as well as concepts in sequence stratigraphy.

We investigated numerically the post-rift evolution of passive margins, testing the influence of the lithosphere's initial geometries, thermal states and stretching profiles as well as the efficiency of the surface processes. In all simulations, the initial flexural rift-shoulder is eroded away within 10 to 20 Myr. In the following stages, the sedimentary supply and the evolution of the margin are mostly controlled by the flexural response to the thermal relaxation of the isotherms by cooling and the (un)loading mass transfer at the surface. Both the sediment accumulation (controlled by relief relaxation) and the subsidence rates decrease exponentially with time. The evolution of their relative values forms a regressive/transgressive sequence. We show that variations in the efficiency of the surface processes may impact the uplift/subsidence histories and the long-term stratigraphic trend within the same range of magnitude as lithospheric parameters such as pre-rift crust thickness or depth dependency of stretching. The initial crustal thickness is then determinant in the denudation/accumulation history whereas the margin width will impact the uplift/subsidence history the second most. Depth of necking and effective elastic thickness are critical mostly during the initial phase of the margin history (syn- and immediate post-rift) whereas bulk sediment density and lithosphere thickness become critical in the late post-rift.

1. Introduction

The basins of passive margins preserve the terrigeneous sediments resulting from the erosion of the adjacent continental areas contained within their contributing drainage areas (Fig. 1). The thermal evolution and flexural isostasy of these highly stretched lithosphere are impacted by the (un)loading effects of erosion/sedimentation processes that, in return, affect the relief evolution along the margin (e.g. Burov and Cloetingh, 1997; Gilchrist and Summerfield, 1994; Kooi and Beaumont, 1994; Van der Beek et al., 1994, 1995; Watts, 1989; Watts et al., 1982). These complex couplings are recorded by the geometries of the sedimentary wedges preserved in passive margin basins. They also affect their long-term stratigraphic trends controlled by the balance between the sediment accumulation, basement subsidence and eustasy.

In the early phases of the study of Atlantic-type passive margins, the long-term regressive trends (seaward migration of the shoreline) often characterizing their post-rift evolution was generally attributed to the

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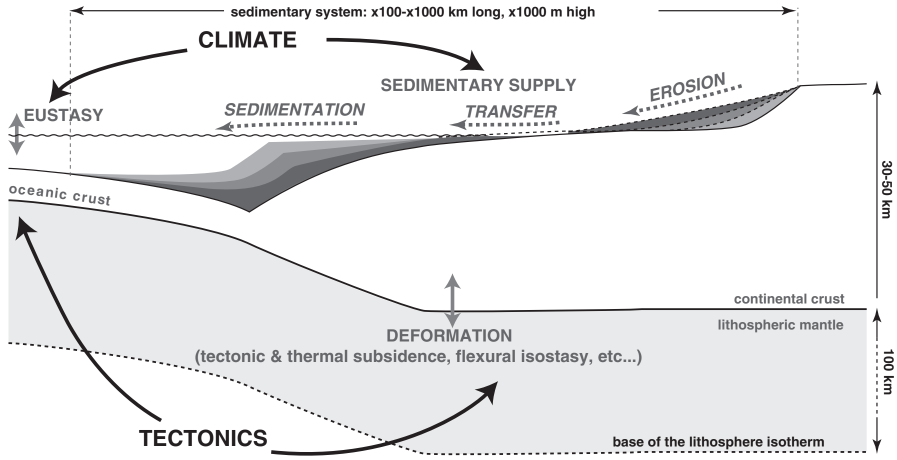

Fig. 1. Sketch of a passive margin. The post-rift evolution of a passive margin results from the interactions between the smoothing out of the thermal structure of the lithosphere (i.e. thermal subsidence), the flexural isostasy (i.e. rift-related relief) and the load/unload effects of surface transfer (denudation, sedimentation). Modified after Guillocheau et al. (2012).

combination of (i) the exponentially decreasing rate of the thermal subsidence of the basement (the smoothing out of the lithosphere thermal structure by conduction; Bally, 1981) and (ii) a sedimentary supply that was always much larger than the space available for sedimentation (i.e. accommodation, the sum of subsidence and eustasy; Jervey, 1988). This configuration results in a long-term regressive trend of the sedimentary wedge (Bally, 1981) modulated by higher frequency stratigraphic regression/transgression sequences controlled by eustatic sea-level variations (e.g. Vail et al., 1977). This simple view of the evolution of passive margin accommodation/accumulation balance did not include the flexural behavior of the underlying stretched lithosphere. Many authors have then underlined the impact of the flexural response to the isostasy of the lithosphere on the uplift of the rift flanks (e.g. Gilchrist and Summerfield, 1994; Kooi and Beaumont, 1996; Ten Brink and Stern, 1992; Van der Beek et al., 1994, 1995). Other authors have highlighted the (un)loading effects by denudation/accumulation resulting from surface processes on the flexure (e.g. Braun and Beaumont, 1989; Reynolds et al., 1991; Van Balen et al., 1995; Watts, 1989). For example, the sedimentary supply resulting from the rift-related relief erosion is expected to decrease exponentially with time (e.g. Kooi and Beaumont, 1996); in other words, it will not provide a constant supply to the passive margin basins. Also, the flexural component of the subsidence may migrate seaward under the weight of a prograding sedimentary wedge (e.g. Watts, 1989). These coupled effects between erosion/accumulation and flexure thus have a complex impact on the distribution, in time and in space, of both accumulation and subsidence, i.e. on the long-term stratigraphic trend of the passive margin basins. However, no comprehensive synthesis, predicting the impact of the flexural behavior of the lithosphere on the long-term stratigraphic trend of passive margin basins, is currently available. Indeed, modeling coupling lithosphere deformation and surface processes usually address large-scale deformation processes, i.e. they cannot resolve the stratigraphic trend of the simulated basins (e.g. Burov and Cloetingh, 1997; Huismans and Beaumont, 2008). On the other hand, models dedicated to stratigraphic simulation (e.g. Granjeon, 1997; Kaufman et al., 1991; Kenyon and Turcotte, 1985; Reynolds et al., 1991) do not include these feedbacks of erosion/sedimentation on deformation processes. The recent development of a numerical modeling tool, coupling the thermal and flexural evolution of the lithosphere to surface processes in 3D (Flex3D; Braun et al., 2013), has however provided a tool to investigate these effects.

The aim of this study is thus to revise the early view of long-term stratigraphic trend of the Atlantic-type passive margins to include the impact of the flexural component of the isostatic response of the stretched lithosphere. We performed a parametric analysis of Atlantic-type passive margins designed to constrain the relative contribution of both the evolution of a stretched lithosphere (initial geometry, thermal state and stretching profile) and the (un)load effects of surface processes on: (i) the accumulation and subsidence histories of the basin (as determined by backstripping), (ii) the denudation and uplift histories of adjacent continental areas (as determined by cooling histories measurements) and (iii) the long-term stratigraphic trends of the sedimentary wedge (as determined by seismic and sequence stratigraphy methods). The novel aspect of our approach is to define a predictive framework integrating the evolution of both domains in erosion and in sedimentation. We use state of the art modeling of the lithospheric flexure combined with a surface processes model and a quantitative estimate of the thermal evolution of the lithosphere (Braun et al., 2013) and sequence stratigraphy concepts (e.g. Jervey, 1988; Posamentier et al., 1988; Posamentier and Vail, 1988) to interpret the resulting simulations. This work, along with two companion papers (Braun et al., 2013; Dauteuil et al., 2013), constitutes a first step into a broader perspective, which is to provide basin geologists with quantitative tools to use the stratigraphic architectures of passive margin basins to track variations in the continental relief triggered by either climatic or deformation processes.

To achieve this, we simulated the long-term (>100 Myr) evolution of passive margins, testing various initial geometries, thermal states and thinning profiles of the lithosphere as well as various efficiencies of surface processes. We first calibrated the coefficients of the surface transfer law using accumulation histories, relief lengths and sedimentary slopes as measured on several Atlantic-type passive margins. We then discuss the relative contribution of surface vs. deformation process and draw general implications for natural examples that might help basin geologists to assess the primary controls on the evolution of a given passive margin basin.

2. Modelling principles: Flex3D

2.1. Principle

We used the numerical Flex3D model of Braun et al. (2013) to simulate the flexural response of the continental lithosphere subjected to an instantaneous stretching. Flex3D calculates the surface deflection of a thin, yet of variable thickness, elastic plate. It is coupled to (i) a three dimensional thermal model incorporating the effects of conduction, advection and production (Pecube; Braun, 2003), which allows to take into account the thermal evolution resulting from the stretching-induced perturbation of the isotherms.