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Numerical modeling of spatially-variable precipitation and passive margin escarpment evolution

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ABSTRACT

Passive margin escarpments are long-lasting landforms which can remain steep and high over tens of millions of years. Precipitation variability has seldom been considered as a contributor to passive margin escarpment evolution. However, large and distinct variability in precipitation rates with elevation is observed in mountainous landscapes. We assess the potential impacts of spatially variable precipitation on passive margin escarpment evolution with a numerical model that couples a simple elevation-dependent precipitation rule with the CASCADE surface processes model and a simple flexural uplift model. Modeled topography is more sensitive to the elevation of the precipitation maximum than to the effective elastic thickness of the lithosphere. If precipitation is maximized at the escarpment crest, the escarpment decreases in elevation, slope and proximity to the coast more rapidly than if precipitation is focused at low elevations. Low elevation precipitation maxima contribute to increasing escarpment slope over time and preservation of a high-elevation escarpment. Using Tropical Rainfall Measuring Mission (TRMM) precipitation radar data, we establish precipitation/elevation relationships at high-elevation passive margins across the tropics and document the occurrence of patterns similar to those included in our model. Despite uncertainty as to the robustness of precipitation patterns and the simplified tectonic and geomorphic framework of our model we conclude that spatial variability in precipitation is a potentially significant contributor to passive margin escarpment evolution.

1. Introduction

Passive margin escarpments stretch for hundreds of kilometers along rifted continental margins including the southwest coast of Africa, southeast coast of Australia and west coast of India. These topographic features separate coastal plains tens to hundreds of kilometers in width from low relief, high-elevation interior plateaus. The formation and evolution of passive margin escarpments has been the subject of considerable debate stretching over more than a century (e.g., Suess, 1906; Penck, 1924; King, 1955; Gilchrist and Summerfield, 1991; Tucker and Slingerland, 1994; Gunnell and Fleitout, 1998; Bishop and Goldrick, 2000; van der Beek et al., 2002; Petit et al., 2007; Vanacker et al., 2007; Prince et al., 2010).

The style and pace of evolution of escarpments vary. In southeastern Australia (Moore et al., 1986; Nott et al., 1991; Bishop and Goldrick, 2000; Heimsath et al., 2000; Persano et al., 2002) and southern Africa (Gilchrist et al., 1994; Cockburn et al., 2000; Brown et al., 2002), an initial rapid phase of landform development appears to have given way to a period of long-term stability. Decreasing rates of erosion and escarpment retreat over time are deemed universal by some (Matmon et al., 2002; Vanacker et al., 2007). However, a different view is motivated by suggestions of more dynamic and ongoing evolution in southeastern Brazil (Gallagher et al., 1994; Brown et al., 2000), eastern North America (Spotila et al., 2004; Prince et al., 2010), and western India (Harbor and Gunnell, 2007). Periods of stability punctuated by rapid evolution following stream capture (Harbor and Gunnell, 2007; Prince et al., 2010) and climatically driven changes in escarpment erosion rates (Partridge, 1988; Burke and Gunnell, 2008) have been introduced as contributors to temporal variability in escarpment evolution rates. We suggest that spatial variability in climate may influence escarpment form and evolution and may contribute to the observed variability in escarpment evolution styles and rates.

The role of climate in influencing spatial and temporal variability in escarpment evolution has received relatively little study to date. One exception to this generalization is Partridge (1988), who ascribes a decrease in the rate of retreat of the South African escarpment in the Cenozoic to increasing aridification since the Cretaceous. Petit et al. (2007) examine the influence of changes in aridity along the length of the Dhofar passive margin, Oman, on escarpment form, finding that in the wetter stretch of the margin, the escarpment is more rounded and has lower relief than in drier sections. Additionally, Gunnell (1998) notes that the uplifted passive margins of western India and northeastern Brazil have influenced spatial patterns of climate in the late Cenozoic and suggests that retreat and flexural uplift of these passive margin great escarpments were driven by climatic change.

We examine the influence of climate on passive margin evolution, specifically focusing on spatial variability in precipitation and its

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influence on the morphology and temporal evolution of passive margin escarpments. Spatial variability in precipitation has a profound impact on topographic form in coupled models of precipitation and actively uplifting topography (Anders et al., 2008). When precipitation is maximized high in a modeled landscape, it does work throughout the drainage network, and the resulting topographic steady-state has lower slopes and lower elevation peaks than are seen in models where precipitation is maximized at low elevations (Anders et al., 2008). We explore the interactions between topography and precipitation patterns in a different tectonic setting: a passive margin in which uplift is determined by the flexural response of the lithosphere to changes in loading. We hypothesize that the location of the precipitation maximum with respect to topography will strongly influence passive margin escarpment form and evolution. Specifically, if precipitation reaches a maximum high in the drainage network, we expect more rapid retreat of the escarpment and lower escarpment slopes than if precipitation reaches a maximum at a low elevation (Fig. 1).

We use an idealized numerical model of landscape evolution to explore the possible influence of spatial patterning of precipitation on escarpment form and evolution. The numerical experiments provide an indication of the tendencies of the much more complex natural system. As the effective elastic thickness of the lithosphere has been identified as one of a number of important controls on passive margin evolution (e.g., Braun and Sambridge, 1997; Gunnell and Fleitout, 1998; Petit et al., 2007; Campanile et al., 2008), we present models spanning a range of elastic thickness. We then consider how we may gain insight into natural systems using numerical experiments. Documenting precipitation/elevation relationships at existing passive margin escarpments and evaluating their robustness are crucial first steps toward assessing the applicability of the model to specific settings. We use a new data set from the Tropical Rainfall Measuring Mission (TRMM) satellite to examine precipitation variability at passive margins across the tropics.

2. Numerical modeling methodology

The numerical surface processes model CASCADE (Braun and Sambridge, 1997) is coupled to a simple precipitation rule to test the effects of spatially varying precipitation on escarpment evolution. This coupled model solves for precipitation, erosion, and isostatic and flexural uplift on a regular grid of nodes with 1-km spacing and a small amount of noise added to the horizontal nodal positions. The square model domain is 400 km^2 and includes an initial topography representing an idealized passive margin escarpment 1000 m high located 30 km inland of the upwind side of the domain. The downwind side of the domain represents the continental interior and a second ocean basin is located ~350 km downwind of the escarpment. Slopes are initially gentle, rising linearly from the coasts to the escarpment crest. Sensitivity tests indicate that the model is not sensitive to details of the initial condition including the slope and position of the initial escarpment. The initial escarpment crest represents a pre-existing drainage divide, in accordance with the recognized importance of a drainage divide located at or near the escarpment crest. This choice of initial conditions allows us to isolate the impacts of spatial variability in precipitation on evolution of a passive margin great escarpment with a shoulder-type morphology already present. In particular, we examine the impact of different climatic conditions on the timescale over which the escarpment form is maintained and the extent to which escarpment morphology changes over time.

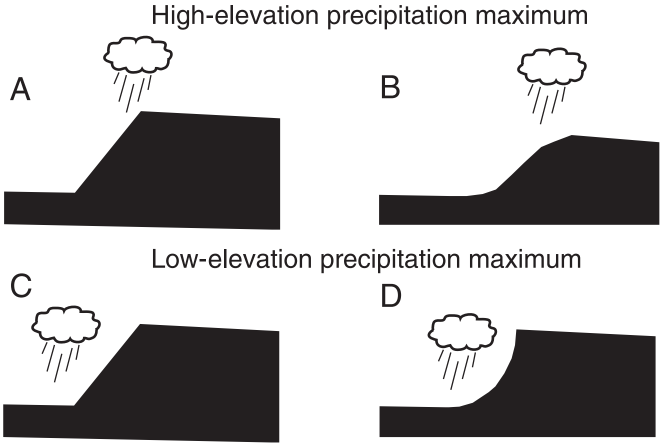

Fig. 1. Schematic drawing of the hypothesized relationship between precipitation pattern and escarpment form. A) Initial condition of a rifted margin where precipitation is maximized at high elevation. B) Expected evolution from panel A: the escarpment retreats and becomes gentler over time. C) Initial condition of a rifted margin with a low-elevation precipitation maximum. D) Expected evolution from panel C: the escarpment steepens with time.

To investigate the role of the relationship between elevation and precipitation, the model includes a precipitation function that is dynamically related to topography. The precipitation function consists of a Gaussian distribution with its maximum centered at a chosen elevation. This formulation is chosen to represent an average timescale for growth of convective cells with smooth variability around that average. The atmosphere contains a set amount of water vapor, w_{tot}, which is rained out as air parcels traverse the landscape from one side of the domain to the other along the x axis of the model. Beginning on the upstream end of the domain, precipitation at nodes closest to the upstream boundary is calculated as:

$$P = C_1 + C_2G(i) \tag{1}$$

where, C_1 and C_2 are constants and $G(i)$ is a Gaussian distribution of the form:

$$G(i) = G_{\max} e^{\frac{-[h(i)-G_{\mathrm{center}}]^2}{2G_{\mathrm{width}}{}^2}} \tag{2}$$

where i is the node index, and $h(i)$ is the elevation at that node. G_{center}, $G_{\max}$ and G_{width} are constants that determine the elevation of the maximum of the Gaussian curve, the amplitude of the curve and the width of the curve, respectively. G_{width} varies with elevation such that at elevations below G_{center} a large value for G_{width} (200 m) is used and above G_{center} a smaller value (80 m) is used. The amount of water present in the atmosphere is now w:

$$w = w_{\mathrm{tot}} - P. \tag{3}$$

Precipitation is then calculated sequentially for nodes farther downstream as:

$$P = [C_1 + C_2G(i)]\frac{w}{w_{\mathrm{tot}}}. \tag{4}$$

We hold the constants C_1 and C_2 fixed at 0.6 and 0.3, respectively and vary G_{center} to produce different precipitation distributions similar to those observed across the tropics. Fig. 2 shows the precipitation/elevation relationship produced windward of the drainage divide for the initial topography for each of the precipitation functions studied. Hereafter, these precipitation functions and the modeled topography resulting from them are designated as peak, mid, and foot as shown in Fig. 2. The spatial pattern of precipitation evolves with the changing landscape. The large amount of available water and close proximity of the escarpment to the coast ensures that the relationship between precipitation and elevation remains nearly constant over the duration of the model runs. We also compare simulations with spatially variable rainfall with a simulation in which the same total amount of water is distributed uniformly in space and time throughout the model domain.

CASCADE routes the precipitation across the landscape with a bucket-passing algorithm that moves water downhill in the direction