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Invited research article

The Amazon at sea: Onset and stages of the Amazon River from a marine record, with special reference to Neogene plant turnover in the drainage basin

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ABSTRACT

The Amazon submarine fan is a large sediment apron situated offshore Pará (Brazil) and represents the most distal extent of the Amazon River. The age of onset of this transcontinental river remains debated, yet is of great importance for understanding biotic evolutionary processes on land and at sea. Here we present new geochemical and palynological data from a borehole drilled at the continental slope and dated based on nannofossil biostratigraphy. We found that sediments of mixed source (craton and adjacent) occur at least from the late Oligocene (NP25) to late Miocene (NN9), and that the earliest Andes-derived sediments occur in NN10 (late Miocene). Our geochemical record indicates an onset of the transcontinental Amazon River between 9.4 and 9 Ma, which postdates the regional unconformity by 1 to 1.5 My. The shift in sediment geochemistry is more gradually replicated in the palynological record by a change from coastal plain and tropical lowland taxa to a mixture of tropical lowland, and montane forest to open Andean taxa. In particular, the appearance of taxa such as *Jamesonia* and *Huperzia*, followed by *Valeriana*, *Polylepis-Acaena*, *Lysipomia* and *Plantago* (with a current altitudinal range from 3200 to 4000 m) suggests the development of open, treeless, vegetation between 9.5 and 5.4 Ma, and highlight the presence of a high Andes in the late Miocene hinterland. Poaceae progressively increased from 9 Ma, with a notable rise from 4 Ma onwards, and percentages well above post-glacial and modern values, particularly between 2.6 and 0.8 Ma. We hypothesize that the rise of the grasses is a basin-wide phenomenon, but that the Plio-Pleistocene expansion of open, treeless vegetation on the Andean slopes and foothills are the main contributor. This rise in grasses was likely caused by climatic fluctuations, and subsequent changes in relief and erosion rates. We conclude that the onset of the Amazon River is coupled with Neogene Andean tectonism and that subsequent developments, both of river and biota, are closely linked to the Plio-Pleistocene climatic fluctuations. From latest Neogene onwards these major landscape changes determined the composition of the montane and lowland forest in the Andes-Amazonian system.

1. Introduction

The Amazon River accounts for a fifth of the total volume of fresh water input into the global oceans, it has the highest volume of sediment discharge and also accounts for the largest drainage basin (Nittrouer and DeMaster, 1986; Milliman, 2001). In spite of its global importance, the age of onset of the transcontinental Amazon River is still subject of debate. It divides scientists depending on the type of data set (marine- or land-derived) and the analytical methods that are applied (e.g. seismic stratigraphy, geochemistry, sedimentology, phylogeography).

Marine data from the westernmost Atlantic point to a late Miocene age of onset of the Amazon River (Damuth and Kumar, 1975; Milliman, 1979; Hoorn et al., 1995; Dobson et al., 2001; Pasley et al., 2005; Figueiredo et al., 2009, 2010; Gorini et al., 2013). Instead, continental data are taken as indicative for a Plio-Pleistocene age of onset

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(Rossetti et al., 2005, 2015; Campbell et al., 2006; Campbell, 2010; Latrubesse et al., 2010; Ribas et al., 2012; Horbe et al., 2013). Considering the global and regional influence of the Amazon River on continental and marine processes (Davidson and Artaxo, 2004; Subramaniam et al., 2008; Yoon and Zeng, 2010) the age of its onset is thus a matter of the highest interest for the wider scientific community including biologists, geoscientists and paleoceanographers.

To resolve this debate it is important to define the key characteristics of the Amazon River and use these parameters in the research set up. According to the Encyclopedia Britannica (2016) the Amazon has "*its westernmost source high in the Andes Mountains, within 100 miles (160 km) of the Pacific Ocean, and its mouth is in the Atlantic Ocean, on the northeastern coast of Brazil*". This implies that an inherent characteristic of the Amazon River is it's birth in the Andes and it's end in the Atlantic. Extending on the geographical definition, sedimentologists and geochemists describe the characteristic mixed sediment load of the modern Amazon River as of predominantly Andean origin with a significant tropical lowland component (Gibbs, 1967; Meade, 1994; McClain and Naiman, 2008). Taken together, this means that the oldest Amazon River sediments should: a) be found in the westernmost Atlantic and, b) have an Andean geochemical signature. This makes the Amazon submarine fan, a sediment apron formed by Amazon River deposits along the Atlantic Coast (Damuth and Kumar, 1975), the perfect setting to study the evolution of this river.

The Amazon submarine fan deposits were accumulated in the Foz do Amazonas Basin (FAB), a sedimentary basin situated at the Brazilian Equatorial Margin (BEM), where the Cretaceous-Cenozoic sedimentary succession is relatively complete (Fig. 1A and B) (Figueiredo et al., 2007). In this respect, the oceanic record strongly contrasts with the continental basins in Amazonia, where a more fragmented stratigraphy is preserved. Academic drilling programs, such as the Ocean Drilling Program (ODP), have focused on the uppermost Pleistocene section in the distal submarine fan. Yet the pre-Quaternary sedimentary section so far remained out of reach (Flood et al., 1995). Nevertheless, the FAB has been well studied by the industry because of its presumed hydrocarbon potential. Most of this extensive knowledge and data archive is confidential though. Exceptions are published work on evolutionary stages of the Amazon submarine fan (Pasley et al., 2005; Figueiredo et al., 2007, 2009; Gorini et al., 2013).

The recent (partial) disclosure of borehole data of an exploration well, known as Algodoal or BP3, by the Brazilian oil company Petrobras and the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP), presents an exceptional opportunity to investigate the age and evolution of the transcontinental Amazon River. This well (here Well 2) was previously described by Figueiredo et al. (2009) and is situated on the upper slope of the continental shelf at a water depth of 754 m (Fig. 1B). In this section an almost complete Neogene stratigraphy occurs with ages well constraint by nannofossil biostratigraphy (Varol Research, 2004; Figueiredo et al., 2009).

In this study we review the general stratigraphy of the FAB, and combine the results of our geochemical and palynological study from the Neogene section of Well 2 into a new model for the evolution of the Amazon River. In this model we link changes in sediment and pollen source area to an expanding drainage basin, that shifts from a proto-Amazon River in eastern Amazonia to the continent-wide transcontinental Amazon drainage basin as we know it today. We also observe that changes in biotic composition likely occurred in parallel with the Neogene landscape changes.

2. Regional geological framework

On arrival at the western tropical Atlantic Ocean the Amazon River sediments are partially deposited in the subaqueous delta (Nittrouer and DeMaster, 1986; Nittrouer et al., 1986; Nittrouer and DeMaster, 1996), in Portuguese this is called the Foz do Amazonas or 'mouth of the Amazon', and it is also the name of the sedimentary basin that records the marine extent of the Amazon River in the Atlantic Ocean (Fig. 1B). The bulk of the Amazon River sediments, however, are transported towards the Caribbean by the North Brazil Current (Nittrouer and DeMaster, 1996, and references therein). From May to October, a retroflection of this current also moves a fraction of the sediments towards Africa via the North Equatorial Counter Current

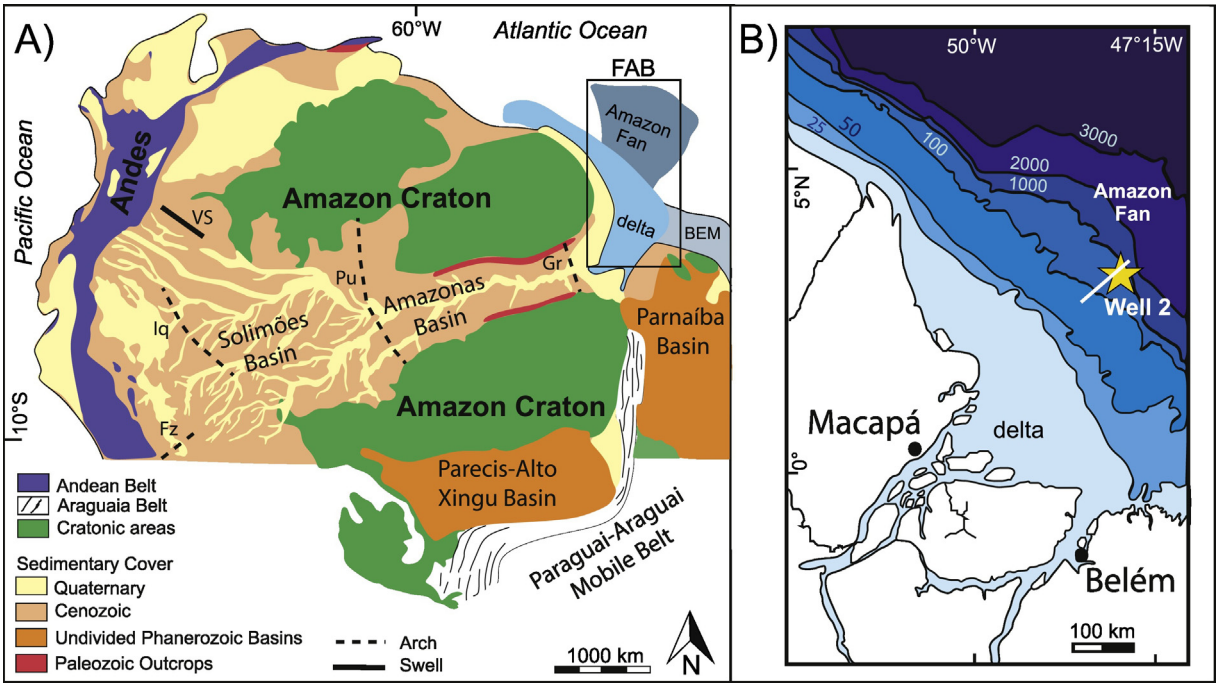

Fig. 1. A) Overview map of northern South America with the location of the Amazon drainage basin, and the geological units that formed the provenance area for the sediment input into the Amazon River through it different stages. The Amazon subaqueous delta and submarine fan are in the inset. The following structures are abbreviated, Archs: Fitzcarrald (Fz), Iquitos (Iq), Purus (Pu) and Gurupá (Gr); and Swell: Vaupes (VS). 1B) The location of Well 2 and the seismic section in the Foz do Amazonas Basin; the contours of water depth are indicated in meters.

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