Late Miocene onset of the Amazon River and the Amazon deep-sea fan: Evidence from the Foz do Amazonas Basin

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ABSTRACT

New biostratigraphic, isotopic, and well log data from exploration wells on the outer continental shelf and uppermost Amazon deep-sea fan, Brazil, reveal that the Amazon River was initiated as a transcontinental river between 11.8 and 11.3 Ma ago (middle to late Miocene), and reached its present shape and size during the late Pliocene. Prior to the late Miocene the continental shelf was a carbonate platform that received moderate siliciclastic sediment supply from the Proterozoic basement in eastern Amazonia. Average sedimentation rates on the Amazon Fan show three stages of development: (1) 11.8–6.8 Ma ago, low sedimentation rates (0.05 m/ka) prevailed on the fan, because the Amazon River was not yet entrenched and some sediments were partially trapped in continental basins; (2) 6.8–2.4 Ma ago, sedimentation rates (0.3 m/ka) increased, the river entrenched, and deposition fully migrated onto the Amazon Fan; (3) 2.4 Ma ago to the present, very high sedimentation rates (1.22 m/ka, with peaks of 11 m/ka) prevailed on the fan and the modern Amazon River developed. All these paleo-geographic and depositional events are closely related to Andean tectonism (late Miocene–Pliocene) and were exacerbated by global cooling and sea-level fall during the late Miocene.

INTRODUCTION

The Amazon Fan is composed primarily of Andean-derived sediments that were delivered to the Atlantic Ocean by the Amazon River (Milliman, 1979; Damuth et al., 1988). Although age and source area of the uppermost Pleistocene succession are known (Flood et al., 1995; McDaniel et al., 1997; Mikkelsen et al., 1997), the ages and sediment provenances for the pre-Quaternary fan section have remained uncertain. The only precise age indication for the onset of both the Amazon River and its submarine fan came from the Ceará Rise in the deep sea (Dobson et al., 2001).

In the past two decades numerous exploration wells were drilled on the shelf of the Foz do Amazonas Basin (for location map see Appendix 6 in the GSA Data Repository1), but none provided a complete insight into the Neogene fan section due to the poor temporal continuity of the geological record (Pasley et al., 2005). However, in recent years Amazon Fan oil exploration extended into deep water, and wells on the uppermost fan (Upper fan of Damuth et al., 1988) provided an unprecedented insight into the entire fan succession. These new data permit an accurate reconstruction of the interlinked history of both the Amazon River and Amazon Fan.

In this paper we present new biostratigraphic, sediment provenance, and well log data from two wells; one is located on the basin shelf (well 1), and the other is on the uppermost fan (well 2) (Appendix 6). The integrated data from these wells reveal a precise date when the first Andean sediments reached the Foz do Amazonas Basin and identify the onset of the transcontinental Amazon River. In addition, sedimentation-rate analysis of the fan identifies three stages of development. The interpretation of this data set reveals the intimate relationship between Andean tectonics and late Miocene climatic change, which together were definitive for the paleogeography of northern South America.

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METHODS AND RESULTS

Biostratigraphy

Nannofossil marker species were retrieved from ditch cutting samples of two wells in Foz do Amazonas Basin (Fig. 1). These species ranged in age from early Miocene (biozone NN4b; late Burdigalian) to Pleistocene (biozone NN19a) and formed the basis for a confident biostratigraphic framework that enabled us not only to date the sediments, but also to calculate the sedimentation rates within the fan (Fig. 1; Appendices 1, 2, and 3). Well 1 (shelf) comprises carbonate and siliciclastic sediments of early Miocene to Pliocene age. This well was crucial for the provenance reconstructions as it recorded in detail the middle to late Miocene transition from carbonate deposition to siliciclastic deposition (Fig. 1). Well 2 (uppermost fan) includes an almost continuous record of the Amazon Fan from biozones NN9 to NN19, except for subdivisions e, f, g, and h of biozone NN19 (Fig. 1).

Provenance

The proportion of samarium-neodymium (Sm-Nd) and lead-lead (Pb-Pb) in rocks is applied in sedimentary studies to establish the age of the sediment source area. Following McDaniel et al. (1997), the Neogene section in well 1 was analyzed to distinguish sediments derived from the old cratonic source from the younger sediments of Andean origin (Fig. 1; Appendices 4 and 5). The Andean source is defined by an age younger than 1.6 Ga; the cratonic source, however, is defined by sediments older than 1.6 Ga (e.g., Basu et al., 1990; McDaniel et al., 1997). Isotope results from well 1 showed three groups of sediment ages (Fig. 1 and Appendix 5) that correlate with data from...
McDaniel et al. (1997) and geochronological provinces in the Amazon craton (Tassinari and Macambira, 1999) (Fig. 2). Samples of early Miocene and early Pliocene age (depleted mantle modal, \( T_{DM} \) age 1.946–2.113 Ga old) correlate with the Maroni-Itacaiúnas province (1.95–2.2 Ga old, middle Paleoproterozoic), which is the nearest Precambrian terrain to the Foz do Amazonas Basin. Samples of the middle Miocene (\( T_{DM} \) age 1.641–1.689 Ga old) correlate with the Rio Negro–Juruaena province (1.8–1.55 Ga old, late Paleoproterozoic) situated in western Amazonia. Samples of late Miocene age (\( T_{DM} < 1.6 \) Ga old) presented the same signature as those analyzed and interpreted by McDaniel et al. (1997) as Andean sourced. Hence, the late Miocene section in well 1 was interpreted as Andean sourced and the underlying middle and early Miocene succession was interpreted as cratonic sourced.

Well Logs
In well 1 (Fig. 1) there is a marked unconformity at a depth of 2115 m below sea level (bsl) that, according to biostratigraphic and isotopic data, separates the middle (pre-Amazon Fan) and late Miocene (Amazon Fan) successions with a hiatus of ~0.7 Ma (absence of NN8 and NN9). In well 2 (Fig. 1) the transition from middle to late Miocene occurs at 4140 mbsl. At this level well logs shift, the lithology changes, and biozone NN8 is missing. Both well 1 and 2 thus present erosional surfaces at the middle to upper Miocene contact, albeit in a different sedimentary succession. Well 1 (shelf) shows carbonates underlying the erosional surface; conversely, in well 2 (upper fan) carbonates appear overlying the erosional surface. The presence of carbonates underlying an erosional surface in a shallow water environment and overlying another coeval erosional surface in deep water suggests that the latter are allochthonous reworked deposits from the former. The erosional surfaces in both wells are therefore interpreted as a sequence boundary that separates the middle and late Miocene sections. Moreover, biostratigraphic data show that the oldest non-reworked sediments overlying the sequence boundary in well 2 are contemporaneous with biozone NN9 (11.8–11.3 Ma ago). Sequence stratigraphic analyses suggest that these sediments are genetically related to the Andean sediments present above the sequence boundary in well 1. In spite of the lack of isotopic data in well 2, sequence stratigraphic interpretation allows us to conclude that the sediments overlying the sequence boundary in well 2 are also Andean sourced. Considering that these sediments are contemporaneous with biozone NN9, it is possible to say that the initiation of the Amazon Fan, and consequently the onset of the transcontinental Amazon River, occurred during the time span of biozone NN9, i.e., between 11.8 Ma and 11.3 Ma ago.

DISCUSSION AND CONCLUSIONS
The drainage history and buildup of the siliciclastic Neogene coastal systems in the Foz do Amazonas Basin, Brazil, are controlled by periods of the geological evolution of the Amazon craton, the Andes, global sea level, and climatic change (e.g., Damuth and Fairbridge, 1970; Milliman, 1979; Dobson et al., 2001; Harris and Mix, 2002). Our new data from the Foz do Amazonas Basin date the transition from
Pre-Fan Period—Early to Middle Miocene

Early Miocene eastern Amazonia was dissected by a fluvial system, the ancestral Amazon River, that transported relatively modest volumes of clastic sediments to the continental margin. This system, mainly sourced by the Maroni-Itacaiúnas province (Fig. 2A), intermittently interrupted carbonate development in the Foz do Amazonas Basin. The geological setting of eastern Amazonia further suggests that this fluvial system followed the west-east direction on the preexisting Amazonas Paleozoic basin, and its mouth was near the present Amazon River’s mouth. Later, during the middle Miocene, this fluvial system migrated westward, sourced mainly by the Rio Negro–Juruena province (Fig. 2A). Meanwhile, in western Amazonia a large wetland system of shallow lakes and swamps existed, which received Andean sediment input and minor sediment fluxes from the craton (Hoorn, 1994; Hoorn et al., 1995; Wesselingh, 2006). The stratigraphic records of the Solimões (western Amazonia) (Eiras et al., 1994) and Amazonas Basins (central-eastern Amazonia) (Cunha et al., 1994) suggest that during the middle Miocene the fluvial system (east) and the wetland (west) were separated by the Purus arch.

Fan Period—Late Miocene to Present

Sediments of Andean origin (i.e., T$_{2na}$ < 1.6 Ga old) for the first time reached the Foz do Amazonas Basin between 11.8 and 11.3 Ma. The sediment accumulation rates in the Foz do Amazonas Basin are indicative of the development of both the Amazon River and Amazon Fan and can be divided into three phases.

1) Onset phase (11.8–6.8 Ma ago). By the end of the middle Miocene, the combination of accelerated Andean uplift (e.g., Garzione et al., 2008), climatic variability (Miller et al., 1987; Uba et al., 2007), and global sea-level fall (Haq et al., 1988) resulted in adjustment of the equilibrium profile of the paleo–Amazon River. As a consequence a connection was established between the river and the western Amazonian wetland through breaching of the continental divider, the Purus arch. This event is registered in the Foz do Amazonas Basin as a regional unconformity, a sequence boundary that marks the onset of the Amazon River and fan system and can be divided into three phases.

2) Middle phase (6.8–2.4 Ma ago). The start of this phase coincides with a rise in global sea level (Haq et al., 1988). At the same time sedimentation rates on the fan increased to 0.3 m/ka (mean value), a sixfold increase in the
rate of deposition of the previous phase (Fig. 1). Between 7.9 and 6.0 Ma ago, Andean erosion was of such intensity (Uba et al., 2007) that sediment discharge to the continental margin greatly increased despite global sea-level rise. This phase coincides with the demise of the western Amazonian megawetland; deposition in the continental basins virtually ceased, and most sediments were deposited on the Amazon Fan. An increase in deposition on the Ceará Rise during this time is also identified (Dobson et al., 2001). These facts indicate that from 6.8 Ma ago onward, the Amazon River has been a large entrenched river with main sediment input from the Andes and additional supply from the craton.

(3) Late phase (2.4 Ma ago to present)
A fourfold increase in sedimentation rates occurred on the fan; the mean value was 1.22 m/ka and there was a peak of 11.16 m/ka (bionozo NN19c, well 2; Fig. 1). The Amazon River acquired its present shape as a result of increased incision followed by aggradation during glacial and interglacial periods, respectively. During the early Pliocene (ca. 4.2 Ma ago), Andean sedimentation on the fan was overprinted by a sediment pulse of middle Paleoproterozoic source that coincided with an increase in sedimentation rates. A similar phenomenon was observed 5 Ma ago on the Ceará Rise (Dobson et al., 2001). This renewed importance of the middle Paleoproterozoic Maroni-Icacuãnas province indicates a possible uplift of a peripheral bulge due to basin subsidence in response to the increased sedimentary load.

In summary, the Neogene sedimentary sequence of the Foz do Amazonas Basin illustrates well the direct relation of tectonic evolution in the Andes, global sea-level changes with the onset of the modern Amazon River, and deposition of the Amazon deep-sea fan system. The eastern west-east-oriented early and middle Miocene fluvial system progressively migrated westward while the western wetland expanded eastward. Between 11.8 and 11.3 Ma ago this process led to the connection of these two systems, culminating with the birth of the transcontinental Amazon River and the development of the Amazon submarine fan.

ACKNOWLEDGMENTS
We gratefully acknowledge Petrobras E&P—Exploration and its Executive Manager Paulo de Tarso Guimarães for allowing us to publish proprietary data in this paper. We thank Steve S. Flint (University of Liverpool) for his advice during the preparation of the manuscript, and John Damuth, Sarah Harris, David Rea, and an anonymous reviewer for their constructive reviews. We also warmly thank the draftspersons Leila Pezzin, Aline Lima, and Rosalia Amaral (Petrobras, Rio de Janeiro, Brazil) and Jan van Arkel (University of Amsterdam, The Netherlands).

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Printed in USA