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 paleogeographic 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 Repository[1]), 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.

GEOLOGICAL SETTING

The Cenozoic sedimentary history of the Brazilian equatorial offshore basins was dominated by carbonates, except for the Foz do Amazonas Basin, where carbonate production was periodically disrupted by siliciclastic deposition (Wolff and Carozzi, 1984). However, only since the late Miocene has the delivery of siliciclastic sediments to the Atlantic shelf and deep sea been volumetrically high enough to shut down carbonate production, and deposit the thick wedge of sediments that form the Amazon Fan (Brandão and Feijó, 1994). The Amazon Fan covers an area of ~330,000 km^2 and its sedimentary column extends more than 9 km beneath the uppermost part of the fan (Damuth and Flood, 1984; Castro et al., 1978). The bulk of the sediment supply delivered by the Amazon River was deposited on the fan and adjacent abyssal plains during glacially induced sea-level lowstands. However, during interglacial highstands, such as the Holocene, the Amazon River sediments were trapped on the continental shelf, and the fan was dormant (e.g., Milliman, 1979; Damuth and Flood, 1984; Damuth et al., 1988).

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

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[1]GSA Data Repository item 2009145, Appendices 1–6 (biostratigraphic data, figures, and map), is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

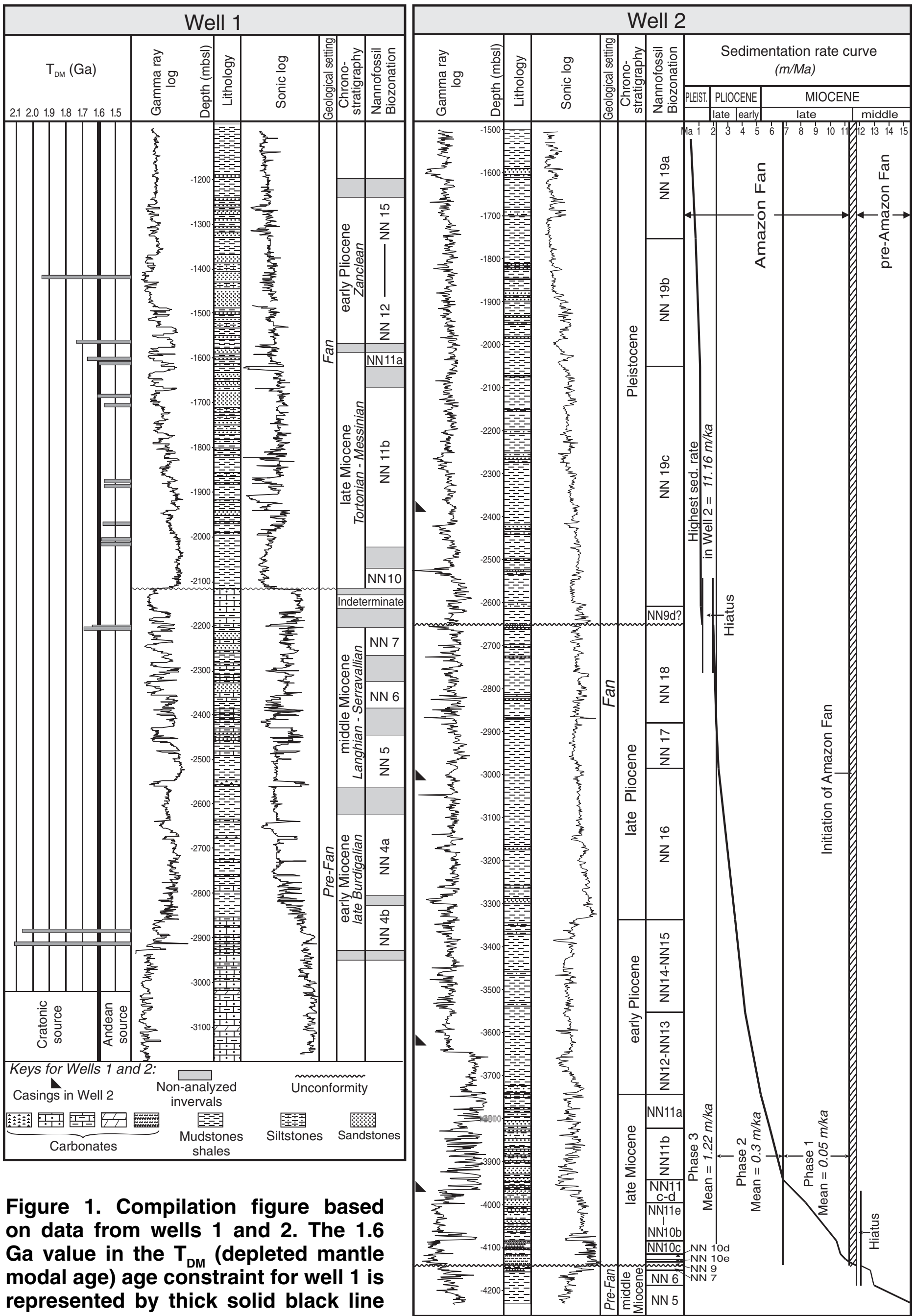

Figure 1. Compilation figure based on data from wells 1 and 2. The 1.6 Ga value in the T_{DM} (depleted mantle modal age) age constraint for well 1 is represented by thick solid black line that separates cratonic and Andean sources (following McDaniel et al., 1997). Chronostratigraphic data are referenced to Gradstein et al. (2004); details about biostratigraphic zonation are in Appendices 1, 2, and 3 (see footnote 1). Sedimentation rate (SR) curve was made using biostratigraphic data from well 2 (thickness in meters of each biozone against its span time in Ma). Two inflection points separate three segments of different SRs at the boundaries of biozones NN11c-d/NN11b (ca. 6.8 Ma ago) and N17-NN18 (ca. 2.4 Ma ago). Highest SRs in well 2 (11.16 m/ka) are during biozone NN19c. Note that shift in gamma ray logs at 3650 m below sea level (well 2) does not represent lithological boundary, but was related to operational change. PLEIST—Pleistocene; mbsl—meters below sea level.

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–Juruena 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

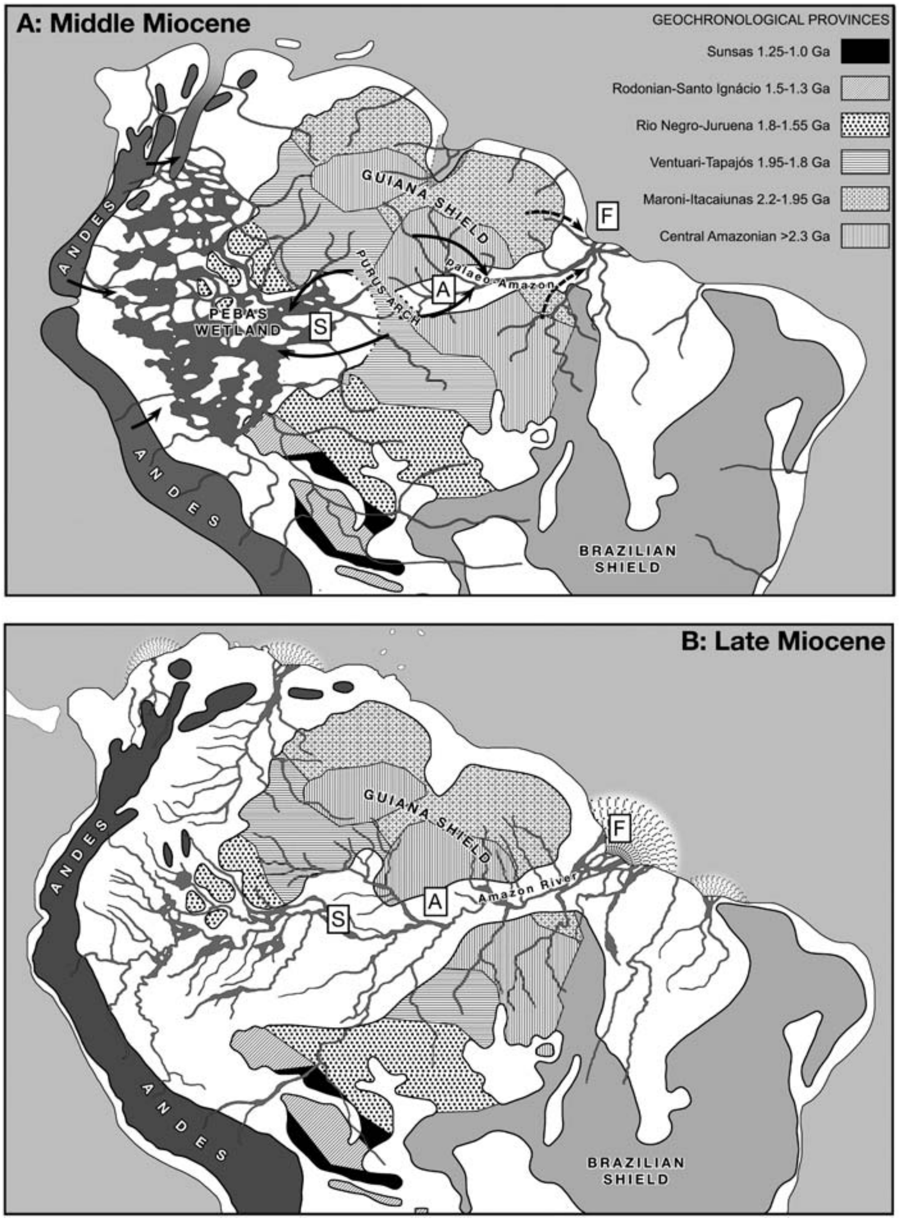

Figure 2. Paleogeographic maps of Amazonia and Atlantic coast, northern South America. During the early Miocene the primary source of sediments was the Maroni-Itacaiúnas province (dashed arrows); however, a range of younger sedimentary deposits (mainly Phanerozoic—white areas) present in eastern Amazonia (Brito Neves, 2002) suggests a long history of reworking for most of middle Paleoproterozoic-aged sediments deposited on continental margin during early Miocene. A: Middle Miocene. Primary source shifted to center of Amazon region (Rio Negro–Juruena province). Although the paleo–Amazon River did not yet extend beyond Purus arch, it is ascribed to multiple reworking since the Mesoproterozoic (Brito Neves, 2002) due to the presence of late Paleoproterozic sediments in Phanerozoic strata dissected by the fluvial system during middle Miocene. B: Late Miocene. West Amazonian wetland and paleo–Amazon River (in eastern Amazonia) connected to form transcontinental river, the modern Amazon River. Merger of these two networks was caused by increased Andean uplift and global sea-level fall. From late Miocene onward, the Andes constituted main source of sediment supply into Amazon Fan. F—Foz do Amazonas Basin, A—Amazonas Paleozoic basin, S—Solimões Paleozoic basin.

a cratonic-derived sediment regime (pre-fan period, early to middle Miocene) to one dominated by Andean-derived sedimentation (fan period, late Miocene to present) that resulted in the onset of the transcontinental Amazon River and buildup of the Amazon Fan.

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., $T_{DM} < 1.6$ 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 Fan and the transcontinental Amazon River. The initial river was not entrenched and deposition partially occurred in continental basins (Hovikoski et al., 2007). Sedimentation rates were low (mean value of ~0.05 m/ka) and the presence of a mixed assemblage of siliciclastics and allochthonous carbonates in a deep-water environment suggests that the sediment yield of the river was even weaker than sedimentation rates indicate (Fig. 1). On a regional level the onset of the Amazon River and fan system is also registered in the terrigenous sediments of the Ceará Rise (Dobson et al., 2001).

(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 (biozone 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-Itacaiúnas 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–orientated 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.

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