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Provenance of quaternary and modern alluvial deposits of the Amazonian floodplain (Brazil) inferred from major and trace elements and Pb–Nd–Sr isotopes

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ABSTRACT

Chemical and Pb, Nd and Sr isotope data from floodplain sedimentary deposits in the Solimões River, northwest Brazil, constrain the variability of the deposits through the Quaternary and help reconstruct the paleogeography of Amazonia since the uplift of the Andes. Compared to the modern alluvial deposits in the active channel, the Quaternary terrace deposits in the Solimões River have a higher chemical index of alteration (CIA), higher SiO_2/Al_2O_3 ratios, higher concentrations of immobile elements, higher radiogenic Sr isotopic compositions, more negative $\varepsilon_{Nd(t\,=\,0)}$ values, and older Nd T_{DM} ages. These geochemical characteristics indicate that the Quaternary sediment sources were composed by more felsic and/or recycled old continental crust derived rock materials than the younger source areas, which contributed major arc volcanic materials to the flood plain deposits. This shift in the composition of the sediment source areas indicates that a significant reorganization of the architecture of the Solimões River has occurred since the uplift of the Andes.

1. Introduction

"Large rivers" are the main arteries that deliver water and sediment from the continent to the oceans (Miall, 2006). Assessing the sediment budgets of "large rivers" is essential for reconstructing sediment redistributions, rearrangement of drainages due to tectonic or climatic changes, global geochemical cycles, and sediment fluxes into the oceans as well as weathering rates and burial of organic carbon in floodplains (Meybeck, 1993; Gaillardet et al., 1999a,b; Galy et al., 2007; Ashworth and Lewin, 2012). Moreover, constraining the processes that control the geochemistry of floodplain deposits is of particular importance for chemical weathering studies (e.g., Singh and Rajamani, 2001) because "large rivers" flow through areas that are subject to continuous deposition and erosion of sediments (Allison et al., 1998; Maurice-Bourgoin et al., 2007). Provenance studies (Singh and Rajamani, 2001; Tripathi et al., 2007) are also central to understanding river dynamics because floodplains are the primary storage sites for river sediments during floods.

The western portion of the Amazonas River, which is called the Solimões River in Brazil, has its headwaters in the Colombian, Ecuadorian and Peruvian Andean Cordillera. This drainage forms the largest river system in terms of mass transfer from the continents to the oceans. The system supplies ~20% of the surface fresh water (Callède et al., 2004), ~10% of the dissolved load (Gaillardet et al., 2007), and ~3% of the suspended load (Milliman and Syvitski, 1992) to the world's oceans. More than 95% of the mean annual suspended sediment flux delivered to the ocean is related to two tributaries of the Amazon that drain the Andes Cordillera (Filizola and Guyot, 2009): the Solimões, which accounts for 2/3 of the flux, and the Madeira, which accounts for 1/3 of the flux. The total contribution of the other large tributaries that have headwaters in the Amazon craton, such as the Negro, Trombetas, Tapajos and Xingu Rivers, accounts for less than 5% of the total sediment flux.

Previous studies have suggested that the Solimões–Amazonas River became transcontinental between 11.8 and 11.3 Ma after the first arrival of Andean sediments in the Amazonas fan (Figueiredo et al., 2009). Between the Late Miocene and the present, the Amazonas drainage network has been subject to several changes that were controlled by tectonic processes, such as flexural and dynamic uplift, subsidence and ridge subduction (Espurt et al., 2010; Shephard et al., 2010). In particular, the uplift of the Iquitos forebulge (Roddaz et al., 2005, 2006), the Fitzcarrald Arch (Espurt et al., 2007) and the Purus Arch (Caputo, 1991) shaped the Pliocene Amazonian drainage network. In addition, neotectonic reactivations occurred during the Quaternary along the

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Solimões, Negro and Amazonas Rivers (Franzinelli and Igreja, 2002; Latrubesse and Franzinelli, 2002; Almeida-Filho and Miranda, 2007) and were responsible for the modern drainage pattern. These and other recent studies of Neogene sediments from the Ecuador (Roddaz et al., 2012) and Amazonian (Horbe et al., 2013) Basins, together with the fourfold increase of sedimentation rates in the Amazonas fan after 2.4 Ma (Figueiredo et al., 2009), also indicate that important and complex changes in the Amazonian drainage network occurred during the Quaternary. However, little is known about the source and the effects of sorting and weathering that may control the geochemical composition of the Amazonian floodplain sediments and their variability over time as a result of tectonic activity. Previous studies have examined the source of sediments to reconstruct the geological history of the transcontinental Solimões–Amazonas Basin. These studies focused on the sediments of the Amazonas fan (McDaniel et al., 1997; Figueiredo et al., 2009), the sediments of the Amazonian foreland basin at the head of the Solimões–Amazonas Basin in Ecuador, Peru, Bolivia and Brazil (Basu et al., 1990; Roddaz et al., 2005, 2012; Horbe et al., 2013), and the sediments that are transported through the modern active channel river (Allègre et al., 1996; Gaillardet et al., 1997; Mapes, 2006; Viers et al., 2008; Santos et al., 2014). In addition to tectonics, the source and the quantity of sediments were also controlled by several episodes of wet to dry climatic changes that have affected the Amazon region (e.g., Van der Hammen and Hooghiemstra, 2000; Sifeddine et al., 2001).

Sedimentary source areas with different crustal histories and distinct ages, lithologies, and chemical compositions are usually suitable for identifying changes in the primary source of sediments. However, geochemical changes during sedimentary transport or after deposition may make the interpretation of provenance complex (Nie et al., 2012). In these cases, an integrated geochemical approach involving major and trace elements as well as isotopes is usually helpful. For instance, cratonic rocks have lower Nd isotopic ratios, more negative $\varepsilon_{Nd(t=0)}$ values, and higher $^{86}Sr/^{87}Sr$, $^{206}Pb/^{204}Pb$, SiO_2/Al_2O_3, CIA, Th/Sc, Th/U, La/Yb, and Eu/Eu* ratios than juvenile crustal sources (e.g., DePaolo, 1988; Asmeron and Jacobsen, 1993; McLennan et al., 1993; Allègre et al., 1996). Based on these characteristics, we used major and trace elements and the Pb, Sr, and Nd isotopes of the sediments of the Solimões River Basin to: i) determine the influence of the temporal variability of the chemistry and source of the sediments; ii) provide new records of the most recent reorganization of the architecture of the transcontinental Solimões–Amazonas River; and iii) identify the effect of climate on the geochemistry of the sediments. These points were addressed by investigating eight sites along 450 km of the Solimões River between the towns of Coari and Manaus, where Quaternary terraces and modern deposits from the active channel are present along the riverside cliffs (Fig. 1).

2. Geological background and potential source

The Solimões River has extensive fluvial plains that are tens of kilometers long and overlie the Miocene Solimões Formation and the Plio-Pleistocene Içá Formation (Fig. 1). The fluvial plain is divided into the Quaternary terrace, which is not flooded during the rainy season, and the active channel flood plain (Latrubesse and Franzinelli, 2002). Based on ^{14}C geochronology of organic matter, Rossetti et al. (2005) estimated a maximum age of 43,000 ^{14}C yr B.P. for the Quaternary terrace deposits along the Solimões River. The main minerals in these deposits are quartz and kaolinite, and the minor constituents are smectite, illite, muscovite, chlorite, and goethite (Behling et al., 2001; Horbe et al., 2011). The transparent mineral grains indicate that the Mio-Pleistocene units contain more zircon, tourmaline, rutile, kyanite, sillimanite and andalusite, while the Quaternary sediments contain more epidote, amphibole and pyroxene (Landin et al., 1983; Rossetti et al., 2005; Horbe et al., 2013). The U–Pb ages of detrital zircons from these sediments indicate that the western portion of the Mesoproterozoic Amazonian craton and the basement of the Andes Cordillera were the primary sediment source areas of these Quaternary deposits (Mapes, 2006; Horbe et al., 2013).

Modeling the sediment source regions is hindered by the limited geochemical and whole-rock isotope data that are available. Existing geochemical data include Pb isotope data of the Peruvian Precambrian complexes and Cretaceous sedimentary rocks (Gunnesch et al., 1990; Kontak et al., 1990; McFarlane and Petersen, 1990) and Sr and Nd isotope data of Andean volcanic rocks from southwestern Ecuador and northern Chile (Rogers and Hawkesworth, 1989; Redwood and Rice, 1997; Barragan et al., 1998; Bosch et al., 2002), the western portion of the Amazon Craton (Santos et al., 2000; Geraldes et al., 2001; Teixeira et al., 2002; Ruiz et al., 2004), Ordovician igneous and metamorphic units from northwestern Argentina (Viramonte et al., 2007) and Grenville-age rocks from the Colombian Andes (Restrepo-Pace et al., 1997). Sr and Nd isotope data of Cenozoic sediments of the Bolivian, Peruvian and Ecuadorian foreland basins (Basu et al., 1990; Pinto,

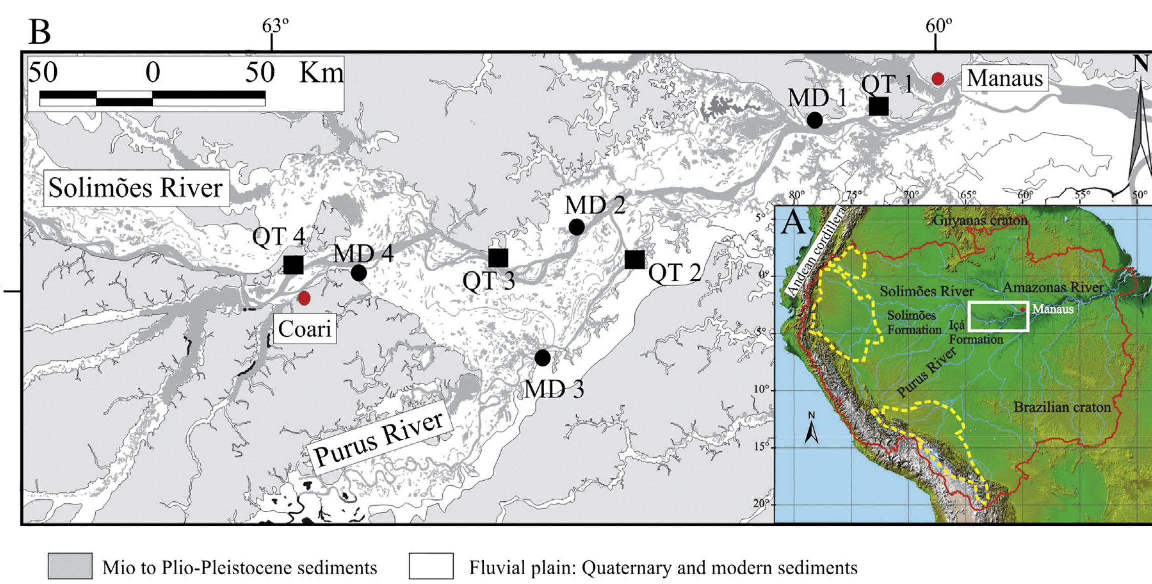

Fig. 1. A — Geographic and lithologic maps of western Amazonia after Roddaz et al. (2005, 2006); B — sampling locations. The square and the numbers 1 to 4 are the samples of the Quaternary terraces (QT), and the spot and numbers 1 to 4 are the samples of the modern alluvial deposits (MD). The limits of the Solimões–Amazonas Basin are shown in red, and the Bolivian, Peruvian and Ecuadorian foreland basins are shown in yellow. The Brazilian craton and the Guyanas craton are named in the text Amazon craton. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)