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Application of SRTM images and sedimentology to characterize Neogene and Quaternary deposits of the Brazilian Amazon

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Abstract Radar image interpretation, combined with sedimentological studies and radiocarbon dating, allowed the mapping of Plio-Pleistocene to Holocene units along the Solimões-Amazonas River, Brazil. This integrated work led to the characterization of five sedimentary successions overlying Miocene deposits of the Solimões/Pebas Formation, which include: Içá Formation (Plio-Pleistocene), Deposits Q1 (37,400-43,700 ^{14}C yr B.P.), Deposits Q2 (27,200 ^{14}C yr B.P.), Deposits Q3 (6,730-2,480 ^{14}C yr B.P.), and Deposits Q4 (280-130 ^{14}C yr B.P.). These deposits are distributed mostly to the west of Manaus, forming NW-SE elongated belts that are progressively younger from SW to NE, indicating a subsiding basin with a depocenter that migrated through time to the NE. The reconstruction of the depositional history is consistent with significant changes in the landscapes. The data presented herein support that, rather than being a monotonous area, the Amazonia was a place with frequent changes in landscape throughout the Neogene, probably as a result of climatic and tectonic factors.

Key-words: radar image, Amazonia; Pleistocene, sedimentology, radiocarbon dating, landscape evolution.

1. Introduction

Resolving the problem with lack of geological data in the Amazonia is a long-term commitment, but basic mapping and adequate characterization of the geological units are crucial to motivate this process. In the particular case of the Western Brazilian Amazonia, there is a huge bias because the available geological maps oversimplifies the post-Miocene history with the inclusion of many sedimentary units (equivalent to 1,000,000 km^2) in the Içá Formation of Plio-Pleistocene age, with few areas of Holocene fluvial terraces.

To fill this gap, we mapped and characterized the sedimentary units overlying the Miocene deposits of the Solimões and Barreiras formations with basis of an integrated study combining analysis of radar images, field and laboratory sedimentologic data, and C^{14} dating. The area emphasized in this work includes a 300-m-wide belt on both sides of the Amazonas-Solimões River that extends from the vicinity of Tabatinga, near the Colombia border, to Gurupá, in the State of Pará (**Fig. 1**). The results of this approach provide new elements for the reconstruction of the Amazon geological history.

2. Methods

The morphological and topographic characterization of the sedimentary units mapped in the study area was based on the analysis of SRTM-1 and SRTM-3 radar images provided by NASA (*National Aeronautics and Space Administration*), NIMA (*National Imagery and Mapping Agency*), DLR (*German Space Agency*) and ASIA (*Italian Space Agency*). These images are available for free access through the site: http://www2.jpl.nasa.gov/srtm/. The software Global Mapper was used to process the images and access digital elevation data. The spatial data were combined with fieldwork including facies and stratigraphic descriptions of exposures along riverbanks in order to better characterize the sedimentary units. For age control, a total of 20 samples were also dated at the Beta Analytic Radiocarbon Dating Laboratory, using accelerator mass spectrometer (AMS) for small size samples. The samples were pre-treated with acid to remove carbonates and weaken organic bonds, washed with alkali to remove secondary organic acids, and then combined with acid again to provide more accurate dating. Conventional ^{14}C ages were calibrated to calendar years using the Pretoria Calibration Procedure program, based on tree-ring data as calibration curves (Talma and Vogel, 1993).

3. Characterization of the depositional units

The Brazilian Amazonia to the east of Manaus is mostly floored by Cretaceous rocks of the Alter do Chão Formation, which forms a W-E oriented belt overlying Paleozoic rocks of the Amazon Basin, and a variety of igneous and metamorphic Precambrian rocks of the Guianas and Central Brazilian Shields (**Fig. 1**). After the late Cretaceous, this area showed scarce deposition, represented by spotty occurrences of fluvial Miocene deposits known as the Barreiras Formation (Albuquerque, 1922; Oliveira and Leonardos, 1943), as well as a few un-named late Pleistocene-Holocene alluvial deposits formed along riverbanks. In contrast, the area located to the west of Manaus remained as a depositional site throughout the late Cenozoic, as revealed by a variety of sedimentary units that overlies the lacustrine to transitional marine Miocene Solimões/Pebas Formation. Our mapping (**Fig. 1**) shows that the post-Miocene deposits, represented by the Içá Formation, are much more restricted than previously thought (p.e., Maia *et al.*, 1977), with an exposure of only 300,000 km^2. In contrast, 700,000 km^2 of Pleistocene-Holocene deposits are exposed. These are referred to herein as Deposit Q1 (base) to Deposits Q4 (top).

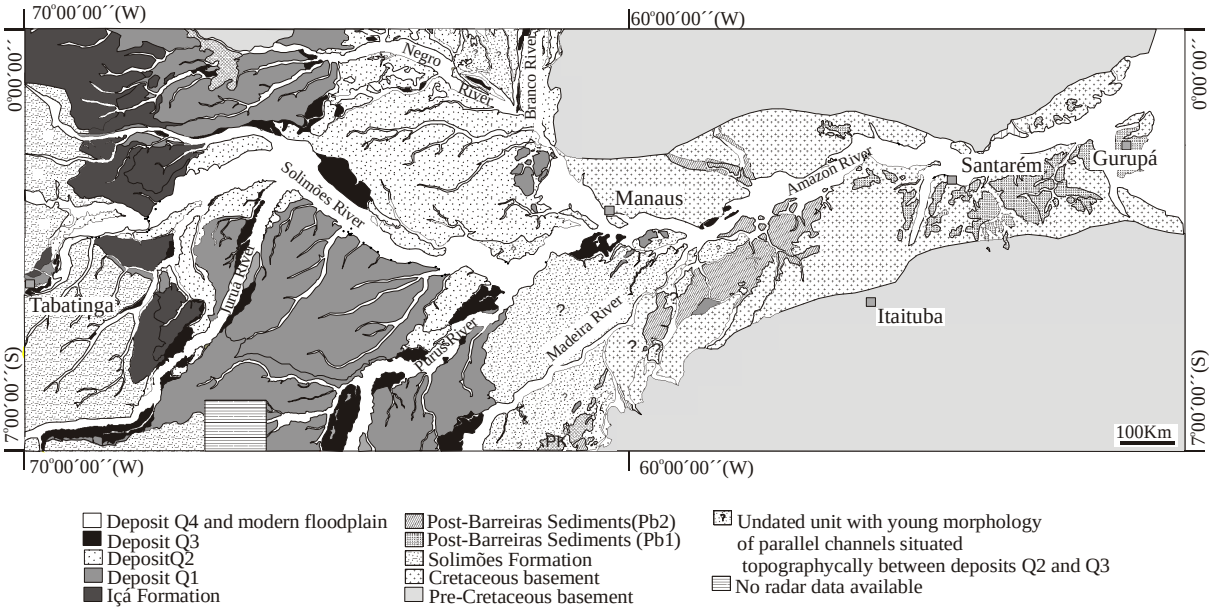

Fig. 1: New geological map for the Western and Central Amazonia along the Solimões-Amazonas River. Discrimination among Plio-Pleistocene to Holocene sedimentary units was possible with basis on the integration of radar images, sedimentological data and radiocarbon dating.

Içá Formation: This unit lies unconformably on early to middle Miocene Solimões Formation (Maia *et al*., 1977; Latrubesse *et al.*, 1994), cropping out in a N/NW-SE elongated belt in the west of the study area. It is characterized on the radar by a land surface displaying smooth hills and dense dendritic to sub-dendritic drainage patterns located at altitudes between 100-140 m. Exposures of this unit along riverbanks are up to 25 m thick, but total thickness may be as much as 80 m (Maia *et al*., 1977). In the field, the Içá Formation is characterized by afossiliferous, white to light reddish feldspathic, fine- to coarse-grained, poorly cross-bedded sandstones and sub-arkoses, and secondarily argillites. The deposits are arranged into fining/thinning upward successions with planar erosional surfaces mantled by intraformational conglomerates. Given the absence of fossils, this unit could not be dated, but its position overlying an Upper Miocene unconformity and underlying deposits dated to the late Pleistocene provides an estimated Plio-Pleistocene age for this unit.

Post-Barreiras Sediments: These deposits occur at two topographic levels, each with distinctive morphological and topographic characteristics. One stands at ca. 200 m above the modern sea level, and is located between the Xingu e Tapajós rivers and on the left margin of the latter, and along the right margin of the Madeiras River, close to the confluence with the Amazonas River; these deposits are cut by deeply incised, V-shaped rivers arranged into a trellised pattern. The other deposits occur at altitudes between 45 and 60 m located near the town of Óbidos, being characterized by a dense drainage with dendritic and, less commonly, sub-parallel channel patterns. At the outcrop scale, two corresponding sedimentary successions were also recognized: a lower one (Post-Barreiras 1), consisting of light red, fine- to coarse-grained, massive sands; and an upper one (Post-Barreiras 2), represented by typically yellow and dominantly fine-grained sands. The base of these deposits is an

unconformity with erosional relief of up to 6 m at the outcrop scale, which is mantled by a lag of reworked laterite concretions, as well as quartz and ferruginous sandstone pebbles.

Deposits Q1: These deposits are only 10 m thick at the outcrop scale, occurring along a wide belt paralleling the Içá Formation, as well as in a few isolated areas southeast of Manaus and on the right margin of Negro River. Between 85-100 m above the present sea level, this succession forms a plateau that is distinguished from the Içá Formation in the radar images by the planar morphology with less dense drainage arranged dominantly into a trelised to rectangular pattern. Q1 Deposits consist of yellowish-white, fine- to medium-grained, moderately sorted and mostly angular sands. These deposits occur as lobes averaging 1.5 m thick and 15-20 m long. The sand lobes are either amalgamated or separated by thin mud layers, and internally display medium-sized (thickness averaging 0.4 cm) tabular and cross stratification, and abundant climbing-ripple cross lamination. The strata are organized into coarsening/thickening upward successions; locally, there are fining upward deposits bounded at the base by erosive surfaces and a lag of mud intraclasts. Organic plant debris preserved in the mud layers provided ages between 37,400 and 43,700 ^{14}C yr B.P.

Deposits Q2: These deposits are volumetrically best represented in a large area (i.e., nearly 12,000 km^2) between the Solimões and Negro rivers, with minor occurrences forming narrow belts along the Solimões River near Colombia and in the confluences of the Içá, Jutaí, Japurá and Juruá rivers. This sedimentary unit stands at mean altitudes of 70 m, forming a planar area characterized in the radar images by a low-density drainage system with incipient sub-dendritic channels. One interesting characteristic of these deposits is the ragged, “half-moon” morphology of their margins, denoting strong erosion by younger channel migration. The facies of Q2 are distinct from Q1, consisting of 0.3-1 m thick, coarsening upward successions formed by dark gray, parallel laminated muds that grade upward into light gray to brown, fine- to medium-grained, moderately to poorly-sorted, angular to sub-angular, sands. Internally, they display parallel or climbing ripple cross lamination. Fining-upward sequences are locally present, and the sandy component displays medium- to small-scale sets (<0.4 cm thick) of trough cross stratification. Plant remains dispersed in the muds were dated at 27,160 ^{14}C yr B.P.

Deposits Q3: These deposits are areally much more restricted than Q1 and Q2, occurring discontinuously around the riverbanks throughout the study area, reaching as far east as the locality of Santarém, from where they become spottier. In the radar images, these deposits form a flat area at mean altitude of 55 m, with a very low density of meandering channels that cut into flood plain areas having abundant abandoned loops. As with deposits Q2, these deposits display ragged margins with “half-moon” morphology. Planar areas without any channels are common. Deposits Q3 are up to 7 m thick at the outcrop scale, and consists of 0.2-1.8 m thick, fining and coarsening upward successions formed by light gray to brownish massive muds that grade into light gray to brownish, moderately sorted, mostly angular, siltic- to fine-grained, sands (60% muscovite, chlorite and biotite; 40% polycrystalline quartz). The clay layers frequently display plant remains, which locally form peats that are up to 0.6 m thick and 6,700 to 2,480 ^{14}C yr B.P. old.

Deposits Q4: These deposits are distributed throughout Western Brazilian Amazonia, corresponding to fluvial terraces that stand only at 3 m higher than the dry-season water level. In the radar images, these deposits could not be separated from the modern flood plain and river complex, being mapped altogether (**Fig. 1**). In the field, deposits Q4 cut deposits Q3,

forming a listric contact at a slightly lower topographic level. They consist of dark gray to black, moderately to well sorted, angular to sub-angular, very fine to fine-grained, sands. As opposed to deposits Q3, these sands are very well structured, being represented by ripple cross lamination and, secondarily, medium-scale trough cross stratification. The sands are interbedded with dark gray to back, parallel-laminated muds. The volume of plant remains is high in these deposits, which display ages between 280 and 130 ^{14}C yr B.P.

4. Geological evolution

Application of radar images in combination with sedimentological studies in the field revealed to be of great success to map Neogene and Quaternary sedimentary units from the Brazilian Amazon. Considering the large extension of this area, the accessibility problems and the overall lack of detailed geological data, the use of SRTM radar images was crucial to complete the field mapping, allowing to identify the geological units far beyond where exposures were available. The resulting geological map lead to state that the study area was a scenario of several environmental changes during the Neogene and Quaternary. The distribution of the sedimentary units as belts progressively younger from southwest to northeast suggests that the Western Amazonia behaved as a subsiding basin, with the depocenter migrating to the northeast in the late Tertiary-Holocene. This basin is bounded to the east by Cretaceous rocks of the Alter do Chão Formation, as well as older Paleozoic and Precambrian rocks. In addition, our sedimentological record indicates a huge area located to the west of Manaus that was undergone to several phases of subsidence and stability since the early/middle Miocene.

The reconstruction of the depositional history is consistent with significant changes in landscapes from the Neogene to the Quaternary. Hence, the closure of a large lake system (Solimões Formation) at the end of the Miocene gave rise to the development of a Plio-Pleistocene fluvial system (Içá Formation). This was yet very distinct from the modern drainage, with shallow, energetic, highly migrating, braided to anastomosed channels having an overall northeast outlet. This fluvial system formed probably under climatic conditions relatively drier than today´s. During the early Pleistocene, there was pronounced erosion, followed by a renewed depositional phase at ca. 40,000 ^{14}C yr B.P. (Deposits Q1), when prevailed the development of prograding lobes and/or crevasse splays associated with lake system (i.e., fan-delta) and/or fluvial flood plain areas. After a period of erosion, a fluvial system with eastward draining channels started to develop at around 27,000 ^{14}C yr B.P. (Deposits Q2). The fluvial channels were over flooded in mid-Holocene time (Deposits Q3). This flooding is attributed to an increased period of humidity, with a peak between 5000 and 2500 ^{14}C yr B.P. The data presented herein support that, rather than being a monotonous area, the Amazonia was a place with frequent changes in landscape since the Neogene, probably as a result of climatic and tectonic factors.

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