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Geomorphological evidence of recent tilting in the Central Amazonia Region

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A B S T R A C T

Geomorphometric techniques applied to remote sensing data represent powerful tools as an aid for detecting terrain features produced by recent vertical crustal movements in a variety of landscapes. In this work, geomorphometric analysis of the Central Amazonia drainage network using Shuttle Radar Topography Mission (SRTM) data was carried out to determine surface water loading and tectonic influence on the development of the Uatumã and Urubu river basins since the Miocene. The main objective was to detect geomorphological domains of lateral stream migration and channel sinuosity changes that could indicate recent vertical crustal movement. To achieve this, the Transverse Topographic Symmetry Factor and Sinuosity Index were applied to analyze the study area drainage network. Comparison of the geomorphological domains with structural field data and records of seismicity suggests that they are influenced by subsurface fault reactivation, which coincides in space with faults mapped in outcrops that have activated since the Miocene. This interpretation is corroborated by the spatial correspondence between these faults with domain boundaries and shapes, by river sinuosity change when crossing these boundaries, and by a high concentration of seismic activity along one of these limits. The crustal movement caused by hydrological loading can also influence such geomorphological features. Such is the case of lateral stream migrations of a domain in the opposite sense to the Amazon River flow. This may be a consequence of the more pronounced expression of hydrological loading in the Negro and Solimões river confluence region.

1. Introduction

The interaction of tectonic and climatic driving forces forms, modifies and destroys geomorphic features on the landscape (Wobus et al., 2006). Tectonic influences generate topography and establish the boundary conditions for surface processes. In turn, climatic drivers redistribute the loading on the lithosphere and can also cause, even at a local scale, crustal deformation (Koons and Kirby, 2007). As many of these phenomena induce vertical crustal movement and the consequent tilting of the topographic surface, various geomorphological features can be used to characterize the interaction between tectonics (Cox et al., 2001) and crustal deformations caused by surface processes, such as water loading (Bevis et al., 2005). These features are mainly derived from analysis of the drainage network, such as channel sinuosity and migration.

Rivers are particularly sensitive to such tilting because of the gradient changes imposed on them (Holbrook and Schumm, 1999). Streams can respond to these changes, among other processes, by migrating laterally in a down-tilt direction. A record of this migration is preserved as a preferential direction of the drainage basin transverse asymmetry in the tilted region (Garrote et al., 2006). Moreover, rivers can undergo minor variations within their pattern without undergoing complete shifts in pattern type. The most commonly observed of these intra-pattern adjustments is a channel to increase or decrease of sinuosity (Holbrook and Schumm, 1999; Zámolyi et al., 2010). These changes are especially true of low-gradient rivers, which are characteristic of continental interiors (Holbrook and Schumm, 1999), such as in Central Amazonia.

The Central Amazonia region is located within the world's largest river basin, which occupies approximately 6.1 million km^2 (Guyot et al., 2007). In the Uatumã and Urubu river basins, located in this region (Fig. 1), the topographic framework consists of straight river segments, islands, plateaus, small water courses ("igarapés"), colossal rivers and lakes. These morphological features are generally associated with reactivation of basement structures (e.g. Almeida-Filho and Miranda, 2007; Hayakawa et al., 2010) caused by intraplate tectonics since Miocene times (Costa et al., 2001; Riccomini et al., 2012). These relief elements have also been influenced by climatic fluctuations (Müller et al., 1995). In addition, seasonal variations in rainfall further translate into hydrological loading and consequent crustal vertical movements (Bevis et al., 2005). This type of loading can promote more intense tilting over certain areas and even change the upper crust stress regime (e.g. Luttrell et al., 2007; Bettinelli et al., 2008).

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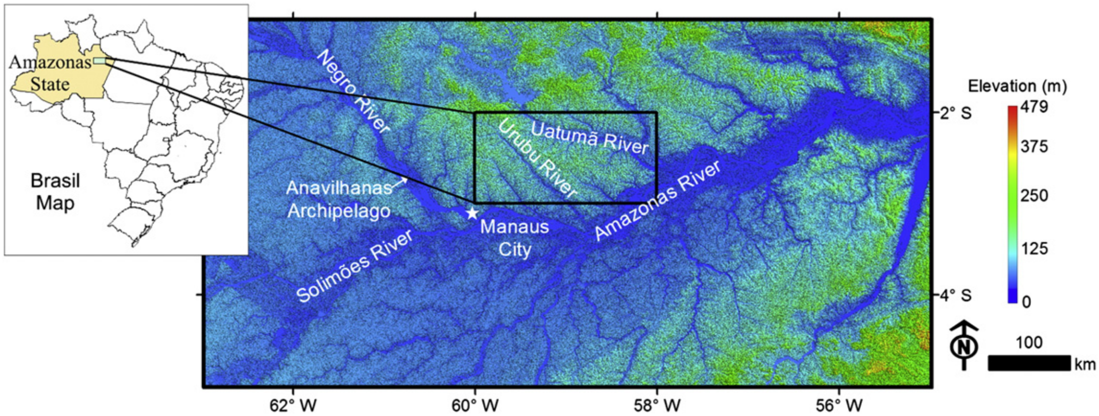

Fig. 1. Central Amazonia topography (SRTM DEM), including the study area location (black rectangle) and major rivers. The Manaus city is the Amazonas State capital, northern Brazil.

Direct observation of densely vegetated tropical areas, such as the Central Amazonia, is hindered by difficult access, thus remote sensing imagery can be of particular interest to detect geomorphological features produced by tilting. Furthermore, recent studies have shown the potential of digital elevation model data from SRTM (Shuttle Radar Topography Mission) in the geological investigation of terrains with geomorphological (e.g. Lahiri and Sinha, 2012), ecological (e.g. Kusky et al., 2010) and topographical (e.g. Sreedevi et al., 2009) characteristics similar to Amazonian region. Likewise, geomorphometric techniques applied to SRTM data, such as basin asymmetry (Cox, 1994) and channel sinuosity (Petrovszki et al., 2012), offer the opportunity to evaluate the impacts of vertical movements on the Earth's surface that can be caused by both tectonic and superficial processes.

This paper seeks to evaluate the role of recent vertical crustal movements over the drainage pattern in the Amazonian humid tropical region, Brazil, by detailed analysis of the lateral stream migration and channel sinuosity changes. To this end, geomorphological domains were determined by transverse topographic symmetry factor and sinuosity index applied to SRTM data. The geomorphic data obtained suggest that the recent tectonic activity affects the boundaries and shape of these domains. Furthermore, we propose that the annual hydrological cycle of loading and unloading is also capable of inducing lateral stream migration.

2. Physiography and geological framework

The investigated area is located northeast of Manaus city, northern Brazil. It is drained by the Preto da Eva, Urubu and Uatumã rivers, right-bank tributaries to the Amazon River (Fig. 1). The region's drainage network is generally classified as dendritic to sub-dendritic (Silva, 2005). However, pinned, trellis, rectangular, radial and annular patterns are also observed locally (Silva, 2005). The relief consists predominantly of extensive low plateaus dissected differently, but flood plains, fluvial terraces, sandy plains, tabular and hilly surfaces are also observed (Pellin et al., 2010).

The climate is equatorial, with a mean annual temperature of 26 °C. In the study site, the monthly rainy season (November to May) precipitation is above 205 mm, while in the dry season (June to October) it is below 110 mm (Pellin et al., 2010). This seasonal precipitation distribution is the main reason for variation in hydrologic loading and the consequent regional crustal deformation (Guimarães et al., 2012). Bevis et al. (2005), using data from a Manaus city GPS station, coupled with a simple hydrologic model related to the water level in the flood-prone areas, confirmed an annual vertical displacement cycle with a 75 mm peak, approximately 2 to 3 times larger than expected for this region. Guimarães et al. (2012) performed a similar study and observed a vertical displacement up to 100 mm. Both studies noted the crustal oscillation is strongly related to the Amazon River flooding period, suggesting a lithosphere elastic response to the hydrological cycle loading change.

Geologically, the investigated area is part of the Amazonas Basin. This is an intracratonic Paleozoic sedimentary basin, occupying about 500,000 km^2, in which the basement is dominated by high and medium grade metamorphic complexes, greenstone belts, and Proterozoic sedimentary covers (Milani and Thomaz Filho, 2000). The basin was installed in an extensional regime that generated a Paleozoic rift controlled by NE–SW and NW–SE basement faults (Wanderley-Filho et al., 2010). The basin sedimentary section, which is 6500 m thick, is comprised of four Paleozoic sequences affected by post-Paleozoic magmatism and two Cretaceous and Tertiary sequences (Cunha et al., 2007; Caputo, 2011). In the northwesternmost portion of the study area, there are three outcropping Paleozoic lithostratigraphic units of the Trombetas Group (CPRM, 2004): the Nhamundá Formation, which combines neritic and glacigenic Silurian sandstones; the Pitinga Formation, which includes Silurian marine shales and diamictites; and the Manacapuru Formation, which is composed of shales and subordinate sandstones ranging in age from Upper Silurian to Lower Devonian.

In addition, the remaining areas are largely occupied by Alter do Chão Formation rocks (Fig. 4), which is made up of quartz arenites coarse to medium grained, locally conglomeratic, red to variegated, kaolinitic, poorly sorted and with low consolidation. Subordinately, red mudstones and siltstones are also found (Costa, 2002). This formation has bedding dips gently to the SE (Neves, 1990). This unit's development is associated with a high-energy river system developed from Paleocene to Miocene (Caputo, 2011). According to Ibanez (2012), tectonism was active during the Alter do Chão Formation deposition, involving NE–SW normal faults and indicative of a relationship with a NW–SE extensional stress field during the Middle Miocene.

It is also worth noting that, throughout the alluvial plains of the region's main rivers, there are Pleistocene–Holocene deposits formed on clay and sand-rich sediments with cross- and plane-parallel stratification, which were derived from the floodplain, levee and abandoned channels, overlying the Alter do Chão Formation rocks (Latrubesse and Franzinelli, 2002). These sediments fill graben-like basins controlled by a NW–SE oriented normal fault (Riccomini et al., 2012). They also display earthquake-induced soft-sediment deformation (seismites), which indicate active tectonics during sedimentation (Riccomini et al., 2012).

The Amazonas earthquake records indicate focal mechanisms of reverse faults with a NNW–SSE SHmax direction (Assumpção and Suárez, 1988). This current stress field is related to the resulting balance that includes, on the one hand, spreading along the Mid-Atlantic Ridge and, on the other, resistance imposed by the Nazca and Caribbean plates (Mendiguren and Richter, 1978), as well as by local stress generated by the Amazonas Basin Paleozoic Rift (Assumpção, 1992; Zoback and Richardson, 1996).