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Age and evolution of diachronous erosion surfaces in the Amazon: Combining (U-Th)/He and cosmogenic ^{3}He records

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Abstract

(U-Th)/He geochronology of two weathered plateaus in the Carajás Mountains, Pará, Brazil, reveals a history of weathering spanning from ca. 80 Ma to the present for this high elevation (~720 m) land surface. Cosmogenic ^{3}He measurements of hematite pebbles and blocks cemented onto the plateaus at two sites, N1 and S11D, yield erosion rates as low as 0.09 and 0.08 m Ma^{-1}, respectively. Thus, these results confirm that the plateau surfaces are nearly immune to physical erosion for tens of millions of years. (U-Th)/He geochronology of ferruginous duricrusts blanketing the low elevation (250–100 m) plains surrounding the Carajás Mountains yield results consistently younger than ~10 Ma. The geochronology results also reveal that the low elevation plain is diachronous, becoming progressively younger towards the receding plateaus. The spatial distribution of (U-Th)/He ages permits reconstruction of the history of scarp retreat for the Carajás landscape, showing that scarp retreat along major river valleys may have been as fast as 20 km Ma^{-1} during tectonically active and humid periods in the Cenozoic. The cessation of scarp retreat at some sites suggests that metamorphosed banded iron-formations and quartzites provide effective barriers to retreating escarpments, helping to preserve some of the oldest continuously exposed land surfaces on Earth.

Keywords: (U-Th)/He geochronology; cosmogenic ^{3}He; goethite; hematite; Carajás; Amazon

1. INTRODUCTION

Ancient landscapes in relatively stable cratonic areas of Australia, Africa, and Brazil host deeply weathered plateaus surrounded by undulating lowlands that are blanketed by shallower and less evolved soils and weathering profiles (King, 1956). Classical landscape evolution models often attribute ages to these distinct elevation landsurfaces, where the higher elevation deeply weathered plateaus are purportedly older than the surrounding low elevation plains (King, 1956). These higher elevation plateaus are interpreted as remnants of old erosion surfaces now undergoing destruction by scarp retreat.

^{40}Ar/^{39}Ar geochronology of supergene Mn oxides from both high and low elevation surfaces in Australia (Vasconcelos, 2002), Brazil (Carmo and Vasconcelos, 2006; Vasconcelos and Carmo, 2018), Africa (Colin et al., 2005; Beauvais et al., 2008), and India (Beauvais et al., 2016; Bonnet et al., 2016) confirms that weathering profiles on the elevated plateaus are older than those on lower elevation surfaces. ^{40}Ar/^{39}Ar geochronology also shows that weathering profiles on the highest elevation plateaus are as old as ~70 Ma, suggesting that remnant plateaus erode very slowly (Vasconcelos et al., 1994; Vasconcelos, 2002; Vasconcelos and Carmo, 2018). These observations and

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conclusions are confirmed by completely independent methods. For example, the combination of (U-Th)/He geochronology of supergene goethites (Shuster et al., 2005) with cosmogenic ^{3}He (Shuster et al., 2012) measurements at Carajás, Pará, Brazil, confirm the longevity of the surfaces overlying the plateaus and their low rates of erosion. Low rates of erosion are confirmed by cosmogenic ^{53}Mn analysis (Fujioka et al., 2010). (U-Th)/He geochronology of supergene goethites and cosmogenic ^{3}He measurements from plateaus at the Quadrilátero Ferrífero (QF), Minas Gerais, Brazil corroborate the low rates of erosion for the ancient (>60 Ma) plateaus (Monteiro et al., 2014, 2018).

Here, we expand on those studies and apply a similar approach to that used by Monteiro et al. (2014, 2018) for the QF. We investigate, in addition to ages, possible mechanisms controlling the formation and preservation of ancient weathering profiles at Carajás. We also take advantage of iron cementation and duricrust formation to investigate whether the low-lying undulating plains surrounding the ancient Carajás plateaus are indeed younger than the surfaces defining the high-elevation plateaus. Lastly, we test the hypothesis that the low elevation surface evolves by scarp retreat, expanding at the expense of the receding plateaus. If that hypothesis is correct, the low-lying surface should be diachronous, becoming progressively younger in the direction of scarp retreat.

2. GEOLOGY AND GEOMORPHOLOGY OF THE CARAJÁS PLATEAUS AND ADJACENT AREAS

The Carajás plateaus are located on the southeastern margin of the Amazon Craton ~540 km inland from the mouth of the Amazon River. They comprise Archean granitoid-greenstone units (*Andorinhas Supergroup* [2.9 Ga] (Docegeo, 1988; Huhn et al., 1988a, 1988b; Araújo and Maia, 1991)) and metavolcanic and metasedimentary sequences, including banded iron-formations (BIFs) (*Itacaiúnas Supergroup* [2.73–2.84 Ga] (Machado et al., 1991; Trendall et al., 1998)), intruded by granitic and ultramafic to mafic magmas of distinct ages (2.76–2.56 Ga alkaline and calc-alkaline granites and mafic dykes; and 1.88 Ga anorogenic granites). The most recent granitic intrusive event in the area occurred ~600 Ma during the formation of the Neoproterozoic Araguaia Fold Belt (Grainger et al., 2008).

Climate in Carajás is tropical monsoonal (***Am*** in Köppen-Geiger's classification) with annual rainfall ranging from 1700 to 2800 mm (Alvares et al., 2014), a wet period from December to May and a dry season from June to November. The area is drained by the Itacaiúnas, Parauapebas, and Vermelho rivers and several small creeks that ultimately deliver their water and sediment loads to the Tocantins River, near Marabá (Fig. 1). There are no perennial rivers or creeks on the Carajás Surface, but iron-cemented channels drain the plateau surfaces. These iron-cemented channels turn into intermittent creeks flowing torrentially during and immediately after major storms. Rainfall also accumulates in lakes associated with internal collapse basins on the Carajás Surface. Water from natural springs (Bahia, Sumidouro, Bacelar, and Vizinho) draining the Igarapé Bahia (IB) plateau are slightly acid (pH = 4.6–6.3), show low salinity (TDS = 8.75–16.64 mg L^{-1}), contain low dissolved oxygen loads (2.1–8.3 mg L^{-1}), and very low concentrations of dissolved Ca, Mg, and Fe (0.43–1.62, 0.40–2.40, and <0.2 mg L^{-1}, respectively) (Andrade et al., 1989). Lush tropical rainforest used to blanket most of the region until the uncontrolled deforestation that started in the 1970s and denuded most of the region turning it into cattle pasture, except for some protected areas (indigenous reservations and national parks, mostly). Tropical rainforest, however, remains in parts of the Carajás Surface, except for areas underlain by BIFs, where iron duricrusts – cangas – host endemic epilithic ("rupestre") vegetation (Viana et al., 2016 and references therein). Climatic conditions are (at least were until the 1970s) conducive to deep weathering throughout the entire region.

Deep weathering on the Carajás Plateau has resulted in karstic landscapes, particularly over weathered BIFs, where caves form by significant mass loss during leaching of quartz and carbonates; internal lakes fill collapse basins. The plateaus are thoroughly covered by iron duricrusts, which range in thickness and mineralogical complexity depending on the underlying lithology. In some areas, the duricrust is exposed at the surface (e.g., plateaus blanketing weathered BIFs), while throughout most of the Carajás plateau duricrusts sit below soils and sedimentary layers of variable thicknesses (0–15 m). The duricrust is not horizontal, and local depressions in duricrusts may be filled with sediments containing pebbles and cobbles, suggesting that an ancient paleodrainage once drained the plateaus. This ancient paleodrainage, possibly Mesozoic or Cenozoic, is presently unrecognizable under a thick layer of very-fine-grained soil (Sombroek, 1966; Lucas, 1989; Lucas et al., 1993) that attenuates any previous undulation of the Carajás Surface. Late Cenozoic sediments, mostly Quaternary, also fill karstic lakes (Sahoo et al., 2016).

In addition to its geomorphic significance, weathering in the region has a major economic impact. The Itacaiúnas Supergroup hosts Cu-Au (e.g., Igarapé Bahia, Salobo, Sossego) (Fig. 2a and b), Cu-Zn (e.g., Pojuca), Mn (e.g., Azul), and Fe (e.g., N1, N4, N5) mineralization (Fig. 3a–c). On the Carajás Plateau, mineralized areas are covered by thick (100 to >500 m) weathering profiles and supergene enrichment blankets, forming classic lateritic Fe (Tolbert et al., 1971), Mn (Coelho and Rodrigues, 1986), Au (Netuno Villas and Santos, 2001), Ni (Alves et al., 1986), and Al (Costa et al., 1997) deposits. These mineralized areas constitute some of the largest open pit mining operations on the planet today, and they offer access to the entire stratigraphy of the deep weathering profiles.

While lateritic ore deposits are common on the Carajás Plateau, they are absent in the surrounding low elevation plains of the Itacaiunas Surface. In these areas, weathering profiles are relatively shallow (commonly <30 m), and they contain saprolites directly below soils or, locally, ferruginized sediments. The sediments are intermittent, generally <10 m thick and composed of strongly weathered alternating sand and gravel layers, often capped by a goethite-cemented duricrust (Fig. 4). The sediments are