Accepted Manuscript

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PII: S0016-7037(18)30135-2
DOI: <https://doi.org/10.1016/j.gca.2018.02.045>
Reference: GCA 10688

To appear in: *Geochimica et Cosmochimica Acta*

Received Date: 24 July 2017
Accepted Date: 28 February 2018

Please cite this article as: Monteiro, H.S., Vasconcelos, P.M.P., Farley, K.A., Lopes, C.A.M., Age and evolution of diachronous erosion surfaces in the Amazon: combining (U-Th)/He and cosmogenic ^3He records, *Geochimica et Cosmochimica Acta* (2018), doi: <https://doi.org/10.1016/j.gca.2018.02.045>

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

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Key Points:

- (U-Th)/He geochronology of goethites in stepped landscapes shows that older surfaces are higher and younger surfaces are lower.
- Cosmogenic ^3He in hematites from the Carajás Plateau indicate extremely low rates of erosion.
- (U-Th)/He geochronology of goethites reveals that low-lying surfaces are diachronous, younging towards receding escarpments surrounding older plateaus.

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 ^3He 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.

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.

$^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of supergene Mn oxides from both high and low elevation surfaces in Australia (Vasconcelos, 2002), Brazil (Carmo and Vasconcelos, 2006; Vasconcelos and Carmo, *in press*), Africa (Beauvais et al., 2008; Colin et al., 2005), 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. $^{40}\text{Ar}/^{39}\text{Ar}$ 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, *in press*). These observations and 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 ^3He (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 ^3He measurements from plateaus at the Quadrilátero Ferrífero (QF), Minas Gerais, Brazil corroborate the low rates of erosion for the ancient (> 70 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; Araújo et. al., 1991; Huhn et. al., 1988a,b)) 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 plateau are slightly acid ($\text{pH} = 4.6$ to 6.3), show low salinity ($\text{TDS} = 8.75 - 16.64 \text{ mg.L}^{-1}$), contain low dissolved oxygen loads ($2.1 - 8.3 \text{ mg.L}^{-1}$), and very low concentrations of dissolved Ca, Mg, and Fe ($0.43\text{-}1.62$, $0.40\text{-}2.40$, and $<0.2 \text{ mg.L}^{-1}$, 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. 2 a,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 afossiliferous and their ages are unknown, but they are interpreted as Cenozoic, and have been informally grouped as the

Monte Lopes Formation (Lopes, 1999). The low elevation Fe-cemented sediments or bedrocks are identifiable from a distance by their tabular aspect (Fig. 4). Iron cementation in these sediments make them potentially datable by the (U-Th)/He method.

Here we will refer to the high elevation (~ 900-600 m) plateaus hosting deeply weathered lateritic profiles as the Carajás Surface (CS) (Fig. 1, 2, 3), and the low elevation (~250-100 m) undulating plains hosting intermittent duricrusts as the Itacaiunas Surface (IS) (Fig. 4). We investigated weathering profiles blanketing both surfaces.

3. SAMPLING AND ANALYTICAL METHODS

The various weathering profiles were sampled by distinct methodologies, and each profile will be discussed separately below.

The most extensively sampled weathering profile is the Igarapé Bahia (IB) lateritic gold deposit, which was mined from 1989-2002. The deposit was sampled multiple times as the mine expanded. In addition to the samples collected from different stages of the open pit mining operations, we collected samples from each meter of a suite of drill cores illustrated in Figure 2c. These drill-core samples were crushed, homogenized, and split into representative aliquots, which were further split for mineralogical investigations (sample fragments) and crushed for major and trace element analysis. Additional pure goethite from selected depths were sampled for petrographic analysis, further mineralogical investigations, and geochronology. A total of > 900 individual samples from the IB profile were available for this investigation. Unfortunately, the limited time and the amount of work involved in sample preparation for (U-Th)/He analysis precluded investigation of all selected samples potentially suitable for geochronology.

The N1 iron plateau was also sampled multiple times from 1988 to 2013. The main samples used for this investigation were collected along NW-SE traverses on the plateau (Fig. 3d). The plateau surface itself is not flat along our traverse, ranging from ~ 780 m in the NW to about ~ 650 m in the SE. Several karstic lakes along the traverse provided samples for mineralogical and geochronological investigation. The sampling exercise at the N1 plateau focused solely on surface samples. Similarly, a N-S traverse along the S11D plateau provided the few samples from Serra Sul investigated here (Fig. 1c).

The samples from the dissected plains and rolling hills between Carajás and the Tocantins river (Fig. 1) were collected along a traverse from Carajás to Marabá that targeted four sites: a ferruginized low elevation duricrust near Canaã dos Carajás (Fig. 1, 4a,b); a duricrust along the state highway PA275, near Curionópolis (Fig. 1, 4a,c); and two ferruginized sedimentary deposits near Marabá (Fig. 1, 4a,d).

3.1. Optical and scanning electron microscopy

Mineralogical investigation followed procedures outlined in Monteiro et al. (2014). Polished thin-sections and grain mounts were investigated to determine mineralogy, texture, paragenesis, and modes of goethite precipitation (e.g., pseudomorphic replacement, pore space fill, empty cavity precipitation). We paid particular attention to the identification of potential primary mineral contaminants within goethite.

3.2. X-ray diffraction

Hundreds of grains from each sample were powdered using an agate mortar and pestle. Powder XRD was performed in a Bruker D8 Advance X-ray diffractometer equipped with

either a Cu- (1.5405 Å) or a Co-source (1.7889 Å) operated at 40 kV and 40 mA. Scans were collected from 5° to 90° 2 θ at 0.02° intervals.

3.3. Electron microprobe analysis (EMPA)

Electron microprobe analyses of mounts of visually pure grains (similar to ones selected for geochronology) were performed with a JEOL JXA-8200 EPMA at the Centre for Microscopy and Microanalysis (CMM) of the University of Queensland, Brisbane, Australia. All runs were performed using a beam current of 15 nA, accelerating voltage of 15 kV, and highly focused spot sizes (except for Na, K, Ca, and S, for which spot size = 10 μ m). Samples and standards were carbon coated together before EPMA sessions. During sample analysis, some spots were programed on mineral standards to ascertain the accuracy of the results. Between 14 and 21 elements were measured in each individual analytical session.

3.4. (U-Th)/He geochronology and $^4\text{He}/^3\text{He}$

Goethite grains for (U-Th)/He geochronology were selected, photographed, encapsulated, and analyzed following procedures outlined in Monteiro et al. (2014). Helium extractions were performed by heating encapsulated goethite with a diode laser at 900 °C for 6 minutes. Purified gas was spiked with a known amount of pure ^3He and analyzed in a Pfeiffer Prisma quadrupole mass spectrometer. A second extraction was performed for all samples to ensure complete degassing.

After helium extraction, degassed goethite grains were transferred to Teflon vials and pipetted with 100 μ l of Seastar HCl solution and 25 μ l of spike solution (containing known amounts of ^{235}U and ^{230}Th). Closed vials were placed in the oven at 90 °C overnight. The

solutions were allowed to evaporate completely in a hot plate at 95 °C. 50 µl of HNO₃ was added to each Teflon container to dissolve the golden salt accumulated at the bottom. 1000 µl of Milli-Q water was added to the Teflon beakers and the diluted solutions were decanted into a 1.5 ml ICP-MS cup. Measurements of U and Th were carried in an Agilent 8800 ICP-MS in the Environmental Analysis Center, Caltech, USA.

Three samples from the IB profile were also investigated by the ⁴He/³He method (Shuster et al., 2005; Monteiro, 2017). Goethite grains selected for ⁴He/³He experiments were proton irradiated at the Francis H. Burr Proton Therapy Center at Massachusetts General Hospital, Boston, MA as outlined in Shuster et al. (2004). Helium extraction by incremental heating is described in Monteiro (2017).

3.5. Cosmogenic ³He

Samples for ³He measurement were prepared in two ways: (1) crushing of hematite (± magnetite) fragments extracted from duricrusts, and (2) micro-drilling of loose pebbles of hematite (± magnetite) scattered on plateau surfaces. Canga fragments and drill-cores were crushed, sieved, ultrasonicated in distilled water, absolute ethanol or acetone, and air-dried. For the micro-drilled samples, magnetic separation was used to isolate magnetic from non-magnetic fractions. Approximately 15 mg of sample were loaded into Sn foil packets and degassed at 1200 °C in a resistance furnace. Re-heating to 1200°C was performed to assure complete gas extraction. Analytical procedures are described elsewhere (Patterson and Farley, 1998; Amidon and Farley, 2011).

To calculate apparent exposure ages for each sample, we used a sea level high latitude ³He production rate of 68.1 ± 8.1 atoms g⁻¹ yr⁻¹ for hematite (Shuster et al., 2012) corrected for

latitude and elevation following procedures outlined in Stone (2000). We cast the same results in terms of erosion rates by using an average density of 2.88 g/cm^3 (Santos, 2006) for duricrusts, and calculate erosion rates ($\dot{e}$ in $\text{g/cm}^2/\text{yr}$) as $\dot{e} = P\Lambda/N$, where P is the production rate (atoms/g/yr); Λ is an attenuation lengthscale (160 g/cm^2); and N is the nuclide concentration (atom/g) measured at the surface (Lal, 1991). Recurrent dissolution-reprecipitation of iron-cements in the duricrusts makes sampling relic goethites challenging. Hematite grains may contain areas partially recrystallized to goethite (Monteiro et al., 2018), which potentially results in partial ^3He loss. Therefore, we interpret all results as minimum values and refer to all results as apparent exposure ages (aEA).

4. RESULTS

4.1. Microscopy

The purest and most crystalline goethites (Fig. 5a,b) occur in the Igarapé Bahia gossan. Goethite often occur in association with other supergene phases (e.g., Mn oxides, cuprite, native Cu, supergene gold) but are devoid of relict hypogene contaminants, making them ideally suited for geochronology. In contrast, goethites from the duricrust have complex textures (Fig. 5c) where several generations of intergrown goethites occur intermixed with gibbsite, anatase, rutile, hematite, tourmaline, and clay minerals.

Similarly, vitreous goethites cementing N1 plateau duricrusts are Al-rich (Fig. 5d) and often contain relict primary hematite, quartz, ilmenite, and rutile (Fig. 5e). Goethite also occurs as pisoliths cemented by a mixture of poorly crystallized porous yellow goethite and gibbsite. Goethite comprising ferruginized organic material (e.g., plant roots) (Fig. 5f) and microbial mats (Levett et al., 2016) occurs in these samples.

Goethite cementing sediments and duricrusts from the Itacaiunas Surface are less crystalline and host significant amounts of kaolinite, quartz, and hematite (Fig. 5g-i).

4.2. Mineralogy

X-ray diffraction patterns (Electronic Appendix 1 - EA1) reveal that goethite varies in crystallinity and purity, depending on underlying lithology, mode of precipitation, and proximity to the surface. Goethites from the gossans at the Igarapé Bahia deposit are purest and most crystalline, where mm- to cm-wide goethite bands alternate with μm to mm bands of cryptomelane, or contain minor inclusions of cuprite and native Cu and Au. In contrast, goethite cements from the duricrust incorporate hematite, gibbsite, kaolinite, and minor anatase. Goethite cements from the N1 plateau host minor hematite, gibbsite, quartz, lepidocrocite, and anatase. Finally, duricrust samples from the Itacaiunas Surface contain goethite cements contaminated with minor quartz, hematite, and kaolinite.

Broadening of the main goethite peaks in X-ray diffraction patterns reveals distinct goethite crystallinities. For most goethites, except IBH-13-09h, there is a strong correlation of decreasing crystallinity with increasing Al content ($R^2 = 0.83$).

4.3. Goethite composition

Electronic Appendix 2 (EA2) contains all electron microprobe analyses used in this study. Most goethites investigated here are not stoichiometric FeOOH but contain a significant amount of minor and trace elements ($\text{Al}+\text{Mn}+\text{Cu}+\text{V}+\text{Co}+\text{Cr}+\text{Ni}+\text{Ti}+\text{Zn}+\text{Pb}$) substituting for iron (Fig. 6,7). Electron microprobe analyses showing low totals ($< 90 \text{ wt\%}$) correspond to analyses of porous goethite, while high totals ($100\text{-}104 \text{ wt\%}$) are associated with the analysis of grain interfaces in contaminated goethite cements (Maaskant and Kaper, 1991). Minor and

trace element contents vary inversely with Fe-contents, and the nature and amount of trace elements are distinct for the three types of weathering profiles investigated (Fig. 7). Igarapé Bahia goethites are the most complex, hosting significant amounts of Al, Mn, and Cu and low Si and P contents. Goethites from the N1 profile and from the four sites on the Itacaiunas Surface contain large amounts of Al and Si. The N1 goethites also contain significant Ti, suggesting contamination with ilmenite or rutile (now weathered to anatase) inherited from the underlying volcanic units (Fig. 3c). Itacaiunas Surface goethites also contain some Ti (Fig. 7c), suggesting contamination by detrital ilmenite or rutile.

Goethite compositions are strongly dependent on mechanisms of precipitation and depth within the profile. At the IB deposit, goethites precipitated in the duricrust are usually enriched in Al, while those precipitated at depth are commonly depleted in Al (< 1 wt%). Mn and Cu-concentrations are high for goethites precipitated at depth (2-7wt% Mn, 2-5wt% Cu), suggesting effective leaching of these elements from the upper parts of the profile and their enrichment at depth (EA2). In addition to Mn and Cu, P also becomes significantly enriched in goethites precipitated at depth (1.5-3.2 wt% P).

4.4. (U-Th)/He geochronology

Table 1 lists U, Th, and ^4He contents and (U-Th)/He precipitation ages (*pAs*) for goethites from the IB, N1, and Itacaiunas Surface sites. Age distributions for these sites are illustrated in Figure 8. [U], [Th], and [He] concentrations vary from 1.5 to 1640 ppm [U], 0 to 109 ppm [Th], and 0.04 to 336 nmol/g [He] for the IB profile; from 0.05 to 35 ppm [U], 0.2 to 232 ppm [Th], and 0.001 to 6.6 nmol/g [He] for the N1 plateau; and from 3 to 24 ppm [U], 2.5 to 59 ppm [Th], and 0.1 to 1.1 nmol/g [He] for the Itacaiunas Surface. Th/U ratios range

between 0 - 5.4 (usually < 1 ; 80 out of 107) for IB, 0.5 - 12.7 (~ 5 on average) for N1P, and 0.8 - 6.7 (~ 3 on average) for the Itacaiunas Surface.

The oldest (U-Th)/He ages (~ 80 -70 Ma) were obtained for the IB and N1 sites. (U-Th)/He ages for the four sites on the Itacaiunas Surface vary from 9.4 ± 0.9 Ma to 7.5 ± 0.8 for site BOI 014, 8.5 ± 0.8 to 7.4 ± 0.8 Ma for site BOI 013, 4.3 ± 0.4 Ma to 2.0 ± 0.2 for site BOI 002, and 1.3 ± 0.1 to 0.5 ± 0.1 Ma for site BOI 004. Replicate (U-Th)/He analyses of IB and Itacaiunas Surface goethites usually yield reproducible results, while ages obtained for replicates of N1 goethites show large variability (Table 1).

4.5. Cosmogenic ^3He

Cosmogenic ^3He concentrations in hematites from the N1 and S11D plateaus are shown in Table 2. All samples yield significant amounts of ^3He , with minimum and maximum ^3He concentrations ranging from 100 to 495 Mat.g^{-1} for surface hematites. Maximum apparent exposure ages ($aEAs$) of 7.3 ± 0.9 Ma and 6.5 ± 0.8 Ma were calculated for the canga plateaus at S11D and N1, respectively. When cosmogenic isotopes are cast in terms of erosion rates, values obtained from S11D and N1 are as low as 0.08 and 0.09 m.Ma^{-1} , respectively (Table 2).

5. DISCUSSION

The significant sample population in this study (177 (U-Th)/He pAs and 9 cosmogenic ^3He $aEAs$), combined with additional results from Shuster et al. (2005, 2012) (55 (U-Th)/He pAs , 2 $^4\text{He}/^3\text{He}$ profiles, and 25 cosmogenic ^3He erosion rates) and Monteiro (2017) (1 $^4\text{He}/^3\text{He}$ age profile), constitute a comprehensive dataset suitable for addressing the histories of weathering, exposure, and erosion of the Carajás plateaus and surrounding plains. The results provide useful constraints on the ages of the various landsurfaces and on the rates and

mechanisms involved in the evolution of long-term landscapes in the region. Thus, the results help to resolve long-standing questions about the hierarchy of landsurfaces and the mechanisms involved in their formation and destruction. However, the results also reveal a complex surficial history in these old landscapes, suggesting that additional sites and samples are required to identify all the processes shaping these continental land forms, quantify rates of weathering and erosion through time, unravel the influence of climate in accelerating or decelerating these processes, and properly determine the controls imposed by tectonics on the formation and preservation of stepped landscapes in cratonic settings.

Before presenting and discussing the main conclusions in this study, we will address some issues related to the types of samples analyzed; their mineralogical complexities and suitability for (U-Th)/He dating; issues related to U, Th, and He incorporation, mobility, and retentivity in goethite and hematite; and factors associated with bedrock controls on the precipitation and preservation of iron oxyhydroxides suitable for geochronology.

5.1. The goethite (U-Th)/He record: chemical processes controlling the formation of saprolites and cangas

The Igarapé Bahia profile provides a comprehensive goethite dataset, where samples were collected at the surface, within the duricrust immediately beneath the thick soil that blankets most of the plateau, at various depths within the saprolite, and at the contact between the weathering-bedrock interface (Fig. 2).

The Igarapé Bahia lateritic profile was produced by oxidation of massive hydrothermal Fe-Cu sulfide orebodies, which released large quantities of sulfuric acid and iron in solution. Iron

reprecipitated as massive colloform and essentially monomineralic goethite bands, sometimes alternating with bands of Cu-cryptomelane, and containing variable amounts of Al, Mn, Cu, Si, and P. Some of these elements replace Fe in solid solution. Other elements are possibly present as nano-scale mineral contaminants not yet identified (e.g., iron phosphates). These massive colloform goethites are the purest and most suitable samples for geochronology. Exotic mineral phases intergrown with colloform goethites (Cu-cryptomelane, native Cu, cuprite, Au) also precipitated during weathering. These phases may precede, be coeval, or postdate goethite precipitation, but they all formed during weathering and, fortunately, do not contain any He memory from the underlying Archean bedrock. Concentric growth patterns in the colloform samples permits identifying, selectively sampling, and separately dating distinct generations of these supergene minerals (Vasconcelos et al., 1995; Shuster et al., 2005).

In contrast, goethites from duricrusts (Fig. 2b), the result of several events of iron dissolution-reprecipitation or Fe-metasomatism of soils and previously formed weathered material (Monteiro et al., 2014), contain a diverse assemblage of primary and supergene minerals recemented by supergene Fe and Al oxyhydroxides. The presence of minerals inherited from the bedrock may influence the (U-Th)/He ages (Vasconcelos et al., 2013; Monteiro et al., 2014; Monteiro, 2017). These goethites also show evidence for biological control on iron cycling, where relatively pure Al-rich goethite surrounds root cavities or replaces roots (Figure 5f) and microorganisms (Levett et al., 2016). These goethites are relatively enriched in Th with respect to U (Fig. 9), suggesting that both U and Th enter solution by complexation with organic ligands, but that Th readily reprecipitates while U remains in solution and is leached towards the bottom of the weathering profiles. The clear enrichment in Th and depletion of U for goethites from near surface sites at Igarapé Bahia are similar to

the relative U-Th enrichment/depletion previously observed for Fe-duricrusts at the QF, Minas Gerais (Monteiro et al., 2014).

A similar trend is noticeable for goethite samples from N1 (Fig. 9). As all N1 samples investigated in this study are derived from the present surface, they probably reflect a protracted history of iron dissolution-reprecipitation, leading to the observed U depletion and Th enrichment. Samples with high Th/U values are more complex, contain multiple generations intimately intergrown, and show greater variability in (U-Th)/He apparent ages for replicate grains from a single sample. N1 goethites are also compositionally complex because the plateau is underlain by both BIF and volcanic units, leading to high Al and Ti contents in the supergene Fe-Al oxyhydroxides (Fig. 7b). Results for the nearby N4 plateau (Shuster et al., 2012) show similar trends in U and Th distribution with depth in the profile.

Finally, goethites from the Itacaiunas Surface display the preferential enrichment in Th vs U observed in the IB duricrusts and in the N1 cangas, common for goethites formed by cementation and pseudomorphic replacement of other minerals (Vasconcelos et al., 2013; Monteiro et al., 2014; Riffel et al. 2015). They are also rich in Al and Ti, which is consistent with their mode of formation.

5.2. The (U-Th)/He age record

The comprehensive (U-Th)/He record for the Igarapé Bahia profile reveals a complex age pattern, but two distinct features are obvious from the record. First, on average, samples collected from the upper parts of the weathering profile, mostly from the duricrust, are older than samples collected at the bottom of the profile (Fig. 10). The oldest result (70.8 ± 7.1 Ma) occurs in the duricrust and the youngest result (0.82 ± 0.08 Ma) comes from a sample at 100

m below the surface (Figure 10, Table 1). Second, samples as old as ~ 58 Ma occur at depth, suggesting that the oxidation front that formed the lateritic gold deposit had reached great depths early in the history of weathering. The geometry of the profile (Fig. 2c), where depth of weathering appears to follow mineralization, suggests that, early in the history of exhumation, the oxidation of sulfides generated acid-oxidizing solutions that carved a preferential path downward into the bedrock along the mineralized zone, allowing the oxidation front to reach great depths rapidly. This deeply oxidized and mineralized breccia zone (gossan) focused subsequent percolation of weathering solutions. The descending meteoric solutions that traversed less mineralized, less reactive, and probably less permeable lithologies supplied, slowly through time, dissolved species that added to the complexity of the weathering assemblages at depth. An age vs depth relationship for the IB profile shows a minimum rate of penetration of the oxidation front from ~ 70 to 58 Ma of ~ 8.5 m.Ma⁻¹ (Fig. 10). This rate is indistinguishable from that obtained for weathering profiles in SE Brazil (8.9 ± 1.1 m.Ma⁻¹) (Carmo and Vasconcelos, 2006), but more than twice the rate calculated for advancing weathering fronts in Australia (Vasconcelos and Conroy, 2003; Heim et al., 2006).

The distribution of ages for the N1 plateau also reveals that weathering has been active for at least 25 Ma and possibly had begun developing much earlier in the Cenozoic. The paucity of results and the fact that all samples come from the surface precludes determining whether the weathering history (as recorded by mineral dissolution-reprecipitation, which should be reflected by ⁴He age frequency) preserved at N1 is continuous or episodic, but the combined results from N1 and IB (this study) and N4C (Shuster et al., 2005, 2012) suggest a history of continuous surface exposure of the Carajás surface throughout the Cenozoic.

Significantly, all the results obtained for the Itacaiunas Surface goethites are younger than 10 Ma, suggesting a much shorter history of exposure and weathering for this low elevation landscape. This shorter history of weathering is consistent with the shallower and less evolved weathering profiles devoid of significant supergene enrichment in the undulating plains (Fig. 4). This shorter history is also consistent with the thin, immature, and intermittent nature of the duricrusts distributed throughout the Itacaiunas Surface (Fig. 4c).

5.3. The cosmogenic ^3He record: the relative stability of duricrusts

Cosmogenic ^3He concentrations were measured for surface samples from the N1 and S11D plateaus (Fig. 1, Table 2). The results for exhumed hematite blocks presently cemented in cangas and for loose hematite pebbles yield compatible average rates of erosion of $0.20 \pm 0.02 \text{ m.Ma}^{-1}$ for N1 and $0.24 \pm 0.2 \text{ m.Ma}^{-1}$ for S11D, confirming that the plateaus are largely impervious to physical erosion for tens of millions of years. The relatively higher erosion rates obtained for partially hydrated hematite (e.g., $0.44 \pm 0.06 \text{ m.Ma}^{-1}$, Table 2; Monteiro et al., 2018) suggest that the plateaus evolve by slow hydration and dissolution-reprecipitation, with some mass loss resulting from downward leaching of soluble species. These chemical processes are very slow, and the plateau suffers very little chemical and virtually no physical erosion.

5.4. Age vs elevation relationships for the Carajás and Itacaiunas Surfaces

The long history of exposure and weathering obtained from the (U-Th)/He record is compatible with the history of weathering obtained from the $^{40}\text{Ar}/^{39}\text{Ar}$ Mn oxide geochronological record (Vasconcelos et al., 1994, 2015; Ruffet et al., 1996). Both records confirm that the Carajás surface is one the oldest continuously exposed land surfaces on Earth. The low erosion rates implied by the long history of surface exposure revealed by the

two independent weathering geochronology records ($^{40}\text{Ar}/^{39}\text{Ar}$ on Mn oxides and (U-Th)/He on Fe oxyhydroxides) are confirmed by the cosmogenic ^3He (Shuster et al., 2012; this study) and ^{53}Mn (Fujioka et al., 2010) records. By targeting the magnetic fraction of hematite ($\pm$ magnetite) pebbles, we were able to obviate the effects of partial ^3He loss during hydration of hematite to goethite, and are able to demonstrate that erosion rates at N1 and S11D are compatible with but even lower than that obtained from a 10m deep profile at the nearby N4C iron deposit (Fig. 1; Shuster et al., 2012).

The long history of exposure and weathering and the extreme resilience of the Carajás surface contrasts with the much shorter history of weathering and exposure derived from the more recent weathering geochronology results obtained for the four sites investigated on the Itacaiunas Surface. If we take these results at face value, they imply that the Itacaiunas Surface was exhumed and has been exposed to weathering and erosion for ~ 10 Ma.

5.5. Formation and evolution of the diachronous Itacaiunas erosion surface

The differences in elevation, depth of weathering, complexity of weathering profiles, and ages of weathering for the Carajás and Itacaiunas Surfaces lead to the conclusion that these land surfaces represent different stages of the geomorphological evolution of the Carajás region. The physical and chronological differences and the topographic relationships between the two surfaces (~ 720 m elevation average for the Carajás Surface and ~ 250 m for the Itacaiunas Surface) also suggest that the Itacaiunas Surface evolved at the expense of the Carajás Surface. To destroy a land surface, it is necessary to erode it. In this study, both the weathering geochronology and the cosmogenic isotope ^3He records indicate that the surface of the Carajás plateaus undergo negligible erosion (for example, in 80 Ma the surface of the N1 and S11D plateaus would have been lowered less than 30 m). Therefore, another

important conclusion is that the process that forms the Itacaiunas Surface at the expense of the Carajás Surface is scarp retreat. In fact, landslides are commonly observed in the major gullies and steep escarpments after the rainy season, suggesting that scarp retreat is the most active landscape evolution process modifying the Carajás Surface today and, most likely, throughout the Cenozoic.

Given the longevity of the Carajás Surface revealed by the weathering geochronology and cosmogenic isotope records, it is also reasonable to conclude that scarp retreat of a proto – Carajás Surface, presumably much more extensive than the present surface, has been ongoing since the beginning of the Cenozoic. Plate reconstructions show that the Carajás plateau region has been emergent for a long time, certainly since 160 Ma (Fig. 11; Amante and Eakins, 2009). Plate reconstructions also show that the Amazon plain has been intermittently submerged by advancing seas. In fact, until about 15 Ma the sea occupied areas close to Marabá (Fig. 11), as evident from fossiliferous calcareous units from the Pirabas Formation that crop out in this area (Petri and Fúlfaro, 1983). Renewed tectonic activity (Hoorn, 1993; Hoorn et al., 2010 and references there in) in the Andes at the time likely promoted uplift of the Brazilian shield, marine regression, and the onset of the scarp retreat that shaped the present Carajás landscape.

Weathering geochronology may help in the reconstruction of the history of scarp retreat, slow destruction of the Carajás Surface and consequent formation of the Itacaiunas Surface. The freshly exposed landsurface, or the sediments deposited on them by a retreating scarp, will be immediately subject to weathering and erosion. Under favorable conditions (low relief, abundant vegetation cover, humid climate, active biota), weathering will be more effective than erosion, and stratified weathering profiles blanketed by iron duricrusts will start to

develop locally. As the scarp retreats, a new surface is exposed, and the process repeats itself, forming a new duricrust. Therefore, the age of ferruginisation and duricrust formation on the Itacaiunas Surface should track the receding escarpment.

Another important inference is that scarp retreat will proceed from the coastline and along major drainages inward into the continent. Since the sea was near Marabá at ~ 15 Ma, sea level drop initiated at that time, possibly linked to the tectonic uplift event that tilted the continent towards the NE and drove the Amazon drainage into the Marajó graben (Shepard et al., 2010 and references therein), would have triggered the onset of the scarp retreat event that formed the Itacaiunas Surface. Using our geochronological results as markers of when the Itacaiunas Surface was exposed and stabilized at a given point, it is possible to reconstruct the patterns and retreat rates for the receding scarp (Fig. 12).

The reconstruction on Fig. 12 illustrates the possible sequence of events, and the rates of scarp retreat that shaped the present landscape at Carajás and adjacent areas. Assuming that the scarp initiated at the margins of the present Tocantins river at Marabá (Fig. 1, 12a), it would have reached and exposed our sites BOI 013 and BOI 014 by ~ 10-8 Ma (Fig. 12b), implying a rate of scarp retreat of 5-7 km.Ma⁻¹. From sites BOI 013 and BOI 014, the scarp retreats towards the Carajás plateau along the two major drainages, the Itacaiunas and the Parauapebas rivers (Fig. 1). The old duricrust at our BOI 002 site suggests that the Parauapebas river had eroded into approximately its present level by ~ 3 Ma. Given that the duricrust at this site is very close to escarpments to the east and west (Fig. 4d, 12e), it suggests that only a narrow valley was necessary for formation and stabilization of the duricrust. The rate of downward incision of the proto-Parauapebas river would have been 150 m.Ma⁻¹ at the site of the duricrust near Canaã dos Carajás, and the rate of scarp retreat along

the valley, from sites BOI 013 and BOI 014 to site BOI 002, would have been $\sim 20 \text{ km.Ma}^{-1}$. Finally, westward scarp retreat from the Vermelho River and eastward retreat from the Parauapebas River or vicinity would have partially consumed a then more extensive proto Serra Leste (SL), and the retreating escarpment would have exposed our BOI 004 site at $\sim 1 \text{ Ma}$ (Fig. 12d).

Independent of assumptions about the time of initiation of marine regression and possible uplift that would have triggered scarp retreat, the minimum and maximum scarp retreat rates estimated here are greater than rates of retreat of bedrock escarpment in East Australia ($0.003\text{-}0.035 \text{ km.Ma}^{-1}$; Heimsath et al., 2006), the Drakensberg in West Africa ($0.05\text{-}0.095 \text{ km.Ma}^{-1}$; Fleming et al., 1999), or the Serra do Mar escarpment in southeastern Brazil ($0.013\text{-}0.09 \text{ km.Ma}^{-1}$; Gonzalez et al., 2016), but they are comparable to rates estimated for scarp retreat on the Colorado Plateau ($0.5\text{-}6.7 \text{ km.Ma}^{-1}$; Schmidt, 1999 and references therein). If rates of scarp retreat at Carajás appear fast, it is relevant to consider that deep weathering profiles already blanketed the Carajás Surface by about 50 Ma, and that rivers and the receding scarps were eroding into deeply weathered bedrock. Deeply weathered granites, gneisses, schists, and other mineralogically complex lithologies would erode relatively easily. But when strong silica-cemented quartzites or iron-cemented banded iron-formations were encountered by the receding escarpment, scarp retreat rates would decrease. The remnant quartzite ridge at “Serra da Redenção” and the close proximity between the ferruginous duricrust at the Canaã dos Carajás and nearby Carajás surface BIF plateaus (Fig. 1) suggest that these resistive lithologies slowed or nearly stopped the receding scarp.

An important conclusion from this study is that the landscapes in the Carajás region are not in steady state, as steady-state landscape evolution models (Hack, 1960) require mountains and

valleys to erode at the same rate, which is incompatible with our geochronological results. On the other hand, the preservation of topographic summits completely immune to erosion for tens of millions of years (e.g., the Carajás Surface) is incompatible with a Davisian perspective on landscape evolution where the highest divides would progressively erode to a peneplain (Davis, 1899). Preservation of the Carajás Surface for > 70 Ma is also incompatible with Penck's model of landscape ablation towards an endrumpf in mature landscapes (Penck 1924, 1953). Therefore, the distribution of ages of weathering profiles at the Carajás-Marabá landscape is only compatible with King's scarp retreat model (King, 1956), where the Itacaiunas Surface is the pediplain that will ultimately consume the retreating Carajás Plateaus, erasing any memory of a past event of uplift.

This tentative landscape evolution history, informed by our weathering geochronology record, would benefit from refinement and a more comprehensive reconstruction through geochronology of additional sites. It would also benefit from cosmogenic isotope measurements at these same sites. Nevertheless, using the distribution of dated weathering profiles to infer processes and rates of landscape evolution is a novel, informative, and powerful new and quantitative way of tracking the evolution of landscapes through time. Expansion of this approach at Carajás and other similar land surfaces elsewhere will certainly improve our understanding of the climatic and tectonic history that shaped long-lived continental landscapes.

6. CONCLUSION

The weathering profiles of the Carajás Plateau record goethite precipitation spanning the entire Cenozoic. Cosmogenic ^3He concentrations suggest that the plateau surfaces have been essentially immune ($< 0.1 \text{ m.Ma}^{-1}$) to physical erosion throughout its Cenozoic history of

exposure. The paleosurface that was carved by scarp retreat to form the present Carajás Plateaus landscape may have extended at least to the Tocantins River in the Miocene. Sea level drop and tectonic uplift at ~ 15 Ma may have initiated river incision and scarp retreat. Apparent exposure ages as old as ~ 7 Ma suggest that the Carajás Plateau has eroded very slowly for most of the Cenozoic. The landscape investigated in this study developed through scarp retreat since the end of the Lower Miocene. Our (U-Th)/He results suggest at least two phases (different rates) of erosion. Retreat of the scarp at rates of 5-7 km.Ma⁻¹ initiated the destruction of the Carajás Surface. Exposure of fresh or partially weathered bedrock and fluvial sediments filling river channels to intense weathering led to the formation of incipient weathering mantles in the landscape. Between 8 – 3 Ma the scarp continued to retreat, now at an average rate of 20 km.Ma⁻¹, along the Itacaiúnas river and its tributaries. Ferruginization of the low-lying surface at the foot of the Carajás Plateau started around 3 Ma. Therefore, the low-lying surfaces surrounding the plateaus of Carajás are diachronous.

Acknowledgments

We thank present and past colleagues from Vale, particularly Carlos Monte Lopes, Luzimar Rego, Clovis Maurity, Paulo Sérgio Machado, Fernando Greco, Fernando Martins, Henrique Meireles, Carlos Augusto de Medeiros Filho, Augusto Kishida, and Felipe Porto for field support and heated discussions on the evolution of Carajás region. This project was funded by the Australian Research Council (ARC Discovery Grant DP160104988), Australian Research Council (ARC Linkage Grant LP4001008005), and the Brazilian Research Council (CNPq), which sponsored Hevelyn Monteiro's PhD studies. Electronic appendices are available at <http://dx.doi.org/10.17632/fgtdnjw3mn.2>

REFERENCES

- Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. de M., and Sparovek, G. (2014) Köppen's climate classification map for Brazil, *Meteorologische Zeitschrift*, **22** (6), 711-728.
- Alves, C. A., Bernardelli, A. L., and Beisegel, V. de R. (1986) A Jazída de níquel laterítico do Vermelho, Serra dos Carajás, In: Principais Depósitos Minerais do Brasil Vol. II, 325-334, Ed. Schobbenhaus, C. and Coelho, C. E. S., DNPM.
- Amante C. and Eakins B.W. (2009) ETOPO1 1 Arc-Minute Global Relief Model: Procedures, Data Sources and Analysis. NOAA Technical Memorandum NESDIS NGDC-24. National Geophysical Data Center, NOAA. doi:10.7289/V5C8276M.
- Araújo, O.J.B., Maia, R.G.N. (1991), Serra dos Carajás, folha SB.22-Z- A, Estado do Pará. Programa Levantamentos Geológicos Básicos do Brasil. Companhia de Pesquisa de Recursos Mimerais. 136 pp.
- Amidon, W. H., and Farley, K. A. (2011), Cosmogenic ^3He production rates in apatites, zircon and pyroxene inferred from Bonneville flood erosional surfaces, *Quaternary Geochronology*, **6**, 10-21.
- Andrade, W. O., Machesky, M. L., and Rose, A.W. (1989) Gold distribution and mobility in the surficial environment, Carajás region, Brazil, *Journal of Geochemical Exploration*, **40**, 95-114.
- Beauvais, A., Ruffet, G., Hénocque, O., and Colin, F. (2008) Chemical and physical erosion rhythms of the West African Cenozoic morphogenesis: The ^{40}Ar - ^{39}Ar dating of supergene K-Mn oxides: *Journal of Geophysical Research*, v. 113, F04007, doi:10.1029/2008JF000996.
- Beauvais, A., Bonnet, N. J., Chardon D., Arnaud N., and Jayananda M. (2016) Very long-term stability of passive margin escarpment constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of K-Mn

- oxides, *Geology* 44, 299-302.
- Bonnet, N. J., Beauvais, A., Arnaud N., Chardon D., Jayananda M. (2016) Cenozoic lateritic weathering and erosion history of Peninsular India from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of supergene K–Mn oxides, *Chemical Geology*, 446, 33-53.
- Carmo, I. O., and Vasconcelos, P. M. P. (2006) $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology constraints on late Miocene weathering, Minas Gerais, Brazil, *Earth Surface Processes and Landforms* 29, 1303-1320.
- Coelho, C. E. S. and Rodrigues, O. B. (1986) Jazida de Mnagães do Azul, Serra dos Carajás, Pará. In: *Principais Depósitos Minerais do Brasil Vol. II*, 145-152, Ed. Schobbenhaus, C. and Coelho, C. E. S., DNPM.
- Colin, F., Beauvais, A., Ruffet, G., Hénocque, O., (2005) First $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of lateritic manganese pisolites: implications for the Palaeogene history of a West African landscape. *Earth Planet. Sci. Lett.* 238, 172–188. <http://dx.doi.org/10.1016/j.epsl.2005.06.052>.
- Costa M. L., Lemos V. P., and Villas R. N. N. (1997) The bauxite of Carajás Mineral Province. In: *Brazilian Bauxites*, A. Carvalho, B. Boulangé, A. J. Melfi, Y. Lucas (eds), - São Paulo: USP, FAPESP; Paris: Orstom, 1997, 331p.
- Davis, W. M. (1899) The rivers and valleys of Pennsylvania, *Natl. Geog. Mag.*, v. 1, 183-253.
- DOCEGEO (Rio Doce Geologia e Mineração S.A.) (1988) *Província Mineral de Carajás. Litoestratigrafia e principais depósitos minerais*. 35 Congresso Brasileiro de Geologia, vol. 165.
- Fleming A., Summerfield, M. A., Stone, J. O., Fifield, L. K., and Cresswell, R. G. (1999) Denudation rates for the southern Drakensberg escarpment, SE Africa, derived from in-situ-produced cosmogenic ^{36}Cl : initial results. *Journal of the Geological Society*,

- London, 156, 209-212.
- Fujioka, T., Fifield, L. K., Stone, J. O., Vasconcelos, P. M. P., Tims, S. G., and Chappell, J. (2010). In situ cosmogenic ^{53}Mn production rate from ancient low-denudation surface in tropic Brazil, *Nuclear Instruments and Methods in Physics Research B*, 268, 1209-1213.
- Gonzalez, V. S., Bierman, P. R., Fernandes, N. F., and Rood, D. H. (2016) Long-term background denudation rates of southern and southeastern Brazilian watersheds estimated with cosmogenic ^{10}Be , *Geomorphology* **268**, 54-63.
- Grainger, C. J., Groves, D. I., Tallarico F. H.B., and Fletcher I. R. (2008) Metallogensis of the Carajás Mineral Province, Southern Amazon Craton, Brazil: Varying styles of Archean through Paleoproterozoic to Neoproterozoic base- and precious-metal mineralisation, *Ore Geology Review* 33, 451-489.
- Hack, J. T. (1960) Interpretation of erosional topography in humid temperate regions, *Amer. Jour. Sci.*, vol. 258-A, 80-97.
- Heim, J.A., Vasconcelos, P.M., Shuster, D.L., Farley, K.A. and Broadbent, G.C., (2006). Dating palaeochannel iron ore by (U-Th)/He analysis of supergene goethite. *Geology*, 34(3): 173-176.
- Heimsath, A. M., Chappell, J., Finkel, R. C., Fifield, K., and Alimanovic, A. (2006) Escarpment erosion and landscape evolution in southeastern Australia, in Willet, S. D., Hovius, N., Brandon, M. T., and Fisher, D. M., eds., *Tectonics, Climate, and Landscape Evolution: Geological Society of America Special Paper 398, Penrose Conference Series*, p. 173-190.
- Hoorn, C. (1993) Marine incursions and the influence of Andean tectonics on the Miocene depositional history of northwestern Amazonia: results of a palynostatigraphic study, *Palaeogeography, Palaeoclimatology, Palaeocology*, 105, 267-309.

- Hoorn, C., Wesselingh, F.P., ter Steege, H., Bermúdez, M.A., Mora, A., Sevink, J., Sanmartín, I., Sanchez-Meseguer, A., Anderson, C.L., Figueiredo, J.P., Jaramillo, C., Riff, D.D., Negri, F.R., Hooghiemstra, H., Lundberg, J., Stadler, T., Särkinen, T., Antonelli, A. (2010). Amazonia through time: Andean uplift, climate change, landscape evolution and biodiversity. *Science* **330**:927–931. <http://dx.doi.org/10.1126/science.1194585>.
- Huhn, S.R.B., Santos, A.B.S., Amaral, A.F., Ledsham, E.J., Gouveia, L.J., Martins, L.P.B., Montavo, R.M.G., Costa, V.C., (1988a), O terreno granite greenstone da regio de Rio Maria — Sul do Pará. Congresso Brasileiro de Geologia, Belém, Anais, vol. 35, pp. 1438–1452.
- Huhn, S.R.B., Santos, A.B.S., Amaral, A.F., Ledsham, E.J., Gougêa, J.L., Martins, L.P., Montalvão, R.G.M., Costa, V.G., (1988b), O terreno “granito greenstone” da região de Rio Maria — Sul do Pará. XXXV Congresso Brasileiro de Geologia, vol. 3, pp. 1438–1452.
- King, L. C. (1956), A Geomorfologia do Brasil Oriental *Revista Brasileira de Geografia*, 2, 147-265.
- Lal, D. (1991), Cosmic ray labeling of erosion surfaces: in situ nuclide production rates and erosion models, *Earth and Planetary Science Letters*, 104, 424-439.
- Levett, A., Gagen, E., Shuster, J., Rintoul, L., Tobin, M., Vongsvivut, J., Bambery, K., Vasconcelos, P., and Southam, G. (2016), Evidence of biogeochemical processes in iron duricrust formation, *Journal of South America Earth Sciences*, 71, 131-142.
- Lopes, C. A. M. (1999) As lateritas de Carajás. Relatório interno CVRD.
- Lucas, Y. (1989) Systemes pedologiques en Amazonie Brasilienne. Equilibres, desequilibres et transformations. Poltiers 159 p. (Tese de doutoramento, Université de Poltiers).
- Lucas, Y., Luizão, F. J., Chauvel, A., Rouiller, J., and Nahon, D. (1993) The relation between biological activity of the rain forest and mineral composition of soils. *Science*, vol. 260,

521-523.

- Machado, N., Lindenmayer, Z., Krogh, T.E., Lindenmayer, D. (1991) U–Pb geochronology of Archean magmatism and basement reactivation in the Carajás area, Amazon Shield, Brazil. *Precambrian Research* 49, 329–354.
- Maaskant P. and Kaper H. (1991) Fluorescence effects at phase boundaries: petrological implications for Fe-Ti oxides. *Mineral. Mag.* 55, 277-9.
- Monteiro, H. S., Vasconcelos, P. M. P., Farley, K. A., Spier, C. A., and Mello, C. L. (2014), (U-Th)/He geochronology of goethite and the origin and evolution of cangas, *Geochimica et Cosmochimica Acta*, 131, 267-289.
- Monteiro, H. S. (2017) Paleoenvironmental Evolution of Continental Landscapes Through Combined High-Resolution Geochronology and $\delta^{18}\text{O}$ Ion Microprobe Analysis of Goethite. PhD Thesis, The University of Queensland, Australia.
- Monteiro, H. S., Vasconcelos, P. M. P., and Farley K.A. (2018) A combined (U-Th)/He and cosmogenic ^3He record of landscape armoring by biogeochemical iron cycling. *JGR Earth Surface*, accepted manuscript online: 29 January 2018.
- Netuno Villas, R., and Santos, M. D. (2001) Gold deposits of the Carajás mineral province: deposit types and metallogenesis, *Mineralium Deposita*, 36, 300-331.
- Patterson, D. B., and Farley, K.A. (1998), Extraterrestrial ^3He in seafloor sediments: Evidence for correlated 100 kyr periodicity in the accretion rate of interplanetary dust, orbital parameters, and Quaternary climate, *Geochimica et Cosmochimica Acta*, 62(23/24), 3669-3682.
- Penck, W. (1953) Morphological analysis of landforms: New York, St. Martin's Press, 429 p.
- Penck, W. (1924) Die morphologische Analyse. Ein Kapitel der physikalischen Geologie: Stuttgart, Geog. Abh., 2 Reihe, heft 2, 283 p.

- Petri, S. and Fúlfaro, V. J. (1983) *Geologia do Brasil (Fanerozóico)*, - São Paulo: T. A. Queiroz: Ed. da Universidade de São Paulo, p. 631.
- Rezende, N. P. and Barbosa, L. M. (Eds.) (1972), *Relatório de Pesquisa de Minério de Ferro, Distrito Ferrífero da Serra dos Carajás, Estado do Pará - Brasil - Volume II*.
- Riffel, S.B., Vasconcelos, P.M., Carmo, I.O., Farley, K.A. (2015) Combined $^{40}\text{Ar}/^{39}\text{Ar}$ and (U–Th)/He geochronological constraints on long-term landscape evolution of the Second Paraná Plateau and its ruiniform surface features, Paraná, Brazil. *Geomorphology* 233, 52–63. <http://dx.doi.org/10.1016/j.geomorph.2014.10.041>.
- Ruffet, G., Innocent, C., Michard, A., Féraud, G., Beauvais, A., Nahon, D., Hamelin, B., 1996. A geochronological $^{40}\text{Ar}/^{39}\text{Ar}$ and $^{87}\text{Rb}/^{81}\text{Sr}$ study of K–Mn oxides from the weathering sequence of Azul, Brazil. *Geochim. Cosmochim. Acta* 60, 2219–2232. [http://dx.doi.org/10.1016/0016-7037\(96\)00080-4](http://dx.doi.org/10.1016/0016-7037(96)00080-4).
- Sahoo, P. K., Guimarães, J. T. F., Souza-Filho, P. W. M., Silva, M. S., Júnior, R. O. S., Pessim, G., Moraes, B. C., Pessoa, P. F. P., Rodrigues, T. M., Costa, M. F., and Dall'agnol, R. (2016) Influence of seasonal variation on the hydro-biogeochemical characteristics of two upland lakes in the Southeastern Amazon, Brazil. *Annals of the Brazilian Academy of Sciences*, 88(4): 2211-2227.
- Santos, P. A. dos (2006) *Estudo de densidades de rochas e comparação de técnicas de medição, Região do Quadrilátero Ferrífero, Minas Gerais, Brasil, Dissertação de Mestrado, ISEI: p. 58*.
- Schmidt, K.-H. (1999) The significance of scarp retreat for Cenozoic landform evolution on the Colorado Plateau, U.S.A. *Earth Surface Processes and Landforms* 14, 93-105.
- Shepard, G. E., Müller, R. D., Liu, L., and Gurnis, M. (2010) Miocene drainage reversal of the Amazon river driven by plate-mantle interaction. *Nature Geosciences*, vol. 3, 870-875.

- Shuster, D. L., Farley, K. A., Sisterson, J. M., and Burnett, D. S. (2004), Quantifying the diffusion kinetics and spatial distributions of radiogenic ^4He in minerals containing proton-induced ^3He , *Earth and Planetary Science Letters*, 217, 19-32.
- Shuster, D. L., Vasconcelos, P. M. P, Heim, J. A., and Farley, K. A. (2005), Weathering geochronology by (U-Th)/He dating of goethite, *Geochimica et Cosmochimica Acta*, 69(3), 659-673.
- Shuster, D. L., Farley, K. A., Vasconcelos, P. M. P, Balco, G., Monteiro, H. S., Waltenberg, K., and Stone, J. O. (2012), Cosmogenic ^3He in hematite and goethite from Brazilian "canga" duricrust demonstrates the extreme stability of these surfaces, *Earth and Planetary Science Letters*, 329-330, 41-50.
- Sombroek, W. G. (1966) Amazon soils. A reconnaissance of the soils of the Brazilian Amazon region. Wageningen, Holland. 292 pp.
- Stone, J. O. (2000), Air pressure and cosmogenic isotope production, *Journal of Geophysical Research*, 105(B10), 23,753-723,759.
- Trendall, A.F., Basei, M.A.S., Laeter, J.R., Nelson, D.R. (1998) SHRIMP zircon U–Pb constraints on the age of the Carajás formation, Grão Pará Group, Amazon Craton. *Journal of South American Earth Sciences* 11, 265–277.
- Tolbert, G.E., Tremaine, J.W., Melcher, G.C., Gomes, C.B., 1971. The recently discovered Serra dos Carajás iron deposit, northern Brazil. *Economic Geology* 66, 985–994.
- Vasconcelos, P. M. P., Rene P. R., Brimhall G. H., and Becker T. A. (1994), Direct dating of weathering phenomena by $^{40}\text{Ar}/^{39}\text{Ar}$ and K-Ar analysis of supergene K-Mn oxides, *Geochimica et Cosmochimica Acta*, 58(6), 1635-1665.
- Vasconcelos, P. M. P (2002), $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of supergene processes in ore deposits, *Reviews in Economic Geology*, 12, 73-113.

- Vasconcelos, P. M. P and Conroy, M. (2003) Geochronology of weathering and landscapes evolution, Dugald River valley, NW Queensland, Australia, *Geochimica et Cosmochimica Acta*, **67**, 2913-2930.
- Vasconcelos, P. M. P., Heim, J. A., Farley, K. A., Monteiro, H. S., and Waltenberg, K. M. (2013) $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th)/He - $^4\text{He}/^3\text{He}$ geochronology of landscape evolution and channel iron deposit genesis at Lynn Peak, Western Australia. *Geochimica et Cosmochimica Acta* **117**, 283-312.
- Vasconcelos, P. M. P and Carmo, I. O. (*in press*) Calibrating denudation chronology through $^{40}\text{Ar}/^{39}\text{Ar}$ weathering geochronology, *Earth-Sciences Review*.
- Viana, P. L., Mota, N. F. de O., Gil, A. dos S. B., Salino, A., Zappi, D. C., Harley, R. M., Ilkiu-Borges, A. L., Secco, R. de S., Almeida, T. E., Watanabe, M. T. C., dos Santos, J. U. M., Trovó, M., Maurity, C., and Giuliatti, A. M. (2016), Flora of the cangas of the Serra dos Carajás, Pará, Brazil: history, study area, and methodology, *Rodriguésia* **67**(5), 1107-1124.

FIGURE CAPTIONS

Figure 1: (a) An GMTED2010 (Global Multi-resolution Terrain Elevation Data) image illustrates the stepped landscape of the region encompassing the study area. The highlands of the Carajás Surface (CS) (900-600 m asl) (red in the DEM) contrasts with the surrounding low-lying Itacaiunas Surface (IS) (250-100 m asl). The CS is dissected to the north by the Itacaiunas and Parauapebas rivers and to the east by the Vermelho River. Three sites on the CS (Igarapé Bahia [IB], N1, and S11D) and four localities on the IS (BOI-002, BOI-004, BOI-013, BOI-014) were investigated in this study. A-A', B-B' and C-C' identify the Google Earth topographic transects presented in Fig. 1b, Fig. 4 and Fig. 1c, respectively. Shapes along B-B' transect correspond to each locality on the IS – B002 (star), B004 (circle), B013 (hexagon), and B014 (square). The N4 site is the locality investigated by Shuster et al., (2012).

Figure 2: Deep weathering profiles underlay the Carajás Plateau. At Igarapé Bahia (IB), (a) the 150 m thick weathering profile is covered by a 0 – 15 m thick soil layer. (b) A duricrust delimits the contact (dashed line) between goethite-gibbsite-quartz-rich soils and sediments and the underlying mottled zone and gossan. (c) Major element analyses of drill core samples from the IB profile reveal that Fe is preferentially enriched within the duricrust and gossans. (U-Th)/He ages obtained for goethites selected from 5 drill cores are presented in Fig. 2c. Ages obtained for core F124 are in black, while ages of goethites from adjacent drill holes (not in the plane of this cross section) are in red. Goethites from the duricrust and saprolite are commonly older than 30 Ma, while younger goethite generations (He ages < 5 Ma) were only found at great depths. The results imply that the weathering profile had already reached its currently depths at ~ 60 Ma.

Figure 3: (a, b) Deep weathering profiles developed on BIFs are also found in the N1, N4, N5, and S11D plateaus. (c) The plateaus are blanketed by a thick canga (~ 10 m) that varies in composition depending on the underlying lithology (BIF or volcanic units) (Rezende and Barbosa, 1972). Geological cross-section A-A' as indicated in (d). (d) Samples for geochronology and cosmogenic studies were collected at the surface along NE-SW transects on the N1 plateau. There is no clear pattern in the distribution of ages on the plateau surface.

Figure 4: (a) Field photo showing the topographic positions of the Carajás (background) and the Itacaiunas Surfaces (foreground) near the city of Canãa dos Carajás. (b) Basement rocks and Cenozoic continental sediments (Monte Lopes Formation) are overlain by shallow weathering profiles covered by an iron-cemented duricrust. This indurated, ferruginous horizon forms small and discontinuous plateaus at 200-285 m elevation widely distributed throughout the Itacaiunas Surface (c, d). (d) Location of topographic cross-section illustrated in Figure 1. Duricrusts are older ($9.36 \pm 0.94 - 7.44 \pm 0.74$ Ma) near the city of Marabá and become younger ($4.32 \pm 0.43 - 0.55 \pm 0.05$ Ma) inland towards the Carajás Plateau.

Figure 5: Photomicrographs of representative goethite grains from the IB, N1, and Itacaiunas Surface weathering profiles. (a) At the IB profile, pure colloform goethite occurs throughout the profile, particularly below the duricrust. This type of goethite is commonly devoid of contaminants and ideal for geochronology. (b) Pure, botryoidal goethite may also coexist with other supergene phases (e.g., Mn-oxides). (c) Goethites from the duricrust occur as complex layers of Al-rich and Al-poor goethites, intergrown with hematite and cementing gibbsite-rich pisoliths. They usually contain relict primary minerals. (d) The coexistence of multiple

goethite generations reveals the very dynamic nature of goethite cements in cangas of the N1 plateau. (e) Primary mineral (arrow), possibly containing significant amounts of ^4He , survives weathering and is incorporated within goethite masses. Degassing of goethites at temperatures above 900°C will release ^4He from these relic phases and generate discrepant ages. (f) During iron cementation, goethite replaces root fragment in the duricrust. (g-i) Typical goethite cements in sediments from the Itacaiunas Surface. They are usually less crystalline and less pure.

Figure 6: Electron microprobe analysis (1003 spots) for the Fe-oxyhydroxides investigated reveal that most goethites show some degree of elemental substitution. For example, well-crystallized IB goethites (Carajás Surface) may incorporate high concentrations of Mn, Cu, and P. N1 goethites (Carajás Surface) show large Al contents, while all Itacaiunas Surface goethites significant Al and Si contents.

Figure 7: Correlation diagrams for the elemental contents of goethite cements, as determined by EMPA, for the three distinct sites (IB, N1, and IS) illustrates goethite's propensity to reflect the composition of the underlying bedrock, as discussed in the text.

Figure 8: The distribution of (U-Th)/He ages shows the large discrepancy between the older results obtained for goethites from the IB and N1 sites (as old as ~ 80 Ma) and the ≤ 10 Ma results obtained for all four sites on the Itacaiunas Surface.

Figure 9: Trends in Th/U vs depth illustrate the effective leaching of U from surface sites and the progressive enrichment of Th towards the surface. In fact, a high Th/U value is indicative

of iron oxyhydroxides that have undergone several events of iron dissolution-reprecipitation that results in U loss. Samples with high Th/U values are also more complex, contain multiple generations intimately intergrown, and show greater variability in (U-Th)/He apparent ages for replicate grains from a single sample.

Figure 10: An age vs depth diagram for all goethites from the IB profile reveals that, on average, goethites are older near the surface, while younger generations are more frequent at depth. The results also show that the weathering profile had already reached depths of ~ 100 m by ~ 58 Ma. The calculated rate for weathering front propagation is similar to those obtained for Miocene weathering profiles in SE Brazil (Carmo and Vasconcelos, 2006), and twice as fast as similar rates obtained for weathering profiles in Australia (Vasconcelos and Conroy, 2003; Heim et al., 2006).

Figure 11: Plate reconstruction for South America shows that the Carajás region has been continuously emergent since 160 Ma, and that the sea has flooded areas adjacent to the Carajás Plateaus intermittently throughout the Mesozoic and Cenozoic, and as late as ~20-15 Ma. Renewed tectonic activity in the Andes at ~15 Ma likely promoted uplift of the Brazilian shield, marine regression, and the onset of the scarp retreat that shaped the present Carajás landscape.

Figure 12: The spatial and temporal distribution of dated duricrusts on the Itacaiunas Surface can be used as time markers of the relative positions of the receding escarpment that now surrounds the Carajás Plateaus and nearby ridges. Rates of scarp retreat and nickpoint propagation appear to vary through time (from 5-20 km.Ma⁻¹), and they are greater than

similar rates calculated for retreating bedrock escarpments in more arid landscapes. The rapid rate of scarp retreat derived from dated weathering profiles in this study are consistent with the fact that the Carajás Surface was already deeply weathered before the onset of scarp retreat.

Table 1: U, Th, He contents and (U-Th)/He ages for goethites from the different weathering profiles in the Carajás region, Brazil

Site	Sample Name	Coordinates	Elevation (m)	Calculated Age (Ma)	$\pm 1\sigma$ (Ma)	Age + 10% (Ma)	$\pm 10\%$ (Ma)	U (ppm)	$\pm 1\sigma$ (ppm)	Th (ppm)	$\pm 1\sigma$ (ppm)	He (nmol/g)	$\pm 1\sigma$ (nmol/g)	Th/U
Igarapé Bahia	B-93-01	S 06° 01' 46.6" W 50° 34' 6.55"		56.6	1.1	62.3	6.2	27.914	0.098	0.000	0.020	8.637	0.398	0.000
	B-93-01			64.3	1.3	70.8	7.1	8.464	0.037	0.010	0.012	2.979	0.229	0.001
	BA-P010-surface			61.9	1.3	68.1	6.8	123.191	0.448	0.133	0.013	41.742	3.510	0.001
	BA-P010-surface			60.8	1.2	66.9	6.7	111.338	0.393	0.096	0.031	37.023	1.128	0.001
	BAH 3 cml 7 3 bottom layers			14.0	0.3	15.5	1.5	141.685	0.510	0.025	0.016	10.830	0.477	0.000
	BAH 3 cml 7 3 bottom layers			13.2	0.3	14.5	1.5	153.012	0.554	0.031	0.015	10.976	0.499	0.000
	BAH 3 cml 7 3 bottom layers			12.3	0.3	13.6	1.4	117.608	0.424	0.011	0.013	7.899	0.442	0.000
	BAH 3 cml 7 3 bottom layers			10.1	0.2	11.1	1.1	176.009	0.626	0.096	0.029	9.697	0.241	0.001
	BAH 3 cml 7 3 bottom layers			10.3	0.2	11.4	1.1	117.498	0.424	0.039	0.013	6.598	0.372	0.000
	BAH 3 cml 7 3 bottom layers			14.9	0.3	16.4	1.6	99.298	0.352	0.190	0.021	8.038	0.303	0.002
	BAH 3 cml 7 large goethite layer			15.4	0.3	16.9	1.7	75.352	0.266	0.046	0.020	6.304	0.220	0.001
	BAH 3 cml 7 large goethite layer			14.2	0.3	15.6	1.6	81.710	0.289	0.065	0.018	6.310	0.250	0.001
	BAH-03 cml 6 LT100_black			4.3	0.1	4.8	0.5	135.483	0.485	0.026	0.018	3.182	0.166	0.000
	BAH-03 cml 6 LT100_black			4.3	0.1	4.7	0.5	126.224	0.446	0.000	-0.027	2.962	0.100	0.000
	BAH-03 cml 6 LT100_brown			7.0	0.1	7.7	0.8	52.988	0.186	-0.009	-0.029	2.019	0.064	0.000
	BAH-03 cml 6 LT100_brown			7.0	0.1	7.8	0.8	38.328	0.135	0.022	0.039	1.469	0.035	0.001
	BAH-100_black			31.0	0.6	34.1	3.4	1133.154	4.976	0.080	0.014	191.610	12.560	0.000
	BAH-100_black			38.2	0.8	42.0	4.2	311.649	1.278	0.043	0.008	64.923	7.825	0.000
	BAH-100_black			38.7	0.8	42.5	4.3	401.412	1.696	0.125	0.009	84.641	10.598	0.000
	BAH-100_black gt			32.4	0.7	35.6	3.6	1640.393	7.170	0.417	0.025	289.690	10.228	0.000
	BAH-100_black gt			42.7	0.9	47.0	4.7	1439.420	6.225	0.224	0.022	335.614	12.028	0.000
	BAH-100_brown gt			50.8	1.0	55.9	5.6	351.768	1.292	0.146	0.028	97.706	2.533	0.000
	BAH-100_brown gt			46.7	1.0	51.4	5.1	368.534	1.425	0.156	0.017	94.001	4.391	0.000
	BAH-100_brown gt			48.9	1.0	53.7	5.4	431.101	1.735	0.097	0.013	115.015	6.815	0.000
	BAH-99-01 gr1			23.5	0.5	25.9	2.6	111.593	0.392	0.073	0.041	14.301	0.247	0.001
	BAH-99-01 gr2			18.5	0.4	20.3	2.0	83.292	0.294	0.010	0.020	8.368	0.287	0.000
	BAH-99-01 gr3			26.4	0.5	29.0	2.9	70.571	0.248	0.060	0.027	10.133	0.264	0.001
	BAH-F115-15-16G			23.1	0.5	25.4	2.5	162.941	0.605	0.194	0.013	20.471	1.363	0.001
	BAH-F115-15-16G			22.9	0.5	25.2	2.5	160.235	0.568	0.090	0.030	19.964	0.480	0.001
	BAH-F124-111.2B			33.6	0.7	36.9	3.7	186.996	0.676	0.028	0.019	34.243	1.254	0.000
	BAH-F124-111.2B			37.3	0.8	41.1	4.1	130.926	0.471	0.016	0.015	26.647	1.255	0.000
	BAH-F124-112			48.9	1.0	53.8	5.4	38.800	0.136	-0.038	-0.018	10.356	0.489	-0.001
	BAH-F124-112			46.7	0.9	51.4	5.1	57.095	0.201	-0.060	-0.020	14.569	0.608	-0.001
	BAH-F124-112			49.8	1.0	54.7	5.5	35.899	0.126	0.000	-0.013	9.756	0.698	0.000
	BAH-F124-112			46.6	0.9	51.3	5.1	69.645	0.246	0.240	0.021	17.732	0.935	0.003
	BAH-F124-114			9.8	0.2	10.7	1.1	295.670	1.105	0.038	0.018	15.673	0.620	0.000
	BAH-F124-114			10.2	0.2	11.2	1.1	272.695	1.006	0.021	0.020	15.077	0.540	0.000
	BAH-F124-123.1 (black)			34.5	0.7	37.9	3.8	86.357	0.307	-0.004	-0.016	16.242	0.879	0.000
	BAH-F124-123.1 (black)			41.1	0.8	45.2	4.5	94.404	0.344	-0.015	-0.008	21.177	2.206	0.000
	BAH-F124-123.1 (sparkling)			10.4	0.2	11.5	1.1	27.129	0.095	-0.028	-0.010	1.536	0.127	-0.001
	BAH-F124-123.1 (sparkling)			11.9	0.2	13.1	1.3	20.446	0.072	-0.029	-0.016	1.321	0.070	-0.001
	BAH-F124-123.2 (weird gt)			25.1	0.5	27.6	2.8	32.090	0.113	-0.033	-0.011	4.380	0.330	-0.001
	BAH-F124-123.2 (weird gt)			28.3	0.6	31.2	3.1	18.450	0.065	-0.010	-0.011	2.847	0.228	-0.001
	BAH-F124-123.2 (black)			34.6	0.7	38.1	3.8	128.825	0.461	-0.061	-0.017	24.301	1.214	0.000
	BAH-F124-123.2 (black)			35.9	0.7	39.5	4.0	145.267	0.534	0.023	0.012	28.474	2.186	0.000
	BAH-F124-123.7			52.6	1.1	57.8	5.8	211.215	0.785	0.009	0.014	60.642	3.793	0.000
	BAH-F124-123.7			50.1	1.0	55.1	5.5	174.039	0.644	0.029	0.013	47.594	3.398	0.000
	BAH-F177-115			2.7	0.1	2.9	0.3	187.297	0.715	0.021	0.009	2.704	0.267	0.000
	BAH-F177-115			3.0	0.1	3.3	0.3	173.761	0.645	0.018	0.012	2.869	0.214	0.000
	BAH-F177-115 (brown)			21.3	0.4	23.4	2.3	33.400	0.117	0.561	0.035	3.891	0.123	0.017
	BAH-F226-142.7_black			4.4	0.1	4.8	0.5	119.159	0.428	0.013	0.014	2.832	0.186	0.000
	BAH-F226-142.7_black			4.0	0.1	4.4	0.4	107.999	0.384	0.042	0.018	2.334	0.122	0.000
	BAH-F226-142.7_brown			12.1	0.2	13.3	1.3	58.224	0.205	0.069	0.024	3.825	0.152	0.001
	BAH-F226-142.7_brown			13.2	0.3	14.5	1.5	62.647	0.222	0.078	0.012	4.498	0.367	0.001
	BAH-F226-142.7_sparkling			13.0	0.3	14.3	1.4	38.577	0.136	0.001	0.010	2.729	0.244	0.000
	BAH-F226-152.67			49.8	1.0	54.8	5.5	82.651	0.318	0.032	0.004	22.472	3.210	0.000
	BAH-F226-152.67			47.4	1.0	52.1	5.2	85.943	0.332	0.094	0.005	22.243	3.196	0.001
	BAH-F226-157.6_black			9.1	0.2	10.1	1.0	99.147	0.351	0.026	0.020	4.932	0.234	0.000
	BAH-F226-157.6_brown			11.3	0.2	12.4	1.2	49.801	0.175	0.008	0.020	3.064	0.145	0.000
	BAH-F226-157.6_brown			11.2	0.2	12.4	1.2	41.864	0.147	0.858	0.034	2.569	0.109	0.020
	BAH-F226-182.2_stalagmite			74.9	2.3	82.3	8.2	3.507	0.082	0.043	0.045	1.442	0.030	0.012
	BAH-F226-182.2_stalagmite			22.1	0.5	24.3	2.4	10.209	0.064	0.032	0.019	1.229	0.062	0.003
	BAH-F226-182.2_stalagmite			4.4	0.1	4.9	0.5	1.521	0.025	0.091	0.010	0.037	0.004	0.060
	BAH-F226-186.8 (dark grey)			45.3	0.9	49.8	5.0	585.804	2.289	7.605	0.118	145.257	6.332	0.013
	BAH-F226-186.8 (dark grey)			44.2	0.9	48.6	4.9	710.660	2.780	4.484	0.087	171.644	6.246	0.006
	BAH-F226-186.8			11.6	0.2	12.7	1.3	44.166	0.156	1.285	0.029	2.804	0.231	0.029
	BAH-F226-193.5			30.1	0.6	33.1	3.3	48.405	0.171	0.652	0.021	7.968	0.584	0.013
	BAH-F226-193.5			21.0	0.4	23.1	2.3	10.744	0.038	-0.008	-0.012	1.226	0.088	-0.001
	BAH-F282-118.2_black			27.2	0.6	29.9	3.0	39.341	0.140	-0.011	-0.007	5.832	0.671	0.000
	BAH-F282-118.2_black			10.0	0.2	11.0	1.1	21.414	0.075	-0.023	-0.010	1.163	0.102	-0.001
	BAH-F282-118.2_brown			38.0	0.8	41.8	4.2	72.838	0.260	-0.039	-0.010	15.082	1.212	-0.001
	BAH-F282-118.2_brown			29.8	0.6	32.8	3.3	58.836	0.215	-0.009	-0.005	9.559	1.612	0.000
	BAH-F282-118.4_brown			28.0	0.6	30.8	3.1	75.431	0.267	0.020	0.014	11.519	0.573	0.000
	BAH-F282-118.4_brown			35.4	0.7	39.0	3.9	108.357	0.396	0.018	0.009	20.926	1.719	0.000
	BAH-F282-118.4_brown&black			17.1	0.3	18.8	1.9	164.748	0.602	0.052	0.015	15.318	0.944	0.000
	BAH-F282-118.4_black			32.4	0.7	35.6	3.6	98.851	0.360	0.018	0.010	17.437	1.651	0.000

Table 2

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Table 2: Cosmogenic ^3He analysis

Sample	Rock type	Mineralogy	Location	Latitude	Longitude	Elevation (m)	Depth (cm)	Aliquot weight (mg)	^3He (pcc.g $^{-1}$)	^3He (Mat.g $^{-1}$)	$\pm$	Production rate (at.g $^{-1}$.a $^{-1}$)	Exposure age (Ma)	$\pm$	Erosion rate (m.Ma $^{-1}$)	$\pm$
N1P-13-08	canga	hem	N1 Plateau	S 06° 01' 30.9"	W 50° 16' 47.8"	784	0	14.80	6.3	170		73	2.3	0.3	0.24	0.03
N1P-13-20	canga	hem	N1 Plateau	S 06° 01' 45.9"	W 50° 17' 01.8"	724	0	19.28	8.9	241		70	3.4	0.4	0.16	0.02
SS-03-01 o/c	canga	hem	Serra Sul	S 06°24'26.87"	W 50° 19'38.46"	678	0	-	18.4	495	21	68	7.3	0.3	0.08	0.003
SS-03-02 o/c	canga	hem	Serra Sul	S 06°24'26.87"	W 50° 19'38.46"	836	0	-	7.4	199	10	76	2.6	0.1	0.21	0.01
SS-03-03 o/c	canga	hem	Serra Sul	S 06°24'26.87"	W 50° 19'38.46"	884	0	-	3.7	100	13	79	1.3	0.2	0.44	0.06
N1P-13-01 (1)	pebble	hem	N1 Plateau	S 06° 01' 27.3"	W 50° 16' 45.1"	776	0	15.04	10.6	286		73	3.9	0.5	0.14	0.02
N1P-13-01 (2)	pebble	hem	N1 Plateau				0	14.41	7.3	197		73	2.7	0.3	0.20	0.02
N1P-13-16 (1)	pebble	hem	N1 Plateau	S 06° 01' 33.1"	W 50° 17' 02.8"	726	0	17.03	16.7	449		70	6.4	0.8	0.09	0.01
N1P-13-16 (2)	pebble	hem	N1 Plateau				0	16.83	16.9	455		70	6.5	0.8	0.09	0.01