A numerical model for duricrust formation by water table fluctuations

By Caroline Fenske, Jean Braun, François Guillocheau, and Cécile Robin

Review by Paulo Vasconcelos
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Fenske et al. propose to develop and apply a numerical model for iron duricrust formation by water table fluctuations. They interpret their model to be based on sound physical and chemical processes and apply the model to test whether the formation of ferricretes slows erosion. Their main conclusion is that ferricretes have a limited and transient role in slowing erosion and protecting the underlying weathering profiles.

A model that properly couples chemical weathering and landscape evolution is long overdue, and such a model would allow geochemists, geomorphologists, tectonicists, geophysicists, and other geoscientists to test several hypothesis linking paleoclimates and tectonics with landscape evolution. The model advanced by Fenske et al. proposes to do so, but it comes short of its objectives.

The model fails in four aspects:

- the model is based on sound depiction of physical processes, but it does not have any chemical component;

- it is based on a misunderstanding of the mechanisms underlying the formation of iron duricrusts;

- literature review on the topic ignores relevant information demonstrating that iron duricrusts are indeed long-lived and slowly eroding components of cratonal landscapes;

- when the model is applied it produces results that are not substantiated by other models or by observations and measurements of physical reality.

An important shortcoming of the work is that it is based on a misunderstanding of the models proposed for the formation of iron duricrusts, which the authors summarize as:

> "Two hypotheses have been proposed for the formation of duricrusts, i.e., the hydrological or horizontal model where the enrichment in the hardening element (iron for ferricretes) is the product of leaching and precipitation through the beating of the water table during contrasted seasonal cycles, and the laterisation or vertical model, where the formation of iron duricrusts is the final stage of laterisation."

There is indeed consensus that some duricrusts form by lateral introduction of iron into lower parts of the landscape and others form by in situ concentration of iron through time (laterization model); these are the "transported and in situ ferricretes" of Bourman (1996)

Bourman, R.P., 1996. Towards distinguishing transported and in situ ferricretes: data from southern Australia. AGSO Jour. Aust. Geol. Geophys. 16 (3), 231–241.

and discussed previously by several authors (e.g., Maignien, 1959, 1966; Ollier, 1969; McFarlane, 1976).

The ferricrete-producing process addressed by the numerical model in this work does not represent either of the accepted genetic models discussed by Bourman (1996) or Bourman et al. (2020). The lateral model proposes that transported ferricretes form by the lateral introduction of iron-bearing minerals, rocks and solutions into lower segments of the landscape, including channels and river beds, where ferruginization occurs. In this model, there is an unconformity between the ferricrete and underlying lithologies or weathering profiles, as described in Bourman et al. (2020). As the landscape evolves, the ferricrete is more resilient than surrounding rocks, it resists erosion, and relief inversion occurs. The channel iron deposits of Western Australia would represent an extreme example of the transported ferricrete model.

The lateritic model proposes that iron is concentrated in situ, also by physical and chemical processes, through time; the duricrust evolves through the entire history of weathering and it is not "the final stage of laterisation.", as interpreted by the authors. Recurrent physical and chemical transport of iron throughout the entire history of laterization is documented by mineralogical and geochronological work (e.g., Monteiro et al., 2014, 2018a,b).

Water table ferruginization, the issue modelled by Fenske et al., does not represent either of the models above. It does occur in special circumstances, and it is particularly common at the margins of major rivers in the Amazon, along the Atlantic coast of Brazil (Monteiro et al., 2020), in Western Australia (Mann, 1983), and other localities in Africa, India, New Caledonia and elsewhere. Iron oxyhydroxide cementation occurs in places where reducing groundwaters rich in Fe^{+2} ascend towards the surface or interact with O_2-rich meteoric water within permeable units, and iron hydrolyses and precipitates. Such ferruginized horizons occur in areas dominated by Dunne overland flow in the vicinity of BIF plateaus at Urucum, Brazil (Vasconcelos et al., 2018). But these ferruginized horizons are generally thin, of limited spatial distribution, and are not the direct precursors of the ferricretes that control regional landscape evolution. Thus, the water table "ferruginization" problem addressed by the numerical model of Fenske et al. is only marginally related to ferricretes and it does not represent either of the main ferricrete-formation models.

In addition, the physical parameters modelled by Fenske et al. are space, time, elevation (topographic height), surface slope, height of water table, precipitation rate, fluid flow velocity, hydraulic conductivity, regolith thickness, and diffusivity. The "chemical parameters" in the model are a dimensionless quantity that represents hardening or increase in "relative resistance to surface erosion", similar to that introduced by Sacek et al. (2018), and another arbitrary parameter that represents regolith hardening time. There is no chemistry in either parameter. The authors interpret these arbitrary hardening parameters as representing the formation of a ferricrete during "chemical weathering", but as it currently stands, it could be formation of silcrete, calcrete, or any other cement that decreases regolith erodibility. The lack of any chemical parameter relevant to the dissolution and reprecipitation of iron in the near surface environment makes it improper to use these hardening parameters as a model for the formation of ferricretes.

The authors also propose to "present the first numerical model for the formation of iron duricrusts based on the hydrological hypothesis". Numerical models dealing with fluid flow and chemical reactions at geological time scales, where iron dissolution and reprecipitation takes place, have been presented by Lichtner (1988), Lichtner and Waber (1992), Lichtner and Biino (1992) and many contributions since then. Lichtner and Waber (1992) consider the competing effects and the timescales of weathering and erosion, but do not directly model erosion. Thus, numerical approaches that deal with iron dissolution and reprecipitation based on robust thermodynamic, kinetic, and fluid flow models have existed for several decades.

Despite the fact that the basic model proposed by Fenske et al. does not address the accepted end-member models of ferricrete genesis and it does not contain any chemical component, the authors take the model results at face-value, without considering that the model itself may not be a correct depiction of nature. When faced with the fact that the model does not produce a result consistent with other observations and measurements, the authors could revisit the model to assess its applicability. Instead, the authors prefer to conclude that all observations and measurements are wrong. Publication of the manuscript as is will not advance our understanding of the role of weathering in landscape evolution, and it may mislead the uninformed reader into believing that we finally have a modelling approach that couples chemical weathering and landscape evolution, which is not the case.

I will provide below a few specific comments and suggestions, line-by-line or section-by-section, that aim at improving the current version of the manuscript:

- Line 7 and throughout the manuscript.

The authors use the term “water table fluctuations” in their title, a perfect term for describing the vertical movement of the water table through time. They also use water table fluctuation to label the y-axis of their graph in Figure 4. However, in Line 7 of the abstract and throughout the manuscript they replace the perfectly understood and commonly used “water table fluctuation” by the “beating of the water table”. The new term is unusual, confusing, totally unnecessary in face of the already available and perfectly understood “water table fluctuation”. Beating of the water table and water table beating throughout the text should be replaced by “water table fluctuation” to make the text clearer and consistent with Figure 4.

- Lines 18-21.

The statement “Finally we demonstrate that the commonly accepted view that, because they are commonly found at the top of hills, duricrusts protect elements of the landscape is most likely an over-interpretation and that caution must be taken before using duricrusts as markers of uplift and/or base level falls.” ignores the fact that the protection against erosion offered by duricrusts is not an “accepted view” but the result of numerous measurements and field relationships that cannot be simply “modelled away”. If the model does not support the measurements and observations of physical reality, the model should be reconsidered, not alternate realities proposed.

- Lines 23-24.

“Understanding Earth’s surface evolution in cratonic areas remains difficult in part~~s~~ due to its slow and therefore difficultly measurable rates but also due to the important contribution from chemical weathering and the formation of the regolith.”

- Lines 32-33.

“It describes an indurated ~~elemental~~ layer usually found capping hills or surfaces~~,~~ that appears to protect them from erosion (Taylor and Eggleton, 2001).”

Duricrusts are not indurated by elements, they are indurated by minerals.

- Lines 36-37.

“Duricrust formation is likely to depend on water availability, often linked to climatic conditions and, for certain types of duricrusts, on the minerals present in the regolith and/or the underlying protolith.”

Suggestion:

“Duricrust formation depends on water availability, often linked to climatic conditions, and on the minerals present in the regolith and/or the underlying protolith.”

Duricrusts form when elements dissolve and re-precipitate, cementing parts of the regolith. Element dissolution-reprecipitation does not occur in the absence of water or the elements forming the cements.

- Lines 37-40.

“To cite some examples, gypsite crusts form in hyper-arid areas (Watson, 1988), silcretes and calcretes form in arid environments (Nash et al., 1994), whereas iron duricrusts form in areas where more water is available during a certain period of the year (Tardy, 1993), and bauxitisation happens under tropical conditions (Retallack, 2001).”

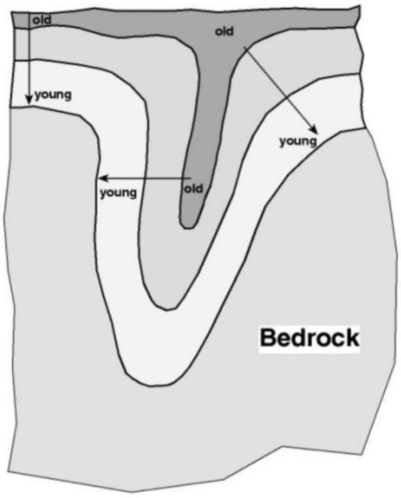
The conditions under which duricrusts form are largely undetermined and the statements above are simply working hypotheses. For example, under similar climatic conditions a gypsum-cemented (gypsite) or a calcite-cemented (calcrete) duricrust may form, depending on the relative amounts of HCO_3^-, $SO_4^=$, and Ca^{++} dissolved in the groundwater.

- Lines 40-42.

“Although no direct measurement of their rate of formation is yet available, one can estimate that the time needed to create a duricrust is of the order of 10^5 or more years (Tardy, 1993; Taylor and Eggleton, 2001).”

In a very simplistic view, determining rate of formation of a weathered zone or duricrust would require measuring when the weathering front arrived at a given position within the weathering profile, as illustrated below:

WEATHERING PROCESSES 187

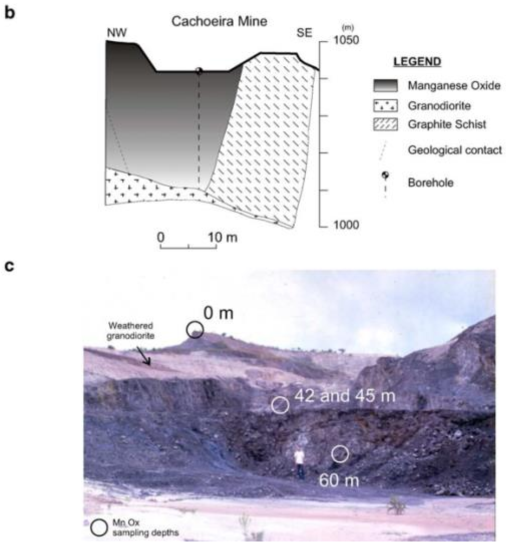


Vasconcelos, 1999

For simple weathering profiles, determining the rate of formation has been successfully carried out, as for a manganocrete in Minas Gerais, Brazil,

$^{40}Ar/^{39}Ar$ geochronology constraints on late miocene weathering rates in Minas Gerais, Brazil

Isabela de Oliveira Carmo [a,1], Paulo Marcos Vasconcelos [b,*]



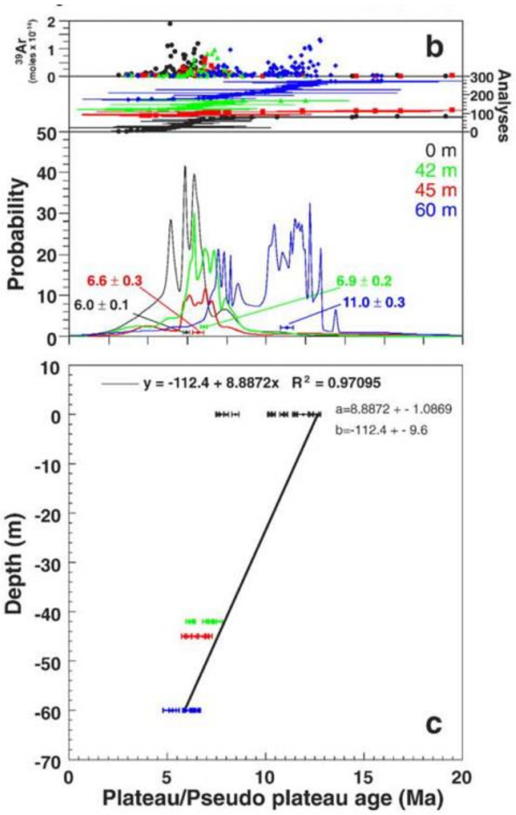


Fig. 4. (a) Histogram representing the modal distribution of the ages, and (b) a probability density plot illustrating the same results. (c) Plateau and pseudo plateau ages vs. depth for the 45 cryptomelane grains analyzed. The best fit line in the age vs. depth plot was obtained by using only the greatest plateau age at each depth, which records the minimum age for the arrival of oxidizing weathering solutions at each horizon. The slope of the best fit line is interpreted as the rate of propagation of the oxidation front (values for the linear fit were obtained by using the software *Ajuste 1.1* available at http://omnis.if.ufrj.br/~carlos/applets/reta/reta.html). Extrapolation of this curve to zero age intercepts the *y*-axis at ~100 m, the approximate depth of the weathering profile revealed by drill-core information.

that suggests that the weathering front advanced at a rate of 8.9 ± 1 $m.Ma^{-1}$ (Carmo and Vasconcelos, 2006)

The problem encountered when trying to apply the same approach to other duricrusts, particularly ferruginous duricrusts, is that recurrent mineral precipitation-dissolution-reprecipitation is the norm, and a simple age versus depth relationship in weathering profiles does not exist in most cases. The best that can be done with geochronology is to date as many samples as possible from various depths within a single weathering profile, such as in the example for a site in the tropical Amazon region illustrated below

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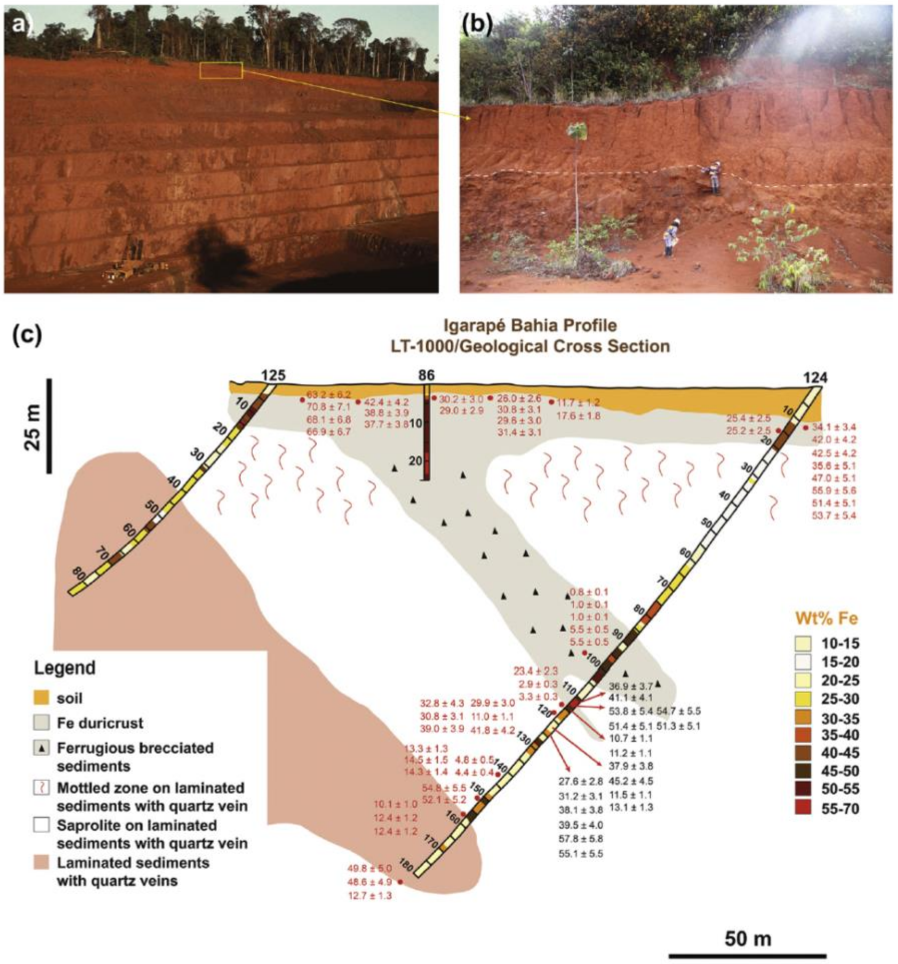


Fig. 2. Deep weathering profiles underlay the Carajás Plateau. At Igarapé Bahia (IB), (a) the 150 m thick weathering profile is covered by a 0–15 m thick soil layer. (b) A duricrust delimits the contact (dashed line) between goethite-gibbsite-quartz-rich soils and sediments and the underlying mottled 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.

and use the age vs depth relationship through the oldest mineral at each depth to derive a weathering front migration rate (8.5 m.Ma^{-1} in the example below):

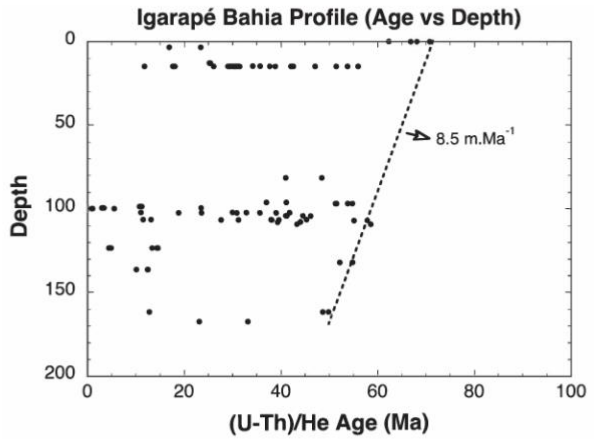


Fig. 10. An age vs depth diagram for all goethites from the IB profile reveals that, on average, goethites are older near the surface, while younger generations are more frequent at depth. The results also show that the weathering profile had already reached depths of ~100 m by ~58 Ma. The calculated 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).

For Australian conditions, Heim et al. (2006) show that channel aggradation probably occurred at ~ 36 Ma, and that for the past 15 Ma the water table has been dropping and iron cementation has also progressed downward at the same rate as groundwater drawdown. Based on the (U-Th)/He results for goethite cements, water table drawdown progressed at a rate of 1.2 to 1.5 m.Ma^{-1}.

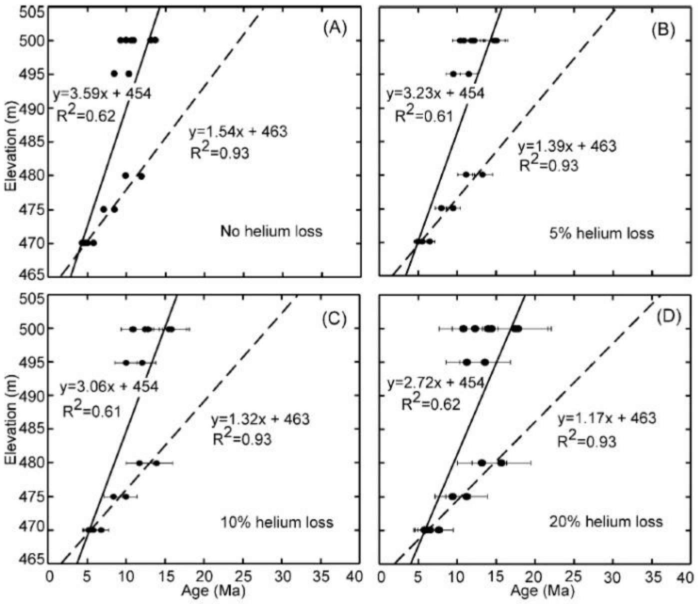


Figure 2. Goethite elevation versus (U-Th)/He ages for (A) uncorrected ages, and ages corrected for (B) 5%, (C) 10%, and (D) 20% ^{4}He losses, showing that the results are statistically reproducible (2σ) when corrected for 10 and 20% ^{4}He losses. Linear regression curves (solid lines) of all samples for each plot show progressively younger results with increasing profile depth ($R^2 \approx 0.61$). Correlation coefficients are much greater ($R^2 = 0.93$) if only lower CID samples are plotted (dashed lines), suggesting the presence of two age populations (see text). Extrapolating the younger results, corrected for 20% ^{4}He losses, to the original channel surface (~505 m) shows an intercept at 36 Ma, consistent with palynological ages for the initiation of channel aggradation (MacPhail and Stone, 2004). Upper CID samples are offset from this trend, suggesting partial dissolution and reprecipitation of goethite cement near the surface, possibly associated with excursion to more humid climates in the Miocene (McGowran et al., 1997).

In addition to the examples above, it is also possible to estimate rates of formation of duricrusts by dating ferruginous horizons at different states of evolution. For example, Riffel et al. (2016) shows that incipient duricrusts form at the 1-2 Ma timescales.

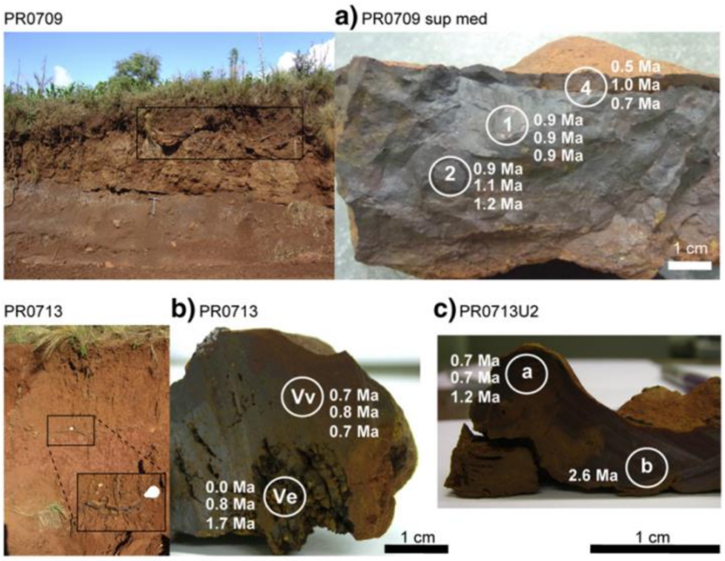
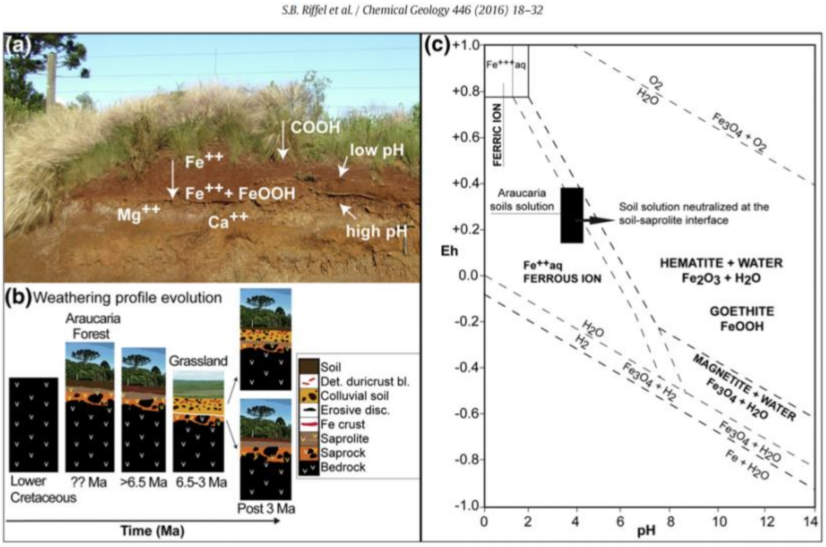


Fig. 8. (U–Th)/He ages for the goethite collected *in situ* (a) and colluvium (b, c) from Guarapuava.



Monteiro et al. (2018) shows that shallow iron duricrusts in the Carajás Region, Brazil, take between 1 and 10 Ma to form:

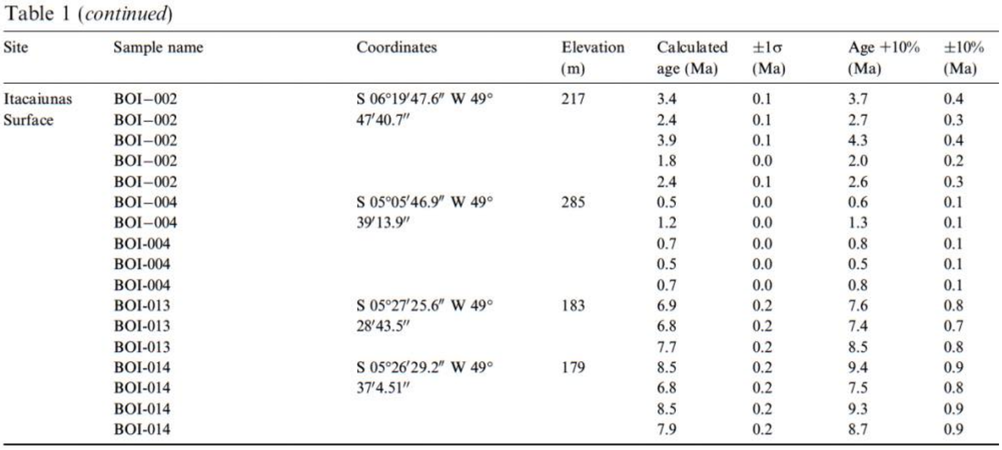


Table 1 (*continued*)

Site	Sample name	Coordinates	Elevation (m)	Calculated age (Ma)	±1σ (Ma)	Age +10% (Ma)	±10% (Ma)
Itacaiunas Surface	BOI–002	S 06°19′47.6″ W 49° 47′40.7″	217	3.4	0.1	3.7	0.4
	BOI–002			2.4	0.1	2.7	0.3
	BOI–002			3.9	0.1	4.3	0.4
	BOI–002			1.8	0.0	2.0	0.2
	BOI–002			2.4	0.1	2.6	0.3
	BOI–004	S 05°05′46.9″ W 49° 39′13.9″	285	0.5	0.0	0.6	0.1
	BOI–004			1.2	0.0	1.3	0.1
	BOI-004			0.7	0.0	0.8	0.1
	BOI-004			0.5	0.0	0.5	0.1
	BOI-004			0.7	0.0	0.8	0.1
	BOI-013	S 05°27′25.6″ W 49° 28′43.5″	183	6.9	0.2	7.6	0.8
	BOI-013			6.8	0.2	7.4	0.7
	BOI-013			7.7	0.2	8.5	0.8
	BOI-014	S 05°26′29.2″ W 49° 37′4.51″	179	8.5	0.2	9.4	0.9
	BOI-014			6.8	0.2	7.5	0.8
	BOI-014			8.5	0.2	9.3	0.9
	BOI-014			7.9	0.2	8.7	0.9

The various approaches available for determining the rates of formation of duricrusts illustrated above are not ideal, but they are the ones imposed by the complexities of physical reality. They also show that the statement "Although no direct measurement of their rate of formation is yet available,… " is incorrect. Much of the literature on the topic has been ignored.

In addition, the absence of any direct geochronological evidence that ferricretes younger then ~ 1 Ma exist also shows that the statement "one can estimate that the time needed to create a duricrust is of the order of 10_5 or more years (Tardy, 1993; Taylor and Eggleton, 2001)." is probably incorrect because it most likely underestimates the time needed for the formation of ferricretes in nature. On the other hand, young duricrusts (< 1-2 Ma) only have a minor role in slowing erosion. They form small steps on the landscape, and they are more easily destroyed by scarp retreat than older, thicker, better cemented duricrusts.

- Lines 47-49. "We will concentrate our study on ferricretes, also called ferruginous duricrusts, iron duricrusts or iron crusts, iron enriched levels or cangas (Tardy, 1993; Tardy and Roquin, 1998; Nahon, 1991; Paton and Williams, 1972; Ollier and Galloway, 1990; Vasconcelos et al., 1992; Monteiro et al., 2014; Vasconcelos and Carmo, 2018)."

Vasconcelos et al. (1992) do not address ferricretes, ferruginous duricrusts, iron duricrusts or iron crusts, iron enriched levels or cangas. However, classical work on the topic by Dorr (1964, 1969), Maignien (1966), McFarlane (1976), Ollier (1966), Tardy (1997), Samama (1986), or those using modern tools by Vasconcelos et al. (1994), Vasconcelos (1999a,b), Shuster et al. (2005), Shuster et al. (2012), or Monteiro et al. (2018a,b,c) were mostly ignored.

- Lines 49-50. “Ferricretes are indurated layers made mostly of iron, with possible traces of other elements, e.g., titanium or manganese.”

The most common elements other than Fe in ferricretes are Al and Si. Ti is common in ferricretes formed over basalts or gabbros; Cr and Al are common in ferricretes formed over ultramafic rocks.

- Lines 57-59. A climate conducive to the formation of iron duricrusts encompasses the following characteristics (Tardy et al., 1991; Tardy, 1993): 1) a mean annual rainfall, P, of around 1450 m.yr^{-1}, 2) a mean annual temperature, T, of ~28°C, a mean relative air humidity of around 70~%, and 4) a long dry period of at least 6 months.

The numbers above are extracted from Tardy (1997) (the English edition of Tardy 1993), fifth paragraph, page 359. Tardy was careful to give ranges for the values above, not absolute figures. Unfortunately, these estimates are derived from current climate data for sites where iron duricrusts presently occur. Evidence that lateritic weathering profiles form during prolonged periods during which climates change suggest that those numbers are simple estimates not based on any direct measurement. They are Tardy’s estimations from mapping the global distribution of lateritic profiles and they should be regarded as such.

- Lines 60-63. The preservation of iron rich levels and duricrusts through time depends on climate too. In semi-arid to arid areas, they are preserved and protect the regolith for longer periods of time than in subtropical to tropical areas as described by Taylor and Eggleton (2001); Tardy (1993).

Some of the oldest preserved lateritic profiles on Earth occur in the Amazon (Carajás) and Minas Gerais (Quadrilátero Ferrífero), both tropical areas. Their ages, distribution, and the regional climatic conditions are thoroughly documented in the literature. Thus, the statement above is not based on any direct measurements of the distribution, ages and longevity of ferruginous duricrusts across the planet.

- Lines 66-69. There are currently two hypotheses for the formation of iron duricrusts: a hydrologically-based process (Taylor and Eggleton, 2001; Achyuthan, 2004; Widdowson, 2009; Bonsor et al., 2014; Riffel et al., 2016; Bourman et al., 2020) and a laterization based process (Tardy, 1986; Tardy et al., 1988; Nash et al., 1994; Tardy, 1993; Theveniaut and Freyssinet, 1999; Taylor and Eggleton, 2001), which are also referred to as horizontal and vertical models.

The authors should consult the literature again to make sure they understand the two models correctly. Their summaries in lines 70-113 could be greatly improved with a better understanding of the two models.

- Lines 71-73. In this model, iron duricrusts form under a contrasting yearly climate, made of primarily wet and dry periods. During wet periods, the water table height is high and minerals, such as Fe^{+2}, are transported from adjacent regions and accumulate. During dry periods, the water table height drops and minerals, such as Fe^{+3}, precipitate.

Availability of aqueous (Fe^{+2}_{aq}) iron species is indeed an important aspect in the formation of iron duricrusts, in conjunction with iron oxidation ($Fe^{+2}_{aq} \Rightarrow Fe^{+3}$) into the trivalent species, which readily hydrolyses and precipitates as goethite or hematite. But Fe^{+2} and Fe^{+3} are chemical species in solution, they are not minerals. Goethite and hematite are the relevant minerals in the case of most duricrusts. Understanding the redox behavior of iron in the near surface environment is key in formulating a credible model for the formation of duricrusts. The redox behavior of iron in the presence of oxygenated rainwater is rather complex. In general, iron solubility requires ligands, such as organic acids, to provide the acid-reducing conditions necessary to stabilize the reduced (Fe^{+2}_{aq}) iron species in solution. Increase in oxidation potential and alkalinity promptly promotes iron reprecipitation. Most oxygenated water tables in the near surface environment are poor in soluble iron because Eh-pH conditions are often within the thermodynamic stability field of goethite-hematite. Simply equating weathering with water table movement and defining that something precipitates when the water table moves up or down is too simplistic an approach, without any chemical basis, to properly model iron mobility and Fe-duricrust formation.

- Lines 73-76. This cycle repeats itself for thousands of years, with the accumulation of iron elements leading to the formation of nodules, which, ultimately, cement into a ferruginous crust. In this case, no genetic link between the bedrock and the regolith beneath is needed nor described (Ollier and Galloway, 1990; Taylor and Eggleton, 2001).

The process repeats itself for millions of years, but the only "element" that accumulates is iron (there are no other "iron elements", there are "iron isotopes"), in the form of either goethite, hematite, or lepidocrocite, depending on water availability, pH, rates of oxidation and precipitation, etc. A genetic link is indeed missing when the duricrust forms by iron cementation of detrital phases deposited unconformably on unrelated bedrock paving valley floors. But the material that is deposited in valleys and eventually becomes iron cemented is generally iron-rich, i.e., the iron is not entirely introduced by the groundwater; it is often locally remobilized.

- Lines 100-103. There exists, at this stage, no numerical model for the formation of duricrusts, apart from the conceptual model developed by Nash et al. (1994) and the highly simplified model developed by Sacek et al. (2019) to estimate the effects of duricrust formation on erosional patterns at the continental scale.

The "model" of Nash et al. (1994) for the formation of calcretes and silcretes in Africa does not provide a suitable analogue for the formation of iron duricrusts. Calcretes and silcretes depend on the amount of Ca^{++} and H_4SiO_4 in solution, and precipitation of $CaCO_3$ (in the form of calcite) and SiO_2 (in the form of opal, chalcedony, or quartz) is readily achieved by supersaturation when water ascends to the surface and evaporates. Iron solubility is much more complex, it depends on pH and redox conditions, it depends on the availability of ligands, iron reprecipitation may be partially catalyzed by microorganisms, etc. Iron is most often locally sourced, mobilized, and reprecipitated. Long-range transport of iron requires special circumstances, such as those documented by Mann (1983) in Western Australia.

In addition, there are numerous numerical models for the formation of Fe-bearing leached caps (Lichtner and Biino, 1992) and of bauxites (Soler and Lasaga, 1996) that are based on fundamental thermodynamics, kinetics, and fluid flow modelling. It is true that there are no models that combine fluid flow, geochemical thermodynamics/kinetics and the physical processes – e.g., hillslope diffusion, channel transport, landslide/rock fall – controlling landscape evolution, i.e., there are no models coupling weathering to erosion. Such models are still missing.

- Lines 76-79. Also, duricrusts form at the water table, which means at multiple metres below the surface. It is generally accepted that, to permit accumulation of materials, the region needs to be tectonically inactive and that later periods of uplift (or base-level drop) are likely to exhume the duricrust to the surface where it becomes more resistant to erosion than the surrounding weathered material.

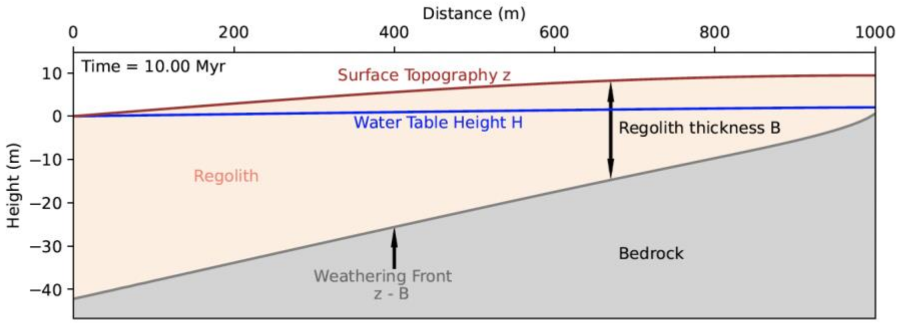
Most authors suggest that iron duricrusts form at the surface, not subsurface. For example, the duricrusts formed from Dunne overland flow at the lowlands at Urucum (Vasconcelos et al., 2018) form at the surface. If there are references that support duricrust formation by an ascending or descending water table (e.g., Mann, 1983), they should be provided. Importantly, duricrusts that form when the water table ascends to the surface, water evaporates, and minerals precipitate are more relevant to calcretes or silcretes than ferricretes.

The model presented by the authors is a modification of a regolith formation model by Braun et al. (2016):

- Lines 114-180. 2 Method and Results

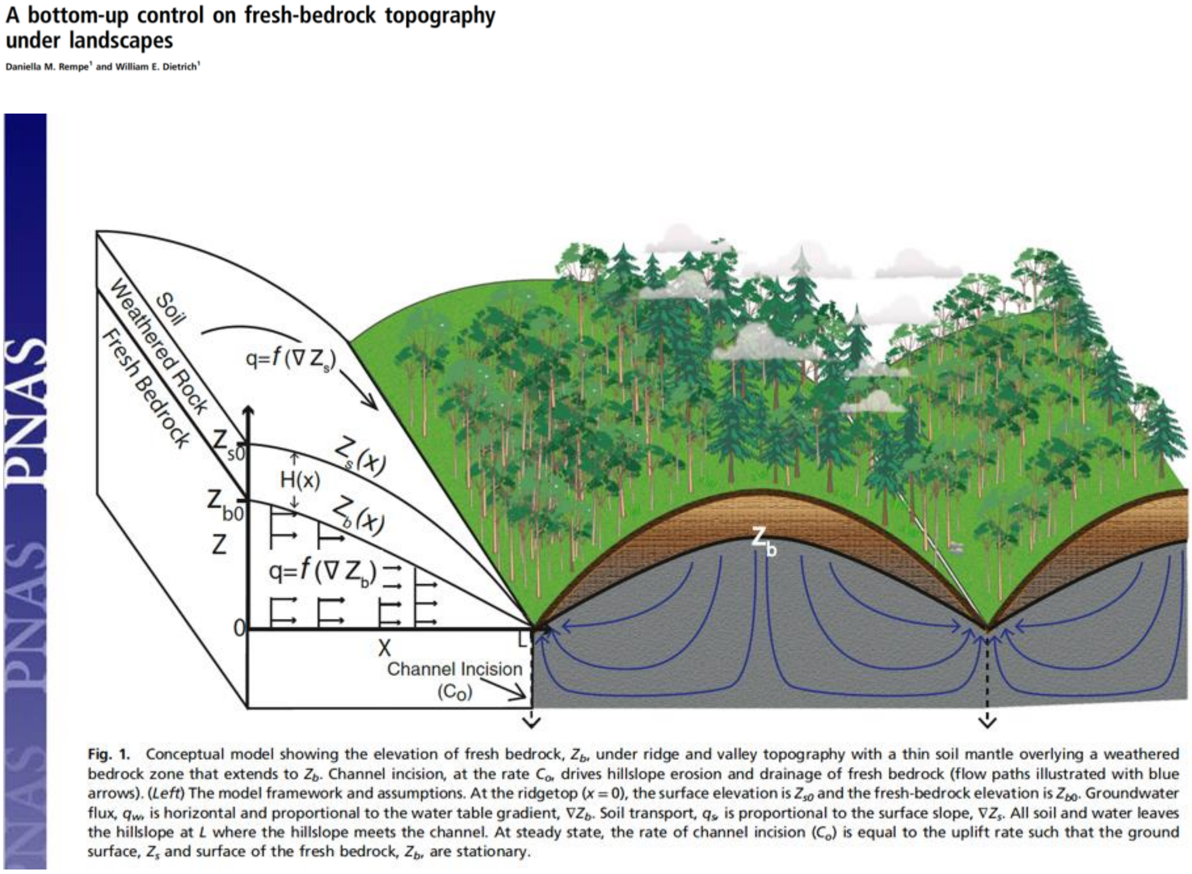
115 2.1 Existing regolith formation model (Braun et al., 2016)

Here we will use the model for regolith formation developed by Braun et al. (2016) that computes the rate of downward migration of a weathering front in proportion to the velocity of the water in the overlying permeable regolith.



Braun et al. (2016)’s model is made of three components: a surface process model, a hydrological model and a weathering model.

The regolith profile produced by Braun et al. (2016)’s model shows a relationship between elevation and depth of weathering that is the opposite of that produced by alternative regolith-forming models, such as the model of Rempe and Dietrich (2014), where deeper regolith occurs at the highest elevations and the regolith shallows towards lower landscape positions



A bottom-up control on fresh-bedrock topography under landscapes

Daniella M. Rempe[1] and William E. Dietrich[1]

Fig. 1. Conceptual model showing the elevation of fresh bedrock, Z_b, under ridge and valley topography with a thin soil mantle overlying a weathered bedrock zone that extends to Z_b. Channel incision, at the rate C_o, drives hillslope erosion and drainage of fresh bedrock (flow paths illustrated with blue arrows). (*Left*) The model framework and assumptions. At the ridgetop ($x = 0$), the surface elevation is Z_{s0} and the fresh-bedrock elevation is Z_{b0}. Groundwater flux, q_w, is horizontal and proportional to the water table gradient, ∇Z_b. Soil transport, q_s, is proportional to the surface slope, ∇Z_s. All soil and water leaves the hillslope at L where the hillslope meets the channel. At steady state, the rate of channel incision (C_o) is equal to the uplift rate such that the ground surface, Z_s and surface of the fresh bedrock, Z_b, are stationary.

or the model by Lebedeva and Brantley (2013), that shows a similar relationship between elevation and depth of weathering:

Exploring geochemical controls on weathering and erosion of convex hillslopes: beyond the empirical regolith production function

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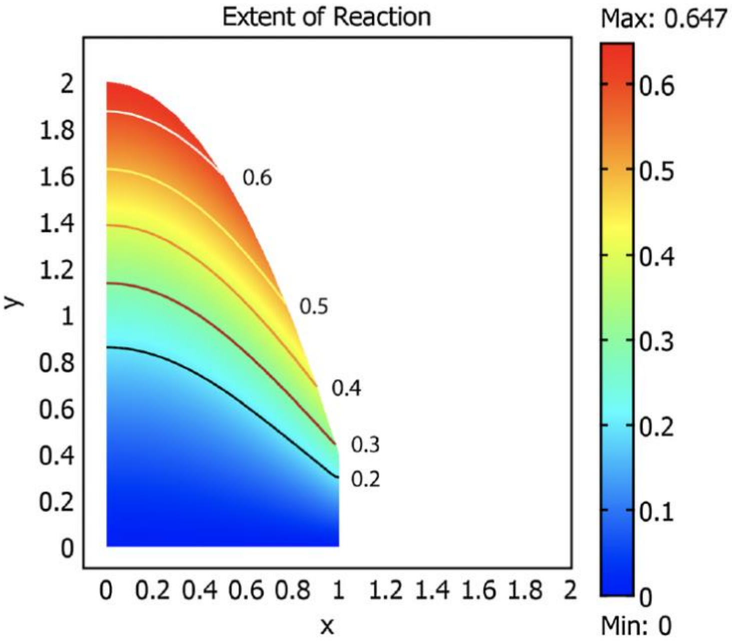

Figure 6. The steady-state solution in the moving system of coordinates for the hill weathering in the weathering-limited regime. Parameters as in Figures 3 and 4 with the exception of $E = 4 \times 10^{-5}$ m/yr, $v = 0 \cdot 6$ m/yr, and $k_{ab} = 1 \cdot 5 \times 10^{-12}$ mol/m^2 s. Parameters were varied from previous figures in order to exemplify weathering limitation. The steady-state profile is the curve $\bar{H}(\bar{x}, \bar{t}) = -1.6\bar{x}^2 + 2 - 0.2\bar{t}$. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

The topography vs depth of regolith produced by Braun et al. (2016)'s model also contradicts observations of weathering profiles throughout Australia, Brazil, Africa, and China, where regolith is deeper at the higher elevation sites and becomes shallower as elevation decreases. For example, in field mapping in deeply weathered terrains we teach our students to go into valleys to look for subcrops of unweathered lithologies. Thus, the starting regolith model illustrated in Figure 1 is a problematic depiction of physical reality and it raises some concerns when further applied to explain landscape evolution. If the thickness of the regolith is easily controlled by the model, as stated in Lines 158-159

Lines 158-159. On the other hand, Γ controls whether the regolith is thickest at the top of the hill, i.e., when $\Gamma > \Omega_2$ Ω_{-1} , or thickest at the base of the hill, i.e., when $\Gamma < (\Omega_2 / \Omega_{-1})$.

why not start with a regolith model that is more faithful to physical reality and to the results produced by other models?

As previously mentioned, the modified model includes physical parameters, such as space, time, elevation (topographic height), surface slope, height of water table, precipitation rate, fluid flow velocity, hydraulic conductivity, regolith thickness, and diffusivity, but the only "chemical parameters" are a dimensionless quantity that represents hardening or increase in "relative resistance to surface erosion" and another arbitrary parameter which represents regolith hardening time. These "chemical parameter" are not directly related to the dissolution and reprecipitation of iron in the near surface environment. Indeed, if the colour in Figure 5 were changed from red-brown to grey-white, the duricrust illustrated could be a silcrete or calcrete. Thus, to equate the duricrust produced by the model with a ferricrete is an unsubstantiated extrapolation of what is essentially a physical model.

Duricrust formation in the new model is directly proportion to the arbitrary hardening parameter (k), it is proportional to precipitation rate, to the range and rate of water table fluctuation, and regolith hardening time. The direct dependence of hardening to precipitation (rainfall) rates in the case of ferricrete formation is counterintuitive. Greater precipitation rates result in greater supply of oxygenated water, which lowers iron solubility. As iron is mobile in its reduced form ($Fe^{+2}{}_{aq}$) in most surficial environments, rainwater by itself will not contribute to iron transport. In surficial environments, organic acids must be added to infiltrating rain to drive iron dissolution and transport. In many cases, iron becomes immobilized when rainfall is abundant, and it enters solution when rainfall decreases and water ponds in the subsurface, becoming reducing.

To constraint model parameters – "2.3 Constraining new model parameters" –, the authors search through the literature for physical studies that may help determining the length of time necessary for the formation of an iron duricrust. In this section, studies based on field observations and educated opinions are evaluated equally and interchangeably with studies based on actual measurement of time of duricrust formation. It would be useful to differentiate the literature into work that uses field observation to infer rates of processes to those that measure or at least attempt to measure rates of processes. And, as outlined above, many of those later studies were largely ignored by the authors.

The authors also evaluate the measured ranges of water table fluctuations across the planet, and show that constraining this parameter is easier.

The model run itself is interesting, even if it is only remotely associated with the formation of ferricretes. Even if the geometry of the regolith is not that commonly measured in the field and the subsurface position of induration is not what is commonly observed in actual ferricretes, the timing of formation of a duricrust and the role of duricrust in slowing erosion is a step towards better understanding these systems. However, as mentioned above, that is only relevant to "duricrust" formation, it has no specificity as which type of duricrusts. Thus, affirming that the study poses some constraint on the formation of ferricretes is an unwarranted extrapolation of the results. And it is only relevant to the formation of duricrusts by groundwaters, which is not the dominant process controlling the formation of ferricretes.

Also a concern is the fact that the model employed by the authors produces weathering profiles that are different from weathering profiles observed in nature and weathering profiles produced by other models. Thus, when the model also shows an ephemeral role of duricrusts in protecting landscapes against erosion, contrary to observations and measurements, its relevance should be taken with some caution. When facing such results, the authors could ask the question: "What is possibly wrong with the model?". However, the authors prefer to take the model results at face-value and question what nature tells us. They dismiss previous observations

> "Many authors have previously described duricrusts in lateritic or regolith profiles (e.g. Tardy (1993); Taylor and Eggleton (2001)) as a protecting layer that should slow down erosion of the underlying topography/hill. We do not observe this in our model, and now proceed to explain it."

but also ignore a now large number of measurements, based on geochronology and cosmogenic isotope studies, that show that the duricrusts that sit on friable and easily erodible saprolites are indeed ancient (Vasconcelos et al. 1994; Vasconcelos, 1999a,b; Hénocque et al., 1998; Shuster et al., 2005; Beauvais et al., 2008; Monteiro et al., 2014; Vasconcelos and Carmo, 2018) and eroded very slowly (Fujioka et al.., 2010; Shuster et al., 2012; Monteiro et al., 2018a,b). Either all these measurements are wrong, and the duricrusts are not as old as determined by both $^{40}Ar/^{39}Ar$ and (U-

Th)/He geochronology, and the very low rates of long-term erosion measured by both ^{3}He and ^{53}Mn (and now ^{21}Ne) are also incorrect, or the duricrust formation model proposed by Fenske et al. is insufficiently robust to properly model the types of landscapes that it attempts to investigate.

Some authors have also demonstrated the mechanisms ("self-healing" of Monteiro et al., 2014) that allow iron duricrusts to continuously regenerate themselves, resist erosion, and protect the material below. Some of these processes have been experimentally reproduced in the laboratory, and given the right experimental conditions, greatly accelerated (Levett et al., 2019; 2020a,b,c). Thus, the longevity, resilience, and mechanisms of formation of ferruginous duricrusts are much better understood than what is portrayed in the current manuscript. Therefore, if the model cannot reproduce what is measured in nature, the model results should be more conservatively interpreted to make the manuscript into the useful and valuable contribution that it could be.

In summary, the authors should treat their duricrust formation process as an emerging approach, accept that their duricrust is a generic indurated material and not a ferricrete, compare their model results to natural settings to see where the model could be improved, and adjust model parameters to see if they can reproduce the measurements that show that duricrusts are actually ancient and erode very slowly.

The authors should also consider introducing actual weathering geochemistry into their model by coupling robust thermodynamic and kinetic approaches available in established geochemical models with their landscape evolution approaches. Only then it will be possible to model the formation and preservation of ferricretes, silcretes, calcretes, bauxites, and other types of duricrusts and the supergene systems that they cover.

In summary, the model in this manuscript can be a valuable contribution if presented for what it is and more reservedly interpreted. As currently presented, it will mislead readers into believing that we currently have a model that couples chemical weathering and landscape evolution, when this is not the case. To be the valuable contribution that it could be, the manuscript should be substantially revised and re-written. I have not checked the references, supplementary materials, etc. I will be willing to do so if a revised version of the manuscript is produced.

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