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Relief evolution of the Quadrilátero Ferrífero (Minas Gerais, Brazil) by means of (^{10}Be) cosmogenic nuclei

by

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with 2 figures and 1 table

Summary. This paper investigates the evolution of the relief within the so-called Iron Quadrangle (Quadrilátero Ferrífero) in Minas Gerais, Brazil, by means of quantification of erosion processes, which affected the principal rock types of the region. The method used is based on measurement of in-situ produced cosmogenic ^{10}Be concentration in fluvial sediments. The results indicate that the regional landscape evolution is controlled by lithotypes: the most resistant areas correspond to substrates developed on itabirites and quartzites (long-term erosion rates between 0.29 to 2.35 m/My), whereas the most fragile ones developed on schist-phyllites (long-term erosion rates between 7.95 to 11.82 m/My) and granite-gneisses (long-term erosion rate at 12.92 m/My).

1 *Introduction*

The quantification of the erosion processes that affect hydrographic basins constitutes an essential element for the understanding of continental landscape evolution. The traditional and indirect quantitative methods only allow for the quantification of present erosion processes by means of the measurement of dissolved (geochemical) and sedimentary (mechanical) charges transported by rivers. The use of these classic methods is limited, since the long-term quantification of the erosion processes would only be possible by extrapolation. Such limitation has only been overcome by the use of cosmogenic nuclides (^{10}Be, ^{26}Al, ^{36}Cl) to measure average long-term erosion rates of surfaces and hydrographic basins (Siame et al. 2006).

In this context, the ^{10}Be method (cosmogenic isotope with half-life of 1.5 My) is extremely useful to understand the evolution of the Quadrilátero Ferrífero relief in Minas Gerais, Brazil (fig. 1). The sole consensus regarding modeling of such area (7,200.00 km^2), characterized by a semi-humid climate (dry winters and humid summers) has been that its relief resulted from differential erosion processes (Hader & Chamberlin 1915, King 1956, Tricart 1961, Barbosa & Rodrigues 1967, Maxwell 1972, Varajão 1991). These authors stated that the evolution of the Quadrilátero Ferrífero relief was controlled by rock type (fig. 1): (i) Quartzites and Itabirites (Rio das Velhas Supergroup, Minas Supergroup and Itacolomi Group) con-

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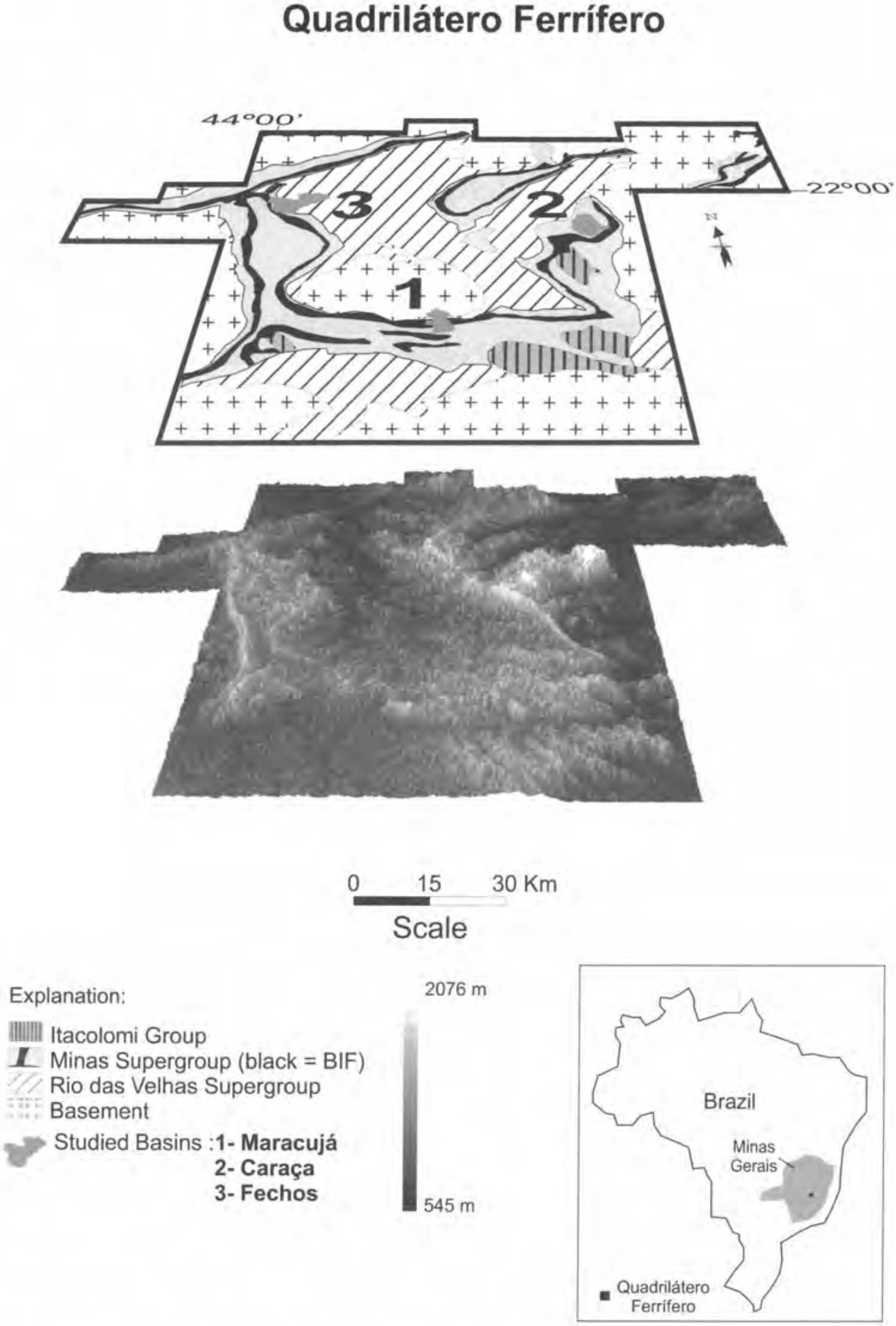

Fig. 1. Quadrilátero Ferrífero geology (ALKMIN & MARSHAK 1998) and relief.

stitute the highlands substrate; (ii) Schists/Phyllites (Minas Supergroup and Rio das Velhas Supergroup) are the midlands substrate, and (iii) Granites-Gneisses (Basement) are the lowlands substrates. However, this consensus resulted from deduction, because none of the studies quantified the resistance of the different rock types to erosion.

Only two works quantified the erosion processes in the Quadrilátero Ferrífero. The first, despite supporting differential erosion, quantified geochemical processes at present (SALGADO et. al. 2004). The second (SALGADO et al. 2007), despite having worked with ^{10}Be, applied the method to a single hydrographic basin, which is situated totally in the mid- and lowlands. Even this study did not prove that the relief in this region resulted from differential erosion, once the processes in the areas located on itabirites and quartzites had not been measured.

From the exposed above, the necessity to extend the ^{10}Be studies to the Quadrilátero Ferrífero highlands is evident, because it has not been proved with quantitative analyses that differential erosion is actually the factor that controls relief evolution. This work is the first attempt at quantification of Quaternary erosion processes, not only in the mid- (schists-phyllites) and lowlands (granites-gneisses), but also in the highlands (itabirites and quartzites).

2 *Methods*

To quantify the erosion processes acting on the rock types that compose the Quadrilátero Ferrífero substrate, ^{10}Be concentrations were measured in fluvial sediments. The main criteria used in selecting the hydrographic basins for fluvial sediment sampling were: (i) rocks (quartzites, itabirites, schist-phyllites and granite-gneisses) have to be outcropped to be exposed to cosmic rays that induced cosmogenic nuclides production; and (ii) human interference is low. As the Quadrilátero Ferrífero underwent intense mining activity, not a single hydrographic basin characterized by the three rock types underwent low human interference. Therefore, it was necessary to sample ^{10}Be in different hydrographic basins. Thus, fluvial sediments were collected in three basins with similar area (fig. 2): (i) Ribeirão Maracujá upper basin (15.368 km^2) formed by schist-phyllites (two sampling points) and granite-gneisses (one sampling point); (ii) Ribeirão Caraça upper basin (20.290 km^2) formed by quartzites (three sampling points); and (iii) Córrego Fechos basin (26.294 km^2) formed by quartzites, itabirites, marbles, dolomites and schist-phyllites (one sampling point). The outlet of the Maracujá basin was also sampled as a way to measure the average erosion in the basin (granite-gneisses and schist-phyllites). In the Fechos basin, only the outlet was tested as a way to sample a basin under the influence of itabirites, quartzites and schist-phyllites. A total of eight fluvial sediment samples were collected in the three basins (fig. 2).

After drying the samples, quartz was isolated from crushed and sieved (250–1000 µm) sediment samples by dissolving all other minerals with mixtures of HCl and H_2SiF_6. Atmospheric ^{10}Be was then eliminated by successive HF sequential dissolutions. The purified quartz was finally dissolved in Suprapur HF and the resulting solution was spiked with 0.3 mg of ^9Be carrier (Merck Titrisol). Beryllium was separated by successive solvent extraction and precipitation steps. All ^{10}Be measurements were performed by accelerator mass spectrometry at the Tandétron AMS facility,

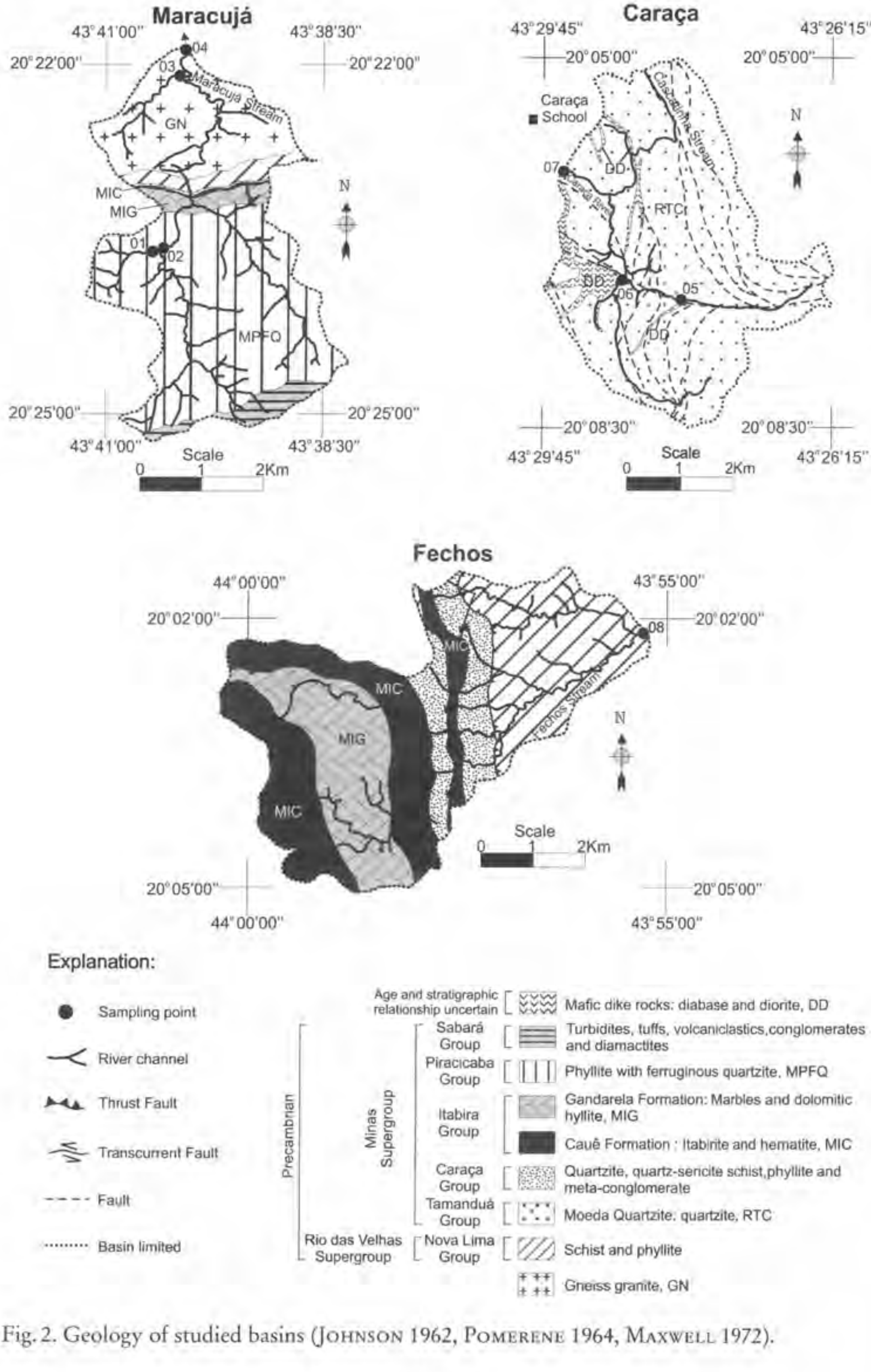

Fig. 2. Geology of studied basins (Johnson 1962, Pomerene 1964, Maxwell 1972).

Gif-sur-Yvette (France). Measured ^{10}Be /^{9}Be ratios were calibrated directly against the National Institute of Standards and Technology (NIST) standard reference material SRM 4325 using its certified $^{10}Be/^{9}Be$ ratio of $(3.06 \pm 1.4)x10^{-12}$. ^{10}Be uncertainties were calculated by propagating a conservative estimate of 3% instrumental uncertainty with (1 λ) uncertainties associated with counting statistics, blank correction and 6% in production rate calculated using Stone polynomial (STONE 2000).

To determine the long-term erosion rate, the following equation was used (LAL 1991, BRAUCHER 1998):

$$C(x;t) = \frac{P_o \times p_n}{\frac{\varepsilon}{\Lambda_n} + \lambda} \times \exp(-\frac{x}{\Lambda_n}) + \frac{P_o \times P_{\mu s}}{\frac{\varepsilon}{\Lambda_{\mu s}} + \lambda} \times \exp(-\frac{x}{\Lambda_{\mu s}}) + \frac{P_o \times P_{\mu f}}{\frac{\varepsilon}{\Lambda_{\mu f}} + \lambda} \times \exp(-\frac{x}{\Lambda_{\mu f}})$$

where C (at/g) is the concentration of radioactive cosmogenic nuclide; x is the depth (g/cm^2); t is the time (years); P_0 is the production rate (atom/g/years); p_n, $p_{\mu s}$, $p_{\mu f}$ refer to the neutron, slow and fast muons contributions, (these are 97.85, 1.5 and 0.65%, respectively, in quartz) Λ_n, $\Lambda_{\mu s}$, $\Lambda_{\mu f}$ are the neutron, slow and fast muons attenuation lengths, that are 150, 1500 and 5300 g/cm^2 (BRAUCHER et al. 2003) respectively; λ (years^{-1}) is the radioactive decay constant, and ε (g/cm^2/years) the erosion rate.

3 *Results and Discussion*

Table 1 presents the deduced denudation rates from ^{10}Be concentrations. A clear relationship between these rates and the rocks resistance is evident. The more resistant the rocks (quartzites and itabirites) are, the less is the denudation rate and conversely, the less resistant the rocks (schist-phyllites and granite-gneisses) are the more the denudation rate. The erosion rate obtained in the sub-basin that drains only

Table 1. Total long-term basin erosion (^{10}Be).

Basin	Sampling Points and its position in the Basin	Geology $^{(1)}$	^{10}Be (10^5 at/g)	^{10}Be denudation rate (m.Myr^{-1})
Maracujá	01 – Tributary (1146 m)	SP	6.60 ± 1.49	7.95 ± 1.86
	02 – Middle (1146 m)	SP	4.60 ± 1.75	11.82 ± 5.54
	03 – Tributary (1072 m)	G	4.24 ± 0.59	12.92 ± 1.97
	04 – Outlet (1072 m)	G, SP, M and Q	13.01 ± 4.62	3.70 ± 1.33
Caraça	05 – Headwater (1281 m)	Q	51.86 ± 4.10	0.29 ± 0.03
	06 – Tributary (1280 m)	Q and MD	29.22 ± 7.59	0.74 ± 0.20
	07 – Outlet (1254 m)	Q and MD	20.70 ± 1.30	2.35 ± 0.20
Fechos	08 – Outlet(958 m)	SP, M, I and Q	8.15 ± 1.19	6.84 ± 0.85

(1) M, D, Q, G, S, P, I, MD refers to Marbles, Dolomite, Quartzite, Granite-Gneiss, Schiste-Phyllite, Itabirite and Mafic Dikes respectively. Measured $^{10}Be/^{9}Be$ ratios were calibrated directly against the National Institute of Standards and Technology (NIST) standard reference material SRM 4325 using its certified $^{10}Be/^{9}Be$ ratio of $(3.06 \pm 1.4) \times 10^{-12}$

quartzites is the lowest erosion rate of 0.29 ± 0.03 m/My (table 1). The erosion rates obtained in the sub-basins that drain quartzites crosscut by mafic dikes were slightly higher, from 0.74 ± 0.20 to 2.35 ± 0.20 m/My. The erosion rates obtained for the other rock types are much higher still: from 7.95 ± 1.86 to 11.82 ± 5.54 m/My for schist-phyllites and 12.92 ± 1.97 m/My for granite-gneisses. The values were a little lower in the Fechos basin, whose substrate is constituted by itabirites, quartzites, schist-phyllites and dolomitic marbles-phyllites. The difference between erosion rates for granite-gneisses and schist-phyllites was not significant enough to attest differential erosion (table 1). Therefore, the results obtained in this work reinforce TRICART's (1961) and BARBOSA's & RODRIGUES' (1967) theory that the schist-phyllites are not resistant to erosion much more than granite-gneisses. The belts of quartzites and itabirites that protect them from total erosion explain their position in high surfaces.

As a result of differential erosion affecting different rock types, it is possible to identify a dissection trend on the regional relief, once the highlands (quartzites and itabirites) are eroded in a much lower speed than the midlands (schists-phyllites) and lowlands (granites-gneisses). Not taking into account the influence of possible neotectonic processes, it is possible to attest that slopes which separate the highlands from mid- and lowlands in the Quadrilátero Ferrífero have increased from 5.60 to 12.63 m in the last million years. This conclusion is based on the fact that the amount of erosion of the highlands substrate, over the last million years, has been from 0.29 to 2.35 m, whereas it has been from 7.95 to 12.92 m for mid- and lowlands substrates (table 1).

4 *Conclusions*

By measuring long-term erosion rates of the rock types of the Quadrilátero Ferrífero, this work shows that the relief evolution is controlled by lythostructure and differential erosion processes. It shows that areas having quartzite and itabirite substrates are much more resistant to erosion than those on schist-phyllites and granite-gneisses.

It is also possible to conclude that cosmogenic analyses, especially ^{10}Be, help check traditional geomorphologic concepts, such as differential erosion. The analyses made not only the quantification of the erosion intensity affecting different lithostructures in the long term possible, but also the identification of areas within hydrographic basins where erosion has been more intense.

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