

A note on ^{10}Be -derived mean erosion rates in catchments with heterogeneous lithology: examples from the western Central Andes

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ABSTRACT: Millennial catchment–mean erosion rates derived from terrestrial cosmogenic nuclides are generally based on the assumption that the lithologies of the parent rock each contain the same proportion of quartz. This is not always true for large catchments, in particular at the edge of mountainous plateaus where quartz-rich basement rocks may adjoin sedimentary or volcano-sedimentary rocks with low quartz content. The western Central Andes is an example of this type of situation. Different quartz contents may be taken into account by weighting the TCN production rates in the catchment. We recall the underlying theory and show that weighting the TCN production rate may also lead to bias in the case of a spatial correlation between erosion rate and lithology. We illustrate the difference between weighted and unweighted erosion rates for seven catchments (16 samples) in southern Peru and northern Chile and show variations up to a factor of 2 between both approaches. In this dataset, calculated erosion rates considering only granitoid outcrops are better correlated with catchment mean slopes than those obtained without taking into account the geological heterogeneity of the drained watershed. This dataset analysis demonstrates that weighting erosion rates by relative proportions of quartz is necessary to evaluate the uncertainties for calculated catchment–mean erosion rates and may reveal the correlation with geomorphic parameters. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: ^{10}Be ; erosion rate; lithology; Andes

Introduction

Since the pioneer works of Brown *et al.* (1995) and Granger *et al.* (1996), the use of terrestrial cosmogenic nuclides (TCNs) to calculate the catchment mean denudation rate has revolutionized geomorphology (e.g. von Blanckenburg, 2005). The method is based on the assumption that there is a secular equilibrium between the production of TCN and the loss by erosion (and radioactive decay for unstable isotopes) everywhere within a catchment, such that the mean TCN concentration of the river sediment is inversely proportional to the mean denudation rate of the catchment upstream. The TCN concentration of river sediment is measured in selected minerals, such as quartz for ^{10}Be . Consequently, it must be additionally assumed that the proportion of quartz is the same

in all eroding parent rocks, such that the quartz and material outfluxes are proportional.

A problem arises if the catchment is composed of lithologies with different quartz content, either naturally (Schaller *et al.*, 2001) or because dissolution has concentrated the quartz at the soil surface (Small *et al.*, 1999). Lithological variation is common in catchments larger than several tens of km². In a magmatic arc such as the Andes, for example, volcanic rocks with small amounts of quartz adjoin quartz-rich granitic terranes (e.g. Kober *et al.*, 2009). In this case, the relative contribution of each lithology to the quartz outflux depends not only on its erosion rate and on the local TCN production rate, but also on its quartz content. As an example, let us consider a granite with 25% of quartz eroding very slowly (high TCN concentration) adjoining a volcano-detritic rock with 2% of quartz eroding very fast (low TCN concentration). If the quartz

content is not taken into account, the TCN contribution of the volcano-detritic rock will be incorrectly interpreted as reflecting a low denudation rate, and thus the catchment denudation rate will also be underestimated. This problem may be critical when comparing catchments along a mountain range with a heterogeneous lithology distribution.

A continuous debate has focused on the relative weight of different denudation factors such as mean slope, river steepness, lithology or precipitation rate. If the lithological variations are not considered, this could affect the correlation between the calculated denudation rates and these factors, and might partly explain why the mean slope, for example, is not always shown as controlling the denudation rate (e.g. Insel *et al.*, 2010; Norton *et al.*, 2011; Hippe *et al.*, 2012). In order to limit this bias, TCN production rates have been weighted by the relative quartz content of each lithology (e.g. Safran *et al.*, 2005; Aguilar *et al.*, 2014; Carretier *et al.*, 2013). However, the theoretical basis of this approach has not yet been described in detail.

In this paper, we analyse the basis and the consequence of this approach for the calculated denudation rates. We first recall the underlying theory and then we illustrate different situations using large catchments in southern Peru draining the central Andes. We present 14 new items of ^{10}Be data and use two items of ^{10}Be data from Carretier *et al.* (2015). These catchments deeply incise the Andean forearc in response to surface uplift that began before ~ 8 Ma (Thouret *et al.*, 2007; Schildgen *et al.*, 2009, 2010). This evolution has progressively exhumed different lithologies during the propagation of erosion upstream. This is a typical situation for a transient topography responding to uplift, which can be generalized to other mountain ranges.

Theory

We recall here the theory (Brown *et al.*, 1995; Granger *et al.*, 1996; Bierman and Steig, 1996; von Blanckenburg, 2005), emphasizing the proportion of the selected mineral (we use quartz here) in the parent lithology. We do not account for the radioactive decay and only consider spallation for a comparison with the initial derivation of Brown *et al.* (1995) and Granger *et al.* (1996). We also ignore variations in rock density associated with different lithologies. Chemical weathering is not considered (Riebe and Granger, 2013). Thus we use the term *erosion* and not *denudation* in the following. These simplifications are further discussed below. The variables used in the following equations are defined in Table 1.

The mean TCN concentration of river sediment gathered at the catchment outlet N is the ratio of the TCN outflux to the quartz outflux:

$$N = \frac{\Psi_c}{\Psi_q} \quad (1)$$

Each flux is expressed as

$$\Psi_c = \sum_1^n N_i \rho \epsilon_i \chi_i dx^2 \quad (2)$$

and

$$\Psi_q = \sum_1^n \rho \epsilon_i \chi_i dx^2 \quad (3)$$

where the sum applies to the pixels of a catchment DEM. This method assumes that the TCN concentration has reached a steady state everywhere within the catchment, such that, if we only consider one particle and no radioactive decay:

$$N_i \epsilon_i = \mu P_i \quad (4)$$

Ψ_c then becomes

$$\Psi_c = \sum_1^n \mu P_i \chi_i dx^2 \quad (5)$$

yielding an expression of N :

$$N = \frac{\sum_1^n \mu P_i \chi_i}{\sum_1^n \epsilon_i \chi_i} \quad (6)$$

Dividing both denominator and numerator by the sum of the quartz fractions, we obtain

$$N = \mu \frac{\sum_1^n P_i \chi_i / \sum_1^n \chi_i}{\sum_1^n \epsilon_i \chi_i / \sum_1^n \chi_i} \quad (7)$$

$$= \frac{\mu P_w}{\sum_1^n \epsilon_i \chi_i / \sum_1^n \chi_i} \quad (8)$$

In the numerator of N , $P_w = \sum_1^n P_i \chi_i / \sum_1^n \chi_i$ is the catchment-mean production rate weighted by the proportion of quartz, and has been used by several authors to take into account the quartz content of the parent rocks (e.g. Safran *et al.*, 2005).

Now, we define a weighted mean erosion rate ϵ_w as the ratio between the quartz flux Ψ_q divided by the catchment area $n dx^2$, and weighted by the mean fraction of quartz in the parent lithologies χ ($= \frac{1}{n} \sum_1^n \chi_i$) and the quartz density:

$$\epsilon_w = \frac{1}{\chi} \frac{1}{\rho} \frac{\Psi_q}{n dx^2} \quad (9)$$

It can be proven that ϵ_w is the denominator of N in Equation (8):

$$\epsilon_w = \frac{\sum_1^n \epsilon_i \chi_i}{\sum_1^n \chi_i} \quad (10)$$

Inserting Equation (9) into Equation (8) leads to a similar form of the original model provided by Brown *et al.* (1995) and Granger *et al.* (1996), where the averaged TCN production rate for the catchment is replaced by the weighted mean TCN production rate P_w :

$$\epsilon_w = \frac{\mu P_w}{N} \quad (11)$$

This original model was constructed following the same reasoning but assuming that the quartz content is homogeneous and can be written as

$$\epsilon_u = \frac{\mu P_u}{N} \quad (12)$$

where ϵ_u and P_u stand for the unweighted erosion rate and the TCN production rate, respectively.

However, there is a problem because the true mean catchment-mean erosion rate ϵ is usually defined as the average of the local erosion rates:

$$\epsilon = \frac{1}{n} \sum_1^n \epsilon_i \quad (13)$$

and ϵ_w defined by Equation (9) is not equal (neither ϵ_u) to ϵ , except for the obvious case where χ_i is homogeneous.

For instance, consider a relatively gentle catchment (homogeneous P) composed of three patches of equal areas eroding at rates of 1, 2 and 3 erosion units. These patches have different lithologies with quartz fractions of 1%, 5% and 20%,

Table 1. Definition of parameters

ϵ_w	TCN-derived erosion rate weighted by quartz content [L/T]
ϵ_u	TCN-derived erosion rate unweighted by quartz content [L/T]
ϵ_g	TCN-derived erosion rate considering granitoids only [L/T]
ϵ	True erosion rate [L/T]
N	TCN concentration in quartz [at/M of quartz]
P_w	TCN mean surface production rate weighted by quartz content [at/M of quartz/T]
P_u	TCN mean surface production rate unweighted by quartz content [at/M of quartz/T]
P	TCN surface production rate [at/M of quartz/T]
μ	Attenuation depth of particles [L]
ρ	Quartz density [M/L ³]
χ	Fraction of quartz in the parent rock [1]
Ψ_c	TCN outflux [at/T]
Ψ_q	Quartz outflux [M of quartz/T]
dx^2	digital elevation model (DEM) pixel area [L ²]
n	Number of pixels of catchment DEM
i	Denotes pixel 'i'

L: unit of length, T: unit of time, M: unit of mass, at: number or atoms

respectively. In this case, $\epsilon_w = 3.4$, while $\epsilon = 2$ erosion units. Also in this case, ϵ_u is 3.4. The ϵ_u and ϵ_w values would be different if the different lithologies were spread out at different elevations. In fact, the mean ¹⁰Be production rate would be calculated differently, either considering P_u or P_w . In order to compare the departure of ϵ_w and ϵ_u from the true erosion rate value ϵ , we take the previous example further. We now consider that χ_i , ϵ and P are different for the three lithological patches. The different P means that the patches are located at different elevations (Figure 1). The mean ¹⁰Be concentration that could be measured at this theoretical catchment outlet is obtained by using Equation (1). The mean ¹⁰Be production rate P_u is calculated by simply averaging the ¹⁰Be production rates. From these two values, we deduce ϵ_u using Equation (12). In order to calculate ϵ_w we use Equation (11). Then we vary χ_i , P_i and ϵ_i for the three areas by permuting the values indicated in

Figure 1 (these values are different in the three areas), yielding different ϵ_u and ϵ_w values for the whole catchment.

Figure 1 shows that both ϵ_u and ϵ_w are different from ϵ . The range of ϵ_w (between 0.5 and 1.5 times the true value) is smaller than ϵ_u (between 0.25 and 2.5 times the true value). For both ϵ_w and ϵ_u , the largest overestimation of ϵ occurs when the erosion rate is locally correlated with the proportion of quartz. The largest underestimation occurs when the erosion is inversely correlated with the proportion of quartz. However, these biases are lower for ϵ_w in both cases, because the weighting used to calculate P_w decreases this bias. The ratio of ϵ_u/ϵ_w varies between 0.6 and 1.5. The largest ϵ_u/ϵ_w values occur when the highest quartz content is found at the lower (¹⁰Be production rate) elevation; the smallest ϵ_u/ϵ_w value arises when the highest quartz content is found at the highest elevation.

For catchments in which the lithology and the erosion rate are correlated or inversely correlated, both strategies (calculating ϵ_w or ϵ_u) are likely to yield a significant bias with regard to the mean erosion rate. In the next section, we show how the calculated mean erosion rate is changed by either considering or not the quartz content for several catchments in the western Central Andes characterized by lithological contrasts.

Application to Catchments in the Western Central Andes

Study area

The forearc of the Andes in southwest Peru and northern Chile, from the coast to the Altiplano plateau, is composed of a coastal scarp reaching 700 m on average, a low-relief Coastal Cordillera with an elevation between 500 and 1000 m, a Pampa surface dipping 2–4° to the west, and the main Cordillera reaching a mean elevation of ~4000 m at the margin of the Altiplano plateau. The main river catchments consist of deep canyons cutting into the Pampa surface and a more dendritic drainage network in the main Cordillera. The climate is dry with precipitation rates lower than 200 mm yr⁻¹ at low elevations, whereas catchment heads on the Altiplano plateau receive more precipitation due to the easterly winds. During the El Niño period, precipitation from the Pacific westerly winds increase on the coast (Garreaud *et al.*, 2009).

The age of the forearc and western Cordillera elevations is a matter of debate, but a significant regional surface uplift (~1000–2000 m) has occurred since 25 Ma, and possibly 9 Ma (Farías *et al.*, 2005; Garzzone *et al.*, 2006;

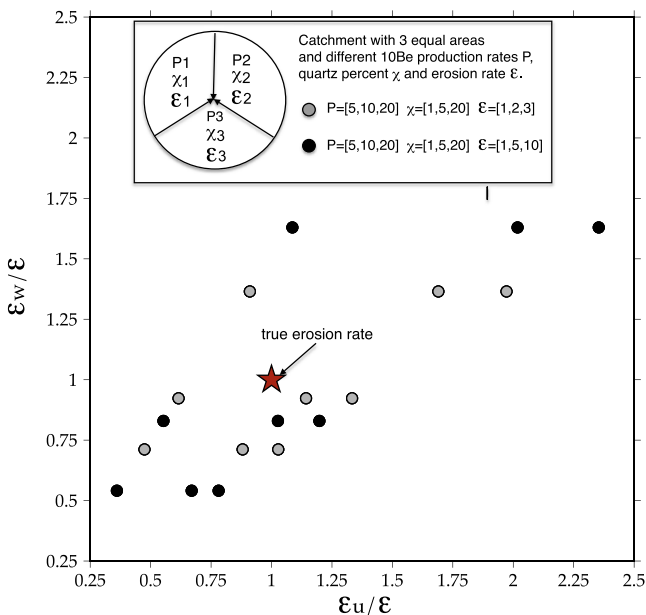


Figure 1. Bias generated by calculating ϵ_u (unweighted by the lithology) and ϵ_w (taking lithology into account). ϵ is the true catchment-mean erosion rate. Values are non-dimensional. A theoretical catchment includes three different lithologies (thus different quartz proportions χ_i) spread out into equal areas, at three different elevations (thus different ¹⁰Be production rates P_i), and eroding at three different rates ϵ_i . By varying P_i , χ_i and ϵ_i according to the values given in the graph, different values of ϵ_u (Equations (1) and (12)) and ϵ_w (Equation (11)) are calculated and divided by ϵ . This figure is available in colour online at wileyonlinelibrary.com/journal/esp

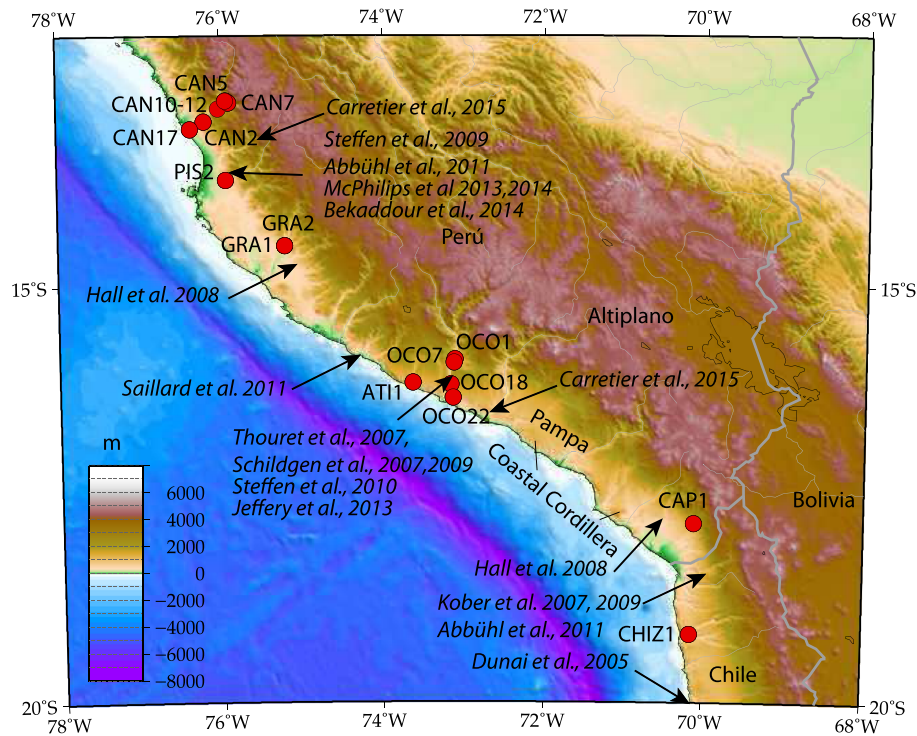


Figure 2. Situation map with locations of the samples. The references are previous works on erosion in this area. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Sempere *et al.*, 2006; Thouret *et al.*, 2007; Hoke *et al.*, 2007; Schildgen *et al.*, 2007; Garzzone *et al.*, 2008; Barnes and Ehlers, 2009; Schildgen *et al.*, 2009, 2010; Garcia *et al.*, 2011). This surface uplift has generated deep incision of canyons and increased the erosion in the catchments draining the Altiplano plateau. River profiles show knick-points of several hundreds of metres, showing that the overall topography is transient (Garcia and Hérail, 2005; Schildgen *et al.*, 2009; Jeffery *et al.*, 2013).

Previous works on erosion in this area

As we are interested in measuring the effect of 'lithological' bias affecting regional variations in erosion rates, in this subsection we briefly review previous works on erosion rates in this region (Figure 2). Abbuehl *et al.* (2010, 2011a, 2011b) obtained ^{10}Be -derived catchment erosion rates in the Rio Piura (5° S), Rio Pisco (13° S) and Rio Lluta (18° S) between 0.01 mm yr^{-1} (Altiplano) to 0.25 mm yr^{-1} (bottom edge of the Andean scarp). Carretier *et al.* (2015) provided ^{10}Be -derived catchment erosion rates at two sampling points in the Cañete catchment (13° S) and Ocoña catchment (16° S). The values are $\sim 0.05\text{ mm yr}^{-1}$ and $\sim 0.15\text{ mm yr}^{-1}$, respectively, but significantly depend on the use of P_u or P_w to calculate the erosion rate. These two samples are included in the present paper (Table II). At these two sample sites, Carretier *et al.* (2015) also analysed the mean ^{10}Be concentrations of granitoid pebbles. They obtained ^{10}Be concentrations that were more than 10 times lower for these pebbles. Granitoid hypsometry cannot explain this difference, thereby suggesting that the granitoid pebbles were derived from granitoid areas that were eroding faster than the rest of the catchment. Kober *et al.* (2009) analysed different cosmogenic isotopes in the Lluta catchment in Chile (18.5° S) and derived catchment-mean erosion rates between 0.01 and 0.05 mm yr^{-1} .

Time variations in these catchment-mean erosion rates were evidenced during the Late Pleistocene from the ^{10}Be analysis

and luminescence dating of cut-and-fill terraces in the Piura, Pisco and Ocoña-Majes catchments (Steffen *et al.*, 2009, 2010; Abbuehl *et al.*, 2011b; McPhillips *et al.*, 2013; Bekaddour *et al.*, 2014). In an affluent of the Pisco River, McPhillips *et al.* (2013) evidenced a decrease by a factor of 2 between the Late Pleistocene and Holocene periods. McPhillips *et al.* (2014) measured ^{10}Be concentration in 70 individual cobbles in a 16 ka terrace and in the river bed and showed that cobbles are mainly derived from landslides, at a rate independent of climate. In the Ocoña catchment in Peru, ignimbrite dates, thermochronological studies and numerical modelling of the river profile evolution were used to quantify the mean river incision rates over a longer timescale (Ma) (Thouret *et al.*, 2007; Schildgen *et al.*, 2007, 2009; Jeffery *et al.*, 2013). Since the last $\sim 16\text{ Ma}$, the mean incision rate has varied between ~ 0.03 and $\sim 0.15\text{ mm yr}^{-1}$ – values of the same order of magnitude as the Holocene estimates given by Carretier *et al.* (2015) in this catchment.

Local surface erosion rates were also obtained in this area, mostly in the most arid downslope part of the forearc. In southern Peru, Hall *et al.* (2008) used ^{10}Be to date surfaces at two sites (14.6° S and 17.5° S) as old as 1 Ma and to infer erosion rates between 0.04 and 0.3 mm yr^{-1} . Near 15.4° S , Saillard *et al.* (2011) obtained ^{10}Be ages of Pleistocene marine terraces consistent with marine isotopic stages, suggesting a very low erosion rate of these terraces. In northern Chile (18.5° S), Kober *et al.* (2007) combined ^{10}Be , ^{26}Al and ^{21}Ne concentrations at the surface of Mio-Pliocene surfaces to calculate extremely low erosion rates ranging between $0.5\text{ }10^{-3}$ and $2.25\text{ }10^{-3}\text{ mm yr}^{-1}$ in the dryer part, and between $4\text{ }10^{-3}$ and $34\text{ }10^{-3}\text{ mm yr}^{-1}$ at higher elevations under a wetter climate. Slightly more to the south (19.3° S), Dunai *et al.* (2005) obtained Oligo-Miocene ages of sediment deposited on the highest desert surface close to the coast, implying negligible surface erosion rates.

Overall, these previous studies indicate local and catchment-mean erosion rates lower than 0.5 mm yr^{-1} with ranges spanning roughly two orders of magnitude.

Table II. Data corresponding to ¹⁰Be measurements from the Cerege ASTER AMS

South lat. (degrees)	South long. (degrees)	Sample	Mass of Qz (g)	⁹ Be (at g ⁻¹)	¹⁰ Be/ ⁹ Be	±	¹⁰ Be (at g ⁻¹)	±
15.8906	73.1149	OCO1†	36.81	2.39E+019	1.24E-013	2.1E-014	8.10E+04	1.4E+04
15.9299	73.1192	OCO7	17.23	2.00E+019	1.49E-013	1.7E-014	1.73E+05	2.0E+04
16.1886	73.1561	OCO18†	37.21	2.39E+019	1.32E-013	8.7E-015	8.49E+04	6.1E+03
16.3476	73.1344	OCO22†‡	46.13	2.40E+019	1.91E-013	2.4E-014	9.95E+04	1.3E+04
16.1657	73.6311	ATI1	37.37	2.04E+019	4.33E-014	1.3E-010	8.34E+05	2.5E+04
14.5173	75.2108	GRA1†	36.89	2.39E+019	5.54E-013	2.7E-014	3.60E+05	2.0E+04
14.5173	75.2108	GRA2	13.5	1.99E+019	5.20E-013	2.8E-014	7.66E+05	5.0E+04
13.7343	75.9309	PIS2	28.27	1.96E+019	1.67E-013	2.1E-014	1.16E+05	1.5E+04
13.0275	76.1932	CAN2‡	24.18	1.95E+019	4.07E-013	2.5E-014	3.28E+05	2.1E+04
12.7766	75.9242	CAN5	24.03	2.00E+019	4.40E-013	2.4E-014	3.66E+05	2.0E+04
12.8306	75.9208	CAN8	27.21	1.96E+019	4.32E-013	2.3E-014	3.11E+05	1.8E+04
12.8000	12.8000	CAN10	16.49	1.98E+019	2.46E-013	1.8E-014	2.96E+05	2.2E+04
12.8000	12.8000	CAN12	15.04	1.97E+019	2.19E-013	3.0E-014	2.87E+05	4.2E+04
13.1247	76.3608	CAN17	17.77	2.09E+019	2.82E-013	2.4E-014	3.31E+05	2.9E+04
17.8500	70.1215	CAP1†	42.09	2.39E+019	6.97E-013	1.5E-013	3.96E+05	8.8E+04
19.1785	70.1561	CHIZ1	3.36	2.03E+019	2.05E-014	2.8E-015	1.17E+05	1.7E+04

Samples with '‡' are from Carretier *et al.* (2015). Samples with † were prepared at GET (Toulouse), the others at Cerege (Aix en Provence).

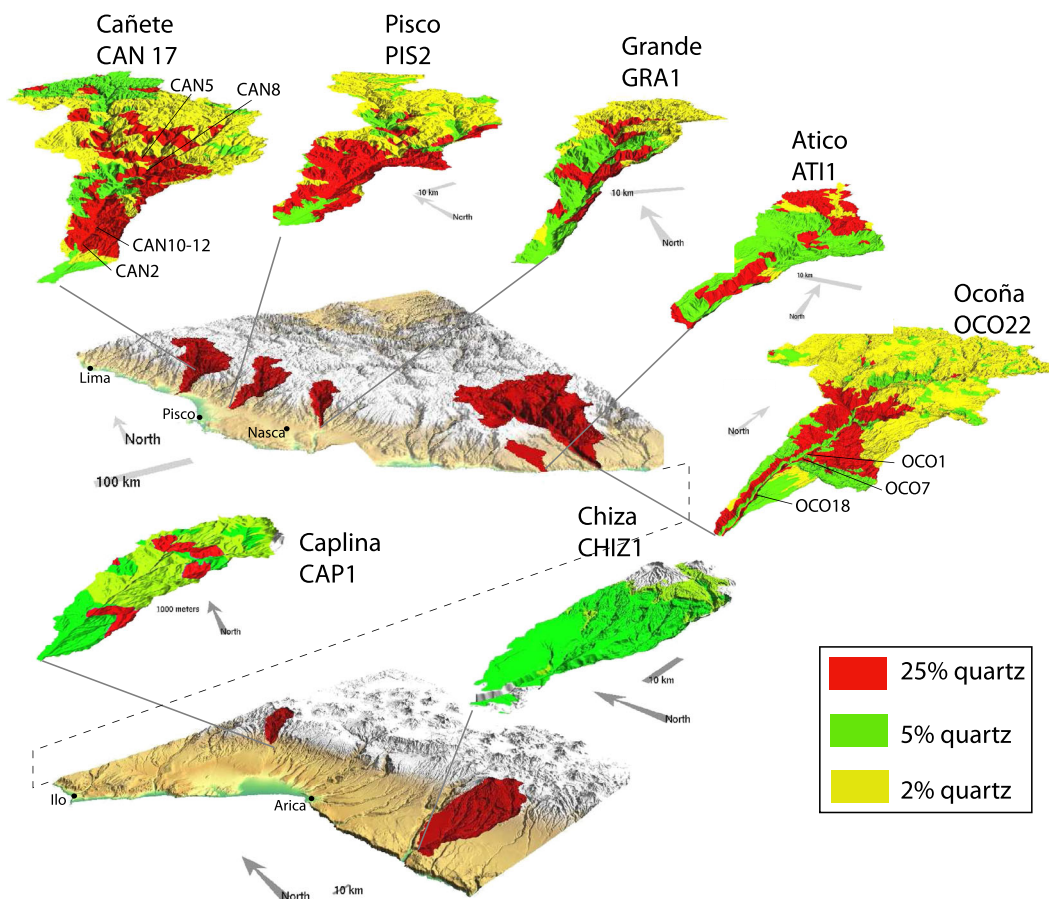


Figure 3. Catchments with their proportion of quartz deduced from the 1/1 000 000 geological maps of Peru and Chile. This figure is available in colour online at wileyonlinelibrary.com/journal/esp

Catchment lithologies

We selected seven rivers: Rio Cañete, Rio Ocoña, Rio Atico, Rio Grande, Rio Pisco, Rio Calientes (in Peru) and Rio Chiza (the only river in Chile). We gathered 16 sand samples at the foot of the main Cordillera (Figure 3). Above these samples, the catchment areas range between 536 (Rio Caplina) and 15 825 (Rio Ocoña) km² and their mean elevations

range between 3000 and 4000 m. Catchment lithologies were obtained from the 1/1 000 000 geological map of Peru (Mapa Geológico del Perú 1/1 000 000; Ingemmet, 1999; www.ingemmet.gob.pe/) and Chile (Mapa Geológico del Chile 1/1 000 000, Sernageomin, 2002; www.sernageomin.cl/). In these seven catchments, the exposed rocks include Precambrian gneiss, Palaeozoic and Cretaceous granodiorites, Jurassic and Cretaceous continental sedimentary deposits,

Oligo-Miocene to Plio-Pleistocene ignimbrites and volcanoclastic deposits (mostly andesites and basalts but also rhyolites) (Figure 3). These rocks have contrasting proportions of quartz, from granitoids that contain ~ 25% of quartz grains, to basalts and andesites that should not contain any quartz at all. We will later return to these assumptions in the discussion. The area covered by granitoids varies from 0 to 36%. Granitoids are spread out in several patches at different elevations in Rio Cañete and Rio Caplina, whereas they are concentrated at lower elevations in the catchments of Rio Pisco and Rio Ocoña. They are absent in the Rio Chiza catchment. For Rio Cañete and Rio Ocoña, we gathered samples along the main channel at sites located several tens of kilometres apart, which can be considered close given that the length of these rivers exceeds 200 km. Their ^{10}Be concentrations can be compared in order to study their variability over short distances. In Rio Grande, which is a braided river, we took two samples on two of the highest banks at a distance of 50 m apart and we treated them separately (GRA1 and GRA2).

Method

At each site, we sampled ~2 kg of sand taken at different places located several metres apart in the river bed. The 0.5–1 mm fraction was processed. Samples were prepared at the Geosciences Environnement Toulouse (GET) ^{10}Be Laboratory or at the Cerege Laboratory following the protocol described in von Blanckenburg *et al.* (1996) and the $^{10}\text{Be}/^9\text{Be}$ ratio was obtained at the ASTER AMS in Cerege (France) and calibrated directly against the National Institute of Standards and Technology standard reference material 4325 by using an assigned value of $(2.79 \pm 0.03) \cdot 10E-11$ (Nishiizumi *et al.*, 2007).

Mean catchment erosion rates were calculated based on the assumption that the ^{10}Be concentration has reached a steady state on the hillslopes, that this concentration did not change with river transportation, and neglecting the radioactive decay. All calculations involving topographic data used the SRTM digital elevation model with a pixel of ~90 m. The ^{10}Be production rate due to spallation at each pixel was calculated using Stone's (2000) production model, and a sea-level production rate of 4.5 at g^{-1} . The muonic contributions used the sea-level production rate from Braucher *et al.* (2003), scaled for elevation. At each pixel, an estimate of the topographic shielding coefficient between 0 and 1 was obtained using the method of Codilean (2006), which was multiplied by the previous total (neutron + muons) ^{10}Be production rate at each pixel. Then, the mean ^{10}Be production at the catchment scale was calculated following two approaches in order to calculate the weighted (ϵ_w) and unweighted (ϵ_u) erosion rates described in the theory section of this article.

In the first approach, the mean ^{10}Be production rate P_u was simply obtained by averaging the ^{10}Be production rates of the pixels, without differentiating between the different lithologies. Ignoring radioactive decay, the erosion rate ϵ_u was then obtained by $\epsilon_u = \sum_{i=1}^3 \mu_i P_i / N$, where i denotes the neutrons, fast and stop muons, μ_i is the corresponding attenuation lengths taken from Stone (2000) (neutrons) and Braucher *et al.* (2003) (muons) and P_i is the associated production rates. The considered rock density was 2.7 g cm^{-3} .

In the second approach, the ^{10}Be production rate of each pixel was additionally weighted by the relative proportion of quartz in the underlying lithology (P_w). This weighting follows the procedure of Safran *et al.* (2005) described by Equation (10). The mean production rate P_w was obtained by

averaging these weighted production rate values, leading to ϵ_w using the same equation as for ϵ_u .

For each lithology, we estimated the proportion of quartz minerals from the description of the 1/1 000 000 lithological maps. The estimated proportions of quartz are: granitoid rocks, 25%; rhyolites, 5%; undifferentiated detritic rocks, 5%; ignimbrites, 2%; and other volcanic rocks, 0%. Possible errors on these values may affect P_w , an issue that we address in the Discussion. In order to evaluate the largest bias that differences in the lithologies may cause, we also assumed that only granitoids contain quartz, as did McPhillips *et al.* (2013), for example, in the Quebrada Veladera catchment, an affluent of the Rio Pisco (Figure 3). This is used to calculate a TCN production rate for granitoids only, P_g , and the corresponding erosion rate ϵ_g .

The uncertainty for the erosion rates ϵ_w and ϵ_u was calculated by propagating the analytical uncertainty for the ^{10}Be concentration measurements (1σ of the order of 3%) and we assumed 15% for the ^{10}Be production rate uncertainty.

Results

The ^{10}Be concentrations range between $81\,000 \text{ at g}^{-1}$ (OCO6) and $834\,500 \text{ at g}^{-1}$ (ATI1). For Rio Cañete and Rio Ocoña, the geographically close samples show less than 20% of difference (Table II). Conversely, the ^{10}Be concentration for sample

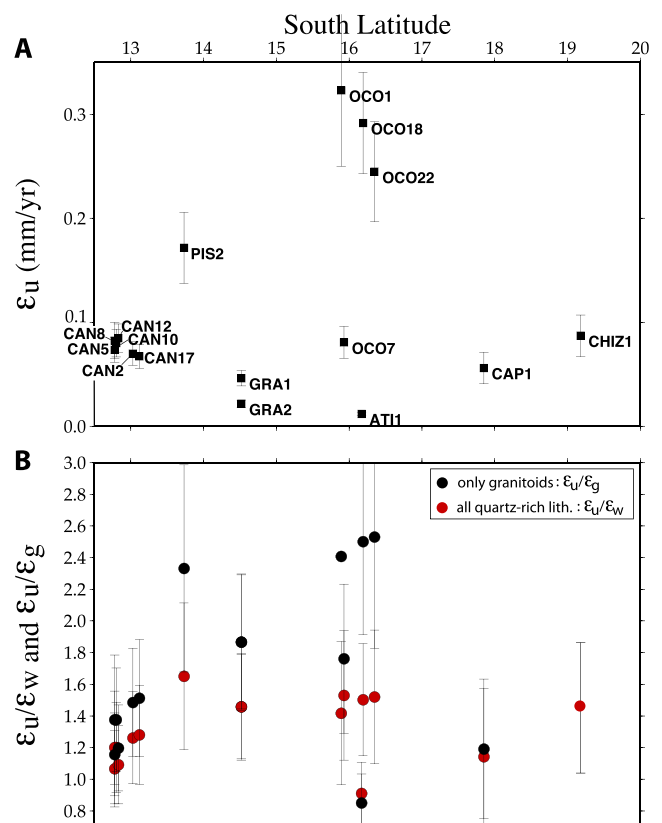


Figure 4. (A) Erosion rates derived from the ^{10}Be concentration in river sand without correcting the ^{10}Be production rate by quartz content. Error bars include the analytical uncertainties of the ^{10}Be concentrations and 15% of uncertainty for the ^{10}Be production rates. (B) Latitudinal variations in the catchment-mean erosion rates ϵ_u over ϵ_w and ϵ_g . The red circles take all quartz-rich lithologies into account, whereas the black points only consider the granitoids. Uncertainties were obtained by $(\epsilon_u/\epsilon_w) \sqrt{(\sigma\epsilon_u/\epsilon_u)^2 + (\sigma\epsilon_w/\epsilon_w)^2}$ where σ is the 1σ uncertainty. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

Table III. Results of the catchment analysis

Sample	A (km ²)	Hmean (m)	Smean (m/m)	P _u (at g ⁻¹ a ⁻¹)	ε _u (mm a ⁻¹)	±	P _w (at g ⁻¹ a ⁻¹)	ε _w (mm a ⁻¹)	±	A _g (km ²)	Hmean _g (m)	Smean _g (m/m)	P _g (at g ⁻¹ a ⁻¹)	ε _g (mm a ⁻¹)	±
OCO1	13972	4006	0.29	41.1	3.0E-01	7.E-02	28.7	2.1E-01	5.E-02	1441	2320	0.54	16.6	1.2E-01	3.E-02
OCO7	1061	2642	0.28	21.6	7.4E-02	1.E-02	13.9	4.7E-02	9.E-03	310	1827	0.39	11.9	4.1E-02	8.E-03
OCO18	15568	3838	0.29	38.9	2.7E-01	4.E-02	25.5	1.8E-01	3.E-02	1907	2139	0.51	15.0	1.0E-01	2.E-02
OCO22	15826	3786	0.29	38.2	2.3E-01	4.E-02	24.8	1.5E-01	3.E-02	1996	2079	0.5	14.6	8.6E-02	2.E-02
ATI1	1352	2194	0.24	15.1	1.1E-02	2.E-03	16.7	1.2E-02	2.E-03	485	2459	0.27	18.0	1.3E-02	2.E-03
GRA1	1855	3076	0.34	26.2	4.3E-02	7.E-03	17.7	2.9E-02	5.E-03	255	2033	0.48	13.7	2.2E-02	4.E-03
GRA2	1855	3076	0.34	26.2	2.0E-02	3.E-03	17.7	1.4E-02	2.E-03	255	2033	0.48	13.7	1.1E-02	2.E-03
PI52	3699	3421	0.35	31.3	1.6E-01	3.E-02	18.7	9.5E-02	2.E-02	885	1958	0.45	13.1	6.6E-02	1.E-02
CAN2	5794	3777	0.44	36.1	6.5E-02	1.E-02	28.4	5.1E-02	8.E-03	1336	2825	0.49	24.0	4.3E-02	7.E-03
CAN5	3369	4244	0.43	42.3	6.8E-02	1.E-02	39.7	6.4E-02	1.E-02	478	3810	0.47	36.5	5.9E-02	9.E-03
CAN8	4319	4188	0.43	41.5	7.9E-02	1.E-02	37.9	7.2E-02	1.E-02	695	3687	0.49	34.5	6.5E-02	1.E-02
CAN10	5581	3872	0.44	37.2	7.4E-02	1.E-02	30.8	6.1E-02	1.E-02	1149	3091	0.5	26.7	5.3E-02	9.E-03
CAN12	5581	3872	0.44	37.2	7.6E-02	2.E-02	30.8	6.3E-02	1.E-02	1149	3091	0.5	26.7	5.5E-02	1.E-02
CAN17	6017	3657	0.43	35.0	6.2E-02	1.E-02	27.1	4.8E-02	8.E-03	1429	2693	0.48	22.8	4.1E-02	7.E-03
CAP1	537	3589	0.36	35.0	5.2E-02	1.E-02	30.4	4.5E-02	1.E-02	74	3323	0.39	29.1	4.3E-02	1.E-02
CHIZ1	2236	2049	0.21	15.3	8.7E-02	2.E-02	11.1	6.0E-02	1.E-02						

A(km²) is the area size; Hmean (m) is the mean elevation of the considered lithology; Smean (m/m) is the catchment-mean slope calculated using the 3 × 3 pixel slope average for the r.slope.aspect command in GRASS; P is the ¹⁰Be production rate; ε is the catchment-mean erosion rate. Subscript 'w' means that this value has been weighted by the quartz content; subscript 'u' means that this value is unweighted by the quartz content; subscript 'g' means that it is restricted to granitoids. Samples with '±' are from Carretier *et al.* (2015).

GRA1 from the Rio Grande is double that of sample GRA2, although these samples were taken approximately 50 m apart. Erosion rates ε_u range between 0.02 and 0.4 mm yr⁻¹, i.e. the same range as obtained in previous studies in this region (Figure 4A). ε_u broadly increases with the catchment area. The largest ε_u is found in the largest Ocoña catchments.

However, ε_u is significantly higher than ε_w, weighted by quartz content, and ε_g, restricted to granitoids. This is illustrated by Figure 4, which shows the ratios of ε_u over ε_w and over ε_g (the ratio for the corresponding production rates are similar – Table III). These ratios range between 1 and 2.5, showing that weighting by quartz content or limiting to granitoid yields lower erosion rate values. There is no relationship between these ratios and the proportion of catchment area underlain by granitoids. The catchments with the largest ratios are those with granitoids mainly located in the lower half of the catchment, where slopes are the largest. These catchments are those of Rios Pisco, Grande and Ocoña. For the other catchments, there is no relationship between lithology and elevation, and the ratio between ε_u and ε_w is smaller.

Discussion

TCN-derived erosion rates have been used to identify the main factors of millennial erosion along a mountain range. The effect of slope and slope threshold has been identified (e.g. Binnie *et al.*, 2007), whereas the effect of mean precipitation remains difficult to establish (e.g. Carretier *et al.*, 2013). In some cases, these classical erosion factors were not able to predict ¹⁰Be-derived catchment erosion rates, with values that were apparently inconsistent with other observations (Densmore *et al.*, 2009). Part of the bias for the estimated erosion rates may be explained by stochastic processes that contradict the hypothesis outlined in Brown *et al.*'s and Granger *et al.*'s methods. For example, landslides in small catchments or incomplete mixing in the river may generate variations in the ¹⁰Be concentration in river sediment, particularly in small catchments (Niemi *et al.*, 2005; Binnie *et al.*, 2006; Reinhardt *et al.*, 2007; Yanites *et al.*, 2009; Savi *et al.*, 2014). In large catchments (> 500 km²) landslides should have less impact on the erosion rates (Niemi *et al.*, 2005; Yanites *et al.*, 2009) but, on the other hand, the lithology may be more heterogeneous or the acquisition of ¹⁰Be during river transport may be more significant (Carretier *et al.*, 2009). Two geographically close samples from the Rio Grande (one of the smallest catchments) gave different results, which may signify an incomplete mixing or a significant difference in the age of the sampled river banks. Conversely, in the large Rio Cañete and Rio Ocoña catchments, the non-significant differences in the ¹⁰Be concentration between relatively geographically close samples from the main channel suggest that the natural averaging of the river sediment is efficient.

The ratio between ε_w or ε_g and ε_u may reach a factor of 2.5. The ε_u/ε_w ratio reaches 1.5, which is similar to the maximum value obtained for the theoretical catchments in Figure 1. The differences between ε_w, ε_g and ε_u are larger than the uncertainties for the ¹⁰Be-derived erosion rates. Moreover, 10 of the 16 erosion rates ε_u differ by a factor of 2, between 0.05 and 0.1 mm yr⁻¹. Thus lithological variations between catchments may add significant and different biases to these values. Note that we did not take the density variations of the parent rocks into account. These variations, potentially correlated with the quartz content, may also bias the calculated erosion rates if there is a relationship between rock density (lithology) and erosion rate, as shown in the Theory section. A particular case illustrating this issue deals with the concentration of quartz

in the soil by chemical weathering of other minerals that dissolve faster. Small *et al.* (1999) and Riebe and Granger (2013) showed that the calculated denudation rate may be biased by a factor up to 2 if the change in the quartz content is not taken into account.

The largest $\epsilon_u/\epsilon_w \sim 1.5 - 2$ ratios (Rio Pisco, Rio Grande, Rio Ocoña) correspond to catchments where granitoids are located in the lowest half of the catchments. These large values are consistent with the theoretical catchment discussed in the Theory section, for which a high quartz content is located at low elevations, and thus results in lower ^{10}Be production rates. Catchments with granitoid patches spread out at different elevations show smaller ϵ_u/ϵ_w ratios, even if they represent a small proportion of the catchment area.

Radioactive decay (neglected in our theoretical analysis and for the studied catchments) would probably increase the difference between ϵ_u and the true erosion rate ϵ . To illustrate this point, we can return to the bi-lithological example given in the Introduction, in which we assume a catchment where a rock with low quartz content erodes quickly, whereas a rock containing more quartz erodes slowly. The TCN concentration

in the rapidly eroding rock is lower than in the slowly eroding rock. The radioactive decay increases this difference such that the amount of TCN from the rapidly eroding rock will be underestimated even more. Thus ϵ_u will also underestimate the true erosion rate. Nevertheless, the radioactive decay can significantly affect the results only if the sediment residence time on the hillslopes is comparable with the TCN half-life, i.e. for catchment erosion rates less than $\text{ca } 10^{-3} \text{ mm yr}^{-1}$, which is not the case in the studied catchments. The relative contribution of muons and neutrons to the surface TCN production rate depends on the elevation. Thus, if muons were included in the theoretical analysis, this would modify the ϵ_u/ϵ_w ratio by several percent only if the different lithologies are found at different elevations. Note that muons are taken into account in the calculation of ϵ_u/ϵ_w for the studied catchments.

It is beyond the scope of this paper to analyse the correlation between erosion rates and geomorphic parameters. Nevertheless, it is useful to analyse how the choice of calculating ϵ_u , ϵ_w or ϵ_g affects these correlations. We illustrate this by comparing these erosion rates with the catchment-mean slope, considered as one of the main erosion factors. A

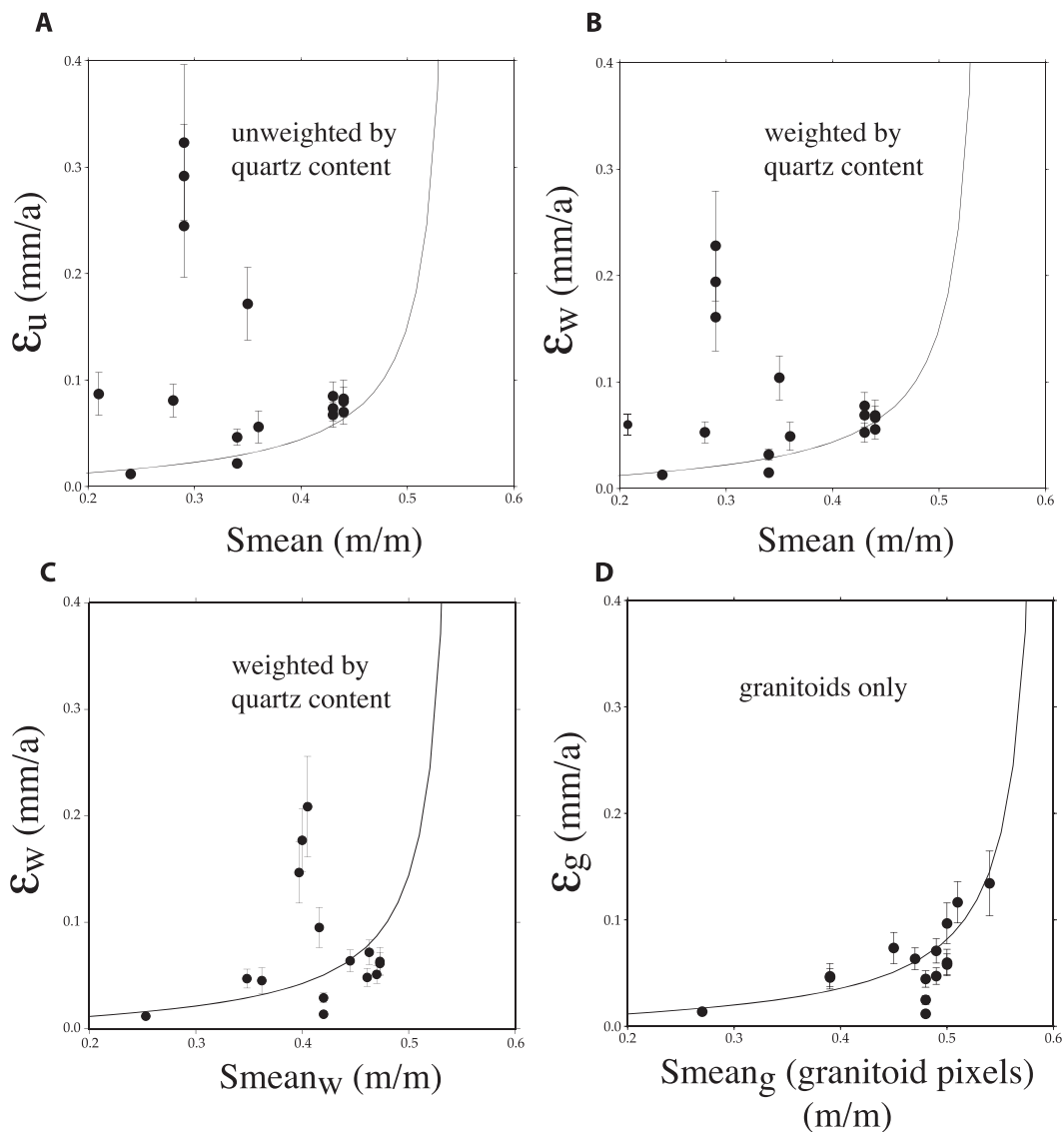


Figure 5. Catchment-mean erosion rate versus 3×3 slope (calculated using the SRTM dem). (A) The erosion rate ϵ_u is calculated without taking into account differences in the quartz content in quartz-rich lithologies. (B) The erosion rate ϵ_w is weighted by the quartz content. (C) The same as (B) but the mean slope is calculated by weighting local slopes by the quartz content. (D) The erosion rate ϵ_g is calculated by assuming that only granitoids provide quartz to the river channel. The mean slope is also calculated for granitoids only. The solid line is a model of the form $\epsilon = \kappa \frac{S}{1 - (S/S_c)^2}$, where κ is a transport coefficient, S is the slope, $S_c = 0.55$ in (A) and (B), and $S_c = 0.6$ in (C) (e.g. Roering *et al.*, 1999).

nonlinear hillslope erosion model has been recently evidenced and seems robust over different tectonic, lithologic and climatic contexts (e.g. Hanks, 1999; Roering *et al.*, 1999; Binnie *et al.*, 2007; Carretier *et al.*, 2013; Godard *et al.*, 2014). This model is illustrated by the curves in Figure 5. In order to test whether lithological variations are able to hamper the correlation of erosion rates with catchment-mean slope, we compare erosion rates ϵ_u , ϵ_w and ϵ_g with the model in Figure 5. ϵ_u does not fit well with this model. The fit is improved using ϵ_w . If we calculate the mean slope by weighting it by quartz content (S_{mean_w}), then the fit between ϵ_w and S_{mean_w} is significantly improved. Finally, the fit is much better when restricting the calculus to granitoids and comparing ϵ_g with S_{mean_g} . Note that in the last case the slope corresponds only to the mean granitoid slope S_{mean_g} (Table III). The improvement of the fit is due to both the change in erosion rate using ϵ_g and to the selection of granitoid pixels to calculate the mean slope. This figure raises a question when a catchment includes rocks with a lot of quartz and other ones that are poor in this mineral, how should we treat this? Should we consider that all of the quartz comes from the quartz-rich rock (as done by McPhillips *et al.*, 2013), or should we consider that all lithologies should be included in the analysis because even a rock that has a low quartz content, but which is eroding fast, may significantly contribute to the quartz and ¹⁰Be fluxes?

Figure 5 apparently suggests the first choice. Nevertheless, the apparent improved model fit using granitoids only does not necessarily support the choice of restraining the analysis to this rock. Other lithologies do contain quartz in a proportion that may be far from negligible, even for rocks mapped as having a lithology without quartz. For example, the Chiza catchment does not have any granitoids but quartz grains are still present in the sampled river sand. Kober *et al.* (2009) made the same observation in the Lluta catchment to the north of Chiza, where granitoids occupy only a small fraction of the catchment. Some ignimbrites in the Andes are dacites and contain phenocrystic quartz in a proportion greater than the several percent assumed from the 1:1 000 000 geological maps. Some carbonate or volcanic rocks may be silicified by processes following their formation. Although they may be interpreted as free from quartz using geological maps, they may contribute significantly to the quartz flux. For example, we observed that the Jurassic Caracoles formation, a carbonate formation of marine origin located in Antofagasta region (further to the south of the study area in this paper), is actually fully silicified. The same observation can be made locally with ignimbrites. Another example is the quartzic lithocap overlaying andesitic porphyries, common in this region of the Andes (e.g. Sillitoe, 2010). In practice, precise geological mapping allows these quartz sources to be identified. Nevertheless, information is not always available for large catchments. The best strategy should be to sample river sand from many subcatchments in order to avoid issues associated with lithological differences. This is not always possible. When sampling at the outlet of a large catchment with different lithologies, comparing P_u and P_w or ϵ_u and ϵ_w provides one way to estimate the possible 'lithological' uncertainty, and to evaluate whether or not the correlation with geomorphic factors may be affected by this uncertainty (e.g. Safran *et al.*, 2005; Carretier *et al.*, 2013, 2014).

Conclusion

Weighting the TCN production rates by quartz content allows different quartz contents to be taken into account. Nevertheless, this approach may also bias the catchment-mean erosion

rate if there is a spatial relationship between lithology and erosion rate. This type of relationship is not known a priori. In the case of the studied Central Andes catchments, the ϵ_u/ϵ_w ratio reaches a factor of up to 1.5–2. Calculating both ϵ_u and ϵ_w should help in evaluating the uncertainty associated with contrasted lithologies and improve the correlation with geomorphic parameters.

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