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Environmental controls on ^{10}Be -based catchment-averaged denudation rates along the western margin of the Peruvian Andes

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Abstract

We present ^{10}Be -based basin-averaged denudation rates for the entire western margin of the Peruvian Andes. Denudation rates range from c. 9 mm/ka to 190 mm/ka and are related neither to the subduction of the Nazca plate, nor to the current seismicity along the Pacific coast and the occurrence of raised Quaternary marine terraces. Therefore, we exclude a tectonic control on denudation on a millennial timescale. Instead, we explain >60% of the observed denudation rates with a model where erosion rates increase either with mean basin slope angles or with mean annual water discharge. These relationships

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suggest a strong environmental control on denudation.

Introduction

The western margin of the Peruvian Andes is considered to be a prime example of a plate boundary where the oceanic Nazca plate has been subducting beneath the continental South American plate since at least Jurassic times (Isacks, 1988). Because of active subduction, the Peruvian Andes have experienced frequent and strong earthquakes during their geologic history and still do nowadays (Noquet et al., 2014). Therefore, it is not surprising that erosion along the western Andean margin has been considered to depend strongly on the occurrence of earthquakes. This interpretation was proposed by McPhilipps et al. (2014) based on ^{10}Be concentrations measured in pebbles in the Pisco valley, 13°S latitude. Contrariwise, Abbühl et al. (2011) reported positive correlations between mean annual precipitation, basin morphometry and ^{10}Be -based catchment-averaged denudation for three basins situated on the western Andean margin, between 5°S and 20°S latitude, thus pointing to an environmental control on denudation. However, because ^{10}Be -based investigations have been conducted at a few sites only, interpretations about the primary controls on denudation have remained non-conclusive (Abbühl et al., 2011; Bekaddour et al., 2014; McPhilipps et al., 2014). Here, we re-address this problem based on a dataset where we measured ^{10}Be -based denudation rates for all >700 km² basins along the entire western margin of the Peruvian Andes. We collected stream-sediment samples from 42 streams (Fig. 1) and analyzed their concentrations of in-situ produced cosmogenic ^{10}Be , based on which we inferred basin-averaged denudation rates. We then explored possible correlations between the denudation rate pattern, the basin's morphometric properties, the stream's mean annual runoff and the seismo-tectonic situation of the region. The scope is to explore whether denudation in this part of the Andes can best be explained by environmental conditions or rather reflects a response to the subduction processes and the related seismicity and uplift pattern.

Setting

The western margin of northern South America has evolved through the subduction of the Farallón-Nazca oceanic plate beneath the South American continental plate and the accretion of crustal blocks since at least Early Jurassic times (e.g., Isacks, 1988). The Western Escarpment, the focus of this study, is a gently folded ramp, connecting the western margin of the Meseta and the Altiplano in northern and southern Peru, respectively, with the Pacific Ocean. It is composed of Late Oligo/Miocene fluvio-volcanoclastic deposits near the Pacific coast that are underlain by Mesozoic tholeiitic arc rocks, marine backarc sediments (Vidal, 1993) and the Cretaceous Coastal Batholith, a suite of granitic to dioritic rocks with varying quartz contents (Fig. 1). The shortening and thickening of the Andes was associated with the topographic rise of the Altiplano Plateau to its current elevation (Barnes and Ehlers, 2009). The topographic rise also resulted in a change in atmospheric circulation and precipitation patterns, and river incision (Schildgen et al., 2007; Thouret et al., 2007). The morphology of the Western Escarpment can be characterized as a steep ramp, which was formed through uplift during the Miocene (Schildgen et al., 2007). Upstream of this ramp on the Meseta/Altiplano (>3000 m a.s.l.) streams have remained graded to a Late Miocene base level constituted by a series of Tertiary volcanic-volcanoclastic rocks, thereby forming a cap rock (Abbühl et al., 2011). Within the ramp, streams have deeply incised into Mesozoic plutonic and metasedimentary rocks via a series of steep, headward-retreating knickzones that grade to the present-day base level defined by the Pacific Ocean (Schildgen et al., 2007).

Strong N–S and E–W precipitation gradients and seasonality in the western Andes are related to the positions of the Andean jet and the Intertropical Convergence Zone, ITCZ (Garreaud et al., 2003, inset of Fig. 1). On the western margin of the High Andes, precipitation rates decrease from ~1000 mm/a near the Equator to <200 mm/a in northern Chile. During austral summer, the ITCZ is at its southernmost extent near the border between Peru and Bolivia, transferring humidity from the tropical Amazon basin and the Atlantic to the Altiplano (Garreaud et al., 2003). During austral winter, the subtropical jet stream and the ITCZ are located close to the Equator, resulting in persistently dry conditions on the plateau.

Sampling strategy, denudation-rate calculations and comparisons with morphometric parameters

We collected 42 stream-sediment samples along the Pacific coast between 6°S and 20°S latitudes for analyses of in-situ ^{10}Be concentrations in detrital quartz (Fig. 1, Table 1). Basins associated with the samples have drainage areas that are $>700\text{ km}^2$. In-situ ^{10}Be concentrations of quartz, extracted from stream sediments of the Piura River in northern Peru (Abbühl et al., 2010), the Pisco River (Abbühl et al., 2011) and the Lluta River in northern Chile (Kober et al. 2009) were also considered (Table 1). All samples were processed for accelerator-mass-spectrometry measurements using the protocols of Akçar et al. (2012). The measured $^{10}\text{Be}/^9\text{Be}$ ratios were normalized to ETH in-house standard S2007N (Kubik and Christl, 2010) based on the ^{10}Be half-life of $1.39\pm 0.01\text{ Ma}$ (Korschinek et al., 2010; Chmeleff et al., 2010). Reported ^{10}Be concentrations are corrected for procedural blanks; associated 1-sigma uncertainties include analytical counting errors on standard, blank and sample measurements (Table 2). The catchment-averaged denudation rates reported in Table 2 were computed using the numerical solutions provided by Mudd et al. (2016), in which production and shielding for in-situ ^{10}Be are calculated on a pixel-by-pixel basis. We did not consider snow cover to have a major impact on the results as the mean basin elevations of the sampled catchments are largely situated below the snow line, and therefore we excluded it from calculations. Spatially variable quartz contents of the source-rock lithologies can add a bias in the determinations of basin-averaged denudation rates (Carretier et al., 2015). We considered this issue by categorizing the bedrock of the sampled basins according to the litho-tectonic architecture of the underlying bedrock (geological map 1:1,000,000 of Peru and Chile; INGEMMET, 2011, SERNAGEOMIN, 2004). Following Carretier et al. (2015), we assigned relative abundances of quartz contents: 25% for plutonic rocks, 5% for Mesozoic to Quaternary sedimentary rocks and 2% for the remaining lithotypes (e.g., volcanoclastic rocks). As will be shown later, this correction generally yields lower denudation-rate estimates, but doesn't affect their spatial pattern.

Catchment-scale morphometric parameters and characteristics (Table 1), including drainage area, mean elevation, slope angle, hypsometry and latitude, were extracted from the 90-m-resolution digital elevation model Shuttle Radar Topography Mission (SRTM; Jarvis et al., 2008). The mean

annual water discharge (Table 3) was obtained by combining hydrological data reported by the Sistema Nacional de Información de Recursos Hídricos and the TRMM-V6.3B43.2 precipitation database (Huffman et al., 2007). Averaged gauging station records were plotted as a function of theoretical runoff, estimated as the product of contributing area and TRMM-based precipitation rate, for a selection of 12 basins for which hydrological stations and river-sediment sampling sites were separated by less than 5 km (Fig. 1). The observed 60% water budget loss, possibly due to evaporation and irrigation, was then used to estimate a TRMM-based runoff for the other basins, where hydrological stations were far from sampling sites. Possible co-variations and correlations between denudation rates and/or morphometric parameters and basin characteristics were evaluated using Pearson correlation coefficients, thus providing corresponding p-values with a significance level alpha of 0.05 (Table 4).

Results

Concentrations of in-situ produced ^{10}Be in the quartz fraction of river sediments range from 6×10^4 to 1×10^6 at./g, with most sites yielding values of c. 4×10^5 at./g. The highest concentration of ^{10}Be was measured for the Quebrada Arunta (18.1 °S latitude), while the lowest one was encountered for the Pativilca River at 10.7 °S latitude (Table 2). The ^{10}Be concentrations result in basin-averaged denudation rates that range between 10 mm/ka and 260 mm/ka (Table 2). Basins located in northern Peru and northern Chile yielded the lowest values, with denudation rates ranging from c. 40 mm/ka to 10 mm/ka. Denudation-rate estimates that were corrected for differences in the relative quartz contents of the bedrock are 30% lower and range from 9 to 190 mm/ka (Table 2, Figs. 2 and 3e), albeit with a similar spatial distribution to the non-corrected ones (Table 2). Note that the lower rates result from low ^{10}Be production rates for the coastal batholith, which has relatively high quartz contents, but is situated at lower elevations. We will use these latter rates, which we have corrected for differences in quartz contents, in the following analysis.

A closer inspection of the denudation-rate pattern shows that the corresponding values are independent of the basins' seismo-tectonic situation. In particular, the coastal segment south of 13°S and particularly 16°S,

where raised Quaternary marine terraces (Regard et al., 2010) suggest the occurrence of surface uplift, does not necessarily correspond with the region where denudation rates are highest (Fig. 3), because values as high as 190 mm/ka are also encountered farther north where the coastal plain has been subsiding (Hampel, 2002). Likewise, segments where the Nazca plate subducts at a shallow angle and where the current seismicity implies a low degree of interseismic coupling (between 4°S and 17°S latitudes; Nocquet et al., 2014) do not correlate with a distinct denudation rate pattern either (Fig. 3). Finally, there is no obvious correlation between the denudation rates and the pattern of earthquake frequencies (Fig. 3c).

Positive correlations, albeit with a rather weak correlation coefficient (Pearson correlation coefficient c , 0.3, $R^2=0.096$, Table 4), exist between denudation and catchment-averaged hillslope angles. Likewise, denudation rates and mean annual discharge are positively linked (Table 4, Fig. 4a). However, the relationships between denudation and mean basin slope are better explained by a non-linear diffusive mass transport model (Fig. 4b; e.g. Roering et al., 1999):

$$D = K \frac{S}{1 - (S/S_{cr})^2} \quad (1),$$

where denudation rate D is proportional to mean basin slope S for low gradients, while these relationships become non-linear for slopes approaching a critical value S_{cr} , which in our case equals 27.5°. Here, K represents the transport coefficient (Fig. 4b).

Because the results of the Pearson correlation coefficient analysis reveal that runoff and mean basin slope are independent (Table 4), we additionally explored whether an empirical bi-linear regression model is capable of explaining the spatial distribution of denudation rates along the western margin of the Peruvian Andes. This model considers runoff and slope as variables and has the form:

$$D = K^* S^* + FR \quad (2),$$

where denudation rate D is predicted as a function of mean basin slope $S^* = S/(1 - (S/S_{cr})^2)$ according to equation 1 and water discharge R . Here K^* and F correspond to transport coefficients. The best-fit model solution, explaining >60% of the observed denudation rates (Fig. 4c) at $P < 0.0001$, yields

additional information on the positive correlations between denudation, mean basin slope and mean annual discharge. In particular, slope exerts an important control on denudation in those basins where mean annual discharge is low. Contrariwise, discharge becomes a relatively stronger control on denudation in basins where hillslopes are shallow (Fig. 4d).

Discussion and Conclusion

It has been proposed that erosion along the western Andean margin is strongly controlled by the seismicity pattern (McPhilipps et al., 2014). Although earthquakes in combination with strong rainfall events (Bekaddour et al., 2014) are likely to release large volumes of debris flows and landslides in individual basins such as in the Pisco valley (McPhilipps et al., 2014), we disregard tectonic processes as the primary driving force on denudation at the scale of the western margin of the Peruvian Andes, at least for timescales spanning millennia. Indeed, south of 13°S latitude, the relatively high frequency of earthquakes and the raised Quaternary marine terraces point towards a strong tectonic driving force at work, which in turn is expected to promote erosion (Fig. 3). Such a relationship, however, cannot be detected in our dataset as the denudation rate pattern is identical north and south of 13°S. Instead, we use the positive correlations between ^{10}Be -based basin-averaged denudation rate, mean basin slope and mean annual discharge to invoke an environmental control on denudation over ^{10}Be timescales spanning millennia. In addition, the correlation pattern outlined in Figure 4d reveals that fast denudation has preferentially been promoted in basins where either slopes are steep or mean annual discharge has been large. Our interpretation about an environmental control is consistent with the results of morphometric analyses conducted over the entire western Andean margin, where erosion indices correlate positively with variables indicative of climate regimes (Montgomery et al., 2001). Similarly, for the Andean margin south of 27°S, where climate shifts from arid to semi-humid, Carretier et al. (2013) reported slope as well as climate variability as primary controls on ^{10}Be -based denudation. Note that our precipitation data is too sparse to explore whether rainfall variability may also exert a measurable control on denudation in Peru, but we consider it very likely that positive correlations between these variables do exist. Finally, basins with higher-than-predicted denudation rates (Rio Ocoña and Pativilca; Fig. 4c) show glacier remnants and glaciogenic-material accumulations in their headwaters that might supply ^{10}Be -depleted sediments to the river-load, and could

yield, in turn, overestimated denudation estimates (Delunel et al., 2014). Contrariwise, Rio Santa's denudation rate appears lower than predicted (Fig. 4c), possibly due to the presence of sedimentary basins at the foothill of the Cordillera Blanca (Margirier et al., 2015) that could act as a sediment-trap, thereby decoupling the basin's sediment and water budgets and yielding an overestimated model prediction of the denudation.

In conclusion, neither flat-slab subduction nor along-strike differences in the seismic coupling between the Nazca and South American plates (Noquet et al., 2014) appear to have exerted a measurable control on the denudation rate pattern at the basin scale along the western margin of the Peruvian Andes. Instead, a combination of runoff and mean basin slope appears to explain >60% of the denudation rate data, thus pointing to a strong environmental control on the erosional pattern in this part of the Andes. Similar relationships have been found for Northern Chile at c. 18°S where the climate is hyper-arid (Kober et al., 2009) and for the western Andean margin south of 27°S, where the climate turns wetter (Carretier et al., 2013). We do not exclude a tectonic forcing on the landscape form, as the initiation of headward-retreating knickzones and the establishment of high topographies were certainly driven by tectonic uplift (Schildgen et al., 2007). While these forces have to be considered for time scales spanning some Ma, we propose that for shorter time intervals spanning some thousand years, erosion along the western Andean margin has primarily been controlled by climate variables.

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Figure captions

Figure 1: Map of the western margin of the Peruvian Andes showing: drainage basins that were sampled for ^{10}Be -based denudation rates, patterns of quartz contents of the underlying bedrock, which were estimated from the geological map of Peru and northern Chile (INGEMMET, 2011, SERNAGEOMIN, 2004) plus assignments of quartz contents for these lithologies (Carretier et al., 2015), and contour lines of mean annual precipitation rates. The map also shows the major Peruvian cities. The inset shows a general overview of the atmospheric circulation pattern around the Intertropical Convergence Zone, ITCZ of South America.

Figure 2: Patterns of ^{10}Be -based catchment-averaged denudation rates plus tectonic situation including the depth of the subducted slab (solid and dashed brown lines); slab depths, taken from earthquake.usgs.gov/data/slab/, are indicated in kilometers. The map also illustrates the locations of active volcanoes during the Holocene, the location of the buoyant Nazca ridge plus patterns of earthquake occurrence. Interestingly, basins with fast and slow denudation rates are situated in all litho-tectonic and geodynamic positions. This implies that tectonic processes do not exert a strong control on the denudation rate pattern. The purple strip east of the trench axis corresponds to the swath over which the historical earthquake data, presented in Figure 3, have been presented. The thick brown line delineates the swath over which elevation data of the coastal segment are displaced in Figure 3.

Figure 3: Topography of the subducting Nazca plate, where slab-depth data have been extracted from earthquake.usgs.gov/data/slab/. This N–S projection also illustrates: a) tectonic lineaments such as submarine ridges and fracture zones – MFZ: Mendaña Fracture Zone; NFZ: Nazca Fracture Zone; b) Holocene volcanoes; c) earthquake data, taken from earthquake.usgs.gov/earthquakes/search/; number of earthquakes $M>4$ within a 30 km radius window; the 100 km wide swath along which earthquake data have been sampled is illustrated in Figure 2 as a purple strip adjacent to the trench; d) coastal elevation; the data have been extracted from a 20 km wide swath profile along the coast; the sampling window is illustrated by a thick brown line in Figure 2; the three lines represent maximum, mean and minimum elevations within the selected swath; e) catchment-averaged denudation rates have been corrected for quartz contents (Table 2). The latitudes represent the centroids of the basins (Table 1), which might deviate from the locations of the sample sites.

Figure 4: a) Basin-averaged denudation rates plotted against mean annual discharge. The blue dots correspond to the data represented in the inset, showing the correlation between the mean annual discharge recorded by the gauging stations of the Peruvian hydrological survey and the theoretical discharge estimated from the TRMM database. b) Denudation rates plotted against mean basin topographic gradients. The dashed red curves represent predictions for

K values of 30 mm/ka and 90 mm/ka, with critical slopes of 0.52, which corresponds to 27.5°. c) Plot showing predicted versus observed denudation rates using the empirical bi-linear regression model and best-fit solutions for K^* and F coefficients of 42.6 ± 5.6 mm/ka and 1.1 ± 0.2 , respectively. Dashed black line represents the 1:1 relationship, and red lines represent $\pm 20\%$ envelope around such an idealized model. The inset shows the standardized residuals from the model predictions plotted as a function of the observed denudation rates. d) Estimated contribution of the slope component to the predicted denudation rates plotted as a function of the mean annual discharge.

Tables

Table 1: Morphometric dataset for the sampled drainage basins. All calculations are based on the 90 m resolution DEM (SRTM; Jarvis et al., 2008). Cosmogenic data from the Lluta basin are taken from Kober et al. (2009), while Abbühl et al. (2010, 2011) presented ^{10}Be concentrations for the Piura and Pisco basins.

Sample name /catchment name	Latitude, °N sample location (DD.DD) WGS84	Longitude, °E sample location (DD.DD) WGS84	Latitude, °N centroid catchment polygone (DD.DD) WGS84	Drainage area [km ²]	Shielding factor	Mean elevation [m a.s.l.]	Mean slope [m/m]	Hypsometric Integral HI
PRCME-1	-18.1191	-70.3274	-17.8424	1659	0.9832	2733	0.28	0.45
PRCME-3	-17.8240	-70.5046	-17.4844	2154	0.9826	3105	0.30	0.50
PRCME-401	-17.9073	-70.9562	-17.3244	5821	0.9913	2668	0.19	0.46
PRCME-5	-17.2865	-70.9895	-17.0601	1785	0.9873	3398	0.26	0.52
PRCME-6	-17.0288	-71.6908	-16.5526	13026	0.9860	3568	0.24	0.63
PRCME-7	-16.5849	-72.7285	-15.6579	17557	0.9851	3635	0.23	0.57
PRCME-8	-16.7192	-72.4187	-16.2168	13862	0.9940	3285	0.15	0.52
PRCME-9	-16.4217	-73.1153	-15.2406	16065	0.9793	3745	0.26	0.59
PRCME-10	-16.2260	-73.6178	-15.8353	1420	0.9886	2155	0.23	0.56
PRCME-11	-15.8460	-74.2607	-15.5630	1244	0.9787	2316	0.34	0.50
PRCME-12	-15.6720	-74.5232	-15.1800	4361	0.9812	2797	0.28	0.54
PRCME-13	-15.6286	-74.6368	-14.8915	4561	0.9840	2895	0.26	0.61
PRCME-1401	-14.6476	-75.2424	-14.2938	5220	0.9806	2716	0.32	0.57
PRCME-15	-14.3448	-75.6858	-13.9437	4715	0.9846	2204	0.26	0.44
PRCME-17	-13.4650	-76.1365	-13.1879	3113	0.9706	3197	0.37	0.60
PRCME-18	-13.3213	-76.2433	-13.1391	726	0.9813	1967	0.33	0.44
PRCME-19	-13.1238	-76.3944	-12.5965	6059	0.9641	3648	0.40	0.62
PRCME-20	-12.6652	-76.6515	-12.3399	2337	0.9650	3294	0.41	0.57

PRCME-21	-12.5005	-76.7412	-12.2700	715	0.9746	1772	0.36	0.42
PRCME-22	-12.2510	-76.8919	-12.0626	1574	0.9710	2568	0.38	0.48
PRCME-23	-11.6083	-77.2387	-11.3225	3070	0.9694	2697	0.39	0.51
PRCME-24	-11.0713	-77.5860	-10.9196	4322	0.9625	3134	0.42	0.56
PRCME-25	-10.8390	-77.6962	-10.8311	1013	0.9707	2365	0.38	0.45
PRCME-26	-10.6551	-77.8337	-10.2753	2365	0.9701	2407	0.39	0.49
PRCME-27	-8.9662	-78.6209	-8.8916	12385	0.9663	3262	0.38	0.48
PRCME-28	-8.4230	-78.7835	-8.2126	1695	0.9802	2246	0.31	0.52
PRCME-29	-8.1400	-79.0076	-7.9708	2120	0.9784	2307	0.32	0.53
PRCME-30	-7.3234	-79.4807	-7.1779	3901	0.9747	2292	0.34	0.54
PRCME-31	-6.9804	-79.6335	-6.8922	1755	0.9840	1142	0.24	0.28
PRCME-32	-6.4519	-79.8572	-6.3479	1378	0.9794	1423	0.28	0.34
PRCME-33	-6.7882	-79.6043	-6.6466	3552	0.9805	1844	0.30	0.44
PRCME-34	-7.8193	-79.1728	-7.6299	4363	0.9655	1985	0.40	0.43
PRCME-35	-9.2627	-78.4313	-9.0937	1777	0.9676	2194	0.39	0.42
PRCME-36	-9.4815	-78.2945	-9.3510	750	0.9683	1938	0.38	0.38
PRCME-3601	-9.4861	-78.2737	-9.5140	1816	0.9677	2595	0.40	0.53
PRCME-37	-9.9359	-78.2186	-9.7839	685	0.9697	1697	0.37	0.36
PRCME-38	-10.0847	-78.1504	-9.9086	2100	0.9723	2337	0.37	0.47
PRCME-39	-11.7923	-76.9914	-11.5598	1764	0.9692	2942	0.39	0.52
PAT-ME	-10.7203	-77.7695	-10.4022	4607	0.9545	3378	0.44	0.52
LIM-ME	-11.9175	-76.6199	-11.8094	1207	0.9545	3936	0.47	0.63
Lluta LLT3	-18.3833	-70.2833	-18.1032	3322	0.9890	3533	0.21	0.58
Piura Piu2	-5.1619	-80.6161	-5.1874	7515	0.9875	632	0.19	0.17
Pisco TRU13	-13.7274	-75.8855	-13.3852	3667	0.9753	3464	0.34	0.63
AZCE	-18.5803	-69.9543	-18.5149	1434	0.9858	3306	0.25	0.56
FRCE	-19.4121	-69.6192	-19.1976	661	0.9914	3801	0.21	0.57

Table 2: Information relevant for interpreting ^{10}Be concentrations. Note that we have used the denudation rates corrected for various quartz contents (indicated in bold) to illustrate the relationships in Figure 4. Catchment-averaged denudation rates were calculated using the CAIRN method developed by Mudd et al. (2016) using the SRTM DEM that we up-scaled to a 200 m resolution for computing efficiency purposes. Calculations were accomplished using the default parameters in CAIRN, which include a ^{10}Be half-life of 1.39 ± 0.01 Ma (Chmeleff et al., 2010; Korschinek et al., 2010) and a SLHL ^{10}Be production rate of $4.30 \text{ at.g}^{-1}.\text{a}^{-1}$ (Braucher et al., 2011) and consider the neutrons, fast and slow muons attenuation lengths and contribution following Braucher et al. (2011). We used a rock density of 2.65 g/cm^3 . Please note that Carretier et al. (2015) reported similar denudation rates for the Ocoña basin.

Sample name	Quartz dissolved	^9Be spike	Measured $^{10}\text{Be}/^9\text{Be}$ ratio	AMS error	^{10}Be concentration	Denudation rates	Denudation rate, corrected for Qz content in bedrock
	[g]	[mg]	[10^{-12}]	[%]	[10^4 atoms/g]	[mm/ka]	[mm/ka]
PRCME-1	40.0348	0.2000	3.06	2	101.9 ± 2.2	13.3 ± 3.6	12.2 ± 3.3
PRCME-3	39.3835	0.1732	1.89	3	55.6 ± 1.4	28.6 ± 5.3	27.7 ± 5.2
PRCME-401	40.8110	0.1998	2.78	2	91.0 ± 1.8	15.2 ± 3.9	12.5 ± 3.2
PRCME-5	39.7310	0.2021	2.46	2	83.4 ± 1.9	21.4 ± 4.8	18.6 ± 4.1
PRCME-6	37.2702	0.1722	0.71	4	21.9 ± 0.8	89.7 ± 16.7	72.1 ± 13.4
PRCME-7	39.8668	0.2009	0.47	3	15.7 ± 0.4	127.5 ± 23.4	106.8 ± 19.6
PRCME-8	38.6178	0.2002	1.47	4	50.8 ± 2.0	34.0 ± 6.4	27.7 ± 5.2
PRCME-9	40.8767	0.2002	0.26	4	8.5 ± 0.4	242.1 ± 45.0	184.1 ± 34.2
PRCME-10	41.0053	0.2022	2.84	2	93.6 ± 1.9	8.7 ± 1.7	9.6 ± 1.9
PRCME-11	40.1231	0.2003	1.98	2	65.9 ± 1.6	14.7 ± 2.9	15.2 ± 2.9
PRCME-12	41.8460	0.1984	1.89	2	59.6 ± 1.2	21.2 ± 4.0	15.3 ± 2.9
PRCME-13	35.5703	0.1736	0.66	4	21.3 ± 0.8	66.5 ± 12.6	40.6 ± 7.7
PRCME-1401	40.1839	0.2022	0.81	3	27.3 ± 0.8	46.1 ± 8.6	29.4 ± 5.5
PRCME-15	39.5359	0.1998	1.09	3	36.6 ± 1.0	27.0 ± 5.7	25.1 ± 5.3
PRCME-17	38.1530	0.1997	0.52	3	18.1 ± 0.5	61.2 ± 11.7	44.1 ± 8.4
PRCME-18	40.2356	0.2004	1.07	2	35.4 ± 0.8	32.9 ± 6.2	27.5 ± 5.2
PRCME-19	25.7694	0.1738	0.64	4	28.8 ± 1.1	66.8 ± 12.3	51.2 ± 9.5
PRCME-20	24.8438	0.1909	0.51	3	26.1 ± 0.8	27.1 ± 5.4	17.9 ± 3.6
PRCME-21	41.3246	0.2019	0.80	3	26.2 ± 0.8	25.9 ± 5.2	21.6 ± 4.4
PRCME-22	39.9407	0.2018	0.91	2	30.6 ± 0.6	38.5 ± 7.1	23.6 ± 4.4
PRCME-23	45.3875	0.2005	0.48	4	14.1 ± 0.5	97.7 ± 18.4	52.8 ± 10.0
PRCME-24	40.1698	0.2008	0.34	3	11.3 ± 0.4	137.1 ± 25.6	82.5 ± 15.4
PRCME-25	40.3298	0.1967	0.78	2	25.4 ± 0.6	41.7 ± 7.7	25.6 ± 4.7
PRCME-26	41.3739	0.2031	0.97	3	31.7 ± 0.9	32.5 ± 6.5	19.6 ± 3.9
PRCME-27	40.0497	0.1992	0.68	4	22.6 ± 0.9	71.2 ± 13.4	70.4 ± 13.2
PRCME-28	10.8368	0.1755	0.58	4	62.0 ± 2.6	14.9 ± 3.0	9.1 ± 1.8

PRCME-29	41.8022	0.2017	1.33	3	42.7 ± 1.4	22.0 ± 5.0	12.9 ± 2.9
PRCME-30	39.6707	0.2008	0.89	3	29.9 ± 0.9	30.5 ± 5.9	25.8 ± 5.0
PRCME-31	37.3769	0.2011	0.99	3	35.4 ± 1.0	14.1 ± 3.0	10.0 ± 2.1
PRCME-32	40.0900	0.1973	0.80	2	26.2 ± 0.6	20.1 ± 4.2	20.8 ± 4.4
PRCME-33	40.8828	0.2003	0.69	3	22.4 ± 0.7	32.5 ± 6.5	25.2 ± 5.1
PRCME-34	40.2766	0.2006	0.44	3	14.4 ± 0.4	50.1 ± 9.2	45.7 ± 8.4
PRCME-35	40.5293	0.1985	0.51	3	16.7 ± 0.4	64.9 ± 12.4	45.9 ± 8.8
PRCME-36	39.6159	0.2003	0.65	3	21.9 ± 0.7	54.3 ± 10.3	43.0 ± 8.2
PRCME-3601	40.0750	0.2009	0.55	3	18.2 ± 0.6	65.6 ± 12.5	38.2 ± 7.3
PRCME-37	39.9118	0.1997	0.62	4	20.8 ± 0.8	35.3 ± 7.1	21.3 ± 4.3
PRCME-38	28.0939	0.1912	1.16	2	52.8 ± 1.1	19.7 ± 4.5	10.1 ± 2.3
PRCME-39	40.5531	0.1989	0.52	3	17.0 ± 0.6	82.2 ± 15.5	53.4 ± 10.1
PAT-ME	50.1067	0.1991	0.24	4	6.4 ± 0.3	260.1 ± 48.8	190.9 ± 35.8
LIM-ME	50.1962	0.1994	0.40	12	10.5 ± 1.3	197.6 ± 43.3	151.7 ± 33.2
Lluta LLT3	-	-	-	-	86.6 ± 5.4	22.1 ± 4.3	20.1 ± 3.9
Piura Piu2	-	-	-	-	19.1 ± 0.0	16.9 ± 4.2	20.4 ± 5.0
Pisco TRU13	-	-	-	-	17.1 ± 1.2	104.1 ± 20.4	69.1 ± 13.5
AZCE	52.78	0.17	3.69	2	80.3 ± 1.5	20.2 ± 3.8	19.1 ± 3.6
FRCE	17.21	0.17	0.91	2	61.3 ± 1.5	35.0 ± 6.8	32.4 ± 6.3

Table 3: Hydrological dataset including information about gauging stations, related records and TRMM-based precipitation rates. The precipitation data are derived from the medium-resolution (ca. 25 × 25 km) rainfall dataset TRMM V6.3B43.2 (Huffman et al., 2007) averaged over 12 years from 1998 to 2010. We resampled this dataset to a 1 × 1 km grid in order to ensure adequate coverage for each drainage basin. The estimated runoff is extracted and computed from this precipitation data. Number of the national gauging station used for averaging an annual runoff. This latter data is taken from the SNIRH (Sistema Nacional de Información de Recursos Hídricos); <http://snirh.ana.gob.pe/consultasSnirh/ConsHidrom2.aspx>.

Sample name	River name	Mean annual precipitation [mm/a]	Mean annual water discharge [m ³ /s]	Code of gauging station SNIRH	Years of observations for stations situated at <5 km distance from the ¹⁰ Be sampling sites	Number of available records
PRCME-1	Quebrada Arunta	149.6 ± 0.1	3.4	191311; 205201; 205202		
PRCME-3	Rio Sama	136.4 ± 0.1	4.0	205103	(1963-89/2000-04/2011-14)	339
PRCME-401	Rio Locumba	115.0 ± 0.1	9.2	205010; 191011; 00858		
PRCME-5	Rio Moquegua	137.8 ± 0.1	3.4	131721000(1/2/3/4); 204804; 204812		
PRCME-6	Rio Tambo	216.3 ± 0.1	38.1	204108; 204905; 204903	1952-86/1995-2010/2011-	442
PRCME-7	Rio Camana	283.9 ± 0.1	68.4	204614; 204621	(1960-63/1971-86/2005-10)	280
PRCME-8	Rio Quilca	170.2 ± 0.1	30.1	204706; 1322310001; 204714		
PRCME-9	Rio Ocona	414.7 ± 0.1	91.1	204504	(1970-73/1984/1986/	64
PRCME-10	Rio Atico	141.3 ± 0.1	2.7	no station		
PRCME-11	Quebrada de Chala	166.6 ± 0.1	2.8	no station		
PRCME-12	Rio Yauca	313.1 ± 0.2	18.5	204002	2014-2016	23
PRCME-13	Rio Acari	318.4 ± 0.2	19.8	203903	2014-2016	25
PRCME-1401	Rio Grande	283.6 ± 0.1	20.4	203802; 203804; 203805		
PRCME-15	Rio Ica	188.4 ± 0.1	12.1	203702; 203703		
PRCME-17	Rio Chico	237.8 ± 0.1	10.1	203501	1950-1990/2002/2008	394
PRCME-18	Quebrada Topara	138.4 ± 0.2	1.3	no station		
PRCME-19	Rio Canete	318.4 ± 0.1	26.4	203302; 203301		
PRCME-20	Rio Mala	257.6 ± 0.2	8.2	203101		
PRCME-21	Quebrada Chilca	116.6 ± 0.1	1.1	no station		
PRCME-22	Rio Lurin	175.5 ± 0.2	3.7	203005; 203006	1950-1961/1972-1984	210
PRCME-23	Rio Chancav	211.4 ± 0.1	8.9	202701		
PRCME-24	Rio Huara	316.9 ± 0.2	18.7	202609		
PRCME-25	Rio Supe	275.4 ± 0.3	3.8	202501; 202502	1964-1973	42
PRCME-26	Rio Fortaleza	355.4 ± 0.2	11.5	202301		
PRCME-27	Rio Santa	571.7 ± 0.2	96.1	211402		
PRCME-28	Rio Viru	330.9 ± 0.2	7.7	201501		
PRCME-29	Rio Moche	383.2 ± 0.2	11.0	201401		
PRCME-30	Rio Jequetepeque	472.8 ± 0.2	25.4	201204		
PRCME-31	Rio Zana	381.3 ± 0.2	9.1	201003	1972-1976	49
PRCME-32	Rio Motupe	297.9 ± 0.2	5.7	200801		
PRCME-33	Rio Reque	438.7 ± 0.2	21.3	200907		
PRCME-34	Rio Chicama	422.5 ± 0.2	24.7	201302; 201303		
PRCME-35	Rio Samanco	248.8 ± 0.2	6.0	201901; 201902		
PRCME-36	Rio Sechin	219.2 ± 0.3	2.2	202003; 202005	(1950/1957/1965/1967	135

PRCME-3601	Rio Casma	345.6 ± 0.3	8.6	202004	1971-1990)	
PRCME-37	Rio Culebras	254.9 ± 0.3	2.4	no station		
PRCME-38	Rio Huarmey	340.1 ± 0.3	9.8	202201; 202202		
PRCME-39	Rio Chillón	204.7 ± 0.1	4.9	202804; 202806		
PAT-ME	Rio Pativilca	490.6 ± 0.2	30.9	202401; 202402		
LIM-ME	Rio Rimac	270.0 ± 0.1	4.4	202905		
Lluta LLT3	Rio Lluta	160.7 ± 0.1	7.3	no station		
Piura Piu2	Rio Piura	352.7 ± 0.0	36.6	200426; 137812004; 200406	(1925-28/1975/1978-82	158
Pisco TRU13	Rio Pisco	272.6 ± 0.1	13.6	203602		
AZCE	Rio Azapa	109.1 ± 0.1	2.1	no station	1981/1991-07/2011-16)	
FRCE	Rio Tiliviche	128.9 ± 0.2	1.2	no station		

Table 4: Results of the statistical investigations, illustrated here as a correlation matrix together with the p-values. Note the slope and discharge do not show any obvious correlations and are thus independent variables. a) and b) statistical results using denudation rates that have not been corrected for various quartz contents in bedrock; c) and d) same as before, but based on denudation rates that have been corrected for various quartz contents. See text for further details.

a: Correlation matrix (Pearson)

Variables	Denudation	Discharge	Slope	Precipitation	Elevation	Drainage area	Latitude	Hi
Denudation	1	0.49	0.37	0.36	0.51	0.41	0.01	0.38
Discharge	0.49	1	-0.13	0.59	0.29	0.88	0.07	0.13
Slope	0.37	-0.13	1	0.33	0.06	-0.36	0.44	0.14
Precipitation	0.36	0.59	0.33	1	-0.12	0.30	0.69	-0.08
Elevation	0.51	0.29	0.06	-0.12	1	0.37	-0.64	0.86
Drainage area	0.41	0.88	-0.36	0.30	0.37	1	-0.17	0.21
Latitude	0.01	0.07	0.44	0.69	-0.64	-0.17	1	-0.54
Hi	0.38	0.13	0.14	-0.08	0.86	0.21	-0.54	1

Values in bold are different from 0 with a significance level $\alpha=0.05$

b: p-values

Variables	Denudation	Discharge	Slope	Precipitation	Elevation	Drainage area	Latitude	Hi
Denudation	0	0.001	0.011	0.014	0.000	0.005	0.963	0.011
Discharge	0.001	0	0.402	< 0.0001	0.057	< 0.0001	0.667	0.407
Slope	0.011	0.402	0	0.025	0.688	0.015	0.002	0.374
Precipitation	0.014	< 0.0001	0.025	0	0.429	0.046	< 0.0001	0.593
Elevation	0.000	0.057	0.688	0.429	0	0.012	< 0.0001	< 0.0001
Drainage area	0.005	< 0.0001	0.015	0.046	0.012	0	0.271	0.174
Latitude	0.963	0.667	0.002	< 0.0001	< 0.0001	0.271	0	0.000
Hi	0.011	0.407	0.374	0.593	< 0.0001	0.174	0.000	0

Values in bold are different from 0 with a significance level $\alpha=0.05$

c: Correlation matrix (Pearson)

Variables	Denudation	Discharge	Slope	Precipitation	Elevation	Drainage area	Latitude	Hi
Denudation	1	0.56	0.31	0.37	0.52	0.47	-0.02	0.35
Discharge	0.56	1	-0.13	0.59	0.29	0.88	0.07	0.13
Slope	0.31	-0.13	1	0.33	0.06	-0.36	0.44	0.14
Precipitation	0.37	0.59	0.33	1	-0.12	0.30	0.69	-0.08
Elevation	0.52	0.29	0.06	-0.12	1	0.37	-0.64	0.86
Drainage area	0.47	0.88	-0.36	0.30	0.37	1	-0.17	0.21
Latitude	-0.02	0.07	0.44	0.69	-0.64	-0.17	1	-0.54
Hi	0.35	0.13	0.14	-0.08	0.86	0.21	-0.54	1

Values in bold are different from 0 with a significance level $\alpha=0.05$

d: p-values

Variables	Denudation	Discharge	Slope	Precipitation	Elevation	Drainage area	Latitude	Hi
Denudation	0	0.000	0.038	0.012	0.000	0.001	0.910	0.017
Discharge	< 0.0001	0	0.402	< 0.0001	0.057	< 0.0001	0.667	0.407
Slope	0.038	0.402	0	0.025	0.688	0.015	0.002	0.374
Precipitation	0.012	< 0.0001	0.025	0	0.429	0.046	< 0.0001	0.593
Elevation	0.000	0.057	0.688	0.429	0	0.012	< 0.0001	< 0.0001
Drainage area	0.001	< 0.0001	0.015	0.046	0.012	0	0.271	0.174
Latitude	0.910	0.667	0.002	< 0.0001	< 0.0001	0.271	0	0.000
Hi	0.017	0.407	0.374	0.593	< 0.0001	0.174	0.000	0

Values in bold are different from 0 with a significance level $\alpha=0.05$

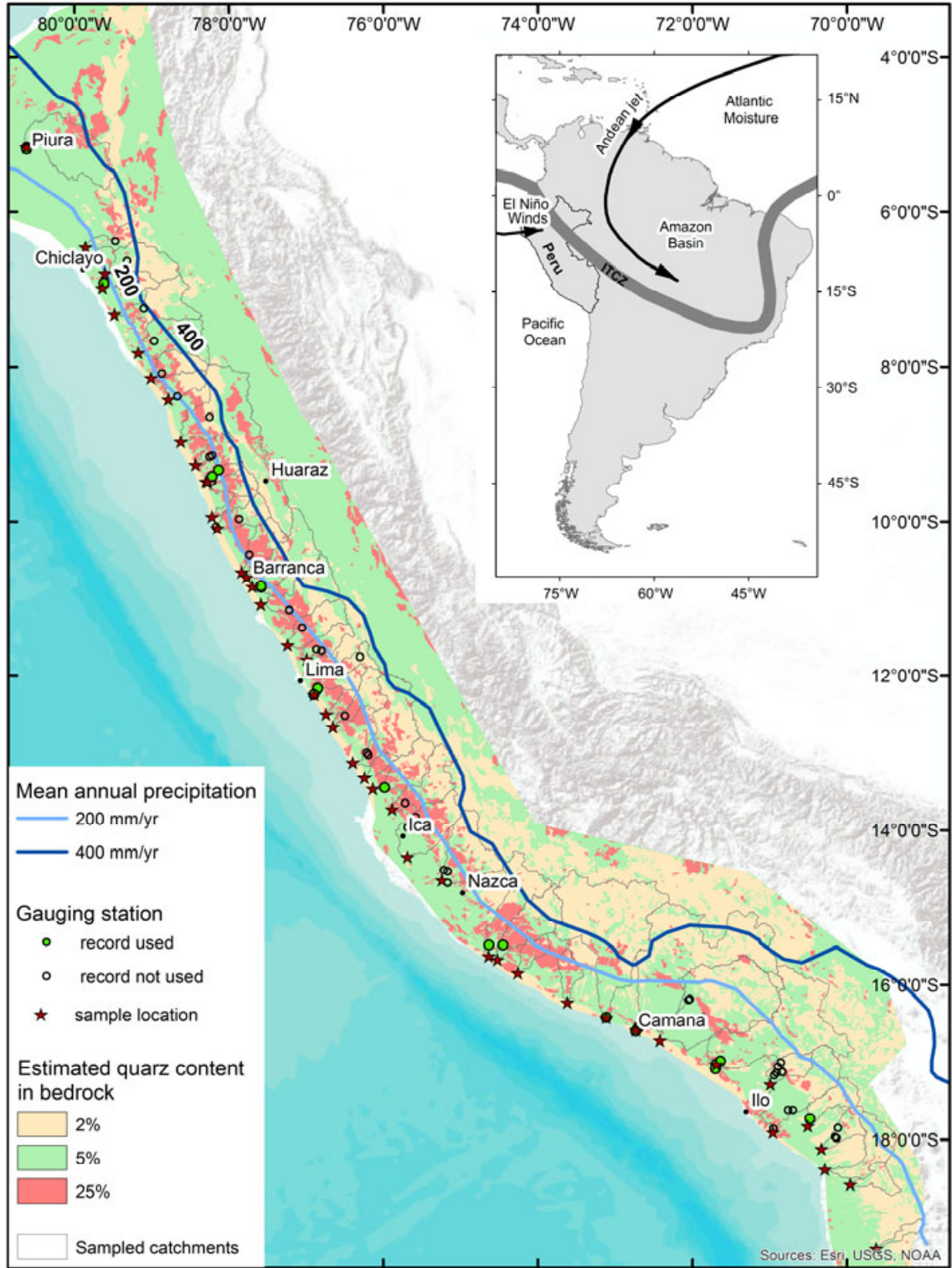


Figure 1

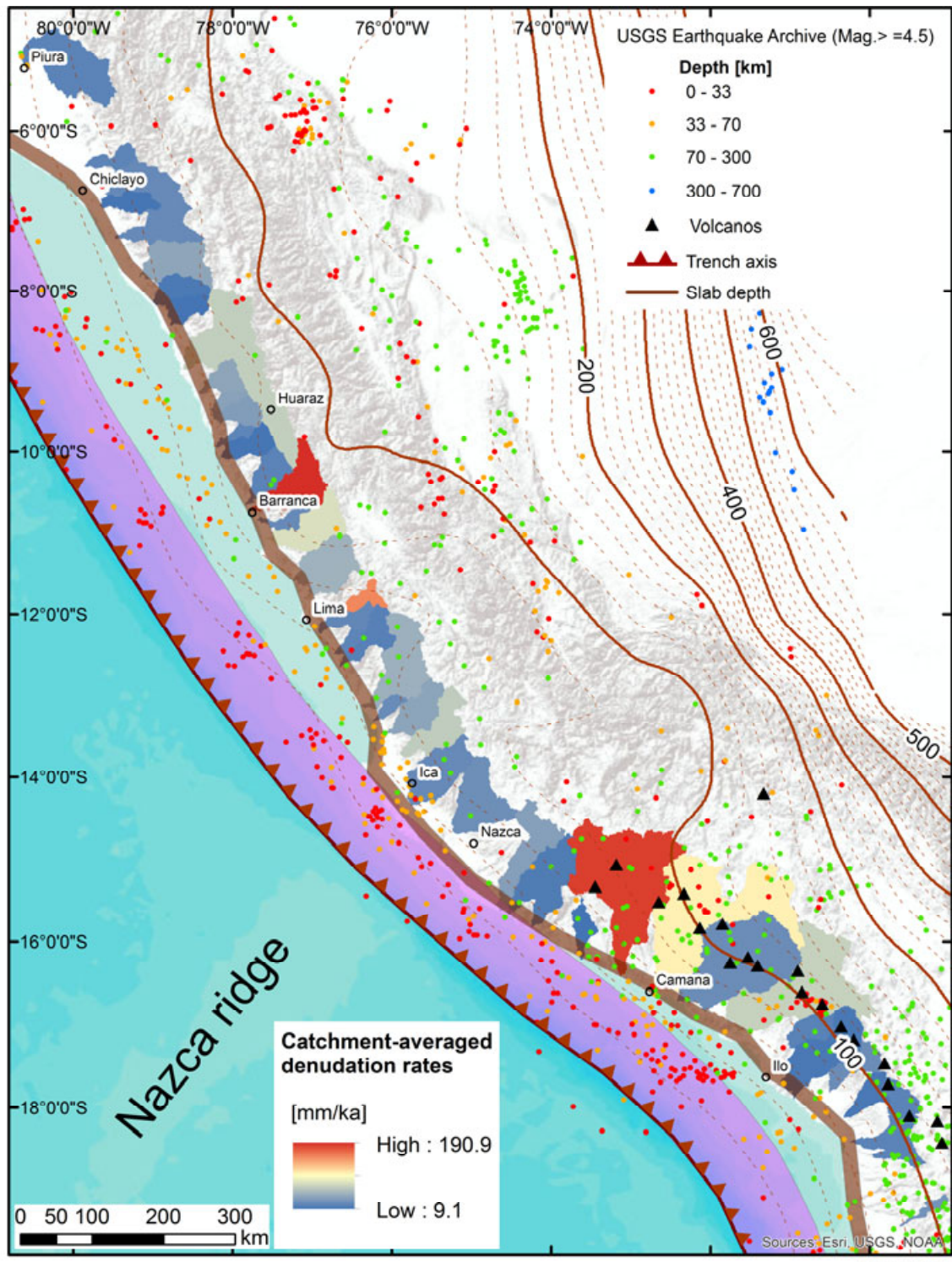


Figure 2

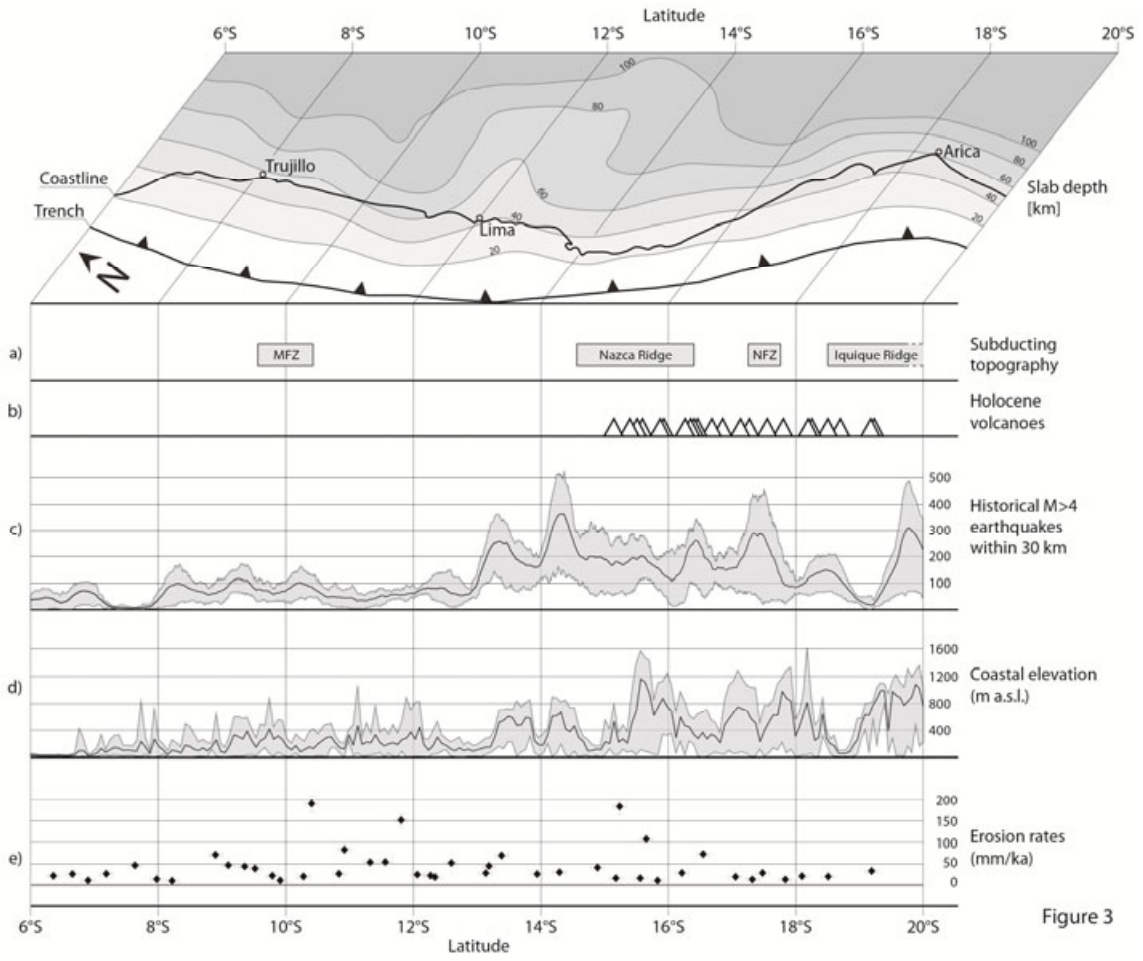


Figure 3

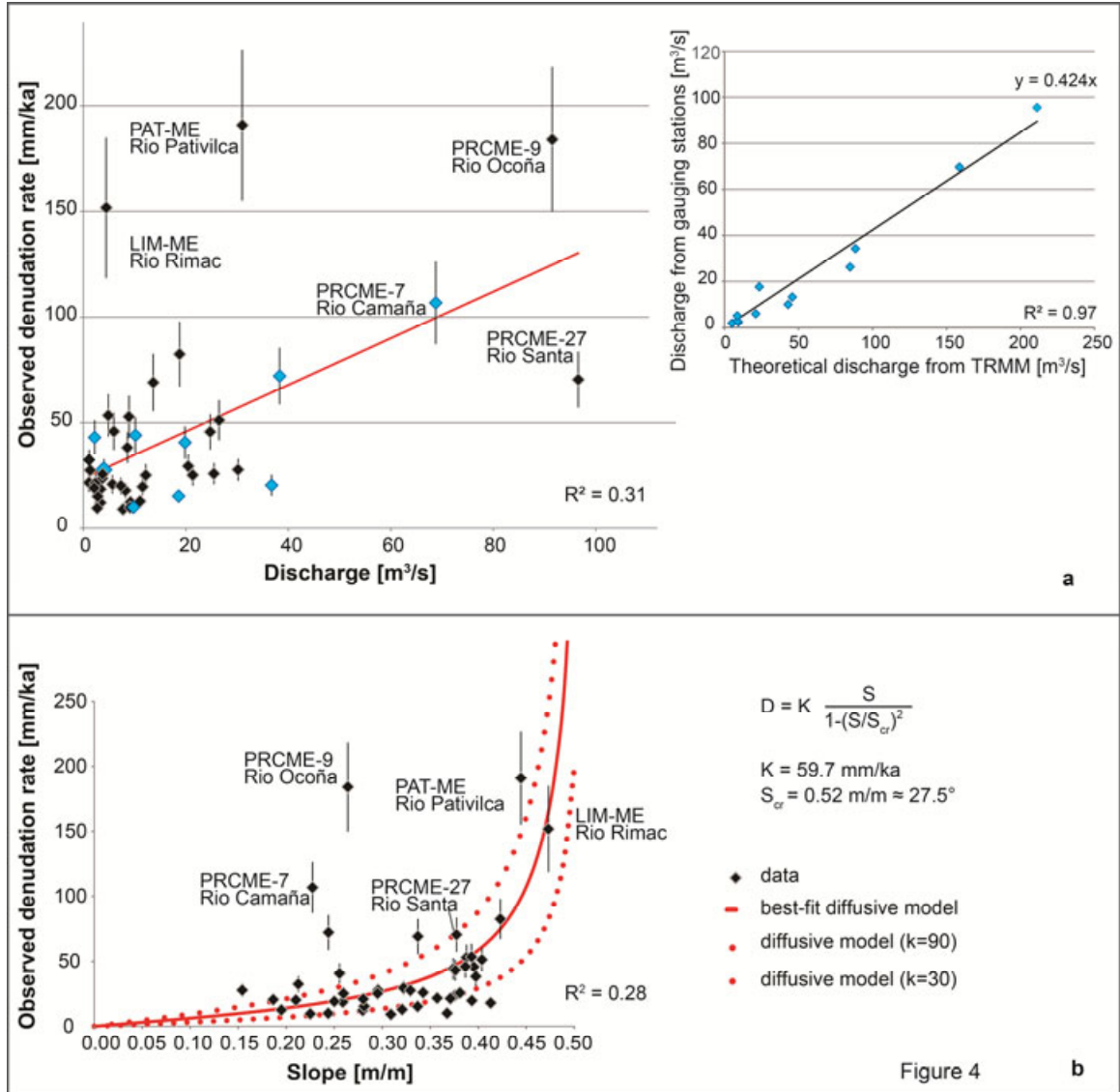


Figure 4

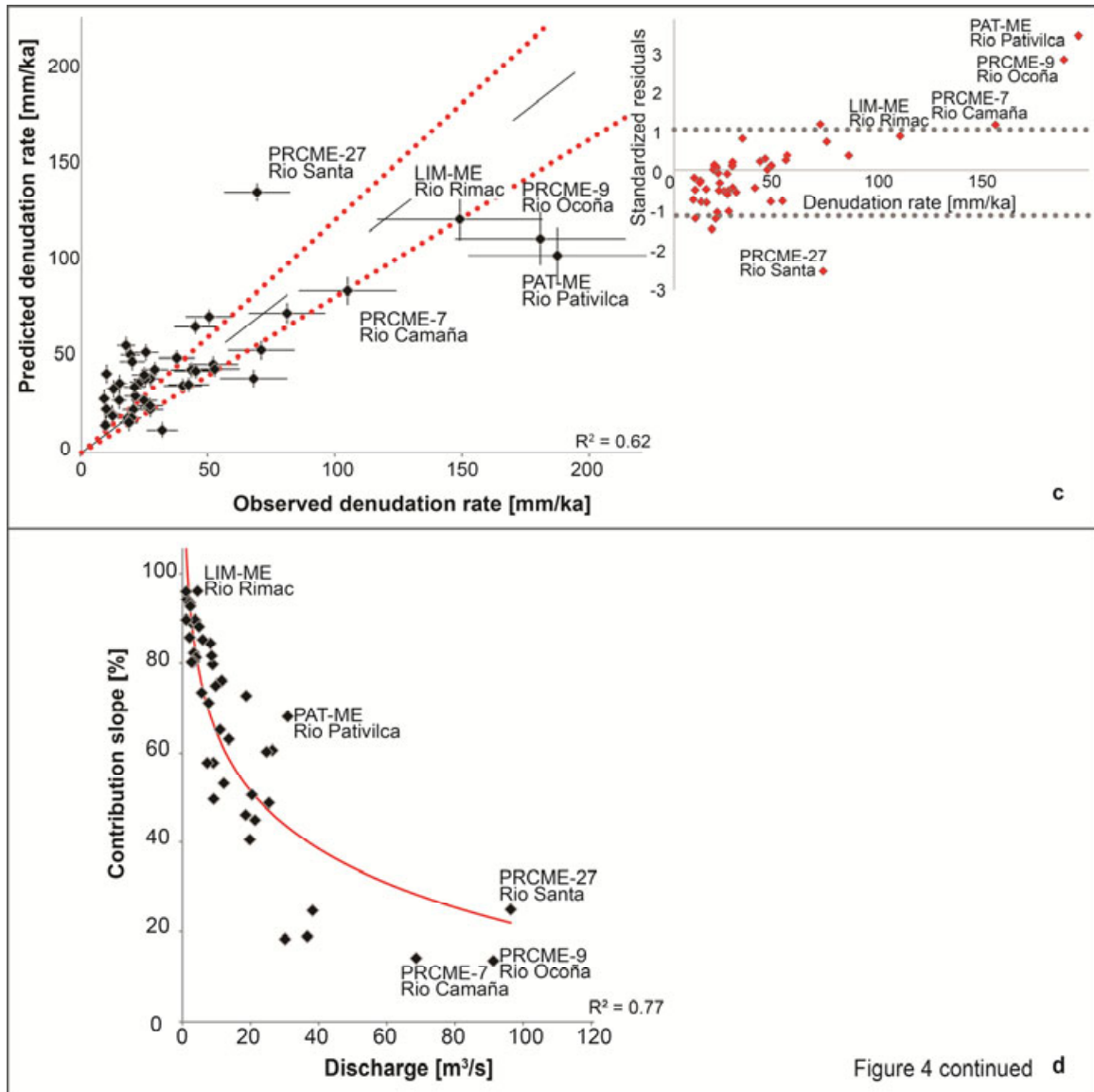


Figure 4 continued d