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The control mechanisms of erosion and weathering at basin scale from cosmogenic nuclides in river sediment

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Abstract

The study of a sample of river sediment enables the determination of spatially averaged denudation rates that provide an exceptional perspective on erosion and weathering processes that have taken place within a landscape. These measurements are done with in-situ produced cosmogenic nuclides (e.g. ^{10}Be, ^{26}Al), mostly in quartz from alluvial sediment. Cosmogenic nuclides are produced when secondary cosmic rays interact with the very uppermost layer of the Earth's surface. They are produced within a characteristic depth scale of about 1 m, which means that the measured concentrations record an integrated denudation history while material passed through this depth interval. Depending on the denudation rate the resulting integration time scales are 10^3 to 10^5 years, and one obtains a robust long-term estimate of natural denudation that is relatively insensitive to short-term changes. The last 10 years have seen significant research activity using these methods, and an array of fascinating tectono-geomorphologic and geochemical insights are emerging. Amongst these is the ability to identify the physical and chemical processes with which a landscape responds to tectonic activity or climate change. A compilation of world-wide denudation rates in non-glaciated areas, that however, does not yet include some of the world's most active mountain belts, has resulted in the following findings, some of which have been unexpected: (1) No obvious relationship between precipitation or mean annual temperature and total denudation is apparent. (2) Topographic relief alone does not result in high rates of denudation. (3) Denudation rates are high in areas of landscape rejuvenation; that is triggered and controlled by tectonic activity (faulting, escarpment formation and retreat, rifting, surface uplift). (4) Rates of weathering (using a combination of cosmogenic nuclides and zirconium-normalised cation loss balances) co-vary primarily with physical erosion rates and much less with temperature or precipitation. (5) In some areas of high land use short-term rates (from river load gauging) exceed those from cosmogenic nuclides by several orders of magnitude, which serves to highlight the severity of geomorphic change caused by human action. In the future, the control mechanisms over denudation will be determined on all spatial scales, ranging from the single soil section to entire river basins. The same analysis can be done back through time on well-dated terraces, lake records, and marine sediment cores, which is possible with ^{10}Be for the past 1–2 My. The rates obtained will be used to develop a quantitative understanding of

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tectonic, geomorphologic, and geochemical landscape processes, which in turn is a prerequisite to design and calibrate models of the response of landscapes to tectonic, climate, and anthropogenic forcing.

Keywords: cosmogenic nuclides; erosion; weathering; geomorphology

1. Introduction

The Earth's surface is constantly being exposed to a stream of particles arising from nuclear processes that take place within our galaxy. The study of the nuclear reactions brought about by these particles impinging upon the Earth has given us a deeper new understanding of the forms of the terrestrial surface and the processes that shape it. The grand pioneer of the study of these natural nuclear processes, Devendra Lal, presented a set of equations that gave us the quantitative tools to use these nuclides to determine ages of landscapes and rates of geomorphic change [1]. Ever since the study of such nuclides has allowed the dating of fault scarps, fluvial and coastal terraces, alluvial fans, lava flows, glacial retreats, moraines, and other primary relief elements [2–4]. However, it is a handful of sediment collected from a river bed that is leading to a profoundly new understanding of the rates of landscape change. First pioneered for ^{10}Be precipitated from the atmosphere [5] it is the in situ-produced cosmogenic nuclides in river-borne quartz from which exact spatially averaged denudation rates have first been determined [6,7]. Although the method is only just emerging from the development phase, a first range of applications have been explored in the last 10 years. The method can be used to determine the rates at which physical erosion is taking place, and has taken place, in anything from an agricultural plot to an entire river basin [6–11]. It can reveal the relationship between sediment generation, and sediment transport [12–14] and mixing [15,16]. It can show which topographic and lithologic features such as relief, slope and substrate characteristics serve to control denudation [17–21]. It can be used to unravel the mechanisms of escarpment retreat [22,23], and to identify sites at which focussed erosional unloading might lead to the initiation of tectonic faulting [24]. In conjunction with short-term sediment load data it can be used to quantify the increase in soil erosion by human-induced land-use change [25–27]. The principle can be used to determine the rates and locations of chemical weathering, the rate of atmospheric CO_2 drawdown by silicate weathering, and the relationships between physical and chemical weathering at diverse sites [28–31]. The function that describes how the soil production rate depends on soil thickness can be related to basin-scale erosion averages to assess the overall state of perturbation of a landscape [32,33], and the effects of soil mixing on erosion can be assessed [34,35]. Last, but not least, the method when applied to buried sediments, can be used to better determine how fast the terrestrial surface has eroded over recent geological time, the Quaternary [36–42].

In this review the principles of using in situ-produced cosmogenic nuclides on a catchment scale are briefly described. The studies cited are strictly limited to those that approach spatially averaged denudation rates using sediment. For a comprehensive explanation of the principles of cosmogenic nuclides the reader is referred to the review by Gosse and Phillips [2]. A more panoptic summary of applications of cosmogenic nuclides in denudation studies has recently been presented by Bierman and Nichols [3]. The purpose of this article is to highlight some of the most exciting discoveries of the past 5 years and the future prospects of this rapidly emerging field.

2. Methodological principles

2.1. Cosmic rays, nuclear reactions, and the production of cosmogenic nuclides

Most terrestrial cosmogenic nuclides are produced in the atmosphere, where high-energy particles (protons, neutrons of GeV energy) impinge on atmospheric molecules, causing nuclear reactions. These reactions in turn produce a cascade of secondary

Glossary of terms

Accelerator Mass Spectrometer (AMS)	Mass-sensitive analysing system that accelerates ions to MeV energy. This technique is necessary to measure the extremely small number of rare cosmogenic nuclide relative to a stable reference isotope that is present in known amounts (e.g. $^{10}Be/^{9}Be$, $^{14}C/^{12}C$, $^{26}Al/^{27}Al$, $^{36}Cl/^{37}Cl$) [43,44]. Isotope ratios are as low as 1×10^{-15}. The precision of these measurements is between 2% and 10%, and depends mainly on the number of counts measured from the sample.
Cosmic ray absorption mean free path and absorption depth scale	The depth Λ at which the intensity of cosmic rays is reduced by a factor of 1/e by interaction with material. Units: g cm^{-2}. 150 g cm^{-2} correspond to an absorption depth scale $z^*=\Lambda/\rho$ of 600 mm in silicate rock of which the density is 2.6 g cm^{-3}.
Cosmic Rays, primary	High energy (0.1 to 10^{20} GeV) galactic particles, composed primarily of protons (83%), α-particles (13%), and heavier nuclei (1%) [2]. When these particles reach the upper atmosphere they cause nuclear reactions that lead to secondary cosmic rays. A 3% electron contribution is not relevant for cosmogenic nuclide production.
Cosmic Rays, secondary	Nucleons (neutrons, protons) and muons of 0.1 to 500 MeV energy that have been produced by interaction between primary cosmic rays and molecules in the Earth's atmosphere. Secondary cosmic rays form a cascade of particles whose flux decreases with increasing atmospheric pressure.
Cosmogenic nuclides	Radioactive cosmogenic nuclides decay, and are therefore usually absent in eroding earth materials prior to exposure (e.g. ^{10}Be, ^{14}C, ^{26}Al, ^{36}Cl). Stable cosmogenic nuclides might be present in eroding surface material from previous exposure episodes. These cosmogenic isotopes are the rare gases (e.g. ^{3}He, ^{21}Ne, ^{22}Ne).
Cosmogenic nuclides, in situ-produced	Nuclides that are produced by interaction of secondary cosmic rays with solids (spallation, negative muon capture) at the Earth's surface. Other acronyms frequently used are "Terrestrial Cosmogenic Nuclides (TCN)" or "Cosmogenic Radio Nuclides (CNR)". In situ-produced cosmogenic nuclides are distinct from meteoric cosmogenic nuclides that are produced in the atmosphere, the flux of some of which (e.g. meteoric ^{10}Be) is 10^3 times greater.
Denudation Rate	The total rate of removal of mass from, and in depths near the Earth's surface. It is the combined effect of physical (? erosion Rate) and chemical (? weathering Rate) processes. Since cosmogenic nuclides accumulate as material moves towards the surface by the removal of material above, they always measure the total (erosion and weathering) rate, and hence the denudation rate [units: e.g. m My^{-1}=mm ky^{-1}=μm $year^{-1}$=t km^{-2} $year^{-1}/\rho$, where ρ is the bedrocks density in t m^{-3}].
Erosion Rate	The rate of lowering of the Earth's surface due to mechanical processes. In the literature, it is a common inaccuracy to call cosmogenic nuclide-derived denudation rates "erosion rates" or even "sediment generation rates". This terminological simplification is a valid approximation only in areas in which the weathering rate is negligible when compared to the (physical) erosion rate. Note that "Soil Erosion" as used by geographers and agronomists describes erosion caused by human action.
Muons, slow negative	Nuclear particles of short lifetime (1×10^{-6} s at rest) and a mass 207 times that of an electron. The probability of their capture by atoms is low; hence the production rate of cosmogenic nuclides by slow negative muons is low. Once a muon is captured by the shell of an atom, it can react with the nucleus to produce a cosmogenic nuclide. The attenuation depth is a few meters [45].
Muons, fast	Fast muons are both negative and positive muons of high (GeV) energy which, when slowed down, emit γ-rays that cause photodisintegration reactions in nuclei, thereby leading to the release of neutrons of sufficient energy to produce cosmogenic nuclides ? spallation. Their attenuation length is of the order of a few 10^1 m [46]. Muonic production dominates at depths >3 m (Fig. 1).
Nucleons	Secondary cosmic rays consisting mainly of neutrons and protons whose flux rapidly attenuates when interacting with solids.
Production Rate	Rate at which cosmogenic nuclides are produced in a given mass of chemically defined target material in a given time [units: atoms $year^{-1}$ $g(mineral)^{-1}$].
Spallation	Nuclear reaction in which a nucleon of several MeV energy interacts with a target nucleus to release clusters of protons and neutrons, resulting in the production of a different nuclide without fission of the nucleus and without necessarily capturing the incoming nucleon.
Time scale of denudation rates	The mean time a cosmogenic nuclide-derived denudation rate integrates over. The rate corresponds to the time denuding material resides in one absorption depth scale z^*.
Weathering Rate	Partial dissolution of bedrock by surficial fluids, and removal of soluble ions in solution. The weathering rate is included in cosmogenic nuclide-derived denudation rates.

cosmic rays (mostly neutrons and muons of MeV energy), some of which reach the Earth's surface where they produce cosmogenic nuclides in situ. The nuclides produced depend on the arriving cosmic ray particles, their energy, and the chemistry of the target mineral. The most widely used cosmogenic nuclides are currently ^{10}Be ($T_{1/2}$=1.5 My), ^{26}Al ($T_{1/2}$=0.7 My), ^{3}He (stable), ^{21}Ne (stable), ^{22}Ne (stable), and ^{36}Cl ($T_{1/2}$~300 ky) [2]. Work is currently underway to develop methods for extraction and assessment of in situ-produced ^{14}C ($T_{1/2}$=5730 years) [47]. However, for catchment-wide studies this nuclide is of value only in areas of high denudation rate (see Section 2.4). For denudation rate studies, ^{10}Be has been the most widely used nuclide. The reason for this emphasis is that ^{10}Be, due to its radioactive nature, is virtually non-existent in rock prior to its emerging into the cosmic ray field. ^{26}Al is also used for the same reason, but currently has much poorer analytical precision than ^{10}Be. For ^{10}Be and ^{26}Al quartz has emerged as the mineral of choice due to its resistance to the loss of most cosmogenic nuclides, its abundance in silicate rocks and sediments, its resistance to chemical weathering, and its simple target chemistry, resulting in uniform cosmogenic nuclide production rates. The stable rare gases have not been used in denudation rate studies. Due to their stable nature, they may accumulate over multiple exposure episodes, have additional contributions from inclusions of atmospheric gas, and consist of isotopes produced by fission of U and radiogenic processes such as capture of α particle [48,49]. Thus the build-up of cosmogenic Ne during a few thousand years of surface residence may be a small fraction of the radiogenic build-up over millions of years since the mineral formed. Their use is restricted to cases where samples have been exposed to exceptionally higher levels of cosmic radiation than are usually experienced by eroding rocks. These restrictions do not necessarily apply to 3 He. However, in quartz, He is prone to post-spallation loss [50].

2.2. Scaling laws, surface production rates, absorption, and analytical techniques

2.2.1. Scaling of cosmic ray intensities

The intensity of primary cosmic rays varies with the strength of the geomagnetic field. The intensity is greatest at latitudes above 60°, and weakest at the equator [1]. The Earth's geomagnetic field varies with time. For example 20 ky ago the intensity was about 60% of today's levels. These variations have to be taken into account. The intensity of secondary cosmic rays also depends on air pressure [51]. The higher the air pressure (i.e. the lower the altitude), the lower the in situ production of cosmogenic nuclides is. Lal [1] has postulated scaling factors that allow the expression of production rates as a function of both geomagnetic latitude and atmospheric shielding. However, both the latitude–altitude correction factors and the paleo-intensity effects are potentially associated with considerable systematic uncertainties that are currently subject of active research [52–55].

2.2.2. Correction for shielding

In steep terrains, an additional correction factor for skyline shielding has to be taken into account, as the presence of objects obstructing the exposure to cosmic rays diminishes the production rate of nuclides [56]. Similarly, additional shielding, for example by snow or vegetation, needs to be corrected for [57].

2.2.3. Production rates in minerals

The production rates of ^{10}Be and ^{26}Al in quartz have been determined on glacially polished surfaces [58] and landslides [59] of known age. When scaled to sea level and latitudes >60° they are ca. 5–5.5 atoms g^{-1} year^{-1} for ^{10}Be. The production ratio ^{26}Al/^{10}Be is ca. 6. A summary of production rates has been given by Gosse and Phillips [2].

2.2.4. Absorption of cosmic rays in rocks and soils

Secondary cosmic rays are absorbed when they interact with matter. Absorption principally occurs within the uppermost layer below the Earth's surface. For nucleons, Lal [1] has established an absorption law

$$z^* = \Lambda/\rho \tag{1}$$

in which the absorption depth scale z^* is the quotient of a cosmic ray absorption mean free path Λ [150 g cm^{-2}] and the absorbing materials' density ρ [g cm^{-3}]. In silicate rock, a typical absorption path length is 600 mm. At 2 m depth the nucleonic production rate is only about 3% of the equivalent surface production rate (Fig. 1). In contrast, the

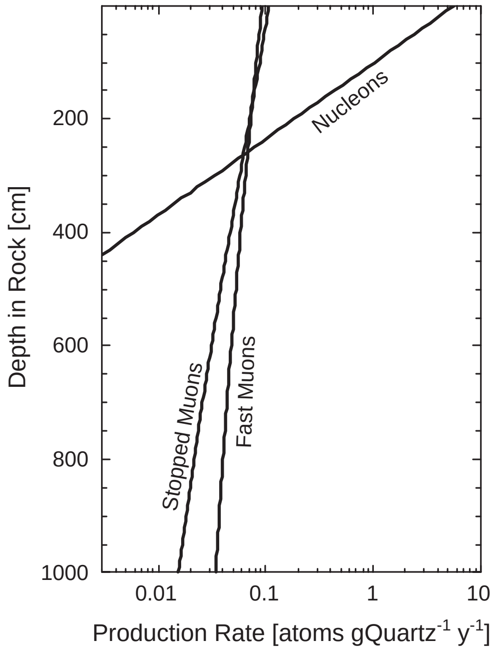

Fig. 1. The depth-dependency of ^{10}Be production by nucleons (neutrons, protons [1] and muons [45,46]. All three scaling laws have been incorporated into Lal's absorption formalism by a series of exponential functions [41]. Note that while most of the nuclide production takes place close to the surface, an eroding rock that is moving towards the surface by removal of material from above is subjected to muogenic production long before the nucleonic component comes into place.

interaction between muons and matter is much less intense, and muonic production decreases only slowly with depth (Fig. 1). Therefore, while the sea level-high latitude production rates of fast and stopped muons are only 0.09 and 0.1 atoms year^{-1} g (Quartz)$^{-1}$, respectively [45,46], they contribute substantially to deep rocks that are moving towards the surface by removal of material from above by denudation.

2.2.5. Measurement of cosmogenic nuclides

Given that the concentration of nuclides is usually in the order of just a few thousand atoms in a gram of sample, large sample amounts have to be processed, using a very sensitive measurement technique. Because most of the ^{10}Be in a surface sample is absorbed meteoric Be, the samples have to be leached extensively in weak hydrofluoric acid to remove such surface contamination. For ^{10}Be and ^{26}Al leached samples of quartz ranging between a few grams and 100 g are dissolved in hydrofluoric acid. Be and Al are extracted using chromatographic techniques. Measurements are performed by accelerator mass spectrometry (AMS) [43,44]. Systematic uncertainties in the production rates and the scaling laws add a further 10–20% uncertainty, but this does not affect any intersample comparison, as is usually the case when samples from one area are measured as a function of certain geomorphologic parameters.

2.3. Denudation rates

Denudation rates, meaning the total rate which includes physical and chemical removal from soil or rock surface, can be calculated from measurements of in situ-produced cosmogenic nuclides. This is possible under the assumption that denudation is steady, and that denudation has been taking place for a period that is long compared to a denudation time scale z^*/ε (ε is the rate of denudation [mm ky^{-1}]). In this case the production of nuclides equals the removal of nuclides at the surface by denudation. Then the surface nuclide concentration of an eroding bedrock or soil (C, atoms g^{-1}) is inversely proportional to the denudation rate ε [1].

$$C = P_0/(\lambda + \varepsilon/z^*) \qquad (2)$$

where P_0 (atoms g^{-1} year^{-1}) is the cosmogenic production rate at the surface in a mineral of known composition, and λ (year^{-1}) is the decay constant of the cosmogenic nuclide. With this relationship a bedrock denudation rate can be estimated from its surface nuclide concentration.

2.4. Let nature do the averaging

A full quantification of the denudation rates of an entire landscape would require the analysis of a large number of representative soil and bedrock samples from various geomorphic settings in that landscape (Fig. 2, e.g. bedrock surfaces, soil-mantled plateaus, hillslopes, river valleys, gorges, land slides, etc.). Alternatively, if such landscape scale denudation information is required, we can let nature do the averaging for us.

A first approach in this regard was published by Brown et al. in 1988 [5]. In that study meteoric ^{10}Be

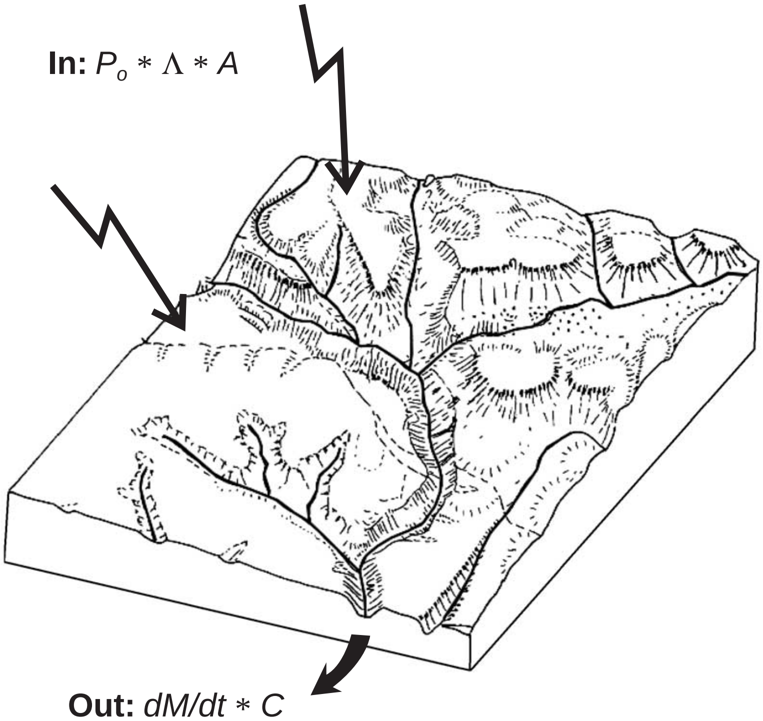

Fig. 2. Illustration of the "let nature do the averaging" principles of the catchment approach. This approach leads to a denudation rate that is averaged over all geomorphic processes contained in the drainage basin. Nuclides are produced in a catchment with the area A "In"; and they are exported by river sediment "Out". If the inbound flux by production equals the outbound flux by denudation the basin is at cosmogenic steady state and the mass flux d*M*/d*t* [tons year^{-1}] can be calculated. Dividing the mass flux by the catchment area and the rocks density results in the catchment-wide denudation rate ε [mm ky^{-1}].

was measured in river sediment. However, since the distribution of atmospheric production rates of meteoric ^{10}Be is not well-constrained, this method did not yet draw much attention. When a few years later the production rates of in situ-produced nuclides, their scaling laws, and their robust closed-system behaviour in most minerals became apparent [1], the obvious step was to estimate spatially averaged denudation rates from in situ-produced cosmogenic nuclide concentrations in creek, stream and river sediments [8]. The first attempts were published almost 10 years after the study of meteoric ^{10}Be [6,7]. The experimental verification of the method was performed by Granger et al. [6]. The principles are as follows.

A sample of sediment collected at the outlet of a catchment is assumed to be an aggregate of grains that originate from all of the different regions of the upstream area (Fig. 2). These sediments are eroded at different rates from different source areas (i.e. from different sub-catchments), and therefore inherit different nuclide concentrations. Thorough mixing of grains through hillslope and fluvial transport processes homogenises nuclides in the downstream sediment load. Spatially averaged denudation rates are calculated from Eq. (2) with exact altitude-dependent surface production rates P_0 for the catchment. In practice, the catchment-wide production rate is scaled using area-weighted elevation bands, or a digital topographic model of the catchment. However, even using the mean altitude and latitude of the catchment only adds a minor inaccuracy in all but high-relief terrains.

This approach is based on several important assumptions. (1) Denudation in the catchment is uniform over time. In this case the catchment is in isotopic steady-state (i.e. cosmogenic nuclide production in the catchment equals the cosmogenic nuclide export via total denudation and radioactive decay, and all sediment eroded is always exported by a river). This is a good assumption if all surfaces are releasing sediment in proportion to their long-term erosion rate. This is a questionable assumption in tectonically active areas, and in areas of intense rainfall, where sediment transport is dominated by mass wasting. In this case sediment leaving a catchment might be dominated by a small area recently affected by landslides, for example. To overcome this problem, the size of an overall catchment can be chosen such that all erosion processes are always represented in the sample. (2) Each eroding area of the catchment must contribute quarks to the mixed sediment sample in proportion to its erosion rate. This will be the case where catchments consist of a single lithology. It is not so in complex (e.g. sedimentary) settings, unless all lithologies are eroding at the same rate. (3) Contributing rock types contain similar grain size distributions, and the grain sizes released do not depend on the erosion processes in operation [7,20]. (4) Quartz is not enriched on its way to the surface by preferential dissolution of other minerals. If this is the case, a correction for this effect has to be applied [60]. (5) Sediment storage in a catchment is minimal, such that the time scale for denudation on hillslopes is much longer than sediment transfer time scales. (6) The denudational time scale (see Section 2.5) is smaller than the time scale for radioactive decay, or $\varepsilon/z^* \gg \lambda$. Therefore, the ^{10}Be method is applicable in those settings where $\varepsilon > 0.3$ mm ky^{-1}, while for ^{14}C $\varepsilon > 80$ mm ky^{-1} (note that the latter condition makes ^{14}C of limited use in catchment-wide denudation studies).

It must be stated that some violation of certain assumptions stated above is often inevitable in complex natural settings. However, the accuracy of the method is usually sufficient for many of the potential applications and would anyway yield a more robust estimate than many other estimates of denudation (e.g. river loads) which are often accurate to only a factor of a few.

2.5. Averaging time scales

The averaging time scale is a function of the denudation rate itself (Fig. 3) and can be calculated by dividing the denudation rate ε by the absorption depth scale z^*. This result is also called "apparent age" since it can be viewed as if the nuclide concentration were to provide an exposure age. However, this apparent age corresponds to the residence time in rock or soil within one absorption depth scale. This would be the top 0.6 m for bedrock, and about 1.0 m for soils. From Fig. 3 it is apparent that characteristic time scales vary between 10^2 years for mountain belts at active margins and 10^5 years for cratonic shield areas.

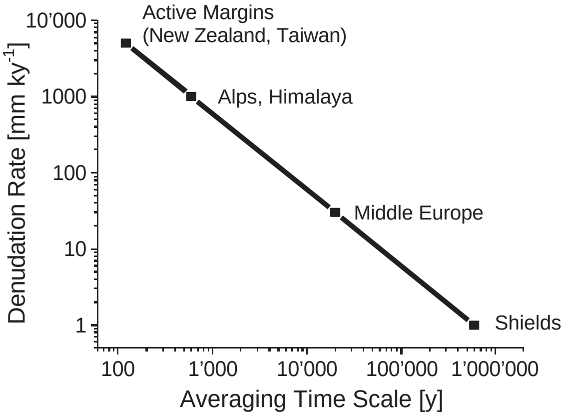

Fig. 3. Time scales over which denudation rates are averaged. These depend on the denudation rate itself, and correspond to the time it takes to erode the upper 0.6 m of bedrock, or ca. 1.0 m of soil.

The great benefit of the method is for those investigating denudation rates over time scales that are relevant to rock weathering and natural geomorphic processes. Unless human-caused soil erosion is so grave that deeply shielded sediment has become exposed [31], cosmogenic nuclides are quite insensitive to short-term change of erosion rates (or, in other words, to temporal violations of the steady-state assumption (1)), and provide instead a robust pre-development estimate of denudation rates. This effect is illustrated in Fig. 4, where a given denudation history (thin black line) has been converted numerically into a model cosmogenic nuclide-derived denudation rate (dashed line). Fig. 4a illustrates the documented historic soil erosion history of Middle Europe [61]. The resulting cosmogenic sequence is strongly damped, and the major variations in erosion rate due to for example a catastrophic flood in 1342, and deforestation during the industrial revolution are barely resolvable. This is due to relatively low denudation rate of 30 mm ky^{-1}, that results in an averaging time scale of 20 ky. In this case cosmogenic nuclides provide a "natural" background denudation rate that can be

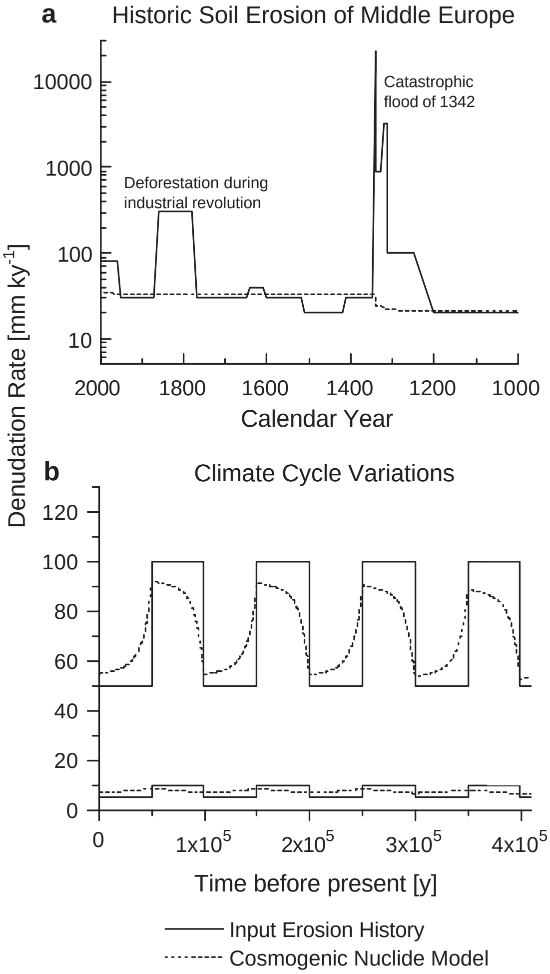

Fig. 4. Theoretical numerical model illustrating the effect of damping of "real" secular changes in denudation rate (thin black line) on cosmogenic nuclide-derived rates (dashed line). This damping is due to the long averaging time scales, which depend on denudation rate. The dashed curve was calculated by numerically integrating the accumulation of cosmogenic nuclides as material moves towards the surface with the changing velocity that is based on the hypothetical denudational input history. Then the concentration of nuclides contained in material eroding at the surface at any time in the past is converted into a model cosmogenic nuclide-derived denudation rate. a) Historic soil erosion of Middle Europe ([61], Table 4.10); b) hypothetical variations that act on climate time scales (100 ky amplitude). In the upper example the denudation rates vary between 50 and 100 mm ky^{-1}; in the lower between 5 and 10 mm ky^{-1}. While in the high-rate model averaging time scales are sufficiently short to resolve climate-induced variations, these variations are damped-out in the low-rate model and these provide a long-term average of denudation. For further models of this kind the reader is referred to Bierman and Steig [8].

used as a benchmark to evaluation of short-term, anthropogenically accelerated soil erosion. In the same way a denudation rate of the order of 10^1 mm ky^{-1} also average over glacial–interglacial climate cycles [41]. In this case variations of denudation rate over climate cycles are barely resolvable. In the lower example of Fig. 4b hypothetical denudation rates oscillate between 5 and 10 mm ky^{-1} over a 100 ky amplitude climate cycle without significant changes in cosmogenic nuclide-derived estimates. A different picture would result in high-denudation rate areas (50–100 mm ky^{-1} example of Fig. 4b), where time scales are sufficiently short to result in a more weakly damped denudation rate signal. There, climate change-dependencies are much better resolvable (see Glossary of terms).

3. Inter-method comparison: why time scale matters

With the advent of cosmogenic nuclide-based methods, we now have denudation rate estimates for three entirely different time scales available to us. First, there is river load gauging (suspended and dissolved loads of rivers) of which the time scale, defined by the gauging period, is usually 10–100 years. Previous large-scale estimates of denudation rates were mostly based on these data [62,63]. Second, cosmogenic nuclide-derived denudation rates average, as stated, over 1–100 ky time scales. Third, zircon and apatite fission track and U–He cooling data average over 1–10 My time scales and typically date the younger exhumational cooling history of mountain belts [64]. Cosmogenic nuclides therefore fill the gap between the "hydrologic" or land use processes, and the "tectonic" time scale. Some fascinating, process-related issues have become apparent from those few studies, where multiple time scales have been considered within a given study area (Table 1).

In the Idaho Mountains, river loads gave much lower denudation rates (1–12 mm ky^{-1}) than cosmogenic nuclides (3–100 mm ky^{-1}; [10]). Kirchner et al. [10] interpreted the river loads as greatly underestimating true sediment delivery, due to the episodic nature of sediment transport. While low-frequency high-magnitude events might not be covered by a gauging period, they would certainly be included in

Table 1
Comparison of denudation monitors at different time scales

Setting	Authors	Denudation rates [mm ky^{-1}][a]		
		River load gauging 10–100 years	Cosmogenics 10–100 ky	Fission track 1–10 My
Namibian Escarpment, Southern Africa	[22]	–	5–15	3–15
Idaho Mountains, Western USA	[10]	1–12	3–100	50–110
Loire, Allier, Regen, Middle Europe	[11]	2–20	30–60[b]	–
Tropical Highlands Sri Lanka	[26,31]	50–800	5–11[c]	4–15[d]
Arroyo Chavez Basin, New Mexico, USA	[27]	44–380 (Slopes) 1200 (Alluvial Valley Floor)	100	
Yael Nahal Desert Israel	[12]	30	14–28	–
Appalachian Mountains, Eastern USA	[19]	5–50	22–37	10–60
Rio Chagres Basin, Panama	[14]	100	100	

[a] Sediment yields [t km^{-2} $year^{-1}$] were converted into denudation rates [mm ky^{-1}] using a density of 2.7 t m^{-3}.
[b] Recalculated in [41].
[c] Unperturbed catchments only.
[d] Fission track data inferred by comparison from South India and Madagascar.

the 5–100 ky averaging period of cosmogenic nuclide-derived estimates. These also appear to provide a more realistic estimate of denudation over geologic time, given their similarity to fission track-derived rates. A similar conclusion was reached by Schaller et al. [11] in a study of Middle European upland catchments. There, river loads yield denudation rates of 2–20 mm ky^{-1}, while cosmogenically constrained rates usually exceed these 3–5 fold (30–60 mm ky^{-1}). Another possibility to explain these differences is climate change. Although these areas have not been glaciated, waxing and waning of vegetation density and periglacial weathering and erosion phenomena with pervasive solifluction and frequent freeze–thaw cycles during the last glacial maximum would be contained in the integration time scale of 10–20 ky [35]. See Section 6.1 for a test of this concept.

An entirely different picture was observed in the tropical Highlands of Sri Lanka [26,31]. In these steep, humid mountains cosmogenic-derived denudation rates are surprisingly low at 5–11 mm ky^{-1}, while river loads yield denudation rates that are sometimes 100 times greater. While the low cosmogenic rates have been interpreted as the "natural background", river loads have been strongly affected by deforestation and land use change, with dramatically increased anthropogenic soil erosion. As a result, Sri Lanka's natural denudation rates range amongst the lowest observed for any mountain range world-wide, while the anthropogenic rates even exceed some of those measured in the Himalayas [26]. Elevated denudation rates due to land use change have also been reported for the semi-arid Arroyo Chavez Basin (new Mexico) [27]. While denudation rates from hill slopes roughly agree between both time scales, the alluvial valley floor is now degrading at 10-times pre-agricultural rates. There are only three study areas in which rates from all three methods seem to agree, suggesting that these basins are in a long-term geomorphic steady state. This means that rates of sediment production equal rates of sediment export that are also invariant with time. These steady-state sites are the Yael Nahal Desert [12], the Appalachians [19], and the Rio Chagres Basin [14].

Overall, these comparisons appear to suggest that cosmogenic nuclides yield meaningful denudation estimates for geomorphic and geologic time scales. Since at steady state the total (chemical and physical) denudation rate at the surface is also equal to the rate of conversion of bedrock into soil, these estimates are also estimates of soil formation rates. We can therefore proceed by using these rates to infer geomorphic and geochemical processes operating on hillslopes. Examples are given in the next two sections.

4. Topography and rates of geomorphic processes

In a much-cited publication, Ahnert [62] has pointed out a correlation between basin relief and erosion rate. This correlation has been confirmed, and refined in several studies that relate coarse geomorphic parameters with denudation rates derived from river loads [63] or from thermochronologic data [65]. The higher the relief or elevation in a river basin is, the higher the catchment-wide denudation rate is. In these studies, relief was used as a combined "proxy" for the parameters that are actually thought to control denudation, such as hillslope, hill curvature, and even rock uplift. Today, the combination of cosmogenic nuclide-derived denudation rates with digital topography allows us to test these hypotheses at virtually any geographic scale, ranging from the soil profile [32], to hillslopes, and entire drainage basins. Some results highlighting the potential of these studies are described as follows.

In three studies, denudation rates determined from cosmogenic nuclides in sediment were compared against catchment relief (Fig. 5). In the Middle European Uplands, denudation rates show a strong dependency on relief, with high-relief catchments eroding up to 5 times as fast as low-relief areas [11]. A possible explanation of this pattern is that the Middle European landscape is currently adjusting to tectonic change, and that the relief is the result of either young surface uplift, or young base level lowering. Indeed, this area has been affected by Neogene graben formation, volcanic activity, and basaltic underplating resulting from a mantle plume [66].

An entirely different picture was obtained in a geomorphological analysis of the Great Smoky Mountains of the Appalachians [20]. There, denudation rates are uniform, mostly lower than in Europe, and independent of relief. Matmon et al. have explained this by the fact that the Appalachians, being an old mountain belt, are in a geomorphic steady state, and relief is maintained over long periods. This means that denudation rates do not vary over space and time, and are possibly the same as the rock uplift rate. This hypothesis is further supported by the fact that denudation rates over the thermochronologic, cosmogenic, and river load time scale are all similar [19] (Table 1).

In a third example, an active mountain belt was investigated in the Swiss Central Alps (Fig. 5c, own unpublished data). There, denudation rates are high, and similar to geodetic uplift rates. However, they are surprisingly uniform; and only a weak correlation exists between relief and denudation rate. This would mean that either the Central Alps are close to geomorphic steady state, or they are in long-term geomorphic steady state that has been perturbed by short-term overprinting of the topography by glaciation that has covered much of the area up to 15 ky ago. Another possibility has been pointed out by Montgomery and Brandon [65]. In rapidly uplifting areas relief often exceeds 1000m. In this case the interfluve height is limited

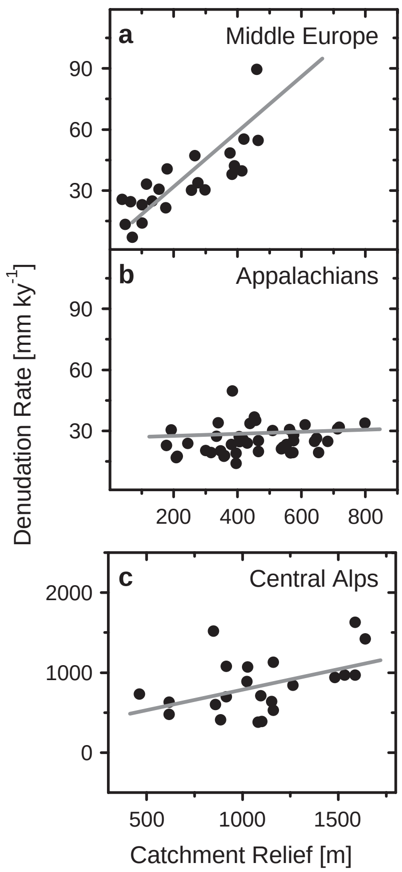

Fig. 5. Cosmogenic nuclide-derived denudation rate as a function of relief (calculated here as mean catchment altitude minus minimum altitude, which was found to be the most meaningful parameter determinable from a coarse-resolution DEM). The data from Middle European Uplands (Massif Central, Ardennes, Bayerischer Wald) is from Schaller et al. [11], denudation rates recalculated in [41]. Data from the Appalachians (Great Smoky Mountains) is from Matmon et al. [20]. Data from the European Central Alps is preliminary unpublished data (H. Wittmann, T. Krüssmann, F. von Blanckenburg, and P. Kubik, in prep.).

by mass-wasting, and denudation rates are independent of relief.

Hillslope gradient is a much more meaningful parameter than catchment relief. It relates directly, and in a predictable way to the rate of denudation [65]. However, it has been shown that the calculation of slopes is highly resolution-dependent [65], with 10 m-spaced grids yielding useful and reproducible slopes. Such data is not always readily available. In a study of seven Sierra Nevada catchments, high-resolution topography data was compared with cosmogenic nuclide-derived denudation rates [6,17]. Four catchments have rather uniform denudation rates over a range of hillslope gradients, three catchments from within the proximity of active fault scarps or young canyons yielded up to 15-times higher denudation rates that also correlate with hillslope gradient (Fig. 6). Riebe et al. have explained the latter with the effects of active tectonic faulting, that would result in a lowering of the local base level, and a readjustment of the drainage network. The ensuing hillslope processes would result in elevated physical denudation, and also elevated chemical weathering [18]. In contrast, the four catchments that are not in the proximity of any young tectonic features appear to be in a geomorphic steady state, and all sections of the landscape erode at the same rate. This is in line with the concepts explained above and shows that active tectonic forcing exerts a dominant control over denudation.

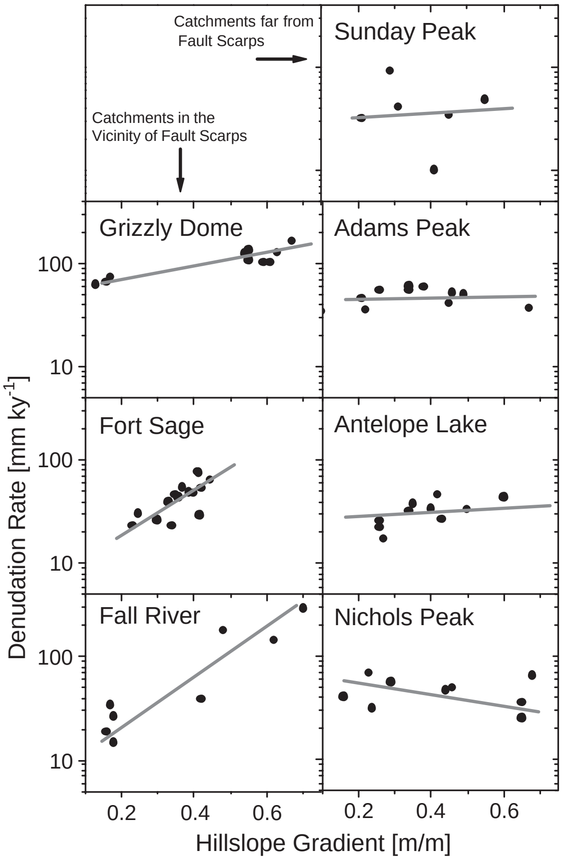

Fig. 6. Cosmogenic nuclide-derived denudation rates as a function of hillslope gradient in seven Sierra Nevada catchments [17] (recalculated by Riebe, pers. comm.). In the three catchments in the left column, denudation and hillslope are strongly correlated. In these, denudation increases with proximity to active fault scarps. The four catchments in the right column denudation rates are far more uniform, and independent of hill slope. These catchments are far from any fault.

5. Climate, erosion and rates of chemical weathering

The relationships between climate, erosion, and rock weathering have been much debated, with one school of thought arguing that they are subject to an internal, CO_2 pressure-driven feedback mechanism [67], while others have argued that any climate control over rock weathering is completely overriden by tectonic effects such as mountain building [68].

Cosmogenic nuclides now allow us to directly measure denudation rates in various climate regimes. A first compilation of the results from catchment studies in granitic lithologies obtained to date [30,31] spans a mean annual precipitation range of 30 to 5000 mm year^{-1}, and a temperature range of -0.4 to 25 °C (Fig. 7). Apparently, denudation is not correlated with mean annual precipitation and temperature. In fact, both the Namib Desert and the tropical Highlands of Sri Lanka experience the highest mean annual temperatures but also the lowest rates of total denudation (Fig. 7b). The Highlands of Sri Lanka are also subject to the highest rates of precipitation, but they denude at rates that are the lowest for any high land measured to date (Fig. 7a). Interestingly, a substantial component of the total denudation in Sri Lanka was shown to be chemical [31].

Singling out the chemical denudation component from the physical erosion would permit a more precise approach to the questions on weathering raised above.

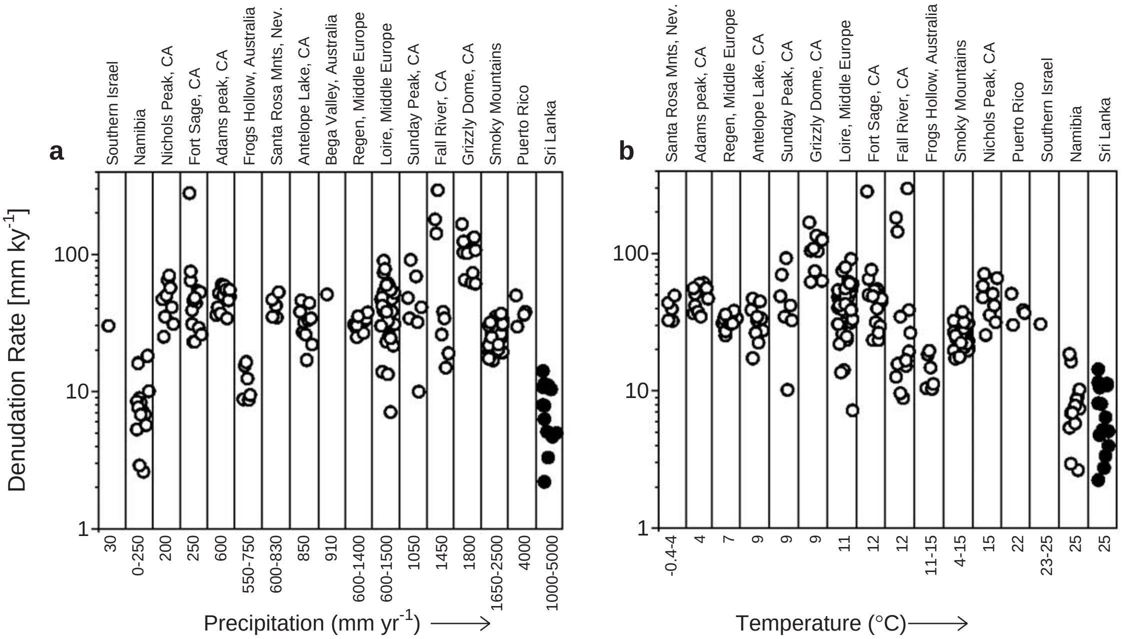

Fig. 7. Global compilation of catchment-wide denudation rates from cosmogenic nuclides as a function of precipitation and temperature. Only granitic catchments have been included, to avoid the introduction of lithology-dependent effects. Figure reprinted from [31]. Copyright 2004 American Geophysical Union. Reproduced by permission of the American Geophysical Union.

Although cosmogenic nuclides yield the total denudation rate (chemical plus mechanical), Riebe et al. have developed a technique that is, in homogenous granitic lithologies, suitable to separate both rates [18,29,30]. The approach is to measure the total denudation rate from cosmogenic nuclides in a given catchment. The time-integrated relative loss of cations by weathering (“Chemical Depletion Factor” CDF) is obtained by measuring zirconium-normalised total chemical concentrations in both bedrock and soils. It is also the rate of chemical weathering to the total denudation rate. Furthermore, since, under steady state conditions, chemical weathering operates on the same time scale as total denudation, the obtained rates all integrate over the same cosmogenic time scale. This time scale is potentially more representative of the assessment of long-term silicate weathering than the short time scale of solute load measurements.

The results of a global survey of chemical weathering rates in granitic catchments are shown in Fig. 8 [30]. At first glance, neither precipitation (Fig. 8a) nor temperature (Fig. 8b) appear to exert any control over silicate weathering. Furthermore, physical erosion and chemical denudation appear to be tightly interlinked (Fig. 8d). The slope of the best fit line through the physical erosion versus chemical weathering data corresponds to a mean global ratio of ca. 0.2. Superimposed on this trend, however is some scatter that is not random. This scatter turns out to be caused by climate-dependent variations in CDF. This climate-dependency only becomes apparent once the chemical weathering rate has been normalised in some way for physical erosion (Fig. 8c). This becomes apparent when the chemical depletion fraction is plotted as a function of annual precipitation (Fig. 8c), showing a positive correlation. A similar observation was also made with regard to temperature [30]. These observations are in line with those made recently in a compilation of modern river flux data [69]: a possible if vague correlation exists between mean annual temperature and weathering rate; precipitation and weathering rate are weakly correlated; chemical weathering rate and physical erosion rate are tightly interlinked.

The conclusion of this analysis is that once the effects of the dominating external physical erosional controls are removed, weak trends become apparent in the weathering data that support the notion that both

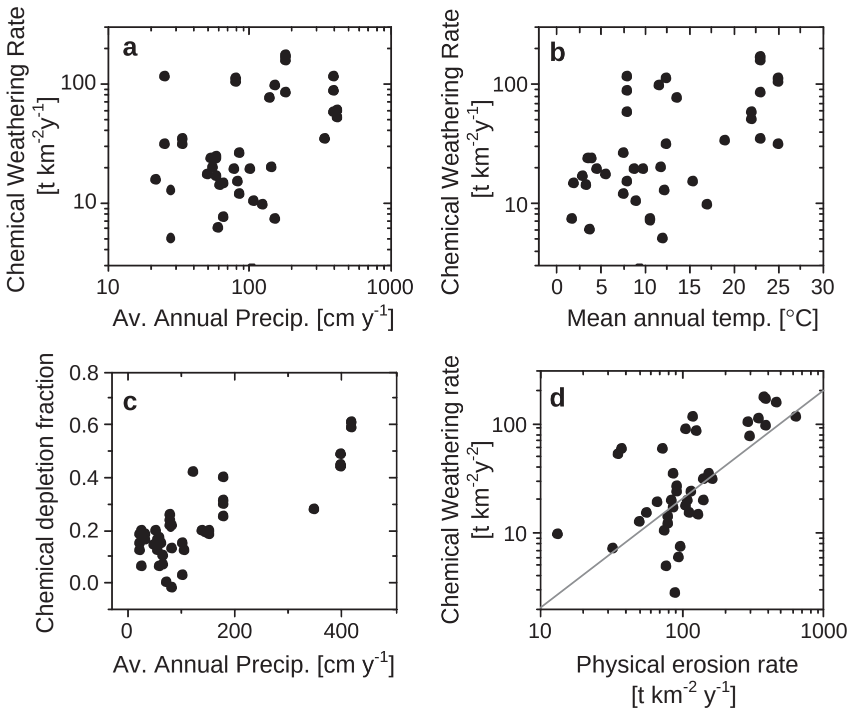

Fig. 8. Chemical weathering rates from the combination of cosmogenic nuclide-derived total denudation rates and the calculation of chemical depletion using zirconium-normalised soil and bedrock chemical compositions [30]. (a) Chemical weathering rate versus mean annual precipitation; (b) Chemical weathering rate versus mean annual temperature; (c) Chemical depletion fraction (ratio of chemical weathering rate to total denudation rate) versus mean annual precipitation; (d) Chemical weathering rate versus physical erosion rate.

temperature and precipitation aid weathering. It is likely that the external physical controls are related with tectonic forcing. In line with the observations laid out in Section 4, tectonic surface deformation would result in landscape rejuvenation, and hence increased weathering and denudation. The "counter-intuitive" findings in Sri Lanka, where steep relief, high altitudes, hot climate and high precipitation would all be expected to result in high rates of weathering and erosion, while in reality the lowest rates of all high land sites studied to date have been observed [31], must be seen in this light. It is the absence of any recent tectonic forcing in this cratonic area that prevents high rates of geomorphic processes.

6. Paleo-denudation rates

We now proceed to explore what is perhaps one of the most exciting future applications of this technique—the estimation of paleo-denudation rates. The principle at the heart of this application is that sediment, buried at some stage in the past, contains an "inherited" nuclide inventory that has accumulated in the sediment source area at the time of its denudation and deposition [36]. The prerequisites for this approach are 1) short sediment transport times as compared to hillslope residence times (which is the same requirement when using modern sediment); 2) a sedimentary sequence with an independently determined chronology (^{14}C, U-series, pollen, magnetostratigraphy, tephra dating), unless this chronology can be determined from simultaneous dating with cosmogenic nuclides of the deposit [38,70,71]; 3) well-shielded deposits so that post-depositional irradiation is minimised. Such sediments can be found in rapidly accumulated river terraces, lake fills, delta or marine fan deposits, or cave sediments; 4) For deposits of which the post-depositional nuclide component is significant relative to the inherited component, a correction must be applied for post-depositional exposure taking into account the age, depth, density, erosional or cover history of the terrace top, and a suitable absorption law for the penetrating cosmic rays. This is necessary because muons penetrate even into deep (>5 m) deposits, resulting in substantial post-depositional irradiation of old buried deposits. Buried sediments with depositional ages exceeding 0.2 My can be dated from the differential decay of ^{10}Be ($T_{1/2}$=1.5 My) and ^{26}Al ($T_{1/2}$=0.7 My). However, unless these sediments have been completely shielded from post-depositional irradiation, for example in caves [37,40], or deep water, the postdepositional exposure history needs to be taken into account [70].

6.1. Climate time scales

Post-depositional irradiation is of little concern if Holocene or Latest Pleistocene deposits are being investigated, and if denudation rates in the source area are low. This is true for <30 ky old terrace deposits in the Middle European Uplands of the Massif Central and the Ardennes [41]. Paleo denudation rates estimated from terrace deposits along the River Meuse downstream of the Ardennes are shown in Fig. 9a. Denudation rates decreased after an assumed maximum in the last cold stage, 18 ky ago. The decrease is thought to result from a switch from periglacial hillslope processes with a reduced vegetation cover to those of the present warm period. Such climate change might exert a much more pronounced control over erosion than the inter-regional climate relationships singled out in Section 5 for today's warm conditions. However, since each of these rates integrates over ca. 10–30 ky, short-term fluctuations in denudation rate are strongly damped (see also model in Fig. 4).

6.2. Tectonic time scales

An extension of the Meuse paleo-denudation sequence back to 1.3 My [42] is presented in Fig. 9b. Each of the data points represents a cold-stage terrace. The chronology is from pollen, geomagnetic reversals, orbital tuning, and tephra dating [42]. Complex corrections for post-depositional irradiation have been applied prior to calculation of paleo-denudation rates. Rates were rather uniform at ca. 30 mm ky^{-1} from 1.3 My to 0.5 My, after which they increased first to 50 mm ky^{-1}, and finally to 80 mm ky^{-1}. Granted, this record is not one of very high resolution. Further, it is based on the assumption that all rates record cold-stage denudation. This is aimed at excluding any variability between warm and cold stage, respectively, as introduced for example into the Pleis-

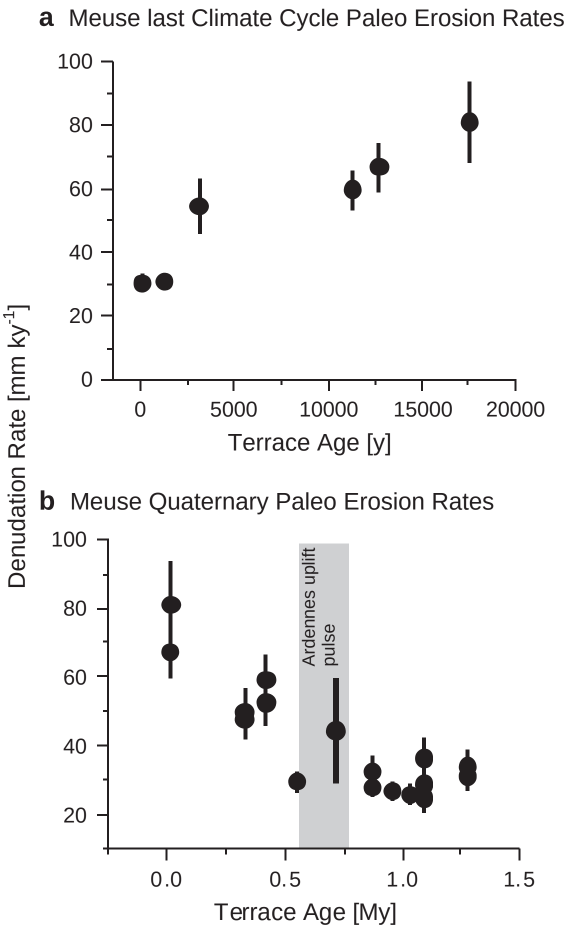

Fig. 9. Paleo-denudation rates from independently dated terrace deposits of the Meuse River, Netherlands. Note that the Ardennes hinterland providing the sediment has never been glaciated. a) Late Pleistocene and Holocene paleo-denudation rates (18 ky to today) showing the decrease in denudation after an inferred maximum in the last cold stage [41]. b) Quaternary denudation rates (1.3 My to 18 ky) of cold-stage terraces. Grey bar represents a pulse of increased uplift of the Ardennes mountains. This is followed by an increase in denudation rate ca. 200 ky later [42].

tocene–Holocene transition (Fig. 9a). It will be essential to obtain more continuous records in the future. However, there is a strong indication of a gradual increase of paleo-denudation rates from about 0.5 My. One explanation of this increase is that an uplift pulse, caused by basaltic underplating of the Ardennes mountains by the Eifel plume around 0.6 My (grey bar in Fig. 9b) led to an almost instantaneous change in trunk stream erosion. This erosional pulse would slowly propagate into spatial denudation within the entire drainage network, a process that may still be ongoing. Alternatively, the increase in denudation rate might be due to the increased climate cycle amplitude following the strengthening of the 100 ky eccentricity cycle ca. 0.7 My ago [42]. This study, and approaches where cave dating using $^{26}Al/^{10}Be$ in buried cave sediments furthermore allows the simultaneous measurement of river incision rates [40] has illustrated how determining paleo denudation rates is at the heart of unraveling the relative influences of climate and tectonics on large-scale denudation rates.

7. Mountains will erode in the future too

One can foresee that this method will be used to determine the relationship between topography and denudation on all spatial scales, ranging from single soil sections to entire river basins. It is indeed the combination of the ability to determine rates of geomorphic processes with the ever improving quality of digital topography that is presently leading to a true surge in understanding Earth Surface Processes and landscape evolution. These data can be used to design numerical geomorphic models. We can assess the effect of land use on geomorphic change by measuring robust background soil formation rates that are combined with short-term erosion indicators. We will be able to unravel the interaction between the uplift of active collisional orogens and the denudational response. Similarly, by simultaneously using sediment yields and cosmogenic nuclides we will be able to quantify the denudational response of a landscape to extensional faulting over multiple time scales, where the rates of faulting have been quantified on multiple time scales too by, for example, thermochronology, paleoseismology, or stationary global positioning system [72]. The exact relationships governing the processes linking soil thickness with soil production on the hillslope [32] and the development of landscapes on the basin scale can be deduced. Weathering rates can be determined in a large variety of climate regimes and different lithologies. This will allow the exact identification of the underlying feedback mechanisms. The contribution of glaciers to mountain denudation will be quantified. Strategies are required for undertaking erosion studies in active, glaciated mountains belts, an experiment still poorly understood [73]. In combination with grain size analyses, the contributions of mass wasting relative to more continuous erosion processes can be identified. An as yet completely unexplored field is the use of the accumulation of cosmogenic nuclides during sediment transport, thereby deriving sediment transfer times [16,39]. Paleo-denudation rate sequences can be determined on well-dated lake records and marine sediment cores back to ca. 3 My (limited by the half-life of the nuclide used). This will allow the tackling of a fascinating range of Earth surface issues relating to continental denudation and changes in denudation [74]. Paleo-denudation time series might also provide entirely new insights into sedimentary basin and hydrocarbon source formation processes, for example by addressing the issue whether variations in turbidite layer thickness are due to changes in sediment supply in the source area (potentially visible from regular changes in measured subaerial denudation rate) or due to marine slope instability.

Applications that cannot yet be exactly predicted can be expected from future technological developments. Amongst these is the continuous improvement of the precision of the method, by improvements of the analytical sensitivity, and its accuracy, by improved calibration of the surface production rates, the absorption coefficients (in particular for deeply penetrating muons, which are so important in denudation studies), and in the atmospheric scaling factors [75]. These are objectives of the international CRONUS cosmic ray calibration effort that is currently underway [76,77]. Nuclides other than ^{10}Be and ^{26}Al will add to the versatility of the method. The recent development of analytical strategies to determine in situ-produced ^{10}Be in carbonates and the determination of the ^{10}Be production rate in carbonate opens up the possibility to derive weathering rates of carbonate terrains [78]. Finally, meteoric ^{10}Be, adsorbed to soils and sediments in much higher concentrations than in situ-produced cosmogenic nuclides [5], might become available as tool in sediment budgeting, provided that laws for atmospheric ^{10}Be production and precipitation can be derived. The cosmogenic sand pit is real, not virtual, and the best discoveries are still waiting to be made.

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