Earth is (mostly) flat: Apportionment of the flux of continental sediment over millennial time scales

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ABSTRACT

We use a new compilation of global denudation estimates from cosmogenic nuclides to calculate the apportionment and the sum of all sediment produced on Earth by extrapolation of a statistically significant correlation between denudation rates and basin slopes to watersheds without denudation rate data. This robust relationship can explain approximately half of the variance in denudation from quartz-bearing topography drained by rivers using only mean slopes as the predictive tool and matches a similar fit for large river basins. At slopes >200 m/km, topography controls denudation rates. Controls on denudation in landscapes where average slopes are <~200 m/km are unclear, but sediment production rates in these areas average ~45 mm/k.y., 75% of the denudation rates being >10 mm/k.y. We use global topographic data to show that the vast majority of the Earth's surface consists of these gently sloping surfaces with modest, but positive, gross denudation rates, and that these areas contribute the most sediment to the oceans. Because of the links between silicate weathering rates and denudation rates, the predominance of low sloping areas on the Earth's surface compared to areas of steep mountainous topography implies that mountain uplift contributes little to drawdown of CO_2 at cosmogenic nuclide time scales of 10^3–10^6 yr. The poorly understood environmental controls that set the pace of denudation for the largest portion of Earth's surface hold the key to understanding the feedbacks between erosion and climate.

INTRODUCTION

Understanding the controls on fluxes of sediment from continents to the ocean is critical for understanding rates of mass transfer among global sediment reservoirs, as well as elemental fluxes (Plank and Langmuir, 1998), nutrient cycles (Meybeck, 1982), inputs to organic carbon sinks (Ludwig et al., 1996), and their respective changes over short and long time scales. Fluxes of variably weathered sediment through rivers are also linked to dissolved solute fluxes (West et al., 2005), a relation of critical importance because weathering and metamorphism of silicate and carbonate minerals serves to transfer CO_2 between the atmosphere and lithosphere, thereby regulating atmospheric CO_2 concentrations over geologic time scales (Berner et al., 1983).

The movement of sediment and chemical solutes through river basins is a highly episodic process (e.g., Kirchner et al., 2001) that empirical relationships have shown to be grossly dependent on watershed topography, climate, and other environmental and cultural factors (Syvitski and Milliman, 2007; Milliman and Farnsworth, 2011). Recent work has shown that significant variability in short-term sediment flux measurements is introduced by stochastic processes such as intermittent release of stored sediment in a watershed (Van de Wiel and Coulthard, 2010). For watersheds with high internal variability of storage and release of sediment, the magnitude of noise (the stochastic contribution to the total flux) can be larger than environmental and/or physiographic forcing (Jerolmack and Paola, 2010) and, in some cases, can completely obliterate long-term signals such as those of climate change and tectonism. Because short-term measurements are more readily masked by noise than are measurements averaged over long time scales, only after thousands of years are sediment and solute fluxes likely to be dominated by actual extrinsic forcing mechanisms (Jerolmack and Sadler, 2007). In such cases, exhumation rates determined via thermochronometry and the rates of geomorphic evolution of the landscape should be, and often are, in agreement (von Blanckenburg, 2005). Sediment yields from the Earth's largest basins may mimic the robust response of long-term measurements to external forcing, like those from cosmogenic nuclides, because buffering mechanisms can integrate change over thousands of years (Métivier and Gaudemer, 1999; Phillips, 2003).

Understanding how sediment flux to modern oceans compares to those over geologic history with decidedly different climates is confounded by comparing noisy, short-term values to those averaged over much longer time scales. Fortunately, average river basin sediment fluxes can be directly determined over long time scales with the use of cosmogenic nuclide geochemical tracers. Since this technique was first applied ~20 yr ago, more than 1500 flux determinations have been published (Portenga and Bierman, 2011). This large data set for a wide range of topographic settings, both stable and tectonically active (Fig. 1), allows us to extrapolate to unmeasured basins utilizing empirical relations derived from available data. With this approach, we assess the production of continental sediments at time scales of 1 k.y. to 1 m.y. and compare this rate to those determined from fluvial suspended sediment loads from large rivers (Summerfield and Hulton, 1994) and from continental sediment and rock volumes over geologic times (Wilkinson and McElroy, 2007).

^{10}BE-DERIVED DENUDATION RATES AND THE DISTRIBUTION OF EARTH'S SLOPES

We have compiled data on concentrations of cosmogenic ^{10}Be in fluvial sediments that have been published in refereed literature from the inception of the technique through 2011 (Table DR1 in GSA Data Repository[1]). Our compilation is similar in scope and size to that of Portenga and Bierman (2011), although it is completely independent from it. All ^{10}Be concentrations and denudation rates were recalculated (for details and data, see the Data Repository).

To complement the ^{10}Be data, we have derived appropriate topographic metrics from 3 arc second (nominally 90 m) Shuttle Radar Topography Mission (SRTM) data (http://srtm.csi.cgiar.org) for each discrete drainage basin whose outlet is the ^{10}Be sampling site. Due to the coarse resolution of the digital elevation model data that we use in our analysis, and given the difficulty of accurately identifying and delineating very small river basins using these data, we limit our analysis to river basins with areas >1 km^2. We also exclude the very large basins (see Table DR1), because mean topographic metrics derived for these will most likely be meaningless. The resulting data set includes 990 river basins with areas between 1 and 10,000 km^2 (Fig. 1), with mean denudation rates derived from ^{10}Be in their sediment, mean

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[1] GSA Data Repository item 2013091, Table DR1 (complete data set of ^{10}Be-derived denudation rates and topographic metrics used in this work), Table DR2 (previous estimates of sediment delivery to oceans), and the original references for these data sets in Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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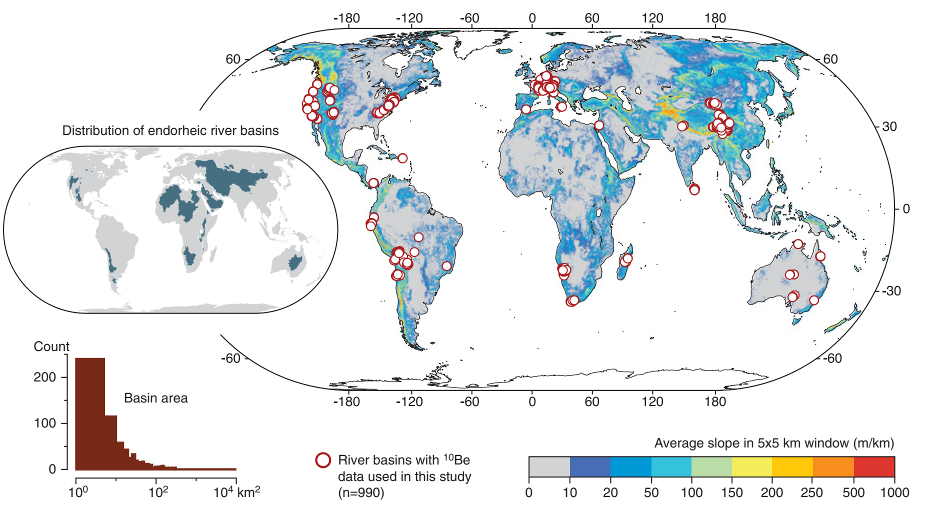

Figure 1. Global distribution of slope as calculated from GTOPO30 digital elevation model (http://eros.usgs.gov) and averaged using a 5 × 5 km moving window, and distribution of river basins that were used to determine global denudation rates (red circles). Top inset: distribution of endorheic basins. Bottom inset: histogram of basin areas in this compilation. Note log scale on the *x*-axis. See text for details.

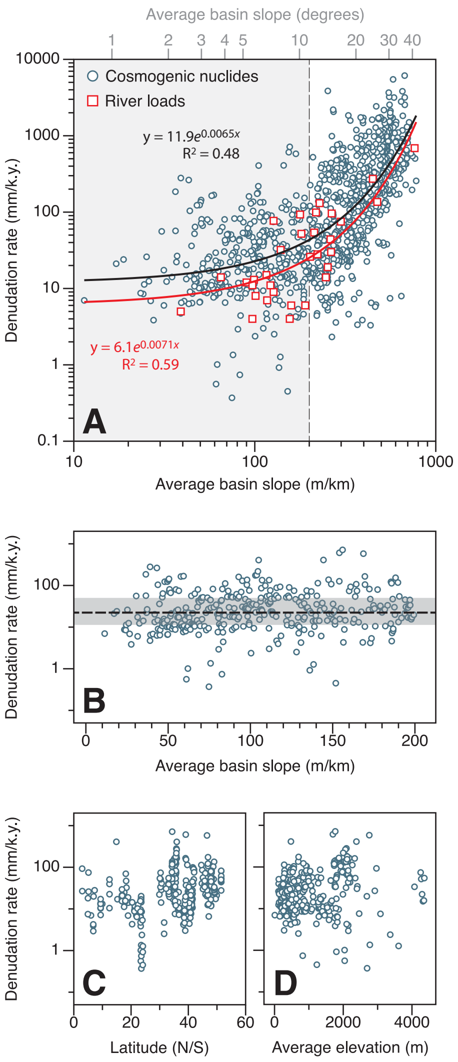

Figure 2. A: Mean drainage basin slopes from 90 m Shuttle Radar Topography Mission topographic data versus basinwide denudation rates from cosmogenic ^{10}Be in river sediment (circles) and large-river denudation rates (squares) from Summerfield and Hulton (1994). B: Same as A, but showing only those basins that have average slope <200 m/km. Black dashed horizontal line is median of data and gray box bounds 50% of data. Note absence of correlation between denudation rate and slope. C, D: Denudation rates of basins with slopes <200 m/km versus geographic latitude and average basin elevation. See text for details.

basin elevation, elevation range, mean basin slope, and standard deviation of slope (see the Data Repository).

Given that the SRTM data are not global in coverage, for our global sediment flux calculations we use the U.S. Geological Survey GTOPO30 (http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info) data and its derivative, HYDRO1K. We calculate slopes for Earth's ice-free areas using a 5 × 5 km moving window, so that the obtained values are comparable to the average basin slopes obtained for the 990 river basins. We chose a 5 × 5 km window because the majority of our basin areas are in this range (Fig. 1, inset). Using larger windows, however, does not significantly change the results (Fig. DR1). We identify and separate endorheic basins from those draining to the ocean (Fig. 1, top inset).

RESULTS

Erosion rates from sediment-derived ^{10}Be concentrations span several orders of magnitude, ranging from <0.5 to >6000 mm/k.y. (Fig. 2A). Given that our compilation of denudation rates does not represent an unbiased sample of erosional, continental environments, the calculation of a global continental sediment production rate must account for a weighting of rate based on area.

At millennial time scales, the functional form of the denudation rate (D, mm/k.y.) versus mean slope (S, m/km) relation, obtained from our 990 river basins, is (Fig. 2A):

$$D = 11.9e^{0.0065S}. \quad (1)$$

Equation 1 is very similar to the one obtained from the river load data of Summerfield and Hulton (1994), i.e., $D = 6.1e^{0.0071S}$ (Fig. 2A), and predicts that the rate of denudation increases exponentially with slope by ~0.65% for each meter per kilometer increase in slope. While substantial variability is present in the data, reflecting the dependence of erosion on other environmental factors (Milliman and Syvitski, 1992; Portenga and Bierman, 2011), here we focus on the fact that mean basin slope explains more than half of the global variance of denudation rates at cosmogenic nuclide time scales ($R^2 = 0.48$; $p < 0.01$) and that the residuals sum to zero. Thus, although the data are "noisy," the best-fit curve still accounts for the majority of variation in average denudation rate in basins all across the globe.

Based on the GTOPO30 data, 52% of the Earth's surface has mean slope below 10 m/km (~0.6°), and 92.5% below 100 m/km (~6°) (Fig. 1). The percentages are virtually the same (50.3% and 92.2%) if endorheic basins are excluded. This means that a global sediment production rate calculated using Equation 1 will be strongly controlled by the intercept; i.e., 11.9 mm/k.y. The functional relationship between denudation rate and slope essentially breaks down for slope values <~200 m/km (~10°), as the subset of the data from 0 to 200 m/km shows no correlation between slope and denudation rate (Fig. 2B). This subset, however, has a minimal influence on the form of Equation 1; when removed the latter becomes $D = 10.7e^{0.0067S}$. Despite the lack of a relationship for slopes <200 m/km between denudation rate and slope, we note that all data in this subset, with the exception of those from extreme desert settings (see Table DR1), have denudation rates >5 mm/k.y., and 75% of the denudation rates are >10 mm/k.y. Further, the data in this subset span a wide range of latitudes and altitudes (Figs. 2C and 2D), and therefore also a wide range of climatic settings. The lack of a relationship between topography and denudation rate over a wide range of climatic settings combined with the fact that 75% of the denudation rates in the 0–200 m/km subset are above >10 mm/k.y. makes us surmise that despite being seemingly large, the intercept of Equation 1 is a valid approximation of the average rate at which ~50% of the Earth's surface is eroding.

Summing the relation between average denudation rate and basin slope for continental slopes derived from GTOPO30 (Fig. 3) yields an annual global sediment production rate of 5.5 Gt (Fig. 3), although this value could be as low as 0.6 Gt or as high as 6.7 Gt based on propagation of a ±1σ standard error estimate. Excluding endorheic basins lowers this estimate to 4.4 Gt, suggesting that as much as ~20% of the sediment produced does not discharge into the oceans. Because cosmogenic nuclide concentrations reflect total denudation, these sediment production rates include both chemical and physical erosion.

DISCUSSION

The relation given in Equation 1 implies orders of magnitude variation in denudation rates across Earth's surface as a function of basin-scale slope alone. This relation saturates (i.e., denudation rates grows very quickly with small slope changes) at ~700–900 m/km (35°–40°), in close agreement with the threshold slope determined by Montgomery and Brandon (2002). This is clear evidence that production of sediment per unit area is much greater in mountainous regions than in lowlands, in agreement with a suite of studies of continental denudation (e.g., Milliman and Syvitski, 1992).

In order to better understand the production of sediment as a function of basin characteristics, the frequency distribution (by area, Fig. 3A) of global basin slopes was used to estimate the total sediment production as a function of slope (Fig. 3B). This displays an overall inverse relation between slope and sediment production, not because lower slopes erode faster, but because they encompass areas vast enough to outweigh the production rate differential between steep and lowland regions. A different conclusion was reached by Milliman and Syvitski (1992), when they estimated that small mountain rivers contribute the most sediment to the world's oceans. We find a potentially opposing result that the low sloping areas of the world erode slowly but steadily over a very large area, overpowering the high mountainous small rivers when one accounts for the relatively small areas of those mountainous regions. It is important to note that because the compiled cosmogenic data in this work were collected in denuding landscapes, these rates are representative of gross denudation (chemical and physical erosion) and not net denudation in their respective environments, like those for the Milliman and Syvitski (1992) estimate. While mountainous areas are likely to have little deposition overall, low-sloping areas are prone to deposition. This complicating factor makes directly comparing the result of Milliman and Syvitski (1992) and our work impossible. Yet, in terms of total gross denudation, large low-sloping areas are sites of the greatest fraction of the total denudation.

Comparison with Other Data on Denudation and Sediment Delivery

Area-slope normalized suspended and dissolved fluxes for the 36 largest river basins draining ice-free continental surfaces exhibit strong similarity to the relation for cosmogenic nuclide-derived denudation rates versus slope; they show equivalent ranges of values and, when normalized for slope, globally averaged cosmogenic nuclide-derived denudation rates are within the range of modern river sediment fluxes to the world's oceans (Summerfield and Hulton, 1994) (Fig. 2A; see also Table DR2). We speculate that sediment fluxes over these two seemingly different time scales are similar because large watersheds serve to temporarily store sediments en route to oceanic delivery over these time scales. This conforms with existing hypotheses that large watersheds act as buffers for climatic and anthropogenic forcing (Métivier and Gaudemer, 1999; Phillips, 2003). As such, the time scale of integration for sediment yield measurements of modern rivers with sediment storage might be better conceptualized as the residence time of sediment in the basin transport system (i.e., the volume of sediment held on the landscape divided by the flux of sediment through the system) rather than the number of years over which the measurements are made. Métivier and Gaudemer (1999) demonstrated that, for the world's largest rivers, this value can be 10–100 k.y.

Compared to rates of sediment cycling based on remnant Phanerozoic sediment stores (5 Gt/yr; Wilkinson and McElroy, 2007), the globally averaged cosmogenic nuclide-derived sediment production rate of 5.5 Gt/yr (4.4 Gt/yr excluding endorheic basins) is essentially equivalent.

Implications for the Global Silicate Weathering Flux

Various studies (West et al., 2005, and references therein) have found a strong relationship between the total denudation rate and the silicate weathering flux in river basins. Our new data set and analysis allow us to estimate the total global silicate flux from these previously published relationships. In the empirical relationship of West et al. (2005), based on the framework of Carson and Kirkby (1972), watersheds are classified as being either (1) transport limited, where minerals are nearly completely altered before their removal, or (2) kinetically limited, where the alteration of minerals is incomplete. The transport limited settings make up most of the land area on Earth, and in these settings the total rates of denudation show a better correlation with silicate cation fluxes. The kinetically limited cases are not well correlated with silicate cation fluxes and are typically found in areas that are rapidly eroding and undergoing uplift, and compose a small portion of the landscape. In these kinetically limited cases, West et al. (2005) noted a case of diminishing returns, where a larger denudation rate does not necessarily result in a larger silicate cation flux as the transport-limited relationship shows.

Using the relationship between river denudation and river chemistry and our estimate of the total global denudation rate, the silicate cation denudation rate is 0.6 t/km/yr. If we assume that each mole of silicate cation reacts with 1 mol CO_2, then we calculate 0.72×10^8 tCO_2/yr for the ice-free area of the Earth. This amount is lower than previously published values

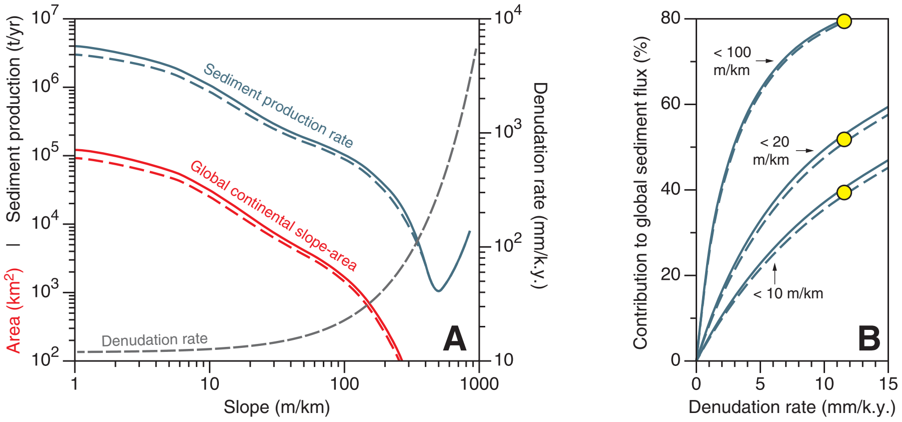

Figure 3. A: Slope (*x*-axis) versus denudation rate predicted by Equation 1 (right axis; gray dashed curve), land area (red curves), and, as product of denudation rate and area, total sediment production rate (blue curves). Dashed blue and red curves mark area and sediment production with endorheic basins removed. Summation over all continental area yields net (chemical and physical) global sediment production rate of ~5.5 Gt/yr. B: Sensitivity analysis exploring contribution to total global sediment flux of areas with slopes <10 m/km (~0.6°), 20 m/km (~1.2°), and 100 m/km (~6°) as function of their average denudation rates; using values predicted by text Equation 1 (yellow circles), these areas contribute ~40%, ~53%, and ~81% of total sediment flux, respectively. Even when denudation rate is lowered to 5 mm/k.y. (see Fig. 2B), these values are ~21%, ~31%, and ~62%, respectively. Dashed curves are obtained when endorheic basins are removed.

($5.1–5.5 \times 10^8$ tCO_2/yr; Meybeck, 1982; Berner et al., 1983; Gaillardet et al., 1999), but close to recent numerical modeling work ($1.5–3.3 \times 10^8$ tCO_2/yr; Hilley and Porder, 2008). Given that our results only constrain denudation rates for fluvially dissected landscapes that contain quartz, our calculated value should be considered a minimum, as mafic rocks have minerals with a greater proportion of Ca and Mg to supply for carbonate formation.

Global compilations show that silicate weathering rates and denudation rates are tightly correlated (West et al., 2005). If this is true, and the greatest sensitivity of the Earth's surface to changes in denudation is in low-sloping areas where small denudation rate changes of these large areas drastically increase the average global denudation rate (Fig. 3B), then this result has great consequences on global changes in the silicate weathering cycle and rates of CO_2 drawdown. Considering that steeply sloping mountain belts such as the Himalayas, Alps, and Andes are only a small proportion of the continental land surface compared to the areas of low slopes (Fig. 1), and that topography (thus tectonics) does not control denudation rates in these low-sloping areas (Fig. 2B), we postulate that increased mountain building represents only a minor contribution to global CO_2 withdrawal unless the total area of the world taken up by mountains increases substantially. Thus, the real driver of denudation and geomorphically or environmentally driven climate change remains unknown.

CONCLUSIONS

We calculate the sum of all sediment produced for the (quartz containing) Earth by extrapolation of a statistically significant correlation between cosmogenic nuclide-derived long-term denudation rates and basin slopes to watersheds without denudation-rate data. This relationship can explain approximately half of the variance in denudation from quartz-bearing topography drained by rivers using only mean slopes. We do not know what controls denudation in landscapes where average slopes are <~200 m/km; however, the control that sets the pace of this zone holds the key to understanding the feedbacks between erosion and climate. The total mass flux determined from our tally is 5.5 Gt/yr and agrees well with the mass flux from previous global studies from solute and sediment gauging data (Summerfield and Hulton, 1994; Syvitski and Milliman, 2007) and Phanerozoic rock volumes (Wilkinson and McElroy, 2007).

We suggest that identifying conditions sufficient to significantly affect the global flux of solid sediments and solutes to oceans in the low-sloping areas is the next crucial area of research to elucidate geologically historical rates and magnitudes of element cycling on Earth.

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