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

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

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 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 CO₂ at cosmogenic nuclide time scales of 10³–10⁶ 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.

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

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11 **ABSTRACT**

12 We use a new compilation of global denudation estimates from cosmogenic
13 nuclides to calculate the apportionment and the sum of all sediment produced on the
14 Earth by extrapolation of a statistically significant correlation between denudation rates
15 and basin slopes to watersheds without denudation rate data. This robust relationship can
16 explain approximately half of the variance in denudation from quartz-bearing topography
17 drained by rivers using only mean slopes as the predictive tool and matches a similar fit
18 for large river basins. Above 200 m/km slopes, topography controls denudation rates.
19 Controls on denudation in landscapes where average slopes are < ~200 m/km are unclear,
20 but sediment production rates in these areas average ~45 mm/k.y. with 75% of the
21 denudation rates being greater than 10 mm/k.y. We use global topographic data to show
22 that the vast majority of the Earth's surface consists of these gently sloping surfaces with

23 modest, but positive, gross denudation rates, and that these areas contribute the most
24 sediment to the oceans. Because of the links between silicate weathering rates and
25 denudation rates, the predominance of low sloping areas on the Earth's surface compared
26 to areas of steep mountainous topography implies that mountain uplift contributes little to
27 drawdown of CO₂ at cosmogenic nuclide time scales of 10³-10⁶ yr. The poorly
28 understood environmental controls that do set the pace of denudation for the largest
29 portion of Earth's surface hold the key to understanding the feedbacks between erosion
30 and climate.

31 **INTRODUCTION**

32 Understanding the controls on fluxes of sediment from continents to the ocean is
33 critical for understanding rates of mass transfer among global sediment reservoirs, as well
34 as elemental fluxes (Plank and Langmuir, 1998), nutrient cycles (Meybeck, 1982), inputs
35 to organic carbon sinks (Ludwig et al., 1996), and their respective changes over short and
36 long time scales. Fluxes of variably-weathered sediment through rivers are also linked to
37 dissolved solute fluxes (West et al., 2005), a relation of critical importance because the
38 rate of weathering and metamorphism of silicate and carbonate minerals serves to transfer
39 CO₂ between the atmosphere and lithosphere, thereby regulating atmospheric CO₂
40 concentrations over geologic time scales (Berner et al., 1983).

41 The movement of sediment and chemical solutes through river basins is a highly
42 episodic process (e.g., Kirchner et al., 2001) that empirical relationships have shown to
43 be grossly dependent on watershed topography, climate, and other environmental and
44 cultural factors (Syvitski and Milliman, 2007). Topographic indices are best correlated
45 with sediment flux, and these empirical fits include linear, exponential, and power law

46 relations between erosion rate and mean elevation (Berner and Berner, 1987), local relief
47 (Ahnert, 1970), and catchment slope (Aalto et al., 2006). Recent work has shown that
48 significant variability in short-term sediment flux measurements is introduced by
49 stochastic processes such as intermittent release of stored sediment in a watershed (van
50 der Wiel and Coulthard, 2010). For watersheds with high internal variability of storage
51 and release of sediment, the magnitude of noise (the stochastic contribution to the total
52 flux) can be larger than environmental and/or physiographic forcing (Jerolmack and
53 Paola, 2010) and, in some cases, can completely obliterate long-term signals such as
54 those of climate change and tectonism. Because short-term measurements are more
55 readily masked by noise than are measurements averaged over long time scales, only
56 after thousands of years are sediment and solute fluxes likely to be dominated by actual
57 extrinsic forcing mechanisms (Jerolmack and Sadler, 2007). In such cases, exhumation
58 rates determined via thermochronometry and the rates of geomorphic evolution of the
59 landscape should be, and often are, in agreement (von Blanckenburg, 2005; Kirchner et
60 al., 2001). Sediment yields from the Earth's largest basins may mimic the robust response
61 of long-term measurements to external forcing, like those from cosmogenic nuclides,
62 because buffering mechanisms can integrate change over thousands of years (Métivier
63 and Gaudemer, 1999; Phillips, 2003).

64 Understanding how sediment flux to modern oceans compares to those over
65 geologic history with decidedly different climates is confounded by comparing noisy,
66 short-term values to those averaged over much longer time scales. Fortunately, average
67 river basin sediment fluxes can be directly determined over long time scales with the use
68 of cosmogenic nuclide geochemical tracers. Since this technique was first applied some

69 two decades ago, over 1,500 flux determinations have been published (Portenga and
70 Bierman, 2011). This large data set over a wide range of topographic settings – both
71 stable and tectonically active (Fig. 1) – allows us to extrapolate to unmeasured basins
72 utilizing empirical relations derived from available data. With this approach, we assess
73 the production of continental sediments at time scales of 1 k.y. to 1 m.y. and compare this
74 rate to those determined from fluvial suspended sediment loads from large rivers
75 (Summerfield and Hulton, 1994) and from continental sediment and rock volumes over
76 geologic times (Wilkinson and McElroy, 2007).

77 **¹⁰BE-DERIVED DENUDATION RATES AND THE DISTRIBUTION OF**
78 **EARTH'S SLOPES**

79 We have compiled data on concentrations of cosmogenic ¹⁰Be in fluvial
80 sediments that have been published in refereed literature from the inception of the
81 technique through 2011 (Table DR1 in GSA Data Repository¹). Our compilation is
82 similar in scope and size to that recently published by Portenga and Bierman (2011),
83 although it is completely independent from it. All ¹⁰Be concentrations and denudation
84 rates were recalculated, full details and data being provided in the Data Repository.

85 To complement the ¹⁰Be data, we have derived appropriate topographic metrics
86 from 3 arc second (nominally 90 m) Shuttle Radar Topography Mission (SRTM) data
87 (<http://srtm.csi.cgiar.org>) for each discrete drainage basin whose outlet is the ¹⁰Be
88 sampling site. Due to the coarse resolution of the DEM data that we use in our analysis,
89 and given the difficulty of accurately identifying and delineating very small river basins
90 using these data, we limit our analysis to river basins with areas >1 km². Further, we also
91 exclude the very large basins (see Table DR1 in the Data Repository), as mean

92 topographic metrics derived for these will most likely be meaningless. The resulting data
93 set includes 990 river basins with areas between 1 and 10,000 km² (Fig. 1), with mean
94 denudation rates derived from ¹⁰Be in their sediment, mean basin elevation, elevation
95 range, mean basin slope, and standard deviation of slope (see the Data Repository).

96 Given that the SRTM data is not global in coverage, for our global sediment flux
97 calculations we use the U.S. Geological Survey's GTOPO30 data and its derivative,
98 HYDRO1K. We calculate slope for Earth's ice-free areas using a 5 × 5 km moving
99 window, so that the obtained values are comparable to the average basin slopes obtained
100 for the 990 river basins. We chose a 5 × 5 km window because the majority of our basins'
101 areas are in this range (Fig. 1, inset). Using larger windows, however, does not
102 significantly change the results (Fig. DR1 in the Data Repository). We identify and
103 separate endorheic basins from those draining to the ocean (Fig. 1, top inset).

104 **RESULTS**

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

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

$$112 \quad D = 11.9e^{0.0065S} \quad (1)$$

113 Equation 1 is very similar to the one obtained from the river load data of
114 Summerfield and Hulton (1994), namely $D = 6.1e^{0.0071S}$ (Fig. 2A), and predicts that the

115 rate of denudation increases exponentially with slope by ~0.65% for each meter per
116 kilometer increase in slope. While substantial variability is present in the data, reflecting
117 the dependence of erosion on other environmental factors (Milliman and Syvitski, 1992;
118 Portenga and Bierman, 2011), here we focus on the fact that mean basin slope explains
119 over half of the global variance of denudation rates at cosmogenic nuclide time scales (R^2
120 = 0.48; $p < 0.01$) and that the residuals sum to zero. Thus, although the data are ‘noisy’,
121 the best-fit curve still accounts for the majority of variation in average denudation rate in
122 basins all across the globe.

123 Based on the GTOPO30 data, 52% of the Earth’s surface has mean slope below
124 10 m/ km (~0.6 degrees), and 92.5% below 100 m/km(~6 degrees) (Fig. 1). The
125 percentages are virtually the same (50.3 and 92.2%) if endorheic basins are excluded.
126 This means that a global sediment production rate calculated using Equation (1) will be
127 strongly controlled by the intercept; i.e., 11.9 mm/k.y. The functional relationship
128 between denudation rate and slope essentially breaks down for slope values $< \sim 200$ m/km
129 (~10 degrees), as the subset of the data from 0 to 200 m/km shows no correlation
130 between slope and denudation rate (Fig. 2B); this subset however, has a minimal
131 influence on the form of Equation 1, when removed the latter becoming: $D = 10.7e^{0.0067S}$.
132 Despite the lack of a relationship for slopes < 200 m/km, between denudation rate and
133 slope, we note that all data in this subset, with the exception of those from extreme desert
134 settings (see Table DR1), have denudation rates > 5 mm/k.y., and 75% of the denudation
135 rates are > 10 mm/k.y. Further, the data in this subset span a wide range of latitudes and
136 altitudes (Figs. 2C and 2D), and therefore also a wide range of climatic settings. The lack
137 of a relationship between topography and denudation rate over a wide range of climatic

138 settings combined with the fact that 75% of the denudation rates in the 0–200 m/km
139 subset are above >10 mm/k.y. makes us surmise that despite being seemingly large, the
140 intercept of Equation 1 is a valid approximation of the average rate at which ~50% of the
141 Earth's surface is eroding.

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

150 **DISCUSSION**

151 The relation given in Equation 1 implies orders of magnitude variation in
152 denudation rates across Earth's surface as a function of basin-scale slope alone. This
153 relation saturates (i.e., denudation rates grows very quickly with small slope changes)
154 around 700–900 m/km (35–40 degrees) in close agreement with the threshold slope
155 determined by Montgomery and Brandon (2002). This is clear evidence that production
156 of sediment per unit area is much greater in mountainous regions than in lowlands in
157 agreement with a suite of studies of continental denudation (e.g., Milliman and Syvitski,
158 1992).

159 In order to better understand the production of sediment as a function of basin
160 characteristics, the frequency distribution (by area, Fig. 3A) of global basin slopes was

161 used to estimate the total sediment production as a function of slope (Fig. 3B). This
162 displays an overall inverse relation between slope and sediment production, not because
163 lower slopes erode faster, but because they encompass areas vast enough to outweigh the
164 production rate differential between steep and lowland regions. A different conclusion
165 was reached by Milliman and Syvitski (1992) when they estimated that small mountain
166 rivers contribute the most sediment to the world's oceans. We find a potentially opposing
167 result that the low sloping areas of the world erode slowly but steadily over a very large
168 area – overpowering the high-mountainous small rivers when one accounts for the
169 relatively small areas of those mountainous regions. It is important to note that because
170 the compiled cosmogenic data in this work were collected in denuding landscapes, these
171 rates are representative of gross denudation (chemical and physical erosion) and not net
172 denudation in their respective environments like those for the Milliman and Syvitski
173 (1992) estimate. While mountainous areas are likely to witness little deposition overall,
174 low-sloping areas are prone to deposition. This complicating factor makes directly
175 comparing the result of Milliman and Syvitski (1992) and this work impossible. Yet, in
176 terms of total gross denudation, large low-sloping areas are sites of the greatest fraction
177 of the total denudation.

178 **Comparison with Other Data on Denudation and Sediment Delivery**

179 Area-slope normalized suspended and dissolved fluxes for the 36 largest river
180 basins draining ice-free continental surfaces exhibit strong similarity to the relation for
181 cosmogenic nuclide-derived denudation rates versus slope; they show equivalent ranges
182 of values and, when normalized for slope, globally averaged cosmogenic nuclide-derived
183 denudation rates lie within the range of modern river sediment fluxes to the world's

184 oceans (Summerfield and Hulton, 1994) (Fig. 2A; see also Table DR2). We speculate that
185 sediment fluxes over these two seemingly different time scales are similar because large
186 watersheds serve to temporarily store sediments en route to oceanic delivery over these
187 time scales. This conforms with existing hypotheses that large watersheds act as buffers
188 for climatic and anthropogenic forcing (Métivier and Gaudemer, 1999; Phillips, 2003).
189 As such, the time scale of integration for sediment yield measurements of modern rivers
190 with sediment storage might be better conceptualized as the residence time of sediment in
191 the basin transport system (i.e., the volume of sediment held on the landscape divided by
192 the flux of sediment through the system) rather than the number of years over which the
193 measurements are made. Métivier and Gaudemer (1999) demonstrate that, for the world's
194 largest rivers, this value can be 10–100 k.y.

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

199 **Implications for the Global Silicate Weathering Flux**

200 Various studies (West et al., 2005, and references therein) have found a strong
201 relationship between the total denudation rate and the silicate weathering flux in river
202 basins. Our new data set and analysis allow us to estimate the total global silicate flux
203 from these previously published relationships. In the empirical relationship of West et al.
204 (2005), they and others (Carson and Kirkby, 1972; Stallard and Edmond, 1983; Hilley
205 and Porder, 2008) note that watersheds may be classed into being either (1) *transport*
206 *limited*—where minerals are nearly completely altered before their removal or (2)

207 *kinetically limited*—where the alteration of minerals is incomplete. The transport limited
208 settings make up most of the land area on Earth, and in these settings the total rates of
209 denudation show a better correlation with silicate cation fluxes. The kinetically limited
210 cases are not well correlated with silicate cation fluxes and are typically found in areas
211 that are rapidly eroding and experiencing uplift, and comprise a small portion of the
212 landscape. In these kinetically-limited cases, West et al. (2005) note a case of diminishing
213 returns where a larger denudation rate does not necessarily result in a larger silicate
214 cation flux like the transport-limited relationship shows.

215 Using the relationship between river denudation and river chemistry and our
216 estimate of the total global denudation rate, the silicate cation denudation rate is equal to
217 0.6 t/km per year. If we assume that each mol of silicate cation reacts with 1 mol of CO₂,
218 then we calculate 0.72×10^8 t_{CO₂}/yr for the ice-free area of the Earth. This amount is
219 lower than previously published values ($5.1\text{--}5.5 \times 10^8$ t_{CO₂}/yr; Meybeck, 1982; Berner et
220 al., 1983; Gaillardet et al., 1999), but close to recent numerical modeling work ($1.5\text{--}3.3 \times$
221 10^8 t_{CO₂}/yr; Hilley and Porder, 2008). Given that our results only constrain denudation
222 rates for fluvially dissected landscapes that contain quartz, our calculated value should be
223 considered a minimum, as mafic rocks have minerals with a greater proportion of Ca and
224 Mg to supply for carbonate formation.

225 Global compilations show that silicate weathering rates and denudation rates are
226 tightly correlated (West et al., 2005). If this is true, and the greatest sensitivity of the
227 Earth's surface to changes in denudation lie in low sloping areas where small denudation
228 rate changes of these large areas drastically increase the average global denudation rate
229 (Fig. 3B), then this result has great consequences on global changes in the silicate

230 weathering cycle and rates of CO₂ drawdown. Considering that steeply sloping mountain
231 belts such as the Himalayas, Alps and Andes are only a small proportion of the
232 continental land surface compared to the areas of low-slopes (Fig. 1), and that topography
233 (thus tectonics) does not control denudation rates in these low-sloping areas (Fig. 2B), we
234 postulate that increased mountain building represents only a minor contribution to global
235 CO₂ withdrawal unless the total area of the world taken up by mountains increases
236 substantially. Thus, the real driver of denudation and geomorphically or environmentally
237 driven climate change remains unknown.

238 **CONCLUSIONS**

239 We calculate the sum of all sediment produced for the (quartz-containing) Earth
240 by extrapolation of a statistically significant correlation between cosmogenic nuclide-
241 derived long-term denudation rates and basin slopes to watersheds without denudation
242 rate data. This relationship can explain approximately half of the variance in denudation
243 from quartz bearing topography drained by rivers using only mean slopes. However, we
244 do not know what controls denudation in landscapes where average slopes are $< \sim 200$
245 m/km, but the control that sets the pace of this zone, holds the key to understanding the
246 feedbacks between erosion and climate. The total mass flux determined from our tally is
247 5.5 Gt/yr and agrees well with the mass flux from previous global studies from solute and
248 sediment gauging data (Summerfield and Hulton, 1994; Syvitski and Milliman, 2007)
249 and Phanerozoic rock volumes (Wilkinson and McElroy, 2007).

250 Finally, we suggest that identifying conditions sufficient to significantly impact
251 the global flux of solid sediments and solutes to oceans in the low sloping areas is the

252 next crucial area of research to elucidate geologically historical rates and magnitudes of
253 element cycling on Earth.

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333 **FIGURE CAPTIONS**

334 Figure 1. Global distribution of slope as calculated from the GTOPO30 DEM and
335 averaged using a 5×5 km moving window, and the distribution of river basins that were
336 used to determine global denudation rates (red circles). Top inset: the distribution of
337 endorheic basins. Bottom inset: histogram (bars) of basin areas in this compilation. Note
338 the log scale on the x -axis. See text for more details.

339 Figure 2. (A) Mean drainage basin slopes from 90 m Shuttle Radar Topography Mission
340 (SRTM) topographic data versus basin-wide denudation rates from cosmogenic ^{10}Be in

341 river sediment (circles) and large-river denudation rates (squares) from Summerfield and
342 Hulton, (1994). (B) Same as (A) but showing only those basins that have an average
343 slope less than 200 m/km. The black dashed horizontal line is the median of the data and
344 the gray box bounds 50% of the data. Note the absence of a correlation between
345 denudation rate and slope. (C) and (D) Denudation rates of basins with slopes less than
346 200 m/km versus geographic latitude and average basin elevation. See text for more
347 details.

348 Figure 3. (A) Slope (x-axis) versus denudation rate predicted by Eq. 1 (right axis; gray
349 dashed curve), cumulative land area (red curves) and, as the product of denudation rate
350 and area, total sediment production rate (blue curves). The dashed blue and red curves
351 mark area and sediment production with endorheic basins removed. The summation over
352 all continental area yields a net (chemical and physical) global sediment production rate
353 of ~5.5 Gt/yr. (B) Sensitivity analysis exploring the contribution to the total global
354 sediment flux of areas with slopes below 10 m/km (~0.6 degrees), 20 m/km (~1.2
355 degrees), and 100 m/km (~6 degrees) as a function of their average denudation rates.
356 Using the values predicted by Eq. 1 (yellow circles), these areas contribute around 40%,
357 53%, and 81% of the total sediment flux, respectively. Even when the denudation rate is
358 lowered to 5 mm/k.y. (see Fig. 2B), these values are still around 21%, 31%, and 62%,
359 respectively. The dashed curves are obtained when endorheic basins are removed.

360

361 ¹GSA Data Repository item 2013xxx, Table DR1 (complete dataset of ¹⁰Be-derived
362 denudation rates and topographic metrics used in this work), Table DR2 (previous
363 estimates of sediment delivery to oceans) and the original references for these datasets in

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364 Tables DR1 and DR2, are available online at www.geosociety.org/pubs/ft2013.htm, or on
365 request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140,
366 Boulder, CO 80301, USA.

Figure 1

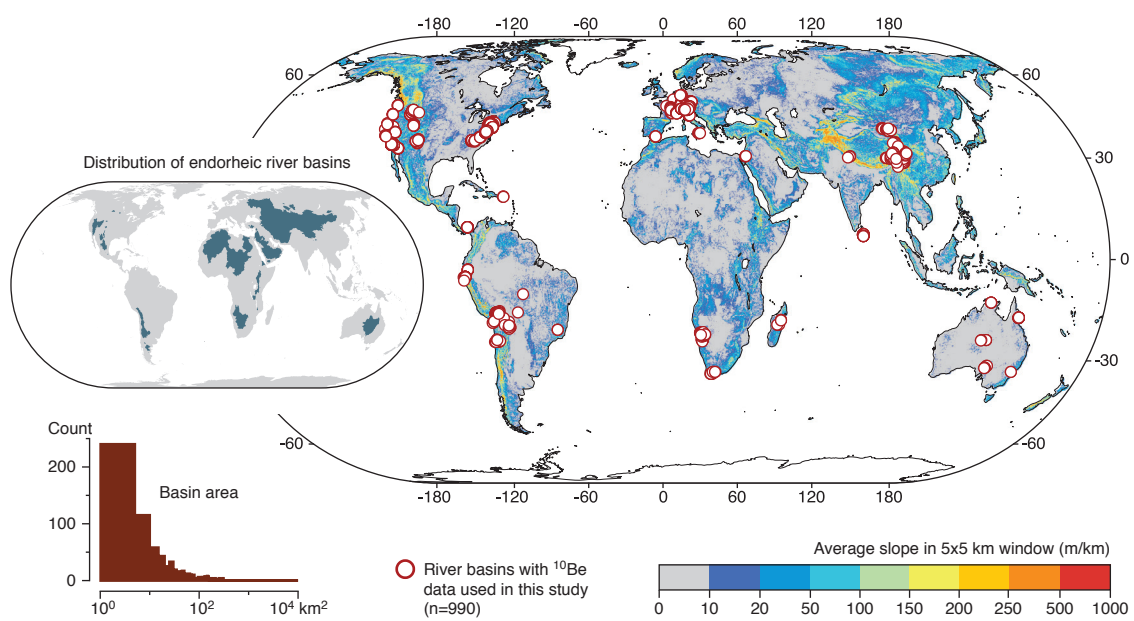


FIGURE 1

Figure 2

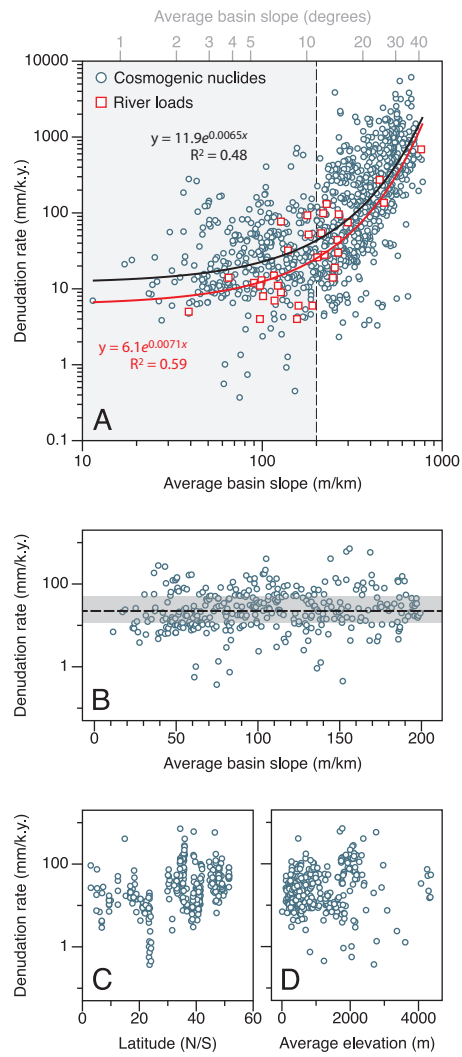


FIGURE 2

Figure 3

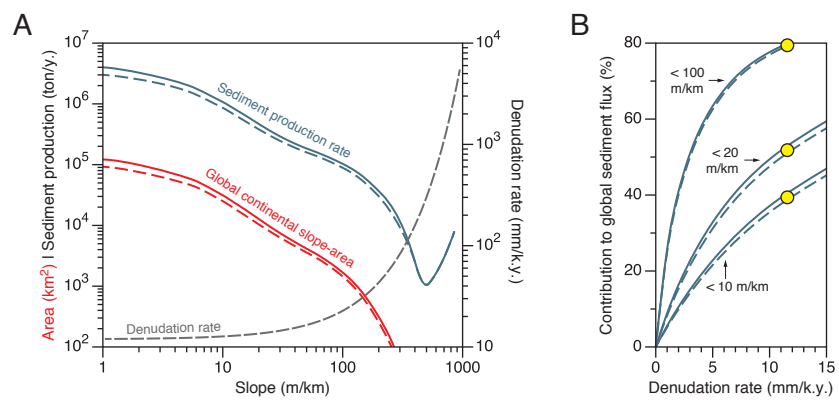


FIGURE 3

GSA Supplementary Material

The Earth is (mostly) flat: Apportionment of the flux of continental sediment over millennial timescales

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Be-10 COMPILATION

Catchment wide denudation rates were calculated using the re-normalised (2007 KNSTD) Be-10 concentrations, and following the formalism of Schaller et al. (2001) with Be-10 sea level high latitude (SLHL) production rates of: 4.5 ± 0.5 atoms.g⁻¹.y⁻¹ for high-energy neutrons, 0.097 ± 0.007 atoms.g⁻¹.y⁻¹ for slow muons, and 0.085 ± 0.012 atoms.g⁻¹.y⁻¹ for fast muons. The Be-10 SLHL production rate for high-energy neutrons was recalculated from Balco et al.'s (2008) Be-10 calibration-site dataset, using the time-independent altitude/latitude scaling scheme of Dunai (2000) and a Be-10 half-life of 1.387 ± 0.012 m.y. (Chmeleff et al., 2010; Korschinek et al., 2010). The Be-10 SLHL production rates for muons were taken from Kubik et al. (2009) and are based on Heisinger et al. (2002a,b). All Be-10 SLHL production rates were corrected for altitude and latitude using the time-independent scaling scheme of Dunai (2000) and for topographic shielding following Codilean (2006). All calculations were performed on a pixel-by-pixel basis using the 90m SRTM DEM (<http://srtm.csi.cgiar.org/>). At sites where duplicate measurements were made or multiple grain-size fractions were analysed, denudation rates were averaged.

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*** ¹⁰Be-10 data recalculated based on: Portenga EW and Bierman PR, 2011, Understanding Earth's eroding surface with ¹⁰Be. *GSA Today*, 21:4-10.**

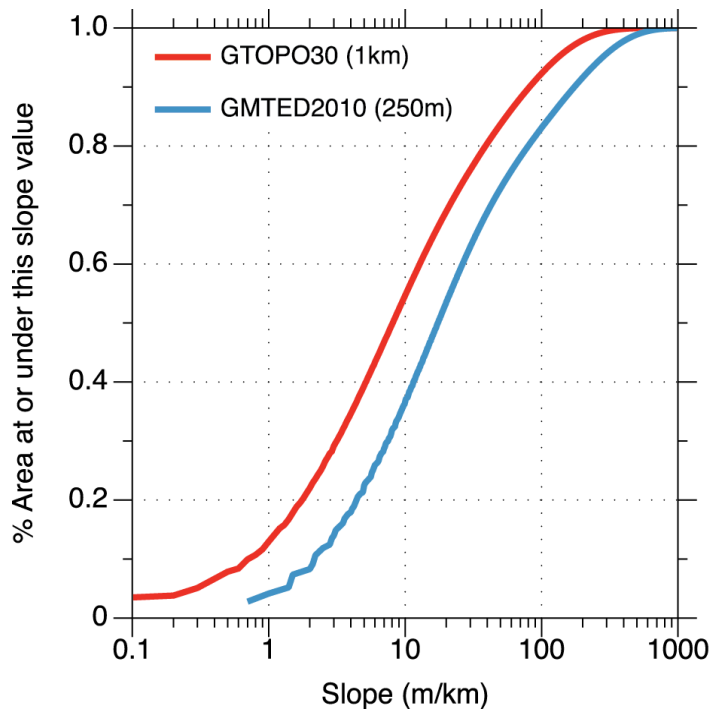
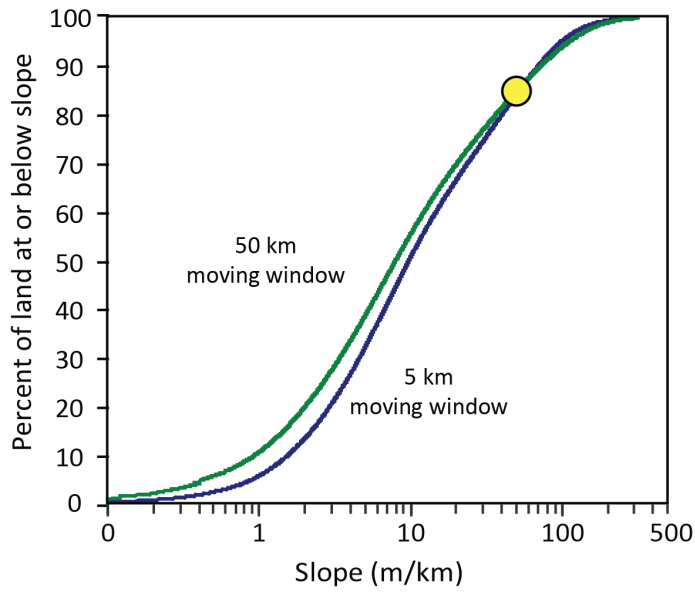


Figure DR1 (Top): Plot of cumulative global slope averaged over 5 km and 50 km moving windows. Note that >90% of the Earth's surface slope is below 50 m/km , and the effect of averaging over smaller or larger spatial scales does not significantly change that figure. **(Bottom):** A comparison of the frequency distribution of slope values obtained for the entire globe excluding Greenland and Antarctica, using the GTOPO30 (1km resolution; red) and GMTED2010 (250m resolution; blue). Note how the two curves are near parallel suggesting that although topography is much smoother in GTOPO30, the relative proportions of the different topographic 'features' are maintained. With other words, on both DEMs, the Andes and the Amazon basin, for example, occupy the same amount of continental area – except that they are both represented with less detail in GTOPO30 than in GMTED2010. For information on GMTED2010, see: <http://pubs.usgs.gov/of/2011/1073/pdf/of2011-1073.pdf>

Table DR2: Previously published estimates of global fluxes of sediment to the ocean and continental denudation rates.

Reference	Sediment load (Gt yr ⁻¹)	Sediment yield (kg m ⁻² yr ⁻¹)	Denudation rate (mm k.y. ⁻¹)
Founier (1960) ^[1]	51.1	0.544	218
Kuenen (1950) ^[1]	32.5	0.346	138
Gilluly (1955) ^[1]	31.7	0.337	135
Jansen and Painter (1974) ^[1]	26.7	0.284	114
Pechinov (1959) ^[1]	24.2	0.257	103
Lvovich(1974) ^[2]	21.7	0.231	92
Safyahov(1978) ^[2]	21.3	0.227	91
Schumm(1963) ^[1]	20.5	0.218	87
Milliman and Syvitski (1992) ^[1,3]	20	0.213	85
Lisitsyn (1974) ^[2]	18.5	0.197	79
Holeman (1968) ^[1]	18.3	0.195	78
Goldberg (1976) ^[1]	18	0.191	76
Makkaveev (1981) ^[2]	17	0.181	72
Milliman (1981) ^[2]	16	0.17	68
USSR National Committee (1974) ^[1]	15.7	0.167	67
Pinet and Souriau, 1998 ^[5]	15.7	0.167	67
Dedkov and Mozhherin (2000) ^[2]	15.5	0.165	66
Sundborg (1973) ^[1]	15	0.16	64
Walling (1987) ^[5]	15	0.16	64
Walling and Webb (1983) ^[1]	15	0.16	64
Ludwig and Probst, (1996) ^[3]	14.8	0.156	62
McLennan (1993) ^[4]	14	0.149	60
Milliman and Meade (1983) ^[1,3]	13.5	0.144	58
Lopatin(1952) ^[1]	12.7	0.135	54
Harrison (1994) ^[5]	11.7	0.125	47
Wold and Hay (1990) ^[4]	10.9	0.116	46
Gregor (1970) ^[4]	10.5	0.112	45
Summerfield and Hulton (1994)	9.7	0.103.	41
Judson (1968) ^[4]	9.3	0.099	40
Syvitski and Milliman, 2007	8.7	0.093	37
Mackenzie and Garrels (1966) ^[1]	8.3	0.088	35
This work (endorheic basins removed)	4.4	0.047	19
Average	17	0.19	75

^[1] Values from References from Walling and Webb (1996)

^[2] Values from References from Jaoshvilli (2002)

^[3] Values from References from Ludvig et al. (1996)

^[4] Values from References from Wilkinson (2005)

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