Title

The null hypothesis: globally steady rates of erosion, weathering fluxes and shelf sediment accumulation during Late Cenozoic mountain uplift and glaciation

Journal

Terra Nova, 28(1)

ISSN

0954-4879

Authors

Willenbring, Jane K
Jerolmack, Douglas J

Publication Date

2016-02-01

DOI

10.1111/ter.12185

Peer reviewed

Terra Nova

doi: 10.1111/ter.12185

Debate Article

The null hypothesis: globally steady rates of erosion, weathering fluxes and shelf sediment accumulation during Late Cenozoic mountain uplift and glaciation

Jane K. Willenbring and Douglas J. Jerolmack

Department of Earth and Environmental Science, University of Pennsylvania, 240 South 33rd Street, Philadelphia, PA 19104-6316, USA

ABSTRACT

At the largest time and space scales, the pace of erosion and chemical weathering is determined by tectonic uplift rates. Deviations from equilibrium arise from the transient response of landscape denudation to climatic and tectonic perturbations. We posit that the constraint of mass balance, however, makes it unlikely that such disequilibrium persists at the global scale over millions of years, as has been proposed for late Cenozoic erosion. We synthesize weathering fluxes, global sedimentation rates, sediment yields and tectonic motions to show a remarkable constancy in the pace of Earth-surface evolution over the last 10 Ma and support the null hypothesis – that global rates of landscape change have remained constant over this time period, despite global climate change and mountain building events. This work undermines the hypothesis that increased weathering due to mountain building or climate change was the primary agent for a decrease in global temperatures.

Terra Nova, 00: 1–8, 2015

FORUM: **The Editors of Terra Nova invite readers to contribute to a discussion of this topic on our forum at https://terranova-debates.wordpress.com/**

Introduction

The evolution of the Earth's surface occurs through the erosion of rock and redistribution of mass. This is ultimately driven by energy from two sources: tectonics, which contributes to erosion indirectly through uplift; and climate, which influences erosion and weathering via temperature and precipitation. Global changes in tectonic motions or climate might be expected to produce global changes in the rate of landscape evolution; however, feedbacks among climate, tectonics and geomorphology may enhance or obscure the relation between 'signal' and 'response'. For example, although the engine for plate tectonics is mantle convection, researchers have proposed that rates of tectonic uplift may depend and feedback on global climate through silicate weathering (which draws down CO_2 and leads to cooling) (Berner, 1991; Berner and Caldeira, 1997; Maher and Chamberlain, 2014) and physical erosion (which causes unloading that can induce a tectonic response; Montgomery, 1994; Whipple, 2009). In order to unravel these feedbacks and linkages, many researchers have turned to global datasets of the relevant parameters.

Of particular interest has been the late Cenozoic period, when a global cooling trend, of unknown origin, began at 50 Ma and culminated in continental glaciations during the last 2–3 Ma in Eurasia and North and South America (Ruddiman, 2010). Global rates of tectonic motion have been either constant over this interval, as determined from ages of crust (Fig. 1; Rowley, 2002, 2013), or decreasing, as determined from slab flux models that incorporate the geometry of the subduction zone (Van Der Meer *et al.*, 2014). Observations also point to an apparent increase (c.f. Sadler, 1981) in landscape denudation over the same time period, as indicated by global sediment accumulation curves from the world's oceans and sedimentary basins (Hay *et al.*, 1988; Molnar, 2004) and, more recently, a global compilation of mountain erosion rates (Herman *et al.*, 2013). Researchers have attempted to causally link these trends to global cooling with two related hypotheses. In the first, rapid erosion associated with Himalayan uplift acted to drive Cenozoic cooling by reducing CO_2 levels through increased silicate weathering (Raymo and Ruddiman, 1992). The second reverses the arrow of causality: in this case it is argued climatic cooling and glacial-interglacial swings acted to increase denudation rates, perhaps even inducing enhanced mountain uplift (Molnar and England, 1990; Zhang *et al.*, 2001; Molnar, 2004).

The climatic cooling trend of the late Cenozoic is not in dispute. We challenge the premise that global rates of landscape denudation have changed, however, on both conceptual and empirical grounds. There are numerous possibilities for feedbacks and linkages among climate, tectonics, erosion and weathering. However, mass balance places a constraint on the magnitude and persistence of denudation rates. Enhanced weathering and erosion reduces slopes and grows valleys, which act to decrease denudation back towards being in balance with tectonic uplift

Correspondence: Dr. Jane Kathryn Willenbring, Department of Earth and Environmental Science, University of Pennsylvania, 240 South 33rd Street, Philadelphia, PA 19104-6316, USA. Tel.: +001 215 746-8197; e-mail: erosion@sas.upenn.edu

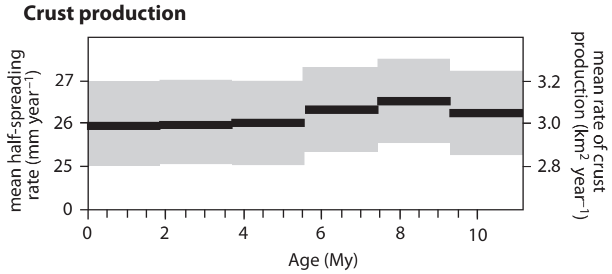

Fig. 1 Rates of tectonic forcing over the last 10 Ma are steady. Figure adapted from Rowley (2002, 2013) and data digitized from Rowley (2002; Fig. 4).

(Whipple *et al.*, 1999). As with many problems, it is an issue of scale. Large regions of the globe may sustain denudation rates that are far from being in equilibrium with tectonics, but for only limited periods of time. Alternatively, at-a-point rates of denudation may be much larger than tectonic rates over long periods of time, but are compensated by lower rates elsewhere. To make the case for sustained and enhanced denudation rates globally over several millions of years, one needs to demonstrate that: (1) erosion and weathering rates are somehow decoupled from tectonics at the largest scales; and (2) there is a convincing and causal relation between climate and denudation rates at the global scale. Regarding (1), while numerous studies have reported disequilibrium between erosion and tectonics over shorter timescales, models and data show a convergence of the two over timescales greater than 10^6 years (Koppes and Montgomery, 2009; Whipple, 2009), although transience may also persist for millions of years (Willenbring *et al.*, 2013). Further, for studies that infer denudation from basin-integrating (i.e. spatially averaging) sediment yields, global rates do not show any significant trend over timescales longer than 10^1 years (Koppes and Montgomery, 2009; Sadler and Jerolmack, 2014). As for (2), global compilations using cosmogenic radionuclides fail to reveal any relation between denudation rates and temperature or precipitation (Portenga and Bierman, 2011). Moreover, a landscape evolution model that can realistically perturb a landscape via climate has not yet been produced. This topic is an active research area, and the not-simple question of how climate impacts landscape probably has as many answers as there are landscapes.

The simplest, that is, null, hypothesis is that global rates of erosion, weathering and sediment accumulation have been constant over the time interval in question. This constancy is expected from the mass conservation constraint, given that global rates of tectonic motion have not varied over the late Cenozoic (Rowley, 2002, 2013). Ultimately, the long time-scales needed to affect global heat production, and the correlation of mantle viscosity to mantle temperature, preclude any global changes in tectonic rates. We do not have sufficient knowledge of the mechanisms of weathering, erosion, geodynamics and climate to address competing hypotheses from a theoretical/modelling perspective. Rather, we must rely on empirical findings, which fall into three main categories. The first approach is finding a geochemical proxy that indirectly records processes such as the flux of erosion or weathering products to the oceans and integrates over large areas (continents, ocean basins or global). The second approach is measuring erosion or weathering rates (or total denudation rate) in as many places as possible and trying to extrapolate to unmeasured areas. The third approach is to use the sedimentary record as a proxy for erosion and weathering loads. Below, we show how converging lines of evidence from these three approaches provide strong support for steady rates of global landscape evolution over the Cenozoic, and find that observed rates are remarkably constant over the last 10 million years. The significance and implications of these results for understanding feedbacks between climate and geomorphology are discussed.

Evidence from geochemical proxies

Recent proxies suggest stabilization of atmospheric CO_2 at near-modern levels since the late Oligocene, despite continued global cooling (Beerling and Royer, 2011; Fig. 2A). This stationary greenhouse gas composition implies nearly constant chemical weathering over the last 10–20 Ma, unless there were significant changes in the organic carbon cycle (Pagani *et al.*, 2009) that somehow compensated for changes in weathering. Several recent hypotheses attempting to relate global cooling to the Northern Hemisphere glaciation have therefore abandoned increased weathering fluxes as a cause (Knies *et al.*, 2014; Woodard *et al.*, 2014). Other proxies brought to bear on this issue have ambiguities that limit our interpretive ability. In the past, the rising late Cenozoic $^{87}Sr/^{86}Sr$ record was thought to be an indicator of increased continental weathering (Raymo *et al.*, 1988; Capo and DePaolo, 1990). However, this record has been shown to be sensitive to the isotopic ratio of the sedimentary source area (Richter *et al.*, 1992) and to the proportion of physical to chemical weathering (Derry and France-Lanord, 1996). Similarly, Nd and Pb isotopes indicate only a change in weathering style or source, not a total weathering flux (Willenbring and von Blanckenburg, 2010a).

Two proxies that are thought to describe the total weathering flux are the $^{10}Be/^{9}Be$ ratio and the δ^7Li record. $^{10}Be/^{9}Be$ systematics are relatively simple, thus may finally constrain the flux of weathering products to the ocean. This ratio is a combination of ^{9}Be that is released from weathering and cosmogenic ^{10}Be, which acts as a constant flux tracer over time periods long enough to average several geomagnetic field cycles. Over the last 10 Ma, this ratio is invariant from ocean basin (Atlantic) (Fig. 2B) to ocean basin (Pacific) (Fig. 2C; Willenbring and von Blanckenburg, 2010a), which precludes the ~2–4-fold increase in weathering flux inferred from records

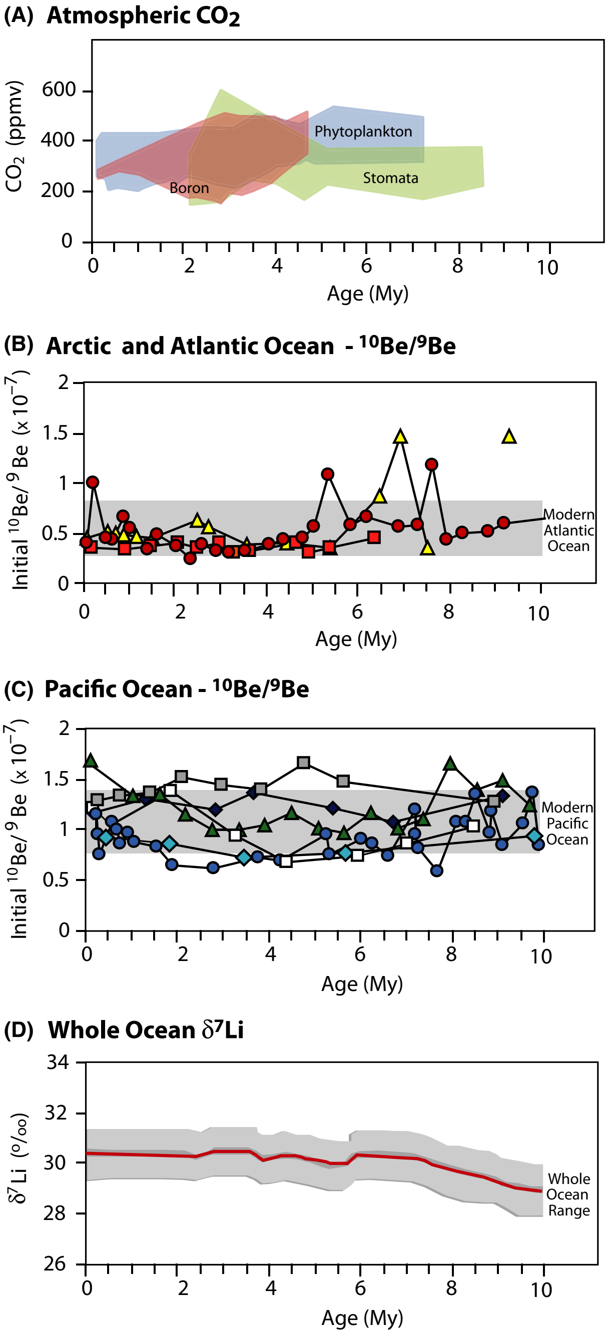

Fig. 2 (A) Palaeo-CO_2 proxy reconstructions from Beerling and Royer (2011) (excluding paleosol proxies) are essentially steady over the last 10 Ma. (B) $^{10}Be/^{9}Be$ from ferromanganese crusts and dated sediments from the Arctic and Atlantic Oceans (adapted from Willenbring and von Blanckenburg, 2010a). (C) $^{10}Be/^{9}Be$ from ferromanganese crusts and dated sediments from the Pacific Ocean (adapted from Willenbring and von Blanckenburg, 2010a). Records in (b and c) were corrected for radionuclide decay of ^{10}Be over time and show no systematic variation over the last 10 Ma. (D) Whole ocean $\delta^{7}Li$ records for the last 10 Ma are essentially steady. Figure adapted from Misra and Froelich (2012).

of sediment accumulation (Zhang *et al.*, 2001; Molnar, 2004). However, the scatter in the plot and uncertainties in the behaviour of beryllium at the neutral pH of the oceans (Boschi and Willenbring, 2013) would allow for a modest (20%) increase in the weathering flux. Moreover, since ^{9}Be does not directly measure erosion, it is indeterminate regarding an erosion rate increase. The ^{9}Be weathering proxy is also not sensitive to basalt or carbonate weathering, and the ^{10}Be flux is assumed to be quasi-constant but also depends on the ocean basin where the samples are taken because of latitudinal variations in the delivery of ^{10}Be from the atmosphere (Willenbring and von Blanckenburg, 2010b). The $\delta^{7}Li$ values over the last 10 Ma are invariant within the range of variability and uncertainty in the measurements (Fig. 2D). Interpreting how the $\delta^{7}Li$ record relates to chemical weathering fluxes is more complex (Misra and Froelich, 2012; Torres *et al.*, 2014). Nonetheless, the $^{10}Be/^{9}Be$ ratio (Willenbring and von Blanckenburg, 2010a) and the original interpretation of the $\delta^{7}Li$ record (Misra and Froelich, 2012) support the view from palaeo-CO_2 proxies that there has been no large change in the silicate weathering flux from the continents over the last 10 Ma.

Measuring erosion, weathering and denudation

The apparent increase in global denudation rates is coincident with the onset of northern hemispheric glaciation. Enhanced glacial erosion in response to global cooling has thus been invoked as the major process responsible, fuelled by a much-cited view that glaciers can be more effective erosive agents than rivers (Hallet *et al.*, 1996), even limiting the height of mountains regardless of tectonics (the glacial buzzsaw hypothesis; Brozović *et al.*, 1997; Mitchell and Montgomery, 2006). This *climate-driven erosion hypothesis* has the potential to feed back to long-term climate: increased denudation and glacial grinding of debris creates fresh mineral surfaces, accelerating weathering rates and thus causing the sequestration of atmospheric CO_2, which further decreases temperatures. Data show, however, that while glacial cover may induce a rapid pulse of erosion, it is not sustained (Koppes and Montgomery, 2009). Further, only some climates produce high rates of glacial erosion (Yanites and Ehlers, 2012); rates may be diminished at high elevations due to intense cold and lack of moisture, which lead to ice-shedding 'Teflon peaks' (Anderson, 2005; Ward *et al.*, 2012). Finally, recent research indicates that pre-Quaternary topography – and not glacial erosion – sets the elevation of high plateaus (Van Der Beek *et al.*, 2009), and that correlations between the occurrence of glaciers and mountain hypsometries are merely coincidental (Hall and Kleman, 2013).

Cosmogenic nuclide data support the idea of fleeting fluxes of sediment from glacial erosion (Charreau *et al.*, 2011); thermochronologic data demonstrate that over the long periods of time recorded by exhumation rates, glaciers do protect some landscape surfaces (Thomson *et al.* 2010). Only approximately half of palaeodenudation records show an increased rate during the last 2 Ma compared to pre-Quaternary time (Granger and Schaller, 2014). Data also show that in the Antarctic, Arctic and sub-Arctic, glaciation may be geomorphically protective on high peaks and flat plateaus (Staiger *et al.*, 2005; Briner *et al.*, 2006), and glacial erosion may recycle past glacial sediment rather than erode rock (Roy *et al.*, 2004; Ebert *et al.*, 2012). In summary, enhanced erosion in some places would be at least partially compensated for by inhibited erosion in others.

Herman *et al.* (2013) recently compiled a global thermochronologic dataset to explore the idea of glacial vs. non-glacial erosion, by comparing cooling rates in the 0–2 Ma time slice to those in the 4–6 Ma time slice and inverse modelling erosion rates based on a set of assumptions. These authors found that the most recent 2-Ma interval often had exhumation rates >4 times higher than the 6–4 Ma interval, when comparing areas covered by glaciers. They acknowledge a bias in the dataset where only sufficiently fast exhumation rates would achieve the precision necessary to answer this question. Another source of bias acknowledged is that the samples were not randomly selected, but occur most often in orogenic belts. While the authors employed a sophisticated inversion technique to account for errors and variability in *measured* rates, results from their statistical model are biased by not accounting for the influence of *immeasurably slow* rates. Naylor *et al.* (2015) have demonstrated the effect of this bias for detrital thermochronologic datasets. The essence of the argument is that slower rates of exhumation are progressively clipped from the measured age distribution of rocks as one approaches the modern because of the precision of the technique. The reason is that thermochronometers measure the time since achieving an associated closure depth; rate is simply the measured time divided by this depth. If erosion rates have not been high enough to bring rocks to the surface, the rates associated with those buried rocks cannot be measured (Fig. 3). While the full distribution of exhumation rates can be measured for rocks older than, say, 20 Ma, slower rates are progressively clipped from the measurable distribution for younger and younger ages. Based on the Naylor *et al.* (2015) model, Sinclair *et al.* (in review) found that, in the western Alps, the effect becomes pronounced for rocks in the range of 3–5 Ma. If the mean of measured exhumation rates is assumed to represent the true mean erosion rate, then any thermochronologic dataset could (mistakenly) suggest an acceleration in erosion rate that is actually an artefact of the technique. In Fig. 3, we plot a variation of an idea of Anders *et al.* (1987) that describes two clipped distributions of sedimentation rate data both in the maximum depth of a population sampled and in the precision possible for the youngest ages. We view this near-reproduction of the Anders *et al.* (1987) figure (intended for sedimentation rates) applied to exhumation rates as a thought experiment. Although that was not the original intent of the figure, the conceptual analogy is useful. The reader is referred to Naylor *et al.* (2015) for a rigorous discussion of bias in thermochronologic systems.

Finally, the data compilation from Koppes and Montgomery (2009) shows that overall rates of glacial erosion are comparable to fluvial values over long timescales, and that both converge with tectonic uplift rates over millennial timescales. Their conclusion was that tectonics, and not climate, is the ultimate driver of landscape erosion rates over long timescales.

Sediment generation and deposition

The primary piece of evidence that past researchers have employed to infer a global late Cenozoic increase in erosion and weathering is the piles of sediment accumulated in the oceans (Hay *et al.*, 1988; Métivier *et al.*, 1999; Zhang *et al.*, 2001; Molnar, 2004) (and, to a lesser extent, on land (Kuhlemann, 2000)). As pointed out by Schumer and Jerolmack (2009), however, the apparent accumulation rates determined from sediment piles do not reflect true sediment accumulation rates and cannot be used as direct evidence for increasing global denudation rates over the late Cenozoic. The confusion in interpreting sediment accumulation arises from the now notorious 'Sadler effect': due to the unsteady nature of sediment deposition, rates of accumulation appear to decrease with increasing measurement interval (Sadler, 1981, 1994). This effect arises from a bias that is not unlike the clipping effect described above for thermochronologic data. Sediment accumulation rates in the modern are only measured where sediment is accumulating, and therefore preclude negative or zero values from being incorporated; as one averages over longer and longer time intervals, measured rates incorporate intervals of non-deposition and erosion. Because measurement interval and age are inseparable (Sadler, 1981), the upshot is an apparent increase in accumulation rates on approach to the present. For every type of accumulation or erosion one could measure, one sees the same kind of apparent increase (Gardner *et al.*, 1987; Sadler, 1994; Schumer and Jerolmack, 2009; Finnegan *et al.*, 2014). Theory shows us that these apparent trends are an inevitable consequence of stochastic variations in erosion and deposition, and likely do not reflect any real change in the mean rate through time (Strauss and Sadler, 1989; Pelletier and Turcotte, 1997; Jerolmack and Sadler, 2007; Schumer and Jerolmack, 2009; Schumer *et al.*, 2011; Finnegan *et al.*, 2014).

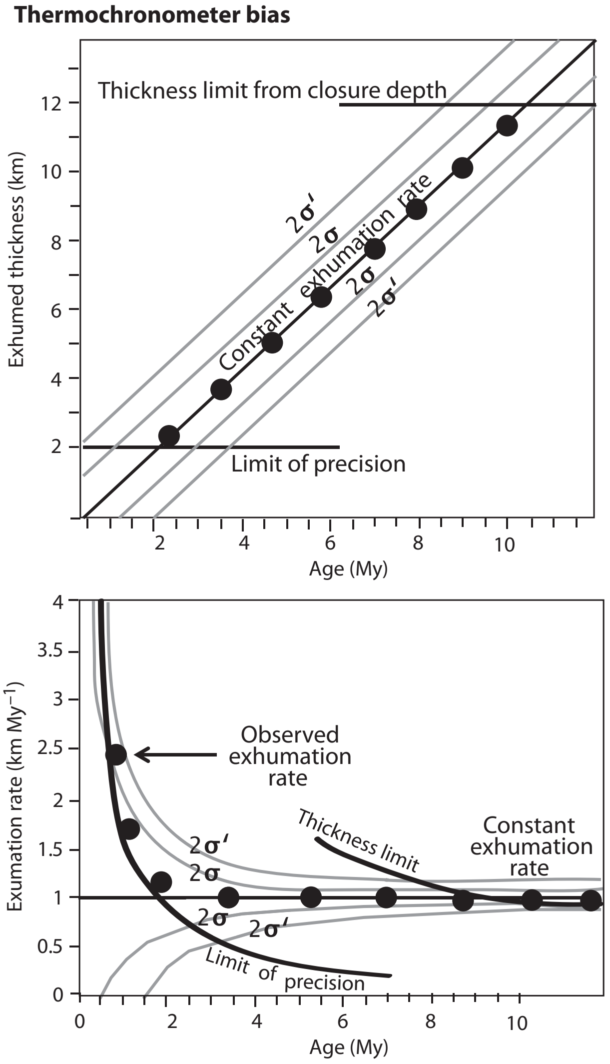

Fig. 3 Figures (thickness – top; rate – bottom) adapted from Anders *et al.* (1987). Illustration of a potential bias in thermochronometers by filtering of exhumation histories (idea by Sinclair *et al.*, in review; Naylor *et al.*, 2015) by the thickness limit from the maximum closure depth and the limit of precision of the method. For the precision limit, in order to resolve an erosion/exhumation rate using a given thermochronometer, there must have been sufficient exhumation since the passage of the rock through the depth of effective mineral closure. Therefore, the younger the time period of interest, the higher the exhumation rate necessary to exhume the rock to the surface to be measured. Due to the vagaries of thermochronometry, the only rates that are recordable during the last few millions of years are those with higher values. Slow rates with insufficient time to reach the surface are clipped for recent times but not clipped for long time periods. The 'limit of precision' denotes a zone of unmeasurable rates. The variance in the dataset is either zero as in the case of 'constant exhumation rate' or increased to 2σ and $2\sigma'$ are the variability around the measurements (see top panel). The running median value is the 'observed exhumation rate.' All rates should be constant, but because of the selective inclusion of only fast rates for recent times and a limit on the thickness possibly exhumed 'thickness limit', the observed exhumation rate increases (black dots) in the lower figure. If these clipped values are assumed to represent the rates for the range as a whole, then it would lead to an observed acceleration in rates for the last 2 Ma.

The 'Sadler effect' bias arises due to the primarily one-dimensional (1D) nature of accumulation and erosion measurements (Sadler and Jerolmack, 2014). If we knew the volumes of sediment deposited and eroded in a given time interval, no measurement bias would exist. This body of work is often ignored in favour of the more 'straightforward' interpretation of a positive trend in curves of measured rates.

Recent work and summaries of the literature (Romans, in press) state there is little expectation that sediment simply records changes in forcing. Even if the climatic or tectonic regime has changed, the sedimentary record might remain constant. Diffusive processes on hillslopes and in other sedimentary bodies are very efficient at filtering climatic oscillations because of slow signal propagation (Métivier *et al.*, 1999; Furbish and Fagherazzi, 2001; Armitage *et al.*, 2013; Godard *et al.*, 2013). Also, the signal response to climate or tectonic forcing is likely nonlinear – at least over some timescales (Jerolmack and Paola, 2010).

A remarkable finding from global data compilations has recently emerged; however, that provides the most convincing physical evidence yet that global erosion rates have been constant over the Cenozoic. Sadler and Jerolmack (2014) show that a newly compiled curve of progradation (lateral migration) rates in continental shelf settings mirrors the compilation of aggradation (vertical deposition) rates. The data shown in Fig. 4 are derived from means of thousands of individual measurements from all over the globe. Based on mass balance, the product of these two curves represents the global sediment flux deposited on shelves, and overcomes many of the problems of 1D measurements. The data show that this flux is constant over timescales from years to tens of millions of years (Fig. 4). This study also presented the most extensive compilation yet of upland denudation rates determined from *sediment yields* – which, importantly, are spatially integrated measurements – and these data also indicate constant rates over a similar time span. In sum, when denudation and accumulation rate measurements incorporate appropriate spatial averaging, they do not support any significant increase in the pace of landscape evolution over the late Cenozoic. Instead, global denudation

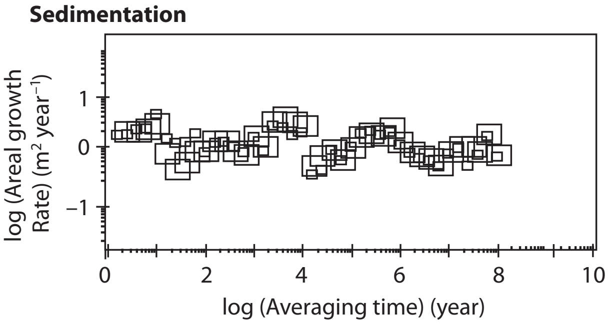

Fig. 4 Sediment flux, expressed as volume discharge per unit width of the transport system (i.e. cross-sectional growth rate, m^2 a^{-1}), does not vary systematically from timescales of years to one hundred million years (Sadler and Jerolmack, 2014). Large rectangles plot growth rates for shelf systems; small rectangles plot growth rates for the shore zone and floodplain systems. These growth rates are products of aggradation and progradation components determined separately from the mean of thousands of empirical values from a global database (described in more detail and adapted from fig. 10 in Sadler and Jerolmack, 2014).

rates have been remarkably constant for tens of millions of years.

Conclusions

A suite of geochemical proxies indicate that global weathering rates have not changed significantly over the last 10 Ma (Willenbring and von Blanckenburg, 2010a; Beerling and Royer, 2011; Misra and Froelich, 2012). Compilations of global denudation rates determined from global sediment accumulation rates determined from 2D data also indicate no significant changes over this time interval. In fact, given the uncertainties and noise in the measurements, the data 'curves' are remarkably flat. In addition, global compilations of cosmogenic radionuclide data fail to show any clear relation between climate and denudation (Portenga and Bierman, 2011). Importantly, these results are robust empirical trends and are not inferred from any model, and are consistent with expectations from mass balance. Application of Occam's razor suggests that the null hypothesis is the most viable.

A steady rate of global denudation provides an important baseline for regional studies, and implies that changes in global climate are accommodated at the largest scales by changes in landscape form rather than the rate of landscape change. At appropriately averaged time and space scales, it appears that rates of landscape change are tied most strongly to tectonics. The constancy of denudation rates does not diminish the importance of feedbacks among climate, tectonics, erosion and weathering; indeed, these feedbacks are likely responsible for returning denudation rates to be in balance with tectonic forcing following a disturbance. In the future, careful attention to how measured rates converge to constant values as a function of spatial and/or temporal averaging may reveal new information regarding the nature of these feedbacks, and provide important constraints for geodynamic models.

Acknowledgement

We acknowledge the NSF grant EAR-1331841 and thank Peter Sadler, Bruce Wilkinson, Friedhelm von Blanckenburg, Shanan Peters, and Hugh Sinclair for ideas and discussions. We thank two anonymous reviewers and Simon Brocklehurst for their constructive reviews.

References

Anderson, R. S., 2005. Teflon Peaks: The evolution of high local relief in glaciated mountain ranges. AGU Fall Meeting Abstracts 1, 04.

Anders, M.H., Krueger, S.W. and Sadler, P.M., 1987. A new look at sedimentation rates and the completeness of the stratigraphic record. *J. Geol.*, 1–14.

Armitage, J.J., Dunkley Jones, T., Duller, R.A., Whittaker, A.C. and Allen, P.A., 2013. Temporal buffering of climate-driven sediment flux cycles by transient catchment response. *Earth Planet. Sci. Lett.*, **369**, 200–210.

Beerling, D.J. and Royer, D.L., 2011. Convergent Cenozoic CO_2 history. *Nature Geosci.*, **4**, 418–420.

Berner, R.A., 1991. A model for atmospheric CO_2 over Phanerozoic time. *Am. J. Sci.*, **291**, 339–376.

Berner, R.A. and Caldeira, K., 1997. The need for mass balance and feedback in the geochemical carbon cycle. *Geology*, **25**, 955–956.

Boschi, V. and Willenbring, J.K., 2013. The behavior of beryllium in soils and acquatic environments. *Mineral. Mag.*, **77**(5), 744.

Briner, J.P., Miller, G.H., Davis, P.T. and Finkel, R.C., 2006. Cosmogenic radionuclides from fiord landscapes support differential erosion by overriding ice sheets. *Geol. Soc. Am. Bull.*, **118**, 406–420.

Brozović, N., Burbank, D.W. and Meigs, A.J., 1997. Climatic limits on landscape development in the northwestern Himalaya. *Science*, **276**, 571–574.

Capo, R. C. and DePaolo, D. J., 1990. Seawater strontium isotopic variations from 2.5 million years ago to the present. *Science*, **249**(4964), 51–55.

Charreau, J., Blard, P.H., Puchol, N., Avouac, J.P., Lallier-Vergès, E., Bourlès, D. and Roy, P., 2011. Paleo-erosion rates in Central Asia since 9 Ma: a transient increase at the onset of Quaternary glaciations? *Earth Planet. Sci. Lett.*, **304**(1), 85–92.

Derry, L.A. and France-Lanord, C., 1996. Neogene Himalayan weathering history and river $^{87}Sr/^{86}Sr$: impact on the marine Sr record. *Earth Planet. Sci. Lett.*, **142**(1), 59–74.

Ebert, K., Willenbring, J., Norton, K., Hättestrand, C. and Hall, A., 2012. ^{10}Be inventories from northern Sweden: implications for dating till and saprolite. *Quatern. Geochron.*, **12**, 11–22.

Finnegan, N.J., Schumer, R. and Finnegan, S., 2014. A signature of transience in bedrock river incision rates over timescales of 10^4-10^7 years. *Nature*, **505**(7483), 391–394.

Furbish, D.J. and Fagherazzi, S., 2001. Stability of creeping soil and implications for hillslope evolution. *Water Resour. Res.*, **37**, 2607–2618.

Gardner, T.W., Jorgensen, D.W., Shuman, C. and Lemieux, C.R., 1987. Geomorphic and tectonic process rates: effects of measured time interval. *Geology*, **15**(3), 259–261.

Godard, V., Tucker, G.E., Burch Fisher, G., Burbank, D.W. and Bookhagen, B., 2013. Frequency-dependent landscape response to climatic forcing. *Geophys. Res. Lett.*, **40**(5), 859–863.

Granger, D.E. and Schaller, M., 2014. Cosmogenic nuclides and erosion at the watershed scale. *Elements*, **10**(5), 369–373.

Hall, A.M. and Kleman, J., 2013. Glacial and periglacial buzzsaws: fitting metaphors and mechanisms? *Quatern. Res.*, **81**, 189–192.

Hallet, B., Hunter, L. and Bogen, J., 1996. Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Global Planet. Change*, **12**(1), 213–235.

Hay, W.W., Sloan, J.L. and Wold, C.N., 1988. Mass Age Distribution and Composition of Sediments on the Ocean-Floor and the Global Rate of Sediment Subduction. *J. Geophys. Res.-Solid Earth*, **93**(B12), 14933–14940.

Herman, F., Seward, D., Valla, P.G., Carter, A. , Kohn, B., Willett, S.D. and Ehlers, T.A., 2013. Worldwide acceleration of mountain erosion under a cooling climate. *Nature*, **504**, 423–426.

Jerolmack, D.J. and Paola, C., 2010. Shredding of environmental signals by sediment transport. *Geophys. Res. Lett.*, **37**, L19401.

Jerolmack, D. and Sadler, P., 2007. Transience and persistence in the depositional record of continental margins. *J. Geophys. Res.*, **112**, F03S13.

Knies, J., Mattingsdal, R., Fabian, K., Grøsfjeld, K., Baranwal, S., Husum, K., De Schepper, S., Vogt, C., Andersen, N., Matthiessen, J., Andreassen, K., Jokat, W., Nam, S.-I. and Gaina, C., 2014. Effect of early Pliocene uplift on late Pliocene cooling in the Arctic-Atlantic gateway. *Earth Planet. Sci. Lett.*, **387**, 132–144.

Koppes, M.N. and Montgomery, D.R., 2009. The relative efficacy of fluvial and glacial erosion over modern to orogenic timescales. *Nature Geosci.*, **2**(9), 644–647.

Kuhlemann, J., 2000. Post-collisional sediment budget of circum-Alpine basins (Central Europe). *Mem. Sci. Geol. Padova*, **52**, 1–91.

Maher, K. and Chamberlain, C.P., 2014. Hydrologic regulation of chemical weathering and the geologic carbon cycle. *Science*, **343**(6178), 1502–1504.

Métivier, F., Gaudemer, Y., Tapponier, P. and Klein, M., 1999. Mass accumulation rates in Asia during the Cenozoic. *Geophys. J. Int.*, **137**, 280–318.

Misra, S. and Froelich, P.N., 2012. Lithium Isotope History of Cenozoic Seawater: changes in Silicate Weathering and Reverse Weathering. *Science*, **335**, 818–823.

Mitchell, S.G. and Montgomery, D.R., 2006. Influence of a glacial buzzsaw on the height and morphology of the Cascade Range in central Washington State, USA. *Quatern. Res.*, **65**, 96–107.

Molnar, P., 2004. Late Cenozoic increase in accumulation rates of terrestrial sediment: how might climate change have affected erosion rates? *Annu. Rev. Earth Planet. Sci.*, **32**, 67–89.

Molnar, P. and England, P., 1990. Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg? *Nature*, **346**, 29–34.

Montgomery, D.R., 1994. Valley Incision and the Uplift of Mountain Peaks. *J. Geophys. Res.*, **99**, 13913–13921.

Naylor, M., Sinclair, H.D., Bernet, M., van der Beek, P. and Kirstein, L., 2015. Bias in detrital fission track grain-age populations: implications for reconstructing changing erosion rates. *Earth Planet. Sci. Lett.*, **422**, 94–104.

Pagani, M., Caldeira, K., Berner, R. and Beerling, D.J., 2009. The role of terrestrial plants in limiting atmospheric CO_2 decline over the past 24 million years. *Nature*, **460**(7251), 85–94.

Pelletier, J.D. and Turcotte, D.L., 1997. Synthetic stratigraphy with a stochastic diffusion model of fluvial sedimentation. *J. Sediment. Res.*, **67**(6), 1060–1067.

Portenga, E.W. and Bierman, P.R., 2011. Understanding Earth's eroding surface with 10-Be. *GSA Today*, **21**(8), 4–10.

Raymo, M.E. and Ruddiman, W.F., 1992. Tectonic forcing of late Cenozoic climate. *Nature*, **359**, 117–122.

Raymo, M.E., Ruddiman, W.F. and Froelich, P.N., 1988. Influence of late Cenozoic mountain building on ocean geochemical cycles. *Geology*, **16**(7), 649–653.

Richter, F., Rowley, D.B. and DePaulo, D.J., 1992. Sr isotope evolution of seawater: the role of tectonics. *Earth Planet. Sci. Lett.*, **109**, 11–23.

Rowley, D.B., 2002. Rate of plate creation and destruction: 180 Ma to present. *Geol. Soc. Am. Bull.*, **114**(8), 927–933.

Rowley, D.B., 2013. History of Global Mean Spreading Rate: 83 Ma to Present. *Geol. Soc. of Amer. Abstr. Prog.*, **45**(7), 87.

Roy, M., Clark, P.U., Raisbeck, G.M. and Yiou, F., 2004. Geochemical constraints on the regolith hypothesis for the middle Pleistocene transition. *Earth Planet. Sci. Lett.*, **227**(3), 281–296.

Ruddiman, W.F., 2010. A paleoclimatic enigma. *Science*, **328**(5980), 838–839.

Sadler, P.M., 1981. Sediment accumulation rates and the completeness of stratigraphic sections. *J. Geol.*, **89**, 569–584.

Sadler, P.M., 1994. The expected duration of upward-shallowing carbonate cycles and their terminal hiatuses. *Geol. Soc. Am. Bull.*, **106**, 791–802.

Sadler, P. and Jerolmack, D.J., 2014. Scaling laws for aggradation, denudation and progradation rates: the case for time-scale invariance at sediment sources and sinks. *Geol. Soc. London Spec. Publ.*, **404**, SP404.

Schumer, R. and Jerolmack, D.J., 2009. Real and apparent changes in sediment deposition rates through time (2003–2012). *J. Geophys. Res.-Earth Surface*, **114**, F3.

Schumer, R., Jerolmack, D. and McElroy, B., 2011. The stratigraphic filter and bias in measurement of geologic rates. *Geophysical Research Letters*, **38**, 11.

Sinclair, H. D., Naylor, M., Kirstein, L.A., Carter, A., Stanton, S., Glotzbach, C., Bernet, M. and van der Beek, P., in review. Decreasing late Cenozoic erosion rates in the Western Alps.

Staiger, J.K.W., Gosse, J.C., Johnson, J.V., Fastook, J., Gray, J.T., Stockli, D.F., Stockli, L. and Finkel, R., 2005. Quaternary relief generation by polythermal glacier ice. *Earth Surf. Process. Landf.*, **30**, 1145–1159.

Strauss, D. and Sadler, P.M., 1989. Stochastic models for the completeness of stratigraphic sections. *Math. Geol.*, **21**(1), 37–59.

Thomson, S.N., Brandon, M.T., Tomkin, J.H., Reiners, P.W., Vásquez, C. and Wilson, N.J., 2010. Glaciation as a destructive and constructive control on mountain building. *Nature*, **467**(7313), 313–317.

Torres, M.A., West, A.J. and Li, G., 2014. Sulphide oxidation and carbonate dissolution as a source of CO_2 over geological timescales. *Nature*, **507** (7492), 346–349.

Van Der Beek, P., Van Melle, J., Guillot, S., Pêcher, A., Reiners, P.W., Nicolescu, S. and Latif, M., 2009. Eocene Tibetan plateau remnants preserved in the northwest Himalaya. *Nat. Geosci.*, **2**, 364–368.

Van Der Meer, D.G., Zeebec, R.E., van Hinsbergena, D.J.J., Sluijsa, A., Spakmana, W. and Torsvik, T.H., 2014. Plate tectonic controls on atmospheric CO_2 levels since the Triassic. *PNAS*, **111**, 4380–4385.

Ward, D. J., Anderson, R. S. and Haeussler, P.J., 2012. Scaling the Teflon Peaks: rock type and the generation of extreme relief in the glaciated western Alaska Range. *J. Geophys. Res.*, **117**, F01031, doi:10.1029/2011JF002068.

Whipple, K.X., 2009. The influence of climate on the tectonic evolution of mountain belts. *Nat. Geosci.*, **2**(2), 97–104.

Whipple, K., Kirby, E. and Brocklehurst, S., 1999. Geomorphic limits to climatically induced increases in topographic relief. *Nature*, **401**, 39–43.

Willenbring, J.K. and von Blanckenburg, F., 2010a. Long-term stability of global erosion rates and weathering during late-Cenozoic cooling. *Nature*, **465** (7295), 211–214.

Willenbring, J.K. and von Blanckenburg, F., 2010b. Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: applications for Earth-surface dynamics. *Earth-Sci. Rev*., **98**(1), 105–122. doi: 10.1016/j.earscirev.2009.10.008.

Willenbring, J.K., Gasparini, N., Crosby, B. and Brocard, G., 2013. What Does a Mean Mean? The temporal evolution of detrital cosmogenic denudation rates in a transient landscape *Geology*, **41** (12), 1215–1218. http://dx.doi.org/10.1130/G34746.1

Woodard, S.C., Rosenthal, Y., Miller, K.G., Wright, J.D., Chiu, B.K. and Lawrence, K.T., 2014. Antarctic role in Northern Hemisphere glaciation. *Science*, **346**(6211), 847–851.

Yanites, B.J. and Ehlers, T.A., 2012. Global climate and tectonic controls on the denudation of glaciated mountains. *Earth Planet. Sci. Lett*., **325–326**, 63–75.

Zhang, P., Molnar, P. and Downs, W.R., 2001. Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates. *Nature*, **410**, 891–897.

Received 26 December 2014; revised version accepted 29 September 2015