Increased sedimentation rates and grain sizes 2–4 Myr ago due to the influence of climate change on erosion rates

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Around the globe, and in a variety of settings including active and inactive mountain belts, increases in sedimentation rates as well as in grain sizes of sediments were recorded at ~2–4 Myr ago, implying increased erosion rates. A change in climate represents the only process that is globally synchronous and can potentially account for the widespread increase in erosion and sedimentation, but no single process—like a lowering of sea levels or expanded glaciation—can explain increases in sedimentation in all environments, encompassing continental margins and interiors, and tropical as well as higher latitudes. We suggest that climate affected erosion mainly by the transition from a period of climate stability, in which landscapes had attained equilibrium configurations, to a time of frequent and abrupt changes in temperature, precipitation and vegetation, which prevented fluvial and glacial systems from establishing equilibrium states.

Two general processes govern rates of regional erosion and associated rates of terrigenous sedimentation. (1) Crustal deformation creates regionally elevated terrain that provides potential energy to rivers and glaciers, the main agents of erosion. (2) Climate, which has changed globally since 3–4 Myr ago (Fig. 1; refs 1–3), controls the abundance and temporal distribution of these erosive agents, as well as the type, density and distribution of vegetation that protects the Earth's surface from erosion. Geologists working in isolated mountain belts have repeatedly concluded that the ranges they studied rose in late Pliocene and Quaternary time (since ~3 Myr ago) (see Supplementary Information), buttressing such inferences with observations that sediment has accumulated rapidly near the ranges since ~5 Myr ago.

Sediment accumulation rates throughout the world show increases of two to as much as 10 times beginning 2–4 Myr ago (Fig. 2). Although some mountainous environments surely have grown since that time, such conclusions for mountain belts throughout the world, when taken together, would call for a global geodynamic process to orchestrate such synchronicity. Astronomical calibration of the geomagnetic timescale rules out globally synchronous changes in tectonic-plate motions since 9 Myr ago (ref. 4). Although rates of motion between pairs of plates have changed in this interval, such changes do not involve all plates. Climate change offers the most plausible, globally synchronous process affecting erosion, especially given that both active and inactive mountain belts show accelerated erosion since ~3–4 Myr ago (ref. 5). The question then arises as to what aspect of climate change is responsible for increased erosion. Different aspects such as sea-level change or increased glaciation, could contribute to increased erosion and sedimentation rates in different regions, but none provides an explanation for all regions, and particularly those unaffected by sea level or glaciation. The most important change may not be the switch from one state (warm and humid) to another (cold and dry) at 3–4 Myr ago. Rather, the change from a virtually unchanging climate to one that has been changing rapidly, as dictated by Milankovitch forcing (related to changes in the orbital parameters of the Earth) and amplified by a periodically ice-covered Earth, might maintain a state in which erosive processes never reach equilibrium with the evolving landscape.

Global increase in sedimentation

In a compilation of data relating to sediment accumulation in the main oceans, Hay *et al.*[6] showed that terrigenous sedimentation has

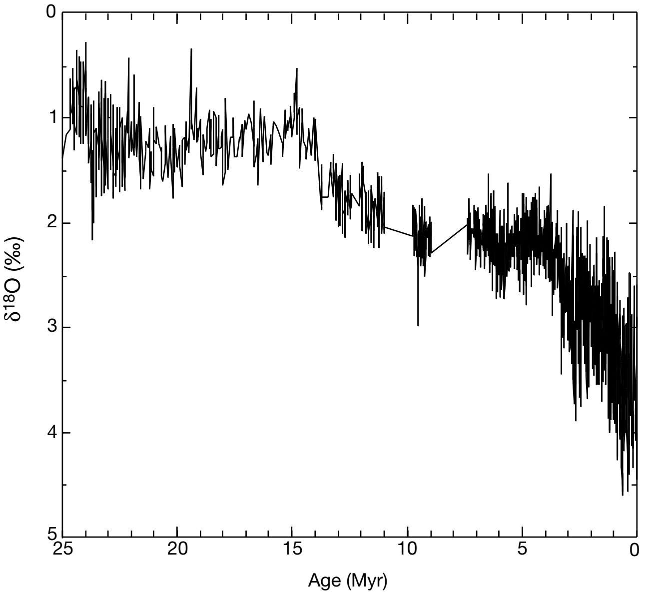

Figure 1 Plot of δ^{18}O from benthic foraminifers since 25 Myr ago, showing increases in mean values and in variability since ~4 Myr ago. The former increases imply cooling, and the latter increases imply an increasingly variable climate. Values (in ‰) have been measured largely (~95%) from fossil tests of *Cibicoides* spp., or adjusted to be equivalent to those of *Cibicoides* (ref. 63), from the Ceara rise in the eastern equatorial Atlantic Ocean (Ocean Drilling Project sites 925, 926 and 926). Values are plotted increasing downwards to reflect cooling. Data are from refs 62–66, and from T. Bickert and W. B. Curry, personal communication.

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increased dramatically in the past 5 Myr (Fig. 3). These authors grouped sediment into 5-Myr bins and separated it into four categories: carbonate and opaline silica (each presumably of organic origin), red clay (transported by wind) and terrigenous. The mass of terrigenous sediment deposited since 5 Myr ago is more than three times that deposited in any other 5-Myr bin. Like others, Hay *et al.*[6] inferred that the high rate of sediment accumulation since 5 Myr ago occurred because during periods of continental glaciation, lowered sea level allowed fluvial systems to attack continental margins[6].

Consistent with this view, sediment deposited on several continental margins—such as on the Mississippi delta and its surroundings[7], the North Sea[8], several basins offshore southeast Asia[9,10], Nova Scotia[11], and the Vøring plateau off Norway[12]—show abrupt, several-fold increases in sediment deposition rates at 2–4 Myr ago (Figs 2, 4 and Supplementary Information). Sea-level change, however, is only one among several possible processes responsible for increases in sedimentation rate in these regions, most of which are tectonically inactive; glaciation offers another likely candidate. Rapid increases in sedimentation on the Vøring plateau (Fig. 4) and elsewhere adjacent to Norway in the Norwegian and Barents Seas logically owe their origin to glaciation, for virtually all late Cenozoic sediment seems to have accumulated after glaciation had begun[12–14]. Bell and Laine[15] estimated that pelagic sedimentation increased throughout the North Atlantic following the onset of the Laurentide glaciation. Sedimentation increased at the same time in the Williston basin in North Dakota[16], far from a continental margin.

Deposition, especially of coarse material, increased abruptly in late Cenozoic times within and adjacent to much of high Asia, a region unaffected by sea level (Figs 2, 4 and Supplementary Information). Rapid Plio-Quaternary deposition of conglomerate[17–19] capping a sequence of finer, older Cenozoic sediment[20,21] near the northern margin of Tibet has been used repeatedly to infer that the plateau rose abruptly in Quaternary times. Magnetostratigraphy[18,19,22] not only calibrates the Pliocene ages, once based on terrestrial fauna, assigned to underlying material, but also puts the boundary between Pliocene and Miocene as used in China near 5–6 Myr ago, close to the internationally recognized date of 5.3 Myr ago (ref. 23). The dark grey colour of the conglomerate contrasts with the reddish and orange colour of the underlying Tertiary fine-grained sediment, and implies a change from a warm, oxidizing, Tertiary environment to the colder, glacial, Quaternary period. Massive layers of poorly sorted cobbles and boulders characterize the Quaternary conglomerate near the mountains, with bedded pebble and cobble layers of conglomerate within the interiors of basins and with till in the lower parts of the conglomerate[21]. Spore and pollen assemblages reveal taxa, mostly *pinus*, characteristic of a cold environment. Moreover, pollen grains are much fewer than in the underlying reddish sandstone and siltstone, consistent with a colder environment with less-diverse flora than before. Finally, an abundance of heavy minerals in the conglomerate attests to less weathering of them than of the underlying sandstone and siltstone[21]. It appears that deposition of these conglomeratic sequences began when the climate became cold. Oxygen isotopes[3] from benthic foraminifers suggest that global cooling began at ~4 Myr ago (Fig. 1); magnetostratigraphy shows that loess deposition started in central and western China at ~3 Myr ago[1,18,22] and accelerated at that time farther east[24], consistent with marked cooling and glaciation.

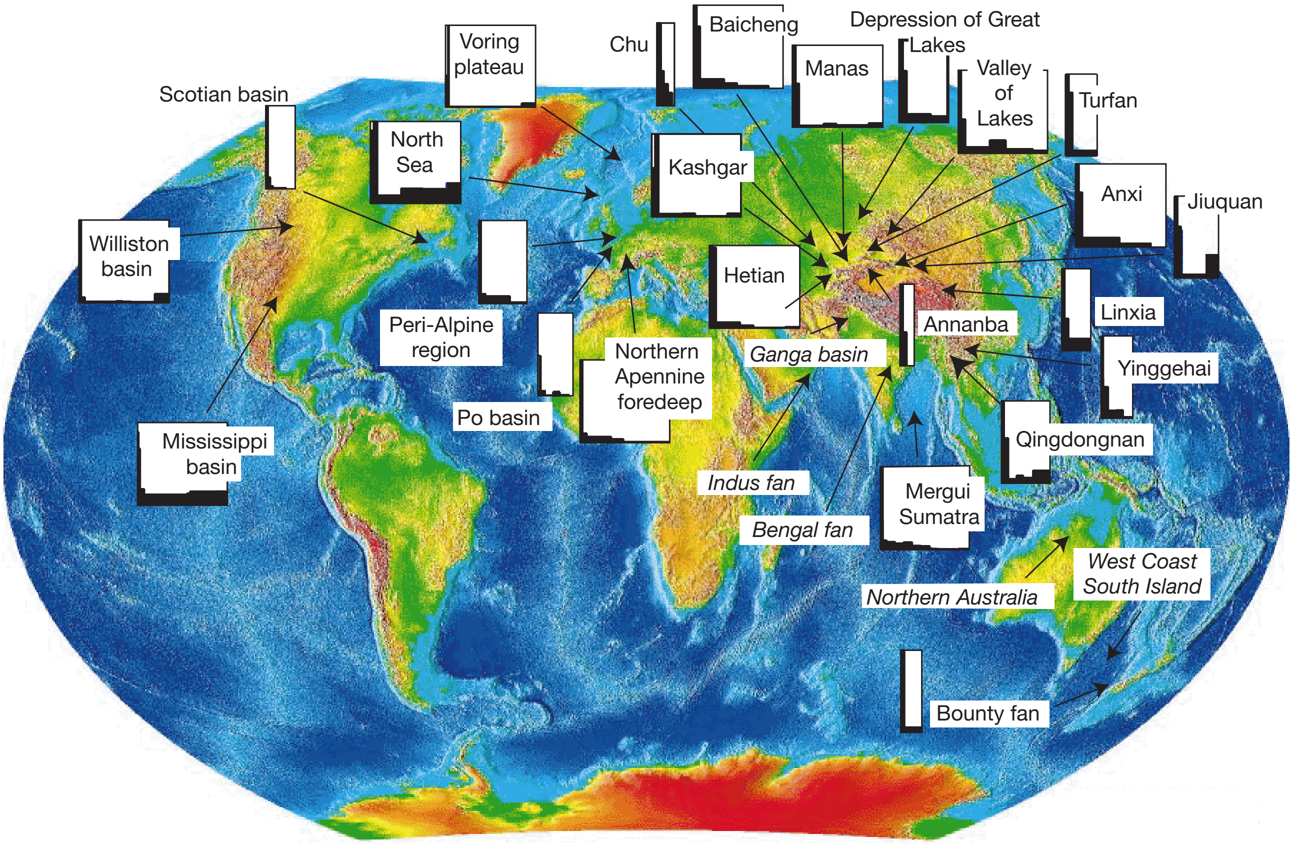

Figure 2 Map of the Earth showing selected areas where sedimentation rates have increased substantially since 2–4 Myr ago. (Details are given in Fig. 4 and Supplementary Information.) For each area, a small histogram is shown. The vertical scale is normalized to the maximum sedimentation rate in that area, and all horizontal axes are plotted at the same timescale; the longest records extend to 65 Myr ago. We show only the part of the Cenozoic for which there are measurements.

Surrounding Tibet, the average sedimentation rate since ~3–4 Myr ago has been roughly twice (or more) that of the preceding few Myr, and considerably greater than that of the preceding tens of Myr (Fig. 2 and Supplementary Information). Using magnetostratigraphy, Zheng *et al.*[19] recently showed that conglomeratic sedimentation began abruptly at ~3.5 Myr ago just west of Hetian (Fig. 2), with an increase in sedimentation rate of nearly ten times. This change in rate corroborates work done earlier and nearer Hetian[21] (Fig. 4) and at other sites along the northern margin of Tibet[18,19,22,25].

Changes in sedimentation at ~3 Myr ago are not confined to the Tibetan region; similar changes, dated with magnetostratigraphy and in one case with radiometric dates on an interbedded basalt flow, can be seen in sedimentary basins that bound the Tien Shan—Kashgar, Baicheng, Turfan, Manas and Chu[21,26–28]—and also in Mongolia[29] (Figs 2 and 4). In the last, such changes are clear both in basins—the Depression of Large Lakes and the Valley of Lakes (Fig. 4)—and in the adjacent Mongolian Altay and Gobi-Altay mountain belts, respectively. Massive sequences of conglomerate overlie finer material assigned a Pliocene age, which in turn overlies thinner sequences of older Cenozoic sediment. Quaternary sedimentation rates are higher than Pliocene rates along the both margins of the Tien Shan except near Kashgar. Moreover, using fission tracks and helium isotopes to date cooling of rock in the Kyrgyz Range adjacent to the Chu basin, Bullen *et al.*[30] found that cooling, and presumably erosion, since ~3 Myr ago exceeded that during the previous 5–7 Myr.

A long tradition associates high rates of deposition, especially of coarse material, with recent uplift of adjacent mountain belts. Such observations, however, characterize tectonically inactive and waning mountain belts. Hay *et al.*[7] suggested that the increased sedimentation rate in the Mississippi drainage basin (Fig. 4), between the Rocky Mountains and the Appalachians—where the last major deformation occurred > 50 Myr ago and > 250 Myr ago, respectively—reflected a recent, abrupt uplift of the Rockies at 2 Myr ago. The widespread belief of late Cenozoic uplift to present-day mean elevations of the Rockies derives both from glacial erosion of the previously relatively flat surface now defining the crest of the range[31] and from Quaternary conglomeratic sedimentation near them[32]. Recent applications of palaeobotany[33,34] to parts of the Rockies, however, indicate that the Rockies were high in mid-Cenozoic time and support the contention that climate change at ~3–4 Myr ago, rather than uplift, caused the increased erosion and sedimentation[5,35].

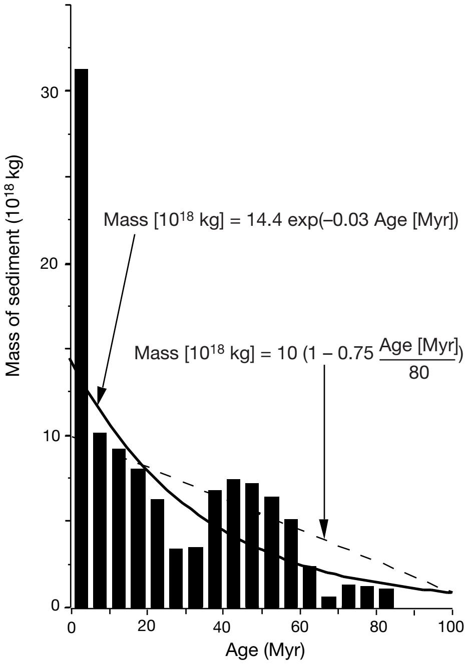

Figure 3 Histogram of terrigenous sediment deposited in the world's oceans, compiled by Hay *et al.*[6]. We note the abrupt increase since ~5 Myr ago. The solid curve is an exponential fit to the data; it deviates markedly from the sedimentation rate since 5 Myr ago. The global sea floor contains nearly all the floor created in the past 5 Myr but only a fraction of that created in earlier periods. Thus, some of the greater amount of young than old sediment results from the age distribution of the sea floor. Parsons[80] showed that the age distribution (Δarea / Δage) of the sea floor decreases linearly with age, and the straight dashed line shows how sediment accumulating at a constant rate would be distributed, given the greater amount of young than old sea floor. The amount deposited since 5 Myr ago is more than twice that expected for a uniform rate.

Although perhaps not inactive, the Alps underwent their major phases of deformation in mid-Cenozoic time, if not earlier. Yet the present relief is commonly assigned a Plio-Quaternary age[36]. In an attempt to test whether sediment deposited in the surroundings of the Alps during Plio-Quaternary times could account for the deep valleys and present-day high relief, Guillaume and Guillaume[37] compiled estimates of volumes of sediment in the main surrounding basins (Fig. 4). Although these authors were forced to make some guesses of ages and of fractions of accumulated material derived from the Alps, their results suggest higher accumulation rates in Quaternary times than before (Figs 2 and 4). Apparently, half of the sediment in the Po basin is Quaternary[37]. Sedimentation adjacent to the Apennines also increased rapidly in late Pliocene and Quaternary times[38–40] (Fig. 2).

Assuming that much of the Cenozoic sediment in basins surrounding New Zealand accumulated since 2.5 ± 0.5 Myr ago, and that rapid tectonic activity began at the same time, Adams[41] argued that present-day erosion of the Southern Alps balances the uplift of rock relative to sea level. An abrupt switch to conglomeratic sedimentation occurred northwest of the Southern Alps at that time[42], and recent drilling[43] of the Canterbury basin and the Bounty fan off the southeast coast of New Zealand (Fig. 2) confirm rapid increases in deposition at ~2–3 Myr ago. Improved plate reconstructions[44], however, require convergence and crustal shortening to have begun at 6–7 Myr ago, and therefore degrade the apparent correlation of rapid sedimentation with crustal shortening and mountain building.

Exceptions to increases in sedimentation at ~2–4 Myr ago

Although increased sedimentation in Plio-Quaternary times has occurred throughout the world (Fig. 2), sedimentation rates did not increase at 2–4 Myr ago in all basins. For instance, although drilling on the continental shelf along the western margin of the North Atlantic suggests a Quaternary increase in sedimentation rate[45], no such increase can be recognized in the adjacent, volumetrically larger, abyssal plain[46].

The Ganga basin, the foredeep of the Himalaya, has recorded little change during the past 7 Myr, though grain sizes increased from relatively fine sediment to conglomerate at ~3 Myr ago[47]. Because this basin formed by flexure of the relatively stiff Indian plate under the load of the Himalaya thrust atop it, neither its depth nor its rate of subsidence should increase with increased sediment supplied to it. As Burbank[48] noted, increased erosion of the Himalaya might reduce the load flexing the Indian plate down, and hence reduce the depth of the Ganga basin and the rate of accumulation of sediment in it. Surplus sediment ought merely to result in increased transport to the Bay of Bengal, one of the world's thickest accumulations of sediment[49].

Existing data do not allow a convincing demonstration of an increased sedimentation rate in the Bay of Bengal. Cochran[50] reported a relatively low sedimentation rate between ~8 and ~1 Myr ago at the distal edge of the Bengal fan followed by an abrupt increase at ~1 Myr ago, but this change is neither dated well nor necessarily representative of the entire basin. Métivier *et al.*[9] inferred Plio-Quaternary deposition 60% more rapid than that in the late Miocene, as well as a threefold increase in accumulation rate in the Indus fan at ~ 2 Myr ago. But because of Curray's[49] more cautious analysis of sedimentation in the Bay of Bengal, we resist using these studies[9,50] as additional support for a late Pliocene increase in sedimentation rates.

The effect of climate change on erosion rates

The onset of widespread glaciation at ~3 Myr ago presents an attractive explanation for increased erosion and deposition, especially because glacial erosion rates can be higher than fluvial erosion rates[51]. Yet many of the areas for which geomorphologists have argued for recent uplift lie in the tropics or sub-tropics, such as southern and eastern Africa[52–54], Australia, and eastern South America[54]. In one tropical region, northern Australia, quantitative estimates of erosion rates suggest a threefold increase in Quaternary times[55]. Most of Australia's landscape appears to be quite old (Mesozoic), and erosion since Cretaceous time has been very slow ($<1\ \mu\mathrm{m\ yr^{-1}}$; refs 56, 57). Yet Nott and Roberts[55] inferred an average denudation rate of $3–4\ \mu\mathrm{m\ yr^{-1}}$ since approximately 0.5 Myr ago. They could not determine precisely when the erosion accelerated, but they recognized that climate change is likely to have effected the increased rate. In addition, Taylor[58] recognized widespread accelerated erosion in southeastern Australia in late Pliocene and Quaternary times. Glaciers cannot have been the erosive agents in either region.

Milankovitch-scale changes in climate also have written their signature on the landscape and on the sedimentary record, without glaciation playing a direct role. The sedimentation rate in part of San Francisco Bay, California, shows large oscillations with a period of ~100 kyr (ref. 59). As the maximum elevation of the drainage basin lies in low hills, glaciers could not have been the erosive agents. Koltermann and Gorelick[59] modelled these changes in sedimentation assuming that rainfall varied markedly with the 100-kyr climate cycle, as the axis of east-to-west atmospheric flow migrated north and south. Elsewhere, in tectonically active regions, the alternation between incision of canyons and widening of valleys to leave strath terraces attests to the effect of a changing climate on fluvial, not glacial, erosion[60].

Apparently neither sea-level changes nor the erosive power of glaciers can account for all increases in erosion rate associated with the change from a warm equable climate (with only rare glaciers) to a cold climate (with widespread glaciers). Is there an aspect of climate change that did play a global role in accelerating erosion, or must we rely on different explanations for different regions?

One aspect of climate change apparent to all workers who study Milankovitch-scale changes is the increasing amplitude of climate variations with periods of ~20, 40 and 100 kyr since 3–4 Myr ago, as revealed by the marine record of $\delta^{18}O$ (Fig. 1). Between 35 and

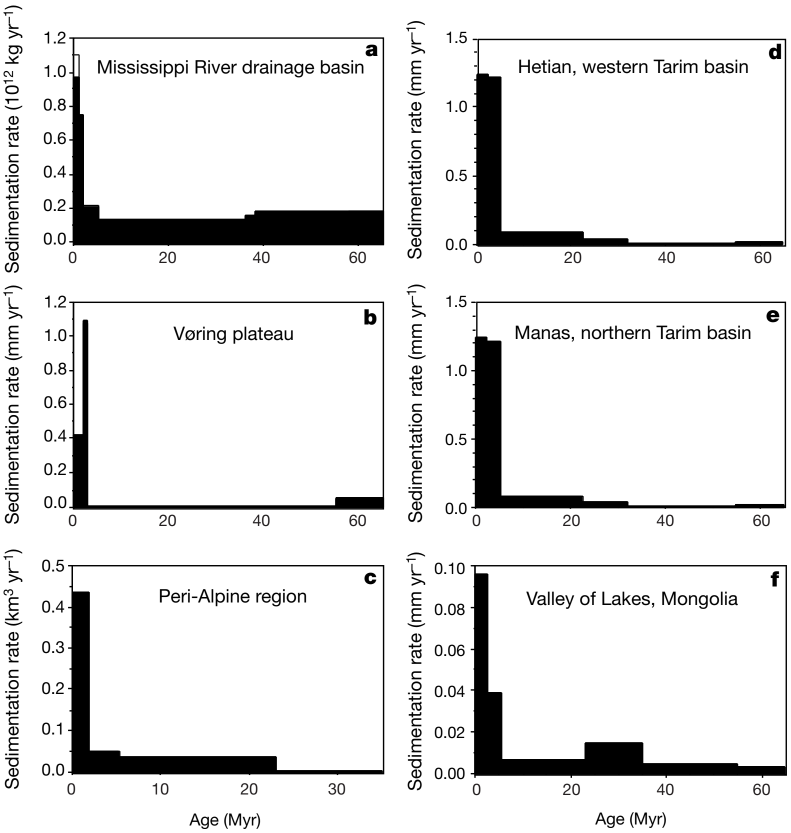

Figure 4 Examples of variations in sedimentation rates, showing an abrupt increase since ~5 Myr ago in different settings. The locations of these settings are shown in Fig. 2. Although for some examples the stratigraphic columns represent only point measurements, they characterize deposition over wide areas and demonstrate regional increases in sedimentation rates. **a**, Total mass accumulation rates for the Mississippi River basin[7], between the Rocky Mountains and the Appalachians. The unshaded area for the past million years shows the estimate by Hay *et al.*[7] for the fraction transported into the basin by Laurentide ice sheets. **b**, Accumulation rates per unit area, without corrections for compaction, on the Vøring plateau, off Norway[12]. **c**, Volume accumulation rates, not corrected for compaction, in basins surrounding the Alps[37]. Despite much of the sedimentation in the Black Sea being Plio-Quaternary in age and deposited in the Danube delta[81], the Guillaumes[37] assumed that only 17% of that material was derived from the Alps. Deep-sea drilling of the Black Sea did not sample the Danube delta, but where it was drilled, sediment that accumulated since 2.5 Myr ago accounts for 50–75% of that deposited since 10 Myr ago[82]. **d**, Sedimentary accumulation rates, not corrected for compaction, near Hetian along the northern margin of the Tibetan plateau[21]. **e**, Sedimentary accumulation rates, not corrected for compaction, from near Manas along the northern margin of Tien Shan in China[21]. **f**, Sedimentary accumulation rates, not corrected for compaction, from the Valley of Lakes basin, which lies along the northern margin of the Gobi-Altay in Mongolia[29].

30 Myr ago, δ^{18}O in benthic organisms varied with amplitudes of 0.2–0.5‰ with periods of 100 kyr or less[61], increasing to 0.5–0.6‰ between 25 and 20 Myr ago[62], and then decreasing to smaller values between ~20 and 6 Myr ago[63], before increasing to more than 1‰ and then nearly 2‰ since 1 Myr ago[64–66]. Variations with periods of 400 kyr, perhaps due to short increases (and more rarely decreases) in ice in Antarctica, contribute most of the large-amplitude variability before 20 Myr ago[61,62]. A similar change from a stable to an oscillating climate occurred in China, where more than 30 layers of palaeosols developed within the sequence of loess deposited since ~2.5 Myr ago indicate frequent changes between cold-dry and warm-wet environments[1,67,68]. Colours, grain sizes, and the composition of underlying red clay in the Chinese loess plateau, however, do not show such large climate variations from 7 to ~2.5 Myr ago[67]. The absence of clearly defined palaeosols in the red clay formation suggests a more stable climate between 7 and ~3 Myr ago than since ~3 Myr ago. The most important aspect of climate change for erosion may have been the change from a stable climate to one with frequent, high-amplitude variations, rather than from a warm, moist Pliocene climate to the cooler and drier ice-age climate.

Recent studies suggest that tens of thousands, and possibly millions, of years must transpire for erosional regimes to reach steady state, and therefore that landforms cannot reach equilibrium in the rapidly changing Quaternary climate[69,70]. Suppose climate changed from a warm-wet to a cold-dry environment. With regard to variations in climate due to precession of the Earth's axis, Gilbert[71] wrote that "a moist climate would tend to leach the calcareous matter from the rock, leaving an earthy soil behind, and in a succeeding drier climate the soil would be carried away." Others[72–74] have developed this further by exploiting the protection afforded the Earth's surface by vegetation. Because rates of soil production decrease as soil thickness increases[75], a long duration of either soil production or aridity is unlikely to lead to sustained rapid erosion, but an alternation between them takes advantage of the initial, rapid response to new, disequilibrium conditions[71–74]. Similarly, a climate oscillating between glacial states and periglacial states, where frost action disrupts the surface, might also accelerate erosion. Periglacial processes would fracture the surface rock and prepare it, so that glaciers could then transport broken rock. Glacial erosion seems to be dominated by quarrying, or plucking; hence preconditioning by periglacial processes should make quarrying easier than if intact rock must be extricated from the bed. Because such fracturing of rock occurs in a narrow, sub-freezing, temperature range[76], only some climates will make periglacial processes effective in producing debris. Yet neither continuous periglacial conditions nor very cold conditions, such that glaciers are frozen to their beds, are likely to remove much debris.

Moreover, glaciers and rivers erode differently; the former creates wide, gently sloping valley floors, and the latter forms steep, V-shaped canyons. Using a scaling that allows incision rates from less than 1 mm yr^{-1} to much higher rates, Harbor[77] concluded that the characteristic timescale for glacial erosion is ~10–100 kyr, comparable with Milankovitch periods. Rivers too must transport debris in order to erode, but much of the debris carried by a river is derived from the adjacent slopes. A river occupying a U-shaped valley, recently abandoned by a glacier, will not be burdened by debris from the neighbouring slopes, and a larger fraction of its stream power will be available to erode. The alternation between landscapes distant from glacial or fluvial equilibrium and the switch from one erosive agent to another might make erosion more rapid than if one or the other were left to do all of the erosive work.

We note that such variations between cold, dry and warmer, moister climates should be more effective than oscillations between warm, wet climates and warmer, wetter ones, because of their effects both on vegetation and on fluvial and glacial processes. Moreover, the most erosive periods in some environments might be different from those in others, and might begin at different times at different altitudes and latitudes. Thus, if an alternation of processes leads to increased erosion and sedimentation, they need not vary perfectly synchronously throughout the Earth.

We may concoct mathematical expressions for erosion that yield enhanced rates due to an oscillating climate, with one erosive process operating in one half cycle and a second in the other. Consider first a simple linear system that approaches equilibrium exponentially, after a step change in forcing. Following Bull[73], we let the erosion rate $\dot{E}$ vary with time as

$$\dot{E} = \dot{E}_0 \exp\left[-\frac{t}{\tau_e}\right] \sin\left[2\pi\frac{t}{T}\right] \qquad (1)$$

for a half-cycle of oscillatory forcing, where τ_e quantifies to time to reach an equilibrium with negligible erosion when forcing is steady, and T is the period of the oscillating amplitude of forcing. Maximum erosion per half period occurs for a vanishing ratio T/τ_e and therefore infinitely rapid oscillations. This pattern will hold for any process whose rate decreases monotonically after a step function in forcing, including soil production[75]. Were erosion governed by such decaying functions, the greater amplitude of climate variability over the past 3–4 Myr should have increased erosion above that in an unchanging climate. Taken to the limit, however, it might suggest that the diurnal cycle should be the most important climate change.

Large drainage basins do not respond simultaneously to changing conditions. Bull[73] emphasized that landscapes responded to climate change only after a finite "reaction time". As summarized by Bull[73], R. J. Weldon demonstrated headward propagation of increased incision rate by Cajon Creek in California for several thousand years. Similarly, treatments of erosion in terms of kinematic waves propagating from one part of a watershed to another require finite intervals of time of thousands to perhaps millions of years before drainage basins can respond to changing conditions[70,78]. Suppose that the response to a step-function change in forcing included an increase over a finite interval, before decaying exponentially:

$$\dot{E} = \dot{E}_0 \frac{t}{\tau} \exp\left[-\frac{t}{\tau_e}\right] \sin\left[2\pi\frac{t}{T}\right] \qquad (2)$$

For this case, maximum erosion during a half cycle occurs for $T \approx 3.9\tau_e$. Because the times necessary for landscapes to respond to changes in climate are comparable to those of Milankovitch forcing, and not orders of magnitude larger or smaller, Milankovitch forcing might even show resonances with natural periods in the erosive response of a landscape to changes in forcing.

Both fluvial and glacial processes are notoriously nonlinear. Even if the thickness of the ice varied linearly with climate forcing, the rate of flow of a glacier scales as the fifth power of that thickness[77], and surely erosion does not scale with the fifth root of the flow rate. Similarly, most characteristics of rivers depend in a nonlinear fashion on discharge[79], which limits sediment transport. Thus, the arguments above that exploit a linear dependence of erosion on an oscillatory forcing must oversimplify the effect of changing climate on erosion. We could include a nonlinear process simply by allowing τ_e in equation (1) to be time-dependent. (For instance, by defining $\tau_e = \tau/[1 - (\tau/t)\ln(t/\tau)]$, equation (1) is transformed to equation (2).) Until the physical processes that govern erosion are better understood, however, it is premature to calculate erosion rates for forcings varying differently with time.

Because late Pliocene and Quaternary times differ so much from the previous 100–200 Myr—which had an equable climate in which large changes were slow and rare—we see landforms today not only being shaped by a wide spectrum of present-day climates, but also inherited from the effects of a spectrum of different past climates. Interpreting the present-day landscape and current geomorphic processes in terms of present climate may mislead even the most careful observer. In some areas, much of the erosion that has shaped the landscape occurred during a past climate different from that of the present. The oscillation between cold-dry and warm-wet climate may incise and denude surfaces more rapidly than would equable climates climate of any kind alone, even if erosion has occurred during only part of the past few million years. We consider that the increased sedimentation of coarser material since 2–4 Myr ago may have been caused by a climate shift. This shift was from a relatively unvarying climate, to one that oscillated between states that prepared the surface during some periods—by chemical weathering, periglacial fracturing, or other forms of mass wasting—and states that transported material.

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