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LATE CENOZOIC INCREASE IN ACCUMULATION RATES OF TERRESTRIAL SEDIMENT: How Might Climate Change Have Affected Erosion Rates?

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■ **Abstract** Accumulation rates of terrestrial sediment have increased in the past few million years both on and adjacent to continents, although not everywhere. Apparently, erosion has increased in elevated terrain regardless of when last tectonically active or what the present-day climate. In many regions, sediment coarsened abruptly in late Pliocene time. Sparser data suggest increased sedimentation rates at ~15 Ma, approximately when oxygen isotopes in benthic foraminifera imply high-latitude cooling. If climate change effected accelerated erosion, understanding how it did so remains the challenge. Some obvious candidates, such as lowered sea level leading to erosion of continental shelves or increased glaciation, account for increased sedimentation in some, but not all, areas. Perhaps stable climates that varied slowly allowed geomorphic processes to maintain a state of equilibrium with little erosion until ~3–4 Ma, when large oscillations in climate with periods of 20,000–40,000 years developed and denied the landscape the chance to reach equilibrium.

INTRODUCTION

For virtually all high terrain on Earth, a respected geologist has written a paper claiming that that region rose rapidly in Late Pliocene and/or Quaternary time. Such a global phenomenon almost surely requires a global explanation. Plate motions show no such globally synchronized change in rates at any time in the past 5–10 million years (Abdul Aziz et al. 2003, Krijgsman et al. 1999, Wilson 1993) that might imply global coordination of Earth's geodynamic engine. More likely, some nongeodynamic, but nevertheless global, change must take responsibility for the observations used to infer the widespread recent increase in elevation of high terrain. The coincidental occurrence of apparent recent increases in elevations and climate change suggests that climate change somehow must be responsible

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for those observations used to infer recent rises of mountain ranges (Molnar & England 1990).

Recent rapid exhumation of high terrain provides the justification for most inferences of recent elevation change, with such exhumation inferred either from rapid cooling of rock that was deeply buried until Plio-Quaternary time or from concurrent rapid deposition of sediment near high terrain. This review focuses on these latter observations and their relevance to the question of how climate change led to increased erosion rates. Toward that end, I ignore careful work designed to quantify recent or Holocene sedimentation rates (e.g., Einsele & Hinderer 1997, 1998; Hinderer 2001; Hinderer & Einsele 2001).

MEASUREMENTS OF ACCUMULATION RATES

To use accumulation rates of sediment as a proxy for erosion rates, obviously accumulation rates must be quantified. Yet, several obstacles make such quantification difficult. Geologists have a long tradition of measuring sedimentary sections, either from exposures in the field or from drill holes through sequences often studied with seismic reflection profiles. Unrepresentative sections or drill holes, owing to poor exposure or unfortunate locations, can yield biased and distorted images of the history of sedimentation. Other aspects of sedimentary basins, however, prevent most point measurements from drill cores and measured sections on land from giving distorted impressions of accumulation rates integrated over large basins. Aspect ratios of most sedimentary basins, whose lateral extent is orders of magnitude greater than its vertical extent, are large. Underlying topography commonly is gentle. Where sediment fills enclosed areas, variations in thickness tend to be small. Point measurements of sediment accumulation rates are most biased where accumulation rates vary markedly across the region of accumulation, such as near the edges of basins, especially where tectonic processes continually change the accommodation space, or where basins grow by progradation of material onto sediment-free regions. In fact, this latter situation poses a problem for the interpretation of sediment derived from the high terrain of Asia; the Bengal fan contains by far the greatest mass of sediment derived from this region, but published logs of cores penetrating into this mass sample only the margins of the fan (Curray 1994, Einsele et al. 1996, Métivier et al. 1999).

More important than the risks of unrepresentative sedimentary sections is interstitial porosity; as sediment is buried, the weight of the overlying material squeezes the pores closed. Thus, sedimentary columns without correction for compaction are biased toward thicker sequences of younger, rather than older, material. Obviously, estimates of masses, or of volumes of the solid fraction, of sediment provide the most definitive constraints on the amounts of erosion. The daunting steps of correcting thicknesses of sediment for compaction and of integrating the thicknesses over area are, however, both sufficiently time consuming and subjective that such estimates have been made for only selected regions, although the number of such regions has grown rapidly in the past few years.

Other aspects of sedimentation patterns potentially bias inferences of erosion or exhumation from accumulation rates. First, sediment eroded and deposited during one period can be eroded again and redeposited. Obviously, such a process makes old sediment rarer than young sediment. Second, on a global scale, all ocean floor made yesterday is preserved, but subduction has removed a fraction of that made tens of millions of years ago. Hence, sediment that lay on subducted ocean floor may either be gone or metamorphosed, and hence not be quantifiable. This latter phenomenon poses an obstacle to interpreting global mass budgets, but on the scale of mountain belts, we may ignore it. Third, when sediment supply greatly exceeds accommodation space in one basin, it can spill over into another. For instance, material eroded from the Himalaya continually encounters a nearly full Ganga Basin just south of the mountain belt, and the vast majority of sediment passes beyond it into the Bengal fan. Burbank (1992) showed that increased erosion of the Himalaya should lighten the load on the flexed Indian plate, which would reduce accommodation space in the Ganga Basin. Although the excess sediment would pass into the Bay of Bengal, the record in the Ganga Basin would record a decreased sedimentation rate when erosion increased.

Finally, whereas layering of sediment in seismic reflection profiles can be obvious, dating of sediment, particularly in continental settings, can be difficult and often is subjective. Although now stabilized well enough for much of the discussion that follows, the geologic timescale undergoes continual revision, and what was once called Pliocene might now be assigned Miocene, or might be several million years younger than it was assumed to be a few years ago. For instance, Wang & Coward (1990, p. 105) wrote, “Note that this paper uses 9 [Ma] as the beginning of the Pliocene following Chinese tradition,” not the commonly assigned 5.3 Ma (Krijgsman et al. 1999).

The preceding discussion may read like a litany of reasons why readers should take what follows with a grain of salt. To help readers, I have separated measurements of sediment mass or volume accumulation rates from point measurements, and I further distinguish those for which compaction has not been taken into account. Where necessary, I also discuss data used to infer ages.

CHANGES IN GLOBAL MASS ACCUMULATION RATES

The global study of sediment accumulation by the Deep-Sea Drilling Project (DSDP) and its successor the Ocean Drilling Project (ODP) has made it possible to estimate masses of sediment accumulation in the deep ocean since Mesozoic time (Davies et al. 1977, Donnelly 1982, Hay et al. 1988). Most recently, Hay et al. (1988) distinguished terrigenous sediment and estimated masses on the ocean floor in bins 5 million years in duration (Figure 1). Their compilation shows that the accumulation in the past 5 million years exceeds that in any other 5-million-year bin by more than two times. Even if one corrects for the fraction of ocean floor that has been subducted, during the past 5 million years, twice as much terrigenous sediment has accumulated as during any other period of similar duration (e.g., Zhang et al. 2001).

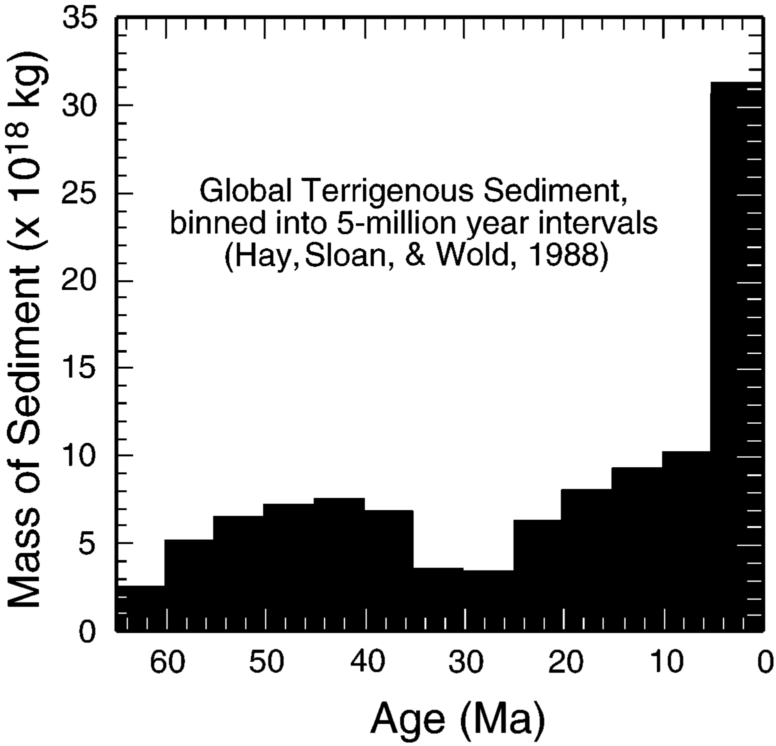

Figure 1 Global terrigenous sediment accumulation estimated by Hay et al. (1988) binned into 5-million-year intervals.

Hay et al. (1988) inferred that the marked increase in accumulation in the past 5 million years resulted largely from lowered sea level and the erosion of newly exposed continental margins. Such an inference, which would be the result of climate change via the transfer of seawater to continental ice sheets, clearly is sensible, and it surely provides a partial explanation for observed Plio-Quaternary increases in sedimentation. Yet, Plio-Quaternary increases in accumulation rates within the Asian continent deny sea-level changes a unique explanation for Plio-Quaternary increases in accumulation everywhere.

EAST ASIAN SEDIMENT ACCUMULATION: IRRELEVANCE OF SEA-LEVEL CHANGE

In most, but by no means all, sedimentary basins on or adjacent to the Asian landmass, sediment accumulation rates increased in Plio-Quaternary time. Shown in Figures 2 and 3 are estimates of dry volume rates averaged over sedimentary basins by Métivier & Gaudemer (1997) and Métivier et al. (1998, 1999); point measurements, in most cases uncorrected for compaction, summarized by

Zhang et al. (2001); and average accumulation rates along profiles (mass per unit area per unit time) given by Clift & Gaedicke (2002) and Clift et al. (2001, 2002).

The majority of estimates, whether dry volume integrated over basins or point measurements, show maximum accumulation rates in Quaternary time. The more pronounced Quaternary maxima for point measurements than for Métivier's estimates of dry volumes derives, in part, from the absence of corrections for compaction to the point measurements. In regions such as Mongolia, a correction for compaction would leave the Quaternary peak still very prominent. A second reason for some differences, however, may be different ages assigned to sediment. Publication of the summary by Zhang et al. (2001) was delayed nearly five years because of doubts about ages based only on fossils. Among those authors, Downs had shown that vertebrate fossils from most regions were not sufficiently diagnostic to allow Cenozoic Epochs to be distinguished. Only with studies of magnetostratigraphy from several sections and some radiometric dates were dates sufficiently reliable to distinguish even crude variations in accumulation rates from different sections. This, coupled with evolving definitions of Pliocene and Quaternary time, can lead to different accumulation rates even if total volumes or thicknesses are established with little doubt. For one area, the Chu Basin of Kyrgyzstan, cooling ages from the adjacent mountain front (Bullen et al. 2003) revealed accelerated exhumation consistent with the steadily accelerating sediment accumulation (Bullen et al. 2001).

Perhaps not apparent from the summary in Figures 2 and 3 is the omission of results from the Bengal Fan, which, in the compilation by Métivier et al. (1999), contains 40% of the Cenozoic sediment for eastern Asia and its surroundings. We omit this region because we doubt that a reliable Cenozoic history of sediment accumulation can be deduced from data in the open literature, although Métivier et al. (1999) showed a maximum accumulation rate in Quaternary time.

In addition, in most regions of eastern Asia for which we have data, very coarse sediment was deposited beginning between 3 and 4 Ma. Such regions include the margins of Tibet (e.g., Pares et al. 2003, Zheng et al. 2000); the surroundings of the Tien Shan (e.g., Bullen et al. 2001, 2003; Makarov 1977); and Mongolia, adjacent to both the Gobi Altay and the Mongolian Altay (Devyatkin 1981).

All of these inland Asian basins remained blind to Plio-Quaternary sea-level change. Accelerating sediment accumulation there cannot be ascribed to such change. The popular explanation for such an increase is tectonically induced increases in elevations of high tracts of land, such as Tibet (e.g., Li Jijun & Fang Xiaomin 1999, Li Jijun et al. 1997, Pares et al. 2003, Zheng et al. 2000), although the only evidence for accelerated tectonic activity is the increased sedimentation itself.

SEDIMENT DERIVED FROM HIGH TERRAIN

The assignment of increased sedimentation rates in basins adjacent to dissected high terrain to rejuvenation of that high terrain is too simple and logical to dismiss without consideration. We noted above that the global increase in sedimentation would require a globally coordinated geodynamic process for which there is no evidence. Here, let us consider mountainous regions in a variety of settings.

Hay et al. (1989) showed that mass accumulation rates in the Gulf of Mexico increased approximately fourfold in late Pliocene and Quaternary time (Figure 3). They argued that only a small fraction of that sediment was brought by the Laurentide ice sheet to the Mississippi River drainage basin and therefore that the increased sedimentation rate implied rapid erosion in Plio-Quaternary time. Studies in the Rocky Mountains had shown that glaciers, presumably of Plio-Quaternary age, had carved much of the relief in the Rockies (e.g., Scott 1975, Tweto 1975). Hay et al. (1989), however, ascribed the increased erosion to Late Cenozoic increase in the elevation of the Rocky Mountain region, despite the late Cretaceous–early Cenozoic age of both the faulting that juxtaposes the crystalline rock of the Rocky Mountains against the sedimentary rock adjacent to the mountain belt and the folding of that sedimentary rock. In short, the Rocky Mountain region is hardly an archetypical tectonically active region.

Although I stubbornly cling to the conviction that the Rockies are dead, an ingenious study by McMillan et al. (2002) does suggest some tilting of the Rocky Mountain–Great Plains region in late Cenozoic time. Hence, it keeps alive the possibility that tectonic processes have played a role in the erosion of the Rockies and the sediment transported to the Gulf of Mexico. McMillan et al. showed that the sedimentary structures of the Mio-Pliocene Ogallala Formation in eastern Wyoming and western Nebraska imply gentler slopes than currently exist. They inferred that since $\sim$17 Ma, the age of the base of the Ogallala Formation, tilting about a north-south axis has raised the Rockies several hundred meters, an amount that is greater than their calculated isostatic response to the removal of material since incision of the Ogallala Formation began at 3–5 Ma (e.g., Chapin & Kelley 1997, Gustavson 1996, Swinehart et al. 1985). In making the isostatic correction, McMillan et al. (2002) used remnants of Ogallala or older formations on the edges of basins to define the amounts of material removed. These estimates are lower bounds on the material removed, and the corresponding isostatic corrections are lower bounds on the part of the tilting that might be explainable by isostatic response. Nevertheless, only if all errors conspired could the remaining, unexplained tilt be sufficiently small that isostatic rebound of mass removed since $\sim$17 Ma could account for it. Thus, I cannot dismiss categorically tectonic processes as playing a role in the acceleration of erosion of the Rocky Mountains.

Leonard (2002) also used the warping of the surface on which the Ogallala formation was deposited east of the Rocky Mountains to study the relative roles of isostatic response to erosion and other processes. He considered warping along east-west axes and showed that at least half of the warping could be explained by the rising of the regions where erosion had removed the Ogallala and underlying formations. Thus, he found isostasy to account for a larger fraction of the warping than did McMillan et al. (2002) for their measured tilting about a north-south hinge.

Although less isolated from active tectonics than the Rocky Mountains, the Colorado plateau appears to have been elevated since mid-Cenozoic time, but erosion of it too seems younger. Holm (2001, p. 1483) wrote, "Except where protected by Miocene and younger lava flows, the Triassic strata were rapidly stripped off the Mogollon Slope during late Pliocene to Pleistocene time, apparently by an abrupt increase in rate of erosion."

The Alps of Europe provide another region of rapid Quaternary erosion where tectonic processes are mild. The question of whether the Alps are tectonically dead or just senile seems more semantic than scientific. Let's choose a middle ground in which the Alps are dead, but occasional small (and rare moderate) earthquakes and internal deformation show that rigor mortis has not yet set in. Rates of deformation determined from GPS measurements indicate, within the uncertainty of 1–2 mm/year, no further convergence between the Adriatic peninsula and Europe (Calais et al. 2002). Stated bluntly, the convergence responsible for the spectacular folding and nappes, which have made the Alps so important in the development of tectonic concepts, has stopped. Those same GPS measurements do indicate internal strain consistent with active faulting and with fault plane solutions of small earthquakes within the Alps (Sue & Tricart 1999, Sue et al. 1999).

Sediment accumulation in basins near the Alps increased in Plio-Quaternary time (e.g., Guillaume & Guillaume 1982, Kuhlemann 2001). Deposition of most of the sediment in the Danube Delta in the Black Sea occurred at this time (Hsü 1978), as did that in the Po and Adriatic Basins (Kuhlemann 2001).

In a tour de force, Kuhlemann (2001) estimated the sediment accumulation in basins surrounding the Alps and then assigned source areas within the Alps to fractions of this debris (Figures 4 and 5). For instance, he assumed that only 10% of that deposited in the Danube Delta was eroded from the Alps. Because he was forced to make many subjective decisions not only for sources of sediment but also for timing, as dates within sequences are sparse, he separated uncertainties owing to errors in volumes of material eroded from different regions from those owing to assumed ages within deposits (Figure 4). His results call for variations in erosion rates for both the Eastern and Western Alps, some of which correlate with tectonic events (e.g., Kuhlemann et al. 2001, 2002; Frisch et al. 2000), but the biggest change in rate occurred in Plio-Quaternary time (Figures 4 and 5). For the better constrained eastern Alps, the increase in erosion rate occurred at 2–3 Ma, when climate changed most dramatically. His history of erosion for the Western Alps shows an abrupt increase at $\sim$5 Ma, followed by a continued increase to the present. The increase at 5 Ma, however, is due in part to his assigning a constant rate for poorly dated material in the Rhone delta; assuming a steady increase in that rate during the period of deposition would smooth the plot in Figure 5 and enhance the late Plio-Quaternary increase. In any case, Kuhlemann's (2001) work calls for a maximum erosion rate long after the deformation that built the Alps, when the convergence responsible for that deformation had essentially stopped.

Of course, it would be preposterous to suggest that nowhere on Earth have surface elevations increased, and further, that in such regions the potential energy gained by erosive agents went unused. Surely, some mountain belts have become higher in the past few million years. My favorite is the axial range that forms the crest of New Guinea, where crustal shortening seems to have begun since 5 Ma (Crowhurst et al. 1996, Hill 1991). Yet, if deep incision and erosion do not correlate well with the timing of tectonic activity on a global scale, ascribing a virtually global increase in erosion and incision to tectonic processes must carry nonfalsifiable (religious?) beliefs, which I do not address here.

SEDIMENTATION AT HIGH LATITUDES AND ALTITUDES: THE ROLE OF GLACIATION

Glaciers seem to have moved much of the rock from regions of high relief in both the Rocky Mountains and the Alps. Because glaciers, especially continental ice sheets, became widespread since global cooling accelerated at ~3–4 Ma, climate's signature on both sedimentation rates and the landscape must be written partly by glaciers. Thorough studies of sediment accumulation in the area surrounding Scandinavia show marked increases in mass accumulation rates in late Pliocene time, when continental glaciation began on the Fennoscandian shield (Fiedler & Faleide 1996; Hjelstuen et al. 1996, 1999; Overeem et al. 2001). Although some assign the accelerated erosion to higher elevations in late Cenozoic time than earlier (Evans et al. 2000; Hjelstuen et al. 1996, 1999; Japsen & Chalmers 2000; Stuevold & Eldholm 1996), an association with climate change is too obvious to dismiss. The uplands of Norway, Sweden, and Svalbard, as well as the Barents Sea floor during sea level low stands, supplied the sediment deposited offshore of Norway and Svalbard, although some sediment obviously derives from the excavation of Fjords. Overeem et al. (2001) recognized that with lowered sea level, a much larger drainage basin furnished sediment to the North Sea than during present-day or pre-Ice Age sea level.

Sedimentation rates near Scandinavia seem to have decreased in Quaternary time (Fiedler et al. 1996, Hjelstuen et al. 1996). Perhaps this reflects a stripping of easily eroded material and the subsequent widespread exposure of unfractured crystalline bedrock, which is resistant to erosion.

The Laurentide ice sheet also seems to have eroded its underlying rock more rapidly than rivers did before the ice sheets formed. Laine (1980) and Bell & Laine (1985) argued this point with much less DSDP and ODP data than currently are available. Deposits on the shelf of the eastern USA and in the adjacent deep ocean show a peak in Quaternary deposition rates, although the maximum appears to have been in Middle Miocene time (Figure 3) (e.g., Pazzaglia & Brandon 1996, Poag 1982, Poag & Sevon 1989, Steckler et al. 1999). Thick Quaternary sediment offshore of Canada (Poag 1982) and within the Williston Basin of the Midwestern USA (Gerhard et al. 1982) also show a marked increased in deposition.

Glacial erosion in Alpine terrain also surely increased, if it did not begin, when global cooling occurred during Pliocene time. As Scott (1975, p. 244) wrote, "Glacial erosion was the chief cause of the destruction of the Eocene surface in the highest parts of the [Rocky] mountains." Glacial erosion seems to have created the relief in the Canadian Cordillera during Plio-Quaternary time (Farley et al. 2001), and glacial erosion has obviously sculpted the high terrain of the Alps, Himalaya, and the Southern Alps of New Zealand. For the latter, conglomeratic deposition increased abruptly on the west coast at 2–3 Ma (Nathan et al. 1986), as did the deposition rate offshore on the east coast, at least where strong deep-sea currents have not swept material away (Browne & Field 1988, Shipboard Scientific Party 1999).

There seems little doubt that glaciers affected erosion at high latitudes and high altitudes, and thus global cooling must have affected erosion rates in such settings. Correspondingly, if glacial erosion alone accounted for the late Pliocene increases in sedimentation and in grain sizes, we might expect the tropics to show no such increase.

SEDIMENTATION AT LOW LATITUDES: THE ABSENCE OF GLACIATION

Some low-latitude regions show increased sedimentation in Pliocene time, but others do not. Whether this constitutes support for glaciers playing the major role in accelerating erosion or evidence that they do not depends on how one views the small number of areas studied.

Mass accumulation rates in the Amazon Fan, albeit measured at only a point and not integrated over the entire fan or even a two-dimensional line, show an increase at $\sim$4 Ma (Figure 3) (Dobson et al. 2001, Harris & Mix 2002). Although Harris & Mix (2002) took a cautious view and allowed for either a rise of the Andes or climate change to have played a role, Dobson et al. attributed the increase to "uplift" of the Andes, citing Hoorn (1993, 1994), Hoorn et al. (1995), and Kroonenberg et al. (1990), all of whom studied only the Colombian Andes. Hoorn (1993, 1994; Hoorn et al. 1995) showed that a change in provenance of sediment in northwestern Brazil implies that the Eastern Cordillera of Colombia did not exist in early and middle Miocene time, and that the rise of that belt occurred since 10–12 Ma. Her work does not concern the Pliocene and Quaternary evolution of that or any other section of the Andes. Kroonenberg et al. (1990) relied on fission tracks and paleobotanical evidence to argue that most "areas above 3000 m reached their present altitude only after 6–4 Ma ago." Fission tracks bear on erosion only and place no constraint on changes in elevation. Paleobotanical evidence has long been used to infer a recent rise of the eastern Cordillera of Colombia, but the timing of that inferred rise continues to be pushed back in time from between 4.5 and 2.3 Ma (Van der Hammen et al. 1973) to between 5 and 3 Ma (Helmens & Van der Hammen 1994) to between 6 and 3 Ma (Hooghiemstra & Van der Hammen 1998). Even if the botanical changes that occurred since 6 Ma do reflect elevation changes, which is only one possible explanation for the differences in fossil and present-day taxa (e.g., Wijninga & Kuhry 1990), the changes do not correlate well in time with the changes in accumulation rates in the Amazon basin. The increased accumulation rate in the Amazon basin does not imply contemporaneous uplift of the Andes.

It might be tempting to infer that the increased sedimentation rate in the Amazon fan reflects increased glaciation in the Andes, from which much of the sediment is derived (Dobson et al. 2001). Harris & Mix (2002) showed, however, that the mass accumulation rate of the terrigenous sediment correlates well ($r^2 = 0.82$) with the ratio of amounts of oxide minerals goethite/(goethite + hematite), which serves as a proxy for the climate of the Amazon lowlands. Low values, suggestive of a dry climate, correspond to rapid accumulation rates. By contrast, ratios of clay minerals chlorite/kaolinite, used as a proxy for Andean versus lowland provenance, correlate poorly ($r^2 = 0.12$) with accumulation rates and therefore deny changes in Andean erosion rates a significant role. Thus, Pliocene climate change over low regions seems to be responsible for the increased accumulation rate.

Glaciation could not have played a role in the apparent Quaternary increase in erosion in northern Australia, where Nott & Roberts (1996) inferred a three-fold (or more) increase in erosion rate in Quaternary time by dating sediment deposited there. Erosion rates throughout most of the Cenozoic Period were very low, 1 μm/year (e.g., Bierman & Turner 1995, Nott 1995, Twidale 1976), but since at least $\sim$0.5 Ma, rates have been much higher in two drainage basins (Nott & Roberts 1996). Similarly, Heimsath et al. (2001) inferred a higher erosion rate for basins and hillslopes in southeastern Australia since 150,000 years ago than the average rate for Cenozoic time.

Elsewhere, the evidence is more ambiguous. Lavier et al. (2001) showed that along a seismic line across the Congo margin the maximum sedimentation rate occurred in the last couple of million years (Figure 4), but farther south, a pulse of increased sedimentation offshore Angola correlates with the 14–15 Ma oxygen isotope shift, followed by a decrease until the present. As these profiles sample two parts of the same deep-sea fan, and that adjacent to Angola contains much more sediment, the recent increase adjacent to the Congo need not reflect increased erosion. Moreover, estimates of erosion rates on the adjacent African continent show no increase in Quaternary time and permit a constant rate throughout Cenozoic time (Bierman & Caffee 2001, Brown et al. 2002).

Thus, some tropical regions offer support for a global increase in sedimentation beginning at 3–4 Ma. Increased glaciation cannot account for these increases, but what aspect of climate change is responsible for them is not obvious.

MID-MIOCENE INCREASES IN ACCUMULATION RATES: THE ABSENCE OF GLACIATION

Changes in sedimentation rates in mid-Miocene time from a few regions show an increase when oxygen isotopes in benthic foraminifera increased, and hence, when the Antarctic ice sheet expanded and perhaps Earth cooled globally. Compilations of sediment accumulation off the east coast of the USA (Pazzaglia & Brandon 1996, Poag & Sevon 1989) show this best, but mid-Miocene increases have been seen elsewhere (Figures 2 and 3): South China Sea (Clift et al. 2002), Indus Fan (Clift et al. 2001), and parts of the west coast of Africa (Lavier et al. 2001). Explanations for the increases differ, but tectonic uplift of the surface with or without expanded drainage basin area (Pazzaglia & Brandon 1996), lowered sea level (Miller et al. 1996), and climate change (Lavier et al. 2001, Steckler et al. 1999) have been offered.

For many of these studies, the timing of changes in sedimentation is imprecise, but again the shelf off the east coast of the USA provides the highest resolution. Katz & Miller (1996) found that organisms that lived on the shelf off the east coast of North America near New Jersey were abruptly deposited at greater depth beginning at ∼13.5 Ma, when at least one submarine canyon was cut (Mountain et al. 1996) and when the sedimentation rate on the continental rise increased. Katz & Miller (1996) inferred that erosion of the shelf had accelerated. The timing of this event is close enough to a drop in sea level that it might be tempting to relate these phenomena to such a drop, but Mountain et al. (1996) showed that turbidites that emanated from the continental rise itself, not from the shelf, cut this canyon. Moreover, Steckler et al. (1999) found that the integrated sedimentation recorded by a seismic line across the shelf to its edge increased abruptly near 13.5 Ma. Thus, relating this increase in sediment supply to the shelf to sea-level change is not straightforward; from the sharply resolved temporal correlation with the δ^{18}O record, Steckler et al. (1999) suggested that climate change played the key role in the increased deposition rate.

Lavier et al. (2001) reported a similar maximum sedimentation rate between 15.5 and 13.5 Ma off the west coast of Africa adjacent to Angola, although its timing is less precisely defined than that off the coast of the eastern United States (Figure 3).

In addition, John et al. (2003) described an abrupt shift from carbonate sedimentation to clay-rich carbonate sediment at ∼13 Ma on a continental slope now exposed in Malta. They correlated this change with the step in δ^{18}O at approximately that time, and they associated it with a shift to a cooler and rainier climate.

Although the shift in δ^{18}O between 15 and 13 Ma is commonly associated with an expansion of the Antarctic ice sheet, glaciation almost surely played no role in the increased sedimentation in the environments discussed above. Only a few examples show an increase at that time, and the records from most regions shown in Figures 2 and 3, do not show such an increase. Thus, perhaps no global pattern exists, and I have just taken note of examples that fit my prejudice that climate has played a key role.

AMPLITUDE AND FREQUENCY OF CHANGING CLIMATE

The examples given above show that sea-level changes and increased glaciation can account for many of the examples of increased sediment accumulation rates beginning at 3–4 Ma, but neither can account for all. Some regions of increased sedimentation seem to be both free of glaciers and isolated from sea-level changes. Let's consider one other aspect of climate change: its variability.

Most of the time, rivers carry little sediment, and what sediment they do carry is largely brought from adjacent hillslopes. Only during brief storms do rivers move bedload and carry abundant suspended load. During such storms, landslides translate large masses of debris downslope into rivers, to be transported later. During more quiescent periods, hillslopes undergo only slow change. All geomorphologists recognize that annual and interannual variability in climate plays a major role in erosion and sediment transport, although which size storms are most important remains controversial. Assuming a lognormal probability distribution of river discharge, Wolman & Miller (1960) concluded that the annual storm [that with a magnitude such that only (approximately) one occurs per year] transported the most sediment. If peak discharges obey a power-law distribution (e.g., Turcotte & Greene 1993), however, then the largest storms should carry the most sediment.

Climatic variability on a longer timescale also surely contributes to erosion and sediment transport in part because of its varying effect on vegetation (Bull 1991; Donnelly 1982; Einsele 2000, pp. 440–41; Knox 1972; Overeem et al. 2001; Zhang et al. 2001). Gilbert (1900), in particular, wrote

> "The time in which the cycle of change is completed, or the period of the rhythm, is not always the same, but averages 21,000 years. It is commonly called the precessional period.... Assuming that climates of many parts of the earth are subject to a secular cycle, with contrasted phases every 10,500 years, we should expect to find records of the cycle in the sediments. 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."

Moreover, both Knox (1984, 1993) and Ely (1997; Ely et al. 1993, 1996) recognized large changes in fluvial incision associated with modest climate changes during Holocene time. The increased amplitude of variability associated with the transition from relatively equable (or only modestly changing) pre-Ice Age climates to larger variability over the past 3–4 million years may have effected increased erosion rates in late Cenozoic time (Donnelly 1982, Zhang et al. 2001). Increased variability not only in vegetated environments but also in cold regions may accelerate erosion by the alternation of periglacial processes, causing mass wasting that transforms rock to debris and then its transport by valley glaciers (Zhang et al. 2001). Finally, variability of climate responding to orbital, or Milankovitch, variations leads to large fluctuations in sea level, which affect erosion of shelves and pelagic deposition.

Over Cenozoic time, both the amplitudes of climate change and the frequency of its change seem to have increased (e.g., Zachos et al. 2001b). Although a biased and inaccurate paleo-thermometer, oxygen isotopes of benthic foraminifera provide the simplest measure of global climate change (Figure 6*a*). Time series of such measurements spanning Cenozoic time show the largest amplitudes since 1–1.5 Ma, with peak-to-peak variations of more than 2‰. Between 3 and 4 Ma, peak-to-peak variations were less than 1‰, and at earlier times variations they were yet smaller (~0.5‰), except for long-period swings with periods of ~400 kiloyears (Figure 6*b*). Part of the large amplitude of variation since 1.5 Ma, and perhaps 3 Ma, does not reflect changes in temperature because expansion of continental ice sheets depletes the ocean of ^{16}O and hence causes larger values of $\delta^{18}O$ in benthic foraminifera during these periods (Figure 6). Measurements of $\delta^{18}O$ from

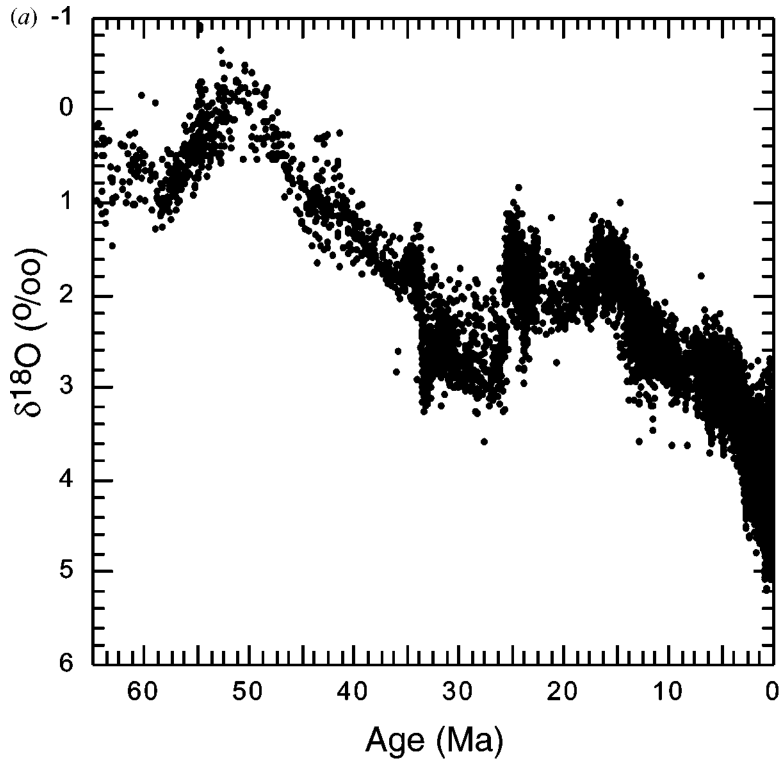

Figure 6 Oxygen isotopes $\delta^{18}O$ measured from benthic foraminifera during the Cenozoic Era. (*a*) The compilation for Cenozoic time by Zachos et al. (2001b) shows a general increase over Cenozoic time, which suggests a global cooling if greater at higher than lower latitudes. In addition, the amplitude of variation increases over time, although the mixing of data from different sites and the use of different organisms (despite corrections for different fractionation of ^{16}O and ^{18}O) adds some noise to this pattern. (*b*) Selected 2-million-year intervals from individual sites and from the same organism in each case show an increase in variability over time. Data for ODP Site 659 are from Tiedemann et al. (1994); for Site 846 from Billups et al. (1999); for Site 588 from Flower & Kennett (1993); for Site 929 from Flower et al. (1997), Paul et al. (2000), and Zachos et al. (1997); and for Site 744 from Zachos et al. (1996).

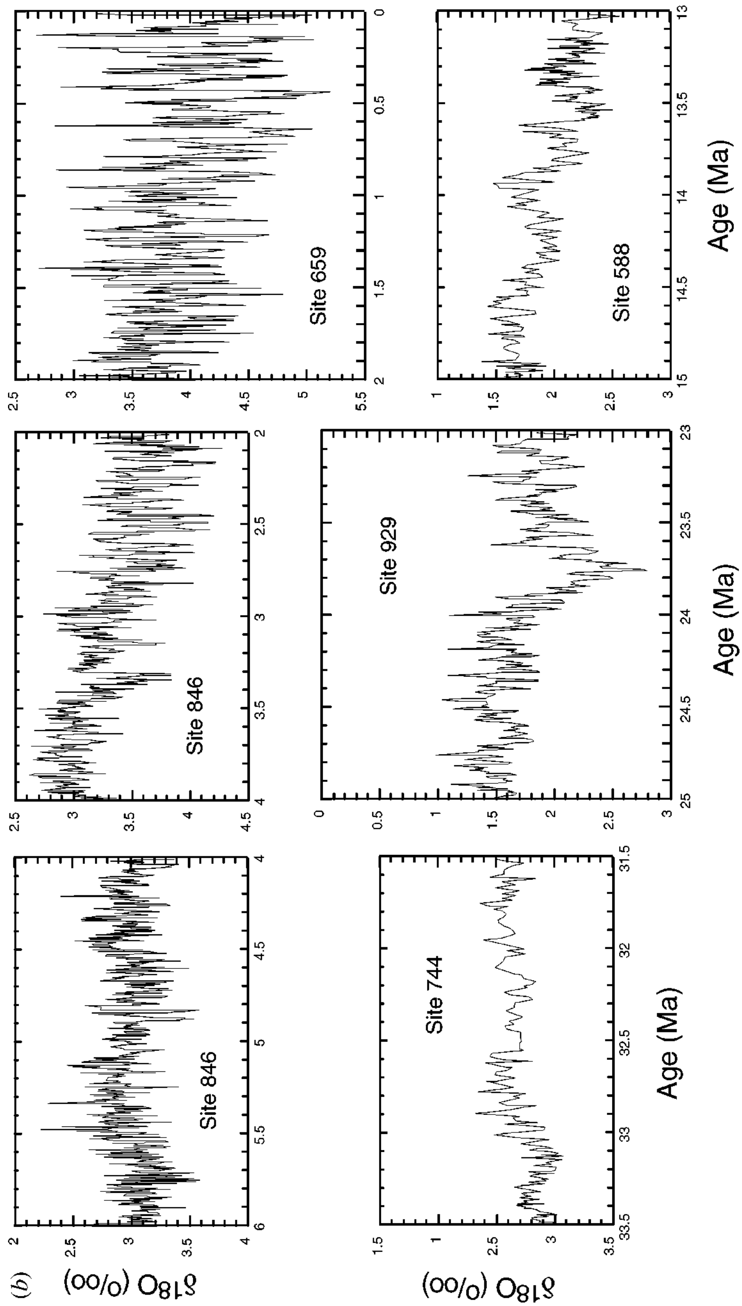

Figure 6 (*Continued*)

pore water trapped in marine sediment at the time of the last glacial maximum, however, imply that roughly 1‰ resulted from depletion of ^{16}O by precipitation of ice sheets, leaving a roughly comparable amount to be ascribed to temperature variations (Schrag et al. 1996). Thus, the depletion of the oceanic reservoir of δ^{16}O by increased glaciation since $\sim$3 Ma cannot account for the increased amplitude of δ^{18}O over Cenozoic time.

Not only the amplitude, but also the frequency of variations has changed over Cenozoic time (e.g., Mix et al. 1995, Pisias et al. 1995, Zachos et al. 2001b). Variations in Earth's orbit call for oscillatory variations in solar isolation, either globally or over the northern hemisphere, with periods of 406, 126, 95, 41, 23, and 19 kiloyears. As in Triassic and Jurassic time (Olsen & Kent 1999), variability with periods of $\sim$400 kiloyears dominates the spectral composition of δ^{18}O variability in Oligocene and early Miocene time (Figure 7) (Zachos et al. 1997, 2001a). Moreover, periods of 95 and 126 kiloyears are remarkably well separated (Zachos et al. 1997, 2001a, 2001b), and although a sharp peak identifies a strong response at 41 kiloyears, those at 19 or 23 million years are weak. Since 4 Ma, however, power has been greatest at 41 kiloyears, with clearly resolved peaks near 100 kiloyears and near 23 and 19 kiloyears (Figure 7) (Zachos et al. 2001b). Moreover, between $\sim$5 and $\sim$1 Ma, variability at 41 kiloyears dominates the spectral content, but since $\sim$1.5 Ma, variability with periods near 100 kiloyears and 20 kiloyears have grown to become comparable with that at 41 kiloyears (Mix et al. 1995, Pisias et al. 1995). Thus, there is a progressive increase in high frequency content, both during the Ice Ages and since $\sim$30 Ma.

Suppose that landscapes evolved exponentially from one equilibrium state to another in response to step changes in climatic forcing, and suppose that erosion were the integrated effect of such exponentially decaying changes. If forcing oscillated between two extremes, then obviously erosion would increase with the amplitude of the forcing. Moreover, high-frequency forcing would cause more erosion than low-frequency forcing. (The integral of the product of an exponential function and sine function over one cycle scales with the product of the maximum amplitudes of the two functions and the decay content of the exponential, but not with the frequency of oscillation; the integral over time, however, is then proportional to the number of cycles, and hence to frequency.) Thus, insofar as erosion depends monotonically on climatic forcing measured by δ^{18}O, both the increased amplitude and the increased frequency of variation since $\sim$30 Ma contribute to increased erosion and sediment accumulation.

SUMMARY

Sediment accumulation rates increased on or near continents in late Cenozoic time, near 2–4 Ma. Obviously, such increases in sedimentation suggest increased rates of erosion of nearby terrain. Sources of sediment can be high or low terrains and tectonically active or inactive regions. The least convincing evidence of increased

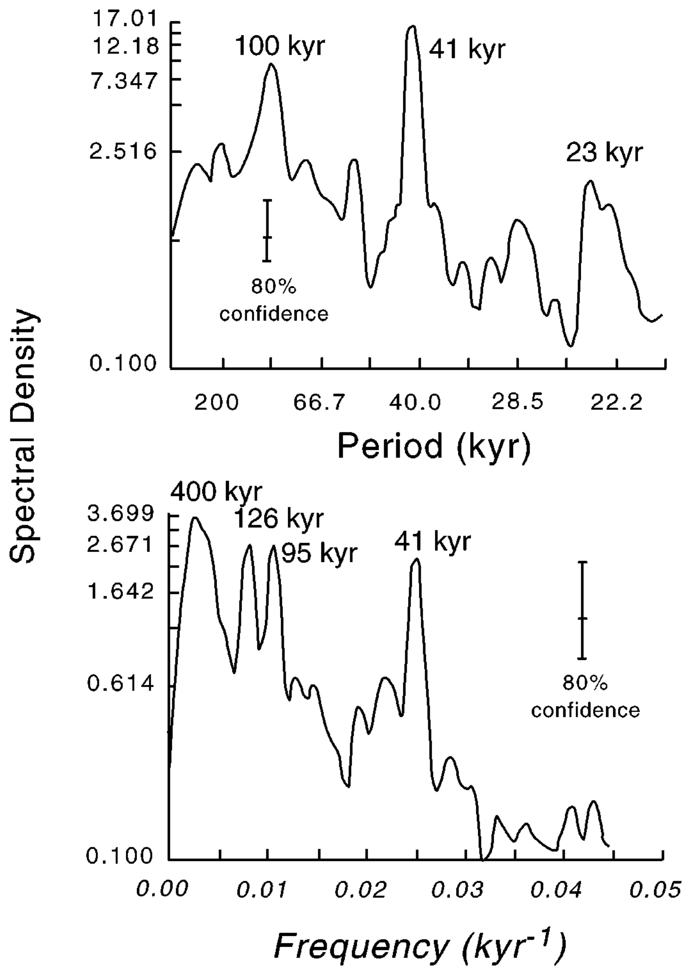

Figure 7 Power spectra of time series of $\delta^{18}O$ from benthic foraminifera (redrawn from Zachos et al. 2001b). The top plot shows the spectrum for the last 4 million years and the bottom plot shows it for the period 24.5 to 20.5 Ma. Note the dominance of power at ~100,000 and 400,000 years for the earlier period, and the much larger contribution at 23,000 and 19,000 years for the recent period.

erosion and sedimentation comes from the tropics, where some regions do not show late Cenozoic changes.

Plate reconstructions do not reveal a globally synchronous change in rates that might suggest a globally synchronized increase in elevation of eroding terrain. Moreover, no globally synchronized increase in accommodation space for sediment occurred. The only plausible phenomenon capable of orchestrating a global increase in sedimentation rates is climate change, which was large at mid to high latitudes and mild at low latitudes. Although climatically induced sea-level fluctuations may account for some offshore increases in sedimentation, increased accumulation on land requires another process to induce a change there. Glaciation accounts for increased sedimentation in high latitude and in some high altitude settings, but it cannot have affected accumulation in other areas. If one unifying aspect of climate change contributed to all increases in sedimentation, an obvious choice is the increase in both amplitudes and frequency of climate change in late Cenozoic time, which may have maintained a state of disequilibrium in which erosive processes continually adjusted to new conditions, as others have suggested for both this and other timescales (Bull 1991; Donnelly 1982; Einsele 2000, pp. 440–41; Gilbert 1900; Knox 1972; Overeem et al. 2001; Zhang et al. 2001).

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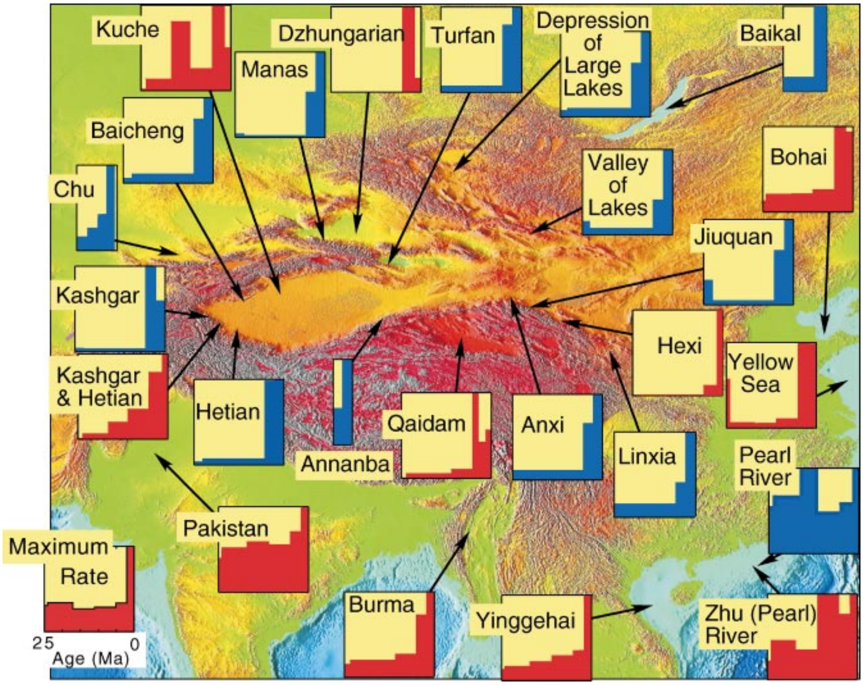

Figure 2 Map of Asia and average sedimentation rates since 25 Ma. All diagrams are scaled to the maximum rate, and all have the same horizontal timescale. Where data do not extend to 25 Ma, diagrams begin at the date of the oldest reported average rate. Red diagrams show mass accumulation rates (or their equivalent) corrected for compaction and integrated over areas of basins. Blue diagrams show point measurements, in many cases without corrections for compaction, with the exception of the Pearl River (*blue*), for which Clift et al. (2002) integrated the mass per unit area along a seismic profile. Other data are from the following sources: Zhu (Pearl) River (*red*), Yinggehai, Burma, Pakistan, Kashgar & Hetian, Kuche, Dzhungarian, Bohai, and Yellow Sea from Métivier et al. (1999); Jiuqian, Linxia, Anxi, Annanba, Hetian, Kashgar, Baicheng, Manas, Turfan, Depression of Large Lakes, and Valley of Lakes from Zhang et al. (2001) and references therein; Chu from Bullen et al. (2001); Qaidam and Hexi from Métivier et al. (1998); and Baikal from Kaz'min et al. (1995).

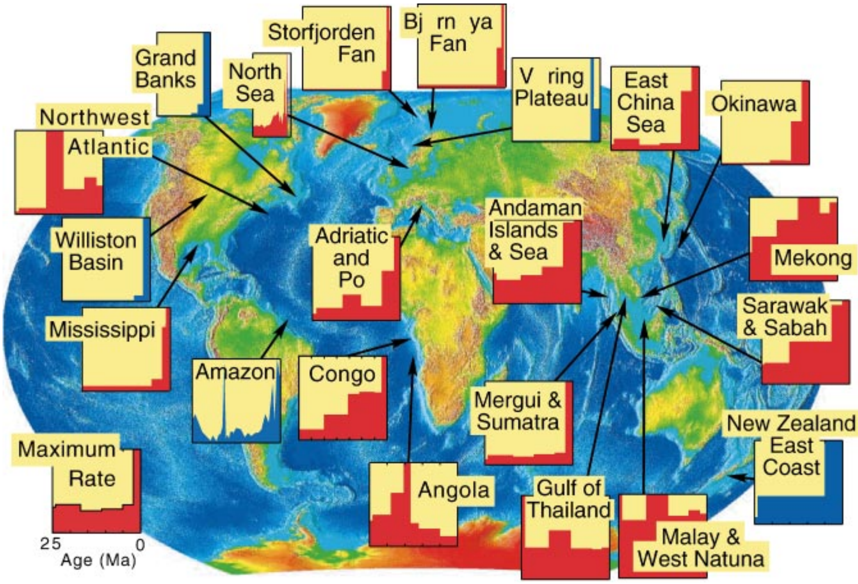

Figure 3 Map of world and average sedimentation rates since 25 Ma. Symbols as in Figure 2. Data from: Mississippi, Hay et al. (1989); Williston Basin, Gerhard et al. (1982); Northwest Atlantic, Pazzaglia & Brandon (1996); Grand Banks, Poag (1982); North Sea, Overeem et al. (2001); Storfjorden Fan, Hjelstuen et al. (1996); Bjørnøya Fan, Fiedler & Faleide (1996); Vøring Plateau, Hjelstuen et al. (1999); East China Sea, Okinawa, Mekong, Sarawak & Sabah, Malay & West Natuna, Gulf of Thailand, Mergui & Sumatra, and Andaman Islands and Sea, Métivier et al. (1999); New Zealand East Coast, Browne & Field (1988); Angola and Congo, Lavier et al. (2001); Adriatic and Po, Kuhlemann (2001); and Amazon, Dobson et al. (2001).

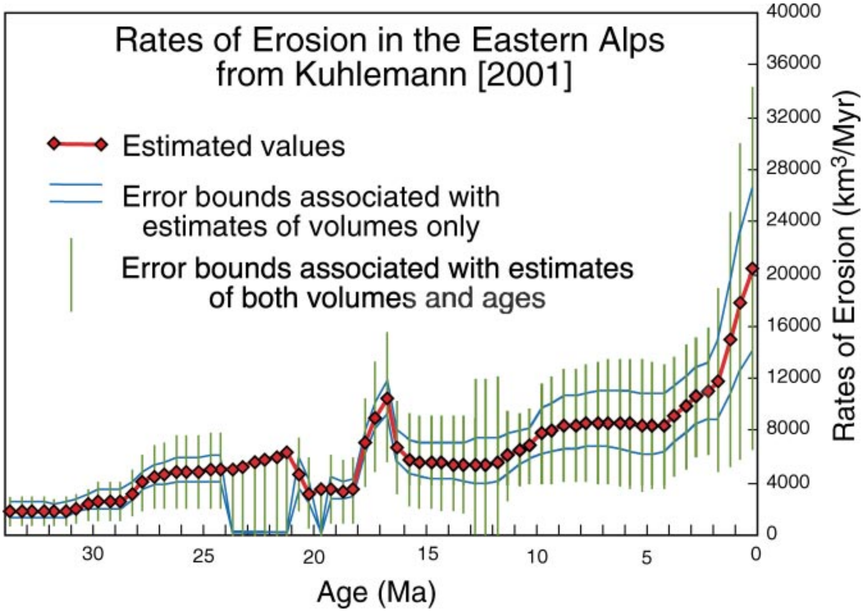

Figure 4 Erosion rates from the Eastern Alps, redrawn from Kuhlemann (2001). Kuhlemann determined amounts of material eroded by estimating the fraction of sediment, corrected for compaction, in various basins surrounding the eastern Alps. The smaller error bars show uncertainties associated only with incorrect assignments of masses of sediment, and the larger error bars also include uncertainties in ages assigned to each package of sediment.

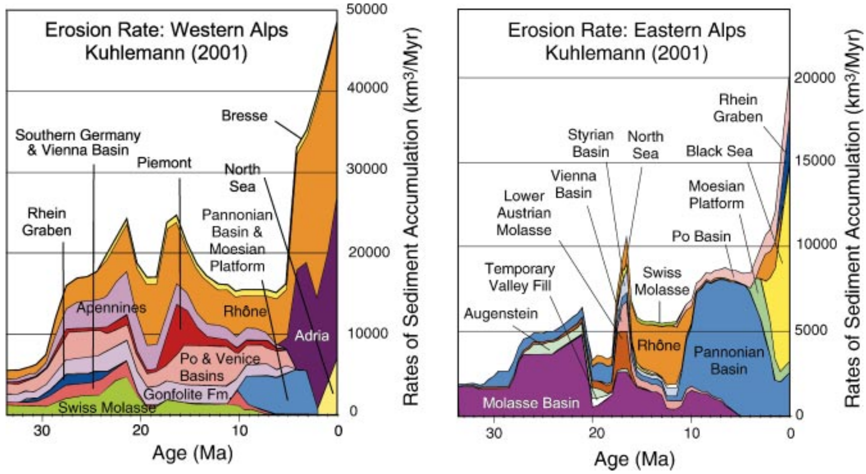

Figure 5 Masses of rock eroded from the western (*left*) and eastern Alps (*right*) summed by considering the basins in which the eroded material was deposited; redrawn from Kuhlemann (2001) and Kuhlemann et al. (2001).

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CONTENTS