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Controls on the erosion of Cenozoic Asia and the flux of clastic sediment to the ocean

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Abstract

Rates of continental erosion may be reconstructed from variations in the rate of accumulation of clastic sediment, most of which lies offshore. Global rates of marine sedimentation are usually considered to have reached a maximum after 3–4 Ma, driven by enhanced erosion in a variable glacial–interglacial climate. However, a new compilation of seismic data from the marginal seas of Asia now shows that only the Red River reached its historic peak after 4 Ma. Sediment flux from Asia first peaked in the early–middle Miocene (24–11 Ma), well before the initiation of a glacial climate, indicating that rock uplift and especially precipitation are the key controls on erosion, at least over long periods of geologic time. Reconstructions of weathering in East Asia show that faster erosion correlates with more humid, warm climates in the early–middle Miocene, changing to less erosive, drier climates after 14 Ma when Antarctic glaciation begins. Average rates of sedimentation on most east Asian continental margins since 1.8 Ma are 5–6 times less than the modern fluvial flux, implying that the flux to the oceans varies sharply on short timescales and is not always buffered over timescales of ~10^4 yr by storage in flood plains.

Keywords: erosion; Asia; cenozoic; climate; monsoon

1. Introduction

Constraining what controls continental erosion is crucial to understanding a variety of earth science processes, including the formation and destruction of mountain chains and the filling of sedimentary basins. Moreover, because erosion and weathering can affect ocean chemistry through fluvial run-off [1] and the atmosphere through drawdown of CO_2 during chemical weathering these processes have the ability to affect the Earth's climate on a range of time scales [2]. Despite their importance the controls on continental erosion continue to be the subject of intense debate. Competing researchers invoke either tectonically driven rock uplift, precipitation, or variability in the climate as the primary determining controls on erosion over geological timescales [3–7]. Such studies of erosion in sediment source areas have resulted in significant advances in our understanding of how rocks are exhumed through both erosional and tectonic methods. Examination of the clastic flux in modern rivers is a direct way to measure how much erosion is occurring in any specific region [8], but this approach can represent only a brief snapshot of how sediment is transported to the oceans. Moreover, it remains contentious how well modern rivers reflect the geological past because of the influence of anthropogenic processes that compete with

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those operating over geological time scales in controlling erosion.

2. Sediment budgets for Asia

Most sediment eroded from mountains is deposited on continental margins rather than onshore because of the much greater accommodation space afforded by a rifted margin compared to a continental basin. Thus a reconstruction of clastic mass accumulation on continental margins can act as a relatively accurate first order proxy for continental erosion rates over long periods of geologic time. Although continental basins can be important sinks of sediment their accommodation space is relatively limited and where sediment flux is great, as in Asia, most of the eroded detritus must be transported to the continental margin. In the example of the western Himalayan Indus drainage around two thirds of the sediment now preserved in that basin are offshore, compared to being preserved in the foredeep basins of India and Pakistan [9]. In the Red River system only 5% of the Cenozoic sediments are present under the Hanoi Basin onshore compared to 95% in the offshore parts of the Song Hong–Yinggehai Basin. Zhang et al. [6] used reconstructions of sediment accumulation worldwide to argue that a sharp increase in sedimentation rates during the Pliocene–Recent (<4 Ma) reflected intensified continental erosion since that time. These authors proposed that a rise in continental erosion worldwide after 4 Ma was most likely driven by the glacial–interglacial climate that rapidly changes on time scales of ~100 Ky [10]. In the case of Asian continental margins much of the data that supported this hypothesis came from the work of Métivier et al. [11], who derived regional sediment accumulation budgets based on 1D drilling, and to a lesser extent seismic reflection data. Unfortunately because this study was based on proprietary, industrial data it is impossible to test these sediment budgets or assess how representative they might be. In contrast, analyses of regional 2D seismic profiles in the Arabian Sea [12] and in the marginal seas of East and SE Asia [13] are thought to better estimate regional sediment volumes by covering much more of each margin than was previously possible. In this paper I use these recently published data, whose coverage is shown in Fig. 1, together with additional new profiles from the Pakistan margin to evaluate the relationships between climate, tectonic and erosion in Cenozoic Asia. The locations of the new data are shown in Fig. 2, while the interpreted stratigraphy derived from these 1977 vintage multichannel seismic profiles is shown in Fig. 3. Although these new estimates are not fully comprehensive, they do represent a major improvement on all previous mass flux estimates, and, crucially, the original data are published [12,13], allowing the uncertainty in the results to be assessed and improved on with further data acquisition.

The mass flux budget of a continental margin is critically dependent on imaging sediment across the entire margin, especially the main depocenters. Lateral variations in sediment thickness mean that a one-dimensional drill site will rarely capture a representative image of the regional sediment budget. Ideally sediment budgets need to be quantified by regional three-dimensional mass estimates [14]. Unless budgets can account for sediment in deeper water, as well as under the shelf, then they will remain unrepresentative. Slow tectonic subsidence or a fall in relative sea level can eliminate space for sediment preservation on the shelf, forcing it to be reworked into deeper water over certain time intervals [15]. Of the different drainage systems examined here only in the Indus River is there a major terrestrial sediment sink, accounting for about one third of the Cenozoic sediment mass [12]. The Yangtze system is not considered in detail here because of the large-scale capture of sediment onshore, which acts to buffer the offshore record. The Bengal Fan is also not discussed, despite accounting for around 50% of the total Cenozoic sediment mass in South and East Asia [9]. This is because there is no dated regional seismic stratigraphy for the fan, except in its most distal regions around Ocean Drilling Program (ODP) Sites 717–719 (Fig. 1). These are located far south of Sri Lanka and it is unclear whether they can be considered representative of mass accumulation on the whole fan. Indeed because of the tendency for fans to prograde through time and for sedimentation to switch between lobes it is unlikely that ODP Sites 717–719 can be used as reliable proxies for mass flux into the Bay of Bengal.

2.1. Sediment volumes from seismic data

Interpreted seismic reflection profiles were converted to eroded rock volumes by converting the sections from a vertical time axis into depth. Of all stages in the sediment budget estimation this process was the most prone to error and results in mass uncertainties of up to 20% due to uncertainties in the velocity–depth conversion. Velocities used to make this conversion are generally taken from the stacking velocities in the multichannel seismic profiles, with additional constraints from sonobuoys where these are available. Decompaction methods [16,17] are then applied to the sections in order to restore each dated sediment

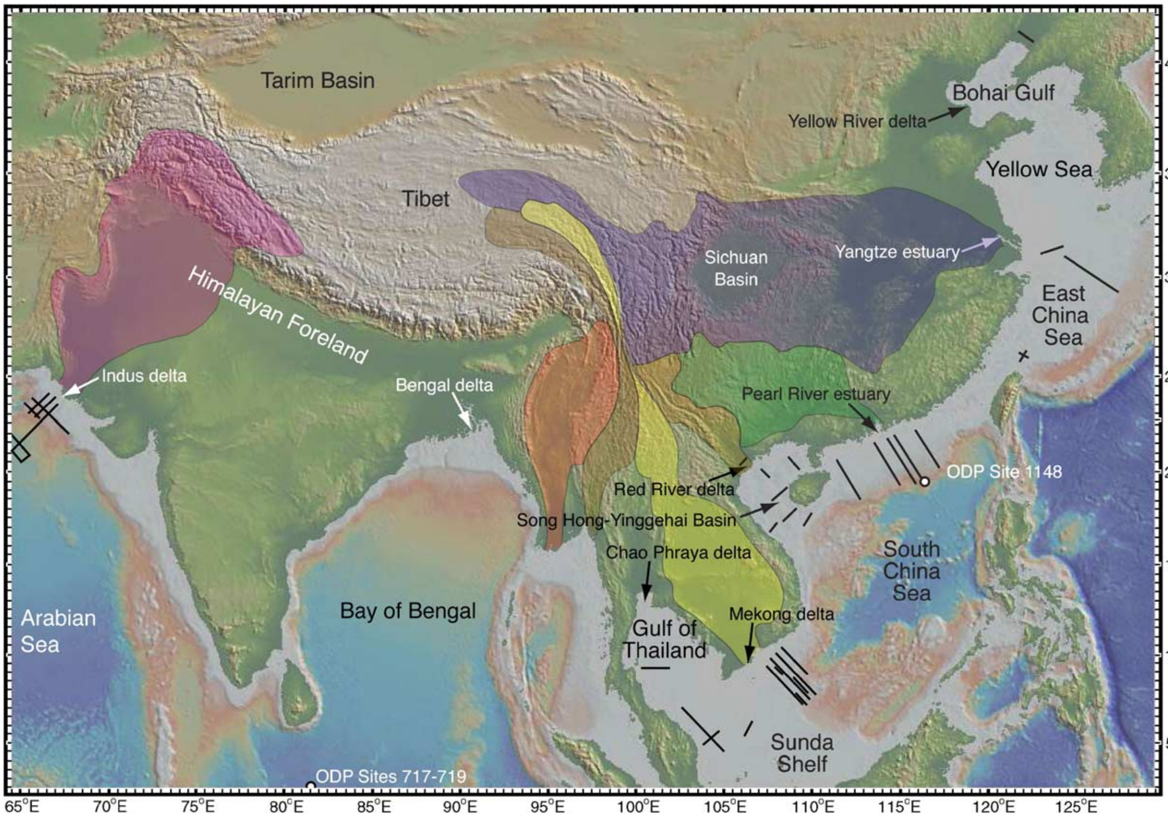

Fig. 1. Map of Asia and surrounding oceans showing the location of sections whose backstripping and decompaction form the basis of the revised sediment budget of Clift et al. [13], as well as the Indus Fan [12].

body to its original thickness prior to burial. Knowledge of the sediment type is important to this calculation because shales experience much greater loss of porosity during burial than do sandstones [16]. Lithological control for the profiles considered here was made through drilling results from petroleum exploration wells located on the shelf regions offshore each river system. The decompaction process involves accounting for the loss of porosity of the sediment during burial, which would otherwise result in an underestimation of deposited volumes for the older, deeper buried sediment packages. Any biogenic component can be assessed and removed from the budget using drill cutting or core samples that determine the fraction of organically produced $CaCO_3$. After the original, uncompacted volume of sediment in each dated interval has been determined, the mass of rock delivered during that time period can be calculated. Errors in estimating sediment age, lithology and compaction history are much smaller than the time–depth conversion and rarely exceed $<5\%$. The process of decompaction was described in detail by Clift et al. [13], and followed routine basin analysis methods, whose results are generally considered robust at the first order level. In this study two-dimensional decompaction was calculated using the program *Flex-Decomp*™ by Alan Roberts and Nick Kusznir [17]. Whole basin budgets were then calculated by adding together the different sections in a given basin and normalizing the rates for each dated interval in order to match the calculated total volume of the basin. It must be assumed that the analyzed profiles from a single system were fully representative of the total mass flux on to that margin during the Cenozoic.

2.2. Results

Although the revised sediment budgets (Fig. 4) do not have the detailed temporal resolution that may be possible when seismic data is tied to fully cored, scientific boreholes, they do have the same temporal resolution as earlier studies [11] and cover much more of the continental margin area offshore many of the major Asian deltas. The new budgets show major discrepancies with the earlier work [18], specifically that only the Red River reached peak flux rates during the Pleistocene, i.e. since 1.8 Ma, and that the Pleisto-

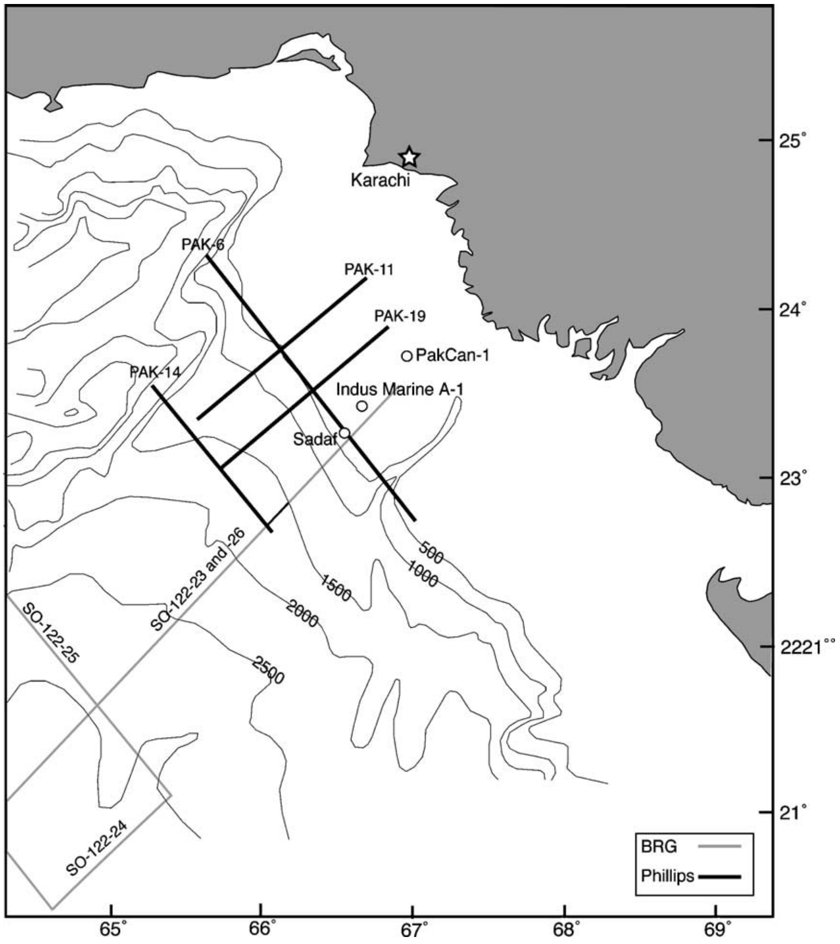

Fig. 2. Bathymetric map of the Indus offshore area, Pakistan, showing the location of the BGR seismic profiles used in earlier sedimentary budgets [7], together with the newly released Phillips PAK77 profiles shown in Fig. 3 that are used in this study to improve the regional sediment budget. Circles show the location of drill sites that provide age control to the interpreted sections.

cene mass flux barely exceeded that attained during the middle Miocene (11–16 Ma). Several other basins show that erosion reached maximum values during the early or middle Miocene (11–23 Ma), e.g., Indus, Pearl and Mekong Rivers [12,13,19].

Several of the systems (e.g., Pearl, Red, Indus, as well as the Yangtze and Irrawaddy (not discussed in detail here)) show falling rates during the late Miocene, similar to the predictions of Burbank et al. [20] for the Himalayan foreland and Bengal Fan. While the Pleistocene does appear to be a period of rapid sedimentation for many basins, it does not seem to be any faster than the middle Miocene. Differences between basins may be caused by tectonic uplift of local sources within a single drainage, regional climatic differences, or the capture of headwaters from one basin to another [21,22]. In some regions, most notably the Gulf of Thailand (Fig. 4), the rate of clastic accumulation has fallen sharply during the late Cenozoic [13,23], reflecting both the lack of accommodation space offshore and the loss of drainage into the trunk river. Drainage capture in East Asia, driven by topographic uplift in Tibet, has been recognized for some time, though the sequence and timing at which river headwaters are transferred from one system to its neighbors are still debated [21,22]. Assuming that rapid early–middle Miocene sedimentation rates reflect fast erosion rates at this time, these data would exclude glacial–interglacial cyclicity from being the primary control on erosion rate, as has been argued [6,24]. The early–middle Miocene in contrast was a period marked as a climatic warm period, with climatic deterioration only starting after 14 Ma as Antarctic glaciation commenced [10,25].

2.3. Controls on erosion

A simpler image of the erosion flux from East Asia, especially Tibet, to the surrounding oceans can be

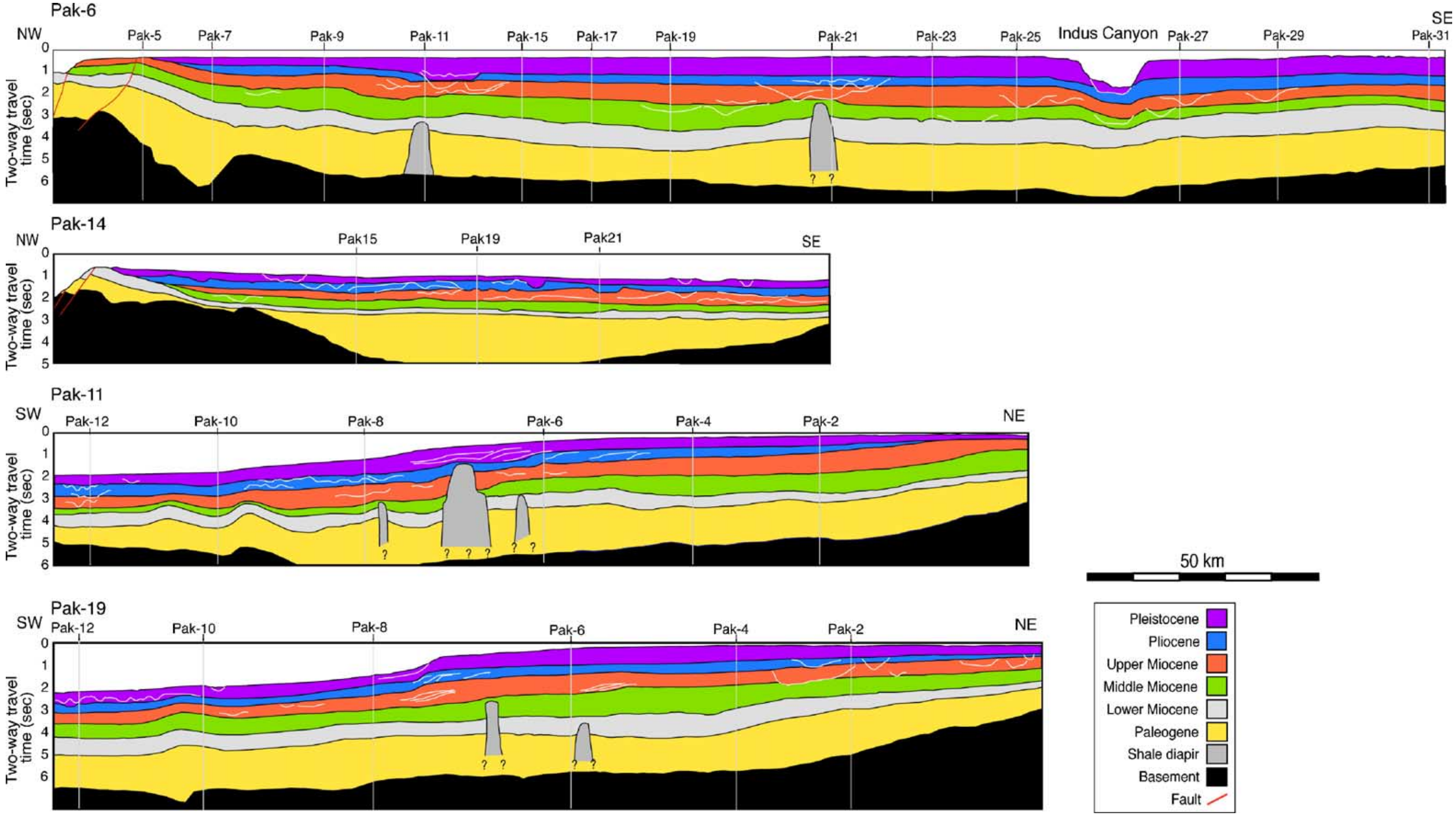

Fig. 3. Interpreted sections drawn from multichannel seismic profiles released by Phillips Petroleum from their PAK77 survey. Location of profiles is shown on Fig. 2.

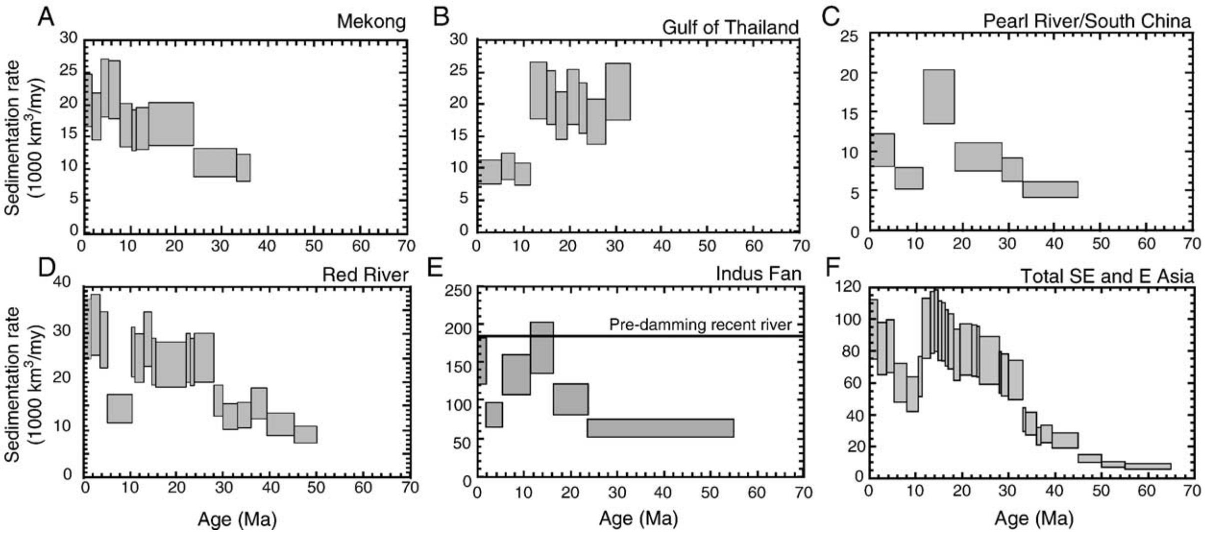

Fig. 4. Sediment budgets for each of the major basin systems of Asia (A) Mekong/Nam Con Son Basin, (B) Gulf of Thailand/Pattani, Malay, West Natuna Basins, (C) South China margin/Pearl River Mouth Basin, (D) Red River/Yinggehai–Song Hong Basin, (E) Indus Fan, and (F) the integrated sediment budget for all these basins, representing the net flux of material from Asia into the marginal seas.

provided by summing the accumulation records from throughout East Asia, rather than looking at a single river system (Fig. 4F). This reconstruction shows that the early and middle Miocene experienced levels of erosion comparable to those known in the Pliocene–Recent. Because there was no variable icehouse climate operating at that time [10], rapid erosion in East Asia and especially eastern Tibet cannot then have been driven by high frequency climate variability. The same is true in the Indus River drainage, where sedimentation rates fell drastically after the middle Miocene [12] before rebounding in the Pleistocene. These patterns indicate that frequency of climate change linked to Pleistocene glaciation cannot have been dominant in controlling erosion in the western Himalaya or East Asia.

If rapid climate variability is not driving fast erosion in the early–middle Miocene what processes are? Clift et al. [13] suggested that the sharp increase in sedimentation rates in East Asia after 33 Ma reflected initial strong surface uplift of the Tibetan Plateau, which is the source of the SE Asian rivers considered, coupled with intensification of the summer monsoon. The importance of bedrock uplift and gorge incision in generating erosion and sediment has been documented in several regions [26,27] and might be expected to be important in both the Indus and East Asian areas. Major deformation and granite genesis are known from the Hindu Kush and Karakoram ranges within the Indus drainage at 20–25 Ma [28,29], followed by a period of rapid cooling from 17 to 5 Ma [30], potentially providing a major new source of sediment during the early and middle Miocene. Rock uplift and gorge incision are less well documented in eastern Tibet, but evidence is now building for at least parts of central and southern Tibet to have been uplifted prior to the late Miocene [31–33], rather than most of the plateau being formed after around 8 Ma [34,35]. Furthermore, radiometric dating of the rocks in the major strike-slip fault zones of eastern Tibet and Indochina indicate rapid cooling in the late Oligocene–early Miocene [36,37]. Deep exhumation along the Red River, Wang Chao and Three Pagoda Fault Zones raises the possibility that rock uplift along those zone driven by the tectonism and matched by river incision could have generated much of the sediment seen offshore.

Until better independent climate and tectonic records exist, it is not possible to uniquely separate the competing influences of a stronger summer monsoon and the elevation of headwaters by surface uplift in controlling regional erosion. However, sediment budgets produced for the European Alps [38] and offshore Angola [39] do show some of the same patterns as seen in Asia, including the high rates in the early–middle Miocene and reduced rates in the late Miocene. This would support the idea of the global climate being dominant in controlling continental erosion, as it is unlikely that bedrock uplift in the Alps, Africa, the Indus drainage and throughout East Asia was synchronous.

Climate records from the South China Sea do seem to show some correlation with the erosional records. Earlier studies from the region indicated a switch to a wetter climate prior to 15 Ma [19,40], consistent with a role for monsoon climate in driving erosion rates. In contrast, the low rates of sedimentation and erosion seen in the late Miocene (11–5 Ma) may be linked to increased aridity and a stronger winter monsoon across Asia at that time [41–43], possibly related to global cooling and an increase in the Antarctic ice sheet volume. Fig. 5 shows two proxies for continental weathering regimes taken from ODP Site 1148, which is located offshore southern China (Fig. 1) and compares them with the benthic oxygen isotope work of Wang et al. [44]. ODP Site 1148 is located at the toe of the Chinese passive margin offshore the Pearl River estuary. Coring at this place extended as deep as the Oligocene, with around 25 Ma of continuous hemipelagic sedimentation providing the best long-term record of climate evolution in East Asia during the Cenozoic. Mass accumulation rates of clastic material at this site were calculated using the biostratigraphic age constraints and density measurements made during the cruise [45], supplemented by carbonate concentrations made by coulombmetry at the Marine Biology Laboratory, Woods Hole. Clastic mass accumulation rates were assumed to be equal to the total rate minus the carbonate accumulation rate because the amount of biogenic silica in the sediment is negligible [45]. In addition, I compare that record with color scanner data that can act as a proxy of relative aridity in the source regions. During ODP Leg 184 the core was measured at 5 cm intervals by a Minolta CM-2002 spectrophotometer that determined reflectance in thirty-one 10-nm-wide bands of the visible spectrum. Giosan et al. [46] have demonstrated that the 565 and 435 nm bands are sensitive to the presence of hematite and goethite respectively. A ratio of the 565/435 color intensity can thus be used a proxy for the relative abundance of these two minerals. Because hematite is preferentially formed in more humid conditions, while goethite is favored by more arid areas [47] the color data can provide a first order measure of weathering conditions in the drainage basin of the Pearl River. Fig. 5 shows that at 25–14 Ma there were variations between drier and wetter climates that sometimes corresponded to faster clastic mass accumulations rates. Resolution in identifying changes in clastic accumulation rates is limited by the age picks in the core. Nonetheless, the periods 23.3–21.4, 19.3–18.5 and 17.3–15.0 Ma appear to be periods of rapid clastic flux, falling within the period of rapid erosion reconstructed from the seismic profiles. The same pat-

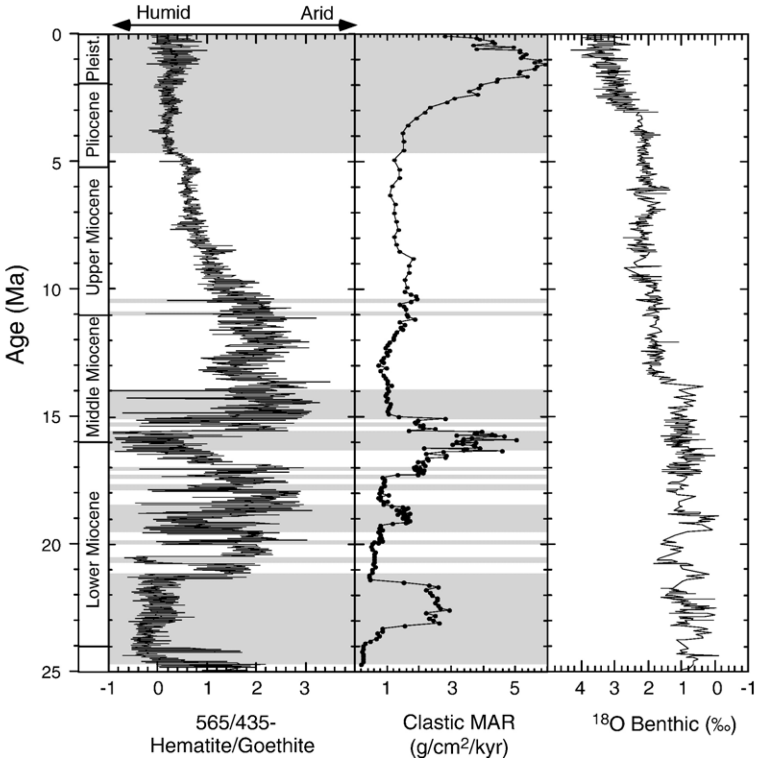

Fig. 5. Core data from ODP Site 1148 from the northern South China Sea showing that the erosional flux from southern China, largely the Pearl River basin, has strong temporal variations in aridity since the start of the Neogene. MAR = mass accumulation rate. Gray-shaded regions indicate periods of greater inferred rainfall and humidity, i.e. stronger summer monsoon. Oxygen isotope data is for benthic foraminifer *C. wuellerstorfi* [44].

tern is seen in the Plio-Pleistocene when erosion was again rapid. However, the Pearl River drainage appears to become much more arid and less erosive after 14 Ma, following the onset of Antarctic glaciation, shown clearly by the step in the benthic oxygen isotope record [44]. The correspondence between low erosion rates in the late Miocene (Fig. 4) and the dry climate in southern China (Fig. 5) argues for precipitation being a key control on continental erosion.

Although Molnar [48] has argued that arid climates are more erosive because of the transportation power of flash floods, geological records from the Bengal Fan [49], Indus Fan [12] and South China Sea [19], together with the data presented above, indicate slower accumulation during periods of regional aridity. Moreover, modern erosion is fastest in the modern Himalaya where precipitation is strongest [50], consistent with the notion that slowing precipitation might be expected to reduce erosion rates.

3. Sediment transport rates

Comparison of the revised average rates of sediment accumulation during the Pleistocene with modern river particulate loads also yields important insights into the nature of sediment flux to the oceans. Métivier and Gaudemer [18] showed that for many Asian river systems the modern particulate clastic flux [8] was similar to the average rate calculated for the Pleistocene from the sediment record, after correcting from anthropogenic influences, such as agriculture, damming and building. This similarity implied that the sediment flux from mountain sources was being buffered in the flood plains prior to entry into the sea, because erosion must change as the climate switched from glacial to interglacial conditions. However, the new budgets [12,13] now show average accumulation values since 1.8 Ma that are much lower than would be expected from the modern clastic flux, with only the Indus River coming close to matching the two (Table 1). The Indus may differ because of the long and actively subsiding character of its onshore basin, which is thus a more effective sediment trap than those seen in SE Asia. The degree of buffering imposed by the flood plains would seem to be very much less than previously supposed for these latter systems.

Table 1
Rates of sediment delivery by the modern rivers of Asia after correction for recent anthropogenic influences [8] compared to the average rate since 1.8 Ma and the peak rate reconstructed from the backstripping analysis

River/basin	Modern discharge (10^6 t/yr)[a]	Average sediment delivery since 1.8 Ma (10^6 t/yr)	Peak average sediment delivery rate (10^6 t/yr)
Mekong/Nam Con Son	160	28 ± 6	31 ± 6
Chao Phraya/Pattani	11	2 ± 0.4[b]	4 ± 0.8[b]
Pearl/S. China Sea	69	14 ± 3	23 ± 4
Red River/Yinggehai	133	42 ± 8	43 ± 8
Yangtze/East China Sea	480	30 ± 6	30 ± 6
Indus/Arabian Sea	250[c]	204 ± 41	227 ± 45

[a] From Milliman and Syvitski [8].

[b] Figure only includes sediments in Pattani Trough, because Malay and Natuna Basins are likely fed by local sources.

[c] Value is only from pre-damming Indus, not other rivers in Arabian Sea.

The implication of this work is that the modern rivers of SE Asia are presently carrying much more material than has been typical since 1.8 Ma, presumably balanced by periods of reduced sediment flux. If modern rates of clastic flux are historically high, then lower rates of erosion and marine clastic sedimentation must occur during glacial intervals. Although the erosive power of glaciers is well documented [51–53], run-off is required to deliver glacial debris to continental margins. Glacial periods are marked by a weaker summer monsoon, greater regional aridity and less run-off [54–56], reducing erosion and rates of marine clastic sedimentation. Despite this the average rate of sedimentation during the Pleistocene is similar to that seen in the middle Miocene, due to rapid erosion and sediment transport during interglacial periods. The new sediment budgets for the Asian marginal seas [12,13] imply that changes in erosion, driven by climate, can and are communicated directly to the stratigraphic record on the continental margins, at least during the Neogene. If so then the general effectiveness of flood plains in buffering flux to the oceans must be seriously called into question.

4. Conclusions

New sediment budgets derived from more extensive, verifiable surveys of the continental margins of South and East Asia than have previously been available now call into question earlier reconstructions of greatly enhanced continental erosion during Plio-Pleistocene glaciation [11]. Rapid erosion is demonstrated in the early–middle Miocene (24–11 Ma), well before the establishment of an icehouse climate, indicating that the varying glacial–interglacial climate may be important in controlling erosion but is not dominant as previously suggested [6]. Instead erosion in Asia is linked to rock uplift and especially precipitation, mostly related to monsoon strengthening. The erosive flux from the mountains appears to be rapidly transferred to the continental margins with limited sediment storage in flood plains. Buffering in these regions may have been more important in the Indus River, where the basin is long and in a state of active tectonic subsidence.

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