Reduced Himalayan sediment production 8 Myr ago despite an intensified monsoon

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UPLIFT of the Tibetan plateau about 7–8 Myr ago[1,2] may have been responsible[3–5] for the apparent intensification of the Asian monsoon [6–10] around that time. Increases in the oceanic $^{87}Sr/^{86}Sr$ ratio during the Neogene period have been attributed[11,12] to increased erosion from the Himalayan orogen. It has been suggested that the monsoonal intensification may have enhanced overall erosion rates in the region[5,13]. If this were the case, sediment accumulation rates would have increased in the surrounding basins at this time. Here we present a reanalysis of stratigraphic data from the Indo-Gangetic foreland and the Bengal fan, which demonstrates that both of these basins experienced a decline in sediment-accumulation rates 8 Myr ago. Thus it seems that monsoonal intensification was accompanied by a decrease in mechanical weathering. This decrease could be due to reduced tectonic activity, decreased Himalayan glaciation or slope stabilization from dense plant cover.

Recent isotope studies of soil carbonates[6–8,14] within Siwalik strata in both Pakistan and Nepal (Fig. 1) show considerable shifts in carbon and oxygen isotope ratios in the Late Miocene. These shifts have been interpreted as signs of climate change, manifested by the replacement of C3 plants (trees and shrubs) by C4 plants (grasses) and decreased soil leaching in response to increased seasonality and monsoonal development in southern Asia. Coupling of these isotope data with magnetostratigraphic studies permits the precise timing of the isotopic shift to be examined. If an intensified monsoonal climate were responsible for the shifts, one would expect generally synchronous changes across the entire sub-Himalayan region. This expectation has been supported by the observation of a coeval reduction in browsers and change in rodent taxa in the Pakistani foreland strata[15] and by palaeoceanographic evidence in the western Arabian sea. There, changes in faunal abundance and in rates of organic carbon and opal accumulation indicate the presence of strong upwelling, which today is driven by the northwesterly monsoon winds[1,9,10]. Together these effects suggest that the monsoon climate system developed in Late Miocene time[1,6,8,10].

Where first documented in northern Pakistan, $\delta^{13}C$ and $\delta^{18}O$ changes in soil carbonates can be dated by comparison with the original, locally determined magnetostratigraphic zonations[16,17] and calibrated against the most recent magnetic timescale[18]. This floral shift was under way by ~7.8–7.6 Myr, and C4 plants dominated the floodplain biomass by 6.0 Myr ago[6]. Similar isotopic shifts in both western and central Nepal[7,8] have been interpreted as evidence for a coherent and essentially synchronous climate change across the entire Himalayan foothill[14]. Two separate magnetostratigraphic studies at Surai Khola[8,19] in western Nepal indicate that the carbon isotope shift began at ~7.4 Myr ago[18]. At Bakiya Khola in central Nepal 250 km farther east, the initiation of the isotope shift occurs at either 6.6 or 5.9 Myr ago[7,14], depending on the chosen correlation with the magnetic timescale[18] Thus, although these two sites in Nepal appear to record increases in the importance of C4 plants that are analogous to those observed in Pakistan, the recorded onset of this change becomes younger toward the east; the isotope shift seems to occur 1–1.8 Myr later in central Nepal than in Pakistan. The apparently diachronous nature of the shift suggests that it should not be considered a precise indicator of monsoonal intensification (which presumably should be a regional, largely synchronous phenomenon). This is consistent with recent interpretations[10,14] which suggest that the transition from C3 to C4 plants in the Himalayan foreland was not a reflection of regional climate change[6–8] but rather was part of a worldwide trend in the Late Miocene.

Given that 25% of the modern strontium flux to the world's oceans is contributed by rivers with headwaters in the Himalaya and Tibet[20], it has been argued that the observed mid-to-late Cenozoic increase in the Sr isotope content of the world's oceans is largely attributable to chemical weathering in the Himalayan orogen[12] It has been further suggested that this increase was accompanied by or driven by a coeval increase in mechanical weathering[11,12], that mean erosion rates have been increasing continuously since 12 Myr ago[12], and that monsoonal intensification in particular should have enhanced overall erosion rates[5,13]. If so, we might expect to see an isotopic signal of this enhanced Himalayan erosion in the foreland and in the Bengal fan, and we would expect to see increased sediment storage in one or both of these sediment sinks, which are the only reservoirs capable of absorbing the large flux of Himalayan detritus.

Isotopic fingerprinting of potential Himalayan and Tibetan erosional source areas and matching with the isotope characteristics of the Bengal fan strata[21] clearly show that the High Himalayan crystalline belt was the main contributor to detrital sediments in the fan during the past 17 Myr, and there is no clear evidence for a change in the relative importance of this source area during that time. Detrital mineral ages, interpreted to represent cooling and denudation in rapidly uplifting source areas, show cooling ages remarkably close to depositional ages

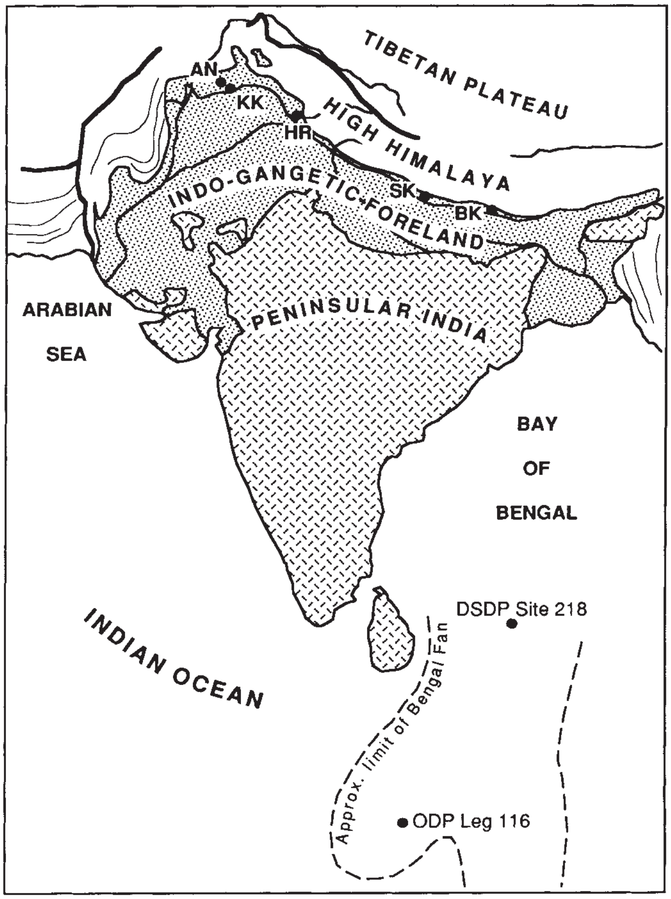

FIG. 1 Location map of Himalayan foreland and Bengal fan showing the locations of marine cores (ODP leg 116, DDP 218) and foreland magnetostratigraphic sections used in this study. AN: Andar Kas; BA: Bakiya Khola; HR: Haritalyangar, KK: Kotal Kund; SK: Surai Khola.

throughout the Neogene strata of the Bengal fan[22], as well as for the Pakistani[23] and Nepali[7] sectors of the Himalayan foreland. Contrary to predictions of enhanced uplift and erosion rates during the Miocene to present[11,12], these isotope data do not indicate significant acceleration in the rates of bedrock uplift and denudation in the High Himalayan source areas in the past 10–15 Myr. It is, however, difficult to generalize about changes in mean erosion rates on the basis of these spatially restricted radiometric data.

A more straightforward approach is to examine the character of deposition and the rate of sediment accumulation in the basins containing the Himalayan detrital record. From ~17–7 Myr ago, the depositional record in the distal Bengal fan (Fig. 1) is marked by rapid sedimentation rates[24] and a coarser-grained illite–chlorite-rich assemblage[21,25]. An interval of accelerated deposition (Fig. 2) is recorded from around 11 Myr ago[24]. Most of the post 7-Myr interval is dominated by finer-grained smectite–kaolinite–rich strata[21,25,26]. This compositional change (and possibly the associated grain-size decrease) is interpreted to result not from a change in provenance[21], but from longer residence on the floodplains of the foreland basin, where the sediment was chemically altered before erosion and redeposition in the Bengal fan.

In the Pakistani[16,17] and Indian[27] forelands (Fig. 1), a strong lithostratigraphic contrast is found between strata younger and older than ~8–9 Myr. The older strata (Nagri lithofacies[16,17] and equivalents) are characterized by thick amalgamated sandstones with reduced preservation of overbank deposits (<30%) that are themselves characterized by deeply leached (1–2m) palaeosols lacking humic (organic A) horizons[6]. The younger Dhok Pathan[16] lithofacies is characterized by thinner sheet sandstones with abundant overbank deposits (50%) and shallowly leached (<50cm) palaeosols with increasingly common humic horizons[6]. The contrast between the Nagri and Dhok Pathan lithofacies suggests that fluvial cannibalization of the floodplain was more frequent and that effective annual rainfall (which modulates leaching depths) was considerably greater before 8 Myr ago. Whereas mean grain-size decreases in the foreland basin, floodplain preservation increases in Dhok Pathan strata in comparison to Nagri strata. These changes are consistent with the interpretations of the finer grain sizes in the Bengal fan after 7 Myr, as well as of concomitant increases in both smectite-kaolinite abundances and the degree of chemical weathering[21]. Although the age (~8 Myr) of the thick-to-thin sandstone transition is very similar in western India[27] and northern Pakistan[16,17], the coeval interval in Nepal is marked by increasing sandstone thickness, abundance of poorly drained soils, and preservation of organic matter[14,19]. Consequently, depositional and soil-forming conditions were not coherent across the entire Himalayan foreland during this interval.

The deep-sea cores from the Bengal fan show a significant drop in sediment-accumulation rates (Fig. 2) after ~7 Myr ago[24]. The succeeding 5–6 Myr of slower deposition correlate with the predominantly smectite-kaolinite assemblage, and they indicate that sediment accumulation in the Bengal fan decreased[21] at a time when mechanical erosion of the Himalaya is suggested to have increased[5,11,13,28]. One possible solution to this apparent contradiction would be to increase the amount of sediment storage within the Himalayan foreland. But sediment-accumulation rates synthesized from across the foreland basin based on magnetostratigraphic data[7,16,17,19,27,29–31] rule this out (Fig.2). Although sediment accumulation accelerated in many localities between 11.5 and 10.5 Myr ago (also in the Bengal fan), nearly all sections show either steady or diminishing rates of accumulation for strata <8.5 Myr old.

It could be argued that the accumulation-rate changes on the Bengal fan that are presented here (Fig. 2) are not representative of the entire fan, or are the result of sea-level changes rather than sediment delivery. Although less well constrained, the only other relevant deep-sea cores (DSDP site 218, Fig. 2) show age–depth trends consistent with coeval decreases in accumulation rates across the fan. Neither the timing and magnitude of sea-level variations nor processes of lobe switching can adequately account for the observed mineralogical and rate changes[21].

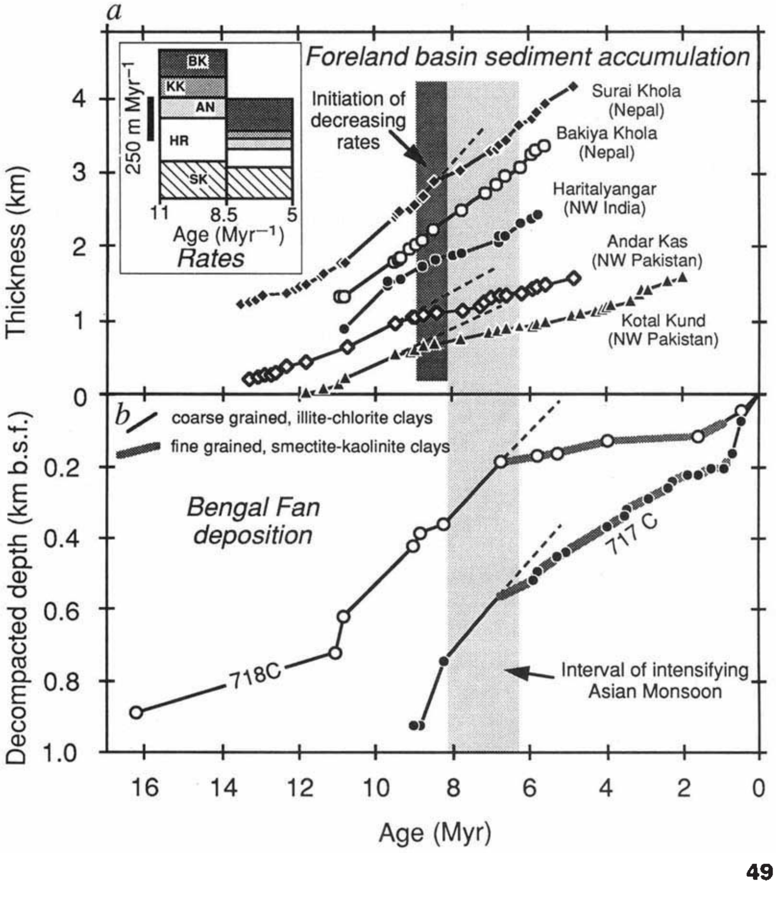

FIG. 2 *a*, Sediment-accumulation curves from the Himalayan foreland basin based on magnetostratigraphic time control[7,8,16,19,27]. Overall, accumulation rates (equal to the slope of the accumulation curve and shown in the inset) decrease after 8.5 Myr ago, and they remain steady or lower during the subsequent interval of intensifying Asian monsoon. Dashed lines show constant accumulation for comparison. AN: Andar Kas; BA: Bakiya Khola; HR: Haritalyangar, KK: Kotal Kund; SK: Surai Khola.*b*, Decompacted sediment-accumulation rates for the cores of ODP leg 116 (sites 717, 718) in the Bengal fan (b.s.f., below sea floor). Stratigraphic and palaeontological control from refs 21, 24, 25. Leg 116 sites show decreasing sedimentation rates beginning ~6.8 Myr ago (dashed lines show constant rates for comparison). The change in sedimentation rate corresponds with a major change in lithology, mean grain size and clay mineralogy which can be correlated at sites 717, 718 and also DSDP 218 (refs 21, 25, 36–38). This change is best dated at site 718, and is inferred to have occurred essentially synchronously at sites 717 and 218 (ref. 21). Rates remain low until the coarse grained illite-chlorite facies returns ~0.8 Myr ago.

It could also be argued that apparent rate changes in the foreland are strongly dependent on either the choice of magnetic timescales or on the precision of measurements of stratigraphic sections. Although we use the recent magnetic timescale of Cande and Kent[18] here, comparable changes in rates with slight shifts in the absolute age of inflections (<0.6 Myr) are obtained based on other widely used timescales[32,33]. Similarly, to reverse the observed slowing of sediment-accumulation rates, either the pre- or post-9-Myr strata would have had to have been systematically mismeasured by $>20\%$, which is considerably greater than the uncertainties associated with these measured sections. Therefore, the calculated rate changes form a firm basis for evaluating sediment storage within the foreland.

Consequently, a consistent picture can be developed for sediment storage in both the Himalayan foreland basin and the Bengal fan for middle and late Miocene deposition. Faster rates of sediment accumulation, coarser mean grain size and shorter residence times on the foreland floodplain in middle Miocene times are succeeded both by finer mean grain size and reduced volumes of sediment storage in both the foreland and the Bengal fan and by increased floodplain residence times in the Late Miocene beginning 8–7 Myr ago. This change to a regime of lower detrital sediment fluxes to the foreland and deep-sea basins corresponds with the timing of apparent intensification of the Asian monsoon and with the increased importance of chemical relative to mechanical denudation[21]. The terrestrial evidence (soil-carbonate isotopes) for this climate change seems moderately diachronous across the foreland. It might be expected that monsoonal intensification would result in increased sediment production and delivery. However, there is no evidence for a concurrent increase in mechanical weathering, detrital sediment delivery, or storage of detrital sediments in the adjacent sedimentary basins. It is possible that, despite increased mechanical erosion, more sediment was stored within the Himalaya itself, rather than being discharged to the foreland. But there is no evidence to support this hypothesis, and in any event, it is doubtful that the Himalaya could have stored enough sediment to account for the long-term changes seen in sediment fluxes downstream.

The cause of the reduced sediment flux to the late Miocene basins is not known. At least three alternative hypotheses are possible. Rates of tectonically induced bedrock uplift may have declined, contributing to overall lower relief and detrital sediment delivery. The development of the monsoon climate may have been associated with decreased glaciation in the Himalaya[1,34], leading to decreased mechanical erosion, but increased chemical weathering rates. Vegetation changes driven by the enhanced monsoon may have caused faster chemical weathering due to changing CO_2 levels in soils, whereas the same vegetation may have stabilized slopes and decreased the detrital sediment flux. If slope stabilization did result from dense plant cover at higher elevations, this would imply that the transition from C3 to C4 plants was confined to lower altitudes. Isotopic evidence of transition from C4 to C3 vegetation with increasing elevation has been observed elswhere[35]. It is perhaps worth noting that today much of the Lesser Himalaya and Siwalik hills in India and Nepal are covered in jungle, despite the strongly seasonal climate. That the development of a monsoonal climate should be associated with decreased sediment yields is perhaps surprising. However, given the present state of knowledge about the functional relationships governing sediment production, there may be other surprises in store for students of the interplay between tectonism, climate and erosion. □

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Timing of Tibetan uplift constrained by analysis of volcanic rocks

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THE Tibetan plateau has had a central role in the development of recent models for the mechanics of mountain belts[1,2] and Cenozoic global climate change[3]. The present elevation and extensional deformation of the plateau probably result from uplift owing to convective thinning of the underlying lithospheric mantle[1,2]. An age for the uplift would provide a valuable constraint on these models; but because recently proposed indicators of uplift are all climate-dependent, they are equivocal, possibly reflecting global cooling rather than regional uplift[4]. Here we present new geochemical data on post-mid-Miocene lavas from the plateau, which show that the lavas were derived from the lithospheric mantle. Simple thermal arguments indicate that the generation of such magmas also necessitates thinning of the lithospheric mantle. Thus volcanism is coincident with uplift, providing a climate-independent means of dating the onset of uplift. Dating by the laser $^{40}Ar/^{39}Ar$ technique places the beginning of this volcanism, and therefore the time of uplift of the Tibetan plateau, at 13 Myr ago.