Rising Himalaya: Advent and intensification of monsoon

K. S. Valdiya

Geodynamics Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Jakkur, Bangalore 560 064, India

Even though the Himalaya had emerged as a highland by middle Miocene, it was not until the late Miocene (11 to 7.5 m.y. ago) that it became a mountain barrier high enough to disrupt west-to-east flow of winds and push low-pressure area over northern India, which attracted moist summer winds from the Indian Ocean. Abrupt increase in the delivery of detritus to foreland Siwalik basin around 11 to 10 m.y. and to Bay of Bengal in the interval 10.9 to 7.2 m.y. and the first appearance of diagnostic minerals of the Great Himalayan complex in Siwalik sediments at 9.2 m.y. and in Bengal Fan between 10.9 and 7.2 m.y. implies that the Himalaya was exhumed and suffered accelerated erosion in the late Miocene, although brisk denudation had begun in mid-Miocene. Apatite fission-track dates and muscovite-cooling ages confirm strong movements on the boundary thrusts in the interval 8 to 6 m.y. The change of palaeoflora in the Siwalik domain from evergreen tall tropical to tall grasses 10 to 7.5 m.y. ago imply sudden change to dry climate characterized by seasonal heavy rains. The sudden appearance of endemic upwelling species at 8.5 to 7.4 m.y. in the Indian Ocean indicate activation of upwelling currents, which were set in motion at about 8 m.y. by southwesterly monsoon winds.

Strong tectonic movements at the beginning of the Quaternary and at 0.8 m.y., as manifest in influence of enormous volumes of sediments in the Siwalik and in the Bay of Bengal, must have lifted up the Himalaya to still greater elevation, and caused diversion of the even flow of moist winds and created large cool areas conducive to precipitation of snow. Cold climatic conditions, which had started 2.5 to 3.0 m.y. ago in the northern hemisphere, culminated in the glaciation of the higher mountains in the Pleistocene. It remains to be seen whether the oscillation of humid and dry phases in the Holocene is in any way related to spurts of tectonic movements on the terrane-bounding active faults of the Himalaya.

RISING 500 to 8000 m above the sea level, the 2400 km long and 250 to 300 km wide mountain barrier sprawling across the northern edge of the Indian subcontinent (Figure 1) vitally affects the atmospheric circulation over the Asian continent including the Indian landmass. Without the Himalayan ranges, which cause precipitation of moisture from the passing clouds, much of the subcontinent would be a dry desolate land. The high ranges that prevent the south-west monsoon clouds to go north are also responsible for the drier conditions in Ladakh and Tibet in the north and western Rajasthan in the south. The snow-covered ranges have exercised a moderating influence on the temperature and humidity in the Indian subcontinent. The Himalaya stops the Siberian wintry cold winds from flowing into India, so that the winters in north India are warmer than they would have been if the Himalaya had not been there (Figure 2).

Even though the Himalaya had become a mountain of prominence by mid Miocene, it could not have been an orographic barrier high enough then to prevent the movements of heavy-bodied bulky quadrupeds like the hippopotamus, rhinoceros and elephant in and across the lake basins of Potwar, Jammu, Kashmir and Kathmandu[1,2]. There was indeed a youthful mountain characterized by mild relief, gentle topography and wide

Figure 1. The girdle of high mountains in the northern edge of the Indian subcontinent controls the climate of the entire Asian landmass. (Bathymetric map from *J. Geol. Soc. Jpn*, 1997, **103**, p. XIV).

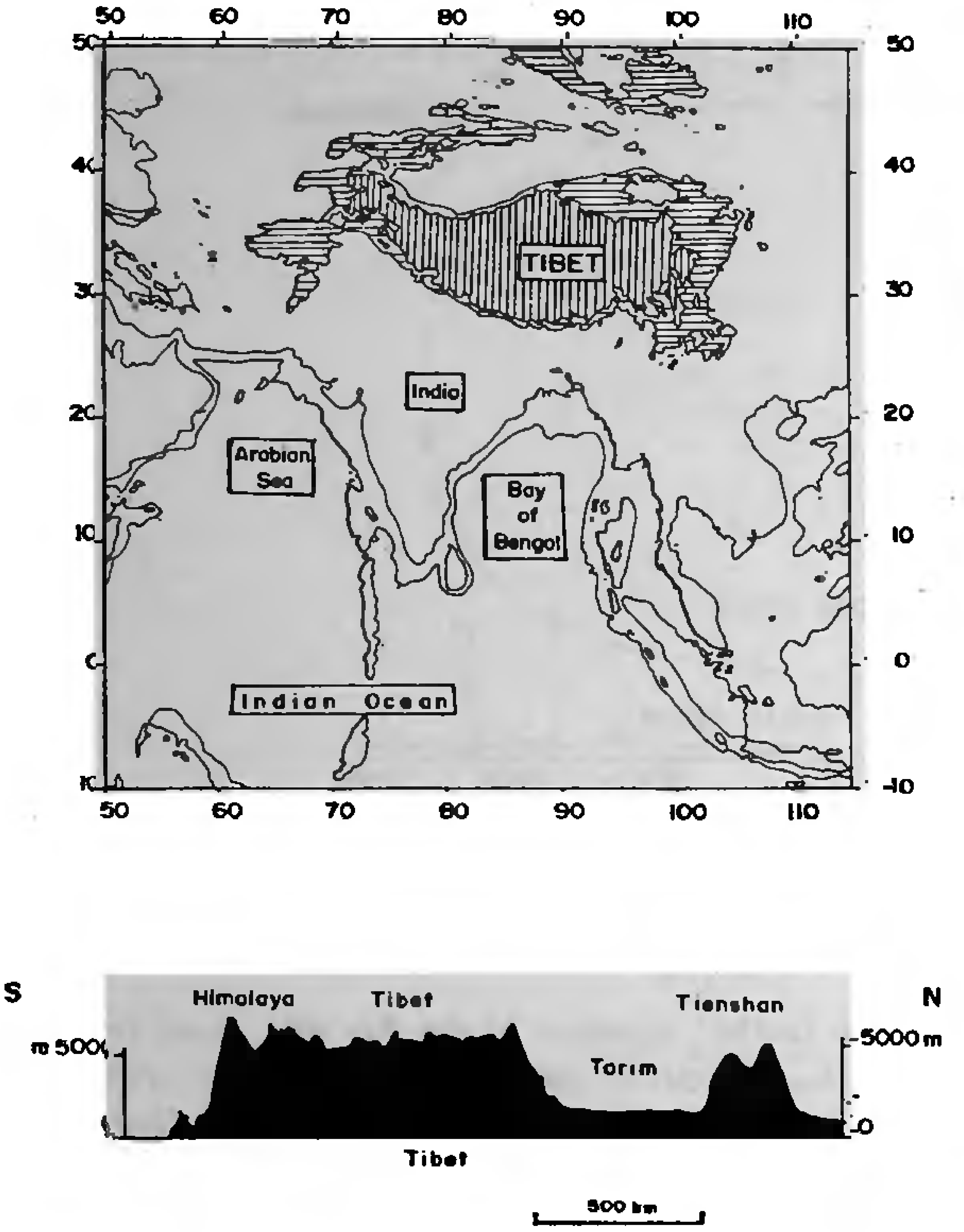

Figure 2. The > 5000 m high mountain barrier made up of the Himalaya and Tibetan Plateau causes not only the change in the wind direction, but also the precipitation of rains and snows. The shaded part in the map (after Molnar *et al.*[7]) shows 2000 m and 4000 m high areas.

valleys in which rivers flowed sluggishly as borne out by meanders that have now become deeply entrenched. The ground was covered by a thick mantle of soil as testified by influx of great quantity of clay in the foreland basin and in the Indian Ocean during that period. The soil also indicates hot-humid or hot-dry conditions than that obtained. Prolonged period of tectonic stability is further indicated by then reduced Himalayan clastic sediment production[3].

The period of tectonic quiescence was broken by a powerful tectonic upheaval in the temporal interval 11 to 7.5 m.y. when the gentle highland became a mountain barrier[2,4]. Revival of movements on faults that delimit the boundaries of four terranes of the Himalayan province was responsible for spectacular uplift of the Himalaya approximately 8 m.y. ago[2,5–7]. Simultaneously, the Tibetan landmass (welded to the Himalaya) was split up by N–S tension faults 8 ± 1 m.y. ago[8], leading to eastward extension of the Tibetan plateau. To the south in the Indian Ocean (Figure 3), the oceanic crust along with its superincumbent sedimentary pile was deformed[9] nearly 8 to 7.5 m.y. ago[5,6] (Table 1).

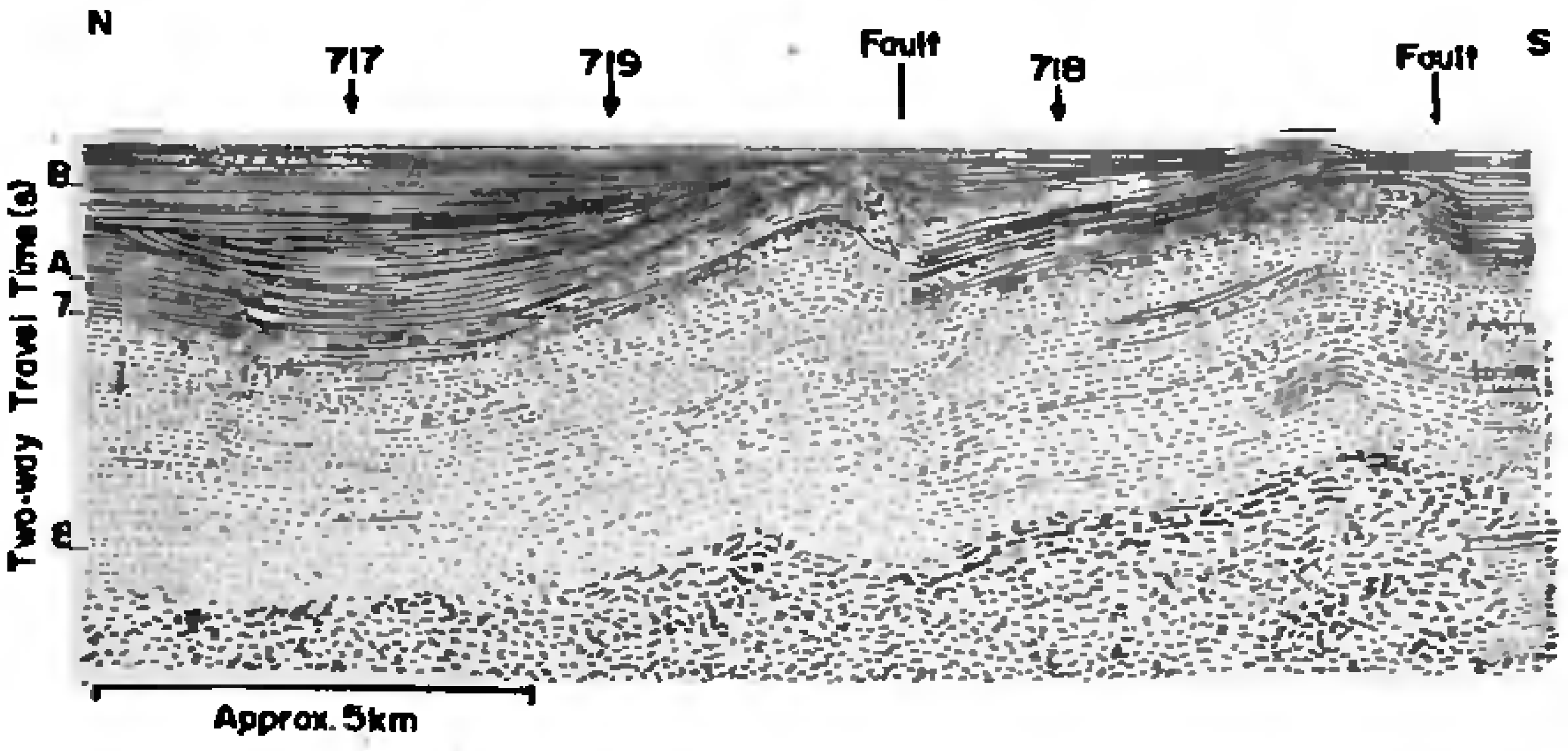

Figure 3. Seismic-reflection profile of a part of the Indian Ocean (at Leg 116 of the Ocean Drilling Programme) shows deformation of the deep-sea sediments. The sediments below the 'A' horizon are warped over folds and faults in the oceanic crust (from Cochran[5]).

Table 1. Late Miocene tectonic movements

Tibet	East–west extension on N-S faults	8 ± 1 m.y.
Himalaya	Reactivation of MBT in Pakistan (FT-dates)	8 m.y.
	Reactivation of MCT zone in NW Himalaya and Nepal (muscovite-cooling ages)	8–6 m.y.
Indian ocean	Deformation of oceanic crust and covering sediments	8–7.5 m.y.

These tectonic events of the late Miocene were accompanied by sudden and drastic change in the climate conditions. The old geomorphically mature topography was rejuvenated, and the landscape underwent reshaping. When heavy seasonal rainfalls started beating the newly emerged mountain, great volumes of detritus eroded from the uplifting terranes found their ways to the foreland basin and to the Indian Ocean.

This paper brings together various lines of evidence which indicate that the changes in the Himalaya and those recorded in the sediments of foreland basin and in northern Indian Ocean are the direct consequences of seasonal monsoon rains resulting from abrupt dramatic though episodic uplift of the Himalaya. As Molnar *et al.*[7] emphatically stated, the near simultaneity (6 to 8 m.y.) of these climatic changes with the attainment of Tibet's highest elevation suggests a relationship between them.

Emergence of the high mountain barrier and Tibetan Plateau

The emergence of the Himalayan barrier, welded to the lofty Tibetan Plateau, must have caused profound perturbations in the circulation of winds including moisture-laden air (Figure 1). The 3500 by 1500 km large plateau with its remarkably uniform flatness (Figure 2, section) and elevation ≥ 5000 m (ref. 10) is beaten increasingly

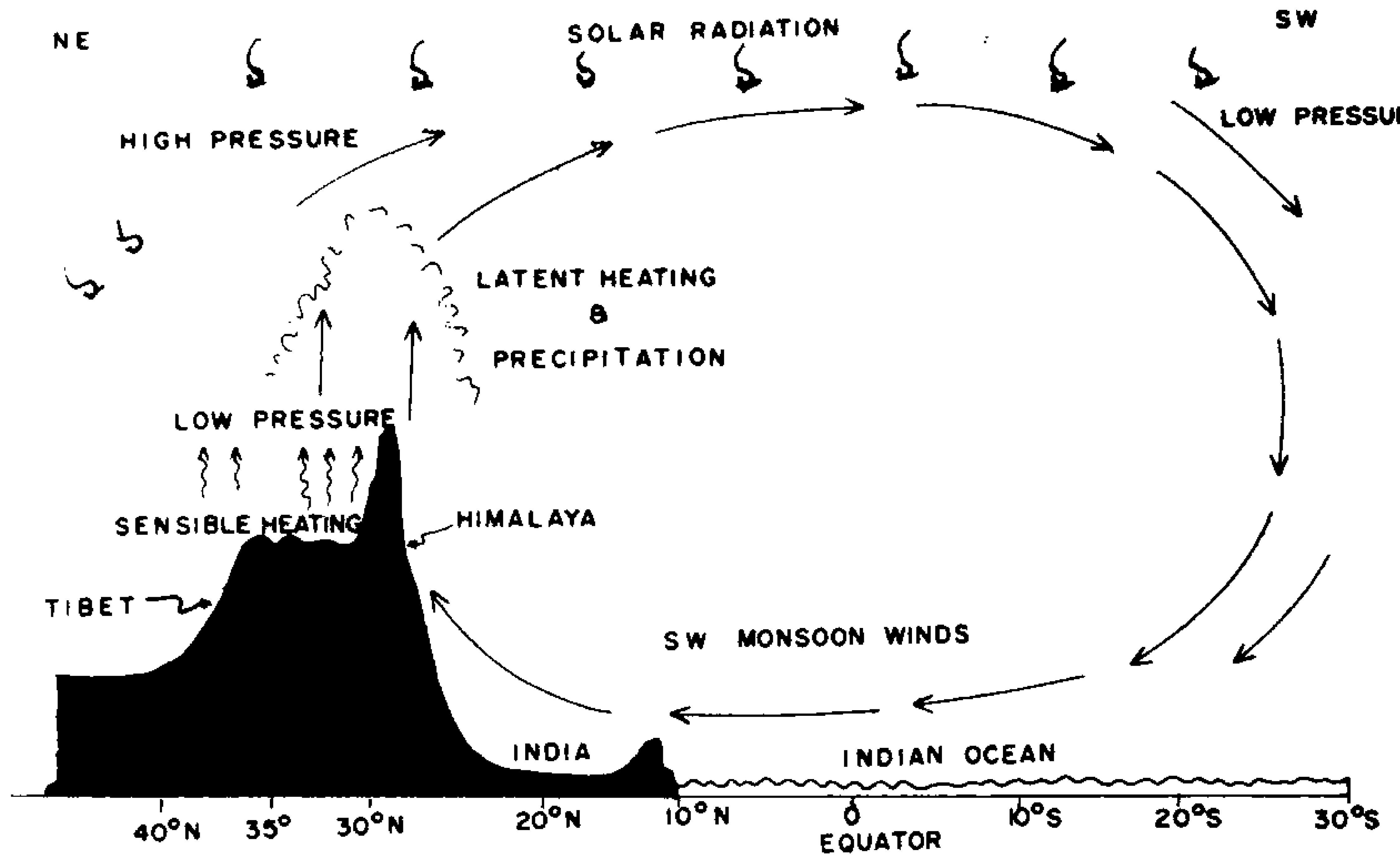

Figure 4. Emergence of lofty mountain barrier disrupted the west-to-east flow of winds and caused northward movement of the high pressure area so that the low-pressure centre moved over northern India in summer. The low-pressure centre attracts the moisture-laden south-west monsoon air from the Indian Ocean.

by solar radiation in large amounts. It provides a heat source at mid latitudes (Figure 4) thus opposing Hadley circulation between the equator and the temperate latitudes[7]. The formation of the mountain barrier must have disrupted west-to-east flow of winds and caused northward displacement of high pressure centre that commonly lies near the 30°–35° latitudes, so that the low-pressure centre moved over northern India in summer (Figure 4). This low-pressure centre attracted moist summer winds from the Indian Ocean to the Indian subcontinent. Thus developed the unique monsoon system characterized by the cycle of six seasons – *Vasant*, *Grishma*, *Varsha*, *Sharad*, *Shishir* and *Hemant*. The climate change took place over the period 9 to 6 m.y. – roughly at 8 m.y. The implication of this development is that since then long dry periods were followed by extremely wet spells, when heavy rains prompted a variety of natural processes such as strong weathering, erosion and generation of detritus, reshaping of landscape and modification of ecosystems, both in the rising mountains and in the plains and the ocean. This view is at variance with Srinivasan's postulation[11,12], on the basis of microfauna of the deep-sea sediments in the Indian Ocean, that there was a profound change in surface as well as deep-water circulation, culminating in the development of the Indian monsoon following the closing of the Indonesian seaway 12 to 11 m.y. ago. Presumably, the closing of the Indonesian seaway was contemporaneous with an early phase of the uplift of the Tibetan Plateau.

Expansion of grassland

The climatic conditions having changed, there was dramatic transition in the period 10 to 7.5 m.y. of the flora in the foothill domains of the Siwalik where tropical trees (C_3 vegetation) gave way to tall grasses with scattered trees and shrubs (C_4 vegetation). The climate became warmer and the rainfalls seasonal. This is evident from the composition of the palaeoflora in the Nepal Siwalik. The assemblage dominated by tropical evergreen large trees such as *Dipterocarpus*, *Shorea*, *Hopea*, *Calophyllum*, etc. before 10 m.y. gave way to the assemblage in which there was great abundance of moist or dry deciduous vegetation including *Bauhinia*, *Terminalia* and tall grasses[13,14]. Strong variations in the carbon isotope ($\delta^{13}C$) values of soil-carbonates of the Siwalik (Figure 5) corroborate vegetation change from C_3 type to C_4 type – around 7.4 to 6 m.y. in the Potwar basin in Pakistan[15], at 10 m.y. in the Arungkhola–Tinaukhola in south-central Nepal[16], and at 7 to 8 m.y. (Figure 5) in the Bakhiya valley in south-eastern Nepal[17]. Increasing abundance of brown mollic soil and marked shift towards heavy carbon isotopes of pedogenic carbonates[18] testify the dramatic floral change in the period 9.5 to 7.4 m.y. in front of the Himalayan mountain.

Immigration of mammals

The tremendous expansion of grasslands, with its rich resources of forage and food in the foothills, attracted grazing animals from the neighbouring lands – from as far as Africa, Europe, Central and Eastern Asia. The immigration of quadrupeds brought about major faunal 'turnovers' about 9.5 m.y. and 7.4 m.y. ago (Table 2, Figure 6) as discernible in the Potwar basin[19]. Introduction of exotic fauna and marginalization or even exter-

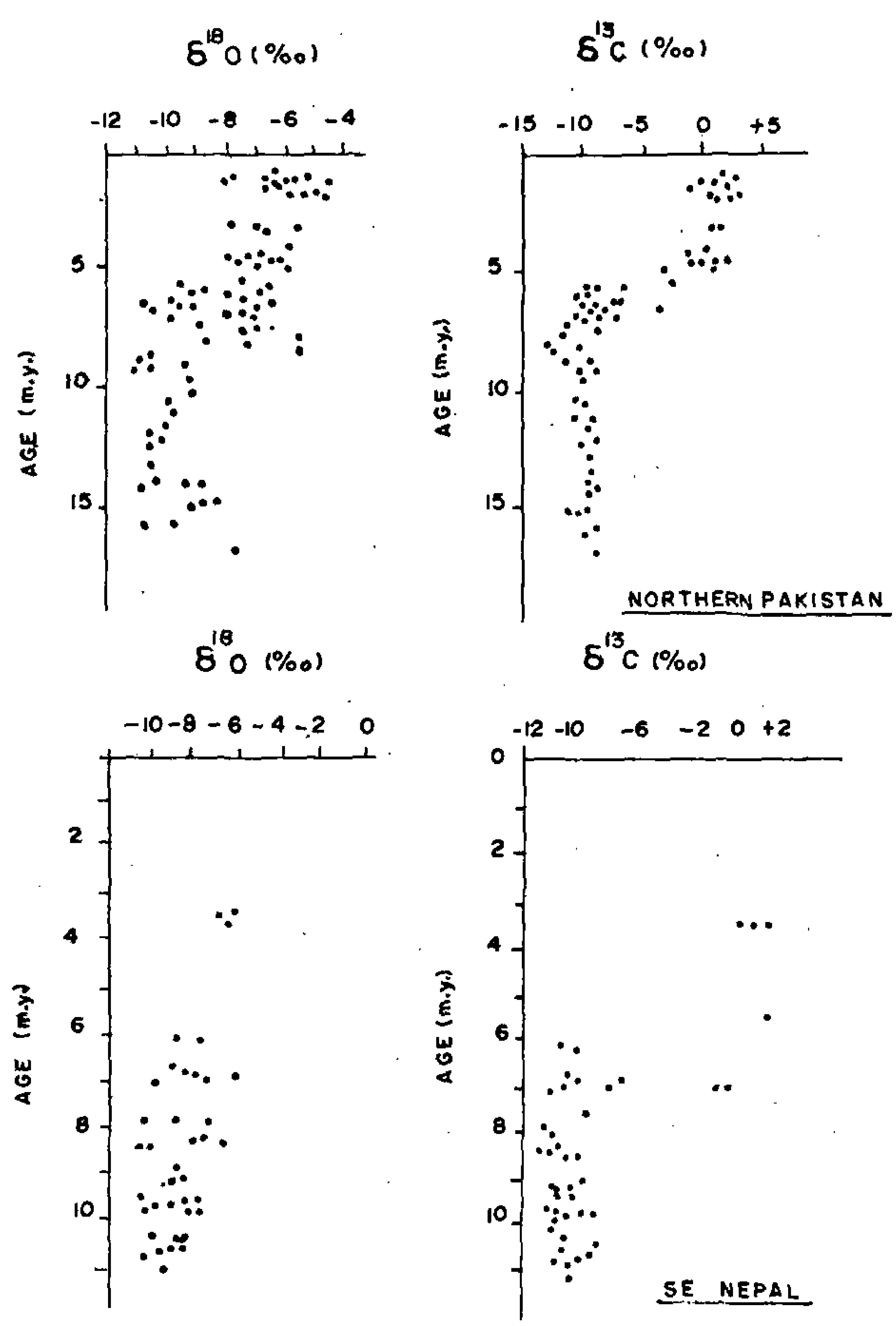

Figure 5. Isotope ratios of oxygen and carbon of the carbonates of the palaeosols in the Siwalik of Potwar in northern Pakistan, and of the Bakhiya Khola in south-eastern Nepal indicate that the climate had become warmer and the rainfall seasonal by 8.5 to 6 m.y. time. (Based on Quade *et al.*[15] and Harrison *et al.*[17], respectively).

mination of indigenous animals brought about substantial compositional change in the Siwalik. The Siwalik faunal assemblage then was three times richer than that of the present – there being 30 species of elephant compared to just one today and 15 genera of anthropoid apes[20]. Among the marginalized indigenous animals were rhinos, buffaloes and cows.

In northern Pakistan the development of arid condition caused rapid change in the rodent species between 9 and 7 m.y. (ref. 21). The three-toed horse *Hipparion* and pigs (Table 2, Figure 7) appeared at 9.5 m.y., having come all the way from Europe. The proboscid elephant *Stegodon* along with the hippopotamus *Hexaprotodon* and the elephant *Elephas planifrons*, among many others, (Figure 7) came to the Siwalik domain about 7.4 m.y. ago[19].

The immigration of heavy-footed large-bodied quadrupeds across the Himalayan domain in the late Miocene (despite the youthful mountain having risen up very fast to great heights over the larger part of its extent) implies that some segments were simply not high and rugged enough to prevent the movements of the bulky animals

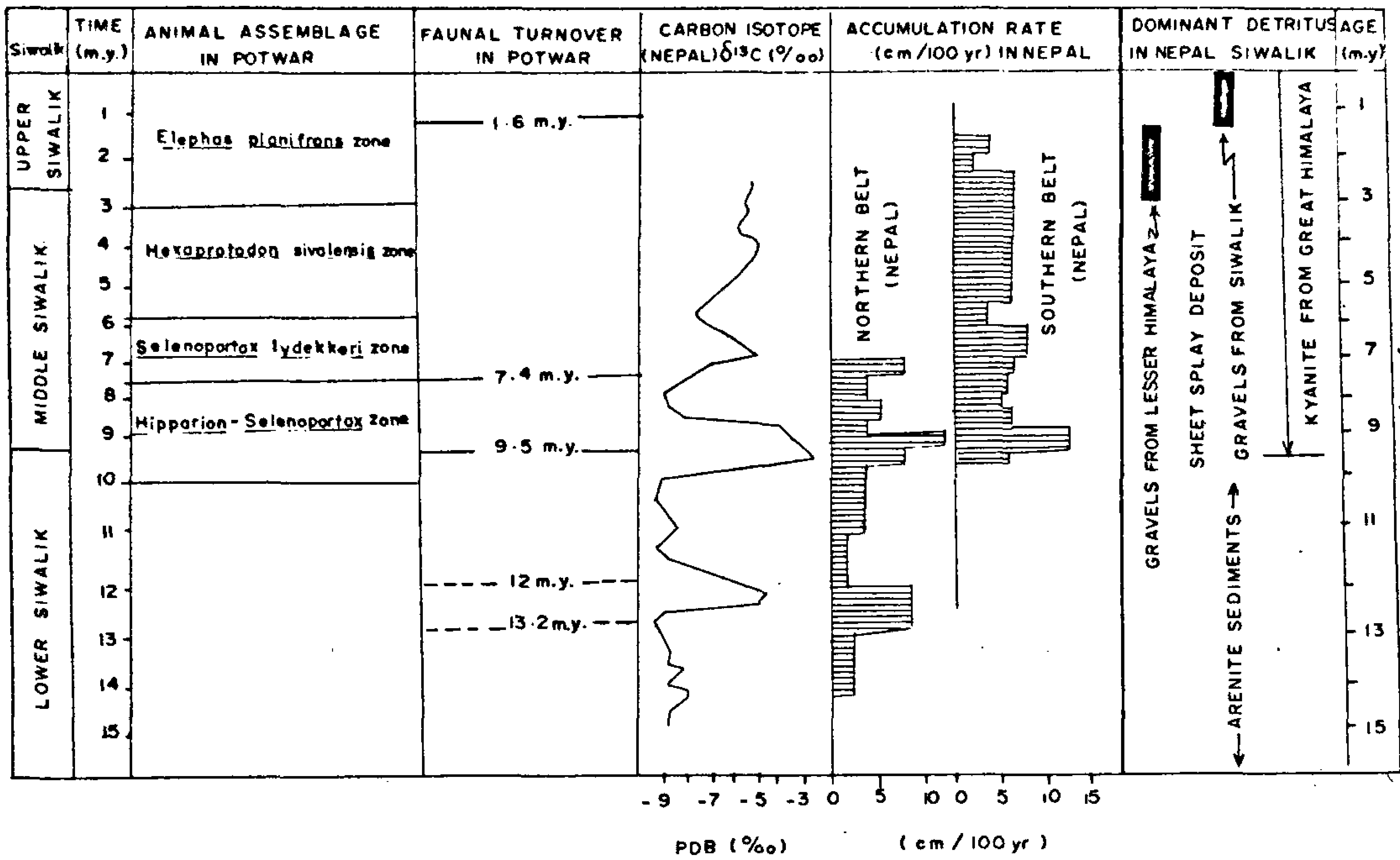

Figure 6. The Siwalik in south-central Nepal shows that detritals like the diagnostic mineral kyanite (along with grains of gneiss) make their first appearance in the sediments at 9.2 m.y., indicating exhumation and uplift of the provenance – the Great Himalaya. Concomitantly, the rate of sediment accumulation increased 2.5 folds in the southern belt of the Siwalik. There was drastic faunal turnover in the Potwar Siwalik at 9.5 m.y. and 7.4 m.y. (Modified after Tanaka[16]).

Table 2. Faunal changes in the Siwalik

Siwalik faunal assemblage was three times richer than that of the present. Compared to just one species of elephant today, there were 30, and there were 15 genera of anthropoid apes.	
Marginalization or even extermination of indigenous animals, including rhinos, buffaloes and cows.	
Faunal turnover in Potwar Basin	9.5–7.4 m.y.
Appearance of three-toed *Hipparion* with pigs	9.5 m.y.
Immigration of *Stegodon* (proboscid), *Hexaprotodon* (hippo), *Selenoportax* (bovid)	7.4 m.y.
Appearance of *Vishnutherium* (giraffe), *Presbytes* (langur), *Elephas planifrons* (elephant)	6–5.3 m.y.

as late as 9.5 to 7.5 m.y. ago[1,2]. Admittedly, a few corridors could have been enough for immigration, however considering the bulky size of the immigrants and their wide distribution in Tibet, in the outer Lesser Himalaya and Siwalik domains, more than corridors were needed to permit this animal influx.

Exhumation of Himadri and acceleration of erosion

Denudation of the Himalayan province had begun in mid-Miocene as evident from the influx of clastic sediments associated with deep-water microfauna in the Bay of Bengal and Andaman-Nicobar domain[22]. There was however greatly increased delivery in the late Miocene of detritus derived through accelerating denudation of the rising mountains to the foreland Siwalik basin and to the Indian Ocean. This is evident from the following facts:

(1) There was nearly 2.5 fold increase in sedimentation rate (Figure 6) resulting from physical weathering due to uplift – from 0.12 mm/y to 0.30 mm/y at 11 m.y. in the Siwalik basin in Potwar (Pakistan)[23] and from 0.2 mm/y to 0.5 mm/y at 10 m.y. in the Arungkhola in south-central Nepal[24]. Obviously, the rapid rise of the mountain coupled with increased rainfall prompted brisk influx of sediments in the foreland basin (Table 3).

(2) The first appearance of diagnostic detrital kyanite in the heavy minerals along with grains of gneiss in the Siwalik sediments (Table 3, Figure 6) of Nepal at 9.2 m.y. (refs 25, 26) implies that the core of the Himadri (Great Himalaya) complex, which constituted high-grade metamorphics, had been exhumed and exposed to erosion by 10 to 9 m.y. ago. Floods or abrupt increase of calcic amphibole at 10.9 m.y. and other heavy minerals between 10.9 and 7.5 m.y. in the Bengal Fan of the Bay of Bengal[27] lends support to the deduction that the Great

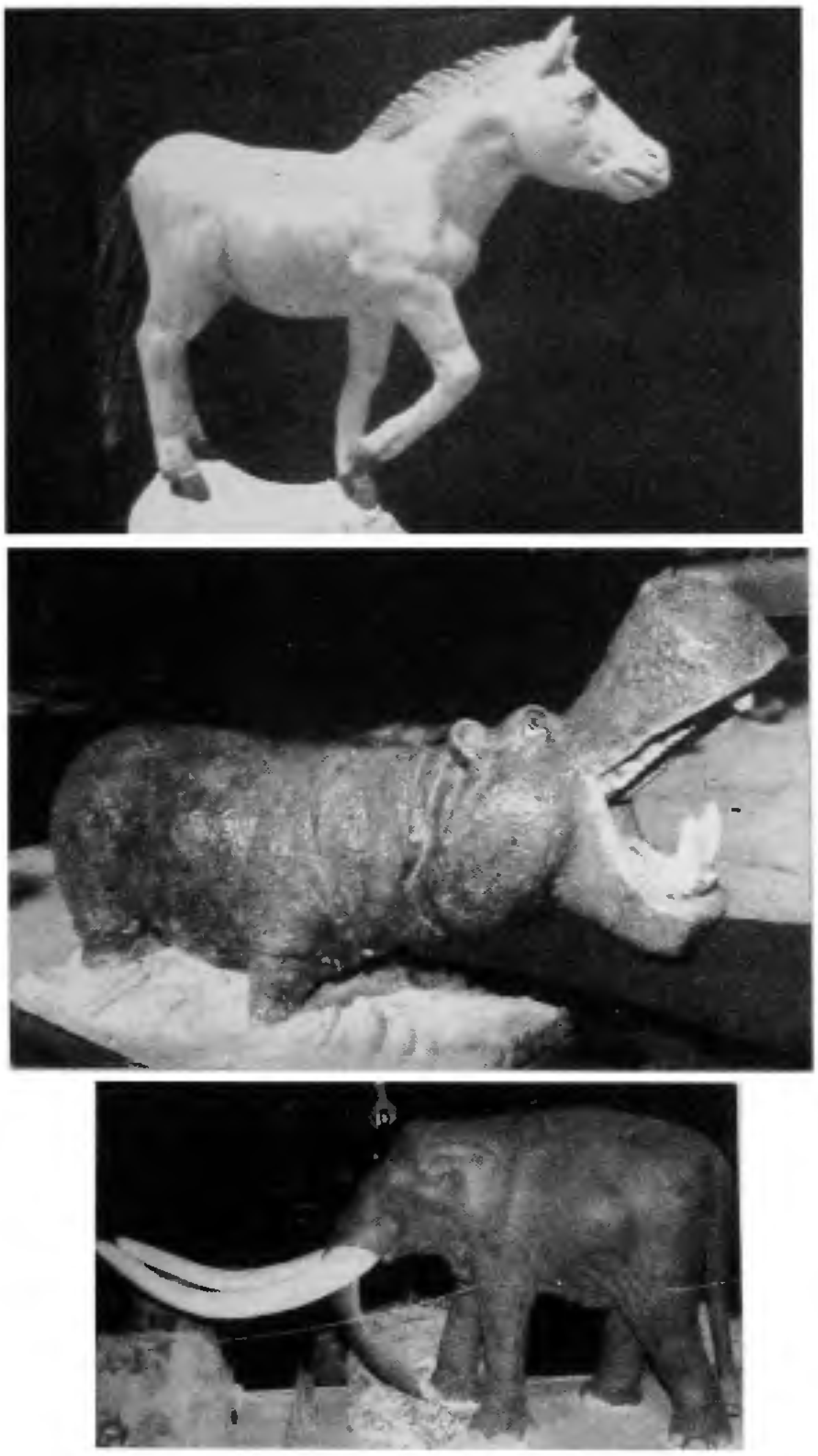

Figure 7. Attracted by extensive grasslands in the Siwalik terrane – as the climate grew warmer with shorter spells of rain – the grazing animals came from far away places. The *Hipparion* came at 9.5 m.y. from Europe and *Stegodon, Hexaprotodon* and *Elephas planifrons* from Africa appeared 7.4 to 6.0 m.y. ago. (Photos: Courtesy A. C. Nanda).

Himalaya rose up rapidly in the late Miocene (10.9 to 7.5 m.y. ago).

(3) The great abundance of sheet splay deposit in the Siwalik in south-central Nepal at about 10 m.y. (Figure 6) reflecting strong floods, obviously resulting from seasonal heavy rains[16] could imply that the climate had changed considerably.

(4) Rivers Ganga, Brahmaputra and Irrawaddy dumped huge quantities of sediments in the Bay of Bengal when intense spurts of upwelling took place in the intervals 8.5 to 7.3 m.y. and 6.3 to 5.0 m.y. (ref. 28). Neogene palaeobathymetry and seafloor tectonism of the Andaman–Nicobar domain also suggest that the Himalaya had started rising up around 9.8 m.y. (ref. 22).

Table 3. Accelerated erosion in the Himalaya and rapid sedimentation

Siwalik Domain	
Sedimentation rate increased 2½ folds:	
From 0.12 to 0.3 mm/y in Potwar Basin	11 m.y.
From 0.2 to 0.5 mm/y in Arungkhola	10 m.y.
First appearance of kyanite and gneiss grains in Nepal Basin	9.2 m.y.
Great abundance of sheet splay deposits in Nepal	10 m.y.
Ganga basin	
Intensity of chemical weathering increased	8–7 m.y.
Bengal fan	
Sediment influx increased five folds	11–7 m.y.
Predominance of smectite–kaolinite clays in fine sediments	7 m.y.
Dissolved material, reflected in strontium isotope ratio, abruptly increased	8 m.y.
Accumulation of phosphorus peaked	8 m.y.
Increase in land-derived organic matter (0.5% to 2%)	9–6 m.y.

(5) Both the Indus Fan and the Bengal Fan bear testimony to the accelerated episode of sudden increase in sediment influx from the terrestrial sources towards the late Miocene. In the Bengal Fan (Table 3, Figure 8), the sand–silt sediments derived largely (nearly 80%) from the Himalayan crystalline complexes – borne out by neodymium, strontium and oxygen isotopic compositional similarity[29] – gave way at 7 m.y. to preponderantly mud–clay material dominated by smectite–kaolinite clays derived from intensely weathered Himalayan rocks[30]. These developments imply a sudden change in climate in the late Miocene. Taking into consideration the whole of the northern Indian Ocean, the sediment influx increased five-fold in the period 11 to 7 m.y. (refs 31, 32).

(6) The rate of influx of dissolved material, resulting from chemical weathering in the provenance (the Himalayan rocks) abruptly increased in the late Miocene. This is reflected in the strontium isotope ratio of the sea water. The Ge/Sr ratio of opaline silica (of diatoms) increased at 8 m.y.[33]. The accumulation rate of phosphorus peaked at this time, implying dramatic transient shift in sedimentary and geochemical records from the oceans in the interval just before the 8 to 4 m.y. period[33]. Records in the basin of the Ganga and Brahmaputra rivers show that the intensity of the chemical weathering had increased to a peak between 8 and 7 m.y.[34]. Increase of land-derived organic matter along with clays (Figure 9) in the northern Indian Ocean from 0.5% to nearly 2% at about 9 m.y. (until about 6 m.y.) (ref. 35) point to the existence of terrestrial vegetations that must have been nurtured by the soil covering the Lesser Himalaya terrane then exposed to brisk denudation.

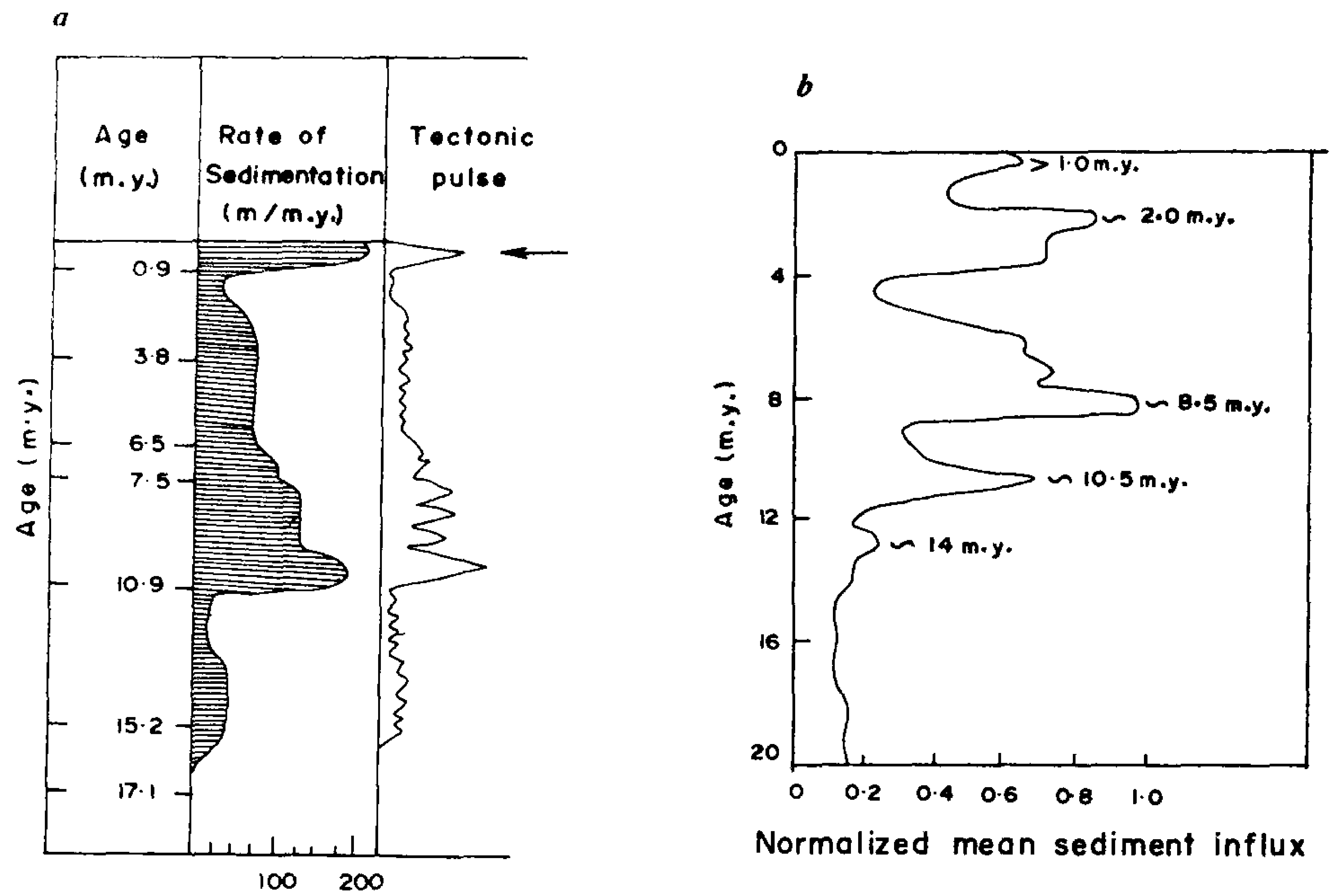

Figure 8. Influx into the Bay of Bengal of terrestrial sediments derived from the Himalayan terranes suddenly increased many fold in the period 11 to 7 m.y., and subsequently at about 0.9 to 0.8 m.y., implying increased erosion due to uplift of the Himalaya, coupled with stronger monsoon rains ((*a*) after Amano and Taira[27] and (*b*) after Rea[32]).

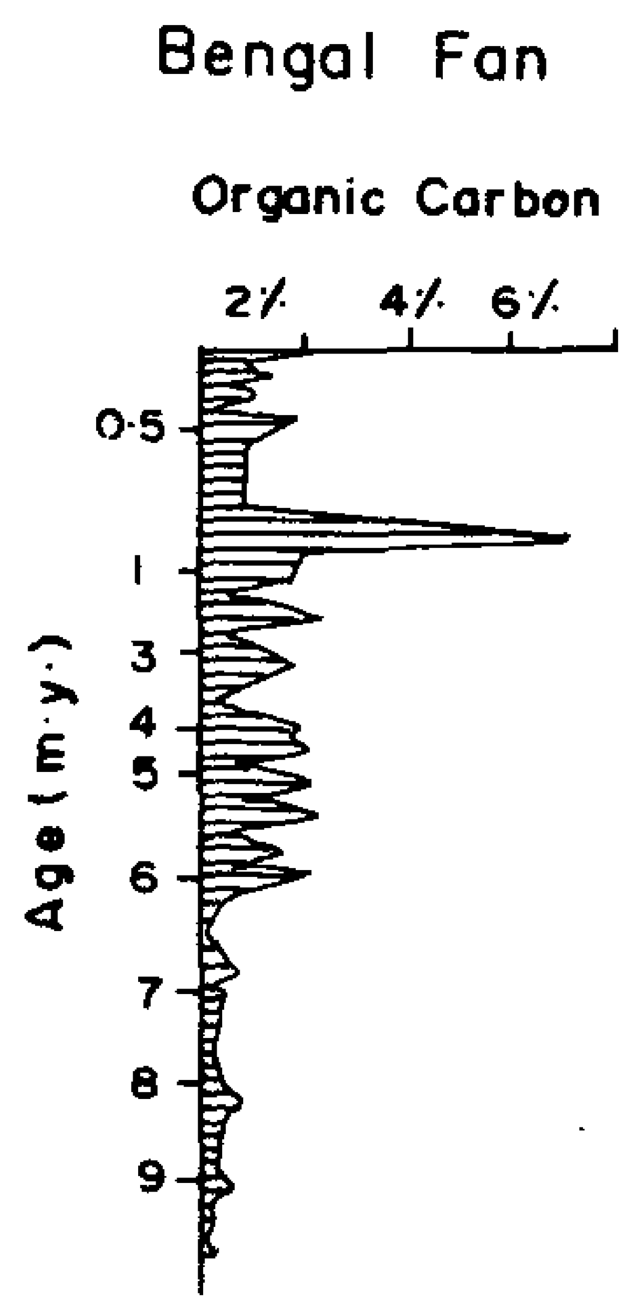

Figure 9. Organic carbon derived from the soils of the Himalayan terranes that were undergoing strong chemical weathering suddenly increased at 9 m.y., substantially at about 6.5 m.y. and very greatly at 0.85 m.y. as the data from Site 117 of the Ocean Drilling Programme show (ref. 35).

It is quite obvious that the period 11 to 7.5 m.y. witnessed accelerated erosion, particularly in the Himadri (Great Himalaya) terrane, which was lifted up rapidly in that period and exposed to heavy rainfall[2]. Revival of movement on the many regional faults of the Himalaya made it a lofty barrier. Apatite fission-track ages of nearly 8 m.y. in the Kohat area in Pakistan indicate movements on the Main Boundary Thrust at that time, and the muscovite-cooling ages from the zone of Main Central Thrust in NW Himalaya and Nepal show major peak of activity about 8 to 6 m.y. (ref. 4). There is little doubt that strong tectonic movements occurred on the boundary thrusts of the Himalaya all over its extent in the late Miocene.

Upwelling currents in the Indian Ocean

There was a sudden change in the nature of pelagic sedimentation in certain parts of the Arabian Sea between 10.5 and 8 m.y. – from the accumulation of opal-rich siliciclastics, which are characteristic of warm water having low surface productivity, to dominantly biogenic deposition of endemic upwelling species (Table 4, Figure 10). For example, *Globigerina bulloides* increased from < 5% to > 50% of the foraminiferal popu-

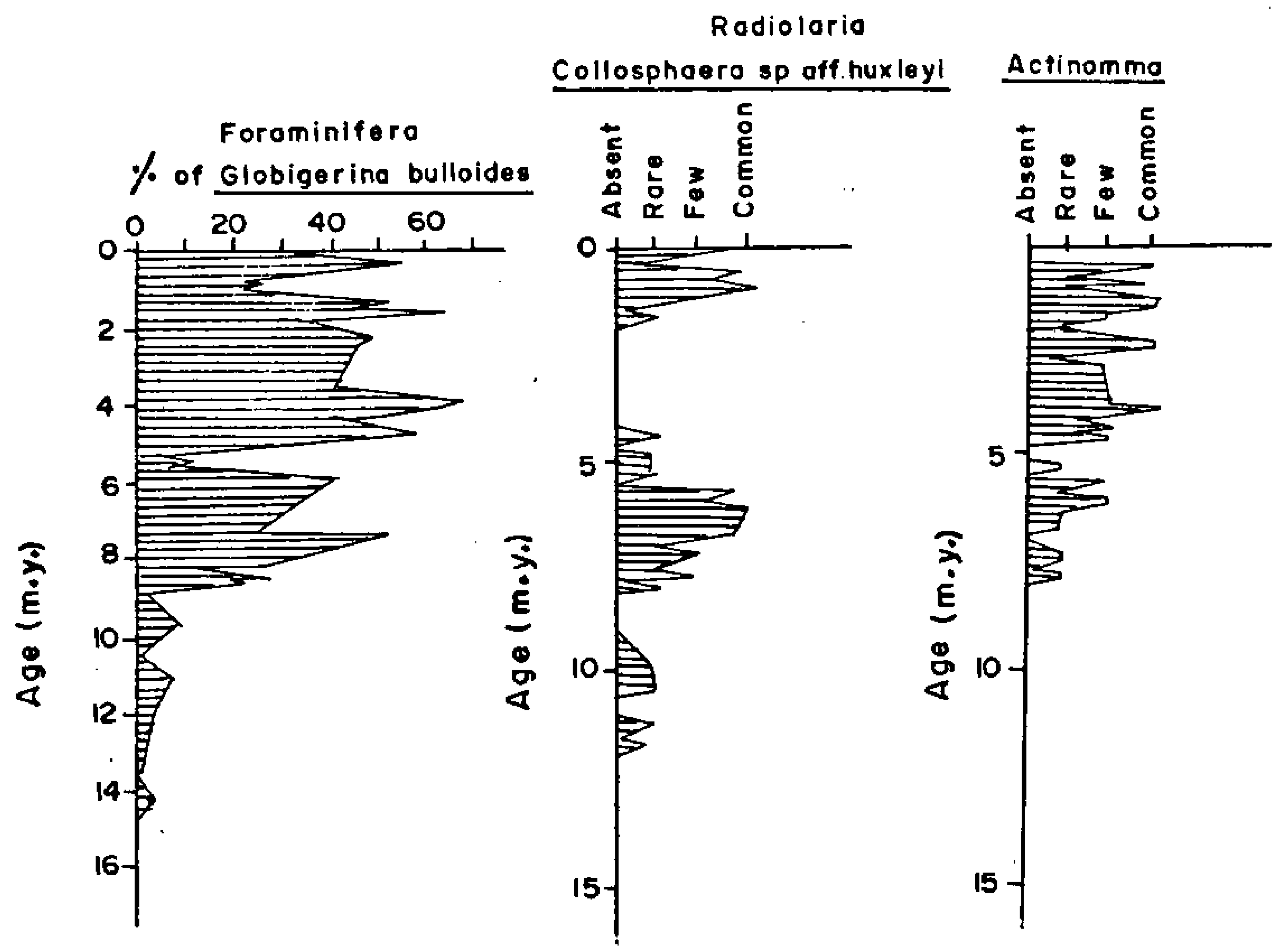

Figure 10. Sudden increase in the short period 8.5 to 7.4 m.y. of endemic upwelling species amongst the planktonic assemblages of foraminifera and radiolaria (at Site 722 on the Owen Ridge) in the Indian Ocean imply availability of nutrients, which only the upwelling currents could have brought to the surface 8.5 to 7.4 m.y. ago. Resurgence of upwelling currents means strong atmospheric currents of the monsoon. (Modified after Prell *et al.*[37] and Nigrini[38]).

Table 4. Beginning of upwelling currents in the Indian Ocean

Globigerina bulloides increased (< 5% to > 50% of forams)	8.5–7.4 m.y.
Actinomma increased suddenly (amongst radiolarians)	8 m.y.
Collosphaera sp aff. *huxleyi* increased	8 m.y.
Extinction of *Fohsella* group (deep-dwelling planktonic forams)	12–11 m.y.
Abundance of dominantly biogenic deposition of endemic upwelling species in place of siliciclastic sedimentation that occurred in warm water of low surface productivity.	

lation between 8.5 m.y. and 7.4 m.y. (refs 36, 37). Likewise, while the radiolarian *Actinomma* made its first appearance at about 8 m.y., the species *Collosphaera* sp aff. *huxleyi* increased in abundance (Figure 10) suddenly at 8 m.y. (ref. 38). These changes in marine planktonic assemblages imply sudden availability of nutrients which must have been brought to the surface by upwelling currents at about 8 m.y. (Table 4).

The activation (or resurgence) of oceanic upwelling currents is attributed to the initiation of the strong SW monsoon[36]. There were indeed great changes in the faunal assemblages of the planktonic foraminifera – including the extinction of *Fohsella* group in the interval 12 to 11 m.y., which is associated with profound changes in the tropical Indian and Pacific Oceans[39]. These climatic events are coincident with regional tectonism and mark the beginning of strong south-westerly monsoon winds in the atmosphere, obviously influenced by severe tectonism. The blowing of the strong south-westerly winds 10.5 to 8 m.y. ago indicates that the Himalaya mountain had suddenly risen up and formed a barrier to the then prevailing smooth west-to-east flow of the air currents. However, Srinivasan and Sinha[39] attribute this change to severance of connection of the tropical Pacific with the Indian Ocean due to northward movement of Australia and resultant evolution of the Indonesian Archipelago, the latter development causing drastic change in the equatorial circulation.

Advent of Ice Age

The Indian Crust in the Central Indian Ocean experienced deformation in the early Pliocene nearly 4 m.y. ago[6]. And the already high Himalaya rose still higher in several pulses in the Quaternary period 4 to 2 m.y. There were revivals of movement on the boundary faults like the Trans-Himadri Fault (THF), the Main Central Thrust (MCT), and the Main Boundary Thrust (MBT), among others, in the late Pliocene–Pleistocene (Table 5). The uplifted ranges of the lofty Himalaya must have diverted the even flow of moist winds and created large cool areas, inducing precipitation of snow[40].

The beginning of the Quaternary witnessed very strong spurt of tectonic movements when the crustal disturbance of an exceptional severity convulsed the outer ranges of the Lesser Himalaya and the Siwalik[2]. The mountain front virtually collapsed as catastrophic landslides ravaged the abruptly uplifted ranges and massive landslides and attendant debris flows piled the detritus in the form of the Upper Siwalik Boulder Conglomerate[2]. The event has been dated 1.7 to 1.5 m.y. (refs 41, 42). Quantitative planktonic foraminiferal data integrated with isotopic record of the Indian Ocean also reveal a major event at 1.8 m.y. (ref. 12). This major event must have made the Himalaya even loftier than it was in the late Miocene. Naturally colder condition conducive to ice formation developed in higher realms[2]. The cold condition precursor to glaciation had set in as early as 2.5 m.y. in the Kashmir Valley as testified by the fossils of rodents *Kilarcola* and *Microtus* found in the upper part of the Karewa Lake succession[43]. The early Pleistocene uplift may have brought a very large part of the Himalaya under severely cold conditions. It may be mentioned that the ice sheets in the northern hemisphere formed about 3 to 2.5 m.y. ago.

Another compressional tectonic build-up in the Oceanic Crust in the Central Indian Ocean was manifest in the perceptible deformation of sediments about 0.8 m.y. (ref. 6). In the Himalayan province the tectonic activity around 0.9 to 0.8 m.y. (Table 5) (ref. 27) caused extremely fast erosion and resultant shooting up of sediment deposition in the Bengal Fan (Figure 8) – from 20–70 m/m.y. to > 200 m/m.y. (ref. 44). Simultaneously there was peak concentration of land-derived organic matter in the Arabian Sea (Figure 9) at 0.85 m.y. (ref. 35), implying uplift of the soil-covered terrains in the Himalaya. (The soils contained organic matter derived from the vegetation that covered the land.) The 1.6 and 0.8 m.y. events of considerable tectonic movement must have lifted up the blocks bounded by active faults to such elevations (Figure 11) that the mountain tops must have become snow-covered. Glaciers spread far and wide over Potwar, Kashmir, Kangra and in the Ladakh and Tibet area, besides the whole of the Himadri (Great Himalaya) terrane.

After large parts of the mountain domain had come under the sway of glaciation, the south-west monsoon weakened, giving way to spells of dry cold climate. There was in fact an oscillation of glacial–interglacial epochs – four successive advances of glaciers from the higher mountains in the NW Himalaya. The glaciers left behind gravelly detritus in the Kashmir valley, the finer material of which was spread far and wide as loess by the dry winds that blew. The 25 m thick loess deposits atop the Karewa Lake sediments contain quite a few horizons of palaeosols, indicating warm humid interludes within an otherwise long period of dry-frigid condition. The monsoon was weaker during the glacial period and stronger during the interglacial epochs.

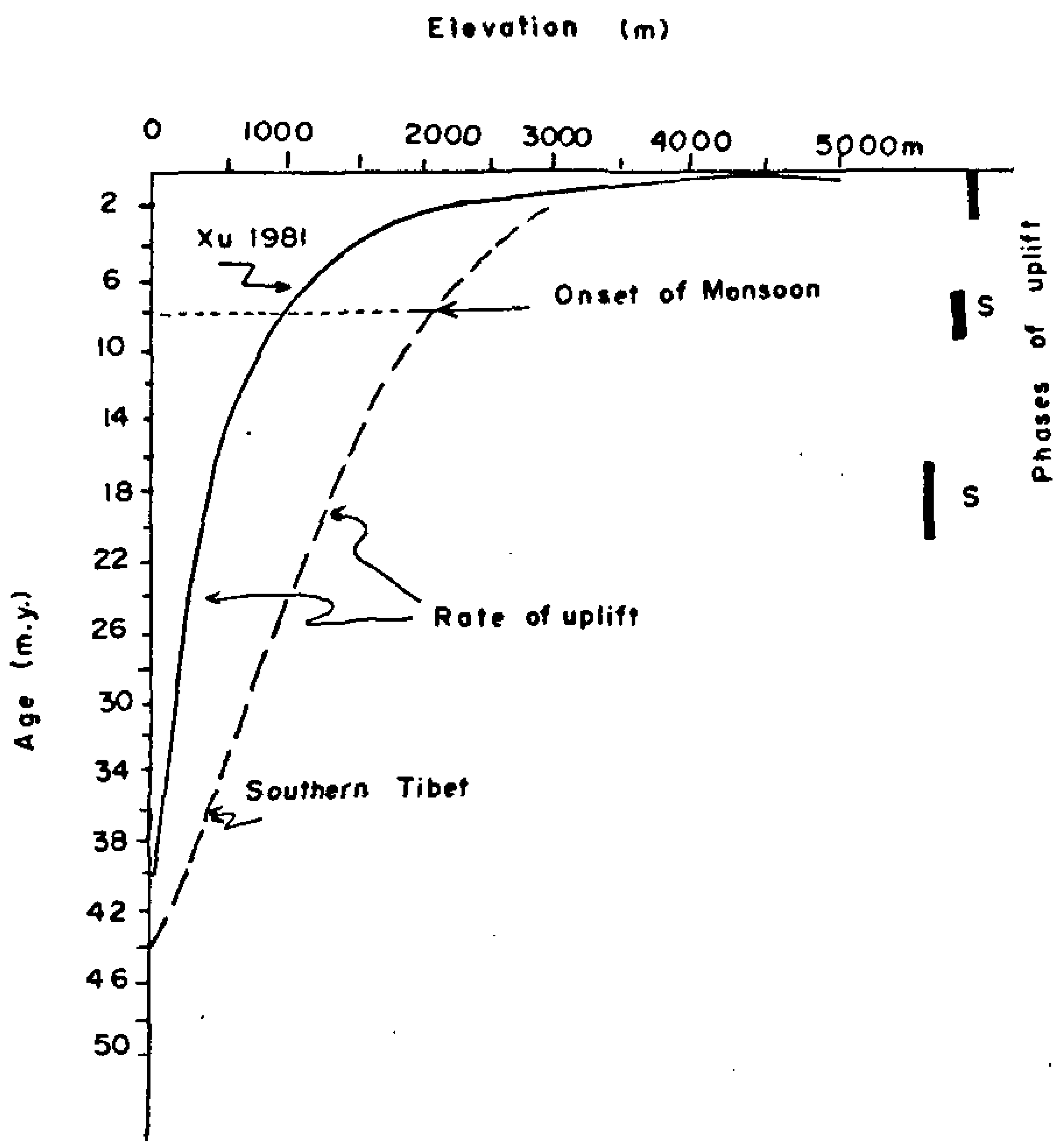

Figure 11. Tibet–Himalaya landmass must have been lifted up to its tremendous elevation very rapidly in the last 2 m.y. (after Sakai[65]). Even though there is slight difference on the perception of the rate of uplift, it will be evident that the Himalaya along with Tibet rose very rapidly in the last 11–10 m.y.

Table 5. Late Quaternary tectonic movements: Consequences

Deformation of the Indian Ocean Crust	4 m.y.
Revival of movement on MCT, MBT, etc. in the Himalaya	4–2 m.y.
Exceptionally severe movements on MBT and in Siwalik	1.6 m.y.
Deformation of the Indian Ocean sediments	0.80 m.y.
Extremely fast erosion in the Himalaya and shooting up of sediment deposition in Bengal Fan from 20–70 m/m.y. to >200 m/m.y.	0.9–0.8 m.y.
Peak influx and concentration of land-derived organic matter in the Arabian Sea	0.85 m.y.

Epochs of high rainfall and aridity in the Holocene

The prolonged period of late Quaternary dryness, including the time of Last Glacial Maximum (20,000 to

16,000 yr BP) persisted until nearly 11,000 yr BP. Then the climate became progressively wetter and warmer as the SW monsoon intensified, reaching its peak in the early to middle Holocene. The wet and warm epoch was followed by a time of severe aridity around 3500 yr BP and lasting until about 2000 yr BP (Table 6).

Warm–wet conditions started about 10,500 to 10,000 yr BP when the south-west monsoon intensified, as evidenced by detritus brought by rivers to the Arabian Sea[45]. Strong upwelling of the oceanic currents in the Arabian Sea[46] generated by intensified monsoon prompted prolific growth and morphological sophistication of certain planktonic foraminifers 10,500 to 5000 yr BP (Table 6) (refs 47, 48). Planktonic foraminifers from the cores of the Oman margin demonstrate intensification of monsoon at 12,000 yr BP and reaching the peak between 10,000 and 5,000 yr BP[49]. Higher rainfall brought to sea the pollens of vegetation that grew on land during that period, such as those studied off Karwar coast[50,51]. The $\delta^{13}C$ values of peats in palaeolakes (e.g. at Colgrain) of the Nilgiri Hills confirm a very wet spell from 9000 to 8000 yr BP[52]. Higher rainfall during the period 10,800 to 3,500 yr BP is testified by the pollen profiles of lakes Didwana and Lunkaransar in western Rajasthan (Table 6) (refs 53, 54) when the lake levels reached their peaks about 6000–4000 yr BP, the rate of inflow having peaked probably at 6000 yr BP[55].

To the east in central Indo-Gangetic plains heavy rainfall washed away salts and carbonates from the soil and caused development of a better drainage around 8000 yr BP[56]. Pollens from the Dokrani peat in the Gangotri glacier area in the Great Himalaya (in Garhwal) indicate a warm–wet spell of climate between 6500 and 4000 yr BP[57]. To the far north-west in Ladakh, pollens of the Tsokar lake testify to the expansion of the *Juniperus* community of flora under warmer–moist condition around 10,000 yr BP[58]. In western Tibet the water level of the BangongCo lake reached the maximum about 6000 yr BP[59]; the lakes in south-eastern and southern Tibet bear testimony to higher rainfall in the period 7500 to 3000 yr BP[60].

Evidently, the larger part of the Indian subcontinent and adjoining Tibet experienced warm and wet climate 10,000 to 4000 yr BP.

By 3500 yr BP the SW monsoon had weakened considerably, the upwelling currents became slack and the land witnessed onset of aridity. Slackening of the upwelling currents and therefore of the monsoon is evident from the decline in planktonic foraminiferal growth in the sea off the Oman coast at 3500 yr BP[49,61]. Reduction of humid conditions and increase in grassland in the continent at this time is borne out by the pollens washed down to the shelf by rivers[50]. The $\delta^{13}C$ value of lake peats from the Nilgiri Hills indicate onset of dry condition around 5000 yr BP and lasting until about 2000 yr BP[52].

The water in the west Rajasthan lakes became increasingly saline and the level dropped around 4000 yr BP[55]. The pollens indicate arid condition prevailing at that time[53]. The pollens of the peat in the Dokrani glacier in Garhwal, likewise point to decline in rainfall, climaxing in high aridity between 3500 and 3000 yr BP[57]. The pollen testimony demonstrates that the arid conditions prevailed around 3500 yr BP (3550 ± 120) in the Bhimtal Basin in south-central Kumaun[62], about 4500 yr BP in the Rara Lake basin in western Nepal[63], approximately 5000 yr BP in the Karewa Basin in Kashmir[64], in the period 4000 to 3000 yr BP in the BangongCo Basin in AksaiChin[59] and 3000 to 1500 yr BP in southern Tibet[60].

The 4000–2000 yr BP period seems to be a time of high aridity all over the Indian subcontinent.

As Wasson[55] argues, 'orbital-forcing is not the only mechanism causing major changes to the monsoon circulation', it is likely that the tectonic uplift of the Himalaya displaced the low-pressure area and brought about an epoch of high rainfall and subsequent aridity. It would be very interesting to find out whether there is any correlation between the oscillation of the climate (and change in the oceanic current circulations) in the Holocene and the spurts of movements on the active faults that delimit the boundaries of the Himalayan terranes.

Table 6. Holocene climate changes

Area	Warm–wet (yr BP)	Hot–dry (yr BP)
Arabian Sea (planktonic forams)	10,500–5,000	3500
Western coast (terrestrial detritus)	10,500–10,000	
Karwar coast (land-derived pollens)	10,500–5,000	3500
Nilgiri Hills ($\delta^{13}C$ values of peats)	9,000–8,000	5000–2000
Didwana–Lunkaransar lakes in Rajasthan (pollen profiles)	10,800–4,500	4000–Present
Gangotri glacier (pollens in sediments)	6,500–4,000	3500–3000
Tsokar lake, Ladakh (*Juniperus* flora)	10,000	
BangongCo lake, AksaiChin (pollens)	6,000 (max.)	4000–3000
South-eastern Tibet (pollens in lakes)	7,500–3,000	3000–1500
Bhimtal Basin, South Kumaun (pollens)		3550 ± 120
Rara lake, West Nepal (pollens)		4500
Karewa lake, Kashmir (pollens)		5000

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