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Palaeosols of the Siwalik Group as a 15 Myr Record of South Asian Palaeoclimate

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Abstract

Detailed measurement and sampling of stratigraphic sections of the Siwalik Group in the Potwar Plateau of Pakistan have revealed abundant buried soils within this thick sequence of Sub-Himalayan outwash deposits. Reconnaissance studies elsewhere indicate that palaeosols are common throughout this extraordinarily thick and complete Neogene succession. The palaeosols have been studied using a pedotype approach, in which they are classified in the field using local names into distinctive types of profiles, analogous to soil series of soil survey. Field, chemical and petrographic data on each pedotype represented is then interpreted as evidence for palaeoenvironmental conditions, such as climate and vegetation.

Interbanded ferruginous and calcareous concretions, diffuse calcareous horizons and both shallow mats and deeply penetrating root traces in the palaeosols are evidence for monsoonal palaeoclimate going back to at least 15 myr ago on the Indian subcontinent. Repeated late Miocene expansion of blue-grey coloured sandstone palaeochannels reflect variation in the extent of axial (Protogangetic) river channels, at the expense of buff-coloured sandstones of alluvial fans draining foothill ranges. Evidence from palaeosols and their carbonate nodules indicate that expansion of the Protogangetic braidplain occurred during drier than normal periods that recurred at a Milankovitch frequency of about 50 kyr. Superimposed on these short term palaeoclimatic fluctuations was a long term climatic drying in the Potwar Plateau from moist monsoon forest to dry monsoon forest by 8 myr ago. Extensive grasslands by 6 myr ago are indicated by an increasing abundance of brown mollic palaeosols and a marked shift towards heavier carbon isotopes of pedogenic carbonate thought to reflect the advent of C_4 vegetation. Furthermore, mollic palaeosols younger than 6 myr ago may have a calcic horizon up to 1 m below the surface, whereas mollic palaeosols before that time are not known with a calcic horizon deeper than a compaction-corrected depth of 32 cm. Considering the relation between mean annual rainfall and depth to calcic horizon, this may indicate climatic expansion of the grassland-woodland ecotone from near the 400 mm isohyet to its present position at about 750 mm. The 6 myr ago isotopic event has now been found also in East Africa and North America, where brown mollic palaeosols also become more common at the same time. The Late Miocene expansion of grasslands was thus a global event and may reflect atmospheric drawdown of $C0_2$, cooling and drying that presaged Ice Ages of the Quaternary.

Introduction

The Siwalik Group is an alluvial apron to the magnificent wreath of mountains, the Hindu Kush, Himalayan and Burmese Ranges, that adorn the northern margins of the Indian subcontinent. Like these great mountains, Siwalik sediments also impress with superlatives. This sequence of sandstones and red claystones is extraordinarily thick, perhaps as much as 8 km (Harrison *et al.* 1993). Recent biostratigraphic and palaeomagnetic studies have also shown that the Siwalik sequence is also remarkably complete at a resolution of 1000 years, accumulating at a rate of 0.1-0.4 mm/yr for the past 15 myr (Johnson *et al.* 1985; Harrison *et al.* 1993). The Siwaliks also provide an exceptionally detailed record of Neogene non-marine environments, which have been interpreted from the evidence of fossil pollen (Mathur 1984), leaves (Awasthi 1982), and bones (Vashisht 1985; Barry *et al.* 1985).

Palaeosols provide an additional source of palaeoenvironmental information and have been widely recognized in Siwalik sediments (G.D. Johnson 1977; G.D. Johnson *et al.* 1981; Visser and Johnson 1978; Tandon and Narayan 1981; Behrensmeyer and Tauxe 1982; Retallack 1985, 1991). Palaeosols can be recognized by means of root traces and other evidence of terrestrial organisms, particularly termite burrows and pellets. They also are conspicuous in their soil-like horizonation, including slickensided clayey (Bt in soil shorthand) and nodular calcareous (Bk) subsurface horizons. In addition, palaeosols can be recognized from distinctive soil structures, including clay-lined clods (peds with argillans in soil terminology) and highly birefringent microfabric (sepic plasmic fabric).

Interpretation of palaeosols is compromised by alteration after burial, particularly by dramatic loss of dispersed organic matter, reddening by dehydration of ferric hydroxide pigments and by local chemical reduction around buried organic matter (Retallack 1991). Other fossil records of ancient environments also are compromised by the vagaries of preservation. Fossil bones are seldom found in the acidic and reducing environments that favour preservation of pollen, and leaves and fossil plants are seldom found in alkaline and oxidizing environments that favour preservation of bones (Retallack 1984, 1991). Palaeosols also are subject to preservational biases. Weakly developed soils are more common than strongly developed ones in fluvial sequences and soils formed under open vegetation are more likely to be eroded away than those under forest (Retallack 1990, 1991). Nevertheless palaeosols are more abundant in Siwalik sediments than fossil localities and are a potentially valuable source of information on the palaeoenvironments of fossils and the conditions of their preservation.

A Pedotype Approach to Palaeosols

The Siwalik Group provides special challenges because of the sheer number of palaeosols and their complex lateral interfingering within a variety of alluvial facies. In the Potwar Plateau of Pakistan near Khaur (Fig. 1), a trench excavated for the detailed study of palaeosols contained 80 separate profiles of eight distinct kinds within 58 m of strata (Fig. 2). This number of palaeosols is typical for clayey Siwalik sediments, and long sections contain literally thousands of successive buried soils. There are too many palaeosols for each to be named and characterized as a geosol, as recommended by the North American Commission on Stratigraphic Nomenclature (1982), or pedoderm of the Australian usage (Brewer *et al.* 1970). In any case each palaeosol is not mappable laterally with any confidence, because it has either been

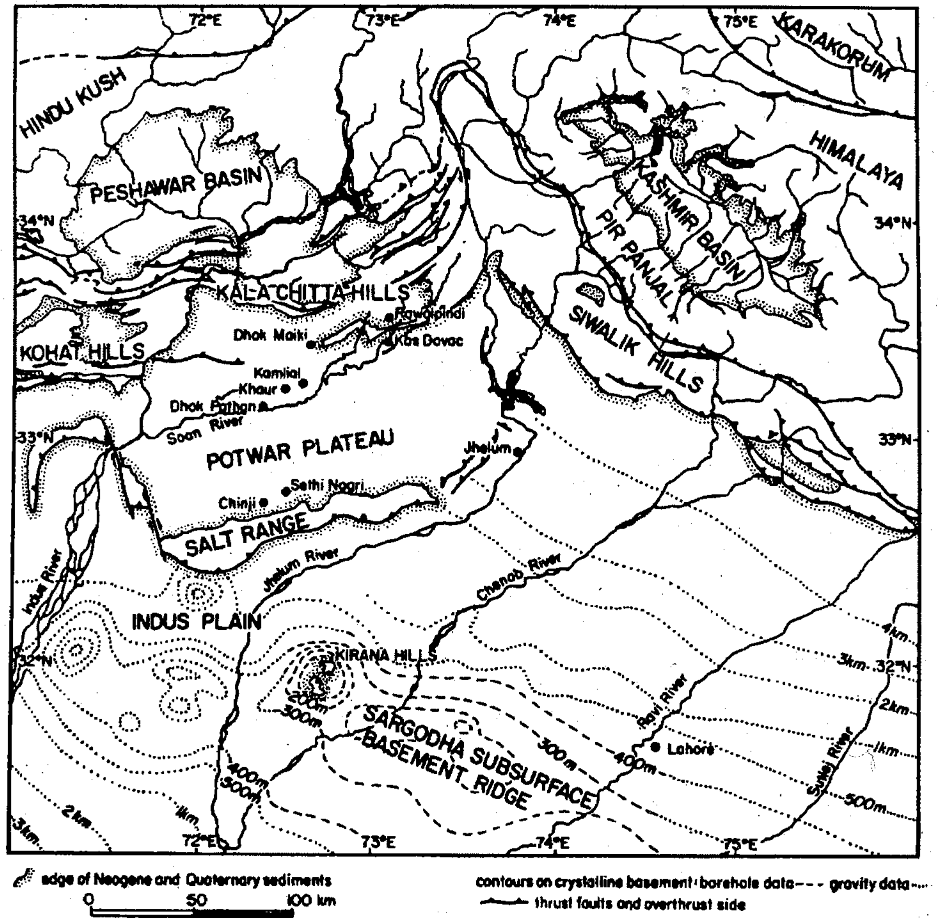

Fig. 1: Studied localities for palaeosols, major faults, sedimentary basins and contoured Precambrian basement to Indo-Gangetic alluvium in northern Pakistan and India (modified from Retallack (1991), with permission of Oxford University Press)

locally eroded away by palaeochannels or merged into other palaeosols. One particularly striking palaeosol traced laterally for 30 km was cut by a palaeomagnetic isochron (Behrensmeyer and Tauxe 1982), and is thus demonstrably of different age along the strike. For these same reasons it is difficult to apply the pedofacies approach of Bown and Kraus (1987) or that of soil facies of Morrison (1978) and of Birkeland (1984). These are commonly conceptually confused (e.g. by McFadden and Knuepfer 1990), and are lateral subdivisions of geosols (soil facies) or of sedimentary facies dominated by one or more palaeosols (pedofacies). These stratigraphically oriented approaches are not appropriate for description of isolated palaeosols, for complexes of profiles whose lateral inter-relationship is unclear or for long sequences of palaeosols studied in order to assess palaeoenvironmental change through time.

An alternative and more flexible scheme for the naming and characterization of palaeosols can be envisaged analogous to the procedure of soil survey (Soil Survey Staff 1951, 1962). Each distinctive kind of palaeosol can be given a descriptive name based on field characteristics. The names can be based on the localities where the palaeosol is found, but so many such names are already employed for geological formations and modern geomorphic and soil mapping units, that it may be necessary to use other names. In Pakistan I employed common Urdu descriptive words (Fig. 2). Lal palaeosols are red and have a clayey subsurface (Bt) horizon as well as scattered calcareous nodules (Bk), whereas Pila palaeosols are similar although less clayey and brown with fine soil clod structure, and Pandu profiles are silty, grey and have sub-

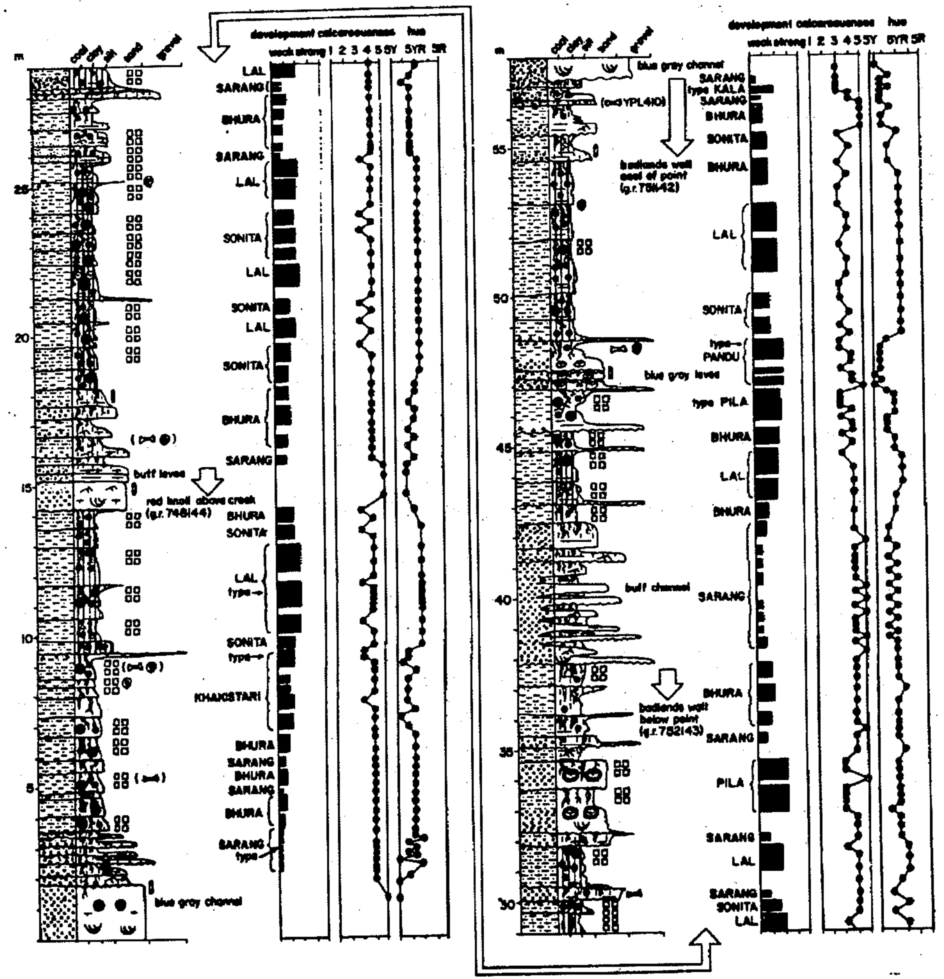

Fig. 2: A measured section of late Miocene (8.5-8.6 myr) palaeosols in the lower Dhok Pathan Formation at a stratigraphic level laterally equivalent to the Nagri Formation, west of Kaulial village, Potwar Plateau, Pakistan. Development and calcareousness from scales explained by Retallack (1990) and hues from a Munsell Colour Chart. (Lithological key as for Fig. 3)

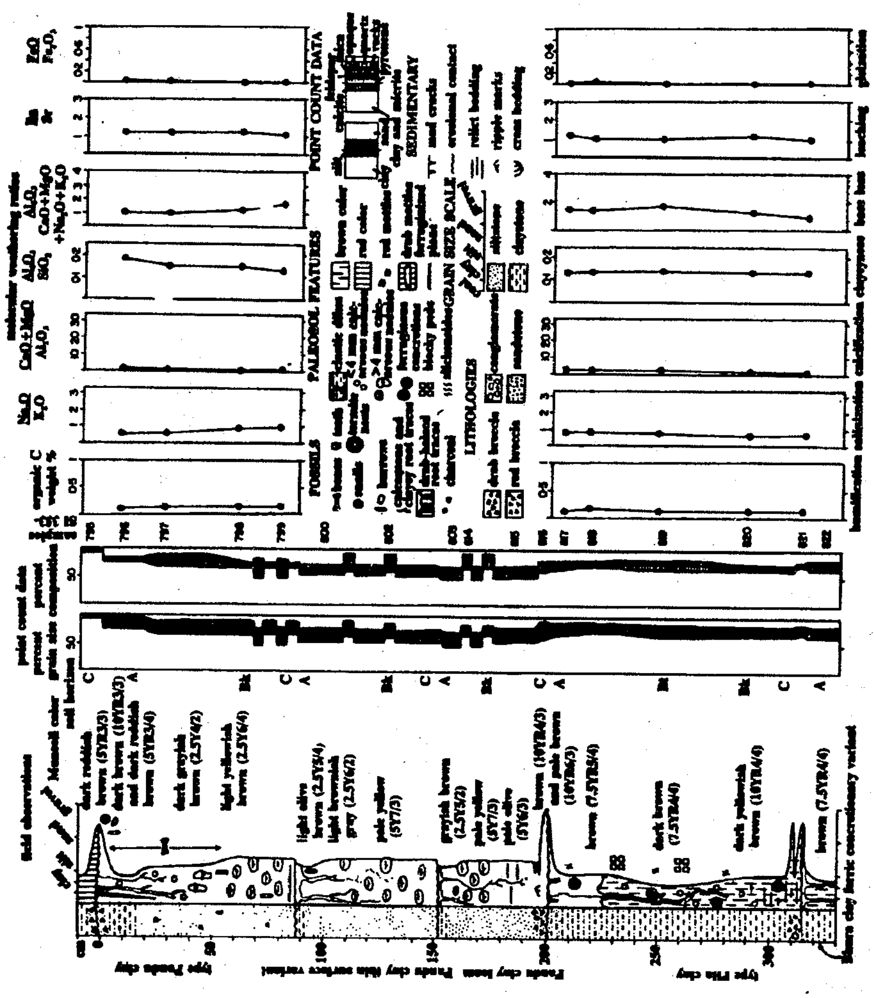

Fig. 3: Detailed measured section. Munsell Colours, soil horizons, grain size, mineral composition, organic carbon content and selected molecular weathering ratios for selected palaeosols at 45.2 to 48.8 m in Figure 2

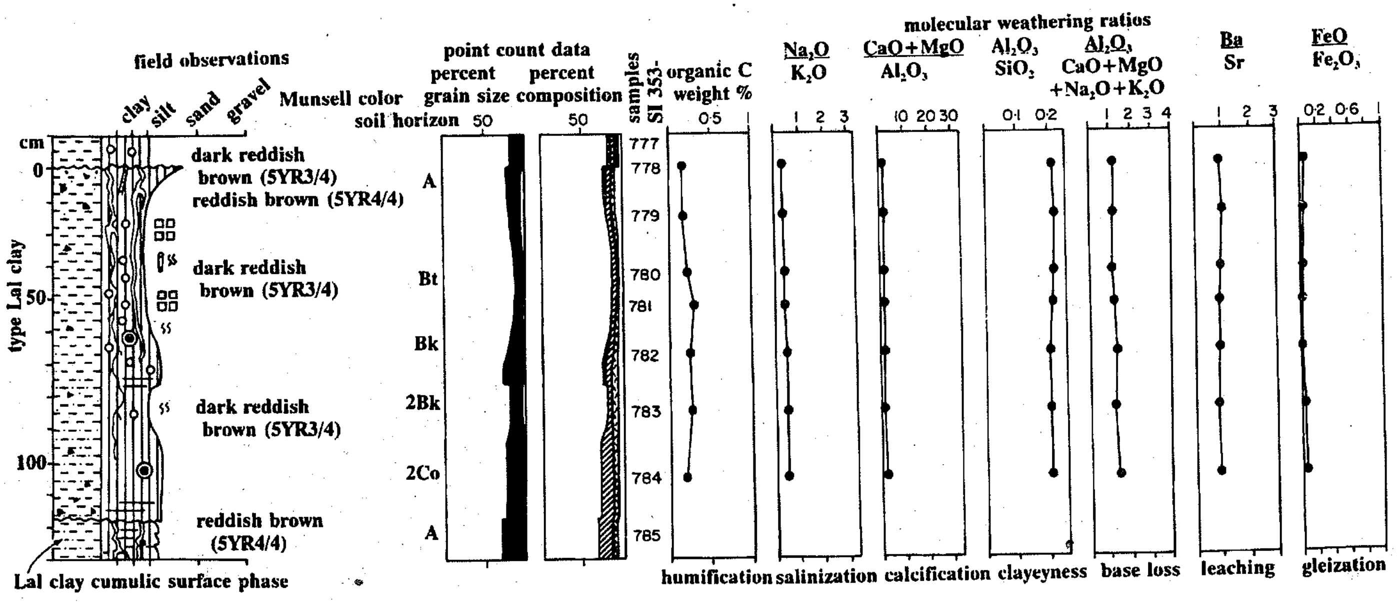

Fig. 4: Detailed measured section, Munsell colours, soil horizons, grain size, mineral composition, organic carbon content and selected molecular weathering ratios for a palaeosol at 11.6-13 m in section of Figure 2. Lithological symbols as for Figure 3

surface calcareous nodules (Bk). Each kind of palaeosol should be based on at least one profile studied in detail (Fig. 3 and 4), designated the type profile. The term "type" can be used to specify the reference profile, and other profiles studied in detail can be specified using textural terms such as "clay loam" or other features such as "nodular variant" (Fig. 3).

In this example it can be seen that Lal, Pila and Pandu are used in a sense analogous to a soil series of a soil survey. For many years, I have used the phrase "palaeosol series" in just this way (Retallack 1977), but recent discussions at the "Second International Palaeopedology Symposium in Monticello", Illinois have persuaded me that this terminology should be abandoned for palaeosols, and perhaps also for soils as well. In soil science, soil series have unfortunate dual usage both as descriptive local mapping units for soil survey (Soil Survey Staff 1951 and 1962) and as the lowest rank in a highly interpretive system of soil classification (Soil Survey Staff 1975). In geology, series are something else again, high ranking chronostratigraphic units also named after localities (North American Commission on Stratigraphic Nomenclature 1982). To avoid confusion, I recommend that descriptive mapping units should instead be called **pedotypes,** meaning simply kinds of soils or palaeosols, such as Lal, Pila and Pandu pedotypes. Apart from the change of name, the *Soil Survey Manual* remains a useful guide to the mapping of both palaeosols and soils.

Pedotypes are established and modified in the field as additional profiles are examined, but each pedotype of palaeosols can also be interpreted in terms of its past environment, in the same way as land use can be inferred for modern soil mapping units. Detailed interpretations of each of the ten pedotypes currently recognized in the Siwalik Group of Pakistan has been presented elsewhere (Retallack 1991). What follows here is a summary and discussion of the palaeoclimatic implications of this work.

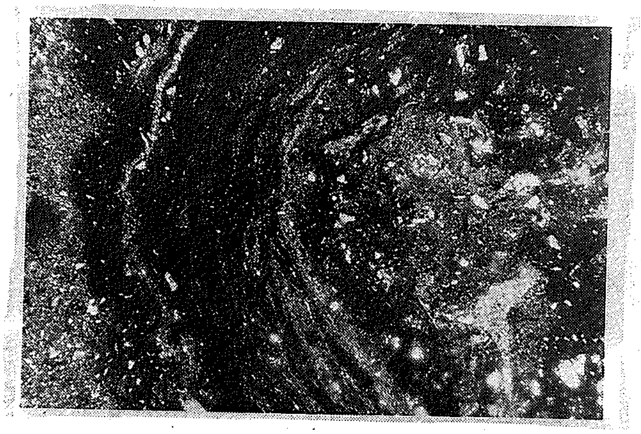

Fig. 5: Petrographic thin section under crossed nicols of admixed sparry calcite (at arrows) as interlayers within and crystal tubes penetrating a ferric concretion from the C horizon of the Pila palaeosol of Figure 3. Smithsonian Institution specimen 353821. Scale bar is 1 mm

Geological Antiquity of Indian Monsoons

Several features of the Pakistani palaeosols studied can be interpreted as evidence for marked seasonality of rainfall during the Late Miocene (Retallack 1991). Similar features were seen in palaeosols as ancient as Middle Miocene (15 myr ago in the Kamlial Formation near Khaur and Talagang) and also have been reported from Holocene Indian soils (Sehgal and Stoops 1972; Courty and Federoff 1985). Especially noteworthy is the intimate admixture of iron oxide with calcium carbonate in Indian soils and palaeosols. Ferruginous concretions in the Miocene palaeosols may include calcareous layers and are penetrated by calcareous rhizoconcretions (Fig. 4). The ferruginous concretionary layers may represent dry season oxidation of iron mobilized in a chemically reduced form in waterlogged soils of a wet season followed by carbonate accumulation later in a dry season. It could be argued that these soils and palaeosols reflect long term climatic change with a period of wet climate followed by a period of dry climate, or vice versa. However, these features are found in soils developed on alluvium overlying archaeological sites no more than 400 years old (Courty and Federoff 1985). Palaeomagnetic dating of the Miocene palaeosols indicates that the entire sequence of 58 m (Fig. 2) accumulated in less than 100 kyr ago (Tauxe and Opdyke 1982). Some 56 of the 80 palaeosols in this section (all except Sarang pedotype) are sufficiently well developed to show intergrown carbonate and iron stain, giving an average duration of only 1.7 kyr for each palaeosol, well short of periods of established Milankovitch climatic fluctuation (Hays *et al.* 1976). The complex intergrowth of iron stain and carbonate is a distinctive feature of Indo-Pakistani Miocene palaeosols, not seen in other Tertiary palaeosols of my experience (Retallack 1990, 1991).

There are other indications that Indian monsoonal circulation extended back at least to the Middle Miocene in the distinctive form of the calcic horizon of Siwalik palaeosols and Indian soils, which are unusually diffuse. These profiles commonly have calcareous nodules scattered throughout the profile, so that identification of a calcic horizon is based on the relative abudndance of nodules (Retallack 1991). This is distinct from the arrangement of calcareous nodules in soils and palaeosols of non-monsoonal climate, where the nodules form a distinct horizon at some depth below soil horizons with few if any nodules (Gile *et al.* 1980; Retallack 1990). The unusually diffuse calcic horizons of monsoonal soils and palaeosols may reflect dry season variation in the wetting front within the soil.

Also documented from Miocene palaeosols of Pakistan was fossil charcoal, identified from its morphology as well as from the characteristic fusion of the middle lamella between cell walls visible under the scanning electron microscope (Retallack 1991). Fires common enough to produce charcoal that could persist in such oxidized palaeosols as the Lal pedotype were probably frequent, and may have burned during dry seasons.

There is other palaeontological evidence for monsoons as ancient as Middle Miocene in the form of pronounced growth banding in a variety of fossils. The opercula of the common fossil pulmonate snail *Pila prisca* commonly show several growth bands. Conspicuous banding was seen in thin sections of gomphothere elephant tooth enamel. Ring porous fossil dicot wood also was found (Retallack 1991).

Assuming that the driving force for the Indian monsoon is thermal contrast between the glaciated Himalayas and the warm Indian Ocean (Prell and Kutzback 1992), it may not be coincidental that monsoonal circulation began with the initial uplift of the Himalayas. It was during the Middle Miocene that distal alluvial fans of the Siwalik Group proper began to prograde over pre-existing basin-filling alluvial sequences (Rawalpindi Group) of the Indo-Gangetic foredeep (Retallack 1991) and there was extensive volcanism and uplift of the Tibetan Plateau (Turner *et al.* 1993). This progradation culminated in widespread deposition of coarse clastic alluvial fans of the Nagri Formation some 8-10 myr ago, after which rates of sedimentation declined (Burbank *et al.* 1993). Additional uplift and thrusting created the Potwar Plateau and Pir Panjal and shed more gravel and sand around 2 myr ago (Johnson *et al.* 1985; Harrison *et al.* 1993). Some 21-17, 11-7 and 2-0 myr ago appear to be times of major Himalayan uplift (Sorkhabi and Stump 1993), and probably also of intensified monsoonal circulation.

Milankovitch Scale Cyclicity of Miocene Palaeoclimate

A striking feature of the Late Miocene Nagri and Dhok Pathan Formations of the Siwalik Group is alternation of blue-grey sheet sandstones rich in little-weathered schist fragments and buff-coloured shoe-string sandstones with more deeply weathered sand grains (Fig. 2). The blue-grey sandstones record episodic expansion of the sandy braidplain of the Protogangetic River which drained the high glaciated Himalayas, at the expense of the buff-sandstone river system of alluvial fans which drained the vegetated foothill ranges (Behrensmeyer and Tauxe 1982).

The duration of these episodes can be estimated from both palaeomagnetic and palaeopedologic data. For example, the two episodes of Figure 2 are in a part of the Dhok Pathan Formation estimated palaeomagnetically to have accumulated at a long term rate of 61 cm/kyr (Tauxe and Opdyke 1982, adjusted to time scale of Berggren *et al.* 1985), which for the 55 m of palaeosols amounts to 90,185 years. Another estimate can be gained by assigning times of formation for each of the observed pedotypes based on the dating of surface soils (by Ahmad *et al.* 1977; Courty and Federoff 1985) determined to be similar to the palaeosols by detailed petrographic and chemical studies (Retallack 1991). Using estimates of 50 years (for Sarang pedotype), 2000 years (Bhura, Khakistari, Sonita), 3000 years (Pila, Lal) and 5000 years (Kala, Pandu), this sequence of palaeosols adds up to 137,200 years. The difference between palaeomagnetic and palaeopedologic estimates may reflect uncertainties of the calculations, as well as unsteadiness of sedimentation, which is especially apparent when palaeomagnetic data are examined on fine (kyr) time scales (Johnson *et al.* 1985). However, in this and other cases (Retallack 1991), expansion and retreat of the Protogangetic braidplain recurred at intervals of the order of 50 kyr.

Palaeosols associated with the expanded Protogangetic braidplain (Pandu and Khakistari pedotypes) are distinct from those associated with the prograded alluvial fans (Sarang, Bhura, Sonita, Lal, Pila and Kala pedotypes). The Protogangetic assemblage has the best developed calcic horizons, is more calcareous and has calcic horizons at a shallower level than the alluvial fan assemblage (Retallack 1991). The degree of development of calcic horizons is known to be related to time for formation of soils

(Gile *et al.* 1980). Thus the Protogangetic assemblage of palaeosols indicates slower rates of sediment accumulation than the alluvial fan assemblage, and is evidence that braidplain expansion was not a response to increased rate of sedimentation initiated by episodic tectonic uplift. Another palaeosol feature, depth to calcic horizons (d in cm) is known to be related to mean annual rainfall (P in mm), with shallower calcic horizons in soils of drier climates, according to the relationship:

$$P = 139.6\text{-}6.388d\text{-}0.01303d^2$$

with a correlation coefficient of 0.79 and 1σ deviation of ±141 mm (Retallack 1993). For palaeosols, depth to calcic horizon needs to be corrected for burial compaction. The degree of compaction (C as a fraction) of a palaeosol due to deep burial (D in km) can be calculated using a formula offered by Sclater and Christie (1980):

$$C = -0.5/([0.49/e^{(d/3.7)}]-1)$$

Depth of burial of the section shown in Figure 2 was about 2 km, based on stratigraphic and palaeomagnetic data (Retallack 1991). Mean annual rainfall at times of maximal extent of the axial braidplain palaeosols was thus about 276-548 mm, whereas at times of progradation of alluvial fans it was 470-640 mm. Thus the spread of the Protogangetic braidplain may have been related to periods of drier climate, with sparser vegetation and lesser discharge of the foothill streams compared with major antecedent Himalayan drainage of the glaciated highlands.

Episodic drying and cooling on Milankovitch time scales has also been discovered in Miocene lake deposits (Barnosky 1984) and was a prominent feature of Pleistocene palaeoclimatic fluctuation (Hays *et al.* 1976). The dominant Milankovitch period of the last 900 kyr ago was about 100 kyr, but before that time it was closer to 41 kyr (Shackleton and Hall 1990) and this may have been true also for the Miocene.

Late Miocene Climatic Expansion of Grasslands

Superimposed on seasonal and Milankovitch palaeoclimatic fluctuation was a longer term palaeoclimatic drying. The suite of palaeosols in the Potwar Plateau of Pakistan some 8.5 myr ago (Fig. 2-4) matches best with modern soils in that part of the lowland plain of the Ganges River near Gorakhpur, Uttar Pradesh (Retallack 1991), where mean annual rainfall is 1274 mm (Champion and Seth 1968). Before human disturbance this area probably supported a moist Gangetic deciduous forest (in soils like the Lal, Sonita and Bhura palaeosols), with local patches of low alluvial wooded grassland (on soils like Kala and Pila palaeosols) and swamp woodland (on soils like Khakistari palaeosols). By 7.8 myr ago another suite of palaeosols, also studied in detail, compared best with soils further west near Roorkee (Retallack 1991) where mean annual rainfall is 1050 mm and vegetation is dry deciduous forest, with local riparian woodland and forest (Champion and Seth 1968). A distinctive suite of yellow to brown palaeosols with the distinctive small, rounded, clay-rimmed clods characteristic of the mollic surface horizon of grassland soils appear at higher stratigraphic levels dated at

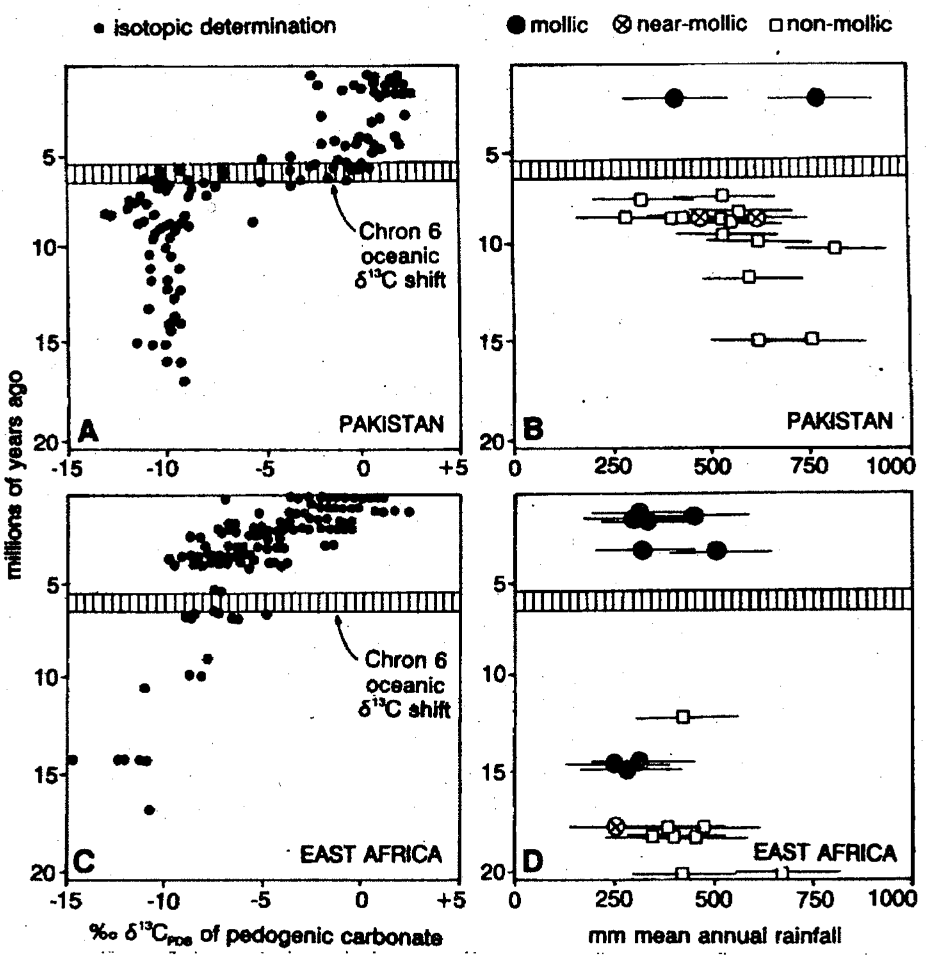

Fig. 6: Carbon isotopic composition of pedogenic carbonate nodules and mean annual rainfall interpreted from depth to calcic horizon of palaeosols in Pakistan and East Africa ranging in age back to 20 myr ago, showing climatic expansion of palaeosols with mollic surface horizon after about 6 Myr ago. Error bars on rainfall estimates are 1σ. Isotopic data are from Cerling (1992) and Quade *et al.* (1992), and palaeosol data from Bishop and Pickford (1975), Burggraff *et al.* (1981), G.D. Johnson *et al.* (1981), Retallack (1990, 1991), Bestland and Retallack (1983), and Retallack *et al.* (in review)

6 myr ago (Johnson *et al.* 1981). Also at this time there is a pronounced shift towards heavier carbon isotopes of pedogenic carbonate, interpreted to indicate an expansion of tropical grasses using the C_4 photosynthetic pathway (Quade *et al.* 1989). Today brown soils around Khaur support sparse, overgrazed thorn scrub, which before human disturbance was probably a mosaic of grassy woodland and wooded grassland (Champion and Seth 1968).

There has been an attempt to attribute the 6 myr ago event to the onset of monsoon circulation and origin of grasslands in south Asia (Quade *et al.* 1989). This now seems unlikely for a variety of reasons in addition to evidence from palaeosols for much more ancient monsoons discussed above. There is also evidence from palaeosols and fossil grasses for grasslands going back at least to the Middle Miocene if not earlier (Awasthi 1982; Mathur 1984; Retallack 1991, 1992a; Morley and Richards 1993). Peak sedimentation rates that would be expected to accompany an intensified monsoon are not seen in the time interval of 8-5 myr ago, which is a time of waning rates (Amano and Taira 1992; Harrison *et al.* 1993; Burbank *et al.* 1993). Even more telling is the discovery of a similar though not so marked isotopic anomaly at 6 myr ago in East Africa (Cerling 1992) and North America (Gardner *et al.* 1992; Cerling *et al.* 1993), where C_4 grassland expansion was remote from the Indian monsoons.

The 6 myr ago expansion of tropical grasslands may instead be related to global drawdown of carbon dioxide levels, because C_4 plants are known to be more frugal with this gas (Ehleringer *et al.* 1991). Late Miocene drawdown of carbon dioxide also has been inferred from change to a more alkaline ocean inferred from the $\delta^{11}B$ composition of foraminifera (Spivack *et al.* 1993). The amount of this drawdown appears to be beyond the resolution of current methods of estimating carbon dioxide abundance from the isotopic composition of palaeosol carbonate (Cerling 1991), but studies of the stomatal index of fossil oak leaves from Europe have been used to quantify a Late Miocene decline from 370 to 280 ppmV of carbon dioxide (van der Burgh *et al.* 1993). This minor change may have had profound effects, not only for the global expansion of grasslands, but for oceanic opal and carbon deposition and strontium isotopic ratios, for initiation of the Messinian salinity crisis in the Mediterranean, for cold water and high nutrient recirculation in the Arabian Sea, and for rodent taxa in south Asia (Harrison *et al.* 1993). Oxygen isotopic data from pedogenic carbonates in Pakistan (Quade *et al.* 1989) can be interpreted as evidence for substantial cooling at about 6 myr ago as well. Cooling, declining precipitation and less climatic variability for Indian monsoons have been predicted as a consequence of declining atmospheric carbon dioxide in modelling studies (Prell and Kutzback 1992; Meehl and Washington 1993). Thus the growing rain shadows cast by Asiatic mountains may have been related to a more widespread atmospheric decline in greenhouse gas.

There remains an intriguing mismatch between mean annual rainfall inferred from depth to calcic horizon of palaeosols and former vegetation reconstructed by a comparison of surface soils with profile form of palaeosols and distribution of fossil root traces. This may be in part due to the crudeness of current estimates, but some regularities have emerged from compilations of data from palaeosols in India, Pakistan and Kenya (Fig. 6) in the Old World tropics, and from Oregon and Nebraska in the United States (work in progress). In all of these places palaeosols with the mollic surface horizon of grassland soils are not found with calcic horizons at compaction-corrected depths greater than 32 cm prior to 6 myr ago, but after that time some of these presumed grassland palaeosols have calcic horizons as deep as 1 m. Using the relationship between depth to calcic horizon and mean annual rainfall already dicussed (Retallack 1993), these data can be taken as an indication that the grassland-woodland ecotone expanded from some 400 mm mean annual rainfall to closer to its present location near the 750 mm isohyet at about 6 myr ago. Late Miocene time thus marks the advent of tall grasslands now common in regions receiving 400-750 mm of rain. It could be argued that tall grasslands expanded their climatic as well as geographic range in response to global climatic and atmospheric change, but then what caused these wider changes?

One idea is that global climatic deterioration was linked to uplift of the Tibetan Plateau (Raymo and Ruddiman 1992). Unfortunately, as already discussed, volcanic and sedimentary indicators show peak uplift at 21-17, 11-7 and 2-0 myr ago, rather than at 5-6 myr ago (Burbank *et al.* 1993; Turner *et al.* 1993; Sorkhabi and Stump 1993).

An alternative possibility is that the expansion of tall grasslands with their distinctive thick organic surface horizons created new storage for carbon taken from the atmosphere. Grasslands today have an above-ground biomass of 0.06-30 kg/m^2 dry weight, comparable to 4-25 kg/m^2 for dry woodlands that they presumably replaced (Retallack 1992b). However, amounts of carbon below ground under grassland is much greater than for woodland. Values of 9.1 kg/m^2 for grassland Mollisols versus 6.6 kg/m^2 for forested Alfisols were used in a recent modelling study (Harden *et al.* 1992). Even in soils of the Indo-Gangetic plain, which are organic-lean by world standards, formerly-wooded Alfisols may have organic carbon up to 2.68 weight percent with values above 1% only within the surface 26 cm (Murthy *et al.* 1982), but grassland Mollisols have organic carbon up to 3.4 weight percent with values above 1% as deep into the profile as 76 cm (Deshpande *et al.* 1971).

These observations suggest an intriguing new hypothesis of biotic control of Neogene climatic deterioriation. Drawdown of atmospheric carbon dioxide and expansion of grasslands can be regarded as the log phase in the coevolution of grass-grazer ecosystems in which grasses withstand better than other plants the hard hooves and high crowned teeth of grazing mammals, and in which bulldozer herbivores such as elephants and browsers such as rhinos prune back trees. These coevolutionary linkages were already established by the Middle Miocene when cursorial limb structure and high crowned teeth appear widely in fossil antelope and fossil grasses already were well armoured with silica phytoliths (Retallack 1992a). Some 6-5 myr ago represents a time of widespread modernization of mammalian fauna of the Old World tropics, when modern elephants, horses and alcephaline antelopes appear (Janis 1989). The Late Miocene was also the time when grasses of the supertribe Andropogonae spread from India to become dominant throughout southern Asia and East Africa (Retallack 1992a). This can be seen as a coevolutionary threshold for these ecosystems in which grasses coped increasingly successfully with the disturbance provided by increasingly destructive mammals. Fire also could have played a role in the climatic expansion of grasslands. Vegetation would have become more flammable as the atmosphere became relatively more oxygenated with drawdown of carbon dioxide, and grasses with their underground rhizomes recover from fire better than trees. Thus the global climatic and isotopic shift that presaged the Messinian salinity crisis and the Ice Ages could be regarded as a consequence of the widespread emergence of tall grassland as a new kind of ecostystem replacing dry woodlands.

Conclusions

Like the mountains from which they came Siwalik sediments impress with superlatives as the thickest and most complete known Neogene sequence of fluvial deposits and palaeosols. These palaeosols reflect variability of past climates on a variety of scales ranging from monsoonal seasonality, to Milankovitch cyclicity and longer term climatic deterioration since the Middle Miocene. They have much to offer for understanding the nature of monsoonal circulation, the consequences of Milankovitch climatic fluctuation in non-glacial times and the interrelationship between ecosystems and climate.

The prospects for further palaeoclimatic studies of Siwalik palaeosols are bright but the scale of the problem is at the same time daunting. Detailed study of even a single complete section of Siwalik palaeosols in the manner reported here will take many years. Much also remains to be done to quantify climatically sensitive features of Siwalik palaeosols, and to calibrate these measurements with observations of surface soils. Siwalik palaeosols have only recently begun to attract researchers and we are on the threshold of an avalanche of new ideas and data about climate, vegetation and soils of the past.

Acknowledgements

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