Sedimentology (1982) **29**, 331–352

Isochronous fluvial systems in Miocene deposits of Northern Pakistan

ANNA K. BEHRENSMEYER* *and* LISA TAUXE†

**Department of Paleobiology, NHB E-206 Mail Stop 121, Smithsonian Institution, Washington, D.C. 20560, U.S.A. and †Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York 10964, U.S.A.*

ABSTRACT

A palaeomagnetic isochron dated at about 8·1 Myr BP and detailed lithostratigraphy of a 40 m interval exposed along strike for 40 km establish the depositional patterns of two contemporaneous, interfingering fluvial systems in the upper part of the Middle Siwalik sequence.

The two systems, referred to as the buff and blue-grey, differ in unit shape, lithofacies, bedding sequence, palaeocurrent direction and sand composition. Interfingering occurs along the south-west–north-east strike of the outcrops, with the palaeodrainage directions of the two systems generally perpendicular to this line. The axis of the blue-grey system, which deposited widespread sheet sands and silts, lay toward the south-west end of the study area. The more complex axis of the buff system, which deposited shoe-string sand bodies and large volumes of silt and clay, lay toward the north-east. The source area for both systems was the rising Himalayan belt to the north and north-east of the study area. At maximum extent the blue-grey system occupied a channel belt at least 25 km wide. Channel belt widths and depths for the buff system are 1–3 km and 3–7 m, respectively. Current directions average 94° for blue-grey sands and 136° for buff sands. Blue-grey sands contain 20% more rock fragments and are otherwise less mature than buff sands.

The buff system shows a vertical pattern of avulsion, palaeosol formation and floodplain aggradation which we attribute to autocyclic processes of parallel rivers. The blue-grey system shows phases of erosion accompanied laterally by palaeosol formation, followed by valley fill and overflowing of interfluve surfaces. This pattern may be caused by allocyclic processes affecting the source area. We interpret the blue-grey system as a major drainage from the interior Himalayas (perhaps the ancestral Indus) and the buff system as a complex of smaller drainages along the mountain front which were probably tributaries to the blue-grey system.

Vertebrate fossils including hominoid primates from the area are almost exclusively associated with lithofacies of the buff system, and this probably reflects both taphonomic and palaeoecological differences between the two systems.

INTRODUCTION AND BACKGROUND

Palaeomagnetic reversal stratigraphy, widely used for dating and correlation of non-marine strata, can provide laterally traceable isochrons through fluvial sediments, permitting unique insights into their depositional history. In this paper we document a palaeomagnetic reversal isochron in Miocene sediments of northern Pakistan and present a detailed examination of the contemporaneous fluvial lithofacies.

0037-0746/82/0600-0331 $02.00

Fluvial deposits forming the Siwalik Group in northern Pakistan have been the object of multidisciplinary study by the Yale Peabody Museum and the Geological Survey of Pakistan since 1973. Research has focused on the central part of a structural unit known as the Soan Synclinorium on the Potwar Plateau (Fig. 1). The deposits in this region are of considerable palaeontological interest because they contain a long and essentially continuous fossil record of terrestrial vertebrates, including hominoid primates, for the period between 13 and 1·5 Myr BP. The palaeomagnetic stratigraphy of the region has been investigated by groups from Dartmouth University (Barndt *et al.*, 1978), the Lamont-Doherty Geological

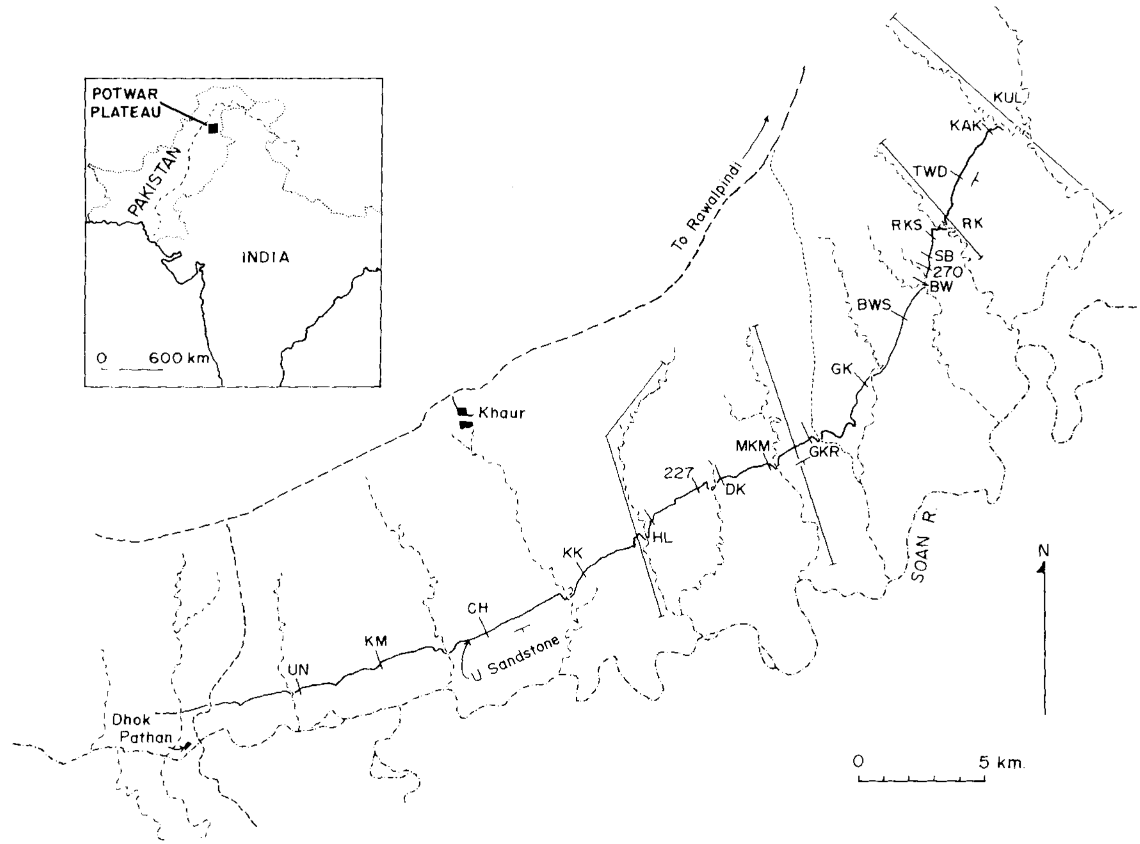

Fig. 1. Khaur study area, showing major canyons that cut across the strike of the sedimentary deposits and empty into the Soan River. The heavy black line traces the outcrop of the U Sandstone, and short lines across it mark the positions of lateral stratigraphic sections used in this study. Long straight lines next to four of the canyons show positions of long sections used for palaeomagnetic stratigraphy of the area. Initials represent abbreviations for the names of canyons or villages near the sections and correspond to abbreviations used in other publications. Inset shows location of study area in northern Pakistan.

Observatory (Tauxe, 1979; Tauxe & Opdyke, 1982) and the University of Arizona, Tucson. In 1978, Tauxe undertook a study of lateral variation in a specific palaeomagnetic reversal sequence occurring within the Dhok Pathan Formation of the Middle Siwaliks. Her sampling was done in collaboration with Behrensmeyer, who documented the detailed stratigraphy of each lateral section. The resulting field and laboratory data provide the basis for this paper. Comprehensive documentation of the overall palaeomagnetic stratigraphy is presented elsewhere (Tauxe & Opdyke, 1982; Tauxe, 1979).

The study area lies within a belt of folded Neogene molasse deposits near the northern edge of the Potwar Plateau (Fig. 1). The plateau is capped by the late Pleistocene Potwar silts that blanket older structures except where there are local uplifted belts or where erosion has cut through to underlying deposits in deep canyons known locally as 'kas'. The northern limb of the Soan Synclinorium, formed by the Miocene sediments, is well-exposed for distances of tens of kilometres along strike due to erosion along drainages emptying into the Soan River. This provides ideal sampling conditions for lateral stratigraphy and fossils, particularly in the vicinity of the village of Khaur. Attempts to define the absolute chronostratigraphy of this area have involved extensive palaeomagnetic sampling since no other means of age-determination, independent of the vertebrate fauna, has yet been found.

The palaeomagnetic reversal stratigraphy of the Khaur area is now well-documented for the upper two-thirds of a measured sequence totalling over 3000 m (Tauxe & Opdyke, 1982). Lateral tracing of palaeomagnetic reversals has proved crucial in tying long vertical sections into an overall chronostratigraphic framework which provides the foundation for evolutionary studies of both faunas and depositional regimes. The broad implications of this work are summarized in Pilbeam *et al.* (1979), Barry, Behrensmeyer & Monaghan (1980), and Barry, Lindsay & Jacobs (1982). In this paper we use the isochron defined by the record of a magnetic field reversal (DN3 to DR3, Tauxe, 1979; DN4 to DR4, Tauxe & Opdyke, 1982) as a reference time line through the fluvial facies of the sub-Himalayan depositional systems.

The isochron lies within the upper half of the Khaur area section, and is dated at about 8·1 My based on correlations of the local reversal pattern with the currently accepted magnetic polarity time-scale (MPTS) (LaBrecque, Kent & Cande, 1977; Mankinen & Dalrymple, 1979; Tauxe & Opdyke, 1982). The absolute age of the isochron is not critical to the lateral facies study except in relating sedimentary phenomena to broader-scale (e.g. global) tectonic or climatic events.

The Siwalik formations of the Potwar Plateau are defined primarily on the basis of their lithologies (Fatmi, 1973) but were traditionally considered to be time units as well. The Middle Siwalik formations, the Nagri and the overlying Dhok Pathan, are distinguished by the dominance of sand in the former and finer-grained sediment in the latter. Study of the contact between these formations using the palaeomagnetic time framework has shown that it is time transgressive over approximately 1 Myr (Barry *et al.*, 1980). The isochron occurs within the Dhok Pathan Formation (Figs 2 and 3) except in the westernmost sections (sections 1–3), where sand units become dominant. Here the isochron is technically within the Nagri Formation. The isochron thus helps to document the time equivalent, interfingering relationship of the two formations (Figs 2 and 3).

A rate of average sediment accumulation for the Khaur area deposits can be calculated using the magnetostratigraphic calibration and will be used in a number of discussions to follow. This is based on the thicknesses representing parts of Chrons 7 and 8 in two long sections: 775 m in Kaulial Kas (section 19) and 545 m in Malhuwala Kas (section 8). These measurements give rates of 0·48 m/1000 yr and 0·55 m/1000 yr, or an average of 0·52 m/1000 yr (data from Barry *et al.*, 1980). We use the rounded figure of 0·5 m/1000 yr as the average sediment accumulation rate for the Middle Siwalik deposits of the Khaur area. There is some variation in rates for individual reversed and normal polarity intervals between the two sections, but an overall consistency indicates steady vertical accretion of the sedimentary deposits in this portion of the Khaur section. Breaks in sedimentation due to local fluvial processes were superimposed upon this relatively constant rate of accumulation.

FIELD AND LABORATORY METHODS

The DN4–DR4 normal-to-reversed transition used for lateral tracing occurs within a 20 m interval below the base of a prominent bluish-grey sand unit, the U Sandstone (Fig. 3). The U Sandstone is a laterally continuous, distinctive unit used as a stratigraphic marker by palaeontologists. It occurs within a 200 m thick interval which is particularly well-exposed and rich in fossil vertebrates. The type area for the stratigraphic relationship of the magnetozones to the U Sandstone is in Ganda Kas (section 10), where the DN4 to DR4 transition was first documented about 16 m below the base of the sandstone. Above this the sediments are dominantly reversed for 20–30 m before returning to normal (Figs 2 and 3). Identification of the same transition in sections east and west of Ganda Kas is based on two lines of evidence: (1) that it is the first reversal following a thick sequence of continuous normal polarization (DN4), and (2) that it occurs within 20 m of the base of the U Sandstone.

The stratigraphic sections spanning the U Sandstone were used in the palaeomagnetic sampling. An attempt was made to space the sites at regular vertical intervals, but suitable fresh, fine-grained sediment with a clear palaeomagnetic signal occurred only at irregular intervals. The resulting palaeomagnetic site distribution is shown in Fig. 2. Three to four samples were taken at each site, using the techniques described by Johnson, Opdyke & Lindsay (1975). The average vertical site frequency is 1/8 m with a range of 1/5 to 1/15 m. Using the sediment accumulation rate of 0·5 m/1000 yr, the average sampling density is equivalent to one site every 16 thousand years.

Sedimentological data were taken from the ten palaeomagnetic columns and nine additional columns spanning the same stratigraphic interval. Lithologic units 10 cm and thicker were recorded using Jacob's staff and tape. Descriptive information included: sediment texture, colour, internal structures, nature

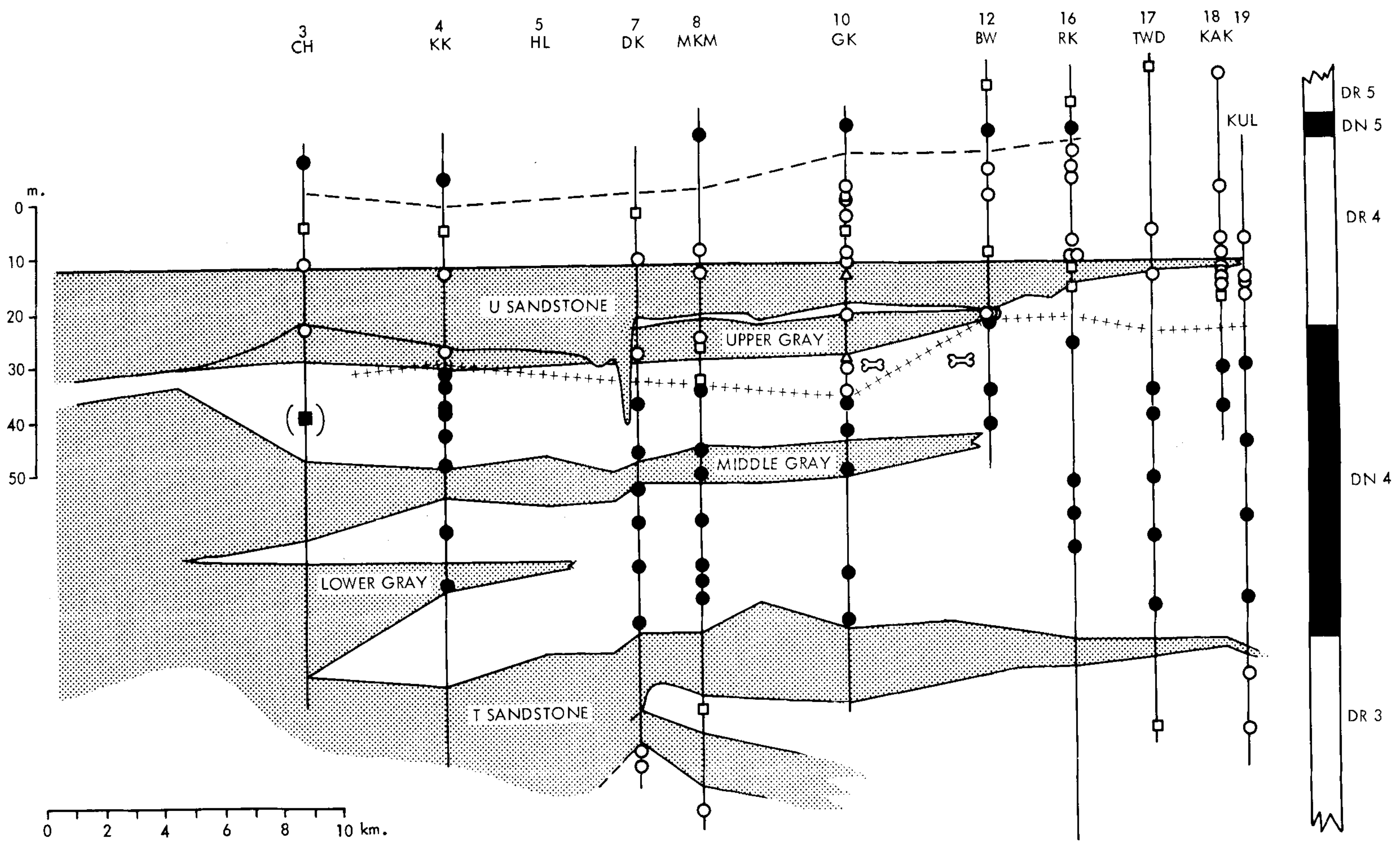

Fig. 2. Correlated sections along the strike of the U Sandstone showing the palaeomagnetic data that define the sub-U isochron. The top of the U Sandstone is used as the horizontal datum. Each symbol represents a palaeomagnetic site where three or four samples were taken; black is normal polarity, white reversed; circles = Class A data, squares = Class B data, triangles = Class C data (see text). Magnetozones are correlated with the upper part of Chron 8 of the Magnetic Polarity Time-Scale and the DN4 to DR4 transition is dated at about 8·1 Myr BP. Vertical exaggeration: V = 180 × H.

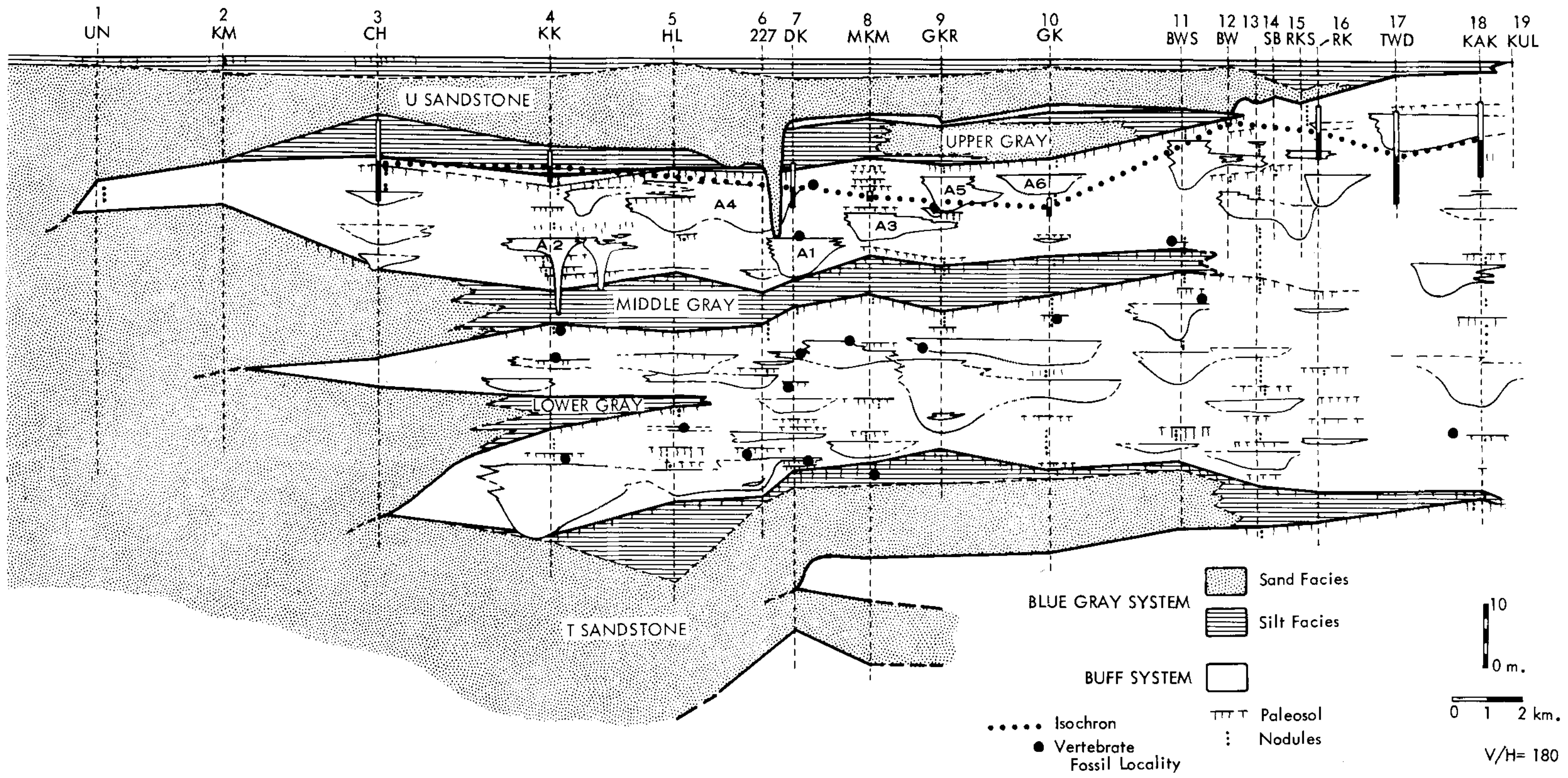

Fig. 3. Relationship of the buff and blue-grey lithofacies (or systems) from the T to the U Sandstones, showing only dominant textures and palaeosol horizons. Edges of sand bodies are drawn where these were observed; dashed edges on sand units indicate uncertainty about their exact nature and position. Vertical bars in sections documenting the isochron indicate the interval between the two closest normal and reversed sites, the stratigraphic range for the actual position of the polarity change (see also Fig. 2).

of bedding contacts, nodule and fossil content and lateral variation. Spacing between measured sections averaged 2·2 km. Many units were traced laterally between sections.

Establishing the correct identity of the U Sandstone in each section was crucial to the interpretation of the lateral palaeomagnetic patterns. For most of the 40 km covered, it was walked out along strike. Where Potwar silts covered outcrops between canyons, similarity in the lithology of the sandstones and the sub-U stratigraphy as well as projection of strike on air photographs were used to bridge the areas blanketed by silt, none of which amounted to more than 1 km.

In a study of the rock magnetic properties of Middle Siwalik Group rocks, Tauxe, Kent & Opdyke (1980) have demonstrated that a primary remanence can be isolated by thermal demagnetization. Based on some 50 demagnetization curves, all specimens used in this study were thermally demagnetized at 550°C. Site means were calculated using Fisher (1953) statistics. Palaeomagnetic sites whose resultant vectors were deemed non-random by Watson's (1956) test for randomness were designated Class A. Class B sites are those sites having two specimens in good agreement in the reversed direction after thermal demagnetization. Class C sites are non-random sites after alternating field demagnetization and Class D sites are those whose specimen magnetizations are strung to the south and are thought to be possibly reversed. Data used in this study are presented by Tauxe & Opdyke (1982), and additional information can be obtained upon request from Tauxe. The palaeomagnetic sections are presented in Fig. 2, where polarity and class information are shown. Only Class A sites (thermally demagnetized) are used to determine normal polarities, as normal sites have been observed to reverse their magnetization on thermal demagnetization.

TIME RESOLUTION AND SEDIMENTARY CONTEXT OF THE ISOCHRON

The assertion that the boundary between rocks recording different magnetic polarities (magnetostratigraphic units) marks an isochronous horizon rests on two basic assumptions. The first is that the remanent direction isolated by demagnetization represents the orientation of the magnetic field during or soon after deposition of the sediments. The second is that sedimentation was continuous during the time of the field reversal so that the boundary marks the actual polarity change and not a hiatus in deposition, some time during which the field reversed. If the polarity change occurred during a depositional hiatus, the lateral correlation of the magneto-unit boundary from section to section is unlikely to be truly isochronous.

The assumption that remanent magnetization formed in the sediments during or soon after deposition was tested using mudclasts from an intraformational conglomerate in the Ratha Kas section (section 16) (Tauxe *et al.*, 1980). A primary component acquired by the sediments before formation of the conglomerate was isolated using thermal demagnitization of magnetic particles is re-established once it ceases. The depth of the most active bioturbation in older than the locally available floodplain sediments, equal in thickness to the depth of the channel. This amounts to 15 m, or 3×10^4 yr, based on the 0·5 m/1000 yr sediment accumulation rate. We therefore conclude that magnetic remanence is acquired within at most 3×10^4 yr after deposition.

Tauxe *et al.* (1980) have demonstrated that the primary remanence is carried by specularite grains and not by red hematite, which stains most of the fine sediment and may often be secondary. The specularite is thought to be detrital in origin, acquiring its magnetic orientation during deposition or after bioturbation has ceased in the aggrading sediments. Kent (1973) observed that bioturbation acts as a reorienting mechanism after deposition, but polarization of magnetic particles is re-established once it ceases. The depth of the most active bioturbation in the Siwalik sediments at any given time was probably 1 m or less, so that the primary remanence could have been acquired in as little as 2000 yr in bioturbated but continuously aggrading sediments.

The behaviour of the magnetic field during a reversal also contributes an inherent inaccuracy in pinpointing an isochron. Most estimates indicate that the field takes 4×10^3 yr to complete a reversal (Opdyke, Kent & Lowrie, 1973). Therefore, any isochron defined by a field reversal must reflect this uncertainty.

Following these lines of reasoning, we conclude that in the Khaur area an isochron ideally represents a 'time zone' between 4×10^3 yr (the period needed for a reversal to occur) and 3×10^4 yr (the maximum period of time needed to 'lock in' the primary remanence), assuming that sedimentation across the reversal is continuous.

This second assumption can be examined for the DN4–DR4 reversal using information on stratigraphic context given in Fig. 3. Within the range of possible positions for the reversal given by the vertical bars, there are no erosional unconformities or laterally continuous palaeosols that might coincide with the isochron. We conclude that it does not fall within a major depositional hiatus, and that overall sedimentation continued across the time period of the reversal, although there is lateral variability in the patterns of aggradation. In a number of sections the isochron falls within local palaeosol units (sections 8, 10 and 12) which, although they may mark the same contemporaneous landsurface, were aggrading at different rates. This is shown by the close vertical spacing (0·5 m) between normal and reversed sites in section 12, contrasted with a more gradual change of polarity in successive sites in section 10. Time resolution along the isochron is therefore laterally variable, as would be expected in fluvial environments where, at any given time, some areas are stable while others are aggrading or eroding.

In practice, the limits of time resolution for DN4–DR4 are also a function of the thickness of sediment between the closest normal and reversed sites. This averages 9 m, representing 18×10^4 yr, with extremes of 22 m or $4{\cdot}4 \times 10^5$ yr in sections 17 and 0·5 m or $1{\cdot}0 \times 10^3$ yr in section 12. In the latter case, there was obviously a local pause in sedimentation; the time period between the normal and reversed sites should be greater than 4×10^3 yr, given that this is the time needed for a reversal to occur.

Considering all the limits to time resolution along the isochron, we conclude that the line shown in Fig. 3 represents a band of sediments that are contemporaneous within the same 5×10^4 yr period overall. This means that a unit within the normal to reversed transition in any given section was deposited within the same 5×10^4 yr period as a unit in the transition interval in any of the other sections. Between many of the sections resolution is better than this; from sections 8 to 12, for instance, it should be at most 1×10^4 yr.

As can be seen in Fig. 2, a reversed to normal transition above the U Sandstone recorded in six of the ten sections establishes a second isochron. This is less well resolved than the sub-U isochron but helps to confirm the overall correlations. According to the average thickness of 34 m for the DR4 interval, it should represent a time span of about $6{\cdot}8 \times 10^4$ yr. This places a maximum time limit on the period of deposition of the U and Upper Grey sandstones.

Time resolution for the biostratigraphic record of the vertebrate fossils in the Khaur area can be estimated using the palaeomagnetic calibration. Two fossil assemblages from the 'same stratigraphic level', measured as distance below or above a marker horizon such as the top of the U Sandstone, would be regarded as contemporaneous by palaeontologists. Assemblages occurring at the positions shown in sections 11 and 12 (bone symbols; Fig. 2), however, lie on either side of the isochron and could be between 2·0 and $3{\cdot}0 \times 10^4$ yr apart in age, using the standard rate of sediment accumulation to calculate time of burial before and after the magnetic transition event. The outside limits on the meaning of 'contemporaneous' for stratigraphically equivalent assemblages in the Khaur area are thus on the order of 10^4 yr, although many are undoubtedly much closer to each other in time than this.

Sedimentary context of the isochron

The DN4–DR4 isochron is generally parallel to the U Sandstone, thus indicating that this blue-grey sand can be regarded as a chonostratigraphic marker unit. Originally the base of the U Sandstone was used as a datum horizon in correlating sections and plotting the isochron (Tauxe, 1978; Pilbeam *et al.*, 1979; Barry *et al.*, 1980). We have chosen the upper contact instead as a horizontal datum in Figs 2 and 3 for the following reasons: (1) the base of the U Sandstone is an irregular erosional contact; (2) the upper parts of the sandstone often include horizontally laminated and bedded silts and marls indicating deposition in standing water. The upper contact is thus more likely to reflect a generally horizontal plane, parallel to the water table of the original land surface.

The U Sandstone is one of many blue-grey sand sheets that occur in the zone of interfingering between the Nagri and Dhok Pathan Formations as they are expressed in the Khaur area. These sheets thin and pass laterally into drab silts from south-west to north-east, and most are capped by laminated, fine-grained, marly deposits indicative of standing water. If the upper contact of the U Sandstone is used as a datum, the upper contacts of three underlying, horizontally bedded blue-grey sand and silt units fall into nearly parallel alignment with the datum (Figs 2 and 3). This supports the hypothesis that the laminated blue-grey units represent roughly horizontal planes on the original depositional surface. The other blue-grey sands are also likely to be chronostratigraphic markers through the Khaur area deposits.

Relative to the top of the U Sandstone the isochron has a rather irregular pattern of relief in the correlated sections shown in Figs 2 and 3. Some of this may be due to the lack of precise placement of the isochron in sections where the stratigraphic distance between the nearest normal and reversed sites is large. Between sections 10 and 12, however, the isochron rises about 15 m toward the north-east over a distance of 5·2 km, and this is greater than what could be ascribed to incorrect vertical placement of the polarity change. The slope of 2·9 m km^{-1} on the isochron between sections 10 and 12 appears to represent original relief on the depositional surface. The eastward pinching out of the Upper Grey unit and the thinning of the U Sandstone over the apparent topographic 'high' lend support to this possibility (Figs 2 and 3). In the laterally correlated sections, however, the isochron does not maintain any consistent relationship to the palaeosols that lie close to it stratigraphically, and comparisons of the sub-U lithofacies, bedding thicknesses and stratigraphic sequence from section to section give no clue concerning the position of the time line through the deposits.

THE CONTEMPORANEOUS FLUVIAL LITHOFACIES

As a time line through the sedimentary deposits, the sub-U isochron provides the basis for examining synchronous fluvial environments in strata immediately above and below it. The general characteristics of ancient fluvial regimes usually are described without benefit of a time datum. Its value lies in making it possible to assess how time-specific or time-transgressive a particular sedimentary unit is and how variable sedimentation and relief may have been in the original land surfaces. This adds significantly to the information that can be derived from the sedimentary record.

Two types of sand units are readily apparent in the Middle Siwalik deposits of the Khaur area: the blue-grey sheet sandstone (such as the U Sandstone) and buff sandstones that occur as laterally restricted lenses. The colour difference results from texture and mineralogy: the blue-grey sands are clean, cemented with sparry calcite and contain fresh, grey schist fragments, biotite and hornblende while the buff sands have silty matrix, iron oxide grain coatings and abundant weathered rock fragments. Using the isochron we were able to test the hypothesis that these two sand facies represent different contemporaneous fluvial systems. The 40 m interval between the base of the Middle Grey unit and the top of the U Sandstone (Figs 2 and 3), which includes the DN4–DR4 isochron, was used for lithofacies analysis and is referred to as the 'sub-U interval'.

The buff lithofacies

The buff lithofacies of the sub-U interval between the Middle Grey and U Sandstones consists of red-brown, fine-grained sediments with discontinuous buff sandstones. For purposes of analysis, the sediments can be divided into seven characteristic subfacies as shown in Table 1. All but 'palaeosol' are based primarily on textural characteristics. The palaeosol horizons represent important post-depositional processes and are recognized by their characteristic internal fabric (ped surfaces, root and burrow traces, nodule zones) and colour zonation (usually brown to yellow or dark grey with sharp upper contacts. Similar criteria have been used to identify palaeosols in other detailed studies of vertebrate-bearing fluvial deposits (see Bown, 1979; Bown & Kraus, 1981a, b.)

Table 1. Characteristics of buff lithofacies in the sub-U interval. Numbers are based on thicknesses recorded in 17 lateral stratigraphic sections. Palaeosols were not included in calculation of percentages in the textural spectrum since they are superimposed on the other lithofacies types. Textures determined from hand specimens

Lithofacies	Sand	Silty sand	Interbedded sand + silt	Silt	Silty clay	Sand + silt + clay
% total	22	17	8	14	36	3
Average unit thickness (m)	2·7	1·3	2·0	1·8	2·0	2·5
Maximum unit thickness (m)	8·1 (12·5)*	2·8	4·6	6·2	7·4	2·9

* Thickest buff sand measured, not on a section line.

The lateral and vertical relationships of the seven sub-facies in the correlated stratigraphic sections provide the primary data for the reconstruction of the fluvial system. In addition, we have used measurements of palaeocurrent directions on large-scale trough axes within the sandstone units, and lateral tracing of 2–3 m thick facies associations. Preliminary results of petrographic study of buff sandstone compositions are given in Table 2.

It is clear that the sandstones represent channel deposits and that the other sub-facies represent

Table 2. Composition of sandstones of the blue-grey and buff lithofacies, determined from point counts of thin sections (200–300 counts per section). All samples were approximately the same grain size (medium sand). Letter abbreviations indicate sections on Fig. 3

	Quartz (%)	Feldspar (%)	Rock fragments (%)
Blue-grey system			
U Sand, MK	29	11	60
U Sand, GKR	29	12	59
T Sand, MK	27	13	61
Buff system			
Buff sand A, MK	51	12	37
Buff sand B, MK	50	11	40
Loc. 260 buff sand, KL	49	11	41
Modern rivers			
Indus river sand	33	18	49 (Primarily metamorphic or granitic)
Soan river sand	45	12	43 (Primarily sandstone or quartzite)

various types of contemporaneous overbank or floodplain deposition (Fig. 3). In many cases it is possible to trace individual sand units laterally through interbedded sand and silt, silt, and finally into silty clay (Figs 3 and 4). Taking the buff facies between the top of the Middle Grey and the base of the U Sandstone, channel deposits represent 22% and floodplain deposits 78% of the sedimentary record, as calculated using thicknesses of sands versus finer subfacies in the measured sections. Of the fine-grained facies, silty clay is dominant (Table 1). Sandstones form the thickest units, but average thicknesses of the different facies are generally similar (Table 1). The thicknesses and frequency of the sands and other units are consistent laterally throughout the sub-U interval.

Figure 3 shows that lateral variation in the lithofacies occurs over distances less than the average spacing between measured sections, i.e. less than 2–3 km. This contrasts markedly with the blue-grey units which are laterally persistent over tens of kilometres. In part, the impression of lateral variability in the buff lithofacies may be due to the fact that we have not yet systematically traced fine-grained units from section to section. The variation in vertical bedding patterns in closely spaced sections lends support, however, to our calibration of lateral variation in the buff lithofacies since it is difficult to match these patterns even over distances of less than 1 km.

Channel belt deposits

The channel lenses shown in Fig. 3 have been reconstructed by correlating sand bodies at approximately the same level in adjacent sections. Detailed study of lateral variation in the sand units near section 4 (C. Badgley, personal communication) and sections 6 and 7 indicates that such correlations tend to oversimplify their cross-sectional shape. The actual lateral variation is probably more like that near section 4, with sand units changing rapidly in thickness and passing into siltier facies, then back into sand. The simpler reconstructions (e.g. sections 9 and 10) shows sands that we believe represent single channel belt systems (in the sense of Allen, 1974) as connected units, even though they may be more complex internally. Because many of the sand units are laterally restricted, it is likely that some were not recorded in our sections, and the lenses shown in Fig. 3 thus represent a minimum estimate for the actual number of discrete channel belt units.

Since channel belt deposits are typically 'shoestring' sand bodies, their shape on an outcrop face is determined by the orientation of the sand body to that face. Most channels were oriented toward the south or south-east, approximately normal to the strike of the outcrops and the orientation of the outcrop surfaces, which trend SW–NE (Table 3, Figs 1 and 3).

Table 3. Summary of current direction measurements in the blue-grey and buff sandstones within ±60 m of the isochron. Downstream orientations of trough axes, taken at different localities along strike, make up the primary data set. Statistical parameters calculated using method described by Reyment (1971). *F* statistic shows that the two samples are significantly different

	Blue-grey system (U Sandstone only)	Buff system
(= *N* localities)	20	41
Direction of mean vector	94° (east)	136° (south-east)
Dispersion (mean angular deviation, enclosing 2/3 of the measurements)	±24°	±50°

Note: *F* statistic for difference = 9·3.

The sand bodies are internally variable, with lenses of carbonate- and clay-clast conglomerate, clay drapes and lenses, and various scales of trough cross-stratification (τ of Allen, 1963). All sand bodies are characterized by erosional bases, which usually take the form of laterally restricted deep scours into underlying sediments. The smaller channels represent simple filling of such scours while the larger show filling followed by vertical aggradation and lateral spread of sand above the level of initial cutting (Figs 3 and 4). There is no striking pattern of upward textural fining within or above the channel lenses, although a Markov Chain analysis indicates a rather weak pattern of upward fining above the sand units (Fig. 5). The upper parts of many of the sand bodies are complex, with alternating sand, silt and clay, while others are overlain by homogeneous sandy silts. There is no indication of upward decrease in the scale of cross-stratification in the sand bodies. We have not observed evidence for quiet water or swamp deposition above the sand lenses as might be expected if they followed the pattern of meander cut-off and clay-plug formation in an ox-bow lake (Miall, 1977).

Overall it appears that the buff channels do not fit the classic models (Allen, 1965; Leopold & Wolman, 1957; Puigdefabregas & Van Vliet, 1978) for deposition by meandering streams particularly well; nor are they obviously braided in origin. They were probably meandering in overall pattern, but did not follow the typical stages of channel migration and fill. This suggests the dominance of avulsion in the fluvial system (as opposed to gradual lateral channel movement), with seasonal influxes of sand that filled and choked off abandoned channels. The active channels probably included both braided and meandering flow patterns, as do many of the sub-Himalayan rivers today.

Reconstruction of four of the channel belt lenses gives actual widths of 2·5, 2·5, 4–5 and 0·7 km. Maximum thicknesses of these lenses are, respectively, 6·0, 6·0, 7·3, and 2·0 m. These are not, however, the actual widths and depths of the Miocene rivers, which occupied smaller channels within the channel belts (except perhaps during floods). According to published relationships between sand body width and meander belt width (Inglis, 1949), the buff sand lenses fall within predicted dimensions for strongly meandering to mildly sinuous streams. The actual active

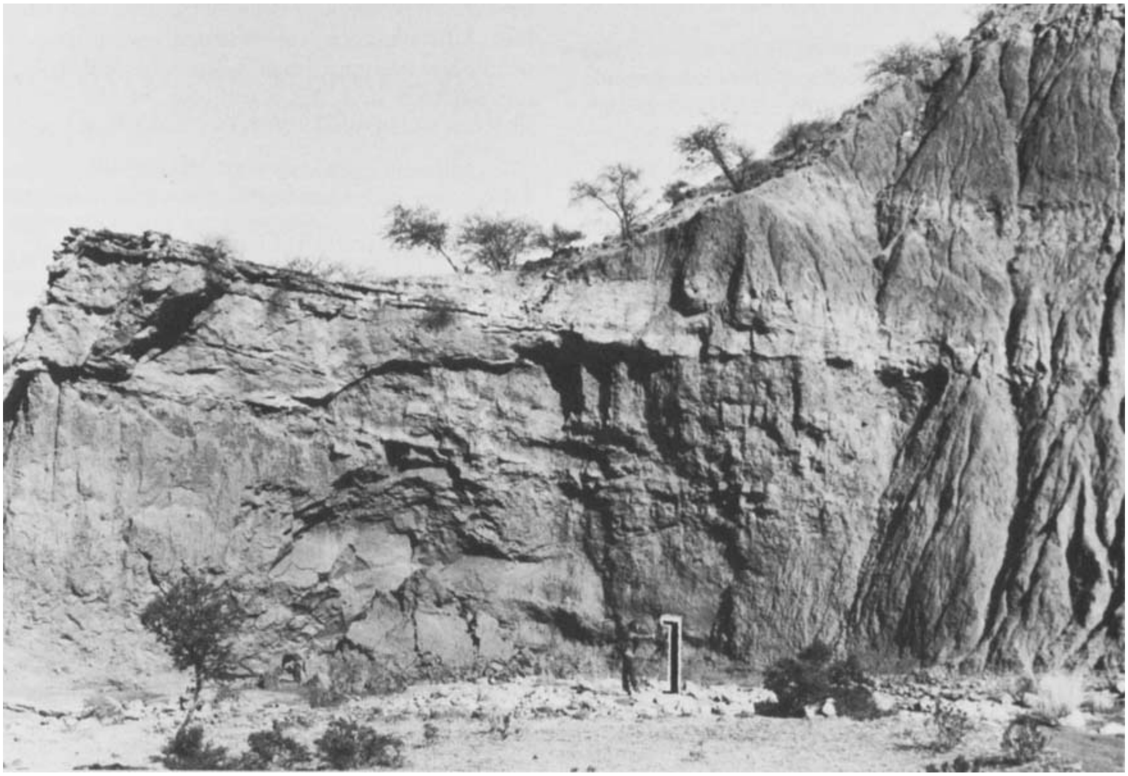

Fig. 4. Typical sand body in the buff system. The sand grades laterally into interbedded sand and silt above the cut-bank eroded into underlying silts. Flow direction is into the picture. Scale (person) is 1·6 m high.

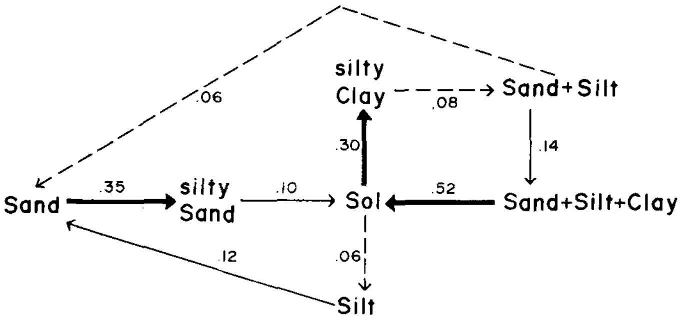

Fig. 5. Markov chain analysis of the buff system lithofacies of the sub-U interval, using the method of Miall (1973). Numbers are probabilities of passing upward from one lithology to another. Heavy lines are for probabilities >0·20, lighter lines for probabilities between 0·10 and 0·19, and dashed lines for probabilities between 0·05 and 0·09. Only three transitions occur relatively frequently, and there are no clearly defined cycles.

channels may have been 50–5000 m wide based on compilations by Leeder (1973).

The larger channel belt lenses appear to be the successive deposits of a river system that followed a pattern of channel cutting, filling, and avulsion to another position on the floodplain combined with overall vertical accretion through time. The deep cuts or troughs at the bases of some of the sand bodies, (to 10 m below the normal base, e.g. section 4) indicate periods of energetic erosion prior to the filling of the channel. This may have been caused by erosion of floodplain sediments during the initial avulsion event or the formation of deep scour pools in the river bed after avulsion occurred. Alternatively, the erosional troughs could have formed during periods of regionally lowered base level, indicating allocyclic influences (i.e. extrinsic to the local system, Allen, 1974) on the deposition of the buff lithofacies. We feel that the troughs are more likely to be the result of avulsion events (autocyclic) than allocyclic processes because there is no evidence for periods of lowered base level and general incision into the floodplain sediments lateral to the channels.

Fine-grained deposits

The bulk (78%) of the sediments between the U Sandstone and the Middle Grey are composed of silt and clay with varying amounts of sand. Bedding units are typically 1–2 m in thickness although some of the silty clays reach 8 m. Contacts between these units are usually diffuse and marked by colour or texture changes. Colours range from red-brown and orange-brown to yellow and light brown.

A general characteristic of the fine-grained units is their lack of primary bedding structures. Disrupted lamination and irregular thin sand beds occur occasionally, but the units are dominated by secondary structures resulting chiefly from bioturbation. These include burrows with allochthonous fill and branching and tubular root traces which occur throughout the unstratified units but are locally more abundant in discrete zones. Carbonate (primary $CaCO_3$) and iron oxide nodules also occur in distinct zones as well as dispersed through the sediments, but are more laterally and vertically restricted than bioturbation structures. The fine-grained sediments often have a blocky fracture with zones of vertical and oblique slickensides and clay-coated peds indicative of clay translocation. Discrete palaeosols indicating temporary stability (non-aggradation) of the floodplain surface were recorded in the stratigraphic sections when a number of the above features coincided in a laterally continuous horizon which was usually marked as well by a distinct colour zonation.

Individual units of the fine-grained deposits can be traced laterally for tens of metres up to several kilometres before passing into another subfacies. Interbedded sand and silts change laterally to sandy silts, silts and finally to silty clays; this progression is sometimes (but not always) found lateral to a sand unit. Thick (>2 m) homogeneous silty clay units pass into more finely stratified sediments along continuous outcrops, suggesting localized dominance of bioturbation processes (e.g. a 'permanent' patch of dense vegetation?) associated with the silty clay facies.

The discrete palaeosol horizons within the fine-grained units change in thickness and internal features over distances of tens of metres, often disappearing as recognizable entities for short distances only to reappear farther on. This small-scale variability is superimposed, however, on a larger-scale continuity over distances of up to 3 km for horizons that have been walked out between sections (4, 12, 15; Fig. 3). Most of the palaeosols shown in Fig. 3 are at least 1 m thick. A second, thinner type of palaeosol is formed by very dark grey to brown silty clays or sandy clays within homogeneous, moderately bioturbated silty clays. Such horizons are 10–20 cm thick, laterally restricted, and have well developed ped texture. Their significance is not yet understood, but attempts to isolate fossil pollen have shown that the colour is not due to organic carbon (B. Fine, personal communication).

An upper time limit for soil formation can be estimated using the average accumulation rate of 0·5 m/1000 yr; if the 18 m interval of buff facies represents $3{\cdot}6 \times 10^4$ yr, and there are an average of two well-developed palaeosols (i.e. with nodules) per section, then soil formation must have occurred in less than $1{\cdot}8 \times 10^4$ yr. The presence of up to six distinct palaeosol horizons (with and without nodules) in section 8 indicates that less than 6×10^3 yr are required for at least some soil development. In his paper on pedogenic carbonate units of a Siluro-Devonian fluvial system, Allen (1974) estimates 10^4 yr for the formation of 'glaebule' zones comparable to those of the sub-U interval. Leeder gives examples indicating that $3{\cdot}5$–$7{\cdot}0 \times 10^3$ yr are needed to reach 'stage 2' profiles ('few to common cylindroids and nodules', Leeder, 1975, p. 258) comparable to carbonate nodule zones of the buff lithofacies. Lower limits on times for soil formation can be estimated based on information on modern soils (Brammer & Brinkman, 1977; Leopold, Wolman & Miller, 1964) at between hundreds and thousands of years. Rates of nodule formation vary depending on local geochemical conditions, and are only loosely time correlated. Given the large number of palaeosol horizons in some vertical sections, we feel it is reasonable to conclude that soil formation occurred over periods near the shorter end of the estimated range, i.e. of the order of a few thousand years.

The calcium carbonate and iron-rich nodules may be indicative of interactions of the sediments with a particular climatic regime, but further study is needed before the nature of this regime can be determined. The nodules or glaebules are most likely to represent calcium carbonate and iron sesquioxide precipitation in the 'B' soil horizon (Brewer, 1964). They occur only rarely in dense concentrations and do not form patches of linked nodules. Occurrences of nodules at low density through several metres of sediment (Fig. 3) may have resulted from the steady upward movement of the B horizon with continued slow sediment aggradation (e.g. section 13), while dense, vertically concentrated nodule zones imply a break in aggradation (all other variables being equal).

The soil nodules are an obvious source for carbonate clasts found in the channels, many of which cut through palaeosols with nodule concentrations (Fig. 3). These clasts are often the coarsest particles in the sand units and typically are concentrated in lenses up to 1·0 m thick. Vertebrate fossils are often found in such deposits. These may be derived from erosion of previously buried bones in palaeosols during avulsion events, i.e. from the same source as the nodules. Bones could also be concentrated from various sources along with the coarser particles in the channels by the kinematic wave effect (Langbein & Leopold, 1968). The presence of $CaCO_3$ may enhance the process of fossilization, thus helping to preserve the bones in this sedimentary context.

Patterns through time

The overall pattern within the buff lithofacies is one of vertical floodplain aggradation with laterally and vertically discrete sand bodies marking the successive positions of one or more major channel belts. The floodplain sediments contain palaeosol horizons that record local hiatuses in deposition, and some of these are truncated by the channel-belt sand bodies. The information given in Fig. 3 can be further refined but, as given, it provides a relatively complete reconstruction of a fluvial system through time which will be termed the buff system.

The buff system can be compared with available models for fluvial systems through time (Visher, 1965, Allen, 1965, 1974, 1978, and Bridge & Leeder, 1979). The variables of importance are channel belt width and depth, sand unit distribution in floodplain sediments and the frequency and continuity of soil horizons. These may change predictably according to the balance between subsidence (tectonics), sediment type, and input rate (roughly correlated with climate), classified by Allen (1974) as allocyclic controls. Given constant allocyclic conditions, the pattern of channel and floodplain deposition is a function of autocyclic processes of channel belt migration.

In the buff system of the sub-U interval between sections 1 and 18 there is a minimum of 14 sand bodies shown in Fig. 3. While these are simplified in shape and represent the minimum number of channel sand units in the interval, they serve to characterize the pattern of the fluvial system through 15–20 m of section, representing approximately $30–40 \times 10^3$ yr. The large sand bodies between sections 4 and 10 could be reasonably attributed to a single river that altered its position on the floodplain by major avulsion events, with each successive sand unit being slightly higher stratigraphically than the previous one (A1–A6, Fig. 3). Some of the sand bodies from section 11 eastward are below the isochron but appear to be topographically above (relative to the top of U) the highest sand to the west which lies above the isochron. Rather than postulating a single river system that switches from one of these positions to the other, it seems more reasonable to reconstruct a second river system to the north-east of section 10 which built up a slightly higher sediment lobe. This may have created the 'slope' between sections 10 and 11 along the sub-U isochron. The reconstructions are in need of further testing, but suggest that channel belts were between 10 and 15 km apart on the original piedmont alluvial plain. Comparable distances occur between small drainage systems along the Himalayan front today east of the alluvial fan of the Sun Kosi River in India (NASA *Landsat* photo E-2 841–03413-5).

The buff system, as reconstructed above, is similar to a model for an alluvial system given originally by Allen (1965, fig. 36c) which shows parallel channel belt systems laying down loose 'stacks' of sand bodies through time, with laterally synchronous fine-grained deposits between the belts (Fig. 6a).

Detailed fluvial facies models given by Allen (1974) are more instructive. His model 3, generated autocyclically by 'lateral-horizontal river movements in large steps' (Fig. 6b) provides a good fit for the patterns of sand, fine-grained sediments and palaeosols shown in Fig. 3. The buff system palaeosols

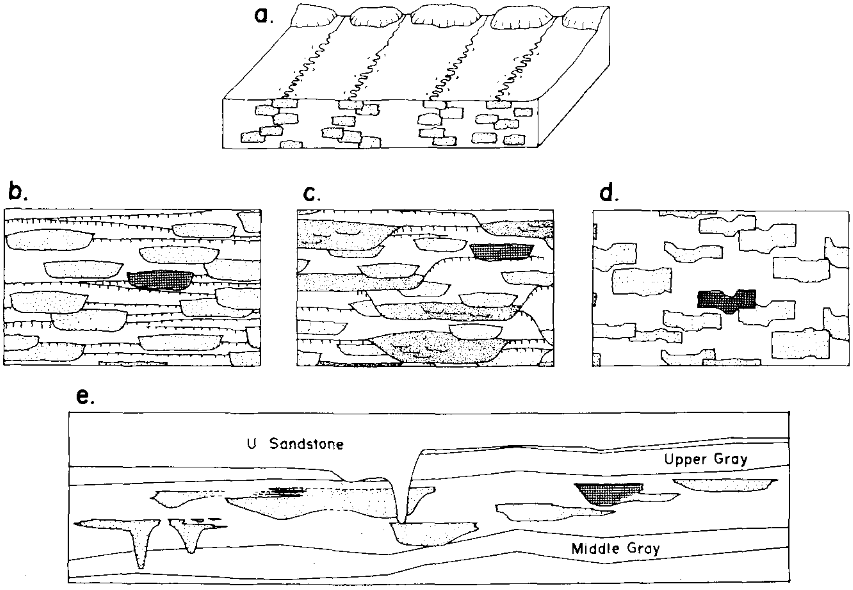

Fig. 6. Comparison of models for aggrading fluvial systems. (a) Schematic representation of aggrading piedmont drainages (Allen, 1965) broadly comparable to buff system depositional patterns. (b) Model for vertical and lateral depositional patterns generated by 'lateral-horizontal river movements in large steps' (model 3 of Allen, 1974). Dark-shaded channel lens is approximately 1000 × 5 m and lenses of the same dimensions and vertical exaggeration are shown in (c), (d), and (e). (c) Model for depositional pattern generated by periodic dissection-aggradation caused by allocyclic processes superimposed on autocyclic channel belt shifts (model 5B of Allen, 1974). Laterally restricted lenses (lighter stipple) in this model would belong to the buff system, not the blue-grey. (d) Part of a computer simulation of a fluvial system (Bridge & Leeder, 1979, fig. 2b). Floodplain width is set at 1×10^4 m, channel belt width at 1×10^3 and bankfull depth at 5 m. Mean channel belt aggradation is $0{\cdot}02$ m/yr^{-1} and the avulsion period is 890 yr. (e) Actual channel belt deposits of the buff system in the sub-U interval, shown at approximately the same vertical and horizontal scale as the models in (b–d). (Vertical exaggeration: × 90). Dark-shaded channel belt unit is comparable in actual size ($\sim$ 1000 m wide and 5 m thick) to shaded units in the models.

appear less continuous than in the model, but this may be due in part to difficulties in recognizing them from section to section. If the six channel units between sections 4 and 10 represent one river system, the period between major avulsion events can be estimated at a maximum of 6×10^3 yr (based on six channel units in 18 m; average rate of sediment accumulation = 0·5 m/10^3 yr). Alternatively, if all 14 major channel belt units in the sub-U interval represent a single river, then the avulsion events occurred at a minimum rate of one every 2×10^3 yr.

An alternative model involves allocyclic valley cut and fill superimposed upon the autocyclic channel belt shifts (Allen, 1974, model 5A). Although the overall pattern is similar, the buff system does not appear to fit this model because none of the documented palaeosols are clearly associated with periods of 'valley' (channel) cutting nor are the sand units demonstrably 'multi-storied'. The possibility that such patterns could occur in the buff system above or below the sub-U interval suggests directions for further study.

Comparisons with computer simulation models of alluvial stratigraphy (Bridge & Leeder, 1979) provide additional insights into the buff system. The models indicate the effects of compaction, vertical tectonic movements and lateral variation in floodplain deposition rates on the positions through time of sand bodies. Channel belt widths and bankfull depths specified in the model are similar to those of the buff system but aggradation rates are higher; the lowest specified in the model being 5 m/10^3 yr while that calculated for the buff system is 0·5 m/10^3 yr. The mean avulsion period is also shorter in the model (0·89 × 10^3 yr) than that estimated for the buff sand system (~2–6 × 10^3 yr). Nevertheless the simulation using channels 1 km wide with 5 m bankfull depths (Fig. 6d) is similar to the pattern reconstructed for the buff system. Slower net aggradation rates combined with slower avulsion periodicity in the buff system apparently compensate to produce a pattern similar to that in the model.

Based on comparison of the buff system with the models of Allen (1974) and Bridge & Leeder (1979), we conclude that the lateral and vertical facies patterns in the sub-U interval can be attributed to autocyclic processes of one or more parallel fluvial systems. The buff system appears similar to relatively small-scale piedmont drainages along the present Himalayan Mountain front of northern India. As such, they might be expected to reflect climatic conditions and tectonic events of a rather narrow belt along the southern edge of the mountains and not the conditions of higher altitude, more interior portions of this uplifted block.

The blue-grey lithofacies

The blue-grey facies can be characterized by three subfacies: (1) sand, (2) interbedded sand, silt and clay, occasionally including marl, and (3) mixed sand, silt and clay with palaeosol development (Table 4). The blue-grey sands pass laterally into the other finer-grained subfacies, which retain a drab grey to blue-grey colour until they pinch out into buff facies (Fig. 3). The U, Upper Grey and Middle Grey units are used in following discussions to characterize the blue-grey facies. Petrographic information on the composition of the blue-grey sands is given in Table 2.

Table 4. Lithofacies characteristics of three blue-grey units, with measurements based on thicknesses in the lateral stratigraphic section

		Sand	Interbedded, sand, silt, marl and clay	Mixed sand, silt, clay (palaeosol)
U Sand	% total	74	21	5
	Average unit thickness (m)	7·8	2·2	1·4
Upper Grey	% total	24	76	0
	Average unit thickness (m)	5·4	3·6	0
Middle Grey	% total	46	51	3
	Average unit thickness (m)	10	5·7	0·58

The U Sandstone

This unit is predominantly sand throughout its extent although it also includes other sub-facies (Table 4). Its lateral patterns, upper and lower contacts and internal structures are similar to those of other major blue-grey sand units (e.g. the T Sandstone; Figs 2 and 3) of the Khaur area. Palaeocurrent indicators measured on other blue-grey sands are also comparable to those of the U (Table 3), directed generally toward the east.

The basal contact of the U Sandstone is comformable to the north-east and erosional to the south-west of section 13. Local scours of depths to 3 m occur along outcrop distances of 20–30 m, and clasts of underlying red-brown silty clays are present in basal portions of the sand body where its lower contact is erosional. This basal relief remains constant south-west as far as section 7, where 19 m of downcutting occur over a distance of less than 1 km between sections 6 and 7. This feature is exaggerated by the vertical scale in Fig. 3; it is nevertheless a striking anomaly along the basal U contact. The U continues south-west of section 13 as a thicker sand body until section 3 where it again thins and in places becomes finer-grained. Between sections 2 and 3 it appears to cut through the Upper Grey unit. The U Sandstone in sections 1 and 2 is internally multistoried. West of section 1 the U and Middle Grey units become parts of a multistoried sand and can no longer be distinguished.

The upper 1–4 m of the U Sandstone consist of medium sand and fine-grained, well-bedded deposits with marl units 5–10 cm thick. The silts and silty clays are well-laminated, with occasional disruptions indicating minor bioturbation. The marl units are also laminated but appear more extensively bioturbated. Good preservation of primary bedding in the upper part of the U Sandstone indicates that deposition was rapid relative to secondary processes such as bioturbation. This contrasts markedly with conditions in the buff system where little primary bedding is preserved in the fine-grained deposits. The horizontal bedding, marls and drab colour of the upper U Sandstone all point to deposition at or below the water table, i.e. in ponds or swamps that did not undergo marked seasonal desiccation. Many of the major blue-grey units are capped by similar deposits which may be locally thicker in small, original, topographic depressions on the underlying sand facies.

Internally, the sand portion of the U Sandstone is massive or complexly cross-stratified. Large-scale sets of trough cross-stratification are typically between 2 and 15 m across and 0·5–1·5 m thick. Axes of troughs measured on dip-slopes are consistently parallel or sub-parallel, and measurements from many such dip-slopes show a 94° mean vector with low dispersion (Table 3). Lenses of carbonate or mudclast conglomerate occur sporadically and help to define the trough structures. Mud-drapes and lenses of red-brown clay with sharp upper and lower contacts are occasionally preserved between the cross-stratified sand units. Extraformational pebbles (primarily metamorphic in origin) occur more commonly toward the south-west. Internal structures and bedding sequences in the U Sandstone are similar to those of models for braided river deposits, particularly for the 'Bijou Creek Type' as summarized by Miall (1978).

The U Sandstone does not appear to be multistoried on a large scale north-east of section 3, although between sections 3 and 5 this is difficult to judge due to its cliff-forming tendencies. On a smaller scale, however, the bulk of the U Sandstone represents complex cut-and-fill episodes in a sand-dominated system that was probably braided for much of its period of lateral and vertical aggradation. During its phase of maximum lateral extent, this channel system was at least 25 km wide normal to the 94° average current direction. The erosional cut between sections 6 and 7 may represent a major axis of the channel system, formed during a temporary shift of this axis from its more normal position south-west of section 1.

The Middle Grey and Upper Grey units

These units vary from sand to silt and thus are referred to as 'units' rather than 'sandstones.' The Middle Grey passes laterally into sandstone toward the south-west, between sections 4 and 3 (Fig. 3). The Upper Grey is also predominantly sand from sections 9 to 10. Otherwise they are characterized by interbedded, finely laminated silts, silty clays, and fine blue-grey sands (Table 4). The mudstone deposits are drab grey to grey-green, with occasional beds of pink, yellow-grey, red and red-brown silty clay or silt. Individual beds are 5–20 cm thick with fine internal lamination that is horizontal, wavy and occasionally ripple cross-stratified. Burrow structures, root traces, and desiccation cracks are uncommon.

Lower contacts of the Middle and Upper Grey units are conformable and rest on palaeosol horizons for most of their lateral extent. These palaeosols are among the best developed within the study interval (Fig. 3). They disappear and are probably cut out where the Middle Grey drops in the section between sections 4 and 3 and where the U Sandstone thickens west of section 3. The presence of palaeosols that continue below sand deposits of the Upper Grey at section 10 shows that deposition there was not preceded by erosion; i.e. that the initial sediment was dropped by overloaded flow regimes incapable of eroding their bed.

The upper contacts of the two units differ, with the Middle Grey capped by one or more palaeosols while the Upper Grey shows no palaeosol development. In the latter case, it appears that deposition of red-brown silty-clay followed deposition of drab silts and sands without a time break sufficient for soil development. The Middle Grey and other underlying blue-grey sand or silt units (e.g. the T Sandstone) typically show soil development as a final phase in their deposition. These palaeosols are consistently dark grey or brown to nearly black at their upper contacts. The palaeosols along the top of the Middle Grey show extensive mottling, ped structures, variable nodule content and root and/or burrow structures. They differ from palaeosols in the buff system primarily in their drab to dark grey colour and lack of colour zonation. The occurrence of these palaeosols at the top of a sequence of quiet water deposits suggests that they could be poorly drained (gley) soils (Hunt, 1972).

Internally the Upper and Middle Grey units are similar, with no consistent lateral or vertical trends in lithology. There is no evidence for internal erosional contacts (i.e. cut-and-fill) between sand and mudstone facies; they interfinger laterally, indicating contemporaneous channel and interchannel areas of a braided system. The overall shape and internal characteristics of the Middle and Upper Grey units can be attributed to deposition in flowing and standing water on a broad plain with a consistently high water table.

Patterns through time

We interpret the three units discussed above as deposits of a single fluvial system based on similarities in their composition, overall shapes and internal structures. We believe that other blue-grey units above and below stratigraphically are also part of this, referred to as the blue-grey system. The pulses of sand and mudstone deposition that spread laterally continuous units east and north-east for 20–30 km were a recurring phenomenon in the Khaur area creating apparent 'cycles' through much of the Middle Siwalik section.

The blue-grey system can be compared to the models for fluvial systems given by Allen (1974). Although the scale of the sand bodies of the blue-grey system is larger, the lateral facies changes, morphology of the lower contacts and association with palaeosol horizons provide a basis of comparison. We propose that the blue-grey system follows a pattern of valley cut-and-fill similar to that formulated by Allen (1974, 'model 5B') in which vertical patterns of cut-and-fill are controlled by allocyclic processes and the vertical extent of valley cutting is greater than channel depth (Fig. 6c). The pattern of the blue-grey system differs from this model in that valley fill spread over the interfluves during the final stage of aggradation.

The evidence for down-cutting by the blue-grey system west of section 3 and particularly at the base of the U Sandstone between sections 6 and 7 shows that substantial erosion preceded deposition of blue-grey units. The laterally extensive palaeosols underlying the Middle and Upper Grey units can be attributed to soil formation during phases of valley cutting, when sediment was not available to interfluves. Subsequent aggradation overtopped the erosional relief and resulted in conformable deposition of sand and mudstone on the interfluve palaeosols. This aggradation may have been laterally time transgressive away from a major drainage axis which lay to the south-west. However, due to the lack of evidence for discrete avulsion events or progressive point-bar accretion within the blue-grey deposits, we feel that the lateral spread is more reasonably attributed to anastomosing, contemporaneous channels that rapidly covered the interfluve surfaces.

The U Sandstone itself does not lie upon a palaeosol. This may be because the terrace surface was stripped off during deposition (in contrast to the conditions accompanying deposition of the other two blue-grey units) or because its valley cutting phase was brief relative to the others.

It has been previously proposed (Pilbeam *et al.*, 1979) that deposition of the blue-grey sands might be similar to the spread of sand by the modern Sun Kosi River (Gole & Chitale, 1966) as it sweeps across its piedmont alluvial plain. This would imply autocyclic controls on the pulses of blue-grey facies. Detailed study of the blue-grey system and consideration of Allen's models (1974) for alluvial deposition argue against this, however. The characteristics of the blue-grey units are better explained by the spread of sediment from a relatively stable south-western source in short-term pulses rather than by progressive lateral movement by avulsion of a river channel across its depositional plain. The distinct pulses of erosion and sedimentation in the blue-grey system could represent some form of autocyclic periodicity in the drainage as a whole, in the sense of Schumm (1977), but if so it is on a scale that would make separation from allocyclic processes difficult.

Our interpretation of the blue-grey system in terms of valley cut-and-fill cycles implies allocyclic controls on this system. Periods of erosion require lowering of base level or increased stream power, due to decreased load or increased discharge (Leopold *et al.*, 1964). Valley depths on the order of 19 m (or more) combined with lengthy periods of soil formation favour overall base level change. Further discussion of possible controls on the blue-grey system will be given in a later section.

Comparison of the blue-grey and buff systems

We conclude that blue-grey and buff systems represent two different types of fluvial regimes. Not only do they differ in scale, both in spatial and temporal patterns, they also represent regimes with different controls, the buff system being dominantly (if not wholly) autocyclic while the blue-grey is dominantly allocyclic. The buff system also, in a sense, is subordinate in that it was periodically displaced or swamped by the blue-grey system, and re-established in the Khaur area after the pulses of sediment from this system ended (Fig. 7). However, through a longer period of time (~ 1·5 Myr) the buff system displaced the blue-grey toward the south-west. The buff system corresponds in general to the Dhok Pathan Formation and the blue-grey system to the Nagri Formation. The time-transgressive boundary between these formations (Gill, 1951; Barry *et al.*, 1980) results from the gradual replacement of the blue-grey fluvial system by the buff system in the Khaur area. The zone of interfingering between deposits of the two systems characterized by the sub-U interval is technically within the Dhok Pathan Formation because of the dominance of fine-grained sediments.

For the slice of the record considered in preceding discussions, a depositional history can be reconstructed as follows (refer to Figs 3 and 7):

(1) Valley cutting and formation of an interfluve palaeosol on buff system deposits.
(2) Valley filling by the blue-grey system and widespread deposition over the interfluve surface by the Middle Grey unit; water table high.
(3) Palaeosol formation on the Middle Grey, pause in sedimentation, water table initially high but gradually recedes.
(4) Re-establishment of the buff sand system, with one or more channel belts undergoing periodic avulsion.
(5) DN4 to DR4 magnetic polarity change.
(6) Buff system (channel system 'A' only) avulses twice more (A5 and A6; Fig. 3).
(7) Valley cutting in the blue-grey system; interfluve palaeosol development on the buff system

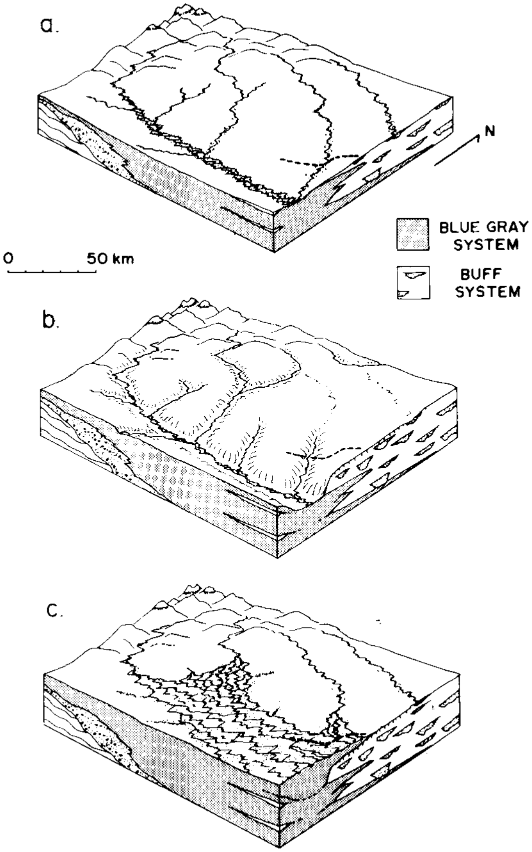

Fig. 7. Reconstructions of the blue-grey and buff fluvial systems to illustrate the interrelationships of the two systems as discussed in the text. The heavy dashed line shows the position of the Khaur area outcrops. Vertical scale greatly exaggerated on the depositional plain. (a) A period of 'normal' aggradation in the buff system, which includes four rivers draining south-east from relatively low-relief foothills to the north-west. These drainages are tributaries to the major blue-grey river which flows eastward as a belt of braided channels along the southern edge of the block. Stratigraphy shown along the eastern edge of the block diagram corresponds to that shown in Fig. 3, from the T Sandstone to just above the Middle Grey unit. (b) Conditions midway through a phase of valley-cutting by the blue-grey system, e.g. prior to deposition of the Upper Grey unit. Headward valley cutting in the largest of the four buff rivers (just west of the centre of the block) has resulted in the capture of the drainage that formerly crossed the Khaur area, temporarily ending buff system deposition there. Soil formation is occurring on the non-aggrading interfluve surfaces. (c) A phase of valley filling by the blue-grey system, corresponding to the deposition of the Upper Grey unit. Deposition of sand has overtopped the valleys and spread out across the interfluves in a broad, braided channel belt. After the influx of sand from the blue-grey system is reduced and the valley-fill phase ends, the two systems will return to approximately the conditions shown in (a) (see text).

deposits, buff channel belts cease to be locally active.

(8) Valley filling by the blue-grey system and deposition over the interfluve palaeosol by the Upper Grey unit, water table high.

(9) Erosion in a second valley-cutting episode and filling by the U Sandstone, with a shift of the channel axis toward the north-east.

(10) Lateral spread of the blue-grey sands at least 15 km laterally from the drainage axis (assuming this was near section 7).

(11) Sand deposition ceases, water table remains high and depressions on the surface of the U sand accumulate lacustrine and swamp deposits.

(12) Quiet water deposition ceases as buff system overbank sedimentation is re-established.

These events take place in approximately 40 m of section, amounting to 8×10^4 yr. If the sub-U interval buff system deposits represent $3{\cdot}6 \times 10^4$ yr then the events of the blue-grey system occurred in a maximum of $4{\cdot}4 \times 10^4$ yr. The two major periods of interfluve palaeosol formation below the Middle and Upper Grey units may represent on the order of 1×10^4 yr each, and the palaeosol at the top of the Middle Grey may also represent $0{\cdot}5$–$1{\cdot}0 \times 10^4$ yr. This leaves approximately $1{\cdot}4 \times 10^4$ yr for the three blue-grey units, or about $4{\cdot}7 \times 10^3$ yr each, for vertical aggradation over the interfluve surfaces and the cut and fill episode of the U Sandstone. Given that sedimentary evidence within the blue-grey units also points toward rapid deposition, this time framework seems reasonable. The apparent wide and rapid fluctuations in the water table during periods when the blue-grey system is dominant contrast with its apparent stability during buff system deposition.

CONTROLS ON THE FLUVIAL SYSTEMS

Comparison of the two systems demonstrates that the blue-grey system was controlled by a larger river, judging by the scale of cross-stratification and depth and width of local cut-and-fill structures. The question arises as to how much of the difference in the two systems can be accounted for simply by differences in the size of active channel belts. The preceding analysis shows that the buff system is not simply a scaled-down version of the blue-grey. There are fundamental differences in the depositional patterns that indicate different overall controls.

Laterally equivalent rates of sediment accumulation indicate that the depositional basin was subsiding evenly, and a local gradient in basin tectonics from south-west to north-east can be eliminated as a possible cause of differences in the buff and blue-grey systems. Any overall tectonic or climatic events affecting the basin should be reflected in both systems. Since both fluvial systems were feeding the same ultimate base level, either the Indian Ocean or Bay of Bengal, changes there should have affected both, although the larger system might have responded sooner to headward erosion or deposition. Middle Siwalik deposits occur along the entire Himalayan front, with no trace of marine or deltaic lithofacies, and the oceanic base level was more than 500 km and probably well over 1000 km from the Khaur area. Given this distance and the demonstrated cyclicity and timing of the valley cut and fill cycles, it seems unlikely that these were caused by base level changes in the world oceans. We cannot rule out the possibility that controls on local base level in the piedmont plain as a whole, such as changes in subsidence rates, could have caused the cut and fill cycles in the blue-grey system. This requires a periodicity in subsidence, with relatively abrupt decreases and increases in rate, superimposed on the overall constant basin lowering indicated by the magnetostratigraphy.

We favour characteristics of the source areas of the two systems as the most probable explanation for their distinctive depositional patterns. A previous hypothesis (Pilbeam *et al.*, 1979) that the blue-grey system drained areas dominated by physical erosion while the buff system drained areas of relatively higher chemical erosion is supported by our further field and petrographic studies. The compositional differences in the two sand types are similar to those of the modern Indus and Soan Rivers (Table 2). This suggests that the blue-grey system was similar in source area to the Indus and that the buff system was similar to the Soan. Given this, how might the observed differences in the fluvial regimes be explained by climatic or tectonic events in the source areas?

The two systems can be viewed as independent monitors of changes specific to their drainage basins; climatic or tectonic events of more regional significance should cause correlated changes in both systems. As reconstructed here, the two fluvial systems are comparable in many respects to contemporaneous drainages of the Gran Chaco in Argentina and Amazon tributaries in Brazil which differ in pattern and scale because of different source areas and responses to recent climate change (Baker, 1978). The fluvial patterns in the Siwalik deposits have the potential for defining climatic or tectonic events of major scale if the internal complexities of each system can be unravelled. We offer the following preliminary models, which can be formulated but not adequately tested, based on present evidence.

(1) Tectonic control: uplift in the source area of the blue-grey system increases upstream slopes.

The blue-grey system responds to increased slope by initial downcutting followed by filling as the river readjusts to an increased sediment load. This model requires a lag time between the effects of increased slope on the river's energy and the effects of increased erosion on the river's load. Filling would proceed upstream from the point where the river was no longer capable of eroding. If this were far enough downstream from the Khaur area then the lag time might be sufficient for terrace soil formation. After the episode of filling, the river returns to a more confined channel belt to the south-west of the Khaur area.

This model implies a direct cause-effect relationship between tectonic events and pulses of blue-grey sand which is maintained throughout the period of interfingering of the blue-grey (Nagri) and buff (Dhok Pathan) lithofacies, i.e. for several million years. Such events affect the buff system by causing temporary abandonment of the normal pattern of aggradation rather than alteration of this pattern *in situ*. This could occur if local base level were lowered (i.e. by the blue-grey system in its erosion phase) causing upstream capture of buff system rivers close to the blue-grey river system (Fig. 7b). Lack of evidence for any direct response to source area uplifts in the buff system implies that such events were not occurring during its periods of aggradation.

(2) Climatic control: changes in rainfall and/or temperature affect the discharge and sediment yield of the source areas.

The possible effects of rainfall and/or temperature changes in the source area are complex and depend to a considerable degree on the preceding state of balance between sediment load, discharge and vegetation cover (Leopold *et al.*, 1964). Two models are given here based on alternate starting conditions.

(2a) The source area of the blue-grey system is initially moist with moderate vegetation cover. A decrease in rainfall (or decrease in temperature) destroys much of this cover, resulting initially in increased run-off which causes valley cutting in the alluvial deposits of the Khaur area. Slopes become unstable in the source area but much of the resulting sediment is not transported far due to low overall discharge. A return to increased rainfall causes transport of large volumes of this sediment on to the alluvial plain, resulting in filling of the valley and deposition of sheet deposits over the interfluve surfaces. Vegetation cover again forms in the source area and the river returns to a more confined channel. The blue-grey system then remains stable and in equilibrium with subsidence, allowing the buff system to reinstate its depositional regime. The buff system might also reflect such changes in rainfall, although the effects would be less marked than in a larger, higher relief drainage. Rainfall also might increase along the mountain front while decreasing in the interior causing out-of-phase responses in the two systems. The buff system shows no evidence of such responses, however, except to become locally inactive during the phase of blue-grey cut-and-fill.

(2b) The source area of the blue-grey system is initially dry with poor vegetation cover. A shift toward more rainfall increases overall discharge, while sediment load is reduced by an increase in vegetation. This results in valley cutting on the alluvial plain. A return to lower rainfall decreases vegetation and releases a large amount of sediment which is carried by the higher run-off to the alluvial plain. The valley fills and the overloaded river deposits a sheet of sand and silt laterally until the gradient again balances the local input and output of sediment. Since there is evidence for a high water table toward the end of blue-grey system deposition, this model requires that the climate of the plain be different (i.e. wetter) than that of the source area or that the increased runoff maintains a high flow throughout deposition of blue-grey sediments.

Other schemes are possible, and much depends on the rate at which slope denudation affects overall runoff versus sediment yield. Model (2a) requires a considerable lag time between runoff and sediment transport while (2b) requires essentially no lag time. Model (2a) provides a simpler explanation for high-water table conditions in the blue-grey sheet deposits, but on present evidence neither model can be favoured. In both cases, the nature of the transition between dry and wet rainfall regimes would be critical in initiating erosion or deposition. It is possible to formulate other models using glaciation and deglaciation as controlling processes, but these might not be justified for the Himalayas of 8 Myr BP.

The possibility that any single mechanism was responsible for the depositional pattern of the blue-grey system seems remote given the complexity of piedmont depositional processes. On the other hand, the repeated patterns of shape, lithology and contact relationships of the blue-grey units suggest that some periodic and persistent allocyclic processes were affecting Miocene sedimentation in the Khaur area. The nature of these processes, even if complex, may eventually be understood through further study of their patterned effects through time.

CONCLUSION

Using the lateral relationships of lithofacies in a 40 m × 40 km slice of the Middle Siwalik rock sequence of the Khaur area combined with a palaeomagnetic isochron traced along 30 km of these lithofacies, we have reconstructed two contemporaneous fluvial systems, the blue-grey and buff systems. These represent fluvial regimes that differed in scale and pattern of deposition through time, above and below the 40 m study interval as well as within it.

Compared to the blue-grey system, the buff system drained areas of lower relief with a greater degree of chemical weathering and erosion and was characterized by channel belts 3 km or less in width that aggraded by avulsion events on floodplains 10–20 km in width. The patterns of aggradation in the buff system can be attributed to autocyclic processes. The spatial pattern of sedimentation within the buff system was patchy but continuous overall, with no marked hiatuses. Channel belts can be compared to those of small-scale, parallel drainages along the modern Himalayan front between major rivers such as the Soan or Jhelum. A reconstruction of topographic relief along the isochron indicates a possible slope of $\sim 3\ \mathrm{m\ km^{-1}}$ between the deposits of parallel channel belts.

The blue-grey system can be compared to the modern Indus River in that it appears to have drained a region of relatively high relief where processes of physical erosion were dominant. The patterns documented in this study indicate one major channel that went through successive valley cut-and-fill cycles, spreading laterally over at least 25 km as a braided system during the last phases of deposition after overflowing the former interfluve surfaces. These interfluves have well-developed palaeosols, attributed to the period of valley cutting, and are conformably overlain by the blue-grey deposits. The pattern of deposition of the blue-grey system can be attributed to allocyclic processes affecting base level, discharge and/or sediment load, but we are not able to specify the nature of the controls at present. The repetition of this pattern through time indicates cyclical controls on the blue-grey system through several million years.

With the time calibration provided by lateral and vertical magnetostratigraphy, we can estimate the amount of time represented in the hiatuses as well as in the sedimentary strata of the Miocene fluvial systems. The buff system avulsion events occurred at a rate of less than one per 6×10^3 yr, and palaeosols formed in 10^3–10^4 yr in areas of temporary non-deposition. Cutting of valleys by the blue-grey system may have occurred in $< 10^4$ yr, coincident with palaeosol formation on interfluve surfaces. Filling and lateral spread of the blue-grey sheet deposits may have occurred in 4–5×10^3 yr. Time breaks in the sequence are primarily at the lower and upper contacts of the blue-grey units; i.e. at the palaeosol horizons, or where downcutting has removed part of underlying section, or where local relief on the sand surfaces formed topographic highs resulting in hiatuses not marked by palaeosol formation. Palaeomagnetic samples taken in fine-grained intervals through such deposits will thus represent a maximum of 50% of the polarity time record, since the other 50% is taken up in periods of non-deposition, erosion, and sand accumulation. The palaeomagnetic record *within* a block of buff system deposits will be relatively complete, hence some continuous segments of the reversal record will be preserved while other segments will not.

Nearly all of the vertebrate and invertebrate fossils in the Khaur area occur in buff system deposits (Badgley & Behrensmeyer, 1980). This indicates that the autocyclic fluvial processes were conducive to bone preservation and that this system also supported a large and varied biota through time. The style of deposition in the blue-grey system was apparently not favourable to bone preservation, perhaps for both taphonomic and ecologic reasons. Within the sub-U interval, fossil localities are most commonly found in areas proximal to or within channels, where the potential for rapid burial was high.

The relatively small piedmont drainages reconstructed for the buff system in the Khaur area probably were subject to marked seasonal fluctuations, and dry conditions may have characterized their alluvial plains during part of the year. The nature of the fluvial systems of the Khaur area during the late Miocene would have had important effects on the spatial and temporal distributions of the mammals and their adaptive strategies. Given that the vertebrate record is linked to the buff system in the Khaur area, faunal samples are similar to palaeomagnetic samples in that they represent distinct blocks of time (e.g. 3–4 × 10^4 yr for the sub-U interval) separated by equivalent or longer periods when the record is missing.

ACKNOWLEDGMENTS

All members of the joint Pakistan Geological Survey–Yale Peabody Museum project, under D. R. Pilbeam and S. M. Ibrahim Shah, have contributed in various ways to this study. We specifically thank D. R. Pilbeam, N. Johnson and N. Opdyke for their support and encouragement. For help in the field we are grateful to J. Barry, N. Hacking, M. Solomon, and Mr Zufar. C. Badgley, M. Monaghan, J. Barry, B. Fine, and D. Pilbeam have offered useful discussion, data and comments throughout. We thank J. R. L. Allen, T. Bown and M. Kraus for comments on the manuscript. Dolores Larkie and Liz Kyburg provided speedy typing of the various drafts of the manuscript and Larry Isham assisted with drafting. The work is supported by NSF Grant #ENS 772-5984 and SFCP Grant #FC80254100.

REFERENCES

ALLEN, J.R.L. (1963) The classification of cross-stratified units, with notes on their origin. *Sedimentology*, **3**, 93–114.

ALLEN, J.R.L. (1965) A review of the origin and characteristics of recent alluvial sediments. *Sedimentology*, **5**, 89–191.

ALLEN J.R.L. (1974) Studies in fluviatile sedimentation: Implication of pedogenic carbonate units, Lower Old Red Sandstone, Anglo-Welsh outcrop. *Geol. J.* **9**, 181–208.

ALLEN, J.R.L. (1978) Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion controlled alluvial suites. *Sedim. Geol.* **21**, 129–147.

BADGLEY, C.E. & BEHRENSMEYER, A.K. (1980) Palaeoecology of Middle Siwalik sediments and faunas, northern Pakistan. *Palaeogeogr. Palaeoclim. Palaeoecol.* **30**, 133–155.

BAKER, V.R. (1978) Adjustment of fluvial systems to climate and source terrain in tropical and subtropical environments. *Fluvial Sedimentology* (Ed. by A.D. Miall). *Mem. Can. Soc. Petrol. Geol.* **5**, 211–230.

BARNDT, J., JOHNSON, N.M., JOHNSON, G.D., OPDYKE, N.D., LINDSAY, E.H., PILBEAM, D.R. & TAHIRKHELI, R.A.H. (1978) The magnetic polarity stratigraphy and age of the Siwalik Group near Dhok Pathan Village, Potwar Plateau, Pakistan. *Earth planet. Sci. Lett.* **41**, 355–364.

BARRY, J.C., BEHRENSMEYER, A.K. & MONAGHAN, M. (1980) A geologic and biostratigraphic framework for Miocene sediments near Khaur village, northern Pakistan. *Postilla*, **183**, 19 pp.

BARRY, J.C., LINDSAY, E.H. & JACOBS, L.L. (1982) A biostratigraphic zonation of the Middle and Upper Siwaliks of the Potwar Plateau of northern Pakistan. *Palaeogeogr. Palaeoclim. Palaeoecol.* **37**, 95–130.

BOWN, T.M. (1979) Geology and mammalian paleontology of the Sand Creek facies, lower Willwood Formation (lower Eocene), Washakie County, Wyoming. *Geol. Surv. Wyo. Mem. No. 2*, 151 pp.

BOWN, T.M. & KRAUS, M.J. (1981a) Lower Eocene alluvial paleosols (Willwood Formation, northwest Wyoming, U.S.A.) and their significance for paleoecology, paleoclimatology, and basin analysis. *Palaeogeogr. Palaeoclim. Palaeoecol.* **34**, 1–30.

BOWN, T.M. & KRAUS, M.J. (1981b) Vertebrate fossil-bearing paleosol units (Willwood Formation, Lower Eocene, northwest Wyoming, U.S.A.): implications for taphonomy, biostratigraphy and assemblage analysis. *Palaeogeogr. Palaeoclim. Palaeoecol.* **34**, 31–56.

BRAMMER, H. & BRINKMAN, R. (1977) Surface-water gley soils in Bangladesh: environment, landforms and soil morphology. *Geoderma*, **17**, 91–109.

BREWER, R. (1964) *Fabric and Mineral Analysis of Soils.* Wiley, New York. 470 pp.

BRIDGE, J.S. & LEEDER, M.R. (1979) A simulation model of alluvial stratigraphy. *Sedimentology*, **26**, 617–644.

FATMI, A.N. (1973) Lithostratigraphic units of the Kohat-Potwar Province, Indus Basin, Pakistan. *Mem. geol. Surv. Pakistan*, **10**, 80 pp.

FISHER, R. (1953) Dispersion on a sphere. *Proc. R. Soc. A*, **217**, 295–305.

GILL, W.D. (1951) The stratigraphy of the Siwalik series in the northern Potwar, Punjab, Pakistan. *Q. Jl geol. Soc. Lond.* **107**, 375–394.

GOLE, C.V. & CHITALE, S.V. (1966) Inland delta building activity of Kosi River. *J. Hydraul. Div. Proc. Am. Soc. civ. Engrs* **92**, 111–126.

HUNT, C.B. (1972) *Geology of Soils, their Evolution, Classification and Uses.* W.H. Freeman, San Francisco. 344 pp.

INGLIS, C.C. (1949) The behavior and control of rivers and canals (with the aid of models), Meandering of rivers. *Res. Publs cent. Wat. Proj. turig. Navig. Res. Stn. Poona*, **13**, 143.

JOHNSON, N.M., OPDYKE, N.D. & LINDSAY, E.H. (1975) Magnetic polarity stratigraphy of Pliocene/Pleistocene terrestrial deposits and vertebrate faunas, San Pedro Valley, Arizona. *Bull. geol. Soc. Am.* **86**, 5–12.

KENT, D.R. (1973) Post-depositional remanent magnetization in deep sea sediments. *Nature*, **246**, 32–35.

LABRECQUE, J.L., KENT, D.V. & CANDE, S.C. (1977) Revised magnetic polarity time scale for late Cretaceous and Cenozoic time. *Geology*, **5**, 330–335.

LANGBEIN, W.B. & LEOPOLD, L.B. (1968) River channel bars and dunes—theory of kinematic waves. *Prof Pap. U.S. geol. Surv.* **422–L**, 20 pp.

LEEDER, M.R. (1973) Fluviatile fining-upwards cycles and the magnitude of palaeochannels. *Geol. Mag.* **110**, 265–276.

LEEDER, M.R. (1975) Pedogenic carbonates and flood sediment accretion rates: a quantitative model for arid zone lithofacies. *Geol. Mag.* **112**, 257–270.

LEOPOLD, L.B. & WOLMAN, M.G. (1957) River channel patterns: braided, meandering and straight. *Prof. Pap. US geol. Surv.* **282–B**, 73 pp.

LEOPOLD, L.B., WOLMAN, M.G. & MILLER, J.P. (1964)

Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco. 522 pp.

MANKINEN, E.A. & DALRYMPLE, G.B. (1979) Revised geomagnetic polarity time scale for the interval 0–5 my. B. P. *J. geophys. Res.* **84**, 615–626.

MIALL, A.D. (1973) Markov chain analysis applied to an ancient alluvial plain succession. *Sedimentology*, **20**, 347–364.

MIALL, A.D. (1977) *Fluvial Sedimentology. Part 2: Analysis of Fluvial Depositional Systems*. Canadian Society of Petroleum Geologists, Calgary. 37 pp.

MIALL, A.D. (1978) Lithofacies types and vertical profile models in braided river deposits: a summary. In: *Fluvial Sedimentology* (Ed. by A.D. Miall). *Mem. Can. Soc. Petrol. Geol.* **5**, 597–604.

OPDYKE, N.D., KENT, D.V. & LOWRIE, W. (1973) Details of mag polar transitions in high deposition rate deep sea cores. *Earth planet. Sci. Lett.* **20**, 315.

PILBEAM, D.R., BEHRENSMEYER, A.K., BARRY, J.C. & SHAH, S.M.I. (1979) Miocene sediments and faunas of Pakistan. *Postilla*, 179, 1–45.

PUIGDEFABREGAS, C. & VAN VLIET, A. (1978) Meandering stream deposits from the Tertiary of the southern Pyrenees. In: *Fluvial Sedimentology* (Ed. by A.D. Miall). *Mem. Can. Soc. Petrol. Geol.* **5**, 469–485.

REYMENT, R.A. (1971) *Introduction to Quantitative Palaeoecology*. Elsevier, Amsterdam. 226 pp.

SCHUMM, S.A. (1977) *The Fluvial System*. Wiley, New York. 338 pp.

TAUXE, L. (1978) *A comparison of isochrons defined by short-term palaeomagnetic events and lithostratigraphic units in Siwalik rocks of the Potwar Plateau, Punjab Province, Pakistan*. Unpubl. Yale College Scholar of the House Thesis. 28 pp.

TAUXE, L. (1979) A new date for *Ramapithecus*. *Nature*, **282**, 399–401.

TAUXE, L., KENT, D.V., & OPDYKE, N.D. (1980) Magnetic components contributing to the NRM of Middle Siwalik Red Beds. *Earth planet. Sci. Lett.* **47**, 279–284.

TAUXE, L. & OPDYKE, N.D. (1982) Magnetic stratigraphy of the Khaur area, northern Pakistan. *Palaeogeogr. Palaeoclim. Palaeoecol.* **37**, 43–62.

VISHER, G.S. (1965) Use of vertical profile in environmental reconstruction. *Bull. Am. Ass. Petrol. Geol.* **49**, 41–61.

WATSON, G.S. (1956) A test for randomness of directions. *Mon. Not. R. astr. Soc. Geophys. Suppl.* **7**, 160–161.

(Manuscript received 6 January 1981; revision received 23 September 1981)