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A Geologic and Biostratigraphic Framework for Miocene Sediments near Khaur Village, Northern Pakistan

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Abstract

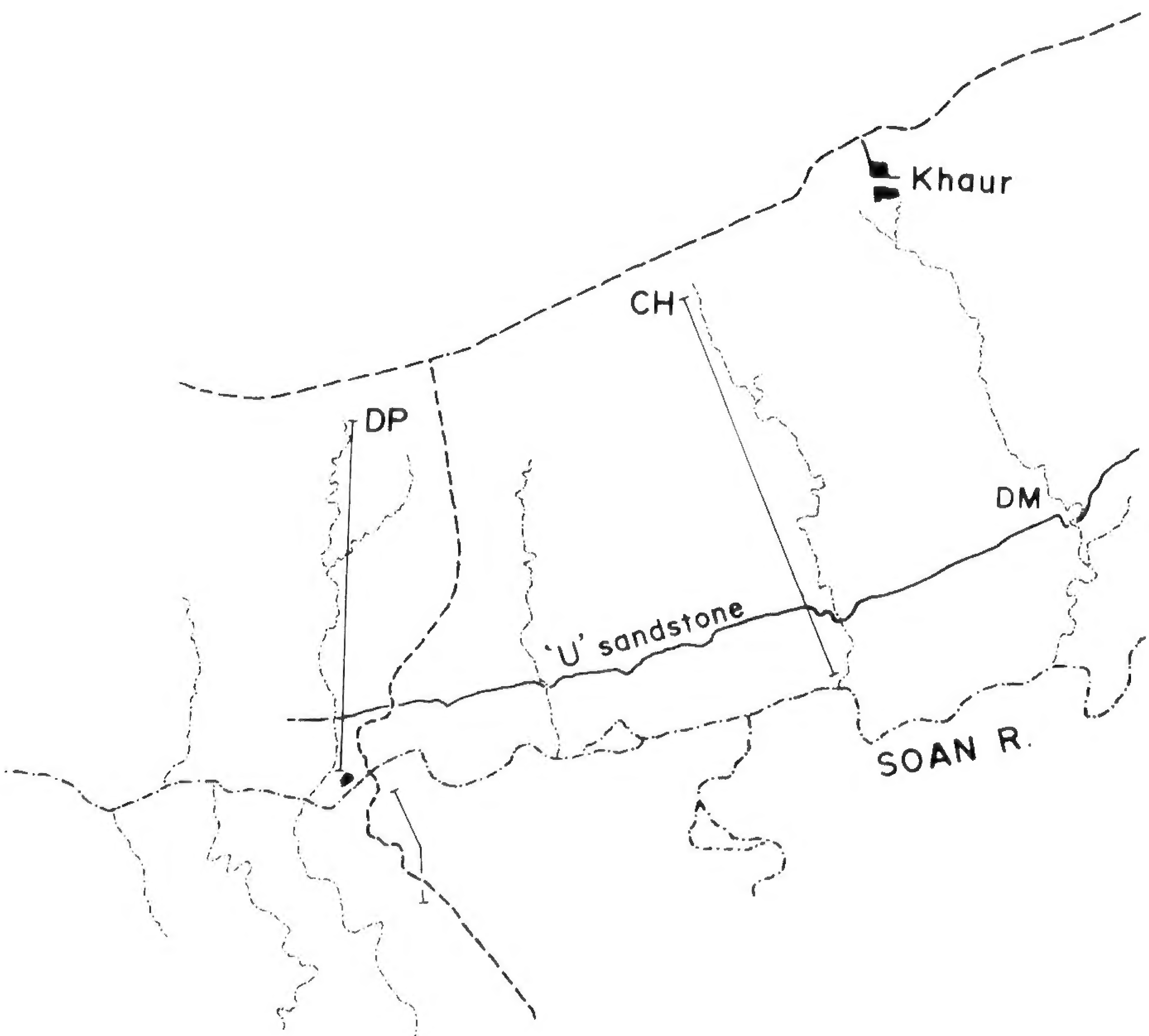
A litho- and chronostratigraphic framework for approximately 3500 m of late Miocene sedimentary deposits with lateral exposure of 30–40 km is now well established for Siwalik deposits in the vicinity of Khaur Village, northern Pakistan. Based on paleomagnetic reversal stratigraphy and the constraints of long range faunal correlations, the time spanned is between 15–12 and 6 my BP. Boundaries of the major lithostratigraphic units are time-transgressive with respect to a paleomagnetic isochron traced laterally for 20–30 km. With reference to this datum, the zone of interfingering of the Dhok Pathan and Nagri Formations moves upward through approximately 1.5 my from east to west in the Khaur area. The major rock units represent adjacent alluvial deposits of two or more major fluvial systems with different characteristics of fossil preservation. Nearly 350 fossil-collecting localities can be placed in this litho- and chronostratigraphic framework. These localities span the entire 6–9 my interval, although the lower half of the section is only poorly fossiliferous. The sequence of faunas encompasses Pilgrim's Kamlial through Dhok Pathan faunal zones, but with this new chronostratigraphic framework it is now apparent that the classic faunal zones must be superseded by a biostratigraphic zonal scheme.

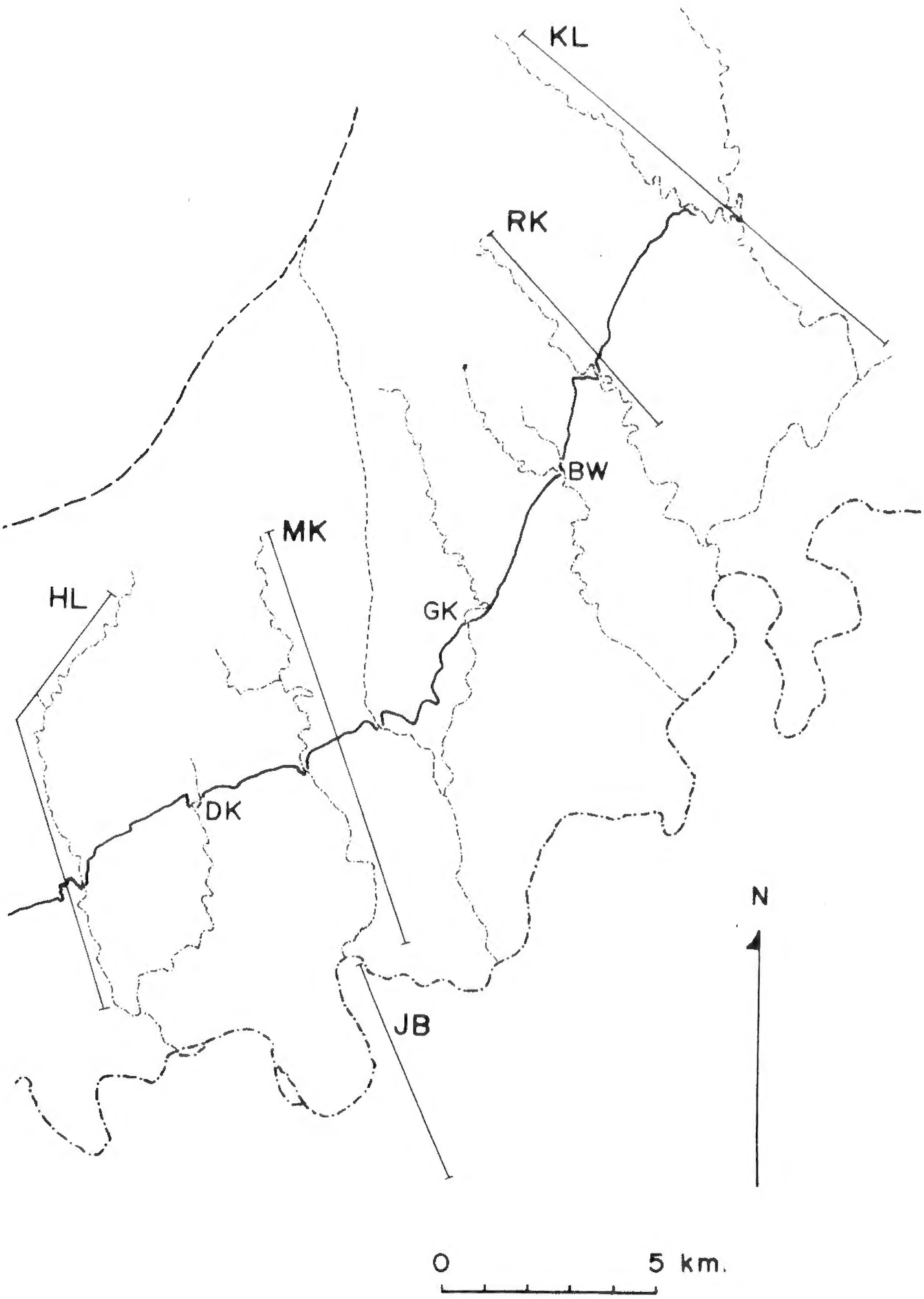
Key words: Siwaliks, stratigraphy, Potwar Plateau, upper Miocene, Hominoidae.

Introduction

The geology and stratigraphy of fossiliferous sediments on the northern limb of the Soan Synclinorium have been summarized in previous publications dealing with the geology and paleontology of the Siwalik formations of the Potwar Plateau as a whole (e.g., Pilbeam et al., 1977; Pilbeam et al., 1979). In this paper we present a comprehensive and updated litho- and biostratigraphic framework for Middle Siwalik deposits found in the vicinity of Khaur Village (Fig. 1), where field research of the joint Yale Peabody Museum-Geologic Survey of Pakistan (Yale-GSP) has concentrated since 1973. The Khaur area provides a continuous stratigraphic section spanning over 5000 m and representing the time period between 12+ and 6 my BP. The section can be traced for tens of kilometers laterally and is fossiliferous throughout, with a diverse mammalian fauna which includes hominoid primates. This combination of features provides a unique opportunity to study the evolution of terrestrial environments and faunas during a critical period of Cenozoic history. The most basic requirement for such goals is an understanding of the litho- and chronostratigraphy of the sedimentary rocks. Through the efforts of many members of the Yale-GSP team, the litho- and chronostratigraphy of a significant portion of the Khaur sequence are now well

Fig. 1
Drainage map of the Khaur area, from Dhok Pathan (west) to Kaulial Kas (east), showing the major canyons or kas' and the positions of long stratigraphic sections (straight solid lines). The outcrop trace of the U sandstone is indicated by a heavy black line. Inset shows position of the Potwar Plateau study area in northern Pakistan. Abbreviations for the stratigraphic sections' locations, from west to east: DP=Dhok Pathan, CH=Choutriwali Kas, DM=Dhok Mila Kas, HL=Hasal Kas, DK=Dinga Kas, JB=Jabbi, MK=Malhuwala Kas, GK=Gandakas, BW=Bhagwa Kas, RK=Ratha Kas, KL=Kaulial Kas.

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documented and are presented here as a basis for further research.

We present the following information in two parts; the first summarizes physical geological and chronological evidence and the second discusses faunal evidence in relation to the overall stratigraphic framework.

The Geological and Chronostratigraphic Evidence

The physiography of the Khaur area is characterized by canyons or "kas" (plural, kas') which cut through dipping strata perpendicular to strike and are spaced at intervals of about 3 km along strike. The measuring of long stratigraphic columns in these kas' is thus a relatively straightforward initial approach to the geology. Sections have been measured using both tape-and-compass and Jacob's staff techniques. Frequent changes in dip and poor exposure, particularly in the lower portions of the sections, limit the accuracy of these methods. Thicknesses presented here are thus subject to possible error which is probably not of great significance with respect to the total sedimentary column.

Since the Khaur area sediments are extremely variable laterally, correlations between sections, measured at approximately 3 to 6 km intervals, cannot be done by simple matching of vertical patterns in the stratigraphy. Lateral tracing of a number of marker horizons is necessary to establish the lithostratigraphic correlations between sections. In the lower parts of many sections, divides between the kas' are mantled with late Pleistocene to subrecent Potwar Silts, and marker horizons cannot be traced with certainty. Toward the tops of the sections, the Soan River meanders across strata, preventing correlation of marker units with areas to the south and west (Fig. 1). In the upper middle portion of the Khaur sequence, however, there are nearly continuous exposures that can be walked out laterally for some 40 km, and these have provided critical horizontal links between all measured sections. Within this belt, a marker unit referred to as the "U" sandstone is the most useful traceable datum.

The large-scale stratigraphic evidence consists of 6 long measured sections and five shorter ones correlated using the U sandstone and two less extensive units. These provide the lithostratigraphic framework for the Khaur area which is presented graphically in Figure 2. We regard the longest measured section, 3240 m in Kaulial Kas, as the best reference section for facies and faunal history of the Lower and Middle Siwalik deposits of the Khaur area. This section has also provided the most complete paleomagnetic sampling because it is generally finer-grained than sections to the west.

The lithologically correlated sections can provide only rough estimates of the relative time relationships between facies changes or faunal events in the different kas' of the Khaur area. Correlations to more distant Siwalik deposits using lithofacies corresponding to formations such as the Chinji or Nagri are far more subject to possible time differences. The strong tendency of previous workers to think of the lithostratigraphic entities (Table 1) as time-specific has led to problems of interpretation and nomenclature which have yet to be completely unraveled (Pilbeam et al., 1979).

Until the development and application of paleomagnetic reversal stratigraphy there was no way to measure time vertically or trace it laterally through the Siwalik sediments of the Potwar, other than through use of the vertebrate faunas. Volcanic ash horizons are very rare and when they occur are laterally discontinuous. Vertebrate evidence has been sufficient to indicate that some lithostratigraphic units were possibly time-transgressive, but it has not provided any firm biostratigraphic marker horizons that could be judged as time-specific events rather than ecological or sampling phenomena.

The obvious need for a chronostratigraphy which is independent of faunas and lithounits, at least in a local sense, has led to intensive sampling and resampling of the paleomagnetic reversal patterns in the Siwalik deposits, particularly in parts of the section yielding large faunal collections. The work of J. Barndt (1977), and more recently L. Tauxe (1978), in conjunction with Dartmouth Col-

Table 1. Siwalik Formations represented in the Khaur area, with local characteristics of the Middle Siwalik formations. Thicknesses vary as indicated in Figure 2; those given here are based primarily on the measured section in Kaulial Kas. Further details concerning lithofacies are given in Pilbeam et al., 1979.

Age	Group	Formation	Thickness and Lithology in Khaur Area
Pliocene to early Pleistocene	Upper Siwalik	Soan	Not yet studied; composed of gravelly sands and brown silts according to Shah (1977).
Upper Miocene	Middle Siwalik	Dhok Pathan	1600 m (5200'); predominantly red-brown silts and clays with thinner sand units (tabular and lenticular): lower 340 m (1100') include both blue-gray and buff sands, middle 400 m (1300') buff to gray sands and upper 360 m (2800') gray sands with coarse gravel.
		Nagri	1300 m (4200'); defined locally as having units of blue-gray sand more than 33 m (100') in thickness, interbedded with thinner units of variegated silts and clays with occasional lenses of buff sand.
Middle to late Miocene	Lower Siwalik	Chinji	Dominantly red mudstones interbedded with lenticular blue-gray sands; not yet studied in detail.
		Kamlial	Sands and gravels with interbedded red and purple mudstones; not yet studied.

lege, the Lamont-Doherty Geological Observatory and the University of Arizona, has established a paleomagnetic reversal stratigraphy for the upper 3000 m of the Siwalik section in the Khaur area. Portions of the reversal pattern are duplicated consistently in seven laterally correlated sections of different kas', helping to confirm the reliability of the data (Tauxe, 1979). In addition, Tauxe has traced one normal to reversed transition below the U sandstone laterally over a distance of about 30 km and the resulting isochron (referred to as the sub-U isochron) closely parallels the upper boundary of the sandstone (Behrensmeyer and Tauxe, in preparation). Thus we have a horizontal time link through the stratigraphic sections as well as an overall vertical reversal pattern. The long, composite column of Barndt and Tauxe can be correlated with the current global reversal pattern for the late Miocene as shown in Figure 2. The approximate age of the sediments based on faunal correlations with radiometrically dated assemblages in Europe was previously stated as between 13 and 8 my, with the bulk of the Khaur area primates and associated fauna estimated at around 9 my (Pilbeam et al., 1977). The revised interpretations of age by Tauxe (1979) show that a more probable date for this fauna is about 8 my. Interestingly, this also indicates an error of at least 1 my in previous attempts at absolute dating based on long-range faunal correlations.

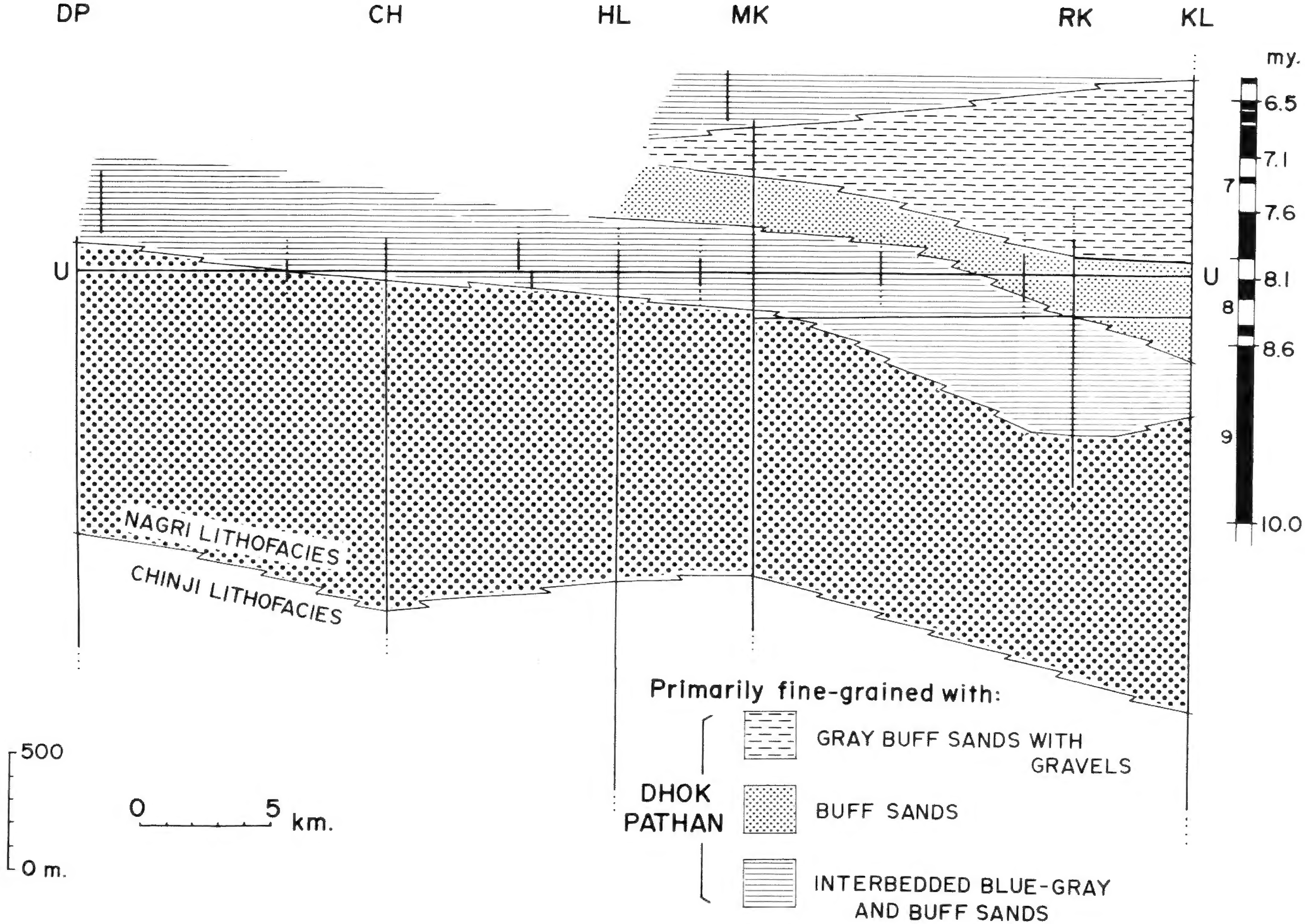
We feel confident that the stratigraphic and chronological framework shown in Figure 2 is now well established and can serve as a reliable basis for analysis of facies and faunas in the upper half of the Khaur area deposits and for correlation with other Siwalik sequences in Pakistan and India. Further work in the Khaur area is planned to extend the paleomagnetic stratigraphy through the lower part of the section.

Major Sedimentary Units

Stratigraphic columns measured in the Khaur area typically begin in sediments characterized by 1) interbedded red mudstones with discontinuous blue-gray sands and continue upward through 2) thick, massive sandstones; they are followed by 3) interbedded sandstones and variegated silts and clays, and (if there are sufficient exposures) end in 4) thick red-orange silts with cobble-bearing sandstone lenses. For anyone familiar with Siwalik formations, as defined by Fatmi (1973), there is little difficulty in assigning 1) to the Chinji Formation, 2) to the Nagri Formation, 3) and possibly 4) to the Dhok Pathan Formation, where the distinguishing lithological features of the units are best expressed (Table 1). However, difficulties are encountered in recognizing boundaries between the units because of their interfingering relationships. It has proved impossible to map recognizable boundaries in the Khaur area based on Fatmi's definitions of the formations.

Originally it was thought important to establish lithological boundaries as reference points for the fossil collections, especially when these boundaries were supposed to be more or less isochronous. Now, however, the paleomagnetic reversal patterns and particularly the tracing of the sub-U isochron show that these lithological boundaries are not only complex in detail but also strongly time-transgressive over distances of 30–40 km, with time differences on the order of 1.0–1.5 my (Fig. 2). The major units of the Khaur area

Fig. 2
Lithostratigraphic framework for Lower and Middle Siwalik deposits in the Khaur area. Vertical lines represent the measured sections, with dotted extensions showing where strata continue beyond what has been measured. The U sandstone, which closely parallels a paleomagnetic isochron, is used as a horizontal datum to align the sections, along with two less extensive horizontal marker units. The boundaries of the Nagri Formation are defined as the points where individual sandstone units exceed 33 m in thickness in each long section. The composite paleomagnetic reversal stratigraphy (Tauxe, personal communication) for the sequence is given to the right of the KL column, with normal zones shown in black, epoch numbers to the left of the column. Abbreviations for sections given in caption to Figure 1. See also Figure 2 in Gill (1951).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Primarily fine-grained with:
DHOK PATHAN
GRAY BUFF SANDS WITH GRAVELS
BUFF SANDS
INTERBEDDED BLUE-GRAY AND BUFF SANDS

actually appear to represent differing broad-scale depositional regimes, some of which were contemporaneous with one another.

The major sedimentary units can be divided into a number of distinctive smaller scale lithofacies which bear a specific relationship to particular depositional regimes (e.g., channels, floodplains). Three important small-scale lithofacies, the blue-gray sand, buff sand and silt/clay facies, have been presented by Pilbeam et al., 1979. Further work on these and additional lithofacies is underway, but details are beyond the scope of this paper. The three lithofacies mentioned above have proven to be consistently recognizable in the field, and distinguishing features of the Nagri and Dhok Pathan Formations in the Khaur area can be described using the relative proportions of the component facies in each (Table 1). These small-scale lithofacies clearly represent depositional environments and conditions that were not specific to any particular time period.

The blue-gray sand and the buff sand facies are strikingly different in composition and in the shape of their sedimentary units. Preliminary petrographic results show a higher proportion of rock fragments in the blue-gray sands. This supports other evidence (Pilbeam et al., 1979) for the less mature nature of the blue-gray sands. We currently favor the hypothesis that the two facies represent two separate fluvial systems with differing drainage basins. Blue-gray sands bear evidence of the dominance of physical erosion while buff sands indicate greater influence of chemical weathering. The former are probably derived from a river system draining tectonically elevated regions within the Himalayas, while the latter represent rivers draining the foothills of the mountain front. The buff sands are more intimately related to the silt/clay facies, in terms of intergradational contacts and lateral interfingering, than are the blue-gray sands. Thus it appears that the buff-sand system deposited more of the silt/clay facies in the Khaur area than did the blue-gray system.

"Cycles" that have been noted in previous publications (Pilbeam et al. 1977, 1979) consist of alternations of one or the other of the sandstone facies with thicker units of the silt/clay facies. The cycles change laterally along with overall trends in the major lithofacies, with blue-gray sand units thickening westward and silt/clay units thickening eastward. The zone of the most characteristic cycles, with 2–10 m thick blue-gray sand units separated by 30–50 m of silt/clay and buff sand facies, is about 500 m thick and is time-transgressive toward the west (Fig. 2). In this zone the alternating dominance of the blue-gray and silt/clay plus buff sand facies appears to reflect cyclic processes intrinsic to one or both fluvial regimes although there may be broader, extrinsic tectonic or climatic influences on these systems which we do not yet comprehend. It may be possible to separate the lithological record of extrinsic processes from intrinsic ones as the latter become better understood, and work is continuing with this goal in mind.

Paleogeography and Sedimentary History

Three lines of evidence may be used to reconstruct the large-scale paleogeography of the Khaur area: 1) the lateral variation of major rock units parallel to the sub-U isochron, along the generally east-west strike of the outcrops, 2) sedimentological characteristics of small-scale lithofacies and larger-scale units which indicate source area and depositional environment, and 3) current directions of channel sandstone bodies as determined from axes of trough cross-beds and linear directions of the sand bodies themselves.

At present we can discuss in detail only the paleogeography of the Nagri and Dhok Pathan Formations in the Khaur area. However, the relationships of these formations indicate what might be expected for the lower part of the section as well as for other areas of the Potwār Plateau.

Along the sub-U isochron blue-gray sands predominate in the western part of the Khaur area and interfinger with the silt/clay facies and buff sands which predominate in the east. Lenses of buff sand occasionally are in direct erosional contact with underlying blue-gray sands. The thickness and lateral extent of the buff sand units do not change along strike, in contrast to the blue-gray sand units which generally thicken westward and gradually predominate over the buff sand and silt/clay facies until they form stacks of "multistoried" sandstones in the vicinity of Dhok Pathan (at the U level).

Paleogeographically, these relationships indicate the presence of two major low gradient distal alluvial fans interfingering in the Khaur area during the late Miocene (Fig. 2). Through time the zone of interfingering moved westward as the fan of the buff-sand system "displaced" that of the blue-gray sand system, resulting in upward time-transgression to the west of the Nagri and Dhok Pathan rock units. The Nagri Formation corresponds to the part of the Khaur section where blue-gray sands are dominant and multistoried, i.e., the alluvial fan to the west. The Dhok Pathan Formation corresponds to the strata with a high proportion of the silt/clay facies and thinner units of either buff or blue-gray sandstones, i.e., the alluvial fan to the east. Along the sub-U isochron the two formations are thus laterally time equivalent. Determinations of current direction show that flow in the buff sand channels trended south to southeast while the blue-gray sand channels flowed more consistently eastward (Behrensmeyer and Tauxe, in preparation). Bedding characteristics of the blue-gray sands imply sedimentation during periods of high flow in a low-sinuosity braided system dominated by sand, while those of the buff sand and silt/clay facies indicate deposition in a more continuously variable regime including both meandering and braided channel belts associated with fine-grained floodplains. Further details concerning the fluvial paleoenvironments are given in Pilbeam et al., 1979 and Badgley and Behrensmeyer, in press.

Modern analogues for the proposed paleogeographic reconstruction of two interfingering fluvial systems are present along the southern edge of the Himalayas, the clearest being that of the Kosi River and adjacent rivers of India (Gole and Chitale, 1966). The Kosi River is known for its rapid lateral shifts, totalling 112 km westward in 200 years, during which it has left behind a persistent unit of sand on the order of 2–3 m thick. The Kosi drains an area of the Himalayas where there are few temporary storage areas (i.e., valleys) so that a large load of sand-grade material is carried to the mountain front and deposited in a piedmont fan. The Kosi also bears a large silt component, but because of the relatively steep gradient on the upper part of the fan (95 cm/km) this is carried farther downstream before being deposited. It seems reasonable to suppose that such circumstances may be analogous to the depositional regime of sand units in the blue-gray sand system. The latter may have been larger in scale than the Kosi River fan, and possibly was deposited by the proto-Indus River.

In the case of the Miocene blue-gray and buff-sand systems, it is interesting to note that deposits of the two fluvial regimes accumulated at nearly the same rate through time, with only gradual lateral displacement of the blue-gray system. An apparently balanced situation occurred in spite of the fact that the buff system was dominated by fine-grained sediments while the blue-gray system was dominated by sand. This implies tectonic control of sediment accumulation rates and overall thickness in the basin of deposition. Fine-grained sedimentation was probably slow relative to sand deposition. In order for equivalent thicknesses to accumulate, east and west, sand deposition must have been considerably more sporadic or punctuated than the build-up of finer sediments. There is no evidence at present to support the possible alternative hypothesis of increased subsidence toward the western end of the basin.

In the upper 860 m of section in the Khaur area (Kaulial Kas), coarse gravels are associated with the buff sands and interfinger with the silt/clay facies. The sands are less clearly of the typical buff-sand facies and often appear to be a mixture of the buff and blue-gray compositions. The zone of contact between the gravelly sands and other lithofacies rises in the section westward (Fig. 2). It appears that a source of coarse clastic material contributed to the later phases of Khaur area sedimentation. This may have been due to contributions from yet another river system draining a relatively local area of tectonic uplift such as the modern Kala Chitta or Khair-i-Murat ranges. Units of blue-gray sand reappear at the top of the Khaur section in Kaulial Kas, indicating the return of this fluvial regime or the influence of a new source area on the already established systems.

In Gill's (1951) study of the Siwalik sequence of the northern Potwar, he notes coarsening and thickening of the Nagri Formation westward, thickening of the Dhok Pathan Formation eastward, and the appearance of coarse clastics in the upper part of the section east of Kaulial Kas. Our study confirms his overall broad-scale picture of lateral variation in the Middle Siwalik formations, and the sub-U isochron provides new information on the relationship of both major and minor lateral facies changes to time.

Paleoecological Implications

Much of the fossil vertebrate material from the Khaur area occurs in the zone of interfingering of Nagri and Dhok Pathan lithofacies, in strata dominated by silt/clay facies with thinner beds and lenses of blue-gray or buff sands. Following strictly lithostratigraphic definitions of the formations, this means that the bulk of the vertebrate collection is derived from the Dhok Pathan Formation. This formation is over 1400 m thick and spans more than 3 my in Kaulial Kas while in its type area 40 km to the west it is about 300 m thick and spans less than 1 my (Fig. 2). The fauna from the lower part of the Dhok Pathan Formation between Ratha and Kaulial Kas' bears many similarities to the fauna from the type section of the Nagri Formation, on the southern limb of the Soan Synclinorium, some 60 km south of Khaur. Referring to the latter fauna as the "Nagri fauna," as has been frequently done in the past, leads to confusion when the name is applied to a similar fauna in the Khaur area which is clearly from the Dhok Pathan Formation. New terminology is needed for referring to the vertebrate faunas as biostratigraphic entities, and an informal preliminary zonation has been suggested in Pilbeam et al. (1979) as a first step in this direction. As previously noted, we are restricting our use of the terms Chinji, Nagri and Dhok Pathan to the major lithofacies units which fit the descriptions of their typical lithologies in the type areas, without reference to faunas or time.

There is a difference in vertebrate fossil abundance between the Dhok Pathan and Nagri lithofacies, which may be due to both taphonomic and paleoecologic factors. The fluvial regimes of the two formations were clearly very different, with the multistoried Nagri sands reflecting extensive reworking by relatively high energy flow, whereas the Dhok Pathan sedimentary units represent variable conditions of deposition with slow vertical accretion of the silt/clay facies and sporadic episodes of channel cut and fill. *A priori,* it seems likely that such differences in the overall fluvial regime would have an effect on the preservation of vertebrate remains. However, exactly why the Dhok Pathan depositional processes should have been conducive to bone burial and preservation, especially in the zone of interfingering, is an intriguing problem which is currently under investigation.

The Biostratigraphic Evidence

Figure 3 shows schematically the geographic and stratigraphic positions of most of the Yale-GSP collecting localities in the area near Khaur. On five of the columns a series of letters or numbers marks the stratigraphic positions of topographic landmarks chosen as reference points and on four columns there is a summary of the paleomagnetic data, details of which can be found in Tauxe (1979) and Behrensmeyer and Tauxe (in preparation).

As discussed above, all 11 sections have been correlated by tracing one or more horizons laterally between adjacent columns. Some of these marker horizons, the principal one of which is the U sandstone, are shown on the figure as horizontal, dashed or solid lines. These marker units are mostly thick sandstones which in some cases can be traced tens of kilometers laterally before they pinch out. In the case of the U sandstone it has been shown by Tauxe (1978) that the unit is essentially an isochron over the whole extent of its outcrop. The paleomagnetic and faunal data suggest that the age of the top of the Kaulial Kas section is probably slightly more than 6 my, the U sandstone horizon 8.1 my, and the Locality 259 level about 9.5 my (Tauxe, 1979, and personal communication). Interpolating downwards then, the oldest localities on Figure 3 might be about 12 to 15 my, and thus the whole sequence might span 6 to 9 my.

Localities and Survey Blocks

The stratigraphic positions of the localities and survey blocks are indicated by letters and numbers at the side of each stratigraphic column in Figure 3. A collecting locality, as we use the term, is a very restricted area of outcrop surface on which one or more fossils have been found. In the Siwalik exposures fossils may occur either as isolated finds or in discrete concentrations which may have only a few specimens or as many as several hundred. Both isolated finds and concentrations occur nearly continuously throughout the stratigraphic sequence in a variety of sedimentary contexts, although some sediment types and some parts of the sequence are more fossiliferous than others. Because few of the isolated occurrences, which are typically unidentifiable bone and tooth fragments, are of particular interest, we have largely focused our efforts on the concentrations of fossils. Such concentrations are usually scattered over a surface area of less than 1000 sq m and are derived from only one sedimentary body. A few of the very largest localities, however, outcrop over much larger areas and may be derived from a complex of sedimentary facies and stratigraphic horizons.

All the Yale-GSP localities have been labeled with sequential numbers and their positions have been marked on topographic maps and, when available, overlays on aerial photographs. The Universal Transverse Mercator grid coordinates and a brief lithological description of each locality have also been recorded in the Yale-GSP field catalogues and, for recently discovered localities, on a card file system which also incorporates sketch maps, small-scale cross-sections, polaroid ground photographs, and related information.

All collected fossils have been catalogued with a field number and notation of the locality from which the specimen comes. This information as well as the taxonomic identification and a description of the specimen are now tied into an electronic data processing system (Pilbeam et al., 1979) so that it is possible to create lists of the taxa and skeletal elements found at each of our over 490 collecting localities.

The fossil collections made by B. Brown in 1922 and G. E. Lewis in 1932 have sufficiently accurate locality data to justify attempts at relocating their exact positions. In both these cases the concept of locality used by the original collectors is the same as that used by the Yale-GSP group and some of these localities are shown on Figure 3, preceded by a B for the American Museum collection and an L for the Yale Peabody Museum collection.

On Figure 3 a series of survey blocks are marked to the left of five of the sections. These survey blocks provide an alternative to assigning individual locality numbers to isolated fossils of biostratigraphic interest, such as single equid or bovid molars, and are useful in areas where fossil concentrations are not common. Each survey block is typically between 30 and 120 m thick and is defined within the local section by prominent upper and lower lithological marker horizons. Most of the survey blocks extend laterally 1 or 2 km. The most complete series is in the Kaulial Kas section where the upper third of the section has 14 separate levels. As may be seen from Figure 3, the upper and lower boundaries of stratigraphically equivalent blocks in separate kas' do not necessarily coincide (for example, KL16 and ML05).

The stratigraphic horizon of each locality on Figure 3 has been determined in the field by tracing its level laterally into one of the nearby measured sections. Because we have also been able to correlate the sections, it is then possible, within limits, to assess the relative stratigraphic positions of all these localities. There are, however, certain problems stemming from the assumptions we are forced to use and the difficulties of precisely locating the localities.

The major assumption we have made when correlating widely separated localities is that the stratigraphic thickness between a locality and the isochronous U horizon is equivalent to time, so that, for example, localities 500 m below the U horizon in Kaulial Kas are approximately the same age as localities 500 m below the U horizon in Hasal Kas. Aside from the sensitivity to error in measuring the sections, this approach depends on the assumption that in the local Khaur area there is not significant thinning or thickening of the section in any direction.

There is also a related question of the fineness of resolution possible in a fluvial system where nondeposition or subsequent downcutting by streams might remove several meters of section, so that two nearby localities at the same stratigraphic level might be of significantly different ages. Study of this problem suggests that the lower limit of resolution, at least in the Dhok Pathan facies, is somewhere near 10 m, although when very detailed stratigraphic work is done it is often possible to refine the resolution considerably (Behrensmeyer and Tauxe, in preparation). On Figure 3 the accuracy with which a locality can be placed is limited by the scale to about 20 m.

A different set of problems results from the fact that many of the Yale-GSP localities were discovered and collected before the stratigraphic sections were completed. Thus we frequently have had to relocate Yale-GSP sites found in the earlier years of work and all of B. Brown's and G. E. Lewis' Dhok Pathan localities. Experience has shown that it is often difficult to relocate a locality unless individuals working with the field party are already familiar with the location of the site. The available topographic maps are hachure maps on which it is difficult to accurately mark locations. Uncertainty about the exact geographic location compounds the difficulty of tracing a locality laterally and there is therefore frequently some question about the exact position of individual localities on the stratigraphic columns, with different localities having different degrees of uncertainty. We have therefore developed a two-part classification scheme to express the degrees of confidence we have in the geographic and stratigraphic placement of our fossil localities (Table 2).

With some exceptions the localities on Figure 3 are all of at least Stratigraphic Class 4 quality. That is, the stratigraphic positions of these localities are accurate to within 50 m and the majority are more accurately placed. The exceptions are all Stratigraphic Class 5 localities, which are of special interest either because of the richness or uniqueness of the fossil assemblage or because the locality lies at a stratigraphic level not otherwise well represented in the Khaur area. The ranges of possible stratigraphic positions for all the Class 5 and some of the marginal Class 3 and 4 localities are indicated on Figure 3 by dashed vertical lines.

Biostratigraphy

A brief review of the history of the stratigraphic nomenclature of the Siwaliks is given in Pilbeam et al. (1977). A short discussion is presented here of various critical biostratigraphic problems and how we have attempted to resolve them.

The definition and use by Pilgrim (1913, 1934) and others (Cotter, 1933; Colbert, 1935; Lewis, 1937) of five successive faunal zones (Kamlial, Chinji, Nagri, Dhok Pathan, and Tatrot) marked an important advance in recognizing that there was a series of successive faunas in the Siwaliks and in attempting to devise a local nomenclature for discussing these important faunas. The terms, as first used by Pilgrim (1913), were conceptually most similar to the stages of the current American Code of Stratigraphic Nomenclature (1961), but subsequent usage has tended to employ them as both lithostratigraphic formations and bio- or chronostratigraphic zones or stages with the distinction not

Table 2. A classification of the quality of geographic and stratigraphic placements.

A. Geographic

Class	Criteria
1	Location known to within 10 m. Location marked on aerial photographs and maps and sketches and ground photographs have been made. The exact position of these localities can usually be confirmed by the presence of bone scrap.
2	Location known to within 100 or 200 m, but either because of the absence or extra abundance of bone scrap it is now impossible to find the exact location. In some cases these are localities which have a very wide collection area, encompassing what are really several distinct localities. Locations are marked on topographic maps and sometimes aerial photographs. Most Class 2 localities probably cannot be upgraded to Class 1.
3	Location is also known to within 100 or 200 m, but not yet confirmed by actually revisiting the site. Locations are marked on topographic maps. In most cases these can be upgraded to Class 1.
4	Location not known to within 200 m. Locations marked on topographic maps, but we have not yet attempted to relocate them. Some, but not all, could be upgraded to either Class 1 or 2.
5	Location not known to within 200 m. Locations marked on topographic maps, but it is not possible to fix the locality's position more precisely.
6	Location essentially unknown other than as to region (i.e. "Chinji," "Hasnot"). Probably cannot be ungraded.

B. Stratigraphic

Class	Criteria
1	Stratigraphic position marked on one or more local measured sections and accurate to within 3 m. It should be possible to unambiguously order stratigraphically all the Class 1 localities tied to each local section.
2	Stratigraphic position marked on a local section with a range of precision between 3 and 15 m. Some placements could be upgraded to Class 1.
3	Stratigraphic position marked on a local section with a range of precision between 15 and 50 m. Composed mainly of Geographic Class 2 localities where the uncertainty about the geographic location makes it difficult to fix the stratigraphic horizon more accurately. Cannot be upgraded.
4	Stratigraphic position marked on a local section with a range of precision between 15 and 50 m. Composed mostly of Geographic Class 3 localities. Could probably be upgraded to either Class 1 or 2.
5	Stratigraphic position tentatively marked on a local section with a range of precision greater than 50 m. May only be possible to state that a locality is older or younger than some datum. Can be upgraded.
6	Stratigraphic position known only in terms of Pilgrim's faunal zones (i.e. "Chinji") or completely unknown. Not marked on measured sections.

always being clear. Used in a very broad and loose sense as stages Pilgrim's faunal zones have been and still are useful, although it is apparent on close scrutiny that there are three fundamental problems associated with their continued use apart from the confusion resulting from lithostratigraphic and bio- or chronostratigraphic terminology.

The first problem results from the lack of demonstrable superposition for four of the original faunal zones. As lithological formations Pilgrim was able to demonstrate by field evidence the superposition of his five units and the sections in his 1913 paper show the same sequences of these rock types throughout the Potwar Plateau. As faunal zones, however, only the Nagri and Chinji faunal zones have any direct evidence of superposition. The other type areas are all widely separated geographically and no one section is fossiliferous throughout. Thus none of the type faunas can be related to the others except by lithological correlation.

The second problem is, like the first, closely related to the confusion between kinds of stratigraphic terms. Since some of his type areas were only poorly fossiliferous, in order to include enough species to make each fauna distinctive Pilgrim used species from distant areas that had more fossils. He was therefore forced to presume that his lithological correlations were also chronological correlations. The Kamlial zone is thus characterized paleontologically by species from Dera Bugti and the Manchars about 500 km to the south, while the Nagri fauna includes species from Haritalyangar which is 1000 km to the east. The Dhok Pathan is a special case. The type area is very fossiliferous, but Pilgrim added distinctive species from the lithologically similar part of the section at Hasnot, which we now believe (Pilbeam et al., 1977; Lindsay, personal communication) may be significantly younger. The Dhok Pathan fauna as a result is mostly characterized by faunal elements younger than the type area.

Finally Pilgrim's zonal concept has no sense of the length of time during which the faunas lasted nor of the length of time, if any, between them. This is the result of not knowing the exact stratigraphic relationships of the faunal zones. We now know from our field research that Pilgrim's Chinji fauna was collected from strata which probably span a very long period of time. We also now know that although the Nagri Formation is thick and obviously includes a considerable length of time, the fossils Pilgrim had available from the type section all came from a single locality which probably spans only a very short period of time. The Dhok Pathan fauna, if restricted to the fossils from near Dhok Pathan Village, is from a 300-meter-thick section with the bulk of the localities being concentrated in the narrow 100-meter middle part of the section, which surely represents only a short period of time.

We have no reason to believe that Pilgrim's faunal zones are other than a series of sequential units. However, we favor discontinuing their use as either biostratigraphic or chronostratigraphic units because, for the reasons just stated, they are poorly defined and not amenable to either more precise definition or further refinement. In particular, because the relationships between faunal zones are not easily demonstrated and their duration is uncertain, we cannot sharply define the boundaries between them nor subdivide them into smaller units. In place of Pilgrim's five faunal zones we have suggested a biostratigraphic zonal scheme (in the sense of the American Code of Stratigraphic Nomenclature, 1961) which is, however, still very preliminary and likely to be changed as study of the faunas proceeds (Pilbeam et al., 1979). Such a scheme can be based on the sections presented in Figure 3 or similar sections from the Hasnot region, which can be correlated independently of the faunas using paleomagnetic reversal stratigraphy.

Faunal Events and Comments

From a preliminary analysis of the Khaur area Yale-GSP collections we have established the approximate stratigraphic levels at which various large mammal species either first appear or finally disappear from the faunal succession. These events are noted on the right margin of Figure 3. Three of the most dramatic faunal events in the Khaur sequence are the successive appearances of equids, large giraffes and a large, hypsodont bovid. Each of these forms first occurs in several localities at approximately the same stratigraphic level, becomes very common, and apparently persists to the top of the local section. Other noteworthy faunal events include the successive disappearances of *Conohyus sindiensis, Giraffokeryx punjabiensis, Listriodon pentapotamiae,* and a species of *Deinotherium,* as well as the appearance of *Hippopotamodon sivalense, Propotamochoerus hysudricus,* a very small *Dorcatherium* species, the small hyaenid *Palhyaena sivalense,* the burrowing rhizomyid *Protachyoryctes tatroti,* and colobine monkeys. In addition, we have established the presence at certain levels of other important but rare taxa and these and the localities at which they are found are listed in Table 3. The difficulties of making identifications on fragmentary material and the uneven distribution of localities throughout the section limit our certainty about the exact level at which each event took place. With more collecting and further analysis we expect to see changes in the level of at least some of these faunal events.

Genera in our Khaur area collections from levels at or below Localities 126 and 259 include *Hyainailouros, Herpestes, Percrocuta, Deinotherium, Listriodon, Conohyus, Merycopotamus, Dorcabune, Dorcatherium, Giraffokeryx, Elachistocerus,* and either *Ramapithecus* or *Sivapithecus*. At or between Localities 259 and 395 we have the highest stratigraphic occurrences of *Listriodon, Conohyus,* and *Giraffokeryx* and the lowest occurrences of hipparion equids and large giraffes (both co-occurring at Locality 395 with *Listriodon*). This short stratigraphic interval (100 m) may prove to be a time of extensive faunal replacement, since we have indications of change of some of the other faunal elements as well. However, the faunal turnover is by no means complete and taxa as different as hominoids, amphicyonids, and anthracotheres survive on into younger ages apparently unchanged. Faunal events above the Locality 395 level seem to be more evenly spaced throughout the stratigraphic sequence.

The oldest Khaur area hominoid is from Locality 259 in Kaulial Kas, but many other specimens from what are undoubtedly older levels have been found near Chinji Village, on the southern side of the Soan Synclinorium. The youngest hominoid we have found in the Khaur area is from Locality 442, which is also in Kaulial Kas. Both of these localities are separated from the other hominoid occurrences by long stratigraphic intervals. We do not yet know whether this pattern is only an artifact of collecting a rare group or if there were actually periods during which hominoids were not members of the region's fauna. Nor do we know whether hominoids later became locally extinct, after their last occurrence in the Kaulial section.

The youngest localities we have found in the area near Khaur are thought to be slightly older than 6 my. None of these localities have any fossils of the Hippopotamus *Hexaprotodon,* which is a common fossil in the Tatrot beds near Hasnot. The absence of *Hexaprotodon* at Khaur is in accordance with its appearance in the region after 5.5 my (Opdyke et al., 1979). The oldest localities shown on Figure 3 are 233 and 234. We have, however, one undoubtedly much older locality near the small village of Gali Jagir, about 15 km south of Fatehjang. This locality is probably in the lower part of the Murree Formation, but it is not possible to correlate it as yet to any of our measured sections. Its fauna includes a shark.

Summary and Conclusions

The combination of litho-, chrono- and biostratigraphic information presented in Figures 2 and 3 establishes a framework for the ongoing study of Siwalik faunas and sedimentary history. The detailed information resulting from seven years of work in the Khaur area will allow us to calibrate local variation in faunal occurrences, lithofacies and the record of paleomagnetic reversals and to discover the consistent patterns that are of more than local significance. These broader patterns, including the time-transgressive nature of the major lithofacies and the appearance and disap-

Table 3. Rare Lower and Middle Siwalik mammal taxa found at Yale-GSP localities in the Khaur area. The stratigraphic horizon of each locality is indicated on Figure 3.

Taxon	Localities
Lorisidae, gen. et sp. indet.	182, 259
?*Presbytis sivalensis*	370
Ramapithecus punjabicus	182, 221, 224, 226, 227, 251, 260, 309, 310, 317, 350, 409, 414, 416, 463
Sivapithecus indicus	137, 182, 191, 207, 211, 224, 227, 230, 260, 261, 309, 314, 317, 328, 350, 410, 414, 416
Hominoidae, gen. et sp. indet.	259, 327, 442
Hyainailouros sulzeri	303, 336
Herpestes spp.	19, 182, 259, 327
Manis sp.	34
Orycteropus sp.	260, 365
Deinotherium sp.	122, 160, 173, 174, 182, 211, 233, 234, 243, 251, 321, 329, 362, 445
Schizochoerus gandakasensis	178, 269
Sivahyus punjabiensis	378
Tetraconodon magnus	251, 329, 493
Chalicotherium salinum	158, 182, 212, 227, 243, 269, 300, 309, 324, 337, 358, 433

pearance of important vertebrate taxa, can then be used as a firm basis of comparison with other regions. Eventually this stratigraphic framework should lead to overall correlations of other major fossil-producing areas of the Soan Synclinorium and Siwalik sequences in India.

At the present stage of analysis, we can offer some preliminary statements concerning faunal and sedimentary history in the Khaur region, based on the newly established chronostratigraphic framework.

The succession of fluvial sediments appears to be continuous throughout the 3250 m documented so far, in the sense that there is no lithostratigraphic evidence for major time gaps (e.g., erosion surfaces, abrupt major changes in lithology). The observed micro- and macropatterns of lateral interfingering of the blue-gray sands with buff sands and finer-grained facies indicates long-term deposition in two adjacent fluvial regimes on the piedmont belt of the Himalayas. Within the upper half of the section, the local dominance of one system to the other in the Khaur area shifted slowly through time. Basin subsidence apparently kept pace with the input of sediment. Within this overall depositional system, there are differences in the two fluvial regimes, particularly exemplified by the apparently isochronous blue-gray sheet sands (e.g., the U sandstone) which may reflect repeated tectonic or climatic events in the source area. The sedimentary record on a fine scale is composed of channel cut and fill episodes, and vertical floodbasin aggradation with local hiatuses during which paleosols formed. The preserved sedimentary and faunal record is thus subject to short-term time gaps in any one section due to such local vagaries of the depositional system. However, for the Khaur area as a whole, the geologic record can be considered essentially continuous, at least over the 6 to 9 my time span indicated by the magnetostratigraphy.

The faunal record is subject to taphonomic processes resulting in a patchy distribution within the sedimentary units, both laterally and through time. This limits the fine-scale resolution of the evolutionary record. Faunal remains from a similar level relative to the sub-U isochron generally must be combined in order to have a large enough sample for comparison with other levels in the section. The net result is that such combined faunal samples may represent time spans on the order of 10,000 to 100,000 years, or more for the lower part of the section. For the upper part of the section, the degree of time-averaging can be made comparable from level to level by combining fossils from equal stratigraphic thicknesses, resulting in a faunal record which is continuous over a 4 million year period, given the stated limits of time resolution. The nature of this record contrasts with that of the well-known, and comparably thick, Clark Fork Eocene sequence of northern Wyoming (Gingerich, 1974; Bown, 1979) in that the latter has more distinct levels of fossil concentration which probably represent shorter periods of time-averaging.

Within the limits imposed by the sedimentary and taphonomic characters of the Khaur Siwalik sequence, we are able to document 13 large mammal faunal events. These include three local extinctions and two appearances which are clustered together about 500 m below the U horizon, and a sequence of events which are more regularly spaced up through the succeeding stratigraphic levels. The large mammals thus suggest that there was a major turnover of the fauna at about 9.5 my BP, at which time such forms as *Conohyus, Listriodon,* and *Giraffokeryx* became locallly extinct and hipparions and large giraffes made their local appearance. This episode was then apparently followed by a long period during which single local extinctions and appearances slowly removed or added species to the fauna. With our present collections from the Khaur area we are not able to determine the nature of faunal change at the stratigraphic levels below the Locality 126/259 level, if there was in fact any change. The paleomagnetic evidence indicates, however, that the underlying sediments were deposited over a considerable length of time and, as discussed in Pilbeam et al. (1979), preliminary analysis of the fossil collections from the Chinji type section suggests that there was some faunal change during the period in which the Kamlial and Chinji formations were deposited.

Aside from the lithofacies changes noted in the above discussions, there is no obvious indication of environmental change in the sedimentary record through the Khaur area sequence. The lithofacies changes bear little relationship to faunal appearances and disappearances, as currently understood. Instead it seems that the biological record is simply superimposed on the succession of facies marking the build-up of the sub-Himalayan alluvial plain. These lithofacies preserve different densities of fossil remains due to variability in taphonomic processes, and possibly also due to differing ecological conditions in the different fluvial systems. Based on our current understanding of the relationship of the faunas to the sediments through time, we do not see any indications that processes affecting the fluvial deposits were linked, in an observable way, to processes affecting faunal change.

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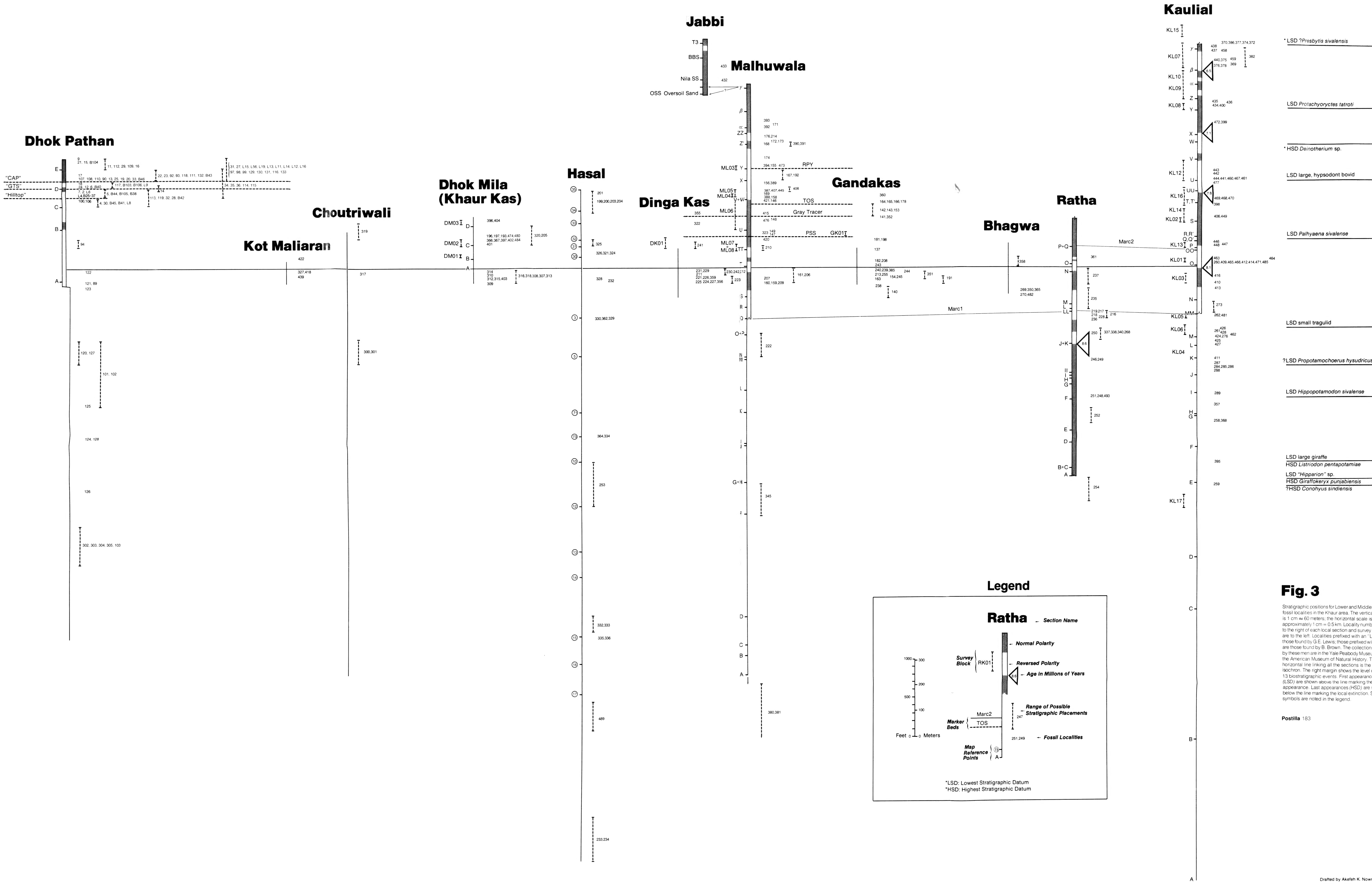

Fig. 3

Stratigraphic positions for Lower and Middle Siwalik fossil localities in the Khaur area. The vertical scale is 1 cm ≈ 60 meters; the horizontal scale is approximately 1 cm = 0.5 km. Locality numbers are to the right of each local section and survey blocks are to the left. Localities prefixed with an "L" are those found by G.E. Lewis; those prefixed with a "B" are those found by B. Brown. The collections made by these men are in the Yale Peabody Museum and the American Museum of Natural History. The horizontal line linking all the sections is the sub-U isochron. The right margin shows the level of 13 biostratigraphic events. *First appearances (LSD)* are shown above the line marking the appearance. Last appearances *(HSD)* are shown below the line marking the local extinction. Special symbols are noted in the legend.

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A Geologic and Biostratigraphic Framework for Miocene Sediments near Khaur Village, Northern Pakistan

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