

MAGNETIC POLARITY STRATIGRAPHY AND VERTEBRATE PALE- ONTOLOGY OF THE UPPER SIWALIK SUBGROUP OF NORTHERN PAKISTAN

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ABSTRACT

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Two hundred and fifty three sites consisting of three samples per site were taken from eight separate stratigraphic sections from sediments of the Upper Siwalik subgroup of northern Pakistan. All samples have been partially demagnetized in alternating fields of from 150 to 300 Oe. The sediments are dipping at angles of up to 75° in a variety of directions, and the locality mean directions improve significantly after correcting for bedding attitude, providing a statistically significant fold test at the 95% level.

The magnetic stratigraphy was obtained based on the statistically significant well-grouped partially demagnetized data. Two prominent bentonitized tuffs occur in several sections above and below a prominent reversal of the earth's magnetic field. Radiometric dates of 2.3 ± 0.4 m.y.B.P. and 2.5 ± 0.4 m.y.B.P. have been obtained by fission track on zircons from these tuffs. This allows the magnetic stratigraphy to be correlated to the standard reversal chronology of the Pliocene and Pleistocene. The longest stratigraphic section (1.87 km in thickness) can be shown to span the time between 0.6 m.y.B.P. and 5.5 m.y.B.P.

The individual stratigraphic sections can be correlated on the basis of magnetic stratigraphy. All sections contain important vertebrate fossil localities which can be placed relative to each other in the time stratigraphic framework provided by the magnetic stratigraphy.

The change from the Pinjor fauna to the Tatrot fauna occurs at about 2.47 m.y.B.P. (the Gauss/Matuyama boundary) based on the simultaneous occurrence of *Equus*-*Elephas*, *Bos* and cervids with antlers. *Hipparion*, the three-toed horse, persists to the lowermost

Pleistocene just after the termination of the Olduvai event. The ranges of other important vertebrate faunas are also discussed.

The folding of the eastern Salt Range has been very recent, beginning within the Brunhes normal magnetic epoch, since sediments of lower Brunhes age are folded on the flanks of the Pabbi and Rohtas anticlines and on the flanks of Chambal Ridge. The rate of uplift of these structures above the present base level is estimated to have a minimum rate of four meters per thousand years for the Rohtas anticline and three meters per thousand years for the Pabbi Hills. The rates of subsidence (i.e., rates of sedimentation) of the various sections are estimated to range from $0.35 \text{ m}/10^3 \text{ yr}$ to $0.50 \text{ m}/10^3 \text{ yr}$. The first occurrence of conglomerate-containing clasts derived from the Himalayan uplift occurs just prior to the Olduvai event at the base of the Pleistocene.

INTRODUCTION

The result of the collision of the Indian Plate with the Eurasian continent can be seen today in the awe-inspiring Himalayan mountain chain. This orogeny is in part recorded in the sediments derived from them and deposited to the south of the mountains in a subsiding foredeep. These sediments, the Neogene and Quaternary Siwalik Group, contain the remains of the vertebrate faunas which lived on the Indian plate during the late Cenozoic. These faunas have been extensively collected and are well-known as the standard land mammal stages of southern Asia. The Siwalik Group has in turn become involved in the continuing orogeny and has become faulted and folded and is now under active erosion, leading to an abundance of excellent exposures available for study.

Stratigraphy

The Siwalik strata in the eastern portion of the Potwar Plateau and in the vicinity of the Jhelum River structural reentrant of northern Pakistan, for the most part have been attributed to the Upper Siwalik subgroup (Wynne, 1875; Pilgrim, 1910 and 1913; De Terra and Teilhard de Chardin, 1936; various unpublished oil company reports; Keller et al., 1977). The combined results of these previous surveys in effect consider the sediments of this region to represent a rather complete record of latest Miocene—Pliocene—Pleistocene sedimentary and paleontologic events in this region of northern Pakistan. Early on in our studies it was recognized that long, continuous stratigraphic exposures of the Siwalik clastic rocks were present in the various structures associated with the Jhelum structural reentrant. These include a number of anticlines on the southwest and the monoclinical structure of the Pir Panjal foothills on the northeast (Fig.1). A sampling program was initiated in rocks exposed in the Mangla—Samwal anticline, near New Mirpur, Kashmir, the Pir Panjal foothills also in Kashmir, and the Rohtas, Chambal and Pabbi anticlines in the Punjab Province. Given the high sedimentation rates that were expected, it was felt that a sufficiently clear record of magnetic reversals

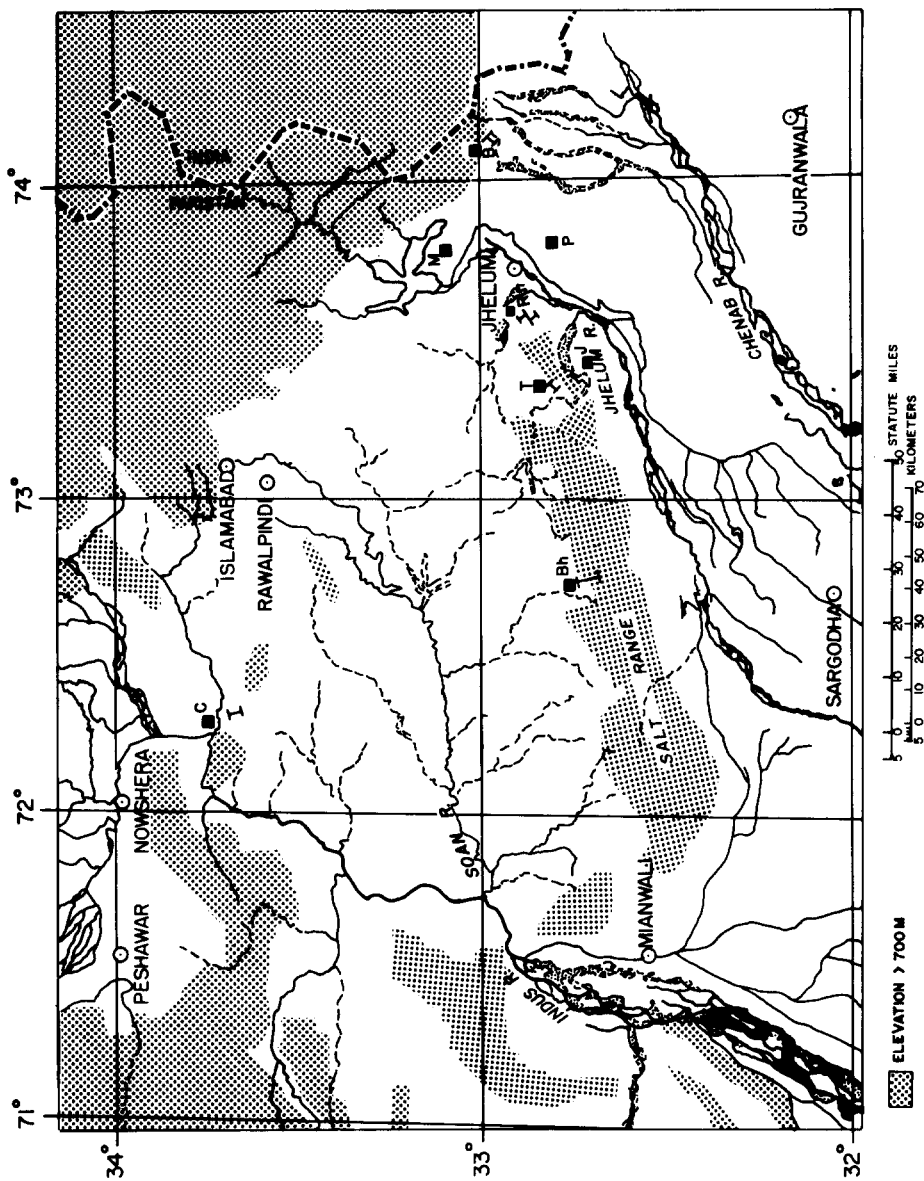


Fig. 1. Location of sections presented in this paper. *C* = Campbellpur Basin; *Bh* = Bhaun; *T* = Tatrof; *R* = Rohtas anticline; *J* = Chamba anticline; *M* = Mangla-Samwal anticline; *B* = Bhimbur.

would be obtained from this sedimentary sequence so as to allow their correlation to the magnetic reversal sequence of the Plio-Pleistocene.

Previous work

The work reported here is part of a cooperative effort by scientists from Peshawar University North West Frontier Province Pakistan, the Geological survey of Pakistan, Dartmouth College, Columbia University and the University of Arizona. An initial study of Upper Siwalik sediments in the Pabbi Hills (Fig.1) was reported by Keller et al. (1977). The Pabbi Hills study showed that the sediments exposed in this asymmetric anticline range in age from the middle Gauss normal magnetic epoch to the middle Brunhes normal magnetic epoch, spanning an interval of approximately 2.5 m.y. During related work two prominent bentonitized volcanic tuff intervals were found in sediments of similar age in the Rohtas anticline northwest of Jhelum, in the foothills of the Pir Panjal in southwestern Kashmir (Fig.6), in the vicinity of New Mirpur and at Chambal Ridge in the vicinity of Jalalpur (J, Fig.1). The distribution and dating of these bentonites, which form convenient marker horizons, are described in Johnson et al. (1979).

PALEOMAGNETIC STUDIES

Three hand samples per site were taken in the fine-grained sediment between the massive sandstones, using methods and techniques described in Johnson et al. (1975) and Lindsay et al. (1978). These samples were returned to the laboratory where they were cut into cubes measuring 2.5 cm on each side and then measured on a commercially available fluxgate spinner magnetometer described by Molyneaux (1971). Selected samples were chosen for stepwise alternating field (a.f.) demagnetization in order to choose a field for blanket demagnetization. An example of a.f. demagnetization curves for typical samples is shown in Fig.2. In many cases the sediments possess minerals with good magnetic stability even though a secondary overprint in the direction of the present earth's field is often observed. A peak a.f. field of 150 Oe to 300 Oe was applied in an attempt to remove this secondary overprint.

The distribution of the intensity of natural remanent magnetization in all the sites, excluding those from Pabbi Hills, is shown in Fig.3. The intensities of magnetization range from 2×10^{-7} emu/cc to 1×10^{-4} emu/cc with the bulk of the determinations falling between 1×10^{-6} emu/cc and 1×10^{-5} emu/cc. These sediments possess a relatively strong remanence for sedimentary rocks, well above the noise level for the magnetometers.

The magnetic minerals from three of the sites were separated from the nonmagnetic matrix using methods and techniques described by Løvlie et al. (1971). The Curie points of the magnetic minerals were determined using the

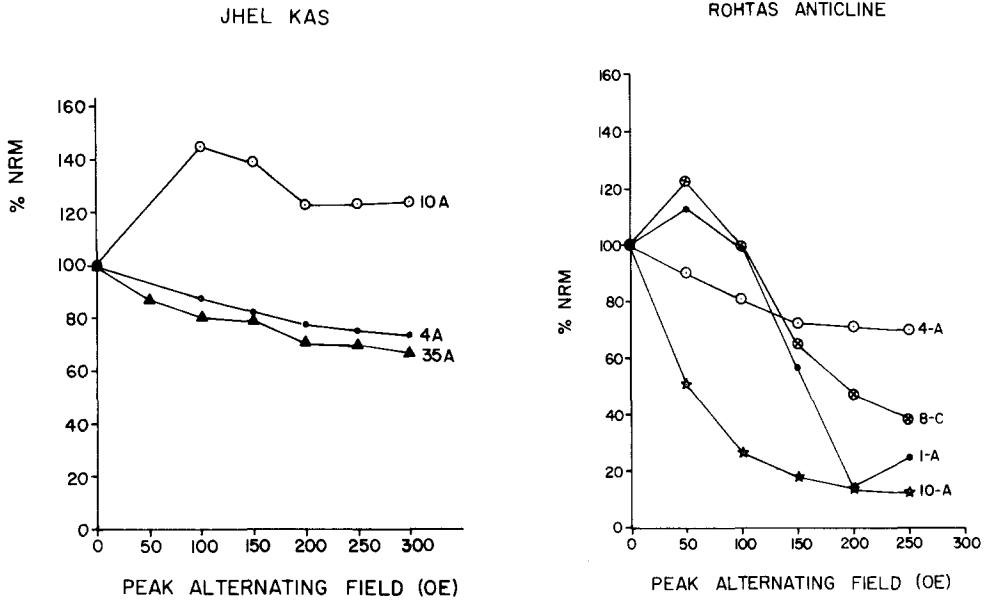


Fig.2. Alternating field demagnetization curves of samples from the Mangla-Samwal (Jhel Kas) and Rohtas anticlines.

techniques given by Kent and Lowrie (1974). Fig.4 shows a plot of saturation magnetization vs. temperature for a sample from the Mangla-Samwal anticline indicating that the magnetic minerals in this sediment possess phases

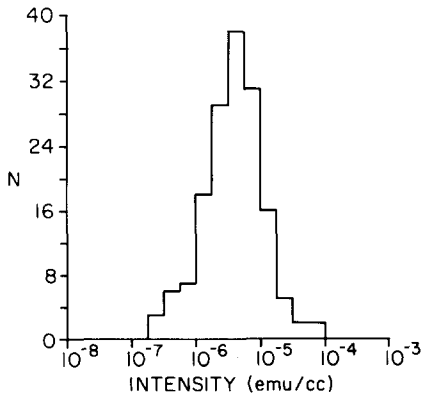


Fig.3. Histogram of intensity of magnetization. Each individual value represents the average intensity of three samples per site. Only those sites with statistically significant site mean directions were used in this analysis. The sites from the Pabbi Hills were excluded.

with two distinct Curie points; one at 465°C the other at 590°C. The higher Curie point indicates the presence of magnetite, while the lower may be due to titanomagnetite. These data suggest that the minerals possessing stable magnetization are magnetites and titanomagnetites, probably of detrital origin.

Paleomagnetic stability

Site mean directions were calculated for each site using the statistics of Fisher (1953). Those sites from each geographic locality (Rohtas, Mangla-Samwal, etc.) which yielded statistically significant mean directions of magnetization (Class I sites; see discussion in Opdyke et al., 1977) were further combined into locality mean directions of magnetization for normally and reversely magnetized sites both before and after correcting for structural orientation of the beds. The bedding orientation from locality to locality is quite diverse, ranging from horizontal strata to those with dips in excess of 40° and covering a variety of strike directions. The results are given in Table I and Fig.5. A marked improvement in the grouping of the locality mean

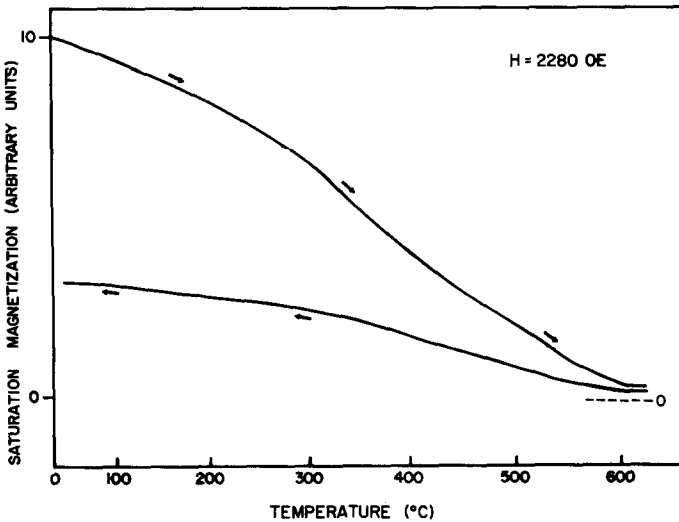


Fig.4. Curie temperature curve of magnetic separates from Mangla-Samwal anticline.

directions occurs after correcting for bedding tilt. The k of the normal sites increases from 31.8 to 73.9. The reversed sites show an even greater improvement, with the k increasing from 8.3 to 39.2. This is significant at the 99% level of confidence according to the tables of McElhinny (1964). The data indicate that a stable direction of magnetization has been isolated

TABLE I

Bedding orientation

	Normal sites				Reversed sites			
	Before bedding correction		After bedding correction		Before bedding correction		After bedding correction	
	Decl.	Incl.	Decl.	Incl.	Decl.	Incl.	Decl.	Incl.
Bhimbur	7.2	24.5	1.6	38.1	180.5	-8.4	177.7	-23.5
Chambal Ridge	338.7	56.0	4.7	31.7	121.6	-51.4	166.4	-40.1
Campbellpore	0.5	45.0	0.5	45.0	176.1	-56.3	176.1	-56.3
Bhaun	339.3	54.2	343.8	40.0	156.9	-42.0	160.2	-30.6
Pabbi Hills	359.2	45.4	354.5	41.2	181.8	-43.5	174.3	-37.1
Rohtas	19.3	56.9	347.7	24.3	249.5	-60.8	180.7	-53.4
Mangla Samwal	1.9	48.3	358.4	42.4	164.6	-41.5	168.0	-37.1

	Before bedding correction				After bedding correction			
	Decl.	Incl.	k	α^{95}	Decl.	Incl.	k	α^{95}
Normal sites	358.8	48.0	31.8	10.9	355.8	37.8	73.9	7.1
Reversed sites	172.2	-47.9	8.3	22.3	171.4	-39.9	39.2	9.8
Combined sites	355.6	48.0	14.1	11.0	353.6	38.9	53.6	5.5

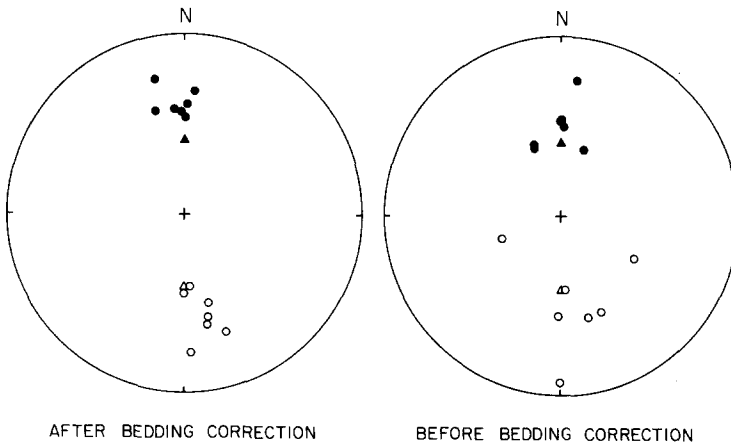


Fig. 5. Locality mean directions of magnetization of normal (filled circles) and reversed (open circles) vectors, plotted before and after correction for bedding tilt using an equal angle (Wulff) net. The triangles indicate the direction of the dipole field at the sampling locality.

from these beds and that the directions of magnetization were acquired before the folding of the beds approximately 500,000 years ago (see below). Fold tests (Graham, 1949) for sediments of these young ages are not common and the successful application of this test tends to support the thesis that the

characteristic direction of magnetization is depositional remanence. However, on examination of the mean directions of magnetization from these localities, it can be seen that the directions of magnetization are shallower than the dipole field for this latitude (Fig.5). This could be due to either a bedding error (King, 1955) or to the incomplete removal of a secondary component of magnetization. The fact that the normally directed magnetic vectors are closer to the earth's dipole field before correcting for bedding tilt would seem to argue for the second possibility. The declinations of the locality means are reasonably well-grouped along a north—south axis, indicating that no detectable rotation of the Indian plate has occurred in the last several million years. The paleomagnetic data for the nine principal study areas of the Upper Siwaliks in the Potwar Plateau are discussed in the following sections.

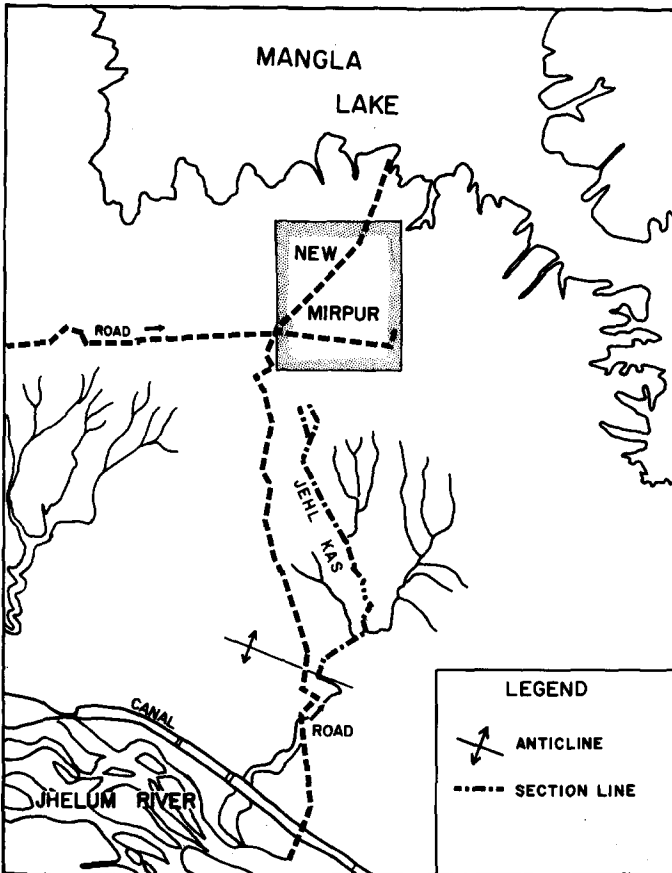


Fig. 6. Line of measured section along Jhel Kas, Mangla—Samwal anticline.

Mangla—Samwal anticline (Jhel Kas section), southwestern Kashmir

An excellent section with 700 m of Upper Siwalik sediments is exposed in the northeast limb of the Mangla—Samwal anticline directly southwest of New Mirpur. Jhel Kas is a tributary of the Jhelum River (Fig.6). The Jhel Kas section consists of alternating sandstones and mudstones, with the percentage of finer grained material increasing higher in the section. The section is capped by a massive conglomerate correlated in the past to the boulder conglomerate of De Terra and Teilhard de Chardin (1936).

Fig.7 shows the mean directions of magnetization for each site that has a statistically significant grouping after demagnetization at 200 Oe. The results are well-grouped, and the mean directions of magnetization of the normal and reversed polarity groups are not significantly different from one another. The inclinations of both sets, however, are slightly shallower than the inclination of the dipole field at the collecting site.

Fig.8 shows a plot of the latitudes of the virtual geomagnetic poles (VGP's) as a function of the stratigraphic position of the sampling site above the base of the section at the axis of the anticline. It can be seen that eight clear reversals of the field are present in the section, and these define the limits of seven magnetic polarity zones. Each magnetozone is defined by more than

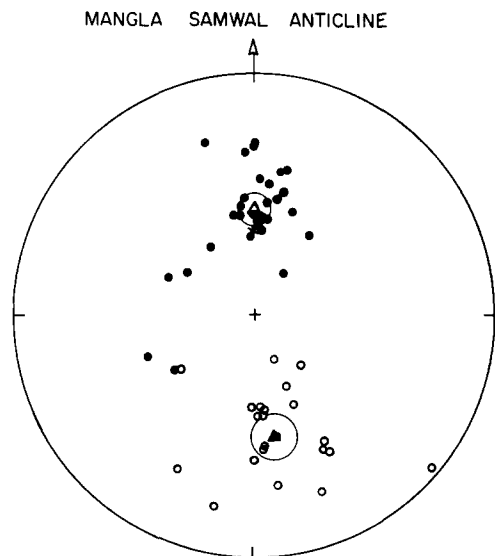


Fig.7. Site mean directions of all Class I sites from Mangla—Samwal anticline after demagnetization at 200 Oe. Open (closed) symbols indicate north-seeking directions on the upper (lower) hemisphere after correcting for the dip of the beds. Mean direction of reversed (normal) sites given by the filled (open) triangle. Asterisk gives the dipole field direction at the anticline. The circles of 95% confidence limits are given for the site mean directions.

MANGLA - SAMWAL (JHEL KAS)

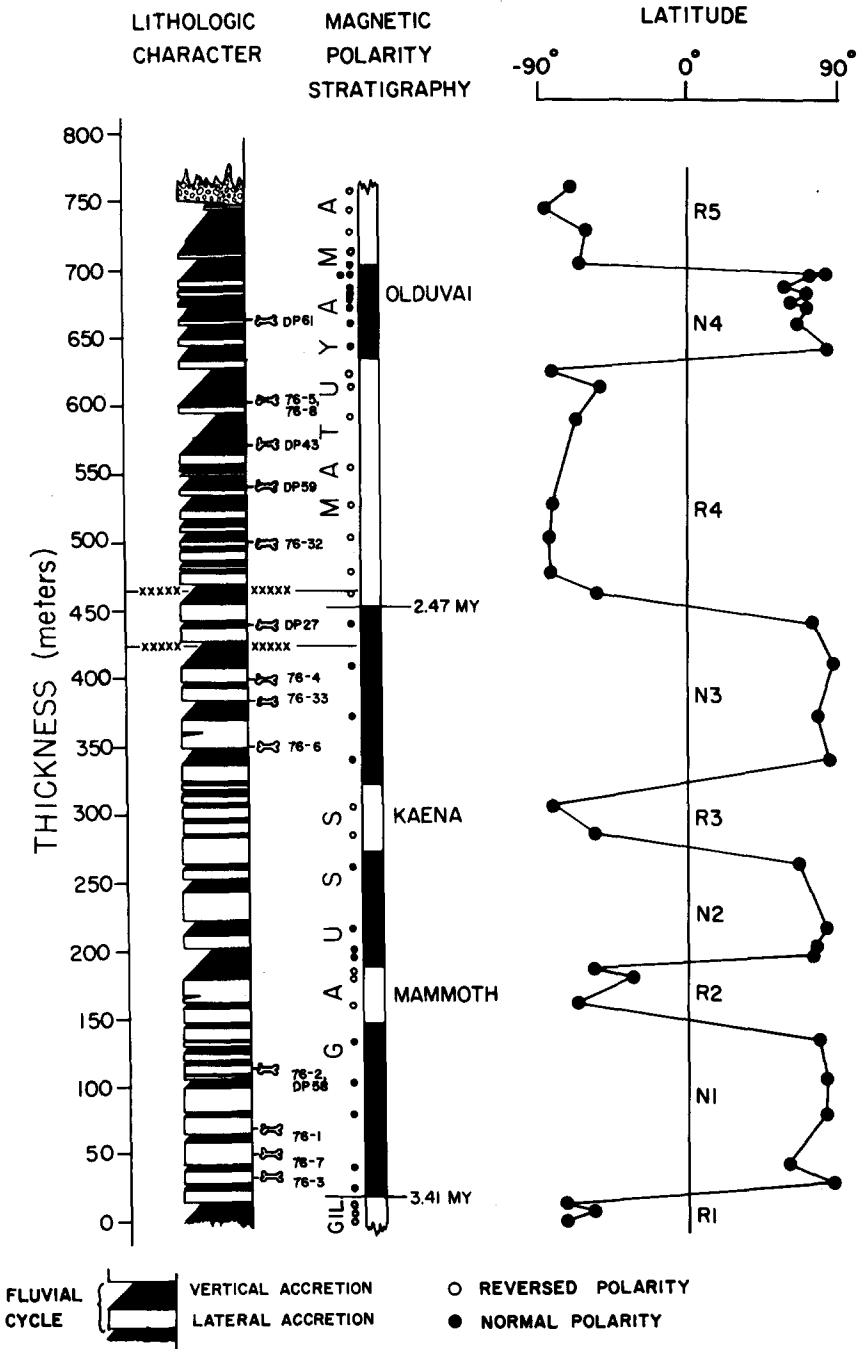


Fig.8. Plot of VGP latitudes, sedimentary cycles and correlation of the magnetozones at the Mangla—Samwal section to the standard magnetic timescale. Stratigraphic position of the fossil localities is shown by the bone symbols and their associated numerical designations. The open (reversed) and closed (normal) circles beside the magnetic polarity stratigraphy column indicate the position (polarity) of the sample sites.

one site. Above and below the boundary of magnetozones N3 and R4 at 450 m above the axis of the anticline are two prominent bentonitized tuffs shown in the measured stratigraphic section. Fission track dates on zircon phenocrysts from these tuffs of 2.3 ± 0.4 m.y.B.P. (upper) and 2.5 ± 0.4 m.y.B.P. (lower) were determined by Naeser (Johnson et al., 1979). These radiometric dates securely correlate the magnetic reversal between the two tuffs to the magnetic transition between the Gauss normal polarity epoch and the Matuyama reversed polarity epoch. This allows an easy correlation of the reversal sequence in the section at Mangla—Samwal anticline to the standard magnetic time scale (Cox, 1969; Opdyke, 1972; McDougall, 1979). The Kaena and Mammoth reversed events are both present within the Gauss normal epoch, and the transition from the Gauss normal magnetic epoch to the Gilbert reversed magnetic epoch occurs near the base of the section in the center of the anticline. Fig.9 is a plot of thickness of section scaled linearly relative to time using the boundaries of the Gauss normal epoch as the tie points. If the rate of sedimentation for the Gauss is extrapolated to the sediments of the overlying Matuyama epoch, the normal event observed near the top of the section would span an age of from 1.9 to 2.1 m.y.B.P. These dates are similar to the known boundaries of the Olduvai event as seen in Olduvai gorge (Brock and Hay, 1976). We therefore correlate this normal magnetozone (N4) with the Olduvai event which in turn has been correlated with the Pliocene—Pleistocene boundary (Haq et al., 1977).

Bhimbur, southwestern Kashmir

The town of Bhimbur lies northeast of the Pabbi Hills and southeast of Mirpur in southwestern Kashmir. North of town an exposure of bentonitized

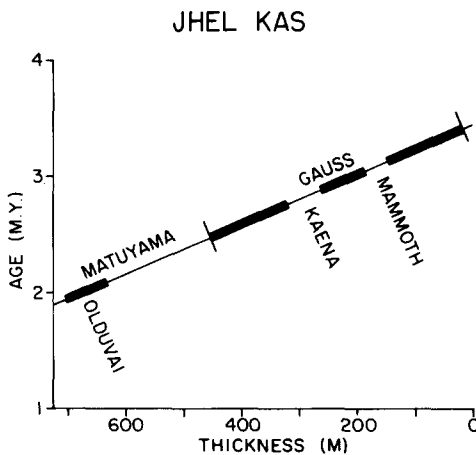


Fig.9. Plot of age vs. stratigraphic distance above axis of the Mangla—Samwal anticline constructed by using the ages of the beginning and end of the Gauss magnetic epoch as tie points.

tuffs has been identified (Visser and Johnson, 1978) in the context of a long section of Upper Siwalik beds. A 350-m section was sampled for paleomagnetic study through the tuffs and above. Because the area is a border region, movement was severely restricted by security considerations and the study of the area was terminated. We feel, however, that it is worthwhile to publish the information that we have available in order to try to encourage future work on this section. The methods and techniques employed in the study are identical to those described previously. The data are of high quality. Fig.10 gives the magnetic stratigraphy for the section studied. Three magnetic polarity transitions have been identified which divide the section into four sharply defined magnetic polarity zones. The doublet of bentonitized tuffs previously identified in the Mangla—Samwal anticline straddle the N1/R1 transition, and on this basis we correlate this magnetic transition to the Gauss/Matuyama boundary. The normally magnetized zone above the 200-m line would therefore be correlative with the Olduvai normal event of the Matuyama reversed magnetic epoch. Although the fauna is sparse, undoubted *Equus* has been found 50 m above the Gauss/Matuyama boundary, thereby indicating the presence of the Pinjor faunal stage (see below) above the Gauss/Matuyama reversal.

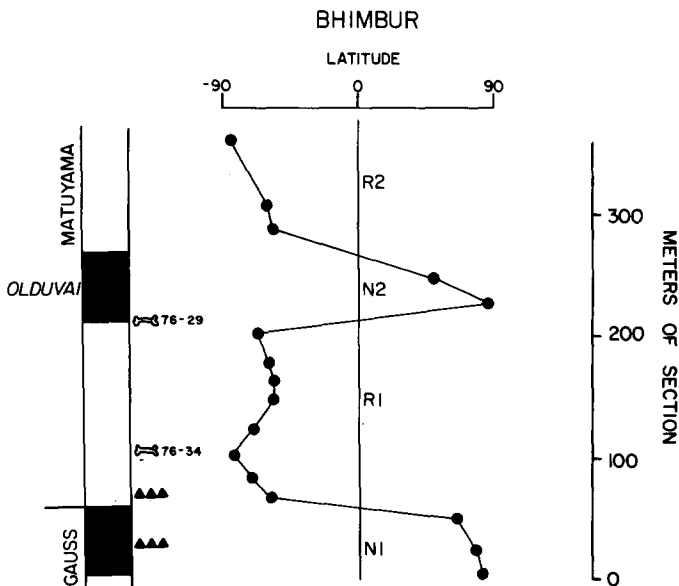


Fig.10. Plot of VGP latitudes and correlation of the magnetozones at the Bhimbur section to the standard magnetic time scale. Stratigraphic separation of the sampling sites was calculated from map distance and keyed to the position of the marker bentonitized tuffs (filled triangles). Fossil localities are indicated by bone symbols.

Rohtas anticline, Jhelum district (Sanghoi/Basawa Kas sections)

A prominent northeast—southwest trending anticline lies immediately to the north of the Pabbi Hills and north of the Jhelum River. Two marker tuffs on the north flank of the anticline drew us to this section where we sampled from the center of the anticline to the highest exposed beds of the north flank. This section, 1800 m thick, contains beds which are inclined at angles of from 2° to 45° and are unbroken by faulting. We collected sixty separate sites in the drainage areas (Fig.11) of Basawa Kas and Sanghoi Kas. The two sections were tied together by walking out a prominent sandstone between the sections.

Magnetic stability is fairly good. However, a highly coercive secondary component is present in these sediments, and therefore a demagnetizing field of 300 Oe was applied to all samples from the Rohtas anticline in an attempt

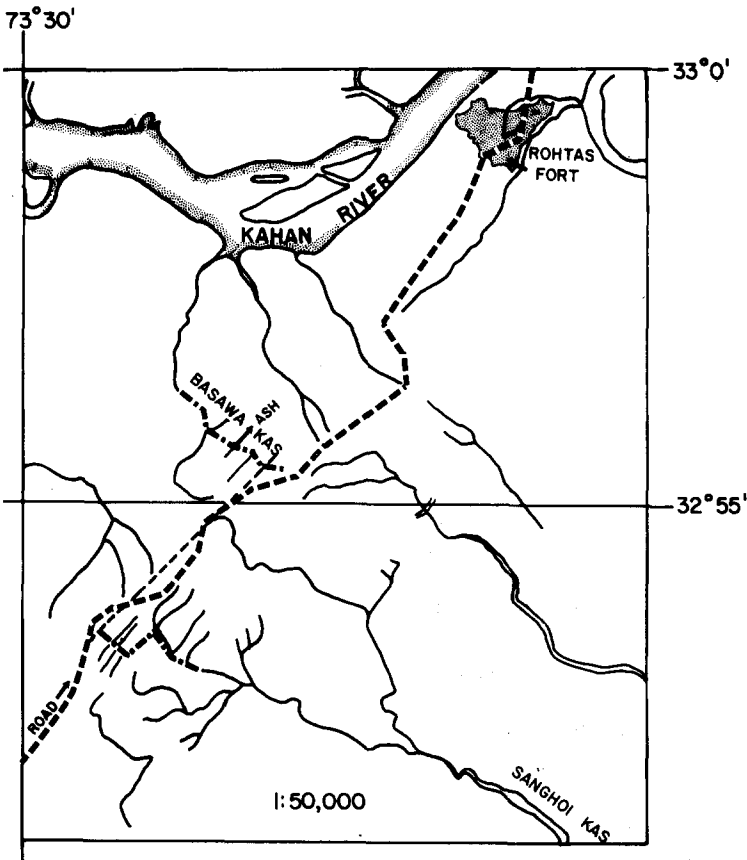


Fig.11. Location of sections on the Rohtas anticline.

to remove it. A plot of the means of the normally and reversely magnetized sites is shown in Fig.12.

The section at Rohtas anticline is composed primarily of sandstone with minor amounts of mudstone and siltstone. Toward the top of the section (above 1400 m) conglomerates appear (Fig.13). Fourteen polarity changes

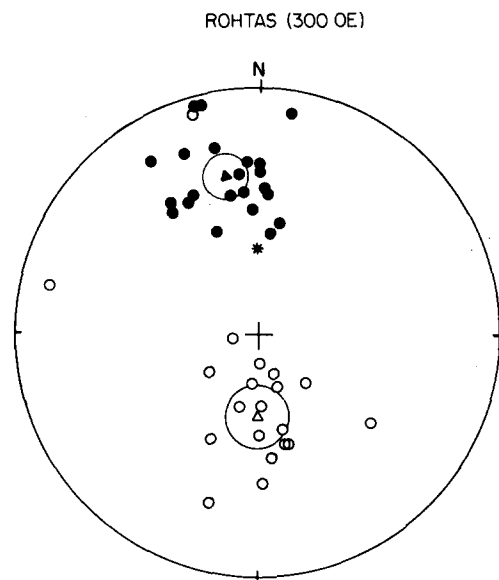


Fig.12. Stereographic projection of site mean directions of statistically significant sites from the Rohtas anticline; open (closed) symbols indicate north-seeking directions on the upper (lower) hemisphere after correcting for the dip of the beds. The mean directions are indicated by the filled (normal) and open (reversed) triangles. The dipole field direction at Rohtas is indicated by the asterisk. The circles of 95% confidence limits are given for the site mean directions.

occur in the section which identify the limits of thirteen magnetic polarity zones. The magnetic reversal (N6/R6) detected at 1250 m is correlated to the Gauss/Matuyama polarity transition by means of a preliminary fission track date of 2.7 ± 0.5 m.y.B.P. that has been obtained for a tuff below this reversal in Basawa Kas. This date is not statistically different from the older bentonite from Mangla—Samwal anticline (Jhel Kas; 2.5 ± 0.4 m.y.B.P.). The correlation of the Basawa Kas bentonite with the lower Jhel Kas bentonite permits our correlation of the section at Rohtas anticline to Jhel Kas section and the magnetic timescale. It is reasonable, therefore, that magnetic polarity zone N6 between 925 m and 1250 m in the Rohtas anticline corresponds to the Gauss normal magnetic epoch. The Kaena and Mammoth events have not been identified in the section, probably because of the presence of massive sandstones in this portion of the section which were not sampled. In Fig.14

ROHTAS ANTICLINE

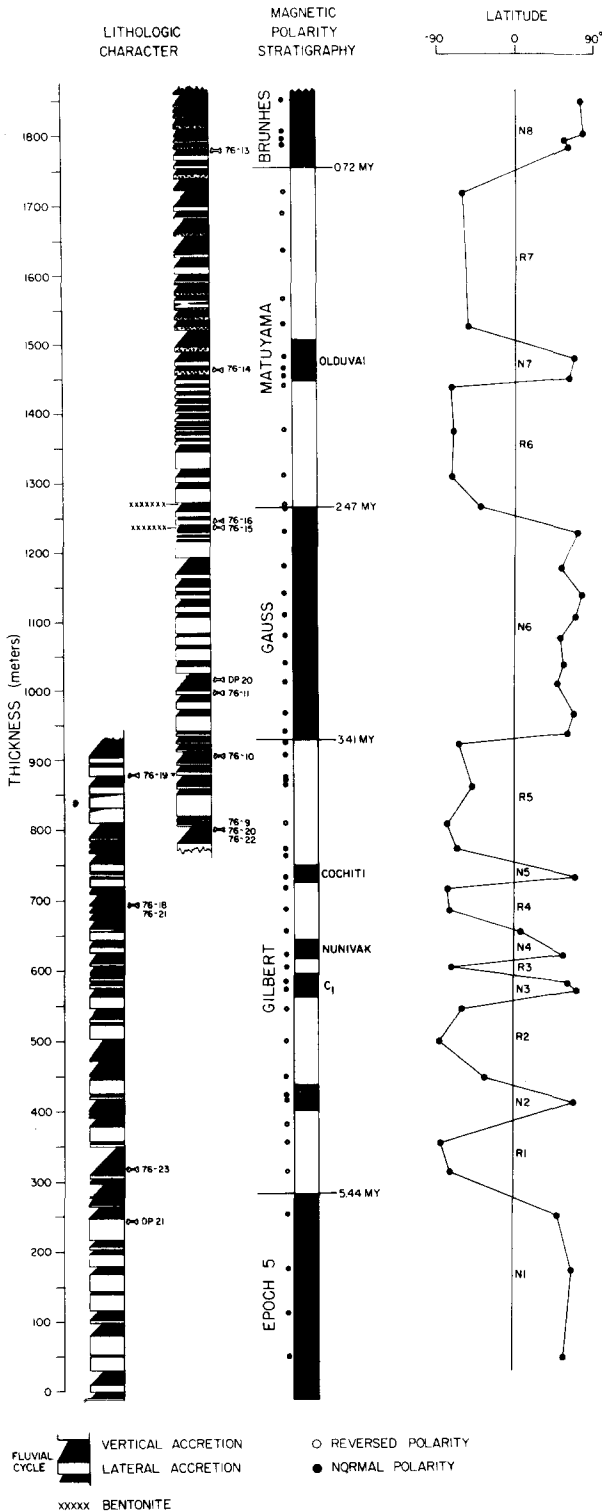


Fig.13. Paleomagnetic sites, VGP latitudes of the Class I sites, sedimentary cycles, magnetozones and fossil localities plotted as a function of the distance above the axis of the Rohtas anticline. The vertical pattern indicates vertical accretion. The other symbols

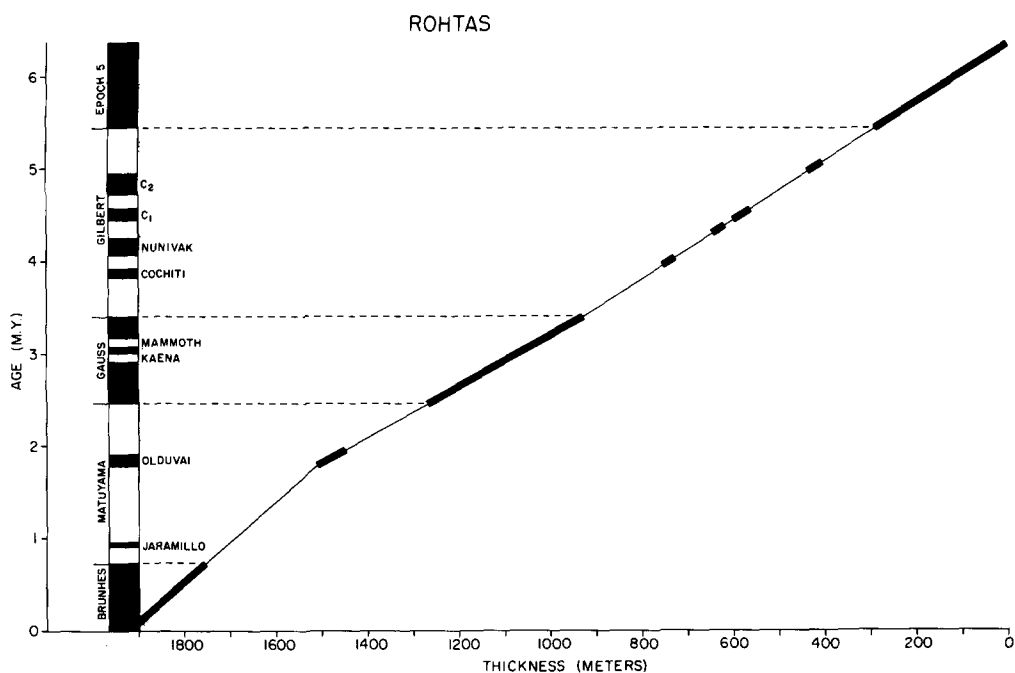


Fig.14. Age vs. distance above the axis of Rohtas anticline. The rate of sedimentation and therefore the ages of the reversal boundaries of the lower part of the section have been extrapolated from the ages of the boundaries of the Gauss normal magnetic epoch. For the upper part of the section the slope was determined by interpolation between the Gauss/Matuyama boundary, the top of the Olduvai event and Brunhes/Matuyama boundary.

the magnetic reversal sequence in the Rohtas anticline has been scaled to a time versus depth plot using the ages of the Gauss normal magnetic epoch boundaries to fix the rate of sedimentation. If the sedimentation rate calculated for the Gauss normal magnetic epoch is extended to older portions of the stratigraphic column, then the magnetic transition at 290 m (N/R) would have an estimated age of 5.44 m.y. This age is close to that suggested for the Gilbert/Epoch 5 boundary (Opdyke, 1972; McDougall et al., 1977). This correlation would allow the short intervals of normal polarity observed between 300 m and 900 m (N2, N3, N4 and N5) to be correlated with events of the Gilbert reversed magnetic epoch. The younger events (N4 and N5) may well correlate with the Cochiti and Nuniyak events; however the event at 420 m (N2) appears too old to be reliably correlated with the "C" event of the Gilbert.

If the sedimentation rate is extrapolated toward the younger part of the section the normal magnetozone at 1475 m (N7) would have an age younger than 2 m.y., very close to ages assigned to the Olduvai event (Brock and Hay, 1976). The magnetic reversal at 1750 m would have an extrapolated

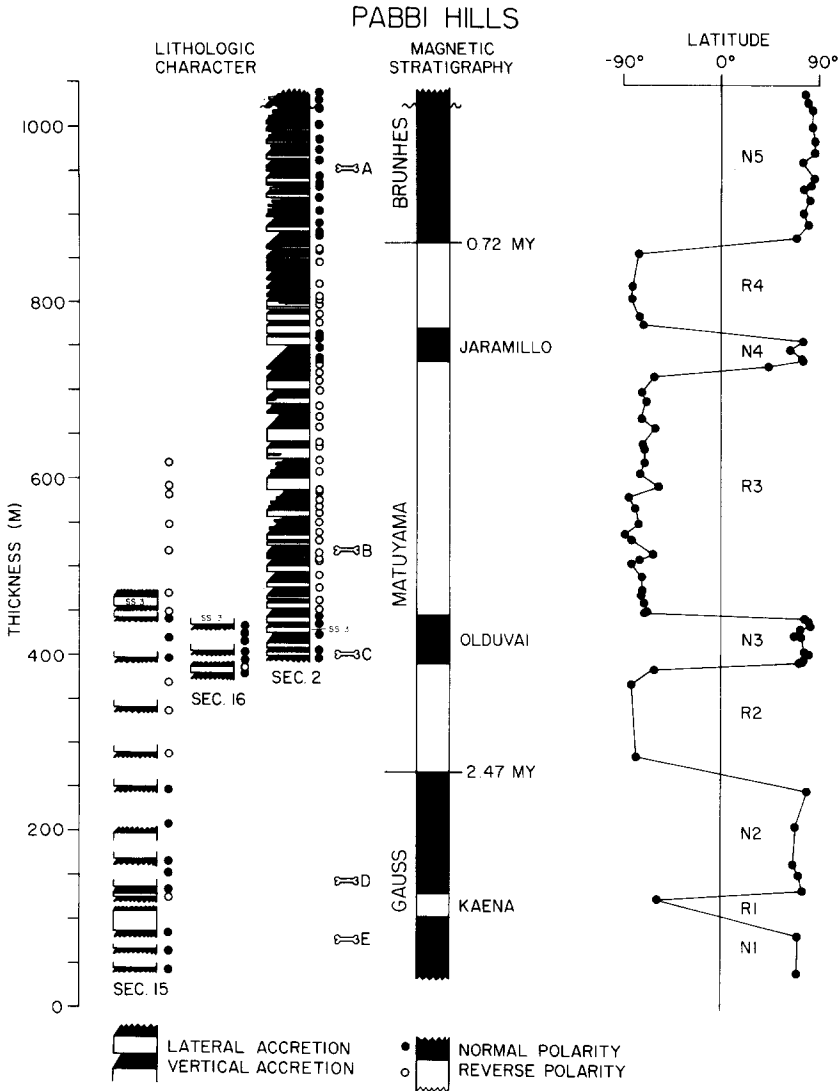


Fig.15. Magnetic stratigraphy of the Pabbi Hills. The VGP latitudes of the Class I sites, sedimentary cycles, magnetozones and fossil localities are plotted as a function of distance above the axis of the Pabbi Hills anticline. The symbols are the same as in Fig.8. The numerical designations of the fossil localities are: A, 76–35; B, DP 24, 25, 33, 44, 56, 57; C, DP 22, 23, 39, 40, 41, 42, 74; D, DP 34; E, DP 36, 76–30. The sections from which this composite was created are given in Keller et al. (1977).

age of about 800,000 years. Since the normal magnetic polarity zone (N8) is greater than 100 m thick, it is most probable that the Rohtas anticline section terminates in the Brunhes normal magnetic epoch. The preferred interpretation of the magnetic stratigraphy of the Rohtas anticline is given in Fig.13.

Pabbi Hills

Southeast of the Rohtas anticline, south of the Jhelum River, another anticlinal structure, called the Pabbi Hills, parallels the Rohtas anticline. Over 1000 m of Upper Siwalik strata are exposed in the Pabbi Hills section. Keller et al. (1977) determined the magnetic polarity stratigraphy of those sediments. Their study rests on a collection of 113 sites, each of which consists of three to five samples, all of which have been subjected to peak alternating fields of 150 Oe or more. The resulting magnetic stratigraphy in Fig.15 is clearly defined. The Pabbi Hills magnetic polarity sequence extends from the Brunhes normal magnetic epoch at the top of the section to the middle of the Gauss normal magnetic epoch at the base of the section. The Jaramillo, Olduvai and Kaena events are all present. The Pabbi Hills section represents approximately 2.5 m.y. of Pleistocene and Upper Pliocene deposition.

Chambal (Jalalpur area)

During the 1977 field season the study of a long (2.2 km) section exposed in Jarmaghal and Nathwala Kas near Jalalpur was initiated. In this paper we report on the magnetic stratigraphy of only the upper 500 m of this section. The magnetic stratigraphy of the remainder of the section will be published after further laboratory and field work are completed. The sediments are similar to those previously described from the Rohtas anticline and consist of cyclic sands and muds deposited by a sinuous river system. These fluvial deposits have been tilted by recent earth movements at angles of up to 70° to the east. Nineteen sites were collected from the upper 500 m of the formation using the techniques previously described. All sites were partially demagnetized in peak alternating fields of 200 Oe. The correlation of this section with those previously studied was greatly facilitated by the recognition of the marker tuffs previously found at Rohtas and Mangla—Samwal anticlines. Fig.16 presents the VGP latitudes of the statistically significant site means as a function of the stratigraphic distance above and below the uppermost of two tuffs that is used as a marker horizon. It can be seen that a prominent magnetic transition from normal to reversed polarity occurs between these two bentonites as previously noted from the areas further to the east. There can be little doubt then that this transition correlates to the Gauss/Matuyama boundary. The stratigraphically lowest reversed polarity zone is therefore most probably the Kaena event. The transition between magnetozones R1 and R2 is most probably the Brunhes/Matuyama transition. The events within the Matuyama have not been detected apparently because the spacing that was used between sites had too large a stratigraphic separation.

CHAMBAL

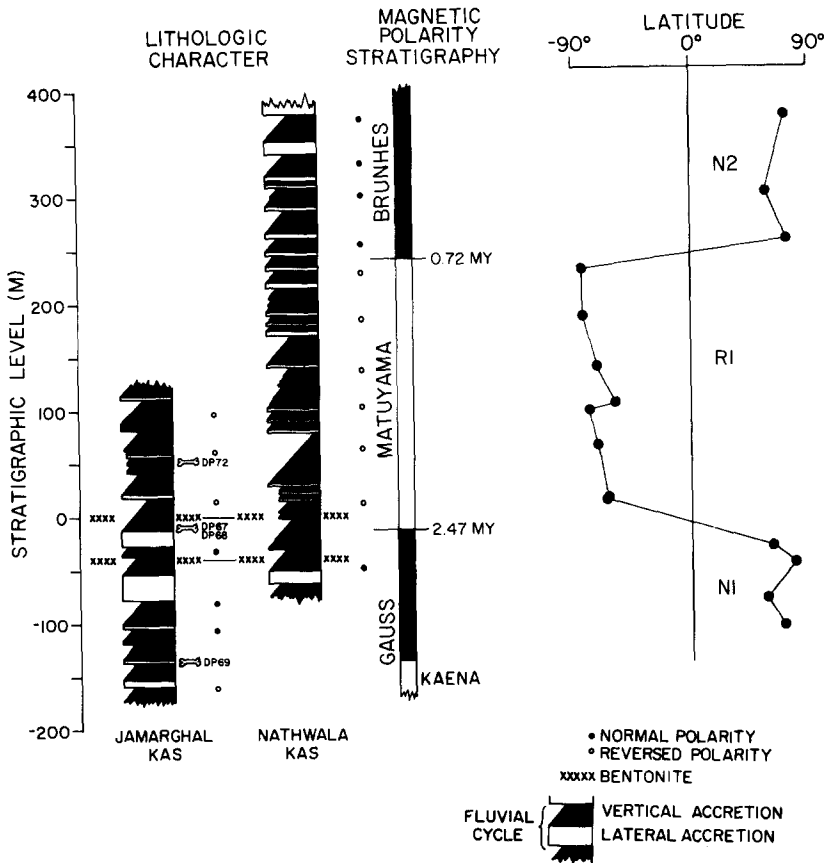


Fig.16. Paleomagnetic sites, VGP latitudes of the Class I sites, sedimentary cycles, magnetozones and fossil localities at Chambal Ridge plotted as a function of distance above and below the upper bentonite. Symbols are the same as in Fig.8.

Tatrot area

The type locality of the Tatrot local fauna (see below) lies immediately to the south of the village of Tatrot. At this locality a thin series (60 m) of conglomerates, mudstones and sandstones lies upon the middle Siwalik, Dhok Pathan Formation with a slight angular unconformity. The exposure is capped by the Late Pleistocene Potwar Silts. Six sites were sampled for paleomagnetic study from this section and studied using the techniques previously described. The lower five sites gave well-grouped normal directions of magnetization, while the upper site gave scattered directions of magnetization which were not statistically significant (Fig.17). We conclude, therefore, that the Tatrot

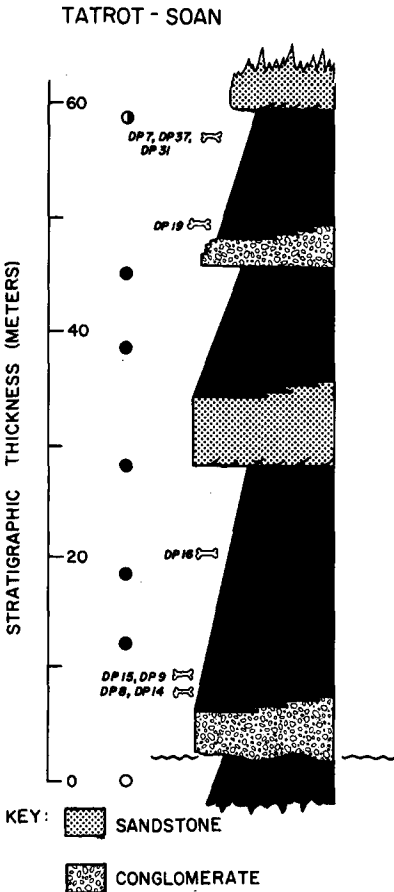


Fig.17. Stratigraphy of the Tatrot section. Paleomagnetic sites are indicated by filled (normal) or open (reversed) circles. Partially filled circle indicates indeterminate magnetization. The unconformity at the base of the Tatrot is indicated by the wavy line. Fossil localities are indicated by the bone symbol along with their numerical designation.

fauna at its type locality is normally magnetized. Directly to the northwest of the type locality a second exposure of Upper Siwalik sediments occurs in Dhok Wazir. The stratigraphic relationship of this locality to the type section of the Tatrot is not clear due to a cover of Potwar Silts. The sediments in this section have coarse lithologies which led by necessity to the sampling of coarser material than usual for the paleomagnetic study. As a result the directions of magnetization within several of the sites are widely scattered; however, no clear reversely magnetized directions were detected which leads us to believe that, like the Tatrot type section, these sediments are also normally magnetized.

Bhaun section

Sediments of Upper Siwalik age are well-exposed in Sauj Kas, a valley immediately south of Bhaun village. The stratigraphic situation here is similar to that at Tatrot. The brown-colored Upper Siwalik sediments in this basin lie disconformably upon Dhok Pathan sediments beginning with a ridge-forming conglomerate. The sequence dips gently toward the north and is capped by the Potwar Silt. Nine paleomagnetic sites were sampled through 70 m of Upper Siwalik sediments and all sites were partially demagnetized in a peak alternating field of 300 Oe. The resulting magnetic stratigraphy (Fig.18) is marked by two normally magnetized magnetic polarity zones (N2, N3) 100–200 m above the base of the Upper Siwalik sediments. At the present time it is difficult to position the observed magnetic sequence within the reversal time scale unambiguously. However, since the section is predominantly of reversed polarity one could expect that the sediments would

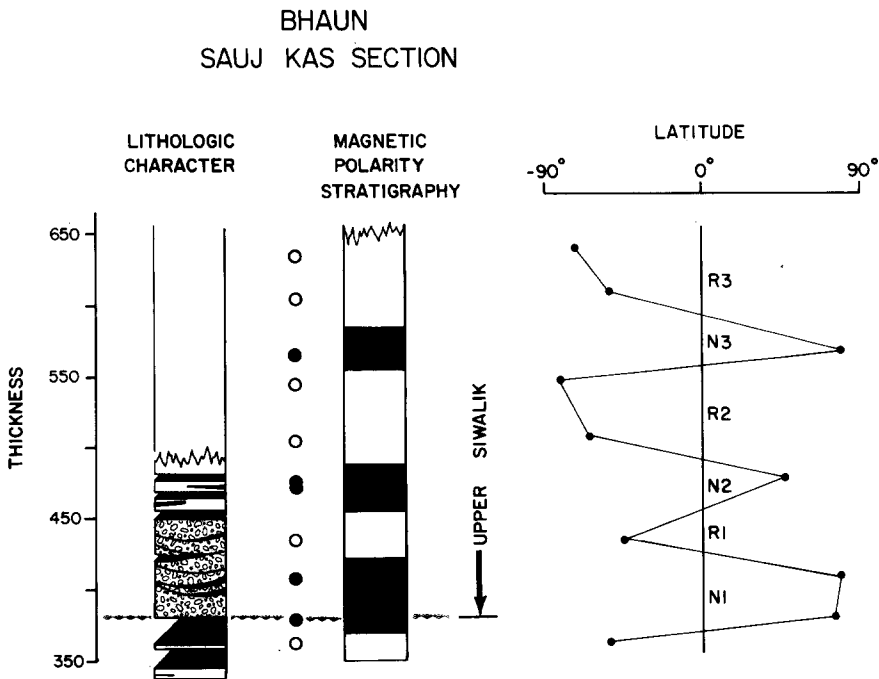


Fig.18. Paleomagnetic sites, VGP latitudes of the Class I sites and fossil localities of the Bhaun section plotted as a function of the distance above the Upper/Middle Siwalik unconformity. The fossil site is indicated by the bone symbol along with its numerical designation. The paleomagnetic sites are indicated by closed (normal) and open (reversed) circles. The unconformity is indicated by the wavy line. The upper part of the section was not measured and is very flat-lying. The stratigraphic position was calculated on the basis of map distance.

be either of Matuyama or Gilbert age. At other sites in this study Matuyama-age sediments are characterized by Pinjor-age fossils. These are not present in the Bhaun section. We believe, therefore, that the magnetic stratigraphy is most likely correlative to middle Gilbert time or older.

The Campbellpore Basin

The most important locality in Pakistan of Pinjor-age fossils occurs in the Campbellpore Basin located near the juncture of the Haro and Indus rivers. De Terra and Teilhard de Chardin (1936) discovered an important bone pocket (their site 103) in gently folded claystones and sandstones along the northern bank of the Haro River. Three kilometers to the south of this bone bed, in the vicinity of Dheri Choan, three separate bentonitized tuffs were found during the 1976 field season and the bone pocket (site 103) was re-located. Unfortunately the sediments within this basin rapidly change character along strike so that it is difficult to make lithologic correlations. However, a bentonitized tuff horizon occurs along the Haro River which may be correlative to the upper bentonite at Dheri Choan (Fig.19). In order to correlate the fossils and the bentonitized tuffs within the basin, three sections of magnetic samples were taken (Fig.19): The first in Dheri Choan Kas, where the bentonitized tuff is being actively mined as a high-grade bentonite; the second in Mara Huwa Kutta Kas, where the tuff is well exposed; and the third in a profile along the Haro River through the fossil site. The sections can be correlated on the basis of the tuff which is present in all of them. The quality of the magnetic data from the area is excellent and most sites are stably magnetized. All sites were partially demagnetized in peak alternating fields of 300 Oe. The resulting magnetic stratigraphy is shown in Fig.19. Four reversals of the magnetic field have been detected. The topmost site at Mara Huwa Kutta Kas is normally magnetized, as are the uppermost two sites along the Haro River. All of these sites were collected in terraces and lake beds unconformably overlying the older upper Siwalik sediments. These sites are very young and are probably of upper Brunhes normal magnetic epoch age. However, the upper site at Mara Huwa Kutta Kas is normally magnetized and was taken in sediments of late Siwalik age. Upper Siwalik sediments with normal magnetization are not seen at presumably equivalent levels along the Haro River; however, a short normal interval may easily have been missed. The remainder of the sites are reversely magnetized, with the exception of the lowermost site below the tuff in Dheri Choan Kas. There can be no doubt, however, that the important fossil site 103 is firmly placed within reversely magnetized sediments. The position of the magnetic section cannot be placed unambiguously within the magnetic time scale because the sections do not span sufficient time. However, we know that Pinjor fossils in other areas of the Potwar occur within the Matuyama reversed magnetic epoch. It is therefore most probable that this is true of the sediment and fauna along the Haro River. It would be of great interest to identify the magnetic reversal

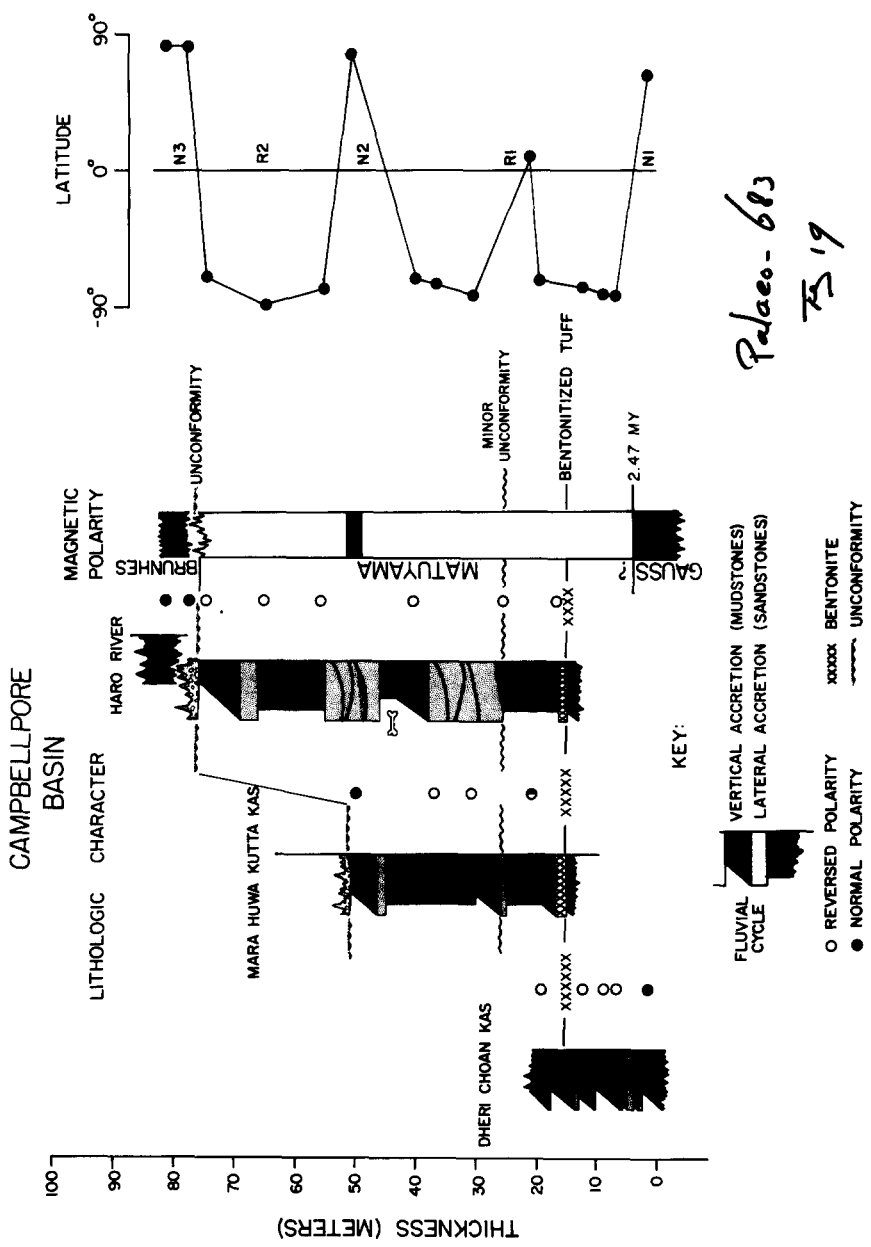


Fig.19. Paleomagnetic sites, VGP latitudes of Class I sites and sedimentary cycles of the Campbellpore Basin. Symbols are the same as in Fig.8. The fossil locality indicated by the bone symbol is site 103 of De Terra and Teilhard de Chardin (1936). The unconformity at the top indicates the appearance of very recent terraces and lake beds which are very much younger than the main part of the sequence.

at the bottom of the Dheri Choan Kas section since this would help to establish the age of the fossils. Fission track dating of the tuffs is in progress and this should allow an unambiguous determination to be made.

Discussion of magnetic polarity stratigraphy

In spite of the fact that the fluvial character of these sedimentary suites allowed for the development of many local unconformities within the stratigraphic section, it has been demonstrated that a good record of magnetic polarity changes is preserved. The general sandstone/mudstone cyclic character of these clastic rocks allows for the preservation of a relatively complete record of basin subsidence, fluvial process and source area denudation (see Visser and Johnson, 1978).

Fig. 20 shows the correlation of the sections included in this study stacked relative to the Gauss/Matuyama magnetic horizon of the region. Because of the occurrence of the two bentonitized tuff complexes straddling this transition, the boundary can be traced throughout the whole area. Above this reversal a prominent normal magnetozone can be correlated with the Olduvai event. The Olduvai event has previously been shown correlative with the Pliocene—Pleistocene boundary on the basis of change of marine biota (Haq et al., 1977). It is therefore possible to precisely determine the Pliocene—Pleistocene boundary in the Upper Siwalik deposits.

VERTEBRATE PALEONTOLOGY

One of the goals of this study is to increase the resolution of Siwalik biostratigraphy. Fossils reported in the faunal lists (below) were collected primarily from sediments in the vicinity of magnetic—stratigraphic sections, and fossiliferous strata were then traced into that section to maintain a comprehensive stratigraphic reference. This method produces a multitude of fossil sites, many of which have only one or two taxa, but it affords the necessary stratigraphic control. Fossil sites are grouped by stratigraphic section and therefore each section contains numerous sites of different temporal interval. It is important to note that this departs from previous studies of the Siwalik vertebrate sequence in which sites are grouped by seemingly similar age. Names of our sections (e.g., Tatrot section) have no chronologic significance. The stratigraphic positions of these localities are indicated on Fig. 20. Fauna from these sites and local range-zones are indicated on Fig. 21. This faunal list includes only those specimens collected during our field study, with the exception of the faunal list for site 103 given by Teilhard de Chardin (in the American Museum of Natural History archives). The local range-zones in Fig. 21 are established relative to the magnetic polarity sequence.

The number of sites and taxa per section is variable and reflects the number of man-days spent searching for fossils and the relative thickness

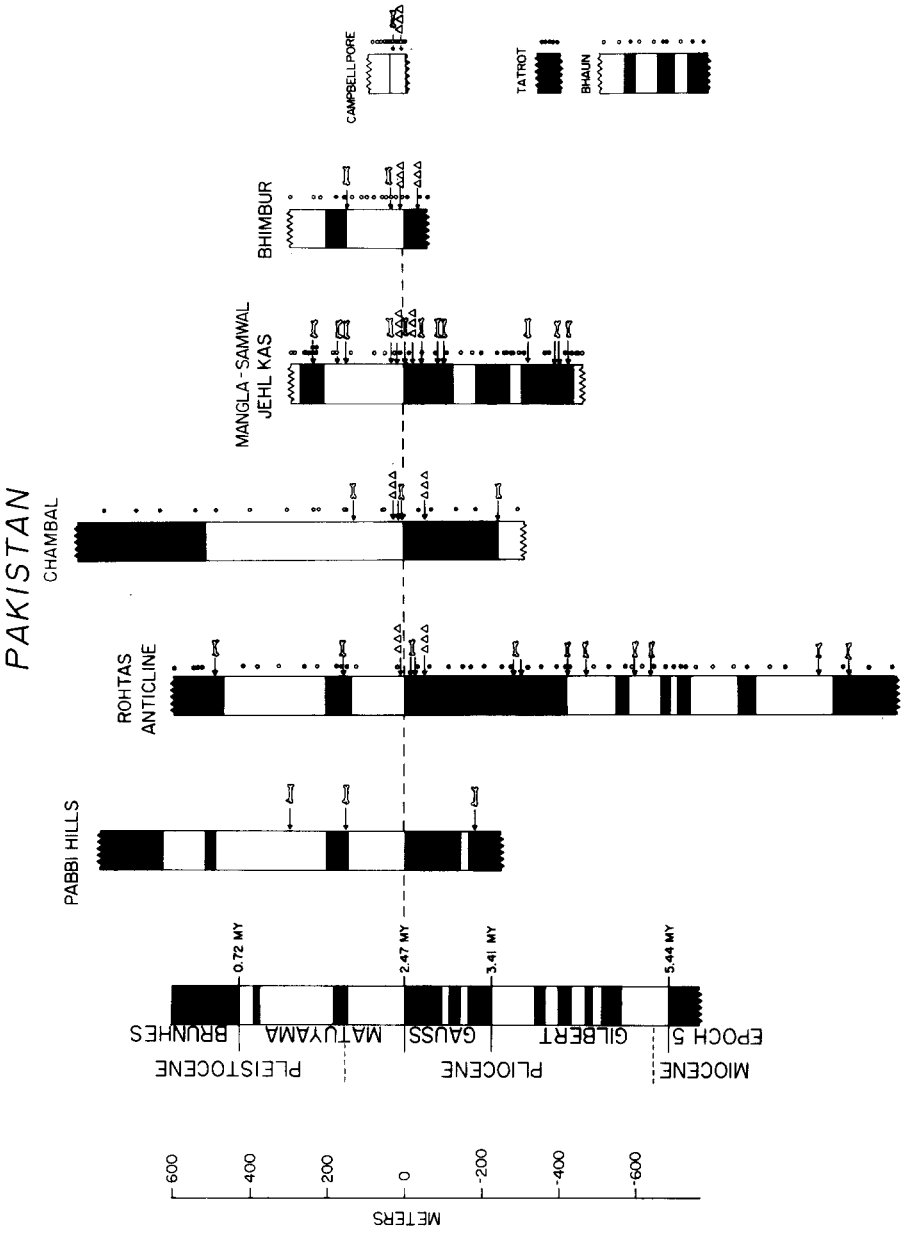


Fig. 20. Paleomagnetic correlation of the Upper Siwalik stratigraphic sections of northeast Pakistan. Bone symbols represent fossil sites, filled (open) circles represent normal (reversed) paleomagnetic sites. Triangles represent bentonitized tuff.

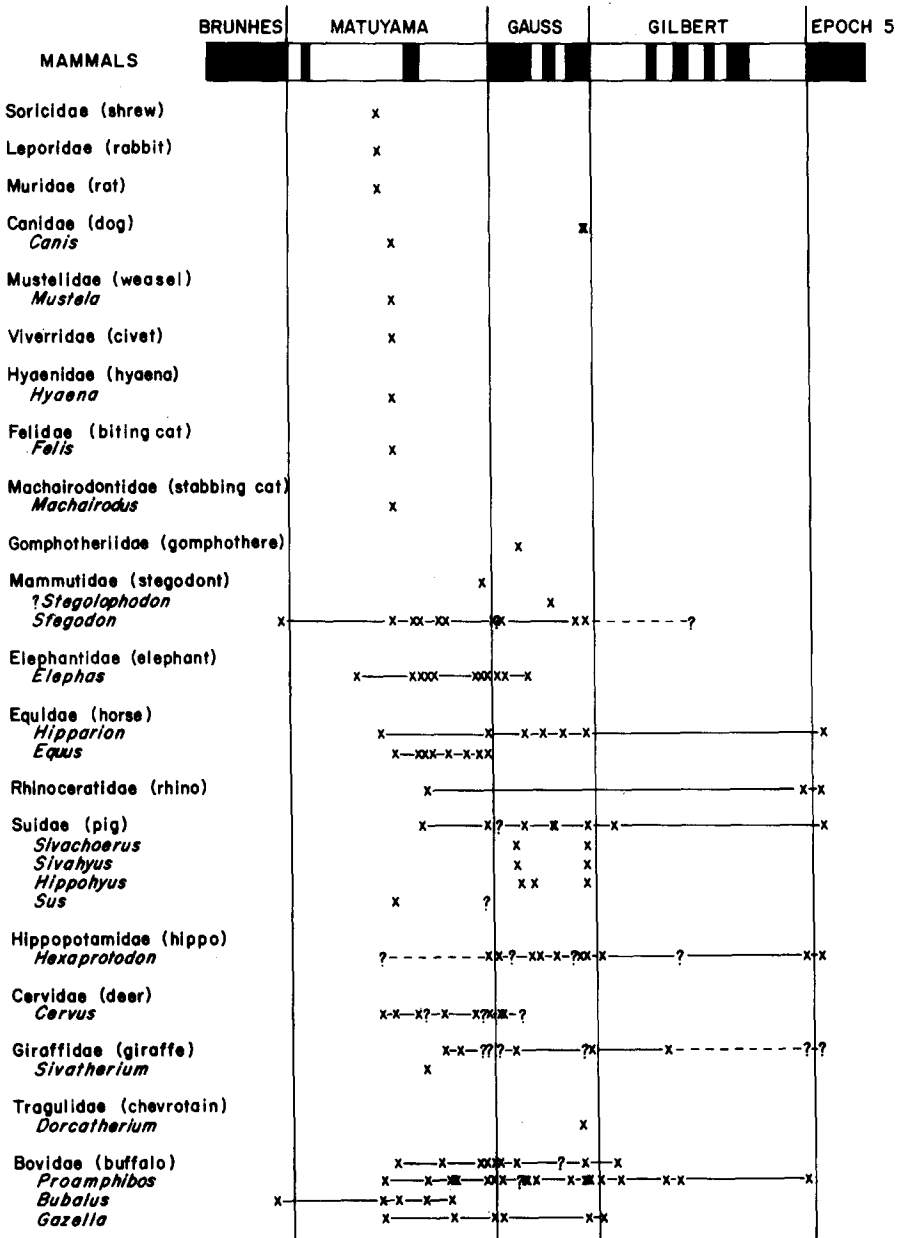


Fig. 21. Occurrence of individual species plotted with respect to this occurrence in the magnetic time scale.

and abundance of fossils in each section. None of these factors is equal for all sections, and no attempt was made to equate them. In the Pabbi Hills section (Fig.15) 23 taxa are recorded from 17 sites. In the Mangla—Samwal section (Fig.8) 12 taxa are recorded from 15 sites. In the Rohtas section (Fig.13) 14 taxa are recorded from 15 sites. We believe further collecting in these areas will produce more sites and more taxa.

The faunal lists are dominated by large mammals, although small mammals were recovered from DP 24 in the Pabbi Hills section by underwater sieving. In the Pabbi Hills section bovids and stegodonts are more common than carnivores, elephants, horses, rhinos, pigs, hippos, deer and giraffes. In the Mangla—Samwal and the Rohtas anticline sections the bovids are more common than other large mammals. In the Tatrot section, pigs are more common than other large mammals. Relative differences in abundance of taxonomic groups noted above probably reflect both chronologic and ecologic differences in the faunal record. We believe the record, represented collectively in these sections, reflects the diversity and abundance of mammals that lived in that area from about one to five millions years ago. Faunal lists are given primarily at the familial and generic level which are sufficient for our purpose.

Several significant faunal changes may be recognized in this fossil record. Some of these are designated as local first or last occurrences of a given taxon. These faunal changes are illustrated relative to the geomagnetic time scale in Fig.22.

Hexaprotodon — The lowest record of the hippopotamus *Hexaprotodon* in these sections is at site DP 21 in the Rohtas section, which occurs at the top of magnetic epoch V. *Hexaprotodon* appears in the Tatrot section at site DP 14 (Gauss magnetic epoch), in the Mangla—Samwal section at site 76—2 (lower Gauss magnetic epoch) and in the Pabbi Hills section at site DP 34 (middle Gauss magnetic epoch). It should be noted, however, that *Hexaprotodon* may be found in sediments of an earlier age when a more thorough search is made.

Hipparion — The highest stratigraphic occurrence of the three-toed horse *Hipparion* in these sections is at site DP 33 in the Pabbi Hills section, which is in the upper Matuyama magnetic epoch. *Hipparion* is recorded from the base of the Matuyama magnetic epoch at DP 67 in the Chambal section, it is not recorded in the Mangla—Samwal section; its only stratigraphic record in the Rohtas section is at DP 21 (top of magnetic epoch V), in the Tatrot section at DP 37 (Gauss magnetic epoch).

Equus — The lowest record of the one-toed horse *Equus* in these sections is at DP 68 at the base of the Matuyama magnetic epoch in the Chambal section. *Equus* is recorded at 76—32 in the Mangla—Samwal section and at Bhimbur in the lower Matuyama magnetic epoch. Its lowest record in the Pabbi Hills section (DP 41) and the Rohtas section (76—14) is at the Olduvai event in the Matuyama magnetic epoch. *Equus* is not recorded from the Tatrot section.

Elephas — The lowest record of the elephant *Elephas* (*Archidiskodon*)

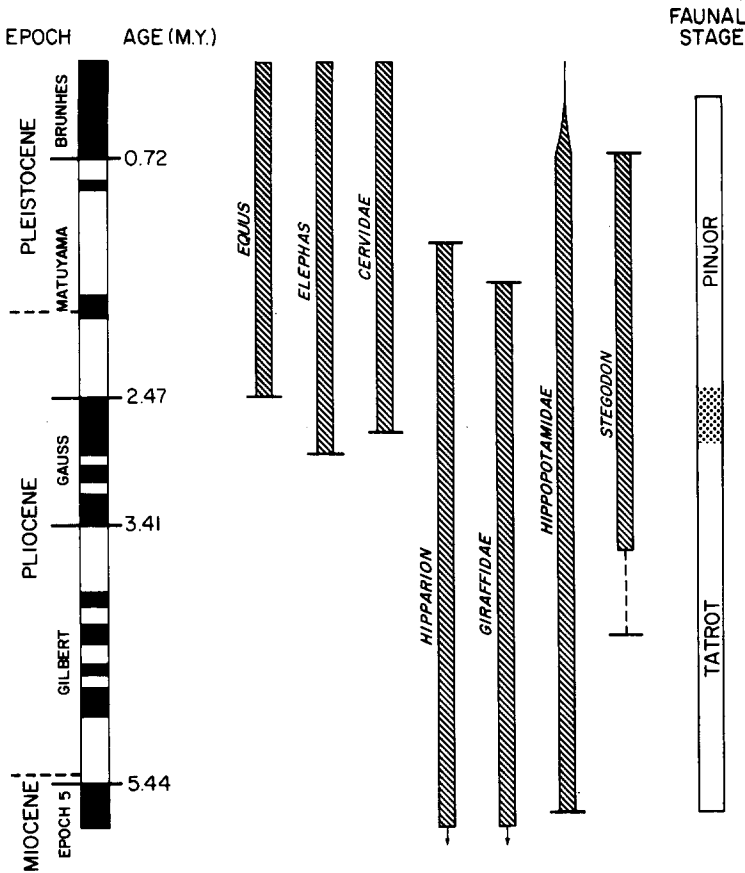


Fig. 22. Range of stratigraphically important taxa in the Pliocene and Pleistocene of the Siwaliks.

planifrons in these sections is in the upper Gauss magnetic epoch, above the Kaena event at DP 69 in the Chambal section. *Elephas* is recorded in the upper Gauss magnetic epoch at 76–33 in the Mangla–Samwal section, from the Olduvai event in the Pabbi Hills section (DP 74) and the base of the Matuyama magnetic epoch in the Rohtas section (76–16); it is not recorded from the Tatrot section.

Giraffidae — The highest stratigraphic record of a giraffe in these sections is DP 42 in the Pabbi Hills section (Olduvai event). Highest record of giraffids in other sections is DP 72 (lower Matuyama) in the Chambal section, DP 43 (lower Matuyama magnetic epoch) in the Mangla–Samwal section, 76–18 (middle Gilbert magnetic epoch) in the Rohtas section and DP 37 (Gauss magnetic epoch) in the Tatrot section.

Cervidae — Another, apparently significant, faunal change we note is the appearance of *Cervidae* (deer) in the Siwalik sequence. An important and

unique character of Cervidae is the presence of antlers in the males (and in some females). We recognize the lowest occurrence of antlers in these sections at 76—15 in the Rohtas section (upper Gauss magnetic epoch). The oldest cervid antlers are recorded at DP 24 (Matuyama magnetic epoch) in the Pabbi Hills section, at DP 67 (lowermost Matuyama magnetic epoch) in the Chambal section and at DP 27 (upper Gauss magnetic epoch) in the Mangla—Samwal section; they are not known from the Tatrot section. Cervids have been reported from Middle Siwalik deposits by Lydekker (Brown, 1927; Colbert, 1935). The Middle Siwalik cervid identifications are based on teeth rather than antlers. Cervid teeth are very similar to giraffid teeth; it is possible that some of the dentitions identified in our faunal list as giraffids may prove to be cervid and conversely, some of the teeth identified as cervids in the earlier faunal lists may prove to be giraffids. Definite identification of the dentitions must await a more detailed taxonomic review of all Siwalik Giraffidae and Cervidae. Until then, we are aware of no antlers recorded from the Tatrot section (or elsewhere in Middle Siwalik deposits), whereas antlers and crania with antlers are fairly common in Upper Siwalik deposits. Lydekker's *Cervus latidens*, based on a right upper molar, is from the Padhri—Hasnot area where we record several dentitions of giraffids. It should be noted that cervids with antlers (e.g., *Procerulus* and *Stephanocemas*) are recorded from Miocene deposits in Europe and northern Asia.

The sequence of faunal change in Siwalik sediments is of primary importance for the correlation of these terrestrial sediments and related geologic events with similar deposits and events in other parts of the world. Paleontologists and stratigraphers have commonly placed the faunal sequence within a framework established by Pilgrim (1913), relating these divisions (Manchar or Kamliar, Chinji, Nagri, Dhok Pathan, Bhandar, Tatrot, Pinjor, and Boulder Conglomerate) to lithologic formations, or biostratigraphic (zones), or time-stratigraphic (stages) units. It is now apparent that these faunal-stratigraphic divisions are fairly reliable for intercontinental correlation but are unreliable for correlation within the Siwaliks. For example, most paleontologists and stratigraphers accept the correlation of Pilgrim's Pinjor fauna with the European Villafranchian or Biharian fauna, but there is little or no agreement on where to place the boundary between Pilgrim's Pinjor and Tatrot faunal intervals in the Siwaliks. For this reason, we have avoided (up to now) placing any sites in Pilgrim's Pinjor or Tatrot faunal intervals, but have placed all of them in an independent, calibrated temporal frame of reference, the geomagnetic time scale. Many composite faunal lists for Pinjor and Tatrot faunal intervals have been made by adding faunal lists of widely separated sites without examining the fossils, or by grouping fossils without precise stratigraphic (or geographic) provenance. The validity of these faunal definitions is open to question.

As seen in Fig. 22 there is a significant faunal change near the top of the Gauss magnetic epoch, at approximately 2.5 m.y. This faunal change, which we suggest is the appropriate boundary (or transition) between Tatrot and

Pinjor faunal intervals, is characterized by the appearance of *Equus* and *Elephas* and by the appearance of cervids with antlers. It is followed slightly by the disappearance of *Hipparion* and giraffids. We assume that with continued fossil collecting in the Siwaliks, the absolute stratigraphic ranges of some of these taxa are liable to change. The faunal "break" as defined above, is not sharp and will probably become less precise with continued fossil collecting. However, we believe the record, as presented in our six reference sections, is reliable and that the faunal change is real. We suggest this faunal change at about the Gauss/Matuyama boundary be identified with the Tatrot/Pinjor boundary. Note that the faunal change occurs in the late Pliocene, so that in general terms, the Tatrot faunal interval as defined by the joint occurrence of *Hipparion* and *Hexaprotodon* is equivalent to most of the Pliocene epoch and the Pinjor faunal interval is equivalent to the last of the Pliocene and all or most of the Pleistocene. We note that Matthew (1929, pp. 445—447) emphasized the joint occurrence of *Equus* and *Camelus* as rationale for recognition of Pleistocene faunas in the Siwaliks. We did not collect any *Camelus* or camelid specimens, even though we sampled through the interval in which it should be represented in both the Pabbi Hills and Rohtas sections. To our knowledge, *Camelus* is recorded only from the Siwalik Hills in India within the Siwaliks. Perhaps, with precise biostratigraphic calibration of the record of *Camelus* in the Siwalik Hills (or elsewhere in the Siwaliks), it might prove useful to divide the Pinjor faunal interval into an earlier and a later (e.g., Boulder Conglomerate) part.

The joint occurrence of *Equus*, the bovid *Proamphibos*, and *Elephas* at about 2.4 m.y. may closely approach the joint occurrence of *Equus*, *Leptobos*, and *Elephas* in Villafranchian or Biharian deposits of Europe. The record of *Proamphibos* in Asia and *Leptobos* in Europe precede the occurrence of *Equus* (from North America) and *Elephas* (from Africa) in both Asia and Europe.

FLUVIAL SEDIMENTATION

The fluvial sandstone/mudstone couplets which characterize the sedimentary facies of the Upper Siwalik subgroup in northern Pakistan suggest that most of these sediments were deposited in a generally well-developed meander-belt regime. This implies that the stream systems existing at the time of Siwalik deposition were characterized by a laterally migrating stream channel in association with a trailing floodplain. The floodplain consists of overbank and associated proximal crevasse splays, soils and other minor landscape features.

The general cyclicity demonstrated in the various stratigraphic columns (for example, the Mangla—Samwal, Rohtas and Chambal sections) suggests a dynamic balance between basin subsidence and fluvial aggradation. Composite, vertically complex sandbodies suggest multiple encounters of laterally migrating stream channels with earlier channel facies deposits. Thus the

vertical complexity or multi-storied character of many of the sandbodies (e.g. Rohtas, Mangla—Samwal) suggests that these localities lay within a proximal position to the recurring loci of occurrence of the major ancestral stream distributary system responsible for Upper Siwalik sedimentation.

An illustration may make this discussion clear: The sandbody and associated overbank deposits located at the 100-m level of the Rohtas section is typical of a relatively simple “single-storied” channel deposit and associated overbank mudstone deposit (Fig.13). In general, basin subsidence coupled with lateral migration of subsequent stream systems allows for the preservation of this single record of stream migration. In contrast, the very thick sand unit lying above the 100-m level is characteristic of a multi-storied channel sandstone. Such an occurrence indicates several episodes of stream migration which have cannibalized older sedimentary units (overbank muds) resulting in an expanded sand section. The Mangla—Samwal, Rohtas and Chambal areas all illustrate episodes of multiple stream encounter, subsequent cannibalization and over-thickening of channel sands somewhere in the stratigraphic column.

Within the Mangla—Samwal and Chambal stratigraphic sections (Figs.8 and 16), there is a marked *decrease* in the amount of multi-storied lateral accretion sandbodies in rocks younger than Gauss time. A similar observation can be noted in the Rohtas stratigraphic section (Fig.13), except the last occurrence of significant multi-storied channel sandstones occurs midway between the end of the Gauss magnetic epoch and the Olduvai magnetic event of the Matuyama.

These changes in sandbody geometry suggest a change in the fluvial regime in post-Gauss time which allows for the preservation of complete sedimentary cycles of single-storied character. Slightly thereafter is the first occurrence of pebbles and cobbles within the traction load of the channel facies which have a lithologic composition which is of distinct Himalayan aspect. The first occurrence of this coarse pebbly phase in the Rohtas anticline is at the level of the Olduvai magnetic event; at Mangla—Samwal it is slightly later than the Olduvai event, while in the Chambal area it occurs in upper Matuyama time. These clasts are derived from the crystalline metasediments and igneous rocks of the higher and lesser Himalaya and mark the first occurrence of a significantly Himalayan suite in the clastic rocks of the Upper Siwaliks. Clasts which occur in channel facies prior to this time are generally of a sedimentary character and most likely represent the unroofing of the outer or lesser Himalaya and the adjacent Salt Range.

Additionally, the development of a braided stream aspect concurrent with thin-sheet conglomerate deposition is suggestive of decreased sinuosity in stream development and associated increase in gradient, possibly related to the uplift in the adjacent mountain system. In general the post-Olduvai record of each of the stratigraphic sections in the southeast Potwar records the first development of higher gradient stream deposits located in this region of the Himalayan foredeep. These conglomeratic, stream deposits have been known collectively as the “boulder conglomerate stage” for many

years. It should be noted, however, that this "stage" is by no means synchronous but in fact represents individual responses of ancient distributary systems to local changes in hydrologic regimen.

SEDIMENTARY TECTONICS

One of the aspects of the geology of the Himalayan foothills is the youthfulness of the topography and of some of the sedimentary structures now being eroded. The youngest sediments in both the Pabbi Hills and Rohtas and Chambal anticlines are of Brunhes age. This shows clearly that 700,000 years ago the sites that these structures now occupy were basins of deposition. In the lower Brunhes these structures began to demonstrate a surface expression. The approximate time that this uplift began may be determined by the sedimentation vs. time plots. In the case of the Rohtas anticline uplift was initiated 500,000 years ago. The maximum rate of uplift thereafter is four meters per thousand years. The maximum rate of uplift of the Pabbi Hills is similar being three meters per thousand years. The section at Mangla—Samwal terminates in sediments at least one million years older than those in the Pabbi Hills and Rohtas anticline.

More than twenty localities which contain the lower and upper bentonitized tuff complex have been studied with regard to sedimentation rate, fluvial stratigraphy and tectonic control. These results are published elsewhere (Visser and Johnson, 1978). Significant variation in rates of accumulation can be noted in these sites throughout the Jhelum structural reentrant, suggesting a highly variable basin subsidence. This sedimentary interval has been studied all along the Pir Panjal foothill belt from the vicinity of Bhimbur in the southeast to Palak in the northwest along the Punch River. Sedimentation rates increase from a minimum at Bhimbur of $0.33 \text{ m}/10^3 \text{ yr}$ to greater than $0.5 \text{ m}/10^3 \text{ yr}$ at Palak. Elsewhere in the Jhelum structural reentrant at the time of the Gauss/Matuyama magnetic transition sedimentation rates vary from 0.35 to $0.50 \text{ m}/10^3 \text{ yr}$. In several cases sedimentation rates are low, possibly in response to sedimentary thinning on top of penecontemporaneously deforming structures. This may explain the low sedimentation rate noted at the Pabbi Hills ($0.31 \text{ m}/10^3 \text{ yr}$) and in the southeastern flank of the Mangla—Samwal anticline ($0.33 \text{ m}/10^3 \text{ yr}$). In all instances there is a general tendency for the sedimentation rates to increase towards the axis of the reentrant structure. It is hoped that future analyses will help to show in more detail the changing locus of tectonic activity in this area through time.

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