Magnetic-polarity stratigraphy of Upper Siwalik of north-western Himalayan foothills

A. Ranga Rao

Wadia Institute of Himalayan Geology, Dehradun 248 001, India

The magnetostratigraphy supplemented by radiometric dates and palaeontological data from Upper Siwalik Subgroup in six sections across the foothills of north-western Himalaya provides absolute ages for the subdivisions of the Upper Siwalik, and a time framework to interpret the lithological information. The formational boundaries drawn on the basis of lithology are strongly diachronous with age deviations ranging from 3×10^5 to 2×10^6 years, and the age of the Upper Siwalik Subgroup extends from 5.6 to 0.22 m.y. (late Miocene to middle Pleistocene). The rate of sediment accumulation ranges from 0.27 to 0.71 m/1000 yr. The decreased sedimentation rates during the Matuyama chron in the northern part, and the accelerated rates for the same interval in the southern parts, as well as the presence of pebbles in the Upper Siwalik in the southern areas derived from the older fordeep-sediments indicate a foreland-directed migration of the depositional centres of the foredeep.

Introduction

SOUTH of the lofty Himalaya a foredeep was formed in the early Miocene times. A thick sequence of terrestrial sediments called the Siwalik was deposited in this foredeep from middle Miocene to middle Pleistocene, covering a period of approximately 14 m.y. The 5000 m thick Siwalik sequence consists of sandstone-claystone-conglomerate alternations. Stated in general terms, the sediments show a coarsening upwards, thus reflecting progressive uplift of the Himalaya from which they are derived. The Siwalik Group is divided into Lower (fine-grained sandstones and clays), Middle (dominantly sandstone) and Upper Siwalik (largely conglomerate). On the basis of rich assemblages of vertebrate faunas Pilgrim[1,2] subdivided the Siwalik into Kamlial, Chinji (Lower Siwalik); Nagri, Dhok Pathan (Middle Siwalik), Tatrot and Pinjor (Upper Siwalik). These faunal zones were correlated with those of the European Upper Tertiary[2].

In its search for oil, the Oil and Natural Gas Commission (ONGC), carried out since 1956, very detailed mapping of the entire Siwalik belt. The investigations demonstrated that the Siwalik sediments exhibit a considerable facies change both along and across the strike and that the vertebrate fossils occur only in certain areas, implying that regional correlation on the basis of vertebrate fossils alone is quite difficult. Moreover, the boundaries of the faunal zones were vaguely defined. Hence the ONGC workers used vertical variation in lithology: sandstone-claystone ratio, hardness of the rocks and presence of conglomerates as the basis of subdivision, leading to identification of scores of lithostratigraphic units of local validity. The analysis of heavy minerals in sandstones indicated that the Lower Siwalik is characterized by epidote and staurolite along with garnet, tourmaline, zoisite, zircon, rutile and opaque minerals; the Middle part by the first appearance of kyanite together with a moderately rich assemblage of garnet, tournaline, epidote, staurolite, zoisite, zircon and sporadic sphene, and the upper unit consists of a complex heavy mineral assemblage which includes mineral assemblages of both the above suites with the addition of sillimanite and hornblende.

In the Jammu area of the Suruin-Mastgarh anticline (Figure 1) the boundaries drawn on the basis of mineral content do not follow the boundaries drawn on the basis of vertical variation in lithology, showing that the appearance of a new mineral is not isochronous throughout the Siwalik basin (Figure 2).

Magnetic polarity stratigraphy

Principle

The last two decades have witnessed development of the branch of magnetostratigraphy based on permanent magnetism of rock sequences. The fine-grained sediments of the flood plain facies preserve a good record of natural remanent magnetization (NRM). This record is composite comprising of the record of the orientation of the Earth's magnetic field prevailing at the time of their deposition — depositional remanent magnetization (DRM) along with the magnetizations acquired after the deposition. Magnetostratigraphic analyses seek to isolate and to record the DRM data in the rocks. This is achieved by employing a variety of demagnetization techniques — alternating field (a.f.), thermal and chemical demagnetization, by which the secondary magnetizations acquired after deposition can be removed to obtain the characteristic magnetization of depositional origin. In a stratigraphic sequence, when samples are collected at regular intervals and analysed in the above manner it is

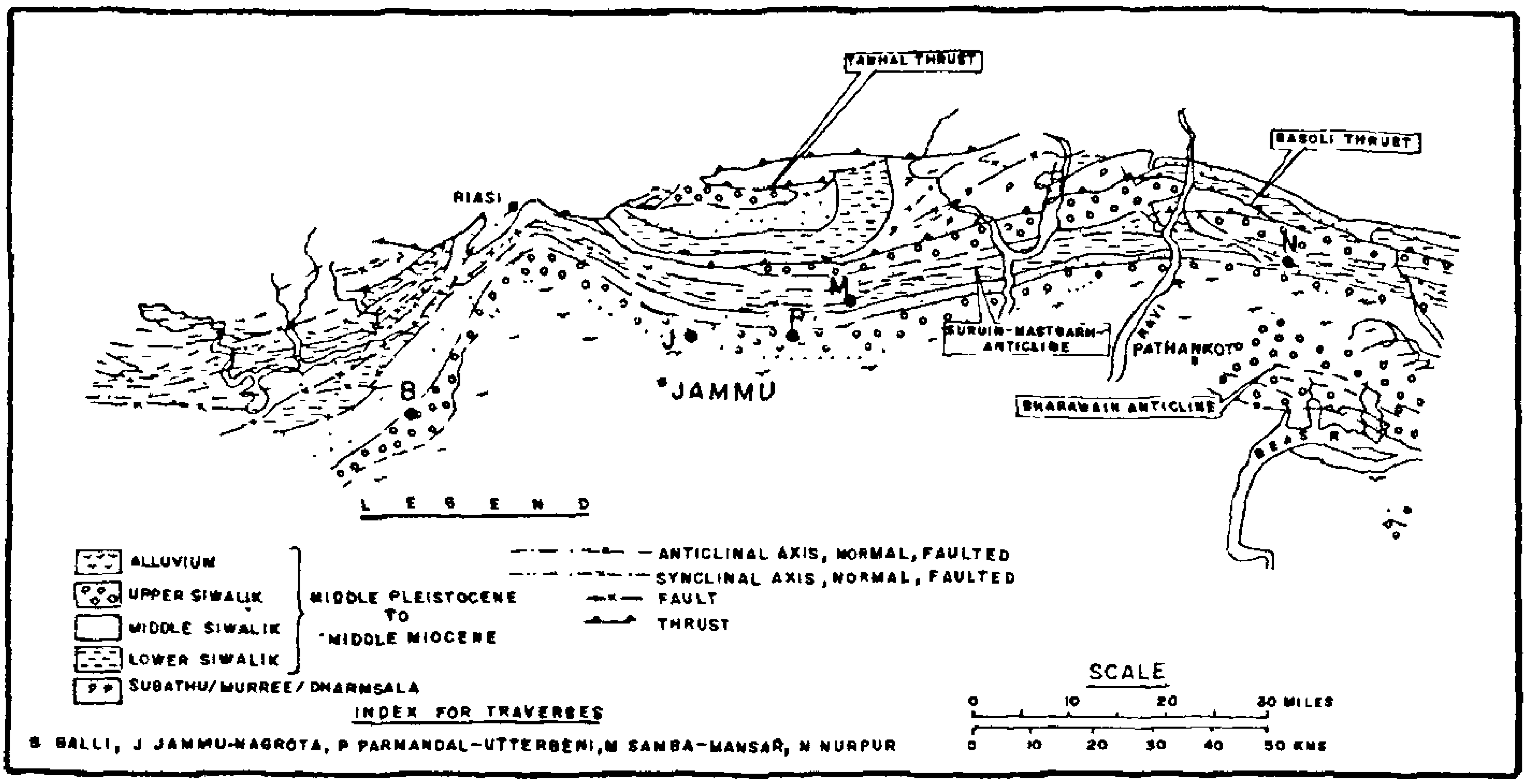

Figure 1. Geological map of a part of north-western Himalayan foothills showing the locations of the sections studied.

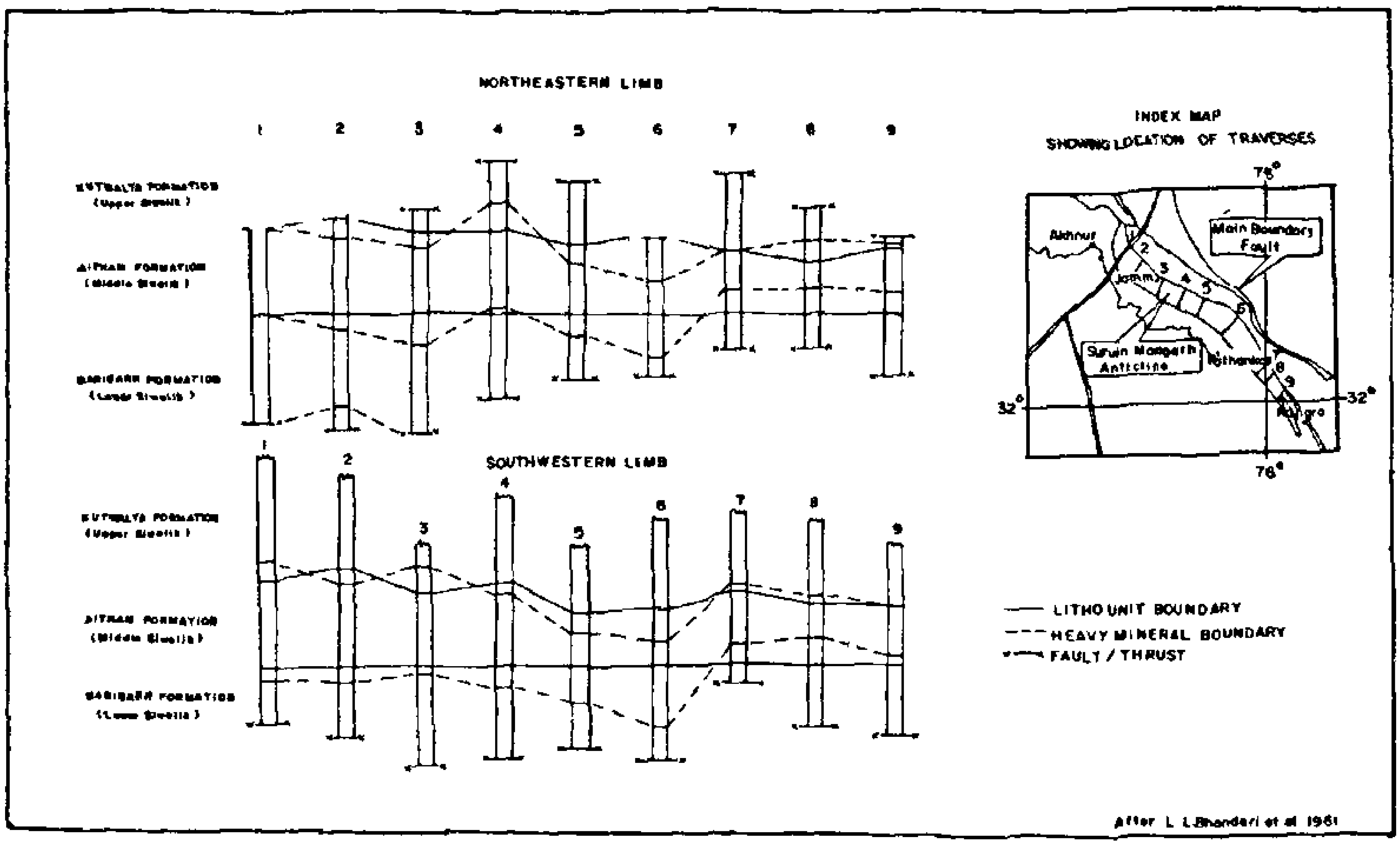

Figure 2. Correlation of the lithological boundaries with the heavy-mineral boundaries in the Siwalik Group.

possible to identify intervals of normal and reversed polarity and to establish a local magnetic polarity stratigraphy (MPS). It signifies a record of changes in the polarity of Earth's magnetic field with time. The local magnetic-polarity stratigraphy can then be correlated with the accepted magnetic polarity time scale (MPTS) applicable worldwide. But additional controls are required to determine which part of the local MPS should be correlated with which part of the MPTS. This is facilitated by the data provided by palaeontology and radiometric dating of suitable lithologies in the section. When all these data are combined, dating of the desired litho- and biostratigraphic intervals in the section would become possible.

ONGC endeavours

In 1979 the ONGC initiated palaeomagnetic studies in the Siwalik sediments of the north-west Himalayan foothills. To date local MPSs were established in seven sections covering the stratigraphical sequence from Upper Murree to Upper Siwalik. In the present paper the magnetostratigraphy of the Upper Siwalik part of the following sections is presented: Balli, Jammu-Nagrota, Parmandal-Utterbeni, Samba-Mansar and Jabbar Khad on the Suruin-Mastgarh-Nurpur anticline (Figure 1). The sixth section is from the Patiali Rao, located southwest of Pinjaur (Figure 3).

Most of the sections yielded vertebrate fauna, characteristic of the Tatrot and Pinjor of the Siwalik Group. In two sections the zircon phenocrysts from a bentonitized tuff horizon could be dated by fission track method. These two constraints permit correlation of the local MPSs with the MPTS. The results show that the Upper Siwalik sediments were deposited in a time span from ca 5.6 to 0.22 m.y.—Late Neogene and Quaternary.

Lithology of Upper Siwalik

The Upper Siwalik was divided by the ONGC into three units solely on the basis of lithologic criteria. The *Parmandal sandstone*, forming the lower part, consists predominantly of multistoreyed sandstone with alternations of subordinate claystone. Several pebble bands containing pebbles of quartzite, vein quartz, trap, sandstone and occasional limestone are common in the sandstone. The *Nagrota Formation*, conformably overlying the Parmandal Sandstone consists of a sequence of pink siltstone-claystone alternations with subordinate earthy sandrock. In the upper part grits and thick conglomerate bands appear, passing gradually into the Boulder Conglomerate. In the middle part are present bands of bentonitized tuff. The upper unit *Boulder Conglomerate*, is composed mainly of conglomerate or boulder beds with pebbles, cobbles and boulders of quartzite, some volcanics, granite, sandstone and rare limestone, loosely cemented by sand. Earthy siltstone and lenticular sand bands are present in the succession.

Magnetic polarity stratigraphy

Samples collected from more than four hundred sites, from the six sections, were subjected to standard treatments in the laboratory[3,4], including thermal demagnetization. The data generated were statistically analysed[5] (Table 1) and graphically represented. The

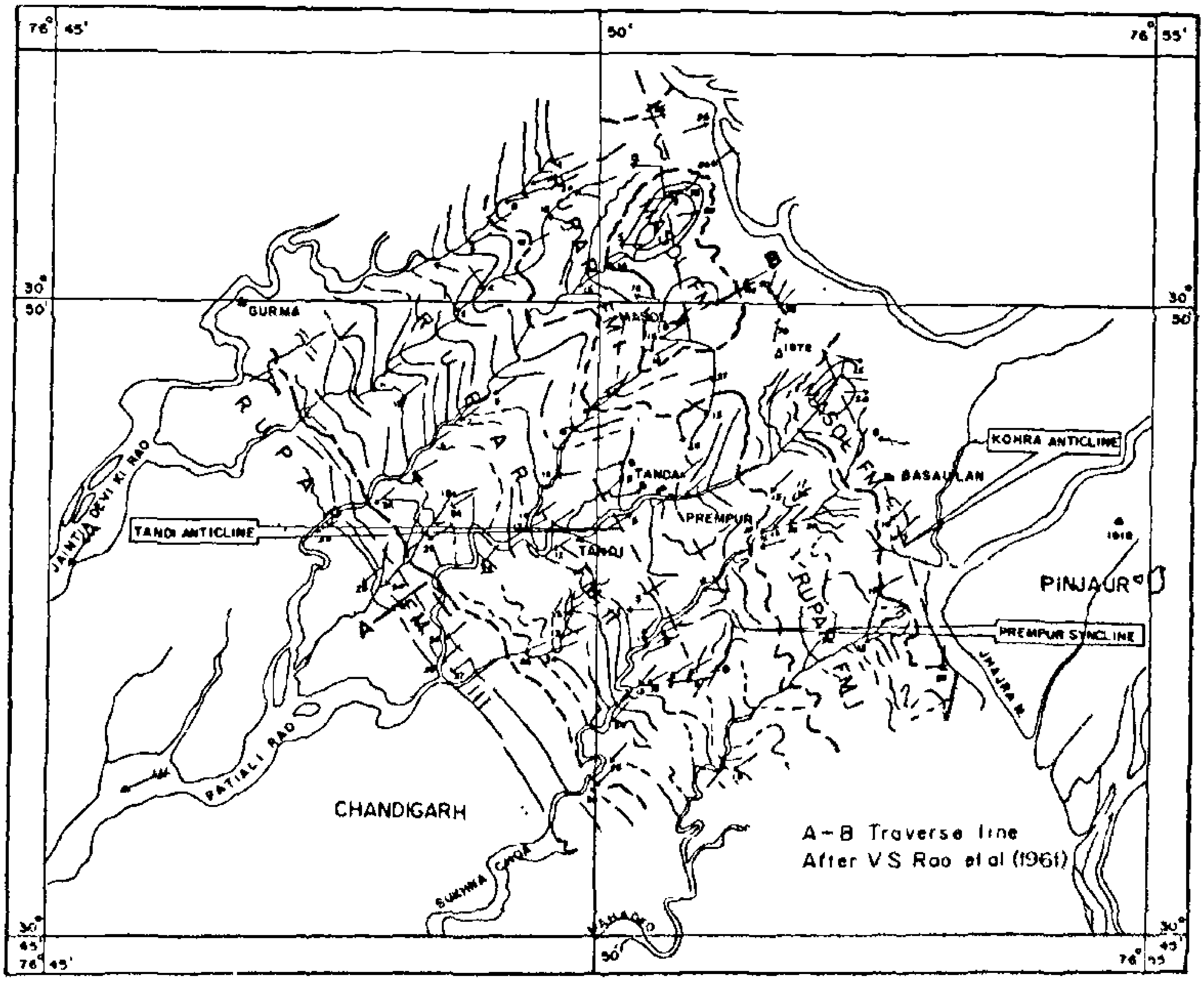

Figure 3. Geological map of a part of the Siwalik Hills near Pinjaur, showing the location of the Patiali Rao

Table 1. Section means for six sections, after bedding tilt correction

Section	Normal sites D	Normal sites I	Reversed sites D	Reversed sites I	Combined sites using antipodes of reversed sites D	Combined sites using antipodes of reversed sites I
Parmandal-Utterbeni	352	+56	175	−35	353.5	45.5
Nagrota-Jammu	343	+39	172	−32	347.5	35.5
Balli	333	+60	178	−38	345.5	49.0
Samba-Mansar	351	+46	169	−30	350.0	37.5
Jabbar Khad	357	+26	167	−45	352.0	35.5
Patiali Rao	352	+45	173	−41	352.5	48.0

magnetic polarity stratigraphy of the six sections (Balli, Jammu-Nagrota, Parmandal-Utterbeni and a part of the Samba sections) is now well established[6,7].

Parmandal–Utterbeni section

The stream section near Parmandal exposes the entire Upper Siwalik rocks notable for their rich vertebrate fauna and a bed of radiometrically datable bentonitized tuff bed. Figure 4 gives the magnetostratigraphy characterized by 17 reversals delineating 15 polarity zones. Each magnetozone is characterized by more than one site except R_6. A notable feature in the section is the presence of a long reversed polarity zone (R_7 and R_8), beginning 15 m below the upper tuff bed. N_7 is a short interval of the normal polarity within this long reversed magnetozone. The beds of this reversed magnetozone yielded characteristic Pinjor fauna, including *Equus*, *Archidiskodon* and *Cervus*.

The zircon phenocrysts from the upper tuff give a fission track age of 2.8 ± 0.56 m.y. This date (with an error envelope of 560,000 years) and the Pinjor fauna above the tuff bed help in identifying this magnetic reversal below the tuff as the magnetic transition between the Gauss normal polarity chron and the Matuyama reversed polarity chron, whose inferred age is 2.47 m.y. (ref. 8). Thus on correlation of the Parmandal MPS with the MPTS, the R_7 and R_8 events identify with the Matuyama reversed polarity chron.

The rest of the Parmandal polarity sequence was dated by extrapolation of sedimentation rates, using the Gauss normal chron boundaries as tie points. The correlation with the MPTS is good, except for the following differences. Against the Gauss there are three reverse polarity magnetozones instead of two in the MPTS. The R_6 (which is based on a single sample) has an estimated age of 2.8 to 2.82 m.y. and is thus too young to correlate with the Kaena reverse subchron. Its validity is therefore questionable.

In the Gilbert Chron there are only two normal polarity magnetozones against four identified in other sections described here as well as in the standard polarity time scale. This may be due to the fact that the section below 152 m falls in the Parmandal Sandstone and is represented by thick multistoreyed sandstone beds which were not sampled. The sampling interval was large and events may have been missed.

Above the Gauss normal polarity chron the two normal magnetozones, the N_8 and N_7 would have estimated ages of 0.87 to 0.94 m.y. and 1.63 to 1.83 m.y., respectively. These ages are close to the suggested ages for Jaramillo and Olduvai normal subchrons of the Matuyama reversed chron[8,9] and may well correlate with them.

The magnetochronology obtained from the MPS of the Parmandal section gives the age of the Upper Siwalik ranging from 4.92 m.y. to 0.42 m.y.—the Parmandal Sandstone 4.92 to 3.90 m.y. and the Nagrota Formation 3.90 to 0.6 m.y.

Jammu–Nagrota section

Only the Nagrota and Boulder Conglomerate formations were sampled. Figure 5 shows the VGP-latitudes plotted against the lithological column. Fourteen polarity changes delimit thirteen magnetozones. The upper bentonitized tuff bed encountered in the Parmandal section extends into this section close to the N_6/R_6 transition. The fission track age of the zircon phenocrysts in the tuff is 2.31 ± 0.54 m.y. (ref. 7). Since this date is not statistically different from that of the Parmandal tuff, the N_6/R_6 magnetic transition can safely be correlated with the Gauss/Matuyama polarity transition and the normal magnetozone recorded within the Matuyama to the Olduvai normal subchron. The Jaramillo subchron has not been recorded here, probably due to the presence of thick conglomerate beds which were not sampled.

The youngest normal magnetozone (N_3) is too young (estimated age 3.48 to 3.6 m.y.) to be correlated with the Cochiti normal subchron within the Gilbert chron. It is not included in the accepted magnetic polarity time scale[10]. The N_2 event (with an estimated age of 3.86 to 3.95 m.y.) is close to the Cochiti normal subchorn, while the N_1 one (with an estimated age of 4.12 m.y.) possibly represented the Nunivak normal subchron of the Gilbert chron. On the basis of these given correlations, the Nagrota Formation is dated 4.49 to 1.68 m.y., while

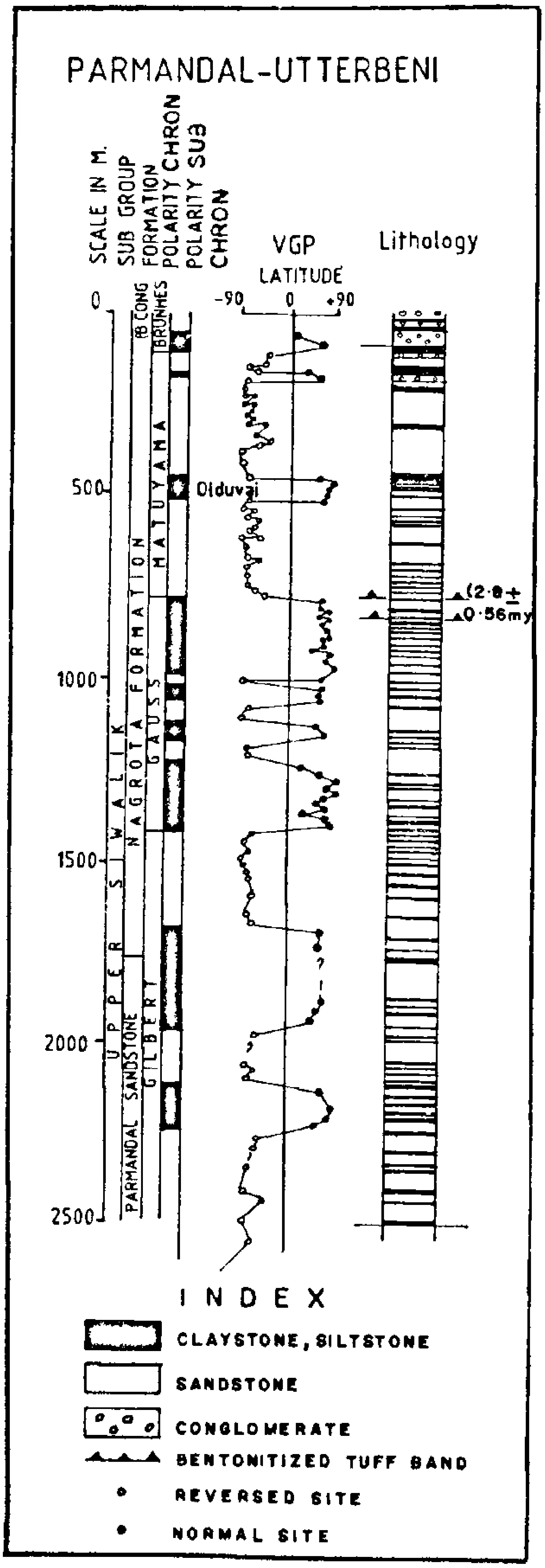

Figure 4. Plot of the VGP latitudes against the lithological column of the Upper Siwalik of the Parmandal-Utterbeni section.

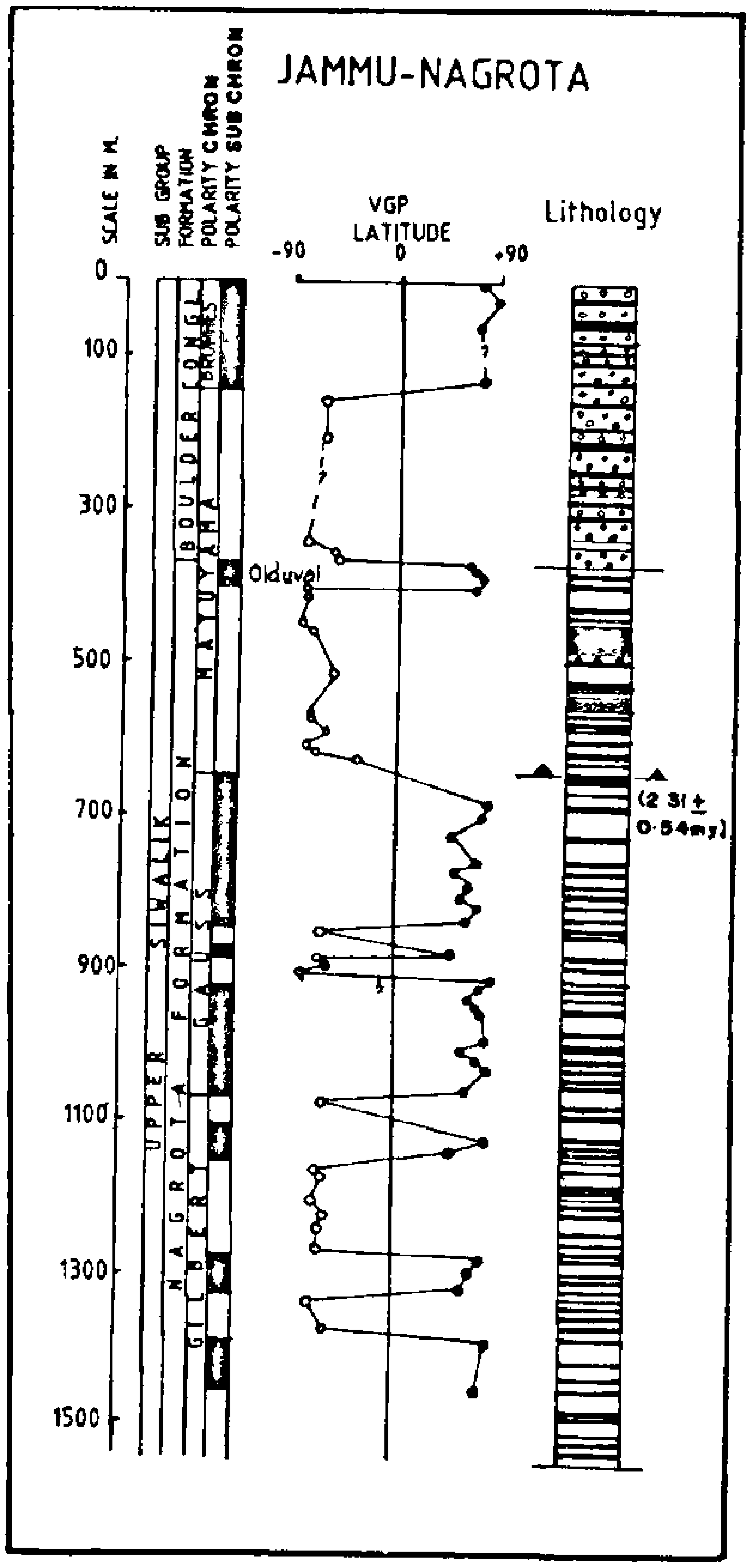

Figure 5. Plot of the VGP latitudes against the lithological column of a part of the Upper Siwalik in the Jammu–Nagrota section.

the sampled part of the Boulder Conglomerate can be assigned an age ranging from 1.68 to 0.22 m.y.

Balli section

Close to the border with Pakistan near the village of Balli, the Nagrota Formation is a fine-grained facies, with bentonitized tuff occurring within the sequence. Figure 6 represents the magnetic polarity stratigraphy. There is only one polarity transition (N_1/R_1). Just above the tuff, in a similar stratigraphic position as in Jammu, Parmandal and Samba sections, *Archidiskodon* sp. a characteristic Pinjor form is found. The magnetic transition (N_1-R_1) can be correlated with the Gauss-Matuyama boundary.

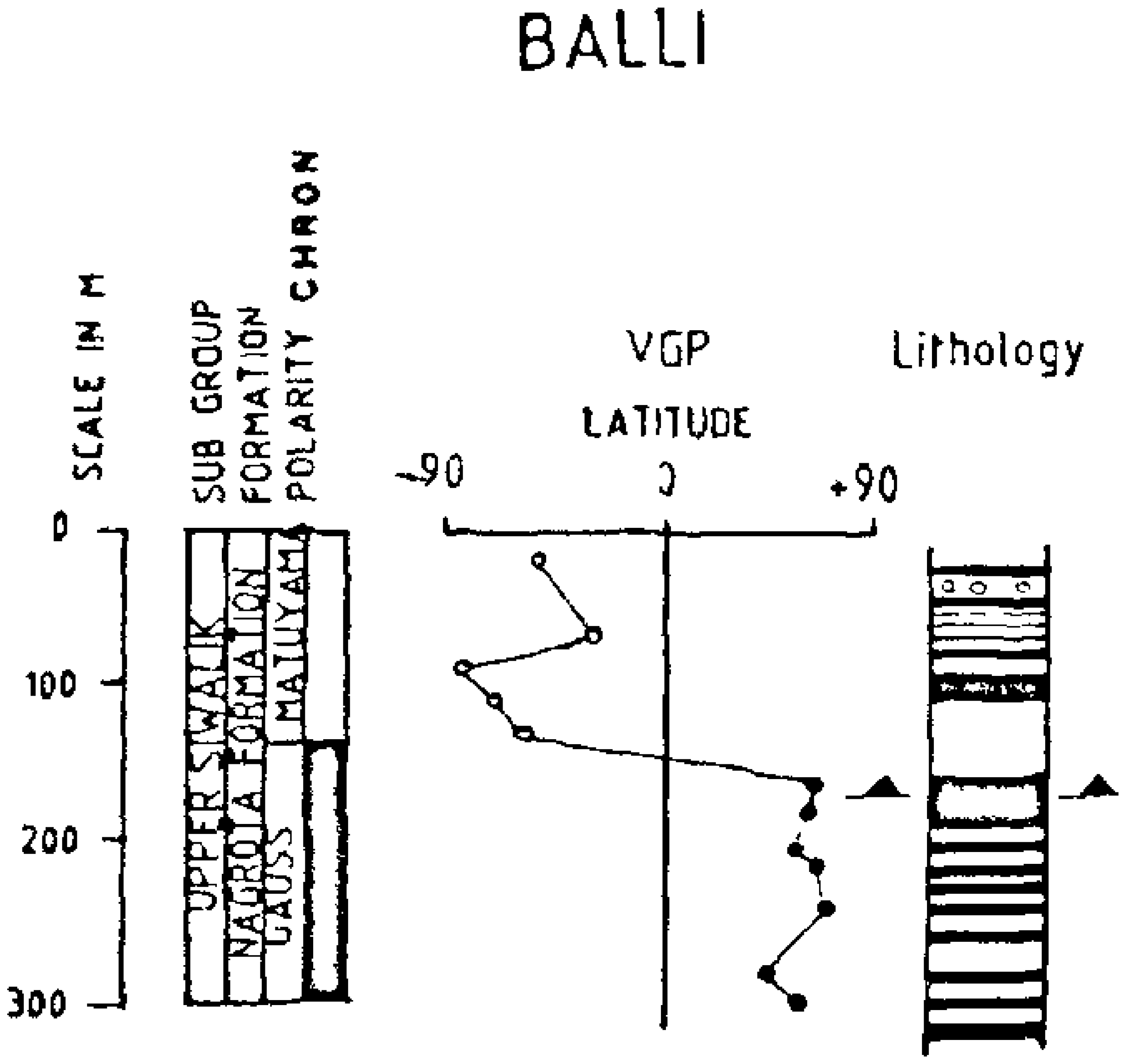

Figure 6. Plot of the VGP latitudes against the lithological column of a part of the Upper Siwalik section near Balli.

Samba–Mansar section

The entire sequence from Lower to Upper Siwalik is exposed in this section; the Upper Siwalik measuring 2393 m and containing a horizon of tuff. Figure 7 shows the magnetic polarity stratigraphy. The Middle Siwalik part is added here, as it records a long normal magnetozone (N_1) opposite the Lower-Middle Siwalik boundary. In the Potwar region in Pakistan a similar long normal magnetozone was recorded in the Nagri Formation which, on the basis of a radiometric date and vertebrate fauna, is correlated to Chron 9 of the MPTS[11] and dated 8.6–10.0 m.y.

In the Samba section the presence of a three-toed horse *Hipparion* among the vertebrate fauna opposite the long normal magnetozone (N_1) allows to correlate it with Chron 9. On the basis of Chron 2–3 boundary at the top and the top of Chron 9 at the lower part of the column, the MPS of Samba has been correlated with the MPTS. A good correlation exists except at Samba, Chron 6 of a dominantly reverse polarity has not been recorded. This position falls at the Middle-Upper Siwalik boundary across which a conspicuous dip discordance occurs. The Middle Siwalik beds show regionally consistent dips of 60° or more while in the Upper Siwalik the dip does not exceed 25° to 30°. These data are indicative of a phase of pre-Upper Siwalik folding and a break in sedimentation. The duration of the missing section computed from the rate of sedimentation is about 0.82 m.y., between 6.50 and 5.68 m.y.

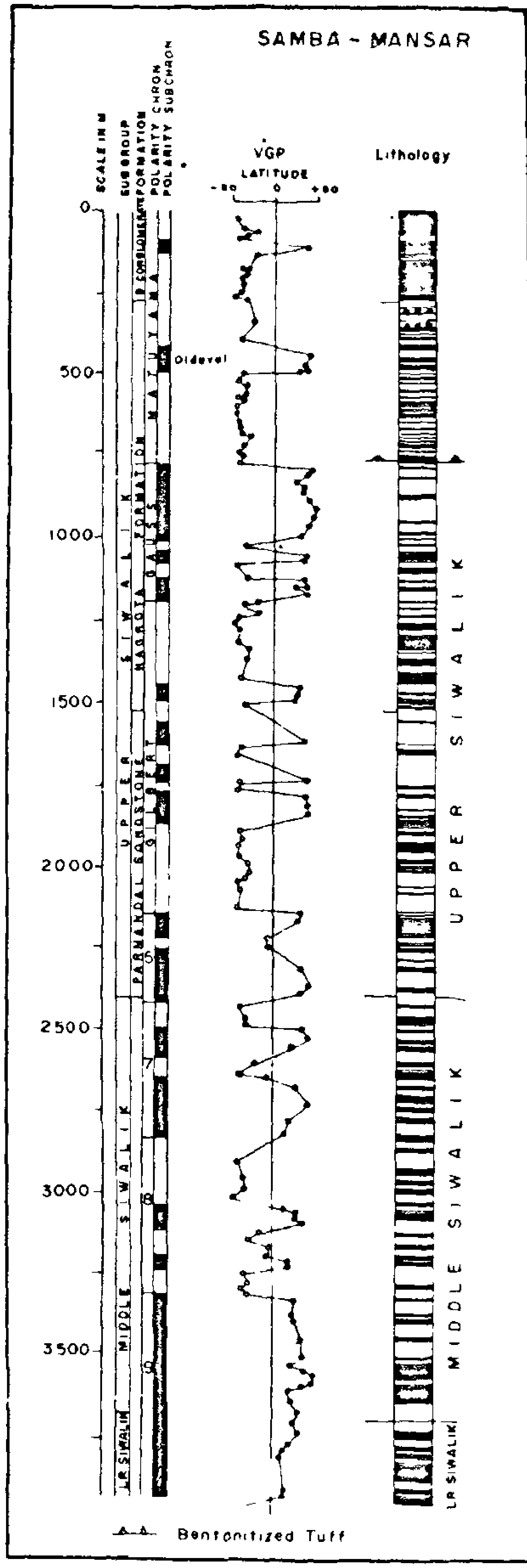

Figure 7. Plot of the VGP latitudes against the lithological column of the Upper and Middle Siwalik of the Samba–Mansar section.

Jabbar Khad, near Nurpur

This section is along the north-eastern flank of the Nurpur anticline which is the south-easterly continuation of the Suruir-Mastgarh anticline. There is a considerable facies change from arenaceous in the south-western side to a argillaceous on the north-eastern flank of the anticline, so that a typical Upper Siwalik lithology (the Parmandal Sandstone and Nagrota Formation) is not discerned in the Jabbar Khad section. Because of this change, the ONGC maps show the Upper Siwalik of the Nurpur locality as consisting of a Lower Conglomerate-Sandstone unit and an upper Massive Boulder Bed unit, the two being separated by an unconformity indicated by dip discordance. Since no diagnostic Upper Siwalik vertebrate fossils are found nor is there any ash bed, it is necessary to incorporate the magnetic data obtained from the underlying Middle Siwalik, which yielded a rich assemblage of vertebrates.

Magnetic polarity zonation

Figure 8 shows the plot of the VGP latitudes against the stratigraphic position of the sampled sites. Twentytwo reversals of magnetic field delineate 20 polarity zones. Excepting the two magnetozones R_6 and R_{11}, every magnetozone is defined by more than one site. For the correlation of the MPS to MPTS to be unequivocal controls from the Middle Siwalik vertebrate fauna were utilized. The most common vertebrate form is *Hipparion*, very characteristic of Middle Siwalik (Nagri and Dhok Pathan faunal zones). Its first appearance in the Jabbar Khad section is at the level 270 m above the base of the exposed section, opposite the lower part of the reversed magnetozone R_2. In the Potwar Siwalik the hipparionine horses first appear in the middle part of the Nagri Formation at about 9.5 m.y. (ref. 12).

Data from the Jabbar Khad section do not indicate long normal polarity magnetozone (correlated to chron 9 of the MPTS) usually found associated with the lower half of the Middle Siwalik. Chron 9 is dated at 8.6–10.0 m.y. The Jabbar Khad section therefore should be considered younger than 8.6 m.y.

The above mentioned constraints help in correlation of the MPS to the MPTS (Figure 9). The magnetic reversal pattern of the Jabbar Khad can be readily matched with the interval from the middle part of Chron 8 to the upper part of the Chron 3 of the MPTS, so that they have an estimated age between 8.14 and 2.5 m.y. The lower Conglomerate-Sandstone unit mapped by ONGC can thus be dated 5.26 to 2.51 m.y.

The correlation of the overlying Massive Boulder Bed unit is not known on the basis of the available data. However, near Kotla, about 20 km along the

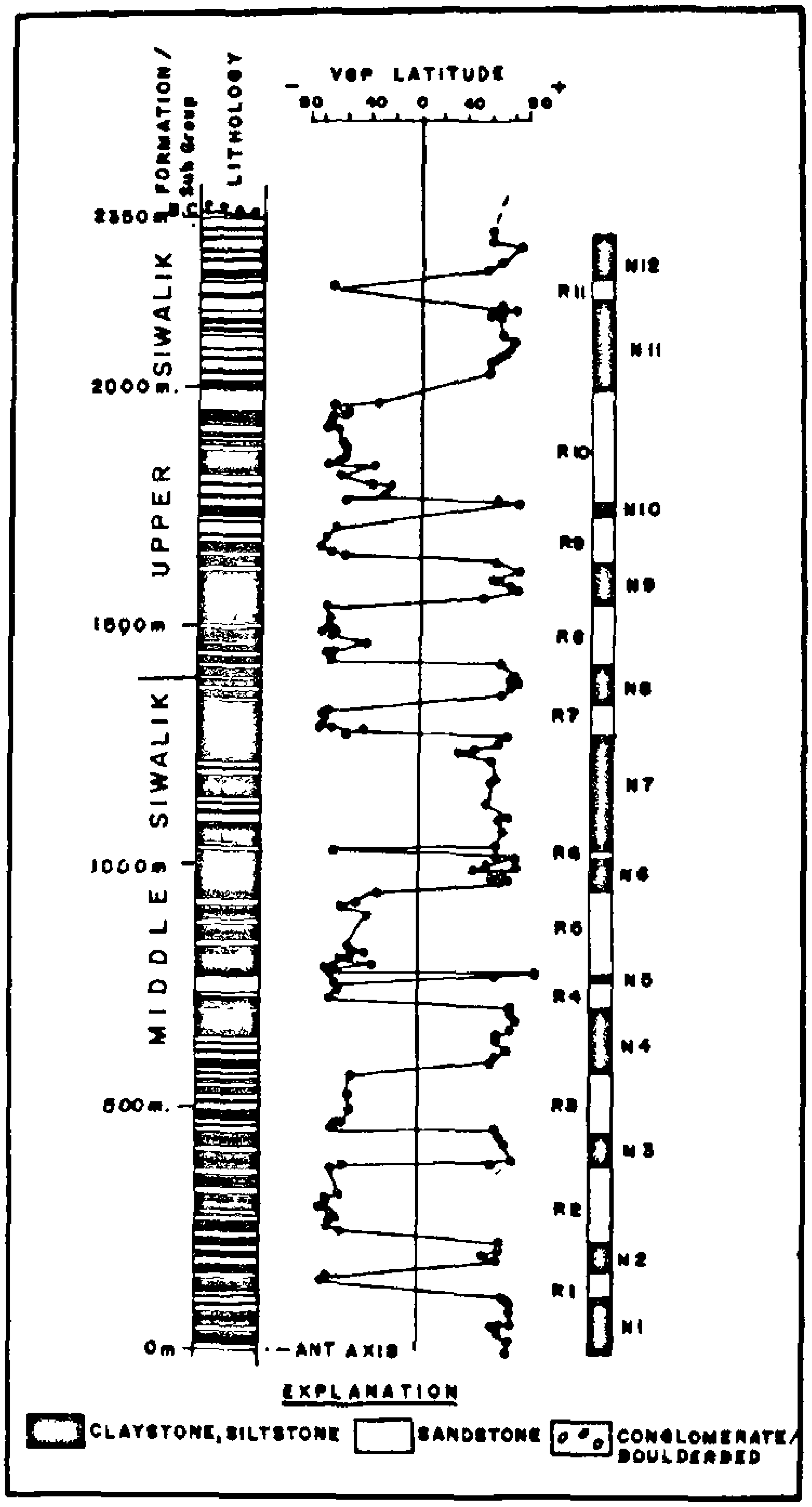

Figure 8. Mangetic polarity stratigraphy of the Jabbar Khad section near Nurpur. Boulder Conglomerate was not sampled. B. C., Boulder Conglomerate; Ant. Axis., Anticlinal axis.

strike from Jabbar Khad typical Boulder Conglomerate sequence crops out. Comparing the lithologies of the two sequences it seems that the Massive Boulder Bed unit of the Jabbar Khad is younger than the Boulder Conglomerate of the Upper Siwalik.

Patiali Rao stratigraphy

The Patiali Rao stream section, southwest of Pinjaur, is the type locality for the Pinjor faunal zone[1]. The ONGC has subdivided the sequence on lithological basis into the Masol Formation (alternation of

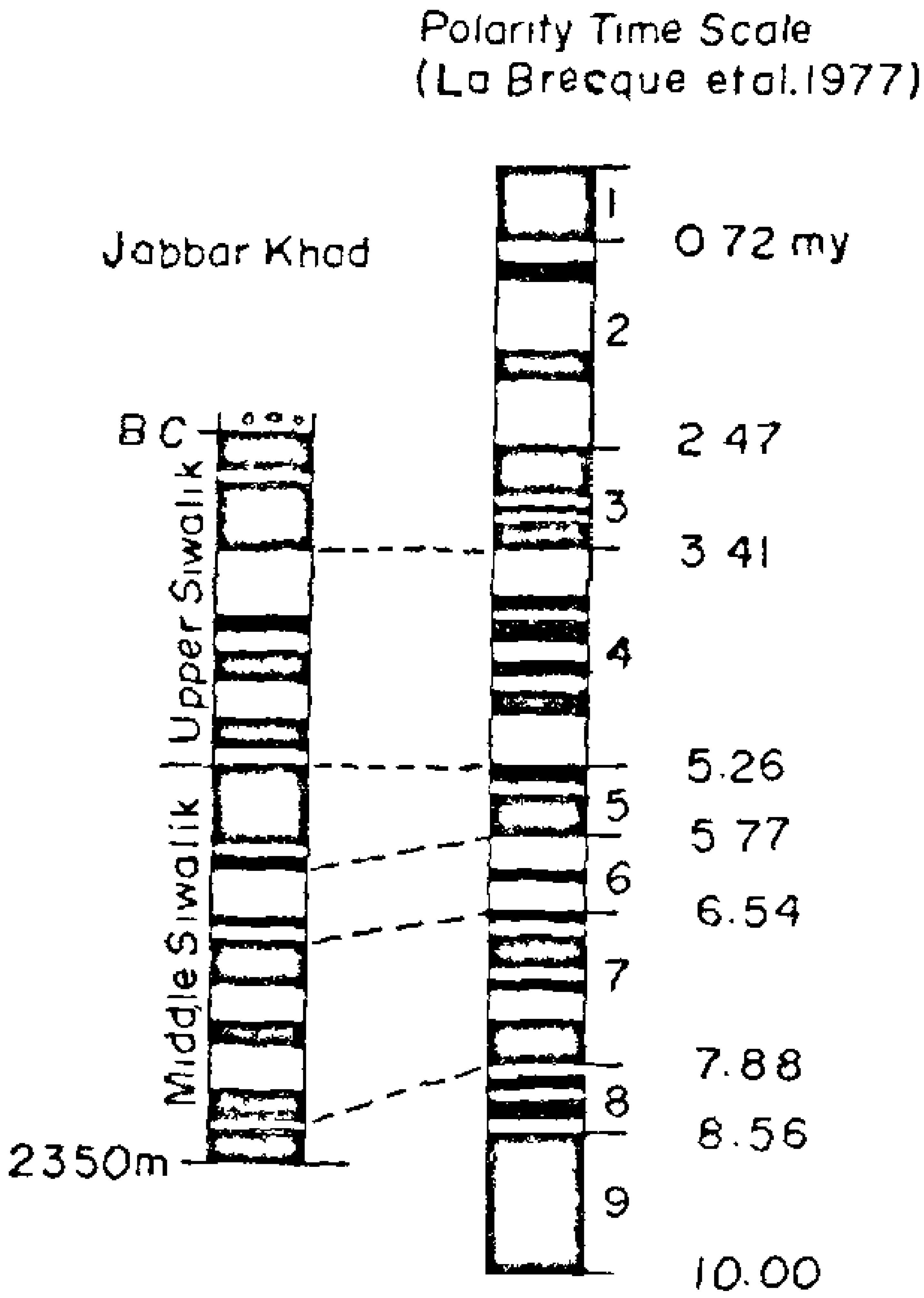

Figure 9. Correlation of the Jabbar Khad magnetic polarity stratigraphy with the La Brecque *et al.*[10] polarity time scale.

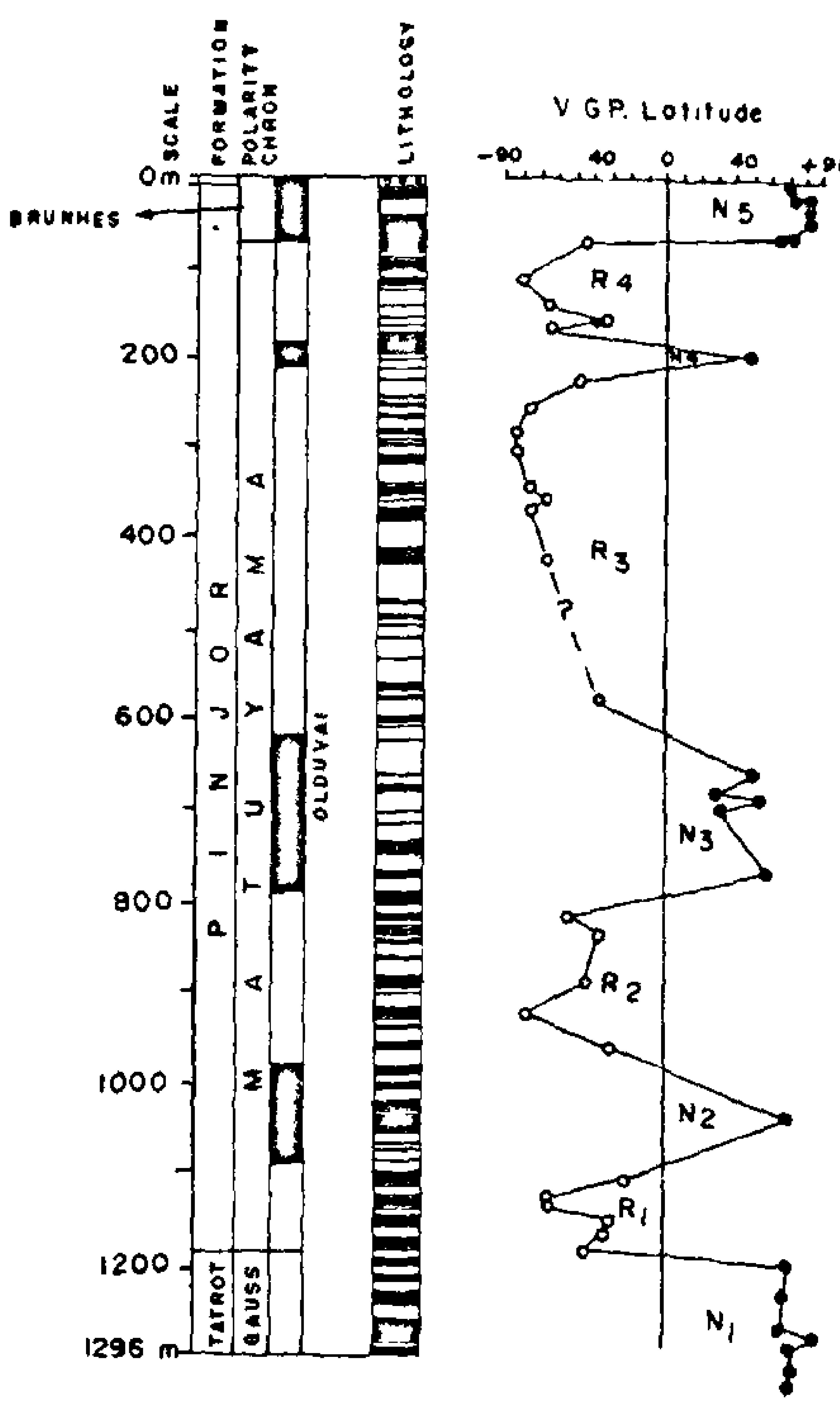

Figure 10. Plot of the VGP latitudes against the lithological column for the Patiali Rao section.

sandstones and claystone), four conglomeratic units Rupar I, II, III and Rupar IV. On faunal evidence, the Masol Formation was correlated with the Tatrot, the Rupar I, II and III with the Pinjor faunal zones, and the conglomerates of Rupar IV with the Boulder Conglomerate. Dividing the sequence into three formations on palaeontological criteria, Sahni and Khan[13] identified a 50-m thick section called Quranwala zone towards the top of Tatrot Formation, characterized by rich vertebrate fossils[14]. The Quranwala zone represents the zone of faunal transition. This is unlike in other localities (Nagrota and Parmandal) where the characteristic taxa of Tatrot such as *Hipparion* is replaced rather abruptly by younger Pinjor fauna like *Equus*, *Cervus* and *Archidiskodon*.

Figure 10 shows the plot of VGP latitudes against the 32 sampled sites. Eight magnetic reversals define three normal and four reversed magnetozones. At the N_1-R_1 boundary the presence of *Archidiskodon planifrons*, *Cervus* (antlers) and *Leptobos* sp.—the characteristic Pinjor fauna—correlate with the Gauss-Matuyama transition in Nagrota and Parmandal sections. Below this level, opposite N_1 magnetozone, *Stegodon* sp. together with *Hipparion* sp. and *Hemibos* sp.[13], the characteristic Tatrot fauna occur. The N_1-R_1 magnetic transition can safely be correlated with the Gauss-Matuyama magnetic polarity transition, and the R_4-N_5 boundary with the Matuyama-Brunhes transition dated 0.73 m.y. Opposite this time interval the section measures 1218 m, yielding an average sedimentation rate of 0.63 m/1000 yr. On the basis of this sedimentation rate, the normal magnetozones N_2 and N_4 would have estimated ages of 2.1 m.y. and 1.0 m.y. These ages are very close to the ages for the Reunion and the Jaramillo normal subchrons of the Matuyama reversed chron and may well correlate with them. The *middle normal magnetozone* N_3 *would* represent the Olduvai normal subchron of 1.86 to 1.67 m.y. range in the MPTS. The Reunion normal subchron has not so far been recorded in any of the studied sections excepting this one of the Patiala Rao valley.

It is therefore concluded that the Pinjor faunal zone of the type area falls opposite the whole Matuyama reversed chron and lower part of the Brunhes normal chron, the time span ranging from 2.47 m.y. to 0.63 m.y. (Figure 11).

Discussion

Siwalik formational boundaries

Many workers believe that formational boundaries drawn on the basis of lithology in the Siwalik are time parallel. The age assignments made possible now to these boundaries by the magnetochronology show that this assumption is not true.

The calibration of MPSs to MPTS dates the Middle-Upper Siwalik Subgroup boundary in the Parmandal section at 4.92 m.y., in the Samba section at 5.68 m.y. and in the Jabbar Khad at 5.26 m.y. Similarly, the Parmandal-Nagrota formational boundary in the Parmandal section can be dated at 3.90 m.y. while in the Nagrota section at 4.49 m.y. These data show the diachronous nature of the lithofacies boundaries.

To the extent that the individual magnetozone boundaries in MPSs represent calibrated time lines, these boundaries would represent isochronous horizons but isochronous only[15] on a scale of 10^3 years because of the inherent inaccuracy in precisely locating the boundary between the adjacent magnetozones, caused by the finite time of the occurrence of magnetic field transition.

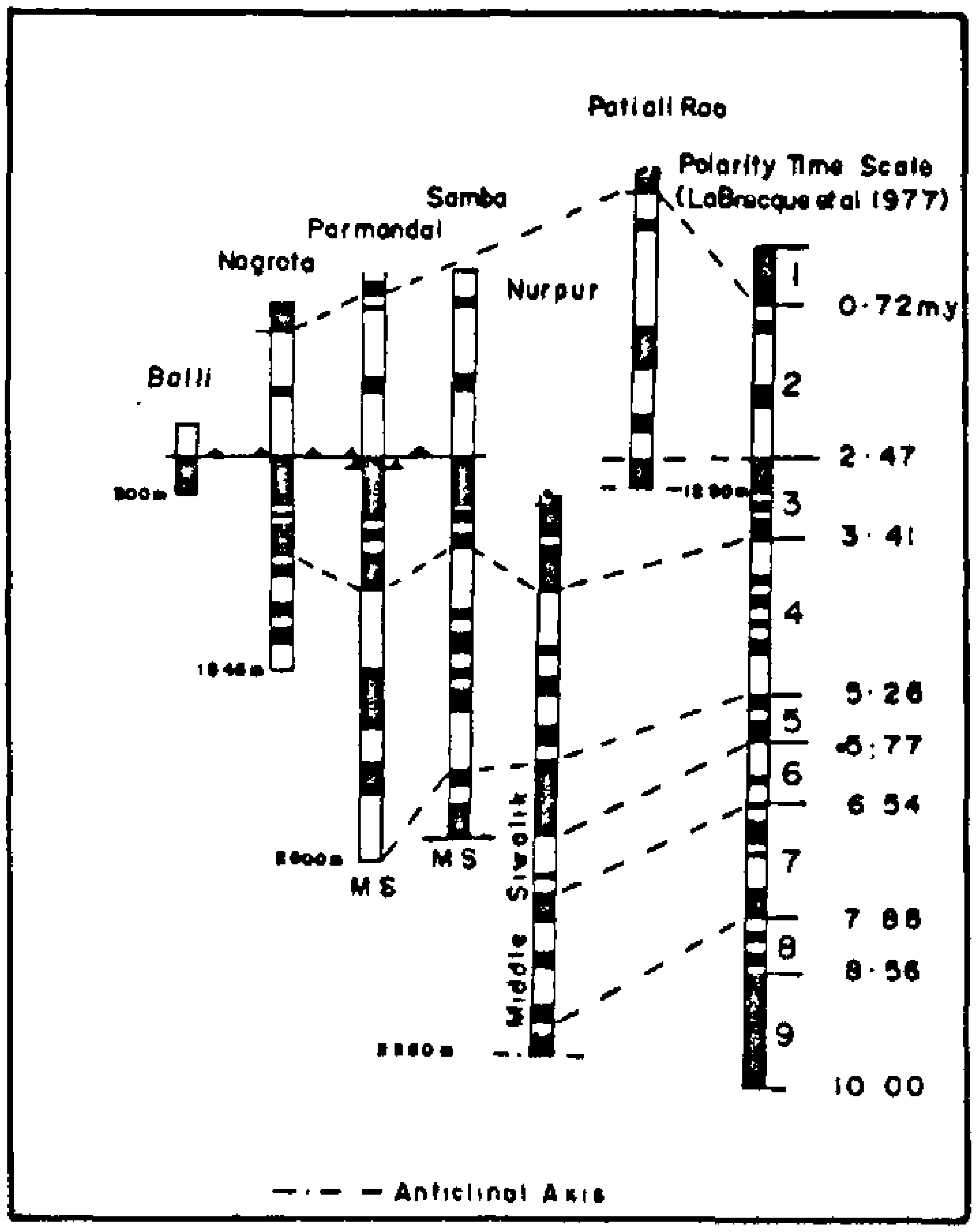

Figure 11. Correlation of the Six Local MPSs with the Brecque *et al.*[10] magnetic polarity time scale. M. S., Middle Siwalik.

In the examples cited above the deviation in time for the lithological unit boundaries from section to section is much larger than this limiting condition. If only the age of the Middle-Upper Siwalik boundary is considered the deviation is about 0.7 m.y. between the Parmandal and the Samba and about 0.3 m.y. between the Parmandal and the Jabbar Khad section. It is even larger, in excess of 2 m.y. if the Lower-Middle Siwalik boundary in the Jabbar Khad is considered. The basal section of 270 m of red beds was mapped by ONGC as Lower Siwalik. However, in the MPS, the upper boundary of the mapped Lower Siwalik falls above the Chron 8–7 magnetic polarity transition, dated at 7.88 m.y. (ref. 7). The oldest outcropping bed in the Jabbar Khad is at the level of 8.14 m.y.

In the stratotype localities of Chinji and Nagri in the Potwar Plateau, the Chinji and Nagri Formations have nominal age ranges of 13.1–10.1 m.y. and 10.1–7.9 m.y.[10,11]. The Nagri faunal zone of Pilgrim[1,2], now named *Hipparion s. L*[16] biostratigraphic interval zone, is estimated to range from 9.5 to 7.4 m.y. The so-called Lower Siwalik in the Jabbar Khad, with an estimated age of about 8.1 m.y. and younger, should therefore be equated with the upper part of the Nagri and the basal part of the Dhok Pathan biostratigraphic zones. Palaeontological evidence supports this deduction.

The lithofacies variations are to be expected, in sediments deposited in the fluvial systems of laterally migrating streams on their floodplains. At any given time on the Siwalik palaeolandscape, the existence of a mosaic of environments consisting of river-channels and floodplains is entirely expected.

The lateral facies variation in the Middle Siwalik from the dominantly arenaceous at Samba (represented by multistoreyed sandstones) to dominantly argillaceous at Nurpur (represented by siltstone-claystone) can be related to streams depositing sediments in the Samba area and development of floodplains in the Nurpur area on which finer overbank sediments were deposited.

Lower boundary of the Boulder Conglomerate

It is generally believed that the first appearance of thick conglomerate beds in the Siwalik succession marks the beginning of the Boulder Conglomerate. Stratigraphic sections measured at different localities show that this is a mistaken notion. The chronometric data of the three MPSs of the Nagrota, Parmandal and Samba, falling in a 40 km strike belt, document the diachronous nature of this boundary. At Parmandal it falls in the lower part of Brunhes normal chron dated at 0.6 m.y. while at Nagrota located 20 km away along the strike the conglomeratic facies appear 1.66 m.y. older than that at

Parmandal. In Samba about 20 km southeast of Parmandal, the same boundary is estimated at 1.32 m.y. (Figure 12).

In contrast, in the Jabbar Khad the 'Massive Boulder Beds' correlated by the ONGC with the Boulder Conglomerate lie with a distinct unconformity over the older stratigraphic horizons of the Upper Siwalik dated at 2.5 m.y.

In all these localities the pebble composition of the conglomeratic facies is indicative of deposition by Himalayan rivers.

It may be concluded that the deposition of the very coarse sediments of the Boulder Conglomerate does not represent a response to a synchronous orogenic event in the Himalayan source area. Instead, the spatial distribution of conglomerate facies may be related to the foreland-directed advance of the Himalayan thrust sheets, and the controls in deposition exerted by the ancestral fluvial systems. In the case of Nagrota and its adjacent areas the deposition was by the ancestral *Chenab River system*.

The Patiali Rao section represents the present southern limit of the deformation of the foredeep sediment—30 km south of the Suruin-Nurpur structural trend. The deposition of the conglomeratic facies in this locality began 0.62 m.y. ago relatively later than in the northern localities of the foredeep (Nurpur, Samba). The dominant constituents of the conglomerate at Patiali Rao are pebbles of sandstone derived from the older foredeep sediments (Dagshai-Kasauli Formations) which presently crop out at the northern periphery of the foredeep. In the evolution of foreland basins, structural developments in the evolving orogens cause progressive shift of the depositional centres towards the foreland[16,17]. In the Himalayan foredeep ONGC borehole data indicate that the foredeep migrated onto the Indian craton at a rate of 10–15 mm/yr, and the Siwalik sediments became younger towards south overstepping the older Siwalik strata.

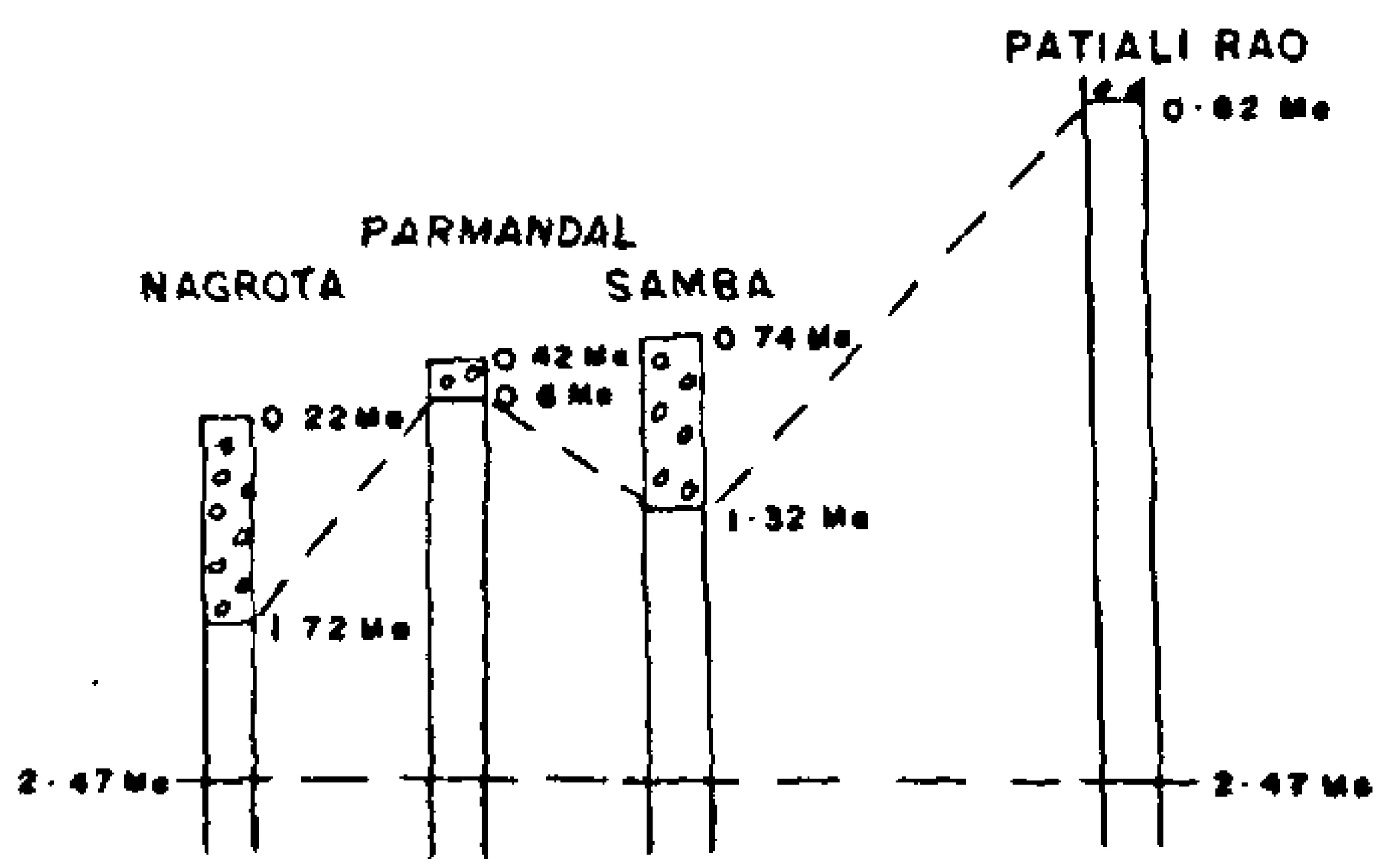

Figure 12. Lower boundary of the Boulder Conglomerate to illustrate the diachronous nature of the conglomeratic facies in the upper part of the Upper Siwalik.

Sedimentation rate

In the area of Suriun-Mastgarh anticline, which lies in the northern part of the foredeep, the MPSs data register (Figure 13) the decreased rate of sedimentation from the Gilbert to Matuyama chron indicate continuing uplift of the structure. The uplift began about 6.0 m.y. ago (reference to the Middle-Upper Siwalik unconformity at Samba). For the same interval (i.e. Matuyama chron), the data indicate an accelerated sedimentation rate (63 cm/1000 yr) in the Patiali Rao region, suggesting southerly shift of the depositional centre during the Matuyama chron.

This foreland-directed shift of depocentres should be attributed to the southerly migration of the Himalayan thrust system which progressively uplifted the proximal foredeep sediments, thus incorporating them in the thrust system. The older foredeep sediments contributed to the younger sediments.

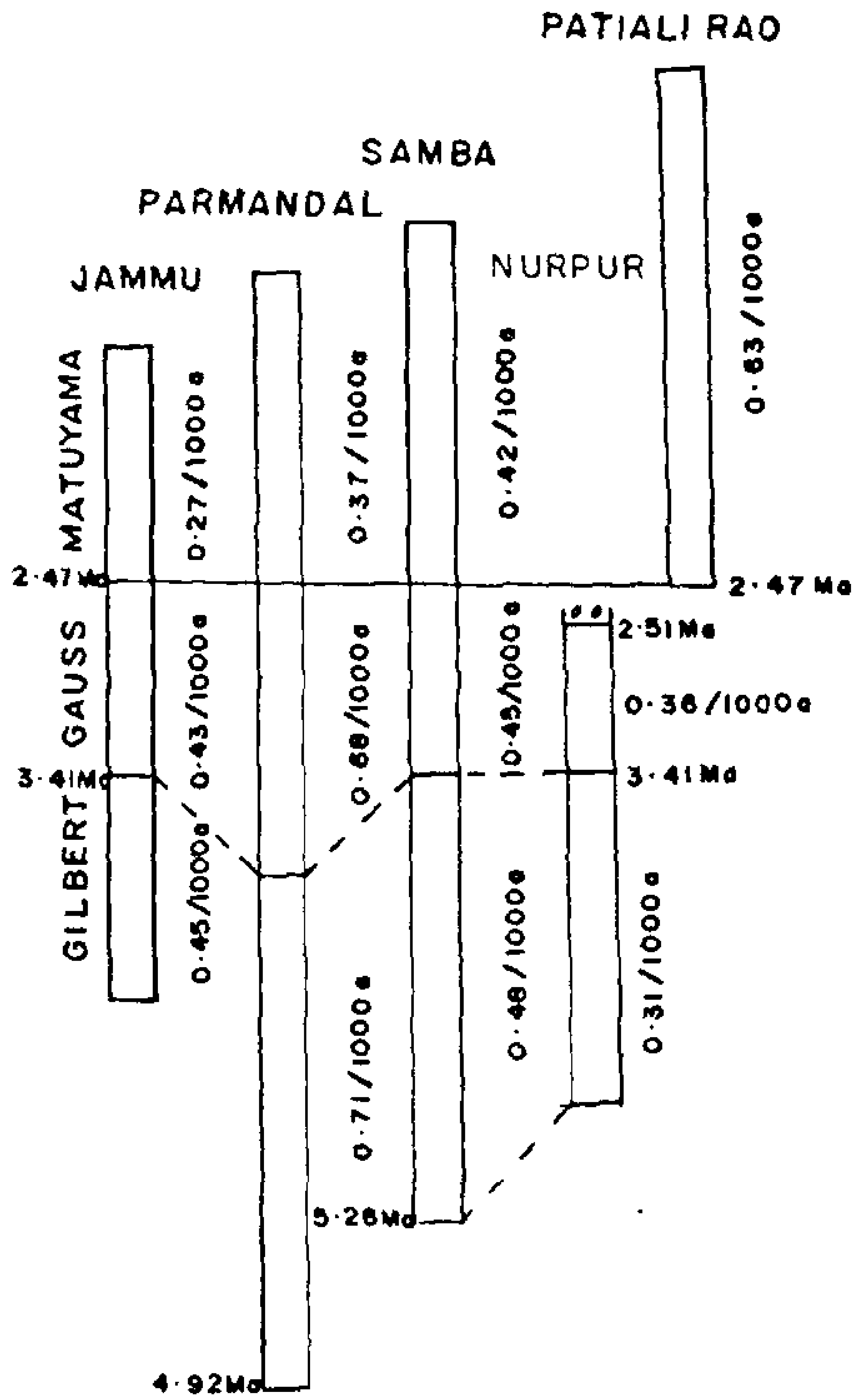

Figure 13. Rates of sedimentation (in m/1000 yr) in the studied sections for three magnetic polarity chrons from a part of the Gilbert to Matuyama, covering the time span from 5.26 to 0.73 m.y.

The sandstone pebbles derived from the Dagshai-Kasauli start appearing in the Tatrot Formation of Patiali Rao (dated about 2.5 m.y.), increasing in number upwards and attaining dominance in the Boulder Conglomerate (dated approximately 0.6 m.y.). The deposition of the Boulder Conglomerate in this region was accomplished mainly by the foredeep-fed fluvial system.

1. Pilgrim, G. E., *Rec. Geol. Surv. India*, 1910, **40**, 185–205.
2. Pilgrim, G E., *Rec. Geol. Surv. India*, 1913, **43**, 264–326.
3. Irving, E. and Opdyke, N. D., *Geophys. J R. Astron. Soc.*, 1965, **9**, 153–167
4. Opdyke, N. D., *et al.*, *Palaeogeogr., Palaeoclimatol., Palaeoecol*, 1979, **27**, 1–34.
5. Fisher, R. A., *Proc. R. Soc. London*, 1953, **A217**, 295–305. 1979, **27**, 1–34.
6. Ranga Rao, A, *Bull. ONGC*, 1986, **23**, 109–128.
7. Ranga Rao, A., Agarwal, R. P., Sharma, U. N., Bhalla, M. S. and Nanda, A. C., *J. Geol. Soc. India*, 1988, **31**, 361–385.
8. Mankinen, E. A. and Dalrymple, G. D., *J. Geophys. Res.*, 1979, **84**, 615–626.
9. Haq, B. U., Berggren, W. A. and Van Couvering, J. A., *Nature*, 1977, **269**, 483–487.
10. La Brecque, J. L., Kent, D. V. and Cande, S. C., *Geology*, 1977, **5**, 330–335.
11. Johnson, N M., Opdyke, N. D., Johnson, G. D., Lindsay, E. H. and Tahirkheli, R. A. K., *Palaeogeogr., Palaeoclimatol, Palaeoecol*, 1982, **37**, 17–42.
12. Barry, J. C., Lindsay, E. H and Jacobs, L. L., *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 1982, **37**, 95–130.
13. Sahni, M. R. and Khan, E., *J. Palaeontol., Soc. India*, 1959, **4**, 61–74.
14. Nanda, A. C., *Abstract–XI INQUA Congress*, Moscow, 1982, vol. 2, p. 210.
15. Tauxe, L. and Opdyke, N. D., *Palaeogeogr., Palaeoclimatol., Palaeoecol.*, 1982, **37**, 43–61.
16. Bally, A. W., Gordy, P. D. and Stewart, R. M, *Bull. Can. Petrol. Geol.*, 1966, **44**, 337–81.
17. Jordan, T. E., *Am. Ass. Petrol. Geol.*, 1981, **65**, 2506–2520.

ACKNOWLEDGEMENTS Excepting the Jabbar Khad section, the present work was carried out by a team of the ONGC consisting of A. Ranga Rao, R. P. Agarwal and U. N. Sharma in a time span of three years from 1979 to 1981. The Jabbar Khad section was studied in 1991 under colloborative project of an ONGC and Wadia Institute of Himalayan Geology by a group consisting of A. Ranga Rao, G. S. Mehra and M. Venkateswarlu. All samples were analysed in the palaeomagnetic laboratory of the NGRI (Hyderabad) with the kind assistance of M. S. Bhalla. The vertebrate fauna were identified by A. C. Nanda of Wadia Institute of Himalayan Geology, Dehradun.

The author thanks the Director, Keshava Dev Malaviya Institute of Petroleum Exploration, ONGC, for permission to publish this paper and the Director, Wadia Institute of Himalayan Geology for providing working facilities.

Uplift and geomorphic rejuvenation of the Himalaya in the Quaternary period

K. S. Valdiya

Department of Geology, Kumaun University, Nainital 263 002, India

Until Neolithic times in the middle Holocene, the populated Lesser Himalaya was a gentle terrain of low relief, less than a thousand metres above sea level, and the Stone-Age people freely migrated across the Himalayan domain, both to north and south. Still earlier, even large-sized heavy mammalian animals like hippopotami, rhinos and elephants lived in and around the lakes, which were formed due to neotectonic movements on faults in Kashmir, Kathmandu, Jammu Siwalik and Potwar basins, now separated by very high mountains. The lofty mountain barriers developed after the Neolithic times, obviously due to Recent movements — at the rate of 3.5 to 10 mm/yr in Pir Panjal Range — on faults of the Main Boundary Thrust Zone. Likewise, the Great Himalayan rampart emerged as a consequence of rapid movements at the rate of 0.7 to 1.1 mm/yr along imbricating thrusts of the Main Central Thrust Zone. The old, mature terrain of the Lesser Himalaya was lifted up episodically leading to its geomorphic rejuvenation.

The Siwalik Zone in the south is being squeezed up at a rate of 0.8 to 1.0 mm/yr between the very active Main Bounday Thrust and Himalayan Frontal Fault and on faults and thrusts which split the Siwalik. Intermittent movements on these faults have resulted in ponding of rivers and formation of lakes upstream of active faults. Rapidly filled up lakes of this kind are now represented by intermontane flat stretches called the 'duns'. Tilting and faulting up — at least in three episodic pulses — of these 'duns' of Upper Pleistocene to Holocene ages imply very recent movements.

The neotectonism of the Himalaya is attributed to northward push of the Indian plate underthrusting the Himalayan province, which reactivated the intracrustal boundary thrusts and faults.

Mature topography of Lesser Himalaya

Looking from a high point in the Lesser Himalaya sprawling between the lofty Great Himalaya and Siwalik ranges one is struck by its remarkably gentle