Magnetostratigraphic correlation of the Late Cenozoic fluvial sequences from NW Himalaya, India

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In this study we have compiled and synthesized the published magnetic polarity data on Late Cenozoic sequences in the Indian sector, and discuss their utility for time stratigraphic inferences useful to constrain tectonic and climatic changes. We also discuss the use of magnetic fabrics over channel sandstones and rock magnetic ratios of the pedogenic horizons as correlation tools. It is observed that the magnetic polarity events (a) the base of long normal (C5*n*) at 10.95 Ma, (b) the base of C4*n* at 8.07 Ma, (c) the base of C3*n* at 5.23 Ma, (d) the Gauss–Matuyama boundary (top of C2An) at 2.58 Ma, and (e) the Brunhes–Matuyama boundary (base of C1*n*) at 0.78 Ma, are the most characteristic events so far reported in the Late Cenozoic Siwalik sequence. It is, therefore, necessary to make more detailed studies on palaeointensity, *in situ* rock magnetic signals, and magnetic fabrics closely around these intervals to strengthen their application to basin-wide correlation. New data in the eastern part, and a more judicious density of magnetic polarity data in the central part of the Himalayan Foreland Basin (HFB) are required for a robust correlation of the Late Cenozoic stratigraphic units from Pakistan, NW India, through Nepal to the northeastern Indian sector. The sediment accumulation rates derived from a total of 56 sections throughout the Himalayan foreland indicate a notable rise during 10.8 to 9.5 Ma (deposition of Nagri sandstone) and records the largest fluctuations after 1.7 Ma (widespread occurrence of boulder conglomerates). Magnetic fabrics provide high resolution information on hydrodynamic changes suitable for correlating the association of major channel sandstones across the basin. The rock magnetic ratios contain information on dynamic pedogenic transformation of magnetic minerals with time, and are envisaged as a high resolution tool of basin-wide correlation for the pedofacies. Further, a use of magnetic susceptibility for basin-source modeling has been demonstrated.

A precedence of 'correlation' over 'definition' is recommended strongly[1] in the revised guidelines of the International Commission on Stratigraphy[2]. In the Late Cenozoic fluvial sequence (Siwalik Group) of the Himalayan Foreland Basin (HFB), the stages are defined on the basis of biostratigraphy with little emphasis on the arrangement and distribution of lithotypes, and chronologic successions and their basin-wide correlation. Stratigraphic correlations in peripheral basins, developed in front of an active orogen like the Himalaya, are difficult because of (1) the time transgressive nature of lithofacies, (2) variability in hinterland setting of the sub-basins of the foreland, (3) endemism of biota, and (4) the complexity of sedimentation in fan–interfan domains. Poor knowledge on these aspects leads to inconsistency in correlation of individual sections of Late Cenozoic fluvial succession of Himalaya. Consequently, the independent technique of magnetostratigraphy has proved more suitable as a tool for correlation of the exposed sequences in the Himalayan foreland.

Magnetic polarity is independent of lithogenic constraints such as lateral lithofacies variations, permitting a good correlation amongst the Late Cenozoic fluvial successions of the Himalayan foreland belt. Relative abundance of the suitable iron oxides that can ideally preserve the *in situ* records (depositional/crystallization remanence) of the contemporary earth's magnetic field permits successful reconstruction of magnetic polarity events of the Late Cenozoic Siwalik Group of sediments in the HFB[3–5]. The deposits of these fluvial sequences show high rates of sedimentation (~ 30–100 cm/1000 years)[3] without major hiatuses; this allows the preservation of uninterrupted magneto-zone records. Therefore, magnetic polarity stratigraphy has allowed a robust correlation of the Late Cenozoic fluvial sequences in the Himalayan foreland belt[3,5,6].

Magnetostratigraphy is a tool for correlating the normal and reversed polarity zones of a rock succession to the magnetic anomalies of the standard geomagnetic polarity time scales (e.g. GPTS of Cande and Kent[7]) by tie-points from independently dated benchmarks (time-constrained stratigraphic horizons), iterative matching of the reversal patterns to GPTS, and sediment accumulation rates. Different versions of GPTS are developed for the Late Cenozoic[7–10] from linear magnetic anomalies

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along the mid-oceanic ridges, and the reversal events are dated/calibrated using isotopic dates on the equivalent terrestrial records throughout the globe. The dates of the individual reversal events are modified periodically in different parts of the globe with subsequent improviz-ation in the GPTS[11–13]. In brief, magnetostratigraphy is a correlation tool rather than an absolute dating method and is often used for refinement of biostratigraphy. Errors in magnetostratigraphy mainly depend upon the non-uniform rate of sedimentation, sampling intervals selected, and the type of sampled material. In routine practice, the quality of magnetostratigraphic data is tested by mineral magnetic analysis and several statistical methods[14,15], before correlation to the GPTS.

Magnetostratigraphy in HFB

Stratigraphic correlation using the records of remanent magnetic polarity has been done extensively in the Late Cenozoic Siwalik Group of the Potwar Plateau of Pakistan the last for two and a half decades. Raynolds and Johnson[16] calculated a rate of southward progradation of lateral facies changes up to 30 m/1000 years together with the southward advancement of basin depo-centers at rates of over 20 m/1000 year in the Potwar Plateau of Pakistan. They suggested a rough equilibrium between the modelled northward plate motion of the Indian subcontinent and the southward displacement of depositional processes within the foredeep. Using magnetic polarity zone boundaries, Berhensmeyer and Tauxe[17] concluded that the formational boundary between Nagri and Dhok Pathan in Potwar Plateau represents complex interfingering of coeval fluvial systems. Johnson and co-workers[18,19] observed that the variation in the rate of molasse sedimentation in the Upper Siwalik succession of southwestern Kashmir and Salt Range is controlled by syntaxial tectonics of the region. Tauxe and co-workers[20–22] studied the carriers of Natural Remanent Magnetism (NRM) in the Siwalik succession of Pakistan and found 'specular hematite' to be responsible for remanence acquisition in these rocks, hence preferring to call them Siwalik red-beds. These and many other combined attempts using magnetostratigraphy and biostratigraphy by the American teams in Pakistan[23–26] produced a strong basis for its extension to the equivalent Indian and Nepalese sequences[27–29].

Status of magnetostratigraphy in the Indian Himalaya

Indian sector of the Siwalik fold-thrust-belt shows relatively more tectonic linearity (Figure 1) compared to the arcuate trends of thrusting in the Potwar Plateau. As a result, several across-the-strike sections are exposed in the Indian Siwalik succession. Many prominent thrusts/faults of the Sub-Himalaya [e.g. Main Boundary Thrust (MBT), Himalayan Frontal Fault (HFF), Jawalamukhi Thrust, Nahan Thrust (Intra-Foreland Thrust, IFT)][30,31]

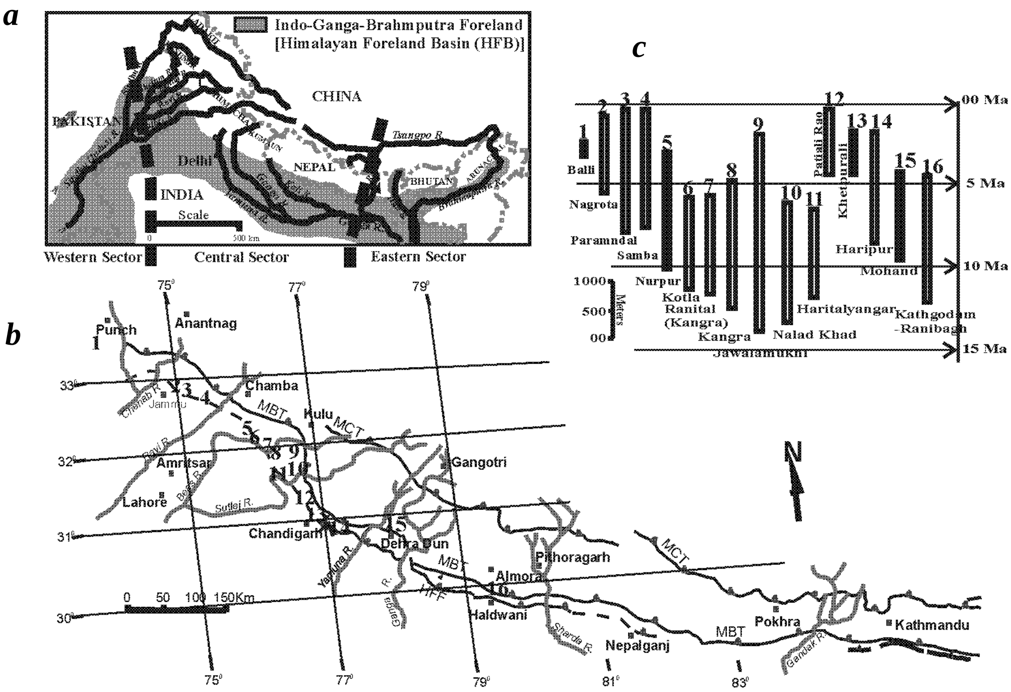

Figure 1. ***a***, Map of the Himalayan region showing (the shaded portion) the Late Cenozoic fluvial sedimentation of the Himalayan and Indo-Ganga–Brahmaputra Foreland Basins; ***b***, Geographic distribution on the well-documented magnetostratigraphic sections denoted by numbers in (***c***) and described in Figure 2 and text. MBT, Main Boundary Thrust, MCT, Main Central Thrust; HFF, Himalayan Frontal Fault.

provide reference horizons to approximately mark the base/top of the exposed sections within a sub-basin. The isochronous occurrence of volcanic ashes (bentonized tuffs) during ca 3.0 Ma to 1.5 Ma, 9.2 Ma, and 13.2 Ma[32] at several localities provide tie-points to magneto-stratigraphic correlation although doubts were raised by Gupta *et al*.[33] on the identity of the ashes at some localities. Biostratigraphy based on faunal assemblage and marker faunas, at many localities, strengthens the chronology and correlations derived from magneto-stratigraphy.

Magnetostratigraphic studies in the Indian sector of the Himalayan Foreland Belt were initiated during the eighties[34–38]. Only the western part of the NW Himalaya (up to Chandigarh) was studied until recently, however, new data are now available to the east of Chandigarh[39–41]. Yokoyama[34] and Azzaroli and Napoleone[35] studied the Tatrot/Pinjor formations in 'Type Locality' of Pinjor near Chandigarh. However, the first detailed magneto-stratigraphic documetation in the Indian part was made by Johnson *et al.*[36] in the Haritalyangar area (H.P). They[36] provided a datum 7–7.5 Ma for the last appearance of *Ramapithecus* and *Sivapithecus*, in Asia. Further, they suggested the 'Nahan Sandstone' as facies being equivalent to the Nagri Formation. Tandon *et al.*[37] carried out detailed magnetostratigraphy and sedimentology in the Upper Siwalik Subgroup of the Subathu sub-basin and inferred that the change in fluvial domains in the post-Gauss time is reflected in terms of increase of single-storied sandstone bodies in the Pinjor Formation. Further, they[37] noted the appearance of first conglomerate bed during post-Olduvai time. In the Kangra sub-basin, using magnetostratigraphic ages Meigs *et al.*[42] constrained the conglomerate dominant section of Jawalamukhi and inferred the initiation of MBT during 11 to 10 Ma. Further westward, Ranga Rao *et al.*[38] using faunal controls made extensive attempts in the Ramnagar sub-basin of Jammu region studying the Paramandal–Uttarbeni, Nagrota, Balli and Samba–Mansar sections. The Nurpur (Jabbar Khad) section in the Kangra Sub-basin and Patiali Rao in the Subathu Sub-basin were further studied by these workers to correlate them with the Middle and Upper Siwalik formations[43]. They estimated the rate of sedimentation as 45–71 cm/1000 year for these sequences of Siwalik Group in Gilbert and Gauss times and 21–37 cm/1000 year during the Matuyama reversal. Ranga Rao[43] ascribed such a decrease in rate of sedimentation of the northern part and accelerated rates in the southern part during Matuyama as a result of forelandward migration of depocentres. Recently, a long sequence mainly covering the Middle Siwalik Sub-group near Bilaspur (H.P.) was studied by Sudheer Kumar *et al.*[45]. Sangode *et al.*[46] reconstructed the magnetic polarity stratigraphy in Haripur section near Nahan (east of Chandigarh) by identification of 18 reversals in the time span of 6 to 0.5 Ma. They estimated average sedimentation rates of 45 cm/1000 year in the Middle and lower part of Upper Siwalik and 54 cm/1000 year in the Upper Siwalik succession and constrained re-activation of IFT and MBT. Sangode *et al.*[5] assigned a magnetostratigraphic age of 9.7 Ma to the base of the Mohand Rao Section near Dehra Dun, and estimated an average rate of sedimentation of 38 cm/1000 year for the Middle Siwalik succession in this section.

Burbank *et al.*[3] synthesized sedimentologic and structural data from 49 magnetostratigraphically constrained sections across the HFB from Pakistan and India through Nepal. They discussed at length the sequential evolution and large-scale control on the geometry of the foreland, using sediment accumulation rates and sediment dispersal pattern. Sangode *et al.*[5] made use of magnetic fabrics along with magnetostratigraphy in the Middle Siwalik succession of Mohand Rao section of Dehradun Sub-basin and Upper Siwalik succession of Haripur section in the Subathu sub-basin. They noted tectonically induced changes in magnetic fabrics and rate of sedimentation mainly during 7.6 Ma, 2.6 Ma and 1.75 Ma and conjunctively used the clast composition data to infer active episodes along Main Central Thrust (MCT), MBT and IFT respectively. Further, Sangode *et al.*[5] compiled the mean palaeomagnetic directions of 1008 sites from published data of the Siwalik successions from India and Nepal, that infers relative counter-clockwise rotations of different tectonic blocks from west towards east. Using magnetostratigraphically constrained sections in two contrasting alluvial fan depositional settings, Kumar *et al.*[47] distinguished supply-driven and subsidence-driven nature of the fans. Further, Kumar *et al.*[48] inferred that the drainage re-organization in this Sub-basin was controlled by different thrusts/thrusting events in the hinterland as well as within the foreland during Plio-Pleistocene. The magnetostratigraphy of Garjiya section near Ramnagar by Kotlia *et al.*[40] is the first report in the eastern part of the Central belt in HFB. Brozovik and Burbank[49] studied Kangra and Nalad Khad sections in the Kangra re-entrant. Using these two sections, together with the previously dated Jawalamukhi and Haritalyangar sections, they[49] documented some of the oldest extensive Siwalik conglomerates yet dated (10 Ma), and suggested the development of significant erosional topography along the MBT prior to 11 Ma. Kotlia and co-workers[41] studied another section at the eastern end of the Central belt between Kathgodam–Ranibagh which consists of late Lower-, and Middle to Upper Siwalik (ca. 12–4 Ma) deposits. Sangode *et al.*[50] recently studied the Ranital–Kangra and the Kotla sections in the Kangra re-entrant area, which encompass the Middle to Upper Siwalik succession (ca. 11–5 Ma).

Good Late Cenozoic sections are reported from Darjeeling, Arunachal Pradesh and Assam[51,52]; the Tipam, Dupi Tila and Dihing formations; and the Irrawaddy System of Myanmar[53]. Unfortunately, there are

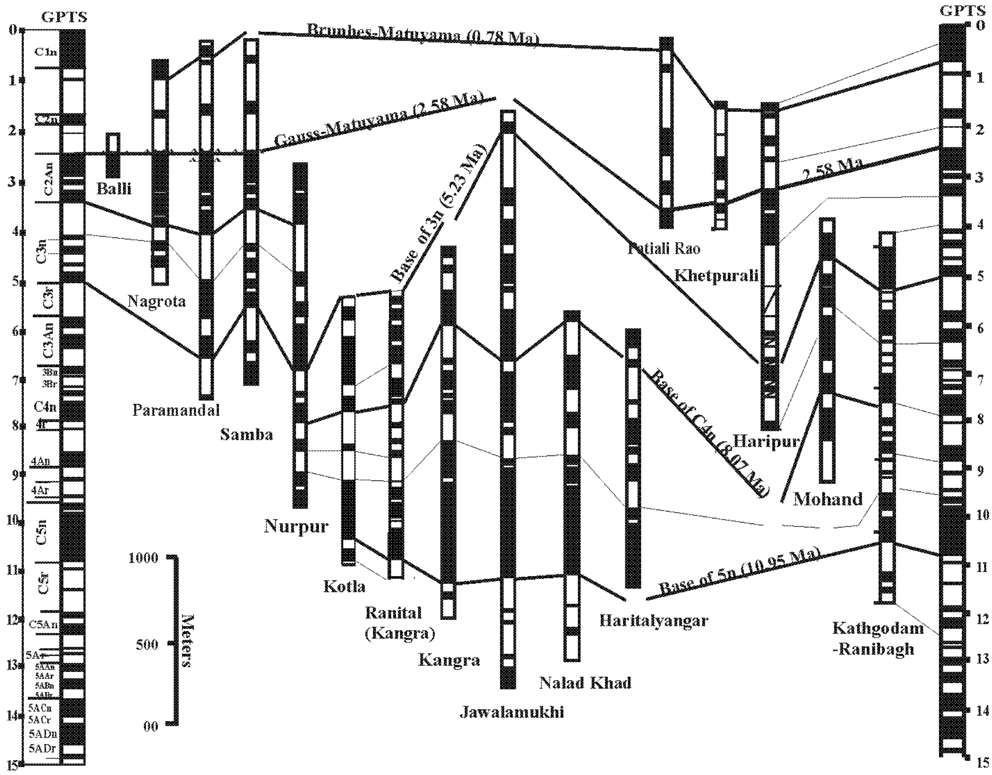

Figure 2. Sixteen well-documented magnetostratigraphic sections in the Indian sector of the HFB brought into the revised GPTS[13]. See text and quoted references for details of the individual sections. Note the divergence of tie-lines in the sections from the Kangra re-entrant depicting the higher sediment thickness for equivalent part in the west and east. Important tie-lines (discussed in text) are labelled and marked thick.

no magnetostratigraphic data from these sections in the eastern sector.

Magnetostratigraphic correlation in the Indian sector

Sixteen well-documented sections in the Indian sector of the HFB are compiled using the revised GPTS[13] to facilitate the correlation (see Figures 1 and 2). Figure 1 clearly reveals that most of the studied sections occur in the central sector in Kangra basin, Jammu and Chandigarh highlighting the need for new data for improved spatial coverage. Also, Figure 2 shows that much of magnetostratigraphic data is for ~ 13 to 1 Ma duration. This is because the exposed base of most of the sections begins with imbricate thrusts, e.g. Jawalamukhi thrust in the Kangra Sub-basin that exposes the upper part of Lower Siwalik succession (~ 13 Ma) in the hanging wall. The upper part of the Upper Siwalik succession is dominated by thick conglomerates that are not suitable for magnetostratigraphic studies, thus rendering the < 1 Ma segment of the sections unsuitable for such studies.

Correlation of the reversal events across the sections suggests that some of the events (hence tie-lines) are more common and pronounced. The base of the long normal event C5*n* (~ 11 to 9.5 Ma) corresponds to the most extensive characteristic occurrence of lithofacies of Nagri type (or the Chinji–Nagri transition)[3,4]. Another reversal (base of C4*n* at ~ 8 Ma) corresponds to the Nagri–Dhok Pathan transition in the lithotypes. This event is also the base of a considerably long normal polarity zone (C4*n*). The base of C3*n* (5.23 Ma) occurs during the transition of Dhok Pathan to Tatrot type facies, that also characterizes the initiation of piedmont drainage as reported in many sections[38,46,47]. The next pronounced event appears at 2.58 Ma (Gauss–Matuyama reversal), that corresponds to the Tatrot/Pinjor formational boundary followed by the abundance of conglomerate facies. The youngest reversal event, i.e. the Brunhes–Matuyama reversal at 0.78 Ma is well marked in many of the sections. The aforesaid five events should be analysed in detail through more detailed rock magnetic and geomagnetic studies (see ref. 54).

Sediment accumulation rates

Change in Sediment Accumulation Rate (SAR) is the most significant parameter of basin tectonic inferences using magnetostratigraphic data. However, its correlation needs a careful examination since the SAR varies with

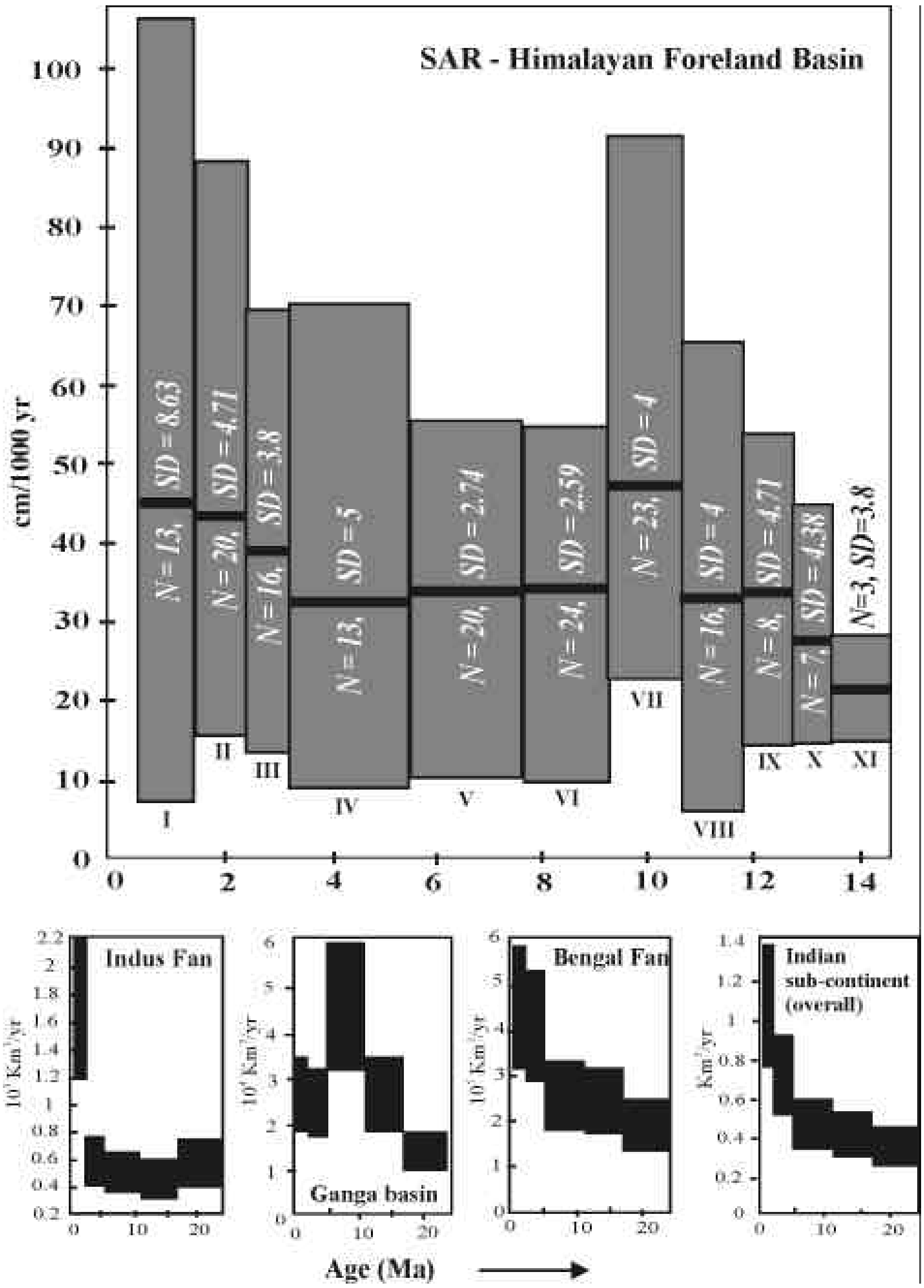

Figure 3. *Top*, Sediment Accumulation Rate (SAR) derived from 56 magnetostratigraphic sections in the Himalayan Foreland Basin north of HFF displaying mean value (solid bar), while the rectangles are bound by minima and maxima in each time zone I to XI. The sedimentation windows approximately define; (I) ~ 0.7–1.7 Ma: Boulder Conglomerate Formation, (II) 1.7–2.5 Ma: Pinjor Formation, (III) 2.5–3.4 Ma and (IV) 3.4–5.6 Ma: Tatrot Formation, (V) 5.6–7.8: Dhok Pathan Formation, (VI) 7.8–9.5 Ma: Nagri Formation, (VII) 9.5–10.8 Ma: C5*n* long normal event and part of Nagri Formation, (VIII) 10.8–11.8 Ma: Chinji Formation, (IX) 11.8–12.8 Ma and (X) 12.8–13.5 Ma: Chinji Formation and (XI) 13.5–14.6 Ma: Kamlial Formation.

the location (distal-proximal) and tectonic setting of the given section within the basin/sub-basin. The sedimentation in HFB is broadly synchronous with the marginal sea basin (Indus and Bengal fan) and the Ganga basin south of HFF. Therefore, we attempt to compare the SAR of 56 magnetostratigraphically constrained sections north of HFF from the Potwar Plateau, NW Himalaya and Nepal (see Figure 3) with the Late Cenozoic mass accumulation rates in Indus fan, Ganga basin and Bengal Fan[55].

Figure 3 shows that there is an increase in sedimentation in all the basins at ~ 10 Ma (the onset of Nagri Formation). Another notable event occurs at ~ 5 Ma where there is increase in Bengal Fan sedimentation but decrease in the Ganga basin. The maxima of SAR in the HFB is increased but it shows notable minimum values too. The overall trend suggests that during this period the SAR has increased in the recesses while it remains unaltered in salients[3]. The episode IV (3.4 to 5.6 Ma) is the largest period where the SAR appears to be constant for long time throughout the HFB. At ~ 2.5 Ma, the variability in SAR throughout the basin has increased and became optimum after ~ 1.7 Ma in all the basins except Ganga basin. This period is the widespread deposition of boulder conglomerates. Thus the SAR variability after 1.7 Ma indicating the large range of maxima and minima, therefore, suggests an enhanced differential tectonic activity in this terminal stage of HFB.

Rock magnetism

Magnetic mineralogy of the Late Cenozoic fluvial sequences of the Himalayan foreland basin is largely controlled by (a) the spatial changes in the source rock all along the hinterland, (b) differential exhumation related temporal variations within the hinterland, (c) genesis of minerals controlled by varied depositional conditions (channel, overbank and interfluve), and (d) large scale tectono-climatic changes. As a result, sediments in the foreland display a large variation in the grain-size, composition, association, and mode of deposition of the magnetic minerals. A lithofacies specific application of rock magnetism (e.g. ref. 5) provides detailed high-resolution multifaceted information on the depositional conditions and environments suitable for making climate and tectonic inferences besides serving the purpose of an independent tool of stratigraphic correlation.

Alignment and style of deposition of magnetic minerals within the channels is expressed in terms of parameters of magnetic fabric ellipsoids/anisotropy of magnetic susceptibility (AMS)[56]. AMS enables a comparison and inference of small as well as large-scale changes in the hydrodynamic regime. Rock magnetic characteristics reflect the change in association and composition of the detrital magnetic minerals useful to infer hinterland tectonics and/or exhumation related settings. Furthermore, the magnetic mineralogy and *in situ* alteration characteristics within the palaeosol profiles are a response to contemporary climate change processes. Therefore, a conjunctive use of rock magnetic (including AMS) and magnetostratigraphic approach can provide a wealth of data on these Late Cenozoic fluvial successions of the HFB. Rock magnetic methods are more rapid, economic and reliable; as a result, exhaustive data can be gathered to provide wide spatio-temporal coverage of the foreland. Initially, such attempts would be useful for the existing magnetostratigraphically constrained sections.

Briefly, the rock magnetic studies in this basin have threefold application in the Late Cenozoic fluvial succession of HFB for improved correlation: (I) Magnetic fabric studies in the channel sandstones, (II) Mineral magnetism of palaeosols, and (III) Mineral magnetism for basin-source modelling. These are elaborated in the following paragraphs demonstrating one example for each case.

Magnetic fabric studies

The study of AMS (Magnetic fabrics) in the Siwalik succession of HFB[5,57,58] revealed a strong hydrodynamic control over magnetic minerals in the channel sandstones. Sangode *et al.*[5,58] have reported that the shortest axis of the magnetic fabric ellipsoid (K3-axis) is aligned parallel to the palaeoflow direction by 'traction carpet mechanism' (see Figure 4). Further, they[58] observed that the channel sands in the Late Cenozoic Siwalik succession exhibit oblate fabrics that change to prolate under the influence of high energy hydrodynamic impulses. They[5,58] noted that the instantaneous changes in the palaeoflow lowers the values of current velocity parameter of magnetic fabrics, and that the bigger channels show lower current velocity and vice-versa. The predominantly oblate nature of background magnetic fabrics tends towards prolateness with observable tectonic signatures[58]. The Virtual Geomagnetic Pole latitudes derived from the orientation of the principle susceptibility axes (K1 and K2) show a response time better by 100 to 250 thousand years than the observable basin tectonic/climatic events recorded in litho-units[58].

Based on AMS data, Sangode *et al.*[5] have suggested enhanced thrust loading in the foreland during the Late Miocene. Changes in AMS parameters and rate of sedimentation allowed them to suggest (a) major reactivation along MCT at 7.6 Ma, coinciding with the climatic shift from C3 to C4 plants, (b) re-activation along MBT at 2.6 Ma, causing regional orographic uplift along the northern front of the foreland that influenced the Late Pliocene climate and (c) reactivation of IFT at around 1.7 Ma. Thus the magnetic fabric technique indicates a wider scope in this foreland basin and needs to be developed for its applications in the active sedimentation zone of the Ganga-plain and adjoining area.

Rock magnetic ratios in palaeosols

Soil formation and its response to climate change is a significant component in the study of long-term evolution of the terrestrial ecosystem. It is therefore appropriate to conduct detailed studies of the long records of Siwalik soils (palaeosols) from the HFB. Rock magnetic signatures have proven useful to reconstruct terrestrial

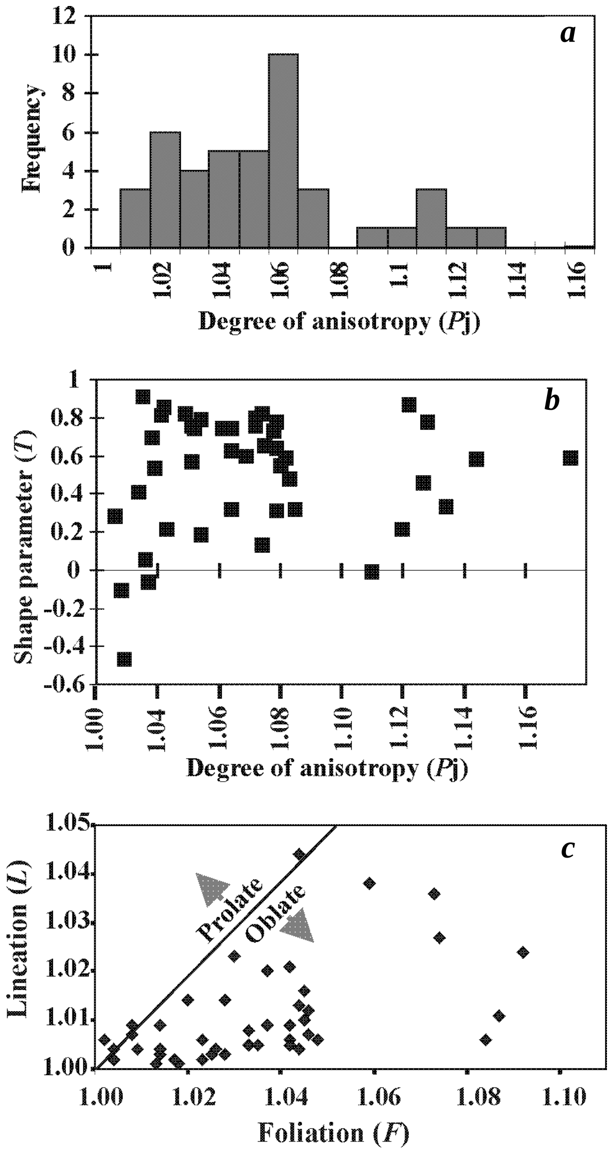

Figure 4. Distribution of the magnitude-related parameters of the magnetic fabrics in the Haripur section[58]. ***a***, Histogram for *P*j (degree of anisotropy of magnetic susceptibility) showing the frequency on ordinate and the bins for *P*j values over abscissa, ***b***, distribution of *P*j versus *T* (shape parameter) indicating a dominantly oblate nature of magnetic fabrics; ***c***, magnetic lineation (*L*) versus foliation (*F*) plot also describing the oblate (disc) shaped nature of fabrics.

climates based on the response of iron minerals to climate-induced changes in soil-forming processes (Maher[59] and references therein). In particular, correlation of the magnetic susceptibility stratigraphy of Chinese loess deposits with the marine oxygen isotope record[60] underlines their potential to infer climatic signatures at regional and global scales. Ratios derived from several rock magnetic parameters (e.g. ref. 61) are found sensitive to pedogenic processes that involve formation of secondary iron oxides and thus allows their estimation. Rock magnetic techniques can also be used to understand the variations in palaeoprecipitation by estimating the production and preservation of iron oxides in soils[62].

Using rock magnetic ratios, Sangode *et al.*[61] demonstrated a large gradient of pedogenic changes in the Haripur section near Nahan; this appears to be useful for regional correlation and climatic aspects of the Siwalik sequence. Figure 5 elaborates some of the important rock magnetic parameters that can be used for climatic inferences and regional correlation. The mass specific magnetic susceptibility (Xlf) is a bulk representation of magnetic minerals, out of which the *in situ* magnetic contribution may be inferred using the susceptibility of anhysteretic remanence magnetization (X_{ARM}) and the coercivity of remanance (B_{oCR}). The parameter reflecting 'oxidation' has been represented by the ratio of the Isothermal Remanent Magnetization (IRM) contribution to ferric iron oxides to that of ferrous oxides. Similarly 'hydration' reflects the contribution from hydrous iron oxides, 'humification' is the ratio of organic carbon to un-hydrous ferric content and 'reduction' is the ratio representing *in-situ* magnetite to the un-hydrous ferric iron oxides. The parameter 'pedogenesis' represents the ratio of an immobile element (Rb) to the mobile element (Sr). It was observed in the studied section that the pedogenic magnetic mineral transformation is governed by the production of the antiferromagnetic minerals during Pliocene, and ferrimagnetic minerals during Pleistocene.

Basin–source modelling

All along its elongation, in the HFB, the source rock has varied with time and space. Such a change in the source rock can be reflected in the magnetic mineral assemblage in the basin with strong signals from one or more characteristic minerals. If the magnetic properties of the source rock catchment are characterized, its inputs in the basin can be modelled statistically to understand the basin–source relations and exhumation history. Figure 6 demonstrates such an approach in the Kangra basin where low frequency magnetic susceptibility (Klf) of the basin sediment has been compared with that of the source rocks (details to be published elsewhere). It can be observed from the figure that the Klf values are quite discriminatory and characteristic for each rock type in the source. Anomalously high values are shown by the Chail metamorphics (mean Klf = 25,622 × 10 E-11), whereas the pink quartzite of Sundernagar Group characterized lowest (negative) susceptibility. The susceptibility of the basin sediments is the lowest at the 400 m level where the pink quartzite clast bearing gritty sandstones occur. Therefore, the sharp troughs may be inferred for the Lesser Himalayan source (footwall of Chail thrust). This shows the use of such approach to reconstruct the exhumation-unroofing history of the hinterland assembly besides significant inputs for basin–source modelling.

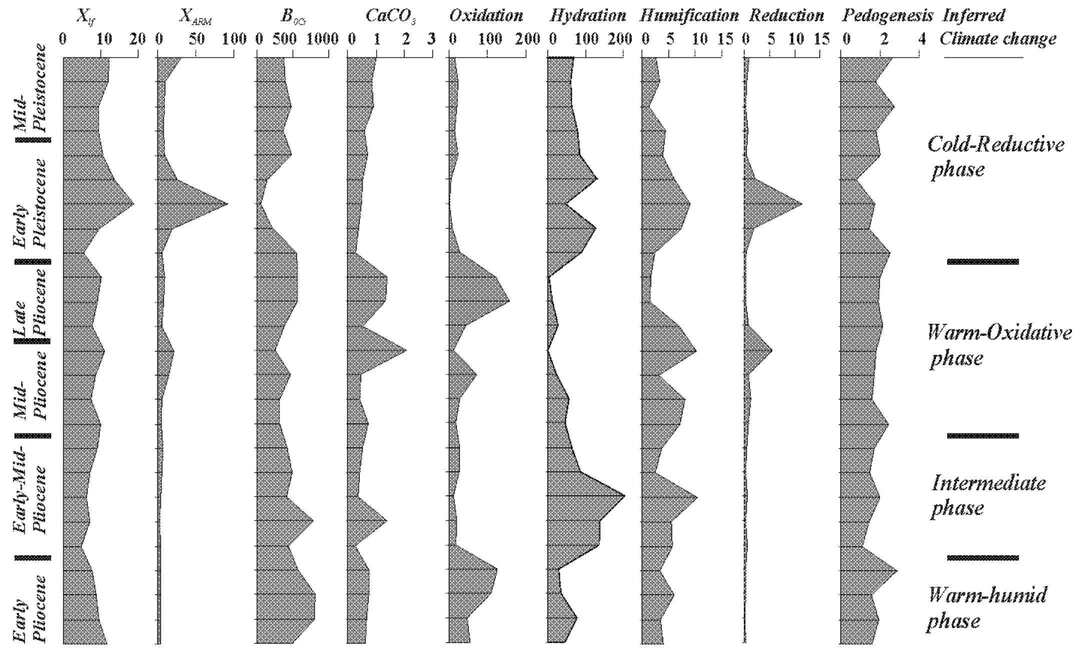

Figure 5. Rock magnetic ratios in the pedogenic horizons of Haripur section near Nahan[61]. Coherency amongst these parameters and their dynamic nature (discussed in Sangode *et al.*[61]) suggests their suitability to regional correlation. Oxidation = H/IRM_{soft}, Hydration = G/H, Humification = TOC/H, and Reduction = c_{ARM}/H, where G = $IRM_{4–3T}$, H = $IRM_{1–0.5T}$. Pedogenesis = Rb/Sr.

On the magnetic remanance

Tauxe *et al.*[63] showed that the ChRM in the Siwalik succession of northern Pakistan is Depositional Remanent Magnetization (DRM) due to specular hematite. Since then thermal demagnetization has been used extensively to isolate the ChRM from specular hematite despite the large variation in the hinterland source with time and space throughout the foreland belt. DRM originates from physical alignment during settling of ferromagnetic grains in the ambient magnetic field of the Earth. An ideal DRM is produced when the grain size is uniform and fine enough to be aligned without interference from gravitational torque and grain interactions in extremely low hydrodynamic force. It is an unlikely situation in channel sediments, but a favourable condition in the overbank/interfluve area where non-pedogenic fine grained sedimentation is under progress. However, even a little pedogenesis may result in maghemitization and production of secondary iron oxides giving rise to a strong Chemical/Crystallization Remanence Magnetization (CRM)[59,64]. During thermal demagnetization of several overbank samples, Sangode *et al.*[5,39] observed a significant drop in the intensity and susceptibility at ~300–400°C, suggesting the maghemite–hematite inversion. Gautam and Rosler[57] reported the abundance of maghemite in the salt and pepper sandstones of the Middle Siwalik succession from Nepal. Maghemite/titanomaghemite forms most favourably due to low temperature *in situ* oxidation of magnetite/titanomagnetite giving rise to fairly strong CRM[64]. Maher[59] suggested that such an oxidation takes place in a very short duration of tens of years of atmospheric exposure. The mineral maghemite (g-Fe_2O_3) has a Neel/Curie temperature of < 645°C (ref. 64) and is closely below that of specular hematite. Therefore, it is likely that maghemitization produced a significant ChRM due to CRM. These studies stress the need for a detailed analysis to determine granulometry and re-assessment of the origin of ChRM in these minerals under varying depositional and source rock conditions throughout the sequence.

Magnetic cleaning

As stated above, the foreland sediments have received a large variety of magnetic minerals, that commonly result in a multi-component assembly of the remanant magnetic vectors, making magnetic cleaning difficult and unsuccessful for most of the samples. Considering this complication, in multicompenent assemblage Sangode *et al.*[50] have suggested a demagnetization strategy using combination of thermal and alternating field demagnetization where the samples are first demagnetized at < 200°C to remove goethite and viscous components and then till ~50 mT to remove the soft multidomain components, followed by thermal demagnetization steps above 500°C. Blanket cleaning is not recommended in such multicomponent mixtures and pilot studies for demagnetization shall be supported by detailed rock magnetism and petrography.

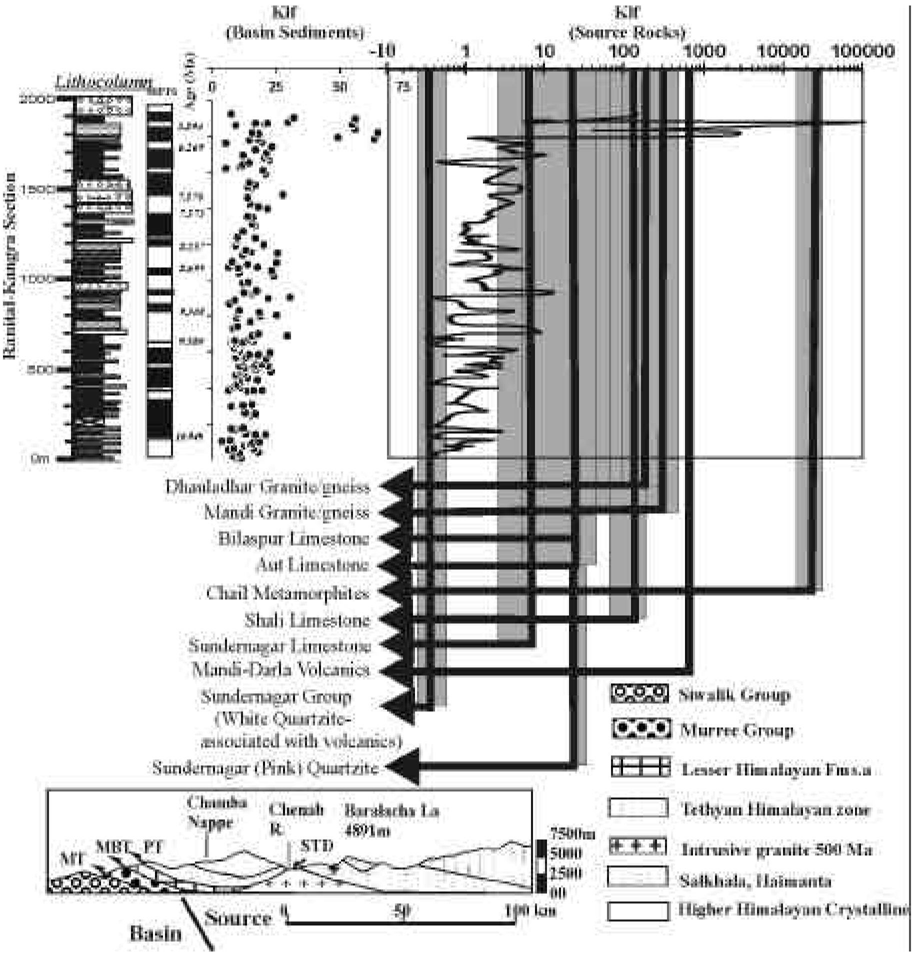

Figure 6. Basin–source low frequency magnetic susceptibility (Klf) relation for the Kangra sub-basin of HFB. The basin Klf is of the channel sandstones from the Ranital-Kangra section of the Kangra sub-basin, and the source rock susceptibility is shown by the arrowed lines bound by grey shade. The arrow marks the sampled rock type in the source area. The grey-shaded envelope is the range of minimum–maximum Klf of the samples in each source type. The curve is the log plot of the susceptibility. Inset below is the sketch of the profile along the source-basin for this location.

Secondary component and inclination error

The secondary component is not uniform throughout the basin. Strong secondary components in the Siwalik succession may be the result of magnetite, maghemite and due to burial compaction or tectonic loading. It appears that secondary component varies regionally across the foreland, e.g. Kangra and Kotla section samples in the Kangra Sub-basin have shown secondary components of high blocking temperature (> 500°C)[50] compared to the relatively low blocking temperature secondary components in Subathu Sub-basin (< 450°C)[39].

It is often observed that the DRM is affected by inclination flattening (inclination error/shallowing) due to the post-depositional effect of compaction. However, the inclination values reported by various workers in different domains of the HFB are within a range of 40–20° with most common value of ~ 30° although an inclination flattening due to oblate fabric of specular hematite has been reported[65].

Rotation of tectonic blocks

Formation of different tectonogenic blocks controlled by subsurface topography, basement rigidity, hinterland tectonic framework, and the rotation of the northwardly drifting Indian plate causes differential activity of thrust-belts throughout the foreland. In the absence of detailed palaeomagnetic data, the sub-surface depressions separated by transverse lineaments[30] can be depicted as individual tectonic blocks within the foreland. Occurrence of the strike-slip faults along the margins of these tectonic blocks[30] supports such an idea. Sangode *et al.*[5] used the mean of palaeomagnetic directions (using direction–space approach) from the magnetostratigraphically constrained sections in some of the sub-surface depressions/sub-basins to calculate the relative tectonic rotations amongst these blocks. Antipodally-combined declination values inferred an increasing counter-clockwise rotation from west to east during Plio-Pleistocene except for the Haritalyangar section which represent a comparatively older sequence (~ 11–8 Ma). The larger counter-clockwise rotation of the Gandak block may reflect activity on the Faizabad ridge during the past 10 Ma. More data from Kangra, Dehra Dun, Ramganga and Sarda Sub-basins are awaited to give a detailed interpretation on this aspect. Earlier, significant clockwise and anticlockwise rotations were detected in the HFB[29,66]. Based on the analysis of northward motion of the Indian plate and ocean floor spreading anomalies, Molnar and Tapponier[67] inferred a counter-clockwise rotation of 6.5° during the last 10 Ma which is in accord with the present observations.

Concluding remarks

A synthesis of the magnetostratigraphic data on the Late Cenozoic succession of the Indian part of HFB has shown that such data is limited to the NW Himalaya, and emphasize the need for new data from the eastern part besides improving spatial density in the northwestern part. New rock magnetic approaches are required to overcome the limitations of magnetostratigraphy (summarized below) and to enable improved basin-wide correlations using the magnetic methods independently. Five benchmark levels are recognized as follows: (a) the base of long normal (C5*n*) at 10.95, (b) the base of C4*n* at 8.07 Ma, (c) the base of C3*n* at 5.23 Ma, (d) the Gauss–Matuyama boundary (top of C2An) at 2.58 Ma, and (e) the Brunhes–Matuyama boundary (base of C1*n*) at 0.78 Ma.

The use of magnetostratigraphic data as a tool for correlation in the Late Cenozoic fluvial successions of Himalaya has been limited to some extent because of

(a) Insufficient knowledge of magnetic mineralogy responsible for the primary and secondary magnetization in different lithofacies in order to select a proper demagnetization technique;
(b) Poor documentation/calibration of magnetic reversal records with lithofacies records;
(c) Large sampling intervals and extrapolations in the unexposed/poorly exposed zones of a section;
(d) Non-judicious selection of sections from the point of view of basin-wide coverage.

To a large extent, such limitations can be overcome using the lithofacies dependent rock magnetic approaches[5] initially for the magnetostratigraphically constrained sections. Such an approach would additionally, produce significant data to infer climatic and tectonic changes. Channel sandstones exhibit depositional magnetic fabrics with dominant shape anisotropy and preserve a high-resolution record of source–basin interactions. The fine-grained, low energy non-pedogenic overbank facies characterize DRM in Single Domain (SD) grains, and are the ideal records of magnetic polarities for determination of sedimentation rates and tectonic impulses in the basin. Vertically accreted palaeosol profiles preserve some of the most important mineral magnetic-climatic records in the HFB.

Magnetostratigraphy in the Late Cenozoic fluvial succession of the HFB of India has been used so far as a dating technique rather than as a correlation tool. More recent attempts[3,42,49] make an exhaustive use of magnetostratigraphic data for sedimentation and tectonic inferences in this basin; however, very little attention has been paid to rock magnetism and the critical behaviour of the vector migration paths, that are often quite complicated in the Siwalik Group. The full potential of magnetostratigraphy as a tool for basinwide correlation has not been achieved. The Late Cenozoic fluvial succession of HFB of India requires renewed attention with the following emphasis:

1. Re-examination of the published magnetostratigraphic data to improve documentation, data-base and tests of accuracy;
2. Extensive application of rock magnetic approaches on the studied magnetostratigraphic sections;
3. Study of effects of post-depositional changes and tectonic block rotations on magnetic properties and magnetic remanence;
4. Establishment of some stratotype sections for the Late Cenozoic fluvial successions of HFB in India.

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