Mio-Pliocene sedimentation history in the northwestern part of the Himalayan Foreland Basin, India

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Two major events of sedimentation pattern and drainage organization at 10 Ma and 5 Ma with minor interspersed events are recognized in a 10–0.5 Ma succession of the Himalayan Foreland Basin (HFB). The first event commencing at around 10 Ma records the predominance of thick, multistoried, grey sheet sandstone over mudstone-dominated succession. The second event at around 5 Ma records the accumulation of extensive and thick conglomerate. These two events are related to tectonic activity along the Main Central Thrust and Main Boundary Thrust, respectively. Fluvial architecture of both the events suggests large river network, with high sediment flux and broad catchment area, which could either be provided by tectonically raised high relief and/or climatic change (high intensity rainfall).

THE Himalayan Foreland Basin (HFB) (Figure 1), similar to other collision-related foreland basins, is developed in front of an active orogenic belt because of lithospheric subsidence induced by topographic load of the hanging wall; as well as sedimentary load in the basin[1–5]. The sedimentary fill of the foreland basin records the interaction between growth of the thrust wedge, isostatic adjustment of the cratonic lithosphere due to thrust loading and resultant basinal subsidence. The development of sedimentary successions in the HFB is related to hinterland and basinal tectonics. For example, the coarsening upward megasequence of the Siwalik Group is related to episodic rejuvenation of relief in the basin margin resulting in source area(s) with increased sediment production[6–8]. However, such a variation can also be the result of climatic changes[9]. Two prominent changes in sedimentation pattern at 10 and 5 Ma in the Siwalik succession of the HFB are observed. The first change that commenced between 11 and 9 Ma records the dominance of thick, multistoried, grey sheet sandstone over mudstone-dominated succession. The second change between 6 and 5 Ma shows the presence of extensive and thick conglomerates. These two changes are related to the deformation along the Main Central Thrust and Main Boundary Thrust, respectively[7,8,10–13]. Fluvial architecture of both the events suggests large river network with high sediment flux and broad catchment area that could be provided by either tectonically raised high relief and/or major change in climatic conditions (high intensity rainfall). The main aim of this article is to assess the fluvial response to tectonic and climatic changes in the Mio-Pliocene HFB fill.

Geological outline

The Siwalik group of the HFB in India is exposed in the southern frontal area of the Himalaya in a WNW to ESE trending belt (Figure 1). The Siwalik succession has been extensively studied, in recent years, for determining the changing rate(s) and styles of sedimentation, and tectonic implications of these changes.

The early collisional facies – Subathu-Dagshai and Kasauli (Eocene to Middle Miocene) pass gradationally up into the Siwalik, a non-marine deposit more than 6 km thick[6,7,12]. The Siwalik succession has been divided into three sub-groups, i.e. Lower, Middle and Upper Siwalik. The Lower Siwalik succession forms the first stratigraphic coarsening upward megacycle. The Middle and Upper Siwalik succession together comprise a second stratigraphic coarsening upward megacycle[6]; and represents increases in topographic slope and basinward advance of thrust sheet during orogenic loading. Also, an upward change in fluvial style from meandering to braided river to alluvial fan has been noted[6–8,13].

The Siwalik Group is bounded by the Main Boundary Thrust (MBT) to the north and Himalayan Frontal Thrust (HFT) to the south (Figures 1 and 2). The Siwalik Group is folded and faulted near the MBT, but pass southward into flat lying beds overlain conformably by the modern alluvium of HFB[14]. The beds generally dip north or northeastward.

The HFB is divided into a number of sub-basins by several basement highs[15] and lineaments[16] (Figure 1 *b*). These lineaments are extensions of basement features from the Indian shield into the Himalaya and formed as normal faults during the tensional regime; these were later reactivated as thrust faults during the Tertiary Orogeny[17]. These faults not only controlled the thickness

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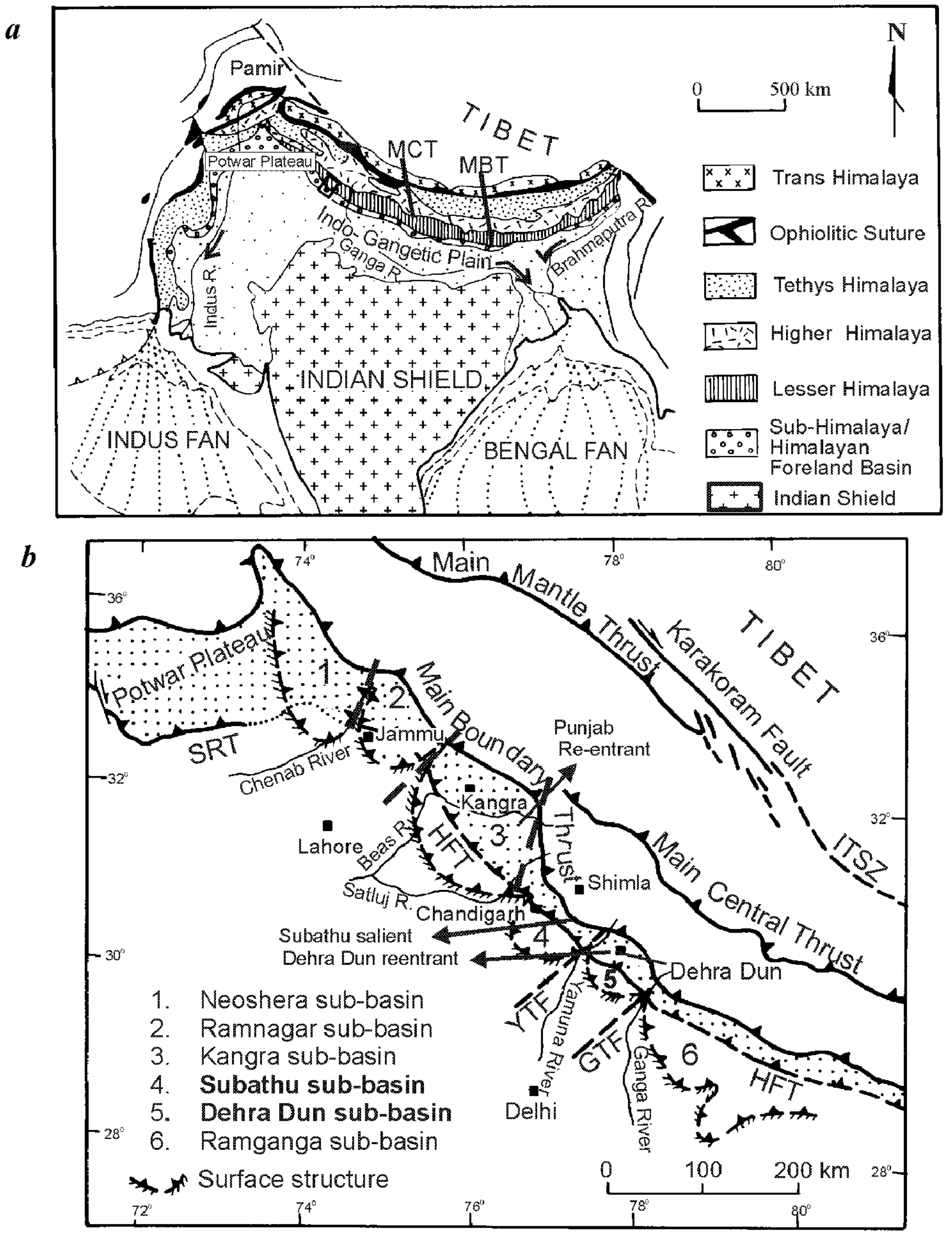

Figure 1. *a*, Simplified geological map of the Himalayan range, Indian shield and the surrounding area. The map shows the locations of Himalayan (Siwalik) foreland basin between the Indus and Brahmaputra rivers. MCT, Main Central Thrust; MBT, Main Boundary Thrust; *b*, Simplified geological map of the Himalayan foreland basin. The sub-basins are demarcated on the basis of geophysical data (after Raiverman *et al.*[15]). ITSZ, Indus-Tsangpo Suture Zone; SRT, Salt Range Thrust; HFT, Himalayan Frontal Thrust; GTF, Ganga Tear Fault; YTF, Yamuna Tear Fault.

of the sedimentary succession but also the sedimentation pattern[15]. The sedimentation pattern, source area, drainage organization, tectonic and climatic conditions differ at the sub-basin level. The thrust belt of HFB is characterized by sinuous traces with alternate, re-entrant (recess) and salient. For example, the Dehra Dun sub-basin is a Dehradun recess whereas the Subathu sub-basin is a salient (Figure 1 *b*).

Sedimentologic observations

The Siwalik succession is divided into three subgroups – Lower, Middle and Upper Siwalik. The Lower Siwalik subgroup is characterized by an alternation of sandstone and mudstone (mudstone >50%). The sandstone is dark grey, fine-grained having both ribbon as well as sheet geometry with occasional multistoried bodies. Sandstone bodies

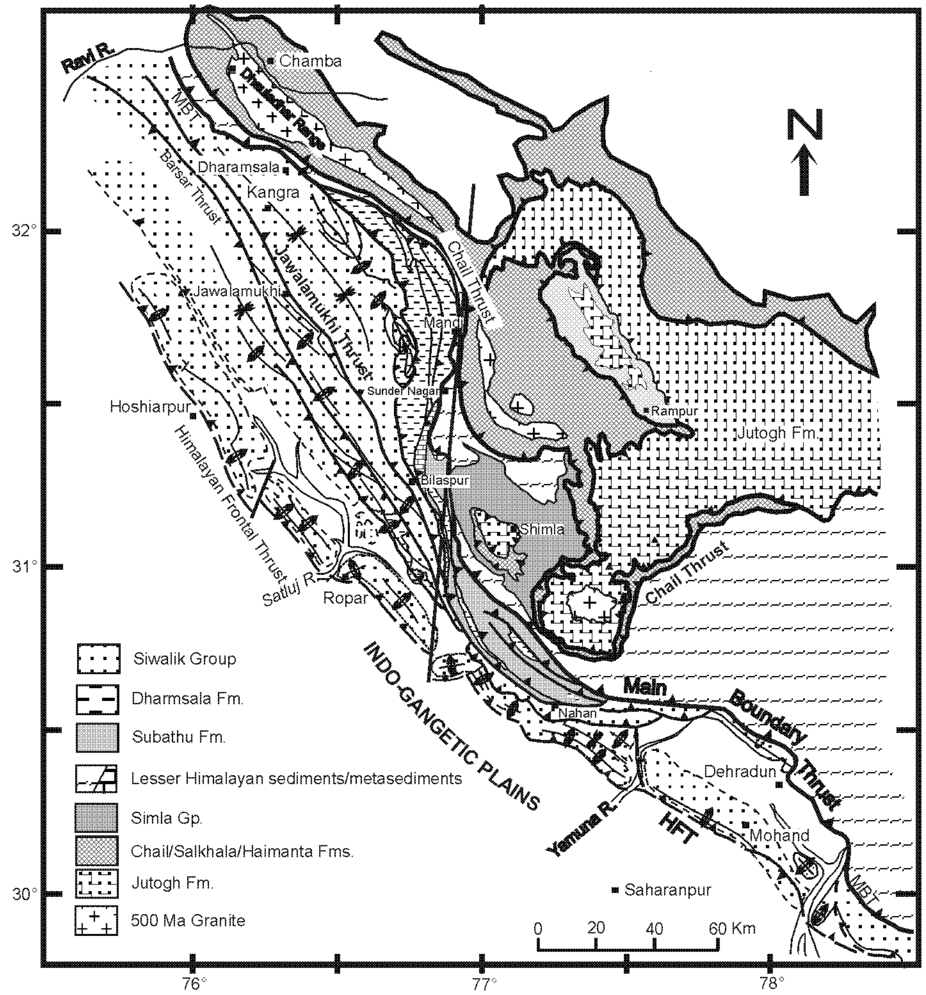

Figure 2. Geological map of the northwestern part of the Himalaya. Chail (MCT) and Main Boundary Thrust are very near to each other in Kangra Sub-basin as compared to Dehra Dun sub-basin (compiled from refs 14, 46).

show fining upwards and gradationally pass upward into thick mudstone. The mudstone is purple and shows pedogenic modification with development of carbonate concretions, rootlets and bioturbation.

The transition from the Lower to Middle Siwalik succession between 11 and 9 Ma shows variation in sandstone geometry and percentage of mudstone. The changeover from mudstone to sandstone-dominated succession through HFB is time transgressive. This changeover occurred at about 11 Ma in Potwar Plateau[18], 10 Ma in Kangra sub-basin (KSB) and 9 Ma in Nepal[19]. Moreover, in the Potwar Plateau, various formations are defined on the basis of proportion of channel bodies, for example the Chinji Formation (prior to 11 Ma) has < 50% and Nagri Formation (between 11 and 9 Ma) has > 50% (ref. 20). This scheme is not applicable in the Indian part of the HFB. For example, Dehra Dun sub-basin (DSB) shows > 90% channel body proportion between 9 and 5 Ma; Subathu sub-basin (SSB) shows > 70% between 6 and 5 Ma; and in KSB between 11 and 5 Ma, the channel body proportion shows rapid changes over short stratigraphic intervals (~ 0.5 Ma; Figure 3).

In general, channel body proportion and storey thickness increase by a factor of 2 to 3 at about 10 Ma. These sandstone bodies can be traced laterally, perpendicular to the palaeoflow direction, for about a kilometer and more. The mean grain-size gradually increases upsection and becomes fine-, medium- to coarse-grained, and in places pebbly. The sandstones are whitish grey and multistoried with interbedded mudstone/siltstone. In places, especially in KSB, conglomerates (0.5 to 3 m thick) are common in the Middle Siwalik Subgroup (between 8.7 to 7 Ma). The individual sandstone body is generally 2 to more than 10 m thick but total thickness of multistoried sandstones may reach 100 m in Potwar Plateau[20] and 400 m in DSB[12,21]. Palaeoflow direction varied laterally from south to southeast to southwest (Figure 4 *a*).

Mudstone in general, is less than 50% but in places its percentage reaches up to 80% together with levee and crevasse splay deposits. Purple and brown paleosols with cal-

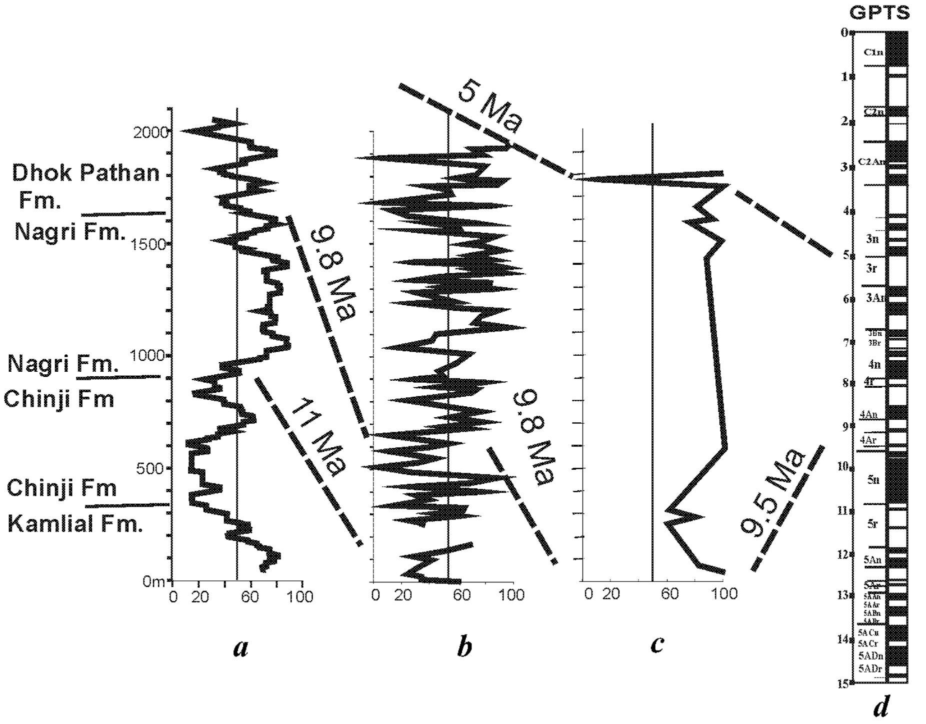

Figure 3. Upsection variation in the proportion of sandstone in relation to mudstone bodies. ***a***, Potwar Plateau[20]; ***b***, Kangra sub-basin (KSB); ***c***, Dehra Dun sub-basin (DSB); ***d***, Global Polarity Time Scale[47]. Note more than 50% channel body proportion between 11 and 9.8 Ma in Potwar Plateau whereas in KSB this proportion varies on the scale of 200 m. Similarly above 9.8 Ma, sandstone body proportion varies in Potwar Plateau and KSB but more than 50% in DSB.

careous concretions are common in the lower part whereas, in the upper part yellow paleosols with iron concretions are also present. Green mottling, bioturbation, rootlets, pedons are commonly present in the paleosol. Near the transition from the Middle to Upper Siwalik succession, calcareous mudstones are common and represent lacustrine condition, especially observed in KSB.

The Middle Siwalik succession gradually passes upwards into thickly bedded conglomerate with lenticular bodies of sandstone and rarely mudstone (particularly in the lower part) of the Upper Siwalik Subgroup around 5 Ma. The fine-grained facies (Tatrot and Pinjor formations) is also observed in restricted parts of the foreland basin, such as Subathu sub-basin (SSB)[13] and Ramnagar sub-basin (RSB)[22]. It is interesting to note that all the recesses, such as Dehra Dun, Ravi and Kangra (Figure 2) show coarse-grained facies at 5 Ma but contemporary salients show relatively fine-grained facies (sandstone and mudstone of Tatrot and Pinjor formations)[13]. The conglomerate facies typically form 3–25 m thick upward fining cycles with erosional bases, and commonly grades upward into coarse-to-fine-grained trough cross-stratified sandstone in the lower part of the succession. The percentage of conglomerate facies gradually increases upsection. The conglomerates are poorly to moderately sorted with sub-rounded to rounded clasts and crudely stratified. The clast fabric commonly shows transverse imbrication (long axis perpendicular to flow) in lower part, and upsection becomes disorganized to crudely stratified. Conglomerates are matrix supported but framework-supported pebbles, cobbles and boulders are also present. Clast size increases upsection and, in places, reaches a maximum of a metre.

Clast composition shows lateral variations from east to west. In the DSB, conglomerates comprise dominantly Lesser Himalayan quartzite (LHQ) clast[23]; SSB has sub-Himalayan sandstone (SHS) clasts[13]; KSB has LHQ; Nurpur salient has SHS; Ravi recess has LHQ and commonly granite/gneiss clasts[24], whereas RSB has LHQ. Palaeoflow directions show major changes at 5 Ma – south to southwest in DSB[25]; southeast to southwest in SSB[13]; southwest to more westerly in KSB[26] and southeast to south in Potwar Plateau[8] (Figure 4 *b*).

Discussion

From the aforesaid observations, two major events are recognized in the HFB during 11 and 0.5 Ma time span. Spatially and temporally, sedimentation patterns show high variability at sub-basin level during this time interval. These variations are mainly controlled by source area lithology, source area tectonics, size of catchment, basinal subsidence, and climate, together with the pre-existing topographic characteristics of the sub-basins. Various factors that control the basin fill geometry for the two

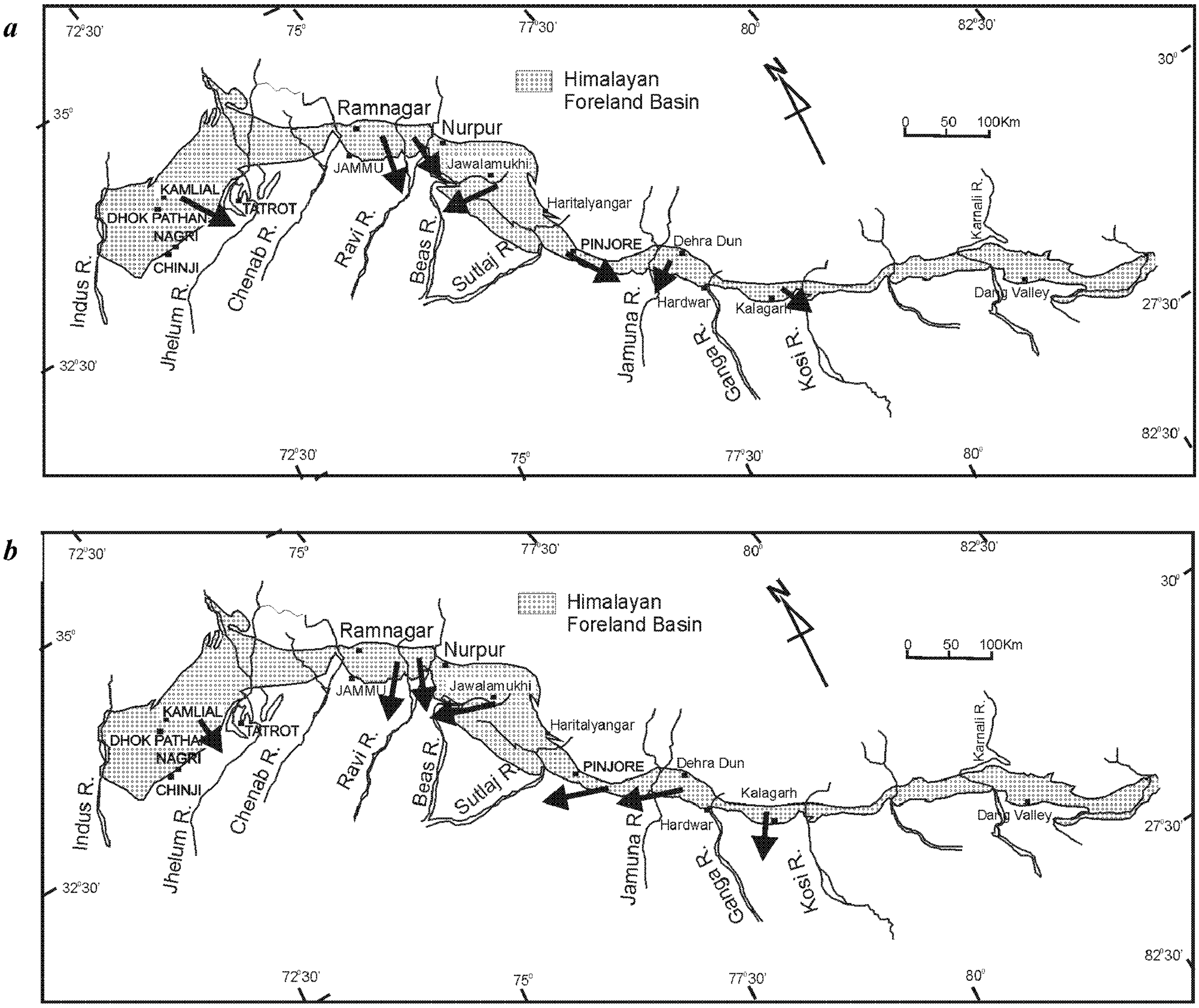

Figure 4. Palaeoflow orientation in the Himalayan foreland basin. ***a***, Variability in palaeoflow around 10 Ma; ***b***, Variability in palaeoflow around 5 Ma. Change in palaeoflow around 5 Ma is related to activity along MBT.

major events – (i) transition of Lower and Middle (~ 10 Ma) and (ii) Middle and Upper (~ 5 Ma) Siwalik succession are discussed separately.

Sedimentation trend around 10 Ma

The fluvial architecture at around 10 Ma shows gradual changes from minor to major sandstone bodies and indicates increase in channel dimension and discharge. The sedimentary succession in this interval is characterized by multistoried sandstone with abundant erosional surfaces, no lateral accretionary surfaces, and low palaeoflow variability. These features indicate that deposition took place in frequently avulsing large braided river system (Figure 5*a*). Net sediment accumulation rate also increased by a factor of nearly 2 to 3. In general, large drainage areas and relief have high potential to supply more sediments than small catchment areas of low relief[27–29]. Several workers have pointed out a log-linear relationship between the size of alluvial fans and areas of their associated catchments[29,30], and suggest first order controls on foreland basin sedimentation. This change may be due to either uplift of source area, which results in an increase in catchment area and high relief producing more detritus, or altered climatic conditions. In either case, sedimentation patterns suggest high discharge in large river systems. However, it is clear from mineralogical evidence that the Central Crystalline zone was further uplifted in response to reactivation of MCT at around 10 Ma which resulted in high relief and increased supply of metamorphic detritus[10,31–33].

Variation in lithofacies across the sub-basins suggests differential basinal subsidence. Available well and seismic

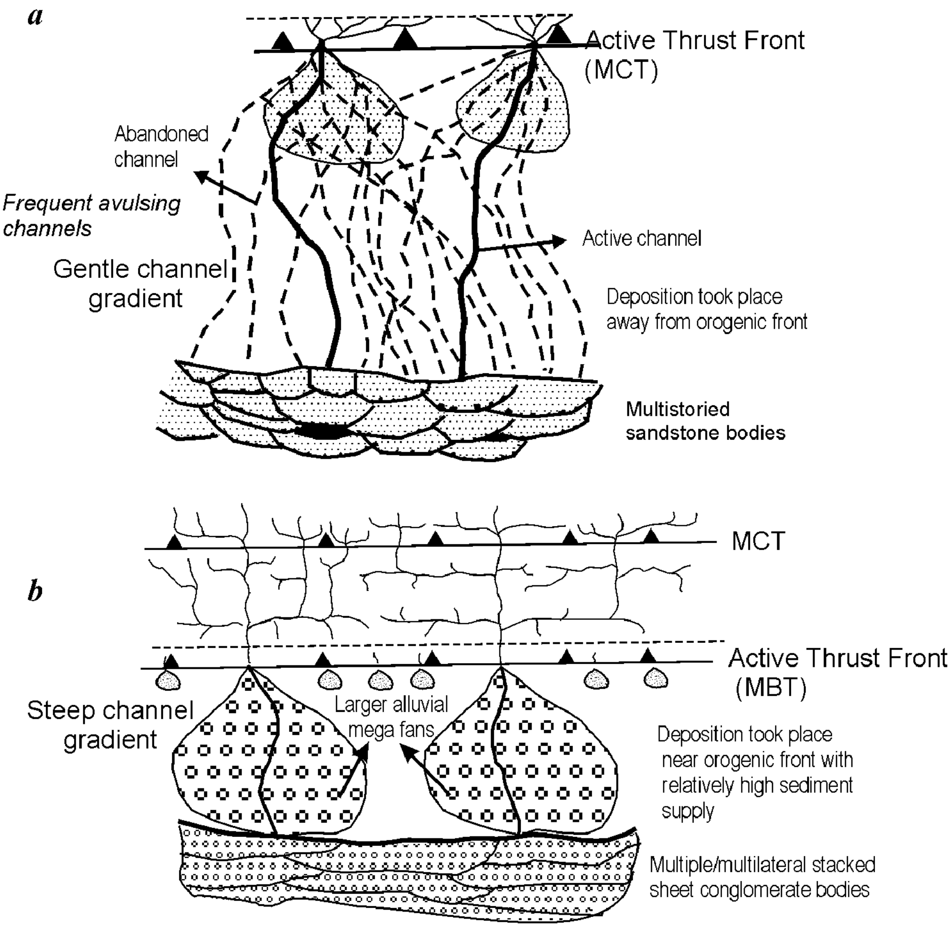

Figure 5. Evolutionary models. ***a***, Around 10 Ma, the multistoried sandstone was formed due to frequent channel avulsion and reoccupation; depositional site predominantly remains as a channel belt for long period with little flood plain; ***b***, Around 5 Ma, the development of coarse clastic alluvial mega fan was resulted due to hinterland uplift in the proximity of depositional site.

data[14] of KSB and DSB, and cross sections show higher thickness of Lower Tertiary and Lower Siwalik succession (prior to ~ 10 Ma) along basin margin, which pinches out in the south against subsurface highs. However, after 10 Ma, sediment piles prograded across the subsurface highs[15]. Bouguer gravity anomaly data of the foreland basin[15] suggest steep slopes in the Punjab recess as compared to DSB. This suggests that, prior to 10 Ma, basinal subsidence is higher than the net sediment accumulation rate in both the sub-basins; however, it is relatively high in the KSB. This may also be due to higher rates of uplift of Dhauladhar ranges which are close to the basin margin whereas Higher Central Crystalline zone is far away from DSB (Figure 2). The 1 km thick multistoried sandstone complex in DSB is formed by the braided river with frequent avulsion events of the order of 4 to 8 × 10^3 years[21]. In KSB, sedimentation rate is nearly similar (~ 0.40 mm/year) but multistoried sandstone bodies are 20 m thick and interbedded with thick overbank mudstone/siltstone. These observations reveal that the basinal subsidence in DSB is lower than KSB.

In the Kangra and Ravi recesses, conglomerates accumulate in the Middle Siwalik (between 8.7 and 7 Ma) possibly because of either the proximity of Dhauladhar granite massif along the basin margin and/or the activation of Manali-Ropar mega-lineament in the east and Ravi lineament in the west[16,17] (Figure 2). Concentration of conglomerate in the eastern side suggests that Manali–Ropar lineament was more active than the Ravi lineament. Similarly, activity of Ganga and Yamuna lineaments resulted in the confinement of palaeodrainage within the DSB, which caused thick accumulation of sandstone complex[21]. This feature suggests that basinal subsidence was high in the axial part of recess mainly due to the activation of marginal fault or lineaments along both the sides of re-entrant as also observed in Black Warrior foreland basin, Alabama[34]. The abundance of metasedimentary–sedimentary fragments, feldspar in the sandstones, and clast composition of conglomerates in the KSB suggests the activity of Chail Thrust (Figure 2) started prior to 10 Ma[35,36]. Therefore, basinal subsidence, source area uplift, basinal topography, and size of catchment exercise first order control on basin fill stratigraphy around 10 Ma.

Apart from tectonic controls on basin fill, climate has exerted an influence on the overall distribution of grain size and rate of sediment supply to the basin. Purple and brown-coloured paleosols with calcareous nodules suggest humid warm climate around 10 Ma. Fluvial architecture during this time suggests gradual increase in river size and its discharge. Schumm and Rea[37] show from Ocean record that there are three major episodes of terrigenous sediment flux, between 11 and 10 Ma; 9 and 6 Ma and 4 and 2 Ma. Mass accumulation rate in the Ganga basin also shows rapid increase around 10 Ma[38]. From the above discussion, it appears that precipitation in the Himalayan region increased around 10 Ma, an inference drawn by field observations, Indian Ocean and Ganga basin data[38]. Tectonism can produce high relief and big catchment areas, but transportation of sediments across the feather end of foreland basins requires high-energy conditions[39]. Beaumont *et al.*[40] based on theoretical model on thrust mechanics in Alps orogen belt also suggest that style of deformation, denudation and transportation of detritus is controlled by interplay of tectonic and climatic conditions.

Sedimentation trend around 5 Ma

The Middle Siwalik sandstone dominated succession gradually passes upward into Upper Siwalik conglomerate dominated succession at about 5 Ma along the northern basin margin in the HFB[7,8,25] especially in the recess; within salients, conglomerates occur commonly after 2 Ma (ref. 41). The widespread and thickly bedded conglomerate succession was deposited by coalescing mega fans in response of activity related to MBT (Figure 5 *b*). Widespread distribution and stacking pattern of conglomerate and progradation of alluvial fan suggests a broad catchment area with high basin relief. It provided a high volume of sediment and consequent distribution of coarse-grained sediments in the proximal part, and fine sediments in the distal part of the alluvial fan system.

This variation in sedimentation pattern at around 5 Ma also shows a change in palaeoflow directions from south to southwestward in the DSB[25], and more westerly in KSB (Figure 4 *b*). Net sediment accumulation rate calculated from magnetostratigraphy[42] and unpublished data show a fairly rapid increase by a factor of 2 to 2.5. The change in fluvial facies, net sediment accumulation rate, and palaeoflow directions may be considered as a response to deformation along the thrust front. The impact of MBT activity at ~ 5 Ma in the margin of HFB is manifold – (a) uplift of Lesser Himalayan ranges, (b) increase in net sediment accumulation rate, and (c) change in palaeoflow direction. This activity resulted in trapping of coarse detritus in the proximity of thrust front and transportation of fine material towards the distal part[4,43]. Transition from sandstone to conglomerate deposition occurred during the period of overall increase in net sediment accumulation rate. This increase in sedimentation rate was coincident with progradation of alluvial fan.

The Upper Siwalik boulder conglomerate presents three distinct sedimentologic signatures: (i) abrupt influx of gravel on a formerly sandy domain; (ii) thickly bedded amalgamated sheet conglomerate with coarsening upward sequence and (iii) size and roundness of the clasts.

The appearance of such a vast and abruptly variant facies could be either due to hinterland deformation or changes in energy conditions (low to high). The dominant clast type of these conglomerates is quartzite (> 80%) belonging to Higher and Lesser Himalayan sequences; these have high resistance to abrasion and rounding[44,45]. Subrounded to rounded large clasts of Upper Siwalik conglomerate suggests a long distance transport up to the depositional site. The various facies and their vertical stacking pattern indicate stream flood conditions with high concentration of sediment load. Thick amalgamated sheet conglomerates with several sedimentation units reveal broad multiple-braided channels. This reflects high water content in the catchment area to mobilize coarse material for long distance downstream transport. High water discharge will be available by either increased rainfall or increased melt water during inter-glacial period. In an evolving mountain system, there could be two controls affecting the geodynamic processes. The first is tectonic uplift and the second is the climatic perturbation. There are periods when the two controls operate together. The evolution of the coarse clastic facies of the Upper Siwalik Subgroup has generally been attributed to tectonic activity. Climatic perturbations linked to various episodes of climate changes, must, in part, have exercised a control along with tectonics for the deposition of the large volumes of the conglomerates of the Upper Siwalik Subgroup.

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