Wave-generated structures in the Siwalik rocks of Tista valley, eastern Himalaya: implication for regional palaeogeography

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The Siwalik foreland deposit was earlier considered as freshwater continental megafan deposit, formed by southward flowing transverse drainages, analogous to modern Kosi-like megafans. However, this analogy remained incomplete due to lack of evidence of a regionally persistent axial stream system or marginal marine depositional system, like the Ganga–Brahmaputra River and Ganga Delta, as in the present-day foreland basin. In this paper, we report the abundant wave-generated structures and marine trace fossils from the Siwalik succession of the Tista valley and infer that they represent the deltaic part of the Neogene foreland basin. This interpretation provides the link between upland fluvial deposits of the western Himalaya and deep marine sediments of the Bengal Fan and is more consistent with available data from the Siwaliks of the eastern Himalaya. It also implies that a marine embayment existed in the eastern part of the Siwalik foreland basin.

Keywords: Deltaic sedimentation, Himalayan foreland basin, sedimentary facies, Siwalik group, Tista valley.

SIWALIK rocks were deposited in the peripheral foreland basin that formed on the southern flank of the rising Himalayan mountain belt following collision between the Indian and Tibetan plates[1]. The structure, sedimentology, vertebrate palaeontology, palaeomagnetism, provenance and tectonic evolution of the Siwalik foreland basin have been studied in different parts of the western Himalaya and Nepal[2–8]. However, in comparison, Siwalik rocks in the eastern Himalaya are much less studied. Sedimentological studies of the Siwalik succession in western and Nepal Himalaya have identified Siwalik succession as meandering to braided stream deposits in a Kosi-like megafan system[4,9–13]. The channel-fill sandstones in these successions are interlayered with purple mudstones with calcareous concretion-bearing palaeosols inferred to have formed in the associated flood plains. However, a preliminary examination of the Siwalik sediments in the eastern Himalayan sector indicates significant differences in the characteristics of these rocks from that of its type section in the western Himalaya. The major differences include remarkable absence of freshwater vertebrate fossils and purple mudstones with pedogenic calcareous concretions. Also, the presence of thick, dark grey mudstones and abundance of wave-generated structures have already been reported from the eastern Himalaya[14,15]. Moreover, lack of evidences of a major axial drainage system or a marginal marine environment in the succession hinders a comprehensive understanding of the Himalayan foreland basin over the length of the foreland, linking it from the mountainous sources to the deep marine Bengal fan system.

In this context, we undertook a sedimentological study of the Siwalik rocks of the eastern Himalaya. One of the main purposes of this study was to explore the depositional environment of the Siwalik Group of rocks in the eastern Himalaya to develop a basin-wide palaeogeographic picture of the Neogene foreland basin. In this communication we focus mainly on the presence of abundant wave- or combined wave- and current-generated-structures from the study area (Figure 1 *b*). We also report here the occurrence of a large number of trace fossils of marine affinity and discuss the implication of these features in terms of depositional environment and palaeogeography of the Siwalik foreland basin.

Geological background and previous studies

The Siwalik succession in the Darjeeling–Sikkim Himalaya is bound on the north by the Main Boundary Thrust which brings up Permian Gondwana rocks against it. The south of the exposure belt is defined by the Quaternary sediments that in many exposures unconformably overlie the Siwalik rocks[16,17]. The Siwalik succession of the Tista valley, in keeping parity with that in the western Himalaya, has been classified into three major units, comparable with the upper, middle and lower Siwaliks of the type area. In the foothills of the Darjeeling–Sikkim Himalaya, these divisions, in a stratigraphically ascending order, are named Gish/Chunabati Formation, Geabdat Formation and Parbu Grit and Murti Boulder Bed[16] (Table 1). The bulk of the Siwalik exposures of the area has been mapped as the Geabdat Formation (Figure 1). Parbu Grit

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Table 1. The lithostratigraphy of the Siwalik Group in the Darjeeling–Sikkim Himalayan region[16]. (Modified after Acharyya, 1976)

Age	Generalized lithostratigraphy	Formation	Description
Pliocene	Upper Siwalik	Murti Boulder Bed	Crude bedded and channelled immature pebble conglomerate and pebbly sandstone
		Parbu Grit	Pebbly sandstone and coarse-medium sandstone
U. Miocene–Pliocene	Middle Siwalik	Geabdat sandstone	Medium-coarse sandstone and shale clast beds and local pebbly beds, shale and minor marl.
Mid Miocene	Lower Siwalik	Gish Clay/Chunabati Formation	Fine-medium sandstone, siltstone, claystone, occasionally variegated in colour, bedded and nodular marl.

occurring at the topmost part of the Siwalik succession of this area, comprises thick beds of pebbly sandstone and interlayered thinner pebble conglomerate beds[16–18]. However, the Chunabati Formation is not exposed in the Gish River or in the adjacent Ramthi Nala sections, the main area of the present study (Figure 1). The Siwalik succession of the study area is folded towards the southern end of the Tista, Ramthi and Gish River sections, and these south to south-east dipping strata define an asymmetric anti-formal fold in the frontal part of the Siwalik succession (Figure 1 *b*). A generally coarsening upward trend, similar to that reported from the western and central Himalaya, is observed in all the Siwalik sections of our study area. The Geabdat Formation exposed along the Gish River and Ramthi Nala sections, is characterized essentially by a succession of alternating fine- to medium-grained sandstone and mudstone, with thin pebble layers at places. The thick units of coarse-grained, pebbly sandstone and interlayered beds of pebble conglomerate become increasingly abundant towards the top of the succession and have been mapped as the Parbu Grit Formation of the Upper Siwalik Subgroup (Figure 1).

One of the first sedimentological studies of the Siwalik succession in the Tista valley inferred these rocks as coalesced alluvial fan deposits prograding to the south[18]. A polymodal palaeocurrent pattern with high dispersion and a significant mode to the north was recorded by the authors of this study[18]. However, such palaeocurrent pattern is difficult to reconcile with their southward prograding coalesced alluvial fan model. More recent sedimentological analysis of these rocks also inferred this succession as representing the proximal, medial and distal parts of an alluvial fan[19–21]. Other recent work reported substantial fine-grained and heterolithic facies from these deposits and, suggested deposition in the point bars or interchannel floodplain facies[21,22].

Methodology

During this study a detailed sedimentological log of the 1.3 km succession of the Siwalik rocks exposed in the Gish River was prepared, documenting the details of lithology, grain size, sedimentary structures and trace fossils. We excluded the southern-most part of the exposed section that forms the southern limb of the asymmetrical fold to avoid structural repetition of strata and confined the measured log in the north-dipping homoclinal part of the exposure belt. About 550 palaeocurrent vectors were measured from the Gish River and Ramthi Nala sections (Figure 1 *c*). The axes of the small asymmetric folds, mentioned before, broadly coincide with the strike of the north dipping strata. All the palaeocurrent data were tilt-corrected by rotating the depositional surface along their strike through the existing formation dip (mostly dipping 15°–40° towards NNW). The rose diagrams were prepared using methods described by Cheney[23] and the program developed by Kutty and Ghosh[24].

Sedimentary structures

Wave ripples

Individual ripples display a near symmetric to slightly asymmetric profile and internal laminations that show draping over adjacent sets, transition from dipping foresets to sub-horizontal laminae, form-discordance and bi-directionality in the foresets (Figure 2 *a* and *c*). The individual ripples vary in height from a few mm to 2 cm with the maximum thickness of rippled sandstone being 0.4 m. In plan view they show straight, bifurcating and joining crests lines. Limited number of plan view exposures show that the mean crest orientations of the wave ripples vary from NE–SW to NNW–SSE (Figure 1 *c*). The wave ripples at many places form a climbing ripple unit that are up to 0.35 m thick.

Internal features of ripples like symmetrical profile view, draping of the foresets, form discordance and their straight, bifurcating and joining crest line in plan view, indicate that they formed as wave or combined wave-current ripples[25–27]. The climbing combined wave-current ripples formed in a high aggradational setting with a superposed weak unidirectional current.

Low-angle trough cross-sets

Low-angle trough cross-sets are one of the dominant sedimentary structures in the well-sorted, fine-grained sandstone units of the Geabdat Formation in the study

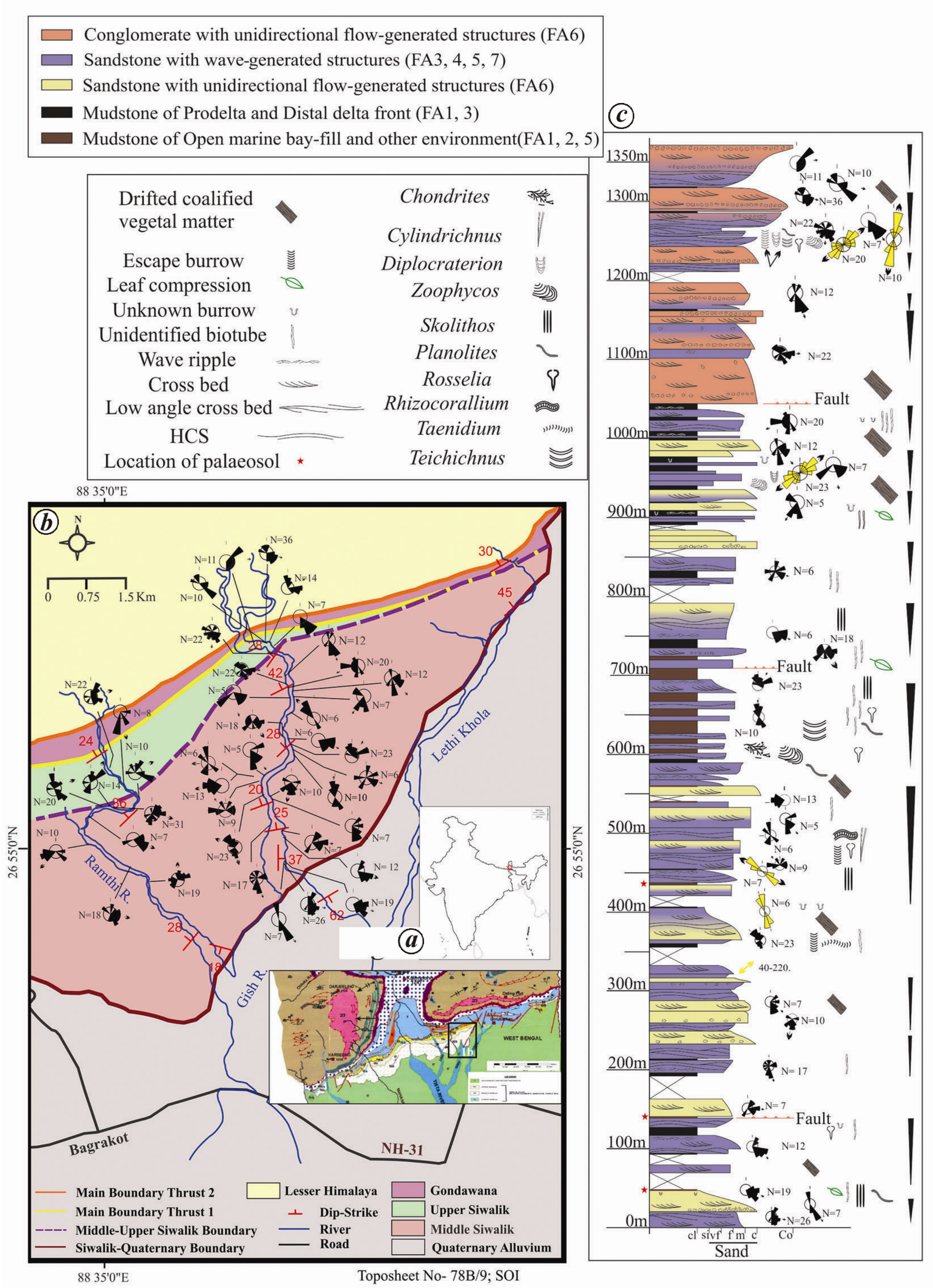

Figure 1. ***a***, A generalized geological map of the Sikkim Himalaya (after Basu[17]). The black rectangle marks the position of the study area shown in Figure 1 *b*. ***b***, Palaeocurrent map of the Siwalik succession in the Gish and Ramthi River. Note the bedding orientations show a general dip of the succession to the N–NW and a reversal of the dip direction at the southern extremity of the exposure belt. In most of the exposures, tilt-corrected palaeocurrent rose diagrams show a high dispersion and a significant component of the palaeocurrent to the north. ***c***, A vertical log of the Siwalik succession exposed along the Gish River showing lithology, sedimentary structure, palaeocurrent and trace fossils observed. The roses with yellow petal indicate trend of wave-ripple crests whereas those with black petals indicate palaeoflow direction measured from cross-strata.

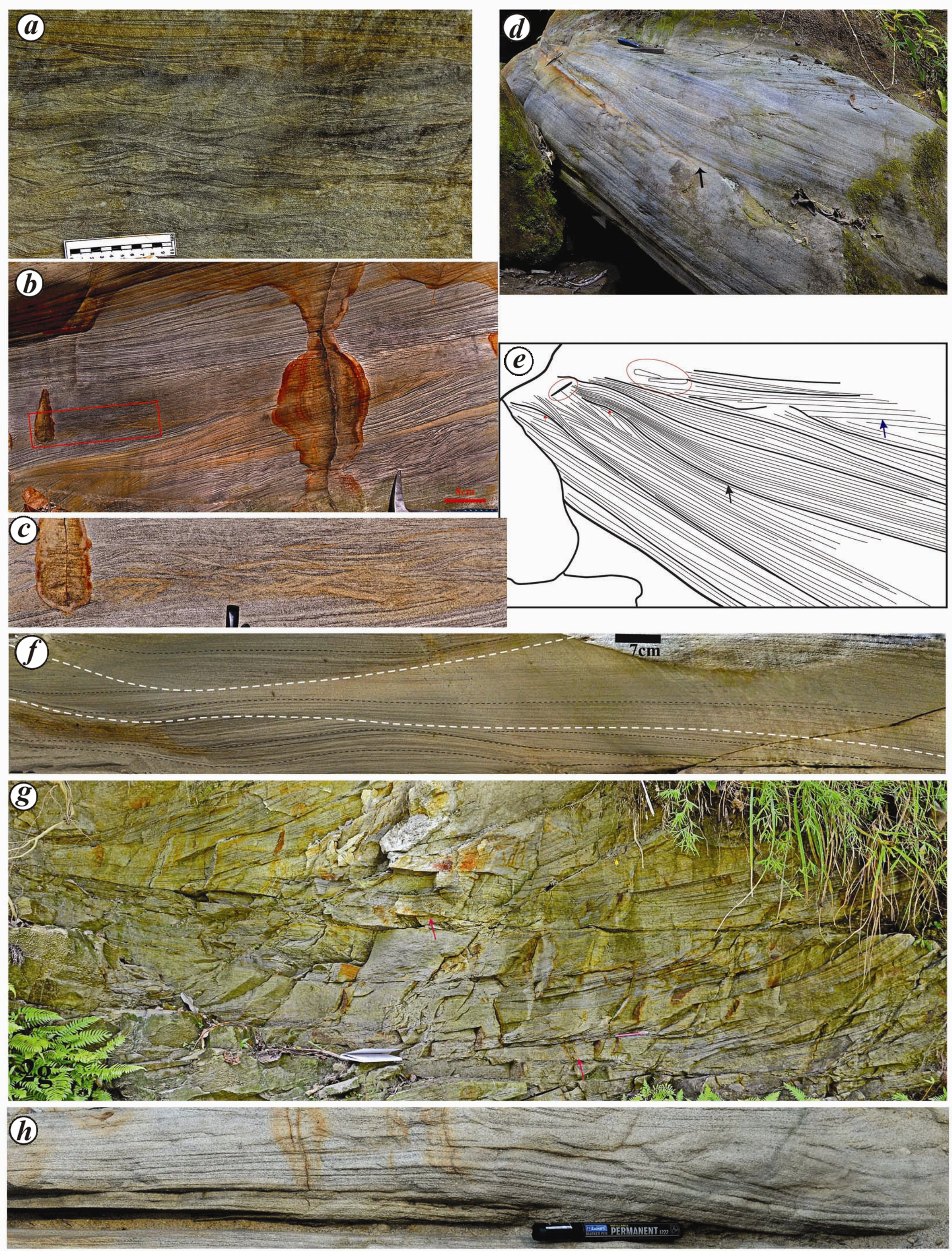

Figure 2. ***a***, Wave ripple lamination in the Gish River section; ***b***, Interlayering of low-angle cross-strata and wave ripple lamination (marked by red box shown in details in Figure 2 *c*), Gish River section; ***c***, Close-up view of wave ripple lamination, marked by a red box in Figure 2 *b*, Gish river section; ***d***, The low-angle and hummocky-swaley stratification, Gish River section; ***e***, Sketch of photo shown in 2d. Note gently undulating erosion surfaces (black arrow); low-angle cross-strata grading into low-amplitude uparched hummocky strata (red arrows) and systematic lateral thickening of strata producing fan shaped patterns, blue arrow marks a cross-stratification overlying the hummocky strata; ***f***, Hummocky cross-stratification in fine-grained sandstone; note 3rd order surfaces (black dotted lines) are parallel to the lower boundary of 2nd order erosional surfaces (white dotted lines), also thickening of the 3rd order surfaces in the swales and thinning of them in hummocks, Ramthi Nala section; ***g***, Coset of combined-flow dune cross-strata showing low dip of the foresets, lack of well-defined coarse-fine alternation in the foresets and long tangential base of each of the foresets (pink arrows). Churanthi River section; ***h***, An aggrading hummocky cross-strata, left bank of the Tista River section.

area. Grain size analysis of five representative samples of this facies indicates that mean grain size varies from 1.4ϕ to 3.5ϕ (medium to very fine) and sorting range from 0.50ϕ to 0.64ϕ (moderately well sorted)[28]. The individual trough cross-sets are 15 to 40 cm thick and occur in bed-sets 0.4–1.2 m thick. The low-angle trough cross-strata have the following characteristics: (1) Foreset dip is ~15° or less (Figure 2 *b* and *g*); (2) foresets are typically fine-grained and lack alternating, graded, coarse-grained avalanche sets (Figure 2 *g*); (3) foresets continue as the low-angle bottomset strata for a significant distance (Figure 2 *g*); (4) low-angle truncation common in foreset and bottomset strata; (5) At places, low-angle cross-strata laterally grade/interlayer with wave ripple laminations (Figure 2 *b*); (6) in rare instances rhythmic mud drapes are associated with cross-sets; at places, these structures are interlayered with plane parallel strata and hummocky and swaley strata. In some exposures, the low-angle cross-sets are closely followed upward by coarse-grained sandstone showing angle-of-repose cross-strata. The palaeocurrent data collected from the low-angle foresets of these cross-beds yield a highly variable flow direction (Figure 1). Synsedimentary deformation is common in the low-angle cross-stratified sandstone.

The interlayering of cross-strata with wave ripples, hummocky/swaley cross-strata imply that these trough cross-beds developed in wave-agitated environment. Low dip of the foresets, lack of coarser avalanche-formed foresets and long toe sets indicate that the precursor bedforms had a gently dipping lee slope and much of the sedimentation was from suspension settlement. Such bedforms typically form in combined wave-current flow regime[27,29,30]. Flume experiments suggest that the lee side dip of these combined oscillatory and unidirectional current (combined flow) generated dune bedform varies between 14°–24° (less than the angle of repose)[29] and in compacted rock record, this dip amount should be probably of the order of ~15° or less[31]. As documented in laboratory wave tunnels, much of the sedimentation on the lee of these bedforms occurs from settlement of a suspension cloud that forms due to reversing flow component of the oscillatory flow[27,29]. The long toe of the low-angle trough cross-beds in the Siwalik outcrops clearly demonstrates high rate of suspension settlement during their formation. Vertical interlayering of these low-angle trough cross-bedded fine-grained sandstone with coarse-grained sandstone with angle-of-repose cross-strata indicates that unidirectional flow at times pervaded these wave-agitated environments.

Hummocky and swaley cross-strata

These bedorms are defined by low-amplitude up- or down-arched lamina set (Figure 2 *d–f* and *h*). The dip of convex- or concave-upward laminae is usually less than 10° and generally becomes flattened away from the broad low-domes or hollows (Figure 2 *f* and *h*). Three-dimensional views of this structure show that the appearance is similar in all cross-sectional orientations. Low-angle erosion surfaces separate sets of strata, and when traced laterally the subtle erosion surfaces become concordant to the overlying and underlying strata (Figure 2 *f* and *h*). Lateral thickening and thinning of laminae at places produce a fan-like pattern (Figure 2 *d–f*). Parting lineation is common on bedding planes of the low-angle strata. Wave-length and amplitude of the hummocky/swaley features range from 115 to 195 cm and 7.6 to 14 cm respectively. At places, the undulating strata overlie flat erosion surfaces marked by mud chips and are overlain by wave ripple laminated units.

The undulating strata described above meet all the four characters of the hummocky stratification, namely, (a) <15° dip of the undulating erosional lower boundary that become concordant when traced laterally, (b) low-angle internal laminae that parallels the erosional undulating surfaces, (c) lateral thickening or thinning of the laminae producing fan-like shape, and (d) variable dip direction of the internal strata and the erosional bounding surfaces[32]. Similar structures have been produced in the laboratory wave ducts using both purely oscillatory and combined flow[29,30,33,34]. Laboratory experiments show that hummocky stratification forms in fine-grained sands under the influence of moderately long period waves with high oscillatory flow velocity and weak superposed unidirectional current ($T = 7$ sec; U_o = >50 cm/sec; U_u = <10 cm/sec)[29,30,34]. Such wave conditions are typical of storm waves in shallow marine/lacustrine setting.

All the above-mentioned wave-generated structures are common in the fine- to medium-grained sandstone of Geabdat Formation, as exposed along in the Gish and Ramthi River sections. More than 47% of the 1.3 km thick succession of the Siwalik Group along the Gish River section (Figure 1 *c*) is made up of these three structures clearly indicating a strong wave-dominance in the depositional environment in the study area.

The other sedimentary structures, noted in the succession, are high angle (angle-of-repose) planar and trough cross-beds in coarse-grained to pebbly sandstone, stratified to massive pebbly conglomerate and thinly laminated and bioturbated mudstone. As mentioned earlier, pebbly sandstone at many places interlayers with fine-grained low-angle trough cross-stratified sandstone.

Palaeocurrent

More than 550 palaeocurrent vectors were measured from low-angle trough cross-beds and angle-of-repose cross-sets in the Gish river section and adjacent Ramthi Nala section. The measured palaeocurrent vectors were rotated for appropriate tilt correction and were plotted in the rose diagrams. Figure 1 *b* and *c* depicts the exposure-wise rose diagrams of the palaeocurrent data. The palaeocurrent patterns throughout the Siwalik succession show a wide range of flow directions. It should be noted that south, southeast or southwest palaeoflow are dominant in many of the exposures. However, a majority of the exposures show a high dispersion of palaeocurrent vectors covering almost the entire compass dial. Also note that in many exposures there is a significant northward component of palaeocurrent vectors (Figure 1 *b* and *c*). In many cases, the rose diagrams show a bipolar pattern. Such palaeocurrent pattern is difficult to reconcile with a southward prograding alluvial fan model envisaged by some of the previous workers[18–21]. It is extremely unlikely that the streams emanating from Himalayan mountain belt and forming southward prograding alluvial fans will show, at different stratigraphic intervals, a significant component of palaeocurrent vectors pointing to the north. It is well-known that a mean palaeoflow direction measured from a fluvial deposit follows the regional slope. However, current system in a shallow marine setting is inherently much more complex due to mutual superposition of onshore–offshore component of the wave-induced flow, tidal current and long-shore drift[35,36]. Therefore, the palaeocurrent pattern observed in the Siwalik succession is more congruent with a shallow marine depositional regime than a fluvial setting.

Fossils and trace fossils

Both coalified and silicified vegetal materials are abundant throughout the succession. Bark, leaf compression and impression, drifted tree trunks are common. Several drifted large plant stems (up to 1.5 m long) are preserved in bedding plane. A significant number of palynotaxa are reported from this area. Diverse types of palm pollen grains, e.g. *Palmidites naviculus*, *Palmaepollenites* sp., *Arecipites indicus*, *Neocouperipollis* sp. and *Dicolpopollis* sp. have been recovered from the dark grey shale beds in the lower-middle part of the Geabdat Formation of the Churanthi River section, about 4 km west of the Gish River section. Pollen grains of *Palaeosantalaceaepites* sp., *Zonocostites* sp. (Rhizophoraceae), *Malvacearumpollis* sp. (Malvaceae), *Araliaceoipollenites* sp. (Araliaceae) and isolated salt glands of mangrove plant leaves (*Heliospermopsis siwalikii* and *Heliospermopsis* sp.) have also been retrieved along with the palms. This palynoassemblage demonstrates the presence of brackish water in a possible nearshore marine environment[37,38].

Mallett had reported a *Venus* sp.[39], which indicates a brackish water influence. A number of planktonic foraminiferal assemblages that include *Globorotalia opima nana* BOLLI, *Globorotalia obese* BOLLI, *Globigerina* cf. *ciperoensis* BOLLI, *Globigerina* spp. have been reported from Chunabati Formation of the Tista River section[40]. We did not find any body fossil from the Siwalik succession of the Tista valley but the trace fossils are common to abundant in most of the exposures, particularly in heterolith and ripple laminated sandstone[38]. Trace fossils, so far identified from the Siwalik deposits of the Tista valley, are *Cylindrichnus*, *Chondrites*, *Rosselia*, *Taenidium*, *Skolithos*, *Planolites*, *Rhizocorallium*, *Diplocraterion*, *Ophiomorpha*, *Skolithos*, *Planolites*, *Taenidium*, *Zoophycos* (Figure 3), reported from a broad range of depositional environment, spanning from continental to shallow marine depositional milieu. Thus, these traces cannot be used as indicator of specific environment. However, *Cylindrichnus*, *Rosselia*, *Rhizocorallium*, *Chondrites*, *Zoophycos* are known to be diagnostic of marine/brackish water environment[41,42]. However, instead of a single trace fossil an assemblage comprising the above mentioned traces as found in the Siwalik rocks of the study area strongly indicate marine environment in the Geabdat Formation.

Depositional environment of the Siwalik foreland basin

Sedimentary structures, palaeocurrent pattern, palynotaxa and trace fossils as documented above indicate a strong influence of wave processes and a coastal marine depositional environment for the Siwalik succession of the Tista valley. In the 1.3 km thick succession logged in the Gish River section we have encountered a wave-dominated shallow marine deposit as well as coarse-grained sandstone of fluvial origin. Based on physical sedimentary structures, trace fossils and palynotaxa, the Siwalik deposits of the study area have been divided into seven facies clubbed together into seven facies associations[15] (Tables 2 and 3). The facies associations indicate depositional regime varying from distal delta front, open marine bay fill to delta mouth bars and delta plain distributary channels[15] (Table 3). Similar depositional environment has been interpreted for the Siwalik Group of rocks exposed along the Dungsam Chu section of the eastern Bhutan[43].

The logged succession of the Gish River comprises three major parts (Figure 1 *c*). The lower 500 m of the succession is dominated by very fine- to medium-grained sandstone with few interlayered grey shale beds. The overlying 300 m of the succession is characterized by the dominance of mudstone with thinner interlayered fine-grained sandstone and the top most 500 m of the succession contains thick units of pebbly coarse-grained sandstone with thin pebble conglomerate beds interspersed with few fine sandstone-mudstone beds (Figure 1 *c*). Throughout the logged succession, the beds are repeatedly organized into 10–60 m thick coarsening-upward units in which the lower parts show abundance of mudstone/fine-grained sandstone with wave-generated structures, whereas the coarser sediments become more abundant in the upper part (Figure 1 *c*). Towards the upper part of the exposed Siwalik succession coarse, pebbly sandstone with unidirectional current-generated bedforms becomes more common. We interpret these 10 to 60 m coarsening-upward depositional units to represent typical progradational units of a delta succession where delta-front finer grained deposits are progressively overlain by delta mouth or distributary channel deposits[15,44] (Figure 4 *a*).

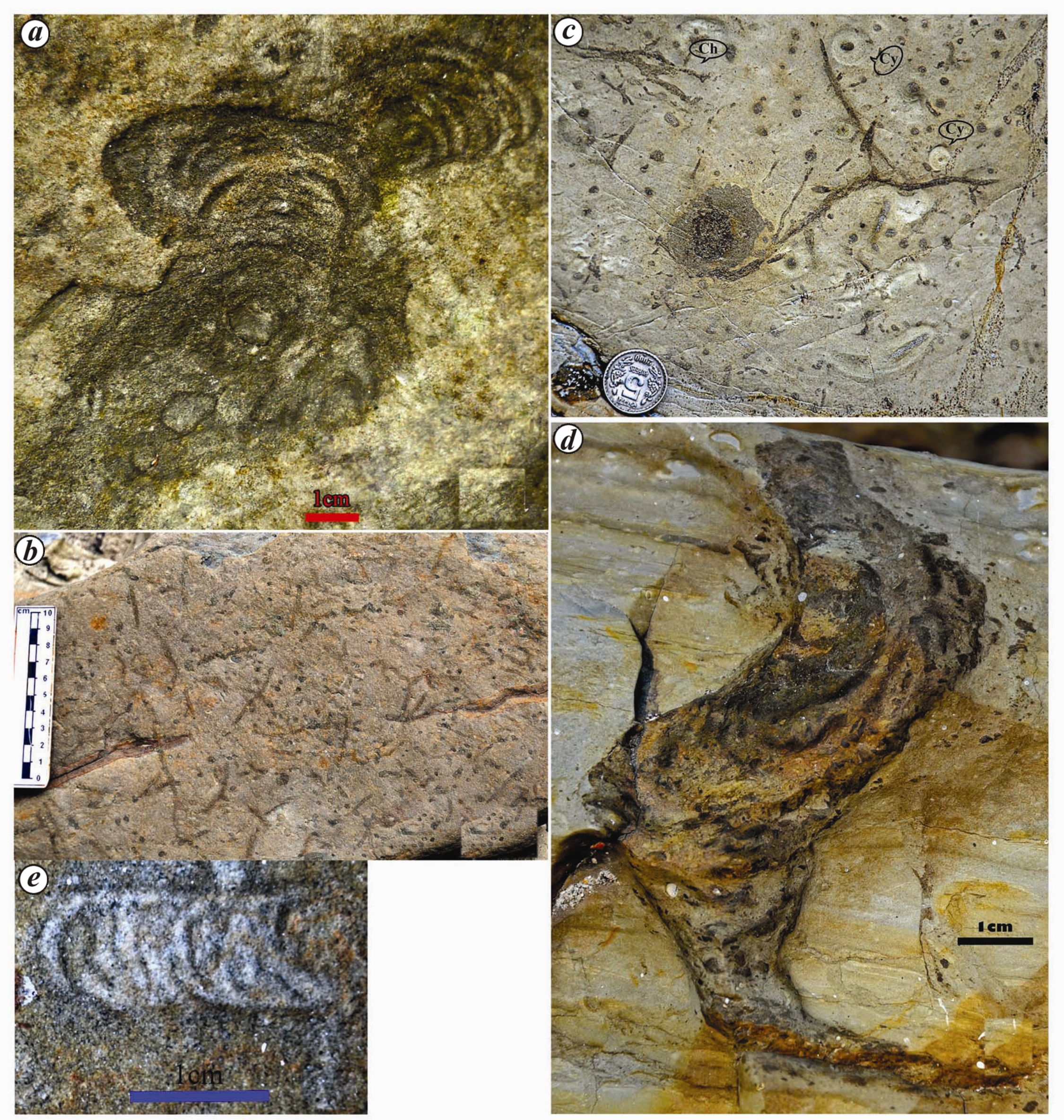

Figure 3. Trace fossils of marine affinity in the Siwalik sediments of the study area. ***a***, flat type, multilobate, *Zoophycos*, showing distinctive rooster-tail like structure, confined to sand-mud interface of F6; bedding plane view, Ramthi Nala section. ***b***, *Chondrites*, root-like small burrow systems (1–2 mm diameter) showing dendritic pattern, bedding plane view, Gish River section. ***c***, Bedding plane view of highly bioturbated very fine sandstone, Kalijhora section showing *Chondrites* (Ch) and *Cylindrichnus* (Cy). ***d***, *Rosselia*, conical, vertical burrow within thinly laminated marlstone; note a series of concentrically arranged conical layers nested convex downward, Tista River section. ***e***, A small *Rhizocorallium*, horizontal, U-shaped, spreiten structures exposed in mud-sand interface, bedding plane view, Gish River.

The overall coarsening upward trend of the Gish River section is similar to the Siwalik succession throughout the Himalaya[1,5,12] and is inferred to indicate a response of the Siwalik depositional system to the propagation of Himalayan thrust front (MBT and its spalys) to the south[1,6].

Discussion and conclusions

In Potwar Plateau, Himachal Pradesh and Nepal Himalaya, sedimentological studies have inferred deposition of the Mio-Pliocene Siwalik strata from a system of transverse drainage similar to those forming the megafans in the Ganga alluvial plain, the modern Himalayan foreland basin[5,10,45–48]. The reported palaeoflow with its radial south-east to south-west spread, coupled with the facies comprising different scales of channel-fill sandstone bodies, is used to infer a depositional setting similar to the Kosi megafan. Decades ago it was suggested that these transverse, megafan-forming drainages must have been joining an east-flowing axial drainage that took a southward turn at the Garo-Rajmahal gap to meet the precursor

Table 2. Facies of the Siwalik rocks, Gish River section, Tista valley

Facies	Description	Palaeocurrent	Interpretation
Clast-supported, massive to stratified conglomerate (F1)	Massive to parallel and cross-stratified (15–60 cm), cobble-pebble conglomerate (0.4–1.5 m) with interbedded pebbly sandstone; sharp base, at places erosive; tabular to lenticular units; sub-rounded to well-rounded clasts (quartzite, schist, gneiss), clast long axis up to 10.2 cm; intraclasts of mudstone and coaly matter common.	Southward flow	Stratification and locally erosively-based, lenticular units of conglomerate suggest traction transported deposits[58]; parallel stratified conglomerates resemble stratification of gravelly longitudinal bars [59]; cross-stratified conglomerates probably formed as bar-flank or in channel deposits; the massive conglomerate beds might represent hyperconcentrated or low viscosity mass flow deposit.
Cross-bedded coarse sandstone (F2)	Fine to coarse, cross-bedded sandstone (0.1–1.1 m); at places, set thickness decreases upward; basal erosional surfaces, at places, are undulating and strewn with pebbles/mud clasts; at other places these erosional surfaces are flat with diffused pebbles; commonly interlayer with F1 units but in many places cross-strata grade into wave-generated structure of F3 and F4; Soft sediment deformation present in this facies.	Mean directions to SE, S, SW; Unimodal, bimodal to polymodal.	Erosional base and upward decreasing set thickness probably denote deposition from migrating 3-D dunes in channelized unidirectional flow. Diffused nature of pebbles over flat erosional surface at some places together with their upward gradation to wave-generated structures probably imply emplacement of the channel in sub-aqueous condition, as in case of terminal distributary channels[44].
Low-angle trough cross-stratified sandstone facies (F3)	Well-sorted, fine- to medium-grained sandstone with low-angle trough cross-strata having following characteristics: (1) Foreset dip is ~15° or less; (2) foresets are typically fine-grained and lack alternating, coarse-grained avalanche foresets; (3) foresets continue as the low-angle bottomset strata for a significant distance; (4) low-angle truncation common in foreset and bottomset strata; (5) At places, low-angle cross-strata laterally grade/interlayer with wave ripple laminations; Soft sedimentary deformation common.	Polymodal pattern often with significant modes in the northern quadrant	Low dip, absence of avalanche foresets and gradation with hummocky bedforms and wave ripples indicate deposition from asymmetric 3d dunes formed under combined flow[29,30]. Brackish water influence is also indicated by trace fossils and palynofossils[38,41,42]. Many of the low-angle bottomsets resemble quasi-planar lamination inferred to have formed under combined flow condition[60]. Such bedforms are omnipresent in shallow shelf and coastal areas.
Hummocky cross stratified sandstone (F4)	Fine sandstone showing low-amplitude, up- and down-arched strata; in different sections the geometry of the strata show similar pattern suggesting presence of low dome and basin structure; low-angle (<10°) strata imperceptibly grade into flat-bedded strata and vice versa; individual strata thicken and thin laterally, resulting in fan-like appearance; low-angle internal discordance surfaces common that become conformable when traced laterally; parting lineation on bed surfaces present at places.	–	Large wave-length 3D dome and basin geometry, low-angle erosional surfaces that become concordant laterally, lateral thickening and thinning of strata and parting lineation on the laminations are typical of hummocky stratification[32,33]. These structures have also been reproduced in laboratory flumes under purely oscillatory and combined flow regime[29,33] and are believed to be related storm waves in shallow seas.
Ripple laminated sandstone-siltstone (F5)	Very fine- to fine-grained sandstone and siltstone beds with ripple lamination; individual strata a few mm to 2 cm thick; individual facies units 12 to 40 cm thick; ripples are dominantly wave and combined-flow types, locally these form climbing-ripple beds.		Migration of small ripple bedforms under a combined flow regime; climbing ripples indicate high suspension settlement during ripple migration.
Laminated dark grey mudstone with thin layers of siltstone and fine sandstone (F6)	Thick units of laminated dark grey shale, at places with interlayered fine sandstone-siltstone. Siltstone-sandstone strata few mm to 3.5 cm thick and wave rippled; mudstone beds 5 to 50 cm thick. Some of the silty layers intensely bioturbated whereas some other intervals show sparse or no bioturbation; large cylindrical biotubes of unknown origin are common; Locally intense soft sedimentary deformation present.		Grey shale deposited from suspension in quiet water environment; periodic incursion of fine sand was marked by wave agitation of different intensities. Some of the layers were colonized by marine organism producing trace fossils; rapid sedimentation and density contrast result in soft sediment deformation. Similar facies are common in the distal delta front or lower shoreface environment[25].
Mottled massive mudstone (F7)	Brownish gray massive mudstone(90 cm–1 m); mottling varying between moderate yellow (5Y7/6) and pale yellowish orange (10YR8/6); bulk of the mudstones are dark grey (Gley1-N3); slickenside surfaces of widely variable orientation present; fracture surfaces are often covered with thin clay coating; massive lower part of the mudstone and intensity of fracturing increases up the section; thin sections show well-developed sepic-plasmic fabric; geochemical analysis shows up the units loss of base and concentration of immobile elements; Fe-concretions and burrows common.		Anglular blocks with surficial clay coating resemble soils peds; intense fracturing and mottling, abundance of variably oriented slickenside, sepic-plasmic micro fabric are typical shrink and swell fabric of the soils. Base loss and concentration of immobile elements are common in palaeosols. Mottled grey colour of the mudstones, Fe-concretions, general absence of calcium carbonate indicate that these are poorly drained gleyed palaeosols[61]

Table 3. Facies Association of the Siwalik rocks, Gish River section, Tista valley

Facies association	Facies	Description	Bed geometry	Palaeocurrent	Ichnofacies	Interpretation
FA1	Mainly F6, subordinate F5	Massive to laminated, dark grey, bioturbated mudstone (5–20 m) with subordinate marlstone and thin layers of wave rippled siltstone or very fine sandstone	Tabular	–	BI (Bioturbtion index) 0–4, rare occurrences of *Zoophycos*, *Planolites*, *Chondrites*	Prodelta
FA2	F6, F5, F3, F4, F2	Massive mudstone (1.5–5.7 m) with alternating very fine- to coarse-grained sandstone (0.5–6 m); abundant leaf impression and unidentified large cylindrical structures; wave ripples, low-angle strata and cross-beds well-developed; sandstones show both C–U and F–U trend.	Tabular	Bimodal to polymodal palaeocurrent	BI 2-4, root structures not identified, *Asteriacites*, *Rosselia*, *Planolites*, *Teichichnus*, *Rhizocorallium*	Open marine bay
FA3	F6, F3, F5 and F4	Flat sharp based, alternating mudstone (massive to laminated) and sandstones beds (low-angle trough *x*-strata, plane beds with common hummocks and swales), organized in coarsening- and thickening-upward successions. Mud: Sand ~1.8 to 0.3	Tabular	Bimodal to polymodal palaeocurrent with significant N-component	BI 0–5; Abundant *Conichnus*, *Cylindrichnus*, *Chondrites*, *Planolites*, *Rosselia*, *Rhizocorallium*, *Ophiomorpha*, *Skolithos*, *Zoophycos* and escape burrow, probable mantle and swirl structure	Delta Front; depending on the ratio of mud: sand the association is inferred to represent proximal or distal part of the delta front
FA4a	Mainly F2, F3 rare F4 and F5	Erosively based, fine- to coarse- grained sst, cross-strata, low-angle strata and rare swales; basal erosion surface flat, low relief and devoid of coarse lags; generally F-U; remarkable variation in grain size; minor mudstone present.	Sheet-like to channelized	Polymodal with a dominant direction to SE- to SW	–	Terminal distributary channel
FA4b	Dominantly F3, F5, F6 and subordinate F2, F4	Rippled, parallel laminated siltstone/v. f. sst, grading upward into low-angle trough cross-stratified med. sst; less common hummocks and swales, coarsening-up trend with flat sharp base.	Lobate	Polymodal palaeocurrent pattern with high dispersion	BI 0–1; Sparse *Skolithos*, *Diplocraterion* and Fugichnia	Mouth bar Delta Mouth
FA5	F5, F6 and F7	Organic material rich, dark gray mudstone, or mudstone-siltstone heterolith, interbedded with thin sst; rare palaeosols; abundant plant litter	Tabular	–	BI 1–3; *Planolites*, *Taenidium*, root traces, cylindrical biotube	Lower delta plain overbank
FA6	F1, F2	Pebbly, very coarse-grained, massive to cross-bedded sandstone to pebble conglomerate. This association form amalgamated sst/conglomerate units 10s of meters thick with erosive base grading upward into muddy units of FA5/FA7	Tabular to lenticular	Unimodal palaeocurent pattern show SE,S, SW direction	–	Distributary channel
FA7	F2, F3, F4, F5	Fine- to coarse-grained sandstone with thin layer or pockets of pebble; parallel lamination, low-angle trough cross-stratification with hummocks-swales and wave-ripple lamination.	Tabular	Highly dispersed polymodal palaeoflow pattern	BI 0–4, *Zoophycos*, *Rosselia*, *Teichichnus*, *Planolites* and sparse *Diplocraterion*	Braid-plain delta mouth/ delta front

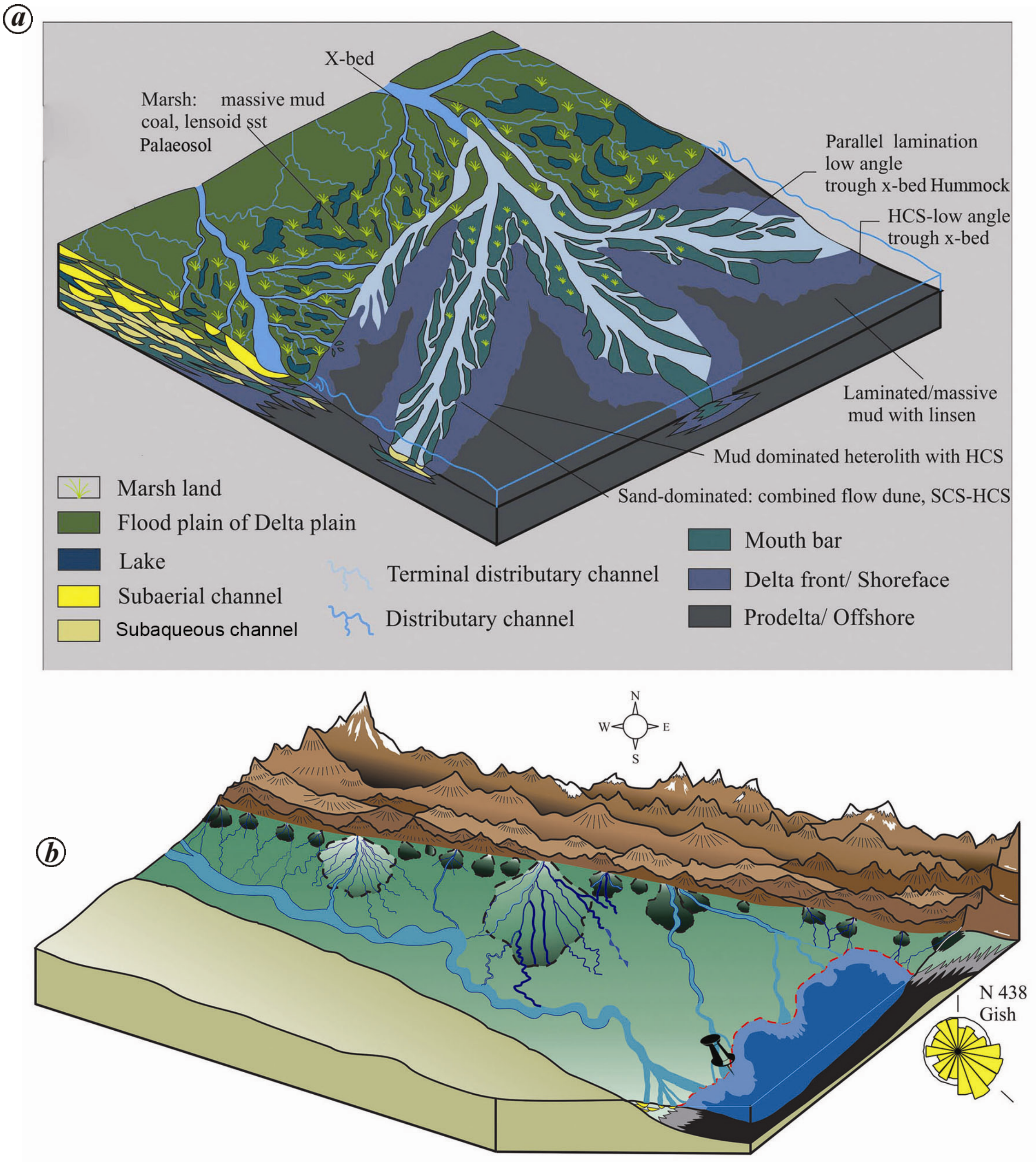

Figure 4. ***a***, Reconstructed paleogeography of a delta from the Siwalik rocks of the Tista valley. Sedimentary structures common in distributary channels, delta mouth bars, delta front and open marine bay are shown. ***b***, A generalized cartoon showing the regional paleogeography of the Siwalik foreland basin. Small alluvial fans and transverse megafans dominate the western part of the foreland; eastern part is dominated by a marine embayment and deltaic coastline. Part of the deltaic environment, marked by board pin illustrated in details in Figure 4 *a*. Rose diagrams show the clubbed palaeocurrent data measured from the Gish River section.

Bay of Bengal through a delta[49]. This suggestion was based on the consideration of geographic setting of the present-day Ganga Basin, inferred antiquity of the major rivers draining the Himalayas and contemporaneity of the Bengal fan deposits with the Neogene Siwalik sediments. So far, no major axial system has been recognized in the Siwalik deposits comparable with large rivers like Ganga or Brahmaputra, though at certain intervals of the Siwalik succession in the western Himalaya, palaeocurrent pattern sub-parallel to the exposure belt has been noted[12,50,51]. As a result, most of the reconstructed scenario and generalized depositional models of the Siwalik rocks emphasize on the transverse, megafan-forming drainage[8,45–47]. Though a marine deltaic sedimentation has been suggested by some workers[2,49], depositional features of a coastal marine setting has never been documented in the Siwalik succession. The deltaic deposition recorded from the Tista valley succession, as described in this paper, is the first detailed documentation of a coastal depositional setting from the Siwaliks and provides the link between sediments deposited by upland transverse drainage and deep marine fan sediments of the Bengal fan.

Our results imply that a marine embayment existed far north of the present-day coastline during the middle Siwalik time in the eastern Himalaya (Figure 4 *b*). Based on available data on the orientation of wave ripple crests that grossly mimic the orientation of the shoreline, the shoreline appears to be broadly N–S to NNE–SSW in the study area (Figure 1 *c*). The elevated sea level during middle Siwalik time must have invaded through the Garo-Rajmahal gap and flooded the foreland basin creating an embayment that extended to the north, near the present study area of the Tista valley. The broadly S to SE-ward flowing streams debouched into this marine embayment forming a delta during the middle Siwalik time.

As already mentioned, in the eastern Himalaya, instead of red mudstones, palaeosols with calcareous nodules, thick grey mudstone is common[14]. Marine bivalves (*Venus* species) and foraminifers have also been reported from the Siwalik succession of the Tista valley[39,40]. More importantly, a number of palaeobotanical studies have reported spore pollen from a number of sections in the Tista valley as well as from the east Bhutan and Arunachal Himalaya, which imply a brackish water influence in these deposits[37,43,52–56]. A similar study carried out in the Churanthi River section, about 4 km west of the Gish River section, has revealed the presence of a number of palm pollens and isolated salt glands of mangrove tree that indicate brackish water influenced coastal environment[38]. Recently, during the palaeomagnetic study of the Kameng River Siwalik section, extensive occurrence of mineral greigite and glauconite, a primary deposit in brackish water, was reported from the Kameng River section, Arunachal and Dungsam Chu section in eastern Bhutan[43,57]. Overall our sedimentological data from the Tista valley is consistent with all the evidence from lithology, invertebrate palaeontology, palaeobotany and mineralogical data from the eastern Himalayan Siwalik succession. This finding thus elucidates a more complete palaeogeographic scenario of the Siwalik foreland basin and provides the link between the record of upland transverse drainage and deep marine sediments of the Bengal fan. This palaeogeographic reconstruction has an important bearing in understanding the evolution of drainage pathways and basin subsidence in relation to the ongoing tectonics in hinterland orogenic belt. The petroleum explorations in these Neogene sediments are likely to be strongly influenced by the record of marine influence in these strata.

Conclusions

The following conclusions can be drawn from the study of Siwalik sediments in the Gish River section of the Tista valley:

(1) A gamut of sedimentary structures including wave ripples, hummocky and swaley strata, low-angle combined flow dune cross-strata indicate a wave-agitated environment in middle Siwalik Geabdat Formation of the study area.

(2) Sedimentary structures, vertical succession of strata, palaeocurrent pattern, trace fossils and palynotaxa are inferred to indicate a marine deltaic environment and strongly argues against a coalesced alluvial fan depositional environment as proposed by earlier workers.

(3) A deltaic interpretation of the Neogene foreland basin resolves a long-standing problem of basinal palaeogeography and provides a link between the deep marine sediments of the Bengal fan and upland transverse drainage recorded from the western part of the foreland basin.

(4) The palaeogeography reconstructed here has important bearing on the reconstruction of drainage pathways, contemporary basin evolution and petroleum prospect study of these successions.

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ACKNOWLEDGEMENT. The research was funded by Indian Statistical Institute and the work carried out during the tenure of a research fellowship from the Institute to S.T. and forms a part of her Ph D thesis.

Received 28 April 2016; revised accepted 12 April 2017

doi: 10.18520/cs/v113/i05/887-901