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Shallow subsurface stratigraphy and alluvial architecture of the Kosi and Gandak megafans in the Himalayan foreland basin, India

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ABSTRACT

The Kosi and the Gandak are two major Himalayan tributaries of the Ganga River in the north Bihar plains India. With a large hinterland in the Nepal Himalaya, both these rivers have generated megafans in the plains over the Quaternary time scale. Both these rivers are known to be highly dynamic and sediment-charged. A few conceptual models and limited field data suggested that these megafans have produced thick sand sheets over Late Quaternary period but these ideas have remained speculative and there is no data on the size and dimension of these sand bodies. This paper attempts to reconstruct the subsurface stratigraphy and alluvial architecture for the upper ~100 m of the megafans based on electrical resistivity soundings, borehole data and drill cores. Alluvial architecture of the Kosi megafan shows significant variability from proximal to medial parts of the fan in terms of sediment grain size and layer thicknesses. While the medial part shows ~20–30 m thick medium to coarse sand sheets which are laterally stacked, the proximal part of the fan has a dominantly gravel unit below ~15 m depth that is underlain and overlain by medium to coarse sand units. Further, the medial fan also shows significant vertical and lateral variability in alluvial stratigraphy. The near-surface (<20 m depth) deposits from the Kosi megafan have pockets of clay and silt within large amalgamated sand bodies whereas the shallow sub-surface (50–100 m depth) sediments are largely sandy and devoid of clay and silt pockets. Alluvial architecture of the Gandak megafan shows two major lithounits; the upper fan succession has a higher stacking density of smaller sand bodies perhaps reflecting the migratory behavior of the river whereas the lower succession shows narrow but thick sand fills reflecting incised channels. The western part of the Gandak megafan has more abundant sand bodies compared to the eastern side of the river along both transects. There are no significant differences between proximal and medial transects across the Gandak megafan. The absence of gravel deposits in the shallow subsurface of the Gandak megafan may be attributed to the presence of a prominent intermontane valley in the hinterland of the Gandak river which has acted as a 'sediment filter' thereby trapping most of the coarser fraction. On the other hand, the Kosi river exits directly through the mountain front, and therefore, has been able to transport gravels into the plains in pre-historic times. Our study thus suggests significant variability in subsurface stratigraphy of the Kosi and the Gandak megafans even though they are located in similar geographic region. Such differences are attributed to the geomorphic diversity of the mountain exits of these megafans and their sediment transport history.

1. Introduction

Fluvial megafans are distinct landforms on the earth's surface and are localized in specific climatic, geomorphic and hydrologic regimes. A 'megafan' has been defined as "a large (10^3–10^5 km^2), fan-shaped (in plan view) mass of clastic sediment deposited by a *laterally mobile river system* that emanates from the outer point of a large mountainous drainage network" (Goudie, 2004). A characteristic geomorphic aspect of megafans is the recognition of expansion of flow downstream of a drainage outlet through a branching distributary pattern of channels. In terms of geologic and geomorphic setting, the megafans generally form in areas of orogenic belt, aggrading river basins with high sediment flux, moderate to extreme seasonal discharge fluctuations (producing channel instability and fan shaped sediment lobes), adequate spacing between river exits from mountains to provide accommodation space (Gupta, 1997) and to allow channel shifting (Leier et al., 2005). In total, Leier et al. (2005) identified 33 megafans worldwide based on their specific characteristics

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such as a large sediment body, abandoned channels on the fan, and low slope etc. The authors also documented that the megafans are mainly localized between 15° to 35° latitude in both northern and southern hemispheres i.e. tropical zone and several workers have documented the morphological and hydrological characteristics of the rivers draining these fans (summarized in Latrubesse et al., 2005). Due to their unique geomorphic setting, climatic conditions, and complex sedimentary processes, the megafans have drawn enormous attention of researchers from all over the world. The avulsive shifts of rivers on the megafans have often caused severe floods (Assine, 2005; Sinha et al., 2008; Sinha, 2009; Bernal et al., 2011). Stratigraphic studies of the exposures of ancient megafans have also been carried out by several workers to understand their geological evolution and for comparison with modern megafans as their ancient analogs (e.g. DeCelles and Cavazza, 1999; Horton and DeCelles, 2001; Latrubesse et al., 2010). In a recent compilation of global database on geometries of fluvial channels and valley fills in the geological record, Gibling (2006) identified the megafan deposits as a distinct class on the basis of their geomorphic setting, geometry and internal structure and noted the lack of data on 3D geometry from modern settings. Gibling (2006) documented that the channel belts of the major river building the megafan such as the Kosi are characterized by extensive sand sheets typical of braided rivers exiting from active orogenic belt. On the other hand, the megafan surfaces are marked by avulsive and aggradational distributary systems, also of braided style, generating ribbons and narrow sheets. However, there are several other megafans such as the Chaco and Okavango in South America where braided systems and sand sheets are not typical or dominant (McCarthy et al., 1991; Assine, 2005; Latrubesse et al., 2010).

The Indo-Gangetic plains in the Himalayan foreland basin host several megafans namely, the Tista megafan in West Bengal (Chakraborty and Ghosh, 2010), the Kosi and Gandak megafans in north Bihar (Geddes, 1960; Gohain and Prakash, 1990; Mohindra et al., 1992; Sinha and Friend, 1994; Chakraborty et al., 2010) and the Sone megafan in south Bihar (Sahu et al., 2010). The Kosi and Gandak are two important megafans that have attracted global attention due to their large dimensions. The Kosi and Gandak rivers draining through these two megafans are characterized by very high suspended sediment fluxes (43 and 79 Mt/yr respectively), low stream power (6.4–20 W/m^2), low slope (0.01–0.05°), hyperavulsive behavior, and frequent flooding (Sinha and Friend, 1994; Sinha and Jain, 1998; Sinha et al., 2005; Sinha, 2009). It has been speculated that the avulsive shift of the rivers may have generated a distinctive stratigraphy below the fan surface (Wells and Dorr, 1987; Mohindra et al., 1992; Jain and Sinha, 2003). However, there is very little systematic data available on the sub-surface stratigraphy of these megafans due to the lack of exposures and sub-surface data.

This paper aims to reconstruct the subsurface stratigraphy of the Kosi and Gandak megafans in the Himalayan foreland basin to understand the spatial variability and inhomogeneity in the alluvial architecture developing below and the controlling factors. In particular, we attempt to answer two fundamental questions: (a) What are the spatial and temporal variability in alluvial architecture below the megafans, (b) What are the implications and causal factors for such variability in terms of sub-surface stratigraphic development e.g. mountain front setting, sediment flux, river dynamics? We have used, for the first time, an integrated approach of resistivity surveys coupled with the groundwater well data and drill cores across the fan surface for this study.

2. Study area description

2.1. General geography and climate

The Kosi River originates at an elevation of 5500 m in Tibet (Fig. 1) and has a very large upland area compared to the plains area (u/p = 5.3, Sinha and Friend, 1994). The river enters the plains at Chatra in Nepal and then flows for a distance of ~40 km to the barrage at Bhimnagar and another 40 km along the India–Nepal boundary before entering the north Bihar plains in India. The river follows a curved path from Bhimnagar to Mansi–Koparia railway line further downstream and then takes an easterly turn and runs parallel to the Ganga river for a distance of about 160 km before joining the into Ganga river near Kursela. The Kosi River drains the total area of 69,300 sq km with 29,400 sq km in China, 30,700 sq km in Nepal and 9200 sq km in India (Virgo and Subba, 1994).

The Gandak megafan is formed by the Gandak River which starts at an altitude of 6268 m from the Nhubine Himal glacier in Nepal close to the Tibetan border. It forms a confluence called Triveni Sangam with the river Pachnad and Sonha at a point close to the Indo-Nepal border. The river enters India in west Champaran district of north Bihar, builds a large megafan spanning into the plains of north Bihar and Uttar Pradesh and then joins the Ganga River near Hajipur.

The plains of north Bihar and Uttar Pradesh where both the megafans are located experience moderate to fairly high monsoonal rainfall of about 1000–1600 mm annually of which ~85% occurs in the monsoon season (June–September) itself. The upstream basin area of the megafans in the foothills receives higher rainfall (>2000 mm annually) (Sinha and Friend, 1994) and the main rains start earlier in this region than on the plains. The high mountainous catchments of both the Gandak and the Kosi megafans have distinctly drier climate and are covered by snow and ice all year.

2.2. Geomorphology of megafans

One of the early systematic geomorphic descriptions of the megafans in the Gangetic plains was provided by Geddes (1960) who showed, using closely spaced contours, that megafans have a positive topography. He used the term 'cone' to describe these features. Gole and Chitale (1966) described the Kosi megafan as 'inland delta' built by large sediment flux from the Himalayan orogen. The term 'megafan' was first used by Gohain and Prakash (1990). The average annual discharge of the Kosi at the most downstream station (Baltara) is 2236 m^3/s. Although a large part of the upper catchments of the Kosi is glaciated and a large proportion of sediment flux is intercepted upstream of the Kosi barrage, the average annual suspended sediment flux for the Kosi at Baltara (43 Mt/year; Sinha and Friend, 1994) is still quite high which results in rapid and extensive aggradation within the channel as well as the floodplains. For a total catchment area of ~88, 500 km^2 up to Baltara, modern sediment (suspended) flux of the Kosi is 0.43 Mt/km^2/yr. Such high sediment flux and rapid aggradation within the embankment have been considered as one of the primary reasons for avulsion and flooding in this region (Sinha, 2009; Chakraborty et al., 2010; Kale, 2011).

The vast plain, on which the Kosi megafan has formed, has a general slope from north to south and west to east, being steeper in the north (55–75 cm/km) and flatter in the south (6 cm/km). Thus, the entire fan surface is nearly flat, which is dissected by numerous 'dhars' (small channels) representing paleochannels of the Kosi river. Some of the paleochannels are vegetated and muddy due to monsoon water and dry season discharges. There are undulations and innumerable depressions called "chaurs" on the megafan surface, where water remains accumulated for most parts of the year. Some of these waterlogged patches in the lower reaches and close to the embankments are very large which may be related to seepage along the embankment but may partly represent accumulation of floodwater after overbank flooding.

Available historical records of last two centuries report that there has been a net (but not systematic) westward shift of the Kosi river by ~150 km across its fan surface during the last 200 years (Wells and Dorr, 1987; Mishra, 2008); however, several eastward shifts

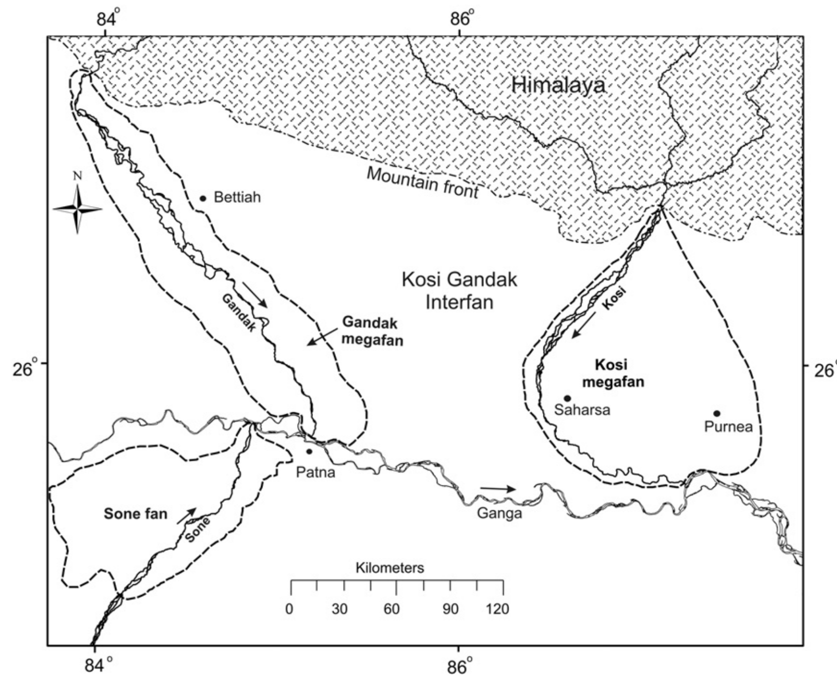

Fig. 1. Landsat TM image showing the Gandak and Kosi megafans in the Himalayan foreland basin. The Ganga is the axial river and both the Gandak and the Kosi rivers join the Ganga. A southern tributary of the Ganga, the Sone River, also forms a large fan and the area further east of the Kosi falls in the Tista megafan region (not see in the figure).

have also been documented including the recent avulsion in August 2008 (Sinha, 2009; Sinha et al., in press). The avulsive movements of the Kosi river have been described as autocyclic and stochastic (Mackey and Bridge, 1995; Stouthamer and Berendsen, 2007), which is typical of most alluvial fans across the world. However, the average avulsion frequency of 24 years for the Kosi is among the lowest in the world compared to 1400 years for the Mississippi river.

The Gandak River, one of the important rivers of Nepal and India, is also characterized by a high ratio of upland source area to plains ($u/p = 3.3$) and high discharge (1555 m^3/s at Dumariaghat) (Sinha and Friend, 1994). The Gandak river is braided throughout its alluvial course with braid channel ratios ranging from 1.33 to 5.38 (Sinha and Friend, 1994). Compared to the Kosi, the Gandak carries a much higher sediment load of 79 Mt/year and with a catchment area of only ~43,000 km^2, modern sediment flux (suspended) of the Gandak river works out to be 0.82 Mt/km^2/yr (Sinha and Friend, 1994). Mohindra et al. (1992) mapped various geomorphological units on the Gandak megafan and the adjoining areas and argued that the development of these geomorphological units was controlled by the climatic change, channel shifting and tectonics in the area over the last 10,000 years. It has also been documented that the Gandak has migrated over its megafan from west to east over a distance of about 80 km in 5000 years (Mohindra and Parkash, 1994) as evidenced from large number of abandoned, highly sinuous, meander loops and waterlogged patches in the lower part of the fan.

The interfan area between the Gandak and the Kosi megafans are drained by the Burhi Gandak, Baghmati, Kamla and Balan rivers that are flowing along south-eastward direction ultimately joining the Ganga in downstream (Sinha and Friend, 1994). Although much smaller in size, the interfan rivers have also been described to be very dynamic (Sinha, 1996; Jain and Sinha, 2003, 2004).

3. Approach and methodology

This study mainly relies on field investigations that include vertical electrical sounding (VES) and drilling of sediment cores. Apart from field data, the study also uses the remotely sensed satellite imagery and the groundwater borehole data as secondary dataset. Borehole data obtained from the Central Ground Water Board (CGWB) and State Groundwater Board (Fig. 2) were analyzed to obtain the first order assessment of the sub-surface stratigraphy of the fans. There are around 100 borehole data points for the Kosi region and 6 points from the Gandak area. The depth of boreholes for both Kosi and Gandak region varies from 15 m to more than 100 m. The main objectives of the borehole data analysis were to record (a) the variation in sub-surface lithology from proximal to medial/distal parts of the megafan, (b) the order of thickness of sand bodies and intermediate clay layers, and (c) the depth of gravely layer and presence of carbonate concretions (locally called 'kankar'). Although limited use of the borehole logs could be made for reconstructing alluvial stratigraphy as the data points were distributed all across the fan, this data was very useful to build a first order stratigraphy, to select transects for resistivity surveys and to calibrate the resistivity data.

For resistivity surveys, two transects were planned for the Kosi region, (a) proximal transect (Kus–Kus'), 6 km long having 4 VES points, and (b) medial transect (Kds–Kds'), 140 km long with a total of 33 points, and (Fig. 2). Similarly, two transects were planned on the Gandak megafan, one in the proximal part (near Bettiah) and another in the medial part (near Motihari). The length of each transect was ~20 km (~10 km on both sides of the main river) and the VES points were selected at ~2 km interval along both transects. A resistivity meter (Aquameter, CRM 500, ANVIC systems) was used for the survey in Schlumberger configuration with a maximum current electrode separation of 400 m in order to get shallow subsurface information as per the previous studies in similar settings (Yadav et al., 2010; Sinha et al., 2012). Yadav et al. (2010) have discussed the detailed methodology and techniques used for interpretation of resistivity data. One of the basic assumptions in most of the interpretation techniques is that the resistivity layers extend horizontally to infinity and are isotropic, homogeneous entities with distinct electrical resistivity contrast and thicknesses. Though all these conditions are seldom satisfied, these techniques are useful for inferring broad scale subsurface hydrogeological conditions.

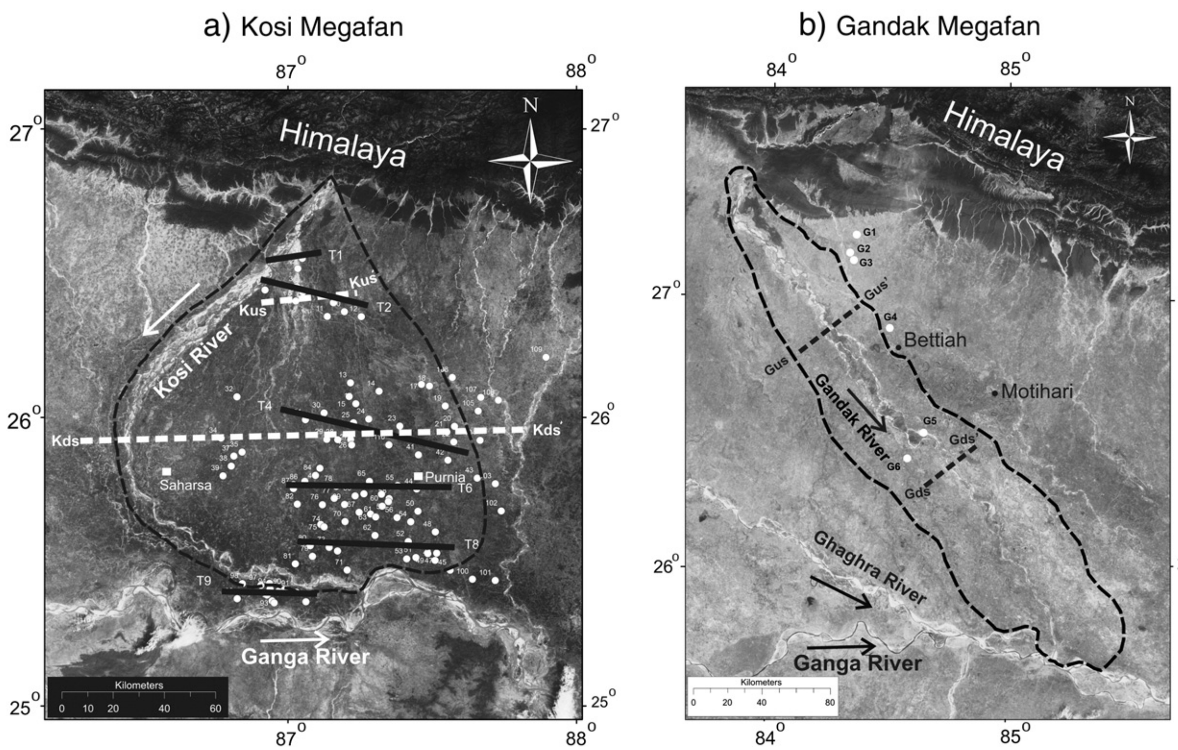

Fig. 2. Locations of groundwater borehole data analyzed from the (a) Kosi and (b) Gandak megafan region. Data for a few selected transects (T1, T2, T4, T6, T8 and T9) have been presented in this paper. Also shown are the proximal (Kus–Kus') and distal (Kds–Kds') transects for resistivity surveys.

Field data was first processed to generate a field curve which was matched with standard master curves for known layer parameters of 2-, 3- and 4-layers (Orellana and Mooney, 1966; Rijkswaterstaat, 1969). This was followed by computer-aided interpretation using 1X1D software developed by the Interprex Limited USA which primarily involved generation of a basic geoelectrical model at each site. Finally, the interpreted results were calibrated with the available lithological information (borehole data and drill cores) to determine resistivity ranges for different lithological units. In alluvial terrain, the stratigraphic boundaries are not always marked by sharp lithological variation and a good correlation may sometimes be difficult due to a variety of reasons viz. thin layers embedded in a thick layer of different material, variations in groundwater salinity. On the other hand, a single lithological unit may include a number of geoelectrical interfaces without any significant variation in its character. Finally, we have integrated all data to generate detailed alluvial architecture below both megafans along pre-defined transects.

4. Borehole data analysis for Kosi and Gandak megafans

4.1. Kosi megafan

Data for more than 100 boreholes for the Kosi megafan (Fig. 2) have been analyzed in different transects from upstream to downstream. Although all data was processed to understand the general distribution of lithology, we present here our analysis of a few selected transects from the proximal, medial and distal regions. Two proximal transects, T1, T2, have been characterized by three and seven boreholes respectively. The K1 and K5 boreholes along T1 transect show the presence of >50 m thick gravel layer starting at 7 m below the surface (Fig. 3a). The K4 borehole shows a coarse sand layer in the upper 30 m and gravels start below 30 m from the surface. There are 7 boreholes along the *T2* transect (Fig. 3a) and several of these boreholes show a mixture of coarse sand and pebbles/gravels at shallow depths (5–10 m). The upper few meters of lithology consists of fine sand and mud.

The boreholes along the medial fan transect, T4, provide information down to 10–20 m and only a few boreholes extend to ~50 m (Fig. 3b). The upper ~5 m of sediments along this transect primarily consist of mud and fine sand which is underlain by a mixture of coarse sand and some gravels/pebbles. Most of the boreholes show a fining upward sequence.

Fig. 3c and d shows two transects (T6 and T8) from the distal fan area and there are 10–12 borehole points of variable depth along each of them. Most of the boreholes along transect T6 provide information for the upper ~30 m out of which the top ~15 m consist of a mixture of silty sand and mud except a few (e.g. K85 and K40) which show 10–15 m thick fine to medium sand with a thin muddy cap. A majority of the boreholes show a fining upward succession with coarse sand layer at the bottom starting at variable depths (8–20 m) which seems to continue to deeper levels. Transect T8 has 10 borehole points and several of them go down to ~75 m depth (Fig. 3c). These boreholes show variable lithology and the only common point is the presence of a coarse sand layer at depth as shallow as 10 m (K79) and as deep as ~50 m (K81). The upper 5–10 m of sediments are invariably muddy or fine sand or a mixture of the two that is comparable to the modern sediment load of the Kosi River in this reach.

Apart from transects discussed above, there are several boreholes available from the confluence zone of the Kosi and the Ganga rivers and they provide information for the upper ~100 m of the stratigraphy and almost all logs are clearly divisible into two distinct units (Fig. 3e). The upper 30–40 m of the succession primarily consist of fine sand with a muddy cap. A sharp change in lithology is noted below 30–40 m depth and the lower unit consists of a coarser unit made up of fine gravels and carbonate nodules in a matrix of coarse sand. In some of the boreholes, this lithology continues down to ~100 m depth intervened by find sand layers.

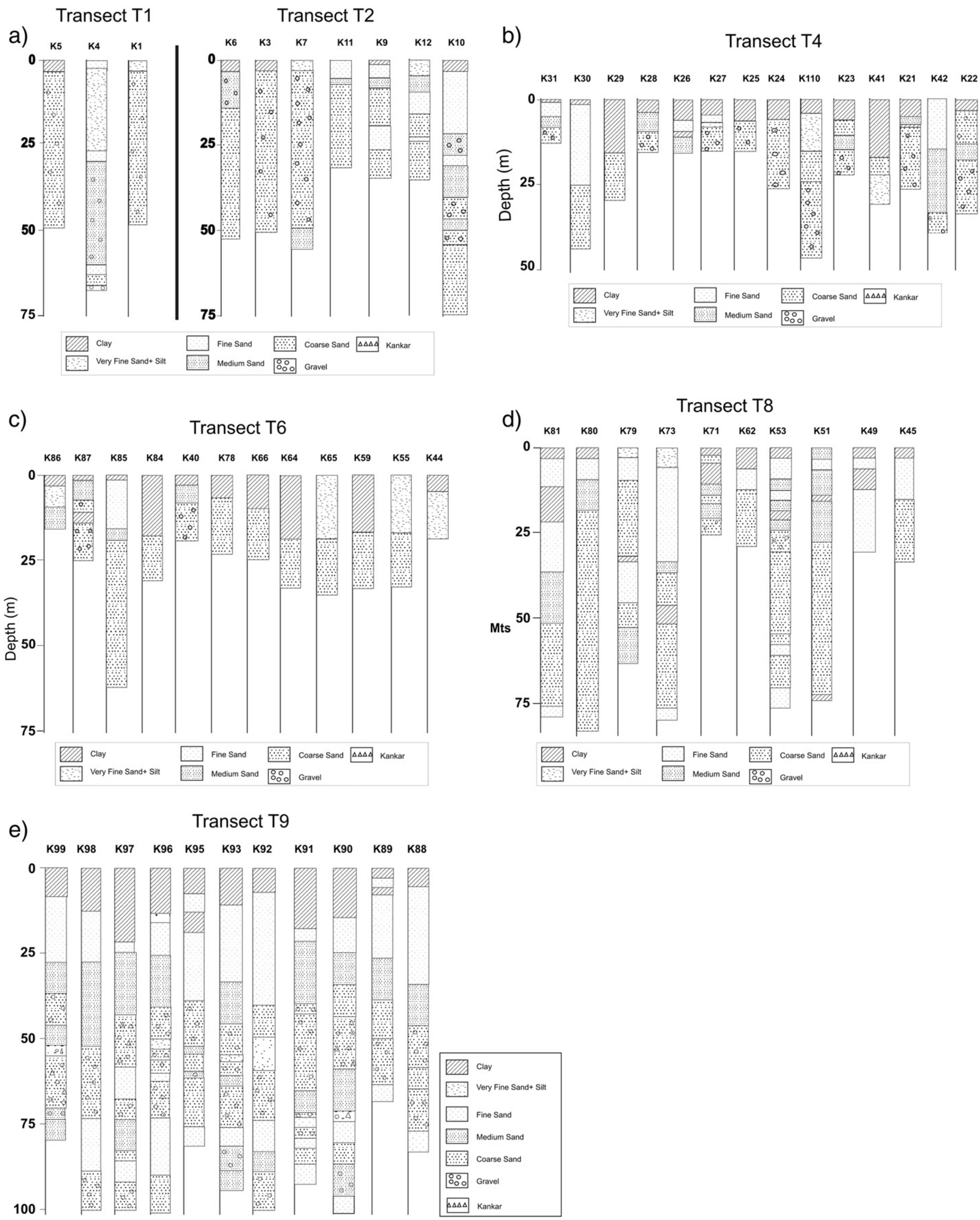

Fig. 3. Groundwater borehole lithologs along selected transects on the Kosi megafan (a) T1 and T2 transects are from the proximal parts and they show the presence of gravels at shallow depths, (b–d) T4, T6 and T8 transects from the medial part of the Kosi megafan where fining upward succession dominates in most of the boreholes starting with coarse sand mixed with gravels and ending with fine sand and mud, (d) T9 transect covering a few boreholes in the confluence zone of the Kosi and the Ganga shows interfingering of coarser and fine sediments possibly reflecting the influence of the southern tributaries of the Ganga (See Fig. 2a for locations).

Borehole data reveal first order stratigraphic variability from the proximal to distal parts of the Kosi megafan and our major interpretations are as follows:

(a) In the proximal transects (Fig. 3a), the presence of gravels at shallow depths (7–30 m) reflects high energy conditions in this region in the past. This is an important finding keeping in view that the gravelly reaches in the Kosi River are currently located upstream of Chatra (~40 km upstream of this transect).
(b) In the medial transect (Fig. 3b), fining upward succession dominates in most of the boreholes starting with coarse sand mixed with gravels and ending with fine sand and mud. These successions suggest several episodes of deposition with a gradual decrease in energy conditions in each. It is also important to note that the present-day sediments of the Kosi River primarily consist of fine sand only and no coarse sand is observed downstream of Chatra. Therefore, sand bodies in the surface represented by these boreholes suggest that the river was able to transport coarser sediments much further downstream in the past.
(c) The boreholes from the distal parts of the fan (Fig. 3c, d) show variable lithology; while some of these are characterized by fining upward succession as in medial parts, several boreboles do not show any definite trend. In distal fan sequences, such variable lithology is generally explained due to distributary channel systems typically of meandering type (Gohain and Prakash, 1990; Singh et al., 1993; Assine, 2005; Gibling, 2006). In such settings, flow becomes poorly channelized and periodic avulsions results in filling by coarser sediments overlain by fine-grained meandering river deposits.
(d) Borehole data from transect T9 in the confluence zone of the Kosi and the Ganga (Fig. 3e) is interpreted to represent interfingering of sediments from two different sources. The upper, finer succession could have formed by the Kosi as most of the boreholes are quite close to its paleochannels. However, the deeper and coarser succession could be related to an older phase of sedimentation related to the southern tributaries of the Ganga. The southern bank of the Ganga in this reach presently flows very close to the cratonic margin due to its southward migration at historical time scale (Phillip et al., 1989). It is likely that older sediments were mainly fed by the smaller cratonic tributaries and were onlapped by the recent sediments brought by the Kosi. Our earlier study in the Yamuna floodplain in the western Ganga plains also recorded a similar event established on the basis of detailed petrographic studies (Sinha et al., 2009). However, more detailed investigations may be necessary to confirm this interpretation in the study area.

4.2. Gandak megafan

Borehole data from only six points are available from the Gandak megafan (Fig. 2). The G1–G4 boreholes are located close to the eastern margin of the present-day fan. The G1 and G2 boreholes show very fine sediments throughout (Fig. 4). The G3 borehole shows coarse sand with gravel below 70 m depth. The G4 borehole shows medium sand, fine sand and mostly finer deposits (clay and silt) down to 200 m. The G5 and G6 boreholes lie close to the medial VES transect and on opposite sides of the Gandak river. The G5 borehole on the eastern side is muddy in the top 50 m underlain by

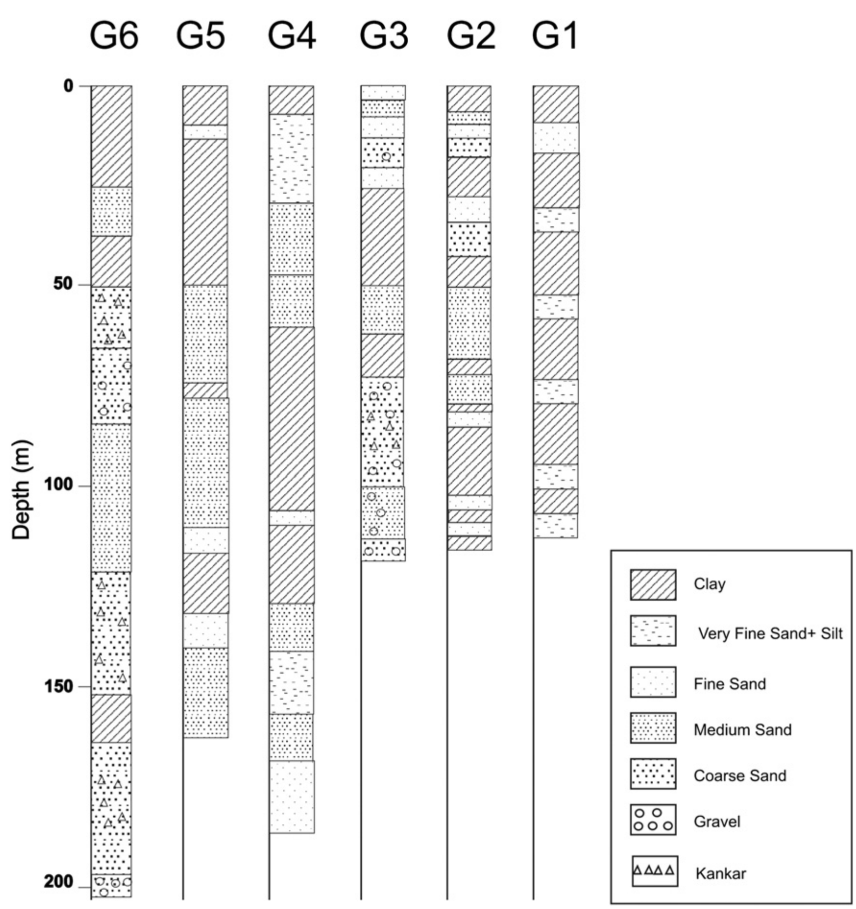

Fig. 4. Groundwater borehole lithologs along selected transects on the Gandak megafan (See Fig. 2b for locations). Only a few boreholes fall within the present boundary of the Gandak megafan and most of them are dominated by fine-grained sediments possibly due to their locations close to the megafan boundary.

several layers of fine to medium sand interleaved by muddy layers. The G6 borehole also shows muddy and fine sand sediments in the top 50 m but is underlain by medium to coarse sand down to ~200 m which contain carbonate nodules and fine gravels between 50 and 83 m and a clay layer between ~150 and 160 m.

In summary, limited borehole data from the Gandak megafan show fine-grained sediments throughout in a few boreholes just outside the fan margin reflecting low energy floodplain environments. Unlike the Kosi megafan, we do not record any gravels at shallow depth in the borehole data from the Gandak. One of the boreholes (G3) records gravel below 70 m depth and this may be associated with a small mountainous stream flowing close to this site.

5. Resistivity data analysis: VES data and layer parameters

5.1. Kosi megafan

The proximal transect (Kus-Kus') has four VES points (Fig. 5). Field curves are not smooth due to large variability in resistivity values. Resistivity data from this transect shows that the upper layers (surface to 25 m depth) have resistivity values between 100 and 300 Ω-m (Fig. 6a) intervened by layers of lower resistivity values (<100 Ω-m). Between 25–30 m and ~50–70 m depth, there is a zone of high resistivity layers (>500 Ω-m) except for an intervening layer of lower resistivity at Kus3. The high resistivity layer is underlain by the layers of moderate resistivity values (<300 Ω-m) in most soundings.

The medial transect (Kds-Kds', Fig. 5) has resistivity values between 100 and 200 Ω-m except for a few layers which have values greater than 1000 Ω-m. Data from the western part of megafan (Kds1–Kds16, Fig. 6b) shows a 20–40 m thick layer of high resistivity (100–500 Ω-m) at depths varying from 25 m to 40 m. This layer is overlain and underlain, at most places, by layers with resistivity values of 10–50 Ω-m and we interpreted this as sharp lithological changes. In the upper 25 m also, there are several thin layers of resistivity 100–300 Ω m. Below 50 m depth, we note large spatial variability in resistivity values; while some profiles show thick (>30 m, base not reached) layers of moderately high resistivity (100–350 Ω-m), others show equally thick layers of lower resistivity (<50 Ω-m) values. Resistivity values of different layers in the eastern part of the Kosi megafan (Kds17–Kds33) generally lie between 100 and 200 Ω-m (Fig. 6c) except for few layers of very high resistivity at different depths e.g. a layer of 4994 Ω-m at Kds19 at ~40 m, 998 Ω-m at Kds24 at ~30 m, and >8000 Ω-m at Kds29 and Kds30 at depths of more than 50 m. Unlike the western part, layers of moderate resistivity (100–500 Ω-m) are exceptionally thick at certain locations (e.g. >90 m thick at Kd23) or occur at multiple depths separated by layers of lower resistivity (<50 Ω-m).

5.2. Gandak megafan

Two transects, each of 10 sounding points, across the Gandak river are located in the proximal and medial parts of the megafan (Fig. 7). The proximal transect on the Gandak megafan is located near Bettiah in West Champaran (Fig. 7). Most of the layers along this transect have resistivity values between 20 and 100 Ω-m (Fig. 8a) except for a few high resistivity (>200 Ω-m) layers at >40 m depth. The western and eastern parts of the megafans have different resistivity values. The sounding points in the western megafan (Gus16–Gus20) have resistivity values ranging from 50 to 100 Ω-m, and there are frequent high resistivity layers at different depths. The eastern megafan

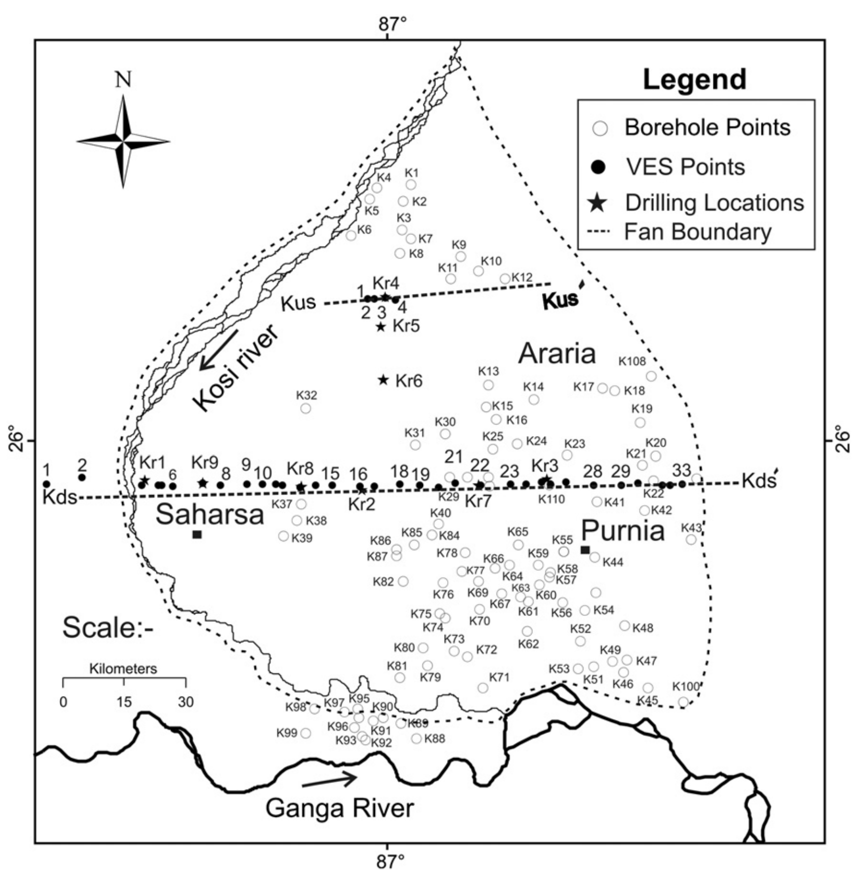

Fig. 5. Location of resistivity sounding points along the proximal and distal transects on the Kosi megafan. A total of 4 soundings were done along the proximal transect whereas 33 soundings were carried out along the medial transect covering the entire stretch of the megafan.

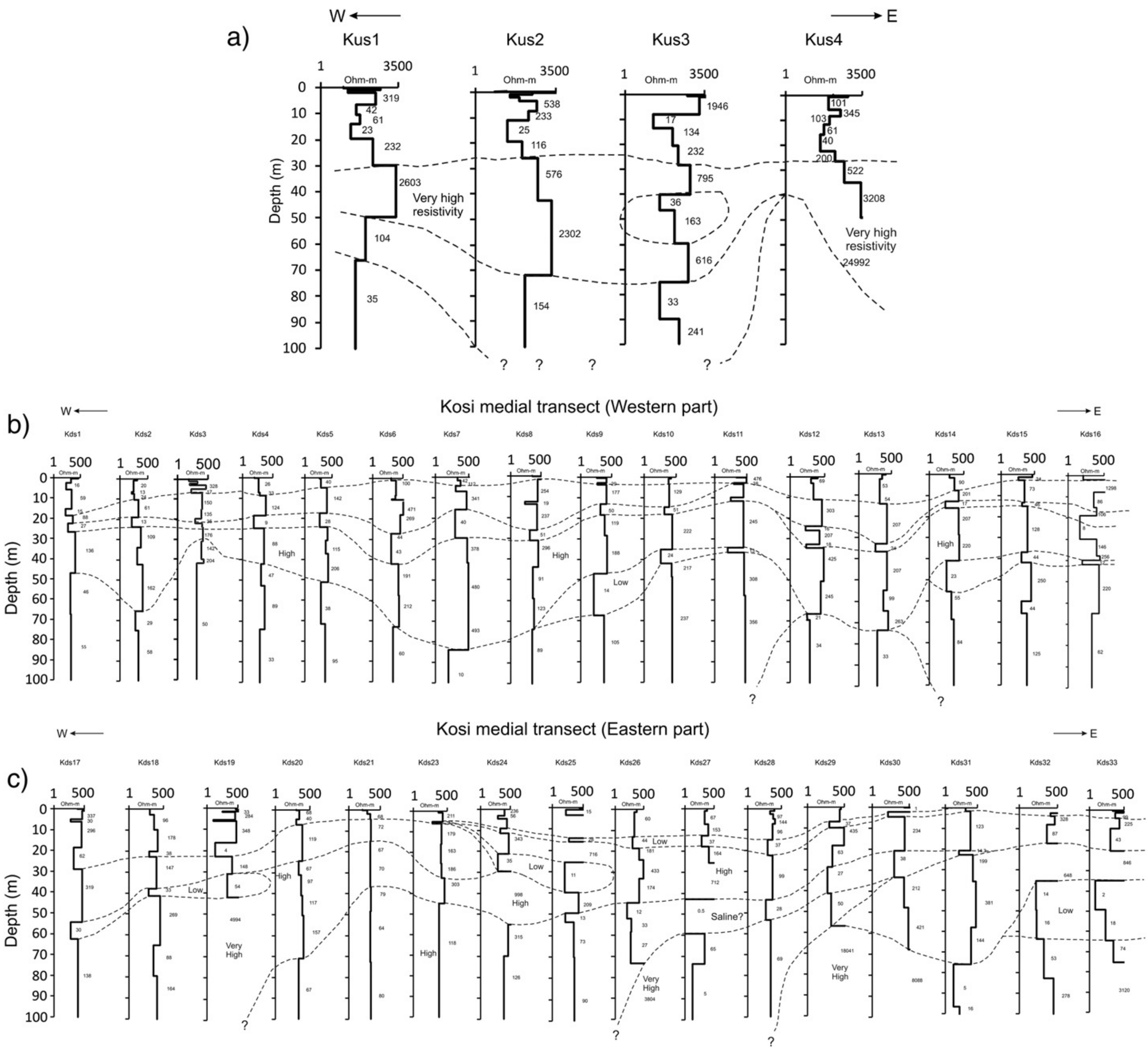

Fig. 6. Resistivity profiles along the (a) proximal and (b, c) medial transects on the Kosi megafan. The proximal transect confirms the presence of gravels at shallow depth as reflected in very high values of resistivity. In the medial transect, the dominance of sandy layers is reflected from the most dominant range of resistivity lying between 100 and 500 Ω-m.

(Gus11–Gus15) has most of the layers showing resistivity values between 20 and 50 Ω-m and once again high resistivity layers at different depths are common.

Data from the medial transect (Fig. 8b) show that most of the layers have resistivity values ranging from 20 to 50 Ω-m. Interestingly, soundings from opposite sides of the river show different resistivity values. Most of the layers from the western part of the megafan (Gds6–Gds10) have two distinct resistivity layers, one with values ranging from 20 to 50 Ω-m and another from 100 to 300 Ω-m (Fig. 8a) except for a few layers with resistivity values in excess of 4000 Ω-m at depths below ~50 m. In contrast, the eastern part of the Gandak megafan (Gds1–Gds5) has most of the layers of resistivity values less than 100 Ω-m (Fig. 8a) intervened by high resistivity layers of 100–300 Ω-m. Two sites, Gds2 and Gds3 show a very high resistivity layer below ~70 m depth.

6. Calibration of resistivity data with boreholes and drill cores

The calibration involves the correlation of layer parameter (layer thickness and its resistivity value) with nearest borehole data and/or drill core data. The VES data of Kosi was calibrated first with the available boreholes, and then with the drill cores to improve the final interpretation. The VES data from the Gandak megafan were calibrated only with drill core data as there were not enough boreholes from this region.

Fig. 9a shows the calibration of the resistivity profile at Kds3 with a drill core at Kr1 (see Fig. 5 for location). The Kr1 is a 44 m deep drill core located in the Saharsa district in the vicinity of the present day Kosi River. This core primarily consists of coarse to medium sand layers interleaved by thin mud layers and sand layers correspond very well with the moderate resistivity layers (150–204 Ω-m) whereas the

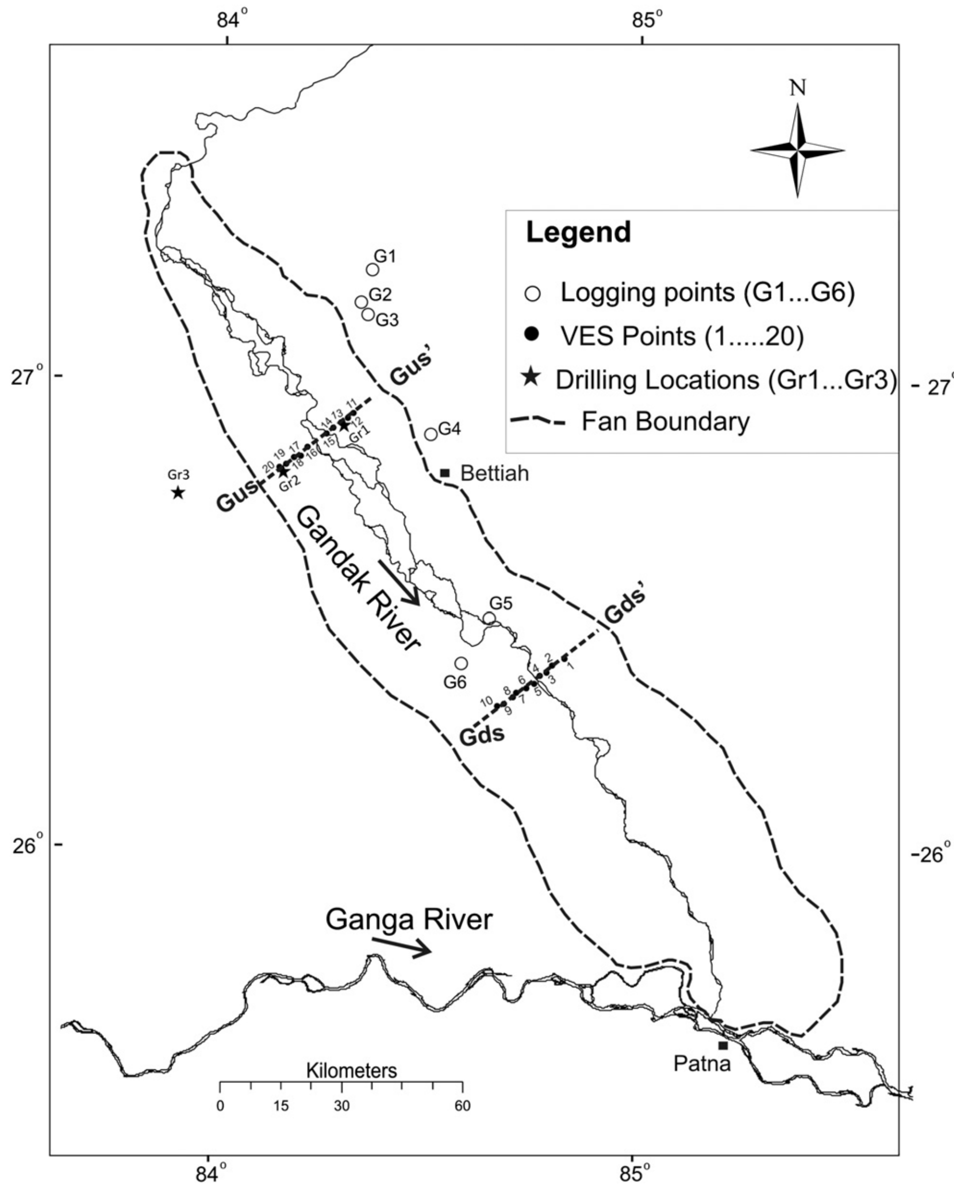

Fig. 7. Location of resistivity sounding points on the Gandak megafan. A total of 10 soundings were carried out for both proximal (Gus11–Gus20) and medial (Gds1–Gds10) transects. Borehole data points (G1–G6) and drill core locations (Gr1–Gr3) are also shown.

muddy layers correspond to low resistivity layers (13–50 Ω-m) (Fig. 9a). At a few sites, some layers show very high resistivity values at depth (>50 m) which has been interpreted as dry sand with kankars as described by Yadav et al. (2010). Similarly, Kds-16, Kds-25, and Kus3 profiles were calibrated with drill cores Kr-3, Kr-3 and Kr-4 (see Fig. 5 for location). Fig. 9b shows the calibration of the Gus-13 resistivity profile with drill core Gr-1. The Gr-1 drill core is dominated by medium sand and most of these layers have resistivity values higher than 100 Ω-m (Fig. 9b). Thin layers of gravel in a sandy matrix were recorded in the core at ~35 m depths and a high resistivity value of 229 Ω-m was measured around this depth. Similarly, Gus20 resistivity profile was calibrated drill core Gr2. Table 1 shows the final calibration results relating the resistivity values with lithology in the Kosi and Gandak megafan region.

Fig. 10 shows that the relative distribution of resistivity classes (interpreted as different lithologies) in the Kosi and Gandak megafans are strikingly different. In the Kosi medial transect, ~50% of resistivity values fall in medium to coarse sand range and only ~5% in the clay range (<20 Ω-m). The proximal transect on the Kosi megafan shows a very different distribution with 28% gravel and <1% clay; medium to coarse sand drops down to ~30% (Fig. 10a). The proximal and medial transects on the Gandak fan also show difference in sediment distribution but there is an overall dominance of silty fraction which decreases slightly from proximal to medial (Fig. 10b). Clay percentage increases downstream and small fractions of kankars are observed in both proximal and medial transects. We also note that the western side is more sandy compared to the eastern side of the fan along both transects.

7. Shallow subsurface alluvial stratigraphy of megafans

Shallow subsurface stratigraphy was reconstructed with the help of resistivity ranges for different lithologies (Table 1) for both the Kosi and Gandak megafans based on the following assumptions and guidelines: (1) the layer has infinite extension, (2) thin, high resistivity layers at surface were ignored for lithological interpretation, and (3) VES data from two consecutive points were correlated when they have similar layer parameters.

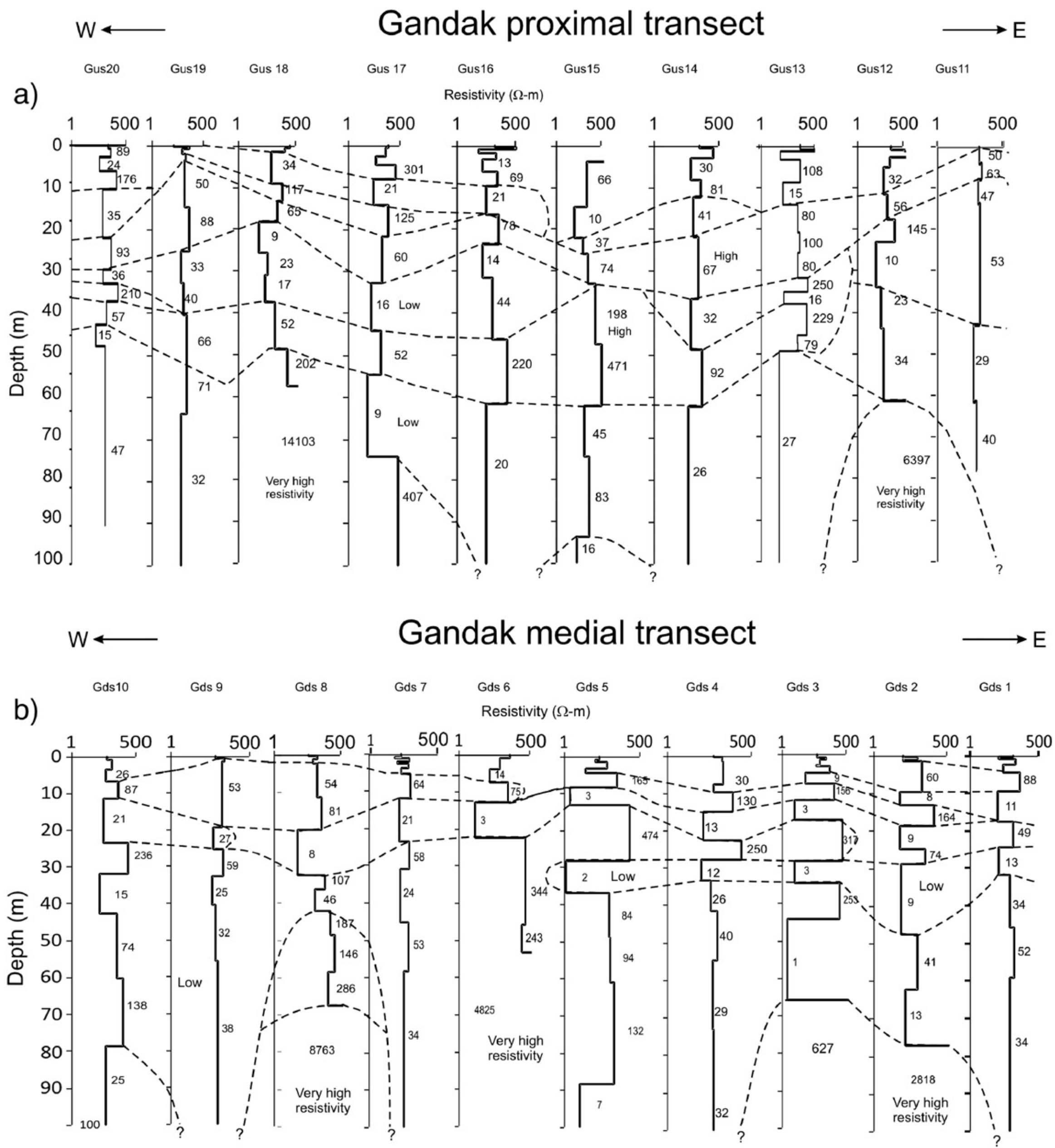

Fig. 8. Resistivity profiles along the (a) proximal and (b) distal transects on the Gandak megafan. Resistivity values along both transects are much lower than those for the Kosi transects suggesting finer sediments below the Gandak megafan.

7.1. Kosi megafan

The subsurface stratigraphy of the proximal transect, ~23 km long, was reconstructed from four resistivity soundings, several boreholes and two shallow drill cores. Panel diagram for this transect shows that the upper 15–20 m of the strata is composed of medium to coarse sand along with thin layers of fine sand and pockets of clay. Below 15–20 m depth, a mix of gravel and coarse sand occurs which continues down to ~30 m. A distinct change is resistivity value around this depth suggests that a gravel-dominated layer occurs below ~30 m depth. Pockets of sand occur within the gravel layer which might represent channel-fill deposits. The resistivity data suggests that the gravel layer is underlain by at least 30 m of medium to coarse sand and pockets of fine sand in the western part of the transect (Fig. 11).

The 140-km long medial fan transect covers almost the entire fan from the western to the eastern margin. The panel diagram presented in Fig. 12 summarizes the alluvial stratigraphy along this transect. The dominant component in the stratigraphy is the sand sheet consisting of medium to coarse sand for most of the upper 100 m of strata penetrated by resistivity soundings. Our drill cores penetrating down to ~40–45 m also confirm the presence of thick sand bodies. We interpret this to be deposits of the Kosi River. The individual sand sheets are 20–30 m thick and the unusual thickness of these sand bodies is due to stacking of multiple sand bodies corresponding to different time periods. Frequent silty layers intervening thick sand bodies both at near surface as well as at deeper levels possibly represent the interchannel areas which were later reoccupied by channels.

7.2. Gandak megafan

We have studied two VES transects across the Gandak megafan in the proximal and medial parts (see Fig. 7 for location of transects).

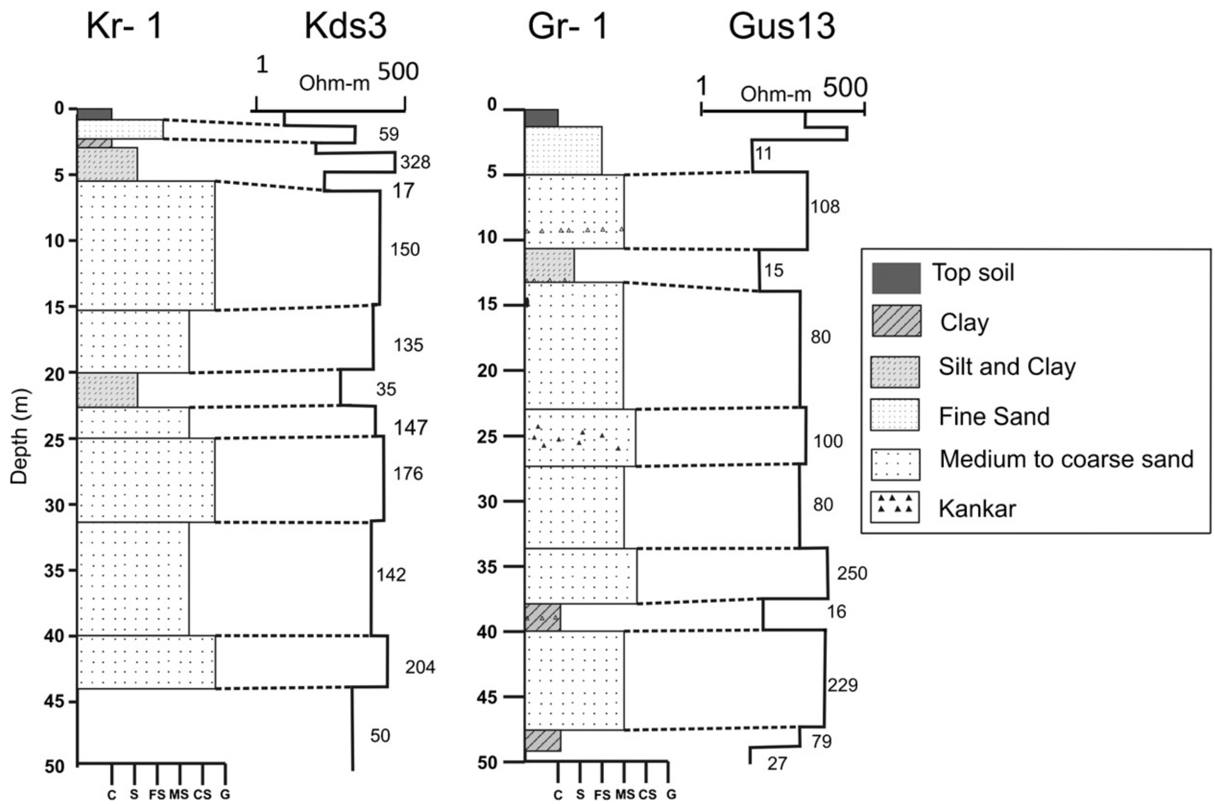

Fig. 9. Calibration of resistivity data with drill core logs (a) Kosi megafan — Kds3 sounding point was calibrated against Kr1 drill core (see Fig. 5 for locations); similar calibrations were done using Kr2, Kr3 and Kr4 drill cores for Kds16, Kds25 and Kus3 sounding points. (b) Gandak megafan — Gus13 sounding point was calibrated against Gr1 drill core and the same process was repeated for Gr2 core and Gus20 (see Fig. 8 for locations). All data was integrated to map the range of resistivity values against lithology as shown in Table 1.

The presence of ~10 to 15 m thick sand is confirmed from drill cores. Resistivity values show finer deposits below 50 m depth and the same is validated from drill cores. Along both transects, the VES data shows significant lateral variability in resistivity values suggesting differences in lithology across the river. Fig. 13 shows the overall alluvial architecture along the proximal transect and unlike the Kosi transect, we record narrow and thick sand bodies instead of sand sheets. The dimensions of these sand bodies are quite variable in the upper (5–20 m thick) and lower (10–30 m thick) parts of the fan succession and these are interpreted as buried channel fills. Thick muddy layers are mapped in the lower part of the succession and interpreted as floodplain deposits. Thin muddy layers in the upper part represent interchannel areas and levees. Drill cores show the presence of kankar (carbonate nodules) at several depths and these layers have high resistivity values in the sounding data. Fig. 14 shows the resistivity-based alluvial architecture for the medial transect. Like the proximal transect, sand bodies in the lower part of the fan succession are relatively thicker (15–25 m). Thick muddy layers and widespread occurrences of carbonate concretions (kankar) are noted in the lower part. The upper part shows significant lateral variation on both sides of the river. While the western part has several smaller (10–20 m thick), laterally stacked sand bodies, mostly fine sand, the eastern part is more muddy and has even smaller sand bodies (5–10 m thick).

Table 1
Range of resistivity values for different lithologies in the Kosi and Gandak megafan region after calibration with drill cores.

Resistivity Range (Ω-m)	Interpreted lithology
<20	Clay
20–50	Silt and clay
50–100	Fine sand
100–500	Medium to coarse sand
500–900	Coarse sand with gravel/Kankar
≻ 2000	Gravel or Kankar rich layer

8. Discussion

8.1. Alluvial architecture of megafan succession

Megafan successions interpreted through resistivity data and borehole records reveal significant variability in alluvial architecture in space and time. The topmost layer (2–4 m thick) in all transects represents the top soil and includes one to three thin layers of variable resistivity — a function of surface moisture and lithology. The Kosi proximal transect shows four distinct litho-units in the upper 100 m (Fig. 11). The lowermost unit 1 of medium to coarse sand (base not reached) is overlain by a gravel-dominated unit 2 (base not reached) and then by ~10 to 20 m thick coarse sand with minor gravels (unit 3). Lithounits 2 and 3 form a major channel fill succession. The uppermost unit consists of medium to coarse sand, ~5 to 10 m thick, immediately below the modern soil. Such marked variation in lithological distribution should reflect a sharp change in energy condition which in turn is a function of sub-environments within the fan system. The presence of gravel at depth in the proximal transect suggests high-energy floods during the monsoon season in the past. We do not have any dates on these cores at this stage and hence it is not possible to constrain the timing of these events. It is important to note here that the modern Kosi river does not carry any gravel downstream of Chatra (~40 km upstream of transect).

Panel diagram along the medial transect on the Kosi megafan shows two major litho-units – lower fan and upper fan – but with significant lateral variability in terms of lithology, depth and thickness of sand bodies. The western edge of the transect falls outside the modern limit of the Kosi megafan; however, we do not record any major change in lithology, except for a thick muddy layer at the surface,

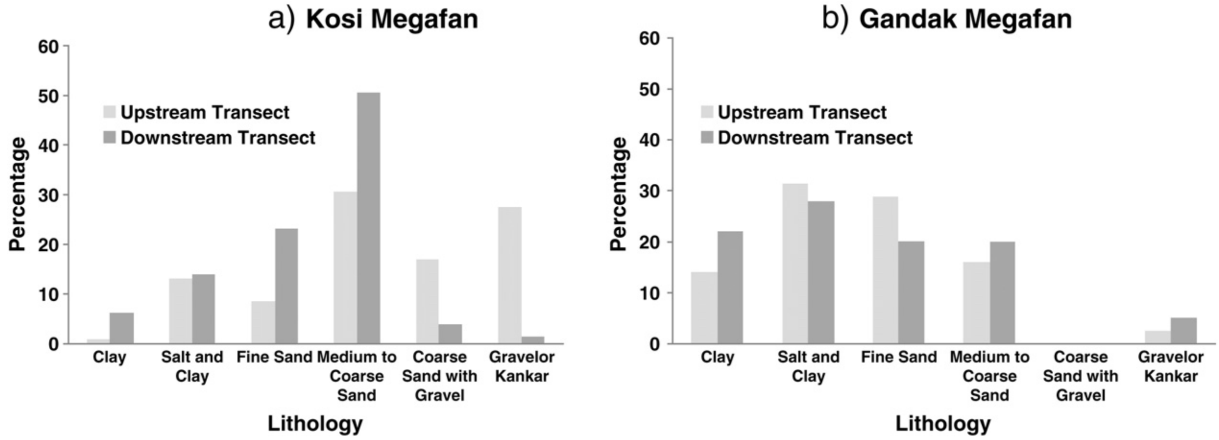

Fig. 10. Histogram distribution of major resistivity classes (interpreted into different lithologies) for (a) Kosi and (b) Gandak megafans. A marked distinction is noted between the Kosi and Gandak megafan in terms of dominant lithology. While the Kosi megafan is dominated by medium to coarse sand and has a marked presence of gravels in the upstream transect, the Gandak megafan is characterized by fine sand and muddy lithologies.

suggesting a continuation of similar deposits westward in the subsurface. The lower unit below 50–70 m depth consists of fine sand (>30 m thick) overlain by ~20 to 30 m thick medium to coarse sand with clay and silt pockets. We interpret this as a major channel fill sequence. The central part of the fan shows a lower unit made up of medium to coarse sand sheet and a number of smaller channel fills consisting of finer sediments. We interpret these as abandoned channel belts that were later filled by flood flows or gradual silting by finer sediments. Some of these fills are 20–30 m thick that might represent stacking of multiple channel fills due to reoccupation of channels. The upper unit, ~40 m thick, is also composed of coarse to medium sand sheet but has much smaller channel fills compared to the lower fan succession (Fig. 12). A major channel fill consisting of fine sand is recorded close to the surface that should correspond to the near-central, prolonged course of the Kosi river in historical time scale (Chakraborty et al., 2010). The eastern part of the megafan has

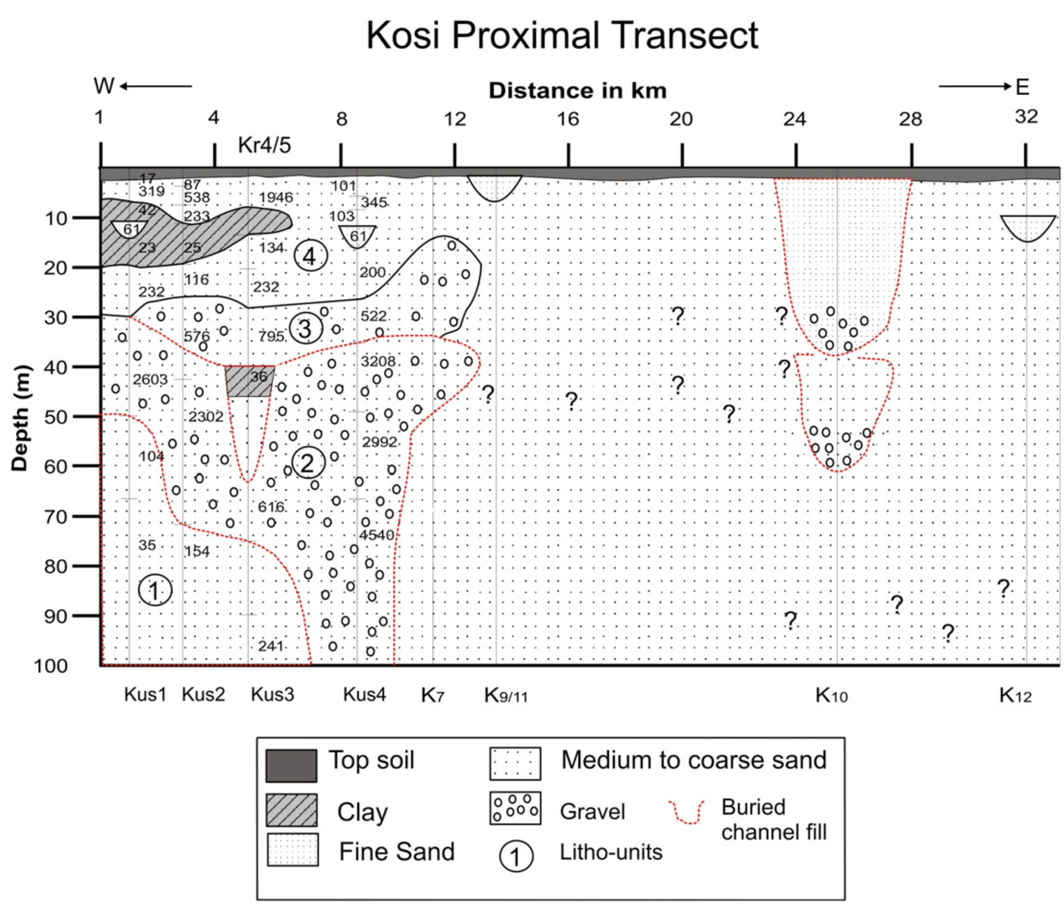

Fig. 11. Alluvial stratigraphy of the proximal part of the Kosi megafan as interpreted from resistivity data, borehole lithologs and drill cores; the most striking feature is the presence of gravels at shallow depths and an overall dominance of medium to coarse sand lithology. There is a data gap for a large part of the section and therefore the interpretations are tentative (shown as ? in the figure).

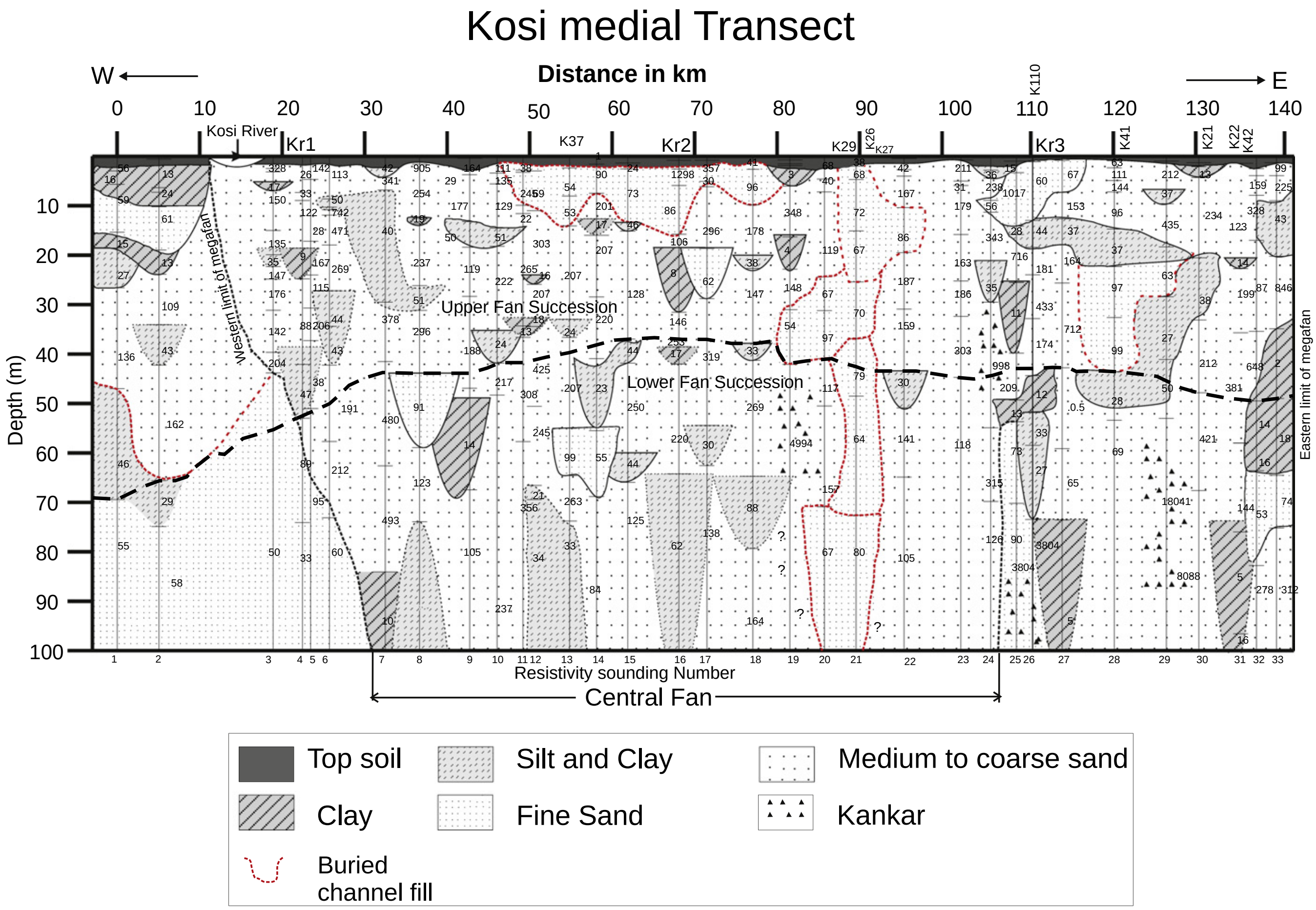

Fig. 12. Alluvial stratigraphy of the medial part of the Kosi megafan as interpreted from resistivity data, borehole lithologs and drill cores. Extensive sand sheets characterize the medial fan succession; upper and lower fan successions (separated by thick black line) are distinguished on the basis of sand body geometry and dimensions which also show significant lateral variability. Both western and eastern limits of the modern megafan surface have also been shown. Major buried channels have been marked in red and uncertainties in the interpretation (?) are also indicated.

medium to coarse sand sheet with intervening clay pockets in the lower part and channel fills of fine sand and thick muddy layers in the upper part.

These large sand bodies primarily represent former channel belts of the river and the unusual width and thickness of these bodies is attributed to lateral as well as vertical stacking of channel deposits resulting in multistoried bodies (Bridge and Mackey, 1993). Typically, such multistoried sand bodies are separated by erosional surfaces as in geological records (Hampson et al., 1999) but it is often difficult to recognize such boundaries in unconsolidated deposits in the absence of a marked lithological contrast. Silt and clay pockets within the sand represent the interchannel areas, channel fills or backswamps (Horton and DeCelles, 2001). The Kosi is primarily a multi-channel system and even though the river is presently confined by the embankments on both sides, it has a ~10 km wide channel belt with wide, muddy interchannel areas some of which have formed large vegetated islands. Outside the channel belt, several paleochannels on the megafan surface primarily transport mud when they flow during the monsoon season. The sub-surface stratigraphy reconstructed in this paper is therefore consistent with the present-day geomorphic set up in this region.

Panel diagram shows that the major sand body is located between Kds7 to Kds24 and, the eastern and western margins of the fan are characterized by relatively finer deposits (Fig. 12). This suggests that the Kosi river has occupied the central part of the fan for a major part of the time represented by the upper ~100 m of the succession. Singh et al. (1993) suggested two different phases of deposition for the Kosi megafan; the upper 8 to 10 m of medium sand associated with historical shifting of river on the megafan and the lower 40 to 80 m of coarse sand with gravel corresponding to the Late Holocene glaciations melting. Chakraborty et al. (2010) have questioned this interpretation and argued that 8 to 10 m of deposition during historical shifting would require a sedimentation rate of ~50 mm/yr which is unrealistic in a fluvial environment. It is difficult to test any of these hypotheses at this stage in the absence of chronology of these sand bodies.

The sub-surface stratigraphy of the Kosi megafan reveals that the multistoried sand bodies are ~8 to 10 km wide and 20–30 m thick. These values are comparable to those of the modern channel of the Kosi which is about 500 to 1000 m wide and the channel belt width varies from 2 to 11 km. Chakraborty et al. (2010) have documented the width of paleochannels on the Kosi megafan to vary from 0.6 to 3.45 km with a mean width of 1.5 km. In the geological record, multistoried sandstones of the Siwaliks in NW Himalaya have been documented to be 300–1000 m wide and 10s of meters thick with lenses of fine grained sediments which represent abandoned channel fills and floodplain deposits (Kumar, 1993; Willis, 1993; Khan et al., 1997; Zaleha, 1997; Jain and Sinha, 2003). Such dimensions of sand bodies are typical of the braided and low-sinuosity rivers as reflected from the compilation of rock record across the globe (Gibling, 2006). It has also been suggested that thick and extensive channel deposits reflect repeated avulsions and lateral amalgamation of sand bodies (Gibling, 2006). The megafan deposits in the ancient record generally comprise of channel deposits, ribbons and narrow sheets (Friend et

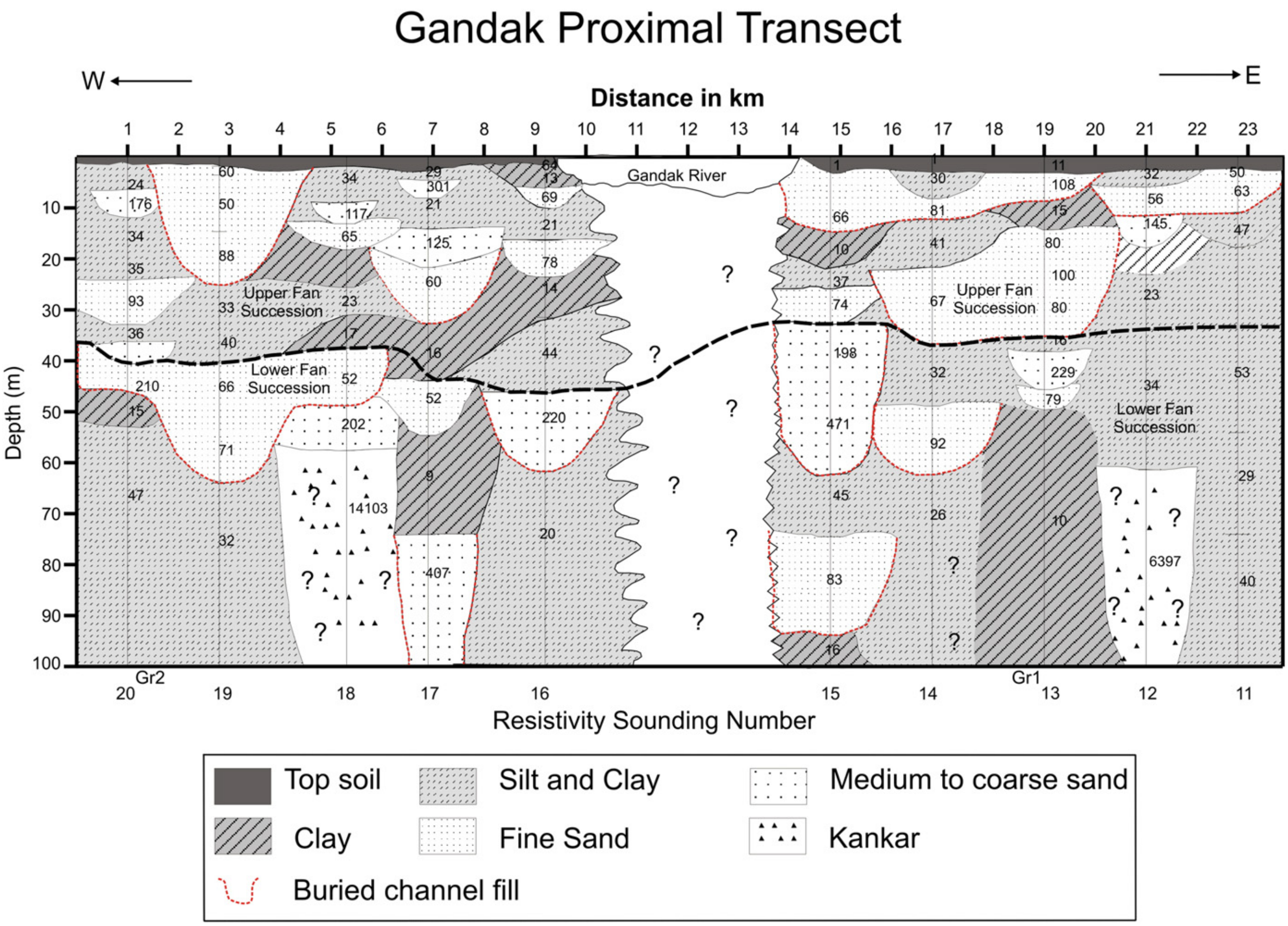

Fig. 13. Alluvial stratigraphy of the proximal part of the Gandak megafan as interpreted from resistivity data, borehole lithologs and drill cores. Unlike the Kosi megafan, narrow sand bodies characterize the Gandak megafan succession. Major buried channels have been marked in red and uncertainties in the interpretation (?) are also indicated. The upper and lower fan succession (separated by thick black line) show some difference in architecture and stacking of sand bodies which is likely to be related to change in avulsion frequency and sedimentation rate.

al., 1979) with only modest evidence of any lateral accretion. Some of these sheets are thicker, typically of braided style and the channel bodies reflect an avulsion and aggradation. The Kosi megafan has often been cited as a modern analog for generating such extensive channel bodies due to rapid lateral sweeping by the Kosi river across the fan over historical time scales (Wells and Dorr, 1987; Friend et al., 2001). Our reconstruction of subsurface stratigraphy of the Kosi megafan has confirmed most of these speculations and has provided the much needed field data.

Alluvial architecture of the upper 100 m of the Gandak megafan shows at least two major litho-units for both proximal and medial transects (Figs. 13, 14). The lower unit (below ~40 to 50 m depth) shows narrow but thick (>40 m) channel fills. The upper unit (above ~40 m) has sand bodies of ~10 to 15 m thickness but several kilometers wide. It is interpreted that the lower and upper units represent two different fluvial processes. The upper unit probably represents frequent migration of the Gandak River on the megafan from west to east (Mohindra et al., 1992) thereby generating laterally stacked sand bodies. This may imply a relatively limited residence time for channels that is in turn related to avulsion frequency and sedimentation rate as demonstrated by recent experiments by Bryant et al. (1995) and Heller and Paola (1996). On the other hand, the lower unit of the Gandak megafan succession represents an incised river system when active channel cutting was followed by rapid vertical accretion. In the ancient record, such 'fixed' river systems are characterized by sand ribbons (Friend et al., 1979; Friend, 1983). Such marked change in the alluvial architecture of the Gandak megafan through time must be related to sharp changes in hydrologic regime and sediment transport characteristics of the Gandak River. It is also important to note that the Gandak megafan is much narrower compared to the Kosi and hence the sediment storage below the Gandak megafan is also smaller. Therefore, a marked variation in sediment flux through time would be sharply reflected in alluvial architecture through adjustments in fluvial style.

Experiments by Bryant et al. (1995) and Heller and Paola (1996) also suggested that an increase in density of stacking pattern of sand bodies depends upon the relative rate of increase in avulsion frequency compared to that of sedimentation rate; however, both increasing and decreasing sedimentation rate can result in a high density of stacking. We do not have sufficient data at this stage in terms of chronology and paleoclimatic reconstruction to constrain the timing and causal factors for such change e.g. increase or decrease in sedimentation rate through time but our ongoing analysis of sediment geochemistry and OSL dating should provide further insights.

8.2. Proximal to distal variability in stratigraphy: implications for sediment flux

The Kosi megafan shows significant variability in alluvial stratigraphy along the proximal and distal transects. Firstly, there is a marked reduction in the overall grain size of sediments from proximal to distal parts of the fan as observed in resistivity data, drill cores and borehole

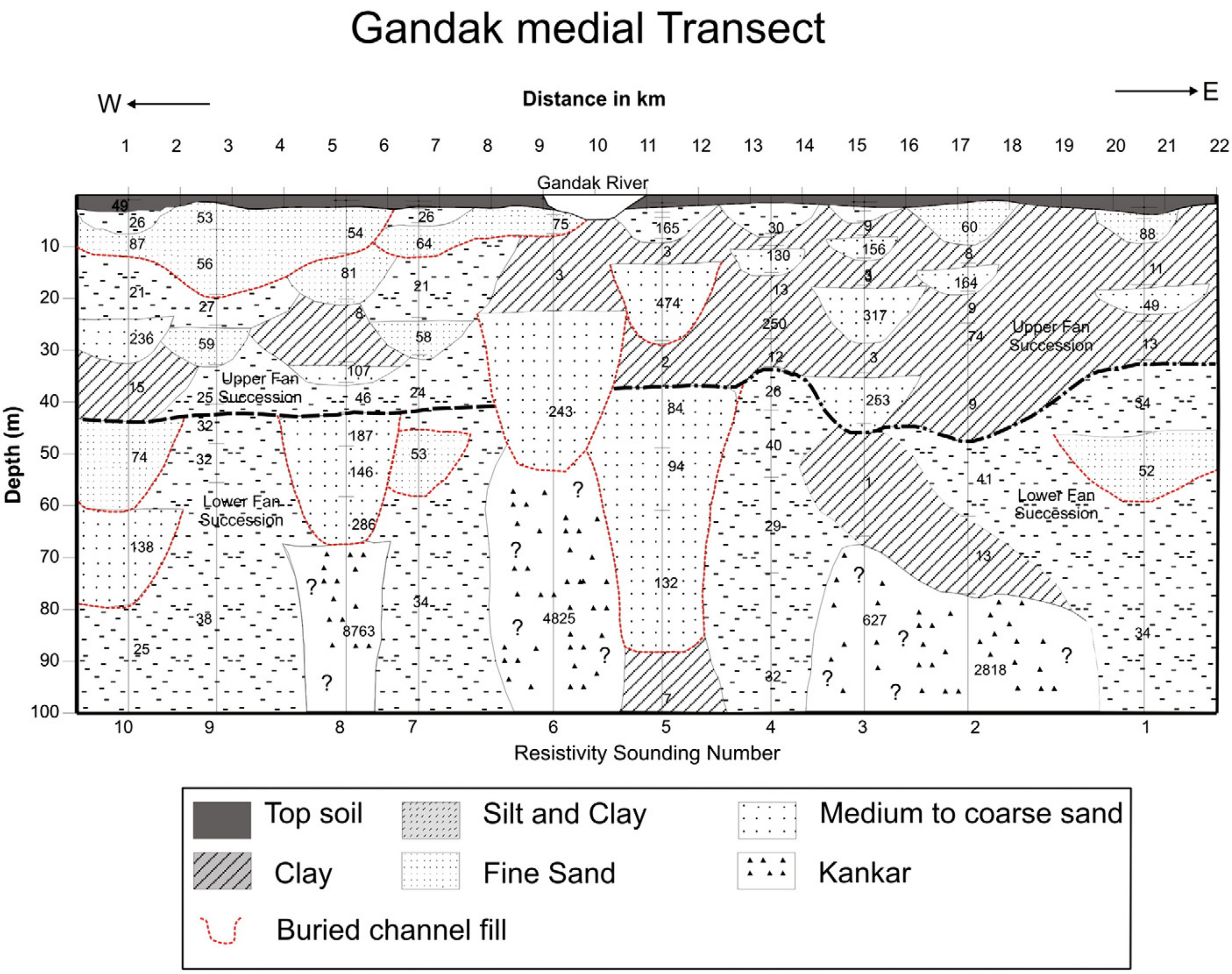

Fig. 14. Alluvial stratigraphy of the, medial part of the Gandak megafan as interpreted from resistivity data, borehole lithologs and drill cores. Major buried channels have been marked in red and uncertainties in the interpretation (?) are also indicated. No major difference is recorded between the proximal and medial transect except for a dominance of muddy sediments in the upper fan succession in the medial transect. Dimensions of the sand bodies and their stacking patterns are comparable in both transects.

logs. The proximal part shows medium to coarse sand layers and gravels, the medial part shows mainly medium to coarse sand and the distal fan is dominantly composed of fine to medium sand and clay. Proximal to distal variability on Kosi fan is very prominent and also has been observed by the previous workers as well (Wells and Dorr, 1987; Singh et al., 1993). The modern Kosi shows distinct downstream change in channel pattern from gravel-braided and sandy-braided to straight and meandering channel as identified by Gohain and Prakash (1990) and Singh et al. (1993). Such sediment grain size reduction is very common on the alluvial fans (Wells and Dorr, 1987; Jain and Sinha, 2003) and is mainly associated with the sediment carrying capacity of the river which decreases from upstream to downstream. However, the present transition from gravel-braided to sandy-braided river occurs 5 km downstream of Chatra, at least 35 km upstream of our proximal resistivity transect (Kus–Kus', Fig. 5). The presence of gravels at shallow depths (<15 m) at this point suggests a much more dynamic regime of the Kosi in the past when the gravel could be transported much downstream. We do not have any chronological data on the cores at this stage, and therefore, we cannot constrain the timing of this change in the hydrologic regime. Although the Gandak fan also shows some reduction in grain size from proximal to medial transects but no gravels are recorded in the subsurface of the Gandak megafan in any of these transects and it appears that the gravel front is much upstream in the case of the Gandak.

Further, thickness of sand bodies decreases and that of the muddy layers increases from proximal to medial transects on the Kosi megafan. The Gandak megafan however does not show a marked variation in thickness of sand bodies from proximal to medial transect. There are high resistivity layers at depth along the medial transect across the Gandak megafan and this is attributed to the presences of kankar (concretions) as in other parts of the Ganga plains (Yadav et al., 2010). Mohindra et al. (1992) have also reported high carbonate content for the Gandak sediments and the borehole data from this region also shows abundant concretions.

An important distinction between the sub-surface stratigraphy of the Kosi and the Gandak megafans is the presence of gravel layers at <15 m depth in the proximal transect of the Kosi whereas the Gandak transect in the proximal part does not show any gravels down to 40 m depth. Although the proximal transects for the Gandak and Kosi are located at different distances from the mountain front, 80–115 km and 50–85 km respectively, this difference is still striking. We suggest that the absence of gravels in the Gandak stratigraphy in the plains may be attributed to the mountain front setting, most importantly the presence or absence of intermontane basin (dun). The Kosi river exits

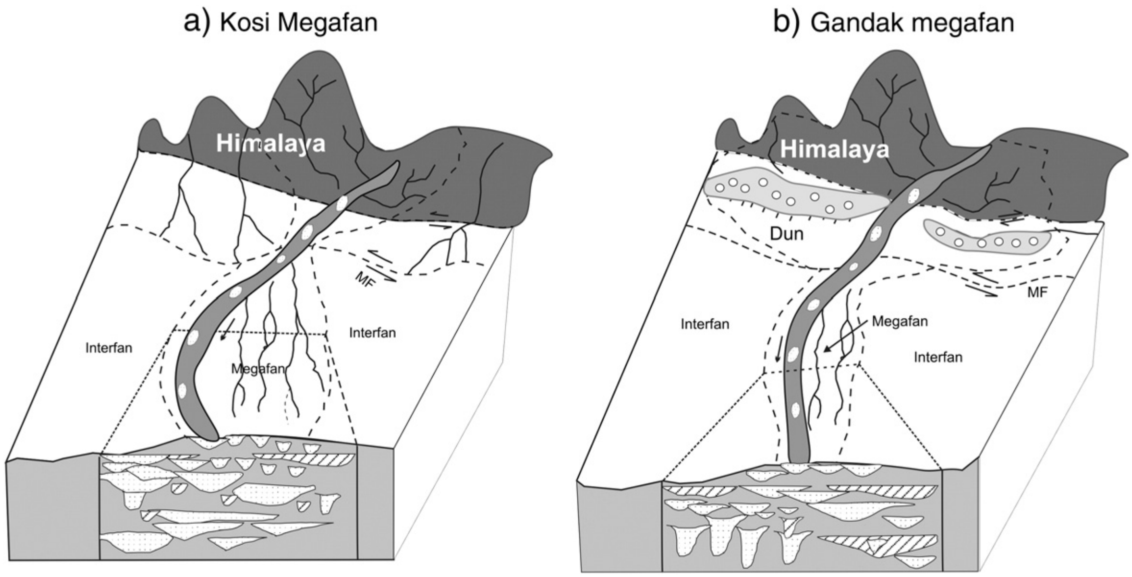

Fig. 15. Conceptual depositional model for spatial variability of alluvial stratigraphy of (a) the Kosi and (b) the Gandak megafans. The Kosi emerges directly from the mountain exit and has therefore carried coarser sediments to much farther parts of the megafan in the past. In contrast, the Gandak has a major intermontane basin ('Dun') before it exits in the plains; the intermontane basin has acted as a 'filter' particularly for the coarse grained sediments. Further, sand body geometries in the sub-surface of the two megafans are strikingly different; while the Kosi shows extensive sand sheets, the Gandak shows narrow ribbons near surface and incised valley fills at depth.

directly from the mountain front (Fig. 15a), and has provided a more efficient conduit for sediments (also due to higher discharge) allowing the coarser fragments to travel into the plains in the past. With gradual reduction in stream capacity of the river due to changes in hydrological regime, the Kosi no longer transports gravels downstream of Chatra as also evidenced in the field. The gravel dominated succession in the proximal part of the megafan is therefore onlapped by sandy sediments. On the other hand, the Gandak has a fairly large intermontane basin in the hinterland (Fig. 15b) which has provided significant storage for the coarse grained sediments originating in the hinterlands. Field observations in the Gandak hinterland in Nepal showed widespread gravel bed streams feeding the dun but very little of them are transported downstream. Due to such 'filtering' of sediments, only finer fraction (sands) were transported downstream, and therefore, the megafan sediments in the plains are devoid of gravels at depth. Apart from generation of distinctive alluvial stratigraphy, filtering of sediments through 'duns' also has implications in terms of documenting stratigraphic response to climate change in the alluvial plains and our ongoing work on sediment cores from both the megafans will provide further insights.

9. Conclusions

Three-dimensional geometry of modern megafans has not received much attention from sedimentologists compared to significant literature available on the geomorphology and process models of megafan evolution. The primary reason for this has been the lack of subsurface data and enough surface exposures to document alluvial architecture. We have documented the subsurface stratigraphy of two well-known megafans from the Himalayan foreland basin, the Kosi and the Gandak, based on an integrated dataset. Our results not only provide the first hand estimates of the dimensions of the sand body geometry below these fans but also demonstrate significant variability in space and time in terms of fluvial style which are in turn related to hydrologic regime and sediment flux from the hinterland. The Kosi megafan is characterized by thick, laterally extensive sand sheet in the medial fan region whereas the proximal part has a prominent gravel layer at shallow depth contrary to the fact that the gravel transport ceases in the modern Kosi at least 40 km upstream. In contrast, the stratigraphy of the Gandak megafan in both proximal and medial transects is characterized by laterally stacked sand sheets in near surface layers — representing migratory behavior and thicker, narrow sand ribbons at depth representing incised channel fills. We suggest that such spatial variability in megafan stratigraphy is a manifestation of mountain front setting (presence or absence of intermontane valleys), sediment flux and variable hydrological regime through time. Our ongoing investigations on the sediment cores from both the megafans would further constrain the chronology and paleohydrological variability which have played a significant role in alluvial stratigraphic development and long-term evolution of these megafans.

Acknowledgments

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