



Kosi megafan: Historical records, geomorphology and the recent avulsion of the Kosi River

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ABSTRACT

It has been proposed that the Kosi River continuously migrated >113 km westward across the surface of the megafan over the last two centuries. Examination of a number of old maps published between 1760 and 1960 shows that during most of this period the Kosi River occupied a position slightly east of the megafan axis. The apparent channel movement shown in these maps is oscillating in nature and not unidirectional. Instead of encountering deposits left behind by a sweeping braided Kosi-like stream, a preliminary study of the uppermost 2–5 m succession in the north-central part of the megafan reveals overwhelming dominance of meandering stream deposits. Assuming the existing notion of Kosi River migration, the rate of deposition averaged over ~100–200 years for the uppermost ~5–10 m of megafan deposits, works out to be unusually high (>50 mm/y). All these observations question the soundness of the hypothesis of rapid westward migration of the Kosi River over the last two centuries. The existing facies model for the uppermost 8–10 m of the megafan deposits also appears untenable.

The three-dimensional geometry of the Kosi megafan is similar to those of typical alluvial fans, but with much gentler gradient (0.05°–0.01°) and with larger area (>10,000 km²). Based mainly on the patterns of paleo and modern channels recognised in the satellite images, three major accretionary lobes can be identified on the Kosi megafan. Relative age of the lobes determined from the truncating relationship of the paleochannels indicates a random shift of the trunk channel forming these lobes. Similar multilobate form and evidences of random switching of the loci of lobe aggradation are also found to be common in the Tista and Taquari megafans.

The factors known to favour avulsion and the results of the recent simulation studies of alluvial deposits are inconsistent with the notion of unidirectional shift of the channels for more than 100 km across the entire megafan surface. This study suggests that the relocation of the Kosi River in the past was through random nodal avulsion rather than systematic unidirectional shift. The recent avulsion of the Kosi channel by a large distance to the east follows this expected pattern. Further study and age dating is required for a comprehensive understanding of the depositional dynamics of the megafan and the pattern of channel movement on it. Future flood predictions and disaster management plans should be based on such comprehensive understanding.

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1. Introduction

Kosi megafan is one of the important examples of megafans occurring in the Ganga plain (Fig. 1; Geddes, 1960; Gohain and Prakash, 1990; Singh et al., 1993; Collinson, 1996). It has been mentioned in many textbooks and a number of research publications that the Kosi River has shifted about 113 km from the eastern margin to its present position at the western extremity of the megafan over the last two centuries (Mookerjea, 1961; Mookerjea and Aich, 1963; Gole

and Chitale, 1966; Wells and Dorr, 1987; Gohain and Prakash, 1990; Duff, 1992; Singh et al., 1993; Mackey and Bridge, 1995; Collinson, 1996; Decelles and Cavazza, 1999; Bridge, 2003; Assine, 2005). The suggested shift was continuous or in discrete steps but always towards west, sweeping across the entire megafan surface at an unusually fast rate. In August 2008, an avulsion relocated the Kosi River by about 60 km to the east (measured in the central part of the megafan) and a major flood water channel, ~20 km wide, started flowing along the axial part of the megafan (Fig. 1), marooning hundreds of villages, destroying croplands and bringing disaster to thousands of people living in these areas (Fig. 2a and b). This region was not considered flood-prone as it was located far off the existing channel belt of the Kosi River. The administration and the people of

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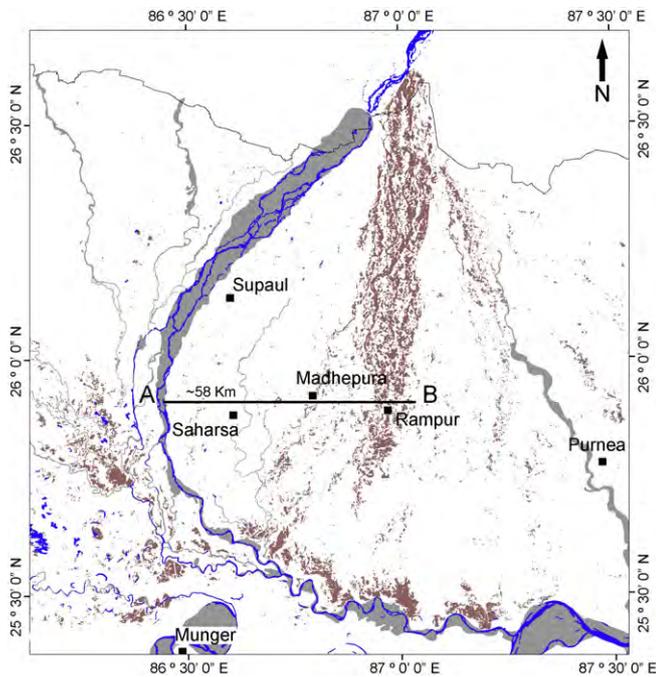


Fig. 1. Kosi megafan showing the flood water flow path after the August 2008 avulsion (after NRSA, http://fimis.bih.nic.in/Kosi_Flood%20Map/avg22-23_Bihar-Nepal-map.pdf). Note a shift of the Kosi channel by about 60 km to the east (as measured along AB).

this area were, therefore, less prepared to face the calamity, aggravating the damage done by the sudden change of the river course. In contrast to overtopping of the banks, an annual phenomenon known to the people living close to the present-day course of the Kosi, this was a major change in the course of the river (Sinha, 2009). The avulsion exposed the inadequacy of the understanding of the behaviour of the Kosi River. A better understanding of the underlying factors that control river course changes are essential for better flood prediction and for adopting more effective strategies for disaster management (Sinha, 2008, 2009).

Behaviour of the Kosi River is inextricably interlinked with the geomorphology of the Kosi megafan and its formative mechanism. A preliminary examination of the published data gives rise to the following questions:

(a) What factor(s) forced the Kosi River to sweep continuously to west for >113 km during the last two centuries, and at times (eastern half of the megafan) up the slope? (b) How reliable and precise are the dates, and a dozen positions of the paleo-Kosi, compiled from the eighteenth or early nineteenth century maps? (c) Can the sandy fining-upwards successions described from the shallow boreholes from the north-central part of the megafan (Singh et al., 1993) be correlated with the characteristic deposit of a large mountain-fed braided river comparable to that of the modern Kosi River? If not, then on what basis is the uppermost 8–10 m of the megafan deposit correlated with the sweeping Kosi River? (d) During the flood of August 2008, the Kosi avulsed to the east (Fig. 1). Why did it stop moving further west and or to the extreme east near Purnea (as predicted by Shillingfield, 1893 quoted in Gole and Chitale, 1966)?

Thus, there is a need to re-examine and critically evaluate the data from the Kosi megafan in the light of the present day understanding of the Himalayan foreland basin and the megafan sedimentation models. As a part of an effort to understand the Kosi megafan-river system, the geomorphology of the Kosi megafan was studied initially using satellite images and processed SRTM data. Following this, preliminary fieldwork in the north-central part of the megafan studied the uppermost megafan deposits exposed in river bank sections (Fig. 3). Also studied were 28 historical maps, published between 1760 and 1960, to re-evaluate the pattern of historical channel changes on this megafan (Fig. 4a). Finally, the observations in this study were compared with observations on some of the other megafans in order to reflect on the general pattern of growth of the megafans and behaviour of the trunk channels.

2. Geologic and geomorphologic setting

A spectacular megafan has developed at the mouth of the Kosi River situated in the eastern part of the Ganga Plain and is much referred to in the literature (Geddes, 1960; Duff, 1992; Sinha, 2008). A



Fig. 2. Photographs showing (in March, 2009) remnants of devastation caused by the August 2008 flood: (a) A broken bridge being repaired over Sursar River near Murliganj. (b) A 'sand channel' (arrowed), deposited by the flood waters, cover wide fertile agricultural land rendering it unsuitable for cultivation.

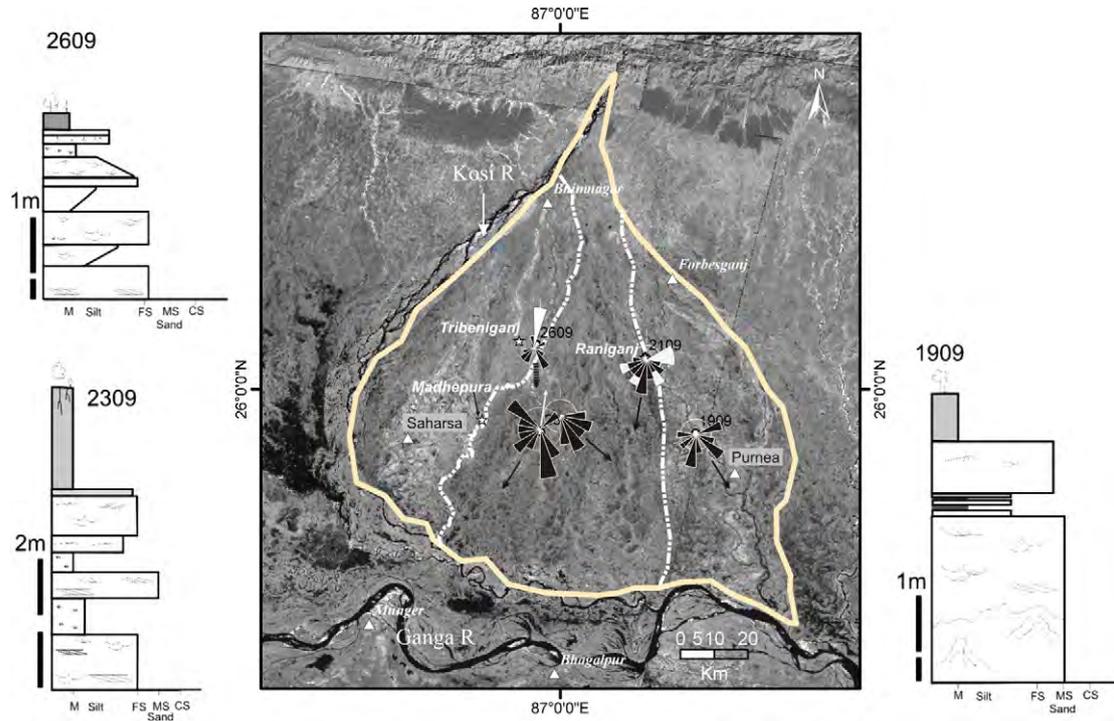


Fig. 3. LANDSAT image (USGS, LANDSAT 7, acquisition date 199/10/28) of the Kosi megafan. The paleocurrent rose diagrams are shown against the study locations. In the rose diagrams the white petals and the arrow represent data from lateral accretion surfaces; the black petals and arrows represent data from cross strata and calculated vector means respectively. Three measured lithologs prepared from river bank sections (location numbers marked on the logs) are shown in the margin.

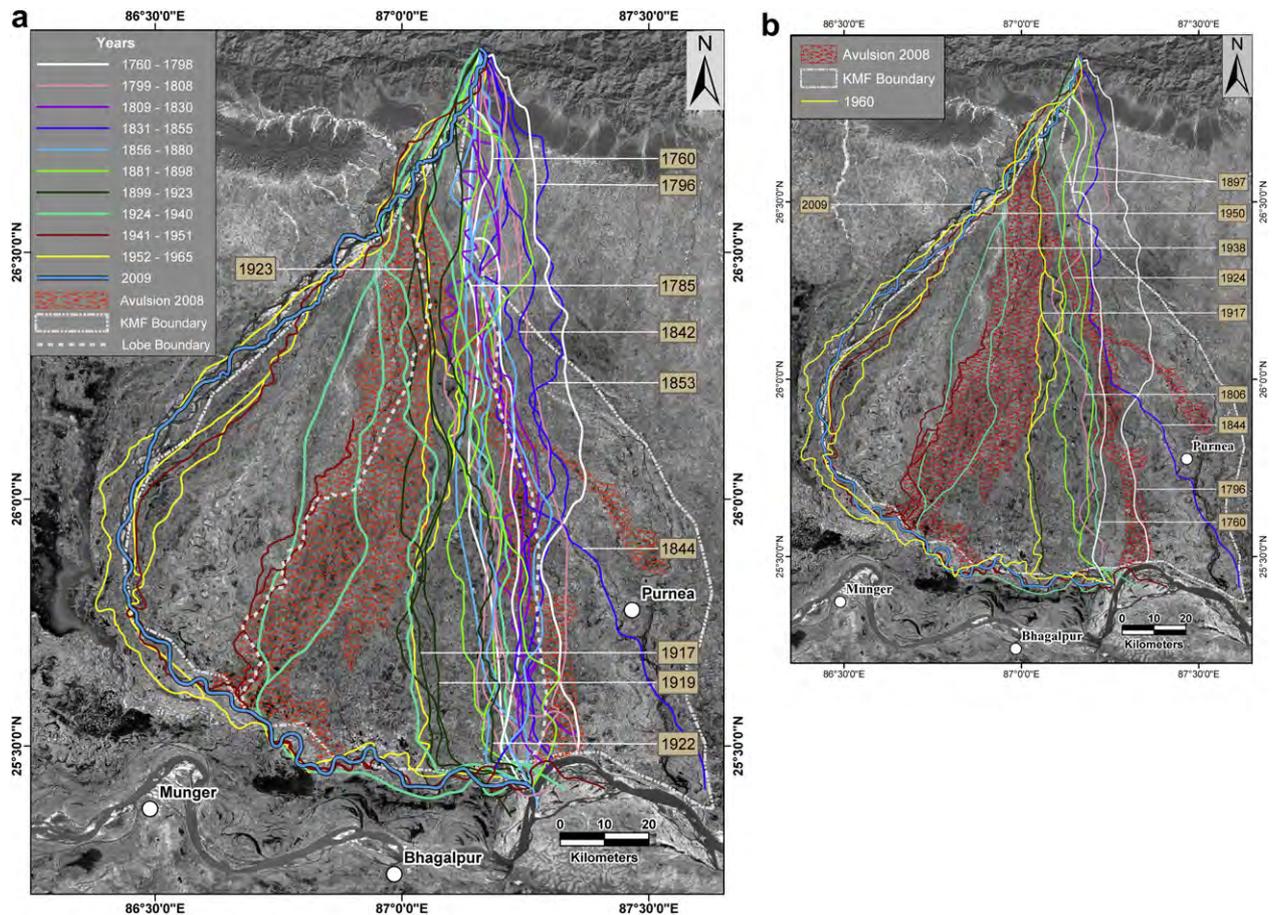


Fig. 4. (a) Overlay of different positions of Kosi River as depicted in historical maps on LANDSAT image (see Table 1 and Appendix 1 for the maps used; for methodology see text). Note positions of the Kosi channels confined mostly to the east-central part of the megafan. (b) Position of Kosi River taken from 11 selected historical maps. The channel positions shown in this diagram, illustrate an east-west oscillating movement of Kosi channel.

Table 1
List of old maps of the Kosi River.

No	Year of publication	Author/Publisher	Description/Position of kosi river	Remarks
1	1760	Public School Historical Atlas. Edited by C. Colbeck, Longmans, Green and Co., 1905.	East-central part of the megafan; far west of Purnea	
2	1785	Samuel Rawson Gardiner D.C.L., L.L.D., <i>School Atlas of English History</i> (London, England: Longmans, Green, and Co., 1914) etc.usf.edu/Maps/pages/400/410/410.jpg	East-central part of the megafan	Almost no change in position. Shows slight westward shift.
3	1796	Publ: M. Carey Philadelphia Title: Hindostan or India Author: Carey, Mathew David Rumsey Digital Map Collection, University of California, Berkeley.	Eastern part of the megafan, west of Purnea	Nodal avulsion to east ~ 13 Km, in upper part of KMF; East of channel position in 1760 and 1785.
4	1800	Delarochette, L. (Louis), 1731–1802. David Rumsey Digital Map Collection, University of California, Berkeley.	East-central part of the megafan	West of the position in 1796; back to its position in 1760.
5	1804 (i)	Arrowsmith, A. J. Conrad and Co., Philadelphia, David Rumsey Digital Map Collection, University of California, Berkeley.	East-central part of the megafan	No change in position.
6	1804 (ii)	Author: Rennell, James, 1742–1830. Published: London: Laurie and Whittle, 1804.	East-central part of the megafan	Avulsion to east by about 18 Km from the previous position; close to Purnea.
7	1806	Author: Cary, John, Publ: John Cary. London	East-central part of the megafan	Avulse to west ~ 18 Km from a point ~ 50 km downstream from the megafan apex: reoccupies the position of 1804(ii).
8	1811	Author: Pinkerton, John, Publ: Cadell and Davies London	East-central part of the megafan	No change in position. Map shows faint radial drainage network.
9	1812	Author: Arrowsmith, Aaron Publ: Thomas and Andrews Boston	East-central part of the megafan	No change in position.
10	1827	Author: Hall, S. (Sidney) Publ: Longman, Rees, Orme, Brown and Green London	East-central part of the megafan	No change in position. Map shows faint radial drainage network.
11	1842	Author: Arrowsmith, John, Publ: John Arrowsmith London DRB MC, UCB	East-central part of the megafan, joins Ghugri, takes a east turn to meet Ganges	No change in position.
12	1844	Author: Radefeld, Carl Christian Franz, 1788–1874 Publ: Bibliographischen Instituts Hildburghausen	Along the eastern margin of the megafan, close to Purnea	Nodal avulsion of the lower part to the east by ~ 20 Km. Well-developed radial drainage network.
13	1853	Author: Walker, John, 1786–1873. Published: [Dublin, Ireland: Irish Academic Press, 1978]	East-central part of the megafan	Upper part moves towards east, Lower part moves ~ 17.5 Km towards west.
14	1857	Ancestry.com http://homepages.rootsweb.ancestry.com/~poyntz/India/ind1857.html	East-central part of the megafan	Nodal avulsion of the course to west by ~ 14 Km.
15	1860	Author: Johnson, A.J Publ: Johnson and Browning New York Title: Hindostan Or British India	East-central part of the megafan	Nodal avulsion to the east, channel comes back and rejoins the previous course in its downstream part
16	1875	Author: Stieler, Adolf Publ: Justus Perthes GothaIndian Empire	East-central part of the megafan	West of the previous position. Map shows radial drainage network.
17	1890	Author: Mitchell, Samuel Augustus Publ: John Y. Huber and Co. Philadelphia	East-central part of the megafan	Upstream part moves eastward No change in position.
18	1897	Author: Rand McNally and Company Publ: Rand McNally Chicago	East-central part of the megafan	Almost in the same position, map shows two channel courses.
19	1917	Survey of India, 1917. Map of India and adjacent countries. Published by Survey of India, Calcutta	East-central part of the megafan	Nodal avulsion to the west by ~ 18 Km. Map shows number of radiating smaller channels.
20	1919	Survey of India, Calcutta	East-central part of the megafan	No change in position.
21	1922	Author: Bartholomew, J. G. (John George), 1860–1920; John Bartholomew and Co Publ: The Times London	East of the previous position East-central part	Moves east through nodal avulsion ~ 11 Km. Map shows number of radiating smaller channels. Prominent lake in the middle part of the course

22	1923	(www.lib.utexas.edu) Historical Atlas by William R. Shepherd, 1923. Perry-Castañeda Library Map Collection India, 1700–1792 (645K) [p. 137] [1923 ed.]	East-central part of the megafan	Nodal avulsion to west by ~15 Km.
23	1924	Survey of India, Calcutta.	East-central part of the megafan	Nodal avulsion to east ~18.5 Km. Shifts ~18 Km west by nodal avulsion. Similar to the position in 1923.
24	1929	Author: Touring club italiano**Publ:Touring club italiano Milano	Central part of the megafan	Faint radial drainage network Major nodal avulsion to west by ~25 Km. Radial drainage network. Map shows two channel courses.
25	1938	Gole, C. V., Chitale, S. V., 1966. Inland delta building activity of Kosi River. Journal of the Hydraulics Division, American Society of Civil Engineers HY-2, 111–126.	Western part of the megafan	Number of radiating channels present.
26	1950	Army Map Services, 1955. Map of India–Pakistan, 1:250,000. Sheet- NG45-6, NG45-10, (compiled from Survey of India, 1:63,360 series, 1939–40).	Along western margin of the megafan	
27	1960	Corps of Engineers, US Army, Washington, D. C. Geddes, A., 1960. The alluvial morphology of the Indo-gangetic plain: Its mapping and geographical significance. Institute of British Geographers Transactions and Papers 28, 253–276.		Numbers of radiating channels are shown. The channel at the central part of the megafan is wider.
28	August, 2008 flood channel	National Remote Sensing Agency, Dept. of Space, Govt. of India. Hyderabad-500037 http://fms.bih.nic.in/Kosi_Flood%20Map/aug22-23_Bihar-Nepal-map.pdf		Major shift towards east, occupying course of 1926–38 or 1929 course.
29	2009	Google earth image http://earth.google.com/	Along western margin of the megafan	Number of radiating channels present.

~2000 km long modern peripheral foreland basin flanks the Himalayan orogenic belt (Burbank et al., 1996) and is traversed by Indus, Ganges and Brahmaputra Rivers. The modern sub-Himalayan foreland basin started forming about 2 Ma, following the activation of the Himalayan Frontal Thrust consequent upon the ongoing convergence of the Indian and Asian Plates (Powers et al., 1998; Wesnousky et al., 1999). Wells and Dorr (1987) explored the history of channel shifting on the Kosi megafan and concluded that the episodes of relocation do not match with the incidents of 74 historic earthquakes in this area. They concluded that the Kosi channel avulsions were autocyclic and stochastic. Gohain and Prakash (1990) studied in detail the geomorphology of the megafan and the Kosi River flowing through the embankments along the western margin of the megafan. They identified four topographic levels in the upstream braided channel belt and documented progressive downstream changes in its planform pattern, from gravelly-sandy braided, to sandy braided to straight and finally to mixed-load meandering pattern. Gohain and Prakash (1990) recognised remnant patches of Old Alluvial Plain (OAP) in the western part of the megafan. They reported that the rest of the megafan surface was covered by different geomorphic elements of the Young Alluvial Plain (YAP) and are characterised by grey unconsolidated sediments. The occurrence of a patch of OAP was inferred by them to indicate that the Kosi River, during its latest sweep, in addition to slow continuous shifting at times moved in discrete steps leaving behind remnants of earlier deposited sediments.

Singh et al. (1993) documented different bedforms/bars and their internal structures within the braided and straight reaches of the Kosi River flowing at present through the western margin of the megafan. They also provided important information on the stratigraphy of the Kosi megafan from shallow and deep borehole data collected from the modern river beds as well as from other areas of the megafan. On the basis of these drill data, geomorphology of the megafan and reported history of its channel migration, they proposed a model for deposition of the Kosi megafan. They related the sandy gravel occupying the lower 60 m of the deeper drill cores to deposition during early Holocene deglaciation. The fining upwards channel-fills, occurring in the upper 4–10 m of the megafan surface, were ascribed to deposition from the ‘latest sweep’ of the braided Kosi-like river across the megafan. They also identified local reworking of the braided river deposits by smaller meandering groundwater-fed channels (Singh et al., 1993, their Fig. 23).

Following the recent flood in August 2008, Sinha (2008, 2009) and Reddy et al. (2008) examined aspects of the Kosi River, the megafan and flood management efforts in this area. Sinha (2008, 2009) pointed out that, to date most of the flood prevention efforts were with a notion of “river control” rather than “river management”. He pointed out that unlike the progressive shift of the Kosi towards west, as reported in the literature, during the last flood it has shifted a long distance to the east. He emphasised that the August 2008 event was a flooding due to avulsion rather than flooding by overtopping of the river banks. He attributed the mis-conceived notions of river management as a major cause for the August, 2008 disaster and called for the development of a system-scale, processes-based understanding of rivers for effective flood management. Reddy et al. (2008) suggested that the river should be allowed to flow through its post-2008-flood course and that a detailed topographic survey and age determination should be carried out for future flood prediction.

3. Geomorphology of the Kosi megafan

The Kosi megafan is spread over ~10,351 km² and the megafan has a maximum length and width of ~155 and ~115 km

Table 2
Geomorphologic Characters of Kosi megafan.

Geomorphologic characters	Description	Remarks
Area	~ 10,351 Km ²	--
Slope of megafan surface	Average slope 0.03° (slope at proximal part: 0.05° and distal part: 0.01°)	Low slope typical of the megafans; average slope is lower than Tista megafan but similar to that of the Taquari megafan
Profile shapes	Transverse profile Convex-upward with laterally stacked smaller up-arched bodies Longitudinal profile Concave-upward	The transverse profiles are complex with smaller up-arched bodies superposed on the broad convex-upward geometry; 3-D geometry is similar to other megafans and alluvial fans.
Catchment area	~ 58152 sq km	Large, low-gradient fan-like body
Maximum elevation	Proximal part ~ 70 m above Ganga alluvial plain Distal part ~ 5–8 m above Ganga alluvial plain	Large, low elevation landform similar in 3-D geometry to smaller, high-gradient, debris flow-dominated alluvial fans
Channel pattern	Radiating modern and ancient channel pattern (Fig. 6); modern channels narrower (av. 58 m), more sinuous (1.2–2.5) and paleochannels wider (av. 1.5 km) and nearly straight; all the channels become more sinuous at the distal part; discordance between sets of radiating channels defines three lobes.	Narrower sinuous modern channels indicate decreased sediment and water discharge; down megafan increase in sinuosity reflect decreasing slope; discordant channels and up-arched smaller bodies in the transverse profile indicate presence of lobes (Fig. 5)
Lobes	Three lobes are observed. Lobe boundary is marked by the crosscutting relation of the channels.	Similar to other alluvial fans and megafans. Inferred lobe chronology indicate random oscillation of the lobes
Mountain front sinuosity (Smf)	2.68	Values 1.4–3 indicate mountain front with lesser activity but still reflecting active tectonics
Asymmetry Factor (AF)	66.6	Value > 50 indicates left (eastward) tilt of the catchment basin

respectively (Table 2). The three major tributaries within the mountain belt are Sun Kosi, Arun Kosi and Tamar Kosi and together they drain a catchment area of ~ 58,152 km². Annual rainfall in the Kosi plains is 1000–1600 mm. Average monthly discharge of Kosi River varies from >6000 m³/s to 500 m³/s and the mean annual flood discharge is of the order of 7000 m³/s (Sinha and Friend, 1994). It is reported that during the devastating flood of August 2008, the peak discharge was around 144,000 m³/s (Sinha, 2008). The proximal part of the megafan has a maximum slope of 0.05° (0.00087) that declines to 0.01° (0.00017) near its toe. Longitudinal profiles of the megafan typically have a concave-up shape and the transverse profiles are broadly convex upward with numerous channels dissecting the megafan surface (Fig. 5). The transverse profiles of the megafan are irregular due to presence of raised and incised regions. However, the best fit curve through the data (fitting a third degree polynomial curve through the elevation points in the section line) displays a broadly convex-upward pattern. Some of the transverse profiles show the presence of laterally stacked smaller convex-up bodies superposed on the broad upward convex profile of the megafan (best developed in profile Tp2, Fig. 5). The eastern margin of the megafan is at a lower elevation than that of its western margin, thus producing an eastward tilted appearance in profile view (Fig. 5).

A radiating network of abandoned and active channels is present on the megafan surface (Fig. 6). On closer examination, the modern and paleochannels form a number of radiating packages/clusters. The apex of each of the packages lies in the upper reaches of the megafan. These radiating packages are referred to here as lobes. At places, discordance has been observed between the orientations of channels in two adjacent lobes (Fig. 6). Based on the pattern of discordances, three lobes can be identified on the Kosi megafan and have been marked as 1a, 1b and 2.

Study of the high resolution satellite images and field visits revealed the presence of several types of channels on the megafan. Besides the Kosi River flowing through the western margin of the megafan, most other modern perennial channels traversing the megafan today are fed by groundwater springs (plains-fed channels sensu Sinha and Friend, 1994). These channels are incised up to 6 m on the megafan surface and are locally reworking the uppermost deposits of the megafan. The incised channel banks at places provide good sections to study the uppermost few metres of the

megafan succession (Figs. 7b, 8a, b). There are numerous other channels on the megafan surface that are nearly dry or with stagnant hyacinth-covered water, and these channels carry significant discharge only during the monsoon (Fig. 7c). There are others that are completely abandoned, mostly converted to agricultural fields, but can be recognised from their relict channel form morphology (Fig. 7d). Many of the latter channels can be recognised in satellite images.

The mountain-fed main Kosi channel at the western extremity of the megafan is braided up to the central part of the megafan and increases its sinuosity downstream. The Kosi channel belt varies in width from 2 to 11 km. Paleochannel belts recognised in the satellite images are wider than the plains-fed channels and vary from 0.6 to 3.45 km. The mean width for 21 measured paleochannels is around 1.5 km. Most of the paleochannels are, however, wider and less sinuous than modern plains-fed channels. Presently active groundwater-fed channels are highly sinuous with sinuosity values varying from 1.2 to 2.5. Widths of the channels vary from 6 to 150 m with a mean of 60 data around 58 m (Table 2). Only a few of these paleochannels are comparable in their widths to the modern Kosi (northeast corner of the megafan, Fig. 6). The majority of these paleochannels are narrower than the present-day Kosi River.

The transverse profiles of the megafan are irregular due to presence of raised and incised regions. However, the best fit curve (3rd degree polynomial) through the profile data displays a broadly convex-upward pattern of the megafan surface. The fitted curve through the profile data is very similar to those of the typical, small, debris flow dominated alluvial fans (cf. Bull, 1977; Blair and McPherson, 1994). The amplitude of the convex-up curve is greater than any one of the smaller undulations on the megafan surface (cf., profile Tp2, Fig. 5). This implies that the broad convex-upward geometry of the megafan is one of its primary attributes and not an artefact of recent deposition and incision by the present-day surface processes.

Increased sinuosity, decreased width and incised nature of the modern plains-fed channels indicate decreased water and sediment load in these channels as compared to some of the wider, less sinuous paleochannels (Fig. 7a) as well as the braided upstream reach of the Kosi River. All the megafan channels; the braided Kosi, the paleochannels, and the plains-fed modern channels, show

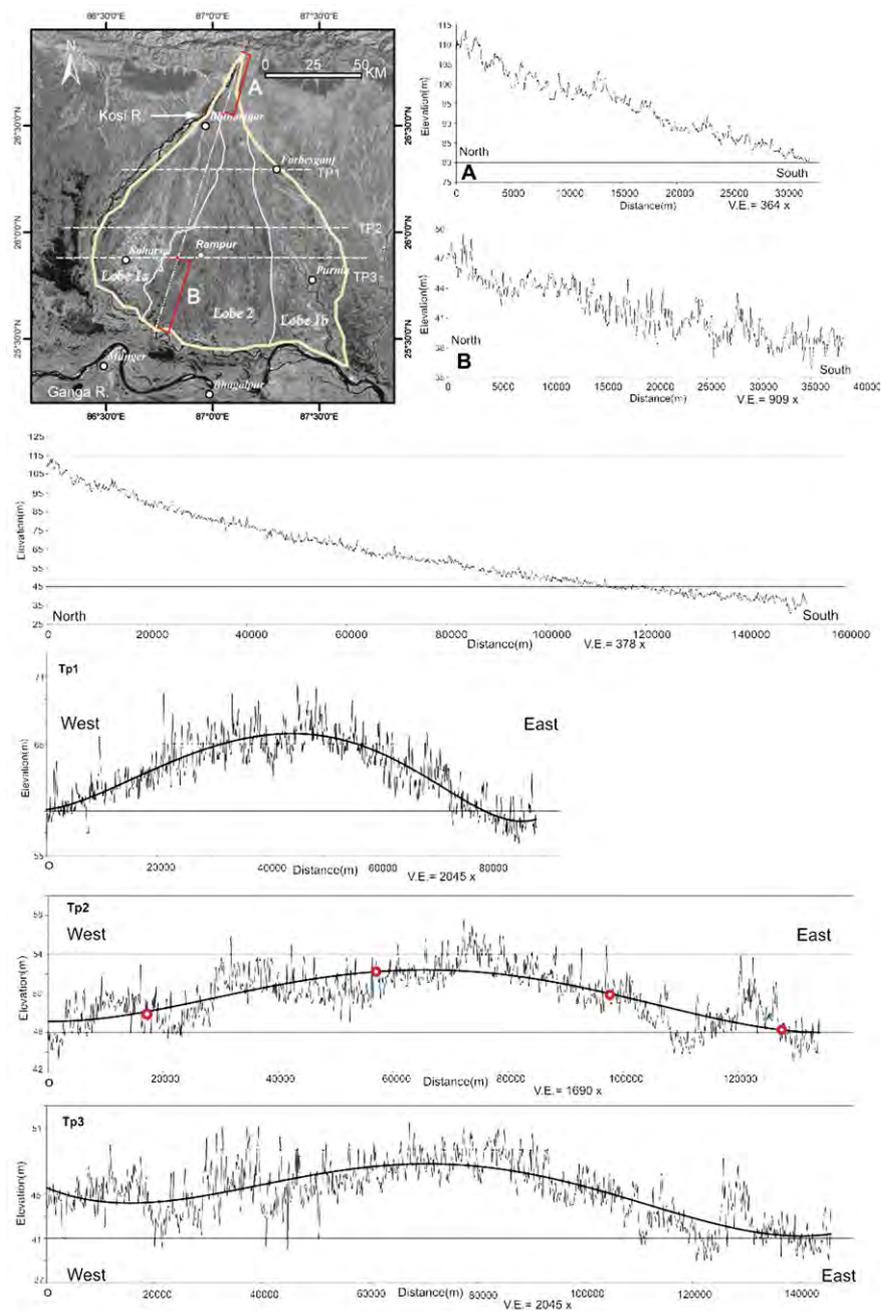


Fig. 5. Longitudinal and transverse profiles of the Kosi megafan prepared from DEM. A, B: longitudinal profiles of the megafan in the proximal and distal regions respectively. Lp: the longitudinal profile of the entire megafan. Tp1–Tp3: transverse profiles. Note smaller, convex-upward segments superposed on the transverse profiles (Tp2). Solid black lines are the third degree polynomial curves fitted through the elevation points on the megafan. Red dots in Tp2 mark the position of the lobe boundaries. Inset image shows the position of the lobes and the section lines.

increase in their sinuosity down the megafan. In an unconfined valley setting, the planform pattern of a river is largely controlled by the available energy and calibre of the sediment load, and both these factors are largely a function of the slope of the channel (Brierley and Fryirs, 2006). Thus the long term spatial changes in the river planform pattern noted above are attributed to the decreasing slope of the megafan surface as noted in its longitudinal profile (Fig. 5). Presence of the radiating channel pattern on the other hand, reflects the divergent surface slope induced by convex-up geometry of the megafan and is common to many of the studied megafans (Geddes, 1960; Decelles and Cavazza, 1999; Assine, 2005; Wilkinson et al., 2006).

Multiple packages of radiating paleochannels indicate development of accretionary lobes fed by a trunk channel and its distributaries. Mutual discordance of the channel pattern between adjacent lobes (Fig. 6) indicates shifting of the trunk channel and locals of megafan accretion. Presence of smaller, laterally stacked, convex-upward bodies seen in the transverse profiles (Tp1–Tp3, Fig. 5) probably reflects these lobes. A similar multilobate pattern, as discussed in a later section, is common in many other megafans as well as in small debris flow dominated alluvial fans (Bull, 1977; Assine, 2005; Chakraborty and Ghosh, 2010).

The satellite images show that the central lobe (lobe 2) cross-cuts the network of divergent channels of both eastern and western

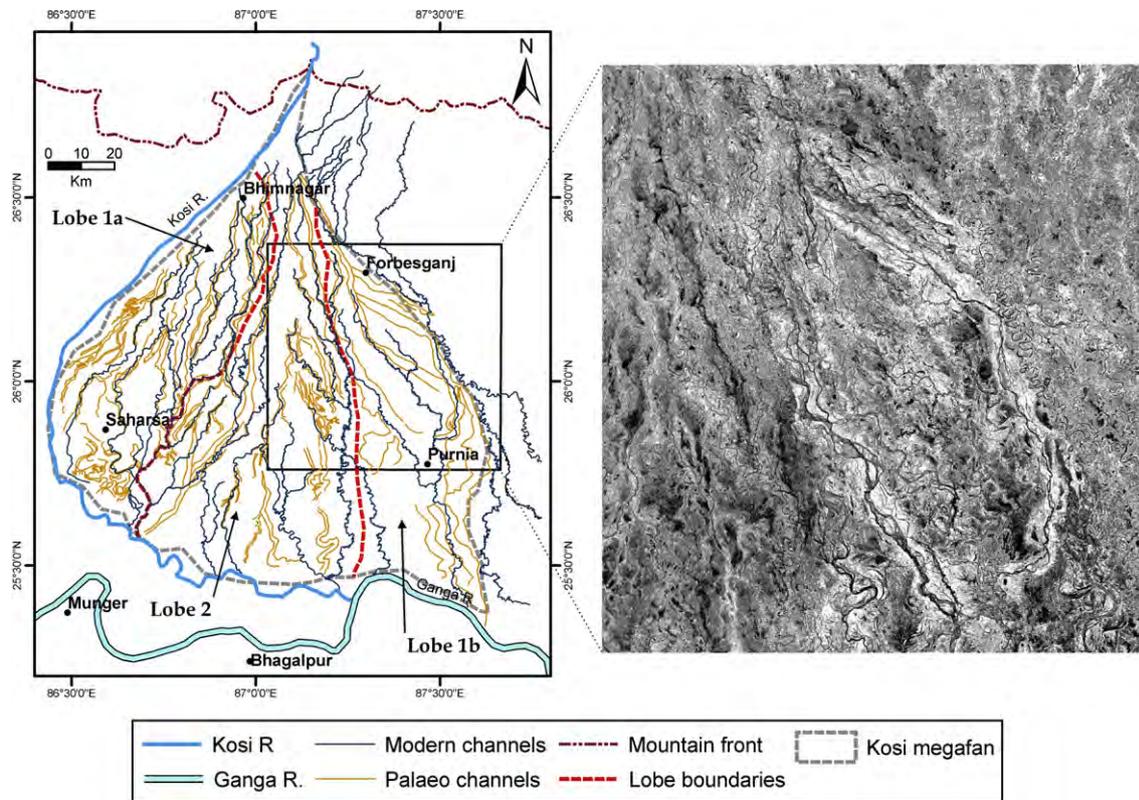


Fig. 6. Line drawing prepared from high resolution satellite pictures (USGS, LANDSAT 7, acquisition date 199/10/28) showing both presently active channels (blue) and abandoned paleochannel belts (yellow/orange). Three megafan lobes defined by channel discordances are also shown. Note paleochannel belts are wider and less sinuous than the modern channels, and also discordance in channel pattern in adjacent lobes. Satellite image of the area marked by a box in the line drawing shows the details of the truncating relationship among channels in lobes 2 and 1b. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lobe (lobe 1a and 1b). Lobe 2 is, therefore, younger than both lobe 1a and 1b. It is difficult to assess the relative chronology between lobe 1a and 1b from remote sensed images alone. Gohain and Prakash (1990) recognised patchy preservation of the Older Alluvial Plain, and the area of OAP broadly coincides with the westernmost lobe. On this basis it appears that the western lobe (Lobe 1a) is older than Lobe 1b in the eastern extremity of the megafan. This chronology is, however, relative and does not provide any numerical time frame for the growth of the lobes. This reconstruction, however, demonstrates random nodal relocation of the trunk channel and its associated lobe across the megafan and is in sharp contrast to the postulated hypothesis of the megafan deposition through continuous westward shift of the Kosi River.

4. Near-surface sediments of the megafan

The existing sedimentation models visualise that the northern part of the Kosi megafan was deposited by braided rivers similar to the present-day Kosi River and these deposits were locally reworked by plains-fed smaller meandering streams (Singh et al., 1993; Jain and Sinha, 2003; Sinha and Sarkar, 2009). A preliminary examination of the surface exposures, mainly in the north-central part of the megafan, was conducted in order to evaluate the facies of the sediments in this context. In interpreting the sedimentology of the deposits besides these data, the sandbody geometry reported from these areas by Singh et al. (1993) was also considered. The examined river bank sections around Madhepura, Tribeniganj, Raniganj are 3–5 m high and are at places several hundreds of metres long, allowing a detailed view of the sandbody geometry and internal architecture of the deposits (Fig. 7b). Nearly 100 paleocurrent data were measured from these sections. The

description of these sections and their paleocurrent constitute the first study of the near-surface sediments of the Kosi megafan away from the modern Kosi channel belt. However, compared to the total size of the megafan, the area covered in this work is small and more work is needed for a comprehensive sedimentological analysis of the near-surface deposits of the megafan.

Four facies recognised in the field on the basis of sedimentary structures have been named following the scheme suggested by Miall (1996) and have been described in Table 3. The facies, on the basis of their preferred association and architecture of the sediment bodies, can be grouped into three major associations that can be inferred in terms of the depositional environments (Table 4). These facies associations are discussed briefly below.

4.1. (FA-I) meandering river association

This is the most common association in the sections examined. It typically forms 1.5–3.5 m thick fining upward units comprising dominantly of fine to medium grained sand with coarse sand at the base (Fig. 3). Gently inclined silt-mud (Fm) layers separating sandy cross-stratified units (Sp and St) characterise these sand bodies (Fig. 8a,a1,b). The silt-mud layers are greyish to yellow, few cm to 20 cm thick, and contain burrows, iron-rich concretions and root traces (Fig. 8d). Cross-sets are 5–30 cm thick and organised in thinning-upwards cosets. In a few sections, comparatively thicker sub-horizontal mud layers occur at the top of the fining-upwards units (Fig. 3).

The inclined fine-grained surfaces dip in different directions. The mean directions of the cross strata vary between southeast and southwest, but in individual exposures are usually at high angle to the dip direction of the inclined surfaces (Figs. 3 and 8b).

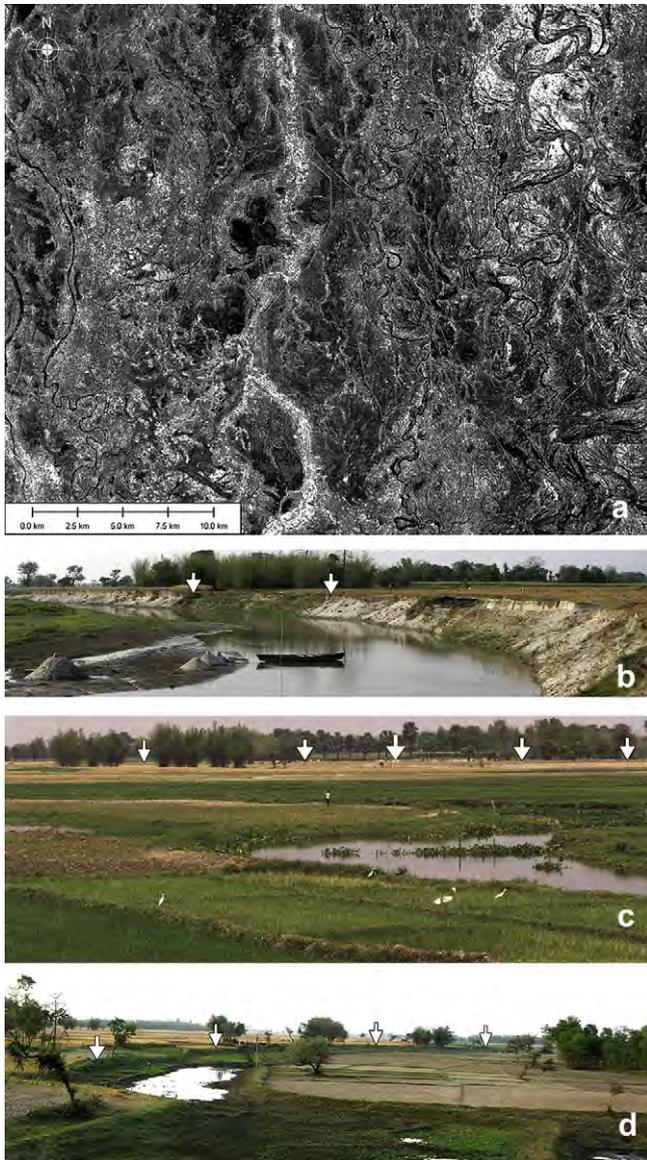


Fig. 7. (a) Highly sinuous, narrow modern perennial channels and wide straight paleochannel belts on a part of the Kosi megafan; LANDSAT image. (b) Incised plains-fed perennial stream. The river bank (orientation broadly NE-SW) exposes the topmost megafan deposits. Note wide belts of sandy channels (arrowed) that lack internal muddy lateral accretion surfaces; Kamla River section; near Raniganj. (c) Channels with stagnant pool of water in the lean season. Note the channel occupies a small part of the wide channel belt (N-S oriented distal margin of the large channel marked by arrows). (d) Completely abandoned channel bed that has been converted to agricultural field. Arrows mark the distal channel margin.

4.1.1. Interpretation

Fine-grained inclined strata dipping at high angle to the local paleoflow indicate these are lateral accretion deposits (Smith, 1987; Fielding et al., 1993; Ghazi and Mountney, 2009). Fine to medium sand sized deposits with abundant inclined fine-grained layers and well-developed fining upward sequences indicate deposition from a mixed-load sinuous low-energy stream. Maximum channel depth, as estimated from the height of the point bar deposits, ranges between 2 and <5 m. Paleocurrents indicate a broadly southward flow. In the overall context of the Kosi megafan, the association appears to represent deposition from shallow meandering streams similar to the majority of the plains-fed channels.

4.2. (FA-II) braided river association

This facies association is comparatively less common in the study area. The association comprises 3–4.5 m thick, pebbly, coarse to fine sand units. The cross strata sets show a thinning upward trend. The sand bodies are laterally traceable for more than a few hundreds of metres in some of the exposures (Fig. 7b). The inclined muddy layers and comparatively thicker mud layers capping the F-U units, common in the FA-I deposits, are absent in these sand bodies. Paleocurrent measurements yield an overall southward trend (Fig. 3). Extensive sand bodies of this association are found to occur laterally with the deposits of FA-I in the same stratigraphic level and exposed in the same river bank sections (Fig. 7b).

4.2.1. Interpretation

The observed large lateral extent of these sand bodies, lack of inclined muddy layers and less obvious fining upward grain size trend is construed to indicate an absence of point bars in the precursor channels. The deposits resemble typical braided river sand described in the literature (Cant and Walker, 1978; Miall, 1996). In a network of channels traversing the megafan, some of the channels might be temporarily transformed to a braided character due to channel capture in the upstream reaches (cf. Willis, 1993). Such changes may produce deposits of two different types in the same stratigraphic level. The deposits, however, might also represent mid-channel bars within a wide sinuous channel (Bridge, 1985). In view of the similarity of sandbody thickness, scale of bedforms and lateral juxtaposition of this facies with the sediments of FA-I, local transformation of channels is suggested rather than the presence of large channels of different order. Noteworthy is the paucity of braided channel deposits (FA-II) as compared to the abundance of lateral accretion deposits of FA-I in the north-central part of the megafan covered in this study.

4.3. (FA-III) floodplain association

This association was encountered in the Sursa River section north of Rampur (Figs. 1 and 3) and occurs extensively over several square kilometres. The association is dominated by dark grey to light grey silt-clay beds. Abundant traces of roots and elongated patches of iron concretions or iron nodules occur near the top of the beds (Fig. 8e1, 2). The deposits of FA-III is up to 3 m thick, in which 30–55 cm thick light grey ripple laminated clayey silt beds alternate with 50–70 cm thick units of darker clay beds with abundant iron concretions and root moulds (Fig. 8e).

4.3.1. Interpretation

The dominance of fine-grained lithology in this association and grey colour of the sediments indicate their deposition under stagnant reducing water. Abundant root traces and iron concretions probably denote incipient gleyed paleosols. In the context of the Kosi megafan, the facies association is interpreted to represent deposition in the overbank floodplain and associated marsh environment. Similar deposits have been reported from modern floodplains (Aslan and Autin, 1999; Pizzuto et al., 2008). The large area over which the association occurs north of Rampur appears to indicate its depositional milieu is similar to the large marshlands common on the megafan surface today.

4.4. Paleocurrent and sedimentation of the Kosi megafan

The paleocurrent pattern as obtained in this preliminary study shows broadly southward transport. The vector means directions vary from exposure to exposure with a radiating pattern of the mean directions (Fig. 3). Although data coverage in this study is not



Fig. 8. (a) Inclined heterolithic strata (arrowed), Sursar River, south of Purnea-Saharsa Road. Orientation of the section NW-SE. Low dip of the accretion surface (arrowed) is due to the section orientation sub-parallel to the local flow. The blow-up (a1) shows the details of the features of LA surface. (b) Lateral accretion surfaces (arrowed) separating cosets of trough cross strata, Kamla Nadi near Raniganj village; section orientation E-W. (c) Burrowed mud and rippled fine sand occurring at the top of the FA-I, Sursar River, south of Purnea-Saharsa Road. The section is oriented 280° – 100° . (d) Coset of trough cross strata in FA-I deposit, south of Rampur. (e) The marsh deposits of FA-III, Sursar River section, Kumarkhand. Two enlarged views (e1 and e2) show details of alternate silt-mud layers and a pedoturbated silty layer with abundant ferruginous nodules.

sufficient to characterise the paleocurrent pattern of the entire megafan succession, the southward radiating pattern obtained is consistent with the observed radiating channel pattern on the megafan (Figs. 3 and 6).

The following aspects of megafan sedimentation are clearly brought out by the limited field study: first, the braided river deposits (FA-II) are volumetrically much less than the meandering stream deposits (FA-I) in the north-central part of

Table 3
Sedimentary Facies of Kosi megafan deposits.

Facies	Description	Paleocurrent	Interpretations/Remarks
(Fm) Clay, mud with Fe-concretions	Laminated or massive greyish, brown mud/clay, 10–55 cm thick; at places with interlayers of rippled silt or fine sand; abundant root moulds and Fe-concretions, in some sections layers have a gentle dip ($\sim 10^{\circ}$)	--	Slack water deposits with growth of vegetation; gentle inclination of the layers orthogonal to local paleocurrent indicate some of these deposits formed as lateral accretion surfaces of the macroforms/bars
(St/Sp) Large-scale trough and planar cross strata	Cosets of trough or planar cross strata varying in size from 15 to 40 cm in medium to coarse sand	Broadly southward, mean directions varying between 131° and 212°	Trains of sandy bedforms, both 2-D and 3-D
(Sh) Horizontal to low-angle laminations	Mm-scale laminae in fine to med sand, form 15–30 cm thick sets of horizontal laminations, laterally traceable up to 15 m; locally showing 5° – 7° dip and may grade into low-angle cross strata	Few low-dipping sets dip north-west	Formed in upper flow regime or transitional to upper flow regime condition
(Sr) Ripple laminated fine to very fine sand	Cosets of climbing ripples, individual sets 0.5–3 cm thick and form sets 15–30 cm thick; climb angle up to 10°	In a few sections ripples migrate towards east	Shallow, lower regime flow with abundant suspended sediment load

Table 4
Facies associations in the near-surface deposits of the Kosi megafan.

Facies Association	Description	Paleocurrent	Interpretation
(FA-I) Meandering River Association	1.5–3.5 m thick, fining upwards sand bodies comprising fine to medium grained sand and clay. Gently inclined silt-mud (Fm) layers separate sandy cross-stratified units (Sp and St). Thinning-upwards cosets of trough and planar cross strata common.	Vector mean from the sandy cross strata vary between 178° and 212°; inclined heterolithic surfaces are variably oriented to east or south	Sinuuous meandering streams transporting sandy bedload; common point bar deposits, depth of the channels vary from 2 to 5 m
(FA-II) Braided River Association	3–4.5 m thick, very coarse to fine sand units with abundant cross strata. The cross strata sets show a thinning upward trend; ill-defined F–U trend; the sand bodies are laterally traceable for more than a few hundreds metre.	Mean paleocurrent direction towards S–SW	Probable sandy braided stream deposits experiencing higher discharge than the FA-I units; channel depth ~3–5 m
(FA-III) Floodplain Association	Dark grey to light grey silt-clay beds with abundant traces of roots and elongated patches of iron concretions or iron nodules; light grey units of ripple laminated clayey silt beds, alternate with dark grey tough, clay-dominated beds; abundant iron concretions and root moulds.	--	Floodplain pond or marsh with stagnant, reducing water and abundant vegetal growth

the megafan. Also, both types of deposits occur at the same stratigraphic level, and form sand bodies and bedforms of similar scale. Secondly, there is an overwhelming dominance of the fine grained lateral accretion deposits in the studied part of the megafan. Both these observations are inconsistent with the existing depositional models that visualise sedimentation of the uppermost megafan succession by sweeping modern Kosi-like, mountain-fed braided streams (cf. Singh et al., 1993; Jain and Sinha, 2003).

Singh et al. (1993) presented three sets of borehole data taken from the megafan deposits away from the Kosi channel belt (Chhatapur, Murliganj and Bihariganj). The present study covers one of the locations (location 2309, Fig. 3). The sandy gravel encountered in the lowest part of the boreholes was inferred as probable old Holocene deposits. The borehole logs show presence of fining upward sandy channel-fill deposits near the top. The uppermost fining upwards sandy deposits in these boreholes were inferred as deposits of a braided Kosi-like river that swept past these locations over the last two centuries (Singh et al., 1993). They also inferred from their correlated shallow borehole data that some of the thinner (up to 4.7 m) and fine-grained units, (cf. Fig. 20, Singh et al., 1993) represent reworking and deposition from meandering, plains-fed ('groundwater spring fed') channels. In the preliminary study of ~5 m thick near-surface deposits in the north-central part of the megafan, extensive braided river deposits were not recognised. The mountain-fed Kosi River, as it exists today in the equivalent radial distance downstream of the megafan apex, is 8–10 km wide, up to 10 m deep, and is dominated by large transverse sandy bedforms and mid-channel bars (Singh et al., 1993). The F-U, grey, medium sand with well-developed muddy lateral accretion surfaces of the dominating the study area (Fig. 8a and b) bears little resemblance to the braided modern Kosi River. The observed relationship of lateral juxtaposition, rather than an overlying–underlying relationship, between the meandering and braided river deposits (FA-I and FA-II), as exposed near Tribeniganj (Fig. 7b), is inconsistent with the existing facies model (cf. Fig. 23 of Singh et al., 1993).

Eight of the ten sections examined comprise medium to fine-grained grey sand and mud succession deposited from LA elements in small sinuous streams. Due to the spatially limited extent of the fieldwork, it is possible that the deposits left behind by a large Kosi-like mountain-fed stream on the megafan surface were missed. Assuming this to be true, the exposures examined should represent reworked deposits left by the 'groundwater-fed' small meandering streams. According to the published data, paleo-Kosi

migrated away from the axial region of the megafan after AD 1873 (Mookerjee, 1961; Wells and Dorr, 1987). Allowing time for development of the modern soil profiles in these sections, the duration of reworking and sedimentation, by plains-fed streams should be less than 100 years. This would require a rate of deposition of ~50 mm/y. Alluvial plain sedimentation rate in the Ganga–Brahmaputra foreland alluvial plain varies from less than 1 mm to about 10 mm/y (Sinha et al., 1996). In the enormous channel belt of the Brahmaputra River in Bangladesh, Allison et al. (1998) determined a sedimentation rate of about 40 mm/y that declines to about 2.8 mm/y within a distance of 5 km away from the channel belt. Estimates for sedimentation rates from the Bengal delta, Indus submarine fan or Neogene Siwalik foreland basin vary between 0.3 and 1.2 mm/y (Worm et al., 1998; Prins and Postma, 2000). The sedimentation rate of Late Miocene to Quaternary deposits in the Andes foreland basin varies from 0.13 to 0.71 mm/y (Uba et al., 2007). A similar sedimentation was assumed in one of the numerical simulations of the channel-belt deposits (Karsenberg and Bridge, 2008). In this backdrop, the sedimentation rate of 50 mm/y implied for the deposits of the Kosi megafan is unusually high. Assuming an average sedimentation rate of 1.0–2.0 mm/y for this region, it would require about 2.5–5 ka to accumulate the successions. This estimation again questions the relation of these deposits with the reported history of migration of the Kosi during the last two hundred years.

5. Old maps of the Kosi river

About 28 old maps with publication dates varying between 1760 and 1960 (Table 1) were examined to assess the historical evidence of channel shift over this megafan. The Kosi channels as depicted on these maps were plotted on a recent satellite image by bringing them to the same scale and same map projection (Geographic coordinate and WGS84 as datum and spheroid). Several fixed locations/settlements and several major geographic landmarks were highlighted for comparison between the Kosi channels from different historical maps (Fig. 4a and b). Notwithstanding many inaccuracies in these maps, the major large-scale geographic features can be readily identified, allowing comparison of the position of Kosi River between these maps. Some key observations from the study of these maps are as follows:

- i) During most of the 200 year period covered in these historical maps, the Kosi River is shown to occupy the east-central part

of the megafan. 20 out of 28 maps show the Kosi River to occupy this position (Table 1);

- ii) Only five maps (1796, 1804 (ii), 1842, 1844, 1853) show the Kosi River flowing along the eastern half of the megafan;
- iii) Some of the nineteenth and early twentieth century maps (maps of 1844, 1875, 1917, 1922, Table 1; Appendix 1) show a radiating network of smaller channels on the megafan along with a trunk channel (Kosi). Many of these radiating channels are shown as plains-fed type;
- iv) The maps published after the late 1940s show the path of the Kosi River coinciding more or less with its present position, that is, at the western margin of the megafan. The Kosi channel was probably diverted westward by constructing guide banks to the western margin of the megafan (Geddes, 1960; p. 262 “upstream embankment built by ‘giants’”), and since 1963 the position of Kosi channel was ‘fixed’ by diverting it through the barrage and constructing embankments all along its course.

Clearly, the investigated maps do not provide evidence for a continuous westward shift of the Kosi River. On the contrary, according to these maps, besides being located slightly east of the axial position for a long duration, the shifting of the river was random and oscillating in nature. Although confined to the eastern half of the megafan, the channel moved to the east and to the west over this period. For example, Arrowsmith’s map published in 1804 shows the Kosi channel flowing through the axial part of the megafan, whereas later maps (Radefeld, 1844) show the Kosi occupying the eastern half of the megafan. The channel again shifted west and occupied a position more or less along the megafan axis (Rand McNally and Co, 1897; Survey of India, 1917; Appendix 1, Table 1, Fig. 4a). Maps since the early 1940s show the Kosi River flowing along the western margin of the megafan (Army Map Services, 1950, using survey data acquired between 1938 and 1950; Table 1). This western course was, at least partly, not the result of avulsion but was forced by the construction of guide banks (Geddes, 1960), barrage and embankments (Sinha, 2009). The avulsion in 2008 relocated the river course to the axial part of the megafan through a breach in the upstream eastern embankment. This breach was repaired after a few months and the flow was forced back to its embanked course along the western extremity of the megafan.

6. Comparison with the other megafans

Summarised below are studies of two other megafans: the Tista megafan, Ganga–Brahmaputra alluvial plain, India; and Taquari megafan, Pantanal wetland, Brazil. Discussion of the geomorphology of the megafans is aimed at understanding the behaviour of the trunk channels on these megafans and to compare it with that found on the Kosi megafan.

6.1. Tista megafan, India

The Tista megafan (TMF), spread over India and Bangladesh, has an area of 18,000 km². The megafan surface has a slope of 0.19° near its apex and 0.01° near its toe. The transverse and longitudinal profiles of the megafan show broadly convex-upward and concave-upward shapes respectively (Fig. 9). The megafan is traversed by a radiating network of narrow, sinuous plains-fed channels, and is flanked on both sides by two large braided rivers, namely the Tista and Mahananda. Numerous less sinuous, wider paleochannel belts can be recognised on the satellite pictures of the megafan (Fig. 9). The network of abandoned and active channels defines four lobes on the Tista megafan (Fig. 9). The

geomorphic evidences suggest accretion in TMF was through lobe construction, and random, nodal switching of the trunk channel constructing these lobes to the east and west of the megafan (Chakraborty and Ghosh, 2010). This method of accretion is in sharp contrast to the postulated sequential migration of the Kosi River towards west.

6.2. Taquari megafan, Brazil

The Taquari megafan (Fig. 10) was investigated using LANDSAT images and SRTM DEM, and these observations combined with the published study of the megafan (Assine and Soares, 2004; Assine, 2005). The megafan is nearly circular in plan with a radial length of ~250 km. It has a concave-up radial profile and convex-up transverse profiles (Fig. 10). The megafan surface has a gentle slope of 0.05° near its apex that declines to 0.01° near the toe. Most of the channels currently traversing the megafan are meandering streams carrying sandy loads (Assine, 2005). In satellite images, several radiating network of old and currently active channels can be observed (Fig. 10). The channel pattern in each of these networks is discordant to the patterns in the adjacent networks. These mutual discordances allow recognition of six major lobes on the megafan (Fig. 10; see also Assine, 2005, his Figs. 4 and 13). Apices of the individual lobes (the channel networks) are situated either at a point close to the head of the megafan or some distance down the megafan, as in the present-day Taquari River (Fig. 10). The Taquari River is incised into the upper part of the megafan and spreads out in the lower part as it crosses the intersection point (Fig. 10). The irregular surfaces of the transverse profiles, on closer examination, suggest the presence of smaller up-arched regions, the boundaries which coincide with the lobe boundaries recognised in plan view. These up-arched bodies in profiles views are probably subtle reflection of the lobes (Fig. 10b).

Due to the large dimension and nearly 180° spread of the megafan from its apex, many of the lobes are not in direct contact with each other. This prevents determination of relative ages of all the lobes by the evidence of channel discordances alone. However, the relative chronology of the lobes (Fig. 10) as far can be determined through this method, cannot be explained by unidirectional shifting of the trunk channel from one end to other, and is rather more consistent with random switching of the trunk channel over the megafan.

7. Discussion

The megafans are important component of the aggradational basins and probable megafan deposits constitute a significant proportion of the continental basin fills, particularly in those of the foreland basins (Kumar, 1993; Willis, 1993; Horton and DeCelles, 2001; Weissmann et al., 2002, 2005; Leier et al., 2005; Wilkinson et al., 2006; Nichols and Fisher, 2007; Fontana et al., 2008). But it is not yet very clear as to why and how the megafans (or Distributary Fluvial Systems) form (Leier et al., 2005; Nichols and Fisher, 2007; North and Warwick, 2007; Hartley et al., 2009). Among the megafans, the well-displayed, large-scale fan-shaped morphology of the Kosi megafan and its ‘documented’ history of unusually rapid channel migration have made this megafan one of the most oft-referred examples in text books and research publications (Duff, 1992; Mackey and Bridge, 1995; Collinson, 1996; Decelles and Cavazza, 1999; Bridge, 2003; Jain and Sinha, 2003; Assine, 2005). The following paragraphs discuss the question of migration of the Kosi channel across the megafan, keeping in view the questions raised at the outset on this issue.

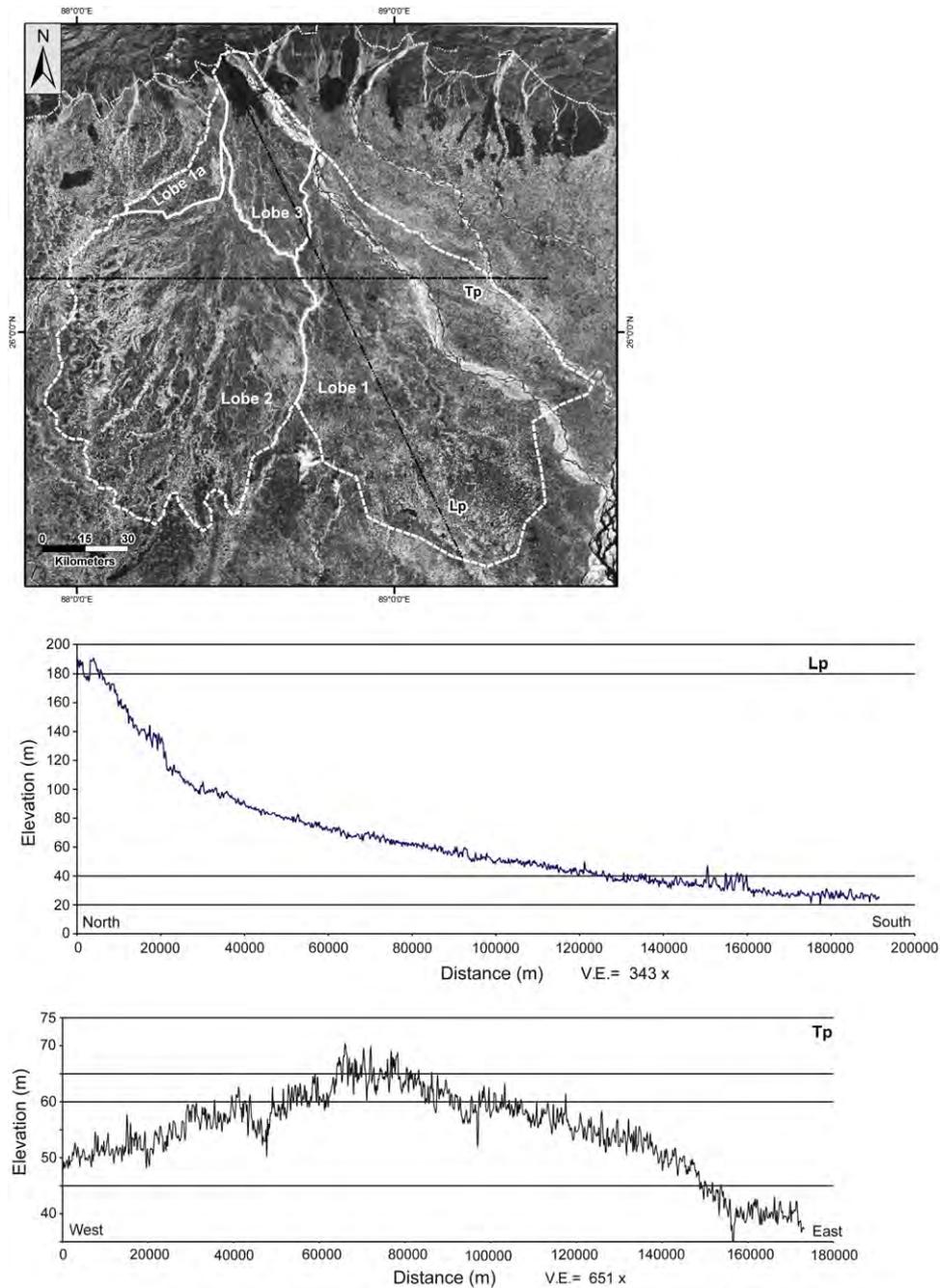


Fig. 9. LANDSAT image (USGS, LANDSAT 7, acquisition date 2001/10/26) of the Tista megafan with lobe boundaries and section lines marked on it. Note radiating pattern of narrow modern and wider paleochannels. Packages of radiating channels mark three major lobes on the megafan. (Lp) and (Tp) show longitudinal profile and transverse profile of the megafan. The smaller undulations on transverse profiles reflect presence of lobes.

Geomorphic analysis shows that the Kosi megafan has a distinct convex-upward shape in transverse profiles with its eastern margin occurring at a lower elevation than that of the western margin (Fig. 5). There is no evidence of a westward tilt of the megafan surface that could have forced the unidirectional migration of the river to the west over the last two centuries as also pointed out by Wells and Dorr (1987). Wells and Dorr (1987) also showed that there is no positive correlation between the avulsions and the historic data on earthquakes of this region, and concluded that the avulsion must have been controlled by auto-cyclic processes.

Close to its apex, width of the megafan is much smaller than that in its central or distal part. Channel relocation in this region (a nodal avulsion) involves a small lateral shift. Also near the apex, for all radial directions, the ratio of radial to transverse slopes is higher than that in any point in the distal part of a semi-conical (fan-like) sediment body (Fig. 11). Here the channels would, therefore, require gaining less vertical height to relocate through an auto-cyclic mechanism (Fig. 11). Further, the rate of sedimentation is highest near the apex of the megafan, aiding the process of channel bed aggradation. Consequently, the rate of channel avulsion is probably highest in this region.

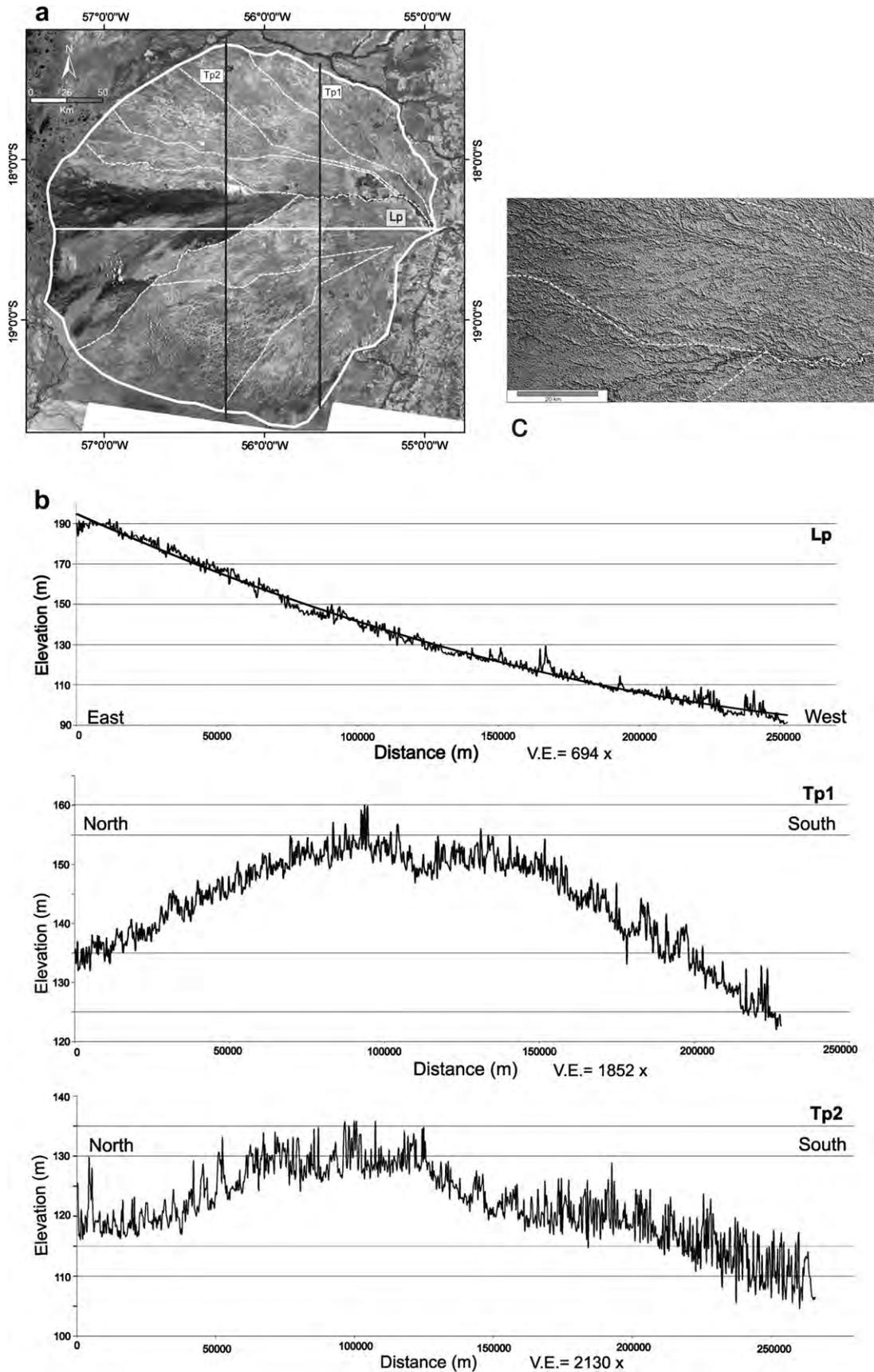


Fig. 10. (a) A view of the Taquari megafan in the LANDSAT image (LANDSAT 7; date of acquisition 2001/08/08). Note six lobes marked on the basis of the divergent orientations of smaller channel networks. Lobe boundaries, line of longitudinal and transverse profiles marked on the image. (b) Lp: Longitudinal profile. Tp1 & Tp2: Transverse profiles; note superposed smaller undulations reflecting multilobate geometry of the megafan. (c) Close up of the part of the fan surface as seen in a DEM visualisation. Note discordance in the channel pattern between adjacent lobes.

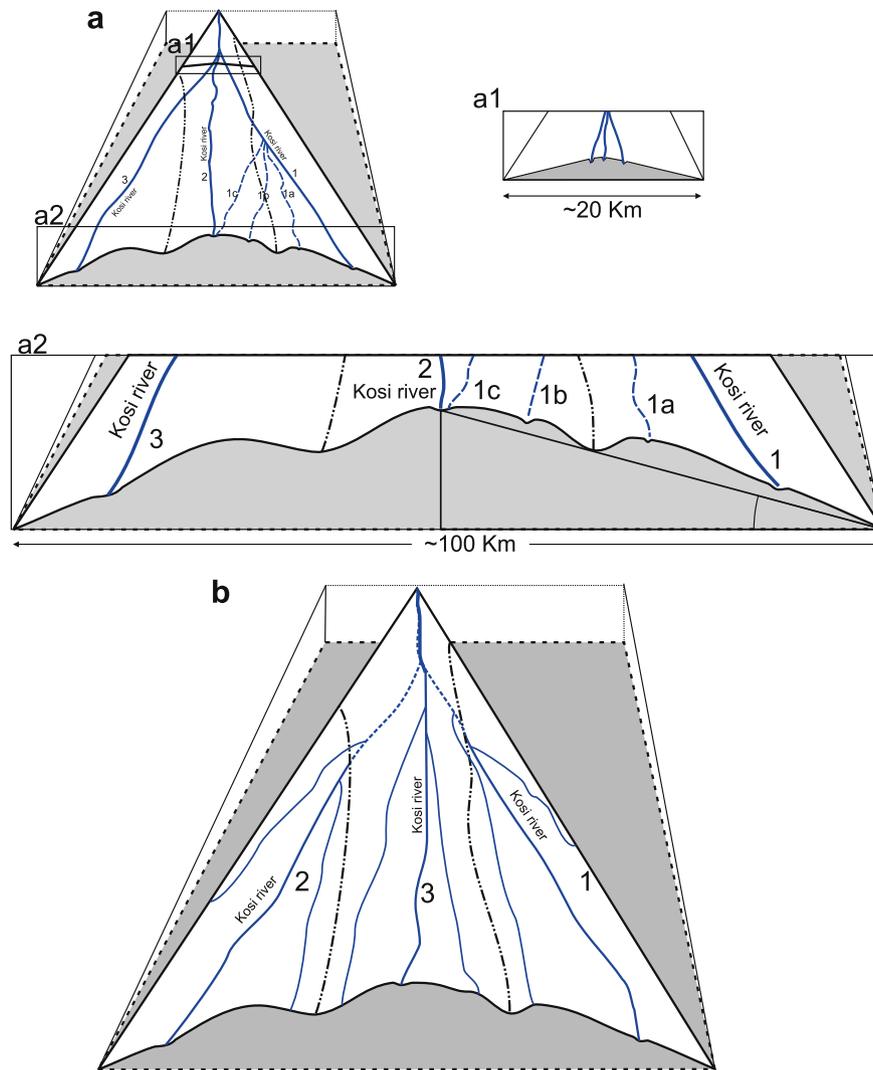


Fig. 11. A conceptual line drawing that shows a semi-conical megafan surface and possible ways of channel migration on it. (a) Postulated continuous westward migration of Kosi River across the fan surface. In the central part of the megafan the channels are required to be relocated upslope (a2). Position of the channels marked with numerals (1a, 1b, ...). 1a represents first branch of crevasse channel formed from trunk channel 1. Lobes marked with dash-dot-dot lines. Note very small width of the megafan surface near its apex (a1). (b) Pattern of channel migration and crevasse formation on the megafan through random, nodal avulsions.

In the central part of the Kosi megafan, the transverse slope of the eastern flank is 0.01° (1.7 m per 10 km) towards the east and away from the megafan axis. In order to achieve a 10 km westward lateral shift in this area, the channel bed needs to aggrade by ~ 2 m above the floodplain (Fig. 11). Assuming an overall sediment accumulation rate of around 2 mm/y in the central part of the megafan, and the differential aggradation rate of the channel belt over the adjacent floodplain to be of the order of 1 mm/y, aggradation of the river bed by ~ 2 m would require about two thousand years. In contrast, the presumed history of shifting of the Kosi channel suggests 50 km lateral movement in the eastern flank of the megafan in only ~ 162 years (from 1731 to 1893). Approaching the problem in another way, deposition of the upper 8–10 m of megafan sediments during the last sweep of the braided Kosi River over the last two centuries, as inferred by Singh et al. (1993), would require a sedimentation rate of >50 mm/y – an order of magnitude higher than the sedimentation rate estimated from alluvial systems in similar settings (cf., Sadler, 1981; Ashworth et al., 1999).

Mackey and Bridge (1995), in their three-dimensional simulation of alluvial stratigraphy, reproduced the unidirectional

migration of the Kosi River. However, their more recent simulation shows that the avulsion of trunk channel over a fan-shaped body follows a random, to-and-fro movement (Karszenberg and Bridge, 2008). It appears that there were inaccuracies in the bounding conditions assumed in the earlier simulation for Kosi River arising out of a lack of appropriate field data. The results produced in the 1995 simulation, therefore, were probably not valid for the Kosi channel (personal communication, Bridge, 2009).

Finally, the study of the available historical maps over the last two centuries does not provide any evidence of continuous westward migration of the Kosi channel for ~ 113 km (see Appendix 1 for 28 historic maps studied here). Compilation of the course of the Kosi River from these maps, contrary to the claims of the earlier workers, shows that the river was mostly flowing through the east-central part of the megafan (Fig. 4a). Allowing for the inherent inaccuracies of these old maps, the compilation further shows that during this period the Kosi River repeatedly shifted its course to the east or to the west in an oscillating manner, rather than continuously shifting to the west. For example, between 1760 and 1796, between 1806 and 1844, and between 1917 and 1924, the river

avulsed to the east (Fig. 4b, Table 1). Similarly, in the years 1806, 1897, 1917, and 1938, the maps apparently show a westward shift of the river compared to the position shown in the preceding years (Fig. 4b).

Also, many of the early twentieth century maps that contain a more detailed information of the drainage networks, display the presence of a radial network of smaller plains-fed channels around the main Kosi channel (maps with publication dates of 1827, 1844, 1875, 1917 and later maps, Table 1, Appendix 1). This radial pattern of minor channels reflects the existence of a convex-upward geomorphology of the megafan. This appears to indicate that the convex-up morphology of the megafan predates the historical record of published maps.

The abundance of ~5 m thick lateral accretion deposits in the north-central part of the megafan, as observed during the preliminary fieldwork, questions the sedimentological model developed on the assumption of a westward sweep of the braided Kosi-like River. If most the precursor streams are not braided, the hypothesis of migrating Kosi-like braided stream across the megafan cannot stand.

The existing understanding about the channel avulsion, more specifically trunk channel relocation on a fan-shaped body, favours predominantly random, nodal avulsion from near the fan apex (cf. Schumm et al., 1987; Whipple et al., 1998; Densmore et al., 2007; Karssenbergh and Bridge, 2008). The presence of active and abandoned lobes, and the random relocation of the feeder channels, are also common features in high-gradient mass flow-dominated fans (Bull, 1977; Blair and McPherson, 1994). The Kosi, Tista and Taquari megafans reveal the presence of multiple accretionary lobes, implying a random relocation of the trunk channels feeding them – an observation consistent with the existing knowledge. In view of the above, the avulsion of the Kosi River in August, 2008, that relocated the river by about 60 km to the east is, therefore, congruent with the expected pattern of random, nodal channel relocation on the Kosi megafan.

Globally, the failure of large dams in ‘taming’ the large rivers (Griggs and Paris, 1982; Goldsmith and Hildyard, 1984; McCully, 2007) points out the necessity of understanding the natural controls of river avulsion and flood (Sinha, 2008, 2009). The engineering solutions of ‘controlling’ large rivers through high embankments and large dams have only complicated the situation. Construction of dams and barrages have enhanced sedimentation in the upstream part, increasing the natural tendency of the rivers to avulse, in addition to the problems created due to flooding upstream of such constructions. More than 100 km long embankments all along the Kosi River have forced aggradation of the channel bed, and in many places channels now flow far above the floodplain (Sinha, 2009, his Fig. 2d) resulting in higher tendencies to breach embankments. The embankments have also prevented the natural path of flood water return and have created severe post-flood water-logging problems, affecting the life and productivity of the adjacent land. Most importantly, all these efforts have failed to prevent regular flooding of the areas adjacent to the present-day Kosi (Mishra, 2008). Humans must concede that, as with earthquakes, we have little means to completely eliminate the hazards of recurring floods, as this is the natural tendency of the rivers. Technology must enable people to devise the best possible means to co-exist with rivers, floods and avulsions. Preparing a very detailed surface topographic maps, particularly near the apex of the Kosi megafan (the likely place for origin of future avulsions), study of its catchments, monitoring its discharge and sediment yield pattern, age determination to ascertain the history of channel movement would help understand this channel system in a better way and would give a better edge in predicting future floods or preparing disaster management plans.

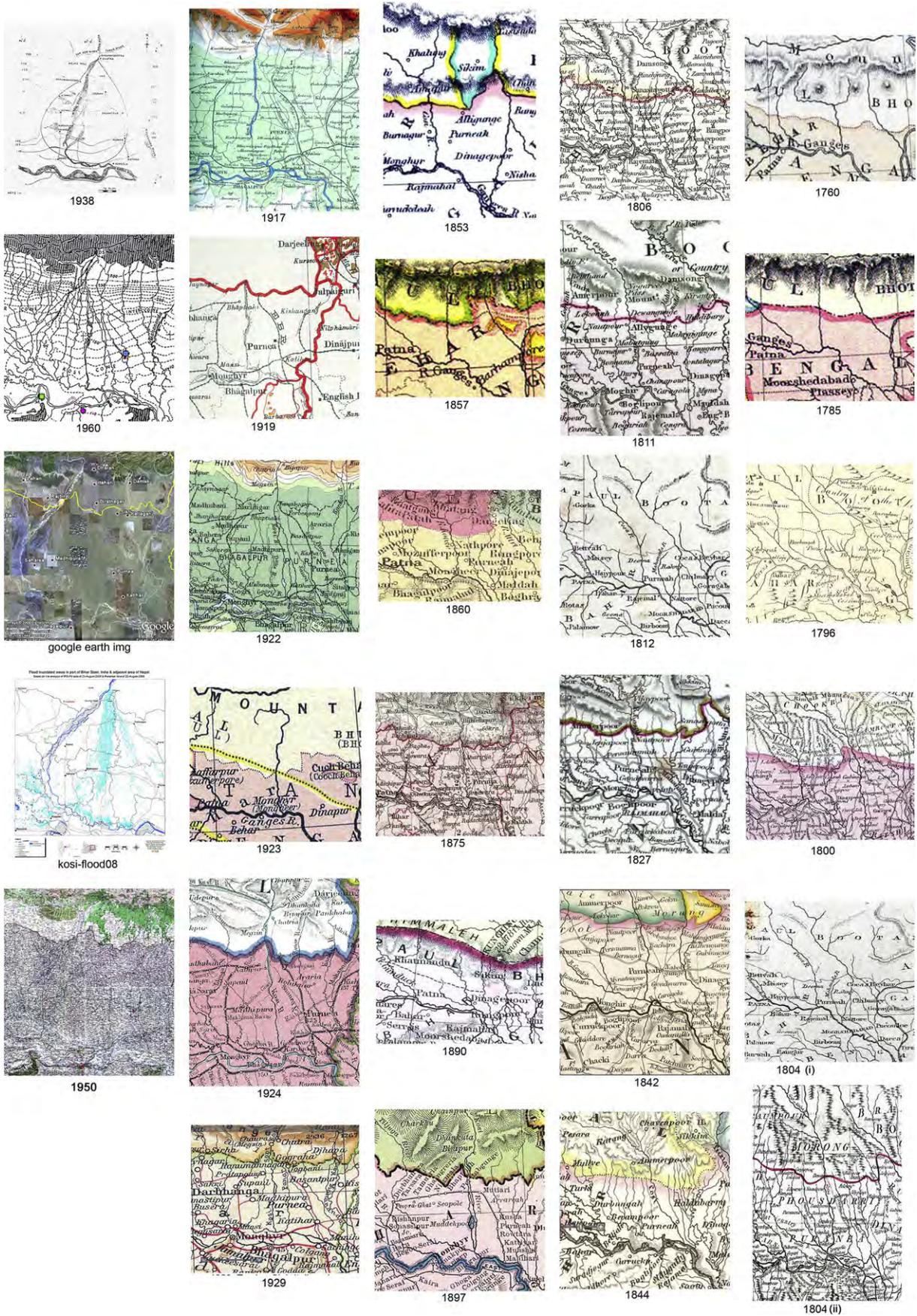
8. Conclusions

1. The Kosi megafan has a convex-up cross profile and concave-up longitudinal profiles. The maximum slope of the megafan surface is 0.05° near its apex and that near the toe it is 0.01°.
2. Three accretionary lobes can be recognised on the fan surface based on the discordant relationship between three smaller packages channel network on the megafan surface. The cross profiles also reflect this multilobate character.
3. The relative chronology of the lobes, determined from channel discordances between lobes, implies random relocation of the trunk channel over the megafan surface.
4. Evidence for westward tilt of the megafan surface, that would have facilitated the westward shift of the Kosi, could not be recognised from the study of the Digital Elevation Model.
5. ~5 m thick successions of near-surface sediments, in the north-central part of the megafan, show overwhelming dominance of fine-grained lateral accretion deposits over braided river deposits. This observation is inconsistent with the extant sedimentation model proposing deposition of the sandbodies from a westward sweeping braided stream followed by localised reworking by smaller plains-fed channels.
6. Study of 28 old maps published between 1760 and 1960 does not show any evidence in favour of the existing notion of unidirectional shifting of the Kosi River from the eastern to western margin of the megafan. On the contrary, it indicates that for most of this period the Kosi channels were occupying a narrow zone in the east-central part of the megafan. The channel position, however, used to oscillate randomly within this zone.
7. The notion of deposition from a braided paleo-Kosi river and subsequent local reworking by plains-fed streams over last two centuries, when combined with our field data, yields a sedimentation rate at least 10 times higher than the known rates in similar settings. The age framework of ~200 years for the accumulation of the top 10 m of megafan sediments thus appears impractical.
8. Theoretical considerations, insights from simulation studies, results of laboratory experiments and comparison with other megafans suggest that random relocation of the trunk channels and resulting lobe formation is the most common mode of growth of a fan-shaped sediment body.
9. In view of the above, the recent nodal avulsion appears to have followed the expected pattern for the Kosi megafan-river system.
10. Further investigation and age dating can generate a better understanding the system and help in formulation of more effective future flood prediction and disaster management plans.

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Appendix A



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