Geomorphologic, stratigraphic and sedimentologic evidences of tectonic activity in Sone–Ganga alluvial tract in Middle Ganga Plain, India

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The basement of the Ganga basin in the Himalayan foreland is criss-crossed by several faults, dividing the basin into several sub-blocks forming horsts, grabens, or half-grabens. Tectonic perturbations along basement faults have affected the fluvial regime and extent of sediment fill in different parts of the basin during Late Quaternary. The East Patna Fault (EPF) and the West Patna Fault (WPF), located in Sone–Ganga alluvial tract in the southern marginal parts of Middle Ganga Plain (MGP), have remained tectonically active. The EPF particularly has acted significantly and influenced in evolving the geomorphological landscape and the stratigraphic architecture of the area. The block bounded by the two faults has earlier been considered as a single entity, constituting a half-graben. The present investigation (by morpho-stratigraphic and sedimentologic means) has revealed the existence of yet another fault within the half-graben, referred to as Bishunpur–Khagaul Fault (BKF). Many of the long profile morphological characters (e.g., knick-zone, low width–depth ratio) of the Sone River at its lower reaches can be ascribed to local structural deformation along BKF. These basement faults in MGP lie parallel to each other in NE–SW direction.

1. Introduction

Active tectonics in any basin is an important forcing factor affecting the river channel dynamics, its sediment load, and morphology. It causes unstable river reaches characterized by channel avulsion, channel incision, bank erosion, meander cut-offs or development of meandering, braided, or anastomosing patterns (Holbrook and Schumm 1999; Schumm *et al.* 2002; Jain and Sinha 2005). When these geomorphic and morphometric characters are related to known basement tectonics, they are helpful conversely as reconnaissance tools to trace the existence of unknown basement structures

(Goldsworthy and Jackson 2000; Burrato *et al.* 2003).

The Ganga basin in the Himalayan foreland forms one of the largest plains world over with ~450 million people dwelling in it. The plain evolved by deposition of huge piles of sediments over the basement within the down-warp between Himalayan Orogenic Belt in the north and Precambrian rocks of the Indian craton in the south (figure 1) (e.g., Morgan and McIntyre 1968; Sastri *et al.* 1971; Singh 1996, 2004; Shukla and Raju 2008; Sinha *et al.* 2009). The basement is marked with linear furrows, ridges and faults, lying obliquely to the Himalayan structural grains

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Figure 1. Parts of Ganga Plain showing the Sone–Ganga alluvial tract as the study area. It is located in the marginal alluvial plain (MAP shown as gray colour) to the south of axial drainages; the Yamuna at the western parts and the Ganga at the eastern parts. It also depicts the major structural features such as faults/lineaments and subsurface ridges running below the alluvium (after Agarwal *et al.* 2002; Singh 2004; Singh *et al.* 1996).

(Rao 1973; Valdiya 1976; Raiverman *et al.* 1983; Dasgupta *et al.* 1987; Parkash and Kumar 1991; Singh *et al.* 1996; GSI 2000; Thakur *et al.* 2009; Jayangondaperumal *et al.* 2010; Goswami 2012). These oblique trending basement structures divide the basin into several tectonic blocks (e.g., Raiverman 2002; Jain and Sinha 2005; Hazarika *et al.* 2010; Dasgupta *et al.* 2013). In many cases, the blocks act as half-grabens with differential uplift and bending.

The fluvial geomorphic processes in the basin have been affected by intra-basinal tectonics along the fault planes during the Late Quaternary (e.g., Valdiya 1976; Srivastava *et al.* 1994, 2003; Singh *et al.* 1996; Prakash *et al.* 2000; Swamee *et al.* 2003). This has been illuminated by the recent studies on the river channel dynamics and their forcing factors. Important among them are the Kosi River (e.g., Gole and Chitale 1966; Wells and Dorr 1987; Agarwal and Bhoj 1992), Bagmati River (Jain and Sinha 2005) and Gandak River (Mohindra *et al.* 1992) in the northern plains and the Sone and Ganga rivers (Sahu *et al.* 2010; Shukla *et al.* 2012) in the southern plains of Middle Ganga Plain (MGP).

Barring few researches (Agarwal *et al.* 2002; Sahu *et al.* 2010; Shukla *et al.* 2012), the southern plains in MGP have remained by and large untouched, as

far as studies related to tectonics are concerned. In contrary to the thick sediment fill in the northern plains (maximum ~5 km), the sediment fill in the southern plains varies from few tens of meters to few hundreds of meters. The north/northeast flowing cratonic rivers, forming the southern tributaries of the Ganga, are mostly ephemeral in character. In such a geological environment, any tectonic activity is expected to leave prominent imprints in river channel morphology, sediment bodies, and stratigraphic architecture. The present study tries to delineate an active zone of faulting in the southern plains of MGP with the help of geomorphologic, sedimentologic and stratigraphic tools.

2. Study area

The study area forms a part of Sone–Ganga alluvial tract, located in the southern half of the MGP adjacent to the Indian craton. It forms the widest part of the marginal alluvial plain (MAP) lying south to the axial drainage; the Yamuna River in the west and the Ganga River in the east in the Ganga basin (figure 1). The Quaternary alluvium (Middle Pleistocene–Recent) directly overlies the Late Proterozoic Vindhyan basement (Om Prakash

et al. 1990). The basement dips north/northeast with depth varying from few meters in the south to ~1000 m in the northeastern parts. The topographic elevation varies between 50 and 120 m above mean sea level (amsl) with the mean slope of land surface at 0.03° – 0.04° towards north. The study area in MGP is located sufficiently upstream to the coastline (~700 km) and has been argued to remain out of reach of the sea level related base-level changes (e.g., Goodbred 2003; Tandon *et al.* 2008). Fluvial regimes controlled by climate (discharge and sediment supply) and tectonics (uplift and tilting) are largely responsible for its geomorphological evolution during the Quaternary.

The Sone River flows from the cratonic side and meets the Ganga River near Babura (figure 2a). The area is bounded by the Vindhyan Ridge

(VR) in the west and Munger Saharsa Ridge (MSR) in the east (figure 1). The East Patna Fault (EPF), lying at the western base of the MSR and West Patna Fault (WPF) on the VR, traverse the area in NE–SW trend. These faults are considered tectonically active and the major earthquakes of the years 1934 and 1988 in the region close to Bihar–Nepal border have been linked with them (Banghar 1991; Dasgupta *et al.* 2013). A few major earthquakes have also been recorded during 1964–1995 (GSI 2000) in the vicinity of the study area in the south (figure 2a). The active Sone River roughly follows a depression in the basement to alluvium between the EPF and the WPF (marked in gray shade, figure 2a), indicating a break in the basement slope between the faults (figure 2b).

Figure 2. (a) Basement depth in m below ground and bouguer gravity anomaly in m gal (both in the form of contours), and faults/lineaments in the Sone–Ganga Plain based on Dasgupta *et al.* (1987); Sahu *et al.* (2010) and GSI (2000). WPF: West Patna Fault, EPF: East Patna Fault. Refer text for details about BKF (Bishunpur–Khagaul Fault). The star marks indicate the recent recorded earthquakes in the region (1964–1995). The circles 1 and 2 show the location of terraces produced as figure 3(b). (b) Schematic cross section along X and Y (location of cross section is shown in figure (a) showing the depression, where the probable fault (BKF) is located in the Sone–Ganga Plain.

The Sone River maintains a braided morphology and follows a rather steep gradient ($\sim 0.04^\circ$) from Rohtasgarh to Dehri, after which the gradient decreases and the river follows an average gradient of $\sim 0.03^\circ$ up to Babura. The river in the plain has remained dynamic, which is indicated by the palaeo-/abandoned channels observed on both sides of the active channel of the river.

The Ganga River forms a wide (5–20 km) flood plain west of Sone confluence, where the river has shown a meandering and migrating character. The flood plain comprising sediments of Holocene age is dotted with a number of meander scars (figure 2a). Towards the east of Sone, in contrary, the flood plain of Ganga becomes narrow and negligible (>1 to 2 km).

The block between EPF and WPF (figure 2a) in the plain has previously been considered as a single entity, forming a half-graben; undergoing uplift at its southeastern end along EPF and subsidence at the northwestern parts along WPF (Jain and Sinha 2005; Sahu *et al.* 2010). The present work tries to gain further insight into the earlier work of Sahu *et al.* (2010) carried out in the Sone–Ganga alluvial tract in the MGP. Through further investigation and supportive data base, the present work tries to establish the existence of yet another active fault in the half-graben between the EPF and the WPF.

3. Methodology

Seismotectonic and bouger gravity anomaly (BGA) maps (GSI 2000) have been used for information on the basement depth and its structural features. The GSI tectonic maps are based on the aeromagnetic contours of Oil and Natural Gas Commission surveys (ONGC) carried out during 1956, and subsequent ground geophysical surveys and deep drillings carried out in the Ganga Plain by several researchers (e.g., Sastri *et al.* 1971; Rao 1973; Valdiya 1976; Dasgupta *et al.* 1987; GSI 2000).

The present study accounts for the channel pattern and morphology of the Banas River in the area, which is a 2nd order ephemeral stream with width varying within 10–20 m. Sinuosity of active and old channels was measured from false colour composite (FCC) satellite images of IRC-IC (Indian Remote Sensing data, 1:50,000 scale). The Shuttle Radar Topography Mission (SRTM) data (source: srtm.csi.cgiar.org) was used to generate the profiles of the flood plains and the channels. In areas of gentle slope, such as floodplains and megafans, the SRTM-DEM has a vertical accuracy of ± 5 m (Rodríguez *et al.* 2006). In the Sone–Ganga Plain, the variation is observed at ± 1 –2 m with 90% confidence interval. SRTM-DEM has been extensively used in geomorphological studies

by various authors (e.g., Kale and Shejwalkar 2008; Kale 2008; Andrades Filho and Rossetti 2012). The channel sinuosity ‘ P ’ (which is defined as $P = L_{\text{cmax}}/L_R$, where L_R is the overall length of the channel reach and L_{cmax} is the mid-channel length for the same reach) was computed following Friend and Sinha (1993) for every 5 km channel length.

A total of 28 sand samples, collected from seven locations from the channel bars between Dehri and Koilwar, were studied for the sediment load grain size variation along the Sone River. The samples were analysed for their size grading using standard sieve sizes of 70, 120, 180, 250, 500, 1000 and 2000 μm . Lithologs of six boreholes drilled by Central Ground Water Board (CGWB 2008) have been utilized to study the subsurface stratigraphic architecture through the preparation of the geologic section.

4. Results

4.1 Geomorphologic evidences

The uplift along EPF has induced avulsions in Sone due to its close proximity and the Ganga River has migrated northward owing to lower tilt rates away from loci of uplift (Sahu *et al.* 2010). The channel profile of Ganga between Buxar and Fatuha shows knick-zones at Revelganj and Patna (figure 3a.i) associated with higher bank heights. At Revelganj, the knick-zone occurs immediate by upstream to the WPF, whereas, at Patna, it is located about 15 km upstream from EPF. The knick-zone at EPF has migrated upstream through channel entrenchment (Sahu *et al.* 2010). However, distinctively separate islands due to multiple channelling at Patna and Fatuha (figure 4a, b, c), and the multiple peaks in the knick-zone at Patna may be indicative of two separate convexities; one for uplift along EPF and the other for uplift somewhere at Patna.

Two knick-zones are also observed in the channel profile of Sone between Rohtash Garh and Koilwar; one at Daudnagar and another at Bishunpur (figure 3a.ii). These knick zones are associated with ~ 16 m high bank cliffs, in contrast to the commonly observed 4–7 m bank heights. These locations are marked with paleo riverbeds where the active channel has gone further deep, cutting across those beds (figure 3b). The morphological anomaly in the channel profile of Sone in the upper reaches at Daudnagar is related to tectonic uplift along EPF (Sahu *et al.* 2010), whereas the same anomaly in the downstream parts at Bishunpur was ascribed to the variation in channel bed lithology, due to lack of sufficient evidence for any local faulting.

In case of the avulsions in Sone River, remarkably, there are two nodal points (X and Y)

Figure 3. (a) (i) Long profiles of Sone (Rohtasgarh to Babura) and (ii) the Ganga (Buxar to Fatuha) rivers with the relative bank heights (modified after Sahu *et al.* 2010). The profiles show relatively higher bank heights at the gradient reversal zones. (b) (i) Shows the paired terraces (I-I, II-II and III-III) at Bishunpur and (ii) unpaired terrace at Daudnagar (for location see figure 2a).

Figure 4. Distribution of palaeochannels of the Sone River (referred as numerals 1–9) and the southernmost palaeochannel of the river Ganga (modified after Sahu *et al.* 2010) with respect to the faults/lineaments. Two control points (X – Daudnagar and Y – Bishunpur) of avulsion in the Sone River channel as indicated by the distribution of palaeochannels; EPF is the main driving force for the avulsion at upstream parts at X, where BKF plays the major role at downstream parts at Y. (a), (b) and (c) show the locations where the Ganga River undergoes multiple channelling. The rectangular inset has been produced in figure 5 for the study of Banas River. The star marks along the river Sone shows the bed load sample collection locations.

Figure 5. In the centre of the figure lies the Banas River with its old (as drawn from satellite image) and present channels. The easternmost abandoned channel of the river is nearly symmetrically meandered. The small lobes within the stretch of CD in the old channel trace are asymmetrically meandered and denote high sinuosity ($P = 3.20-3.50$). The windows W1, W2, W3 and W4 may be tectonically produced ponds/depression along the river channel of Banas, elongated in the direction of alignment of the lineament (BKF) (for details, refer text).

coinciding with the two knick-zones in the river profile, at which the major avulsions have taken place; one at Daudnagar and the other is located ~70 km downstream at Bishunpur (figure 4). This suggests that the high discharge/sediment budget at enhanced precipitation during the late phases of Pleistocene (21–11 Ka) (Srivastava and Shukla 2010) would have hardly remained responsible for avulsion in the Sone River (Sahu *et al.* 2010). The easternmost palaeochannels, referred to as numerals 1, 2 and 3 in figure 4 with their root at Daudnagar (X), have changed their direction of flow towards west/northwest through avulsions as a consequence of uplift along EPF. Since, Daudnagar is closer to EPF, the river has finally undertaken axial deflection towards north to occupy the position of channel no. 4. At Bishunpur (Y), however, there are seven avulsions (no. 4, 5, 6, 7, 8, 9, and 10) which make the location as the axial point. Since, the Sone River possesses a sandy bed and there is no bedrock control on the river, it is illogical to ascribe the knick-zone at Bishunpur to any endogenous forcing factor such as change in channel bed lithology and uneven distribution of erosion and deposition along the channel profile. There is also no tributary of Sone within Daudnagar and Babura, which contributes significant water and sediment. Sahu *et al.* (2010) have argued that the river is degrading in nature and there is no sedimentological control over its avulsions. In this scenario, the knick-zone at Bishunpur can be ascribed to local faulting other than that along the EPF. This is the location, where, the linear depression in the basement (as indicated by basement depth and BGA map, figure 2a) passes across the Sone. The multiple channelling and the knick-zone in the long profile of Ganga at Khagaul near Patna also fall over the same depression passing across the Ganga. The anomalies in the channel morphology of the Ganga and Sone might reflect the uplift along a fault lying along the depression. The fault, henceforth denoted as Bishunpur–Khagaul Fault (BKF), is aligned in NE–SW direction with the fault plane parallel to EPF. It seems to behave as a normal fault similar to the EPF as suggested by Jain and Sinha (2005).

The Banas River lies immediate west to the Sone River and has undergone avulsions within the same avulsive reach of the Sone. Initially it was flowing roughly in northern direction (ABB' in figure 5) with an almost symmetrical meandering pattern. Its eastward deflection resulted in a north-easterly flow (BC'CD in figure 5), roughly coinciding with the alignment of BKF. The channel course developed abnormal sinuosity ($P=3.20\text{--}3.50$) and distorted meanders at its northern parts (CD in figure 5), which was ultimately abandoned again due to westward deflection of the channel. This

abnormally sinuous channel segment has developed ox-bow lakes, the impressions of which are observed at the western side of the palaeochannel. No other river channel in MAP displays such a typical meandering pattern. The abrupt change in sinuosity of the river channel at 'C' suggests a probable fault induced deformation and thus channel evolution. Compressed meanders form when a straight channel is forced to meander because of perturbation of channel by faulting (Schumm *et al.* 1987). Without any lithological control, the asymmetry in river bends and anomalously high sinuosity in river Banas may be attributed to tectonic disturbances along the BKF. Such types of meanders formed as a result of active tectonics have been reported from alluvial plains of the Nile (Schumm and Galay 1994) and Mississippi River (Gregory and Schumm 1987).

There are four zones of depressions/ponds (W1–W4 in figure 5), linearly fashioned in the NE–SW direction of alignment of BKF in MAP. Three of them (W1–W3) are located along the active channel of the Banas, whereas the other one (W4) is observed on the highly sinuous palaeochannel of the river. Further, the zones are elongated in the same direction as BKF. The zones show excessive siltation and lake formation. This kind of ponding with differential erosion is very often associated with faulted lineaments (e.g., Valdiya and Rajagopalan 2000; Sinha-Roy 2001).

4.2 Stratigraphic evidences

The Banas River zone is underlain by the proposed fault. If the morphological anomalies of the Banas (figure 5) have resulted from movement along that fault, then the river course must have been well established at the site before the uplift/deformation began. The alluvial formations underlying the river course/lineament must be of pre-deformation age. Besides, orientation of the active and abandoned channels of the Banas indicates that there was no other significant drainage in the NW direction within the stretch of Banas, which was affected by the uplift. In this context, the pre-deformation alignment of Sone was somewhere in the east of the proposed fault. However, the northern part of the abandoned channel of Banas has been obliterated later on by the Sone (No. 9, see figure 4), which passed through this area towards Ara due to its westward deflection.

In case of any post depositional tectonic perturbations, the deformation is expected to be preserved within the deeper alluvial sediment layers (e.g., Einsele *et al.* 1996; Mazumder *et al.* 2006; Kundu *et al.* 2013). In view of this, a geologic section was (Shahpur–Bikram–Sikaria, figure 6b)

Figure 6. (a) Map showing the location of boreholes and (b) the geologic cross section along the boreholes (Shahpur-Bikram-Sikaria). *a* and *a'*, and *b* and *b'* show the locations of up-warping and down-warping of sediment layers respectively.

prepared based on lithological logs of six boreholes (see figure 6a for borehole locations), and studied for any anomaly/deformation in the sub-surface stratigraphy. The section falling across the suspected BKF and passing across the Sone River reveal that the sediment layers underlying the clayey cover at the top towards west of the faulted lineament are up-arched (marked as *a* and *a'* in figure 6b), whereas, there is a down-warp (marked as *b* and *b'* in figure 6b) in the east. Since the formations at depth have remained untouched in the absence of eroding force, the convexity as a result of uplift is well preserved in them. In the back-tilted side, a thick clayey deposit is observed in the down-warp. In contrast, a thin clayey layer covers the convexity. During the process of surface deformation/warping, the Banas River, flowing along the clayey zone, might have witnessed only removal and redistribution of sediments at ground surface by surficial/fluvial processes. The geologic section with eastward extension across the Sone (figure 6b) depicts continuity of the sediment layers. In the absence of any structural deformation, generally the fluvial sediments tend to get deposited in horizontal/flat beds and at best may follow the local slope. However, the sediment layers exhibit sudden dipping followed by gradient reversal and up-arching around the lineament. Again, in the studied section, the sand beds are nearly uniform in their thicknesses, which indicate that the origin of the depression at the eastern side of BKF is not due to erosion. Along the section, the alluvial cover

over the Vindhyan varies between 300 and 500 m and it is unrealistic to think that the sediment layers at the top 100 m would have followed the sub-surface landscape. The structural elements in the stratigraphic layers might have originated due to post-depositional tectonic warping along the proposed fault BKF.

4.3 Sedimentological evidences

4.3.1 Bed-load grain size

The grain size analysis of bed load samples of the Sone River indicates coarsening of sand (figure 7a) from Dehri to ~10 km downstream of Daudnagar, which has remained tectonically disturbed (owing to its close proximity to EPF). It exhibits medium to coarse sand with larger values of d_{50} and d_{10} (634.82 and 282.2 μm for Dehri, and 629.90 and 280.0 μm for Daudnagar, respectively) (figure 7b), where d_{50} and d_{10} are 50% and 90% retained size, respectively. A similar coarsening trend is found at Sandesh and Bishunpur, where, the suspected fault (BKF) passes across the Sone River obliquely. The average values of d_{50} and d_{10} as 463.0 and 220.9 and 452.5 and 217.6 μm , respectively. The intervening channel stretch from Daudnagar to Arwal (upstream to Bishunpur) registers fine sand. Similarly, at downstream of Bishunpur, the grain size again falls rapidly and reaches a minimum at Koilwar (the last downstream sampling location), with the values of d_{50} and d_{10} as 224.0 and 171.1 μm ,

Figure 7. (a, b) Variation of bed load grain-size along the river in relation to the position of active faults EPF and BKF (for location of sample collection, see figure 4). Coarseness of sand increases around the faults. Note: EPF lies lateral to Sone, whereas BKF passes across the river obliquely.

respectively. The nature of variation of bed load grain size along the channel profile of the Sone, as described above, bears a pattern similar to the channel profile of the river (figure 3a.ii).

As a consequence of uplift, aggradation takes place in its upstream parts and the steepened gradients over the convexity are acted upon by degradation (Humphrey and Konrad 2000). Degradation yields increased bed loads with coarser sediments in the fore-tilted basin and low stream power in the back-tilted basin causes decreased bed load grain size (Holbrook and Schumm 1999). The reach segment at Daudnagar showing coarser bed load may represent the uplifted part along the EPF. In response to uplift and tilting, the river has avulsed towards high slope area in the west. However, in order to restore the slope, a channel scouring process is still taking place in those parts. The other proximal parts to uplift in the hanging block (west to EPF) might have experienced reduction in overall slope, resulting in the finer sediment load in the downstream parts of the channel profile. The second grain size coarsening zone around Bishunpur depicts similar uplift along the proposed fault (BKF) passing across the river in NE–SW direction.

Nevertheless, it can be argued that the above outcomes are the downstream effects of the

Indrapuri barrage (constructed in 1962) on the Sone River (for location of barrage, see figure 4). Under the conditions of seasonal/altered flow regime and low downstream sediment supply, a downstream coarsening of riverbed takes place as a result of erosion of channel bed, bar, and island deposits, which is known as armoring effect (Leopold and Wolman 1957; Williams and Wolman 1984). Though, it may account for the bed load coarsening at Dehri and Daudnagar, it does not explain the same at Sandesh and Bishunpur, after an intervening finer bed load at Barkagaon and Arwal. It might be indicating an extrinsic factor like tectonics, which is affecting the bed load grain size of the Sone. Tectonic uplift followed by channel incision might have yielded coarse sediments in the downstream at Bishunpur. Similar increase in grain size in the downstream of a fault has been observed in the Jefferson River bed in Montana sub-basin, USA (Holbrook and Schumm 1999). Harbor (1998) has observed in Sevier River basin, Utah, that in the case of transverse uplifts, the rivers become narrow, efficiently shaped, coarser-grained, expend a greater proportion of energy on bed deepening and develop terraces on either side of the river.

At Daudnagar, a terrace due to down cutting across an old channel bed is preserved on the eastern side of the Sone and the channel has incised further 4–5 m deep (figure 3b.ii). At this location, the river channel is narrow, deep and has a bend (convex side towards down-tilt direction) with the thalweg opposite to the terrace. Terrace on one side only may indicate an example of lateral tilting of basin and concentration of hydraulic force on the bank at the down-tilt side of the river. However, at Bishunpur (~100 km from Indrapuri barrage), terraces are observed on both sides of the river (figure 3b.i). Transverse uplift and consequent incision might have created the terraces. Indus River in Pakistan has preserved similar type of terraces above the present river channel due to incision across the crest of the active deformation/uplift (Jorgensen *et al.* 1993).

4.3.2 Borehole grain size and lithology

The geologic section (figure 6b) depicts the variation in the nature of sedimentological units across the lineament. It is noticeable that there is increase in the coarse sands and gravels with carbonate concretions (kankars) in the borehole lithology towards west of the line of deformation at both the EPF (the established fault) and the suspected one (BKF) under investigation. The coarser grained kankars and buff coloured sub-rounded quartz grains associated with the deposits might have been derived through reworking of the over-bank flood plains by lateral erosion and/or

channel avulsion. A preferential direction of tilting significantly affects the fluvial succession in a half-graben due to convergence of channel activity and diversion of drainage and sediment to the subsided zone (Bridge and Leeder 1979).

5. Discussion

The Sone–Ganga alluvial tract in MGP has remained tectonically active in the Late Quaternary. Proxy records have been preserved in the geomorphology, stratigraphic layers as well as in the sediments in the plain. The geomorphic indicators along the course of the Sone River in MAP suggest two lines of deformation along two different faults; one is along EPF, and the second one is along BKF, affecting upper (Daudnagar) and lower (Bishunpur) reaches of the river respectively. There exists similarity in the variation of channel morphologic characters of the river at Daudnagar (close to EPF) and Bishunpur (at BKF junction with Sone). The Sone River is wide and shallow with high frequency of braiding in the upstream parts from both the locations whereas in the downstream parts it is narrow and deep with low frequency of braiding. Similarly, the bed load grain size gets coarser peaks at the locations, whereas a fining trend follows in the downstream parts (figure 7). This happens in the case of tectonic uplift and channel slope modification (Schumm *et al.* 2002). The imprints of such changes in the grain size character are also observed in the stratigraphic architecture (figure 6b).

Both the locations register convexities in the long profile, which are considered as indicators of tectonic warping in the absence of bedrock control and local changes in the sediment supply. These might be showing the transient condition of the river to the imposed tectonic warping. There is no tributary joining the Sone in its alluvial stretch which may cause significant lateral sediment input and as such a shift in sediment supply cannot be evoked as an explanation for the knick-zones in the river profile. There are two aspects, which further support that the zones are erosional and not depositional:

1. The preserved terraces, and
2. The coarser bed load observed at those stretches of the river.

The paired terraces at Bishunpur and the unpaired one at Daudnagar might have been formed as a result of channel avulsion due to valley tilting and subsequent deep cutting across the old channel beds. However, multiple paired terraces (I–I, II–II and III–III in figure 3b.i) at Bishunpur might suggest that after straightening of Ara-channel

towards Koilwar, initially the river was flowing in a wide and shallow channel. Gradually, the channel deepened and its width got reduced. The patterns of old and active river channels of Sone suggest that there has not been a major change in the climatic pattern and as such in the discharge regime and sediment supply in the river. The channel stretch showing maximum down cutting is located about 40 km upstream of the local base level created by the axial Ganga River. In this scenario, for channel incision in Sone, overall river valley uplift seems to be the more probable answer rather than lowering of base level.

The linearly distributed ponds/depressions are observed only along the northeasterly (BC'CD) active and old course of the Banas in the direction of alignment of BKF and no such depression is found on its northerly palaeo-course (ABB'). The northerly flowing channel exhibits no such abnormality in sinuosity as shown by the northeasterly channel course. What might have been the cause of such abrupt change in the channel sinuosity? The river might have experienced increased lateral slope. Generally small channels very often fail to keep pace with tectonic uplift and register the effects of tectonics more prominently (Burnett and Schumm 1983). The direction of growth of meander-loops and their preservation in the Banas River is similar to that of the Ganga River as described earlier and as such it indicates an eastward slope in the back-tilt side and migration of the river in that direction (Nanson 1980; Leeder and Alexander 1987).

The alluvial corridor, where, the Banas River displays linear depressions and high sinuosity forms the back-tilted area. The ponds/depressions might have formed where the stream faced lower slope

Figure 8. Map showing the linear clay zones as associated with the faulted lineaments of BKF and EPF.

Figure 9. Schematic diagram showing the basement disposition and nature of fault block movements. (1) East Patna Fault (EPF), (2) Bishunpur Khagaul Fault (BKF) and (3) West Patna Fault (WPF) (modified after Sinha *et al.* 2005 and GSI 2000). It also depicts the back-tilted area with flow congestion and formation of linear ponds/depressions. Note that there is no Siwalik in between the Vindhyan and the Quaternary alluvium in the MAP (Om *et al.* 1990).

and flow congestion due to uplift in the adjacent areas. The linear ponds/depressions on the Banas River and the convexities on the Sone and Ganga river profiles fall approximately on the same line.

The thicker clayey zones displayed in the stratigraphic section (figure 6b) run all along the EPF and the suspected BKF (CGWB 2010; Sahu 2013) (figure 8). Though such clayey patches are also observed along WPF near the Ganga (Sahu 2013), the same could not be detected in the south (where the studied section falls) due to paucity of bore-hole data. This finer sediment zone seems to have been deposited in the back-tilted parts due to uplift along the fault. At the eastern side of the clayey zone (figure 6b) there is recent channel activity, whereas along the zone itself and in the western side, no such channel activity is observed. It indicates the Banas River was active in the alignment of the clayey zone prior to deformation began. Due to uplift along BKF, the river formed the clayey zone in the back-tilted side and at a certain critical limit of uplift and slope generation, the river got deflected towards the down-tilted part of the plain. The section Shahpur–Bikram–Sikaria (figure 6b) shows two distinct sediment-coarsening zones in the stratigraphic profile: one to the west of EPF and the other to the west of proposed fault BKF. This suggests two lines of deformations along EPF and BKF that control the fluvial dynamism in the Sone River at two nodal points; Daudnagar and Bishunpur.

Similar to EPF and WPF (Sinha *et al.* 2005; GSI 2000), the BKF seems to behave as a normal fault in the MAP. The down-bending of the lithosphere because of the thrust sheet loading in the Himalayan orogen might have induced extensional tectonics and normal faulting in the distal part (at the outer part of the bent lithosphere) of the foreland (Agarwal *et al.* 2002). The blocks between the EPF, BKF and WPF act as half-grabens with uplift at the southeastern ends and subsidence at the northwestern parts (figure 9).

6. Conclusion

The part of the basement between EPF and WPF in MGP is not a single block as supposed earlier; rather it is divided into two blocks by another active fault BKF (Bishunpur–Khagaul Fault). These faults (EPF, BKF, and WPF) are parallel to each other trending in NE–SW direction. The two blocks between the faults behave as half-grabens, undergoing uplift at the southeastern parts and subsidence at the northwestern parts. This has rendered dynamism to the rivers in the Sone–Ganga Plain. The close proximity to faults and the consequent high lateral uplift has induced avulsions in the craton-origin Sone River. There are two nodal points of channel switching along the profile of Sone; the upstream one (at Daudnagar) is controlled by the EPF, whereas for the downstream one (at Bishunpur), the BKF has remained as the principal force. Though, the EPF has remained instrumental in the channel morphology (such as knick-zone, bank heights, distribution of braid bars and low width–depth ratio) of Sone at the upstream parts, the same aspects at the downstream parts have been regulated by the BKF.

Tectonic disturbances along the faults EPF and BKF during Late Pleistocene in the Sone–Ganga alluvial plain in the marginal parts of MGP have induced imprints in the stratigraphic columns. There are records of up-arching in sediment layers due to uplift of blocks along fault planes. Back-tilted parts have preserved thick finer clayey deposits, whereas in the fore-tilted parts thick granular sediments are deposited due to convergence of drainage.

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