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Migration of the Ganga River and development of cliffs in the Varanasi region, India during the late Quaternary: Role of active tectonics

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ABSTRACT

The lithofacies constitution of unconsolidated sediments exposed in Ramnagar cliff indicates sedimentation in sinuous channels, associated flood plain areas and ponds that were developed within the Ganga River valley. The Khadar surface represents a raised river valley terrace into which the main river channel along with its narrow floodplain is incised. Ramnagar cliff section has revealed a variety of deformation structures that indicate repeated tectonic activity in the area. Important tectonic features exposed by the cliff section are reverse faults, folds, cracks filled with sparry calcite and soft sediment structures indicating liquefaction of sediments affected by faulting and folding. Optically stimulated luminescence (OSL) dating of sediments and field relationships of tectonic elements indicate that the Ganga River migrated near to Varanasi 40 ka following a tectonic event in the area. Since then, it meandered freely within its valley until 7 ka when another tectonic event took place and Ramnagar cliff was raised to its present heights. The cliff surface was degraded by gulling activity for about 4000 years before it was occupied by man at around 3000 years BP.

1. Introduction

The Ganga River is the trunk river of the Himalayan Foreland Basin system and flows for about 2225 km before reaching the Bay of Bengal where it forms the Ganga–Brahmaputra delta system and the world's largest submarine fan, the Bengal Fan (Fig. 1A). Along its journey from source to sink, the Ganga River flows within an incised valley with rather narrow floodplains. The river valley itself is incised in a regional upland interfluve surface and bordered by cliffs of variable heights. Ganga Foreland Basin is an active fluvial sedimentation region, which offers an opportunity to study the response of a fluvial system to foreland basin processes, namely intra- and extra-basinal tectonics, climate and base-level changes. The Ganga Basin is a low relief geomorphic system, but the deep incision of all its major drainages is feature that is unique to this basin. The Ganga River incision has been explained due to (1) increased rainfall subsequent to the Last Glacial Maxima (LGM) (Tandon et al., 2006; Ray and Srivastava, 2010), (2) Sea level fall during the LGM (Singh, 1996), (3) intra-basinal tectonics (Singh, 2001) and (4) combined effect of climate and tectonics. Kalpi cliff section of Yamuna River shows evidences of change in provenance and tectonic activity (Singh et al., 1997; Tewari et al., 2002). A study based on amount of incision and cliff heights along the Gomati River, a tributary of Ganga River suggested that tectonic-driven incision is superimposed over the base level-linked incision (Thakur et al., 2009). However, except for the Kalpi cliff section, these studies are general in nature; they do neither provide information on stratigraphy of the cliffs and chronology of events nor any tectonic evidences leading to cliff development.

We investigated a 750 m long cliff section exposed on the right bank of the Ganga River near Varanasi, namely the Ramnagar section (Shukla and Raju, 2008; Srivastava and Shukla, 2009) (Fig. 1B–C). Sedimentological studies, particularly lithofacies analysis, have been carried out to interpret the depositional processes and variation in sediment provenance. Tectonic deformation features affecting these deposits have been documented in detail. Luminescence dating provided a chronological framework during the development of this cliff. It has been possible through this study to identify tectonic events responsible for the formation of Ramnagar cliff, which also assisted the understanding the chronological framework of processes responsible for the incision, lateral migration of Ganga River.

2. Fluvial geomorphology

2.1. Ganga Plain

Ganga Plain is part of the Indo-Gangetic Foreland Basin system that formed as a consequence of collision between the Indian and Asian plates and thrust sheet loading in the Himalaya (Lyon-caen and Molnar, 1985; Singh, 1996; DeCelles et al., 1998). Geophysical surveys show that the basement of the Indo-Gangetic Basin is

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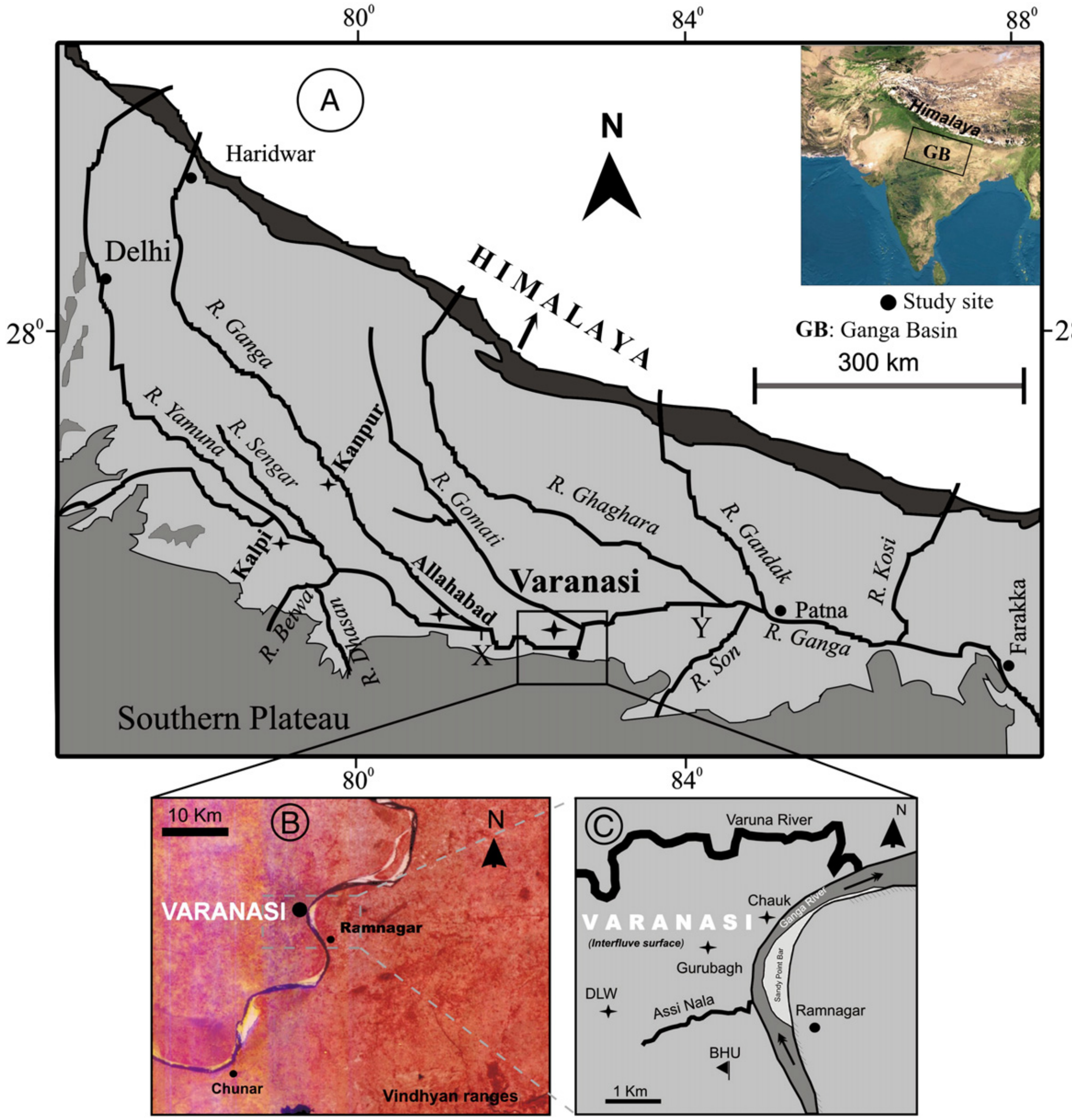

Fig. 1. A) Map showing the major rivers of the Ganga Plain emanating from Himalaya in the north and peripheral craton in the south respectively. Location of the studied section is also shown near Varanasi. B) Landsat imagery showing north-eastward flowing Ganga River with its narrow valley and location of studied section at Ramnagar. Vindhyan Plateau is shown in the south of the River Ganga. C) Blow up of the Ganga River course near Varanasi, showing borehole location (stars) inside Varanasi City, point bar and channel incision near Ramnagar.

dissected by a number of lineaments, faults and structural deformations (Sastri et al., 1971; Rao, 1973), which have also controlled the foreland basin fill history through time (Singh, 1996; Singh et al., 1999b; Shukla et al., 2001; Singh, 2004; Shukla, 2009), and also have affected the behavior of river-channels on the surface (Singh, 2001). The down flexing of the rigid crust beneath the Ganga Plain is minimal, resulting in the formation of wide but shallow basin with a relatively thin sediment wedge (Singh, 1996; Srivastava et al., 2003a). The Ganga foreland possesses a prominent cratonic peripheral bulge. This is a mature, under filled basin; though with an oversupply of sediment, where sedimentation is taking place by fluvial processes (Singh, 1996). Bulk of the sediments in the Ganga Plain comes from the Himalaya (gray micaceous subgreywacke in nature); but the craton also contributes a good amount of sediment (brown subarkosic in nature) to the craton-ward margin of the basin (Singh, 1996, 2004). In response to the thrust sheet loading in the Himalayan Orogen, the foreland basin has been expanding southwards; the last major tectonic activity in the Himalaya took place around 500 ka and the basin expanded on the craton by about 100 km (Singh and Bajpai, 1989; Singh, 1996, 2004). The rivers of northern Ganga Plain carrying Himalayan derived sediments have been shifted toward the southern craton over the sediments deposited by rivers draining the craton (Singh and Bajpai, 1989; Singh et al., 1999b; Singh, 2004; Shukla and Raju, 2008). The geomorphology of the Ganga Plain is believed to have evolved under changing climatic conditions, intra- and extra-basinal tectonics and sea-level induced base-level changes during the late Quaternary (Singh, 1996; Shukla et al., 2001; Srivastava et al., 2003a; Singh, 2004; Tandon et al., 2006; Srivastava and Shukla, 2009). Based on the study of topographic maps, remotely sensed data, cliff sections along several rivers distinctive regional geomorphic features have been identified. Radiocarbon and luminescence dating of selected sections has helped in developing chronology of the generalized model for geomorphic evolution of Ganga Plain during the late Quaternary (Singh, 1996; Srivastava et al., 2003a,b; Singh, 2008; Srivastava and Shukla, 2009).

The Ganga Plain is a tectonically active basin. Neotectonic activity in the Ganga Plain has been recorded in a number of studies (Singh and Rastogi, 1973; Singh and Bajpai, 1989; Misra et al., 1994;

Mohindra and Praksh, 1994; Singh, 1996; Singh et al., 1996, 1997, 1999b; Prakash et al., 2000; Agarwal et al., 2002). The pattern of neotectonic activity varies from Himalayan Orogen toward peripheral bulge. Near the Himalayan Orogen is the compressional regime, while near the craton margin it is the extensional regime (Agarwal et al., 2002). The southern part of the Ganga Plain near the craton exhibits W–E lineaments, normal faults, graben like structure. Close to craton, SW–NE tectonic trend of the basement rocks has controlled the alignment of river channels. This area shows incision of channels, conjugate set of fractures, bending, tilting and updoming of sediment deposits. Another important feature of the Ganga Plain is presence of tens of kilometer scale undulations producing upwarped areas with relief of 5–10 m adjacent to low areas often occupied by ponds. These features were formed during a tectonic event dated about 8–5 ka (Singh et al., 1999a,b; Srivastava et al., 2000; Singh, 2001; Srivastava et al., 2003a,b).

2.2. Ganga River

The Ganga River originates from Gangotri glacier in Garhwal Himalaya and enters the alluvial plain at Haridwar at an elevation of about 290 m. Within the alluvial plain (Ganga Foreland Basin), the Ganga River flows for about 2200 km to meet the Bay of Bengal. It is the trunk river of the Ganga Plain to which many tributaries from Himalaya, alluvial plain and peninsular craton join. The Ganga River initially flows southwards, swinging to SE direction, and ultimately flows in E direction close to the craton margin. From Haridwar to Allahabad, the Ganga River is the trunk river, while Yamuna River is the axial river; beyond Allahabad Ganga River becomes axial river. Ganga River all along its length flows through a well defined valley. Singh (2008) provides an overview of the geomorphology and processes of the Ganga River.

The most consistent feature of the Ganga River throughout the alluvial plain is that the active river channel along with its narrow floodplain is incised in the river valley terrace surface (Khadar surface). The river valley terrace surface is about 2–5 m higher than the active channel and shows minor non-leveed river channels, floodplains and ponds. The river valley terrace surface is incised in the regional upland terrace surface making 5–20 m high cliffs along the valley margins (Singh, 1996, 2008). The characteristics and downstream changes in the Ganga River Valley and active Ganga River are related to variation in sediment and water discharge, tectonic setting and geology along with the late Quaternary changes in climate, tectonics and base-level (Singh, 2008). Along the length, the Ganga River Valley is subdivided in to distinct segments with their characteristic features (Singh, 1996, 2001; Singh et al., 2007). The segment between Allahabad to Buxar, designated as GRV–III, is characterized by narrow river valley and flows over the Vindhyan Plateau basement high. At the beginning of the GRV–III, the river flows east up to Chunar, where basement rocks are exposed. Between Chunar and Buxar, the river flows ENE, which is aligned with a basement lineament. The channel gradient is 11 cm/km. The river channel is meandering with large point bars shifting from one margin of the valley to other. Meanders increase in dimensions downstream; those of the distal are rectangular. Cliffs are often present on both sides of the valley. On the River valley terrace surface meander scars, ponds and minor channels are present. Valley width is 2–10 km with marginal cliffs of 10–30 m height.

3. Ramnagar study area

The present study area, located near Varanasi, exhibits 1–2 km wide channel of the Ganga River. The area is located on the flank of the peripheral bulge marked by Vindhyan ranges which is experiencing extensional tectonics (Fig. 1). The Ganga River makes a prominent meander loop with cut side towards Varanasi (Shukla and Raju, 2008; Srivastava and Shukla, 2009). On the opposite side a wide point bar is developed followed by a vertical cliff along the valley margin on which Ramnagar town is located (Fig. 1B–C). This cliff extends in NNE–SSW direction; in upstream part of the area the Ganga River flows along the cliff as no sandbar is developed here. In the NNE part, about 20 m high cliff is present that runs for 750 m laterally (Fig. 2A).

The top 4–10 m thick deposits are anthropogenically modified cultural deposit (Jayaswal and Kumar, 2006; Jayaswal, 2007). Below the cultural deposit, fluvial deposits showing diverse facies are present (Fig. 2B). At present, the Ramnagar cliff is undergoing gully erosion, and contributing some sediment to the Ganga River.

3.1. Ramnagar section

The cliff section under this study is about 750 m long and is referred as the Ramnagar section, after the Ramnagar township located near the cliff (Srivastava and Shukla, 2009). The degraded surface of the cliff has variable relief on a scale of tens of meters. The cliff wall shows prominent layering of strata, which can be traced laterally. To document the lateral distribution of beds, nine vertical profiles (I to IX in Figs. 2–4) spaced 70 to 150 m apart were measured. The individual lithological units were traced laterally and vertically to reconstruct their geometry in the field. A schematic lateral cross section of the cliff was prepared. For OSL dating, the samples were collected along the profile III. In this

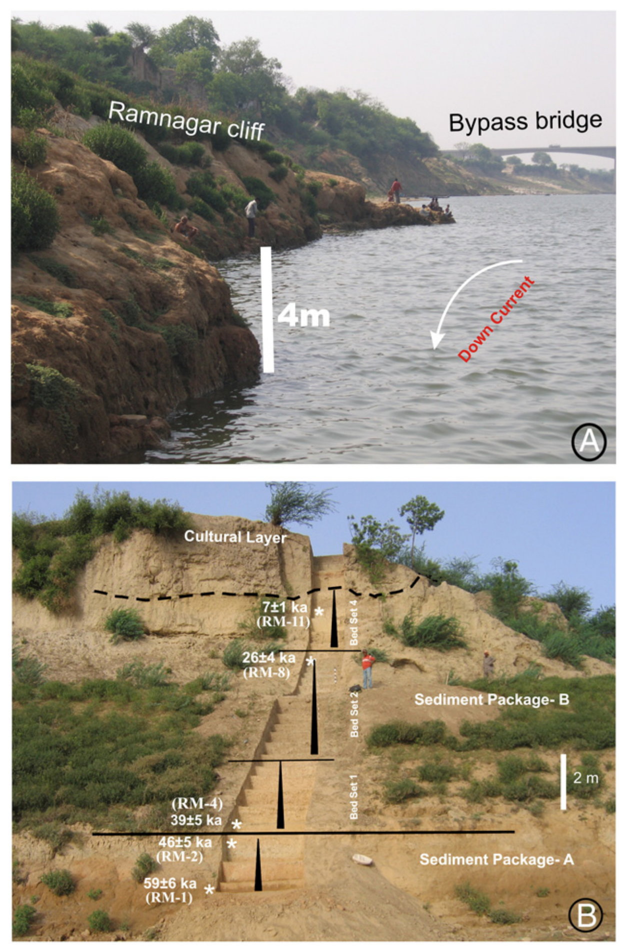

Fig. 2. A) Photograph showing steep cliff along the Ganga River over which Ramnagar township is located. River is flowing to NE. B) Excavated profile at Oriya Ghat (see Fig. 4) of the Ramnagar cliff section studied for lithofacies analysis and OSL dating. Two Sedimentary Packages A (pink colored, craton-derived) and B (gray colored, Himalayan sediments) are distinct, and are made up of sand to mud fining upward (FU) cycles shown by wedges. Sedimentary Package B is followed by cultural layers with a degraded undulatory surface relief marked by dashed line.

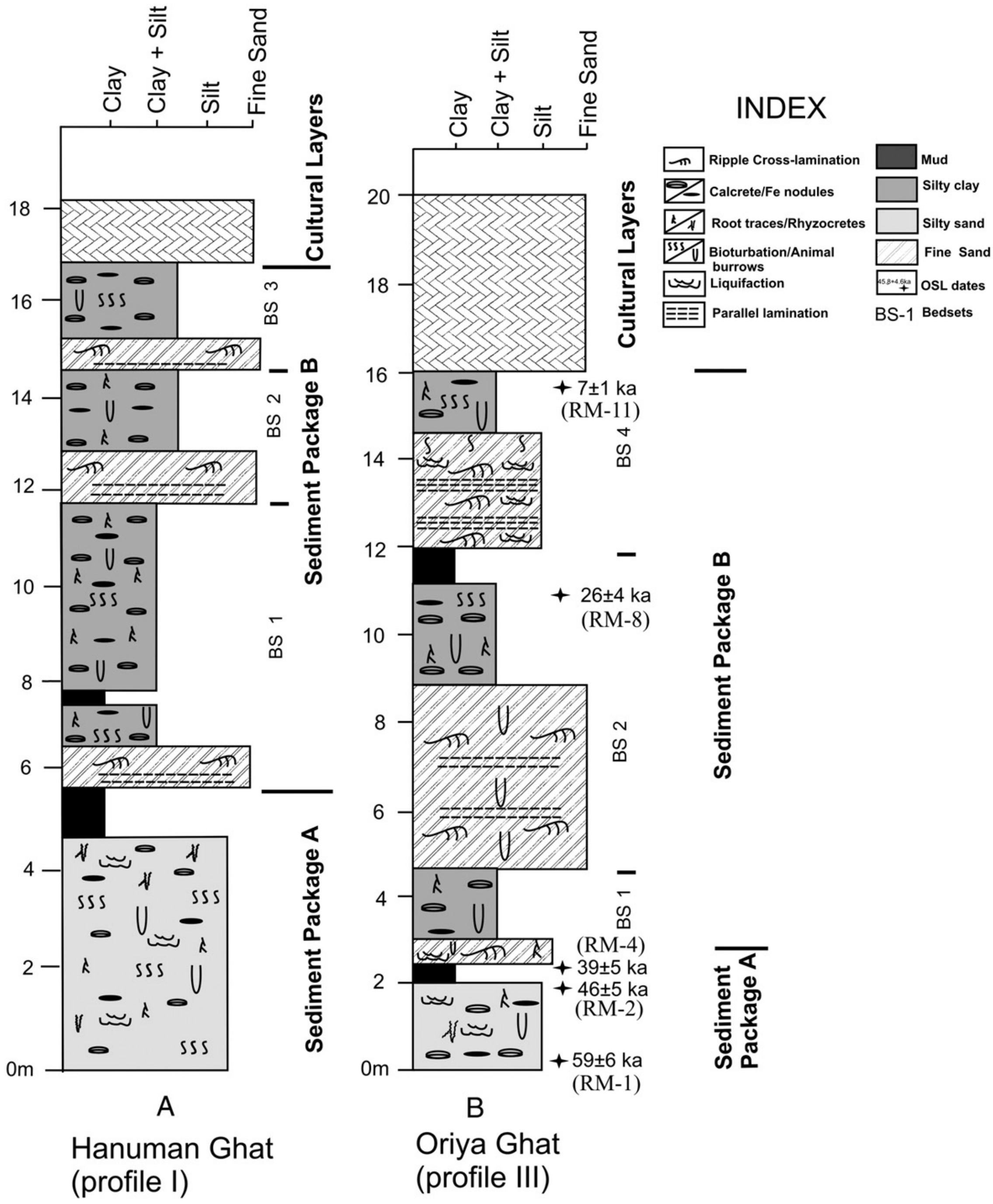

Fig. 3. Lithologs showing major lithology, Sedimentary Packages A and B comprising deposition Bed Sets 1–4, distribution of primary physical structures along two vertical profiles measured at Hanuman Ghat (a) and Oriya Ghat (b). OSL dates are also shown beside the Oriya Ghat profile (for legend and dates also see Fig. 4).

profile systematic stepwise benches were cut to expose the entire lithological succession (Figs. 2B and 3B).

Starting from northern end near the fort, the vertical profiles I to IV are 18–20 m thick while remaining profiles V to IX are 12–14 m thick above the low water level (Fig. 4). In all the profiles, two distinct sedimentary packages are discernible. These packages are physically as well as lithologically distinct, show prominent lateral and vertical variations in thickness and geometry of the litho-units (Figs. 2B, 3 and 4). Based on field parameters such as grain-size, geometry of litho-units, primary physical structures, palaeocurrent patterns and bioturbation structures, lithofacies analysis of the Ramnagar cliff section has revealed that in fact, the Sedimentary Packages A and B represent two different facies associations generated under differing hydrodynamic, climatic, source and tectonic conditions (Fig. 2B). Variability in the mutual association of constituent lithofacies occurs within each of the packages. A brief description of the lithofacies associations A and B are given below and their constituent lithofacies are summarized in Table 1.

3.2. Sediment Package A

This package forming the lower part of the section is brown in color, muddy in nature with intense calcretization (Figs. 2B and 5A–B). The basal sandy part that constitutes most of the thickness of the package is multistoried in character with individual units separated by erosional but diffused undulatory contacts because of

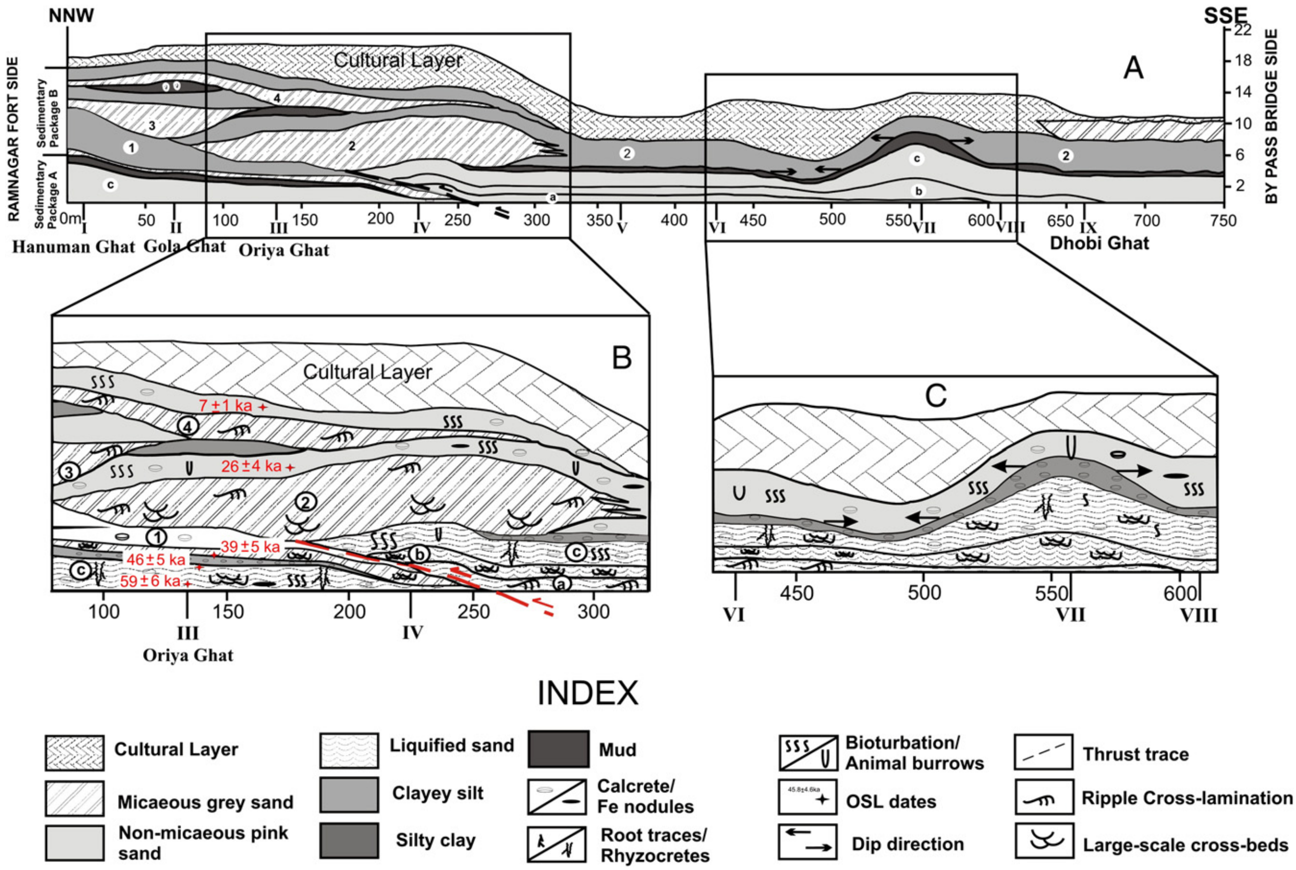

Fig. 4. A) Schematic lateral profile of the Ramnagar cliff section between Ramnagar Fort in the NNW and bypass bridge in the SSE. Lateral profile is based on nine vertical profiles (I–IX). Degraded undulatory top surface of the Sedimentary Package B and differential relief of the cultural layer, a fault at the Oriya Ghat profile III and a syncline followed by an anticlinal developed between profiles VI to VII are distinct. Sand bodies are lensoidal and sheet like (sometimes tabular) and interfinger with muddy units. A mud unit of the Bed Set 3 contains molluscan shells. B) Details of profiles III and IV showing fault zone, distribution of primary sedimentary structures and OSL dates. Lensoidal sandy units show small to large-scale cross-bedding, while muddy horizons are highly mottled and contain plant and animal generated burrows, calcrete and ferromagnesian nodules. C) Close up of profiles showing the syncline and corresponding anticline and their effect on the surface relief of the cliff section.

liquefaction of the sediments. The individual units are 1 to 6 m thick, tabular in geometry and laterally persistent over hundreds of meters. Three such units (numbered a, b and c in Fig. 4) are identified by distinct grain size and sedimentary structures. The unit-c is encountered in all the profiles and comprises mud-rich sandy silt. It shows distinct mottling, prominent calcretization and variable iron colouration (Figs. 2B and 5B). In profile II, it shows northwardly dipping unidirectional lateral accretion elements separating 1–2 m thick lensoid layers. Units a and b are sandy in nature, 1–2 m thick, and exposed in profiles IV to IX only (Fig. 4). The unit-b shows soft sediment deformation structures consistent with liquefaction that obliterated of primary physical structures (Fig. 5A). The unit-a exhibits parallel and ripple cross-lamination along with little deformation near the top. Within the Sediment Package A, a number of lithofacies are discernible suggesting sedimentation by small river channels and associated floodplains (Table 1).

Characteristically, the Sediment Package A shows structural deformation in the form of faults and folds, represented by a syncline and anticline and changes in dip directions of the beds over short distances. In addition, near vertical to steeply inclined fractures filled with carbonate are present (Figs. 4 and 6).

3.3. Sediment Package B

The Sediment Package B is 3 to 14 m (average 7 m) thick and made up of repetitive units of gray micaceous fine sand, silt and mud erosionally resting over the Sediment Package A (Figs. 2B and 4). This package contains diverse lithofacies (Table 1), and shows four depositional Bed Sets (BS 1 to 4) characterized by specific color, grain-size, and sand to mud ratio (Figs. 3and 4).

Bed Set 1 encountered in profiles I to IV, is 2–6 m thick and made up of micaceous gray silty sand followed by thickly developed calcretized mud horizon (Figs. 2B and 3A,). The sand unit is partly liquefied and shows penecontemporaneous deformation (Fig. 5C). This horizon is dissected by a fault plane in profile IV where it terminates (Fig. 4).

Bed Set 2 is characterized by gray coloured fine-grained micaceous sand which is 2–8 m thick, large-scale cross-bedded and gradationally capped by a prominent mud horizon (Figs. 2B, 3B, and 5D). It exhibits about 6 m thick and 240 m wide lensoid channelized sand body between profiles II to V that interfingers laterally with the mud layers in SSE direction (Fig. 4). Palaeocurrent are directed to SW and SE directions.

Bed Set 3 is about 6 m thick and encountered in northernmost profiles I and II (Fig. 3A). It is represented by 1–3.5 m thick, about 120 m wide, lensoidal sand body showing parallel lamination and small-scale cross-bedding (Fig. 4). Palaeocurrent directions are in E to ESE. The fine grained mud units associated with sands are calcretized and mottled. A brownish gray coloured gastropod bearing mud horizon is encountered in profile II (Fig. 5E).

Bed Set 4 is developed in profiles I to IV and is 3.5 m thick (Figs. 2B and 3B). It is made up of a 240 m wide sand sheet unit succeeded by mottled and calcretized mud layers (Fig. 4). This horizon shows liquefaction and deformation of primary physical features (Fig. 5F). The Sedimentary Package B is succeeded by the cultural deposits which are 4–10 m thick (Fig. 2B).

Table 1
Summary of lithofacies analysis of the Ramnagar section.

Sediment packages	Lithofacies	Character	Interpretation
Sediment Package A (Figs. 2–5)	Rippled-parallel laminated fine sand	400 m wide, 1–1.5 m thick, yellowish-buff nonmicaceous feldspar-rich fine sand, ripple-parallel-laminated, small-scale cross-bedded (rare solitary large-scale trough cross-beds), top liquefied, animal and plant traces, minute calcrete nodules	Deposition in channels under lower flow regime, and fluctuating energy forming both 2D and 3D bedforms (Kraus and Aslan, 1993; Nichols and Fisher, 2007)
	Liquefied fine sand (Fig. 5A)	Erosional base, 500 m wide, 1–1.5 m thick, liquefied yellowish-buff nonmicaceous feldspar-rich fine sand, structures obliterated, convolute bedding, slump structures, sagging effect, calcrete nodules common	Deposition in channels, deformed by seismicity related liquefaction covering wide aerial extent
	Mottled clay-rich silty sand (Fig. 5B)	1–5 m thick, yellowish pink in colour, outcrop wide aerial extent, multistoried with FU cycles, lateral accretion elements common, intensely calcretized, ferruginous nodules common, 7–9 cm wide rhyzocretes, sparry calcite filled vertical cracks, bioturbation common	Deposition in low-energy aggrading sinuous river channels under alternating dry and wet conditions (Ghazi and Mountney, 2009; Shukla et al., 2009, 2010)
	Calcretized mud (Fig. 5B)	Gray colored, sheet like, 0.75–1 m thick, outcrop wide aerial extent, highly calcretized, a few cm thick calcretized muddy beds alternate with silt beds showing burrow structures, root traces	Abandoned channel fill deposits showing vegetation and animal activity (Kraus, 1999; Alonso-Zarza, 2003; Shukla et al., 2009)
Sediment Package B (Figs. 2–5)	Large-scale cross-bedded micaceous sand (Fig. 5D)	Gray micaceous fine sand, 1–5 m thick, 300 m wide developed between profiles II — erosional base, lensoid morphology, fining upward fill, large scale (7–10 cm thick) cross-beds, ripple cross-lamination, parallel lamination, animal burrows	Deposition in high energy sinuous channels under lower flow regime fluctuating energy conditions (Allen, 1982; Ashley, 1990)
	Small-scale cross-bedded sand (Fig. 5C, F)	Yellowish buff channelized micaceous silty very fine sand, 1–4 m thick, 170–300 m wide sheets, occurring at three levels between profiles I–V, ripple-parallel-laminated, low-angle planar cross-beds, liquefied, animal and plant traces minute calcrete nodules	Episodic deposition in shallow channels under lower flow regime conditions (Kraus and Aslan, 1993; Nichols and Fisher, 2007; Ghazi and Mountney, 2009)
	Interstratified sand–silt–mud	Micaceous, silty fine sand, 1–3 m thick, a few cm thick lensoid beds of sand–silt and mud, ripple-parallel-laminated, animal and plant traces, fining up character, muddy beds calcretized	Deposition in wide shallow ephemera channels under lower flow regime conditions (Rygel et al., 2004; Shukla et al., 2006)
	Calcretized clayey silt	Common lithofacies developed in sand, silt and mud units,1–4 m thick, sheet like, calcrete nodules range from mm size to 10 cm size, rhyzocretes, animal burrows, charcoal and plant remains common, occasionally ferruginous nodules developed, iron pigmentation	Deposition in low-lying over-bank areas by suspension fall out followed by diagenetic changes (Farrel, 1987; Kraus and Gwinn, 1997; Citterio and Pié Gay, 2009)
	Shell-bearing mud (Fig. 5F)	Developed in profile II, 60–70 cm thick, 150 m wide clayey beds succeeded by silt–sand beds forming coarsening up sequences, gastropod shells, charcoal, plant debris, poorly preserved lamination, minute calcrete and iron nodules	Deposition in ponds related to overbank areas (Singh et al., 1999a; Srivastava et al., 2003a; Citterio and Pié Gay, 2009)

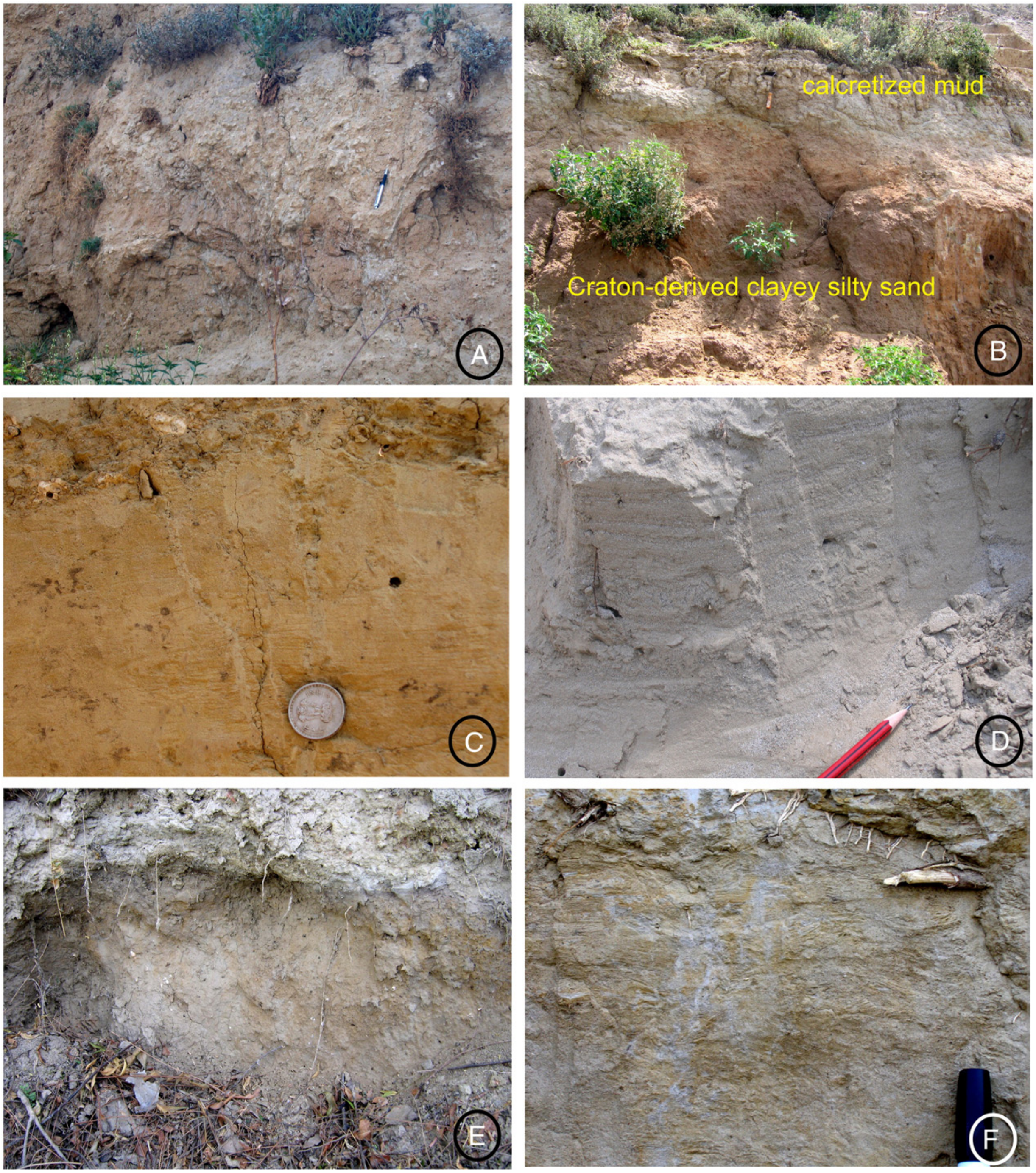

Fig. 5. A). Photograph showing complete liquefaction of silty fine sandy unit b of the Sediment Package A exposed in profile III (also see Figs. 3 and 4). Primary sedimentary structures are completely obliterated, slumping and incipient calcretization is obvious; pen length is 13 cm. B) Photograph showing clay-rich sandy silt lithofacies forming unit c of Sediment Package A in profile III. High degree of mottling, iron pigmentation, calcrete and ferruginous nodule development is ubiquitous. Top is represented by gray coloured calcretized mud, scale; scraper length is 25 cm. C) Small-scale cross-bedded silty fine sand lithofacies of the Bed Set 1 in Sediment Package B at profile III (also see Fig. 4). Animal and plant created vertical burrows filled with grayish clayey silt, liquefaction deformation of primary sedimentary structures and reworked calcrete are common features; diameter of the coin is 2 cm. D) Small to large-scale cross-bedded, micaceous and gray coloured fine sand lithofacies of the Bed Set 2 in Sediment Package B at profile IV; pencil length is 10 cm. E) Photograph showing shell-bearing mud lithofacies developed in the Bed Set 3 of Sediment Package B at profile I. Millimeter to centimeter sized gastropod shells (rarely bivalves) are concentrated in patches and also sparingly distributed throughout the bed thickness; scale bar is 25 cm. F) Silty fine sand lithofacies of the Bed Set 4 in Sediment Package B showing liquefaction deformation of ripple cross-lamination, differential mottling and ferruginization at profile III; pen cap length is 5 cm.

4. Sedimentation model

The Ramnagar section shows two distinct sedimentary packages, namely Sedimentary Package A and Sedimentary Package B (Fig. 2B and 3). The Sedimentary Package A is made up of brown sandy deposits with muddy components, derived essentially from the peninsular craton by the rivers flowing from the craton northwards (Fig. 5A–B). Present-day rivers draining the craton transport similar brown colored sediments. The three units (a, b, and c) identified in this package are channelized and exhibit fining upward nature, indicating deposition in fluvial channels (cf. Nichols and Fisher, 2007; Ghazi and Mountney, 2009; Shukla et al., 2010) (Fig. 4). The units a

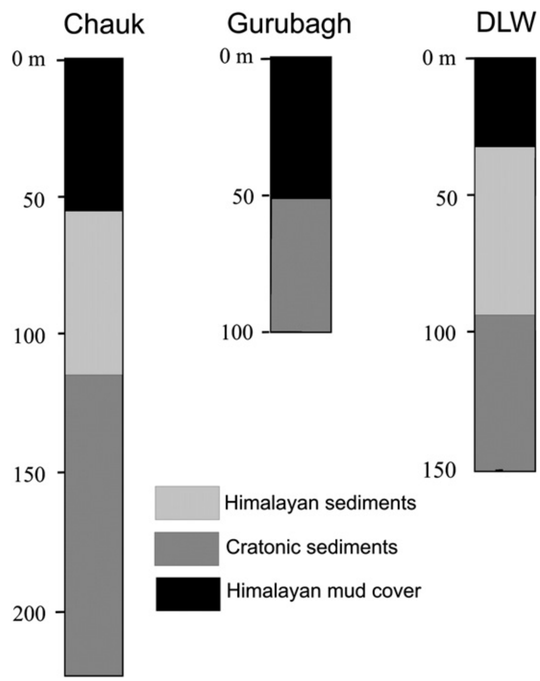

Fig. 6. Boreholes drilled inside Varanasi City located on interfluves surface a few kilometers away from the incised Ganga River channel. The DLW (Diesel Locomotive Works) and Chauk-Thana boreholes are 150–200 m deep and contains Himalayan derived sediments (about 30–60 m thick) sandwiched between craton-derived sediments. The Gurubagh borehole profile is about 100 m deep and contains only cratonic sands capped by a thick muddy horizon (modified after Shukla and Raju, 2008).

and b show prominent bedform generated cross-bedding in about 3–5 m deep and few hundred meters wide channels. The fluvial channel bars during dry season were vegetated and burrowing animals caused prominent bioturbation and mottling of the sediments. The unit c is mud-rich with prominent mottling and lateral accretion. This was deposited when the river channel became abandoned and was filled by fine-grained sediments. The liquefaction horizon may be related to seismic event.

The Sedimentary Package B overlies the Sedimentary Package A separated by a sharp and erosional contact (Figs. 2B and 4). It seems that after deposition of Sedimentary Package A, the surface was eroded to produce an undulatory surface. In contrast to the brown craton-derived sediments of Sedimentary Package A, the Sedimentary Package B is made up of gray, micaceous Himalayan derived sediments (Fig. 5C–F). It may be pointed out that even today craton-derived sediments are brown in colour, while Himalayan derived sediments are gray micaceous (Singh, 1996).

The Sedimentary Package B is made up of four Bed Sets, namely 1, 2, 3 and 4, each consisting of a lower channelized sand body followed by a mud layer, defining upward-fining sequence (Figs. 2B and 4). The channels were 2–5 m deep, tens of meters wide. Palaeocurrent data shows a flow toward SW and SE. Deposition in the river channels took place by migrating megaripples (dunes) and ripple bedforms. The muddy layers represent deposition in over bank areas of the channels on a poorly developed levee and floodplain (cf. Filgueira-Rivera et al., 2007; Citterio and Pié Gay, 2009; Shukla et al., 2010). The muddy sediments show prominent mottling due to activity of plant and animals. At places, within the over bank areas small ponds and lakes developed depositing muddy sediments with molluscan shells (Fig. 5E). The muddy sediments show both ferruginous nodules and calcrete nodules indicating moist conditions alternating with prolonged dry seasons and fluctuating groundwater conditions (Shukla et al., 2010).

The rivers depositing Sedimentary Package B, were small, carrying very fine sand load, much finer than the present-day Ganga River. The probable area of deposition of this package is Khadar (river valley terrace surface) of the Ganga River (Mukerji, 1963; Singh, 1996). Present-day Khadar rivers carry very fine sand and they are non-leveed with narrow floodplains, small lakes and ponds. It seems that after the deposition of Sedimentary Package A, the Ganga River system shifted craton-ward to occupy the area of Ramnagar. The main Ganga River did not deposit the sediments of the Ramnagar cliff section as the sand of the Ganga River is much coarser than the sand of the Ramnagar cliff section. It seems likely that in the past also, the Ganga River developed a broad River valley terrace surface similar to the Khadar surface of today. The small rivers carrying finer sand than the Ganga River, ponds and floodplains of this Khadar surface contributed to the deposition of the Ramnagar cliff section. The Ganga River itself was several kilometers away from the Ramnagar area.

5. Variations in sediment provenance

The Ganga Plain receives sediment from the Himalaya ranges and the southern craton (Fig. 1). Petrographically, these sediments are distinct. The Himalayan sourced sand is mica-rich (mainly muscovite) and contains feldspars, rock fragments, and dark coloured heavy minerals. This gray coloured fine-grained sand brought by the present day Himalayan rivers including the Ganga River can be classed as subgreywacke sand (Shukla and Raju, 2008). Whereas, craton-derived sediment is feldspar-rich, brown in colour and with very low mica content, though, dark coloured heavy minerals and rock fragments (mainly quartzite) are present. Based on mineral content, the sand can be classed as subarkose (Shukla and Raju, 2008). Therefore, Sedimentary Packages A and B of the Ramnagar cliff section are sourced from two different areas lying in the south and north of the axial Ganga River respectively (Figs. 2B and 5).

Studies on the borehole samples inside Varanasi City located on the southern side on the western bank of the Ganga River revealed occurrences of both Himalayan and craton-derived sediments in the subsurface as well (Shukla and Raju, 2008) (Fig. 6). The craton-derived sediments make lower part of the borehole succession, are 35–105 m thick and made up of fine to coarse-grained, subarkose sand. It is followed by 30–60 m thick the Himalayan derived sediments composed of micaceous, fine-to-medium grained subgreywacke sand. The topmost part of the succession is made up of 30–60 m thick muddy sediments of Himalayan origin interlayered with few meter thick gray sandy units (Fig. 6). This data shows that in the Varanasi region, initially craton-derived sediments were accumulating. Later in response to tectonic activity rivers bringing Himalayan sediments moved in the area. These rivers were associated with the Ganga River system.

6. Structural elements in Ramnagar cliff

In the Ramnagar cliff, several prominent tectonic structures are present which are described below.

6.1. Fault

A reverse fault inclined at about 8–10° is present close to the profile IV (Fig. 4). This fault has affected the Sedimentary Package A and the lower part of the Sedimentary Package B (Bed Set 1). The fault strikes in NE–SW direction and dips toward the SSW. Across the fault trace repetition of beds is very clear. The foot wall is made up of the unit-c of Sedimentary Package A followed by a sand–mud units of the Package B (Bed Set 1). In the hanging wall heaved up units a and b that underlie the unit c of the Sedimentary Package A, are not exposed in profiles I to III (Figs. 4 and 7A). The fault has a

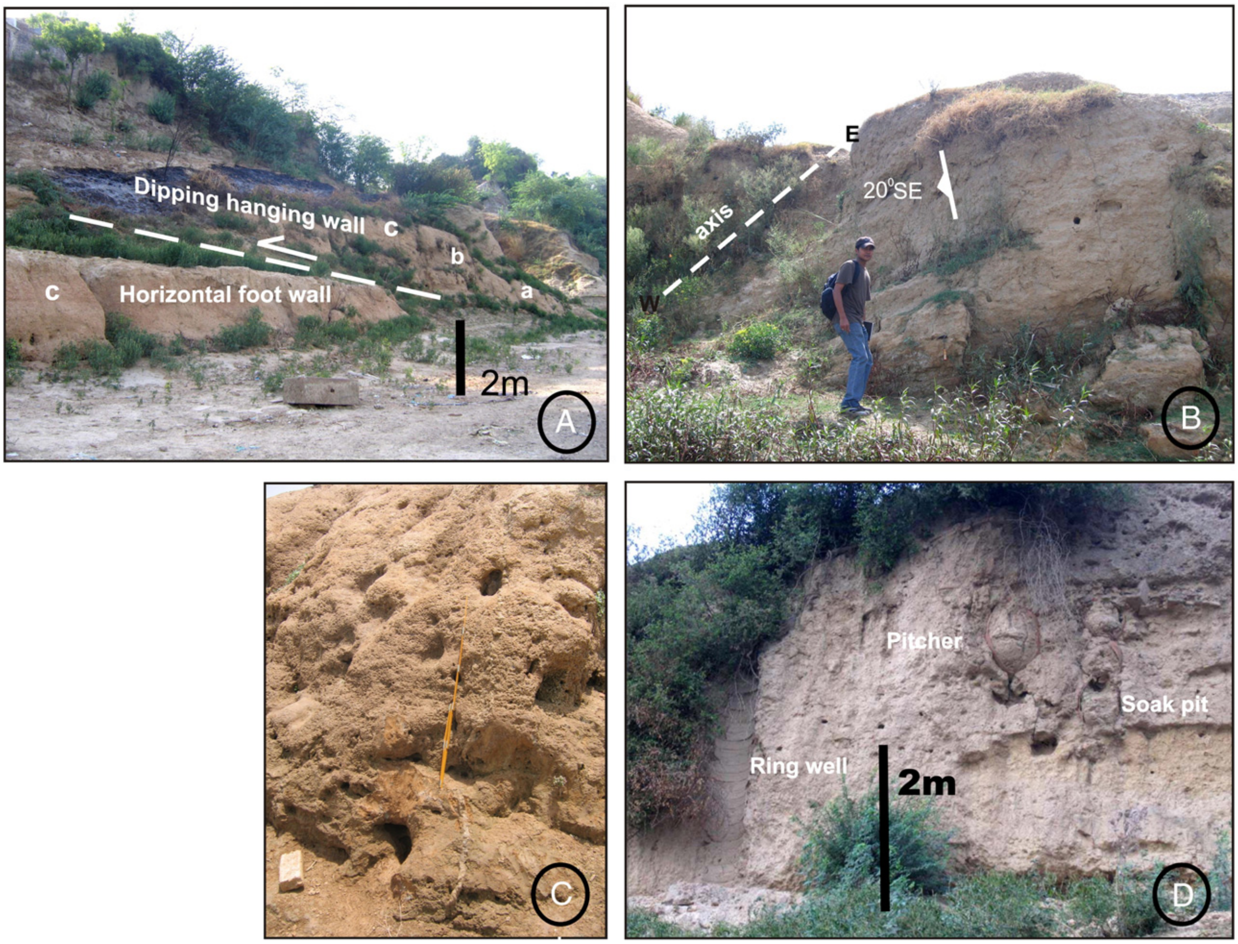

Fig. 7. A) Photograph showing a reverse fault juxtaposing Sedimentary Package A and the basal part of depositional horizon 1 of Sedimentary Package B at profile IV (also see Fig. 4). Foot wall represented by the unit-c is horizontal, while the hanging wall up-heaving units a, b and c is gently dipping at angle of about 8°. Having a throw of about 4 m, the fault is dipping to SSE at about 10°; bar length is 2 m. B) Photograph showing a syncline developed between profiles VI and VII and folding both the Sedimentary Packages A and B. Fold axis run E–W and limbs dip at angles of 10–15°; length of the person is 160 cm. C) Photograph showing 3 to 4 cm wide vertical fractures filled with sparry calcite developed in profiles I to IV and extending across the whole exposed thickness of Sedimentary Package A; scale length 1 m. D) Photograph showing cultural layer containing brick and pottery pieces, ring well, and soak pit and a pitcher representing human skills at about 3000 ka BP.

throw of about 4 m. The fault has also caused arching of Sedimentary Package A in the hanging wall showing increased dips of 7–8°, while the beds of the foot-wall dip gently at 1–2° away from the river channel (Fig. 7A). Except the depositional horizon (bed) 1, the beds of the Sedimentary Package B are horizontal without any marked deformation at the profile IV.

6.2. Fold

Between profiles VI to IX, a syncline followed by a corresponding anticline is well developed (Fig. 4B, C). The wavelength of the fold is 110 m, and height is about 4 m. The syncline shows a gentle rounded core where beds forming the limbs are dipping at about 15° to 20° (Fig. 7B). In contrast, the adjoining anticline shows semi-rounded crest with dips of 10–15° at the limbs. The fold axes are directed roughly to E–W direction. These open type folds have deformed the whole cliff thickness involving both the Sedimentary Packages A and B.

6.3. Fractures

Vertical to sub-vertical fractures are common in Sedimentary Package A throughout the lateral profile, though they are more

Table 2
Radioactive element concentrations, dose rate, paleodose and ages of the samples collected from Ramnagar section.

Sample no.	Lab no.	Depth (m)	U (ppm)	Th (ppm)	K (%)	Paleodose (Gy)	Dose rate (Gy/ka)	Age (ka)
RM-1	LD-248	20.0	5.4 ± 0.5	16.7 ± 1.7	1.4 ± 0.1	186 ± 11	3.2 ± 0.3	59 ± 6
RM-2	LD-249	18.5	4.5 ± 0.5	14.3 ± 1.4	2.5 ± 1.2	171 ± 10	3.7 ± 0.3	46 ± 5
RM-4	LD-250	17.5	2.9 ± 0.3	20.2 ± 2.0	2.4 ± 0.2	145 ± 17	3.7 ± 0.3	39 ± 5
RM-8	LD-252	10.0	2.8 ± 0.3	11.2 ± 1.1	2.3 ± 0.2	92 ± 12	3.5 ± 0.3	26 ± 4
RM-11	LD-253	4.0	4.0 ± 0.4	15.5 ± 1.5	3.0 ± 0.3	30 ± 3	4.4 ± 0.3	7 ± 1
Zero age sample								
RM-7	LD-251	0.5	3.8 ± 0.4	14.0 ± 1.4	1.9 ± 0.2	1.2 ± 0.6	3.3 ± 0.3	360 ± 180 years

Water content: 15 ± 5% by weight; cosmogenic Gamma contribution: 150 ± 30 μGy/a; mean age model with 20 aliquots is used.

prominent in profiles I to IV (Fig. 4). The cracks are 3 to 4 cm wide and extend across the whole exposed thickness of Sedimentary Package A in these profiles (Fig. 7C). Normally they are parallel to each other and spaced 40–50 cm apart. They dip to N and NE at 70° to 85°, and are filled with calcrete. Some of the fractures show gentle curvatures.

7. Luminescence chronology

Samples for optically stimulated luminescence (OSL) dating were collected in opaque stainless steel pipes from the Ganga River section exposed at Ramnagar, Varanasi (Shukla and Raju, 2008). Five samples from different levels of the cliff, RM-1, -2 and -4 represented Sedimentary Package A, while RM-8 and RM-11 Sedimentary Package B (Figs. 2B, 3B and 4B) and sample (RM-7) from the recent flood deposits to test the bleaching extent of quartz at the site were obtained. This dating technique relies on the premise that prior to burial geological luminescence stored in the minerals that constitute the cliff sediments is zeroed by daylight exposure during erosion and transportation (Aitken, 1998). This section was previously dated by Srivastava et al. (2003a,b) largely using fine-grained feldspar at Physical Research Laboratory, Ahmedabad.

The detail of the chemical treatments used to separate the datable fractions of quartz is from Srivastava and Shukla (2009). OSL was recorded for 60 s at 125 °C. A $^{90}Sr/^{90}Y$ beta source delivering a dose rate of 3.6 Gy/min was used for irradiation. A 5-point Single Aliquot Regeneration (SAR) protocol suggested by Murray and Wintle (2000) was used to determine paleodose where a linearly fitted growth curve was utilized (Table 2). A preheat of 220 °C/40 s and a cut heat of 160 °C for test doses were used. 20 aliquots were used for measurement, out of which aliquots yielding (1) higher paleodose error (2) higher than 1.1–0.9 recycling ratio were eliminated and the weighted mean of around 10–19 aliquots was considered for final age calculations. Uranium, thorium and potassium concentrations were determined by XRF analysis.

Paleodose estimation was done by integrating initial 2 channels (1 channel = 0.24 s of exposure) of the shine down curve that constitutes the fast component was utilized. In the samples, the OSL fast and medium emissions decay to >95% in the first 5 s of the blue light exposure and hence can be utilized in fluvial environment (Singarayer et al., 2005). The ages thus obtained are stratigraphically consistent (Figs. 2B, 3B and 4B) and suggest that deposition of the succession exposed in Ramnagar cliff started before 59 ± 6 ka and ended soon after 7 ± 1 ka. The recent flood deposits that can be considered as zero age sample, yielded an age estimate of 360 ± 180 years, suggesting that any discrepancy in the dated samples arising due to improper bleaching may be of couple of hundred years only. Table 2 provides detail on the dose rate and paleodose. The results are largely in conformity of the earlier studies (Srivastava et al., 2003a,b).

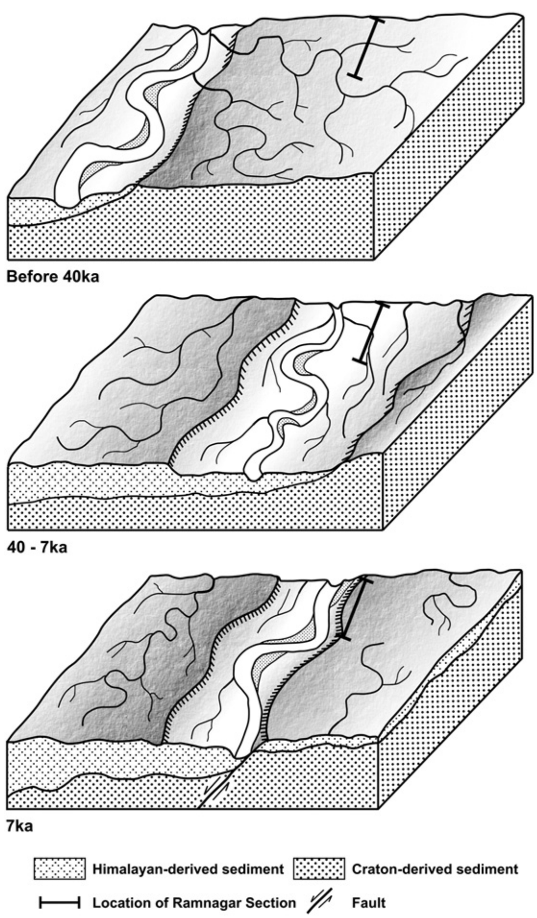

Fig. 8. Schematic model of incision of Ganga River at Varanasi. Before about 40 ka, Ganga River was flowing away from Varanasi further west and was not incised free to migrate. Himalayan derived sediments were reaching Varanasi and beyond. Between 40 and 7 ka, in response to a major tectonic event in the Ganga Plain, it migrated eastward to Varanasi and beyond Ramnagar, and Himalayan sediments were deposited over degraded craton derived sediments (also see Figs. 2B, 4 and 7). Finally about 7 ka, The Ganga River came back to its present position and got incised in response to renewed upheaval in the area.

8. Discussion

8.1. Chronology of the depositional and tectonic events in the Ramnagar section

Study of the Ramnagar section demonstrates that until about 40 ka the Varanasi area was receiving sediments from the craton by a number of small rivers flowing toward the north and northeast (Sediment Package A). The rivers were small (few meters deep and tens of meters wide) with well developed channels and poorly developed levee, over bank and interfluve areas (Figs. 2–4). It appears that around 40 ka the area was uplifted in response to a major intra-basinal tectonic event and active sedimentation ceased. The surface was subjected to erosion and gullying forming an uneven paleosurface. This event was followed by a craton-ward shift of river systems carrying Himalayan derived sediments (Ganga River system; Sediment Package B), onlapping on to the previously deposited southern craton-derived sediment. The Himalayan-derived sediments in the Ramnagar section were deposited on an uneven, erosional surface (Fig. 8). However, in the absence of any defined pedogenic horizon between the two Sedimentary Packages A and B, it appears that the hiatus between upliftment of the area and initiation of the river system carrying Himalayan derived sediments was only about 1–2 ka.

The Ganga River system (carrying Himalayan-derived sediments) migrated into the Varanasi region around 40 ka and extended SE wards beyond the Ramnagar area over a surface underlain by craton-derived sediments (Fig. 8). After deposition of the Bed Set 1 of the Sedimentary Package B (Himalayan-derived sediments) around 39 ± 5 ka, compressive tectonic process caused reverse faulting and development of fault having a throw of about 4 m, tilting of beds to 10–12° dip, and liquefaction of sand horizons in Sedimentary Package A and Bed Set 1 of Sedimentary Package B (Figs. 4, 5A and 7A). Prominent fractures developed in Sedimentary Package A, were later filled by calcrete (Fig. 7C). Deposition of the Himalayan-derived sediments in the Ramnagar area continued until 7 ± 1 ka with subsidence accommodating for channel–floodplain deposition events under similar depositional conditions. The tectonic event at 7 ka produced folding, liquefaction and tilting of beds up to 15°, affecting both Sedimentary Packages A and B (Figs. 4 and 7A, B, C). This event also caused upliftment of the surface as a warp and the surface became beyond the reach of fluvial processes. It is also likely that some incision of the Ganga River system took place. The deposition on this surface ceased. This event also shifted Ganga River system westward toward the present position (Fig. 8).

Archeological studies at Ramnagar site, near profiles II and III (Figs. 2, 4 and 7D), have revealed the presence of the oldest cultural horizon containing Northern Black Polished Ware (NBPW) and Black-slipped Ware potsherds dating back to the seventh/eight century BC, at different levels ranging from 4.50 m to 9.50 m below the surface in different pits excavated for the archeological investigation (Jayaswal and Kumar, 2006; Jayaswal, 2007). This implies that prior to human settlement; the Ramnagar area was already degraded by ravine development due to gullying activity for at least 4000 years before it attained an irregular topography with relief of 4–10 m (Figs. 2B and 4). The highly undulatory surface and was objectively utilized by the settlers for different purposes (Fig. 7D). In the last approximately thousand years, the Ganga River has moved eastward eroding the Ramnagar cliff laterally. The Ganga River thalweg presently flows along the Ramnagar cliff for the most part (Fig. 2A).

Shukla and Raju (2008) described subarkosic, reddish brown sediments (craton-derived) in the Varanasi area, west of the present day Ganga River, at a depth of 50–100 m below the surface, followed by gray micaceous sediments (Himalayan provenance) up to the surface (Fig. 6). On the other hand, subarkosic sediments (craton-derived) are exposed on the surface in the Ramnagar area as seen in the Ramnagar section, located east of the Ganga River (Fig. 2). These sediments are overlain by Himalayan-derived gray micaceous sediments. This elevation difference for occurrence of top of the craton-derived sediments on either side of the Ganga River in Varanasi region indicates that the Ganga River is flowing along the NW–SE trending fault (Shukla and Raju, 2008), where the western side is the down thrown side — while the eastern side (Ramnagar cliff) is the up thrown block. It seems probable that the fault documented in the Ramnagar section is a splay fault related to a major fault present along the Ganga River having a gravity component and present along the Ganga River (Figs. 7A and 8).

It may be pointed out here that along the Yamuna River near Kalpi, there is evidence of southward shift of the river system carrying Himalayan derived sediments over the fluvial deposits of craton-derived sediments around 40 ka (Singh et al., 1999b). A two meter thick silty fine sand sediments are liquefied for several hundred meters and show minor sand dykes, sand volcanoes etc. pointing to a seismic event around 40 ka (Singh et al., 1997; Tewari et al., 2002). The area is located about 350 km WNW of Varanasi. It seems likely that around 40 ka there was an important tectonic event or pulse of tectonic events in the craton-ward margin of the Ganga Plain, causing craton-ward shift of the river systems, faulting and folding and synsedimentary deformation and liquefaction of sediments.

8.2. Development of cliffs and the Ganga River incision

Fluvial systems respond to the climate change, extra- and intrabasinal tectonics and sea-level related base-level changes. To incise a river and generate cliff along its banks requires (1) a high relief and (2) sufficient hydraulic energy to cut through the increased relief leading to river incision and generation of graded profile. The Ganga River exhibits cliffs along the valley margins throughout its course in the Ganga Plain from Haridwar to Farakka; the height of the cliffs is variable and generally shows kilometer-scale undulations. Near the mountain front between Haridwar and Hastinapur prominent cliffs are developed exposing megafan sediments where incision took place at about 7 ka (Ray and Srivastava, 2010). Further downstream between Hastinapur and Kanpur, cliffs are present and expose deposits of doab or interfluve facies (Singh et al., 1999a, b). Near Kanpur, two sections have been studied. In Bithur section a date of 13 ka is available few meters below the top; while in Jajmau section a date of 8 ka is present few meters below the top (Singh et al., 1999a). These cliffs have several meter thick cultural deposits starting with an age of about 3500 years BP formed on an eroded surface. Between Kanpur and Patna similar cliffs are present; where the Ramnagar cliff at Varanasi is studied in detail. Between Patna and Farakka also prominent cliffs are developed, but so far no detailed studies are available. It is significant to note that between Hastinapur and Farakka, there are a large number of cliffs showing evidence of human settlement around 3500 years BP on an eroded, gullied surface. There are evidences that the Ganga Plain witnessed pulses of tectonic activity during 8–5 ka, which immensely modified the surface morphology. It produced kilometer-scale undulations, disruption and abandonment of minor tributaries to form linear lakes, eolian sand ridges (bhur) on the abandoned tributaries, alkaline soils due to lowering of groundwater (Srivastava et al., 2000; Singh, 2001, 2004; Srivastava et al., 2003a,b). At present, the entire Ganga Plain exhibits undulatory landscape, the magnitude of undulations changes from one area to the other. Digital elevation model (DEM) has helped in identifying warped and depressed areas; they are more prominent in the craton-ward margin of the Ganga Plain (Saxena et al., 2006; Saxena and Singh, 2011). These undulations are manifested in the variable heights of the cliffs along the valley margin of the rivers. A systematic study of the cliff heights along the valley margins of the Gomati River (about nine hundred kilometer long tributary of the Ganga River) shows general downstream decreasing cliff heights with wave like features and zones of high cliff heights. The incision of the Gomati River is linked to base-level (Ganga River) and intra-basinal tectonics, climate-driven features are subordinate (Thakur et al., 2009). This suggests that the Ganga channel, during the processes of incision has responded to upwarping events and the climate was conducive that provide optimum hydraulic energy. This implies that the foreland tectonic processes played an overriding role in the development of the cliffs.

In the view of above we can try to evaluate the evolution of Ramnagar area in terms of changes in climate, base level and intra-basinal tectonics. The Ganga River between Chunar and Buxar flows essentially in SW–NE direction and Varanasi is located in the middle part of this segment. This SW–NE direction is the general direction of basement lineament of the craton in the area. It has been discussed earlier that in Varanasi region this lineament has acted as gravity fault during late Quaternary. It has been pointed out that SW monsoon was strong during 12–5 ka, with much higher rainfall; hence high river discharge and sediment load. During 11–7 ka rapid sedimentation occurred in the Ganga delta region (Goodbred, 2003). The tectonic activity around 7 ka and hydrologic amelioration led river to produce Ramnagar cliff. Thus, development of Ramnagar cliff is essentially by intra-basinal tectonics and its affect on Ganga River system in Varanasi area.

8.3. Dynamics of the Ganga Foreland Basin

Foreland basin develops as a result of continent–continent collision in front of orogen on the underthrusting flexed lithosphere (Dickinson, 1974). The dynamics of the foreland basins show many specific features (Beaumont, 1981; Cant and Stockmal, 1993). The primary control on the sedimentation in a foreland basin is the tectonic processes of the orogen. However, the sedimentation is also affected by changes in sediment supply, base level changes or sea level changes, influence of pre-existing basement structures, climate and intra-basinal tectonics (Einsele, 1992; Cant and Stockmal, 1993).

Ganga Foreland Basin exhibits many specific features (Singh, 2001, 2004). Despite the large scale thrust–fold loading in the Himalaya, the down flexing of crust below the Ganga Plain is insufficient. The result is development of a wide but shallow foreland basin despite very high sediment input and sedimentation above sea level by fluvial processes.

Morphologically, the surface of Ganga Foreland Basin is a shallow asymmetrical depression with a gentle easterly slope. Superimposed on this easterly slope is a southerly slope in the northern part and a northerly slope in the southern part. The deepest part of the Ganga Plain in the west is located close to its southern margin occupied by the axial Yamuna River. In the middle part of the Ganga Plain, the lowest altitude zone is the central area occupied by Ghaghra River system. While the Ganga and Yamuna rivers are present at a higher level near the southern margin. In the eastern part of the low altitude zone is present close to the southern margin occupied by the axial Ganga River. It has been argued that late Quaternary sedimentation has been mostly controlled by expanding and contracting fan systems (megafans and piedmont fans) (Singh and Ghosh, 1992; Singh, 1996). The surface morphology and flow direction of the rivers is a combined effect of sedimentation pattern and tectonics. Mostly, the rivers coming from the Himalaya flow south to southwest, but swing to southeast direction. The rivers coming from the peninsular craton flow in northeast direction. The rivers in the axial drainage follow E to ENE direction.

The active river channels of the Ganga Plain exhibit prominent incision in the upland interfluves surface. However, there are distinct variations in the degree of river incision. The northwestern part of the Ganga Plain exhibits prominent river incision and cliff development along the river valley margins. In the middle part of the Ganga Plain degree of river incision increases from north to south direction, namely in the north the height of cliffs is mostly 2–5 m, in the central part it is 5–10 m; while in the southern part it is 10–20 m. In the eastern Ganga Plain incision is low in northern and central part (2–4 m), but high near the southern margin (10–20 m).

The last major tectonic activity in the Himalayan Orogen took place around 500 ka BP causing Upper Siwalik to uplift and expansion of foreland basin over the craton (Singh and Bajpai, 1989; Singh, et al., 1999b). At present the Ganga Foreland Basin is in relaxation phase and there is evidence of tectonic activity in the peripheral bulge (Agarwal et al., 2002).

It is conceived that during relaxation phase of a foreland basin axial rivers shift toward orogen and there is erosion of deposits of the peripheral bulge (Heller et al., 1988; Burbank, 1992). However, in Ganga Foreland Basin, the river systems have incised in the present position and there is net deposition on the peripheral bulge region (Singh, 2004). It is reasonable to think that in the Ganga Foreland Basin the rigid old under thrusting Indian plate is unable to bend, but often broken to produce extensional tectonic features in the axial zone and peripheral bulge of the basin. It produces gravity faults, horst-graben structures, rugged topography and cliff development. The rivers are incised and remain at the same place for tens of thousands of years. The extensional tectonics produces accommodation space where net sedimentation takes place during relaxation phase of the basin. The study of the Ramnagar section demonstrates strong role of extensional tectonics near the peripheral bulge. The rigid nature of the Indian lithospheric crust below the Ganga Foreland Basin is responsible for many unique features and strong tectonic control on fluvial system of the basin.

9. Conclusions

At Varanasi, the Ganga River flows along a gravity fault where the Ramnagar side is the up thrown block. The lower part of the Ramnagar cliff sediments represent deposits of rivers coming from craton. The upper part was deposited by rivers bringing Himalayan-derived sediments from the north. Deposition of Himalayan-derived sediments took place in Khadar area within the Ganga River Valley. The area witnessed two significant tectonic events; first ca. 40 ka BP when Ganga River system moved to near Varanasi, and second at 7 ka BP causing the uplift of Ramnagar area and incised nature of the Ganga River. After the uplift of Ramnagar area the surface was degraded by gulling activity for about 4 ka, before it was occupied by humans around 3 ka BP. Near Varanasi the river incision and cliff development is essentially related to the intra-basinal tectonics; the casual roles of climate are subordinate. The strong extensional tectonics leading to development of incised river valleys, gravity faults causing thick basin fill near the peripheral bulge are due to rigid nature of the Indian lithospheric crust.

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