Aggradation, incision and interfluve flooding in the Ganga Valley over the past 100,000 years: Testing the influence of monsoonal precipitation

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1. Introduction

Over timescales of thousands to a few tens of thousands of years, inland river systems undergo phases of aggradation and incision induced by tectonic, climatic and intrinsic factors. Consequently, fluvial stratigraphy typically displays complexity in architecture and internal heterogeneity (Ambrose et al., 1991), dependent on the interplay between autocyclic and allocyclic variables. These variables include the magnitude and rate of channel scour, channel deposition and migration rate, downstream change in grain size and varied sediment flux, channel belt avulsion, base-level change, climatic fluctuations, and tectonic subsidence patterns and local fault movement (Miall, 1996; Blum and Törnqvist, 2000; Catuneanu, 2006; Gibling, 2006). The effects of these complex variables on sediment preservation form the basis for alluvial-architecture models that seek to predict subsurface sandbody geometry.

Valleys are prominent landforms in many coastal and inland alluvial settings, and their cutting and filling exert a major influence on alluvial architecture. Valley filling and incision are commonly episodic in space and time due to changes in external forcing factors, especially stream-power variations linked to the balance between discharge of water and sediment (Bull, 1991; Bogaart et al., 2003; Strong and Paola, 2008; Martin et al., 2011). Such cut-and-fill architecture can be studied to understand the rhythmic control of external forcing (Bull, 1991; Bestland, 1997; Weissmann et al., 2002; Gibling et al., 2005; Mack et al., 2006). Architectural models for valley fills need to be tested for well-dated Quaternary successions where proxy records for forcing factors are available. However, only a few modern plains have been studied in sufficient detail to test the models effectively (Blum and Aslan, 2006; Stouthamer and Berendsen, 2007; Amorosi et al., 2008).

The Ganga Plains in the Himalayan Foreland Basin of India are underlain by sediment laid down by the Ganga River, among the world’s largest rivers. The plains have a well preserved alluvial record accessible through drilling, and strata are locally exposed in cliff sections along incised reaches. These records form important continental archives for understanding landscape dynamics against the backdrop of late Quaternary environmental changes driven mainly by hinterland (Himalayan) tectonics and palaeo-monsoonal dynamics (Gibling et al., 2011). The present paper extends previous research through a detailed study of the Ganga Valley near Kannauj in Uttar Pradesh (Fig. 1). In this area, a long stretch of previously
undescribed cliffs, ~10–20 m high, allows a high-resolution analysis of floodplain facies and their architecture at a relatively high elevation along the valley margin. Seven drill cores with near-complete recovery down to a depth of 32 m were organised in two traverses across the valley to a distance of 14 km from the cliffs (Fig. 1). Cliff and core strata were placed in a chronological framework that spans the past ~100 ka based on 25 samples dated using luminescence methods. Comparison with available information on palaeo-monsoon intensity suggests that, to a first order, major monsoonal fluctuations governed fluvial events of aggradation, incision, and inundation of the interfluve adjoining the Ganga Valley.

2. Geographic and geomorphic setting of the Ganga Plains

The study area falls in the middle Ganga Plains and is located ~300 km downstream of the Himalayan tectonic front and more than 1200 km upstream of the modern day tidal limit. Of the total catchment area of 2435 km², an area of about 206 km² (8.5%) is presently glaciated. The glaciated area was only slightly larger during the LGM (13%) (Owen et al., 2002), and glacial melt water may have played a modest role in the Ganga River's water and sediment flux through the Late Quaternary. The study area experiences monsoonal rainfall of about 60–80 cm per year. The hinterland of the Ganga receives N >200 cm/year and that of the Ramganga receives 160–180 cm/year. Most of this rainfall is concentrated during July–September, while the rest of the year is dry or has little rainfall. The monsoonal rainfall therefore exerts an important control on the hydrology and sediment flux in the basin. The winter temperature varies from 2 to 15 °C and the summer temperature from 25 to 45 °C (Singh, 1994). The hydrology of the Ganga River is strongly controlled by the monsoonal rainfall, and the proportion of glacial melt where the Ganga enters the plains, although debatable, has been estimated at 15% (Das Gupta, 1975).

Topographic analysis based on SRTM data (Fig. 2a) and a regional geomorphic map of the study area (Fig. 3) show that the modern Ganga River flows in an asymmetric valley (Fig. 2a). Field observations also confirm that the right channel bank is incised, exposing a 15–20 m high cliff line (Fig. 2c) that also marks the right valley margin. The left channel bank borders a flat-lying active floodplain tract (Fig. 2d) with palaeochannels and meander scars. Fig. 3 suggests long-term southwest migration of the channel (see also Roy and Sinha, 2005, 2007). The left valley margin does not form a prominent geomorphic feature but is delineated where the active floodplain passes northeastward into an inactive floodplain belt.

Fig. 3 shows five major geomorphic units in the study area, namely (i) the major active channel belt of the present Ganga and its large tributary, the Ramganga, currently about 5–7 km and 2.5–3 km wide, respectively; (ii) the active floodplains of these major channels within the valley margin; (iii) the active minor channels and floodplains of other smaller tributaries; (iv) wide inactive floodplains northeast of the Ganga; and (v) a slightly dissected interfluve surface southwest of the Ganga that extends as far south as the Yamuna River near the southern margin of the plains (Gibling et al., 2005; Sinha et al., 2005a). The southern margin is strongly gullied and degraded, forming irregular cliffs along the river.

![Figure 1](image1.png)

Fig. 1. (a) Location map of the study area in the western Ganga plains, Uttar Pradesh, India. (b) Band 4 satellite imagery (IRS LISS 3, dated April, 2000) showing active and palaeo-fluvial features having different radiance property. Note drill core location along two transects from left to right valley margin. Dashed line indicates left valley margin. Right valley margin is very close to the Ganga River. (c) Headwaters of the Ganga River showing the presently glaciated area and the extent of the LG glaciation.

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Present-day Ganga and Ramganga channel belts are braided, but the Ramganga shows significant sinuosity as well, particularly upstream of its confluence with the Ganga. The Ganga with a higher ‘braid-channel ratio’ (Friend and Sinha, 1993) flows in a nearly straight reach near Farrukhabad and a change in flow direction occurs downstream of Fatehgarh from NW–SE to nearly E–W down to its confluence with the Garra River, after which it resumes its NW–SE trend. The active floodplain of the Ganga is generally wider than that of the Ramganga, but their widths vary significantly along the channel. Among the active minor channels, the sinuous Garra River is slightly migratory. A large part of the study window is occupied by numerous inactive channels and floodplain features such as meander scroll bars, cut-offs (both neck and chute cut-offs), and abandoned channel belts.

3. Methods

3.1. Cliff section mapping and raising of drill cores

The valley-margin stratigraphy was studied in an exposed section 1.3 km long and 10–20 m high along the Ganga bank at Mehdipur Ghat close to Kannauj. Continuous overlapping photographs were taken from a boat to prepare a photomosaic on which major lithological units and breaks were traced. Ten stratigraphic logs at carefully chosen locations were prepared for documentation of grain size, sedimentary structures and features, recorded on centimetre scale to establish lateral correlation between logs and across the photomosaic. Based on the availability of reliable information on sedimentary structures and geometry, the facies interpretations (Table 1) are considered robust.

The valley-fill deposits were studied through seven cores collected along two transects 20 km apart downstream from Kannauj, with core spacings of 3 to 8 km along each transect (Fig. 1). Three cores were raised from each transect, and a single core was collected 10 km downstream of transect 2. The core locations were selected where past fluvial features were observed on the geomorphic map. Prior to drilling, a ground electrical resistivity survey was performed with a Schlumberger array to have prior information about the occurrence of major channel bodies before selecting the drill-core locations. Resistivity methods used in the research are outlined in Yadav et al. (2010). Locations of drill cores were determined by a handheld GPS accurate to less than a metre, and core tops were plotted on the topographic profile based on SRTM-based digital elevation maps.

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Drilling employed a diamond core drilling bit involving a double barrel core tube. A PVC pipe was inserted inside the core tube. In relatively stiff muddy strata, a slow rotary method was used with close to 100% core recovery. In unconsolidated sandy strata, a combination of rotary and percussion methods was used to arrest the core with slightly lesser core recovery (70–80%) including a slight compaction due to percussion. The core obtained in the PVC pipes was taken to the laboratory and split into halves. One half was preserved and the other half was used for logging and sampling. Geoelectrical logging (SP and resistivity) was carried out for all drill holes after the coring was completed. Apart from providing the first-level lithological characteristics, the geoelectric logs also helped in reconstructing facies in areas of core loss during drilling.

The cores were logged at centimetre scale. Munsell colour chart (Munsell colour chart, Year 2000) was used to describe colour. Textural description included grain size (visual estimation), compactness, primary structures and lamination, and grading. Special features include carbonate nodules (kankar) and rhizoconcretions, and dark nodules probably rich in iron and manganese. Dark (black), drab (grey), and red-brown soft mottles in silt/clay were noted, as were reworked carbonate nodules, shell material, burrows and root fills. The contacts between units were noted as sharp, gradual or wavy. Because the cores were more difficult to characterise and interpret than the outcrops, a separate facies scheme was utilised (Table 2), and description and a brief interpretation are presented together.

3.2. Luminescence dating

Samples for luminescence dating were collected in light-proof PVC pipes, and the locations were marked on the cliff section and on borehole logs (Figs. 4, 5). From each sample, a coarse grain-size fraction (63–90 or 90–180 or 180–250 μm) of quartz and feldspar was extracted and was further processed following standard laboratory
treatments (Stokes, 1992) to isolate quartz and feldspar. A single-aliquot regenerative dose protocol (Murray and Wintle, 2000) was employed to yield a palaeo-dose estimate from quartz and feldspar after successfully passing standard tests (Wintle and Murray, 2006) for reliability. The distribution of palaeo-dose estimates from individual aliquots was fitted with a normal distribution to obtain the mean.

4. Valley-margin section at Kannauj

4.1. Facies description

The section is composed of mud and sand sheets with decimetre-to-metre-scale thickness (Fig. 4). Three depositional groups were identified, namely floodplain (IF) with seven component facies, aeolian (IE) and channel (IC) with one facies each (Table 1). Five stratigraphic units were identified on the photomosaic and image logs (Fig. 4a, b). The units can be correlated for the length of the exposure, although Unit 5 has been eroded to the south.

Table 1

<table>
<thead>
<tr>
<th>Litho-facies</th>
<th>Description</th>
<th>Interpretation</th>
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<tbody>
<tr>
<td>Floodplain facies (IF)</td>
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<tr>
<td>IF1. Clayey silt with greater than 30% carbonate nodules.</td>
<td>Dark brown clayey silt. Reddish brown to dark brown, yellow, grey mottles are present. Large carbonate nodules (2 to 5 cm), comprised &gt;30% of the facies. Minor dark mottles and black Fe–Mn nodules are present.</td>
<td>Floodplain deposits with soil carbonate formation. Variable degrees of pedogenesis. Pedogenesis and floodplain aggradation occurred alternately. Commonly occur as thick interfluve floodplain of a major river.</td>
</tr>
<tr>
<td>IF2. Clayey silt with few carbonate nodules (&lt;5%).</td>
<td>Pale brown clayey silt, locally silt rich. Drab mottles, vertical to sub-vertical drab pipes dispersed or in horizons. Small carbonate nodules (mm size) comprised ~5% of the facies. In places rhizoconcretions comprise up to 30%.</td>
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<tr>
<td>IF3. Silty clay with less than 10% carbonate nodules</td>
<td>Yellow brown silty clay with less than 10% kankars and minor rhizoconcretions. Black and drab mottles and plant roots are present.</td>
<td>Floodplain deposits with moderate degree of pedogenesis as floodplain deposits (&lt;1 m thick) of local river.</td>
</tr>
<tr>
<td>IF4. Sticky clay with rhizoconcretions and carbonate nodules</td>
<td>Dark yellow tight silky clay, minor kankars but many rhizoconcretions and mottles (red-brown) are present, strongly cohesive. Efflorescence present on weathered surface. Fragmented gastropod shells at the base.</td>
<td>Shallow water bodies in a large depression and abandoned channel areas; minor pedogenesis, but strong carbonate diagrasis.</td>
</tr>
<tr>
<td>IF5. Laminated sandy silt with few small carbonate nodules.</td>
<td>Dark yellow to pale yellow sandy silt, weakly cohesive materials with poor lamination preserved. Kankars comprise ~10% of the facies. Large grey mottles and roots. Black Fe–Mn nodules are common.</td>
<td></td>
</tr>
<tr>
<td>IF6. Massive sandy silt with &gt;10% carbonate nodules.</td>
<td>Pale yellow massive, tight sandy silt with scattered kankars (mm size). Yellow brown mottles and dark Fe–Mn nodules present. Coalesced nodules a few cm to dm in diameter, nodules are sand to silt particles bound by carbonate cement. Carbonate is mostly micritic, but locally has coarser sparry fabric. Nodules interspersed with mud, fine sand and silt. Rhizoconcretions locally are up to 30 cm long. Kankar nodules are disseminated in the floodplain mud, while kankar lumps (centimetre-scale-thick) are laterally amalgamated and persistent carbonate layers between floodplain layers. The carbonate nodules from floodplain facies show higher δ13C values compared to those in eolian facies (average δ13C = −5.86 in floodplain and δ13C = −2.76 in eolian facies).</td>
<td>Floodplain deposits. Weakly pedogenised, Fe–Mn nodule indicates gleying effect.</td>
</tr>
<tr>
<td>IF7. Calcrete</td>
<td>Pale yellow massive, tight sandy silt with scattered kankars (mm size). Yellow brown mottles and dark Fe–Mn nodules present. Coalesced nodules a few cm to dm in diameter, nodules are sand to silt particles bound by carbonate cement. Carbonate is mostly micritic, but locally has coarser sparry fabric. Nodules interspersed with mud, fine sand and silt. Rhizoconcretions locally are up to 30 cm long. Kankar nodules are disseminated in the floodplain mud, while kankar lumps (centimetre-scale-thick) are laterally amalgamated and persistent carbonate layers between floodplain layers. The carbonate nodules from floodplain facies show higher δ13C values compared to those in eolian facies (average δ13C = −5.86 in floodplain and δ13C = −2.76 in eolian facies).</td>
<td>Floodplain deposits with greater water availability as indicated by high C3/C4 plant ratio, whereas eolian facies were deposited with less water availability supported by low C3/C4 plant.</td>
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<tr>
<td>Aeolian facies</td>
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<tr>
<td>IE: Very fine sand and silt</td>
<td>Off-white silt to very fine micaceous sand, moderate sorting of grains, no recognisable stratification, non-cohesive with minimal clay and plant roots and few carbonate nodules present.</td>
<td>Windblown sand and silt from nearby source.</td>
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<tr>
<td>Channel facies</td>
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<tr>
<td>IC: Very fine micaceous silty sand, laminated</td>
<td>Very fine micaceous sand, basal part show curved laminae, finer particles in the upper part.</td>
<td>Minor channel deposits.</td>
</tr>
</tbody>
</table>

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Unit 1 (base not exposed) is 3.8 m thick with modest lateral variation, and comprises weakly stratified clayey silt (facies IF1and 2). Scattered to concentrated kankars of various sizes (mm to cm) are relatively small in the upper part, where rhizoconcretions up to 10 cm long and traces of oxidised rootlets are also present. At the unit top, the clay is more silty and has vertical drab pipes (maximum 30 cm long and traces of oxidised rootlets are also present. At the unit top suggests that the area was closer to a floodplain surface that appeared across the southern Ganga Plains (see descriptions in Gibling et al., 2005, 2008). Unit 2 developed over an irregular floodplain surface that appears to mark a discontinuity. A major change is marked by Unit 3 which consists of aeolian deposits, the base marking a discontinuity. An aeolian interpretation is based on the predominance of near-structureless silt to very fine sand with little evidence of pedogenesis; similar units are locally present across the southern Ganga Plains (see descriptions in Gibling et al., 2005, 2008).

Unit 4 is made up of stratified floodplain deposits and may indicate a floodplain environment closer to a major conduit. A composition of silty clay, clayey silt and sandy silt, together with poorly developed palaeosols and the fill of a shallow channel, suggests deposition as a natural levee (Tyler and Ethridge, 1983; Thomas et al., 2010).
Such interbedding of floodplain facies with varied grain size, in addition to occasional breaks in deposition manifested as kankar layers, suggests deposition during flood cycles of varied intensity. The channel body may represent a crevasse through the levee or a small floodplain channel. Unit 5 is interpreted as a package of alternate aeolian, lacustrine and floodplain deposits, as identified by the presence of weakly cohesive sandy silt, fine lamination and plant roots.

4.3. Chronology and architecture

Table 2 lists sample dates from the valley-margin section and from cores (discussed later). Quartz fractions of 90–180 μm from Unit 1 yielded ITL dates of 89±10 ka from the lower parts and one date of 41±4 ka from the unit top at the position of Log 1. Another sample from Log 9 position gave a date of 100±11 ka for this unit. Unit 3 yielded an ITL date of 35±4 ka. Unit 4 yielded ITL dates of 34±4 ka and 26±3 ka, the latter from the topmost beds of the unit. Although all OSL samples yielded saturated signals, the minimum dates of 15 to 29 ka suggest that the exposed section entirely predates this period.

For Unit 1, dates between 100 and 41 ka indicate that the strata represent much of Marine Isotope Stages (MIS) 3, 4 and 5. Although too few dates are available to estimate sedimentation rate, the small thickness (4 m) of the unit, along with the fine grain size and abundant kankar, suggests slow floodplain aggradation and probably the presence of discontinuities. Although the topmost beds were not dated, the bulk of sediment accumulation in Units 2–5 (8 m) apparently represents a relatively short interval of more rapid
accumulation, with much coarser sediment, between about 39 and 23 ka (including error ranges), late in MIS 3 through to early MIS 2. The repeated intercalation of thin aeolian and lacustrine deposits in Unit 5 may reflect climatic fluctuation. At present, there is no indication of deposition since about 23 ka, and the cliff-line may have been degrading through this time.

5. Ganga Valley cores

5.1. Facies description and interpretation

Three channel facies are present (Table 3), namely sandy silt/silty sand (VC1), fine to very fine sand (VC2) and medium sand (VC3). The coarser channel sands have ‘salt and pepper’ texture due to the abundance of dark, dense minerals, which is characteristic of Himalayan-derived sediment. Among the channel facies, the finer grained facies VC1 generally occurs as relatively thin bodies up to 3 m thick within muddy successions and contains mottles and sparse carbonate nodules. These bodies are inferred to represent small tributary or floodplain channels. In contrast, the fine- to medium-grained facies VC2 and VC3 form continuous sand bodies up to 10 m thick that are interpreted as the deposits of major trunk rivers.

Flooding facies form only a modest proportion of most drill cores and consist mainly of silty clay with pedogenic features that include dark brown, yellow brown, and grey motles, and carbonate nodules that are disseminated or locally concentrated in bands. The flooding facies are classified into grey silty clay (VF1), pale yellow silty clay (VF2), brown silty clay (VF3), and prominent bands of carbonate nodules (VF4) (Table 2). Aeolian deposits (facies VE) consist of structureless, soft clay-rich silt that varies from light yellowish brown to pale yellow. Carbonate-cemented layers and thin clayey silt and silt laminae are characteristic, probably reflecting the presence of low mounds of wind-blown material. This facies appears more clay rich and better stratified than inferred aeolian facies in the cliff section, and the aeolian interpretation must be considered provisional.

Lacustrine deposits (facies VL) were identified as a 4-m-thick, organic-rich layer in one log (core 7) above thick channel sand, and are present in other logs as a thin layer above channel fills. The lacustrine interpretation is based on the sheet-like geometry, the fine lamination, and the distinctive lithology of dark olive grey, stiff and sticky clay. This facies is similar to the floodplain marsh deposits in Unit 2 in the cliff section. Carbonate nodules and locally prominent motting point to a moderate degree of pedogenesis. This facies is attributed to temporarily or permanently abandoned channels, probably under backswamp/marshy conditions.
5.2. Chronology and architecture

Fig. 5 shows seven drill core logs in two cross-valley transects (Fig. 5a, b) and one transect along the valley (Fig. 5c; see locations in Fig. 1b). The cores consist of channel bodies separated by floodplain, lacustrine and probable aeolian deposits that cover a time span from about 74 ka to 0.1 ka (Table 2). Five stratigraphic units were identified on the basis of lithology and age. In contrast to the sheet-like nature of valley-margin units, the cored units appear to be lensoid and locally incised into underlying units, making unit designation less reliable. Although the seven cores are insufficient for a complete valley-scale correlation, some units can be traced between the two transects.

**Unit 1** (cores 1, 2, 4 and 5, base not penetrated) consists of 2 m of fine to very fine channel sand (facies VC2). The channel sand yielded IRSL dates of 74 ± 3 ka and 61 ± 2 ka, and a minimum OSL date of 55 ka (Table 2) suggests that this channel activity corresponds to topmost MIS 5 and MIS 4. The considerable difference in dates from cores 2 and 4 suggests more than one episode of channel activity, possibly with associated incision. Unit 1 is present in cores close to the modern, southern Ganga Valley margin, but in neither transect were the lowermost channel sands fully penetrated, and the unit may be widespread below the modern Ganga Valley.

**Unit 2** consists of alternate floodplain (VF1–VF3) and aeolian (VE) beds. Thin sand layers (splays) yielded an IRSL date of 37 ± 2 ka which corresponds to late in MIS 3, and two OSL samples provided minimum dates of 27 ka and 23 ka (Table 2). Grey mottles indicate a weak degree of pedogenesis. In core 2, a sharp break within Unit 2 is marked by the presence of a concretion zone at 25 m depth. Moderately pedogenised muds suggest slow deposition or periods of non-deposition. In core 2, a kankar horizon at the 25 m level (Fig. 5a) above 3 m of undated floodplain deposits may represent a significant discontinuity. Although shown within Unit 2, fine sediments below this kankar level are provisionally taken to mark the termination of MIS 4/5 deposits.

New channel activity during MIS 3 (37 ka) is recorded from thin sands below a thicker (3 m) channel body in core 2 (Fig. 5a). Channel deposits are also recorded prior to 27 ka (a minimum OSL date) in core 4 (Table 2). Both of these channel sediments are capped with
thick, strongly pedogenised overbank deposits 7 m thick, suggesting reduced sedimentation late in MIS 3. In contrast, floodplain deposits lower in Unit 2 show less intense pedogenesis, probably within cumulative floodplain soils. Similar weak pedogenic activity during floodplain aggradation has been documented from eastern Ganga Plains interfluves (Mohindra et al., 1992; Sinha and Friend, 1994).

**Unit 3** consists of 3 m of medium sand (VC1) and we interpret this as the top of a thick channel body that extends below the base of core 3, the only place where it is recorded. An OSL date of 28±2 ka from core 3 (Table 2) suggests deposition late in MIS 3. The channel sands lie close to the left margin of the present Ganga Valley and their elevation indicates that they are incised into older strata.

**Unit 4** constitutes one or more major channel bodies composed of very fine to fine sand (VC1 and VC2), recorded in cores 6 and 7 only. In core 6, two distinct sand bodies are separated by 5 m of floodplain mud (VF2). Five dates bracket the channel sediments between 15 and 11 ka (Table 2), representing MIS 2 to early MIS 1 (latest Pleistocene to earliest Holocene) and suggesting that 20 m of strata were deposited in as little as about 4000 years. The channel body is interpreted as a braided-fluvial deposit, and it lies close to the left valley margin where it appears deeply incised (Fig. 5b).

**Unit 5** is represented by a sand body (VC1–VC3) more than 15 m thick, capped by thin muddy deposits that were probably laid down within abandoned channels. Seven dates range between 2.5±0.16 ka and 0.18±0.02 ka (Table 2), representing late Holocene channel activity. These channel deposits at the top of the succession are widespread and were penetrated in five cores, variously incised into Units 2, 3 and 4 (Fig. 5b). The sediments resemble those of the modern river, and they are interpreted as braided-fluvial deposits.

6. **Synthesis of Ganga Valley and valley-margin records, in comparison with the monsoon record**

The Ganga Valley-margin exposures and subsurface deposits are illustrated schematically in Fig. 6, along with proxy records for monsoon intensity based on stacked core records for the Arabian Sea (Clemens and Prell, 2003) and modelling results for the SW Indian Monsoon (Prell and Kutzbach, 1987). The latter curve is closely linked to insolation trends, and changes in modelled intensity approach 30% of present values. The two proxy records differ in detail but show broadly similar high- and low-intensity periods, fluctuating over periods of a few thousand to about 20,000 years. The fluctuations show general accord with marine isotope stages determined from offshore cores (Waelbroeck et al., 2002; Fig. 6).

In interpreting our records, we have drawn strongly on the range of dates provided by the 13 finite OSL dates and 9 ITL and IRSL dates to establish periods of channel aggradation and incision. Although more dates are necessary to provide a comprehensive understanding, the dates were obtained from precisely documented strata, commonly to test the age of key boundaries, and they suggest several distinct periods of fluvial activity, which are especially clear from about 30 ka onwards.

The interfluve successions are characterised by overbank fines, whereas the valley succession comprises channel bodies and fines, and the relationship between them is a key issue. The valley-margin deposits have a sheet-like geometry and aggradational style, in...
Table 3

<table>
<thead>
<tr>
<th>Facies group, facies, description, association and interpretation of cores below the Ganga Valley.</th>
<th>Facies</th>
<th>Description</th>
<th>Abundance and associated facies</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floodplain facies</td>
<td>VF1. Grey silty-clay</td>
<td>Silty clay, structureless, moderately tough, sticky due to high clay concentration, rare mottles. Tiny kankar nodules and Fe–Mn black coated nodules (2–3 mm size) are rare. Munsell colour brown grey (2.5Y6/2) to grey (5Y6/1) with a greenish tinge.</td>
<td>Present in three cores (5, 2, 4), in units with maximum thickness up to 1 m (Core-2), forms incomplete cycle; commonly truncated below base of channel sand.</td>
<td>Floodplain deposits: dark colour suggests deposition under reducing condition</td>
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<tr>
<td></td>
<td>VF2. Pale yellow silty-clay</td>
<td>Soft silty clay with high clay proportion, sticky and tough with uncommon reddish brown and yellowish brown mottles in Core-5. Kankars from 1 mm to 2 cm are scattered and fairly abundant. Munsell colour: pale yellow silty clay (5Y8/4 to 5Y7/3) with a greenish tinge.</td>
<td>Abundant facies, present in Core-5 and Core-4. Maximum thickness is 2.7 m. This facies frequently interrupted by kankar zones (20–30 cm thick). Commonly associated with silty sand (VC1) and locally clayey silt (VF1).</td>
<td>Floodplain deposits, weakly pedogenised with soil carbonate nodules</td>
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<td></td>
<td>VF3. Brown silty clay (with/without mottles)</td>
<td>Soft clay and silt mixture; cohesive, sticky nature — due to relatively enrichment in clay. Mottles are common to few, scattered to concentrated. Black mottles are common and yellow brown mottles are frequent. Fe–Mn nodules and kankars are abundant. Munsell colour: brown silty clay (2.5Y 5/4 to 2.5Y 6/4).</td>
<td>Maximum thickness 4 m, associated with silty sand, clayey silt facies.</td>
<td>Floodplain deposits: moderate to strong pedogenesis, with abundant soil carbonate formation, Fe– Mn nodules indicate gleying effect.</td>
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<td>VF4. Carbonate nodules</td>
<td>Layers of concentrated carbonate nodules (diameter varies from 2 to 3 cm up to 5 cm), rounded to angular. Most nodules are carbonate-cemented sand.</td>
<td>Layers maximum 50 cm thick associated with facies VF1, VF2 and VC1.</td>
<td>Layered concretion, probably of groundwater origin.</td>
</tr>
<tr>
<td>Lacustrine facies</td>
<td>VL. Dark silty clay</td>
<td>Sheet like geometry and fine lamination, stiff and sticky clay, maximum 1 cm diameter kankar nodules sparsely distributed, mottles are uncommon to common. Munsell colour: dark olive grey (5Y3/2).</td>
<td>Maximum thickness 3 m, associated with channel sand facies in Core-7, in other cores thickness is a few centimetres.</td>
<td>Floodplain deposits with low degree of pedogenesis formed under reducing conditions created due to ponding within channels. Presence of carbonate nodules points to moderate degree of pedogenesis.</td>
</tr>
<tr>
<td></td>
<td>VE. Yellow clayey silt</td>
<td>Silt with few clay, non-cohesive, low skewness relative to other facies, small kankars sparsely distributed, rare black nodules and yellow brown mottles. Carbonate cemented bands, and thin lamination of clayey silt and silt material are characteristic. Munsell colour: light yellowish brown (2.5Y6/3, 2.5Y6/4) to pale yellow (2.5Y7/3; 5Y8/3)</td>
<td>Maximum thickness 3.5 m in the Cores-1 and -5; mainly associated with floodplain facies</td>
<td>Weakly pedogenised sheets of massive windblown massive sheet sand; thin lamination probably reflects the presence of low mounds of wind-blown material.</td>
</tr>
<tr>
<td>Channel facies</td>
<td>VC.1. Yellow silty sand</td>
<td>Silty and very fine sand, with minimal clay, slightly micaceous, mottles and sparse carbonate nodules. Units fine upwards.</td>
<td>Maximum thickness 3 m in Core 4 associated with floodplain facies.</td>
<td>Coarse sediment body associated with small channel, probably a tributary or floodplain channel. Dark yellow silt resembling eolian facies suggests that deposition occurred in drier climatic phase. Thick channel body indicates large trunk channel, probably braided deposits.</td>
</tr>
<tr>
<td></td>
<td>VC.2. Very fine sand and fine sand</td>
<td>Very fine and fine sand mixture. Sharp break occurred with medium sand facies. Small kankars are sparsely distributed.</td>
<td>Maximum thickness 7.4 m in Core-6, commonly associated with medium sand facies, and channel fill top.</td>
<td>Thick channel deposits of large trunk river laid down under high energy condition. Rare thin beds intercalated with floodplain deposits are interpreted as splays from major channel.</td>
</tr>
<tr>
<td></td>
<td>VC3. Medium sand</td>
<td>Medium sand, off-white to white, mixed with fine and very fine sand, highly micaceous, presence of heavy minerals gives ‘salt and pepper’ appearance. Small kankars sparsely distributed. Generally well sorted.</td>
<td>Maximum thickness of 10 m in Core-3, at the base of the core reworked carbonate gravel present.</td>
<td>Five major aggradational periods can be recognised, based on dates and error bars. They are shown as schematic cross-sections (1 to V) in Fig. 6, and their inferred age ranges are shown alongside the proxy records for climate change. Probable periods of incision are also shown.</td>
</tr>
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6.1. Period I: MIS 5 to early MIS 3 (111–59 ka)

The lowermost floodplain deposits (Unit 1) of the valley-margin section are bracketed between 100 and 41 ka (Fig. 4a), a period of...
nearly 60,000 years. Floodplain development during this period was interrupted by multiple pedogenic events, possibly indicating slow sedimentation or short-term discontinuities, and more intense pedogenesis is apparent in the topmost beds.

Below the modern valley, the oldest channel bodies (partly penetrated in Unit 1) yielded finite dates of 74 ka and 61 ka, and thus appear to be in part time-equivalent to the basal floodplain unit of the valley margin (Fig. 6). However, a difference in elevation of 25–30 m is recorded between the base of floodplain deposits (Unit 1) in the cliff section (Fig. 4a) and the top of channel deposits of Unit 1 below the valley (Fig. 5a, b). This elevation difference suggests the presence at this time of an incised valley with channels that were capable of intermittently flooding the interfluve to the south. Minor discontinuities in the valley-margin deposits are inferred from the varied intensity of pedogenesis and may reflect the episodic nature of this inundation. Over the past century, low- to high-stage seasonal fluctuations of the Ganga and Yamuna rivers have often been extreme (in excess of 20 m: Gibling et al., 2005), and the highest flows may inundate parts of the proximal interfluves, depending on the local height of the cliffs.

An alternative interpretation is that alluvium had built up in the area of the modern valley to a higher level than that presently recorded, allowing frequent interfluve inundation. Valley incision may have subsequently removed much of this sediment and detached the interfluve from the trunk channel, reducing sediment supply and initiating interfluve pedogenesis.

Cliff sections along the modern Yamuna River, 70 km southwest of the study area, also expose a thick floodplain succession dating back to ~100 ka, with prominent discontinuities (Gibling et al., 2005; Sinha et al., 2005b; Tandon et al., 2006). Although Unit 1 in the Ganga Valley was incompletely penetrated, the range in ages for channel bodies suggests multiple channel events and possibly incisional discontinuities, perhaps in accord with modelled strong fluctuations in monsoon intensity in MIS 4 and 5 (Fig. 6).

In general, we infer prolonged channel activity during MIS 5 and 4 and at least some interfluve flooding, followed by a reduction in channel activity associated with pedogenesis of floodplain muds. A similar period of persistent channel activity in MIS 5/4 was inferred for strata in the Belan River at the southern margin of the Ganga Plains (Gibling et al., 2008).  

6.2. Period II: MIS 3 (45–30 ka)

Deposits that correspond to MIS 3 are represented by Unit 2 of the valley-fill, where a splay associated with minor channel fills yielded a date of 37 ka. Probable aeolian strata of pale, friable silt are prominent in this unit. During late MIS 3, the valley-margin succession records thin, non-fluvial deposits (floodplain marsh and aeolian sediments of Units 2 and 3). This suggests that flow through the channel was either drastically reduced or that the trunk river migrated away from the southern valley margin, reducing sediment supply to the area. A period of floodplain degradation, possibly associated with reduced
sediment supply, is recorded in the Yamuna valley ~70 km south of Kanpur (Fig. 1a) between 30 and 40 ka, manifested as the cutting of deep gullies and their subsequent filling with colluvium (Gibling et al., 2005). Period II may correspond with reduced monsoon activity, although the two proxy records show some differences through this period.

6.3. Period III: latest MIS 3 and early MIS 2 (30–23 ka)

Renewed fluvial activity is recorded in the cores late in MIS 3. High-energy channel activity (gravelly sands) dated at 28 ka are recorded near the left margin of the present Ganga Valley (Fig. 6), and their relative depth suggests that incision occurred prior to alluviation. This channel activity is time-equivalent to a channel fill recorded at Bithur 40 km downstream from the study area by Sinha et al. (2007a).

In the valley-margin succession, levee deposits of Unit 4 yielded dates of 34 and 26 ka, the latter from a small channel body. There is some uncertainty as to whether these correspond to Periods II or III, but the unit top (at least) is attributed to Period III because the younger date is time-equivalent to channel deposits below the valley, and because the presence of renewed overbank deposition along the valley margin is consistent with high discharge late in MIS 3. As with Stage I, the deposition of sediments in both geomorphic areas may reflect extreme floods from an incised valley or alluviation within the valley to an elevation higher than presently recorded. Goodbred (2003) suggested that high-intensity floods would have been active during a period of strong solar insolation at about 31 ka, associated with large-scale sediment production from the Himalayan source area (see also Sharma and Owen, 1996; Taylor and Mitchell, 2000). The proxy and modelled monsoon curves suggest that the south Asian climate was wetter late in MIS 3 or in earliest MIS 2 (Fig. 6).

No channel deposits are recorded below the Ganga Valley between 28 ka and 15 ka, suggesting that this interval, which includes the global Last Glacial Maximum (LGM), experienced reduced fluvial activity. Relatively strong pedogenesis is noted below much younger deposits in the topmost muddy parts of Unit 2 in cores 2, 4 and 5, and an interval of soil formation may accord with reduced activity, although these strata are not constrained by dates.

The valley-margin succession is capped by aeolian, lacustrine and floodplain deposits of Unit 5. Although undated, these suggest a cooler and drier climate towards the LGM. Aeolian accumulation on the valley margin may reflect “underfit” of the Ganga River during the LGM and exposure of the river bed, from which silt was preferentially picked up by winds. Similar relationships have been documented from Bithur (lake and aeolian deposits at ~27 ka; Gibling et al., 2005) in the Ganga Valley and in the Belan valley (aeolian deposits with broken gastropod shells at ~17–20 ka; Williams et al., 2006; Gibling et al., 2008). Evidence of reduced siliclastic supply in the Ganga–Brahmaputra delta (Goodbred, 2003; Weber et al., 2003) in the later part of MIS 3 is consistent with reduced hinterland supply or possibly some sediment storage in inland valley areas.

6.4. Period IV: late MIS 2 and early MIS 1 (16–11 ka)

Channel aggradation was recorded in Unit 4 of cores 6 and 7, where five finite OSL dates in the topmost 20 m of strata range between 15.1 and 11.7 ka. The presence of muds between channel bodies suggests channel switching in a braided depositional environment. These thick braided-channel deposits imply high sediment supply from the hinterland. This may reflect landscape instability due to monsoon intensification following the LGM (Overpeck et al., 1996; Fig. 6), inducing extensive slope failure and transport of hillside regolith to the valley floor (Pratt et al., 2002). The valley margin appears to have been largely inactive and possibly degrading during both Periods IV and V, as indicated by ITL dates and by minimum OSL dates >15 ka, although later gully erosion (Fig. 4) may have removed much of the record.

Dates of 13.0±0.7 ka and 11.7±0.7 ka for the top of the Unit 4 channel bodies in cores 6 and 7 suggest that the channels aggraded rapidly during a period of reduced discharge between 13 and 11 ka. This interval corresponds to the Younger Dryas, for which lake records at Sanai Tal 200 km east of Kanpur document a period of reduced monsoonal strength between 13.4 and 12.2 ka (Sharma et al., 2004). Elsewhere in the Ganga Plains, evidence for reduced monsoonal strength and decreased discharge at this time includes the presence of aeolian and lacustrine strata at Bithur on the Ganga Valley margin with dates from the topmost part at ~13 ka (Srivastava et al., 2003; Gibling et al., 2005), gully erosion and aeolian accumulation at Mawar on the Sengar River between 13 and 9 ka (Gibling et al., 2005), aeolian sands in incised channel in the Belan valley between 12.2 and 13.4 ka (Gibling et al., 2008), and aeolian sands east of Delhi dated at 12.3 ka (Tandon et al., 2006). Cool, dry conditions associated with the Younger Dryas event have been widely identified in other Asian continental deposits (Porter, 2001).

The alluviation episode followed an earlier period of channel incision (Fig. 6). This lowering of the channel’s equilibrium profile accorded with a period of monsoon intensification following the Last Glacial Maximum — a pattern observed across much of southern Asia (Tandon et al., 2006).

6.5. Period V: MIS 1 (2.7 ka to present)

Late Holocene channel bodies aggraded across much of the present valley area, and sediments accumulated within a short period of 2.7 to 0.1 ka, based on seven OSL dates. The base of these deposits lies adjacent to much older strata and directly overlies MIS 3/2 deposits, suggesting that valley incision preceded filling. Rapid accumulation during the late Holocene was also observed in the Yamuna valley, 70 km to the southeast, where a 20 m core penetrated a 12 m channel-margin succession of interbedded sand and clay, yielding two dates of 2 ka or younger from the lower strata (Sinha et al., 2005b, 2009). Late Holocene aggradation is inferred to reflect a pronounced decline in monsoon intensity and transport capacity since the mid Holocene (Overpeck et al., 1996; Fig. 6). In the case of the Yamuna succession, accumulation may be associated with a recent onset of Yamuna river deposition in the area (Sinha et al., 2005b, 2009).

During this period, there is no indication of deposition along the valley margin, which was probably undergoing degradation as recorded in the modern gullied landscape adjacent to the valley. The river’s equilibrium profile was apparently so low in the post-LGM period that the river was not able to overtop the interfluve valley margin. Southward migration is manifested by the Ganga’s present position at a cliff line along the southern valley margin, indicating widening of the valley floor.

7. Discussion

The Ganga Valley in the study area is 1200 km inland from the tidal limit, and it is unlikely that depositional architecture was affected by sea-level changes in the past to such a distance inland (Sinha et al., 2005b; Tandon et al., 2006; Sinha et al., 2007a,b; see also Blum and Törnqvist, 2000). The valley deposits are entirely terrestrial facies of the foreland-basin fill, and no marine beds have been encountered. There is no recorded history of seismic events from this region, nor indications of seismic-related deformation in core or outcrop as observed at other sites (Gibling et al., 2005), and basement faults are buried under a thick alluvial cover. Some workers (Singh et al., 1997; Agarwal et al., 2002) suggested a tectonic influence on major river incision due to forebulge activity, but this has not been
established by regional geological mapping or convincing geomorphic evidence. It is unlikely therefore that the Ganga Valley fine-scale architecture in this area was controlled by tectonic activity and sealevel change during the late Quaternary.

Paola (2000) suggested that, over time scales of $10^3$ to $10^5$ years (Milankovitch time scale), patterns of deposition for foreland-basin settings reflect cyclical change in water and sediment supply due to climate shifts; over longer time scales, the influence of basin subsidence and other tectonic factors may be more apparent. Flume experiments and field studies in the Himalayan Foreland Basin and elsewhere have identified sequences generated as a result of alternate low and high discharge, without any change in subsidence rates, (Bull, 1991; Milana, 1998; Weissmann et al., 2002), and an analysis of successions in southern Asia supports Paola’s assertion (Gibling et al., 2011).

Quaternary records suggest that the strength of the Southwest Indian Monsoon has varied significantly on a timescale of centuries to millennia. Evidence of such variations is provided by well-dated, multi-proxy records from cores in the Arabian Sea (Clemens and Prell, 2003; Rao et al., 2008) and Bay of Bengal (Chauhan et al., 2004), continental fluvial records (Gibling et al., 2005, 2008; Tandon et al., 2006; Sinha et al., 2007a,b), and lake records (Sharma et al., 2004; Prasad and Enzel, 2006) from northern India, as well as from records on the Tibetan Plateau (van Campo and Gasse, 1993). For the western Ganga Plains, Gibling et al. (2005, 2008), Tandon et al. (2006), and Sinha et al. (2007a) inferred strong correlation of fluvial sedimentation with variation of monsoonal rainfall regime, and a similar conclusion was reached on a basin scale by Goodbred (2003). Based on the continental alluvial record from the southern margin of Thar Desert in northwest India, Juyal et al. (2006) showed strong monsoonal variability over the last 130 ka, and Bryson and Swain (1981) documented a period of strong early Holocene precipitation, decreasing by about one third by the late Holocene.

Such fluctuations in monsoon intensity should have resulted in significant change in effective discharge of the Ganga River, causing rise and fall of the river’s equilibrium profile. These discharge changes are likely to be manifested in alluvial architecture in the valleys and on interfluves, especially if the magnitude of change was sufficient for the system to cross a geomorphic threshold. The availability of a robust proxy record for monsoonal fluctuations extending back beyond 100 ka has allowed us to compare climatic events with alluvial events of incision and aggradation in the Ganga River area at Kannauj. Our results suggest that, to a first order, alluvial events correspond well with monsoonal fluctuations, and this correspondence is especially evident for the well dated record after 30 ka.

A particularly provocative conclusion is that several well-dated periods of channel aggradation correspond to times of decreasing monsoonal precipitation (Fig. 6): during latest MIS 3 and earliest MIS 2 (Period III), during the Younger Dryas (Period IV), and during the late Holocene (Period V). These are inferred to record decreased discharge and rise in the river’s equilibrium profile. In all these cases, elevation considerations indicate that aggradation was preceded by incision, suggesting that periods of increasing monsoonal precipitation were associated with high river energy and a lowering of the equilibrium profile. Spatial considerations suggest that these were also times of channel relocation within the valley (Figs. 5, 6). Occurrences of aeolian and lacustrine deposits, as well as intensity of pedogenesis, also play an important role in “reading” palaeoclimatic changes. Earlier alluviation and incisional episodes have less well-constrained durations, and are less readily compared with monsoonal changes.

For the latest Holocene aggradation (Period V), low effective discharge of the river channel is in accord with a wealth of data across Asia that documents severe weakening of Southwest Indian Monsoon, evident in records of Arabian Sea upwelling (Gupta et al., 2005; Thamban et al., 2007) and in historical records from north India (Pande et al., 2003). Low percentage of Globigerina bulloides in sediments from the Oman coastal margin indicate reduced upwelling and a monsoonal minimum about 2000 years B.P. (Gupta et al., 2005). Aridity records based on dolomite percentage from the Arabian Sea margin (Sirocko et al., 1993), biological productivity off the Somali margin (Ivanocho et al., 2005), precipitation records off the Indus river mouth (Staubwasser et al., 2003) and from the southwest Indian margin (Sarkar et al., 2000) further suggest a declining monsoon about 2000 years B.P. Such a climatic change would have reduced sediment transport capacity of the river system, triggering aggradation. This inference is borne out impressively by the presence of more than 15 m of late Holocene sands below a considerable part of the Ganga Valley, deposited within a period of less than 2000 years.

Numerous studies have demonstrated that periods of increased precipitation are marked by river incision (Porter et al., 1992; Jones and Schumm, 1999). Pratt et al. (2002) observed that early Holocene incision in the central Nepal Himalaya was driven by enhanced monsoon precipitation, although some deposition was also evident. Although enhanced precipitation commonly results in higher discharge, increased sediment supply during the same period may reduce the stream’s erosive power and the ability to incise its thalweg, at least locally.

The High Himalaya source area of the Ganga and its tributaries contains large glaciers. Meltwater apparently contributes only modest volumes to Ganga flow (15%, according to Das Gupta, 1975), but meltwater contributions could have been greater in the past. The areal extent and timing of glacial events in the Himalaya and Tibetan Plateau are poorly defined, but compilation of cosmogenic isotope dates for moraines and glacially eroded surfaces indicate that the mountain belt experienced numerous glacial advances from MIS 5 onwards (Owen et al., 2002, 2008). However, glacier ice during the LGM covered about 539 km² of the headwater area of the Ganga River catchment (Fig. 1c), about 22% of the total area. For the central Himalayan area in the Ganga headwaters, Owen et al. (2008) recorded a general correlation between glacial advances and the monsoon intensity peaks identified by Prell and Kutzbach (1987), including advances during a peak monsoon condition in MIS 3 (Fig. 6). This correlation suggests that alluvial events are likely to be a consequence of variations both in direct monsoonal runoff and in meltwater supplied to the plains. In the western Himalaya, correlation is less clear, due to the availability of precipitation supplied by westerly winds. We conclude that 1) alluvial events on the Ganga Plains are likely to reflect in part meltwater contributions, 2) meltwater pulses are likely to coincide with enhanced monsoonal runoff, and 3) meltwater was probably not the dominant discharge factor, based on estimates of modern meltwater contributions and past glacier area.

Episodes of aggradation and incision may be attributed to variations in transport capacity of river systems and/or sediment supply from the hinterland (Julien, 1995; Houben, 2003) linked to changes in catchment physiography and external forcing. Assuming that catchment physiography and valley gradient remained relatively unchanged during the late Quaternary, a change in the balance between sediment supply and river discharge (from hinterland and adjacent plains) should change the river’s equilibrium profile on the plains. The terms capacity-limited system and supply-limited system have been used to explore this balance (Brown and Keough, 1992; Lewin, 1992; Macklin, 1992; Julien, 1995; Bisson and Montgomery, 1996; Montgomery and Buffington, 1997). In a capacity-limited system, the amount of transported load is limited by water supplied to the river, whereas in a supply-limited system, sediment in the river is controlled by sediment availability. Goodbred (2003) emphasised the importance of upland supply in a source-to-sink consideration of the Ganga–Brahmaputra system, and strong variations in sediment flux from the Himalaya are indicated (see, for example, Pratt et al., 2002). We are currently not able to discern which events in the
Ganga Plains reflect supply- or transport-limited scenarios. However, late Holocene channel aggradation followed a period of high sediment supply in the Ganga Delta (Goodbred, 2003), suggesting that deposition reflected transport-limited conditions.

Despite the availability of data from both valley-margin and intra-valley areas, it is difficult to be certain when the Ganga River occupied a channel attached to the adjoining alluvial tract or floodplain, and when the river occupied a valley that was detached and rarely or never flooded the adjoining interfluves (attachment terminology from Gibling et al., 2005). Strong and Paola (2008) distinguished stratigraphic valleys (the valley-form erosional surface preserved in the stratigraphic record) from topographic valleys (the topography at an instant in time). As noted by Gibling et al. (2011), the Ganga Valley in the Kannauj to Kanpur area (Fig. 1) is a stratigraphic valley that contains smaller channel bodies or valley fills, as illustrated in Fig. 6, with internal sequence boundaries (bases of channel bodies and carbonate-rich palaeosols) and facies discontinuities. It is not certain that deposition commenced in a large, deeply incised hollow, as shown schematically in Fig. 6. More probably, the body of alluvium laid down by the Ganga is underlain by a composite valley-fill unconformity (Blum and Aslan, 2006), and long-term southward migration of the Ganga has created a composite, diachronous valley fill with dimensions that greatly exceed the instantaneous topographic. The relocation of channels within the valley area, evident from the cores (Figs. 5, 6), may in part record the influence of the Ramganga and other tributaries (Fig. 1) in modifying the trunk-river position due to confluence dynamics (Roy and Sinha, 2005, 2007).

8. Conclusions

The exposed cliff section and valley cores from the southern Ganga Plains provide an integrated picture of valley and proximal interfluve development for the Ganga River at Kannauj over the last 100 ka. Comparison with proxy records for monsoon strength, which show strong fluctuations driven largely by solar insolation, indicate a first-order fit between monsoonal fluctuations and alluvial events, with a tendency for incision during periods of monsoonal intensification and aggradation as monsoon strength decreased. The valley cores record episodes of aggradation during Marine Isotope Stages (MIS) 4 and 5; the mid part of MIS 3; late MIS 2 to early MIS 1 (11–16 ka), especially around the Younger Dryas; and in the latest Holocene (~2.5 ka). The Last Glacial Maximum was a time of greatly reduced fluvial activity, and no channel sediments have yet been identified that correspond with this period.

Along the southern valley margin, bordering a wide interfluve, there was modest accumulation of floodplain, lacustrine and aeolian deposits, punctuated by discontinuities, through to early MIS 2. The Ganga probably varied in its degree of attachment to the interfluve, periodically inundating the adjoining, more elevated alluvial tract but at other times unable to flood this zone. Thus, the Ganga probably fluctuated from being a channel with a broad floodplain to a valley confined by an elevated plain to the south. There is no indication that the Ganga has inundated its southern interfluves since the end of MIS 3.

We infer that the Ganga River experienced strong variation in its equilibrium profile over relatively short periods (centuries to thousands of years), linked to varied sediment and water discharge from the Himalayan mountains and the lowland alluvial plain.

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