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Late Cenozoic fluvial successions in northern and western India: an overview and synthesis

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Abstract

Late Cenozoic fluvial successions are widespread in India. They include the deposits of the Siwalik basin which represent the accumulations of the ancient river systems of the Himalayan foreland basin. Palaeomagnetic studies reveal that fluvial architecture and styles of deposition were controlled by Himalayan tectonics as well as by major climatic fluctuations during the long (~13 Ma) span of formation. The Indo-Gangetic plains form the world's most extensive Quaternary alluvial plains, and display spatially variable controls on sedimentation: Himalayan tectonics in the frontal parts, climate in the middle reaches, and eustasy in the lower reaches close to the Ganga–Brahmaputra delta. Climatic effects were mediated by strong fluctuations in the SW Indian Monsoon, and Himalayan rivers occupy deep valleys in the western Ganga plains where stream power is high, cut in part during early Holocene monsoon intensification; the broad interfluves record the simultaneous aggradation of plains-fed rivers since ~100 ka. The eastward increase in precipitation across the Ganga Plains results in rivers with low stream power and a very high sediment flux, resulting in an aggradational mode and little incision. The river deposits of semi-arid to arid western India form important archives of Quaternary climate change through their intercalation with the eolian deposits of the Thar Desert. Although the synthesis documents strong variability—both spatial and temporal—in fluvial stratigraphy, climatic events such as the decline in precipitation during the Last Glacial Maximum and monsoon intensification in the early Holocene have influenced fluvial dynamics throughout the region.

1. Introduction

The Indian sub-continent preserves nearly continuous records of fluvial sedimentation for the past 20 million years; these records constitute one of the world's most important fluvial archives for the late Cenozoic. The Himalayan foreland basin (HFB) formed in response to the continent–continent collision of India and Asia in the early Cenozoic (Yin et al., 1996) and since then basins on the northern Indian continent have been accumulating fluvial sediments, much of which was derived from the collisional zone. The Neogene fluvial sediments of the HFB, known as the Siwalik Group (Pascoe, 1950), are known not just for the excellent preservation of fluvial architecture but also for their remarkable record of vertebrate fossils (Nanda, 1973; Keller et al., 1977; Opdyke et al., 1979; Johnson et al., 1983). Excellent outcrops of the Siwaliks in India are present in the western Himalaya in the Dun and Kangra valleys (Fig. 1) in addition to good exposures in the eastern parts notably in the Nepalese Himalaya. These fluvial deposits have provided important insights into ancient river processes in a tectonically controlled setting with a strong monsoonal climate, tectonics and climate being closely interlinked. Uplift of the Himalaya during the Cenozoic has had a profound effect in regulating the monsoon, vegetation and atmospheric CO_2 (Sanyal et al., 2004) over 10^4–10^7 year time scales.

The coupling of tectonics and climate-related processes is an intensely debated topic, and the HFB and its deposits are often the central focus of these discussions. It has been

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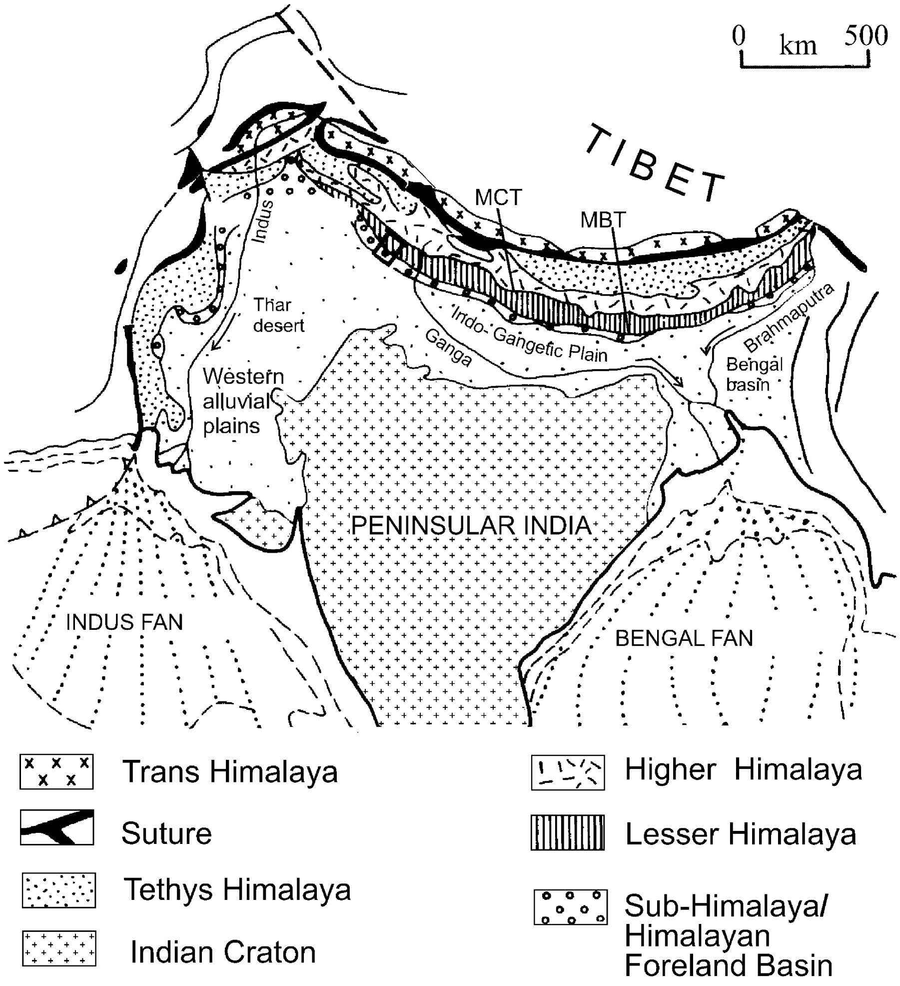

Fig. 1. Simplified geological map of India showing major Late Cenozoic fluvial deposits (compiled from various sources).

argued that the uplift of the Earth's surface to higher elevations can alter regional and global climate through a number of physical and chemical mechanisms that involve changes in the earth's atmospheric and oceanic circulation (Burbank et al., 2003; Thiede et al., 2005). In turn, climate changes, whether driven by uplift or otherwise, can alter the atmospheric and oceanic circulation in such a way that rates and styles of erosion in high mountain terrain are affected (Thiede et al., 2005). As noted commonly, increased erosion also causes rebound of underlying layers (isostatic uplift). The Siwalik successions have been intensively studied to provide answers to some of these questions (Kumar and Tandon, 1985; Burbank et al., 1993, 1996; Burbank, 1992, 2005; Kumar et al., 2003a; Sinha et al., 2007a). In addition to intensive research on fluvial architecture and processes (Willis, 1993), recent developments in paleomagnetic stratigraphy have provided insights into long-distance correlation of sequences, tectonic and climatic controls on depositional packages, basin evolution, and regional paleogeography.

The post-Siwalik fluvial deposition in the HFB has continued through the Quaternary without any break. This has generated very thick alluvial successions (more than 4 km in some parts) below extensive alluvial plains (known as the Indo-Gangetic plains), which runs west to east along the strike of the Himalaya. The Ganga river forms the axial drainage system of the Indo-Gangetic basin in India and has tributaries from two distinctive terrains, one from the Himalaya to the north and the other from the peninsular hills to the south. Sediments derived from these two terrains have accumulated in the basin throughout the Quaternary and a large proportion of this sediment is delivered to the Bay of Bengal where the Ganga and the mighty Brahmaputra rivers form one of the largest delta systems in the world. Analysis of records extending back to 100 ka and beyond show that sedimentation patterns and stratigraphic development in the Ganga basin are extremely variable from source to sink due to variable controls of hinterland tectonics and climate in the upper segment, dominantly climatic influences in the middle segment, and strong eustatic effects in the lower segment (Tandon et al., 2006).

In addition to the Indo-Gangetic records, long fluvial records are available from the western Indian plains of Gujarat and Rajasthan and from basins in the northern part of the peninsular India. Many of these successions date back to the pre-Quaternary and show strong variability in terms of facies and alluvial architecture. Strong climatic controls influenced by monsoonal fluctuations are implied by several workers and variable effects of tectonics and subsidence, particularly in the coastal parts, are well-documented (Prasad and Gupta, 1999; Juyal et al., 2000; Chamyal et al., 2002, 2003; Bhatt and Bhonde, 2003). Some of these successions are well dated using luminescence chronology, particularly for the last 200 ka, facilitating reliable comparison with the independent climatic proxies.

We review and synthesize the available information for fluvial successions covering both Quaternary and Neogene periods across northern and western India and build upon an earlier compilation on Late Cenozoic fluvial deposits of India (Sinha and Tandon, 2003). *This review is not intended to be exhaustive and emphasizes fluvial records that provide some insights into controls on fluvial sedimentation in a setting dominated by continent-to-continent collision, with monsoonal conditions that vary greatly in their intensity in time and space*.

2. Fluvial successions in the Himalayan foreland (Siwaliks)

The high elevations of the Himalaya and associated Tibetan Plateau are a manifestation of continent–continent collision of the Indian and Eurasian plates. The timing of this topographic rise is important in understanding the relationship between mountain belt tectonics, evolution of drainage system, and activation of the monsoon system that controls sedimentation in the Himalayan Foreland region (Harrison et al., 1995; Sanyal et al., 2004; Clift and Blusztajn, 2005; Molnar, 2005). These records are well preserved in the Miocene–Pleistocene fluvial succession of the HFB, known as the Siwalik Group. The Siwalik strata are exposed in the Siwalik Hills along the northern margin of the present foreland basin, where the strata have been uplifted and eroded as a result of thrusting along the Main Boundary Thrust (MBT) and related thrusts.

Work on the Siwalik basin has been summarized previously (Tandon, 1991; Burbank et al., 1996; Kumar et al., 2003a); the following section builds on those summaries by synthesizing subsequently published data. The Himalayan peripheral foreland basin is interpreted as having formed in response to flexure of the Indian plate due to the large crustal load of the evolving Himalaya (Molnar, 1984; Lyon-Caen and Molnar, 1985; Duroy et al., 1989). Accommodation in this foreland basin is controlled primarily by flexural subsidence driven by the topographic load of the thrust belt and sediment loads (Beaumont, 1981; Jordan, 1981; Karner and Watts, 1983; Flemings and Jordan, 1990). The foreland basin is also affected by regional isostatic uplift during erosion of the orogenic belt, and by uplift associated with the advancing thrust wedge or retrograde migration of the forebulge (e.g., Quinlan and Beaumont, 1984; Heller et al., 1988; Flemings and Jordan, 1990; Sinclair et al., 1991). The HFB is elongated and bounded by a set of thrust faults that include the MBT and Himalayan Frontal Thrust (HFT), and the basin is divided into sub-basins demarcated by lineaments, some of which are particularly evident in the Himalayan Foothills (Fig. 2). These lineaments delineate a succession of spurs and depressions in the underlying Indian craton (Raiverman et al., 1983), oriented obliquely to the structural trend of the Himalayan thrust belt. These transverse lineaments not only control the thickness of the Cenozoic sedimentary successions but also the sedimentation patterns in the individual sub-basins (Raiverman et al., 1983; Raiverman, 2002). Representative stratigraphic sections through the Siwalik deposits and a correlation table for these deposits

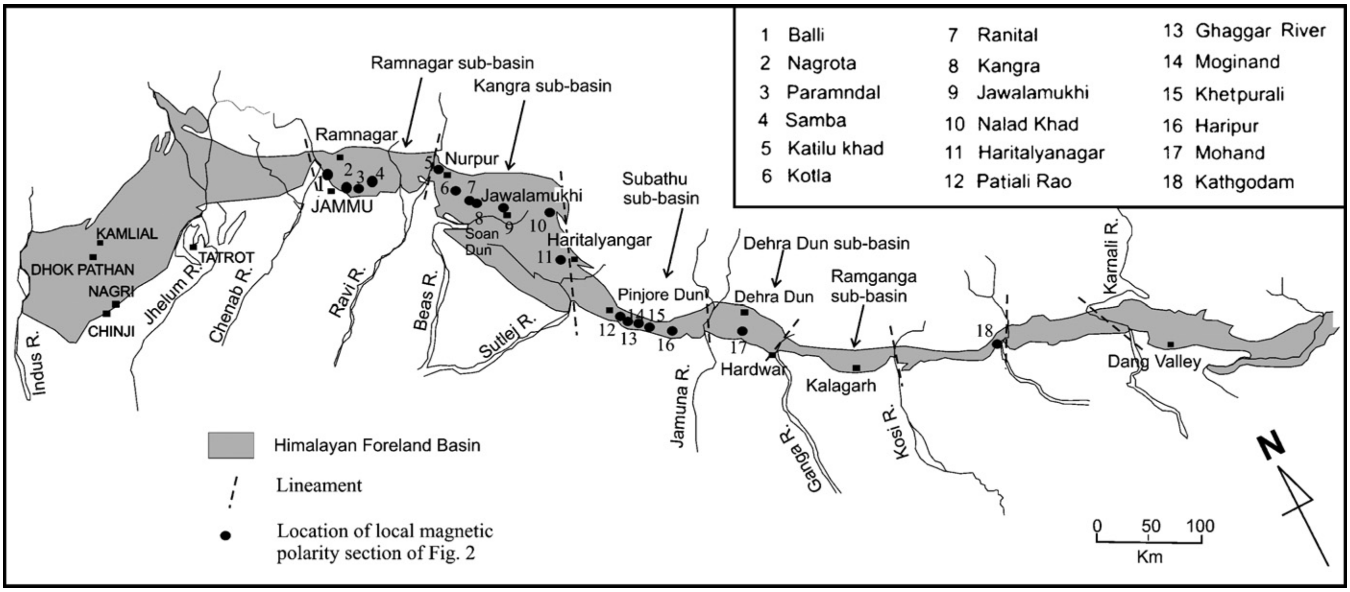

Fig. 2. The Himalayan Foreland Basin. Sub-basins are demarcated on the basis of geophysical data, after Raiverman et al. (1983).

between different parts of the HFB are provided in the online supplement.

2.1. Stratigraphy

"Pre-Siwalik" and "Siwalik" define the synorogenic strata of the HFB (Tandon, 1991; Burbank et al., 1996; Raiverman, 2002), following the lithostratigraphic distinction defined by Meddlicott (1864). The Upper Paleocene to Upper Eocene shallow marine Subathu Formation (pre-Siwalik) is composed of mudstone and sandstone with minor limestone (Karunakaran and Ranga Rao, 1979). This is overlain by the continental Dharamsala Formation of sandstone and mudstone, the stratigraphic equivalent of the Dagshai and Kasauli formations in the Simla Hills (Raiverman and Raman, 1971; Karunakaran and Ranga Rao, 1979) with either conformable (Bhatia and Bhargava, 2006 and references therein) or unconformable contact, with a duration of ~12 Ma (Najman, 2006 and references therein). Overlying these deposits in the southern part of the basin is the Siwalik Group (with its base at 13 Ma in the Indian Siwalik; Meigs et al., 1995). The Siwalik Group is well known for its abundant vertebrate fossils and has been divided into three lithostratigraphic units: Lower, Middle and Upper Siwaliks (Pilgrim, 1910, 1913). The Siwalik Group coarsens upward from mudstone–sandstone (Lower Siwalik), to sandstone dominated (Middle Siwalik), to conglomerate, sandstone and mudstone (Upper Siwalik) facies. The Upper Siwalik succession varies laterally across the foreland basin, exhibiting an increase in conglomerate towards the MBT. The Lower Siwalik and older strata are typically well indurated, whereas the Middle and Upper Siwalik strata are normally friable. The Siwalik Group is overlain by Quaternary conglomerates in broad synclines, as in the Dehra Dun re-entrant of the foothills, and is also presumed to underlie the younger Quaternary strata of the Indo-Gangetic Plain to the south.

Stratigraphic correlations in peripheral basins associated with an active orogen such as the Himalaya are difficult because of (1) the time transgressive nature of lithofacies; (2) variability in the hinterland setting of the foreland sub-basins; (3) endemism of biota; and (4) the complexity of sedimentation in fan–interfan domains. To overcome the aforesaid difficulties, the remnant magnetic polarity, which is independent of lithogenic constraints such as lateral lithofacies variations, has been intensively used for stratigraphic correlations of these Late Cenozoic fluvial successions (Tandon, 1991; Burbank et al., 1996; Sangode and Kumar, 2003).

Magnetostratigraphic studies have facilitated correlation of the Siwalik Group of the Potwar Plateau of Pakistan for the last two and a half decades (Opdyke et al., 1979; Johnson et al., 1985). A suite of formations were defined in that area, and the lithofacies assemblages of these formations, as well as events at the boundaries between them, can be correlated elsewhere in the region (see below). In the Indian sector, these studies were initiated during the 1980s (Yokoyama, 1981; Azzaroli and Napoleone, 1982; Johnson et al., 1983; Tandon et al., 1984a; Ranga Rao et al., 1988) but only the western part of the Indian outcrop belt was studied until recently. However, new data are now available from the Kangra sub-basin (KSB) (Meigs et al., 1995; Brozovic and Burbank, 2000; Sangode et al, 2003; Sinha et al., 2005), the Subathu sub-basin (SSB) (Sangode et al., 1996; Kumaravel et al., 2005), the Dehra Dun sub-basin (DSB) (Sangode et al., 1999), and the Ramganga sub-basin (Kotlia et al., 2001).

2.2. Magnetostratigraphic correlation in the Indian sector

Eighteen well-documented Siwalik sections in the Indian sector of the HFB have been compiled (Sangode and Kumar, 2003) using the revised Global Polarity Time Scale (GPTS; Cande and Kent, 1995) to facilitate correlation (Fig. 3). Most of the studied sections are in the Ramnagar, Kangra and SSBs and one section each in Dehradun and Ramganga sub-basins have been studied. Fig. 3 shows that the magnetostratigraphic data span the ~13–1 Ma period. Correlation of the reversal events suggests that some events are more widely represented and pronounced (hence designated by tie-lines). The base of the long normal event C5*n* (~11–9.5 Ma) corresponds to the most extensive and characteristic occurrence of lithofacies of Nagri type by comparison with the Potwar succession (or the Chinji–Nagri transition, Tandon, 1991; Burbank et al., 1996). Another reversal (base of C4*n* at ~8 Ma) corresponds to the Nagri–Dhok Pathan transition. This event is also the base of a considerably longer normal polarity zone (C4*n*). The base of C3*n* (5.23 Ma) is related to the transition of Dhok Pathan to Tatrot type facies, that also characterizes the initiation of piedmont drainage as reported in many sections (Ranga Rao et al., 1988; Sangode et al., 1996; Kumar et al, 1999). The next pronounced event at 2.58 Ma (Gauss–Matuyama reversal) corresponds to the Tatrot/Pinjor formational boundary (Opdyke et al., 1979), marked by the abundance of conglomerate facies. The youngest reversal event, i.e. the Matuyama–Brunhes reversal at 0.78 Ma, is well marked in many of the sections.

2.3. Sedimentologic observations and fluvial architecture

Sedimentary sections through the Siwalik deposits have been logged in a range of localities (e.g., Tandon et al., 1984a, b; Kumar et al., 1999; Brozovic and Burbank, 2000; Sangode et al., 2003; Kumaravel et al., 2005; Sinha et al., 2007a), representative details being compiled in online supplement. The Siwalik succession shows cyclic alternation of sandstone and mudstone in the lower part and predominantly conglomerate in the upper part, with marked variation in style and occurrences of facies both spatially and temporally (see online supplement).

The Lower Siwalik subgroup is characterized by an alternation of sandstone and mudstone (mudstone >50%). The sandstone is dark gray and fine-grained, and channel

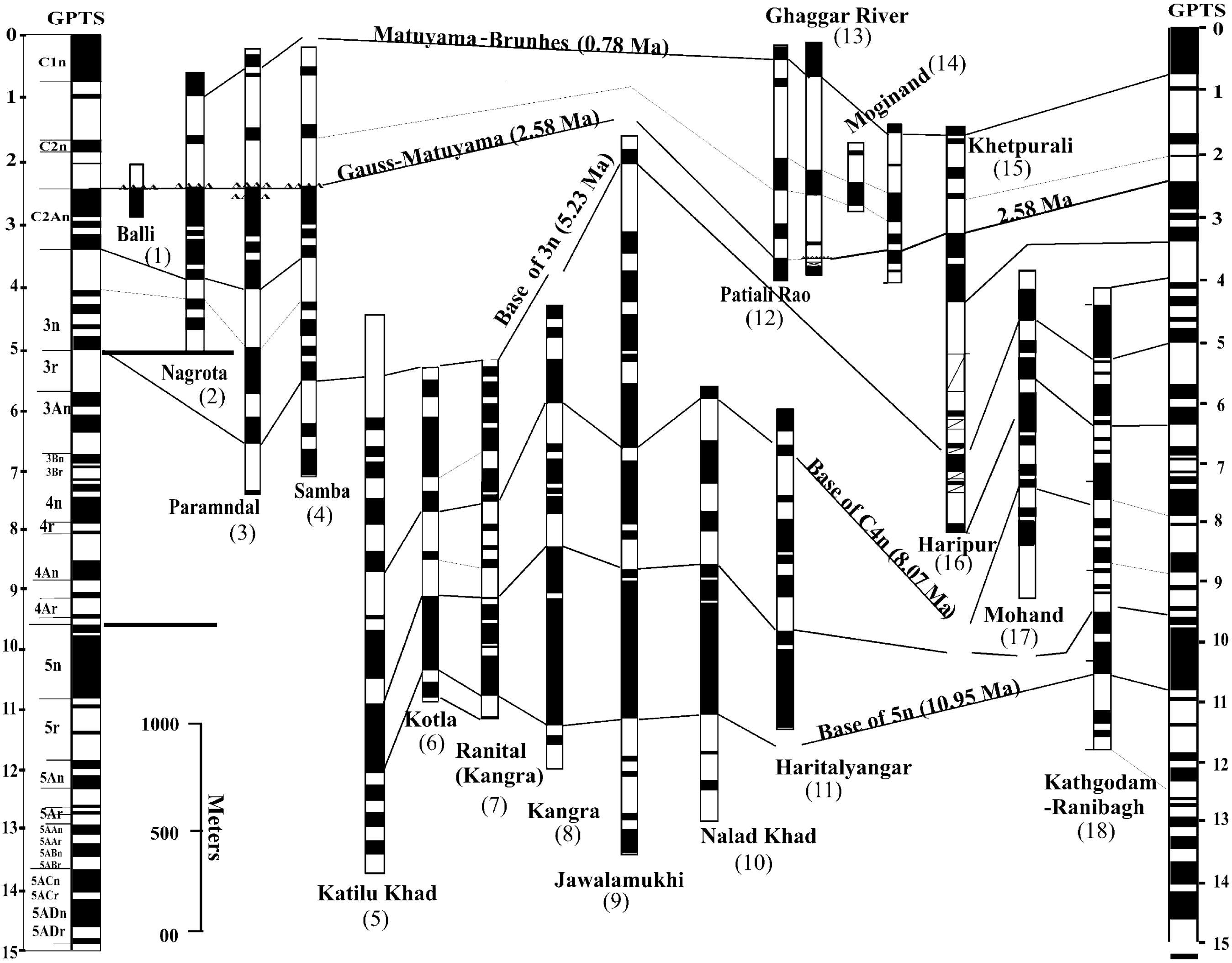

Fig. 3. Correlation of magnetostratigraphy along E–W extent of the Indian part of Himalayan Foreland Basin. Data are from Tandon et al. (1984), Ranga Rao et al. (1988), Meigs et al. (1995), Sangode et al. (1996, 1999, 2003), Brozovic and Burbank (2000), Kotlia et al. (2001), Kumaravel et al. (2005), and Sinha et al. (2005). See Fig. 2 for site locations.

bodies have ribbon and sheet geometry, with occasional multistoried bodies. Sandstone bodies pass gradationally upward into thick, purple mudstone units that show pedogenic modification in the form of carbonate concretions, rootlets and bioturbation (Tandon, 1991).

The transition from the Lower to Middle Siwalik succession between 11 and 9 Ma represents an increase in the proportion of sandstone (e.g., Kumaravel et al., 2005; see, e.g., section E in online supplement) although this change is time transgressive. The change occurred at about 11 Ma in Potwar Plateau (Johnson et al., 1985), 10 Ma in KSB (Meigs et al., 1995; Sangode et al., 2003), and 9 Ma in Nepal (DeCelles et al., 1998). In the Potwar Plateau, formations are defined on the basis of channel-body proportion: channel bodies comprise less than 50% of the Chinji Formation (prior to 11 Ma) whereas they comprise more than 50% of the Nagri Formation (11–9 Ma) (Willis, 1993). This approach to subdividing the Siwalik Group is not applicable in the Indian part of the Siwalik belt. The succession in the DSB (9–5 Ma) has >90% channel bodies; that in the SSB (6–5 Ma) has >70%; and that in the KSB (11–5 Ma) shows rapid changes in channel-body proportions over short stratigraphic intervals of ~0.5 million years (Kumar et al., 2003a). In general, channel-body proportion and storey thickness increase by a factor of two to three at about 10 Ma. The mean grain-size gradually increases upsection and becomes fine-, medium- and then coarse-grained and in places pebbly. The sandstones are whitish gray and multistoried with interbedded mudstone/siltstone. In places, especially in the KSB, conglomerates (0.5–3 m thick) are common in the Middle Siwalik Subgroup (between 8.7 and 7 Ma). In the northwestern part of the KSB, repetitive cycles of facies assemblages belonging to axial and piedmont stream deposits reflect phases of contraction and changes in dominance of these systems (Sinha et al., 2007a), the estimated durations of cycles being 0.1–1.02 million years. Individual sandstone bodies are generally 2 to >10 m thick; the total thickness of multistoried sandstones may reach 100 m in the Potwar Plateau (Willis, 1993) and 400 m in DSB (Kumar, 1993).

Mudstone generally comprises <50% of the stratigraphic units, but in places comprises as much as 80% together with levee and crevasse splay deposits. Purple and brown palaeosols with calcareous concretions are common in the lower part of the succession, whereas in the upper part yellow palaeosols with iron concretions are also present. Green mottling, bioturbation, rootlets and pedons are commonly present. Near the transition from the Middle to Upper Siwalik succession, calcareous mudstones are common and represent lacustrine conditions in the latter, being especially well observed in the KSB (Zaleha, 1997). Fig. 4a indicates the interpreted sedimentary environment.

The Middle Siwalik succession gradually passes upwards at ~5 Ma into the Upper Siwalik strata, comprising thickly bedded conglomerate with lenticular bodies of sandstone and rarely mudstone (particularly in the lower part) (Fig. 4b). The fine-grained facies (Tatrot and Pinjor formations) is also observed locally in the SSB (Kumar et al., 1999) and RSB (Ranga Rao et al., 1988). As noted previously (Kumar et al., 2003a), all the re-entrants (Dehra Dun, Ravi and Kangra; Fig. 1), reveal the development of coarse-grained facies at 5 Ma but contemporary salients show relatively fine-grained facies (sandstone and mudstone of the Tatrot and Pinjor formations) (Kumar and Tandon, 1985; Kumar et al., 1999). In the lower part of the succession, the conglomerate facies typically forms bodies consisting of 3–25 m thick fining-upward cycles as described earlier (Kumar et al., 2003b). Conglomerates are matrix supported but framework-supported layers of pebbles, cobbles and boulders are also present. Clast composition changes from east to west. Thus, in the DSB, KSB and RSB, clasts comprise mainly Lesser Himalayan quartzite, which is also present along with granite/gneiss clasts in the Ravi Recess; in contrast, the SSB and Nurpur Salient are typefied by sub-Himalayan sandstone (Tandon and Rangaraj, 1979; Kumar and Ghosh, 1991; Kumar et al., 1999, 2004; Sinha et al., 2007a).

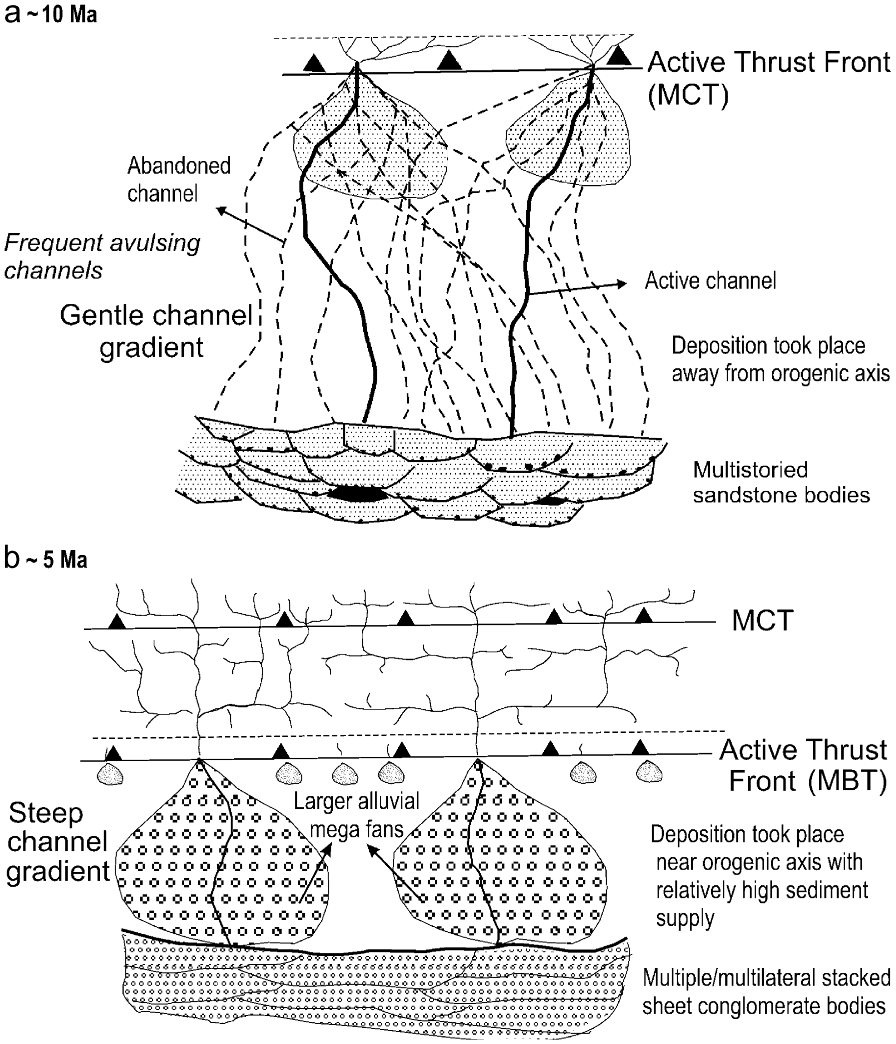

Fig. 4. Evolutionary models and fluvial architecture of the Siwaliks: (a) The Middle Siwaliks. Around 10 Ma, deposition began of multi-storied sandstone, related to frequent channel avulsion and reoccupation. Deposition was mainly in channel belts, not floodplains. (b) The Upper Siwaliks. Around 5 Ma, coarse clastic alluvial megafans developed, due to hinterland uplift adjacent to depositional sites (after Kumar et al., 2003a).

2.4. Palaeoflow variability

Siwalik Group palaeoflow was highly variable in space and time. This variability is observed at the sub-basin level and also within sub-basins. The DSB reveals palaeoflow directions that varied from south to SE to SW between 9.5 and 5 Ma (Kumar and Nanda, 1989; Kumar et al., 2003b). In contrast, the SSB reveals SE palaeoflow before 5 Ma (Kumar et al, 1999, 2003b). However at 5 Ma, the main palaeoflow directions changed in many parts of the Siwalik belt: from south to SW in the DSB; from SE to SW in the SSB (Kumar et al., 1999); from SW to more westerly in the KSB (Meigs et al., 1995; Brozovic and Burbank, 2000; Raiverman, 2002; Kumar et al., 2004); and easterly in the Ravi re-entrant for the Middle Siwaliks (Tandon and Rangaraj, 1979; Sinha et al., 2007a). In this area, Sinha et al. (2007a) also observed southerly palaeoflow in buff ribbon-sandstone bodies, interpreted as piedmont stream deposits. In the Potwar Plateau, Burbank et al. (1996) documented a SE palaeoflow pattern until 5 Ma, and used these data to support Pilgrim's (1919) hypothesis that the Siwaliks were deposited by an easterly flowing Ganga axial river. Although some data support this view in the NW part of the KSB and the SSB (Tandon and Rangaraj, 1979; Kumar et al., 1999; Sinha et al., 2007a), the Indian and Nepal Siwaliks typically reveal predominantly transverse palaeoflow (DeCelles et al., 1998). Furthermore, as already noted, lithological data show compositional variation between and within sub-basins, representing the adjacent hinterland litho-types (Tandon, 1976; Tandon and Rangaraj, 1979; Ghosh and Kumar, 2000; Ghosh et al., 2003; Sinha et al., 2007b), consistent with the interpretation of transverse river deposits and contrary to what would be expected for an axial river system.

3. Fluvial systems in Himalayan inter-montane basins

Several inter-montane basins developed in the Himalaya during the later stages of the orogeny (Burbank and Johnson, 1982; Burbank et al., 1996). In India, the Kashmir Basin in the NW Himalaya preserves a record of synorogenic sediments that spans almost 4 million years. The sediments of this basin are referred to as the Karewa Group (Burbank and Johnson, 1982; Burbank, 1983)—a 1300 m thick succession that has been used to understand basin evolution in the context of tectonic activity of the structures of the adjoining Pir Panjal and Zanskar ranges. Burbank and Johnson (1982), along with several others, indicated initial ponding of fluvial systems at ~4 Ma, which caused the widespread occurrence of lacustrine conditions in the basin. Fault-related uplifts along parts of the basin margin resulted in the influx of conglomeratic detritus into the basin until ~3 Ma. Burbank and Johnson (1982) recorded a ~300 m succession of conglomerates and coarse sandstones encased in lacustrine strata, which were fed from the east and northeast in response to deformation along the basin margin. Strata younger than 3 Ma are mainly lacustrine, and are interrupted by fluvial coarse clastic facies, formed in response to episodic tectonic activity of the basin-margin structures.

Along the foothills of the Himalaya, a series of intermontane valleys called 'duns' (Nossin, 1971) occur to the south of re-entrants and trend parallel to the Himalayan strike. These duns preserve Early and Late Quaternary deposits in the form of alluvial fans and terraces (Nakata, 1972) which are generally in direct contact with the underlying Siwalik successions, and reflect interplay of Quaternary tectonics and climatic controls. Some of the best exposures of the intermontane valley deposits occur in the foothills of northwestern India, at Dehra Dun, Soan Dun, and Pinjaur (Pinjore) Dun (all west of the Ganga exit; Fig. 2).

Based on magnetostratigraphic data (Tandon et al., 1984; Cande and Kent, 1995; Sangode et al., 1996; Kumaravel et al., 2005), Early Quaternary fan sedimentation near Chandigarh and Dehra Dun started ~1.77 Ma, and was largely aggradational, within a setting influenced by intra-foreland thrusting (Kumar et al., 2007; Suresh et al., 2007). The lower fan deposits consist of fining-up cycles of conglomerate to sandstone and mudstone, characteristic of gravel bed braided rivers (Kumar et al., 2007). The thickness and clast size of the conglomerate beds increases up-section, the upper parts consisting of sheets of conglomerate interpreted as sheet-flood deposits. Sediment flux was high and creation of accommodation space favored aggradation during this phase, which ceased about 0.25 Ma.

The late Quaternary fan system (~96–5 ka; Suresh et al., 2002) is characterized by the formation of a piggyback basin as the thrust systems evolved, and a more variable pattern of aggradational and entrenchment behavior in space and time (Kumar et al., 2007). Alluvial fans of varying dimensions developed along the western Himalayan foothills in the Chandigarh and Dehra Dun areas (Fig. 3), with drainage basins from 10 to 95 km^2 in area and fans from 11 to 87 km^2 in area. These fan deposits have been discussed in detail by Singh et al. (2001), Kumar et al. (2007), Singh and Tandon (2007), and Suresh et al. (2007), so details are not repeated here. Representative lithologs of early and late Quaternary alluvial fans have been provided in the online supplement.

Both phases of early and late Quaternary fan sedimentation in the intermontane basins have similar clast composition and depositional settings but some differences have been noted in terms of their evolutionay history (Kumar et al., 2007). The early Quaternary fans have been reported from the Pinjor area only and they show major aggradation phases with only minor distal fan entrenchment. These fans were deposited under Pleistocene climates and were strongly influenced by the growing tectonic activity which provided considerable accommodation space (Kumar et al., 2007). Many late Quaternary fans have been described in the western Himalaya and, although they show significant variations, a common characteristic is synchronous periods of aggradation and fan entrenchment. Significantly less accommodation space was available during the deposition of these fans, perhaps due to ongoing uplift and reduced subsidence under strong monsoonal conditions with higher sediment yields. Stronger control of climate is implied in the development of late Quaternary fans, although tectonics also played an important role. In the later phases of this fluvial succession, terrace development took place in response to water and sediment budget variations following the Last Glacial Maximum (LGM) (Kumar et al., 2007).

4. Late Quaternary stratigraphy of the Ganga plains

Fluvial sedimentation in the Ganga basin can be regarded as a continuation of the fluvial history in the HFB since the deposition of the Siwaliks. Such a comparison is not just based on location relative to the Himalaya; there are also gross similarities reported in terms of alluvial architecture, fluvial processes, sedimentation rates and depositional environments (discussed later, see summary by Jain and Sinha, 2003). The sub-surface extension of the Ganga basin is limited to the west by the Aravalli–Delhi ridge and to the east by the Monghyr–Saharsa ridge. Several transverse faults are present in the subsurface, and a major structural high, Faizabad ridge, divides the basin into the West Ganga plain (WGP) and East Ganga Plain (EGP) (Sastri et al., 1971; Rao, 1973; Valdiya, 1976). The Gangetic plains are neotectonically active as evidenced by recent earthquakes (1833, 1906, 1934, 1987; Bilham, 1995). The seismic activity is related to sub-surface transverse faults below the plains (Karunakaran and Ranga Rao, 1979; Valdiya, 1976; Dasgupta et al., 1987; Dasgupta, 1993), which do not break surface in the modern alluvium, to longitudinal faults within the Himalayan Foothills and to zones of emergence of the HFT above the modern plains. Models of Himalayan seismotectonics suggest a westward decrease in crustal shortening and uplift rate as a consequence of convergence along the HFT from Nepal to Dehradun (e.g., Peltzer and Saucier, 1996; Bilham et al., 1997; Wesnousky et al., 1999; Lave and Avouac, 2000).

The Ganga is the axial river of the basin, originating in the Himalayan orogen and draining into the Bay of Bengal, being joined by major tributaries from the Himalayan side, principally the Yamuna, Ramganga, Ghaghra, Gandak, Kosi, and Tista. Tributaries also join the Ganga from the Indian Craton and Deccan Basalt terrain to the south, including the Chambal, Betwa and Ken (which join the Yamuna), Son, and Punpun. Together with the Brahmaputra (Fig. 1), this is the largest sediment dispersal system in the world, carrying ~1 billion tonnes of material every year (Hovius, 1998). The Bengal basin acts as a large sink for this huge sediment dispersal system, about 80% of which is delivered during the monsoon (Goodbred and Kuehl, 2000a). Although most of the sediment is transferred to the Ganga–Brahmaputra delta, thick fluvial successions have accumulated in the Ganga plains during the late Quaternary. As well as providing a modern analog for the Siwaliks, these deposits also provide insights into the interplay of climate, tectonics and eustasy in the foreland basin.

The Ganga Plain has an annual rainfall gradient from ~600 mm in the west to >1200 mm in the east. Rates of sedimentation likewise generally increase eastward. Thus, in the east, both the Ganga and Bramaputra have produced complex successions of Holocene deposits, up to ~100 m thick, starting ~11–10 ka (e.g., Coleman, 1969; Umitsu, 1993; Goodbred and Kuehl, 2000a; Allison et al., 2003). Beyond ~100 m depth, boreholes penetrate underlying palaeosols attributed to the Late Pleistocene marine lowstand (Umitsu, 1993; Goodbred and Kuehl, 2000b). Kuehl et al. (1997) have studied the young sediment forming the seaward part of the delta. Rising above the level of the Holocene sediment in the inland part of the delta plain are more elevated fluvial deposits, known as the Madhupur Terrace and Barind Tract, thought to date from around the Last Interglacial (130–70 ka; Kuehl et al., 2005; cf. Morgan and McIntyre, 1959; Johnson and Alam, 1991).

Beyond providing the above summary of the nature of the fluvial deposits and associated landscape in the eastern part of the Ganga Plain (see Sinha et al., 2005a, for more detail), the rest of this section will concentrate on localities farther west, where the lower rates of sedimentation mean that river cliff exposures and shallow boreholes can span the Late Pleistocene as well as the Holocene. Emphasis will thus be placed on localities in the vicinity of Kanpur, which were visited by a field excursion as part of the 2001 international meeting of IGCP 449.

4.1. *Cliff section stratigraphy*

The river valleys in the WGP are deeply incised and provide continuous cliff sections for several kilometers in places. The Ganga–Yamuna interfluve has attracted particular attention, and initial work on this area focused on geomorphic mapping using aerial photos (Bajpai, 1989). Singh et al. (1999a) provided brief descriptions of localities including the Kalpi section along the Yamuna river with evidence (worked bone artifacts) of human occupation of the region since ~30 ka. A provisional stratigraphic framework for the section and a small amount of chronological data was presented, and an interplay of climate and tectonics was implied in the deposition of this 33 m thick section (Singh et al., 1999a).

Singh et al. (1999b) described the late Quaternary muddy successions of the Ganga plains as ‘upland interfluve deposits’ and interpreted them as accretionary areas, independent of the major rivers, which developed during late Pleistocene–Holocene times. They argued that the major rivers, such as the Ganga, have occupied their present incised valleys since at least 100 ka, and inferred that these upland interfluve surfaces have not received sediments by overtopping by major rivers during this period. Later research (Sinha et al., 2002, 2005b; Gibling et al., 2005; Tandon et al., 2006) has led to significantly different interpretations. Srivastava et al. (2003) produced luminescence dating evidence, which provided a broad timeframe for the two major geomorphic surfaces in the region, which were dated as 51–7 and 3–0.8 ka. They invoked the upland interfluve model of Singh et al. (1999b) to explain thick muddy successions in the interfluve, and attributed incision to tectonic activity at about 40 and 6 ka, although some control from an inferred humid climate between 50–40 and 13–9 ka was also implied.

Our own recent work on cliff exposures along modern rivers in the western Ganga plains, between the Ganga at Kanpur and the Yamuna at Kalpi (Gibling et al., 2005; Sinha et al., 2005b, c; Tandon et al., 2006) has recognized discontinuity-bounded sequences dating back up to ~100 ka. Representative sections along the Ganga (Bithur, 15 m), Sengar (Mawar, 11 m), Yamuna (Kalpi, 33 m) and Betwa (Kotra, 29 m) rivers in a north–south transect show mud-dominated deposits underlying the modern interfluves (see online supplement for detailed lithologs). These are interpreted as the floodplain deposits of major rivers and plains-fed tributaries and show evidence of moderate pedogenesis. Discontinuities in these sections are thus interpreted as former degradational surfaces in the floodplains in consequence of monsoonal fluctuations (see Prell and Kutzbach, 1987). Dating using radiocarbon, OSL and TL procedures (Gibling et al., 2005) suggest that floodplain aggradation, punctuated by periods of stronger pedogenetic activity and local degradation, dominated the WGP during Marine Isotope Stages (MIS) 5–3 (~100–35 ka). This sedimentation pattern changed significantly late in Stage 3, when gullying commenced at Kalpi. A marked change from floodplain to eolian and lacustrine strata at Bithur is dated at about 27 ka (late in MIS 3) and continued through the LGM of MIS 2. Floodplain degradation also occurred at Mawar at ~13–9 ka.

Middle Pleistocene to Holocene fluvial successions in the Belan and Son valleys (see online supplement), which drain northward from the craton, have evoked significant interest due to the presence of artifacts, ranging from early Acheulian through Middle and Upper Paleolithic to Mesolithic and Neolithic, and due to the presence of an ash bed, attributed to the eruption at 73±4 ka of the Toba volcano in Indonesia (Williams and Clarke, 1984). The Son succession consists (in age order) of the Sihawal, Khunteli, Patpara, Baghor and Khetaunhi formations (Williams and Royce, 1983; Williams and Clarke, 1995; Williams et al., 2006) separated by major discontinuities. The Sihawal formation, containing Lower Paleolithic evolved Acheulian tools and flakes, overlies Early Proterozoic basement and is interpreted as alluvial fan and debris flow gravel. The overlying Khunteli Formation, consisting of fluvial sand and clay, contains the Toba ash bed as a channel fill. The Patpara and Baghor formations also consist of fluvial sand and clay and contain Middle to Upper Paleolithic artifacts. The Khetaunhi Formation forms an inset aggradational terrace of Upper Pleistocene to Holocene age and contains Epi-Paleolithic, Mesolithic and Neolithic artifacts.

The Belan succession, which rests on Late Proterozoic Vindhyan quartzite basement, is exposed in a series of terrace bluffs up to 20 m high and dates back to ~100 ka. It starts with locally derived quartzite gravels with Lower Paleolithic artifacts. These are followed by massive clay loam and fine sandy clay with pedogenic carbonate nodules, interpreted as loess by Williams and Clarke (1984, 1995). On the contrary, our own work (Gibling et al., 2005; Sinha et al., 2005c) interprets these clay-rich materials with ‘kankar’ (carbonate concretions) are floodplain deposits, notwithstanding their superficial loess-like appearance. The overlying strata consist of alternations of sand with mud and thin sheets of reworked carbonate gravel, with Middle and Upper Paleolithic artifacts, dated to 40–16 ka by Williams et al. (2006). Radiocarbon dates (Williams and Clarke, 1995) suggest that some deposition occurred around the LGM; this consisted of sheets of reworked nodules. There is evidence of localized eolian activity interspersed with fluvial activity during 14–7 ka, with the establishment of Paleolithic and Mesolithic settlements after the LGM. The succession is capped by Holocene clays containing Neolithic, Chalcolithic, and Iron Age artifacts.

The Son and Belan fluvial stratigraphies record multiple aggradations and incisions in response to monsoonal fluctuations, and link important events of human occupation with river activity. Repeated aggradational events in the Late Pleistocene correspond broadly to documented patterns elsewhere in the world, when Middle Paleolithic hunter-gatherer and semi-nomadic Upper Paleolithic peoples occupied the region (Williams et al., 2006). Following the LGM, the SW Indian Monsoon intensified overall through to the mid Holocene. The Mesolithic population in this period was migratory and depended on trading (Sharma et al., 1980). The post-6 ka period, characterized by a weaker summer monsoon (Prell and Kutzbach, 1987; Clemens and Prell, 2003), is reflected in the Belan sites by a transition from hunter-gatherers to incipient agriculture and domestication of animals.

4.2. Drill core stratigraphy and valley migration trends

In the WGP, a series of drill cores from the Ganga valley and the adjacent interfluve to the south have further extended and improved our understanding of the region (Sinha et al., 2005b, 2007). Two cores from the Ganga valley (Fig. 5), the Firozpur and Jagdishpur cores, are marked by an alternation of channel and floodplain facies. The upper and lower channel sands are 9–10 m thick, and are separated by ~7 m of floodplain muds which are moderately pedogenized and bounded by prominent kankar layers at

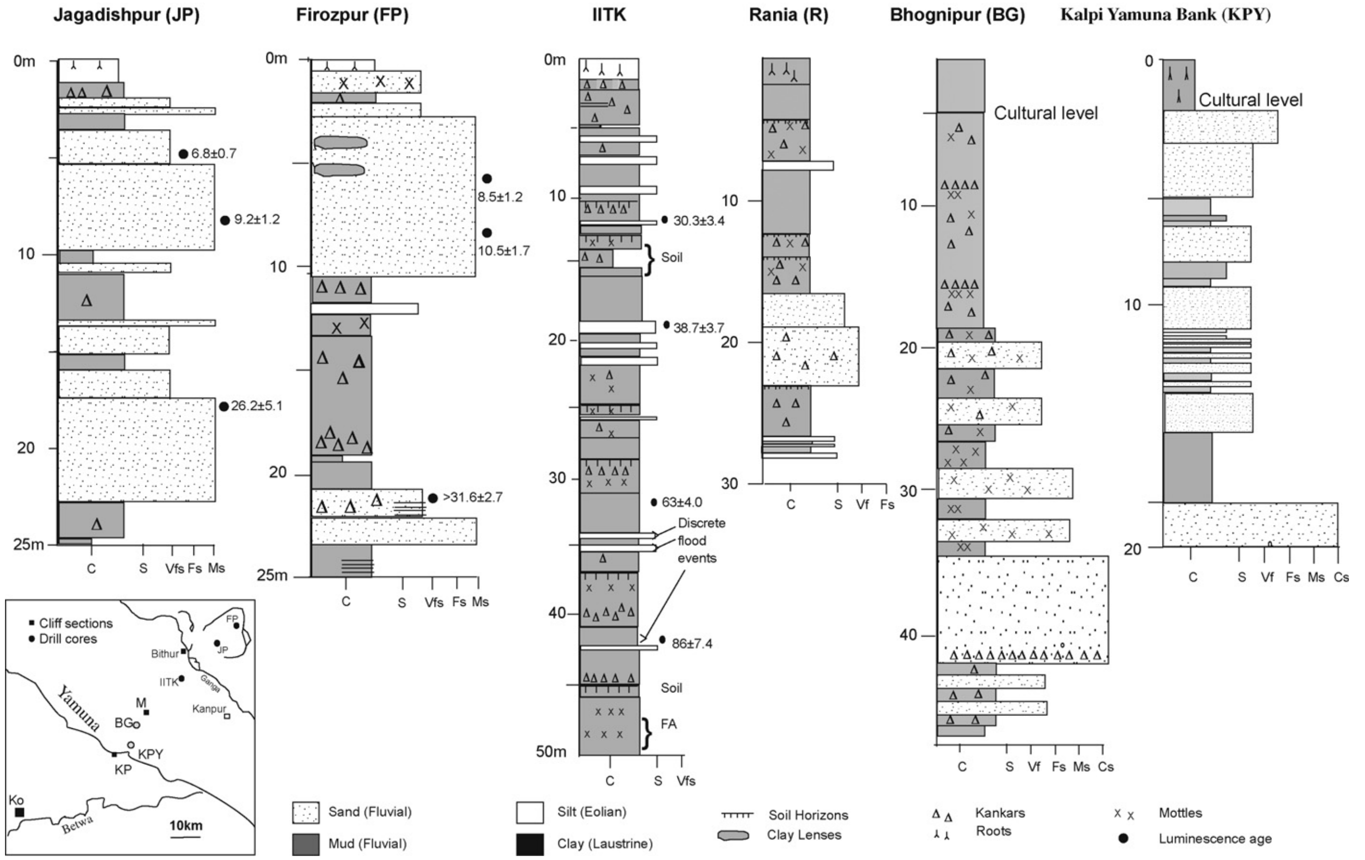

Fig. 5. Summarized logs of the drill cores in the Ganga valley fills (Firozpur and Jagdishpur cores), Ganga–Yamuna interfluve (IITK, Rania, and Bhognipur cores), and Yamuna valley (Kalpi Yamuna bank core). The inset shows the locations of these cores and the Kalpi cliff section (all luminescence dates are from Sinha et al., 2007).

discontinuities. The channel sands are similar to modern Ganga sand, and dating suggests that the Ganga has been near its present location since at least ~30 ka. The cores indicate renewed fluvial activity following the LGM, as well as meander cutoff and southward migration since ~6 ka. The valley margin records a major discontinuity that marks a period of reduced discharge in the Ganga river during the LGM, when monsoonal precipitation was greatly reduced and lakes and eolian dunes occupied areas distant from the main channel (Sinha et al., 2007).

Two cores represent the interfluve area. The Rania core has 15–20 m of floodplain strata with distinct soil horizons underlain by a 6 m channel sand, analogous to present-day plains-fed rivers fed by monsoon-generated springs, such as the Rindi, which flows near the drill site. The 50 m interfluve core (IITK) consists mostly of yellow silty clay with occasional silt layers and scattered 'kankars' (carbonate nodules), intercalated with red, mottled muds with thicker kankar layers. No channel deposits are present, and the core represents a persistent floodplain environment, probably linked to plains-fed rivers that experienced periods of reduced sedimentation and enhanced pedogenesis. This environmental setting seems to have characterized the Ganga–Yamuna interfluve for more than ~90 ka (Sinha et al., 2007; Fig. 5).

Near the southern interfluve margin at Bhognipur, a 50-m core starts with 20 m of floodplain strata with abundant kankars and mottles, and passes up into a sand–silt alternation, perhaps representing a channel-margin facies (Fig. 5). An interesting observation in this core is the presence of a ~7 m thick coarse sand with numerous pink feldspar grains and a few rock fragments, petrographically similar to sands of the modern Betwa river (M.R.Gibling, unpublished data), which traverses the granitic gneisses of the Bundelkhand Complex of the northern Indian Craton.

Within the Yamuna valley, a 20 m core penetrated a 12 m channel-margin succession (levee?) of interbedded very fine sand and silty clay below the modern Yamuna sandbars; two dates of 2 ka or younger from the lower strata suggest rapid accumulation, and possibly a very recent onset of Yamuna river deposition in this area. The sand layers are micaceous with thin patches of white silt; petrographic data suggest a predominantly Himalayan source. The lower part of the core, however, consists of a feldspathic coarse sand unit (base not reached), much coarser than the present-day Yamuna channel sands and petrographically similar to the sands at the base of the Bhognipur core.

The Ganga and Yamuna valley cores contribute significantly to our understanding of Ganga plains history since ~100 ka. They suggest that the Ganga valley and the interfluve to the south have existed for at least tens of thousands of years. The interfluve cores (IITK and Rania) penetrated floodplain deposits with only one small channel body, and do not show any subsurface evidence for major Himalayan rivers since ~100 ka. Drill core data also show that thick wedges of red feldspathic sand and gravel underlie much of the southern foreland basin at shallow depth (>30 m), where the uppermost strata have yielded a date of 119.2±12 ka BP (Gibling et al., 2005). Similar red sediments, petrographically similar to Betwa sand, extend at deeper levels (>540 m) to about one-third of the distance across the foreland basin (Singh and Bajpai, 1989). The apparent vitality of cratonic rivers during this period may reflect strong monsoonal activity in central India, or factors such as river capture and changes in course of Himalayan rivers, altering the relative dominance of cratonic and Himalayan rivers. Our data suggest that, at least in the Kalpi area, the Yamuna may have moved to a basin-margin position (Burbank, 1992) since ~100 ka and possibly within the past few thousand years.

4.3. *Synthesis and regional correlation*

The Quaternary record of the Ganga plain sediments reveals a complex history of dynamics of large and small river systems, and the alluvial stratigraphy is strongly controlled by climatic changes, against a background of geomorphic settings that include deep valleys and interfluves (online supplement shows regional correlation). The upper reaches of the Ganga have numerous gravel bars, and several meters of gravel deposits are the main element of the alluvial architecture. The gravels disappear within about 20 km downstream of the mountain front, and are replaced by coarse sands (Shukla et al., 2001) corresponding to the braided channel belt. The channel belts in the middle reaches of the Ganga show a mean grain size of fine to very fine sand in modern deposits, although layers of medium to coarse sand, 9–10 m thick, have been recorded in deeper valley fills (Sinha et al., 2005b; Tandon et al., 2006). These channel sands are separated by floodplain muds, 5–7 m thick, which are pedogenically altered, indicating switching of the main channel.

In contrast to the trunk river systems, the interfluve successions in the WGP comprise a series of discontinuity-bounded sequences with alternate aggradational and degradational units. The aggradational units are characterized by overbank mud and sand whereas the degradational units show gullied degradation surfaces, palaeosols, lacustrine mud, and eolian silts. The alluvial architecture in the WGP and in the Belan and Son valleys draining the northern craton appears to have been governed principally by fluctuations in monsoonal precipitation (Gibling et al., 2005). MIS 5-3 appear to represent a period of strong fluvial activity. In parts of the Ganga Valley, floodplain deposits capped by eolian and lake deposits record reduced river activity after 27 ka as the region entered the LGM. After the LGM, as the monsoon intensified, fluvial activity resumed, but channels elsewhere (Belan sections) were filled with eolian sediment and windblown shells during the latest Pleistocene and early Holocene, testifying to climatic instability. In interfluve cores distant from the Ganga Valley, we record 50 m of floodplain deposits that date back to ~86 ka (Sinha et al., 2007). The interfluve appears to have been a site of floodplain accumulation from small plains-fed channels over this period, during which Himalayan and plains-fed channels appear to have occupied separate floodplain tracts. Thus, through this period, large parts of the plains were detached from the direct effects of the large rivers. The interfluve floodplains were sites of more intense pedogenesis periodically, and built up by means of cycles of aggradation followed by soil formation, possibly in response to monsoonal fluctuations on a timescale of 1000–10,000 years (Gibling et al., 2005).

5. Fluvial successions of Western India

Western India, including Rajasthan and the Gujarat states, is drained by the Narmada, Tapi, Luni, Sabarmati and Mahi rivers (Fig. 6), and has accumulated significant fluvial deposits spanning most of the Quaternary and part of the Neogene. Older sub-surface deposits occupy structural depressions, and have been related to continental margin rifting and graben formation (Maurya et al., 1995; Merh and Chamyal, 1997; Bajpai et al., 2001). Several rivers draining the Saurashtra peninsula and the Kachchh region have been strongly influenced by sea-level fluctuations.

The Luni is an ephemeral desert river draining the major parts of Rajasthan and constitutes the major drainage in the Thar Desert. The Sabarmati and Mahi rivers in Gujarat originate from the Aravalli mountain range and flow through extensive alluvial plains before finally reaching the Gulf of Cambay (Merh, 1995), thus traversing the

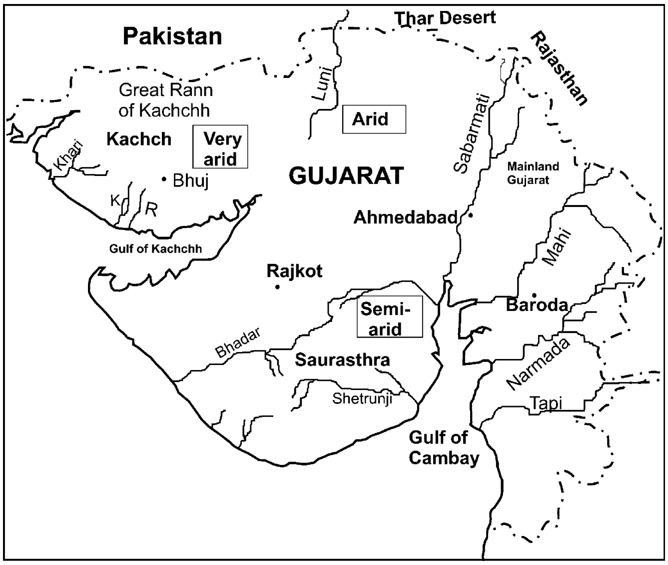

Fig. 6. Location map for the studied rivers in western India. K and R denote the rivers Kharod and Rukmavati. "Mainland Gujarat" is the area between the rivers Mahi and Sabarmati.

tectonically active Cambay Graben. The modern annual precipitation in the region varies from about 300 to 700 mm, indicating a semi-arid climate.

5.1. The Luni basin

Outcrop of fluvial deposits in the Luni basin has been classified into two successions, Type 1 and 2, separated by a prominent hiatus (Jain et al., 1999, 2004). The older (Pre-Quaternary) Type 1 succession is laterally extensive and up to 300 m thick (Bajpai et al., 2001), consisting of multi-storied gravel–sand sheets and a well-developed overbank heterolithic facies with incipient pedogenesis (Fig. 7a). A medium-to-fine sand unit with rhizoconcretions overlies the gravel sheets, and is followed by pedogenically modified fine sand–mud alternations. Several such fining-upward cycles (gravel–sand–mud successions) are recorded, each cycle beginning with gravel sheets overlying the heterolithic facies with an erosive contact. These cycles were deposited by gravelly braided rivers in a subsiding basin in response to autogenic channel avulsion processes (Jain et al., 2004, 2005). This succession remains undated, but has been tentatively assigned to the Pliocene (Jain et al., 2004, 2005).

The Type 2 succession, inset within the Type 1 succession, represents distinct, laterally or vertically juxtaposed depositional environments, including the deposits of gravelly braided streams, debris flows, ephemeral streams, mixed-load meandering streams, overbank and eolian deposition (Fig. 7b). OSL dates on fluvial sediments indicate several phases of deposition in MIS 5a, MIS 2, the Late glacial, and the early to middle Holocene (Jain et al., 2004). Unlike the Type-1 deposits, the Type-2 succession represents deposition by ephemeral streams in a desert environment under the influence of high-frequency climate change during the last 100 ka. Interglacial and interstadial periods were dominated by gravelly braided deposits, whereas the LGM and dry periods within the Pleistocene and Holocene have been dominated by ephemeral sandy braided rivers and intermittent eolian activity. This succession is rich in fossils and artifacts from the Chalcolithic and medieval periods (Mishra et al., 1999).

Jain et al. (2005) noted that the differences between the Type-1 and Type-2 successions indicate a fundamental reorganization of the fluvial system between the Pliocene

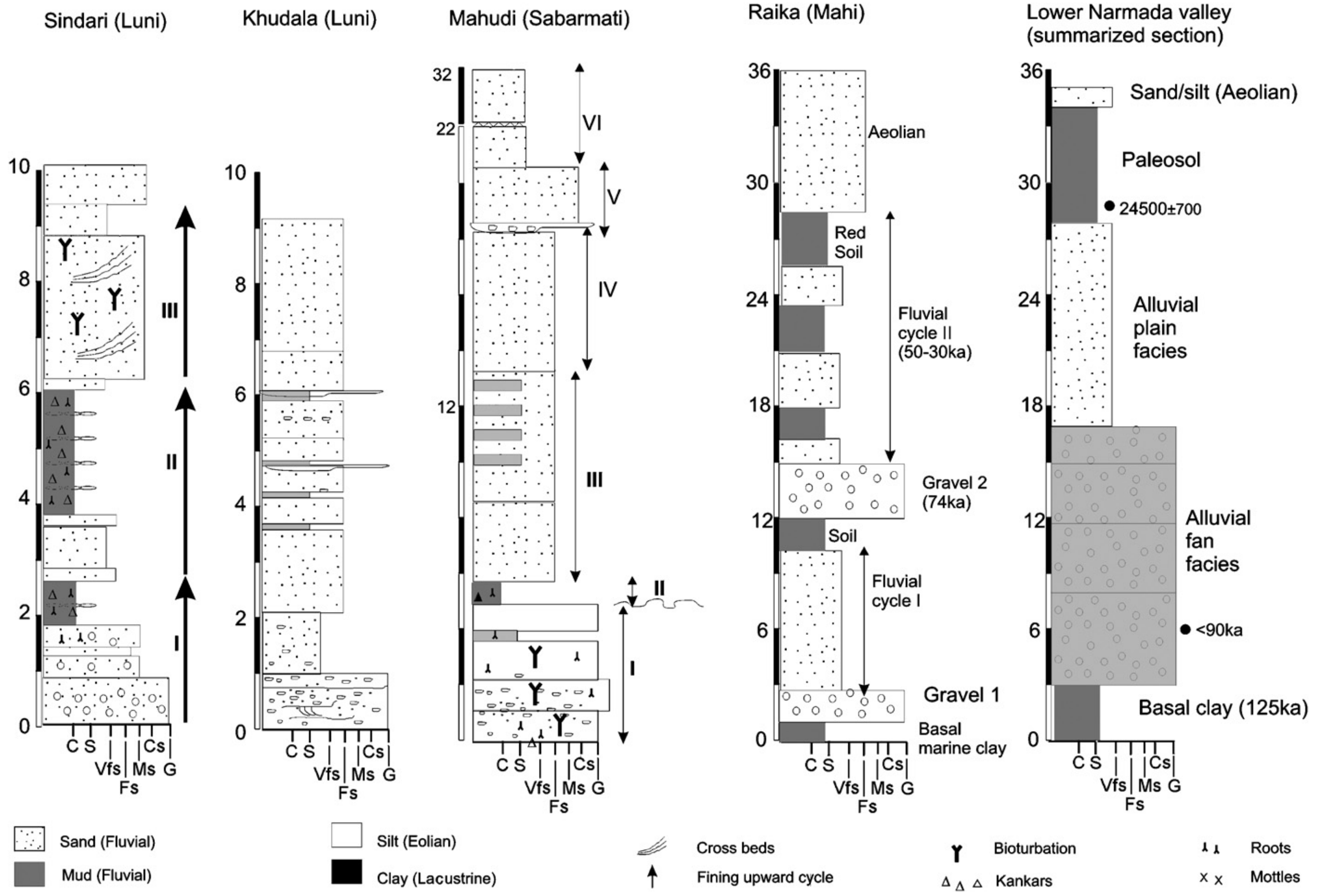

Fig. 7. Representative fluvial successions from western India: (a) Sindari section (Luni river, after Jain et al., 2005); (b) Khudala section (Luni river, after Jain et al., 2005); (c) Mahudi section (Sabarmati river, after Tandon et al., 1997). This section shows a six-fold stratigraphic subdivision based on lithofacies and contact relationships, after Jain and Tandon (2003a, b), rather than the four-fold subdivision discussed in the text; (d) Raika section (Mahi river, after Merh and Chamyal, 1997); and (e) Lower Narmada valley (after Chamyal et al., 2002).

and MIS 5. The Type-1 succession thus represents a distant ancestor of the modern Luni river, which existed long before the development of the present-day Thar Desert system. Apart from the fluvial architecture, there are also differences in vegetational biomass. The stable isotopic (δ^{18}O and δ^{13}C) composition of pedogenic calcrete in the Type 1 succession suggests a relative dominance of C_3 flora and summer-monsoon precipitation, compared with the Type 2 succession (Jain and Tandon 2003a), which shows systematic temporal variations that represent vegetational/precipitation changes during the Late Pleistocene.

5.2. *The Sabarmati basin*

Quaternary sections exposed along the Sabarmati have been described (Sareen et al., 1993; Tandon et al., 1997; Srivastava et al., 2001), and a four-fold stratigraphic subdivision (the Waghpur, Mehsana, Akhaj and Sabarmati formations) has been proposed based on a representative section at Mahudi (Fig. 7c). The basal Waghpur Formation (Unit 1) is pre-Quaternary (Tandon et al., 1997) and consists of conglomerate and pedogenized pale red sand, interpreted as gravelly braided river deposits (Jain and Tandon, 2003b). The succeeding Mahesana Formation (58–39 ka; Tandon et al., 1997) is divided into a lower heterolithic member (Unit 2) and an upper sand member (Unit 3) of predominantly alluvial origin. A pronounced reddened horizon in the upper parts of the Mehsana Formation has often been used for regional correlations from the Thar to the Gujarat alluvial plains (Tandon et al., 1999; Jain et al., 2004). The overlying Akhaj Formation (Unit 4) consists of well-sorted, fine, buff sand which has been attributed to multiple phases of eolian activity (~22, 12, and 5 ka; Wasson et al., 1983; Tandon et al., 1997; Srivastava et al., 2001, respectively). The youngest Sabarmati Formation (Jain and Tandon, 2003b) comprises unconsolidated alluvium (Unit 5) and has been attributed to meandering systems. Jain and Tandon (2003b) identified a fine sand unit (Unit 6) with a dunal morphology capping all the alluvial deposits and interpreted as an eolian deposit dating from 12 ka age (Srivastava et al., 2001). There was incision by the Sabarmati River between 12 and 4.5 ka in response to the early Holocene strengthening of the SW Indian Monsoon (Srivastava et al., 2001), although the river course follows a tectonic lineament.

5.3. *The Mahi basin*

Like the Sabarmati, the Mahi also originates in the Aravalli mountains and drains into the Gulf of Cambay after flowing through the alluvial plains of Gujarat. One of the most representative sections at Raika has been described by Merh and Chamyal (1997). The basal unit consisting of a metre-scale, dark brown, non-stratified sandy mud facies, has been regarded as marine based on the presence of planktonic and benthic foraminifera (Raj et al., 1998), and has been assigned to MIS 5e (Juyal et al., 2000). The overlying fluvial deposits consist of gravels, interbedded alluvial/limnic mud and marl, and a channelised fluvial gravel–sand complex (Fig. 7d). Juyal et al. (2000) provided luminescence chronology for this section and recognized phases of fluvial aggradation in MIS 5 and 3. Gravel capping the first aggradational phase gave a mean OSL age of 74 ka, and several OSL dates in the upper aggradational succession of sandy silt constrain this phase to be 50–30 ka old. This succession is capped by alluvial and eolian silts and silty sands. The silts have distinct pedogenically modified horizons (Khadkikar et al., 1996) and a red soil horizon, attributed to 40–25 ka, provides a chronostratigraphic marker. The Raika stratigraphy records a large earthquake during the Late Pleistocene in the lower gravel and mud-marl units (Maurya et al., 1997; Jain et al., 1998) which is bracketed by OSL to 128–70 ka (Juyal et al., 2000). In the lower Mahi valley, a mid-Holocene marine transgression (Hashimi et al., 1995) is indicated in the fluvio-marine intercalations of valley-fill terraces (Maurya et al., 1997).

5.4. *The Narmada basin*

The Narmada is the largest river of Peninsular India, and provides some of the best examples of tectonically controlled sedimentation, associated with the Narmada-Son Fault (Fig. 7e) for most of its course. In the upper reaches, the Narmada is essentially a deeply incised bedrock channel flowing through the basaltic rocks of the Deccan Traps. In the lower alluvial reaches of the Narmada in Gujarat state a large thickness (~800 m) of Tertiary and Quaternary sediments has accumulated in a fault-controlled basin. The alluvial deposits in the Narmada valley show a high degree of spatial variability, and sedimentary successions are strongly controlled by the geomorphic setting (Chamyal et al., 2002). The successions typically start with marine clay, overlain by stacked alluvial fan deposits followed by alluvial plain deposits (Chamyal et al., 1997, 2002). The alluvial fan facies consists of massive to poorly stratified gravels which are clast- or matrix-supported and are intercalated with coarse pebbly sands. Significant vertical and spatial variability of lithofacies has been noted by Chamyal et al. (1997, 2002); these strata have been attributed to repeated debris flow and sheet flow processes and frequent channel-filling. Age control on these deposits is limited; TL dates from the middle and upper parts of the alluvial fan deposits yielded ages of <90 and 6 ka, respectively (Chamyal et al., 2002) upon which basis these deposits can be correlated with the base of the fluvial deposits in the adjacent Mahi (125 ka; Juyal et al., 2000) and Sabarmati (Tandon et al., 1997).

The upper alluvial plain facies has been described in detail by Bhandari et al. (2005), although some preliminary descriptions were also provided by Chamyal et al. (2002). These facies are dominated by overbank mud and thin stratified sand-silt, interpreted as channel fill and crevasse-splay deposits. The laminated sand sheets, interpreted as channel fills, are laterally extensive with an average thickness of 1.5–2 m and were attributed to a large, single-channel meandering river, 70–80 m wide and 8–15 m deep (Bhandari et al., 2005). Two generations of vertically superimposed sand sheets suggest frequent avulsion, possibly in a rapidly aggrading environment, a view also supported by the absence of any pedogenized intervals. The overbank facies consist of laminated as well as massive sands and clayey sands, interpreted as crevasse splay and backswamp deposits (Bhandari et al., 2005). In the upper parts of the alluvial plain sediments, a 3–6 m thick brownish red to reddish brown paleosol unit has been reported by Chamyal et al. (2002) and Bhandari et al. (2005) and may be correlated with the red soil horizon in the adjacent Mahi and Sabarmati basins.

The succession in the Narmada basin includes a sharp transition from the coarse alluvial fan facies to a much finer alluvial plain facies. The probable cause of this change from a multi-channel river system to a more integrated single channel in an alluvial plain environment was climate change (Chamyal et al., 1997, 2002; Bhandari et al., 2005).

5.5. *The Saurashtra and Kachchh peninsulas*

The Saurashtra peninsula, an important physiographic division of Gujarat in western India, is marked by flat-topped ridges with an irregular coastline. The modern drainage systems of Saurashtra, including the Bhadar, Nali, Hiran, Shetrunji and many others, display a radial pattern (Marathe, 1981; Chamyal et al., 2003a), with the rivers flowing away from the central highland. Most are ephemeral rivers and flow into either Little Rann of Kutch or the Gulf of Cambay. Fluvial landforms and sedimentary records from Saurasthra have been strongly influenced by sea-level fluctuations, and so provide an excellent record of fluvio-marine interactions. The alluvial cover in the region is thin (<10 m) and is generally preserved as terrace deposits.

Merh and Chamyal (1993) proposed a Quaternary stratigraphy for Saurashtra, which overlies basalt and Cenozoic limestone. Starting with gravelly sand deposits (fluvial), the succession shows several phases of marine (miliolite limestone) and eolian deposition during the Pleistocene and Holocene, and it is generally capped by alluvium, beach sands or tidal muds, depending upon the geomorphic setting. Bhatt and Bhonde (2003) described the Quaternary succession from the Bhadar river basin in south Saurashtra. They documented trough cross-bedded gravels, massive sand, and planar cross-bedded sand in 8–10 m high river cliff successions. Two fluvial aggradational phases are typically recorded, consisting of gravelly sands separated by a moderately pedogenized horizon that suggests punctuation in fluvial process. Evidence of a marine incursion between the two fluvial units was recorded in the form of bioclastic carbonate sand-dominated units containing biogenic structures and tidal clays. The age of this marine event is controversial but indirect evidence in the form of archeological tools (Acheulian: Baskaran et al., 1986; Patel and Bhatt, 1995), ESR dating of molluscan shells (115–95 ka: Brückner et al., 1987), and U-series dating of oyster and scallop shells (126 and 87 ka: Juyal et al., 1995) place it in the MIS 5e interglacial. Sedimentation in this region is thought to have been controlled by long-timescale crustal deformation; uplift of the southern Saurasthra coast since 125 ka has been reported (Pant and Juyal, 1993; Sant, 1999; Chamyal et al., 2003a).

The Quaternary deposits of the Kachchh region, consisting of the Ranns, Banni plain and the Island belt, include fluvial, marine and eolian deposits. With the Katrol Hill range forming the main drainage divide in the region, most rivers flow southward into the Gulf of Kachchh and the Arabian Sea and some smaller rivers originating on the northern slopes flow into the Rann of Kachchh. A major proportion of the deposits, composed of clasts of pre-Quaternary rocks, are preserved as fans north of the Katrol Hill fault and Kachchh Mainland fault, and show strong tectonic control (Chamyal et al., 2003b). The colluvial fans are incised by the modern rivers and are overlain by miliolites (Middle Pleistocene) at the base of the Katrol Hill Fault, suggesting that the fans may be Early Pleistocene (Thakkar et al., 1999). The Holocene deposits in the Kachchh region are mostly marine; this region was submerged below sea-level until ~2000 years ago (Chamyal et al., 2003a).

Maurya et al. (2003) described the late Quaternary cliff sections in southern Kachchh, exposed along the south-flowing rivers. Exposed in two distinct patches in the eastern and western parts and separated by a Tertiary peneplain, the base of the sections has coarse gravelly facies overlain by a planar cross-stratified or massive fluvial sand. A prominent red soil horizon, radiocarbon dated (on pedogenic carbonates) to 24–15 ka overlies the alluvial succession, which is in turn overlain by thick sandy gravels. In the western parts, a brown soil occurs at the same stratigraphic level as the red soil in the eastern parts, and is capped by another fining-upward cycle starting with cross-stratified gravel and terminating with pedogenized silty sand. The study delineates two fluvial phases, pre-LGM and early Holocene, separated by a discontinuity represented by the red/brown soil.

5.6. *Synthesis and regional correlations*

The fluvial successions in western India record a systematic variation of the sedimentation pattern in response to the late Quaternary climate changes. The phases of aggradation and incision occurred around the same times in the lower reaches of the three river basins, the Luni, Mahi and Sabarmati (Jain et al., 2004). Variations in fluvial styles in different regions are apparently a function of precipitation gradient which is observed even today. In the Gujarat alluvial plains, the sections along the Sabarmati and Mahi rivers suggest that meandering was prevalent in more humid phases but strong incision occurred in the wettest phases. The gravel-bed braided rivers drained the plains during drier phases due to decreased sediment supply. Eolian deposits are present during the arid phases in the desert—proximal situations only. The Luni river section in the Thar Desert area of Rajasthan presents a different picture. Gravel bedload or gravel–sand bedload streams are inferred to have been active during the wettest phases, based on the fluvial successions at Sindari and Khudala. Progressive desiccation in the glacial period led to the formation of ephemeral sand-bed rivers in this region, perhaps due to vegetation decrease and an increased supply of sand (Jain and Tandon 2003a; Jain et al., 2004). Streams became largely inactive or defunct (due to blocking of the stream courses with eolian sand) during the period of peak aridity. These authors also suggested an important difference between the desert and desert-margin rivers in terms of their 'differential' response to fluctuations such as those in the Lateglacial period. During the Lateglacial, the Luni River in the Thar Desert was very dynamic and experienced frequent transitions from gravel bedload braided streams to ephemeral sand-bed rivers and suspended load-dominated meandering streams. The coeval deposits in the Mahudi section in the Sabarmati, however, show a meandering, floodplain-dominated river during this period. The desert streams thus appear to be more sensitive to climate change, and may have very short response times and low geomorphic thresholds as compared to the desert-margin rivers.

The other important river in western India, the Narmada, follows the Narmada-Son Fault zone, and the fluvial successions in this basin have been tectonically controlled throughout the Quaternary, although a strong climatic signature manifests itself as sharp changes in fluvial style from multi-channel alluvial fan systems to meandering rivers in the late Pleistocene. The coastal systems of Saurashtra and southern Gujarat show distinct effects of incision and aggradation forced by marine regression and transgression, coupled with tectonic uplifts during the late Holocene.

6. Discussion

6.1. Causes of sedimentary architecture and facies variability in Siwaliks

The Siwalik successions in the HFB show facies variation within and across sub-basins as depicted in Fig. 3. The Lower Siwalik sediments were deposited by high-sinuosity rivers with broad floodplains (Rangarao and Kunte, 1987). The transition from Lower to Middle Siwalik deposition shows a marked variation in terms of sandstone/mudstone percentage, fluvial architecture and net sediment accumulation rate (Tandon, 1991; Burbank et al., 1996; Kumar et al., 2003a). The sedimentary succession in this interval is characterized by multistoried sandstone with abundant erosional surfaces, no lateral accretionary surfaces, and low palaeoflow variability. These features indicate deposition in a frequently avulsing braided river system (Tandon, 1991; Kumar and Nanda, 1989; Kumar et al., 2003a, 2004). Increase in net sediment accumulation rate may be due either to an increase in catchment area, increased erosion rates due to greater relief, or altered climatic conditions. For instance, it is clear from mineralogical evidence that the Central Crystalline zone of the Himalaya (Fig. 1) was further uplifted in response to reactivation of the Main Central Thrust (MCT) at ~10 Ma, resulting in increased relief and increased supply of metamorphic detritus (Tandon, 1976, Tandon and Rangaraj, 1979; Ghosh and Kumar, 2000).

Variation in lithofacies at the transition from the Lower to Middle Siwaliks across the sub-basins suggests differential basinal subsidence; prior to ~10 Ma, accommodation space exceeded sediment accumulation. The 1 km thick multistoried sandstone complex in the DSB was formed by a braided river with avulsion events at typical intervals of ~4000 to ~8000 years (Kumar, 1993). On the other hand, Brozovic and Burbank (2000) suggested that in the SW KSB, after 10 Ma alluvial fans gradually prograded south-westward, accompanied by decreasing clast-size and increasing mudstone percentage from SE to NW. The NW part of the basin shows a different style of sedimentation at this time, as already noted (Sinha et al., 2007a; see above).

The Upper Siwalik conglomerate-dominated succession overlies the Middle Siwalik sandstone-dominated succession at ~5 Ma along the northern basin margin in the HFB (Parkash et al., 1980; Kumar and Ghosh, 1991; Tandon, 1991; Burbank et al., 1996), especially in re-entrant areas. Conglomerates are found after 2 Ma particularly in the salients (Kumar and Tandon, 1985; Kumar et al., 2007); these were deposited by coalescing megafans south of the MBT. Activity along the MBT caused the production of high volume of sediment, with distribution of coarse-grained sediment in the proximal part and of fine sediments in the distal part of the alluvial fan system. This variation in sedimentation pattern at ~5 Ma was also associated with a change in palaeoflow directions from south to SW in the DSB (Kumar and Ghosh, 1994; Kumar et al., 2003a, b) and more westerly in the KSB. These prominent and abrupt facies changes at ~10, ~5 and ~2 Ma could reflect either hinterland deformation or change in energy conditions. Sedimentary style in the HFB clearly demonstrates that deformation along the hinterland took place during these times, as discussed above.

Tectonism can produce high relief and large catchment areas, but transportation of sediments across the feather-edge of foreland basins requires high energy conditions (Kumar et al., 2003a, b). Regarding the role of climate change, purple and brown paleosols with calcareous nodules suggest a humid warm climate before 5.5 Ma, after which it gradually became cooler and drier with significant changes taking place at ~2.6 Ma (Thomas et al., 2002). Fluvial architecture during this time suggests a gradual increase in river size and discharge. Based on stable isotope geochemistry, high precipitation is inferred at ~10 and ~6 Ma in the KSB, with a drier phase between (Sanyal et al., 2004). Schumm and Rea (1995) showed from the marine record that there were three major episodes of terrigenous sediment flux: ~11–10, ~9–6, and ~4–2 Ma. The mass accumulation rate in the Ganga basin also increased rapidly at ~10 Ma (Metivier et al., 1999). From the above discussion, it appears that precipitation in the Himalayan region increased at ~10 Ma, an inference drawn from field observations, stable isotopes, Indian Ocean and Ganga basin data (cf. Beaumont et al., 1992).

6.2. *Controls of fluvial sedimentation in the alluvial plains*

As already noted, the Quaternary stratigraphy of the Ganga plains varies from west to east, in accord with the present-day precipitation gradient and geomorphic diversity. In the western Ganga plains where prominent incised valleys expose interfluve successions, we record 'discontinuity-bounded' successions (Gibling et al., 2005). The manifestations of these discontinuities in the muddy interfluve successions are varied. For example, these levels are marked by strong pedogenic events manifested in calcrete development and immature soil formation at Kalpi, whereas eolian and lacustrine deposition occurred at Bithur, and gully development and filling at Mawar and Kalpi (see Section 4, above). It has been argued that these discontinuities in the stratigraphic record of the interfluves have formed due to partial to complete detachment of the floodplains from major rivers. These discontinuity-bound sequences therefore reflect repetitive phases of floodplain aggradation and degradation in response to regional climatic fluctuations during the last 30–40 ka (Gibling et al., 2005).

In contrast, most parts of the eastern Ganga plains are characterized by a rapidly filling aggradational regime. Most rivers in eastern Uttar Pradesh and the north Bihar plains have no incised banks, and the rates of floodplain sedimentation are high (~1.5 mm/yr: Sinha et al., 1996). Major rivers such as the Kosi and the Gandak have continuously moved across their valleys and have formed megafans. Two contrasting types of alluvial architecture have developed below the megafans and the interfluves. The megafan successions consist of thick, multi-storied sandy deposits (Singh et al., 1993) much in contrast to thick muddy deposits in the interfluve, which encase thin sand bodies representing avulsion deposits.

Our work suggests that the contrasting alluvial architecture in the western and eastern Ganga plains is a function of differences in stream power, sediment supply, and rainfall across the plains and the hinterland. The rivers draining the western Ganga plains have much higher stream power and lower sediment supply compared to the rivers in the eastern Ganga plains (Sinha et al., 2005a). As a result, the rivers draining the western Ganga plains are characterized by incised valleys and a degradational regime. Low stream power combined with higher sediment supply in the eastern Ganga plains has resulted in less prominent valleys, frequent avulsion, and the inundation of large areas during monsoon floods. This has resulted in a predominantly aggradational regime in the surface geomorphology, which appears to be reflected in the subsurface stratigraphy in the eastern Ganga plains. In addition to greater proximity to the Himalayan front, higher sediment supply in the eastern Ganga plains is a function of higher crustal shortening rate and a higher average Holocene uplift rate: ~20 and 15 mm/yr, respectively, in the hinterland (Bilham, 1995; Peltzer and Saucier, 1996; Lave and Avouac, 2000) compared to lower values of 11.9 ± 3.1 and 6.9 ± 1.8 mm/yr in the hinterland of the western Ganga plains (Peltzer and Saucier, 1996, Wesnousky et al., 1999). It is believed that spatial variation in rainfall in an west–east transect, inherent in the monsoon system, has been a persistent feature for millions of years (Fluteau et al., 1999), and therefore, such geomorphic diversity and stratigraphic variability between the western and eastern Ganga plains may have existed over ten thousand year to million year time scales.

6.3. *Fluvial history and human response: geoarchaeological context*

The river basins of India are well known for supporting great ancient civilizations.

The earliest reliable stone tool assemblages of the Soanian culture (>2 Ma old) were discovered from the Pleistocene river terraces of the Soan river, a tributary of the Indus, and also from a number of sites in the Siwalik hills in northwest India (de Terra and Paterson, 1939). The Siwalik Hills have also provided the evidence of the Acheulian/Lower Paleolithic culture (2–0.7 Ma) which essentially consisted of hunter-gatherer populations who adapted themselves to a wide variety of climatic regimes including semi-arid regions of western and southern India (Misra, 1989). The Pleistocene period during which Paleolithic colonization took place is marked by significant climatic changes, and several studies have documented the human response to such changes (Misra and Rajaguru, 1986; Misra, 1987). In Peninsular India, Acheulian artifacts are found in fluvial deposits of the Chambal, Son, Mahanadi, Narmada, Godavari, and Krishna rivers and their tributaries. The middle Paleolithic (150–40 ka) culture of stone tools developed during the glacial period of the upper Pleistocene and has been found in the river valleys of western India, e.g. Luni (Misra, 1961) and Narmada (Khatri, 1962) as well as in the Ganga basin, e.g., Belan (Sharma et al., 1980), Son (Sharma and Clark, 1983) and at several other localities. The stratigraphic description from several rivers suggests widespread meandering rivers and muddy floodplains, probably with seasonal flow conditions. The upper Paleolithic (30–10 ka) culture developed during the cold and arid phase of the upper Pleistocene when many drainage systems across the Indian subcontinent became defunct. Fossil records from the Belan and Son valleys suggest the existence of grassland environment with pockets of forests and swamps (Misra, 2001).

The Mesolithic, Neolithic and Chalcolithic, the last phase of prehistoric culture, artifacts are also widely distributed in various parts of the country. Major highlights of this phase are a remarkable growth in human population and a shift from the hunting-gathering way of life to agriculture and food production from ~8 ka BP. One of the greatest ancient civilizations, the Indus valley civilization, flourished during this period and detailed accounts are available in the literature (Oldham, 1887; Wilhelmy, 1969; Yashpal et al., 1980; Allchin and Allchin, 1982; Misra, 2001). The introduction of iron technology around 3000 years ago was of crucial importance to the expansion of agriculture-based settled life, particularly in the sub-humid region of the Ganga valley, apparently linked to abundant iron deposits in south Bihar and central India. The Ganga plains became the focus of development, the birth of the first Indian empire with its capital at Pataliputra (modern Patna, in Bihar). From here, the urban way of life spread to other parts of the country.

7. Conclusions

This review sets out the current status of research on Late Cenozoic fluvial deposits of northern and western India. Not only do some of the great rivers of the world drain the Indo-Gangetic plains today but the ancient fluvial successions record a very active fluvial regime over the past 20 million years or so. The Himalayan orogeny and the subsequent development and growth of the HFB has certainly been one of the most important geological event in this region and has influenced fluvial sedimentation, both directly through several phases of tectonic upheaval and indirectly through its influence on the dynamics of the monsoonal climate system. The Quaternary fluvial succession in the Gangetic plains is perhaps unique in the sense that it displays intricate controls of tectonics, climate and eustatic changes over time and their signatures are often mixed and difficult to resolve.

Other large river systems also drain the western and central parts of India and intensive research has been carried out on the fluvial successions of these regions, particularly western India. These successions represent a climatic regime that contrasts with that of the Himalayan foreland and the Gangetic plains, with the proximity to the Thar Desert and a semi-arid climate. As a result, fluvial–eolian interaction is an important aspect of these successions and a strong influence of sea-level change is also manifested in the coastal region.

One of the most intriguing problems remaining unresolved is the coupling of tectonics and climate in controlling fluvial sedimentation, particularly in the frontal parts of the Himalaya. A second problem is the lack of understanding of the control of base-level changes on the fluvial systems. This is especially important near the ocean, as well as in mountain valleys where blockage and lake formation may cause local base-level to rise, with subsequent breaching. Such changes may influence the erosional dynamics of aggradation and degradation of river valleys and floodplains in a major way, although such effects are also widely generated by changes in water and sediment discharge. Both spatial and temporal variability in base level controls remain poorly studied so far in the foreland basin, and we have yet to determine how far upstream incision generated by sea-level fall progressed in the lower Ganga plain. Thirdly, the Quaternary fluvial successions in the lower Ganga valley and the fluvio-deltaic successions remain relatively poorly documented and little understood. This research holds promise for providing answers to issues related to fluvial sediment flux in some of the largest sediment dispersal systems in the world.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at: doi:10.1016/j.quascirev.2007.07.018.

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