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Intermediate-scale architectural features of the fluvial Chinji Formation (Miocene), Siwalik Group, northern Pakistan

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Abstract: The Lower Siwalik, Chinji Formation (Late Miocene) of the Chinji Village area, northern Pakistan has provided remarkable material for the study of terrestrial fossil faunas, magnetic reversal stratigraphy and fluvial sedimentology. This paper considers patterns in the sedimentary stratigraphy, using magnetic reversals to constrain the time framework, and focusing on an intermediate (kilometre) horizontal length-scale. The project aimed to determine the architecture and time relationships of the channel sandstone bodies in a panel 300 m in stratigraphic thickness, and 11 km in horizontal length (along stratigraphic strike). This panel (the 1990 Fence) trends at a high angle to the flow direction of the Late Miocene river channels, and represents about 2 Ma of sediment accumulation. There is a continuous range in thickness of the sandstone bodies, but they can be usefully classified into (i) microbodies, (ii) minor sheets, (iii) thin mega-sheets and (iv) thick mega-sheets. The microbodies are probably mainly marginal features of the thicker bodies. The minor sheets were formed by small river channels, and the mega-sheets were formed as the deposits of the largest, generally braided, channel belts. Two aspects of the intermediate length-scale architecture of the Chinji Formation are analysed: (1) the presence in the Fence of three thick mega-sheets separated by two mudstone-dominated intervals that lasted for about 0.5 and 1.0 Ma, respectively and (2) the abrupt upwards increase in sandstone/mudstone proportions that defines the upper stratigraphic boundary of the Chinji Formation. We suggest that each of the three thick mega-sheet episodes resulted from avulsions into the area of large-channel belt complexes that formed central features of the Chinji river network and were each constrained by scarps or valley-side slopes during episodes of net deposition that lasted for about 100 ka, and may have resulted from climate and/or sea-level changes. The regional upward change from mudstone- to sandstone-domination at the top of the Chinji Formation resulted from a similar, but one-off, and more widespread, change in plan-view style of the river network, produced either by tectonic change in the mountain source area, or by climatic change.

Keywords: Pakistan, Siwalik Group, Upper Miocene, fluvial sediments.

Many sedimentary formations that have been deposited by rivers consist of distinctive sandstone-and-mudstone alternations (cycles), with repeat thicknesses of a few metres to a few tens of metres. These alternations provide a general stratigraphical structure or pattern in the formations which is conveniently distinguished from smaller and larger-scale effects by the term architecture. In this paper we describe and discuss certain architectural features partly because they may provide greater understanding of the sedimentological systems, and also because we hope they will help us understand better the way that certain kinds of hydrocarbon reservoir may be structured (e.g. Allen 1978; Bridge *et al.* 2000; Miall & Tyler 1991; North 1996).

Early work on sandstone and mudstone fluvial formations was based largely on 'vertical' logs that provide one-dimensional records of net accumulation in space and/or time. As a general interpretation, it is now widely accepted that these successions have been formed by episodes of sand deposition in river channels that alternated with episodes of repeated mud deposition on the river floodplains at some distance from the channels. The major question that is still not clearly answered concerns the reasons for variations in the dimensions and relative proportions of the sandstone and mudstone intervals.

Where outcrops are suitable, two-dimensional studies have always provided valuable further information, and a new standard of detail and completeness has recently been achieved in the work of the Smithsonian–Binghamton group (under A. K. Behrensmeyer and J. S. Bridge) on the Miocene sediments of northern Pakistan (Willis 1993*a*, *b*; Willis & Behrensmeyer 1994; Khan *et al.* 1997; Zaleha 1997*a*, *b*, *c*). The quality of the exposures, and the detail and intensity of these studies have made it possible to reconstruct the evolution of ancient river channels in terms of the form and migration of their banks and bars, and the morphology of the associated floodplains and paleosols, as will be summarized below.

The study reported in the present paper deliberately builds on this remarkable work and uses the same exceptional exposures in northern Pakistan. The special object has been to investigate the deposits on the larger, km length-scale that is necessary to understand whole channel systems and the extensive sandstone bodies they produced.

Siwalik geology of the Chinji area, Pakistan

Setting and stratigraphy

Excellent exposures of Siwalik Group fluvial deposits of Neogene age are a feature of the Subhimalayan belt of northern Pakistan. In recent years, intensive studies of their rich fossil vertebrate faunas (Barry *et al.* 1985, 1995), their palaeomagnetic reversal stratigraphy, and their sedimentology have made this a classic area for the study of fluvial sedimentation and alluvial processes (Raza 1983; Quade *et al.* 1989, 1995; Willis 1993*a*, *b*; Willis & Behrensmeyer 1994; Khan *et al.* 1997; Zaleha 1997*a*, *b*). Within this Subhimalayan belt, the Chinji area of the Potwar Plateau, northern Pakistan offers some of the best outcrops known anywhere in the world for the study of fluvial architecture. The clean exposures are largely devoid of vegetation because of the semi-arid climate and the heavy grazing by local livestock. Outcrops in the area are part of the Salt Range Monocline Zone where the strata dip uniformly at between 10° and 12° which is ideal for the field examination of the lateral and vertical geometry of the outcrops. This Monocline Zone forms the southern margin of the Potwar Plateau (Fig. 1) and is the surface expression of a ramp in the Salt Range thrust (Lillie *et al.* 1987), the outermost thrust of the Himalayan front, that became active about 6.3 Ma ago (Burbank *et al.* 1996). Incision of the landscape over the last few million years since the thrust was first active has created a rugged outcrop relief of a few tens of metres, not too large to make general access to the outcrops difficult on foot.

The Chinji Formation (Fig. 2) is part of the Neogene clastic fill of the foreland basin that is still actively accumulating sediment along many parts of the 2000 km long, southern margin of the Himalayas. The Neogene succession, sometimes at least 5 km in aggregate thickness, consists largely of sediment transferred from the Himalayas, and crops out now along the folded and thrust Subhimalayan foothills belt. This belt is wider in the Pakistani Himalayan syntaxis, where it includes the Potwar Plateau. The Neogene succession has been divided into two stratigraphic Groups (Fatmi 1973), the earlier Rawalpindi Group, and the later Siwalik Group, with the Miocene Chinji Formation forming the upper part of the Lower Siwalik Group. The lithostratigraphic sub-division of the Siwalik Group is based on 'vertical' changes in the proportions of sandstone to mudstone (Fig. 2b,c), and we will discuss the increase in sandstone proportion that defines the upper boundary of the Chinji Formation ('top C' on Fig. 2b), after we have considered the typical mud-dominated architecture of the lower Chinji Formation.

In this paper we concentrate our analysis in an area close to Chinji village that has given its name to the Formation, although our work covers the area extending from Kanatti, via Chinji to the Gabhir River (Fig. 1).

Lithotypes

In earlier studies of the Chinji Formation (Raza 1983), the presence of extensive sandstone sheets spaced at intervals through the predominant red mudstones was used to subdivide the Formation, and to locate specific fossil localities. Figure 3 presents an example of one of our logs (see Fig. 1 for location), illustrating the subdivision of the succession into four main lithotypes (sandstone bodies, heteroliths, mudstones and palaeosols) which are now discussed in more detail.

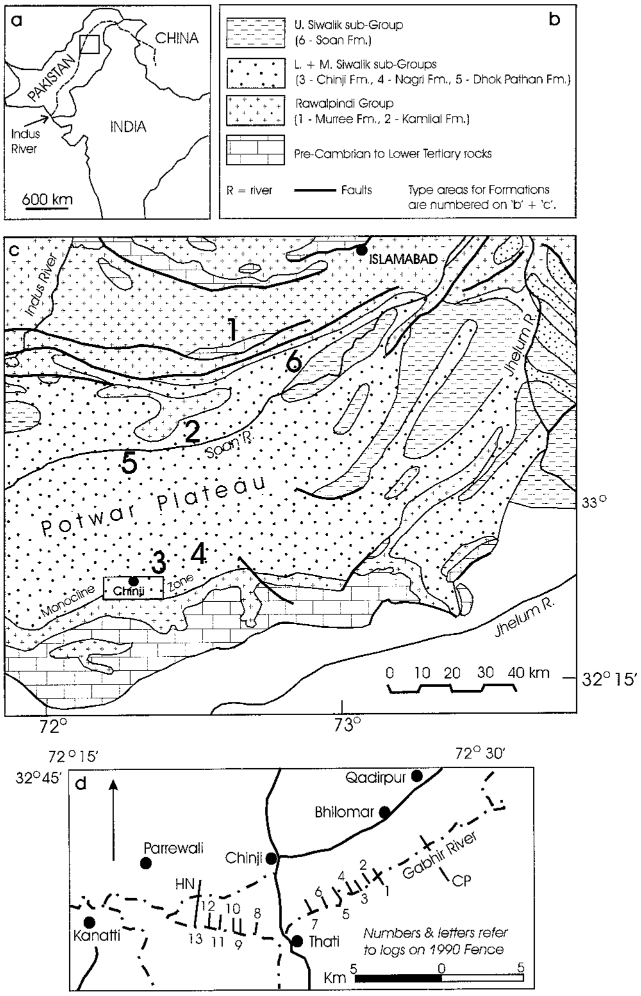

Fig. 1. (**a**) Location map of Potwar Plateau, northern Pakistan (**b**) Key for map. (**c**) Generalized geological map of Potwar Plateau with stratotypes of the component formations of the Neogene molasse-like sediment (1 to 6, see b), and box indicating the study area. (**d**) Detail of the study area, showing Kanatti–Chinji–Gabhir (KCG) area, with locations of vertical profiles measured in the lower Chinji Formation, and discussed here. Sections 1 to 13 are R1, R2 to R13, measured by the present authors; HN (Hutch Nala) and CP (Chitta Parwala) after Johnson *et al.* (1988). Roads are shown as a continuous line, and rivers with a dash-dot line.

Sandstone bodies. These cap the many local escarpments of the badlands of the Salt Range Monocline Zone outcrop area (Fig. 4a,b). The sandstones are grey to greenish-grey, though some outcrops have a brown or yellowish surface. The sandstones are generally fine- to medium-grained, often micaceous, and with a 'salt-and-pepper' appearance due to the admixture of light grains (quartz and feldspar) with dark grains (biotite, hornblende, iron-oxides and pigmented rock fragments). Quartz, feldspar and rock fragments, are usually present in roughly equal proportions. Mudstone clasts are abundant at some levels, and 'stringers' of them (Fig. 4c) often mark erosion surfaces at the bases of stacked storeys (Friend *et al.* 1979, 1986). Most sandstone bodies contain clearly visible flat-bedding and, more locally, cross-stratification. Root marks and other biogenic traces are locally abundant.

Much of this paper is concerned with the external form of these main sandstone bodies. Many of the bodies also contain

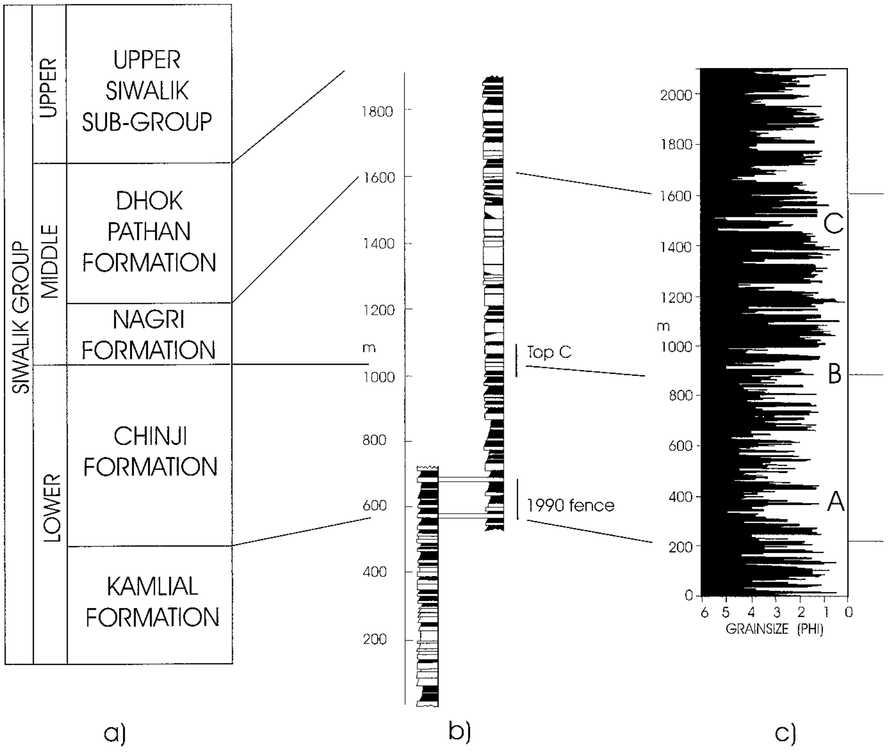

Fig. 2. (**a**) Stratigraphic terminology of the Siwalik Group (Fatmi 1973). (**b**) Log redrawn from Johnson *et al.* (1985, fig. 4) of their Chitta Parwala–Gabhir section, using a classic, one-dimensional representation of the sandstone–mudstone distribution through the stratigraphy. (**c**) Log, redrawn from Willis (1993*b*, fig. 3) showing mean grain-size averaged for every metre interval along the Gabhir Kas section, near Chinji village. Letters A,B and C indicate intervals studied in detail by Willis.

distinct, internal storeys, and these will be discussed further below (Fig. 4c). If sandstones are thin, they may be features of the heterolith lithotype to be described next, as there is a transition in thickness between the individual, usually decimetre thick, sandstone strata of the heteroliths and the thicker sandstone bodies of our analysis. In practice, we have only logged as separate units the sandstone bodies that are 1.2 m or more in thickness.

All our further work supports the conclusion, based on grain-size and internal structures, that the sandstone bodies were deposited by floods in channels, or by levees or splays formed by floods from channels. Willis (1993*a*, *b*), and Willis & Behrensmeyer (1994) have presented a detailed study of the internal structure of some of these sandstone bodies (Fig. 5), with a semi-quantitative interpretation of the size and form of the rivers. Similar detailed descriptions of sandstone bodies in correlative outcrops elsewhere in the Potwar area have been provided by Khan *et al.* (1997) and Zaleha (1997*a*,*b*).

Heteroliths. In common with others (e.g. Thomas *et al.* 1987; Gibling & Rust 1990), we find it useful to distinguish a heterolith sedimentary association. Heteroliths are normally 1–3 m thick intervals, consisting of several couplets of sandstone and mudstone strata, where the sandstone member of the couplet ranges from a few cm up to about 1.2 m in thickness, and the mudstone member is normally tens of cm thick (Fig. 4d). Heteroliths are normally red in outcrop, although they often show mottling of reds, yellows and browns on fresh surfaces. The bases of the thin sandstone strata are sometimes sharp, but otherwise are gradational, probably due to bioturbation. The upper contacts of the thin sandstones against the overlying mudstones are generally gradational. Each couplet therefore appears to be a sandstone-to-mudstone upward-fining unit, and we take this to imply that each resulted from a single episode of waning flow deposition. Heteroliths characteristically consist of several of these alternations, reflecting a regular series of waning flow episodes. Most outcrops of heteroliths show that the sediments were deposited more or less horizontally, but some are distinctively inclined at angles of up to 25°, and appear to have been deposited on the sides of bars or channel banks.

Heteroliths can often be seen to have lost their characteristic appearance of regular bedding where an outcrop has become degraded by weathering round its margins. So in many traverses, heteroliths may have been classed as background mudstones. We have tried to correct for this effect by searching laterally for heteroliths when measuring one-dimensional sections for this study, but we have not been able to systematically represent heteroliths when it comes to the extensive lateral assessment required to produce the panels (Figs 6 and 7). Some of the thin sandstone bodies reported in the literature would probably have been classified as heteroliths in our study, for example the thin sandstones of some overbank sequences (Willis & Behrensmeyer 1994, fig. 6)

Heteroliths often occur close to sandstone bodies, either lateral to channel margins, or just above the bodies. In the latter case, they form transitional intervals between channel sandstones below and the mudstones above. We regard heteroliths as the deposits of regular successions of floods in settings such as abandoned channels, channel margin levees or splays.

Mudstones. The high proportion of red mudstone is the most characteristic field feature of the Chinji Formation. The mudstones weather with a rubbly texture, and this often obscures the primary stratification, but clean exposures show stratification on scales of centimetres and tens of centimetres, picked out by slight differences in texture and colour. Zones of nodular carbonate concretions are also present locally within mudstone intervals, as are rare beds of more continuous, stratified calcium carbonate.

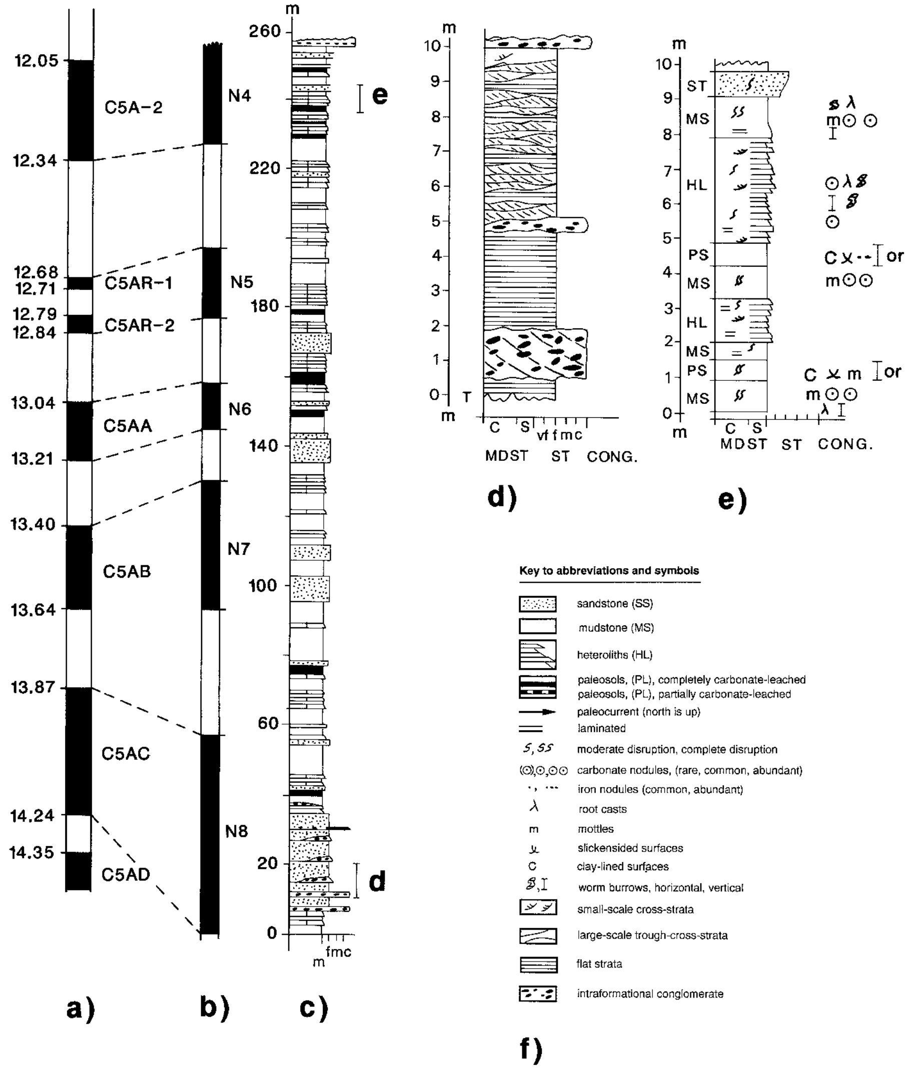

Fig. 3. (**a**) The Magnetic Polarity Time Scale (MPTS) determined for section R11, with ages of the chron boundaries from Harland *et al.* (1990). (**b**) The magnetic polarity stratigraphy of section R11, drawn on the same vertical thickness scale as (c), and following the polarity chron classification of Johnson *et al.* (1988) established in the Hutch Nala–Chitta Parwala area. (**c**) Representative vertical profile of the lower Chinji Formation measured at section R11 (Fig. 1 for location). (**d**) and (**e**) Short vertical profiles at intervals marked on (c) to provide sedimentological detail for the selected intervals in the section R 11. On the horizontal axes, representing grain-size, C and S refer to clay- and silt-grade sediment, and vf, f, m and c refer to very fine, fine, medium and coarse sand-grade. (**f**) Key of abbreviations and symbols used in (c–e) and Fig. 9.

These mudstones are interpreted as overbank or floodbasin mud deposits formed at times of flood or high stage of the rivers. In the Chinji Formation the mudstones are consistently pigmented with red ferric oxides, implying well-drained, non-reducing, floodplain surfaces. Willis & Behrensmeyer (1994) have pointed out that when palaeosols are used as markers to define palaeosol-bounded sequences, these sequences commonly vary from 4 to 10 m in thickness, and can be traced over hundreds of metres or some km. They formed over 20 ka to 60 ka, according to the palaeomagnetic dating. They represent distinct episodes of floodplain deposition that appear to have been relatively local, rather than widespread, and tend to have filled hollows after crevassing and avulsion, rather than reflecting the local growth of major channel ridges.

Palaeosols. This lithotype is important because the relatively mature palaeosols provide markers that allow palaeoland-surfaces to be traced in architectural studies (Willis & Behrensmeyer 1994), particularly in relation to channel sandstone bodies. The Chinji palaeosols occur mainly in mudstone intervals (Willis & Behrensmeyer 1994) and are commonly recognized from a distance by their vivid colours, most often a strong orange, or purple. They usually weather and erode to produce recessive intervals across outcrops. They tend to have lost both primary stratification and carbonate during pedogenesis. Zaleha (1997*c*) has distinguished Non-calcareous/Bk and Calcareous types of palaeosols, where the absence or presence of finely-divided matrix carbonate is the key difference (carbonate nodules can occur in both types). We have distinguished (Fig. 3) palaeosols that have been completely leached of carbonate from those that have been partially leached. Millimetre-size concretions of manganese or ferric iron are locally abundant, as are slickensiding and clay coatings on the surfaces of the rubbly fragments. Zones of calcium carbonate concretions are sometimes typical of the sediments below the leached intervals. Palaeosols often show bioturbation, sometimes including undoubted root traces.

Isotope studies of the carbonates from these palaeosols and associated sandstones have provided information on the changing vegetational ecology of Siwalik times (Quade *et al.* 1989, 1995; Quade & Cerling 1995; Quade & Roe 1999; Zaleha 1997*c*). There is clear evidence for widespread new colonization of the floodplains by C_4 grasses about 7.5 Ma ago, some 2 Ma after the end of Chinji sedimentation.

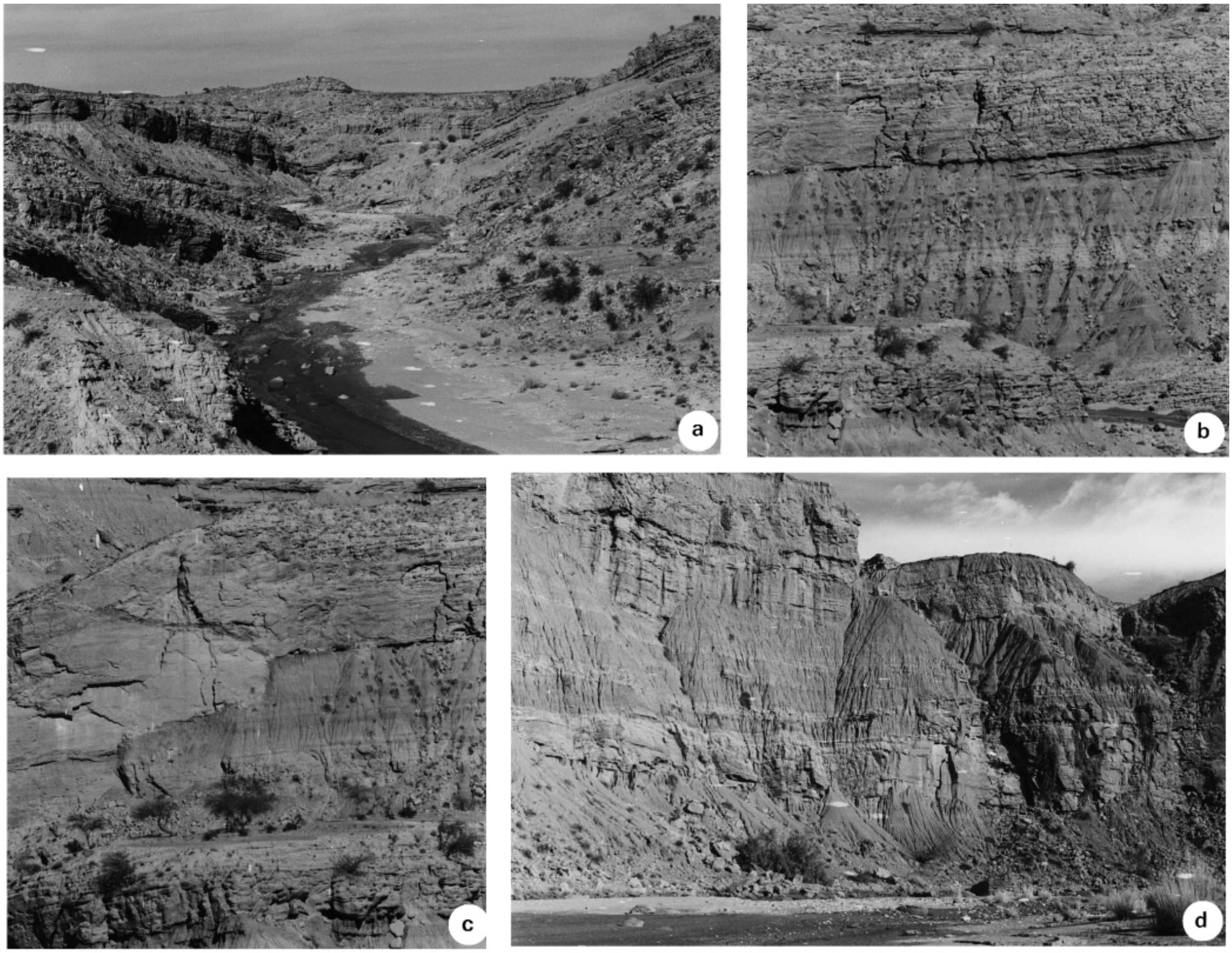

Fig. 4. Photographs showing typical outcrop styles in the Chinji Formation in the Chinji Village area. (**a**) Stream section parallel to the 10–12° dip, showing the major alternations of sandstone bodies, and the three finer-grained lithotypes (heteroliths, mudstones and palaeosols). (**b**) Strike section showing typical sandstone body sheets alternating with the finer-grained lithotypes. (**c**) strike section showing a thick megasheet (20 m thick) storey overlapping and truncating the termination of an underlying storey. A screen of large mudstone clasts rests on the erosion surface between the two. (**d**) Detail of a heterolith interval between two sandstone bodies. The cliff is about 40 m high.

Lower Chinji Formation correlation panel (the '1990 Fence')

Our object has been to extend the architectural information available from the Chinji area of the Salt Range Monocline Zone by adopting a length or distance sampling scale which is intermediate between the earlier gross stratigraphic studies over distances of many tens of km, and the detailed lateral tracing studies carried out more recently, for example by Willis (1993*a*) and Willis & Behrensmeyer (1994). Typical of this detail is Willis's investigation of his Level A (lower Chinji Formation) in which he measured no less than 45 'vertical' logs, 60 m thick, over a strike distance of 4 km, an average strike interval of about 90 m between logs (Fig. 5).

We adopted a different strategy, realizing that in order to achieve coverage on a greater length scale in the available time, our degree of detail would have to be less than that collected by Willis. We decided to:

(1) select for study one stratigraphic interval, in this case the lower third of the Chinji Formation, some 300 m thick, and measure logs at strike intervals of 500–1000 m (Fig. 1) along strike over about 11 km, and then, with less detail, over a further 14 km;
(2) investigate the variation along strike of the numerous sandstone bodies and their stratigraphic level, accepting that many of the storeys recognized by Willis, would not have been differentiated in our more cursory study;
(3) survey the extent and level of the most obvious palaeosols so that they could be used as markers, independent of the sandstone bodies;
(4) extend the tracing of palaeomagnetic reversal surfaces through the interval so that chronological markers could be established.

Our main systematic survey, hereafter referred to as the '1990 Fence' is based on 13 logs measured over a distance of about 11 km (Fig. 1), along with careful walking out of the outcrop to establish lithological correlations. Figures 6 and 7 are portions of the 1990 Fence, using different methods of presentation. Later in the paper, we extrapolate from one level in the

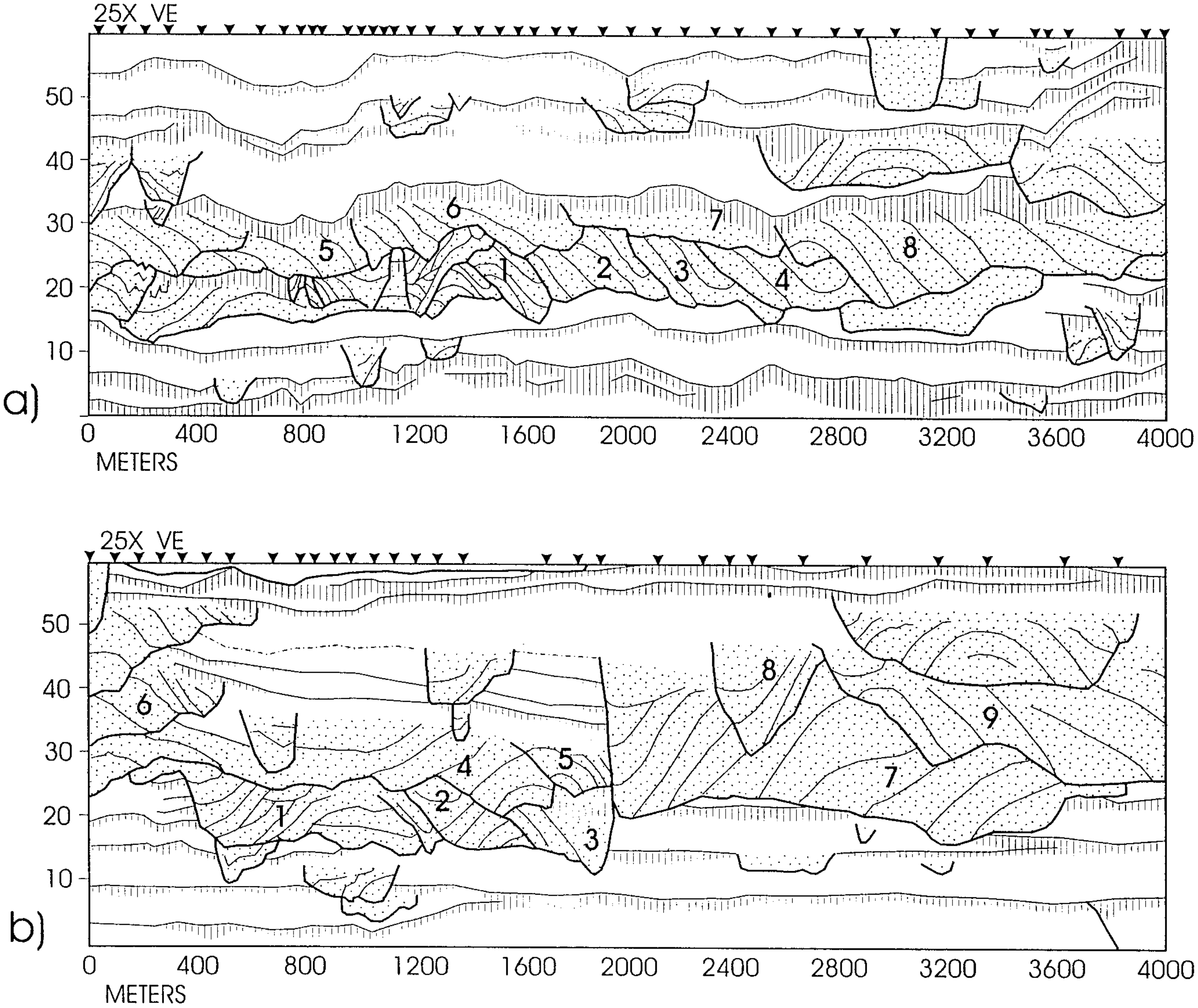

Fig. 5. Two architectural panels, redrawn from Willis & Behrensmeyer (1994, fig. 5). Arrowheads along the upper margins mark the locations of 'vertical' logs; fringes of vertical lines indicate palaeosols. Vertical exaggeration is 25 ×. (**a**) Panel representing the architecture studied at Lower Chinji, Level A (see Fig. 2c). (**b**) Panel representing the architecture studied at lowest Nagri, Level B (see Fig. 2c). Numbers on some of the storeys indicate the relative order of deposition, based on truncations of the underlying surfaces.

Fence to trace the architecture over a total lateral distance of 25 km.

Definitions of sandstone bodies and storeys

In vertical panels such as our 1990 Fence, sandstone bodies are often isolated i.e. completely surrounded by 'floodplain fines', made up of the three finer-grained lithotypes (mudstones, heteroliths and palaeosols). Examples of this are bodies 107, 4, 118 of 21 (Fig. 6). In other cases there may be contact between two sandstone bodies, which we classify as separate bodies provided there is evidence that significant fines have accumulated between the time of deposition of the two. For example, the large sandstone body 19 in the centre of the panel (Fig. 6) is separated from later sandstone body 122 because the eastern termination of body 122 shows that several metres of fine material were deposited between the deposition of the two sandstone bodies. Similarly sandstone body 119 (Fig. 6) was deposited distinctly before the deposition of major body 19.

Sandstone bodies, if isolated, are generally bounded below by erosion surfaces, and above by depositional surfaces. Most outcrops display very little erosional relief on the basal surface, but others display relief of several meters, and the truncation of other sandstone bodies and palaeosols is very clear (e.g. bodies 26 and 130 at the base of the panel, Fig. 6). Lateral terminations of sandstone bodies are often difficult to locate precisely in the field, particularly when they consist of gradual thinning of the sandstone. However some terminations are more abrupt and represent the filling of much steeper channel margins (e.g. body 2 at the top of the panel, Fig. 6).

The thicker sandstone bodies often consist of storeys, divided by erosion surfaces (Friend *et al.* 1979; Willis 1993*a*). The storeys are defined by erosional truncations, and by differences in grain-sizes or the types or orientations of sedimentary structures. These storeys represent discrete episodes in

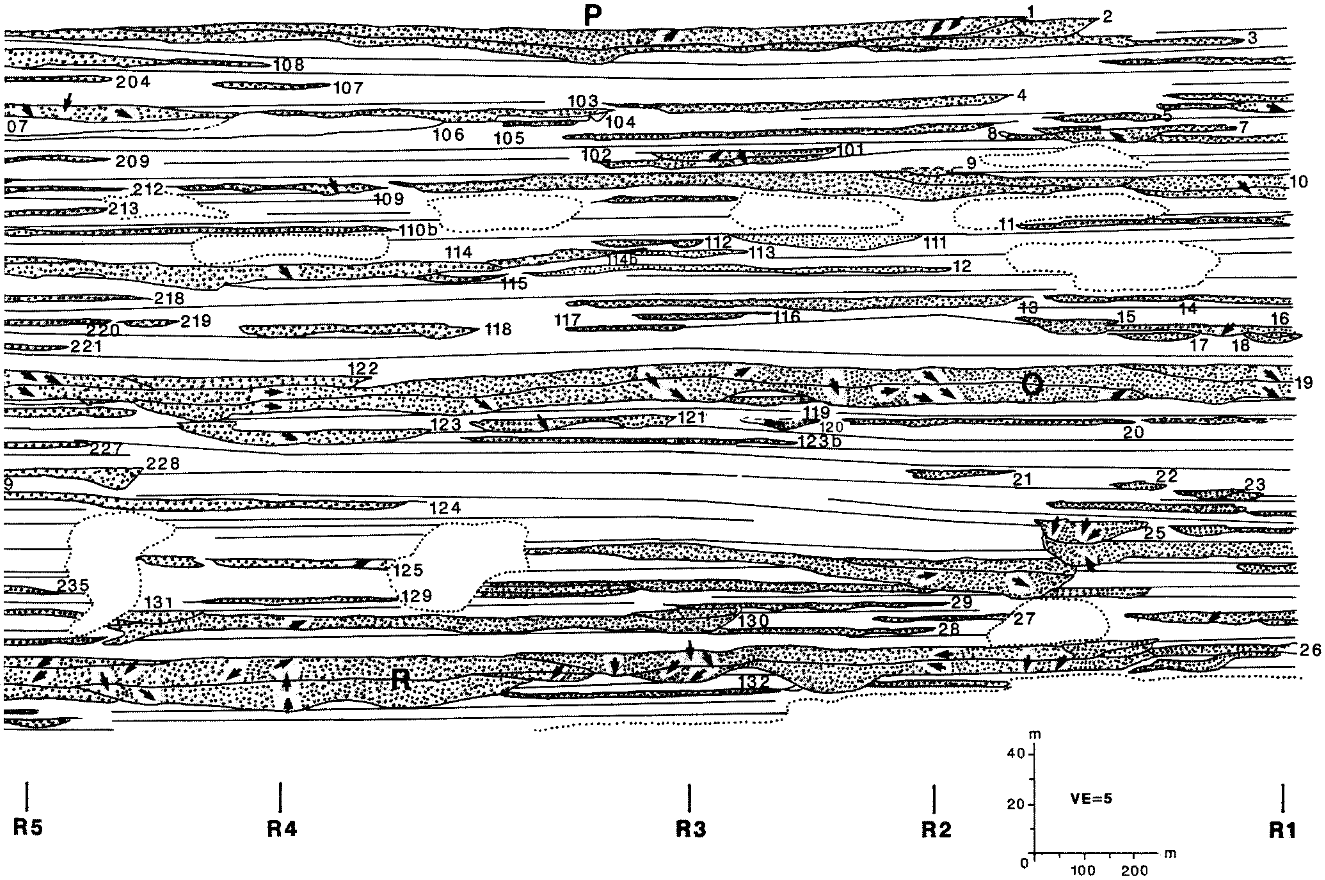

Fig. 6. Segment of lateral mapping of sandstone bodies between sections R1 and R5 (locations on Fig. 1). Sandstone bodies are stippled, and palaeosols are shown by isolated lines. Sandstone bodies are identified using a numbering scheme, and the main mega-sheets are lettered. Palaeocurrent measurements are indicated by orienting the arrows with respect to north vertical on the profile.

the evolution of the sandstone body. The detailed analysis carried out by Willis & Behrensmeyer (1994) is illustrated in Fig. 5, where study of truncations allows the step-by-step movement of storeys in the panel to be tracked through time. We have numbered storeys in the mega-sheets of Fig. 5, to indicate sequences in these movements through time, and this allows sub-horizontal (or multilateral) stacks to be distinguished from more vertical sandbody stacking.

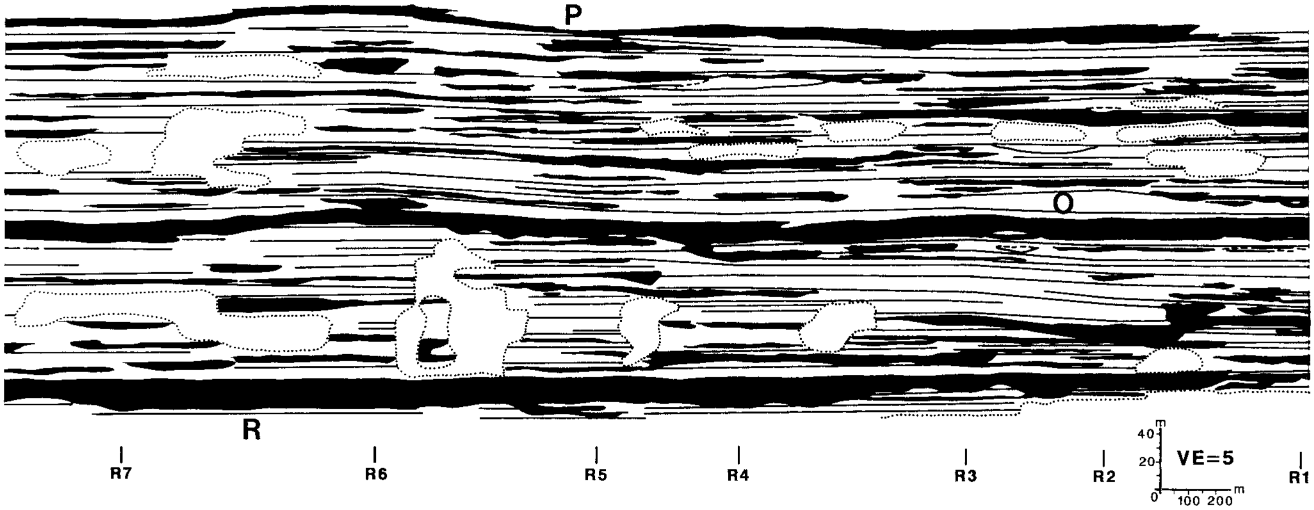

Fig. 7. Longer segment of lateral mapping of sandstone bodies than that of Fig. 6, between sections R1 and R7. Sandstones bodies are shown in black, and palaeosols are shown by isolated lines. Gaps in the outcrop are surrounded by dotted lines. The three mega-sheet sandbodies are labelled R (Rainbow), O (Obstacle) and P (Parking).

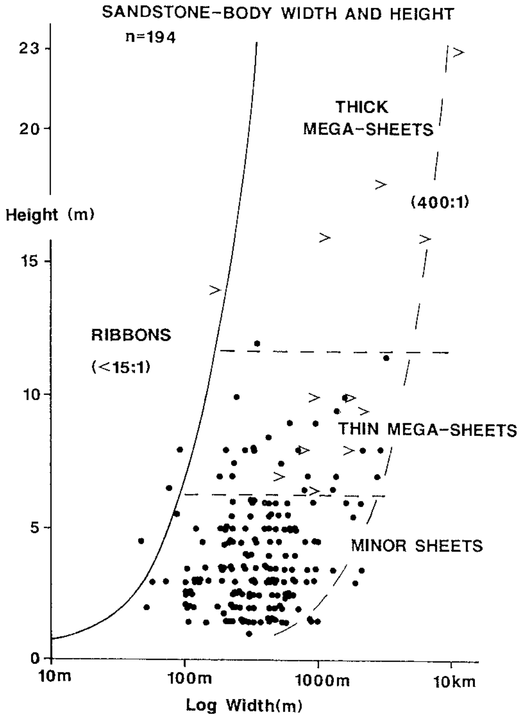

Fig. 8. Semi-log plot of the apparent width and height (thickness) of sandstone bodies in the R1–R11 area (see Fig. 1 for location). Curved lines plot the position on the graph of bodies with width/height ratio of 15 (continuous line) and width/height ratio of 400 (dashed line). Open arrow-heads, pointing to the right, plot the height and minimum apparent body width of sandstone bodies without exposed lateral terminations in the outcrop.

Profile shape of sandstone bodies

The simplest index of profile shape is based on the external sandstone body dimensions (Fig. 7), and consists of the apparent width/height (W/H) ratio. In studies of Cenozoic fluvial sandstone bodies in northern Spain, a distinction was drawn between sheets and ribbons, depending on whether the W/H ratio was more or less than the arbitrary number, 15 (Friend *et al.* 1979, 1986). In the Spanish work, three-dimensional exposure of many of the ribbon bodies showed that they are elongate parallel to the general palaeocurrent, as would be expected if they had been formed as channel fills, or channel belts. The width measured for the Spanish W/H survey, was defined as that perpendicular to the elongation of the body. The height taken was generally the maximum height of the sandstone body.

In our 1990 Fence study in Pakistan, three-dimensional outcrops indicating the trend of elongation of sandstone bodies are rarely available. We therefore had to be content with using apparent widths to calculate apparent W/H ratios of the sandstone bodies in our major profile, and the results of this are discussed below. Palaeocurrent directions were measured at sites indicated by single arrows on Fig. 6, with each arrow representing an average of several readings of cross-stratification made at each site. Systematic correction of the apparent widths to provide estimated widths perpendicular to the sandstone body trend, made no significant difference to the general distribution of W/H ratios, because the general palaeocurrent trend is at a high angle to the overall orientation of the panel.

Figure 8 shows the distribution of sandstone bodies on a plot of apparent width/ maximum height. Only three of the 194 sandstone bodies have ribbon width/height ratios of less than 15, so all the rest of the bodies are sheets, using the terminology of Friend *et al.* (1979).

Sandstone bodies in the 1990 Fence

Using the definition discussed above, we have counted and numbered almost two hundred sandstone bodies that crop out on the 1990 Fence, measuring their maximum height and apparent width. We did not count some of the minor sandstones that were only partially exposed, or occur at the outer (lateral) limits of the Fence.

We find that maximum height is the simplest practical criterion for classification, and we have adopted the following terminology:

(1) micro-bodies, less than 1.2 m thick, often transitional into heteroliths;
(2) minor sheets, 1.2 to less than 6 m thick;
(3) thin mega-sheets, 6 m to less than 12 m thick;
(4) thick mega-sheets, 12 m to our maximum of 23 m thick;

The sandstone bodies described as thick by Khan *et al.* (1997) and Zaleha (1997*a*, *b*) have a thickness greater than 5 m, so are approximately equivalent to our thin and thick mega-sheets together.

A distinctive intermediate length-scale architectural feature of the Fence is provided by the presence of three thick mega-sheets, informally named by previous Chinji area workers, the Rainbow, Obstacle and Parking Sandstones, in ascending stratigraphical order (sandstone bodies numbered 26, 19 and 1 in Fig. 6). These sandstones form the most extensive markers in the stratigraphy, and the Rainbow and Parking Sandstones were chosen by us as the approximate lower and upper limits for the measurement of the Fence. Between these three thick mega-sheets, there are thin mega-sheets, minor sheets and micro-bodies, but we cannot detect any clear pattern in their stratigraphic distribution. We refer to this large-length-scale pattern as the spaced thick megasheet pattern.

Rivers that formed the Chinji Formation sandstone bodies

One of the levels (Fig. 5a) selected by Willis (1993*a*) for detailed work included the ‘Obstacle Sandstone’, our central thick megasheet sandstone body 19 (O on Fig. 6). In the 4 km outcrop length that he studied, Willis (1993*a*, fig 6, table 1) recognized eight storeys, vertically and laterally arranged. On the basis of his measurements of thicknesses, lateral extents, geometries, and grain-sizes, he suggested the following range of palaeochannel statistics: apparent bar width, 45–130 m; estimated bank-full width, 70–200 m; maximum depth, 4–13 m; centreline channel sinuosity, 1.1–1.3; bankfull discharge, 430–810 (m^3 s^{-1}). Willis suggested that these channels existed as active features in channel belts that were 1–2 km wide, and probably contained two or three coeval channels, so that each belt may have experienced a multi-channel bank-full discharge of the order of 1500–2000 m^3 s^{-1}.

Our analysis (Fig. 8) of external width/height ratios for the sandstone bodies in our 1990 Fence shows that the great majority of the sandstone bodies are minor sheets (less than

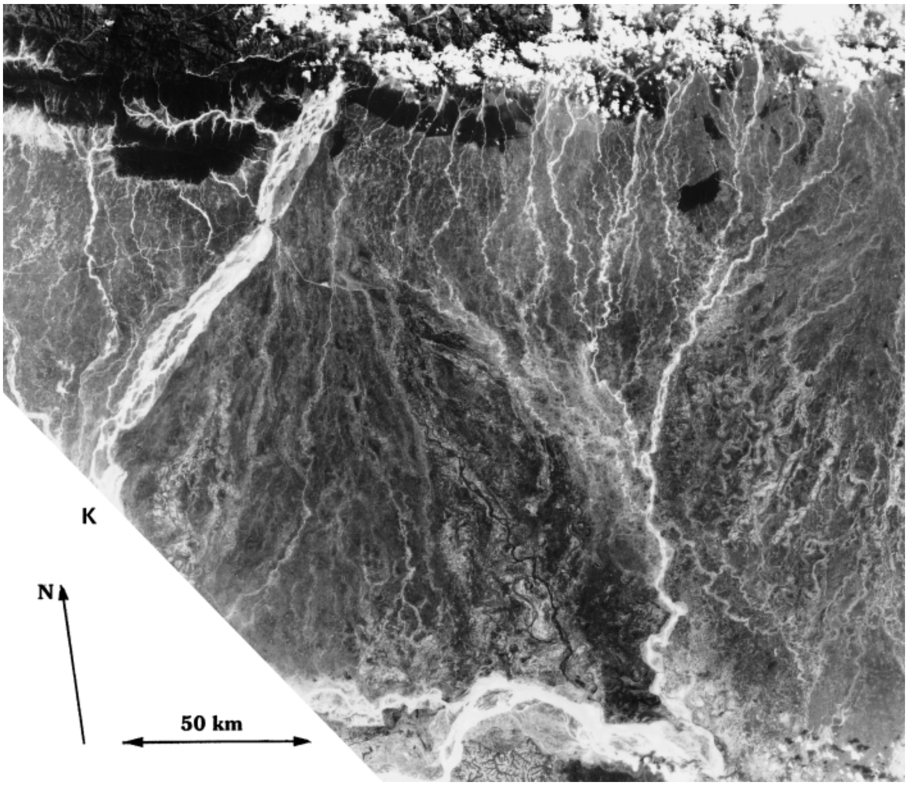

Fig. 9. Shuttle large-format camera photograph of part of the eastern Gangetic plains, India, taken at the time of monsoonal floods. The upper edge of the photograph shows the dark, tree-covered foothills of the Subhimalayas, partly with patchy cloud cover. The lower edge of the photograph shows the complex channel belt of the Ganga River, axial to the eastern plains. To the left, the large channel belt complex is that of the Kosi River (K), and the radial pattern of former channel belts (lighter shade) defines the Kosi megafan. The right-hand edge of the megafan is formed by the Mohananda River. Numerous foothills- and plains-fed rivers are flowing across the alluvial plains in addition to the large, mountain-fed Kosi.

6 m in thickness) that are considerably thinner than the mega-sheet reported above, as analysed by Willis. It therefore seems clear that the thick mega-heets of our 1990 Fence were formed by rivers at the largest end of a continuous range of channel dimensions and discharges represented in the alluvial networks of the Lower Chinji Formation.

Our width/height (W/H) analysis of the 1990 Fence (Fig. 8) has highlighted the relative absence of sandstone bodies that have width to height ratios of less than 15 (ribbons in the sense of Friend *et al.* (1979). This relative lack, at least as far as the larger sandstone bodies are concerned, is also apparent in the detailed work of Willis (1993*a*), Khan *et al.* (1997) and Zaleha (1997*a*,*b*). Another study carried out in younger Siwalik sediments (Dhok Pathan Formation, see Fig. 2) by Behrensmeyer & Tauxe (1982) distinguishes two different sandstone body types and compositions. But the relatively narrow buff bodies are not ribbons in the arbitrary numerical sense used here, even though they appear ribbon-like in vertically exaggerated diagrams. Discussions on the origin of ribbons elsewhere have concentrated on the importance of rapid channel incision and high strength of the bank material (Friend *et al.* 1986; Gibling & Rust 1990). We conclude, therefore, from the rarity of ribbons, that these factors were not important during the deposition of the Chinji Formation

Top Chinji change to multistorey, multilateral stacking

We wish also, in this paper, to discuss the architectural feature that defines the top of the Chinji Formation (Top C on Fig. 2b). This is the change in the sandstone/mudstone proportion that has been used by stratigraphers to define the Chinji–Nagri Formational boundary (Fig. 2b). Although the gross increase in sandstone proportion produces a clear effect on the local topography, the detailed logging by Willis (1993*b*) (Fig. 2c) shows that the increase is not as abrupt as the topography suggests. However detailed study of the sandstone bodies (Willis & Behrensmeyer 1994) shows that the basal Nagri sandstone bodies are altogether larger (Fig. 5b). All recent work on the sandstone-dominated Nagri Formation (Willis 1993*a*, *b*; Khan *et al.* 1997; Zaleha 1997*a*, *b*) has concluded that it was deposited by significantly larger braided rivers transporting coarser sediment than the rivers of the Chinji. Willis found evidence that multi-channel bank-full discharges were of the order of five times as great (10 000 m^3 s^{-1}). The range of estimates by Zaleha (1997*a*) is broadly in line with the estimates of Willis (1993*a*).

Quaternary river networks in the Indian plains as an analogue for Chinji deposition

Present understanding of the tectonic history of the Himalaya and their foredeep suggests that the topographic patterns of source mountains and basin that controlled late Miocene Siwalik fluvial sedimentation 12–14 Ma ago were broadly similar to those that have existed through the Quaternary. It therefore seems reasonable to look to the present-day Indo-Gangetic alluvial plains to provide clues to likely river patterns and behaviour in the late Miocene.

Studies of changes in present-day fluvial geomorphology, and in the geometries of Quaternary architectures are providing important fresh understanding of the controls of changes in river systems (Blum & Tornquist 2000). Quaternary studies may have the advantage of relatively tightly constrained definition of the timing of possible cause and probable effect; but they also have the disadvantage that changes may have been exceptionally strong, short-lived and complex in the Quaternary. Pre-Quaternary events are often more poorly constrained in time, and therefore more open to the dangers of miscorrelation, but, in being less extreme, they may also have been more typical of long continued phases of sedimentation.

The plains of northern Bihar (*c.* 84°–86°E), eastern India, have been studied particularly by Parkash and his group at Roorkee University (Gohain & Parkash 1990; Parkash & Kumar 1991; Mohindra *et al.* 1992; Singh *et al.* 1993; Sinha & Friend 1994). One special reason for selecting this northern Bihar area was the presence of megafans, such as the Kosi megafan (Fig. 9, Wells & Dorr 1987*a*, *b*; Singh *et al.* 1993), where sedimentation appears to have been particularly active. Sinha & Friend (1994) drew special attention to the variety of river morphologies and sizes in northern Bihar, reflecting the large and complex catchment-area patterns with very variable rainfall distribution. Different water and sediment sources give rise to three different types of river: large mountain-fed rivers (which have created the megafans), foothills-fed and plains-fed rivers (the latter including supply from surface run-off and/or ground-water), although the network of rivers results in much downstream confluence and mixing of these types. Figure 9 illustrates an area of the basin margin where the Kosi River emerges onto the alluvial plains of Nepal and northern Bihar. In this area, the large braided complex of the mountain-fed Kosi River dominates the much smaller channel traces of the foothills- and plains-fed rivers. Nearer the basin centre, where the large trunk, or mountain-fed rivers, on their megafans, have bankfull discharges of several thousands of cumecs, and the large foothills and plains-fed rivers have smaller, but important bankfull discharges, generally of several hundreds of cumecs (Sinha & Friend 1994).

One difficulty in comparing present-day river patterns on the plains with Siwalik architectures is the lack of information on the sediment geometry just below the present-day surface, particularly at depths greater than one or two metres. Singh *et al.* (1993) report work on the superficial sediments of the Kosi megafan that demonstrates major downstream changes in the present-day Kosi River channel and bar morphology from Zone 1 (braided channel, with gravelly and sandy sediment), to Zone 2 (braided channel, with sandy sediment), to Zone 3 (straight channel, sandy sediment) and to Zone 4 (forming the toe of the megafan, meandering channel, and silty mud sediment). They also report the results of a programme of cored boreholes that they were able to sink to depths of up to 15 m at different locations across the megafan. This work reveals a complex pattern of sediment bodies of distinct grain-size, generally involving overall fining upwards, with gravels at low levels even in areas of the megafan where gravels are not now being transported, and silts or even clays at superficial levels. Singh *et al.* (1993) report also their compilation of data from tubewells across the megafan that penetrate to depths of as much as 80 m. These again show a gross tendency for the bodies of distinctive grain-size to fine upwards, but in this case the authors distinguish an upper formation, commonly 8–10 m thick, but sometimes up to 40 m thick, which they suggest was deposited during the 280 km, east to west sweep of the Kosi River across the distal megafan, that is well known from historical records over the last 250 years (Wells & Dorr 1987*a*, *b*). Below this younger Formation, the tubewells reveal a complex older Formation with varied bodies of gravelly, sandy and muddy grainsizes.

To the west of Bihar, in the Kanpur–Lucknow area of Uttar Pradesh (*c.* 81°E), I. B. Singh and his group have been studying a very different situation where the present-day major trunk rivers have become constrained between terrace edges that have been formed by the incision of these rivers between 10 and 25 m into a major surface that formed early in the Late Pleistocene (80 ka ago, or more; Singh *et al.* 1999). This incision has isolated 'upland interfluve areas', locally known as Doab, from sediment transported by the main rivers, although sediment transfer by more local stream flows occurs on the Doab surface, and may form sedimentary successions several metres thick (Singh *et al.* 1999). Doab are also a well developed feature of parts of the Indus drainage in the Quaternary plains of Pakistan (73°–74°E; Kazmi 1964). Incision producing alluvial valleys between upland interfluve areas, followed by fluvial aggradation filling the valleys is widely recognized as a response to changing relative sea level in sequence stratigraphic studies (e.g. Blum & Tornqvist 2000).

Control of the Chinji alluviual architecture

General approach to the analysis of mechanisms

Previous discussions of the causes of the alternations or cycles in fluvial formations like the Chinji Formation have recognized autocyclic alternations, where the controls have been internal to the basins, and simply reflect avulsion of channel systems after episodes of localized accumulation have built alluvial ridges. These alternations are the basis of fluvial basin-fill modelling (e.g. North 1996), and we assume that periodic avulsion of this kind was a normal and underlying feature of the Chinji architecture. But a special aim in this paper is to consider the intermediate-scale and rather larger features of the architecture that seem likely to have been allocyclic, or controlled by external mechanisms.

External controls have been usefully studied by investigating historical changes in present-day fluvial geomorphology, and also the architecture of Quaternary deposits where external controls can be relatively well constrained (Blum & Tornquist 2000). Building on the discussion of these authors, we find it useful to clarify thinking by grouping the external controls of fluvial changes in the following way:

(1) *upstream*—changes of water or sediment input to a fluvial reach;
(2) *downstream*—changes in gradient that have migrated upstream from an area of changing base level (sea level, or something more local);
(3) *local tectonics*—creating local changes of gradient.

It has to be realized that these types of controls may be closely linked to each other; i.e. that a change in one may often be correlated directly with a change in another. For example, climate changes are almost inevitably linked to both upstream changes of water and sediment input, and also to downstream control of base level, often sea level.

Alluvial networks forming the Lower Chinji Formation

A regional survey of Chinji Formation palaeocurrent measurements for the Potwar Plateau and some neighbouring outcrops has been provided by Burbank *et al.* (1996). This shows average flow directions to the east and ESE, although some measurements in the area closest to the present-day Indus River have averages to the south. The detailed recent work of Willis (1993*a*, *b*; Khan *et al.* 1997), and Zaleha (1997*a*, *b*) is consistent with this. Friend *et al.* (1999) suggest the existence of a megafan on which the palaeoIndus swung between east or ESE in the Chinji area, and south in the area west of the present Indus River.

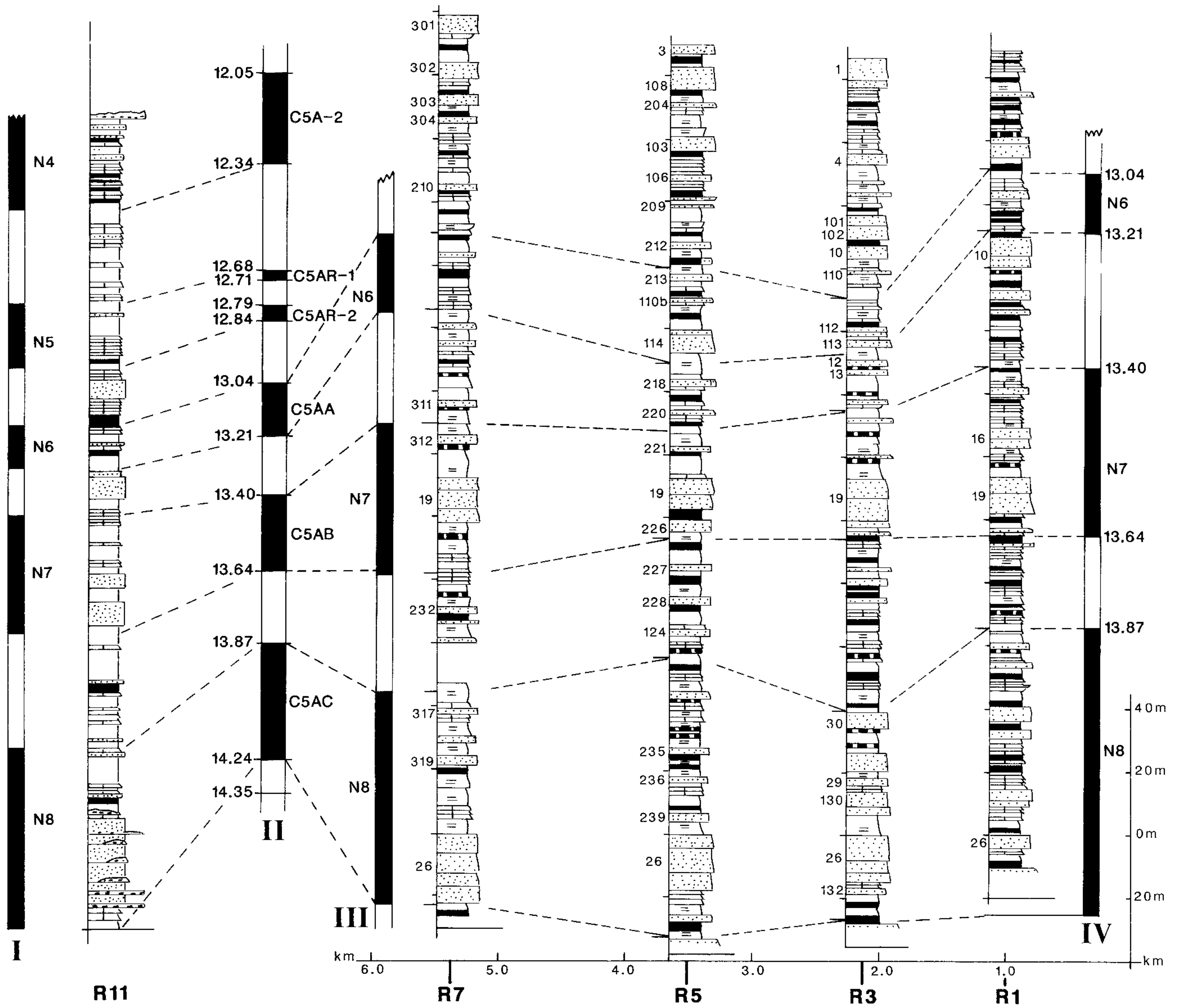

Fig. 10. Vertical profiles with sedimentological details of sections R1, R3, R5, R7 and R11. Lithological symbols are shown on Fig. 4. The local magnetic chrons, and the positions of their boundaries are shown in columns I, III and IV, and column II relates these to the Magnetic Polarity Time Scale with chron ages from Harland *et al.* (1990). The normal polarity chrons numbered N4 to N8 are the same as those established by Johnson *et al.* (1985, 1988) in the Hutch Nala and Chitta Parwala areas. Numbers given to some of the sandstone bodies on the left of the profiles are part of an arbitrary numbering system, also shown on Fig. 6.

Work in the younger Siwalik formations, such as the Dhok Pathan Formation (Behrensmeyer & Tauxe 1982), and the Upper Siwalik Sub-Group (Burbank *et al.* 1996) has found sandstone bodies of distinctive composition and form. Our microscopic examination of many samples from Chinji sandstone bodies has failed to find any similar differences during Chinji sedimentation. We therefore conclude that the Chinji sediments were deposited by a simple river network with uniform sediment provenance and transfer direction.

Timing of the spaced thick megasheet pattern in the 1990 Fence

The occurrence of three thick multilateral mega-sheets separated by stratigraphic intervals of thinner sandstone bodies forms the most obvious intermediate-scale architectural feature in the 1990 Fence, and has been noted above, along with the informal names of the mega-sheets: the Rainbow, Obstacle and Parking sandstones. The upper surfaces of the sheets are spaced stratigraphically at intervals of 110 m (Rainbow to Obstacle) and 135 m (Obstacle to Parking).

Johnson *et al.* (1985) measured the palaeomagnetic reversal succession in the Lower and Middle Siwalik succession of this area, and matched it with the Global Polarity Timescale. They also later (Johnson *et al.* 1988) considered local spatial variability of sediment accumulation rates in the lower Chinji Formation, finding a range from 0.13 to 0.18 m ka^{-1}. We have extended their reversal stratigraphy by locating the reversal surfaces in the section that forms the framework for our 1990

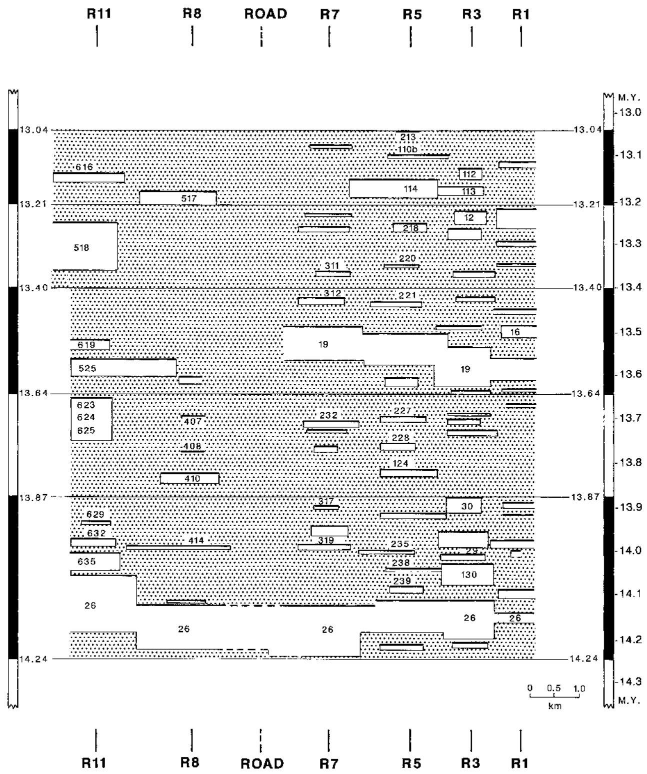

Fig. 11. Temporal distribution of the sandstone bodies in the lower part of the Fence, between R1 and R11 (see Fig. 1 for location). This is based on the magnetic reversal time lines established for the six sections shown here (see Figs 3 and 6), and assuming constant sedimentation rate within each magnetic polarity interval. The lateral extent of the sandstone bodies, and their connectedness, are based on the lateral tracing illustrated in Figs 6 and 7. Thick lines at the top of the sandstone body rectangles indicate the time at which each channel complex avulsed into the area, and eroded the floodplain thus creating a 'window' in the otherwise relatively continuous record of fine-grained 'overbank' sedimentation. The vertical height of each window is proportional to the time interval represented by the overbank material removed before the sandstone body was deposited

Fence (Fig. 10). In spite of some updating of the Global Polarity Timescale (Harland *et al.* 1990), an estimate of 0.15 m ka^{-1} continues to provide an average for the whole Fence that is adequate for our purposes.

Figure 11 presents a simple approach to considering the sandstone-body distribution of the lower part of the Fence on a time basis. The initial assumption is that the generally fine-grained 'background' sedimentation proceeded at the steady rate measured by the palaeomagnetic work, but that the sandstone bodies represent distinct episodes, occurring within this background, and consisting of a rapid channel erosion phase (that was effectively instantaneous, relative to the background rate, see Friend *et al.* 1989), followed by an equally rapid channel sedimentation phase. On the diagram, the timing of these two channel phases is represented by a heavy horizontal line, and a 'window' below the line represents the loss of the background sediment record due to the channel erosion phase.

The first and second thick mega-sheet episodes (Rainbow, body 26, and Obstacle, body 19) are spaced in time by about 0.6 Ma, and the second and third (Obstacle and Parking) by about 0.9 Ma, assuming a uniform rate of net accumulation. Relatively smaller sandstone body-forming episodes occur at intervals of 0.05 Ma (50 ka) on average. This is the same order of magnitude as the 20–60 ka intervals estimated by Willis and Behrensmeyer (1994) for the mudstone/palaeosol episodes that they studied. Table 1 summarizes the general hierarchy of cycles recognizable in our study of the Chinji architecture.

Interpretation of the thick mega-sheets

Our sandstone body thickness analysis shows that the thick mega-sheets exist as the large 'tail' of a distribution that extends continuously from the minor sheets, in terms of thicknesses and width/height ratios. Some of the mega-sheets, and almost all of the small number of thick mega-sheets extend laterally outside the range of the 1990 Fence, and must exceed the 400:1 width/height ratio arbitrarily plotted on Fig. 8. They certainly represent a complex lateral association of distinctive sandstone bodies. To investigate this phenomenon further, we have put together observations from the area east of our 1990 Fence that allow us to represent, over a distance of 25 km, the lateral tracing of our lowest thick mega-sheet (Fig. 12, the Rainbow sandstone body, 26 on Fig. 11).

Although this lateral tracing over 25 km (Fig. 12) lacks the detail (particularly in the recognition of storeys) that is available from the intensive work of Willis (1993*a*), we nevertheless feel that comparisons within this extended tracing have value. This tracing reveals that the western two-thirds of the mega-sheet contains many storeys, and has a relatively irregular erosional base. Connected to this, between sections R1 and

Table 1. *Summary of architectural hierarchy in the Chinji Formation*

	Thickness	Time period	Origin
Local cycles	10^{-1} to 10^{+1} m	10^{-6} to 10^{+4} years	Oscillations due to flow turbulence and flood patterns (a) in *channel sandstone deposits*: strata, sets (dune-scale bed-forms), cosets (bars, channel-fills), storeys; (b) in *overbank mudstone deposits*; micro-sandstone bodies (channel margins), heterolith units (channel margins), mudstone (floodbasins), palaeosols (high floodplain), laminae in mudstones and rare carbonate beds (floodbasin lakes)
General sandstone-mudstone cycles	10 m	10^{+4} to 10^{+5} years	Channel avulsion–overbank accumulation
Spaced thick mega-sheet cycles	10^{+2} m	10^{+5} to 10^{+6} years	Periodic presence of deposits of constrained large channel belt complexes
Formation-scale cycle	10^{+3} m	10^{+6} to 10^{+7} years	Change of river size and behaviour, due to tectonic reorganization in source mountains, or climatic change

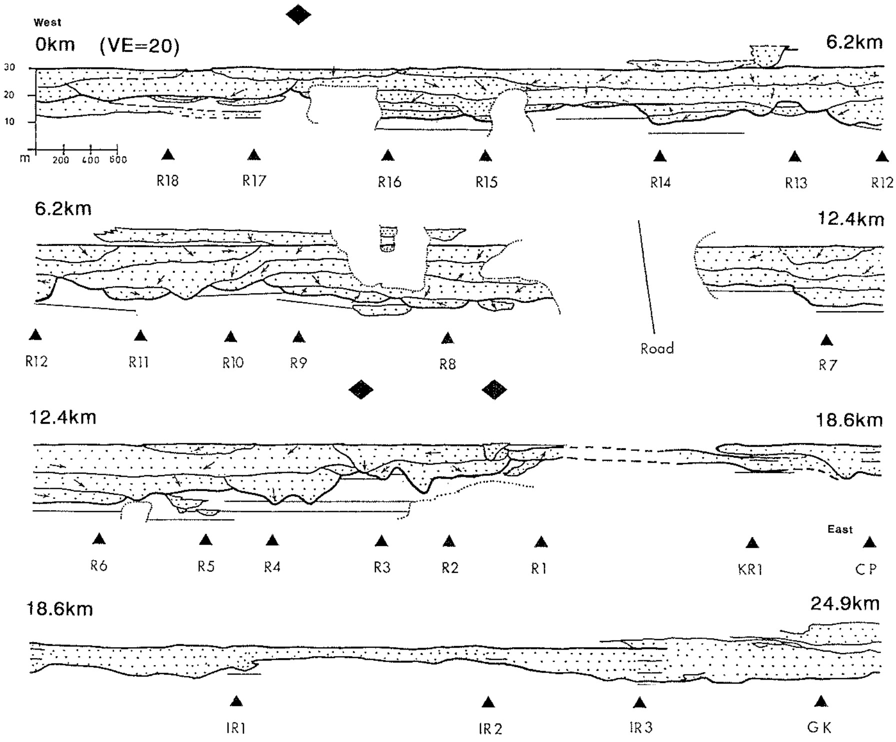

Fig. 12. Profile illustrating lateral tracing of the Sandstone E–Rainbow Sandstone bodies over a distance of 25 km.

KR1, is a relatively thin, single-storey, sandstone sheet, which then leads eastwards into a thicker section of the mega-sheet that, nevertheless, has a generally smoother erosional base, and is not clearly divided into storeys. We also recognize points in the tracing, which we call 'nodes' (marked by diamonds on Fig. 12) at which lateral continuity within the sandstone is broken by an abrupt barrier in the form of a storey boundary. The 'Rainbow' mega-sheet (Fig. 12) reveals some of the regional variation in the history of a braided channel belt complex. Its history of lateral avulsion seems to have been simple and rapid (like the Kosi of the last 250 years) in the eastern part of the tracing, but more complex and long-lived in the west.

We propose that the Chinji mega-sheets were formed by the largest rivers of the Chinji plains and that these resembled smaller versions of the perennial, braided, mountain-fed, rivers of northern Bihar today, like the Kosi (Fig. 9). Whereas the channel belt occupied by one of the Chinji rivers was perhaps 2 km in width, the mega-sheets, and particularly the thick mega-sheets, provide evidence of a history of avulsion of the channel belts, that resulted in lateral stacking, with no preservation of 'islands' of overbank material. The present Kosi has avulsed repeatedly over the last 250 years, and, in that time, it has covered the width of the mega-fan with major spreads of channel-belt sands, extending over distances ranging from 100 km to 10 km at the distal and proximal parts, respectively, of the mega-fan (Singh *et al.* 1993). Some of this Kosi avulsion has very likely left islands of overbank material, but many of the avulsions probably did produce continuous lateral stacking. The nodes of the Fig. 12 lateral tracing may represent episodes where the local continuity of stacking was almost broken.

The important next question about the thick mega-sheets is why they were formed by such persistent and continuous lateral stacking of storeys, whereas the smaller sandstone bodies in the intervals between the megasheets are generally simple. A persistent tectonic tilting of the alluvial surface may have been important, as has been suggested for the Kosi megafan of Bihar (Wells & Dorr 1987*b*). However, in the absence of independent evidence of this persistence, we prefer an answer in terms of the plan-pattern of the river network (Fig. 13). We suggest that the network consisted of a main channel belt complex containing the largest rivers, now represented by the thick mega-sheets, and large numbers of smaller belts containing smaller channels. The pattern might have been similar to that containing the main, axial, Ganga River, in the present-day eastern plains. Relative lateral stability would have been a feature of the main, large-river, channel belt complexes, which were constrained sufficiently by terraces or

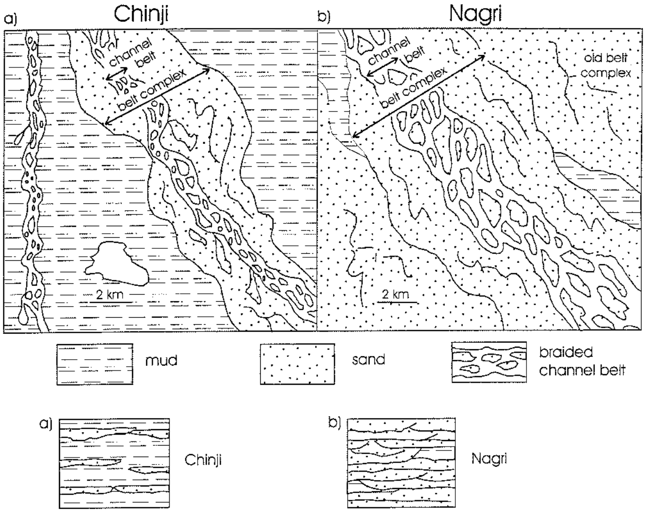

Fig. 13. Sketch plans to illustrate the fluvial geomorphology of the alluvial plains reconstructed in this study as typical of (**a**) the Chinji Formation and (**b**) the Nagri Formation.

low valley walls that the channel belts reoccupied locations often enough to maintain the connectedness of their deposits during aggradation. In contrast, the smaller channel belts were free to switch more widely in response to avulsive floods. The lateral stability of the belt complex could have been provided by periodic valley-form incision, or simply by the regional transverse alluvial surface gradients that constrained the large axial river channel belt as it performed a Ganga-like central drainage role for the whole network. Periodic valley form incision, probably due to upstream and/or downstream changes is a feature of some parts of the Ganga today (Singh *et al.* 1999)

Our study of the architecture of the Chinji Formation has shown that thick mega-sheets occur at thickness intervals of the order of 10^2 m, which implies a time periodicity of the order of 10^2–10^3 ka. The thick megasheets represent an episode in which the 'normal' braided river channel belt continued to occupy a number of different local positions, all within a channel belt-complex that was 10 km or more wide. It is difficult to suggest a mechanism for this periodic phenomenon. Megafans, such as the present-day Kosi, owe their fan form, to the localization on the basin margin of a major river input-point, fixed there during the tectonic growth of structures in the Subhimalayan fold and thrust belt (Friend et al. 1999; Abbasi & Friend 2000). Our understanding of the tectonic setting is that the Chinji village area was hundreds of km south of the tectonically active northerly margin of the basin in Chinji times. This provided considerably more alluvial space for the lateral swinging of the main drainage belt and the periodicity of the thick mega-sheets appears to record this, whereas its periodic constraint may indicate incision due to external (relatively short period, climate or sea level) mechanisms.

Top Chinji change

Any explanation of the relatively abrupt and widespread upward increase in the proportion of sandstone at the top of the Chinji Formation must also reflect the relative (but not complete, see Fig. 2c) lack of the finer-grained lithotypes in the overlying Nagri Formation. This seems most likely to imply a lack of constraint on the lateral movement by avulsion of the channel belt. The channel belt appears to have been able to move freely enough across the alluvial surface to allow most of the finer grained sediments recently deposited to be eroded and transferred downstream. The lack of constraint implies that the major channel belts were not incised into the alluvial surface. In this respect, they would have been similar to the Kosi belt of Bihar, and different from the incised Ganga channel belt of the Kanpur–Lucknow area. Figure 13 attempts to cartoon the probable difference between the Chinji and Nagri environments. In Chinji times the floodplain was traversed by braided rivers, typically 1–2 km wide, and with bankfull discharges for the whole braid belt complex up to 2400 $m^3 s^{-1}$, whereas the equivalent discharge in Nagri times may have been up to thirty times as great (Zaleha 1997*b*). Zaleha argues that this change was not a result of climate change, but probably due to a change in the major floodplain drainage pattern, resulting from drainage reorganization within the tectonically evolving mountain source area. We do not feel able to distinguish between upstream tectonic and climatic controls in our analysis. However, a factor that may have been linked to the change in the amount of incision is the net rate of sediment accumulation in the various intervals. We have suggested above that the net rate of sediment accumulation for the lower part of the Chinji Formation was about 0.15 m ka^{-1}, measuring over time intervals of 10^6 a. The equivalent rate estimated for the Nagri Formation was 0.3 m ka^{-1}, measuring over a similar time interval (Johnson *et al.* 1985), so we suggest that this increase in the rate of net sediment accumulation may have resulted in less incision.

The present-day accumulation estimates for the youngest Quaternary of the Kosi area (Sinha *et al.* 1996) are as high as 1 m ka^{-1}, (although this is measured over relatively short intervals of 10^3 a), and this is an area that lacks major incision and terracing. In contrast, rates for the Kanpur–Lucknow area are considerably lower, and incision is highly characteristic, as pointed out above.

Concluding lessons for reservoir modelling

The 1990 Fence provides new insight into the kilometre-scale organization of alluvial deposits that in a reservoir context can help provide answers to questions such as: given the thickness of a sandstone bed, what is its 2D profile likely to be? How extensive is it likely to be, and how likely is it to be connected to another sandstone body? In addition, the Chinji exposures help reconstruct the geometry of spaced alluvial mega-sheets which are important in reservoir considerations because they can act as stratigraphic markers and are also so laterally continuous (e.g. Fig. 12) that they may form reservoirs that are an order of magnitude more important than any of the lesser sandstone bodies in which they are encased. Our outcrop work has shown that the great majority of the Chinji sandstone bodies (thicker than 1.2 m) lack significant internal mudstone barriers that might restrict permeability. This is not so of the thinner sandstones that make up the heterolith packages, most of which are not likely to be of value as reservoir rocks.

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