ARCHITECTURE OF MIOCENE OVERBANK DEPOSITS IN NORTHERN PAKISTAN

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ABSTRACT: Understanding the geometry of sediment bodies and patterns of sediment disruption in ancient fluvial overbank successions is fundamental to interpretations of overbank deposition. Overbank deposits of the fluvial Chinji Formation (Siwalik Group) can be divided into sequences 1-20 m thick defined by the alternation of stratified sediments and paleosols. Preservation of stratified sequences does not support a gradual vertical aggradation of overbank sediments over the extent of the floodplain, but instead indicates periods of rapid sediment deposition followed by long hiatuses and soil development. Rapid deposition of overbank sequences is predicted by models that hypothesize: (1) episodic vertical aggradation of the entire floodplain, (2) deposition controlled by the growth of alluvial ridges, (3) incision and filling of local valleys, (4) rapid filling of localized low areas, or (5) rapid deposition associated with river-channel avulsion. These models also have important implications for understanding fossil preservation and floodplain paleoecology.

Paleosol-bounded sequences in the Chinji Formation can pinch out laterally over kilometers, indicating that episodes of rapid deposition were restricted to local areas on the floodplain. There is no evidence that bases of sequences are erosional, and they do not appear to record valley incision and filling. Sequences generally do not thin and fine systematically away from the terminating margins of major channel deposits, suggesting they are not related to the growth of alluvial ridges along active channels. Lithologic variations and patterns of sediment disruption within sequences appear to reflect the rapid filling of low areas on the floodplain both adjacent to and distal from the major river channel. This infilling of floodplain topography may reflect a continuous process, whereby local areas were always being filled somewhere on the floodplain by sediments from minor tributary or crevasse channels. Alternatively, the filling of local flood-plain topography may have been caused by widespread but short-lived events associated with river-channel avulsion.

INTRODUCTION

Lithologic variations in overbank sequences generally record sediment deposition during river floods or avulsions, whereas patterns of disruption reflect postdepositional processes and the duration of hiatuses separating depositional events. Although it is now generally accepted that stratal architecture must be documented across large outcrops to characterize ancient fluvial-channel deposits adequately (see discussions in Miall 1985 and Bridge 1985), isolated vertical sections are still commonly used to infer patterns of overbank deposition and the spatial arrangement of floodplain environments. Also, proposed schemes to classify the architecture of alluvial deposits have relegated overbank deposits to a single "architectural element" (e.g., Miall 1985), implying that they are rather homogeneous bodies of sediment. However, the few studies that have documented ancient overbank deposits in detail over scales adequate to characterize patterns of floodplain aggradation (e.g., Behrensmeyer 1987; Bown and Kraus 1987; Kraus and Aslan 1993; Smith 1990, 1993) indicate that overbank successions have complex and varied architectures. Documentation of these complexities is fundamental to interpretations of overbank deposition and floodplain construction.

Overbank deposits commonly are composed of stratified sediment bodies (i.e., containing preserved primary depositional stratification) separated by paleosols, and in ancient strata these paleosols can be used to define the boundaries of large-scale sequences or overbank architectural elements. It is generally accepted that overbank sediments with well preserved primary stratification were deposited relatively rapidly, and that mature paleosols record long depositional hiatuses or at least long periods when local deposition rates were very low (e.g., Retallack 1984; Kraus and Bown 1986). It can also be inferred that sediments between individual paleosols accumulated within the same overall time interval and therefore represent related depositional environments.

This paper documents the geometry and internal lithologic variations of paleosol-bounded overbank sequences exposed in the type section of the Miocene Chinji Formation in northern Pakistan (Fig. 1) and discusses these sequences in terms of models for overbank deposition. Such analyses of overbank deposits have important implications for reconstructions of ancient floodplain environments, for studies of stratigraphic completeness and fossil preservation, and for understanding processes of sediment aggradation on floodplains (see also Kraus and Bown 1986; Bown and Kraus 1987; Behrensmeyer 1987; Smith 1990, 1993; Behrensmeyer et al., in press).

DEFINITION OF PALEOSOL-BOUNDED SEQUENCES

It is important from the outset to define general characteristics of paleosol-bounded sequences in the Chinji Formation (Figs. 2, 3). These sequences commonly are 4–10 m thick and represent sediment accumulation and disruption (including pedogenesis) over periods of 20,000–60,000 yr, assuming constant deposition rates between horizons dated magnetostratigraphically by Johnson et al. (1985). Well developed paleosols in the Chinji Formation are generally 1–3 m thick, lack primary depositional bedding, have heightened red/orange hues relative to subjacent deposits, have a leached horizon that lacks disseminated groundmass carbonate normally underlain by abundant carbonate concentrations, and contain distinctive pedogenic features like calcic and sesquioxidic nodules and cutans, slickensided clay films, birefringent groundmass fabrics, and mottling. Sediments directly below horizons showing distinct pedogenic structures also lack preserved primary stratification, and these sediments probably record either sediment disruption in the lower part of the mature paleosol or reduced sediment aggradation rates during deposition of the uppermost part of the paleosol-bounded sequence.

Sequences with preserved primary stratification between paleosols can show rather complex variations in grain size and patterns of stratal disruption (Fig. 2). Vertical trends in grain size and disruption vary greatly, both between different sequences and for individual sequences measured at different locations. Some sequences fine upwards, others coarsen upwards, and many show more complicated vertical grain-size trends. Grain-size trends and variations in sediment disruption can be used to define smaller-scale sediment bodies within paleosol-bounded sequences. These sediment bodies can also fine or coarsen upwards, but depositional stratification becomes more disrupted upward in all bodies. Disrupted horizons capping sediment bodies within sequences have burrows, root trace fossils, and mudcracks, and can be considered to be minor incipient paleosols. However, these disrupted horizons are distinct from the well developed paleosols that bound sequences in that they are generally only decimeters thick and they do not show distinct pedogenic horizons that can be mapped independently of the lithologic bodies they cap. Sediment bodies are in turn composed of a number of centimeter- to decimeter-thick beds, each interpreted to reflect deposition during an individual flood. Centimeter-

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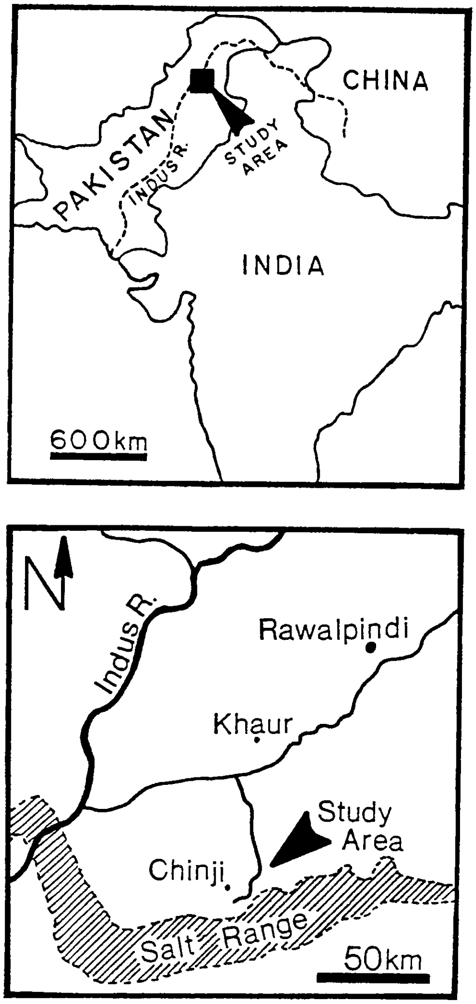

FIG. 1.—Map of the study area.

to decimeter-thick beds, sediment bodies, and paleosol-bounded sequences record a progressively larger-scale and longer-duration hierarchy of depositional events.

Sediment bodies within paleosol-bounded sequences can be mapped in two dimensions across exceptionally continuous exposures in the Chinji Village area of northern Pakistan (Fig. 3; see also Behrensmeyer 1987; Willis, in press). These sediment bodies typically have very broad lobate or wedge shapes recording deposition on crevasse splays or levees, or have channel-form shapes recording deposition within minor floodplain channels. Generally, bodies are coarser where they are thicker, and are finer and more disrupted where they become thinner. Where stratal disruption is less intense, beds within sediment bodies contain fine planar lamination or ripple cross-lamination, and beds within sandstone-dominated channel-form bodies also locally contain large-scale cross-stratification reflecting deposition by migrating dunes. However, it is only rarely possible to document in detail the geometry of centimeter- to decimeter-thick beds within sediment bodies, and sedimentary structures within beds are difficult to discern where bodies become significantly disrupted. Thus, in most cases it is the thickness of paleosol-bounded sequences and the overall geometry of the sediment bodies within sequences that can be mapped reliably in the field.

MODELS FOR OVERBANK DEPOSITION

Lithologic variations and patterns of sediment disruption in overbank deposits record variations in depositional processes and rates. Many past studies have portrayed overbank deposition as a gradual vertical aggradation of sediments from suspension following floods (e.g., Wolman and Leopold 1957; Allen 1965 and references cited therein). Vertical accumulation rates of the Chinji Formation averaged only a few centimeters per hundred years (based on magnetostratigraphic studies of Johnson et al. 1985). If actually aggraded at these average rates, new sediments deposited on floodplains would have been incorporated into active soils, and thus all depositional stratification in Chinji overbank successions would have been disrupted completely by desiccation, bioturbation, and/or pedogenesis. This was not the case, however, and preservation of deposits with primary depositional stratification must record periods when deposition

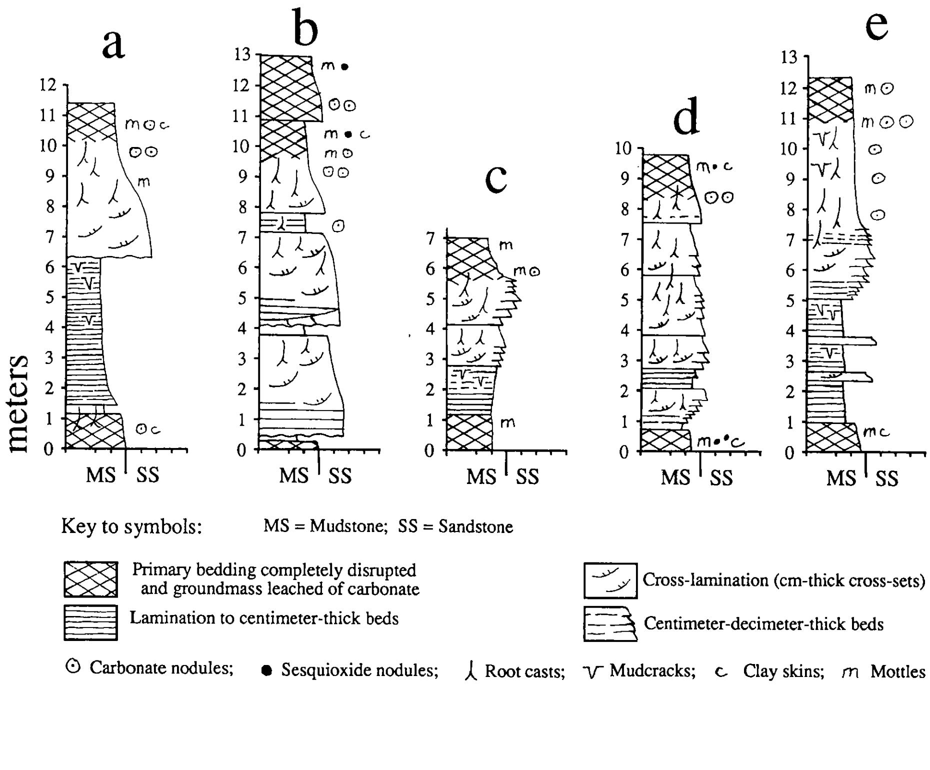

FIG. 2.—Vertical change in sedimentary structures and textures measured across different paleosol-bounded sequences. Deposits containing preserved depositional stratification are bounded by paleosols defined by disrupted layers that lack depositional stratification, lack groundmass carbonate, and contain distinctive pedogenic features, normally underlain by abundant carbonate nodules. Sediment bodies within sequences are defined by vertical variations in grain size and primary sedimentary structures and by changes in the extent of sediment disruption by cracks, burrows, and root traces. Logs presented were measured across different sequences shown in the upper bedding diagram in Figure 5 (the horizontal and vertical position of each log on this bedding diagram is, respectively: (1) 130 m, 32–43 m; (2) 300 m, 33–46 m; (3) 420 m, 3–10 m; (4) 720 m, 41–51 m; and (5) 1660 m, 34–47 m).

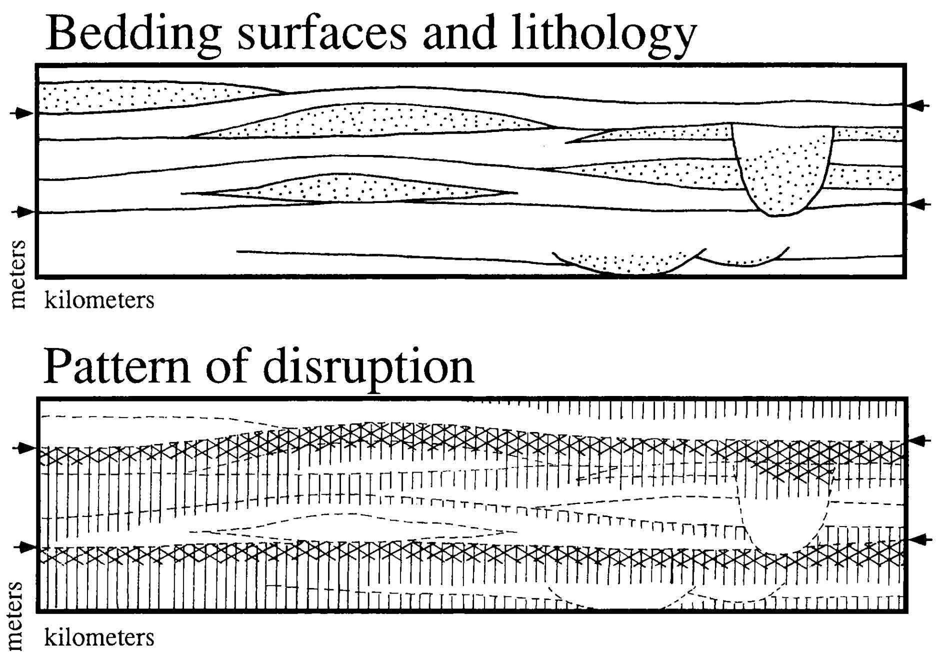

FIG. 3.—Sediment bodies within a hypothetical paleosol-bounded sequence are defined by lithology and depositional bedding (upper box) and by patterns of sediment disruption (lower box). In the upper box: sequence-bounding surfaces are marked by arrows, lines show depositional beds defining the boundaries of sediment bodies, and coarser-grained parts of bodies are marked by dot stippling. In the lower box: deposits with well preserved depositional stratification are unstippled, deposits that are extensively disrupted are marked by vertical lines, and well defined paleosols are cross-hatched. Most sediments are disrupted to some extent by roots, burrows, and mudcracks, reflecting pedogenic disruption; however, the well developed paleosols that bound sequences are distinct layers in which primary depositional stratification is completely disrupted and horizons are defined by the vertical distribution of pedogenic features and color.

rates were orders of magnitude higher than mean values. Overbank sequences with depositional stratification thus suggest patterns of deposition on the ancient floodplains that were episodic.

The idea that overbank sequences of the Chinji Formation record episodic sedimentation is hardly new or surprising. Several models of floodplain aggradation in the geologic literature (proposed on conceptual grounds or from the study of Holocene floodplain deposition) predict such patterns of overbank deposition. These models are presented as hypotheses in Figure 4 and are summarized below. Each hypothesis is presented as an end-member case, but they are not necessarily mutually exclusive. Thus, overbank deposition recorded in any individual fluvial succession may reflect a combination of processes, and separate hypotheses are presented only as a framework in which to interpret overbank sequences observed in the Chinji Formation.

The first hypothesis predicts that the entire floodplain aggraded episodically. For example, Joeckel (1992) suggests that overbank successions can be divided into floodplain-wide "parasequences" separated by paleosols representing "terrestrial condensed sections". Spatial variations of paleosol-bounded sequences are assumed to reflect a control extrinsic to the river system (such as changing base level) that can be resolved despite local "noise" associated with deposition of individual crevasse-splay, levee, and overbank channel deposits. In this hypothesis the thickness of sediments between paleosols may change gradually when traced across the basin, reflecting floodplain-wide changes in the accommodation space that developed during individual episodes of aggradation. However, variations in the thickness of paleosol-bounded sequences measured in a vertical succession would generally reflect changes in the magnitude of the extrinsic mechanism controlling episodes of floodplain aggradation.

The second hypothesis predicts that rates of sediment aggradation are controlled by the proximity of the major channel belt. Thicker and coarser-grained sequences with well preserved depositional stratification represent rapid deposition adjacent to the channel belt, thinner and finer-grained sequences represent deposition farther from the channel belt, and well developed paleosols capping overbank sequences represent depositional hiatuses when the river avulsed to distant locations on the floodplain (e.g., Bridge 1984; Kraus 1987; Smith 1990, 1993). It has been postulated (based on such a model) that vertical trends in the thickness and grain size of successive superjacent stratified sequences reflect progressive stepping of major channel belts across the floodplain (Kraus 1987). This hypothesis is predicated on the observation that deposition rates are elevated directly adjacent to major channels in many modern river systems (e.g., Fisk 1947; Kesel et al. 1974; Farrell 1987; McCarthy et al. 1992; and many others); however, deposition rates also decrease markedly over distances of a few hundred meters to a few kilometers away from channel belts across modern floodplains that can be more than 100 km wide. In spite of this, the hypothesis suggests that channel proximal-distal gradients in river-transverse floodplain slope, deposition rate, and the grain size of deposits are not only local to the major channel belt but that they control deposition of overbank successions across the entire floodplain. The hypothesis also suggests that paleosol-bounded sequences are formed by processes intrinsic to the river system, e.g., processes related to the growth of alluvial ridges along active channels and major channel-belt avulsion across the floodplain.

The third hypothesis predicts episodes of degradation and aggradation on the floodplain. During periods of degradation (perhaps related to changes in base level), river channels incise the floodplain to form valleys (probable ancient examples are described by Behrensmeyer and Tauxe 1982; Kraus and Middleton 1985; Kraus and Bown 1986; Behrensmeyer 1987). Stratified sequences form as the system becomes aggradational again and floodplain deposition is restricted to areas in incised valleys. Once incised valleys are filled, the river is free to avulse to other locations on the floodplain and/or overbank deposition is distributed more evenly across floodplain surfaces and continued sedimentation contributes to developing soils. This hypothesis (like the second) suggests that stratified overbank sequences are restricted to the course of the major channel belt, but here sediment geometries record filling of locally incised valleys and not the growth of topographically elevated alluvial ridges. Coarser deposits associated with degradation may be expected along the base of stratified sequences, with deposits fining as the valleys fill and floodplains widen. Recognition of the erosional nature of the lower contact of these stratified sequences is critical to a test of this hypothesis, but this relationship may be subtle where both valley filling and underlying truncated strata are dominated by mudstone.

The fourth hypothesis predicts an essentially continuous process of localized overbank deposition that shifts as isolated low areas on the floodplain gradually develop and are filled. For example, Tye and Coleman (1987) described sediments rapidly deposited by a minor channel into a locally ponded area on the floodplain of the lower Mississippi River, and

Wells and Dorr (1987) indicated that minor channels on the Kosi Fan deposit fine sediments in ponded areas that are far removed from the present course of the modern Kosi River. Sequences containing preserved depositional stratification that separate paleosols are assumed to be localized bodies that do not extend across significant areas of the floodplain. Thus the floodplain aggrades as a patchwork of stratified sequences formed in areas where floodplain subsidence is locally higher (e.g., due to differential compaction of underlying sediments or local fault control) or in areas where floodplain drainage is locally blocked by the depositional topography of abandoned channel ridges. Sediments filling such low areas could be derived from the major channel belt or from minor overbank channels, and thus in this hypothesis stratified deposits are not necessarily restricted to locations along the path of the major channel belt (contrary to Hypothesis 2). Deposits associated with the development of alluvial ridges are assumed to be restricted to areas directly adjacent to the channel belt, without significant lateral extent relative to the width of the floodplain (also contrary to Hypothesis 2). Stratified sequences fill low areas, but aggradation is not localized in valleys incised into underlying deposits (contrary to Hypothesis 3). Sequence thicknesses would reflect predepositional floodplain topography, but local sediment grain size would reflect the proximity of the sediment source. Thus, the thickest parts of sequences would not necessarily be the coarsest (unlike Hypothesis 2). Sequences may generally coarsen upwards, with fine lacustrine mudstones preserved lower down, indicating progradation of sediments into ponded areas (in contrast to Hypothesis 3).

The fifth hypothesis predicts that periods of rapid overbank deposition are associated with the avulsion of the major river. After the major river avulses to a lower area on the floodplain, rapid overbank deposition occurs as the river creates a new course across an irregular floodplain. Lower areas fill with stratified deposits along the course of the new channel belt, and higher areas that dam local areas on the floodplain may be eroded, until an even grade is established. Once the new channel belt develops, overbank deposition slows (or is spread more evenly) and soils again cover the floodplain. This hypothesis is a simplification of that advanced by Smith et al. (1989) from their study of avulsion of the Saskatchewan River in Canada (details of their model may reflect the special case of river systems with low initial downbasin gradients and water-saturated floodplains). It is distinct from Hypothesis 2 in that sediments fill relief and rapid deposition occurs only during the short period directly following river channel avulsion. Also, deposits are not necessarily related to an adjacent major channel belt in the systematic way predicted by Hypothesis 2 because most deposition occurs before the new channel belt develops. Unlike Hypothesis 3, deposits do not fill incised valleys. Unlike Hypothesis 4, stratified sequences do not reflect a continuous process of localized floodplain deposition but instead reflect a short period when a large number of low areas were filled in rapid succession along the course of a developing channel belt.

Each hypothesis predicts different sequence geometries, grain-size trends, and/or relationships of stratified deposits to major channel bodies. However, it may be difficult in practice to test these different hypotheses in many ancient fluvial successions because geometric relationships usually must be observed over kilometers, and bedding relationships in overbank deposits can be at very low angles, making them difficult to recognize in outcrop. Tests of these hypotheses thus require exceptional exposures like those found in the Chinji Village area of northern Pakistan.

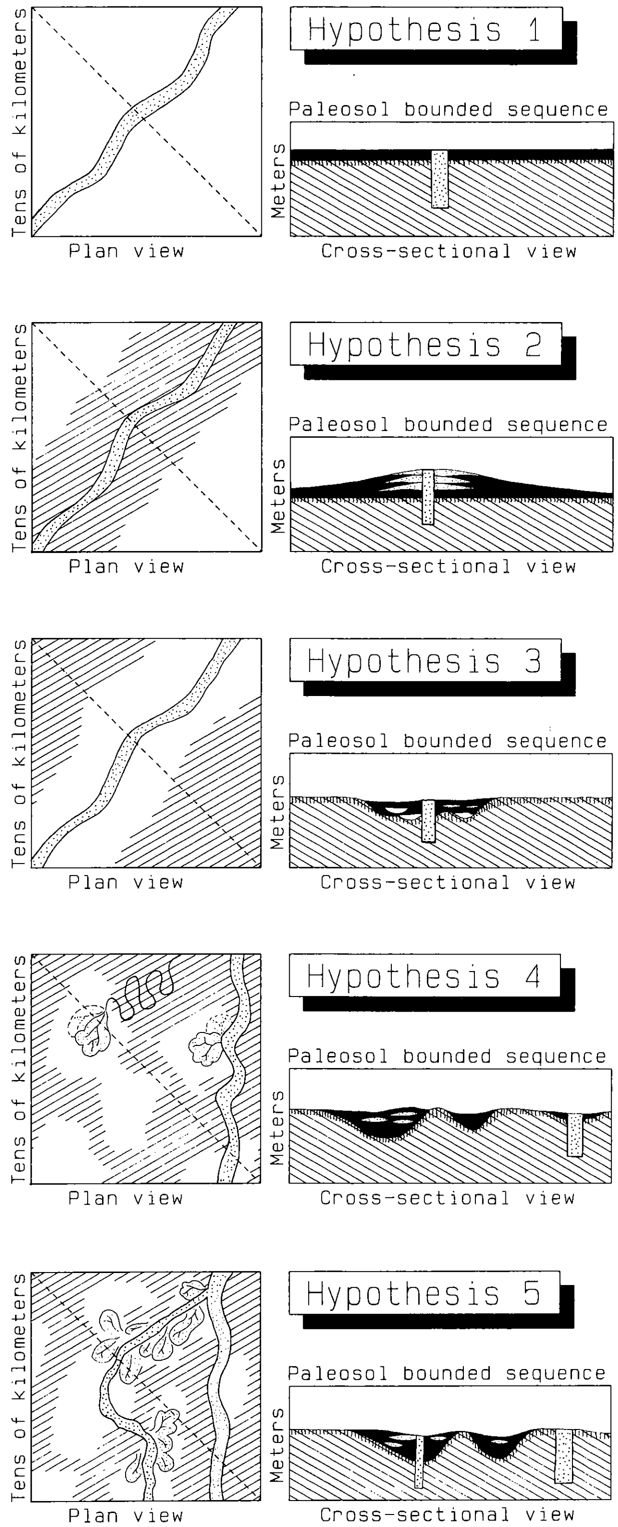

FIG. 4.—Five hypotheses to explain the preservation of deposits with preserved primary depositional stratification in the Chinji Formation (see text). Each hypothesis is shown schematically in plan view and cross section. On plan-view maps, lined hatching marks floodplain areas of above-average topography, dotted stipple shows areas of sandstone deposition including the major channel belt, and the dashed line shows the cross-section orientation. Cross sections show the geometry of paleosol-bounded sequences, with finer-grained deposits of the sequence shown in black and coarser-grained bodies dot stippled.

PALEOSOL-BOUNDED SEQUENCES OF THE CHINJI FORMATION

Continuous exposures of well developed paleosols and channel sandstone bodies have been documented across two east-west-oriented intervals 4 km long by 60 m thick in the Chinji Formation (Fig. 5). Paleosols can be traced for entire intervals studied, except where they are truncated by channel deposits. These paleosols divide the overbank deposits into

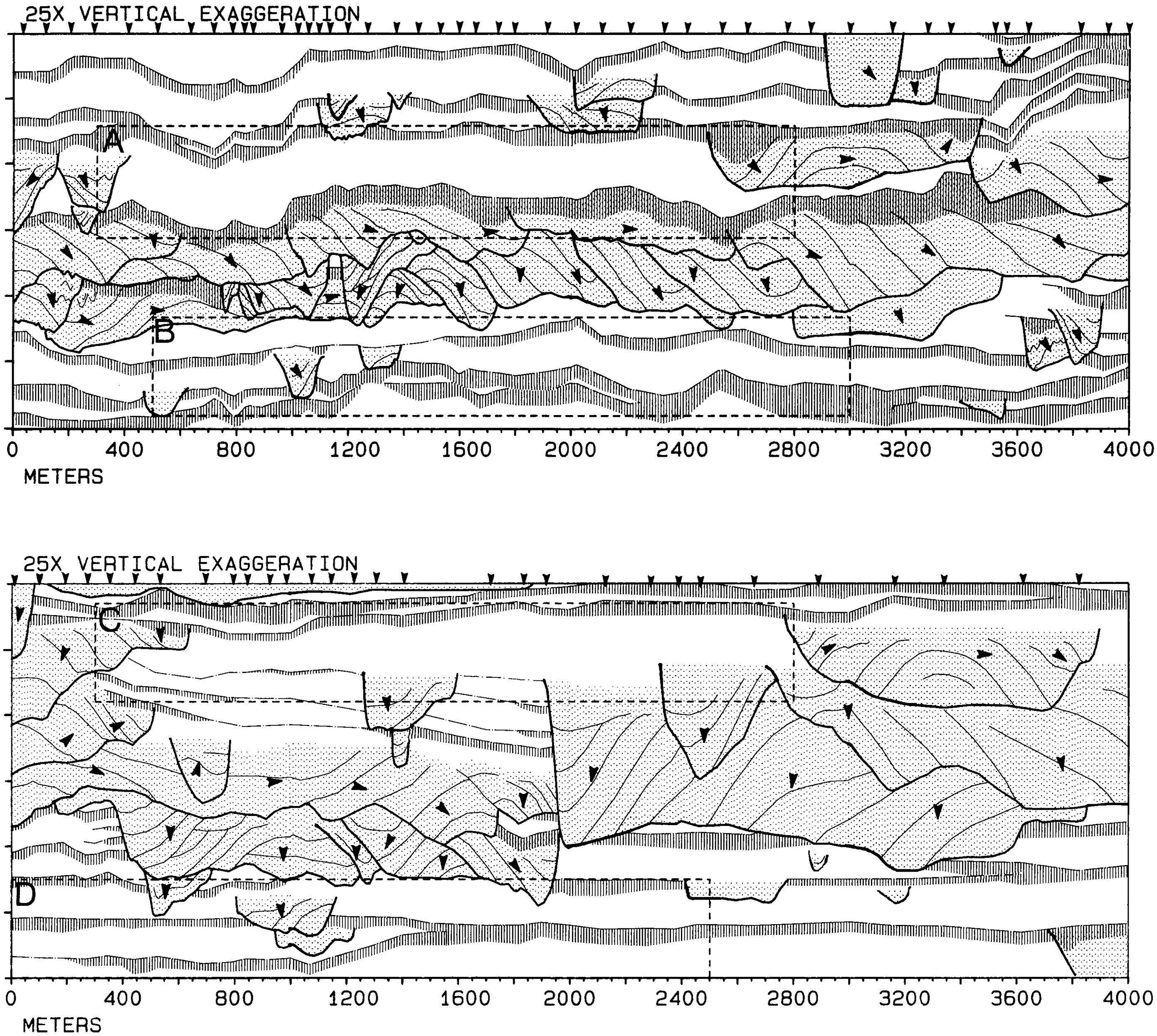

FIG. 5.—Bedding diagrams showing traces of well defined paleosols (vertical-line shading) that bound overbank sequences, and the geometry of major channel sandstone bodies (stippled) in east-west-oriented cross sections. Arrows in sandstone bodies show paleocurrent orientations (down is north; i.e., directly into the outcrop plane). Bedding diagrams are constructed from photomosaics, from the lateral tracing of beds in the field, and from 30–45 vertical logs aligned such that the average vertical distance of all continuous paleosols from a datum was minimized. This method provides a better estimate of how logs align along structural strike than that based on arbitrarily assigning one traceable surface as horizontal, because it is less influenced by the local relief associated with any one bedding surface or paleosol. Positions of measured logs are marked by arrows along the top of the bedding diagram. There is little evidence that sequence geometries are deformed by the differential compaction of lithofacies (e.g., mudstone beds do not appear to drape over margins of sandstone-dominated channel bodies), and thus lateral variations in the thickness of sequences are assumed to reflect changing patterns of deposition. However, compactional deformation of the geometry of sequences cannot be ruled out entirely. Dashed boxes lettered A–D mark sequences documented in Figure 6.

paleosol-bounded sequences. Some of these sequences stay remarkably constant in thickness over the 4 km documented, whereas others change in thickness laterally. In a few locations, paleosols converge (e.g., Fig. 5D, meter 1500), and these locations define the lateral edges of paleosol-bounded sequences. For the most part, traces of paleosols reflect floodplain topography. For example, the paleosol in the lower part of Figure 5A appears to reflect topography associated with the termination of different stories in the underlying sandstone body. Throughout the Chinji Formation, paleosol-bounded sequences generally are not unusually thick or coarse grained directly adjacent to the margins of major channel deposits.

Geometry, internal lithologic variations, and patterns of sediment disruption of paleosol-bounded sequences have been documented in detail across four transects (Figs. 5A–D, 6). The first transect contains the margins of two channels and the deposits in between (Figs. 5A, 6A). On the whole, this sequence coarsens upwards from a basal, finely laminated claystone. The channel deposit on the right side truncates multiple lobes/wedges of sandstone that together form a larger-scale wedge that thins away from the channel-deposit margin over about a kilometer. The base of this larger-scale sandstone wedge rises upwards as it thins across the sequence. Thus it is not clear that this larger-scale sediment wedge records an alluvial

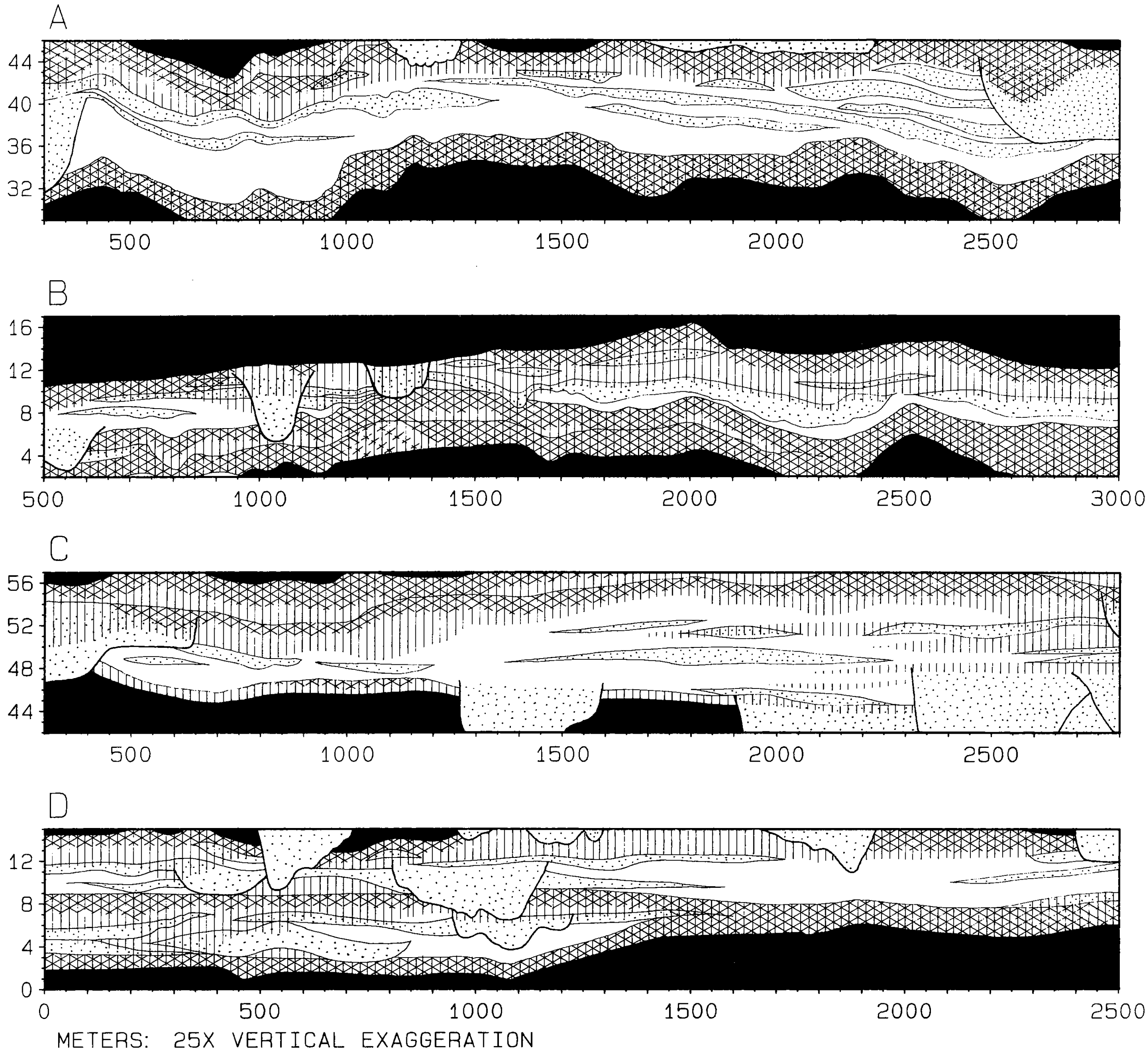

FIG. 6.—Bedding diagrams showing the geometry of paleosol-bounded sequences and the paleosol just below (i.e., areas not colored black), the geometry of coarse-grained sediment bodies (stippled), and patterns of sediment disruption (unlined pattern indicates deposits with well preserved primary depositional stratification, vertical line pattern indicates deposits that show extensive disruption of primary stratification, cross-hatched pattern represents carbonate-leached horizons of well defined paleosols). The alignment of logs used to construct bedding diagrams is based on Figure 5.

ridge with positive relief; instead it may represent a group of sediment lobes filling a low area, which were subsequently cut by the channel. The other channel-deposit margin (to the left side) is continuous with only a single thin sandstone wedge extending over the floodplain. Grain-size variations in this sequence are not related directly to its thickness, but rather thickness variations appear to reflect topography of the underlying paleosol.

The second documented sequence (Figs. 5B, 6B) contains several minor channel deposits and broad lobes of coarse sediment. The sequence is thinner and sediments are more disrupted overall than in the first transect, and undisrupted deposits with primary depositional stratification are generally preserved only where the sequence is relatively thick. It appears that sequences must be at least a few meters thick for stratified deposits to be preserved during subsequent periods of pedogenesis. The paleosol marking the base of this sequence is clearly composite (i.e., representing multiple episodes of pedogenesis and sedimentation), because locally it can be differentiated in two distinct paleosol profiles. The sequence coarsens upward in some locations but fines upward in others, and again grain size is not systematically related to sequence thickness. A minor, relatively coarse-grained channel deposit is present where the sequence is thinnest (Fig. 6B, meter 1300). To the right side there is a thickening of a sandstone lobe where the sequence thickens and then an abrupt thinning of this lobe where the sequence thins again (Fig. 6B, meter 2500). This relationship appears to reflect the topography of the underlying paleosol and thus is not necessarily related directly to the thickness of the paleosol-bounded sequence as a whole.

The third transect (Figs. 5C, 6C) again shows how a sequence varies between two channel margins. The sequence generally thickens to the right, away from a channel margin on the left. Deposits in this sequence are quite fine grained overall (i.e., claystone), except for several thin lobes of silty sandstone. Coarse-grained lobes appear to be slightly more common to the right, where the sequence is also thicker, and somewhat more disrupted along specific bedding planes.

The final transect (Figs. 5D, 6D) contains two paleosol-bounded sequences. The upper sequence continues across the entire interval, and, if channel deposits that cut into the top of the sequence are ignored, it maintains a relatively constant thickness laterally. The lower sequence maintains a relatively constant thickness for the first kilometer (left side) and then thins rather abruptly over a few hundred meters and ends where the bounding paleosols join to form a composite paleosol profile. Deposits in the two sequences vary similarly overall. Both contain some minor channel deposits and associated lobes/wedges of sandstone that extend for only a few hundred meters laterally. However, the upper sequence maintains a constant thickness as it fines to the right, whereas the lower sequence thins and pinches out. Again this demonstrates the lack of correlation between sequence thickness and lateral grain-size trends.

The geometry, internal variations in lithology, and patterns of sediment disruption in the five sequences described above can be compared with the hypothetical sequences in Figure 4. Paleosol-bounded sequences in the Chinji Formation vary greatly in thickness and grain size laterally, and some examples terminate over kilometers. Thus, these deposits do not support episodic vertical aggradation of sediments across the full extent of the floodplain (cf. Hypothesis 1), nor can sequences be assumed to record an extrabasinal control on floodplain construction and overbank deposit architecture. The thickness and grain size of paleosol-bounded sequences do not decrease systematically away from major channel margins, and there is little evidence that these deposits are dominated by sediments associated with the growth of alluvial ridges (cf. Hypothesis 2). There also is no evidence that these sequences have erosional bases (cf. Hypothesis 3; however, see rare examples that do have erosional bases documented by Behrensmeyer 1987). The complex lateral variation of sediment bodies and evidence that these deposits are relief-filling would support either rapid aggradation in localized low areas on the floodplain (as in Hypothesis 4) or the widespread filling of low areas associated with major channel avulsion (as in Hypothesis 5). Distinguishing between these latter two hypotheses is difficult, but Hypothesis 5 would be supported if one could demonstrate that overbank sequences are elongated along the course of major channel deposits and that these sequences were associated with ribbon-shaped channel deposits of greatly varying dimensions (cf. "avulsion belt" deposits described by Smith et al. 1989).

IMPLICATIONS FOR FOSSIL PRESERVATION AND PALEOECOLOGY

Fluvial overbank deposits commonly contain a wide range of organic remains (Behrensmeyer and Hook 1992). Fossil preservation depends on various physical, biological, and chemical processes, but assuming these equal, different patterns of overbank deposition influence the spatial and temporal sampling of plant and animal remains in floodplain environments. Concentrations of vertebrate remains in overbank deposits appear to depend on the distribution of suitable environments for permanent burial and the degree of time-averaging that is represented in paleosol, channel, or crevasse-splay deposits (Behrensmeyer 1982, 1988). Increased time-averaging (i.e., concentration of stratigraphic time) in paleosols with chemical conditions suitable for bone preservation leads to increased fossil abundance, as in the Eocene Willwood Formation of Wyoming (Bown and Kraus 1981). Fossils preserved in sediments containing well preserved depositional stratification reflect taphonomic processes associated with different depositional environments on the floodplain. Differences in the style of overbank deposition predicted by our five hypotheses have important implications for interpretations of the distribution of preserved fossil remains in time, the patterns of fossil preservation in overbank deposits, and the distribution of habitats occupied by living organisms.

Hypothesis 1 implies episodes of basinwide aggradation that would increase the preservation potential of all depositional environments on the floodplain. Thus one would expect faunas preserved in paleosol-bounded sequences to be representative of the floodplain as a whole, and fossil sites located along widely spaced stratigraphic sections would provide faunal samples from the same succession of time intervals. Hypotheses 2 and 3 both imply linear habitats and depositional environments that parallel the channel belt. The linear habitats predicted by Hypothesis 2 would be relatively stable through time, and thus fossil distributions reflecting ecological gradients may be preserved (e.g., Bown and Beard 1990). In Hypothesis 3, some depositional environments and habitats would be restricted to incised valleys during periods of degradation, and environments would become more uniform after valleys filled during periods of aggradation. Lag deposits of reworked bones and terrace paleosol fossil assemblages representing long periods of time-averaging could result from the valley-cutting phase of Hypothesis 3.

Hypotheses 4 and 5 predict similar architecture of overbank deposits. Floodplains formed according to Hypothesis 4, however, would have a patchy mosaic of contemporaneous depositional and soil-forming areas. The continual formation and abandonment of crevasse-splay channels and lobes would provide conditions suitable for localized concentration and burial of bones in channel-related situations as well as in paleosols. Thus sequences should provide more localized and temporally variable samples of the original floodplain communities. In contrast, Hypothesis 5 suggests that soil-forming processes would dominate large areas of the floodplain for long periods between pulses of avulsion-related deposition. Vertebrate remains probably would be concentrated mainly in paleosols representing lengthy inter-avulsion periods rather than in short-term avulsion-related deposits, unless there was substantial reworking of bone-bearing paleosols during avulsion.

In the Chinji Formation, soil chemistry appears to have impeded bone preservation in paleosols, but remains are abundant in floodplain channel deposits associated with crevasse-splay deposition (Behrensmeyer 1987; Behrensmeyer et al., in press), providing support for Hypothesis 4 as a model for Chinji Formation overbank deposition. However, Hypothesis 5 cannot be ruled completely out as a mechanism active during deposition of the Chinji Formation. In many cases, bone-rich floodplain channel bodies appear to cut downward from the upper parts of paleosol-bounded sequences into crevasse-splay deposits that lack concentrations of bone material. In such cases, bone accumulation and deposition in overbank channels appears to have continued after most sediments in the sequence were being modified by a developing soil.

DISCUSSION

Many tens of paleosol-bounded sequences have been examined and traced laterally in the Chinji Formation of northern Pakistan, and the overbank deposits documented above provide a representative sample. Although sequences commonly extend for kilometers, a significant number also gradually pinch out laterally over the 4–10 km distances studied, and it would appear that sequences generally continue for distances on the order of 10 km. Where present, recognizable alluvial-ridge deposits are restricted to areas within a few hundred meters of major channel bodies, and thus alluvial ridge formation cannot be considered the dominant mechanism controlling floodplain construction. A few sequences appear to fill erosional scours that are up to 10–15 m deep and kilometers across, and some of these sequences contain unusually rich concentrations of vertebrate fossils (see Behrensmeyer 1987). However, such erosionally based sequences are observed in only a few stratigraphic intervals, and are not representative of the Chinji Formation as a whole. Most sequences in the Chinji Formation are composed of a complex stack of laterally wedging sediment bodies that are cut by more restricted channel-form bodies (as in the examples presented above). This architecture is interpreted to reflect a complex history of sediment splay aggradation filling low areas on the floodplain, as discussed above. It is less clear whether the deposits that fill these low areas represent crevasse-splay deposition extending significant distances away from the major channel, splay deposition associated with other minor floodplain channels such as tributaries, or splay deposition related to avulsions.

We would not suggest that the style of overbank deposition recorded in the Chinji Formation is characteristic of all fluvial successions. Rather we would emphasize the importance of documenting the architecture of overbank deposits for interpreting the style of floodplain construction, for reconstructing the distribution of ancient floodplain environments, and for understanding the taphonomy of fossil accumulations. We would also suggest that documenting patterns of sediment disruption, including evidence of pedogenesis and the geometry of deposits bounded by paleosols, is at least as important as the mapping of lithologic variations in defining overbank deposit architecture. Any or all of the hypotheses of episodic floodplain aggradation presented above, and the hypothesis that the floodplain aggraded gradually, could describe floodplain construction in a given fluvial succession. The challenge is to determine which mechanisms were most important in the construction of a given fluvial succession and to understand how these different processes control the architecture of fluvial overbank deposits.

CONCLUSION

Overbank deposits in the Chinji Formation of northern Pakistan show complex lithologic variations and patterns of sediment disruption. Sequences of stratified sediment separated by paleosols define large-scale architectural elements in these deposits. Paleosol-bounded sequences are composed of multiple crevasse-splay and minor channel deposits that record periods of rapid deposition extending for distances of at least several kilometers, followed by long hiatuses and the development of soils. The architecture of these overbank deposits does not support models that predict (1) a gradual vertical aggradation of sediments on the floodplain, (2) episodes of rapid deposition extending across the full extent of the floodplain, (3) patterns of floodplain deposition controlled by channel-belt proximal-distal gradients in deposition rate, or (4) periods of valley incision and rapid filling. Instead, lithologic variations and patterns of sediment disruption appear to reflect the rapid filling of low areas on the floodplain. This infilling of floodplain topography may reflect a continuous process of shifting localized overbank deposition, or it may reflect widespread but short-lived events associated with river-channel avulsion.

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