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Conceptual problems and recent progress in fluvial sequence stratigraphy

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ABSTRACT: Although sequence stratigraphic analysis on marine successions have revolutionized interpretation of sedimentary records since the 80's, those on inland fluvial successions have been hampered due to complex responses of a fluvial system to allogenic and autogenic controls. Such a complexity combined with the vague definition of accommodation in an inland fluvial setting, makes it difficult to divide the fluvial successions into genetic packages based on key surfaces such as sequence boundary, marine flooding or regressive surfaces. It means that the application of sequence stratigraphic concept to fluvial successions requires quite different approach to the definition and recognition of fluvial sequence. Current fluvial sequence stratigraphy models emphasizing the role of base-level in accommodation change are not the cases. They oversimplify the relationship between accommodation and alluvial architecture, without considering the difference in organization and nature of stratigraphic records between the marine and the inland fluvial system. The models do not provide a standard procedure for the analysis of fluvial successions without detailed studies on the key surfaces and thus do not predict the nature of stratigraphic records of an inland fluvial system. In this article, recent reports and different perspectives on the spatial and temporal variation of fluvial successions are reviewed in order to shed light on the efforts toward the establishment of new fluvial sequence stratigraphy model which should be conceptually sound and methodologically objective, enabling the fluvial successions to be interpreted in the more flexible and predictable way even in subsurface data.

Key words: fluvial sequence stratigraphy, fluvial system, alluvial architecture, paleosols, stream power

1. INTRODUCTION

The advent of sequence stratigraphy as the third revolution in geoscience in the 20th century (Miall, 1995) has provided an important unifying concept for interpretation of depositional patterns on a basin scale (Van Wagonor et al., 1988; 1990). Sequence stratigraphy as a process-oriented stratigraphic analysis of the sedimentary record predicts stratal architecture and its origin within a time framework of unconformity surfaces. Its studies range from delineating sequences and their boundaries to revealing three-dimensional arrangement of systems tracts (subdivided units of a sequence) that are defined as a linkage of contemporaneous depositional systems. In these studies, it is imperative to recognize sequential development pattern of systems tracts to predict facies relationships that are related to accommodation changes. If sediment supply and tectonic movement are constant, accommodation change in marine settings can be expressed as a sinusoidal curve of relative sea-level change. As such, the concepts of sequence stratigraphy have been successfully applied to marine successions formed on passive continental margins, where tectonic movements are relatively inactive. In the model, sequences are fundamental sequence stratigraphic unit of genetically related strata bounded by unconformities and their correlative conformities and can be divided into systems tracts representing deposits formed during particular stage of relative sea-level (Fig. 1). They reflect changes in accommodation, the space available for potential sediment accumulation. Depending on their relative position to basal sequence boundary, they are designated lowstand, transgressive, highstand and shelf margin systems tracts composed of parasequences or parasequence sets. Stacking patterns of the parasequences are referred to as an indicator of the ratio (A/S), the rate of accommodation creation versus that of sediment supply. This ratio defines progradation (shallowing-up facies change: $A/S<1$), retrogradation (deepening up: $A/S>1$) and aggradation (stationary: $A/S=1$) (Fig. 1).

There have been various attempts to apply the concept of sequence stratigraphy to fluvial successions formed in inland fluvial systems or coastal plains (Westcott, 1993; Wright and Marriott, 1993; Shanley and McCabe, 1994; Olsen et al., 1995; Van Wagoner et al., 1995; Currie, 1997; Dalrmple et al., 1998; Ethridge et al., 1998; Milana, 1998; Martinsen et al., 1999 and others). In alluvial settings, it is questionable to interpret fluvial sequences in terms of the accommodation change because the nature and existence of an equilibrium surface defining alluvial accommodation is debatable. However, broadly similar fluvial sequence stratigraphic models (Fig. 2) predict fluvial architecture and its geometry based on the change in the accommodation rate or base-level. The essential concept of the models is that during times of low accommodation rate, the channels will amalgamated (as during the LST and late HST), while during times of high accommodation rate (during the TST), channels will become isolated and floodplain deposits will be more widespread. According to the model, stratigraphic variations of the proportion and interconnectedness of channel sandbodies encased by floodplain deposits reflect the

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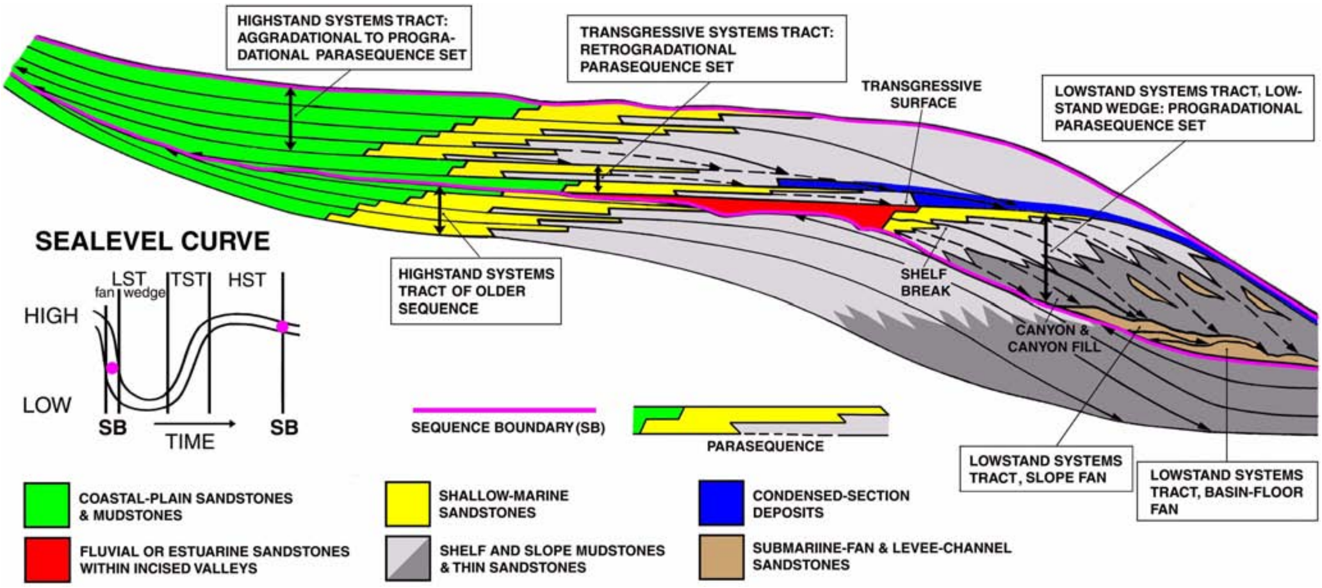


Fig. 1. Cross section of an idealized marine sequence. It shows the geometry of systems tracts with depth and characteristic facies present in them. The sequence is associated with type 1 sequence boundary (SB 1) and forms in a basin margin with a shelf break. Spots on relative sea-level curve represent the timings of formation of sequence boundaries. Type 1 and 2 sequence boundaries (SB 1 & 2) are formed when the relative sea-level falls below and above shelf break, respectively. At the time for SB 1, accommodation rapidly decreases, and incised valley develops. (Modified from Van Wagoner et al., 1988).

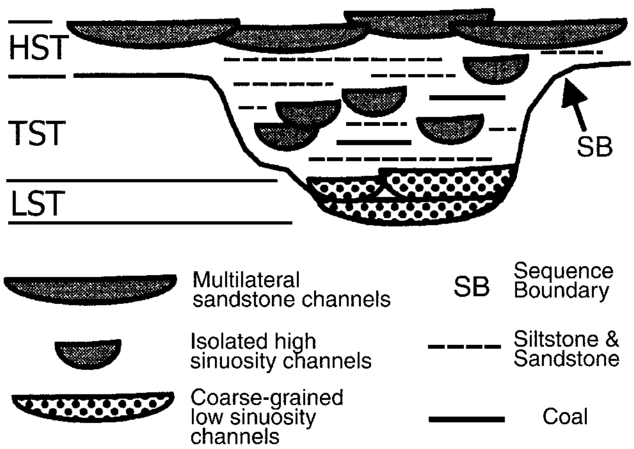


Fig. 2. Cross section of a typical fluvial sequence perpendicular to channel axes. An alluvial sequence commonly comprises three parts, showing an overall fining-upward trend from prominent basal scour. The lower part (LST, lowstand systems tract) consists of amalgamated, coarse-grained sandstone bodies representing low sinuosity (or braided) river deposits. The middle (TST, transgressive systems tract) is characterized by isolated, high sinuosity (or meandering) river channel deposits encased with fine-grained floodplain deposits. The transition between the lower and middle parts is distinct but gradational. In the uppermost part of the sequence (HST, highstand systems tract), the proportion of floodplain fine-grained deposits decreases and thus sandstone channel bodies are slightly interconnected due to lateral migration of channels. This figure is from Ethridge et al. (1998).

changes in the ratio of accommodation to sediment supply rate (A/S) with time. In addition, a fluvial sequence is divided into systems tracts on the basis of stratigraphic variations in proportion and characteristics of channel fills instead of strata configuration and significant stratigraphic discontinuities (Wright and Marriott, 1993; Shanley and McCabe, 1994; Olsen et al., 1995; Van Wagoner et al., 1995; Currie, 1997; Dalrmple et al., 1998; Ethridge et al., 1998; Milana, 1998; Martinsen et al., 1999). It means that current models on fluvial sequence stratigraphy lack a consensus on the procedure defining sequence stratigraphic units based on objective criteria or correlation.

Existing models of fluvial sequence stratigraphy are basically derivatives of the Leeder-Allen-Bridge (LAB) model which stresses the importance of avulsion frequency, sedimentation rate, and the ratio of channel belt and floodplain width in stacking of channel-bodies (Allen, 1978; Mackey and Bridge, 1995; Heller and Paola, 1996; Leeder et al., 1996). The LAB model assumes that channels avulsion more frequently with increases in sedimentation rate, promoting the formation of isolated meandering channel fills. But the relation among the avulsion frequency, the sedimentation rate and resultant channel fill architecture is not so simple (Bryant et al., 1995). The controls of the LAB model influence mobile channel belts, but for fixed-channel systems they are less effective than the local geomorphic factors such as bank erodibility and channel aggradation (Gibling, 2006). On the other hand, variation in channel pattern or architecture of systems tracts of the models cannot be readily and securely related to the change in accommodation or vice versa because different channel types of various dimensions

Fig. 3. Coexistence of rivers of different channel patterns. Meandering (left) and braided (right) rivers develop side by side from the same glacial source (top) in Iceland. As the two streams occur in the same area where there is seemingly no difference in the accommodation potential, the photograph indicates that the transition from braided to meandering river types cannot be directly related to the accommodation change or vice versa. It was provided by J. Fredsøe, Technical Univ. of Denmark.

coexist simultaneously (Fig. 3) or within a limited stratigraphic range (Bristow, 1993; Miall, 2002). Therefore, the present model of fluvial sequence stratigraphy needs to be refined in view of the nature of stratigraphic record of inland fluvial systems. Towards a proper understanding of fluvial sequence stratigraphy, following questions are important: (a) Can an fluvial sequence be divided into a few building blocks comparable to systems tracts within marine sequences? (b) What is the condition to form a particular building block? (c) How are the building blocks organized into a fluvial sequence? (d) Can transitions among them be related to changes in accommodation? These key issues are concerned with definition and interpretation of fluvial sequences. The purpose of this paper is to examine current fluvial sequence models in terms of distinctive features of stratigraphic records representing inland fluvial system and to review recent approaches to fluvial sequence stratigraphic analysis.

2. PROBLEMS IN THE CURRENT FLUVIAL SEQUENCE MODEL

2.1. Definition of Accommodation

It is clear that the nature of fluvial sequences differ considerably from that of marine sequences except that accommodation is a primary control on the sequences. Compared with marine sequence stratigraphy, the most peculiar feature of fluvial sequence stratigraphy is that the accommodation in inland settings cannot be easily defined (Ethridge et al., 1998; Cross and Lessenger, 1998). In marine settings, accommodation is bounded by sea level and sea bottom, and the sites of sediment accumulation move upslope and downslope in response to the accommodation changes mainly due to relative sea level fluctuations. Such sediment spatial or volume partitioning along depositional slope with time (Homewood et al., 2002) and resultant geographic facies variations are prominent in coastal plain through marine shelf environments where progradational, retrogradational and aggradational units (systems tracts) form (Van Wagonor et al., 1988; 1990; Cross and Lessenger, 1998) (Fig. 1). In contrast, accommodation in inland fluvial settings is commonly defined by (stratigraphic) base level which is an undulating, abstract, lithosphere surface representing equilibrium between aggradation and degradation (Cross and Lessenger, 1998; Wheeler, 1964). The abstract base level makes it difficult to figure out how the accommodation works in alluvial settings.

Although there are considerable differences in depositional regime between the upstream and downstream river systems (Smith, 1973; Todd, 1996; Knighton, 1998, 1999; Schumm, 1977), sediment partitioning and resultant downslope facies differentiation equivalent to those in marine settings are not so prominent. This remarkable contrast between marine and fluvial sequences is shown in the model diagrams: marine sequences commonly are displayed in a dip section (Fig. 1), whereas fluvial sequences typically are shown in a strike (cross) section perpendicular to channel axes (Fig. 2). This means that dip-oriented marine accommodation model may be inappropriate for explaining strike-oriented fluvial facies variation reflecting fluvial accommodation change according to base level fluctuation.

2.2. Difficulty in the Recognition of Sequence Boundary

It is very difficult to recognize sequence boundaries in fluvial successions because there are a range of stratigraphic discontinuities caused by complex responses of a river system to geomorphic thresholds, as well as external disturbances such as tectonics and climate change (Westcott, 1993; Ethridge et al., 1998; Schumm, 1991). In addition, similar stratigraphic discontinuities can be formed by different causes (convergence) and similar disturbances can produce different discontinuities (divergence) (Westcott, 1993; Ethridge et al., 1998; Schumm, 1991). Consequently it is nearly impossible to recognize neither progradational nor retrogradational units except for those near the upstream basin margins where stacking patterns of fluvial strata can be discerned (Milana, 1998). It is noteworthy that lack of significant facies shift along depositional slope (channel axis), is adverse for any reliable correlation for recognition of stratal stacking patterns or types of key surfaces. Such a disadvantage is also due to both the presence of diverse discontinuities and scanty fossils.

Although the present fluvial sequence stratigraphy model assumes a drastic change of river types from meandering to braided channel fills (or from channel belts to paleovalley fills) across the sequence boundary, there have been few reports on significant changes in channel fills above and below a sequence boundary (Adams and Bhattacharya, 2005; Guow and Berendsen, 2006). The tricky distinction between paleovalleys and channel belts also increase the difficulty to recognize sequence boundary in fluvial successions. Unequivocal recognition of paleovalleys requires incision that must substantially exceed channel depth, with interfluves topped by mature paleosols. As for incised channel bottoms indicating sequence boundaries, Best and Ashworth (1997) suggested that the depth of incision should be at least up to 5 times the channel depth. Such a deep incision might have been caused only by external disturbances enough to decrease accommodation in the river system. However, standard fluvial sequence models do not embrace detailed analysis on the key surfaces. The recognition of sequence boundaries requires considerable efforts and diverse data including sedimentological measurements and paleosol (fossil soil) analyses, because alluvial sequence boundaries extend from incised channel bottoms through the floodplain to interchannel areas which are not inundated by floods and lie above floodplains (interfluves; McCarthy and Plint, 1998).

2.3. Oversimplication of Dynamic Fluvial Systems

As the sequence stratigraphy is a study on the evolution of depositional system represented by systems tracts and key surfaces (Van Wagonor et al., 1988, 1990; Cross and Lessenger, 1998), it is more reasonable to track down nature of the stratigraphic records on longer term and wider spatial scale. However, the LAB model-based fluvial sequence stratigraphic analysis is largely focused on the architecture and geometry of channel bodies and neglects the importance of floodplain deposits that are a major portion of fluvial successions and sometimes control behavior of the associated channel through bank erodibility. In this respect, fluvial sequence stratigraphy should be concerned with deposit of a river system as a whole. Even if an entire river system should be considered, it is impossible and unreasonable to trace and put together all strata formed over various regions ranging from drainage area to coastal plains because a river flows across diverse regions differing either in climate, lithology, gradient, or vegetation etc (Knighton, 1998; Schumm, 1977). For example, a river channel can be subdivided into incised channel sector without natural levees and leveed channel sectors along downstream. The two segments can form a continuum irrespective of planform. Relative importance of the two segments in a river system largely depends on the relief, the basin physiography, and sediment caliber, vegetation and sand trap up slope. Unfortunately, the fluvial sequence models do not mention the possible presence of the two varieties of channel fills, let alone dimensional variability.

The typical fluvial sequneces only comprise two or three parts irrespective of the relative position (i.e., upstream vs. downstream) within a whole river system. They are largely represented by a bi-partite, fining-up succession consisting of basal amalgamated (or multi-stories), coarse-grained, channel fills (lower unit) and overlying isolated (or single story) channel fills with abundant floodplain deposits (upper unit) (e.g., Rhee et al., 1998, Pedersen and Steel, 1999 and many others) (Fig. 2). Such a sequence has been interpreted in terms of the accommodation change: transitions from high to low accommodation (Wright and Marriott, 1993; Currie, 1997; Milana, 1998), or rapid to slow rise of baselevel (Shanley and McCabe, 1994; Olsen et al., 1995; Van Wagoner et al., 1995; Dalrymple et al., 1998), or low to high A/S ratio (Martinsen et al., 1999). However, the degree of interconnectedness of channel sandstone bodies can be explained solely by the differing aggradation rate (Bryant et al., 1995). Changes in river channel patterns accompanying changes in the architecture cannot be the rule because braiding pattern can be explained in terms of abundant supply of coarse-grained sediments (Murray and Paola, 1994), whereas meandering pattern can be caused by the relatively poor bedload and presence of suspended sediments if longitudinal slope and water discharge are similar. In some multi-channel river systems (e.g., anastomosing), the two channel patterns can coexist in an area (Nanson et al., 1986). On the other hand, transitions from braided to meandering rivers or vice versa can occur as a result of drastic changes in sediment and water discharge due to avulsion (Bristow, 1999), without any implications for accommodation change. It should be noted that fluvial sequences have been documented in terms of stratigraphic variations in alluvial architecture that is, the degree of interconnectedness and proportion of channel sandstone bodies rather than using stratal patterns representing lateral facie shift with the change of the ratio of accommodation rate to sediment supply rate.

Although paleosols have been used in reconstructing paleoenvironments and subdividing a particular alluvial succession, few floodplain deposits including paleosols have been incorporated into fluvial sequence stratigraphic analyses. It has been noted that boundary between the LST and TST is characterized by the development of hydromorphic soil horizons (Wright and Marriot, 1993). However, some paleosols develop at major unconformities during the prolonged period (about 10^6-10^7 years) of landscape stability, whereas most paleosols form under the aggrading condition in which the rate of sedimentation does not overwhelm the rate of soil-forming processes (Kraus and Aslan, 1999; Wright, 1992). Based on the soil-landscape relationships, Kraus and Aslan (1999) suggested that macroscale changes of paleosol properties are associated with episodic events of floodplain incision and aggradation and occur over an area of 10-10^3 km^2 and periods of 10^3-10^4 years. Macroscale change involves stratigraphic sections >10 m thick. Megascale paleosol variability involves hundreds of meters of alluvial successions and covers an entire basin. Its development would take at least 10^5-10^7 years. In this respect, differentiation of these discontinuities within floodplain deposits will contribute to the establishment of fluvial sequence and its division into systems tracts. The present models do not care for the potential use of the fine-grained floodplain background deposits in characterizing varieties of fluvial sequences.

On the other hand, the current models on fluvial sequence stratigraphy do not pay proper attention to the role of tectonics. Tectonic events play a major role in drainage basin development and river channel relocation (Leeder, 1993). Gradient change along river profile due to uplift or subsidence also leads to planform change (Ouchi, 1985) or channel piracy (Calvache and Viseras, 1997) which can produce marked facies change. Leeder (1993) explained that gradient changes caused by tectonic movements give rise to differing channel belt behavior: vertical incision, migration and asymmetric incision, or avulsion which results in confined channel belt with terraced floodplain, terraced asymmetric meander belt, and discrete isolated channel belt deposits, respectively. However, the transition from the lower unit to the upper unit of a fluvial sequence can be explained only by avulsion without any tectonic movements. It can be referred to as either increase or decrease in avulsion frequency, depending on the nature of the relationship between the frequency and the sedimentation rate to form alluvial ridges of Allen (1978) (Bryant et al., 1995; Heller & Paola, 1996). In fault-controlled basin, the effect of tectonic events on river channel and floodplain response differs according to the location of the components. River channels on the hanging wall tend to be clustered as an axial drainage to form amalgamated channel belts, whereas those on the foot wall at best develops as a part of alluvial fan system. There is also a contrasting development of paleosols on floodplains between the footwall and hanging wall river systems (Alonso-Zarza et al., 1999).

3. RECENT EFFORTS TOWARD A NEW FLUVIAL SEQUENCE STRATIGRAPHY MODEL

3.1. Accommodation and Downstream Variability of Fluvial Systems

Within the fluvial system defined by Schumm (1977), an alluvial river occupies an area in the transfer zone (Zone 2) that lies between the drainage basin (Zone 1) and the area of deposition (Zone 3). In this zone, alluvial rivers change their channel patterns to form a continuum through continual interactions of river flows with the erodible solid boundary, a part of the floodplain. Notwithstanding these diversities, it is meaningful to distinguish the upstream river system from the downstream river system because the two systems are considerably different in depositional features and relative importance of controls related to climate, tectonics and sea level (Shanley and McCabe, 1994; Todd, 1996; Currie, 1997). Depositional features in the downstream river system are determined by the efficiency to deposit coarse-grained sediments selectively in the upstream river system. Rivers tend to erode upstream and deposit their load downstream. Gravel beds are prevalent at upstream and sand beds are common at downstream. The partitioning and transition result from a dynamic interplay between hydrology and sediment characteristics, probably due to nonlinear downstream changes in stream power along the concave longitudinal profile that asymptotically flattens downslope (Knighton, 1999).

In pursuit of this direction, Holbrook et al. (2006) suggest a "buffers and buttresses model" that provides a practical

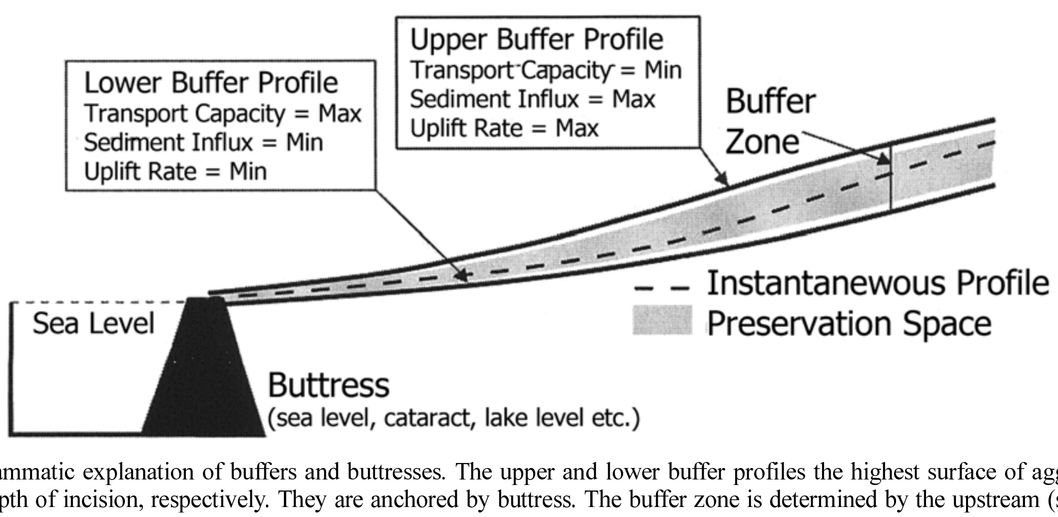


Fig. 4. Diagrammatic explanation of buffers and buttresses. The upper and lower buffer profiles the highest surface of aggradation and the lowest depth of incision, respectively. They are anchored by buttress. The buffer zone is determined by the upstream (sediment flux and water discharge; stream power) and downstream (base level) controls. Note differing depth of the buffer zone along depositional slope, which can give rise to variations in the preserved stratigraphic records along the slope. (Modified after Holbrook, 2006).

insight into the accommodation in an inland fluvial setting and its dual control on the stratigraphic records in upstream and downstream reaches. Their model assumes that fluvial stratigraphic records are formed between the buffer zone bounded by upper and lower buffer profile (Fig. 4). Buffer profiles, similar to the stratigraphic base level, are determined by a function of transport capacity, sediment influx and uplift rate. The upper and lower profiles roughly represent the highest surface of aggradation and the lowest depth of incision, respectively. The two buffer profiles are anchored at a buttress such as sea level, cataract or lake level etc (Fig. 4). Lateral and vertical movements of the buttress control the buffer zone, which is vertical range of preservation space and is similar to the accommodation. The concept of the buffer zone is much more realistic than the fluvial accommodation determined by an abstract stratigraphic base level in that it is defined by real surfaces, and assumes the preservation potential of deposits. As a series of discontinuities of fluvial successions implies the partial preservation of fluvial deposits, the size of the buffer zone can be directly related to contrast in dimension, architecture and type of channel fills between upstream and downstream. Shallow buffer zone in the downstream sector are prone to produce interconnected thin channel fills or belts, whereas deep buffer zone in the upstream sector, isolated thick channel fills encased by floodplain deposits. This model will serve as a framework to investigate 'dip-oriented contrasts in number and architecture of surfaces formed by incision-aggradation'. If the model succeeds in describing the difference combined with other approaches to downstream change in fluvial architecture (for example, Strong et al., 2005), fluvial sequences can be constructed using the vertical facies shift like the marine sequences.

3.2. Characterization of Channel Deposits

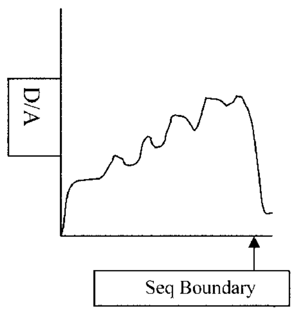
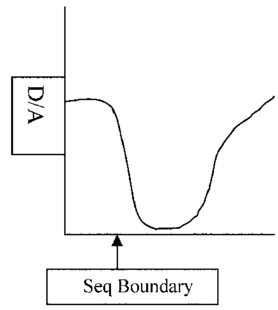
Reconstructing fluvial architecture is to resolve temporal changes in modes of sediment dispersal (partitioning) and reworking across the floodplain. In this respect, the classification scheme of river systems should be inclusive of efficiency of sediment transport and shifting modes of channel or channel belt across the floodplain: sudden, large-step relocation (avulsion) vs. gradual lateral migration (combing). This conjecture is analogous to the seemingly obvious notion that geomorphic features reflect interactions between available energy for geomorphic modification and resistance to the modification (thresholds) within a geomorphic system (Schumm, 1991; Westcott, 1993; Knighton, 1998). As for ancient alluvial successions, it is appropriate to consider the two variables with respect to preservation of particular deposits: types of fluvial strata reflecting channel patterns and behavior, and their preservation potential determined by a fuction of transport capacity, sediment influx and subsidence rate. Given subsidence necessary for net accumulation (false-bottomed "withdrawal" or "tectonic drawdown" concept of Leeder et al. (1996)), it is assumed that the nature of fluvial strata preserved is determined by the channel pattern and geomorphic factors including bank strength and channel aggradation (Gibling, 2006). Understanding the variety of channel bodies requires systematic description and classification of their composition, three-dimensional form and internal discontinuities. Gibling's seminal paper (2006) will provide a reference scheme for the detailed analysis of a whole range of channel deposits including channel belts, irrespective of depositional settings. As data on channel bodies are gathered using the scheme, it will be possible to predict the fluvial sequence and nature of channel body reservoir which is far from our expectations (Miall, 2006).

As preservation of fluvial deposits basically implies an aggrading rivers and floodplains, any fluvial sequences can be related to one or more among following conditions such as continuous subsidence, base level rise, and decrease in transport efficiency of rivers due to large sediment input or decrease in water discharge. According to relative importance of sediment flux and base level change in the preservation ('withdrawal' of Leeder, 1997), alluvial sequences can be divided into two types: flux-controlled and subsidence-controlled sequences (Table 1). The former will be primarily affected by climatic change which induces changes in sediment and water discharge, and then resultant adjustments of fluvial depositional system. Such climate-induced changes appear to be easily recorded in the alluvial deposits rather than marine deposits (Blum, 1990; Blum and Price, 1994; Blum and Valastro, 1994; Fuller et al., 1998; Ruegg, 1994; Vandenberghe, 1995; Vandenberghe et al., 1994; Gibling et al., 2005). The latter would be similar to the present fluvial sequence in that they are insensitive to geomorphic controls, and reflect overall variations of channel bodies controlled by smooth base level change.

3.3. Usefulness of Floodplain Deposits and Paleosols

With regard to the depositional system, alluvial sequence stratigraphy relies on unraveling temporal variations of alluvial architecture (or alluvial stratigraphy), referred to as the geometry, proportion and spatial distribution of relatively coarse-grained channel-belt deposits within finer-grained floodplain alluvium (Mackey and Bridge, 1995; Heller and Paola, 1996; Leeder et al., 1996). It implies that "matrix" floodplain facies is as important as channel or channel-belt facies (Wright and Marriott, 1994). Floodplains are not only in contact with river channels, but also act as a ubiquitous sink for river-borne sediments, recording depositional events of the river system. They are largely composed of a combination of with-in channel and overbank deposits, and their composition influences channel form and behavior, and type of sediments transported by river channels (Nanson

Table 1. Two end-members of alluvial sequences (compiled from Catuneanu, 2006)

	Sediment supply-controlled alluvial sequences	Tectonic-controlled alluvial sequences
Geomorphic Threshold	Sensitive	Insensitive
Paleosol Maturity	Immature/Complex	Mature/Simple
Sequence Boundary	Impersistent/Transitional	Persistent/Abrupt/Catena
Climatic Change	Sensitive	Insensitive/Neutral
Baselevel Change Pattern	Localized/Segmented	Overall/Regional
Avulsion	Frequent/Random	Neutral/Nodal
Floodplain Development	Partial Association with Channel (contrasts before and after avulsion)	Closely conjugated with Channel
Channel Incision	Common	Rare
Internal Discontinuities	Complicated	Simple/Aggradational Surfaces
Change of the ratio of Deposition and Accommodation		

and Croke, 1992; Knighton, 1998). The close linkage between the channel and its associated floodplain should be a basic premise for the description of alluvial strata, but it should not be ignored that there can be time lags or leads between them in adapting to inherent or external disturbances (Schumm, 1991; Westcott, 1993; Knighton, 1998).

Detailed study on the Miocene overbank deposits of the Chinji Formation (Pakistan), Willis and Behrensmeyer (1994) argue that the preserved succession is a product of sedimentation followed by long periods of nondeposition and soil formation. They suggest five hypotheses to explain the preservation of the floodplain deposits (Fig. 5). Their first hypothesis states that the entire floodplain aggrades episodically. The second hypothesis assumes that rate of sediment aggradation is controlled by the proximity of the channel: sedimentation rate is greater in the proximal part near channel than in the distal part. The third hypothesis explains episodes of degradation and incision, and aggradation after rise in base level. It implies that channels and floodplain deposits are within the valley until it is filled up. The fourth hypothesis predicts a continuous process of localized overbank deposits across the floodplain, resulting in a patchwork of stratified floodplain deposits. The fifth hypothesis predicts that channel avulsion occurs during periods of rapid overbank deposition. These hypotheses will help to delineate facies relationship between channel fills and the associated overbank deposits, making it clearly and easily to recognize stratigraphic discontinuities based on maturity of soil horizons (Kraus, 2002). Furthermore, such a result combined with the channel classification of Gibling (2006) would refine the establishment of fluvial sequence.

3.4. Aggradation Rate in a River System

Aggradation or incision in a river system occurs either in channel proper or on floodplain. Whether a river channel is aggraded or incised is largely determined by longitudinal channel profile (concavity vs. convexity) and climate regime (Kirkby, 1999) (arid or humid). And incision of river channels only means that the channel experienced bed-level lowering regardless of dissection on a wider, associated floodplain. Therefore, the incised channel cannot be a decisive evidence for the lowering of baselevel, indicating decrease in accommodation (Ethridge et al., 1998). In fact, during the deep incision of trunk channels, a net accumulation can occur on the adjacent, upland interfluve where is not affected by flooding of the major rivers within the incised valley (Singh et al., 1999). On the interfluve surface, small drainages can develop temporarily(Singh et al., 1999). Regarding the preserved channel deposits, it has been argued that channel sandstone beds formed in slowly aggrading rivers preferentially preserve the deeper parts facies of a channel deposits (Bristow, 1996). On the other hand, aggrading channels in anastomosing river system with low stream power ultimately leads to avulsion (Makaske, 1998) (a capacity-based avulsion model).

In floodplains, the aggradation rate has been considered as a primary control on interconnectedness and proportion of channel sandstone bodies (Mackey and Bridge, 1995; Heller and Paola, 1996; Bryant et al., 1995). Influences of the aggradation rate on alluvial architecture are prominent with respect to the avulsion. As the tendency to avulse is determined by the ratio of the slope of the potential avul-

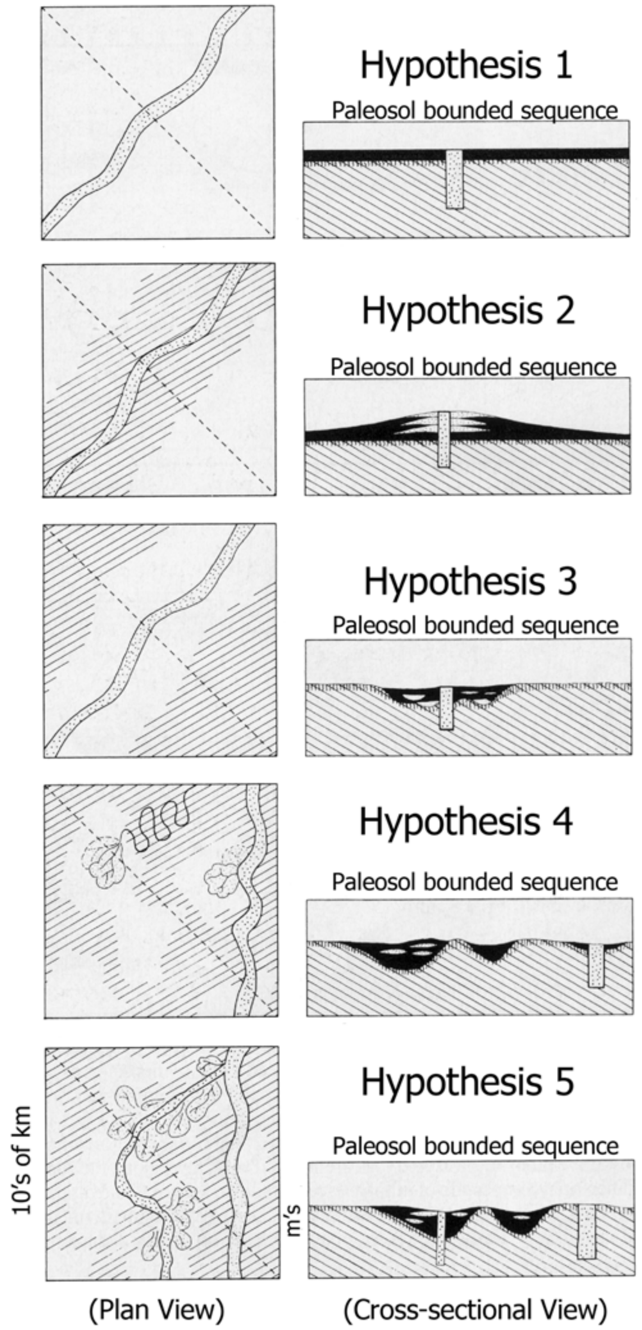


Fig. 5. Five hypothses to explain the preservation of floodplain deposits, as presented by Willis and Behrensmeyer (1994). On plan-view maps, lined hatching represents floodplain areas of above-average topography, dotted stipple represents areas of channel or channel belt. Note internal organization and geometry of floodplain (black) deposits bounded by paleosol surfaces and the relationship between the floodplain deposits and channel fills (stippled).

sion course to the slope of the existing channel (topography-based avulsion model: Makascke, 1998), high aggradaton rate would lead to frequent avulsion through the rapid establishment of local relief (alluvial ridge) favouring avulsion. However, the relation between the avulsion frequency and the floodplain aggradation rate may not be so linear as expected (Bryant et al., 1995). With regard to avulsion style, Aslan and Blum (1999) argued that avulsion by channel reoccupation (AC) occurs under the condition of slow aggradation in the floodplain at the early and late stages of valley filling, whereas avulsion by diversion into flood basins (ADFB) occurs in rapidly aggrading floodplains at the middle stage of valley filling. Accordingly, the recognition of avulsion sequences is very important for constructing alluvial architecture and deciphering changes in a river system as a whole rather than at channel-scale (Mackey and Bridge, 1995; Heller and Paola, 1996; Jones and Harper, 1998; Kraus and Wells, 1999). In light of the importance of the floodplain aggradation rate, two types of river systems are envisaged: river systems with rapidly aggrading floodplains and river systems with slowly aggrading floodplains (Aslan and Blum, 1999). This classification scheme can be matched with the five hypothses of Willis and Behrensmeyer (1994) on floodplain preservation. The former river systems can be roughly related to the hypothsis 1 and 2 of Willis and Behrensmeyer (1994), whereas the latter the hypothesis 3 to 5. This similarity suggests that fluvial sequence models should represent change in the preservation potential, that is change in aggradation rate with time and space.

3.5. Stream Power and its Implication in Classification of River Systems

From the perspective of channel patterns, classifying river systems would be equivalent to suggesting a discriminatory parameter for channel patterns because a river system forms a continuum of straight-meandering-braided channels (Schumm, 1977; Knighton, 1998). Since channel pattern is a function of available sediments and energy for erosion and transport, continual changes of channel patterns is accompanied by the increase in stream power, width-depth ratio and amount and grain-size of bed load (Knighton, 1998). The last two trends are relevant to the stream power in that they are associated with bank erodibility and bed-load transport. According to recent studies on channel forms and processes of fluvial systems, these trends are basically determined by specific stream power (ω) (Knighton, 1998; Nanson and Croke, 1992; Van den Berg, 1995; Dade, 2000): $\omega=\Omega/w =\tau_0*v$ (W/m), where Ω is total stream power, w is channel width (m), τ_0 is mean boundary shear stress (N/m^2) and v is mean velocity (m/s). The total stream power is defined as the rate at which potential energy of flowing water is supplied to a unit area of bed, $\Omega=\gamma$ QS where, γ is specific weight of water (=9810 N/m^3), Q is water discharge (m^3/s), S is channel gradient (dimensionless). As the stream power is a function of slope and discharge, the classification based on the stream power can be served as a guide for distinguishing the upstream (steep) from downstream (gentle) river systems (Knighton, 1999). Using the relation that the stream power is proportional to grain size of bed material ($\omega \propto d^{3/2}$, where d is median grain size of channel bed material), downstream fining can be explained as a result of nonlinear downstream decrease in stream power (Dade, 2000). On the other hand, the tendency of river channels to migrate laterally increases as stream power increases (Friend et al., 1979). Thus, the specific stream power can be selected as a discriminatory variable for the classification of fluvial system. If there are few available data like cores, it is inevitable to characterize the fluvial deposits through textural analysis. Therefore, it would be necessary to classify fluvial system using hydrodynamic parameters such as the stream power.

4. SUMMARY

The definition, recognition and interpretation of alluvial sequences are not so systematic and clear as those of the marine sequences because there are considerable differences in the controls and internal organization between the two sequences. The application of sequence stratigraphic concepts to fluvial successions does not imply to consider the alluvial sequence as an extrapolated variety of marine sequence or to seek alluvial counterparts of the components of marine sequence stratigraphic analyses. However, the current fluvial sequence models have several limitations: 1) accommodation definition based on an abstract (stratigraphic) base level, 2) poor definition of a fluvial sequence and its components, 3) ignorance of the dynamic depositional regime of the inland fluvial system. In order to overcome the limitations of the LAB model-based sequence model, various approaches to fluvial deposits have been suggested. Recent progress in the fluvial sequence focuses on the clear definition of accommodation (Fig. 4; Holbrook, 2006) as well as objective classification and recognition of channel fills and channel belts. In addition to the introduction of the new basic premises, proper understanding varieties of fluvial successions proposes several classification schemes of fluvial successions based on the relative importance of controls on the fluvial system. Sediment-supply-controlled sequences and tectonics-controlled sequences (Table 1) can be compared to each other. Detailed studies on styles of preservation or floodplain deposits and paleosol formation also enhance the possibility to divide the fluvial succession into a sequence and its component units based on the concrete evidences (Fig. 5; Willis and Behrensmeyer, 1994). Discussion on the condition of aggradation through avulsion development will contribute to discriminating allogenic and autogenic controls (Kraus, 2002). The possibility to classify fluvial systems on the textural scale can be examined through stream power. These diverse trends should be united into a new sequence model that will shed light on the understanding of fluvial stratigraphic records and their organization into sequences. As shown in this paper, fluvial sequence stratigraphy should be accepted only as a search for the linkage between the discontinuous stratigraphic records and the changes in the fluvial regime in terms of the accomommodation change. It cannot be simply an alluvial version of the marine sequence stratigraphy.

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