Annu. Rev. Earth Planet. Sci. 2004. 32:257–285
doi: 10.1146/annurev.earth.32.101802.120201

First published online as a Review in Advance on December 12, 2003

RIVER AVULSIONS AND THEIR DEPOSITS

Rudy Slingerland[1] and Norman D. Smith[2]
[1]Department of Geosciences, Penn State University, University Park, Pennsylvania 16802; email: sling@geosc.psu.edu
[2]Department of Geosciences, University of Nebraska, Lincoln, Nebraska 68588-0340; email: nsmith3@unl.edu

Key Words stream channels, floodplains, floods, alluvial, fluvial

■ **Abstract** Avulsion is the natural process by which flow diverts out of an established river channel into a new permanent course on the adjacent floodplain. Avulsions are primarily features of aggrading floodplains. Their recurrence interval varies widely among the few modern rivers for which such data exist, ranging from as low as 28 years for the Kosi River (India) to up to 1400 years for the Mississippi. Avulsions cause loss of life, property damage, destabilization of shipping and irrigation channels, and even coastal erosion as sediment is temporarily sequestered on the floodplain. They are also the main process that builds alluvial stratigraphy. Their causes remain relatively unknown, but stability analyses of bifurcating channels suggest that thresholds in the relative energy slope and Shields parameter of the bifurcating channel system are key factors.

INTRODUCTION

June of 1855 brought a great flood to the lower reaches of the Yellow (Huanghe) River in Henan Province, China. Plentiful rains on the lowlands around the city of Tongwaxiang raised local streams to bankfull, and to this was added a flood wave from the upper Yellow River and its tributary, the Qinhe. On June 19, 1855, waters overflowed the levees of the Yellow River at Tongwaxiang, and the north levee almost instantaneously failed, opening a rapidly widening crevasse (Qian 1990). By the next day, the new crevasse, or break in the levee, was taking the entire flood discharge of the Yellow River. Over the next 20 years, a region of approximately 31,000 km^2 was subject to repeated floods, rapid sedimentation, and wandering, short-lived braided channels (Qian 1990) as the Yellow River, which formerly had flowed southeast and directly into the Yellow Sea, alluviated its floodplain and established its main channel to flow northeast reaching the Bohai Gulf some 300 km to the north. Estimates of deaths over the 20 years range in the tens of thousands.

Abrupt natural relocations of rivers such as this are called avulsions by geomorphologists. In its nearly 2000 years of recorded history, the Yellow River has experienced seven major avulsions affecting 250,000 km^2, each time disrupting the lives of eight to fourteen million people with countless loss of life and property damage (Soong & Zhao 1994). Beyond these immediate effects of channel relocation lie a host of related effects. Near the apex of the resulting alluvial cone, once-fertile soil is buried by meters of new sediment, and drainage and irrigation canals are silted up. Farther downstream and after much of the sediment load has been dropped, the relatively clear water scours new channels and destabilizes channel banks. Even farther downstream along the deltaic coast, coastal erosion increases dramatically as sediment supply is cut off for hundreds of years. Upstream from the avulsion site, the river channel is destabilized by a knickpoint. In the case of the 1855 Yellow River avulsion, a 5- to 10-m-high knickpoint migrated upstream approximately 100 km (Qian 1990), thereby perching a floodplain on the northern bank so high “that even today it remains beyond the reach of flood water” (Qian 1990, p. 8). And lest we think that modern engineering has reduced the threat, the most recent flood events on the Yellow River occurred in 1996 and 1998. Although not a true avulsion event, the 1996 flood nevertheless affected over 5 million houses, caused 4400 deaths, impacted 31 million hectares of farmland, resulted in monetary losses of Y220.8 billion ($26.7 billion), and reduced the gross domestic product (GDP) of the People’s Republic of China by approximately 4% (Anonymous 2001). Thankfully, avulsions also have benefits. By forcing large-scale repositioning of stream channels, avulsions are a major source of wetlands and a dominant mechanism in the construction of river floodplains, deltas, alluvial fans, and their associated sedimentary deposits, including reservoirs for potable water and valuable hydrocarbons.

What are the causes of avulsions and how can we better predict them? The immediate cause of the 1855 avulsion on the Yellow River would seem to be apparent from a comment by Li Hongzhang, a minister of the Qing Dynasty, who wrote in 1873, “The elevation of the original river bed is 7–10 m above the water surface downstream of the breach” (as quoted in Qian 1990, p. 2). Such perched or “suspended” rivers where the river bottom sits higher than the floodplain would seem to create ideal conditions for an avulsion. But Zhou & Pan (1994) estimate that approximately 1600 levee breaks occurred on the Yellow River between 602 BC and 1949 AD, whereas only 7 resulted in full avulsions. Does the rate of aggradation or the amount of sediment load also matter? The bed of the lower Yellow River each year rises an astonishing 10 cm, and the average sediment concentration of its waters is 30 kg/m^3, the highest among large rivers of the world (Soong & Zhao 1994), implicating these factors as possible causes too.

At present, we simply don’t know the necessary and sufficient conditions causing a river avulsion, but numerous studies over the past decade have begun to focus on the problem. In this paper, we summarize the various styles of avulsions, review our present knowledge of their causes, and describe the sedimentology and stratigraphy of alluvial floodplain deposits, emphasizing the role avulsions play in creating them.

DEFINITIONS AND TERMINOLOGY

Avulsion is the process by which flow is diverted out of an established river channel into a new course on the adjacent floodplain. Although the term is usually intended for major discharge diversions that result in new channels, it is sometimes used in reference to short-term flow switching within braided channels or cut-offs of meander bends. In its traditional sense, avulsion is virtually synonymous with the term diversion when applied to rivers [and indeed, Fisk (1944) used only diversion in describing the classic avulsions of the Mississippi River]. In more recent usage, however, avulsion and especially its adjective form avulsive are commonly applied to a variety of physical and temporal features associated with the diverted flow and its related effects, a practice used in this paper. The parent channel is the established channel whose flow is diverted; an avulsion channel is one formed as a result of the avulsion (Figure 1). Avulsions may be full, in which all flow is transferred out of the parent channel, or partial, where only a portion of the flow is transferred. Full avulsions result in abandonment of the parent channel downstream of the diversion site, whereas partial avulsions lead to new channels that coexist with the parent channel. Partial avulsion results in anastomosing channels (if the divided channels are active and rejoin downstream) and distributary channels (if the divided channels do not rejoin), the latter a common feature of alluvial fans and deltas. Additional classificatory terms to distinguish avulsion behavior include nodal versus random and local versus regional. Nodal avulsions are recurring events that originate from a relatively fixed area of a floodplain, e.g., at the apex of an alluvial fan, whereas random avulsions may occur anywhere along an active channel system (Leeder 1978). A local avulsion is one that forms a new channel that rejoins its parent channel downstream; a regional avulsion, implicitly a larger scale event, affects the location of the channel everywhere downstream from the site of origin (Heller & Paola 1996). The patterns implied by these terms are not mutually exclusive for any given floodplain. For example, a nodal avulsion may include one or more random avulsions downstream from the node, and a regional avulsion may include smaller local avulsions as a new channel system evolves. Random avulsions may be local or regional. Avulsions are commonly hierarchical, i.e., an upstream diversion, full or partial, may develop a new channel system that undergoes numerous smaller avulsions as it evolves. Avulsion belt refers to the entire area of a floodplain affected by an avulsion (Figure 2) and is usually applied in the context of regional avulsions where significant new deposition has occurred (Smith et al. 1989).

Avulsions may be abrupt or gradual. For example, in contrast to the catastrophically abrupt avulsion of the Yellow River described above, full avulsions in the Meuse-Rhine delta often require several centuries to complete, and durations of up to 1250 years have been estimated (Stouthamer & Berendsen 2001).

Avulsions are primarily features of aggrading floodplains. They are not restricted to any particular pattern or size of river channel and may recur in any fluvial system for as long as some aggradation continues. Avulsion frequency varies

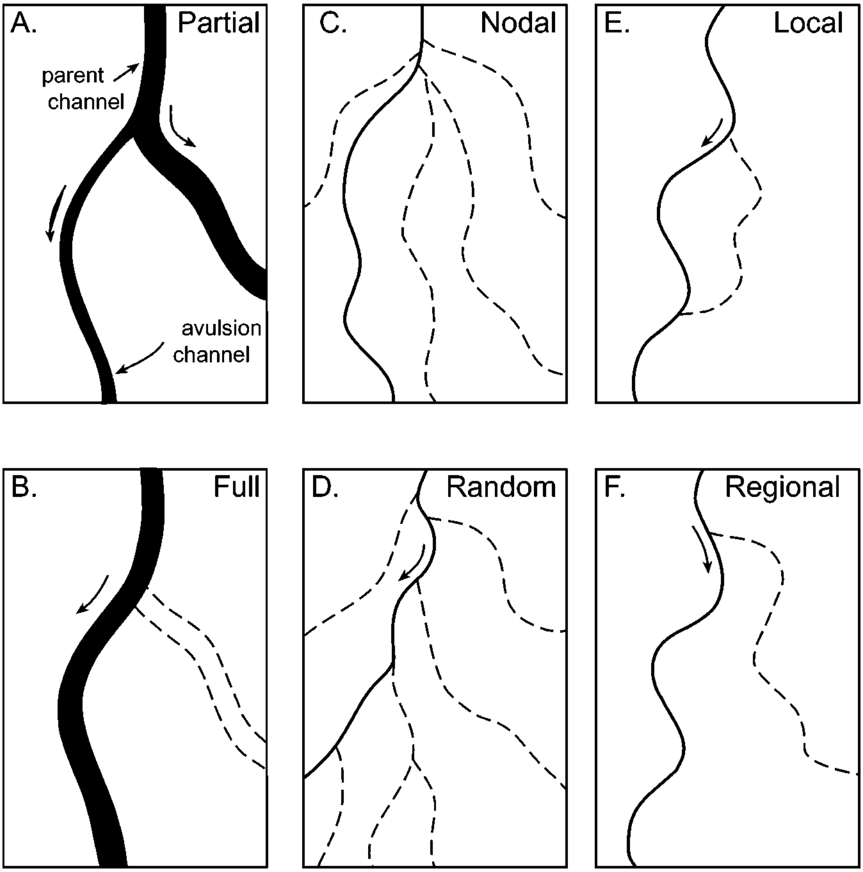

Figure 1 Sketches illustrating avulsion terminology used in this review. Solid lines = active channels; dashed lines = abandoned channels. Pairs A-B, C-D, E-F refer, respectively, to proportion of diverted discharge, location of avulsion sites, and areal scale of avulsion. See text.

widely among the few modern rivers for which such data exist, ranging from as low as 28 years for the Kosi River (India) to up to 1400 years for the Mississippi (see table 4.2 in Stouthamer & Berendsen 2001). Data from the stratigraphic record suggest that much larger intervals between successive avulsions may have existed (e.g., Kraus & Aslan 1993). In reality, however, there are probably no theoretical limits in assessing avulsion frequency over the spectrum of natural rivers. In unconfined glacial outwash streams, for example, avulsion of braid channels may be a quasicontinuous process, and at the other end of the probability scale, avulsion might never occur in rivers whose aggradation rates range from negative to barely above zero.

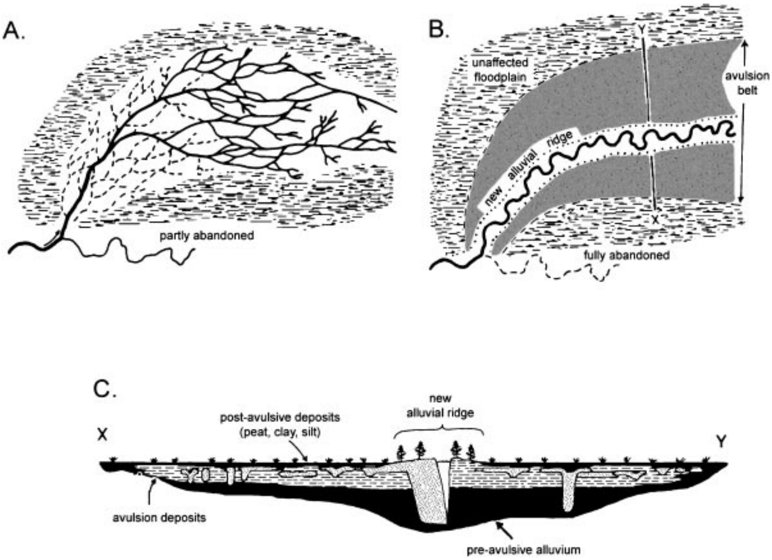

Figure 2 Schematic model of progradational avulsion based on the 1870s avulsion of the Saskatchewan River at the Cumberland Marshes. (*A*) Following initial diversion, progradational sediment wedge migrates down-floodplain, sustained by interconnected networks of rapidly evolving distributary channels. As new channels form at and near active margins of the wedge, others are abandoned and their flow captured into fewer and larger channels. (*B*) By the completion of avulsive deposition, all flow is captured into a new single-thread channel similar to the parent channel that initiated the avulsion, now abandoned. (*C*) Cross section showing stratigraphic relationships of avulsion-belt deposits relative to pre- and postavulsive alluvium. Horizontal scale on order of kilometers; vertical scale on order of 10^0 to 10^1 m. (After Smith et al. 1989.)

STYLES OF AVULSION

Whenever flow is initially diverted away from its parent channel, it will seek pathways of highest gradient advantage or greatest flow efficiency. The extent of avulsive flooding and subsequent channel development is then governed by a variety of factors, which include the size and duration of the avulsion, size and configuration of the invaded flood basin, and the character of the flood basin surface, e.g., its topography, water-table elevation, vegetative cover, resistance to erosion, and presence or absence of pre-existing channels. In the parent channel, reduced discharge downstream from the avulsion site leads to classic underfitting (Dury 1964), sometimes with dramatic modification in channel behavior (Bristow 1999a). Although every avulsion experiences a unique combination of factors that control how the affected portions of a floodplain respond, at least three broadly different styles have been so far recognized. We call these (*a*) avulsion by annexation in which an existing channel is appropriated (if active) or reoccupied (if abandoned); (*b*) avulsion by incision, where new channels are scoured into the floodplain surface as a direct result of the avulsion; and (*c*) avulsion by progradation, characterized by extensive deposition and multi-channeled distributive networks.

Avulsion by Annexation

A variety of active, partially active, and abandoned channels lying outside the dominant trunk channel is a nearly ubiquitous feature of river floodplains. Some of these are connected directly to the dominant channel as in the case of tributaries, distributaries, or subordinate branches of anastomosed networks. Others, usually abandoned, are unconnected to the active dominant channel but may have been formerly joined by floodplain erosion (Gilvear & Harrison 1991) or earlier avulsions. Some avulsions follow channelways developed by repeated overspilling at local sites of the channel bank (Speight 1965, Brizga & Finlayson 1990). Compared to flat and rough floodplain surfaces, such floodplain channels, if intercepted and optimally oriented, are efficient ready-made conduits for routing some or all flow away from diversion sites and thus comprise a common style of avulsion (Coleman 1969, Wells & Dorr 1987, DesLoges & Church 1987, Smith et al. 1998, Aslan & Blum 1999, Morozova & Smith 2000, Stouthamer 2001a). We prefer the term annexation to reoccupation because it includes avulsive takeover of either active or inactive channels. Nanson & Knighton (1996) refer to such annexation of preexisting floodplain channels as second-order avulsions (their first-order avulsions identify channel shifts to entirely new parts of the floodplain).

In most cases of avulsion by annexation, the intercepted floodplain channel is either smaller or larger than necessary to convey the flow imposed upon it. In cases where it is too small, the annexed channel may respond by overspilling, enlarging its cross section, or breaching its levees to form a form of alluvial fan called a crevasse splay. All three of these responses are observed in the avulsion belt of the Saskatchewan River (Smith et al. 1998, Pérez-Arlucea & Smith 1999). If the intercepted channel is larger than necessary to convey the avulsive flow, underfitting results with little immediate effect on the floodplain other than reactivation of the channel itself. Richards et al. (1993) suggest that in certain alluvial settings, repeated avulsive switching of flow between nearby channels may control long-term sedimentation patterns in which first one, then the other, channel becomes dominant in response to long-term aggradation. These authors cite examples from the northern alluvial plains of India where repeated abandonment and reoccupation of channels appear to be common (see also Sinha 1996).

Given the frequency of active and abandoned channels in typical alluvial floodplains, it is likely that annexation plays at least a partial role in most large regional avulsions, although this may be difficult to ascertain where channel histories are obscured by erosion or burial. Of 91 Holocene avulsions examined by Stouthamer (2001a) in the Rhine-Meuse delta, she recognized at least 24 with significant reoccupational histories. Morozova & Smith (1999, 2000) infer that channel annexation played roles in at least five of eight Late Holocene avulsions in the lower Saskatchewan River. Mohrig et al. (2000) report that up to 24% of the ancient channel fills they examined show evidence of reoccupation. Although the underlying mechanisms that govern the frequency of annexation relative to other styles of avulsion remain largely obscure, there is some evidence that reoccupation is favored by comparatively lower rates of aggradation (Aslan & Blum 1999, Stouthamer 2001a).

Avulsion by Incision

Incisional avulsions involve the erosion of new channels directly into the floodplain surface. As proposed by Mohrig et al. (2000), an initial avulsion event permits flow from a parent channel to spill into a floodplain. As the flow proceeds down the floodplain slope, it seeks paths connecting areas of lowest elevations until it eventually intercepts another channel, perhaps a tributary or a downstream reach of the parent channel. The initial pathway is likely to be irregular and inefficient early in the avulsion; however, upstream migration of a knickpoint from the point of re-entry, possibly combined with downstream extension from the initial diversion site, eventually leads to a well-defined new channel that carries all or part of the discharge from the parent (Schumann 1989, McCarthy et al. 1992, Schumm et al. 1996, Smith et al. 1997).

In the scenario of Mohrig et al. (2000) in which long-term aggradation is assumed, deposition by in-channel aggradation and overbank flooding proceeds as the new channel matures, eventually building a new channel belt perched above the floodplain so that avulsion again becomes possible. However, anabranching channel systems probably built by incisional avulsions are known to occur in regions undergoing very low or no aggradation (King & Martini 1983, Miller 1991, Gibling et al. 1998, Nanson & Knighton 1996), suggesting that superelevation of a channel belt above the floodplain is not a strict requirement for all avulsions. Nanson & Huang (1999), in considering low-gradient, slowly aggrading anabranching rivers in Australia, suggest that creation of multiple channels is a mechanism by which rivers can increase their transport efficiency where increases in channel slope are precluded. In such cases, avulsion may occur after a new floodplain channel has already formed by repeated flooding, possibly becoming later connected to an active parent channel by headward migration. Once the new channel is formed, the two origins (avulsion as a cause versus avulsion as an effect) may be indistinguishable.

Floodplains that drain quickly, e.g., those with high gradients, sparse vegetation covers, little relief, and water tables below the floodplain surface, likely favor avulsions by incision. Such features will lead to rapid runoff to enhance channel incision and minimize deposition. Mohrig et al. (2000) consider this style to be one end of a two-end-member spectrum in which incision occurs early in the avulsion process, before deposition. The other end member (see below) is characterized by early deposition followed by incision.

Avulsion by Progradation

When discharge is initially diverted from a parent channel into an adjacent flood basin, it experiences an abrupt decrease in competence and sediment-carrying capacity unless the flow is immediately intercepted and conveyed by an incised or annexed channel (see above). Such reduction in competence and capacity, caused by abrupt expansion of the cross-sectional area of the flow, results in immediate deposition of the coarser sediment fractions, while finer material is carried further onto the floodplain. As the avulsion continues, a sediment wedge is constructed, headed at or near the avulsion site and growing downcurrent as additional avulsion-borne sediment is transported and deposited at the margins. Because the typical growth pattern of the sediment wedge is by downstream expansion, we refer to these as progradational avulsions (Morozova & Smith 2000). This style is termed diversion into flood basins by Aslan & Blum (1999) and aggradational avulsion by Mohrig et al. (2000). Because they are characterized by deposition of sediment transported out of the parent channel into the invaded floodplain, progradational avulsions are favored by slow runoff promoted by low floodplain slopes; dense vegetation; and high water tables that encourage ponding, slow drainage, and settling of fine suspended sediment.

In many cases of partial avulsion, the initially formed sediment wedges are common crevasse splays, crevasse referring to a channel breach in the levee connecting the parent channel with the sediment wedge (splay). Crevasse splays assume a variety of lobate, elliptical, or elongate shapes and usually contain multiple and variously sized distributary channels that route water and sediment to and beyond the splay margins (Smith 1986, O'Brien & Wells 1986, Bristow 1999b). After a period of progradation and basin filling, splays commonly become abandoned as the gradient advantage between the channel and flood basin is reduced by deposition. If avulsive flow continues, however, the splay typically develops a single dominant channel; if the flood basin is constrained by valley walls or levees of neighboring channel belts, the channel is directed down-floodplain to merge with another channel, commonly rejoining the parent itself. This sequence of partial avulsion, splay deposition, splay incision, and channel rejoining is a dominant process for forming and sustaining anastomosed channel patterns (Smith & Smith 1980, Smith 1983, Nanson & Knighton 1996, Makaske 2001, Makaske et al. 2002, Abbado et al. 2004).

In cases of regional avulsion where the diverted flow does not quickly merge with another active channel within the same system, the prograding sediment wedge may become large and complex, with profound effects on the floodplain. For example, since its inception in the 1870s, a regional avulsion of the lower Saskatchewan River has transformed 500 km^2 of floodplain into a complex terrain of interconnected channels and small isolated flood basins (Smith et al. 1989, Pérez-Arlucea & Smith 1999) (Figures 3–6). The avulsion began by channel annexation, but quickly changed to a progradational style when the appropriated channel was unable to contain the full discharge of the diversion (Smith et al. 1998). Deposition then proceeded by basinward extension of coalescing splays and lacustrine deltas fed by anabranching networks of distributary channels (Figure 5). In the process of progradation, new channels formed by crevassing and bifurcation at channel mouths, and others lengthened by basinward extension, both serving to deliver new sediment to the flooded basin so that further progradation could continue (Figure 4). As new channels originated, others became abandoned when flows were diverted into the new channels or appropriated by older ones. The present avulsion belt, up to 16 km wide, is presently evolving into a state of fewer and larger channels, and the eventual outcome is expected to be a new dominant meandering channel dissected through and laterally contiguous with contemporaneous deposits of the newly aggraded floodplain (Figure 2). A somewhat similar pattern of prograding sediment wedges, particularly lacustrine deltas, has followed the invasion of the Atachafalaya River into its flood basin following a partial avulsion of the Mississippi River in historical times (Tye & Coleman 1989a,b).

CAUSES OF AVULSION

Many crevasse channels cut through levees, but the vast majority heal in a matter of decades. What conditions distinguish these channels from those that enlarge to take the whole flow? The answer almost certainly depends upon the style of avulsion and factors such as the area and configuration of the invaded flood basin, and the character of the basin surface, e.g., its topography, water-table elevation, vegetative cover, resistance to erosion, and presence or absence of pre-existing channels. If we group these factors together in a few parameters such as friction factor and hydraulic energy slope, a rational basis for an answer can be found from a stability analysis of bifurcating channels (Slingerland & Smith 1998, Bolla Pittaluga et al. 2003).

Theoretical Considerations

Consider an alluvial main channel *a* that bifurcates into two channels *b* and *c*, each of arbitrary initial cross section and water surface slope (Figure 7). The bottoms of channels *b* and *c* at the bifurcation lie at arbitrary heights relative to the main-channel bottom (Figure 7*B*). The bifurcation branches may, respectively, represent a recently opened small crevasse through a levee and the continuation of channel *a*, or they may be two channels receiving more nearly equal water discharges as in distributive or anastomosed systems. Whatever the case, any given configuration of channels will be stable only if the sediment moving through channel *a* is partitioned between channels *b* and *c* in exact proportion to their sediment-carrying capacities. If it is not, then deposition or erosion will occur in one or both channels, thereby changing their discharges, slopes, or cross sections, and consequently changing their capacities. Modifications to channels *b* and *c* will proceed until either their capacities equal their loads, at which time the channel system will be stable (and anastomosed or distributive), or until one channel closes completely and the remaining channel assumes the characteristics of channel *a* (a full avulsion if the secondary channel remains open; otherwise, a healed crevasse). Thus, if one assumes that incipient bifurcations occur randomly in space and

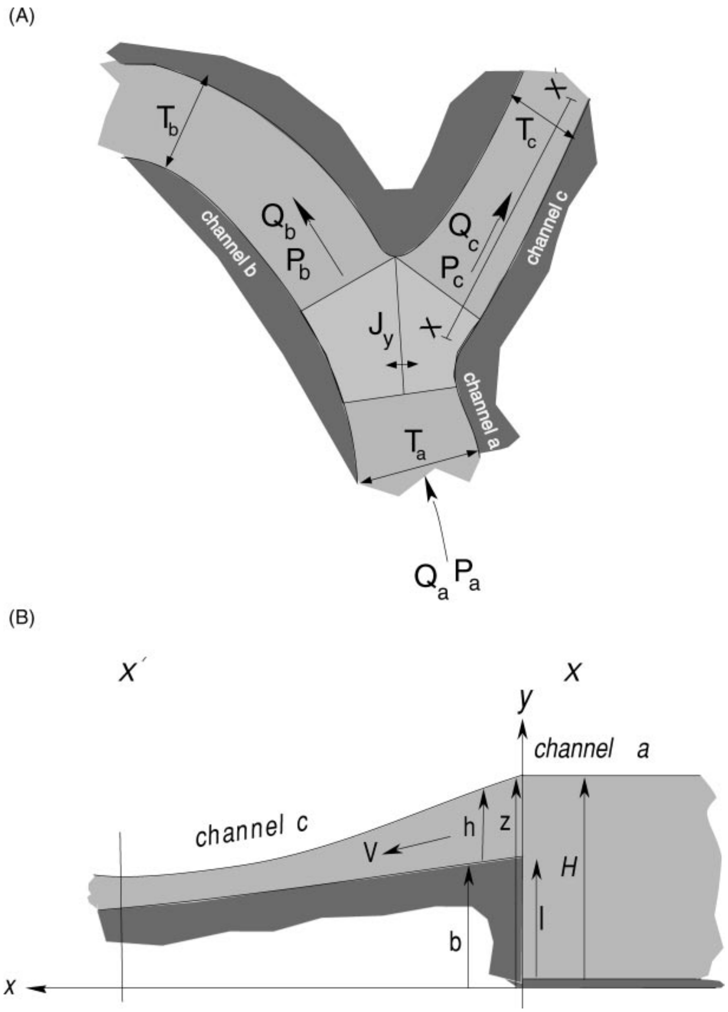

Figure 7 Definition sketch of a branching network. (*A*) An alluvial main channel (*a*) bifurcates into two channels (*b* and *c*) each of initial arbitrary width (*T*) and water surface slope. Water (Q_a) and sediment discharge (P_a) of the main channel are partitioned between channels *b* and *c* in proportion to their relative discharges, channel widths, bottom elevations, and the transverse bedload flux (J_y) arising from water discharge and bed elevation differences at their entrances. (*B*) Definition sketch for variables used in text. The bottoms of channels *b* and *c* at the bifurcation lie at arbitrary heights relative to the main-channel bottom.

frequently (see The Trigger, below), whether or not an avulsion occurs depends upon two factors: (*a*) the processes of sediment partitioning at the bifurcation and (*b*) the ability of the bifurcated channels to change their capacities.

The processes of sediment partitioning at a bifurcation depend upon the mode of sediment transport. Suspended sediment loads will be delivered from channel *a* to channels *b* and *c* in proportion to their partitioned water discharges and in inverse proportion to the relative elevations of their channel floors. The latter is due to the fact that a channel with a high floor draws waters from the top of channel *a* where it contains less suspended solids because suspended sediment concentrations decrease exponentially upward (Slingerland & Smith 1998). If the suspended load is computed using McTigue's (1981) suspended sediment concentration profile, then the steady-uniform suspended load at capacity for a rectangular wide channel can be given as:

$$I = \frac{QC_r}{\zeta}(e^{\zeta} - 1) \tag{1}$$

$$C_r = \frac{\tau_0 - \tau_c}{(\tan\alpha)2dg(\sigma - \rho)},$$

where I = suspended sediment discharge ($\mathrm{m^3 \cdot s^{-1}}$); Q = water discharge ($\mathrm{m^3 \cdot s^{-1}}$); C_r = reference concentration for the suspended load; ζ = Rouse number, equal to $-w/(kU_*)$, where $k = 0.1$ for grain sizes of about 0.1 mm, w = fall velocity ($\mathrm{m \cdot s^{-1}}$), and U_* = bed shear velocity ($\mathrm{m \cdot s^{-1}}$); τ_o = fluid shear stress on the bed ($\mathrm{kg \cdot m^{-1} \cdot s^{-2}}$); τ_c = critical shear stress for the grain size d($\mathrm{kg \cdot m^{-1} \cdot s^{-2}}$); $\tan\alpha$ = dynamic friction coefficient (approximately 1/2; see Bridge & Bennett 1992); σ = grain density ($\mathrm{kg \cdot m^{-3}}$); and ρ = fluid density ($\mathrm{kg \cdot m^{-3}}$). Sediment entering the throat of a bifurcation channel is assumed to originate from the layer of water in the main channel that lies above the elevation of the throat bottom. The mean concentration of sediment in that layer is given by:

$$\bar{C} = \frac{1}{H - l}\int_l^H C_r\left[\frac{\zeta}{H}(y - y_r)\right]dy = \frac{HC_r}{\zeta(H - l)}(e^{\zeta} - e^{\zeta l/H}),$$

where H and l are heights of the water surface and throat bottom above a datum (Figure 7*B*). Then the volumetric flux of suspended sediment entering channel i is given by

$$I_i = \frac{Q_i HC_r}{\zeta(H - l)}(e^{\zeta} - e^{\zeta l/H}), \tag{2}$$

where i indicates either channel b or c, Q_i is the water discharge entering channel i, and all other values on the right-hand side are evaluated in channel a immediately upstream of the bifurcation. Equation 2 shows that I_i is linearly proportional to the discharge entering the branch and decreases as a nonlinear function of lip height.

Note that as l approaches H, Q_i decreases as well, thereby amplifying the decrease in I_i.

In contrast to suspended load, bedload partitioning at the bifurcation depends upon local bed slopes and transverse velocities immediately upstream. As a first approximation, Bolla Pittaluga et al. (2003) divide the reach immediately upstream of the bifurcation into two cells (light-colored boxes in Figure 7) of widths equal to the widths of channels b and c and lengths of αT_a, where α is an order 1 parameter. Sediment coming into the two cells from upstream is assumed to be uniformly distributed across their two upstream faces such that channel a feeds each cell a fraction of its total equal to $T_i/(T_b + T_c)$. Sediment leaving each cell feeds its respective branch. Transverse exchange of sediment between the two cells, J_y, occurs owing to transverse flows between the cells and transverse bed slopes. This flux can be estimated (Bolla Pittaluga et al. 2003, Ikeda et al. 1981) as

$$J_y = J\left[F_1(Q_y) - F_2\left(\frac{\partial b_i}{\partial y}\right)\right], \tag{3}$$

where $J =$ the steady-uniform longitudinal bedload transport rate per unit width at capacity for channel a in the vicinity of the bifurcation ($m^2 \cdot s^{-1}$), F_1 and F_2 are dimensionless functions, Q_y is the transverse water discharge between cells, b_i are the bed elevations of the cells, and y is the transverse direction. If the Meyer-Peter Müller relationship is used, then

$$J = 8K(\theta - \theta_c)^{3/2}, \tag{4}$$

where K is a function of grain size and density and θ is the Shields parameter with a critical value equal to about 0.047. Note that because $\theta \propto (Q^2/h^2)$, doubling water discharge (while holding depth constant) produces an eightfold change in bedload transport. The transverse water discharge Q_y is proportional to the disparity in water discharges between channels b and c. Equation 3 indicates that if the bed of one branch sits at a higher elevation or receives less water discharge than the other, bedload destined for that branch will be redirected proportionally to the other branch.

The second factor governing whether an avulsion will occur is the ability of the bifurcation channels to change their capacities. The capacities of channels b and c depend upon their water discharges, hydraulic geometries, and water surface slopes. These variables can be approximated by the conservation equations written, for example, in one dimension:

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}QV + gA\frac{\partial h}{\partial x} + \frac{TV^2}{C_f^2} + gA\frac{\partial b}{\partial x} = 0, \tag{5}$$

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0, \text{ and} \tag{6}$$

$$\frac{\partial b}{\partial t} + \frac{1}{pT}\frac{\partial P}{\partial x} = 0, \tag{7}$$

where $Q =$ water discharge ($m^3 \cdot s^{-1}$); $t =$ time (s); $x =$ distance along channel (m); $V =$ cross-sectional average flow velocity ($m \cdot s^{-1}$); $g =$ gravitational acceleration ($m \cdot s^{-2}$); $A =$ cross-sectional area (m^2); $h =$ water depth (m); $C_f =$ dimensionless friction factor; $b =$ bed elevation (m); $p =$ volume of sediment in a unit volume of bed layer; and $P = I + TJ$, the total sediment transport rate ($m^3 \cdot s^{-1}$).

The complete solution to the dynamical evolution of a bifurcating network can be obtained by the simultaneous solution of Equations 1, 3, and 5–7, written for the main channel and two branches to create a closed system of equations. Boundary conditions to close the system include (*a*) prescribed water and sediment discharges at the entrance to channel *a*, (*b*) prescribed water surface elevations at the exits of channels *b* and *c*, and (*c*) internal conditions at the bifurcation:

$$Q_a = Q_b + Q_c$$

$$H_a = H_b + H_c$$

$$\frac{\partial b_i}{\partial t} = -\frac{1}{pT_i}\frac{\partial P_i}{\partial x} \pm \frac{J_y}{p\alpha T_{\mathrm{a}}},$$

where J_y is obtained from Equation 3.

Solutions to this system have been computed by Slingerland & Smith (1998) for the suspended load case, and Wang et al. (1995) and Bolla Pittaluga et al. (2003) for the bedload case. Their results show that the following parameters determine the stability of the bifurcating network: the Shields parameter (ratio of fluid shear stress on the bed to the weight of a layer of grains per unit area), friction coefficient, median grain size, and aspect ratio (half-width to depth) of channel *a*; the water surface slopes in channels *b* and *c* relative to *a* and to each other; and the initial elevation differences of the channel beds in the vicinity of the bifurcation. For suspended-load systems carrying grains of 0.4 mm diameter, solutions show that a branch captures all of the flow if its water surface slope is greater than approximately four to five times the slope of the other branch (Figure 8) (Slingerland & Smith 1998). For finer sizes this number is more strongly dependent upon the lip height.

For bedload streams in which the Shields parameter in channel *a* is sufficiently large ($\theta_a \cong 0.3$), there is only one combination of hydraulic variables that allows both branches to remain open (Bolla Pittaluga et al. 2003). In this solution, the ratio of water discharges of the branches must bear a strict nonlinear relationship to the inverse ratio of the energy slopes. For example, for a system in which channel *a* possesses a Shields parameter of 0.3, a half-width approximately eight times the water depth, and $C_f = 12.5$, and $S_c/S_b = 1.2$, Q_c must approximately equal three times Q_b; if Q_c is less, channel *c* sediments shut.

As the Shields parameter in channel *a* decreases, a threshold value is reached after which an increasing transverse sediment flux at the bifurcation allows three families of stable solutions (Figure 9). The critical Shields parameter at this transition depends upon the aspect ratio and dimensionless friction factor of channel

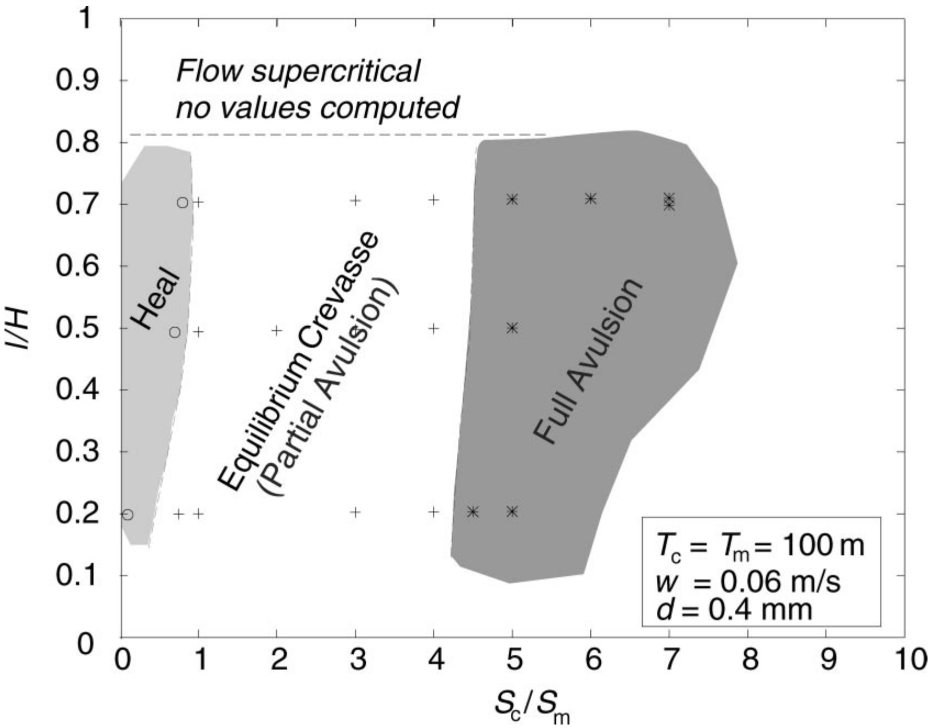

Figure 8 Predicted behavior of a bifurcating suspended-load river carrying grains of 0.4 mm diameter. S_c/S_m is the ratio of the water surface slopes of the two branches, one labeled "c" for crevasse and one labeled "m" for main stem. Vertical axis is initial lip height of the crevasse throat (*l*) relative to water depth of the main channel (*H*) (see Figure 7*B*). Solutions show that the crevasse captures all the flow if its water surface slope is greater than approximately four to five times the slope of the main channel (from Slingerland & Smith 1998)

a. For example, under the conditions $\theta_a = 0.1$, $\beta_a = 8$ and $C_{f_a} = 12.5$, three discharge ratios Q_a/Q_b equal to approximately 4.3, 1, and 0.3 are theoretically possible even though the two branches possess identical water surface slopes. Are these three equilibrium solutions stable to small perturbations, say from sediment bars migrating into the throat of a branch? Bolla Pittaluga et al. (2003) show by a linear stability analysis of channels with equal energy slopes that only the two solutions with unequal water discharges are stable. Furthermore, relatively large aspect ratios of channel *a* cause sediment transport to vanish in one or the other branches, leading to its demise.

In summary, theoretical considerations indicate that whether or not an avulsion will occur depends strongly upon the Shields criterion, channel aspect ratio, dimensionless friction factor, bed geometry at the bifurcation, and the relative sediment-transporting capacities of the branches, especially as the latter are controlled

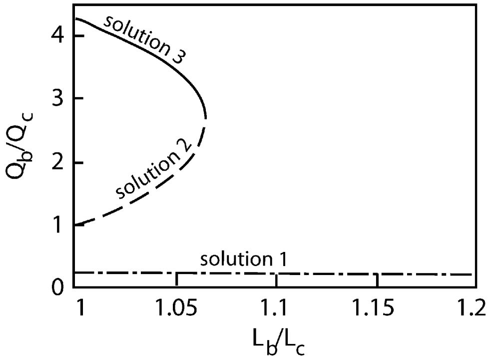

Figure 9 Predicted behavior of a bifurcating bedload river carrying grains of 5.6 cm diameter. A main channel with low Shields parameter ($\theta = 0.1$), moderate aspect ratio ($\beta = 8$), and moderate dimensionless friction factor ($C_f = 12.5$) bifurcates into two channels of lengths L_b and L_c with equal widths and equal water surface elevations at their downstream ends. When the water surface slopes of the branches are equal or nearly so ($L_b/L_c = 1$), three equilibrium solutions of discharge exist in which both branches remain open. Water discharges are highly unequal in solutions 1 and 3; in solution 2 the discharge is apportioned evenly between the branches. Linear stability analysis indicates that only solutions 1 and 3 are stable to perturbations, however. At higher slope ratios only one solution exists that maintains both branches (redrawn from Bolla Pittaluga et al. 2003)

by their water surface slopes. Although the parameter space has yet to be explored thoroughly, we conjecture that the following factors promote avulsions:

1) Rapid alluviation of the main channel. This will cause increased overbank flooding, which in turn will grow ever-higher levees above the floodplain and increased water-surface slopes in crevasse channels relative to the parent channel. Frequency and size of crevasses will increase as increased thalweg wandering leads to whole-levee collapse (Ren & Shunan 1990). Channel aspect ratio will increase as bars grow and the channel widens, thereby reducing the number of possible stable solutions to the flow equations. Within the main channel, the growth of bars and their downstream migration will perturb bed elevations at the bifurcation, thereby increasing the probability of abandoning one branch.
2) A wide unobstructed floodplain able to drain down-valley. This allows water surface slopes from the parent channel to the flood basin to remain high during flooding, thereby maintaining crevasse flow. Pre-existing hydraulically efficient channels also help in this regard.
3) Frequently recurring floods of high magnitude (Knighton & Nanson 1993). The flow history of a channel plays an important role because floods are of limited duration, whereas crevasse enlargement proceeds at a finite rate. In

> the few reported cases, such as the Poydras crevasse of 1922 below New Orleans (Barry 1997) and the upper Mississippi crevasses of 1993 (Gomez et al. 1995), crevasse throats did not deepen beyond half the main-channel depth before the flood waters abated. During the following normal river stage, the crevasse channel may still pass water, but its cross-sectional area will likely be too large for its discharge. Through-flowing waters will deposit side-channel bars, and suspended sediment advected transversely from the main-channel flow into the crevasse throat will form a bar, thereby partially filling the crevasse. During the next flood, the cycle of erosion and subsequent partial healing is repeated. This line of reasoning suggests that there may be a maximum return period for a flood or a minimum depth of throat scour during a flood that will cause crevasse enlargement to be cumulative and, with time, capture the total discharge of the main channel. Lacking that, partial avulsion may be maintained indefinitely, or more commonly, the crevasse seals within a few decades.

Changes in hydraulic conditions and bed geometry at bifurcations by such processes as bar migration and logjams can occur during a single flood, whereas changing the relative sediment transporting capacities of the branches might take millennia. These different time factors led Jones & Schumm (1999, see also Mohrig et al. 2000) to subdivide the conditions required for avulsion into two groups: (*a*) a long-term setup in which the channel gradually increases its susceptibility to avulsion and (*b*) a short-term trigger that initiates the avulsion.

The Setup

In light of the theoretical considerations above, any evolution of the fluvial system leading to increasingly divergent sediment-transporting capacities of the branches should be a necessary condition for a full avulsion. High aggradation rates in the main channel were suggested as a key process to bring this about, a point made earlier by Bridge & Leeder (1979). Support for a causal connection between channel aggradation rate and avulsion frequency comes from Törnqvist (1994) who points out that the number of avulsions during Holocene development of distributaries in the Rhine-Meuse delta increased during times of rapid sea-level rise (when sedimentation rates were high) and decreased when the rate of sea-level rise decreased (but see Stouthamer & Berendsen 2000, p. 597, using the same Rhine-Meuse data for an alternative interpretation). The high number of partial avulsions of the Niobrara River where it enters the Missouri River is interpreted by Ethridge et al. (1999) to be caused by channel aggradation owing to base level rise, and experimental evidence also suggests that avulsion frequency rises with increasing sedimentation rate (Bryant et al. 1995, Heller & Paola 1996). Similar support is given by Makaske (1998), who shows that among different anastomosing rivers, avulsion frequencies decline with decreasing channel aggradation rates.

In many fluvial systems, high aggradation rates are correlated with superelevated alluvial ridges and dominant channels. Perhaps for this reason, some researchers have focused on high water-surface slopes of levee crevasses relative to the slope of the parent channel as the single most important criterion for avulsion (Allen 1965, Wells & Dorr 1987, Brizga & Finlayson 1990, Slingerland & Smith 1998, Ethridge et al. 1999, Jones & Schumm 1999, Mohrig et al. 2000, Makaske 2001, Törnqvist & Bridge 2002). This criterion is variously expressed as (*a*) a threshold elevation difference between an alluvial ridge and its adjacent flood basin, (*b*) a normalized superelevation (e.g., height of natural levees above the adjacent floodplain divided by the parent channel depth), or (*c*) a critical topographic or energy slope from the alluvial ridge to the flood basin measured as a multiple of the down-channel or down-valley slope. Exactly how this measure of relative branch capacities should be measured is not well understood. Mackey & Bridge (1995) define it as the topographic slope at the margin of the channel belt divided by the down-valley topographic slope of the channel belt, but Mohrig et al. (2000) point out that ratios of levee slope to downstream slope in modern rivers vary by an order of magnitude, whereas normalized superelevations do not. Törnqvist & Bridge (2002) argue that neither one is an adequate single measure.

Slope ratios in the range of 3 to 5, consistent with theoretical predictions noted above, have been reported by Guccione et al. (1999) for a partial avulsion in the lower Mississippi Valley, by Peakall et al. (2000) for avulsing rivers influenced by tectonic tilting, and by Törnqvist & Bridge (2002) for simulations of the Rhine-Meuse and Mississippi systems. However, slope ratios an order of magnitude higher can be measured on some nonavulsing systems (Törnqvist & Bridge 2002).

If avulsion frequency increases with increasing aggradation rates in a channel, what causes the increased aggradation? Several mechanisms have been proposed: (*a*) increase in sediment load relative to capacity, (*b*) change in peak water discharge, or (*c*) decrease in channel gradient owing to any of such factors as sinuosity increase, delta extension, base-level fall that superimposes the river on a shallower slope, downstream tectonic uplift, or rising base level (Kuiper 1960, Ren & Shunan 1990, Törnqvist 1994, Schumm et al. 1996, Jones & Schumm 1999, Ethridge et al. 1999, Stouthamer & Berendsen 2000).

The Trigger

Triggering events initiate crevassing, which may immediately lead to partial or full avulsion (as in the case of the Yellow River described in the Introduction), or they may promote full avulsion of a partially avulsed parent channel. In the latter case, with continued differentiation of branch capacities, the channel network becomes increasingly unstable, and only a triggering event is required to send it seeking a new stable geometry. Such triggers are events that abruptly modify channel capacities by changing bed geometry, discharge, or other hydraulic conditions at the bifurcation. These events are typically floods, but also include such processes as abrupt neotectonic movements, ice jams, log jams, vegetative blockages, debris dams, beaver dams, bank failures, or migration of bars downstream that temporarily block the throat of a branch (see Jones & Schumm 1999 for a review). These same processes may trigger initial crevassing and partial avulsion as well.

When general setup conditions are sufficient to permit avulsion, the actual site at which the avulsion takes place is likely to be opportunistic and determined by such local factors as channel geometry, bank stability, or topography, as well as confluence with any of the trigger mechanisms mentioned above. As indicated earlier, avulsion sites commonly begin as crevasses that enlarge until flow is permanently diverted from the parent channel. They commonly occur at the outer banks of meander bends where flow velocities are high, confining levees are narrow, and flood flows impinge the banks at high angles. Floods continually test weaknesses in the channel banks, and local areas of relative instability, e.g., intersected sand bodies of former channels, are potential locations for avulsion (Chrzastowski et al. 1994, Smith et al. 1998).

AVULSION DEPOSITS

Avulsion is an essential process in the construction of floodplains, deltas, and alluvial fans because it forces spatially wide distribution of sediment by relocation of channels. River channels are basically linear transport systems, and short-term deposition tends to concentrate in and near channels. In aggrading river systems, such localized deposition builds alluvial ridges with levees that slope toward the flanking flood basins where deposition proceeds more slowly. If aggradation continues long enough, avulsions become inevitable because the entire floodplain surface must continually aggrade to approximately the same elevation, minus normal relief developed by construction of alluvial ridges. Therefore avulsions should be a chronic feature of aggrading river basins (Richards et al. 1993).

Because avulsions are expectable consequences of long-term aggradation and are required for forming laterally extensive alluvial deposits, we should expect avulsion-belt deposits to abound in stratigraphic successions. They probably do, but as yet only a few studies have specifically inferred the presence of avulsion deposits in ancient river sediments. A likely reason for this is that although avulsion has been long recognized as an important process of rivers, past workers have tended to emphasize channel relocations per se rather than any depositional outcomes of those relocations other than their generation of new channel belts (e.g., Allen 1965, Bridge & Leeder 1979, Walker & Cant 1984, Mackey & Bridge 1995). Past avulsions are readily inferred, for example, from photographs or maps of floodplains showing one or more currently active channel belts lying amid similarly sized but (avulsively) abandoned channel belts that provide little indication of their depositional histories (e.g., Mathews 1984, figure 11.19; Mike 1975; Smith et al. 1997, figure 3; Berendsen & Stouthamer 2000, figure 2). Other evidence for avulsion is often straightforward but indirect. For example, the presence of a peat layer or well-developed paleosol in a succession of fine-grained alluvium may have resulted after a nearby dominant channel diverted to a more distant position in the floodplain so that the site was no longer reached by flooding. Likewise, the radial geometry of typical alluvial fans is strong testimony for nodal avulsions even if the avulsions themselves are never observed. We here briefly discuss deposits of river avulsions in which both sand and fine-grained suspended sediment are significant components of the sediment load.

Deposits of Incisional and Annexational Avulsions

Because incisional avulsions are characterized by their erosive behavior early in the event, there is apt to be little about their subsequent in-channel deposits that distinguishes them from other avulsion styles. In cases where the avulsion pattern is one of either incision or annexation, deposition may be confined to channels with little aggradation of the floodplain surface. However, avulsion might begin with incision or channel annexation but develop significant overbank deposition in later stages. In a detailed study of Cenozoic channel-fill sandstone bodies in Spain and western Colorado, Mohrig et al. (2000) inferred floodplain incision early in the avulsion process. The bodies display well-defined basal scour surfaces and occur as isolated, low-sinuosity ribbons, typically 10–30 m wide, set within thin-bedded to massive mudstones that comprise the majority of the stratigraphic successions. Wedge-shaped wings, interpreted as levee deposits, extend and thin basinward from the tops of many of the channel fills, grading into floodplain mudstones and abruptly overlying older mudstones. These relationships between facies suggest that following incision, fine sediment was supplied to overbank areas by intermittent flooding of the new channel and deposited more or less contemporaneously with channel filling.

Once formed, channels formed by incisional avulsion are subject to annexation by subsequent avulsion. If annexation results in significant widening or deepening, all vestiges of the original channel may be removed (e.g., the annexed Torch Channel of the Saskatchewan River avulsion; see Smith et al. 1998), and classification becomes a point of semantics. If earlier deposits are not completely removed, however, evidence of reoccupation is commonly noted in the character of levee and channel-fill deposits (Kraus 1996, Aslan & Blum 1999, Stouthamer 2000a, Mohrig et al. 2000, Makaske et al. 2002). Multistorey and multilateral channel-sand bodies, particularly if separated by weathered horizons or mudstone layers, are likely indicators of abandonment and later reactivation, as are stepped channel margins, suggesting successive episodes of reoccupation and widening (Mohrig et al. 2000). Multiple levels of levee deposits associated with the same channel fill, or a multistoreyed channel fill adjoining unusually thick levee deposits, are also indications of reoccupation (Stouthamer 2000a,b).

Deposits of Progradational Avulsions

Progradational avulsions are primarily depositional in nature and serve to aggrade low-lying portions of the floodplain (Figures 3–6, 10). Because progradational avulsions tend to generate a variety of fluvial subenvironments, their deposits are typically heterogeneous (Figure 10). At the risk of oversimplification, five principal groups of deposits are commonly recognized in both modern and ancient alluvial successions in which avulsion has played a seminal role (Smith et al. 1989, Nadon 1994, Smith & Pérez-Arlucea 1994, Kraus 1996, Kraus & Wells 1999, Pérez-Arlucea & Smith 1999, Aslan & Blum 1999, Makaske 2001, Makaske et al. 2002):

1. Bounding strata
2. Mud(stone)
3. Sheet sand(stone) bodies
4. Ribbon sand(stone) bodies
5. Large channel sand(stone) bodies

BOUNDING STRATA Avulsions in fine-grained floodplains are usually highly intermittent such that portions of the floodplain become isolated from normal flooding for long time periods. This permits their surfaces to develop weathering profiles or, under suitable conditions of climate and water-table elevations, organic-rich sediment, such as a peat or carbonaceous mud. Eventually, these surfaces become buried with avulsive sediment and form stratigraphic markers that indicate the initiation of avulsion. When avulsive deposition is completed and the channel diverts elsewhere, the newly aggraded surface again becomes subject to weathering, forming the top layer of a sandwich of avulsion-derived sediment lying between two weathered or organic-rich horizons. Such paleosol-bound packages are common in the alluvial stratigraphic record (e.g., Willis & Behrensmeyer 1994, Kraus 1996, Kraus & Wells 1999, Davies-Vollum & Kraus 2001), although such packaging by itself does not assure an avulsion origin. Nor are such readily recognized bounding strata always present, for example, in cases where avulsion overtakes and sustains ongoing deposition in floodplain lakes (Morozova & Smith 1999), or where avulsive deposits remain subjected to normal overbank flooding if insufficiently isolated after avulsion is completed. However, all avulsions begin and end, and these two events are commonly marked by recognizable surfaces or horizons, indicating zero or low deposition rates. Contained within these bounding strata are typically heterogeneous mixtures of the next three sediment groups.

MUD(STONE) This facies comprises varying proportions of clay, silt, and very fine sand and is the dominant sediment group for most progradational avulsions. Transported mainly in suspension, mud is deposited in interchannel lows and in other ponded or otherwise slow-moving water bodies associated with the advancing sediment wedge (splay, delta, or coalesced complexes of either) (Figures 4 and 10). As the smallest particles transported by the avulsive floodwaters, mud is also generally carried the farthest before settling, forming a base over which the coarser portions of the progradational wedge advances. This commonly produces coarsening-upward units whose thickness approximates the depth of the

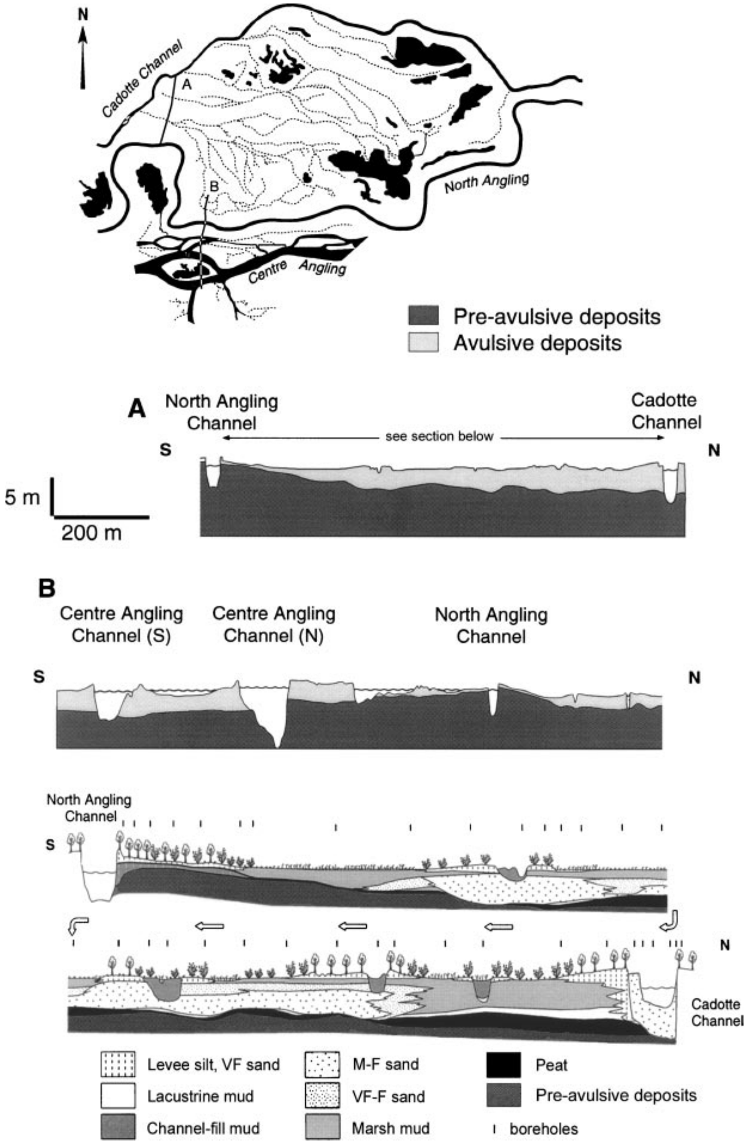

Figure 10 Two cross sections (*A*, *B*) showing avulsive deposits in a portion of the Saskatchewan River avulsion belt. Note thickening of sediments away from both sides of alluvial ridge of the North Angling Channel, an older channel belt that pre-dates the avulsion. The Centre Angling Channel is currently incising the pre-avulsive substrate and is currently becoming the dominant channel of the avulsion belt. The bottom two panels show the lithologic heterogeneity of avulsion deposits in cross-section *A*: sheet sands, ribbons, various mud facies, and a lower peat layer representing the pre-avulsive floodplain surface. (After Pérez-Arlucea & Smith 1999.)

flood basin (Smith & Pérez-Arlucea 1994; Pérez-Arlucea & Smith 1999; Tye & Coleman 1989a,b). Mud(stone) also forms in marshy wetlands and floodplain lakes outside the immediate path of the advancing wedge. Depending on the particular environment of origin, mud(stones) commonly display a wide variety of faunal and floral remains.

SHEET SAND(STONE) BODIES Thin sand sheets represent both simple crevasse splays (where fed by discrete crevasse channels) and channel-mouth bars (where flow at the prograding sediment-wedge margin is channelized). The former (Figure 5) is most common in local avulsions where the splay does not enlarge far from the avulsion site. In large regional avulsions, sand sheets commonly form by coalescence of channel-mouth bars at the leading edge of the progradational wedge. Sometimes mouth-bar coalescence leads to merging of distributary channels to form anastomosed patterns (Smith & Pérez-Arlucea 1994).

RIBBON SAND(STONE) BODIES Ribbon sand bodies, sometimes called ribbons or stringers, represent fills of small channels that distribute water and sediment to the margins of the sediment wedge. They are usually composed of fine to coarse sand and commonly display cross-sectional dimensions similar to those of the original channel, indicating channel stability and little lateral migration (Figure 10). Most ribbons are encased in mudstone and defined by sharp erosional contacts. Although many ribbons result from complete filling of their channels by sand, others represent only partial channel filling, with the upper portions filled with fine sediment representing slow abandonment. Ribbons are characterized by extensive channelwise lengths and low width/thickness ratios, usually <25 or <15, depending on definitions. Ribbons and sheets are often found mutually associated, which is to be expected because many ribbons represent channels that follow basinward progradation of their mouth bars. Ribbons are commonly interpreted as crevasse channel fills, often in the context of anastomosed stream origins.

LARGE CHANNEL SAND(STONE) BODIES These represent the dominant channel belts through the alluvial history of the aggrading sedimentary basin. They are complex features that commonly display histories of lateral migration, scouring and filling, flow variation, and changing bedform patterns (e.g., Willis 1993, Zahela 1997, Khan et al. 1997). If they are single-storeyed, representing single-channel belts not overlapped by successive belts, their dimensions approximately scale to the maximum depths of the original channels and widths of the channel belts as defined by the extent of lateral channel migration. They are both the parents and the end products of major avulsions (Figures 2 and 3).

Stratigraphic Relationships

The first four sediment groups listed above commonly combine to form genetically distinct horizons (avulsion-belt deposits) within thick successions of alluvial

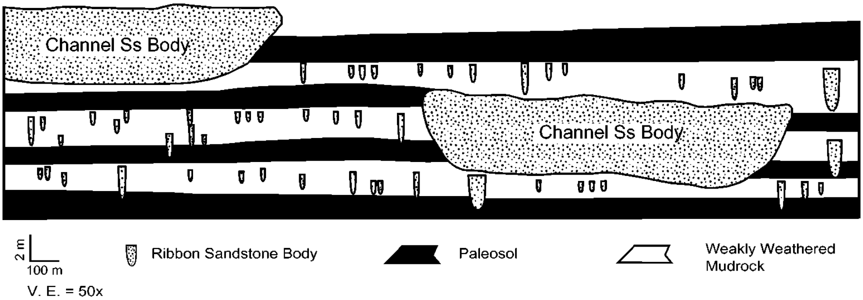

Figure 11 Cross section showing stratigraphic relationships in floodplain deposits of the Willwood Formation (Eocene, USA). Intervals of weakly weathered mudrock and ribbon sandstones sandwiched between well-defined paleosols are interpreted as avulsion deposits. Bounding paleosols represent periods of exposure and low deposition preceding and following avulsion. Note that major channel sandstone bodies locally overlie and truncate avulsion deposits (cf. Figure 2) (modified after Kraus & Wells 1999).

sediments. Their characteristics include (*a*) rapid deposition, in most cases with relatively distinct beginnings and ends; (*b*) rapid spatial distribution, with areal limits governed by floodplain topography and size and duration of the diverted discharge; and (*c*) thickness controlled by the elevation difference between the parent channel belt and invaded flood basin. Because avulsions will repeat for as long as aggradation continues, avulsion-belt deposits will eventually succeed each other vertically, forming tiers of heterogeneous deposits (groups 2–4 above) marked by bounding strata of paleosols, organic-rich sediments, or overbank flood deposits supplied by succeeding channel belts (Figure 11).

All avulsion-belt deposits have a close genetic relationship to their parent channel, and accordingly, any suite of sediments representing a single avulsion belt will occur within the same stratigraphic horizon as the parent channel (large channel sandstone body). Because the bases of dominant channels incise well below the floodplain surface, and because avulsive deposition elevates the floodplain surface by filling in the lows, the stratigraphic horizon occupied by the avulsion-belt deposits will tend to lie near the top of the horizon defined by the parent channel belt. The limiting elevation of the top surface of the avulsion belt will be approximately defined by the levee elevation of the parent channel. The avulsion belt may overlap the margins of any pre-existing channel belt that confines it, including the parent, particularly in local avulsions where avulsive deposition does not stray far from the parent channel.

Stratigraphic relationships are different, however, for the channel belt that remains after avulsion is completed (Figure 2). This channel belt is the result rather than the cause of avulsion, and it will incise well below the level of the avulsion belt deposits that immediately preceded it. The new channel belt subsequently develops levees, aggrades a new alluvial ridge, occasionally floods the surface of the just-formed avulsion belt, and with continued net aggradation eventually matures to a state in which a new avulsion becomes increasingly probable.

Avulsion Versus Traditional Concepts of Alluvial Deposition

Although deposits of avulsion have not yet been widely reported, the prominent roles they are known to play in the development of alluvial floodplains, especially floodplains undergoing long-term net aggradation, makes it likely that this process will be increasingly recognized and appreciated in future investigations of rivers and their deposits, both modern and ancient. Avulsion offers alternate or complementary viewpoints for a number of features associated with the development of floodplains and alluvial deposits. These include the following:

AVULSION VERSUS OVERBANK FLOODING Overbank flooding is a feature of most alluvial rivers and occurs episodically when bankfull discharge is exceeded. As such, the floodplain is replenished with fine sediment and water only during short periods and is exposed the rest of the time. Avulsion provides "through-bank" flow and sediment continually to certain portions of the floodplain, creating wetlands and new alluvial topography.

ORIGIN OF FLOODPLAIN FINES Complementary to the above, episodic overbank flooding may provide thin suspended sediment deposits to the floodplain surface, but commonly only faint records of deposition remain after a flood (Gomez et al. 1995). Conversely, avulsion provides a longer-term mechanism for continuous supply of fine sediment to low parts of the floodplain where preservation is enhanced. In studies of avulsive deposition where both coarse and fine material comprise the succession, fine sediment clearly dominates the avulsive intervals (Smith et al. 1989, Kraus & Gwinn 1997, Pérez Arlucea & Smith 1999, Aslan & Blum 1999, Kraus & Wells 1999). Avulsions, not levee-topping floods, are the principle cause of floodplain growth.

AVULSION AND ANASTOMOSIS Anastomosing channel networks are sustained by partial avulsions and are particularly well developed in confined systems (e.g., with valley walls) where newly formed avulsion channels are forced to rejoin the parent (Makaske 2001, Makaske et al. 2002). Under conditions of continuous aggradation, anastomosis may be a stable pattern of dynamic equilibrium in such settings (Abbado et al. 2004); incisional avulsions may also form stable anastomosed configurations. Anastomosis is more likely to be a short-term transitional pattern forced by the need to supply a large sediment sheet, and disappearing when the low areas of the flood basin are aggraded and flows are captured into a new single-thread channel (Figure 2). In such cases, anastomosis is in part a product of small local avulsions hierarchically superimposed on a regional avulsion.

THIN SAND SHEETS AND RIBBONS These are common features of alluvial deposits dominated by avulsion. They usually have been interpreted in two different contexts: (*a*) products of crevasse splays and small channels formed by local avulsion in anastomosed systems (e.g., Smith 1983, Nadon 1994, Makaske 2001) and (*b*) products of regional avulsion, associated with widespread and coalesced deposits of prograding splays, mouth bars, and their feeder channels (e.g., Smith et al. 1989, Kraus and Gwinn 1997, Pérez-Arlucea & Smith 1999, Kraus & Wells 1999). The former implies limited areal extents, random occurrence in stratigraphic sections, and close associations with the parent channel, whereas the latter suggests areally extensive deposits occurring in narrow stratigraphic intervals and far away from the parent channel. Kraus & Wells (1999) discuss criteria for distinguishing the two contexts.

ROLE OF THE DOMINANT CHANNEL A traditional view of the dominant channel in an alluvial floodplain is that it provides the floodplain with suspended sediment during floods and thus is the main supplier of fine-grained deposits in alluvial successions. This view is probably incorrect. Rather it is avulsions, especially progradational avulsions, that create floodplains, a task accomplished in a relatively short interval. This results in abandonment of the parent channel and generation of a new dominant channel after most new deposition is completed. The new dominant channel may then disperse additional fine sediment by overbank flooding until it too is abandoned by avulsion. Much of the floodplain aggradation, however, may in fact be a relatively rapid product of avulsion rather than a slower incremental product of normal flooding. "How much?" and "How important?" remain questions for research, but recent work suggests that at least half is not unreasonable (Kraus & Gwinn 1997, Aslan & Blum 1999, Kraus & Wells 1999, Morozova & Smith 2000), although this is likely to vary widely from case to case.

ACKNOWLEDGMENTS

This work was supported by grants from the National Science Foundation, Division of Earth Sciences to Slingerland and Smith. Fellow scientists, students, and field guides contributing to this work include Marta Perez-Arlucea, Galina Morozova, Dan Cazanacli, Kathleen Farrell, Remus Lazar, Gary Carriere, Steve Nelson, Dan Ombalski, Peter Adams, and Dimitri Abbado.

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Figure 3 Site of the 1870s avulsion of the Saskatchewan River, now nearing full avulsion stage as only approximately 5% of the annual flow is still carried by the parent channel (Old Channel, *lower right*). Flow in avulsion channel (New Channel) is away from viewer.

Figure 4 Active crevasse splay in avulsion belt of the Saskatchewan River, an example of partial avulsion. Note levee of older pre-avulsive channel in the background, confining the local flood basin into which the splay is prograding.

Figure 5 Older and more proximal portion of the Saskatchewan River avulsion belt showing mostly abandoned anastomosed channels and small isolated flood basins (*light areas*). Flow is generally away from viewer.

Figure 6 Tree trunk buried by the 1870s Saskatchewan River avulsion, now exhumed in cutbank of active channel. Enclosing sediment is mostly fine to coarse silt. Exposed portion of trunk is approximately 1.4 m high.