Experimental study of avulsion frequency and rate of deposition

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ABSTRACT

In existing models of alluvial architecture it is typically assumed that mean avulsion frequency is independent of sedimentation rate. However, if avulsion is driven by super-elevation of a river bed above its surrounding flood plain, one might expect avulsion rate to increase with sedimentation rate. We have carried out a series of experiments with laboratory-scale fluvial fans in which we measured the frequency of apical avulsions as a function of mean sedimentation rate on the fan. Avulsion frequency increased strongly with increasing sedimentation rate and then stabilized as mass flows began to influence deposition. In the regime of increasing avulsion frequency, the added volume of sediment needed to trigger an avulsion decreased with increasing sedimentation rate. Although our experimental results cannot simply be scaled up to natural rivers, they suggest the possibility of coupling between avulsion frequency and sedimentation rate that would be strong enough to change qualitatively the results of existing models of alluvial architecture. These models should be applied with caution until avulsion mechanics are better understood.

INTRODUCTION

One of the most important and influential contributions in alluvial stratigraphy has been the series of models of alluvial channel-belt stacking and architecture developed by M. R. Leeder, J. R. L. Allen, J. S. Bridge, and their coworkers (Allen, 1978; Leeder, 1978; Allen, 1979; Bridge and Leeder, 1979; Alexander and Leeder, 1987; Bridge and Mackey, 1993). Successive versions have elaborated on the original basic model; we will refer to the whole suite as the “LAB model,” distinguishing individual versions as needed. The theme of the LAB model is that as channel belts avulse (switch paths abruptly) in a depositional river system, they produce a distribution of channel-belt sands in the vertical plane (“alluvial architecture”) that depends on, among other things, the geometry and rate of deposition and the dynamics of avulsion. A simple and widely used outcome of the LAB model is that channel belts avulse (switch paths abruptly) in a depositional river system, they produce a distribution of channel-belt sands in the vertical plane (“alluvial architecture”) that depends on, among other things, the geometry and rate of deposition and the dynamics of avulsion. A simple and widely used outcome of the LAB model is that, if the frequency of avulsion is constant, the cross-sectional density of buried channel belts should be inversely correlated with sedimentation rate: widely dispersed, isolated “ribbon” channel-belt sand bodies represent high sedimentation rates, when a substantial accumulation of overbank fines is deposited between avulsion events. More densely connected, coalescing sand bodies represent periods of low sedimentation rate, when little overbank material is deposited and channel systems rework the flood plain, redepositing fines downstream. Other possible influences on alluvial architecture in the LAB model include sediment compaction, tectonic tilting, and variation in width of the channel belt (Bridge and Mackey, 1993).

The LAB model has been widely applied in the interpretation of alluvial deposits (Bennetmeyer and Tauxe, 1982; Nichols, 1987; Kumar, 1993; Mack and James, 1993; Olsen and Larsen, 1993; Wizevich, 1993). It also has important economic implications, since the connectedness of channel sands exerts a strong control on reservoir volume. The model has not been easy to test, however, because of the difficulty of both constraining input parameters for ancient systems and obtaining the chronostratigraphic resolution needed to determine how observed changes in stacking pattern correlate with changes in sedimentation rate. Cases where independent estimates of variation in sedimentation rate are available indicate both negative (Visser and Johnson, 1978; Kraus and Middleton, 1987; Shuster and Steidtmann, 1987) and positive (Read and Dean, 1982; Johnson et al., 1985; Willis, 1993) correlations between channel-belt sand fraction and sedimentation rate.

Development of alluvial-architecture models has been hampered by the lack of a well-founded physical understanding of avulsion mechanics. In the absence of any compelling reason to do otherwise, the original authors in the LAB series (Allen, 1978; Leeder, 1978) assumed constant avulsion frequency. Subsequent workers (Bridge and Leeder, 1979; Bridge and Mackey, 1993) have elaborated by allowing the avulsion frequency to vary randomly about a constant mean value. The most widely used result of the LAB model—the inverse relation between sedimentation rate and channel-belt stacking density—depends crucially on the assumption that mean avulsion frequency remains constant as sedimentation rate changes. How realistic is this assumption? The difficulty of obtaining well-constrained field data on avulsion dynamics prompted us to study the problem experimentally. We measured avulsion frequency as a function of sediment-feed rate in a series of small-scale model fluvial fans. These experiments show a strong positive relation between avulsion frequency and sedimentation rate. Such experiments are subject to problems of their own, the most important of which is determining if and how the results can be scaled up to field conditions. We do not claim that natural river systems behave exactly as our experiments did. However, the experiments, together with field data and simple physical reasoning about how avulsion works, suggest that avulsion frequency and sedimentation rate are strongly coupled.

AVULSION MECHANICS AND AVULSION FREQUENCY

Observations of avulsion in modern rivers consist primarily of case studies of at most a few events (Fisk, 1951; Gole and Chitale, 1966; Schumm, 1968; Wells and Dorr, 1987; Smith et al., 1989; Brizga and Finlayson, 1990; McCarthy et al., 1992; Richards et al., 1993). Although these case studies have not yet led to a comprehensive physical theory of avulsion, the common thread running through them is that avulsion is driven by local superelevation of some part of the channel or channel complex above its surroundings. This superelevation is produced by sediementation, which tends to occur at higher rates near the channel than farther out in the flood plain (Pizzuto, 1987). A sketch of the process is shown in Figure 1. A simple view would be that the likelihood of avulsion increases with greater perching of the channel above the flood plain, so that...
channel superlevelation leads to a critical state in which a variety of perturbations can trigger an avulsion. Brizga and Finlayson (1990) showed a good example (their Fig. 6) of abandonment of a channel perched above its flood plain in favor of a parallel but lower channel. Ashmore (1991), in a notably thorough laboratory and field study of braiding dynamics, observed that periodic increases in local sedimentation rate caused by sediment pulses traveling down the flume were associated with increases in the number of simultaneously active channels, the rate of local channel switching, and the likelihood of a major avulsion. Hooke and Rohrer (1979), in a study of laboratory fluvial fans, concluded that depositional increases in slope increase the probability of diversion of the flow from areas of active deposition into adjacent low areas.

The connection between avulsion and channel superlevelation resulting from preferential deposition near the channel axis suggests that avulsion rate could be related to sedimentation rate, if differential sedimentation between channels and flood plain is scaled to overall sedimentation rate. A study that helps span the gap between modern and ancient fluvial systems is that of Törnqvist (1994), who measured variations in overall avulsion frequency in the Rhine-Meuse Delta in the Netherlands by $^{14}$C methods. Törnqvist found a higher rate of avulsion in the delta system during the interval 8500 B.P.–4300 B.P. than from 4300 B.P. to the present. The high-frequency interval corresponds to a period of faster sea-level rise and was thus inferred by Törnqvist to represent a period of increased fluvial aggradation rate as well.

LABORATORY MODEL AND PROCEDURE

We performed our experiments in a stream box 1.6 m wide, 3 m long, and 0.3 m deep. Sediment and water were introduced at the head of a channel, dipping 25°, that entered the box in the center of one of the short (1.6 m) sides. This arrangement allowed development of a fan with a maximum radius of 0.8 m. Sediment was fed through a 2000 cm$^3$ cylinder that was kept filled. Sediment discharge was controlled via calibrated, interchangeable end caps on the feed tube. A steady water discharge was provided from a constant-head tank that introduced water just above the sediment-feeder cylinder, entraining sediment at the head of the channel and depositing it as a fan in the box. The sediment was a well-sorted quartz sand [mean size $= -0.83 \psi$, standard deviation 0.33 $\psi$, where $\psi = \log_{2} (\text{grain size in mm})$]. Fans were built up in an initially empty basin with a horizontal floor. At no time during the runs was clear water allowed to flow, so the system was always depositional. With constant grain size and water discharge, overall fan geometry was controlled by the sediment flux. The downstream boundary condition was a constant water elevation controlled by a stilling well.

During the runs we monitored channel configuration and overall fan slope. Once a run was started it was continued without interruption to minimize effects of water infiltration into the fan surface. Runs were stopped either when the fan edges reached the sides of the basin or when the fan volume became enough to produce infiltration rates that significantly reduced the discharge.

We were interested in distinguishing avulsions from crevasse splays or minor local flow diversions. Thus we defined an avulsion according to two criteria: the newly created channel had to carry over 50% of the discharge of the old channel, leading to the eventual abandonment of the previous channel; and the diversion of flow had to begin within the upstreammost 10% of the fan length. We term these major avulsions “apical avulsions.”

We conducted 12 runs with eight sediment-feed rates and a constant water discharge of 0.151 l/s. Sediment feed rates ranged from 10.25 cm$^3$/s to 34.00 cm$^3$/s.

RESULTS

The results for eight runs are shown in Figure 2, which also includes the input sediment discharge and final fan slope. Runs below a sediment flux of 15.75 cm$^3$/s never developed stable avulsing channel systems whereas runs above 19.25 cm$^3$/s always evolved into an avulsing system. We performed duplicate runs for sediment discharges of 15.75 cm$^3$/s, 19.25 cm$^3$/s, and 22.7 cm$^3$/s. For these discharges the fan slope given in Figure 2 is the average of the observed final values.

At a sediment flux of 15.75 cm$^3$/s, avulsion began in the second run (shown in Fig. 2) after 3200 s whereas the first one reached the sidewalls before avulsion began. Of the two runs at 19.25 cm$^3$/s, the first (shown in Fig. 2) began to avulse after 3000 s whereas the second began to avulse after 5200 s, at which time the fan filled the basin and the experiment was stopped. Both runs at a sediment flux of 22.7 cm$^3$/s began to avulse after 600 s, and all runs above a sediment flux of 22.7 cm$^3$/s developed into avulsive systems.

The fans typically developed in three phases. In the first phase, more than 50% of the fan was covered by water. No clear channels were present and no avulsions occurred. Sediment distribution occurred by sheet flow. As the fan continued to grow, distinct channels developed but were unstable and prone to bifurcation. Sediment distribution in this second phase was mainly caused by short-lived crevasse splays that developed off the main channel but never carried more than 50% of the total discharge. The third phase was characterized by a single channel that was solely responsible for sediment distribution. Areal distribution occurred incrementally through apical avulsions that systematically swept one side or the other of the fan. A secondary sediment supply mechanism involved crevasse splays that locally distributed sediment but never took more than 50% of the discharge. We did not classify these crevasse splays as avulsions. Nonavaline fan systems that developed at low sediment discharges did not reach the third phase and thus distributed sediment areally via secondary channels and broad, poorly channelized sheet flows.

The primary goal of this series of experiments was to determine how avulsion rate depends on deposition rate. Figure 2 shows that avulsion as defined above occurred reg-
The present series of experiments did not allow us to determine why the sediment volume needed to trigger an avulsion decreases with sediment-feed rate. A likely contributor to this effect, however, is that the fan slope overall increases as sedimentation rate increases (Fig. 2). Although the channels were too shallow to permit accurate depth measurements, one would expect increasing slope to decrease mean channel depth (Parker, 1978). It seems reasonable that the super-elevation ($h_i$ in Fig. 1) needed to trigger an avulsion would scale with channel depth $h_i$; in that case, one would expect that less sediment would be required to force an avulsion as overall slope increases and channel depth decreases.

The increase in sediment-feed rate for the runs shown in Figures 3 and 4 is a factor of 1.4. Figure 2 shows that further increases in the sediment-feed rate (by a factor of 1.5) did not cause further increases in avulsion rate. The sediment-feed rates associated with this “saturation” regime of constant, high avulsion frequency were marked by development of short-lived mass flows near the inlet. Thus the saturation in avulsion frequency developed as we approached the maximum sediment flux for fluvially dominated transport, given the (constant) water discharge we used.

**DISCUSSION**

The LAB models demonstrate how interconnectedness and channel deposit density vary inversely with sedimentation rate, assuming a constant avulsion rate. Our data suggest that increasing the sedimentation rate can strongly increase the rate of avulsion. This conclusion leads to qualitative ambiguity in interpreting the relation between stacking density of channel sands and sedimentation rate.

The experiments we report here were not intended to be scale models of any particular river system, and they cannot be extrapolated quantitatively to natural rivers. They do suggest that the “saturation” of avulsion frequency at a stable maximum value (Fig. 2) is restricted to conditions in which the external sediment-supply rate is near the maximum for fluvial transport for a given water discharge. Thus we believe that an increase in avulsion frequency with sedimentation rate is probably more characteristic of purely fluvial transport systems. There is good reason to think that this dependence of avulsion frequency on sedimentation rate is not unique to our experimental setup. First, it is consistent with the avulsion-frequency data of Törnqvist (1994) from the Rhine River system. Second, the physical mechanism by which avulsion rate and sedimentation rate would be coupled—differential deposition leading to channel superelevation above its surroundings—is not fundamentally scale-dependent (although the detailed physical mechanism of avulsion could be). It is worth examining the consequences of various forms of coupling between avulsion frequency and sedimentation rate. If $F_a$ is the frequency of avulsions and $R_e$ is the sedimentation rate, then $F_a \propto R_e^\beta$, where $\beta$ is a positive, real-valued exponent. This relation gives three qualitatively different regimes (Fig. 5):

1. **$0 \leq \beta < 1$**. The original LAB relation between channel-belt stacking density and sedimentation rate, based on assuming constant mean avulsion frequency, would still be valid. (Varying sedimentation rate with constant mean avulsion frequency amounts to assuming that $\beta \approx 0$.) However, the relation between sedimentation rate and channel-stacking density would weaken as $\beta \rightarrow 1$.

2. **$\beta = 1$**. The stacking pattern would be independent of sedimentation rate.

3. **$\beta > 1$**. The regime for $\beta = 1$, shown in Figures 3 and 4, results from a relation between stacking and sedimentation that is opposite to that in the LAB models. Increases in sedimentation rate would lead to higher switching rates, more effective removal of floodplain fines, and higher density of sand bodies.

These three regimes obviously cloud the relation between alluvial architecture and sedimentation rate. As we mentioned in the Introduction, cases where independent estimates of variation in sedimentation rate are available indicate both negative and positive correlations between channel-sand fraction and sedimentation rate. Negative correlations are consistent with case 1 above, and positive correlations are consistent with case 3.

Mackey and Bridge (1995) have described a new three-dimensional alluvial-stratigraphy model that includes three types of avulsions. Avulsions originating at or upstream of the upstream end of the simulated fluvial section occur according to an imposed prob-
CASE 1 (β < 1)

CASE 2 (β = 1)

CASE 3 (β > 1)

Figure 5. Relation between channel-belt stacking density and sedimentation rate for three possible regimes defined by the exponent β in a power-law relation between avulsion frequency and sedimentation rate. Black is channel-belt sand bodies; dash pattern is flood-plain deposits. Top panel corresponds to a regime in which avulsion frequency is taken to be independent of sedimentation rate; bottom panel is that suggested by experimental results shown in Figures 3 and 4.

ability distribution with constant mean frequency, as in the earlier LAB models. Avulsions originating within the modeled section may be either coupled or uncoupled to the local sedimentation rate. The new Mackey-Bridge model is consistent with the findings we report here as long as (1) the option for local avulsion coupled to sedimentation rate is selected and (2) local sedimentation rates in the area of application are uncoupled from sedimentation rates farther upstream. In any case, it is clear that development of alluvial-architecture models that are even qualitatively accurate requires a better understanding of avulsion dynamics than we have at present.

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