A mass-balance framework for quantifying downstream changes in fluvial architecture

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ABSTRACT

It is still commonly believed that channel stacking density in alluvial cross-sections is controlled mainly by local subsidence rate, despite new models that emphasize the three-dimensionality of alluvial architecture. New data are presented from an experimental alluvial basin that show variation in the spatial distribution of deposition to be the main control on architecture, rather than subsidence per se. A simple coordinate transformation is proposed that maps downstream distance into the fraction of the sediment supply deposited to that point. Transforming measured sections into this ‘mass balance’ coordinate system removes much, although not all, of the observed variability in channel stacking density and grain size. Furthermore, removal of the dominant mass-balance effects via transformation to fraction deposited reveals more clearly those residual architectural effects that are not mass-balance controlled: for example, changes in channel size associated with fluctuations in water supply.

INTRODUCTION

Most workers think of physical stratigraphy as being controlled by three main allogenic drivers: climate, tectonics and eustasy. For analytical purposes, the first two of these must be distilled into specific governing variables, of which the main ones are rate and size distribution of sediment supply, space–time distribution of crustal deformation, and space–time distribution of water runoff. It follows that alluvial architecture should be controlled by these same variables.

One of the major effects of changes in any of these governing variables is to alter the distribution of deposition (referred to here as the depositional mass balance) within the fluvial system. Deposition preferentially extracts the coarser fraction of the sediment supply, so both the amount and the size distribution of sediment available to the fluvial system at a given point are strongly controlled by upstream sediment extraction. Thus a direct effect of changing the sediment mass balance is to cause longitudinal (streamwise) migration of facies belts in concert with changes in the distribution of deposition. In general one would expect the architecture at any point to reflect a superposition of these direct mass-balance effects and changes in other relevant variables, such as local sedimentation rate, avulsion frequency and pattern, and channel belt geometry. Note, however, that although sedimentation rate and depositional mass balance are related, they are not the same: sedimentation is a local variable, but depositional mass balance is meaningful only in the context of the whole fluvial system. The relationship between the two is made precise later in the paper. At this point, little is known about the relative importance for alluvial architecture of direct mass-balance effects versus the other variables listed above, although the latter have been the exclusive focus of architecture models to date (Allen, 1978, 1979; Bridge & Leeder, 1979;
Alexander & Leeder, 1987; Leeder & Gawthorpe, 1987; Bridge & Mackey, 1993a,b; Mackey & Bridge, 1995). In this paper, an experimental case study is presented in which changes in the depositional mass balance turn out to be the dominant control on alluvial architecture.

BACKGROUND AND GOALS

Alluvial architecture was one of the first problems in physical stratigraphy to be analysed quantitatively, thanks to the model proposed by Leeder (1978) and subsequently expanded upon by Allen (1978) and Bridge & Leeder (1979). These models and their many descendents will be referred to as the Leeder–Allen–Bridge (LAB) models. In Leeder’s original model, the main control on architecture was sedimentation rate, assumed equal to subsidence rate, relative to avulsion frequency. The main result of this early work was that low sedimentation rates cause randomly avulsing channels to stack more densely upon one another, assuming constant avulsion frequency. The Leeder model led to a series of refinements and extensions (Allen, 1978, 1979; Bridge & Leeder, 1979; Alexander & Leeder, 1987; Leeder & Gawthrop, 1987; Bridge & Mackey, 1993a,b; Mackey & Bridge, 1995) as well as a variety of tests (Behrensmeyer & Tauxe, 1982; Kraus & Middleton, 1987; Leeder et al., 1996, Guiseppe & Heller, 1998; Aslan & Blum, 1999; Ashworth et al., 1999; Kraus, 2002).

Two major shortcomings of the original LAB approach have been addressed in recent years. First, one would expect avulsion frequency to depend strongly on sedimentation rate, as avulsion is largely driven by sedimentation. This was shown experimentally by Bryant et al. (1995), who also pointed out that, even at a qualitative level, the relation between architecture and sedimentation depends on the relationship between avulsion frequency and sedimentation rate. Heller & Paola (1996) went on to examine the consequences of this in more detail. The second major shortcoming was that the original LAB models were two-dimensional, focusing on channel stacking in panels taken in the cross-stream direction, i.e. perpendicular to the mean flow direction (depositional strike). This was addressed by Mackey & Bridge (1995) and Heller & Paola (1996), who extended the domain to the third, streamwise, dimension. Two points about the LAB model series are particularly important to the work we describe here:

1. despite efforts to uproot it, the aspect of the LAB models that persists in common stratigraphical wisdom is that greater channel stacking density (i.e. a more sheet-like sandbody geometry) implies lower sedimentation (subsidence) rate and vice versa;

2. despite considerable effort, even the most basic predictions of the LAB models remain largely untested.

In this paper the importance of mass balance in the streamwise (depositional dip) direction is examined in alluvial architecture. Data from a recent experiment in a new subsiding-floor sedimentary basin (Paola, 2000; Paola et al., 2001; Sheets et al., 2002) are used to demonstrate that fluvial morphology and preserved alluvial architecture in the subsurface are strongly controlled by the spatial distribution of deposition in a basin. The importance of downstream (downdip) location in terms of deposition is studied as a control on channel stacking density and overall grain size, and it is suggested that vertical changes in channel stacking density seen in many field cases (e.g. Fig. 1) may simply reflect variation in depositional mass balance owing to any of a number of possible external causes. A simple coordinate transformation is proposed that allows for the comparison of cross-stream panels in a framework that accounts for changes in mass balance. Although applied here to alluvial architecture, it is believed that the approach can be applied to interpreting any mass-conserving stratigraphical system.

EXPERIMENTAL SET-UP

Experiments were conducted in the Experimental EarthScape (XES) Facility at St Anthony Falls Laboratory, University of Minnesota, USA. The XES facility is a large (6 m × 3 m × 1.3 m) experimental basin with a programmable subsiding floor. Water discharge and sediment discharge into the basin, as well as base level, are also fully controllable. This particular XES run modelled basin filling by a braided river system prograding.
into a standing body of water—a braided fluvial fan delta as defined by Nemec & Steele (1984). The main focus of this run was to test the effects of changes in subsidence and water supply on alluvial architecture. Base level was thus held constant throughout the experiment. Sediment composition was also held constant, the sediment mixture consisting of 40% by volume crushed anthracite coal and 60% by volume 120 µm white quartz sand. These materials served as experimental proxies for fine and coarse-grained sediment respectively, coal serving as the fine-grained proxy owing to its lower density (1.4 g cm$^{-3}$) thus greater mobility relative to the quartz sand (2.65 g cm$^{-3}$). The total volumetric sediment feed rate, i.e. integrated net deposition, was matched to the volumetric rate of accommodation produced by subsidence throughout the experiment. This choice was intended to minimize facies migration, but this was only partially

Fig. 1 Montsant alluvial fan (middle Eocene to late Oligocene: Anadón et al., 1986), Villanova de Prades, Spain.
successful. This point will be discussed later in greater detail.

The experiment comprised four stages, analogous to four geological units in a sedimentary basin, each representing alluvial-basin filling under distinct climatic and tectonic conditions (Fig. 2; Sheets et al., 2002). Stages 1 and 2 were designed to study the sensitivity of the depositional system to changes in subsidence geometry. Stage 1 was characterized by a complex varying subsidence geometry, with both streamwise and cross-stream variability, whereas stage 2 used a simple linear-hinge subsidence pattern. Stages 2 and 3 were designed to study the sensitivity of the depositional system to changes in mean subsidence rate. As such, the rate of subsidence during stage 3 was four times slower than that of stage 2, and sediment and water supply were scaled back proportionally. Finally, stage 4 was designed to study the sensitivity of the depositional system to changes in water supply; the water discharge was approximately doubled relative to that of stage 3 whereas all other variables were held constant.

During the experiment, the surface flow pattern was recorded using video and still cameras. Surface topography was recorded with a laser scanning system, allowing the tracking of fluctuations in the spatial distribution of deposition and erosion within the basin. After the experiment was completed the resultant deposit was sectioned in the cross-stream (strike) direction to produce a series of parallel faces spaced 2 cm apart. These faces were imaged and these images compiled into a three-dimensional visualization of the basin stratigraphy.

### EXPERIMENTAL OBSERVATIONS

This paper focuses on stages 2 and 3 of the experiment. As mentioned above, these two stages were designed to examine the effects of changes in mean subsidence rate on alluvial architecture. By holding constant the ratio of water supply to sediment supply, the ratio of sediment supply to accommodation, and base level, it was hoped to isolate the effects of reduction in subsidence on alluvial architecture.

Considering the ‘synthetic outcrop’ in Fig. 3, which consists of a cross-stream (strike) section located at a downstream distance of 2.64 m, it is evident that stage 3 has fewer channels than any of the other stages and is clearly richer in coal, the experimental proxy for fine-grained sediment. A similar scenario in a natural outcrop, an abrupt decrease in channel-stacking density, could be interpreted according to conventional wisdom as indicating an increase in subsidence rate. In the experiment, however, the subsidence rate in stage 3 was approximately four times lower than that of stage 2. Why then does stage 3 look less channelized? To answer this question the three-dimensional character of the experimental basin stratigraphy and experimental conditions prevalent during stage 3 must be compared with those in the other stages.

One advantage of experimental stratigraphy is that it can be sectioned at sufficiently close spacing so as to reconstruct a reasonably complete view of the three-dimensional structure of the deposit. For this experiment, the three-dimensional
than in the other stages, increasing the depositional slope and the ability of the system to transport sediment. This was most pronounced at the beginning of stage 3 when, relative to stage 2, most of the coarse (sand) component was being deposited rapidly in the upstream portion of the system. The relative amounts of coal and sand in the sediment mixture remained constant throughout the experiment, but sand was removed from the system more rapidly in stage 3 than in any of the other stages, causing the sand–coal transition (and, to a lesser extent, the shoreline) to retrograde abruptly at the beginning of stage 3. An abrupt facies retraction is shown clearly in the deposit (Fig. 4).

Thus, the spatial distribution of deposition in stage 3, i.e. the mass balance of deposition, was different than in the other stages, increasing the depositional slope and the ability of the system to transport sediment. This was most pronounced at the beginning of stage 3 when, relative to stage 2, most of the coarse (sand) component was being deposited rapidly in the upstream portion of the system. The relative amounts of coal and sand in the sediment mixture remained constant throughout the experiment, but sand was removed from the system more rapidly in stage 3 than in any of the other stages, causing the sand–coal transition (and, to a lesser extent, the shoreline) to retrograde abruptly at the beginning of stage 3. An abrupt facies retraction is shown clearly in the deposit (Fig. 4).

Fig. 4 Flow-parallel sectional image of the experimental deposit. Notice the upstream migration of the sand to coal transition in stage 3. Breaks in the image result from loss of data during the process of slicing the deposit.
effects resulting purely from the reduced water and sediment discharges in stage 3. How can these two independent controls on the observed alluvial architecture be separated?

MASS-BALANCE TRANSFORMATION

Instinctively, ‘proximal’ and ‘distal’ are thought of in terms of distance from a sediment source. The terms are generally understood in a relative sense: for instance, 10 km from source might be proximal in a large basin and distal in a small one. An alternative conceptualization would be to think of proximity not in terms of physical distance, but rather in terms of the fraction of all supplied sediment deposited upstream of that point. The motivation for adopting this point of view is that one of the strongest drivers of changes in the morphodynamic character of sedimentary systems induced by deposition. Of course, downstream sediment loss and associated grain-size decrease are not the only causes of down-transport facies changes. The mass-balance signal is often sufficiently dominant, however, so as to mask other effects unless it is accounted for correctly. The goal here is to develop a transformation that facilitates this accounting. This effectively isolates that part of the depositional signal that is directly linked to changes in mass distribution in the depositional system. Removing the mass balance signal allows us to compare facies deposited under different depositional geometries on a consistent basis, and to distinguish those aspects of stratigraphy that are directly linked to changes in mass distribution from those that are not.

Consider a measure of downstream distance not in terms of an absolute length x, but in terms of a non-dimensional number χ(x), where χ(x) is equal to the fraction of all supplied sediment deposited between the sediment source at x = 0 and a distance x downstream. Formally χ(x) is defined by:

\[
\chi(x) = \frac{\int_0^x r_{\Delta T}(x)\,dx}{\int_0^L r_{\Delta T}(x)\,dx}
\]

where \( r(x) \) is the rate of deposition in units of \( (L^3 T^{-1}) \) at a given downstream distance x, measured over a time interval \( \Delta T \). Here \( \Delta T \) is chosen to be long enough to average out intrinsic, flow-controlled (autogenic) fluctuations (Sheets et al., 2002) but shorter than the time-scales of changes in external variables. Variable L is the total length of the depositional system. The term in the numerator of equation (1) is equivalent to the width-averaged volume of sediment deposited between the sediment source and a distance x. The term in the denominator of equation (1) is equivalent to the width-averaged volume of sediment deposited over the entire length of the system and, for a closed system, is equal to the total volume of sediment supplied over the time interval in question.

For example, if at some downstream distance x, \( \chi(x) = 0.3 \), then 30% of the sediment has been extracted from the system at that point, and 70% is still in transport. Likewise \( \chi(x) = 0.5 \) is the downstream distance at which half the sediment has been extracted from the system. The physical distance \( x_{0.5} \) corresponding to \( \chi(x) = 0.5 \) is in effect the ‘depositional mid-point’ of the system. It is important to note that \( \chi(x) \) is a non-dimensional function that reflects the spatial distribution of the local rate of deposition \( r_{\Delta T}(x) \) over the entire basin. It is not hard to imagine scenarios in which either \( \chi(x) \) or \( r_{\Delta T}(x) \) changes when other variables remain constant.

Figure 5 illustrates the transformation from x to \( \chi(x) \). In the example basin in Fig. 5 sedimentation rate decreases exponentially downstream. At a downstream distance of one-quarter the total basin length, 63% of the sediment has been extracted from the system, and at a downstream distance of one-half the total basin length, 86% of the sediment has been extracted from the system. These downstream distances correspond to \( \chi(x) = 0.63 \) and 0.86 respectively. Figure 6 illustrates how the shape of a basin affects the downstream distance x corresponding to the depositional mid-point \( \chi(x) = 0.5 \). For example, in a tectonically foretilted basin (e.g. a passive margin) sediment deposition occurs farther downstream (Fig. 6a) than in a backtilted (e.g. foreland) basin (Fig. 6b) of the same size. Likewise \( \chi(x) = 0.5 \) occurs farther upstream in a short basin (Fig. 6c) than in a long basin of the same shape (Fig. 6d).
fraction increases, analogous to downstream fin-
ing in a natural system. This downstream decrease
in luminosity occurs at different rates for stages 2
and 3 in $x$ coordinates (Fig. 7e), whereas in $\chi(x)$
coordinates the rates of decrease in luminosity for
stages 2 and 3 are nearly identical (Fig. 7f).

Transformation to $\chi(x)$ coordinates has a similar
effect on downstream trends in channel stacking
density. Although stage 3 shows generally fewer
channel deposits than the other stages for a par-
ticular downstream location, $x$ (Fig. 8a), much of
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The most obvious difference between the two
images of the experimental surface in Fig. 7(a, b)
is that the sand–coal transition occurs farther
upstream in stage 3 than it does in stage 2. This is
important with respect to alluvial architecture,
because at the sand to coal transition a few large
fluvial channels bifurcate into numerous smaller
channels, as evident in both the overhead images
taken during the experiment (Fig. 7a, b) and the
images of the topography of the experimental
deposit (Fig. 7c & d). The power of the $\chi$ trans-
formation can be seen by comparing the location
of this transition in standard dimensional coordi-
nates (left side of each image, Fig. 7a & b) with
transformed $\chi$ coordinates (right side of each
image, Fig. 7a & b). It can be seen that for similar
values of $\chi$ the fluvial system seems to behave
similarly. For instance in both images $\chi(x) = 0.25$
occurs upstream of the coal–sand transition,
$\chi(x) = 0.5$ occurs near the transition, and $\chi(x) = 0.75$ occurs downstream of the transition.

This observation can be made quantitative by
estimating the volume of coal versus that of quartz
sand that has been deposited in a given stage for
a given downstream location. To do so, mean lumi-
nosity, a measure of brightness that varies in value
between 0 (black, i.e. pure coal) and 255 (white, i.e.
pure quartz sand), may be used. For each stage
total luminosity decreases downstream as the coal

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Fig. 5  A schematic representation of a sedimentary
basin, where sediment thickness decreases
exponentially downstream, illustrating the fundamental
difference between measuring distance in terms of $x$
(linear scale in back) and measuring distance in terms
of $\chi(x)$ (non-linear scale in front).

Fig. 6  Schematic representation of the effect of basin
shape on the downstream location of $\chi(x) = 0.5$,
corresponding to the downstream distance, $x$, where
50% of the sediment has been extracted from the
system.
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Further, general down-stream trends in preserved channel fraction are more similar between stages in the $\chi(x)$ coordinate system than in the $x$ coordinate system (Fig. 8c, d). Transformation into the $\chi(x)$ coordinate system does not, however, remove all of the observed variability: for instance stage 3 has a lower overall channel deposit density than stage 2 (Fig. 8c & d) even for the same value of $\chi(x)$. This was due to the presence of more and larger fluvial channels during stage 2, accommodating sediment and water discharges four times those of stage 3. The important point is that transformation from $x$ to $\chi(x)$ makes it possible to discriminate the effect of more and larger fluvial channels, owing to a relatively greater water discharge, from the stronger mass-balance-controlled variation in the preserved channel fraction.

Fig. 7 (opposite) Images of the experimental surface taken in plan view: (a) during stage 2 of the experiment (high subsidence rate, sediment supply and water supply); (b) during stage 3 of the experiment (low subsidence rate, sediment supply and water supply). (c & d) Topographic images of the depositional surface during stages 2 and 3. (e & f) Mean luminosities for stages 2 and 3 as a function of downstream distance, in terms of $x$ and $\chi(x)$.

Fig. 8 (a, b) Channel mapping (channels are in black) for different downstream locations in terms of $x$ and $\chi(x)$. (c) Channel stacking densities for stages 2 and 3 as a function of $x$ and $\chi(x)$. 
CONCLUSIONS

1 In an experiment with independently controlled subsidence, sediment supply and water supply, a four-fold reduction in rates of these three variables produced an abrupt reduction in channel stacking density in vertical section. This change was caused by an abrupt migration of facies towards the sediment source, which was in turn induced by upstream storage of sediment associated with a small increase in fluvial slope.

2 The effect of varying the distribution of basinal deposition can be quantified using a simple coordinate transformation, from downstream distance \( x \) to a non-dimensional mass-balance coordinate \( \chi(x) \), where \( \chi(x) \) is the fraction of all supplied sediment deposited upstream of distance \( x \).

3 For the experimental data presented here, transformation into this mass-balance coordinate system leads to internally consistent down-transport decreases in sand content and channel stacking density. In particular, many of the vertical changes in architecture resulting from the imposed changes described in (1) above disappear upon transformation to mass-balance coordinates.

4 The most important control on alluvial architecture in the experiment reported here was the spatial distribution of sedimentation, i.e. the sediment mass balance. Other allogenic controls, such as sediment supply, water supply and subsidence, mainly exerted influence indirectly by changing this mass balance.

5 After removal of mass-balance effects by transformation into the \( \chi(x) \) coordinate system, the main residual architectural effect of reducing water discharge in the experiment reported here was a decrease in channel stacking density associated with a decrease in channel size.

6 Transformation to a mass-balance coordinate system provides a unifying quantitative framework for analysing the role of external variables such as subsidence, sediment supply and water supply in controlling alluvial architecture. The dominant role played by changes in mass balance in controlling alluvial architecture also illustrates a basic limitation of the present generation of ‘stand-alone’ alluvial architecture models: architecture at any particular location has at least as much to do with relative net sediment extraction upstream as it does with avulsion dynamics or channel geometry. Future generations of architecture models should be tightly coupled with models for alluvial deposition and erosion on basin scales to account for these effects.

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