Significance of channel-belt clustering in alluvial basins

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ABSTRACT

The distribution of channel deposits in alluvial basins is commonly used to interpret past changes in climate, tectonics, and sea level. Here we present preliminary evidence that long-time scale (~10^3–10^5 yr) self-organization in fluvial systems may generate structured stratigraphic patterns spontaneously, in the absence of, or independent from, changing basin boundary conditions. A physical experiment and an ancient alluvial succession (Ferris Formation, latest Cretaceous–Paleogene, south-central Wyoming) both show stratigraphy where clusters of many closely spaced channel deposits are separated from each other by extensive intervals of overbank mudstones. Analysis using spatial point process methods shows that channel deposits in both basins are statistically clustered over intermediate basin length scales. In the experiment, external controls (base level, subsidence rate, and sediment/water supplies) were not varied, and therefore not factors in cluster formation. Likewise, the ancient system lacks stratigraphic and sedimentologic evidence of external controls on channel clustering. We propose that channel clusters, as seen in this study, reflect a scale of fluvial self-organization that is not usually recognized in ancient deposits. This type of internally generated stratigraphy should be considered when reconstructing tectonic, climate, and sea-level changes from ancient basin fills and when correlating between outcrop belts or subsurface wells.

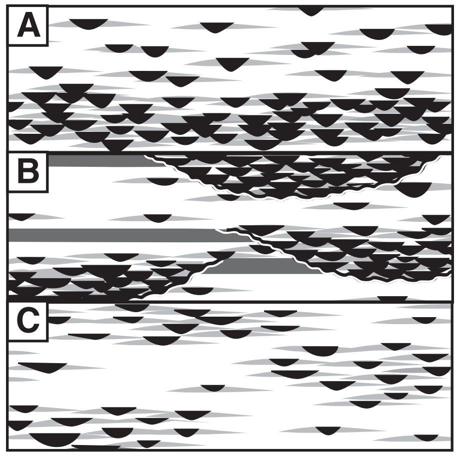

Figure 1. Example alluvial stratigraphy models. Cartoons represent strike sections of basin-scale deposits kilometers in width and hundreds of meters in thickness. Black is coarse-grained channel belt, light gray is proximal overbank (e.g., levees and crevasse splays), and white is fine-grained floodplain. A: Channel body distribution predicted by models wherein changes in basin boundary conditions produce basin-wide changes in channel body proximity. In this example, early, slow aggradation resulted in closely spaced channel bodies, and later, higher aggradation rates produced more isolated sand bodies. B: Example stratigraphy resulting from incised-valley filling due to relative sea-level change. Wavy black lines indicate erosional surfaces formed during valley incision; dark gray represents interfluve regions of intense paleosol development. Channel bodies are spaced closely within the valley fill. C: Model of channel clustering formed during basin aggradation by nonrandom channel avulsion. The basin depocenter lingers in a portion of the basin, producing closely spaced channel bodies, and periodically relocates to a new portion of the basin forming another "cluster" of channel deposits.

INTRODUCTION

Modeling and field studies have shown how the stratigraphic arrangement of fluvial channel-belt sandstone bodies (henceforth "channel bodies") may record the tectonic, eustatic, and climatic histories of alluvial basins (e.g., Allen, 1978; Bridge and Leeder, 1979; Leeder, 1978). These studies assume that during channel avulsion, rivers relocate randomly or to the lowest point on the floodplain, and that broad-scale fluvial deposition is dominantly controlled by basin boundary conditions. For example, tectonically driven changes in subsidence rate or sediment supply can affect the stratigraphic distribution of channel bodies within the basin (Fig. 1A). Alternatively, valley incision and filling caused by sea-level fluctuation (e.g., Shanley and McCabe, 1994; Wright and Marriott, 1993) or changes in discharge (e.g., Demko et al., 2004) can produce zones of closely spaced channel bodies juxtaposed among overbank deposits containing more isolated channel bodies (Fig. 1B). These types of models, in which external factors are the primary control on stratigraphic patterns, have been used as a means for interpreting geologic history as well as a basis for lithostratigraphic correlation among wells and between isolated outcrop belts.

In contrast, recent physical and numerical modeling has shown that some sedimentary systems exhibit internal self-organization on relatively long time scales, which can produce nonrandom stratigraphic patterns (e.g., Jerolmack and Paola, 2007; Kim and Paola, 2007; Sheets et al., 2007). Such intrinsic organization complicates how we interpret basin histories and correlate strata in alluvial successions.

Here we compare deposits produced by a physical experiment designed to isolate intrinsic fluvial behavior to natural stratigraphy in the Upper Cretaceous–Paleogene Ferris Formation (Hanna Basin, Wyoming, United States). Both basins comprise deposits produced by channel avulsion and show channel body clustering, but lack the traditional hallmarks of external forcing such as basin-wide changes in channel stacking density (Fig. 1A) or evidence of degradation and incised-valley formation (Fig. 1B). We use a new application of spatial point process methods to characterize channel body distributions in each basin and demonstrate that both the natural and experimental systems exhibit statistical spatial clustering. Further, given the absence of external influence in the experimental basin, the presence of stratigraphic channel clustering indicates that river avulsion processes can lead to complex, organized stratigraphy arising spontaneously over long time scales. We propose that this type of stratigraphic self-organization must be considered when making interpretations about changing boundary conditions from the rock record or when correlating strata based on channel body distributions. Intrinsic processes may produce measureable long-term stratigraphic patterns in a variety of sedimentary systems, and we suggest that the statistical approach employed herein can be used more generally to characterize the degree of organization in other alluvial basins.

EXPERIMENT

The Delta Basin facility at the Saint Anthony Falls Laboratory, University of Minnesota, is a 5 m × 5 m tank, 0.5 m in depth, used to build physical stratigraphy. Sediment and water supply and base level are controlled independently, and aggradation is achieved by gradually increasing base level in a manner analogous to slow, spatially uniform subsidence. During the DB 03-01 experimental run, detailed in Sheets et al. (2007), constant supplies of sediment and water were fed into the basin, producing an approximately radially symmetric fluvial fan, averaging 2.5 m from source to shoreline (Fig. 2A). Upon completion of the experiment,

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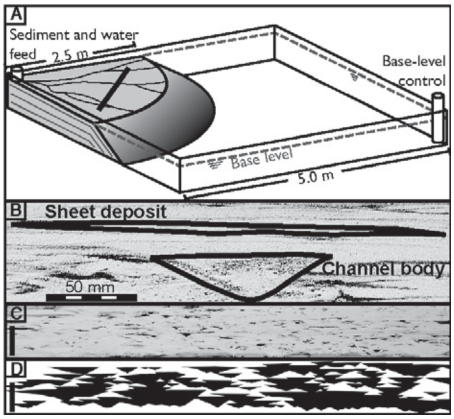

Figure 2. Delta Basin 03-01 experiment conducted at the Saint Anthony Falls Laboratory, University of Minnesota (Sheets et al., 2007). A: Experimental design. B: Depositional elements in the experiment include low width-to-thickness-ratio channel deposits and sheet deposits that are laterally extensive and thin. These are roughly equivalent to channel-belt and overbank deposits, respectively, in natural basins. C: Cross section of the experiment at 1.5 m downstream of the sediment and water source. Location indicated by black line in A. D: Channel deposit locations of cross section shown in C are mapped in black. Scale bars in C and D are 15 cm.

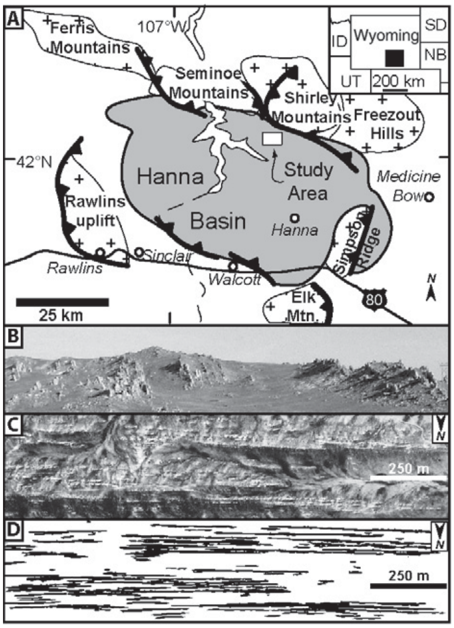

Figure 3. A: Location map of the study area (after Eberle and Lillegraven, 1998) showing the greater Hanna Basin (gray) and major structures and uplifts (crosses). B: Field photo of the Ferris Formation study area. Strata dip 80° (to the right), and sandstone channel deposits stand out in relief against more heavily weathered overbank mudstones. C: Air photo of study area showing a cross section of the Ferris Formation exposed across the land surface. Average paleoflow direction is into the photo. Channel-belt sandstones are visible as white elongate bodies. D: Channel sand bodies (black) from C mapped with differential GPS.

the basin was drained, and the deposit was sectioned along strike-oriented transects.

Because it was conducted with constant boundary conditions, stratigraphic architecture in the experiment is entirely the result of internal variability in the depositional system. There are two major depositional forms that build stratigraphy in the experiment: low-aspect-ratio channel-fill deposits and sheet-like deposits resulting from unconfined flows, which are first-order analogs to channel and overbank deposits in natural systems, respectively (Fig. 2B) (Sheets et al., 2007). As measured from topographic scans, the most active zone of deposition episodically shifted across the basin throughout the 30 h long experiment, returning to a particular portion of the basin on average every 4 h (Sheets et al., 2007). The alluvial system was self-organized such that it lingered in a portion of the basin until a low spot was filled, and then the channel system relocated to a new, lower position within the basin. This style of cyclical deposition to achieve steady basin-wide aggradation is referred to as "compensation" (cf. Straub et al., 2009).

FIELD AREA

The Upper Cretaceous–Paleogene Ferris Formation was deposited by a distributive fluvial system (cf. Weissmann et al., 2010) in Hanna Basin, southeast Wyoming (Fig. 3A) during the early Laramide orogeny and after the Western Interior Seaway retreated to the northeast (Eberle and Lillegraven, 1998). In the study area the Ferris Formation dips at ~80°S (Fig. 3B), exposing a basin cross section nearly orthogonal to paleoflow direction (Fig. 3C). The unit comprises lenticular coarse-grained channel bodies and mudstone-dominated overbank deposits. Channel bodies range from 1 to 10 m thick, typically contain two or three stories, and are separated from one another by laterally extensive floodplain mudstone deposits. The basal scour surfaces below and extending the length of each individual sand body are the largest erosional features found within the study area, and channel deposits can be tracked laterally into contemporaneous floodplain deposits.

Individual channel bodies were mapped using differential GPS (Fig. 3D). The Ferris Formation exhibits well-developed stratigraphic organization seen in the field (Fig. 3B), where clusters of closely spaced channel bodies are separated from each other by mudstone-dominated intervals containing rare channel deposits. This clustered pattern is observable throughout the outcrop belt, which extends several kilometers beyond the mapped study area and does not form stratigraphic layers across the basin. Rather, discrete zones in which clusters of channel deposits are found trace laterally into overbank-dominated zones (Fig. 3C).

The character of stratigraphy seen in the Ferris Formation differs from previously proposed models of alluvial basin filling wherein overall changes in subsidence and/or aggradation rates result in basin-wide changes in channel distributions (Allen, 1978; Bridge and Leeder, 1979; Heller and Paola, 1996; Leeder, 1978). Additionally, other than minimal erosion during channel relocation, the studied succession is overall depositional, indicating that channel clusters were not the result of incised-valley formation restricting the depositional system (Demko et al., 2004; Shanley and McCabe, 1994; Wright and Marriott, 1993). The fact that the distribution of sand bodies in the Ferris Formation cannot be explained by models of basin-scale subsidence changes or incised-valley formation begs the question: Does the stratigraphic pattern seen in the Ferris Formation reflect processes similar to those observed in the DB 03-01 experiment?

STATISTICAL COMPARISON

Qualitatively, channels in two-dimensional cross sections of both the DB 03-01 experiment and the Ferris Formation appear to be clustered. To quantitatively characterize and compare the stratigraphic architecture in these two deposits, we use spatial statistical methods. River avulsion can be treated as a stochastic process that generates discrete sand bodies in a stratigraphic cross section and so can be evaluated as a spatial point process (Diggle, 2003). Spatial point process statistics are designed to evaluate the distribution of points (or "events") on a plane and determine whether they are positioned randomly—a condition called complete spatial randomness (CSR; Diggle, 2003)—or exhibit some sort of spatial organization such as clustering or regularity over a range of length scales (Fig. 4).

The K function provides a way to assess the spatial distribution of events of a point process (Cressie, 1993). $K(h)$ compares the expected number of events within a distance h of each event in a study area to the average rate of the process, λ, as

$$K(h) = \lambda^{-1}E(N(h)) \text{ for } h > 0, \qquad (1)$$

where λ is the number of points in the study region (N) divided by the area of the study region, and $E(N(h))$ is the expectation or mean number of points within a distance h from each point. The K function can be used to test for CSR and characterize the degree to which events are spatially organized over a variety of length scales within a study area (Diggle, 2003; Cressie, 1993).

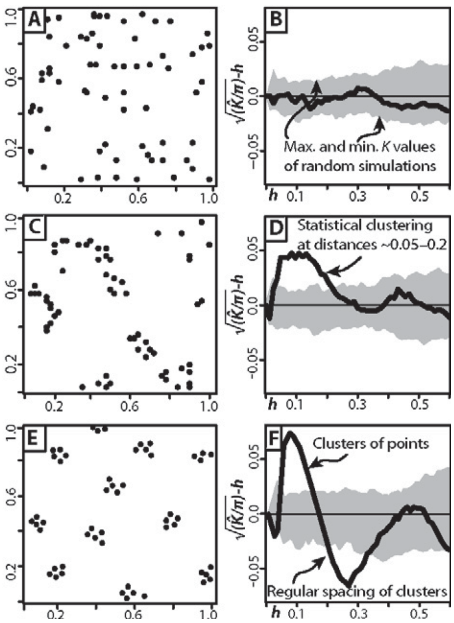

Figure 4. Examples of spatial point processes with different distributions shown within unit squares (A, C, E) and plots of the *K* function for each distribution (B, D, F, respectively). For B, D, and F, a transformed version of the *K* function is used so theoretical CSR values plot as zero, and the horizontal axis is *h*, or distance. B: The *K* function for a CSR point process (A) plots entirely within the envelope (gray) for 99 Monte Carlo simulations of a CSR process. In contrast, the *K* function for a clustered pattern plots outside the MC envelope in a positive direction (D) at distances of ~0.05–0.02 units. The significance level of the MC test is 0.02 for 99 simulations. F: A multiscale pattern with small clusters of points that are regularly spaced across the study area. The *K* function for this pattern shows clustering (positive, outside MC envelope) over short scales, and regularity (negative, outside MC envelope) at scales approximately the distance between clusters.

To estimate the *K* function ($\hat{K}$) for a point process in a plane, a formulation that includes an adjustment for points located near the edge of the study area can be used (Cressie, 1993):

$$\hat{K}(h) = \hat{\lambda}^{-1} \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{j=1}^{N} w(s_i, s_j)^{-1} I(\| s_i - s_j \| \leq h) / N, \quad (2)$$

where $\hat{\lambda}$ = total number of events/study area, s_i and s_j are two different events within the study area, $w(s_i, s_j)$ is a weighting factor that is the proportion of the circumference of a circle centered at s_i passing through s_j that is located within the study area, and $I(.)$ is the indicator function, which is 1 when the Euclidian distance between s_i and $s_j \leq$ distance h, otherwise $I(.) = 0$. Figure 4 shows three example point processes with random, clustered, and multiscale patterns, respectively. The *K* function for randomly distributed point patterns plots near zero and within the envelope from 99 Monte Carlo (MC) simulations (Figs. 4A and 4B; MC significance level = 0.02), indicating that the number of points within *h* of any event in the study area is close to the expected number given the intensity of the point process. When more events are found within a given distance than are expected given the overall intensity of the point process, the *K* function plots positively and outside the MC envelope, indicating event clustering (Figs. 4C and 4D). Conversely, when fewer events than expected are found for a given *h*, they are distributed regularly across the study area and the *K* function is negative (Figs. 4E and 4F).

To compare the stratigraphic distributions of channel bodies in cross sections from the DB 03-01 experiment and Ferris Formation, we use the *K* function to test for CSR and characterize the degree of spatial organization of channel deposits in each basin. We evaluate the *K* function using the centers of mapped channels in each basin (Figs. 5A and 5C). The estimated *K* function of the experiment shows regularity (plots negatively, outside the MC simulation envelope) at small scales (<50 mm) and clustering (positive *K*, outside the MC simulation envelope) over the 150–250 mm range. Likewise, the Ferris Formation exhibits statistical clustering at distances >120 m, meaning that over these distances, more closely spaced channel deposits are found than are expected for CSR distributions. Based on this analysis, we reject the hypothesis of CSR for the DB 03-01 experiment and the Ferris Formation over the indicated ranges.

Because channel bodies in both the experiment and the ancient deposits occupy significant area (relative to the study area), representing them as points is only a first approximation of the degree of clustering in either basin.

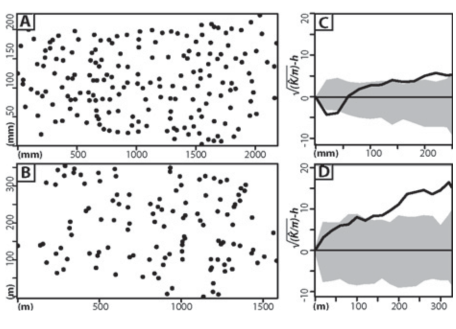

Figure 5. Point patterns of channel centers for the DB 03-01 experiment (A) and the Ferris Formation (B). C: The *K*-function plot for the experimental data shows statistical regularity for distances less than ~50 mm and statistical clustering for distances of ~150–250 mm. D: The *K*-function plot of the Ferris Formation shows clustering for distances greater than ~120 m.

Likewise, the shape of channel deposits (very wide relative to their stratigraphic thickness) imparts an anisotropy that is not adjusted for in this preliminary analysis. Additionally, uncertainties associated with estimating the *K* function increase as *h* reaches the limits of the study area, so thicker deposits are needed to fully characterize organization at longer length scales. Future work will address these issues. However, even with this simplified approach, it is clear that both deposits exhibit channel clustering, suggesting that river avulsion is structured and should not be considered a random process on basin-filling time scales.

DISCUSSION

For both the experiment and the field data sets we find that the spacing of channel bodies is more organized than what would be expected from a random process. Stratigraphic organization in the DB 03-01 experiment is a direct result of intrinsic fluvial organization under steady boundary conditions. The Ferris Formation shows a degree of organization similar to that seen in the experiment. At this point there are insufficient data to rule out possible allogenic origins for sand body clustering in the Ferris Formation; however, the ancient deposit's similarity to the experiment is provocative and raises questions about how common this type of stratigraphic organization is in the rock record and whether it could have formed autogenically.

It is not surprising that the Ferris Formation shows a stronger spatial pattern than the physical experiment, which lacks cohesive sediments that promote channelization and more discrete partitioning of channel and overbank deposits. The regularity (or anticlustering) seen in the physical experiment at short length scales is a function of mean channel size (i.e., the center points of adjacent channels are approximately one channel width apart). Sheets et al. (2007) also describe how in this experiment, subtle, positive topographic relief that formed in the final stages of channel filling acts to repel subsequent channels over short length scales.

It is unclear how frequently channel body clustering occurs in alluvial basin fills, in part because most studies are focused on finding basin-wide changes in alluvial architecture or incised valley–generated channel body groupings. Some workers have observed apparent channel body clustering in ancient deposits (e.g., Zaleha, 1997), but this analysis of the Ferris Formation provides the first quantitative data from a sufficiently large basin cross section to be able to confidently observe channel clustering. Channel clustering may not be readily apparent in other basins with larger-scale fluvial deposits where exposures are not laterally or vertically extensive enough to show dozens of channel bodies within the same outcrop belt. Likewise, subsurface deposits sparsely sampled by wells may show clustering, but lithostratigraphic correlation schemes would have a tendency to tie channel-rich intervals to similar sand-dominated zones in adjacent wells, emphasizing stratigraphic continuity instead of clustering. The clear presence of depositional channel body clusters in the Ferris Formation highlights the potential for this type of stratigraphy in other alluvial basins. Determining whether the Ferris Formation is a representative or unique example of avulsion-dominated stratigraphy will require clustering to be evaluated in other basins.

In the absence of changing external controls, channel-belt clustering could be driven by long-time scale organization in river avulsion and migration around a basin, as is the case in the DB 03-01 experiment. This type of autogenic avulsion clustering suggests that there is a stochastic (e.g., power-law or bimodal) distribution of avulsion lengths where commonly channels don't move very far from one another but occasionally larger-scale avulsions move the system to a new location within a basin. Jerolmack and Paola (2007) show that this may happen due to floodplain topography from remnant channels that act to steer avulsion paths back toward the main channel. Mackey and Bridge (1995) observe a similar pattern with a more deterministic channel avulsion model.

Channel clustering may reflect compensational filling within alluvial basins where topography builds near the active depocenter to a point when the depositional system reorganizes and relocates to a new, relatively low region of the basin. Consequently, the relative cross-stream length scales over which a depositional system has influence within a basin at any given time would affect the degree of channel clustering in stratigraphy. For example, a large and/or laterally mobile depositional system in a relatively small basin might fill in regional topography relatively quickly and readily relocate to new positions within the basin, resulting in unclustered or weakly clustered stratigraphy. Conversely, a relatively small system or one with limited lateral mobility might require more avulsions within a portion of the basin to build sufficient topography to generate a larger-scale shift of the basin depocenter. More systems need to be studied to constrain the range of and potential for such behaviors.

CONCLUSIONS

Organized stratigraphic patterns of channel deposits are commonly interpreted as resulting from changing basin boundary conditions. Similarity between stratigraphy developed intrinsically in the DB 03-01 experiment and that of the Ferris Formation raises questions about whether this is always true. The potential for autogenic channel organization adds a new perspective from which subsurface or distantly spaced outcrops may be correlated. Further characterization of this phenomenon in other basins will provide constraints as to characteristic length scales of channel clusters, which would aid correlations and have implications for predicting reservoir distribution and connectivity. The degree, geometry, and distribution of cluster development may vary with subsidence rate, sediment and water supply, or other factors, so ancient basin fills should be further mined for data on this process. Spatial statistical methods such as the *K* function allow for comparison between natural basins and physical and numerical models, as well as a means of imparting stochastic structure to numerical models in order to more richly represent natural processes. Ultimately, combining these approaches and data sets may help elucidate the potential for and mechanisms driving intrinsic channel clustering in alluvial basins.

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