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Predictable patterns in stacking and distribution of channelized fluvial sand bodies linked to channel mobility and avulsion processes

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ABSTRACT

Despite the importance of channel avulsion in constructing fluvial stratigraphy, it is unclear how contrasting avulsion processes are reflected in stratigraphic-stacking patterns of channelized fluvial sand bodies, as a proxy for how river depocenters shifted in time and space. Using an integrated, geospatially referenced, three-dimensional data set that includes outcrop, core, and lidar data, we identify, for the first time in an outcrop study, a predictive relationship between channelized sand body architecture, paleochannel mobility, and stratigraphic-stacking pattern. Single-story sand bodies tend to occur in vertically stacked clusters that are capped by a multilateral sand body, indicating an upward change from a fixed-channel system to a mobile-channel system in each cluster. Vertical sand body stacking in the clusters implies reoccupation of abandoned channels after "local" avulsion. Reoccupational avulsion may reflect channel confinement, location downstream of a nodal avulsion point that maintained its position during development of the sand body cluster, and/or aggradation and progradation of a backwater-mediated channel downstream of a nodal avulsion point. Sand body clusters and additional multilateral sand bodies are laterally offset or isolated from each other, implying compensational stacking due to "regional" switching of a nodal avulsion point to a new, topographically lower site on the floodplain. The predictive links between avulsion mechanisms, channel mobility, and resultant sand body distributions and stacking patterns shown in our findings have important implications for exploring and interpreting spatiotemporal patterns of stratigraphic organization in alluvial basins.

INTRODUCTION

River avulsion, which switches flow from a parent channel to a new or previously abandoned channel on the adjacent floodplain, is a crucial process in building fluvial stratigraphy. Avulsion processes are incompletely understood (Slingerland and Smith, 2004), but they are considered to be controlled by floodplain dynamics (e.g., Hajek and Edmonds, 2014), substrate erodibility (e.g., Aslan et al., 2005), and backwater hydrodynamics in coastal regions (Blum et al., 2013; Ganti et al., 2014; Fernandes et al., 2016). For avulsion analysis, we commonly invoke two contrasting mechanisms. First, reoccupation of abandoned channels that form topographic lows on the floodplain leads to a configuration where channelized fluvial sand bodies (henceforth "sand bodies") become vertically stacked (e.g., Mohrig et al., 2000; Jerolmack and Paola, 2007). Such vertical stacking via channel reoccupation (henceforth "reoccupational stacking") implies sand body clustering. Second, modeling experiments suggest that the avoidance of previous, topographically high channels and alluvial ridges during avulsion leads to compensational stacking (e.g., Allen, 1978; Mackey and Bridge, 1995), which results in isolated and evenly distributed sand bodies that infill differential floodplain topography (Straub et al., 2009). Although both mechanisms are plausible, it is unclear under what circumstances each one is predictable (Hajek and Wolinsky, 2012; Miall, 2014).

Examples from Quaternary and ancient fluvial systems substantiate the observation that avulsion-generated successions contain a range of sand body distributions, reflecting inferred compensational stacking (e.g., Pisel et al., 2018), reoccupational stacking (e.g., Sinha et al., 2005), or a combination of both patterns (e.g., Morozova and Smith, 2000; Pranter et al., 2009). The presence of floodplain deposits between and at the margins of vertically amalgamated sand bodies is diagnostic of avulsion-generated reoccupational stacking (Fig. 1A; Bridge, 2006; Chamberlin and Hajek, 2015). Avulsion may instead result in sand bodies arranged in a laterally offset manner, which can be a proxy for compensational stacking (Fig. 1B). Because sand body stacking patterns control the connectivity of subsurface reservoirs, they have important implications for socio-industrial projects like CO_2 sequestration, hydrocarbon extraction, and groundwater management in fluvial strata (e.g., Larue and Hovadik, 2006). Using an integrated, geospatially referenced, three-dimensional (3-D) data set of outcrop, core, and lidar data, we used stratigraphic-stacking patterns of sand bodies to link paleochannel mobility and avulsion style across a range of spatiotemporal scales. Our findings are validated with scaling relationships derived from both ancient and Quaternary-to-modern systems.

OUTCROP DATA SET AND METHODS

The study area lies in the Wasatch Plateau, Utah, USA (Fig. 2A), where Upper Cretaceous coastal-to-alluvial-plain deposits of the Blackhawk Formation exhibit sand body architecture that was dominantly controlled

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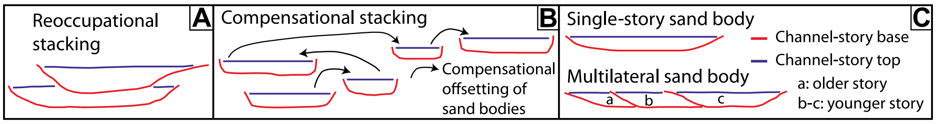

Figure 1. Definition sketches of stratigraphic-stacking patterns (A,B) and sand body types (C) analyzed in our study. For simplicity, stacking patterns in A and B are illustrated with single-story sand bodies only. Floodplain deposits occur around the sand bodies. Compensational stacking, characterized by the arrangement of sand bodies in a laterally offset manner (B), is interpreted by analogy to the results of physical and numerical modeling studies (e.g., Allen, 1978; Mackey and Bridge, 1995; Straub et al., 2009).

by avulsion (Hampson et al., 2012, 2013; Rittersbacher et al., 2014; Flood and Hampson, 2014, 2015). The Blackhawk Formation represents ~4–6 m.y. of deposition, and accumulated during 110–120 km of shoreline progradation (Hampson et al., 2012; Pettit et al., 2019).

In the Cottonwood Creek study area (Fig. 2A), the entire Blackhawk Formation succession (~300 m thickness) is continuously exposed over a large lateral extent (~5 km × 5 km; Figs. 2B and 2C). The outcrop data set offers three advantages for analysis of sand body distribution: (1) its depositional strike extent (~5 km) is >20 times larger than the inferred paleochannel width (~100 m; cf. Rittersbacher et al., 2014); (2) it consists of six nearly vertical, contiguous cliff faces that include both depositional-dip–oriented and depositional-strike–oriented segments (Figs. 2B and 2C; see the Supplemental Material[1]); and (3) the six adjoining cliff faces form a near-semicircular 3-D data set, in which common uncertainties and constraints in interpretation due to two-dimensional (2-D) outcrop extent, orientation, and geometry are small.

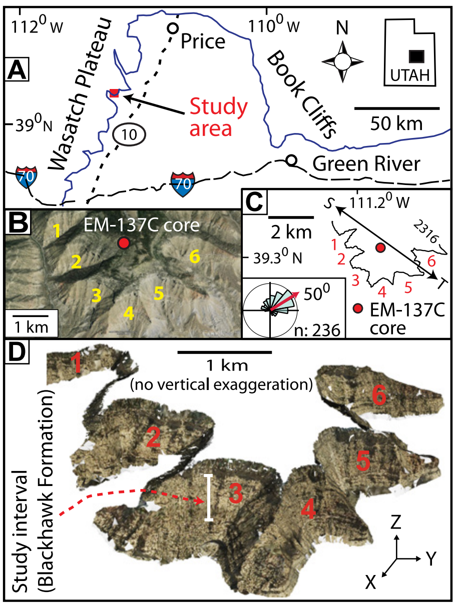

Figure 2. (A) Location of the study area in the Wasatch Plateau, central Utah, USA. (B) Google Earth™ image of the study area showing six contiguous and nearly vertical cliff faces with a centrally located core. (C) Map view of study area (2316 m contour line is shown for reference). Line S-T has been used as a projection plane through the middle of the study site for strike-transect analysis of sand body stacking and distribution. Paleocurrent rose diagram shows an overall northeast (vector mean N050) paleoflow direction. (D) Lidar data, illustrating a three-dimensional virtual outcrop model of the study area.

Sand body architecture was characterized using high-resolution (~10 cm) lidar data covering the cliff faces (Fig. 2D) and geographic information system (GIS) application. For procedures of lidar acquisition and processing, and 3-D sand body mapping, see the Supplemental Material, and Sahoo and Gani (2015). Lidar-based sand body mapping and architectural analysis were constrained by paleocurrent, facies, and architectural data of sand bodies collected from accessible parts of the cliff faces (Fig. 2C) and from nearby Blackhawk Formation outcrops (Hampson et al., 2013; Sahoo and Gani, 2016; Sahoo et al., 2016), and by facies analysis of a centrally located core (Figs. 2B and 2C; Fig. S9 in the Supplemental Material). Based on their internal architecture and prior interpretation (Hampson et al., 2013; Sahoo and Gani, 2015, 2016; Sahoo et al., 2016), all sand bodies were grouped into two categories (Fig. 1C; *sensu* Potter, 1967; Gibling, 2006): (1) single-story sand bodies have a single flat to concave-up erosional surface at their base; and (2) multilateral sand bodies are produced by lateral amalgamation of channel-story sand bodies at the same stratigraphic level, and they have a composite basal erosion surface (see the Supplemental Material). To analyze their stratigraphic organization in a strike-oriented transect, width-corrected sand bodies were projected onto a 2-D plane that is oriented perpendicular to the mean paleoflow direction (Figs. 2C and 3A).

RESULTS AND DISCUSSION

Sand Body Dimensions and Internal Architecture

Multilateral sand bodies are more abundant ($n = 47$, containing 107 stories) than single-story sand bodies ($n = 34$) in the study area (Fig. 3A). The corrected, near-true widths of single-story sand bodies are significantly smaller (mean: 93 m) than those of multilateral sand bodies (mean: 627 m); moreover, the aspect ratios (width/thickness) of single-story sand bodies are much lower (mean: 15) than those of multilateral sand bodies (mean: 129; Figs. 4A and 4B; Table S1).

Diagnostically, the internal architecture of each multilateral sand body shows lateral amalgamation of two to four stories at the same stratigraphic level (labeled a–d, from older to younger stories, in Figs. 3A–3E). The internal architecture of each story consists of a single bar macroform and a laterally adjacent channel-fill deposit (see the Supplemental Material). Estimated paleohydraulic characteristics (e.g., paleochannel flow depth, bedload grain size) were similar for both types of sand bodies (Fig. 4C; Figs. S9, S10A, and S10B), suggesting that such characteristics were not responsible for the pronounced variation in geometry between single-story and multilateral sand bodies.

Paleochannel Dimensions and Mobility

Paleochannel dimensions were estimated from paleohydraulic analysis of dune-scale cross-strata and bar-accretion surfaces within the single-story and multilateral sand bodies (see the Supplemental Material), since only one fully preserved, abandoned-paleochannel fill was found in the study data set (Fig. S11B). The estimated mean, median, and range of flow depths of paleochannels in all sand bodies varied little (Fig. 4C); bedforms were predominantly dunes, and average bedload grain size was medium sand (Figs. S9, S10A, and S10B).

We also evaluated channel mobility, defined as the degree of lateral channel migration prior to avulsion (cf. Jerolmack and Mohrig, 2007; Gibling, 2006), for the sand bodies using a dimensionless channel-mobility index (M), where M = true sand body width/estimated paleochannel width (see the Supplemental Material). Because paleochannel width was estimated by paleohydraulic analysis, rather than measured directly, values of M are approximate (e.g., physically unrealistic values <1 were calculated); nonetheless, they allowed relative comparison. A high value of M indicates high channel mobility. Estimated M values of multilateral sand bodies were significantly higher (mean 6; 5–10 range had ~80% frequency) than those of single-story sand bodies (mean 0.9; 0.5–1.5 range had >90% frequency; Figs. 4D and 4E). Lower values of M for single-story sand bodies imply restricted lateral migration of channels (mode of one formative-channel width; Fig. 4E) prior to avulsion. In contrast, higher values of M for multilateral sand bodies indicate substantial lateral migration of channels (mode of five formative-channel widths; Fig. 4E) prior to avulsion.

[1]Supplemental Material. Information on data collection and processing, paleohydraulic analysis, definition of channel-mobility index, Table S1, and Figures S1–S12. Please visit https://doi.org/10.1130/GEOL.S.12307475 to access the supplemental material, and contact editing@geosociety.org with any questions.

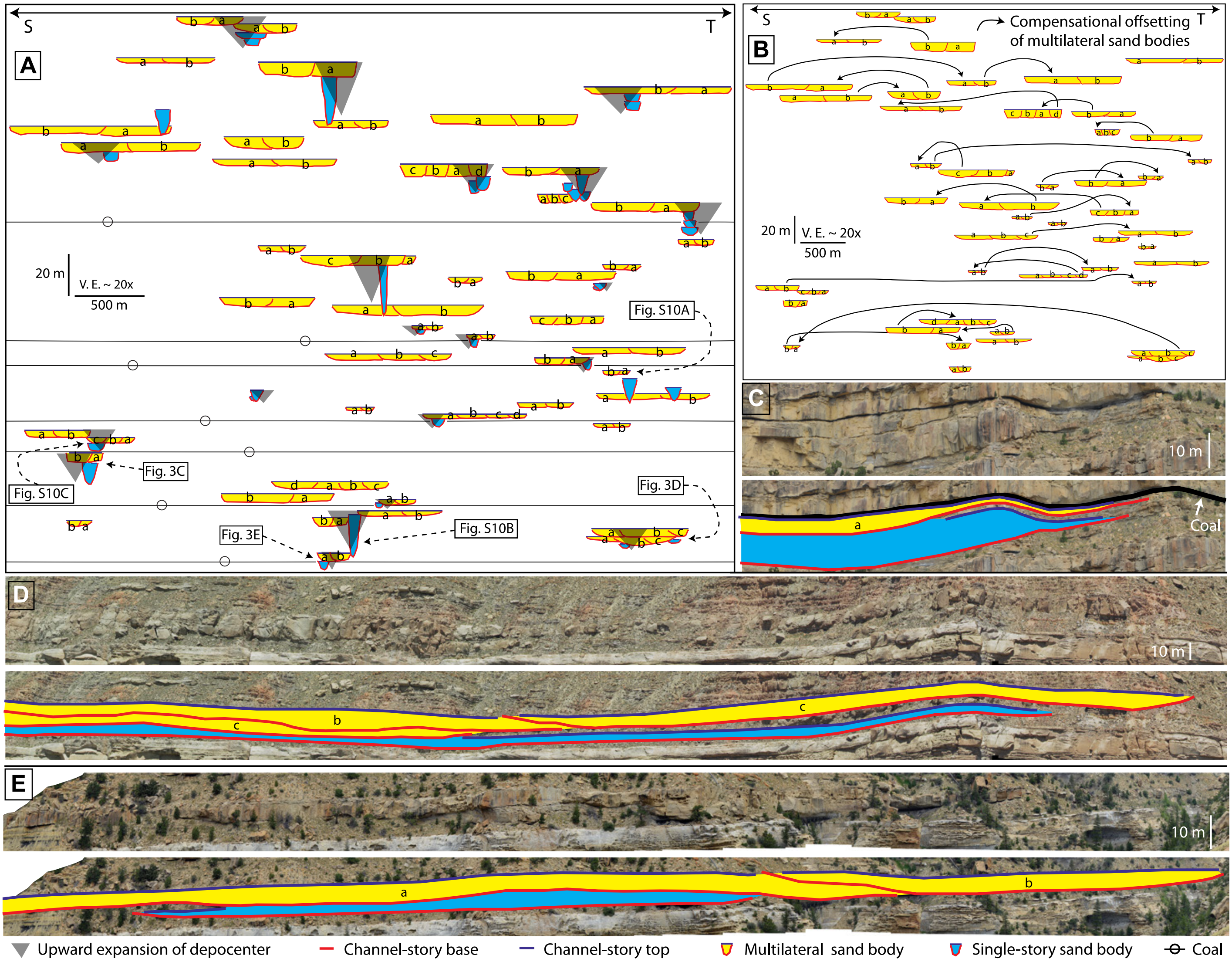

Figure 3. (A) Two-dimensional projection of sand bodies in a depositional-strike transect (Fig. 2C) through the Blackhawk Formation, central Utah, USA. Single-story sand bodies show vertical, reoccupational stacking, whereas multilateral sand bodies show laterally offset, compensational stacking. Internal architecture of each multilateral sand body shows lateral amalgamation of two to four stories at the same stratigraphic level (labeled a–d, from older to younger stories). Stratigraphic positions of Figures 3C–3E and Figures S10A–S10C (see footnote 1) are shown. V.E.—vertical exaggeration. (B) Examples (*n* = 23) in which river depocenter shifted in a laterally offsetting manner (compensational stacking pattern) between successive multilateral sand bodies. (C–E) Field documentation of examples of single-story sand bodies overlain by multilateral sand bodies. Uninterpreted (upper) and interpreted (lower) photographs are shown for each example. Floodplain deposits are intercalated between underlying single-story sand bodies and overlying multilateral sand bodies. Lidar data for Figure 3C are shown in Figure S3.

Sand body aspect ratios match well with published data compilations (Figs. 4A and 4B). For example, when compared to other, previously interpreted ancient (pre-Quaternary) sand bodies, the single-story and multilateral sand bodies in our data set plot, respectively, inside and outside of the fixed-channel envelope (Fig. 4A; Gibling, 2006). Single-story and multilateral sand bodies in the study data set are comparable in scale and aspect ratio to, respectively, channel fills and channel belts (which represent lateral channel migration of ~10 times channel width; Blum et al., 2013) in Quaternary-to-modern systems (Fig. 4B), and hence they are comparable to fixed and mobile channel belts (*sensu* Friend, 1983), respectively.

Sand Body Stacking and Distribution

The stacking and distribution of sand bodies indicate two distinct, but recurrent, patterns of stratigraphic organization occurring at different spatial scales.

First, single-story sand bodies are prone to vertical amalgamation, resulting in seven multistory bodies composed of 2–4 vertically stacked, single-story sand bodies (Fig. 3A). Five such multistory bodies and 13 individual single-story sand bodies are erosionally overlain by multilateral sand bodies (Figs. 3A and 3C–3E; Fig. S10C). In contrast, only three single-story sand bodies overlie multilateral sand bodies. All 20 multistory, clustered sand bodies that result from vertical stacking of single-story and/or multilateral sand bodies (Fig. 3A) show irregular, "sawtooth" boundaries (e.g., Figs. 3C–3E; Figs. S3 and S10C), consistent with their genesis by avulsion (cf. Chamberlin and Hajek, 2015). The consistent vertical stacking of single-story sand bodies in these 20 clusters implies that new channels reoccupied former abandoned channels (e.g., Mohrig et al., 2000) after "local" avulsion (*sensu* Slingerland and Smith, 2004), whereas the generally multilateral character of the uppermost sand body in the clusters indicates lateral channel migration away from reoccupation sites.

Three mechanisms, which are not mutually exclusive, can potentially account for the vertical stacking of single-story sand bodies by "local" reoccupational avulsion of a fixed-channel system. (1) The paleochannel was initially

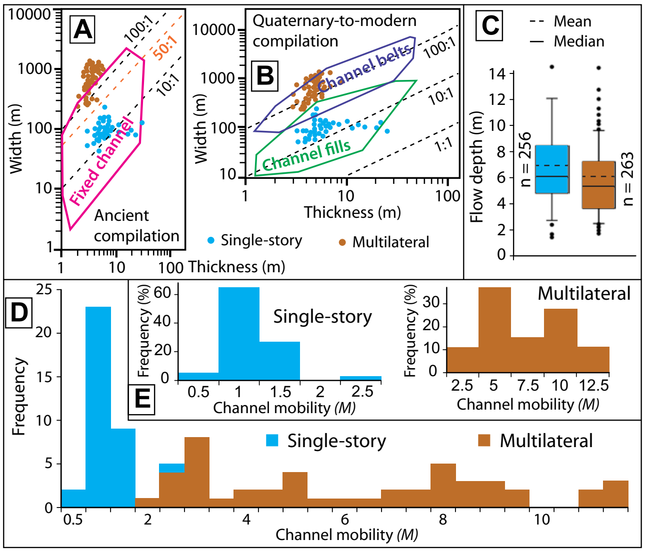

Figure 4. (A,B) Scaling relationships of single-story and multilateral sand bodies against published data compilations of pre-Quaternary (A; after Gibling, 2006) and Quaternary-to-modern systems (B; after Blum et al., 2013). In A, the 50:1 aspect-ratio line, which serves as a key boundary for fixed (<50:1) versus mobile (>50:1) channel bodies (Gibling, 2006), distinctly separates the two sand body types in the study data set. (C) Paleochannel flow depths of single-story and multilateral sand bodies, estimated using outcrop data. Data points (*n*) denote number of estimated flow-depth values. (D) Channel-mobility indices (*M*) of single-story and multilateral sand bodies. (E) Frequency (%) of channel-mobility indices (*M*) plotted separately for single-story and multilateral sand bodies.

confined (e.g., by a resistant vegetated floodplain or subtle incised floodplain relief). Vertical sand body stacking lessened the degree of confinement, resulting eventually in development of a mobile-channel system represented by the capping multilateral sand body (cf. Marzo et al., 1988). (2) Vertical stacking of progressively more mobile channel deposits may record deposition downstream of an upstream-migrating nodal avulsion point that did not switch lateral position laterally (i.e., an "avulsion sequence" of Mackey and Bridge, 1995). (3) Vertical stacking of progressively more mobile channel deposits may also record aggradation and progradation of a backwater-mediated channel downstream of a nodal avulsion point. The initial location of the paleochannel would have been inside the backwater hydraulic reach of the river system, characterized by fixed channels, and its final location would have been upstream of the backwater reach, where channels are markedly more mobile (Blum et al., 2013; Fernandes et al., 2016). This mechanism is most plausible for the lower Blackhawk Formation, which was deposited relatively close to the paleoshoreline.

The second recurrent pattern of stratigraphic organization is exhibited at a larger spatial scale. Multilateral sand bodies are rarely stacked directly vertically (only one example in Fig. 3A), but instead tend to be stacked in a laterally offset pattern (23 examples in Fig. 3B; ~50% of multilateral population) and/or are isolated from each other (41 examples in Figs. 3A and 3B; ~90% of multilateral population). After deposition of a multilateral sand body, the river depocenter shifted via avulsion, such that the preceding sand body was multilateral and the succeeding sand body is either multilateral ($n = 23$; Fig. 3B) or single-story ($n = 16$; Fig. S12). Both cases ($n = 39$) are interpreted to illustrate compensational stacking, since the preceding multilateral sand body is not vertically stacked (i.e., no channel reoccupation). They hence imply that, after deposition of a multilateral sand body, "regional" avulsion occurred that resulted in abandonment of a nodal avulsion point (Mackey and Bridge, 1995); channels avoided formerly abandoned channels and instead occupied new sites on the floodplain (i.e., compensational stacking; *sensu* Mutti and Normark, 1987; Straub et al., 2009).

CONCLUSIONS

In our million-year-scale data set, although paleochannel characteristics (e.g., bedload grain size, flow depth, dominant bedform structure) were similar for all sand bodies, the internal sand body architecture (single-story versus multilateral) and a related correspondence in sand-body stacking patterns are apparent. Single-story sand bodies tend to occur in vertically stacked clusters that are capped by a multilateral sand body, and these clusters together with additional multilateral sand bodies are laterally offset or isolated from each other. This pattern is interpreted to record "local" reoccupational avulsion of a channel that evolved from fixed to mobile within each cluster, and "regional" avulsion-generated compensational stacking of multilateral and clustered sand bodies. Thus, for the first time in an outcrop study, we demonstrate that the internal architecture of sand bodies, river channel mobility, and stratigraphic-stacking patterns of sand bodies are predictively linked in an avulsion-dominated succession. This linkage is readily testable in future field and modeling studies, and has wide implications because deposition driven by river channel mobility is ubiquitous.

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