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Scale-dependent compensational stacking: An estimate of autogenic time scales in channelized sedimentary deposits

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ABSTRACT

Recent studies show that paleoenvironmental (allogenic) signals preserved in the stratigraphic record may be contaminated or overprinted by internally generated (autogenic) sedimentation. This is problematic, but it is unclear over what temporal and spatial scales autogenic patterns are most prevalent. We propose that scale breaks in basin-filling trends can be used to identify the transition between allogenic and autogenic stratigraphy. Using data from numerical and physical experiments and an ancient outcrop, we explore how compensation, the tendency for sediment transport systems to preferentially fill topographic lows, varies with stratigraphic scale. Object-based models demonstrate the temporal scales at which stratigraphy changes from being partially influenced by autogenic processes to being completely determined by allogenic forcings and suggest that this transition occurs at a time scale set by the maximum scale of surface roughness in a transport system divided by the long-term aggradation rate. This hypothesis is validated in a physical experiment where delta topography was monitored along flow-perpendicular transects at a high temporal resolution relative to channel kinematics. The strength of compensation in the experiment changes at the predicted time scale, where the maximum surface roughness is equal to the depth of the experimental channels. Above this compensation time scale deposits stack purely compensationally, but below this time scale deposits stack somewhere between randomly and deterministically. Similar scale-dependent stacking is also observed in the Ferris Formation (Cretaceous–Paleogene, Hanna Basin, Wyoming, United States). This study demonstrates that scale-dependent compensational stacking may be useful for isolating allogenic and autogenic stratigraphy in sedimentary basins.

INTRODUCTION

Alluvial basins contain the most complete record of information necessary to quantitatively reconstruct paleolandscape dynamics across many time scales (Ager, 1973; Paola, 2000). Unfortunately, developing quantitative stratigraphic models is complicated because the internal dynamics of depositional systems convolve with external boundary conditions that control basin sedimentation. This internal (or autogenic) variability is often presumed to impart relatively small amplitude, high-frequency noise in sedimentary successions that otherwise reflect large-scale external (or allogenic) forcings (Slingerland, 1990). Recent theoretical and experimental work shows that autogenic dynamics in sedimentary systems can occur over large temporal and spatial scales (Ganti et al., 2011; Jerolmack and Paola, 2007; Sheets et al., 2002; Straub et al., 2009). These behaviors are particularly vexing because they can produce stratigraphic patterns that are similar to stratigraphic architecture heretofore considered the result of changing climate, tectonics, or sea level (Hajek et al., 2010; Kim and Paola, 2007), and in some cases can destroy or overprint the stratigraphic record of environmental signals (Jerolmack and Paola, 2010). Autogenic processes acting over long time scales control the evenness or unsteadiness with which basins fill. These fluctuations in sediment transport are controlled by inherent characteristics of sedimentary systems, including channel mobility and avulsion frequency. Consequently, these properties of sedimentary systems can impose first-order controls on stratigraphy. The time scale at which autogenic processes supplant allogenic forcing in different systems is currently unconstrained (Covault et al., 2010; Paola et al., 1992; Sheets et al., 2002).

One way of describing autogenic organization is to characterize the degree of compensation observed in a basin fill. Compensation describes the tendency of deposits to preferentially fill topographic lows, smoothing out topographic relief and "compensating" for localized deposition from discrete depositional elements. This tendency is thought to result from periodic reorganization of the sediment transport field to minimize potential energy associated with elevation gradients (Deptuck et al., 2008; Mutti and Sonnino, 1981). Compensational stacking has been used to describe large-scale architecture in deep-water, fluvial, and deltaic packages (Mohrig et al., 2000; Olariu and Bhattacharya, 2006), wherein avulsions reorganize the sediment transport field along local topographic lows. A metric was developed to quantify the strength of compensation in sedimentary basins by comparing observed stacking patterns to what would be expected from simple, uncorrelated stacking (Straub et al., 2009). Here we utilize the compensation index in conjunction with numerical, experimental, and field data to (1) determine how compensation varies with scale, and (2) define a compensation time scale that predicts when the transition from autogenic to allogenic deposits is complete.

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COMPENSATION INDEX

Straub et al. (2009) quantified compensation in basin filling by comparing the spatial variability in sedimentation (σ_{ss}) between select depositional horizons with increasing vertical stratigraphic averaging distance:

$$\sigma_{ss}(T) = \left\{ \int_L \left[\frac{r(T;x)}{\hat{r}(x)} - 1 \right]^2 dL \right\}^{1/2}, \quad (1)$$

where $r(T; x)$ is the local sedimentation rate measured over a stratigraphic interval T, x is a horizontal coordinate, L is the cross-basin length, and $\hat{r}(x)$ is the local long-term sedimentation (or subsidence) rate. Straub et al. (2009) showed that σ_{ss} decreases with increasing T, following a power law trend in six study basins:

$$\sigma_{ss} = aT^{-\kappa}, \quad (2)$$

where the exponent, κ, was termed the compensation index, and a is a leading coefficient; κ was found theoretically to be 0.5 for random stacking that is uncorrelated in space and time, and 1.0 for perfect compensational stacking. Values <0.5 indicate anticompensation. The decay of σ_{ss} with stratigraphic scale can be understood as follows: over sufficiently long time intervals a transport system is able to visit every spot in a basin repeatedly; consequently the ratio of the sedimentation to subsidence at any point in the basin should approach unity. Over short time intervals, however, depositional geometries within a basin are controlled by the configuration of the transport system. As a result, the ratio of sedimentation to subsidence at any point in the basin is highly variable. Generally as the time scale of averaging increases, this variability diminishes.

One mechanism that results in periodic reconfiguration of transport systems toward topographic lows is avulsion (Mohrig et al., 2000). We explore how avulsions influence compensation using two-dimensional (2-D) object-based

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stacking models. We model basin filling with discrete triangular elements that are meant to represent channel or lobe deposits. During each time step one element is deposited in the basin while the subsidence is set to balance mean basin aggradation. An approximation of the avulsion process is modeled by placing channel elements with the following rules. At every *n*th time step during basin filling, the active channel relocates to the absolute topographic low in the model domain. For all other time steps deposition follows a random walk with elements moving one channel width left or right of the previous element. Figure 1 shows a sample stratigraphic section generated by this model and the corresponding plot of σ_{ss} as a function of T. We identify two regimes in the plot of σ_{ss} versus T where (1) κ increases from a value of 0.28–1.0 and (2) $\kappa = 1.0$.

The time scale at which κ first reaches unity represents a shift from stratigraphy that partially records stochastic autogenic processes to stratigraphy determined purely by regional sediment supply and accommodation. We hypothesize that this transition occurs at the time necessary to generate a deposit with a mean thickness equal to the maximum topographic relief on the transport system at any time. We therefore define a compensation time scale (T_C) as:

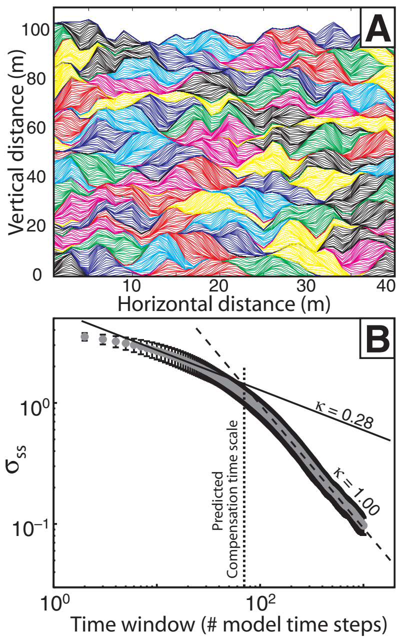

Figure 1. A: Output from object-based stacking model. Deposits of single color represent deposition between avulsion events. In this model avulsion occurs every 30 time steps. B: Over short time scales, depositional elements cluster to form anticompensationally stacked deposits, while over long time intervals, above T_C, deposits stack in purely compensational manner (see text). Error bars represent geometric standard deviation.

$$T_C = \frac{l}{\bar{r}}, \qquad (3)$$

where l is a roughness length scale and $\bar{r}$ is the basin-wide long-term sedimentation (or subsidence) rate. In our numerical models l represents the maximum amount of topographic mounding that occurs between the avulsions, which occur at every *n*th time step; Equation 3 correctly predicts the change from stochastic to deterministic dynamics.

EXPERIMENTAL STRATIGRAPHY

In order to test this model, we conducted an experiment, Tulane Delta Basin 10–1, (TDB 10–1), in order to obtain a time series of topographic evolution and resulting stratigraphy of a fluvial deltaic system at time scales above and below T_C. The experimental basin, located at Tulane University, is 4.2 m long, 2.8 m wide, and 0.65 m deep and is used to build physical stratigraphy (Fig. 2). During TDB 10–1 constant supplies of water and sediment were delivered to the basin, producing a delta that covered the width of the basin and extended 3.1 m from source to shoreline. Long-term aggradation was promoted by a steady base-level rise with a constant rate ($\bar{r}$ = 5 mm/hr) equal to the sediment discharge (Q_s) divided by the fluvial system plan-view area (for further details on experiment see the GSA Data Repository[1]). Topography was monitored at 2 min intervals along three flow-perpendicular transects located 1.6 m, 2.1 m, and 2.6 m from the infeed point. Topography on these transects was measured every 1 mm across the basin with a vertical resolution of 0.5 mm (Fig. 2C).

We calculated σ_{ss} at each topographic transect for every possible pairwise combination of topographic surveys, allowing us to define the decay of σ_{ss} over time windows of 2–1000 min (Figs. 3A–3C). During the experiment the maximum roughness on the transport system was associated with channels that had depths between 10 and 14 mm. As such we calculate T_C with Equation 3, where l represents the maximum depth of channels along a given topographic transect. This process resulted in predictions of T_C between 120 and 168 min. Our T_C values are in good agreement with the location of sharp inflections in plots of σ_{ss} as a function of T where κ values shift from 0.55–0.7 below T_C to 1.0 above T_C.

The degree of age control associated with natural basins is always less than what can be achieved in laboratory experiments. The compensation index proposed by Straub et al. (2009) is constructed using plots of σ_{ss} against the measurement window in time. Here we demonstrate that the measurement window can also be spatial, namely the average thickness of deposit between two stratigraphic surfaces. Comparison of σ_{ss} for this experiment shows a good match between κ calculated in time and space (Fig. 3D). This indicates that stratigraphic horizons may be used in place of timelines for analysis of deposits lacking adequate age control.

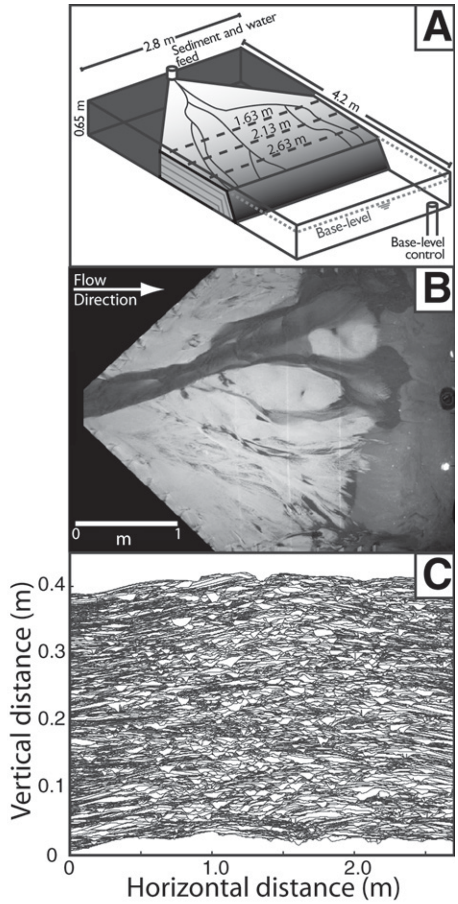

Figure 2. A: Schematic diagram of Tulane Delta Basin facility. Positions of topographic transects in TDB-10–1 experiment are indicated by black dashed lines on fluvial surface. Note that base-level control is in opposite corner of basin from infeed point. B: Photograph of active delta top at 10.2 h run time. C: Synthetic stratigraphy for proximal laser transect generated through stacked delta-top profiles with topography clipped to account for sediment removed during erosional events.

FIELD STRATIGRAPY

Previous studies that investigated the decay of σ_{ss} with scale examined either experimental systems or stratigraphy imaged in industry-grade seismic data (Lyons, 2004; Sheets et al., 2002; Straub et al., 2009). Unfortunately,

[1]GSA Data Repository item 2011239, experimental methods and a movie of the experiment between run hours 70 and 79 (Video DR1), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

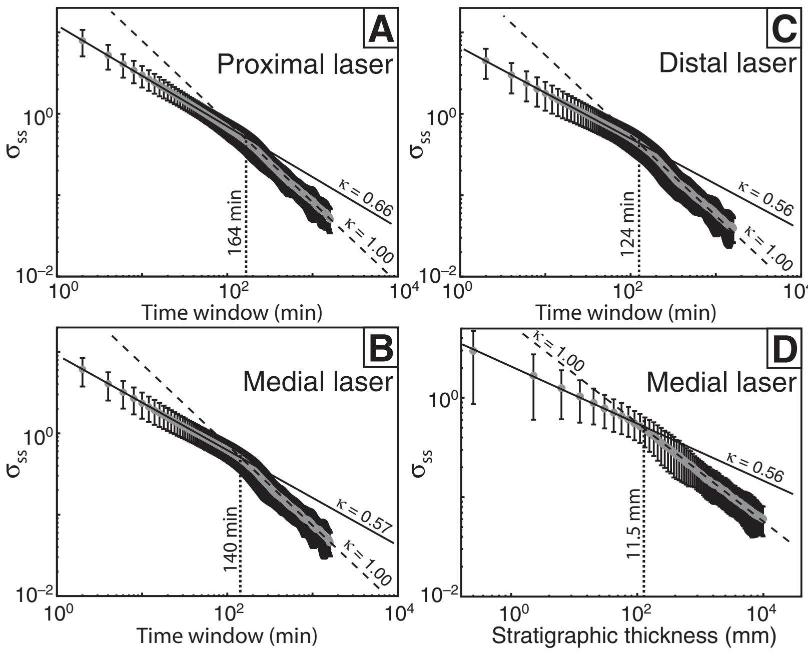

Figure 3. A–C: σ_{ss} decays in the time domain as a power law for the three laser locations with $\kappa < 0.7$ beneath T_C and $\kappa \cong 1.0$ above T_C (see text). Trend lines and associated κ values represent best-fit linear regression to log-log data with data in each plot separated into two segments at T_C. D: σ_{ss} decays in space domain as power law with nearly identical values of κ as found in time domain. Error bars represent geometric standard deviation.

industry-grade seismic data resolution is such that σ_{ss} cannot be measured for deposits with mean thicknesses <~20 m, a thickness of similar magnitude to many channel depths. Therefore, scale dependence in compensation set by channel dynamics cannot be examined with these field data sets. To examine this problem in field stratigraphy, we use an outcrop-based study where stratigraphic architecture can be mapped above and below the scale of individual channel bodies.

The Late Cretaceous–Paleogene Ferris Formation was deposited by a rapidly aggrading fluvial system in southeast Wyoming during the early Laramide orogeny (Eberle and Lillegraven, 1998). In the study area the Ferris Formation dips ~80° S (Fig. 4), exposing a basin cross section nearly orthogonal to paleoflow direction. The unit exhibits well-developed stratigraphic organization (Figs. 4C and 4D) where clusters of closely spaced channel bodies are separated from each other by mudstone-dominated intervals. This clustered pattern is observable throughout the outcrop belt, which extends several kilometers beyond the mapped study area. Channel bodies mapped in the field are between 1 and 10 m thick and can be tracked laterally into their contemporaneous floodplain deposits.

The distribution of channel deposits at this field site was shown to be statistically clustered (Hajek et al., 2010). No evidence for external controls on the spacing of channels was found within the outcrop (Hajek, 2009), and this pattern is interpreted to indicate autogenic avulsion behavior, similar to that found by Jerolmack and Paola (2007). To quantify the decay of σ_{ss} for the Ferris Formation, stratigraphic horizons that we infer as pseudo time horizons were mapped based on the stratigraphic order of channels (Fig. 4E). These horizons track the basal scour surfaces of channels up the flanks of channel bodies and extend laterally into presumed contemporaneous floodplain deposits. As seen in the model and experiment, σ_{ss} versus stratigraphic thickness calculated for this data set shows two regimes, where: (1) κ steadily increases from a value of 0.5–1.0, and (2) κ is constant and equal to 1.0 (Fig. 5). We note that the transition to pure compensation is complete for basin-wide deposits with mean thicknesses >40 m. This thickness is four times greater than the maximum thickness of channel bodies at this site.

DISCUSSION

In the experimental and field basins analyzed in this study we find that the strength of compensation is scale dependent. For these two case studies κ increases with stratigraphic scale until saturating at a value of 1.0. In the laboratory experiment, where we can link surface dynamics directly to the architecture of preserved stratigraphy, the time scale at which these systems transition to pure compensation ($\kappa = 1.0$) is correctly predicted by Equation 3. This result has implications for stratigraphic architecture and our ability to invert stratigraphy for paleoenvironmental

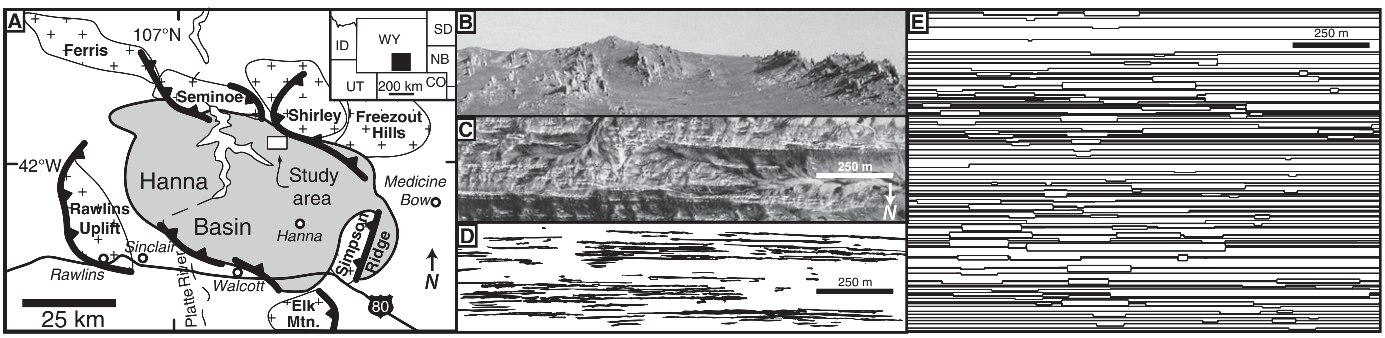

Figure 4. A: Location map of study area (after Eberle and Lillegraven, 1998) showing greater Hanna Basin (gray) and major structures and uplifts (crosses). ID—Idaho; WY—Wyoming; UT—Utah; SD—South Dakota; NB—Nebraska; CO—Colorado. B: Field photo of Ferris Formation; strata dip 80° (to right) and sandstone channel deposits stand out in relief against more heavily weathered overbank mudstones. C: Air photo of study area showing cross section of Ferris Formation exposed across land surface. Average paleoflow direction is into photo. Channel-belt sandstones are visible as white elongate bodies. D: Channel sand bodies (black) from C mapped with differential global positioning system. Centroids of these bodies were used for clustering analysis. E: Pseudohorizons used for compensation analysis follow mean base of each sand body and extend laterally away from sand body into floodplain deposits. Vertical exaggeration is ~2.5.

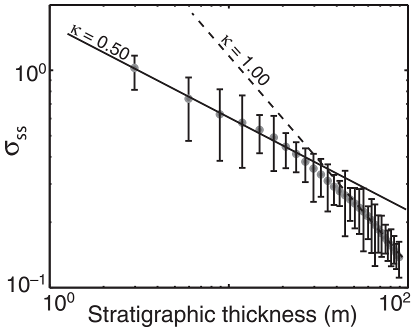

Figure 5. Decay of σ_{ss} as function of stratigraphic thickness for Ferris Formation showing random filling at small (<10 m) of thickness and compensational filling for large (>40 m) stratigraphic thickness (see text). Error bars represent geometric standard deviation.

conditions. Equation 3 essentially states that the geometry of deposits carries the signature of stochastic autogenic dynamics out to a time scale equal to the time necessary to fill a basin to a depth equal to the amount of surface roughness in a transport system. It is interesting that T_C for many systems extends into time scales commonly associated with large-scale allogenic cycles (e.g., Milankovitch cycles). For example, we calculate T_C for the Lower Mississippi Delta. We assume that the roughness length scale in Equation 3 is well approximated by mean channel depth for lowland deltas. Using a channel depth for the Lower Mississippi River of 30 m and a subsidence rate of 0.26 m/k.y. estimated for the past 8 m.y. (Straub et al., 2009), we calculate a T_C of 115 k.y. We note that this value is ~100 times greater than the ~1300 yr reoccurrence interval for large avulsions of the Lower Mississippi River (Aslan et al., 2005).

This example highlights the large amount of time necessary for autogenic surface-process dynamics to average out in the stratigraphic record. The intermingling of T_C with time scales associated with some large-scale allogenic cycles presents a challenge to sedimentologists when interpreting paleoenvironmental records preserved in stratigraphy. T_C provides an estimate of temporal or spatial scales below which stratigraphers should be wary about interpreting allogenic signals.

In our laboratory experiments the appropriate scale of surface roughness in our T_C formulation was identified as the depth of the system channels. We hypothesize that channel depth is the appropriate length scale to use when estimating T_C for systems where the avulsion cycle is the lowest frequency autogenic process. Recent studies have identified autogenic processes that happen over time scales significantly longer than the avulsion cycle. Examples include autogenic lake formation and filling (Kim and Paola, 2007) and channel belt clustering (Hajek et al., 2010; Jerolmack and Paola, 2007). These long-period autogenic dynamics appear to occur in environments with strong tectonic forcing and/or significant sediment cohesion. We predict that these newly identified autogenic dynamics result in surface roughness scales that exceed the depth of a system's channels and thus could result in T_C values that further overlap some long-period allogenic forcings. Thus solving Equation 3 with a roughness length scale equal to one channel depth results in a minimum estimate of T_C. This hypothesis likely explains why pure compensation was only observed beyond stratigraphic scales four times the measured sand-body thickness in the Ferris outcrop stratigraphy.

Further questions that remain to be answered include what sets the value of κ below T_C and how κ might be influenced by channel mobility, characteristic avulsion frequency, the scale of depositional systems with respect to the size of basins, and external forcings. Further numerical and laboratory experiments in addition to field work that use quantitative parameters like κ will be needed to answer these questions and thus enhance our understanding of the parameters that influence stratigraphic architecture.

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