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

Yinan Wang1*, Kyle M. Straub1, and Elizabeth A. Hajek2
1Department of Earth and Environmental Sciences, Tulane University, New Orleans, Louisiana 70118, USA
2Department of Geosciences, The Pennsylvania State University, University Park, Pennsylvania 16801, USA

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 Bhatthacharya, 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 might 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.

COMPENSATION INDEX
Straub et al. (2009) quantified compensation in basin filling by comparing the spatial variability in sedimentation ($\sigma_s$) between select depositional horizons with increasing vertical stratigraphic averaging distance:

$$\sigma_s(T) = \sqrt{\int L \left[ \frac{r(T, x)}{\bar{r}(x)} - 1 \right]^2 dL},$$

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 $\bar{r}(x)$ is the local long-term sedimentation (or subsidence) rate. Straub et al. (2009) showed that $\sigma_s$ decreases with increasing $T$, following a power law trend in six study basins:

$$\sigma_s = aT^{-\kappa},$$

where the exponent, $\kappa$, was termed the compensation index, and $a$ is a leading coefficient; $\kappa$ 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 $\sigma_s$ 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 nth 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 $\sigma_{ss}$ as a function of $T$. We identify two regimes in the plot of $\sigma_{ss}$ versus $T$ where (1) $\kappa$ increases from a value of 0.28–1.0 and (2) $\kappa = 1.0$.

The time scale at which $\kappa$ 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:

$$T_c = \frac{l}{\sigma},$$

where $l$ is a roughness length scale and $\sigma$ 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 nth 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 ($\tau = 5$ mm/hr) equal to the sediment discharge ($Q$) 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 $\sigma_{ss}$ at each topographic transect for every possible pairwise combination of topographic surveys, allowing us to define the decay of $\sigma_{ss}$ 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 $\sigma_{ss}$ as a function of $T$ where $\kappa$ 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 $\sigma_{ss}$ 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 $T_c$ for this experiment shows a good match between $\kappa$ 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.

**FIELD STRATIGRAPHY**

Previous studies that investigated the decay of $\sigma_{ss}$ 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,
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 $\sigma_s$ 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, $\sigma_s$ versus stratigraphic thickness calculated for this data set shows two regimes, where: (1) $\kappa$ steadily increases from a value of 0.5–1.0, and (2) $\kappa$ 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 $\kappa$ 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...
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 allochthonous events (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 \( T_c \) for the Lower Mississippi Delta. We therefore estimate that \( T_c \) 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 large-scale allochthonous events, 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 allochthonous 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 allochthonous 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 \( \kappa \) below \( T_c \), and how \( \kappa \) 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 \( \kappa \) will be needed to answer these questions and thus enhance our understanding of the parameters that influence stratigraphic architecture.

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