SUPPLEMENTAL MATERIAL

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Elevation gaps in fluvial sandbar deposition and their consequences for paleodepth estimation

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The supplementary text and figures provide additional explanation of the datasets and analysis methods used to obtain observations of sandbar slipface heights and to scale these observations to measures of channel flow depth at bankfull.

A. Explanation of primary datasets

1. Digital elevation model (provided by U.S. Army Corps of Engineers, Omaha District)

The digital elevation model (DEM) used to identify and extract clinoform heights was derived from aerial light detection and ranging (LiDAR) scans flown on December 1st and 2nd, 2011 when releases from Gavins Point Dam (GPD) were at baseflow conditions (SUPPLMENTARY FIGURE 1). The LiDAR scans were flown by a private contractor, hired by the U.S. Army Corps of Engineers, Omaha district. Although the metadata associated with the flights did not indicate exact dates of the flight, we contacted the contractor, they reviewed the flight lines and confirmed that the LiDAR in the study reach was acquired on December 1st and 2nd . The native coordinate system of the DEM is NAD83, UTM Zone 15 N and the native units are imperial (ft-pound). Thus the actual grid resolution of the DEM was 5 ft. For the purposes of the paper we rounded to the nearest decimeter and reported 1.5 meters as the grid resolution. We converted to meters for all final calculations associated with these data.

2. Digital aerial photography (provided by U.S. Army Corps of Engineers, Omaha District)

The three-band, natural color digital aerial photographs used for our analysis were acquired in the study area between November 15th and 22nd, by a private contractor hired by the USACE-Omaha District. The native coordinate system of the digital photos was NAD83, UTM Zone 15 N and the native units are imperial (ft-pound). Thus, the original resolution was 1-foot. For the purposes of our paper, we rounded to the nearest decimeter and reported a resolution of 30 cm. We converted to meters for all final calculations associated with these data.

3. ***Water surface profile (provided by U.S. Army Corps of Engineers, Omaha District)***
The water surface profile was taken on June 24th, 2011 (the first day of the peak discharge) using a real-time kinematic global positioning system onboard a boat. Average point spacing of the water surface profile was about 150 meters (SUPPLEMENTARY FIGURE 1). The native coordinate system of the digital photos was NAD83, UTM Zone 15 N and the native units are imperial (ft-pound). We converted to meters for all final calculations associated with these data.

4. ***Channel transects and 1-D hydraulic model outputs (provided by U.S. Army Corps of Engineers, Omaha District)***
Two sets of channel topographic/bathymetric transects were surveyed in the study segment after the flood of 2011. The first survey was performed from October 4th to November 16th, 2011; a second survey was performed in April 2013. The first survey was along historic USACE transects spaced approximately every 1.6 km downstream from the dam and had a total of 8,172 observation points within the study segment. The second survey established new transects spaced systematically at 150-meter intervals and had a total of 342,479 observation points within the study segment.

The November 2011 survey was used to calculate local and grand-mean flow depths at bankfull across the study segment. Local mean flow depth ($\bar{h}_j$), shown in figure 3A of the main text, was calculated as:

$$\bar{h}_j = \frac{\sum_i^n \left(Z_{w_{ji}} - Z_{b_{ji}}\right)}{n_j}$$

where $Z_{w_{ji}}$ is a local water surface elevation measurement i at peak discharge (taken from the June 24th water-surface profile survey) along transect j, $Z_{b_{ji}}$ is local bed elevation measurement i along transect j (taken from Oct.-Nov. 2011 topographic surveys), and n_j is the total number of observations at transect j. Grand mean flow depth at bankfull ($\langle h_i \rangle$)was calculated as:

$$\langle h_i \rangle = \frac{\sum_i^n \left(Z_{w_i} - Z_{b_i}\right)}{n_i}$$

where Z_{w_i} is a local water surface elevation measurement i at peak discharge (taken from the June 24th water-surface profile survey), Z_{b_i} is local bed elevation measurement i (taken from Oct.-Nov. 2011 topographic surveys), and n_i is the total number of observations made across the ~80 kilometer study segment.

A reduced set of transects from the April 2013 survey data were used by the USACE to construct the 1-D hydraulic model, which we used to estimate reach-scale velocities, and ultimately Froude conditions at sandbar crests. The HEC-RAS model was constructed and calibrated by the USACE-Omaha district, and the basic outputs of the model (mean channel depth, mean velocity, flow width etc.) and locations of the transects used were provided to the authors.

A comparison of the distribution of bed topographies from the Oct.-Nov. 2011 survey and the April 2013 survey indicates that, although the range of elevations was similar, the grand mean depth calculated from the April 2013 survey data was deeper (5.9m) than grand mean depth calculated using the Oct.-Nov. 2011 survey data (5.3m). The shapes of the distributions (SUPPLEMENTARY FIGURE 2) suggest that the 2011 topography had substantially more mass in shallow regions than the 2013 topography. To examine if the difference in topographic distribution was a function of the much larger sample size of the 2013 survey, we sub-sampled the 2013 survey data by selecting only data near the 2011 transects. As SUPPLEMENTARY FIGURE 2 shows, the sub-sampled April 2013 distribution is remarkably like the full April 2013 distribution. Thus, we interpret the reduction in shallow regions in the April 2013 topography to lateral erosion of sandbar, which would result in net lowering of the river bed. Likewise, our analysis demonstrates that the lower spatial density of data from the Oct.-Nov. 2011 survey was likely adequate to represent the full bed topography.

Although comparison of topographic distributions demonstrates that the April 2013 topography was different than the topography of the 2011 flood, output from the HEC model indicated channel width (and thus channel conveyance) was the primary control on estimated channel velocities (SUPPLEMENTARY FIGURE 3). These data indicate differences in local distributions of bed topography were unlikely to substantially change the reach-scale velocity estimates used to calculate Froude conditions at bar crests.

B. Explanation of data extraction methods

1. Along-stream linear referencing system

The locations of all data used in our analysis were converted into an along-stream reference coordinate system based on a channel centerline. Creation of the coordinate system required two primary steps: (1) creation of a channel centerline; (2) linear referencing of all data points to the centerline coordinate. The channel centerline was created by digitizing the high-banks of the active channel. The high banks were digitized manually, on-screen, at 1:2500 scale in ArcGIS. The centerline tool of Lauer and Parker (2004) was then used to interpolate a centerline between the high banks (SUPPLMENTARY FIGURE 1). The 'create routes' tool in ArcGIS 10.3.1 was used to convert the centerline to a route feature which could be used to reference all data into the along-stream coordinate system.

2. Extraction of bar features known to have been created by the peak-flood discharge

We used the fundamental assumption that bars exposed immediately after the abrupt 1.5m stage drop which began on August 18th were those most in equilibrium with the peak discharge. We identified these bars by assuming normal flow, subtracting 1.75m from the peak water surface profile (the sum of 0.25 m for the smaller stage drop in July 2011, and 1.5 m for the drop beginning on August 18th) and extracting only those portions of the channel above this local elevation (SUPPLMENTARY FIGURE 4). In some cases, the bar top was exposed after August 18th, but the base was not exposed until later stage drops occurring prior to the LiDAR flight (or not at all in the case of censored measurements). Polygons approximately 5m wide were digitized along the crest and base of clinoforms visible using the assistance of a DEM of local topographic slope. Point grids with 2m spacing were created within each extraction polygon, and these points were used to extract elevation samples. To extract maximum crest elevation and minimum base elevation along each avalanche face, a polyline was drawn between the crest and base extraction polygons, and the polyline was converted to a route in ArcGIS. The route was used to locate the local measurements of crest and base elevation along the avalanche face. The route location then allowed us to bin the elevation measurements, and obtain the local (2m) maximum crest elevation and minimum base elevation.

3. ***Estimation of time required to 'fill' space occupied by range of probable sandbar sizes***
We suggest that the most straightforward way to estimate any time limitation on bar growth is to estimate a range of bar sizes, and divide these sizes by an estimate of the bed-material transport rate:

$$\frac{A_{bar}}{q_s}$$

Where A_{bar} is width-normalized bar volume in units of m^2, and q_s is the unit bed material transport rate in units of $m^2 t^{-1}$, where t is time. A general way to estimate mean bar length is to use the mean advection length of bed material:

$$\frac{q_w}{w_s}$$

Where q_w is unit discharge in units of $m^2 t^{-1}$ and w_s is the settling velocity of the median bed material size in units of $m\ t^{-1}$. Unit discharge in the river at peak flow was about 5 m^2/s, and we estimated the settling velocity of the D_{50} reported in Galloway et al. (2013) as 0.05 m/s, giving a characteristic bar length of about 100 meters. We estimate that the largest bar would be no more than the mean channel width of around 900 meters (Elliott and Jacobson, 2006), giving us a range of bar lengths from 100 to 900 meters. Using the equation for the area of a half ellipse, with the mean water depth and half the bar length as radii, and assuming a porosity of 35%, we get a range of along-stream bar areas of 300 to 2,700 m^2.

To obtain a unit bed-material discharge, we divided the total load measurements of Galloway et al. (2013) by the mean channel width of 900 m, to give us an estimated unit discharge of about 30 m^2/day. Using this value and the equation above, we get a range of times to fill sandbars of about 10 to 100 days. Although the high-end of our estimation might suggest that the 2011 flood was about 30 to 40 days short of the time required to fill the largest bars, most of the top-surfaces of sandbars exposed after the flood recession were about 150 to 300 meters long. These values would indicate fill times closer to 30 days, and thus the 2-month long flood was likely more than adequate to fill the required space. Regardless, we suggest that the 2011 flood was well beyond the typical steadiness of a natural flood, and thus exceeded any natural steady fill times.

C. ***Explanation of distribution and survival modeling of censored base elevations***
Despite the fact that the LiDAR dataset used to calculate slipface heights was acquired during baseflow conditions, some base elevations were obscured by water. Thus, raw calculations of clinoform height from differencing local crest and base elevations were incomplete or, using statistical terminology, 'censored'. We used survival analysis, a common statistical technique for estimating censored values, to estimate slipface heights for incomplete samples and obtain posterior estimates of parameters for gamma-distributed ratio of slipface heights to global mean flow depth at bankfull. Incomplete height samples were treated as right censored:

$$H_o \leq H_a$$

Where H_o is the observed incomplete slipface height and H_a is the actual slipface height. In reality, the incomplete samples are interval censored because H_a cannot exceed the maximum depth of the river at bankfull, and the additional unobserved length of slipface cannot exceed the maximum depth of the water during the baseflow conditions when the LiDAR was acquired. That is, the following statement *must* be true:

$$H_o \leq H_a \leq h_{max}$$

Where h_{max} is the estimated maximum depth of water at the time of the LiDAR data acquisition. Using an estimate of the water surface profile on the day of LiDAR acquisition and the high-resolution topographic dataset from April 2013, we estimated the mean depth of the river on the day of LiDAR acquisition as 2.7 m, with a 95th percentile of 4.9 m, suggesting the interval is narrow. When the interval is narrow, it is common to ignore it and assume the data are simply right-censored at some larger unknown value (Christensen et al., 2011).

We used the Bayesian survival analysis theory outlined in Christensen et al. (2011) [pgs. 301 to 314] whereby the probability of observed slipface heights (H_o) being greater than some discrete slipface height value (H_a) can be described by some survival function:

$$S(H_a) \equiv P(H_o > H_a)$$

Where $S(H_a)$ is the survival function describing the probability (P) of an observed slipface height (H_{o_i}) being greater than some value (H_a). Because the data lie on an interval greater than 0 (slipface height cannot be negative), and observations presented elsewhere (Paola and Borgman, 1992; Mohrig et al., 2000) indicate barforms and bedforms follow right-skewed distributions, we assumed a Gamma-distributed survival model. That is:

$$H_o | \alpha, \beta \sim \Gamma(\alpha, \beta)$$

Where Γ is the Gamma distribution with parameters α and β. Thus, the slipface height density distribution was modeled as a Gamma distribution with density:

$$f(H_a | \alpha, \beta) = \frac{\beta^\alpha {H_a}^\alpha e^{-\beta H_a}}{\Gamma(\alpha)}$$

and survival function:

$$S(H_a) = 1 - I_\alpha(\beta H_a)$$

Where I_α is the incomplete Gamma distribution. The survival function $S(H_a)$ for the Gamma distribution does not have a closed form, but can be approximated using statistical software. The survival analysis was implemented in language *R* using techniques and code outlined in

Farrow (2016), and the MCMC package 'Rjags' (Plummer et al., 2016) was used to simulate posterior estimates of α and β, and values for censored observations of H_o. The simulation used three Markov chains of 20,000 steps each, with 1,000 burn-in steps to generate the posterior values. The model simulation assumed non-informative priors for parameters of the Gamma distribution (i.e. $\alpha, \beta \sim Uniform[0,10]$)

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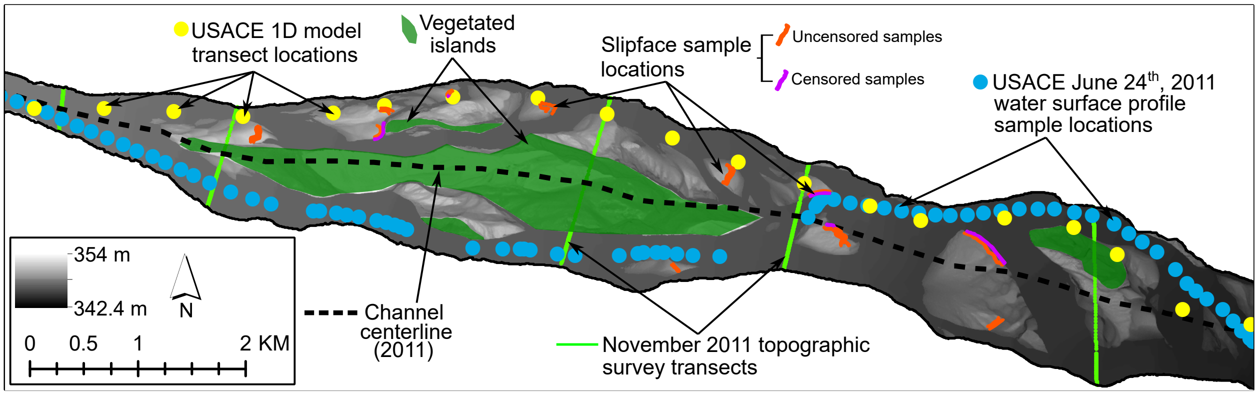
FIGURE CAPTIONS

FIGURE S1. Depiction of spatial overlay of primary datasets used to extract and calculate sandbar slipface heights on the lower Missouri River. Flow direction is left to right. The spacing of the USACE 1D model transect locations are shown along the 1960 USACE channel centerline. The slipface sample elevations, water surface elevation samples, and velocity data from the USACE 1D model were referenced to the 2011 channel centerline coordinate system to calculate crest gaps and estimate Froude conditions near bar crests. The slipface sample locations with uncensored crest and base are climbing bars, while those with censored bases are channel-terminating. The local mean and maximum depth profiles shown in Figure 3A of the main text are based on topography data from the transects surveyed in October-November 2011. The geometry used to construct the USACE 1D model was based mainly on topography surveyed in April 2013.

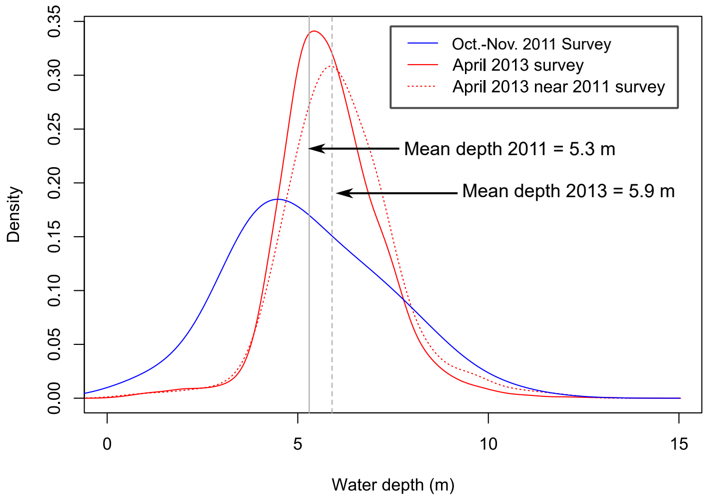
FIGURE S2. Density plots showing distributions of water depth in the lower Missouri River during the flood of 2011 calculated using two different bed topography surveys. The October-November 2011 survey was done along transects spaced approximately every 1.6 kilometers (about two channel widths), while the April 2013 survey was done along transects spaced every 150 meters. The Oct.-Nov. 2011 survey had a sample size of 8,172 while the April 2013 survey had 342,479 sample points. Subsampling of the April 2013 survey using only datapoints on transects near those from the Oct.-Nov. 2011 survey (red dotted line) does not change the distribution substantially. The similarity of the complete and subsampled April 2013 distributions indicates that the smaller sample size of the Oct.-Nov 2011 survey was adequate to represent the full bed topography during the bankfull flood. The distributions indicate the increase in mean depth from Oct.-Nov. 2011 to April 2013 was associated with losses in the shallow parts of the distribution, which we interpret to be the consequence of lateral erosion of sandbars created by the flood of 2011.

FIGURE S3. Scatterplot showing estimates of mean channel velocity made using a 1D hydraulic model (HEC-RAS) of the 2011 flood in the lower Missouri River. The model was built using topography surveyed at transects spaced approximately every 600 meters along the 80-km study reach of the lower Missouri River in April 2013. The plot demonstrates the first-order control of bankfull channel width on reach mean velocity.

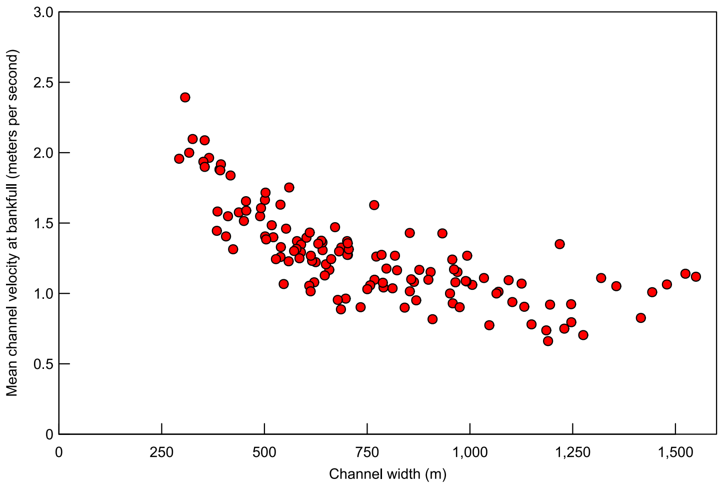
FIGURE S4. Images depicting process of elevation data extraction to calculate slipface height. The first step identified areas of the riverbed exposed after the abrupt stage drop of 1.5m beginning on August 18th which ended the bankfull flood: (A.) Aerial image taken during LiDAR data acquisition on December 1st, 2011 depicting portions of the LiDAR digital elevation model (DEM) calculated as emergent after abrupt 1.5 m stage drop on August 18th. The next step used a raster of local slope in the DEM to identify the location of the bar slipface: (B.) Raster of local slope calculated from LiDAR DEM used to identify location of slipface of the barform. The final step used sampling boxes to extract elevations of the crest and base, and a linear-referencing system to identify local maximum crest elevation and local minimum base elevation in 1.5-meter increments: (C.) Image depicting sampling areas of crest and base, and linear-reference line along the slipface of the barform.



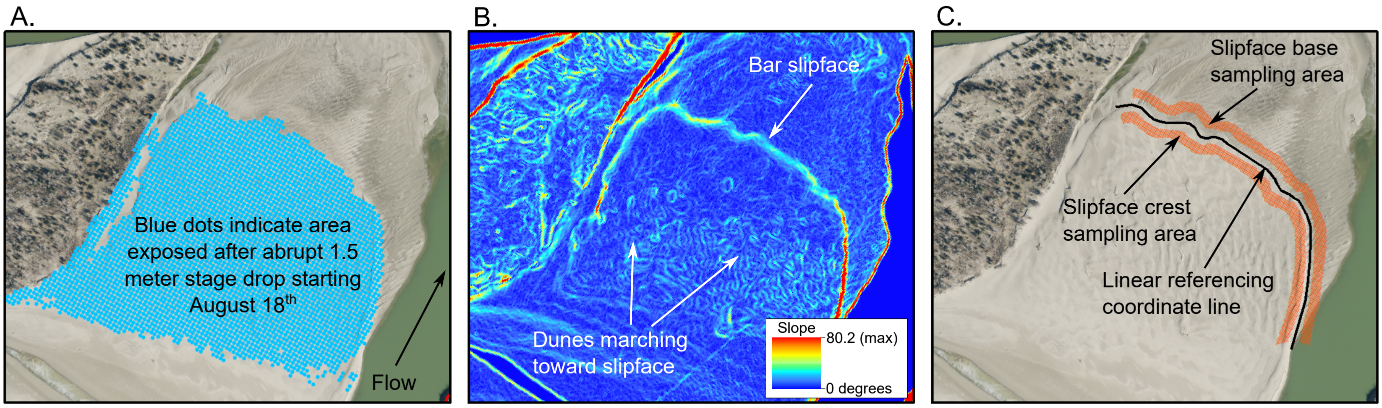
SUPPLEMENTARY FIGURE 1. Depiction of spatial overlay of primary datasets used to extract and calculate sandbar slipface heights on the lower Missouri River. Flow direction is left to right. The spacing of the USACE 1D model transect locations are shown along the 1960 USACE channel centerline. The slipface sample elevations, water surface elevation samples, and velocity data from the USACE 1D model were referenced to the 2011 channel centerline coordinate system to calculate crest gaps and estimate Froude conditions near bar crests. The slipface sample locations with uncensored crest and base are climbing bars, while those with censored bases are channel-terminating. The local mean and maximum depth profiles shown in Figure 3A of the main text are based on topography data from the transects surveyed in October-November 2011. The geometry used to construct the USACE 1D model was based mainly on topography surveyed in April 2013.



[SUPPLEMENTARY FIGURE 2.] Density plots showing distributions of water depth in the lower Missouri River during the flood of 2011 calculated using two different bed topography surveys. The October-November 2011 survey was done along transects spaced approximately every 1.6 kilometers (about two channel widths), while the April 2013 survey was done along transects spaced every 150 meters. The Oct.-Nov. 2011 survey had a sample size of 8,172 while the April 2013 survey had 342,479 sample points. Subsampling of the April 2013 survey using only datapoints on transects near those from the Oct.-Nov. 2011 survey (red dotted line) does not change the distribution substantially. The similarity of the complete and subsampled April 2013 distributions indicates that the smaller sample size of the Oct.-Nov 2011 survey was adequate to represent the full bed topography during the bankfull flood. The distributions indicate the increase in mean depth from Oct.-Nov. 2011 to April 2013 was associated with losses in the shallow parts of the distribution, which we interpret to be the consequence of lateral erosion of sandbars created by the flood of



[SUPPLEMENTARY FIGURE 3.] Scatterplot showing estimates of mean channel velocity made using a 1D hydraulic model (HEC-RAS) of the 2011 flood in the lower Missouri River. The model was built using topography surveyed at transects spaced approximately every 600 meters along the 80-km study reach of the lower Missouri River in April 2013. The plot demonstrates the first-order control of bankfull channel width on reach mean velocity.



SUPPLEMENTARY FIGURE 4. Images depicting process of elevation data extraction to calculate slipface height. The first step identified areas of the riverbed exposed after the abrupt stage drop of 1.5m beginning on August 18th which ended the bankfull flood: (A.) Aerial image taken during LiDAR data acquisition on December 1st, 2011 depicting portions of the LiDAR digital elevation model (DEM) calculated as emergent after abrupt 1.5 m stage drop on August 18th. The next step used a raster of local slope in the DEM to identify the location of the bar slipface: (B.) Raster of local slope calculated from LiDAR DEM used to identify location of slipface of the barform. The final step used sampling boxes to extract elevations of the crest and base, and a linear-referencing system to identify local maximum crest elevation and local minimum base elevation in 1.5-meter increments: (C.) Image depicting sampling areas of crest and base, and linear-reference line along the slipface of the barform.