Fluvio-deltaic avulsions during relative sea-level fall

A.G. Nijhuis[1], D.A. Edmonds[2], R.L. Caldwell[2], J.A. Cederberg[3], R.L. Slingerland[3], J.L. Best[4], D.R. Parsons[5], and R.A.J. Robinson[6]

[1]*Department of Earth and Environmental Sciences, 140 Commonwealth Ave, Boston College, 213 Devlin Hall, Chestnut Hill, MA 02467*

[2]*Indiana University Department of Geological Sciences and Center for Geospatial Data Analysis, 1001 East 10th St. Office GY425, Bloomington, IN, 47405, USA.*

[3]*Department of Geosciences, The Pennsylvania State University, University Park, Pennsylvania 16802, USA.*

[4]*Departments of Geology, Geography and Geographic Information Science, Mechanical Science and Engineering and Ven Te Chow Hydrosystems Laboratory, University of Illinois, 133 Computer Applications Bldg,605 E. Springfield Ave., Champaign, IL 61820*

[5]*Department of Geography, Environment and Earth Sciences, University of Hull, Cottingham Road, Hull, HU6 7RX*

[6]*Department of Earth & Environmental Sciences, University of St Andrews, Irvine Building, North Street, St Andrews, Fife KY16 9AL, Scotland, UK*

ABSTRACT

Understanding river response to relative sea-level (RSL) changes is essential for predicting fluvial stratigraphy and source to sink dynamics. Recent theoretical work has suggested that during RSL fall rivers can remain aggradational. However, field data are needed to verify this response and investigate sediment deposition processes. We show with field work and modeling that during RSL fall fluvio-deltaic systems can remain aggradational or at grade, leading to superelevation and delta lobe avulsions. Our field site is the Goose River in Newfoundland-Labrador, which has experienced steady RSL fall of around 3 to 4 mm yr^{-1} in the past 5 ka from post-glacial isostatic rebound. Elevation analysis and optically-stimulated luminescence dating suggest that during RSL fall the Goose River avulsed and deposited three delta lobes. Model

results from Delft3D show that if the characteristic system fluvial response time is longer than the duration of RSL fall, then rivers remain aggradational or at grade and continue to avulse due to superelevation. Intriguingly, our results also suggest that avulsions become more frequent at faster RSL fall rates, provided the system response time remains longer than RSL fall duration. This work suggests that the rate of RSL fall may play an important role in setting the architecture of falling stage deposits.

INTRODUCTION

Predicting how rivers erode or deposit sediment in response to relative sea-level (RSL) change is critical for understanding sequence stratigraphy (Catuneanu, 2006) and source to sink dynamics (Romans and Graham, 2013). Despite this importance, it is unclear if during RSL fall rivers incise and bypass sediment to the deep marine (e.g. Vail, 1977), or if they deposit sediment on the coastal plain starving the deep marine (e.g. Holbrook and Bhattacharya, 2012). In the latter case, strata deposited during RSL fall are typically terraced deposits with a descending shoreline trajectory (Posamentier and Morris, 2000; Catuneanu, 2006; Helland-Hansen and Hampson, 2009, Li and Bhattacharya, 2013). While the incisional model has received considerable attention, there is mounting theoretical evidence (Muto and Steel, 2004) that deposition during RSL fall may be common, yet few studies have focused on the processes that deposit these sediments.

For example, experimental work shows that a coastal river with constant sediment supply, prograding over a linear basin slope, does not just incise during steady RSL fall. Instead the river experiences an autogenic response of multiple episodes of deltaic lobe deposition, incision through the lobe, and abandonment (van Heijst and Postma, 2001; Muto and Steel, 2002, 2004; Swenson and Muto, 2007). But, these ideas have not been tested on field-scale rivers, nor have they been investigated with channel-resolving morphodynamic models.

Our goal here is to understand the processes that control sediment deposition during RSL fall by combining elevation analysis, and optically stimulated luminescence (OSL) data from the modern Goose River, Newfoundland-Labrador, and morphodynamic modeling. Our observations show that as RSL falls Goose River avulsions create multiple delta lobes at progressively lower elevations. Delft3D models simulating RSL fall confirm these field observations and suggest that the number and size of delta lobes scale with the rate of RSL fall.

STUDY AREA

The Goose River empties into Goose Bay at the western edge of Lake Melville—a fjord-type estuary located 200 km inland of the Labrador Sea, Labrador, Canada (Liverman, 1997) (Fig. 1). The majority of Goose Bay water depths range between 20 m and 40 m, but nearshore depths shallow to 10 m (Blake, 1956). The bay is stratified with a 5 m-thick stable fresh water surface layer overlaying saline bottom waters. The tidal amplitude within Goose Bay is ~0.4 m (Vilks et al., 1987). The Goose River has a drainage area of 3,450 km^2. In its lower reaches the river averages 100 to 200 m wide and 2 to 3 m deep. Water discharge ranges from 5 $m^3 s^{-1}$ during winter to 500 $m^3 s^{-1}$ during the spring and early summer (Coachman, 1953).

This region of Labrador has experienced considerable RSL fall following retreat of the Laurentide ice sheet over Goose Bay at ~8 ka (Syvitski and Lee, 1993). While, the initial RSL fall rate was around ~50 mm yr^{-1} (Clark and Fitzhugh, 1991), it has slowed to steady rate between 3 and 10 mm yr^{-1} over the last 5 ka (Fitzhugh, 1973; Clark and Fitzhugh, 1991). These rates are also consistent with radiocarbon dating of stranded shorelines (Blake, 1955), and with geodetic monitoring over the past two decades (Henton, et al., 2006).

FIELD DATA COLLECTION and RESULTS

We mapped four extant delta lobes within the Goose River system. At the mouth of the Goose River there is an active, sandy delta (Fig. 1D), and upstream there are at least three moribund delta lobes (Fig. 1A-C), as recognized by their lobate planform shape and visible distributary channel networks. The median grain size is between 330 and 350 μm for all delta lobes.

To constrain the timing of fluvio-deltaic deposition on the Goose River, we conducted a topographic analysis using 30-m shuttle radar topography mission (SRTM) data and collected sediment cores for OSL dating from delta lobes B and C (Fig. 1). We compared the accuracy of the SRTM data with survey points from a fully corrected Leica 1320 global positioning system and found good agreement with a root mean square error of less than 1 m. The sediment cores for OSL dating (Fig. 1) came from overbank locations that were between distributary channels (i.e. centers of mouth-bar areas) to minimize contamination from recent sediments deposited during floods. Within the sediment cores, two samples were collected at different stratigraphic elevations (Fig. DR1) to constrain lobe activity and aggradation rate. The single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000) was used to determine equivalent doses (D_e) and subsequent OSL ages of each sample. Based on the character of the age distributions, we used a central age model for the lobe B samples and the minimum age model for lobe C samples (see data repository for more information on sample collection and OSL dating).

Our OSL results and topographic analysis shows that during RSL fall the Goose River avulsed to create at least three delta lobes at progressively lower elevations (Fig. 1 inset). OSL ages suggest the Goose River delta avulsed from lobe B to C between 1 and 2 ka. During deposition lobes B and C possessed vertical aggradation rates of ~4 and ~3 mm yr^{-1}, respectively. Although we did not collect OSL samples for lobe A, we can estimate its age using the surface elevation and the local sea-level curve. This method suggests it dates to ~3 ka.

NUMERICAL MODELING SETUP AND RESULTS

To understand the behavior of the Goose River in more detail we conducted a series of modeling experiments of delta growth under RSL fall using Delft3D. Our model setup uses boundary and initial condition measured on the Goose River. We simulate a fluvial system entering a standing body of water with no tides, waves, or buoyancy forces. The river has a constant bankfull discharge of 300 m^3 s^{-1} and carries an equilibrium concentration of 350 μm sediment. Along the seaward boundary we specify constant RSL fall rates varying from 0 to 10 mm yr^{-1} (consistent with temporal variability at Goose Bay) using 1 mm yr^{-1} increments and we simulate rates of 16 and 20 mm yr^{-1} to explore all of parameter space; this results in 13 runs total (Table 1). Before RSL fall begins, a delta progrades basinward until the average topset slope reaches dynamic equilibrium. We used this delta topography as the starting point for each RSL fall scenario (see Data Repository for more information on model setup).

For analysis we mark the durations of all avulsions during RSL fall that create new, distinct delta lobes. An avulsion is considered complete after water and sediment transported in the initial delta lobe diminishes to zero. We define a delta lobe as a set of contemporaneous channels feeding a topset of relatively constant elevation that is separated from neighboring depocenters by an abrupt change in elevation (Fig. 2). We ignore the smaller intradelta lobe avulsions (*sensu* Edmonds et al., 2009).

In our model runs, during RSL fall there is fluvio-deltaic deposition on the coastal plain that is punctuated by fluvial avulsion (Figure 2A-C). This is consistent with observations on the Goose River and recent work (Muto and Steel, 2004). No delta lobe avulsions occurred for runs with RSL fall of 0 to 2 mm yr^{-1}. We find that avulsion period decreases with increasing RSL fall rate (Fig. 2D). Avulsion number also increases with RSL fall, until a point is reached and they decline rapidly (Figure 2D).

DISCUSSION OF FIELD DATA AND MODELING

Our field and numerical modeling results show that rivers can avulse and deposit multiple delta lobes on the coastal plain during RSL fall. This result is significant as RSL fall should suppress avulsions because channel incision, if fast enough, counteracts normalized superelevation (height from water surface to sea-level relative to parent channel depth) that commonly precedes avulsion (Slingerland and Smith, 2004).

We reason that avulsion can persist during RSL fall provided the channel becomes superelevated. This would occur if the RSL fall signal does not cause enough incision in the channel. This idea was quantified by Muto and co-workers (Muto and Steel, 2002, 2004; Muto and Swenson, 2005, 2006; Swenson and Muto, 2007) who showed that a fluvio-deltaic system will not incise when RSL falls if the fluvial response time τ is longer than the duration of RSL fall T (i.e. $\tau > T$). Similarly, we define the fluvial response time as $\tau = \frac{q_s \cdot S}{r^2}$ where q_s is the sediment supply per unit width of the active delta lobe (m^2 s^{-1}), S is the water surface slope, and r is the rate of RSL fall (m s^{-1}). We take T to be the avulsion period, since that sets the duration a given delta lobe is exposed to RSL fall, or in the case of no avulsions we use the total duration of RSL fall.

Both the Goose River and our model runs with RSL fall of 1 to 10 mm yr^{-1} possess τ/T >> 1 (Table 1) suggesting in these cases the fluvial system has not responded to RSL fall. This is further supported by modeled channel bed elevations that show little incision (Fig. 3A). We suggest avulsions continue because RSL fall superelevates the fluvial system, and also creates surface gradient advantages where steeper delta front foresets are exposed due to shoreline retreat. Consider that prior to the avulsion in Fig. 2C the channel does not incise (because τ/T >> 1, Table 1) and sea-level decreases faster than the water surface elevation in the channel. This leads to a normalized superelevation of ~0.4 before avulsion (Fig. 3B), which is a reasonable value for avulsion initiation in other systems (Hajek and Wolinsky, 2012). New delta lobes are created as overbank flow accelerates down steeper pathways and forms incisional avulsion channels (e.g., Hajek and Edmonds, 2014) (Fig. 3). Thus, the avulsion period decreases with faster RSL fall rates because channels superelevate faster (Fig. 2D).

At higher RSL fall rates of 16 and 20 mm yr^{-1} the model runs are characterized by $\tau/T < 1$ (Table 1). In these runs, the channel bed quickly erodes through the initial delta lobe (Fig. 4C), entrenching the active channel and suppressing future avulsions. The few avulsions that do occur arise from upstream migrating knickpoints that capture the river. The fluvial system continues to deposit sediment and prograde as it follows the rapidly falling shoreline, but there are no terraces and the surface grade is set by the RSL rate and underlying slope (Muto and Swenson, 2006).

IMPLICATIONS

Our field and numerical results suggest that for a given fluvio-deltaic system, if $\tau/T \gg 1$ falling-stage deposits are characterized by a series of terraced, downstepping deltaic lobes, whereas if $\tau/T \leq 1$ incision occurs through pre-existing lobes and falling-stage deposits lack well-defined terraces ('smooth-topped' *sensu* Posamentier and Morris, 2000). These are some of the first field-based results that verify the predictions of Muto and others (e.g. Muto and Steel, 2004) and also illustrate that avulsion plays a key role in depositional mechanics during RSL fall.

Moreover, these results have important implications for sequence stratigraphic models. Consider that sequence-bounding unconformities created during RSL fall may not always be an erosive/bypass surface. Rather, deltaic lobe formation during RSL fall on the Goose River, suggests that sediment is burying the unconformity as it forms ('cut and cover' model of Holbrook and Bhattacharya, 2012). Though, it is admittedly not clear how much of this deposition during RSL fall will be preserved in the geologic record. Our results also suggest avulsion is an important process in emplacing falling-stage strata. Given this, the stratigraphic architecture of falling-stage deposits depends on the rate of RSL fall, since the number of terraced deltaic lobes scales with RSL fall rate (Fig. 2D). This result has implications for reservoir properties, such as sand-body connectivity, which may decrease at higher rates of RSL fall due to the presence of more terraced deltaic lobes.

CONCLUSIONS

The response of fluvio-deltaic systems to relative sea level (RSL) fall has received considerable attention in the past, but new views, suggesting sediment deposition is common (e.g. Muto and Steel, 2004, Swenson and Muto, 2007; Holbrook and Bhattacharya, 2012), are emerging that require field and model verification. Herein, using observations of the Goose River delta and Delft3D simulations, we have shown that fluvial avulsions can occur during RSL fall. Optically-stimulated luminescence ages show that during RSL fall the Goose River delta has avulsed on multiple times creating three delta lobes terraced at different elevations. Numerical modeling with Delft3D shows that, similar to the Goose River delta, fluvio-deltaic systems can produce avulsions and multiple terraced delta lobes during RSL fall. Avulsions persist because the fluvial response time is slower than the duration of RSL fall, and rivers can remain aggradational, causing superelevation and avulsions to occur during RSL fall. Moreover, our modeling results suggest that the number and size of deltaic lobes scales with RSL fall, suggesting that the sedimentary architecture of falling-stage deposits changes with the rate of RSL fall.

ACKNOWLEDGEMENTS

The authors would like to thank A. Burpee, J. Royce, and A. McGuffin for field assistance. This research was funded by NSF grants OCE-1061380 and EAR-1123847 awarded to DAE, OCE-1061495 awarded to RLS, the Threet chair funds to JLB, and a Geological Society of America student research grant to AGN. R. Somerville of the University of St Andrews is thanked for his assistance with OSL samples.

[1]GSA Data Repository item 2014xxx, containing additional information on methods, is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

REFERENCES CITED

Blake Jr, W., 1955, Note on the dating of terraces in the Lake Melville District, Labrador. *Science*, v. *121* no. 3134, p 112.

Blake Jr, W., 1956, Landforms and topography of the Lake Melville area, Labrador, Newfoundland. Geography Bulletin, Department of Mines and Technical Survey, Ottawa, Canada, Volume 9, p 93-97.

Catuneanu, O., 2006, Principles of sequence stratigraphy, Elsevier.

Clark, P. U., & Fitzhugh, W. W., 1991, Postglacial relative sea level history of the Labrador coast and interpretation of the archaeological record, *in* Johnson, L.L.., ed., Paleoshorelines and prehistory: An investigation of method: Boca Raton, FL, CRC Press, 189-213 p.

Coachman, L. K., 1953, River flow and winter hydrographic structure of the Hamilton Inlet-Lake Melville Estuary of Labrador. Blue Dolphin Labrador Expedition – Winter Project 1953, 19 p.

Fitzhugh, W., 1973, Environmental Approaches to the Prehistory of the North: Washington, D.C., J. Wash. Acad. Sci, Volume 63, no. 2, 40 p.

Hajek, E.A., and Edmonds, D.A., 2014, Is river avulsion style controlled by floodplain morphodynamics?: Geology, p. G35045. 35041.

Hajek, E. A., and Wolinsky, M. A., 2012, Simplified process modeling of river avulsion and alluvial architecture: Connecting models and field data: Sedimentary Geology, v. 257, p. 1-30.

Helland-Hansen, W., and Hampson, G., 2009, Trajectory analysis: concepts and applications: Basin Research, v. 21, no. 5, p. 454-483.

Henton, J. A., Craymer, M. R., Dragert, H., Mazzotti, S., Ferland, R., & Forbes, D. L., 2006, Crustal motion and deformation monitoring of the Canadian landmass. Geomatica, v. 60, no. 2, p 173-191.

Holbrook, J. M. and J. P. Bhattacharya 2012, Reappraisal of the sequence boundary in time and space: Case and considerations for an SU (subaerial unconformity) that is not a sediment bypass surface, a time barrier, or an unconformity. Earth-Science Reviews **113**(3): 271-302.

Li, Y. and J. P. Bhattacharya, 2013, Facies-Architecture Study of a Stepped, Forced Regressvie Compound Incised Valley in the Ferron Notom Delta, Southern Central Utah, USA, Journal of Sedimentary Research, **83**(3): 206-225.

Liverman, D.G.E. 1997, Quaternary Geology of the Goose Bay Area, Geological Survey Report 97-1. Newfoundland Department of Mines and Energy, St. John's, pp. 173-182

Murray, A. S., & Wintle, A. G., 2000, Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements, v. 32, no. 1, p 57-73.

Muto, T., and Steel, R. J., 2002, In Defense of Shelf-Edge Delta Development during Falling and Lowstand of Relative Sea Level: The Journal of Geology, v. 110, no. 4, p. 421-436.

Muto T., and Steel, R.J., 2004, Autogenic response of fluvial deltas to steady sea-level fall: Implications from flume-tank experiments: Geology, v. 32, no. 5, p. 401-404.

Muto, T., and Swenson, J. B., 2005, Large-scale fluvial grade as a nonequilibrium state in linked depositional systems: Theory and experiment: Journal of Geophysical Research: Earth Surface (2003–2012), v. 110, no. F3.

Muto, T., and Swenson, J. B., 2006, Autogenic attainment of large-scale alluvial grade with steady sea-level fall: An analog tank-flume experiment: Geology, v. 34, no. 3, p. 161-164.

Posamentier, H. W., and Morris, W. R., 2000, Aspects of the stratal architecture of forced regressive deposits: Geological Society, London, Special Publications, v. 172, no. 1, p. 19-46.

Romans, B. W., and Graham, S. A., 2013, A deep-time perspective of land-ocean linkages in the sedimentary record: Annual review of marine science, v. 5, p. 69-94.

Slingerland, R. and N. D. Smith, 2004, River avulsions and their deposits, Annual Review of Earth and Planetary Sciences **32**: 257-285.

Swenson, J. B., & Muto, T., 2007, Response of coastal plain rivers to falling relative sea-level: allogenic controls on the aggradational phase. Sedimentology, v. 54, no. 1, p 207-221.

Syvitski, J. P., & Lee, H. J., 1997, Postglacial sequence stratigraphy of Lake Melville, Labrador. Marine Geology, v. 143, no. 1, p 55-79.

Vail, P. R., 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level, *in* Seismic stratigraphy - applications to hydrocarbon exploration. Mem. Amer. Assoc. Petrol. Geol., v. 26, p 83-97.

Van Heijst, M. W., & Postma, G., 2001, Fluvial response to sea-level changes: a quantitative analogue, experimental approach. Basin Research, v. 13, no. 3, 269-292.

Table 1: Data used for τ/T calculations from Delft3D experiments and Goose River system. q_s for Goose River is calculated from average sedimentation rates for lobes B and C derived from

OSL dated horizons. 3 mm yr^{-1} is considered to be a reasonable RSL fall rate for the Goose River for the last 5 ka. Delft3D results consist of average conditions during the model run.

Figure 1. Google Earth image of the lower Goose River (53°21'48.32"N, 60°23'1.85"W, DigitalGlobe, June 14, 2012). Delta lobes A, B, C, and D are marked by black outline in the large image. Delta lobes were defined by their distributary-channel networks and overbank deposits. Inset plot shows spatially averaged elevation and ages of the four delta lobes (A-D). Boxplots show SRTM elevation distributions, where solid horizontal lines and cross-hairs are the median elevations and outliers for each lobe. The OSL age is listed below each boxplot. OSL sample locations are marked on lobes B and C. Inset map shows the Goose River relative to Lake Melville.

Figure 2. Serial maps of Delft3D simulation with a RSL fall of 3 mm yr^{-1} showing initial condition (A) and two subsequent delta lobe avulsions (B, C). Elevations seaward of the delta shoreline are clipped. Thick black lines indicate the position of the delta shoreline at the previous time step. White boxes in A and B show the locations for measurements in Fig. 3A and B, respectively. (D) Results of all Delft3D simulations show that as the rate of RSL fall increase, avulsion period decreases, while number of avulsions (listed above each point) increase and then decrease. Note that a RSL fall ≥3 mm yr^{-1} is required to produce delta lobe avulsions.

Figure 3. (A) Spatially averaged channel bed elevations (η) at delta head remain roughly constant for RSL fall rates below 10 mm yr^{-1} and become incisional at higher rates of RSL fall. See Fig. 2A for location of spatial averaging. (B) In the time period prior to the lobe avulsion in Fig. 2C, the normalized superelevation of the channel, defined as height from water surface to

RSL relative to channel depth, increases to ~0.4 before the avulsion occurs. The superelevation occurs because RSL decreases faster than the water or bed surface. See Fig. 2B for location of spatial averaging.

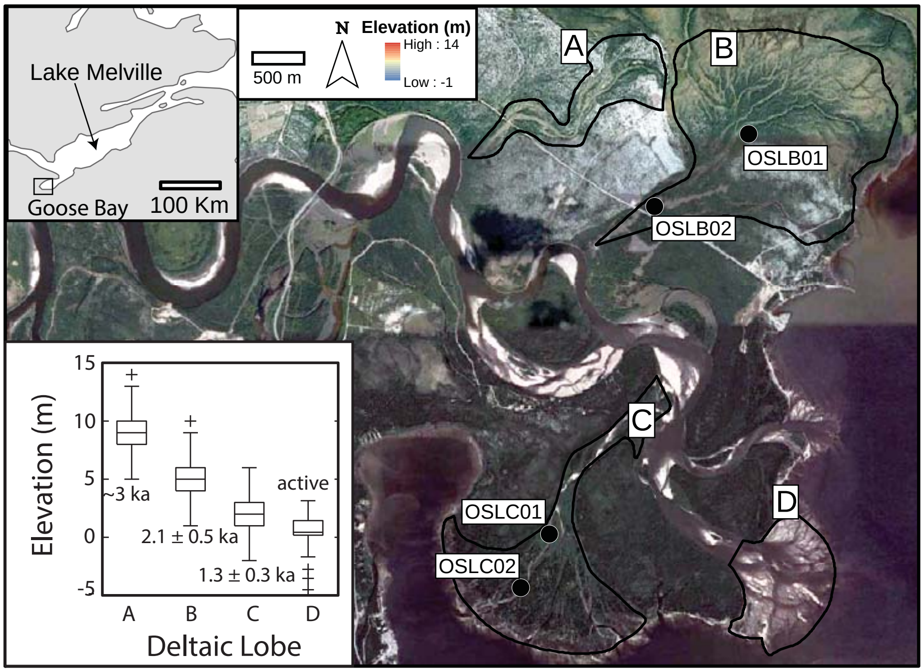

Figure 1. Google Earth image of the lower Goose River (53°21'48.32"N, 60°23'1.85"W, DigitalGlobe, June 14, 2012). Delta lobes A, B, C, and D are marked by black outline in the large image. Delta lobes were defined by their distributary-channel networks and overbank deposits. Inset plot shows spatially averaged elevation and ages of the four delta lobes (A-D). Boxplots show SRTM elevation distributions, where solid horizontal lines and cross-hairs are the median elevations and outliers for each lobe. The OSL age is listed below each boxplot. OSL sample locations are marked on lobes B and C. Inset map shows the Goose River relative to Lake Melville.

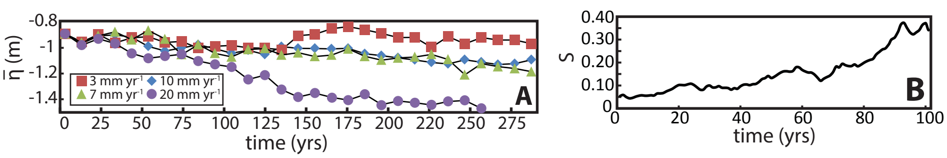

Figure 3. (A) Spatially averaged channel bed elevations (η) at delta head remain roughly constant for RSL fall rates below 10 mm yr-1 and become incisional at higher rates of RSL fall. See Fig. 2A for location of spatial averaging. (B) In the time period prior to the lobe avulsion in Fig. 2C, the normalized superelevation of the channel (S), defined as height from water surface to RSL relative to channel depth, increases to ~0.4 before the avulsion occurs. The superelevation occurs because RSL decreases faster than the water or bed surface. See Fig. 2B for location of spatial averaging.

RSL fall (mm yr^{-1})	Number of avulsions	q_s (m^2 s^{-1})	Slope	T (yrs)	τ (yrs)	τ/T
DELFT3D RUNS						
0	0	3.10E-06	2.11E-04	-	-	-
1	0	2.10E-06	2.16E-04	298.0	14260.3	47.9
2	0	2.06E-06	2.80E-04	298.0	4544.3	15.2
3	3	6.64E-06	3.06E-04	100.0	7130.7	71.3
4	4	1.03E-05	6.19E-04	74.8	12616.5	168.8
5	5	1.08E-05	9.07E-04	60.2	12363.6	205.4
6	6	1.61E-05	3.38E-04	49.7	4759.5	95.8
7	8	1.52E-05	7.89E-04	37.8	7707.6	204.2
8	7	1.74E-05	6.97E-04	43.0	5969.2	138.8
9	8	2.02E-05	1.20E-03	37.4	9461.7	253.2
10	9	2.75E-05	1.67E-03	33.4	14451.0	432.1
16	2	5.25E-06	1.40E-04	145.0	90.6	0.6
20	1	6.06E-06	1.70E-04	185.0	81.2	0.4
GOOSE RIVER (averages of lobes B and C)						
3.00	3	2.27E-07	2.30E-03	1000.0	1833.6	1.8

Table 1: Data used for τ/T calculations from Delft3D experiments and Goose River system. qs for Goose River is calculated from average sedimentation rates for lobes B and C derived from OSL dated horizons. 3 mm yr-1 is considered to be a reasonable RSL fall rate for the Goose River for the last 5 ka. Delft3D results consist of average conditions during the model run.

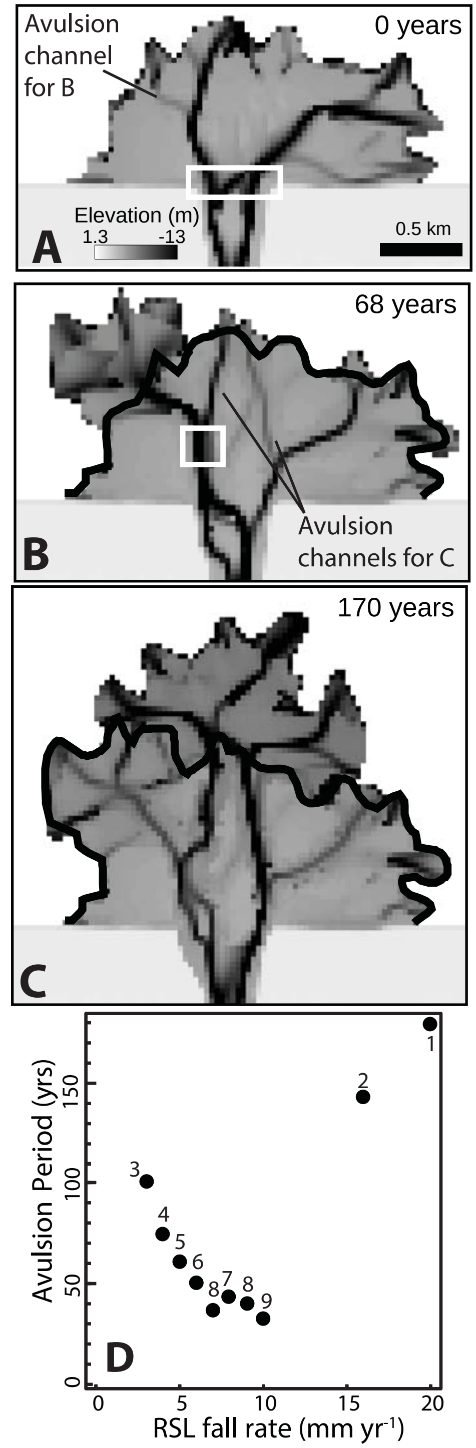

Figure 2. Serial maps of Delft3D simulation with a RSL fall of 3 mm yr-1 showing initial condition (A) and two subsequent delta lobe avulsions (B, C). Elevations seaward of the delta shoreline are clipped. Thick black lines indicate the position of the delta shoreline at the previous time step. White boxes in A and B show the locations for measurements in Fig. 3A and B, respectively. (D) Results of all Delft3D simulations show that as the rate of RSL fall increase, avulsion period decreases, while number of avulsions (listed above each point) increase and then decrease. Note that a RSL fall ≥3 mm yr-1 is required to produce delta lobe avulsions.