Fluvio-deltaic avulsions during relative sea-level fall

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ABSTRACT

Understanding river response to changes in relative sea level (RSL) is essential for predicting fluvial stratigraphy and source-to-sink dynamics. Recent theoretical work has suggested that rivers can remain aggradational during RSL fall, but field data are needed to verify this response and investigate sediment deposition processes. We show with field work and modeling that fluvio-deltaic systems can remain aggradational or at grade during RSL fall, leading to superelevation and continuation of delta lobe avulsions. The field site is the Goose River, Newfoundland-Labrador, Canada, which has experienced steady RSL fall of around 3–4 mm yr⁻¹ in the past 5 k.y. from post-glacial isostatic rebound. Elevation analysis and optically stimulated luminescence dating suggest that the Goose River avulsed and deposited three delta lobes during RSL fall. Simulation results from Delft3D software show that if the characteristic fluvial response time is longer than the duration of RSL fall, then fluvial systems remain aggradational or at grade, and continue to avulse during RSL fall due to superelevation. Intriguingly, we find that avulsions become more frequent at faster rates of RSL fall, provided the system response time remains longer than the duration of RSL fall. This work suggests that RSL fall rate may influence the architecture of falling-stage or forced regression deposits by controlling the number of deposited delta lobes.

INTRODUCTION

Predicting how rivers erode or deposit sediment in response to changes in relative sea level (RSL) is critical for understanding sequence stratigraphy (Catuneanu, 2006) and source-to-sink dynamics (Romans and Graham, 2013). Despite this importance, during RSL fall, it is not clear what controls whether rivers incise and bypass sediment to the deep ocean (e.g., Vail et al., 1977), or deposit sediment on the coastal plain, reducing sediment flux to the deep ocean (e.g., Holbrook and Bhattacharya, 2012). While the “incision and bypass” model has received considerable attention, there is stratigraphic (e.g., Posamentier and Morris, 2000) and theoretical evidence (e.g., Muto and Steel, 2014) that deposition during RSL fall is common. 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; Zhu et al., 2012). Experimental work shows that a coastal river with constant sediment supply and RSL fall rate experiences an autogenic cycle of deltaic lobe deposition, incision through the lobe, and subsequent lobe abandonment (van Heijst and Postma, 2001; Muto and Steel, 2002, 2004; Swenson and Muto, 2007). This autogenic cycle has only been inferred from Quaternary stratigraphic deposits (e.g., Sydow and Roberts, 1994; Anderson et al., 2004).

The conditions that produce sediment bypass or nearshore deposition during RSL fall are not clear. Moreover, when deposition during RSL fall does occur, it is not clear what processes emplace sediment. Toward this end, we combine elevation analysis and optically stimulated luminescence (OSL) data from the modern Goose River, Newfoundland-Labrador, Canada, with morphodynamic modeling. Our results show that as RSL falls, Goose River avulsions create multiple delta lobes at progressively lower elevations. Delft3D models (oss.deltares.nl/web/delft3d) simulating RSL fall help explain causes of 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 freshwater surface layer overlaying saline bottom waters. The tidal amplitude within Goose Bay is ~0.4 m. The Goose River has a drainage area of 3450 km², and its lower reaches have average widths of 100–200 m and depths of 2–3 m. Water discharge ranges from 5 m³ s⁻¹ during winter to 500 m³ 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 ca. 8 ka (Syvitski and Lee, 1997). Modeling suggests that the initial RSL fall rate was ~50 mm yr⁻¹ (Clark and Fitzhugh, 1991) and slowed to a steady rate between 3 and 10 mm yr⁻¹ over the past 5 k.y. (Fitzhugh, 1973; Clark and Fitzhugh, 1991). These rates are 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. 1, lobe D), and upstream there are at least three moribund delta lobes (Fig. 1, lobes A–C), as recognized by their lobate planform shape and visible distributary channel networks. The median grain size, determined from sieved samples from a suite of cores taken across each lobe, lies between 330 μm 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 lobes B and C (Fig. 1). We compared the accuracy of the SRTM data with survey points from a fully corrected (OPUS solution) Leica 1230 differential GPS and found good agreement with a root mean square error of <1 m. The sediment cores for OSL dating (Fig. 1) came from overbank locations between distributary channels to minimize contamination from recent flood-derived sediments. Within each of the sediment cores, two samples were collected at different stratigraphic elevations to constrain lobe activity and aggradation rate (Fig. DR1 in the GSA Data Repository¹). The single-aliquot regenerative...
aggradation rates of \~4 and \~3 mm yr\(^{-1}\) from lobe B to lobe C between 1 and 2 ka. Dur-
ages suggest that the Goose River delta avulsed
lower elevations (Fig. 1, inset plot). OSL
fall to create at least three delta lobes at progres-
show that the Goose River avulsed during RSL
minimum age model for lobe C samples (see the
Data Repository for more information).

OSL sample locations are marked on lobes B and C. Inset
map shows Goose River relative to Lake Melville.

Our OSL results and topographic analysis
show that the Goose River avulsed during RSL
fall to create at least three delta lobes at progressively
lower elevations (Fig. 1, inset plot). OSL
ages suggest that the Goose River delta avulsed
from lobe B to lobe C between 1 and 2 ka. Dur-
ing deposition, lobes B and C possessed vertical
aggradation rates of \~4 and \~3 mm yr\(^{-1}\), respec-
tively. Although we did not collect OSL samples
for lobe A, we can estimate its age using the sur-
face elevation and the local sea-level curve, as-
suming minimal post-deposition erosion, which
suggest that it dates to ca. 3 ka.

**NUMERICAL MODELING SETUP AND RESULTS**

We conducted a series of modeling experi-
ments of delta growth using Delft3D to under-
stand the behavior of the Goose River under
RSL fall. Our model setup uses boundary and
initial conditions 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 dis-
charge of 300 m\(^3\) s\(^{-1}\) and carries an equilibrium
concentration of 350-\(\mu\)m-diameter quartz sedi-
ment. We specify linear RSL fall rates along the
seaward boundary that vary from 0 to 10 mm yr\(^{-1}\)
consistent with temporal variability at Goose
Bay over the past 5 k.y.) in 1 mm yr\(^{-1}\) increments, and we also simulate rates of 16 and 20 mm yr\(^{-1}\)
to explore a larger parameter space; this results in
13 runs total (Table 1). Before RSL fall begins, a
delta progrades basinward until the average top-
set slope reaches dynamic equilibrium. We used
this delta topography as the starting point for each
RSL fall scenario (see the Data Repository for
more information on model setup).

For analysis, we record the period of avul-
sions that create new delta lobes. Avulsion pe-
riod is defined as the duration from delta lobe
initiation until water and sediment transport
in the delta lobe diminishes to zero and a new
delta lobe is created. 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 Ed-
monds et al., 2009).

For RSL fall greater than 2 mm yr\(^{-1}\) there is
fluvio-deltaic deposition on the coastal plain that
is punctuated by fluvial avulsion (Table 1 and
Fig. 2). The presence of avulsions in our simula-
tions for this range of RSL fall rates is consistent
with observations on the Goose River. We find
that avulsion period decreases with increasing
RSL fall rate until a minima is reached, after
which period increases rapidly (Fig. 2D).

**DISCUSSION OF FIELD DATA AND MODELING**

Our field observations and numerical mod-
eling results show that rivers can avulse and
deposit multiple delta lobes on the coastal
plain during RSL fall. This result is significant

![Figure 1](image-url)

**Figure 1.** Google Earth image of Goose River, Labrador, Canada (53°21′48.32″N, 60°23′1.85″W, June 2013). Delta lobes A, B, C, and D are marked by black outline. 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 Shuttle Radar Topography Mission (SRTM) elevation distributions, where solid horizontal lines are median el-

| Table 1: Data Used for \(t/T\) Calculations from Delft3D Simulations and from the Goose River System, Newfoundland-Labrador, Canada |

<table>
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<tr>
<th>RSL fall (mm yr(^{-1}))</th>
<th>Number of avulsions</th>
<th>(q_s) (m(^3) s(^{-1}))</th>
<th>Slope</th>
<th>(T) (yr)</th>
<th>(t) (yr)</th>
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</table>

| Goose River (averages of lobes B and C) | 3 | 3 | 2.27E-07 | 2.30E-03 | 1000 | 1833.6 | 1.8 |

**Note:** RSL—relative sea level; \(q_s\)—temporally averaged sediment supply per unit width of the active delta lobe; \(T\)—duration of RSL fall; \(t\)—fluvial response time. \(q_s\) for Goose River is calculated from average sedimentation rates for lobes B and C (see Fig. 1) derived from opti-
cally stimulated luminescence–dated horizons. We consider 3 mm yr\(^{-1}\) a reasonable RSL fall rate for the Goose River for the past 5 k.y. Delft3D (oss.deltares.nl/web/delft3d) results consist of average conditions during the model run.
because earlier work suggested that RSL fall should suppress avulsions when fast channel incision counteracts the superelevation that commonly precedes avulsions (Slingerland and Smith, 2004).

We reason that avulsion can persist during RSL fall provided the channel becomes superelevated, and this can occur if RSL fall does not cause sufficient channel incision. This idea was quantified by Muto and co-workers (Muto and Steel, 2002, 2004; Muto and Swenson, 2006; Swenson and Muto, 2007) who showed that a fluvio-deltaic system will not incise when RSL falls if the fluvial response time, $\tau$, is longer than the duration of RSL fall, $T$ (i.e., $\tau > T$). Similarly, we define the fluvial response time as

$$\tau = \frac{q}{r} S,$$

where $q_r$ is the temporally and spatially averaged sediment supply per unit width of the active delta lobe ($m^2 s^{-1}$), $S$ is the spatially and temporally averaged water surface slope, and $r$ is the rate of RSL fall ($m s^{-1}$). We take $T$ to be the avulsion period, because this time sets the duration that 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 rates of $1–10$ mm yr$^{-1}$ possess $\tau/T > 1$ (Table 1), suggesting that the modeled systems have not incised in response to RSL fall. This is further supported by modeled channel bed elevations that show that the elevation at the delta head shows minimal incision, indicating sustained alluvial grade (Fig. 3A). Avulsions continue because RSL fall superelevates the fluvial system. For example, prior to the avulsion in Figure 2C the channel is not incised (Fig. 3A). Sea-level elevation decreases faster than the water surface elevation in the channel at the avulsion location, leading to a normalized superelevation of $\sim 0.4$ before avulsion (Fig. 3B), which is a reasonable value to precede avulsion (Hajek and Wolinsky, 2012). New delta lobes are thus created as overbank flow accelerates down steeper pathways and forms incisional avulsion channels (e.g., Hajek and Edmonds, 2014). Thus, for systems with $\tau/T > 1$ the avulsion period decreases with faster RSL fall rates because channels superelevate more rapidly (Fig. 2D).

At faster 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 erores through the initial delta lobe (Fig. 3A), entrancing the active channel and suppressing future avulsions. The few avulsions that do occur at these higher rates of RSL fall arise from upstream-migrating knickpoints that capture the river. The fluvial system continues to deposit sediment and prograde as it tracks the rapidly retreating shoreline, but few terraces are generated 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 $\tau/T > 1$ then falling-stage or forced regression deposits are characterized by a series of terraced, downstepping deltaic lobes, whereas if $\tau/T \leq 1$ then 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-scale results from modern systems that verify the theories of Muto and others, and they also illustrate that avulsion plays a key role in depositional mechanics during RSL fall, something that previously has only been inferred (e.g., Sydow and Roberts, 1994).

These results have important implications for sequence stratigraphic models. Our results demonstrate that sequence-bounding unconformities created during RSL fall may not always be an erosive and/or bypass surface, and that delta lobe formation during RSL fall on the Goose River suggests that sediment is burying the unconformity as it forms (i.e., the “cut and cover” model of Holbrook and Bhattacharya [2012]), though it is unclear how much of this deposition occurring during RSL fall will be preserved in the geologic record. Our results also suggest that 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, because the number of deltaic lobes scales with RSL fall rate (Fig. 2D). This result suggests...
that hydrocarbon reservoirs may be more compartmentalized at higher rates of RSL fall due to the presence of more terraced deltaic lobes. Additionally, this finding may also allow a re-examination of fluviodeltaic stratigraphy in terms quantifiable $t/T$ ratios and thus RSL fall predictions in the ancient sedimentary record.

CONCLUSIONS

The response of fluviodeltaic systems to RSL fall has received considerable attention in the past, but new views, suggesting that sediment is deposited during RSL fall, 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. OSL ages show that during RSL fall, the Goose River delta has avulsed, creating three delta lobes terraced at different elevations. Numerical modeling with Delft3D shows that, similar to the Goose River delta, fluviodeltaic systems can produce avulsions and multiple terraced delta lobes during RSL fall. Avulsions persist because the fluvial response time is shorter than the duration of RSL fall, and rivers can remain aggradational, causing supererevation and avulsions to occur during RSL fall. Moreover, our modeling results suggest that the number of deltaic lobes deposited during regression scales with RSL fall rate, suggesting that the sedimentary architecture of falling-stage deposits changes with the rate of RSL fall.

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