Grain-Size Controls on Planform Morphology and Stratigraphy of River-Dominated Deltas*

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Abstract

The proportions of sand and mud that make up a river-dominated delta strongly determine its topset morphology, which in turn controls its internal facies and clinoform stratigraphy. Here we show how these relationships allow one to predict the stratigraphy of a delta from the character of its topset or reconstruct its planform from measures of clinoform geometry. We used Delft3-D to simulate nine self-formed deltas having different sediment loads and critical shear stresses required for re-entrainment of mud. The deltas prograded into a shallow basin absent of waves, tides, Coriolis forcing, and buoyancy. Model results indicate that sand-dominated deltas are more fan-shaped and mud-dominated deltas are more bird-foot in planform because the sand-dominated deltas have more active distributaries and a smaller variance of topset elevations, and thereby experience more equitable distribution of sediment to their perimeters. This results in a larger proportion of channel facies and autogenic parasequences in sand-dominated deltas, and more uniformly-distributed clinoform dip directions, steeper dips, and greater clinoform concavity. These conclusions are consistent with data collected from the Goose River Delta, a coarse-grained fan delta prograding into Goose Bay, Labrador, Canada. These results allow a re-interpretation of the Kf-1 parasequence set of the Cretaceous Last Chance Delta, a unit of the Ferron Sandstone near Emery, UT. Inversion of Ferron grain size data, clinoform dips, clinoform concavity, and variance of dip directions suggests that the Kf-1 Last Chance Delta was more fan-delta than bird-foot, and therefore more consistent with Cotter (1976) and Thompson (1986) than Gardner (1995) and Anderson et al. (2004). It likely possessed numerous distributaries with at least five orders of bifurcation, and would be a high quality reservoir.

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Grain-size controls on planform morphology and stratigraphy of river-dominated deltas

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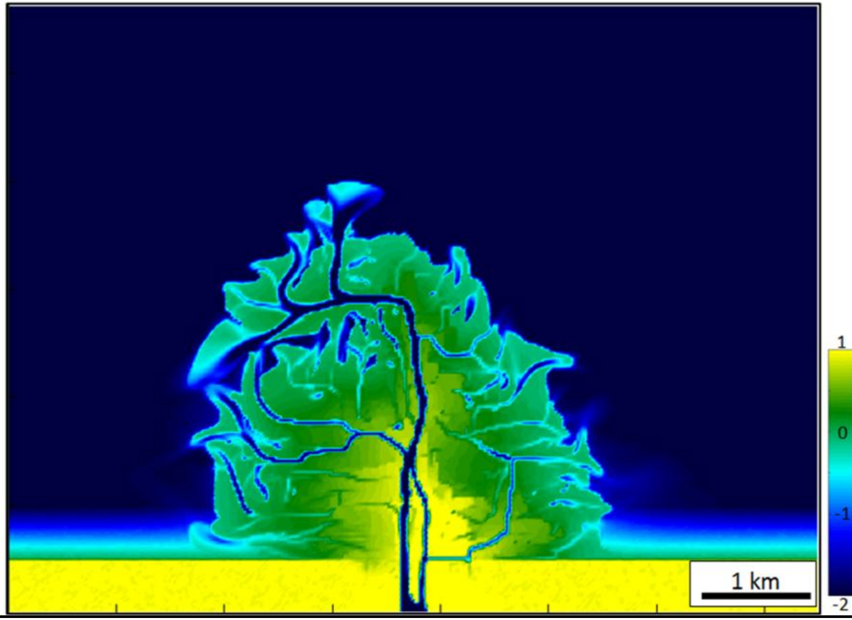
Outline

- Objectives and Approach
- Methods
- Results
- Application
- Conclusions

Objective and Approach

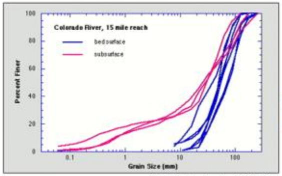


Presenter's notes: An example of this reverse approach is the Cretaceous Last Chance Delta. There we see an outcrop exposure showing very prominent clinoforms of the ancient delta. These are depositional features, and they reflect the growth and progradation of a delta. The Last Chance Delta has been well studied and has excellent exposures; yetl paleo-interpretations vary. Some have interpreted it as a fan delta, while others have interpreted it as a highly rugose bird's-foot delta.

We hope to reinterpret the Last Chance Delta and determine what the planform was and how its topset behaved.

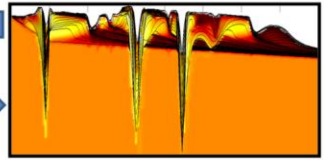
Objective and Approach

Hypothesis: for river-dominated deltas with no waves or tides --



(Pitlick et al., 2001)

(Google Maps)



- Geology of fluvial catchment controls sediment properties:
  - Sand/mud ratio
  - Mud stiffness (cohesion)
- Sediment properties control delta topset:
  - # of distributaries
  - Shoreline rugosity
- Delta topset controls delta stratigraphy:
  - Clinoform geometry
  - # of parasequences
  - Sand bodies

Reservoir prediction depends on depositional models

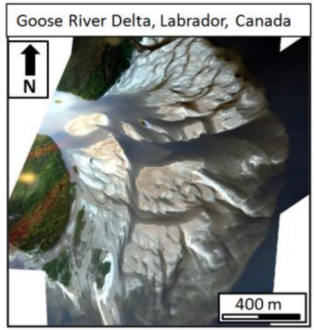
Presenter's notes: Our hypothesis is for river-dominated deltas in the absence of waves and tides: the geology of the fluvial catchment (here we mean sand-to-mud ratio and mud cohesion) sets delta-planform morphology (number of distributaries, bifurcation order, shoreline shapes, and the roughness of the delta topset), and delta topset controls the delta stratigraphy (clinoform geometries, parasequences, sand bodies).
If this is all true then if the stratigraphy of the delta is known, but the planform of the delta is unknown; we must be able to work backwards and predict delta planform.

Objective and Approach

a) Perform numerical experiments in the absence of waves and tides; vary sediment properties

b) Validate the model results using a modern delta

c) Quantify stratigraphy of the Last Chance Delta to hindcast its planform morphology

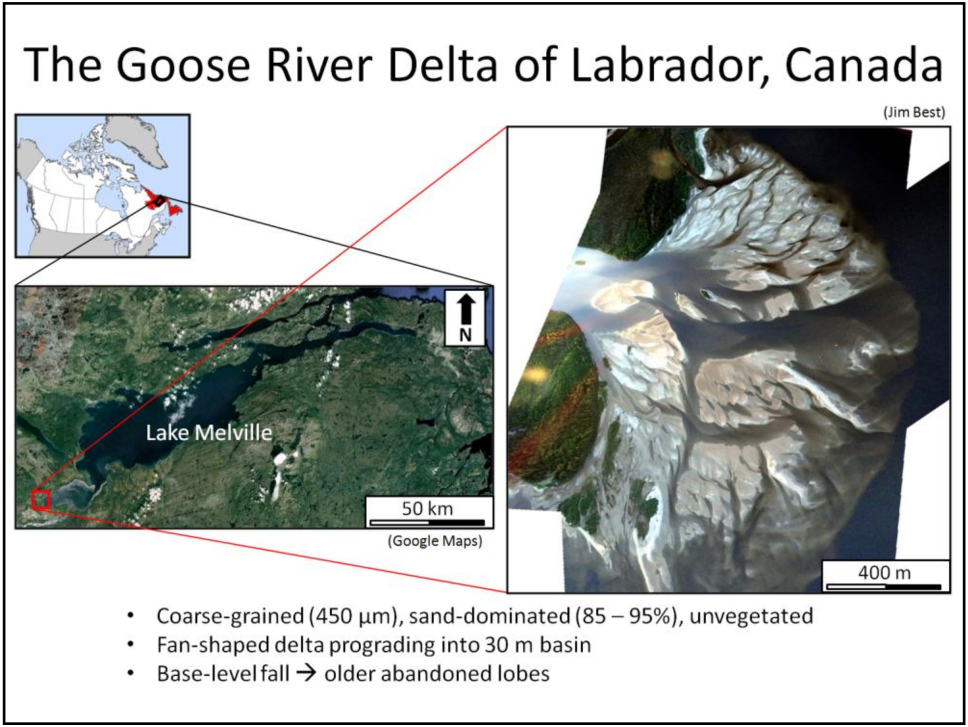


(Jim Best, Doug Edmonds)

Presenter's notes: We use a three step approach whereby we begin with numerical experiments of river-dominated deltas in the absence of waves and tides, and we vary sediment properties to generate a range of delta planforms.

We then try to validate the model results by comparing them to a modern delta, the Goose River Delta, a sand-dominated, unvegetated fan delta.

Finally, we quantify the outcrop stratigraphy of the Last Chance Delta and apply the results of our numerical models to interpret the paleo-morphology.



Presenter's notes: We measured a modern delta, the Goose River Delta of Labrador, northeastern Canada. The Goose River Delta is prograding into Lake Melville which is a fjord loosely connected to the ocean. There is a small tidal amplitude of about 0.5 m and prevailing winds are from the west.

As determined from hand samples collected on the delta topset, the delta is extremely coarse-grained; we estimate the sediment load to be 85-95% sand, based on lack of mud on the topset and lack of mud found in bottom-grab samples in the foreset/bottomset of the delta. This fan-shaped delta is also experiencing relative base-evel fall due to isostatic rebound after glacial retreat. This has stranded older delta lobes, and the Goose River has incised these deposits, meaning that there are outcrops of older delta deposits from a delta that was abandoned 500 years ago. We compare this delta to a low-cohesion, sand-dominated numerical delta.

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Methods

Conduct nine numerical experiments using Delft3D. Vary sand proportion and critical shear stresses required for re-erosion of cohesive sediment (τ_{cr}):

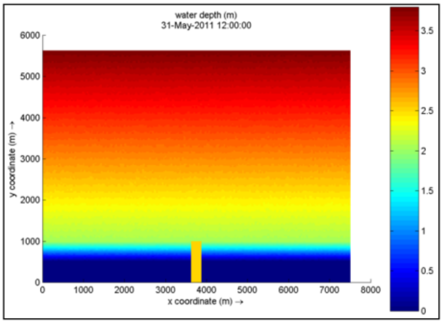
Sand Proportion

- 90% = sand-dominated
- 50% = sand-mixed
- 10% = mud-dominated

$\boldsymbol{\tau_{cr}}$

- 0.25 N m^{-2} = low-cohesion
- 1.75 N m^{-2} = medium-cohesion
- 3.25 N m^{-2} = high-cohesion

Model design:



- Initial bathymetry
- 25 x 25 m cell size
- No waves, tides, Coriolis, salinity
- Constant water temperature
- Q = 1000 m^3 s^{-1}
- Six sediment sizes (300, 150, 80, 32, 13, 7.5 μm)
- Q_s = 0.1 kg m^{-3}
- Morph scale factor = 175
- Open boundaries on top and sides

Presenter's notes: The experimental design is to create nine different deltas constructed by different sand proportions and critical shear stresses required for re-erosion of cohesive sediment. We want to construct sand-dominated deltas with 90% sand, sand-mixed deltas of 50% sand, and mud-dominated deltas of 10% sand.

These three delta types will be subjected to 3 different degrees of cohesion: low, medium, and high.

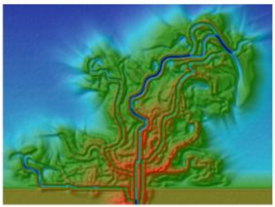
We think that these nine deltas will reflect a range of topset character and stratigraphy.

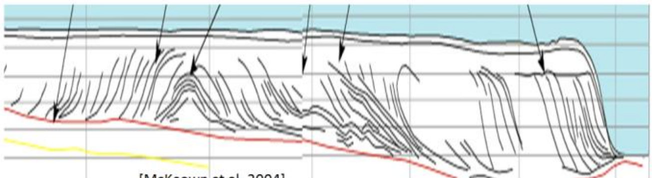
To create our suite of numerical experiments, we use Delft3D, an engineering-grade hydrodynamic and morphodynamic model. In these experiments, we start out with a basin that is approximately 5.5 km by 7.5 km with a n initial bathymetry that slopes from 2 m to 3.5 m. Each cell is 25 m x 25 m. We have a 500-m wide beach and a 250-m wide truck stream. There are three open boundaries with a constant water elevation; and both sediment and water are allowed to pass. Waves, tides, and Coriolis are absent, we have no salinity or temperature variation, but a constant discharge. We have six different sediment fractions being carried by the trunk stream at a constant concentration. Cohesive sediments may only travel in suspension, and non-cohesive sediments may travel as bedload or suspended load. A morphological scale factor is applied to speed-up processes for a more geological time scale.

Methods

Metrics:

– Number of active distributaries [unitless]
  - Participating in morphodynamic change at shoreline
– Clinoform concavity [unitless]
  - 2nd derivative of function fit to clinoform
– Number of parasequences [unitless]
  - Separated by flooding surfaces
– Sand body shapes and connectivity





[McKeown et al. 2004]

Presenter's notes: How are we going to measure the delta topsets? We introduce 3 new metrics.
We start with the number of active distributaries which we define as any distributary that connects the trunk stream and the delta shoreline and maintains 0.5 m depths and water velocities in excess of 0.1 m/s over its entire course.
Shoreline rugosity is defined as the complexity of the geomorphic shoreline and we measure it using the IQ (isoperimetric quotient). A is the area of the delta, and P is the perimeter of the shoreline. A semi-circle has a value of 0.75 and bird-foot deltas have smaller values.
Topset roughness is defined as the standard deviation of topset elevation points along a strike line and it should reflect distributary levee geometry. Topset elevations are defined as any elevation above -0.1 m. This should reflect the nature of distributary levees. Stable levees that aggrade should mean higher topset roughness.

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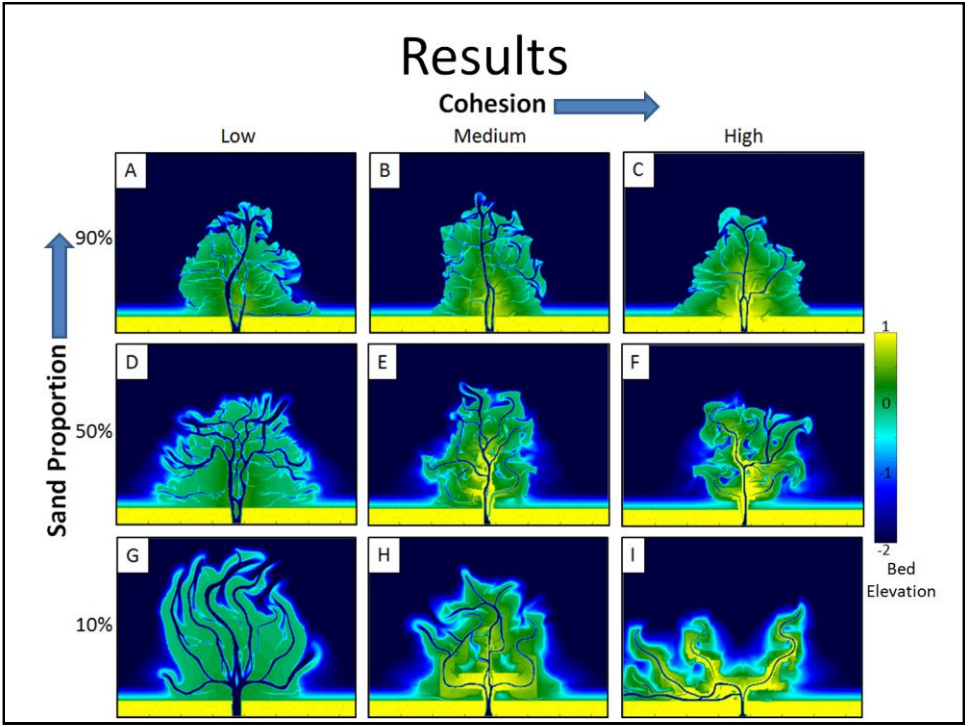
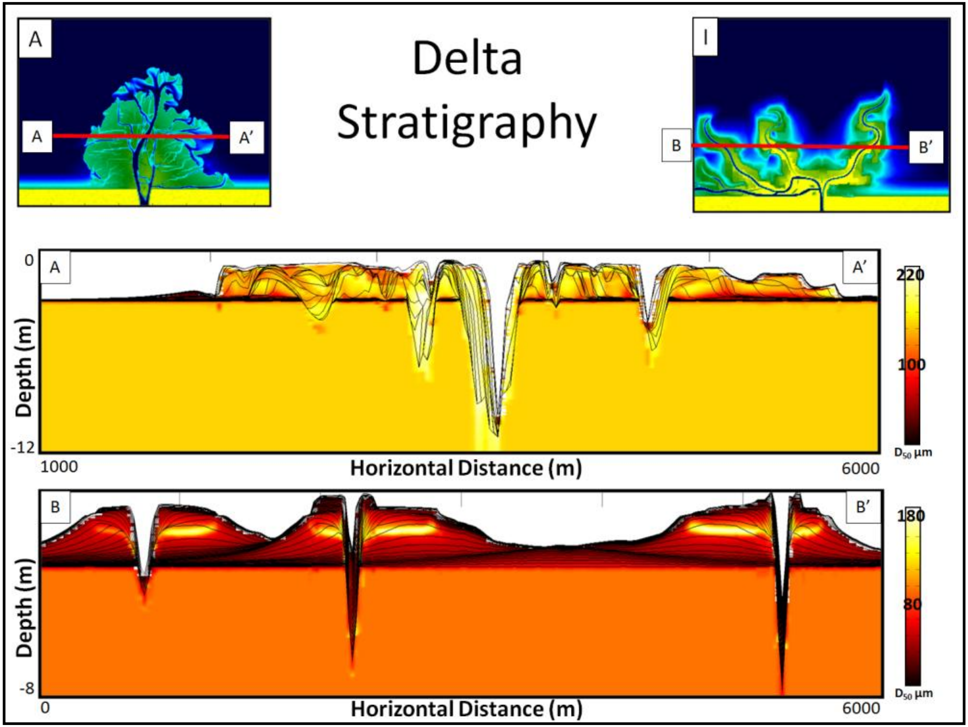
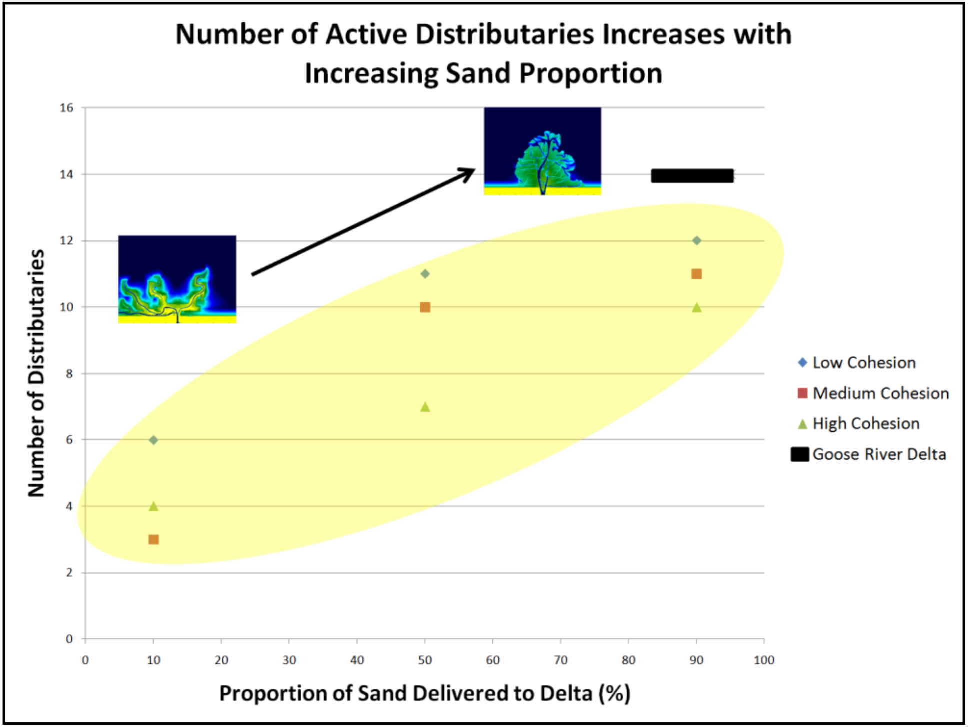


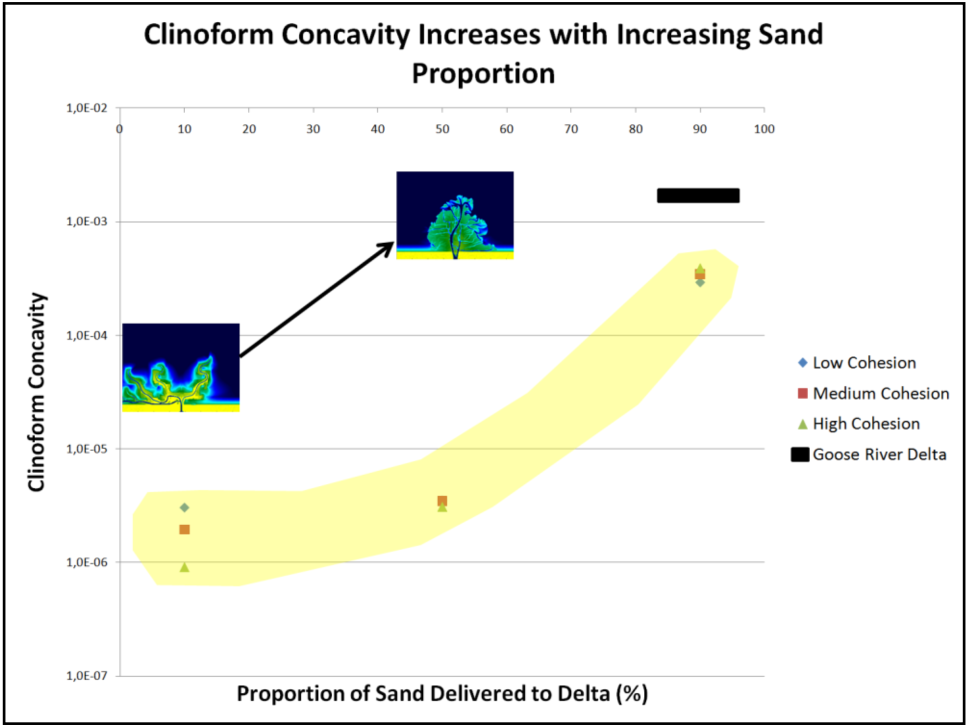
Presenter's notes: The numerical modeling experiments have resulted in nine deltas of varying shoreline and topset character. The y-axis shows the different sand proportions that make up each delta, and the x-axis shows the different degrees of mud cohesion used to construct each delta. Sand-dominated deltas always take a fan shape, and mouth-bar size seems to decrease with increasing cohesion. Mud-dominated deltas become very irregularly and bird-foot shaped, and sand-mixed deltas have attributes of both types. Topset elevations in yellow increase with increasing cohesion.



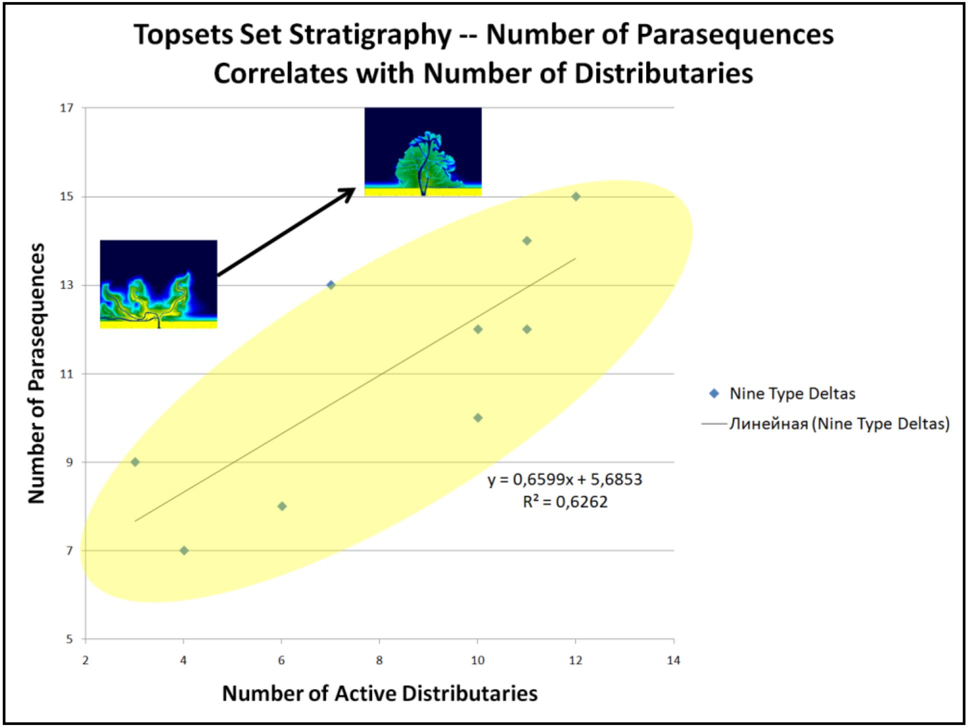
Presenter's notes: These cross-sections (A-A' and B-B') show the stratigraphy of the low-cohesion, sand-dominated delta and the high-cohesion, mud-dominated delta, respectively. Black lines represent chronostratigraphic surfaces which are constructed from equally spaced time slices of bed elevation points. Scale bar indicated D50 grain size. Stratigraphy shows differences.



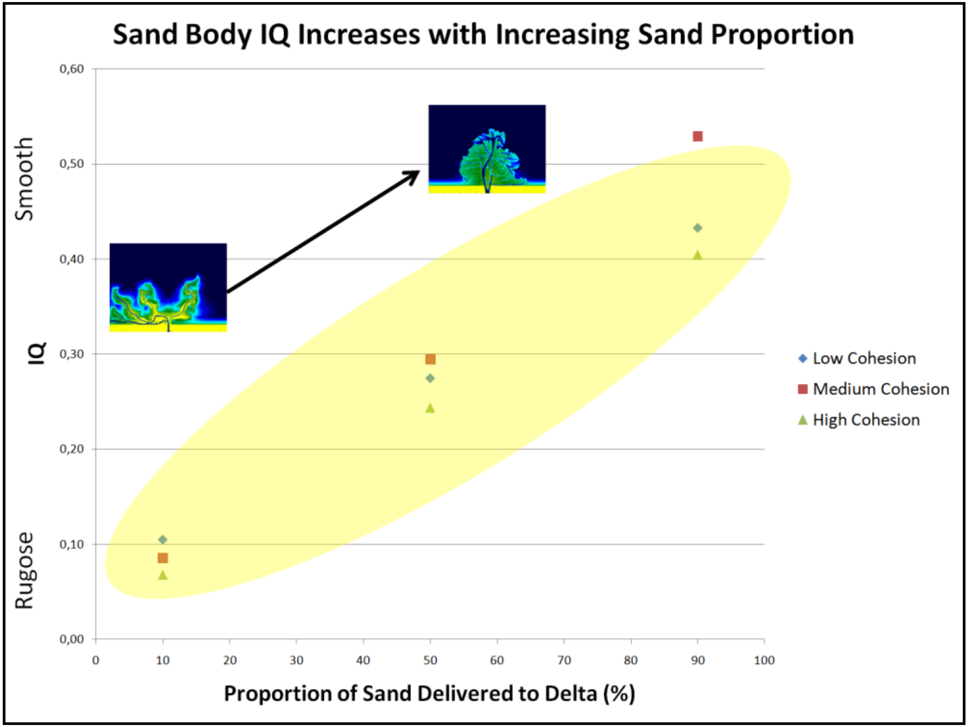
Presenter's notes: The number of active distributaries increases with increasing sand proportion delivered to the delta. Mud-dominated deltas have few distributaries; sand-dominated deltas have many distributaries. The Goose River delta follows this trend. Also, low cohesion promotes additional distributaries, probably associated with bank stability issues at low cohesion. The Goose River Delta is consistent with this trend.



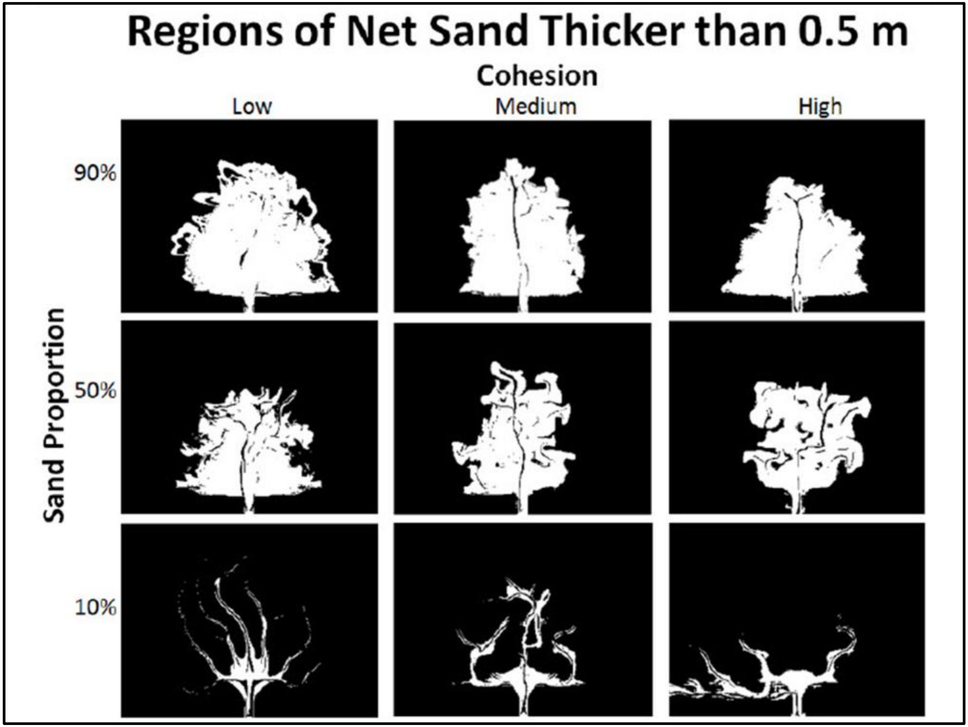
Presenter's notes: Clinoform concavity increases with increasing sand proportion. Mud-dominated deltas have low concavity and sand-dominated deltas have high concavity. Cohesion does not seem to effect concavity. The Goose River Delta plots close to the sand-dominated numerical deltas.



Presenters notes: Topset attributes correlate with stratigraphy, and here the number of parasequences is reasonably correlated with number of distributaries on the delta topset. Mud-dominated deltas have few distributaries and few parasequences; sand-dominated deltas have more distributaries and more parasequences.



Presenter's notes: The rugosity of the sand bodies increases with increasing sand proportion. Mud-dominated deltas have low IQ's and, therefore, very irregular shapes, and sand-dominated fan deltas have high IQ's with uniform shapes. Sand-body rugosity could not be measured in the Goose River Delta.



Regions of Net Sand Thicker than 0.5 m
Cohesion
Low
Medium
High
Sand Proportion
90%
50%
10%

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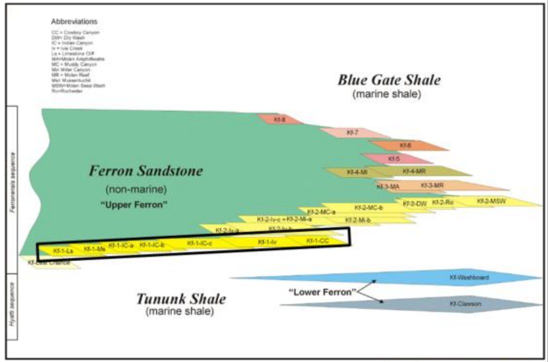
Application

What is the paleomorphology of the Last Chance Delta?

- Turonian (90.3 – 88.6 ma) Upper Ferron Member of Mancos Shale Formation
- Microtidal, river-dominated, 80% sand proportion
- World-class fluvial-deltaic outcrops, studied as reservoir analog

(Bhattacharya and MacEachern, 2009)

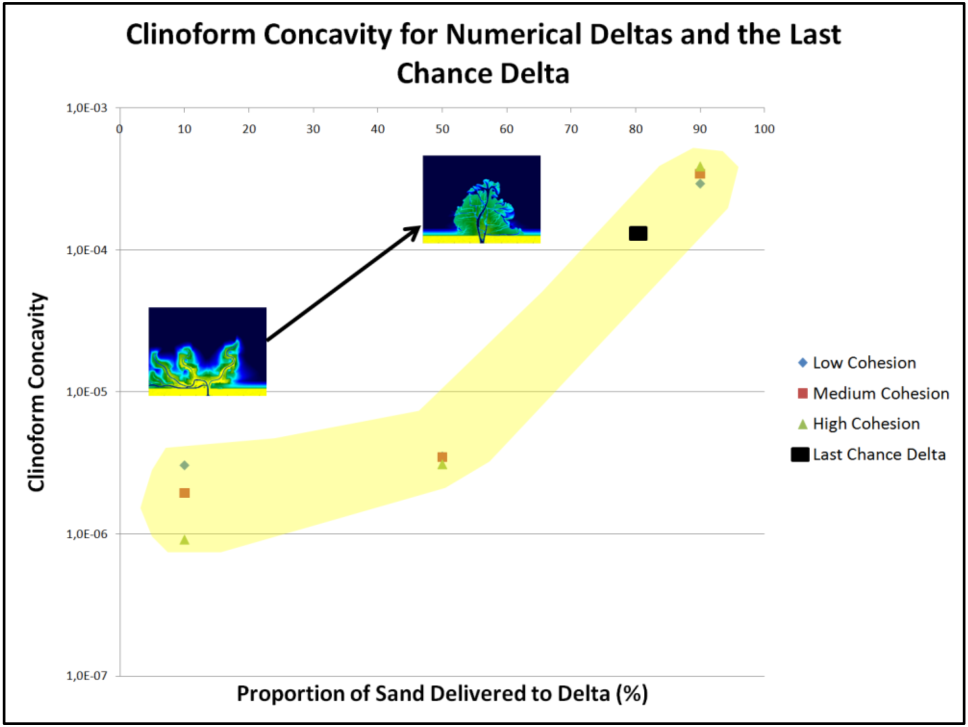


(Anderson et al., 2003)

Presenter's notes: Is the Last Chance Delta a fan delta or is it a bird-foot delta? The Last Chance Delta formed as the Upper Ferron Sandstone of the Mancos Shale Formation, and it prograded into the Western Interior Seaway. Source area was the Sevier Orogenic Highlands to the west. It is estimated that it was characterized by microtidal amplitude, and it was river-dominated (81% sand). The Last Chance Delta is one of the most studied of all fluvial-deltaic environments preserved in outcrop. It is often used as an oil and gas reservoir analog. In four weeks in the field, we encountered four different oil company groups, and that is over a 60 km outcrop belt.

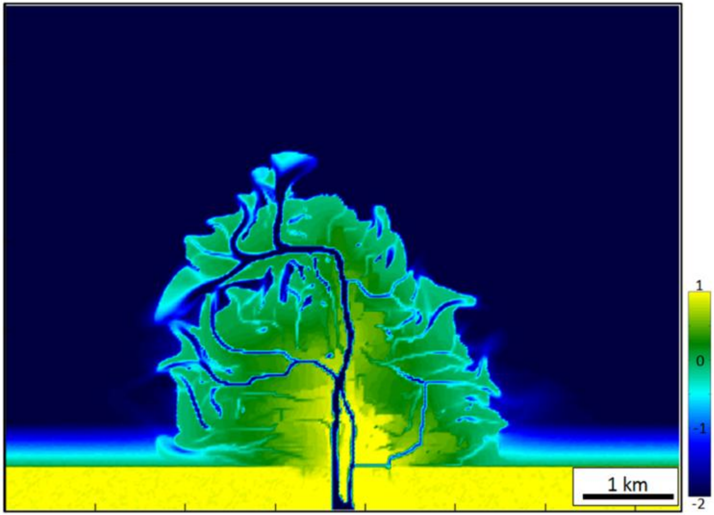
Here a dip cross section of the Upper Ferron shows the parasequence sets of the Last Chance Delta.

For the purposes of this study, we look at the lowermost parasequence set, Kf-1.

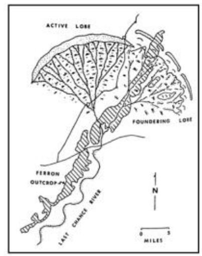


Clinoform Concavity for Numerical Deltas and the Last Chance Delta
Clinoform Concavity
Proportion of Sand Delivered to Delta (%)
1,0E-03
1,0E-04
1,0E-05
1,0E-06
1,0E-07
0
10
20
30
40
50
60
70
80
90
100
Low Cohesion
Medium Cohesion
High Cohesion
Last Chance Delta

Last Chance Delta



(Gardner, 1995)



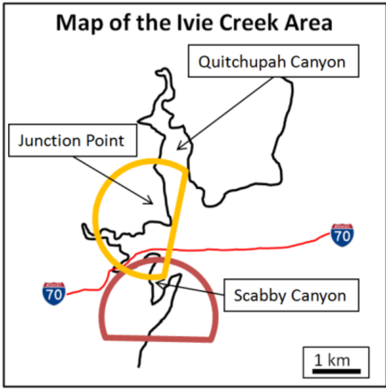
(Cotter, 1976)

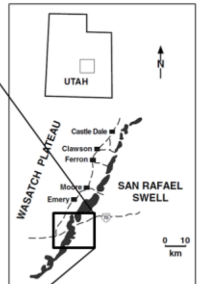
Presenter's notes: We compare the results of our model to what we observe in outcrop, and we see lobes of similar scale and sequence. The model shows an earlier portion prograding generally north and a younger lobe prograding generally west and onlapping the older lobe. We can also estimate that the eastern portion of the delta may have been completely eroded; this is consistent with a lack of finding any true dip azimuths which show eastward progradation.

As previously shown, the clinoform concavity of the Last Chance Delta outcrops and the Last Chance Delta model plot very close to each other and very close to the sand-dominated deltas. Because concavity is a reflection of deposition and is not a function of basin depth, we think that the model is accurately representing foreset growth processes of the Last Chance Delta.

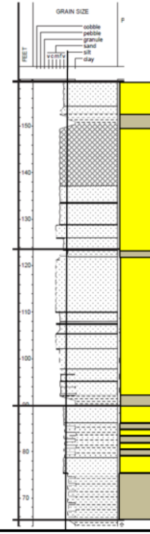
Field Observations

- Utah Geological Survey Open File Report 412 (Anderson et al., 2003)
  - Sand proportion (81%) estimated from six measured sections
  - Channel facies measured from photomosaics (12%)
  - Clinoforms measured with laser rangefinder
    - Dip magnitude (7 degrees), concavity, dip azimuth U^2 (1.1)



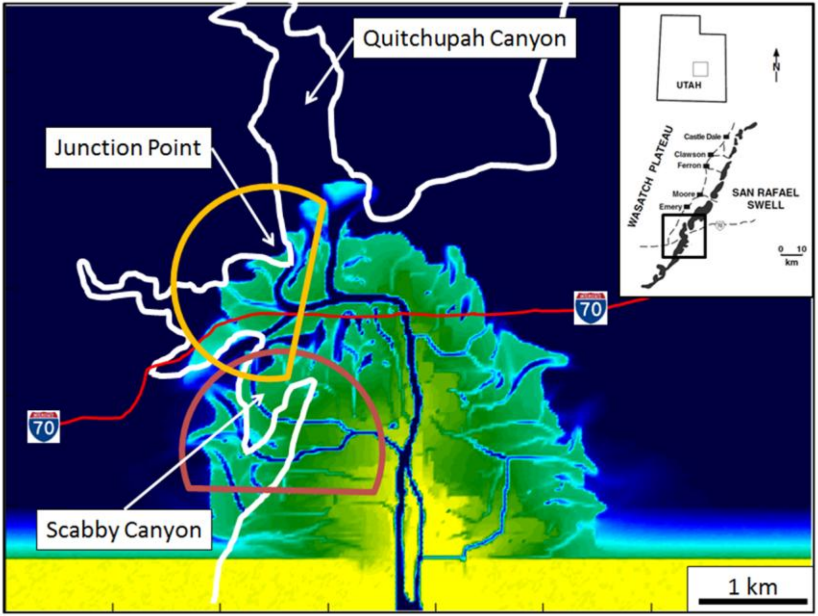


(Zeng et al., 2004)



Presenter's notes: Using data from the Utah Geological Survey Open File Report 412, we were able to estimate sand proportion delivered to the delta by taking the average sand composition of six vertical measured sections (e.g., the one on the right). We used a cutoff at the lower very fine sand and silt boundary to define sand and mud. The delta was likely deposited by an 81% sand sediment load. To measure channel facies, we used a random generator to select 50 of roughly 150 photomosaics of Kf-1 outcrops. The photos were shot by helicopter. Finally, in the field, we measured clinoform dips on photomosaics using a laser rangefinder. The average clinoform dip is 7 degrees. In the lab, we were able to measure clinoform concavity and compute true clinoform dip azimuths from 3D exposures of clinoforms. In the image on the left, a portion of the 60-km long outcrop map is blown up to show where we measured true dip directions from outcrops which are indicated by the black line. Parasequence Kf-1-Iv (in dark red) progrades roughly due north in the Scabby Canyon area where it is onlapped by the younger Kf-1-Iv-a. Kf-1-Iv-a progrades south in Scabby Canyon, almost due west around Junction Point, and more to the north in Quitchupah Canyon. The uniformity of the foreset dip azimuths is 1.1.

Last Chance Delta



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Conclusions

- Fluvial catchment sets topset, topset sets stratigraphy
- Sand proportion may be estimated from clinoform concavity
- Ancient delta topset properties can be recovered from stratigraphy using validated models
- Last Chance Delta was a fan delta

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- Sarah Prozeller
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Questions?

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