PS Quantifying Architectural Controls on Reservoir Behavior in the Turonian Wall Creek Member of the Frontier Formation in the Powder River Basin, Wyoming*

Nathan La Fontaine[1] and Michael Hofmann[1]

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[1]University of Montana, Missoula, MT, United States (nathan.lafontaine@umontana.edu)

Abstract

Inter-well heterogeneities controlling fluid migration in deltaic reservoirs exist as low permeability beds within a hierarchical stratigraphic system. The vertical stacking and spatial extent of these low permeability facies within a three-dimensional stratigraphic architectural framework greatly influences connectivity and flow behavior in a reservoir. The estimation of effective reservoir properties, as influenced by these low permeability beds, is a significant source of uncertainty in modeling the subsurface, as common subsurface tools cannot resolve their spatial distribution and continuity.

This study aims to address this subsurface conundrum by quantifying heterogeneities in a mixed delta system spatially and stratigraphically. To accomplish this, an integrated sedimentological, stratigraphic, and geocellular modeling approach is employed on the Wall Creek Member (WCM) of the Upper Cretaceous Frontier Formation. Exceptional exposures of the WCM in the Tisdale Anticline, on the western limb of the Powder River Basin, are crosscut by a series of intersecting canyons, providing the three dimensional control necessary to adequately quantify these parameters. A 1 km^2 digital outcrop model (DOM) of the WCM was constructed using photogrammetric methods and georeferenced using field survey data. In addition, stratigraphic sections were measured in ~150m intervals providing facies constraint in both depositional strike- and dip-oriented outcrops. Within the DOM, surfaces bounding depositional elements of different hierarchies are mapped and quantified into categories. For example, thickening upward tidal bars (~5m thick bed sets), the highest order depositional element included in this study, are bound by low permeability surfaces spanning >500m across the study area; conversely surfaces bounding dunes (beds to bed sets) typically extend <50m. Initial measurements of dunes show width to length ratios that on average are 1:1 or greater, putting them in stark contrast to the higher order hierarchical elements (tidal bars) that are commonly much longer than wide.

The stratigraphic interpretations traced in the DOM, and constraint by the measured sections, are directly exported into a Petrel geocellular model to help resolve progressive levels of stratigraphic hierarchy and their respective influences on reservoir flow. Results from this study are intended to assist with well placement and completion strategies. In addition, derived effective properties can also educate groundwater and CO_2 sequestration modeling efforts.

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[1]Nathan La Fontaine, [2]Michael Hofmann
University of Montana, Missoula, MT
Email: Nathan.Lafontaine@umontana.edu

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SM ENERGY

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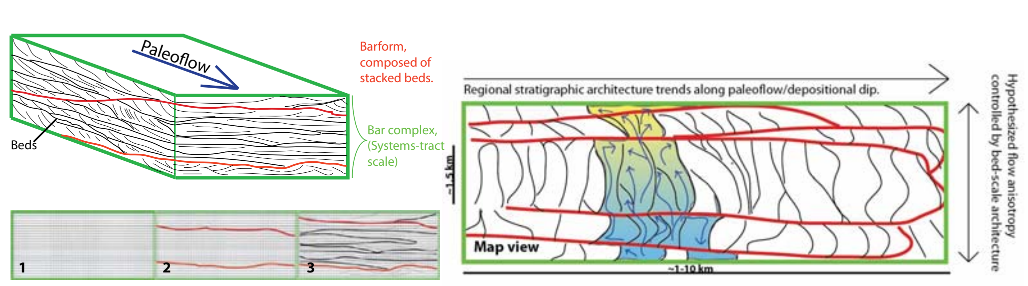
Motivation for Research

Recovering hydrocarbons from heterolithic tight oil plays, such as the WCM, require accurate high resolution geological modeling of the reservoir architecture and reservoir quality. Resolution limitations of subsurface data, stratigraphically and spatially, results in an inadequate characterization of the stratigraphic complexity. The integration of traditional outcrop measurements with high resolution photogrammetry provides a critical data set that helps filling the resolution gap.

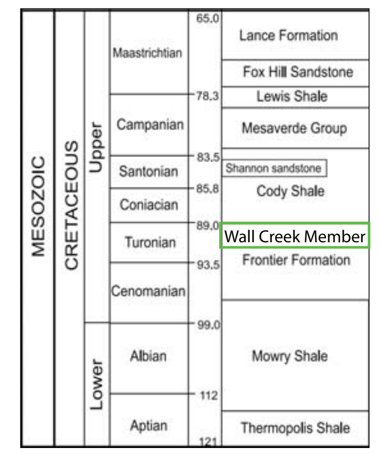
Research Objectives

- Define stratigraphic hierarchies of surfaces and depositional environments.
- Quantify dimensions of depositional elements and surfaces.
- Evaluate spatial and temporal relationships of depositional elements.
- Provide an accurate high resolution geocellular model for flow characterization.
- Create fine-scale nested models to help guide the upscaling process.
- Quantify the width:length ratios of depositional elements and study the impact on fluid migration in the reservoir (see figure below).



Study Area and Stratigraphy

- The Cenomanian-Turonian Frontier Formation was deposited on the western margin of the Cretaceous Western Interior Seaway. It overlies the Mowry Shale and is capped by the Cody Shale.
- The Frontier Formation consists of three members: the Belle Fourche Member, the Emigrant Gap Member, and the Wall Creek Member , which is the focus of this research.
- Beginning in the Campanian, Laramide deformation segmented the KWIS sediments into a series of smaller basins separated by basement uplifts and compressional structures, including the Tisdale Anticline, south of Kaycee, Wyoming, which hosts this study's outcrop exposures.



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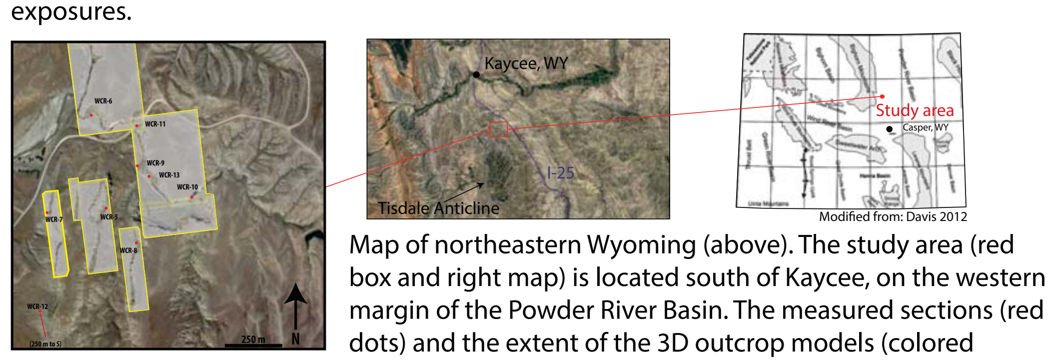


Map of northeastern Wyoming (above). The study area (red box and right map) is located south of Kaycee, on the western margin of the Powder River Basin. The measured sections (red dots) and the extent of the 3D outcrop models (colored boxes) are highlighted in the left map.

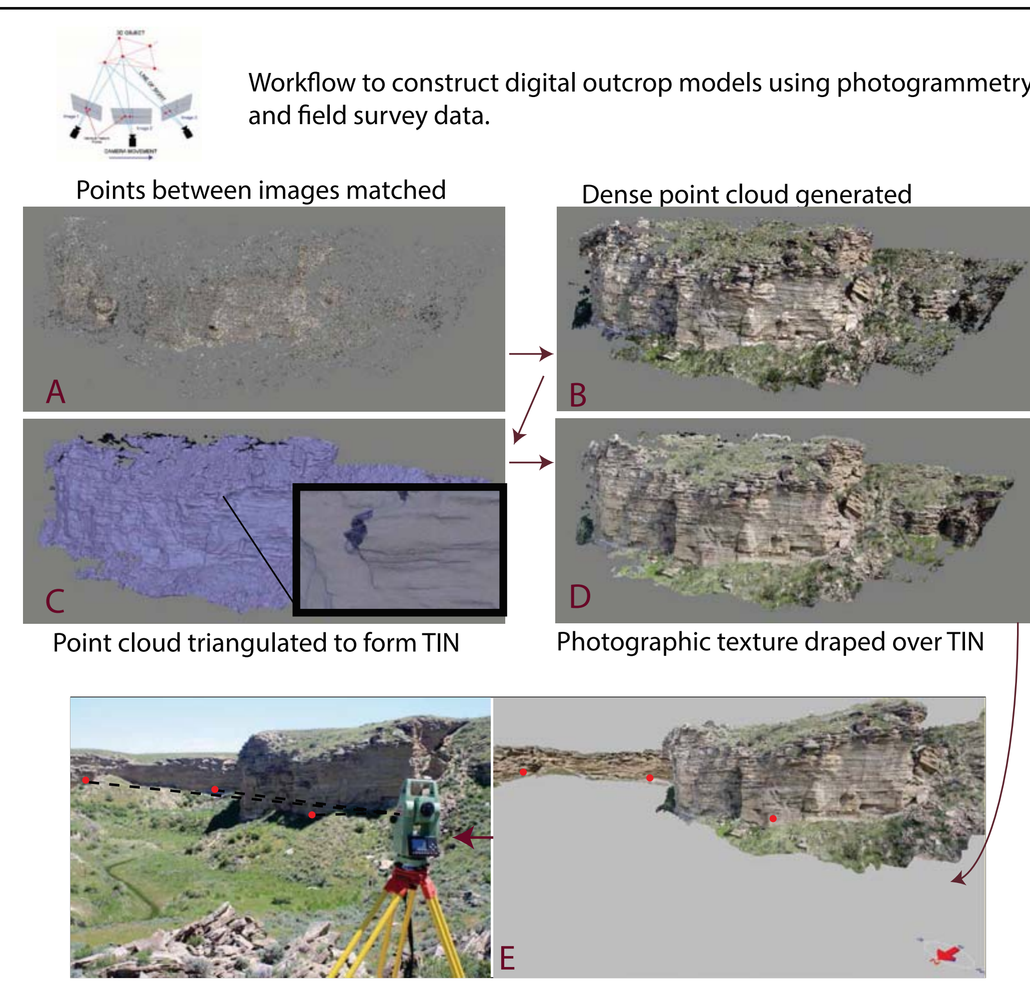
Methods and Datasets

Sedimentological data:

9 measured sections provide facies constraint throughout the study area. Grain size, bed thicknesses, sedimentary structures, bioturbation, and paleoflow were logged. Samples from significant stratigraphic locations were collected for petrographic studies.

Modelling data:

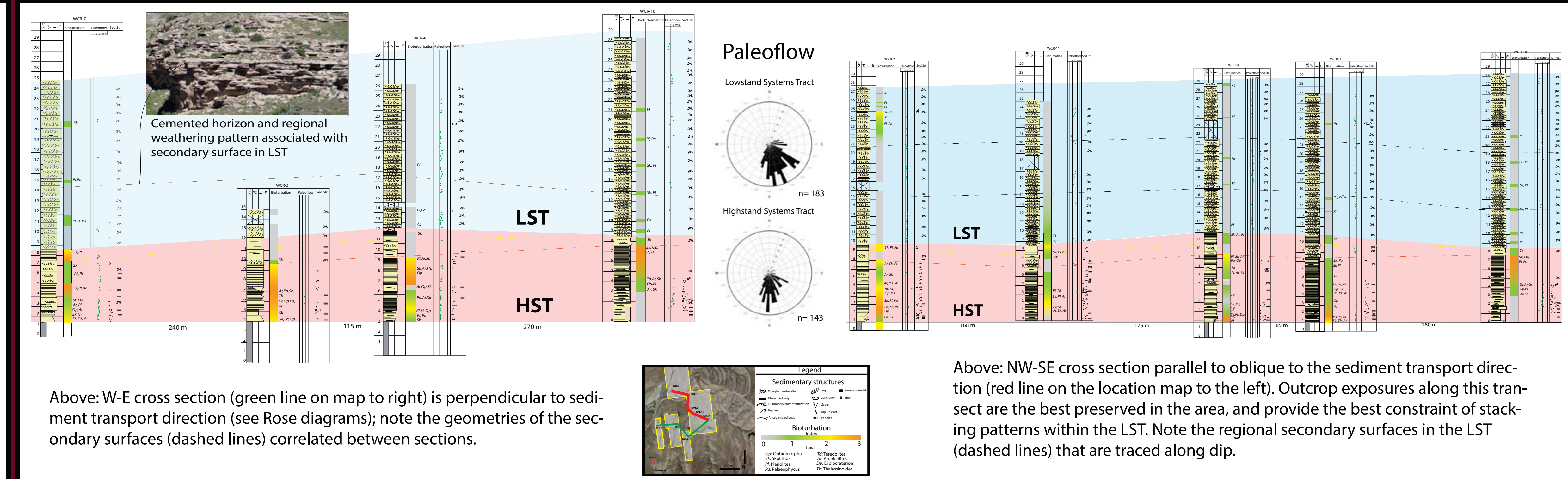
- >5000 photos were acquired to provide the imagery data necessary for digital outcrop model construction.
- 52 survey points on outcrop were recorded using a GPS and Leica Total Station for sub-meter resolution georeferencing capabilities.
- The above datasets and material are integrated to produce 3D models (Agisoft Photoscan software; see detailed workflow below), quantify architectural geometries and interpret a regional stratigraphic framework (Virtual Reality Geological Studio), and construct geocellular models (Petrel software).



Workflow to construct digital outcrop models using photogrammetry and field survey data.

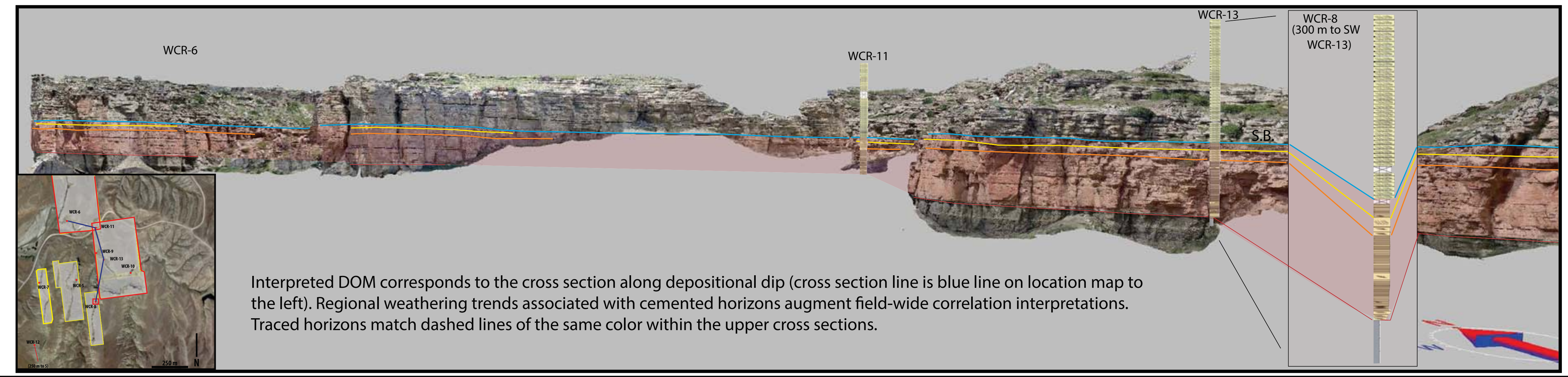
Survey points placed near the base and top of outcrop sections accurately georeference each model produced in Photoscan.

Cross Sections



Above: W-E cross section (green line on map to right) is perpendicular to sediment transport direction (see Rose diagrams); note the geometries of the secondary surfaces (dashed lines) correlated between sections.

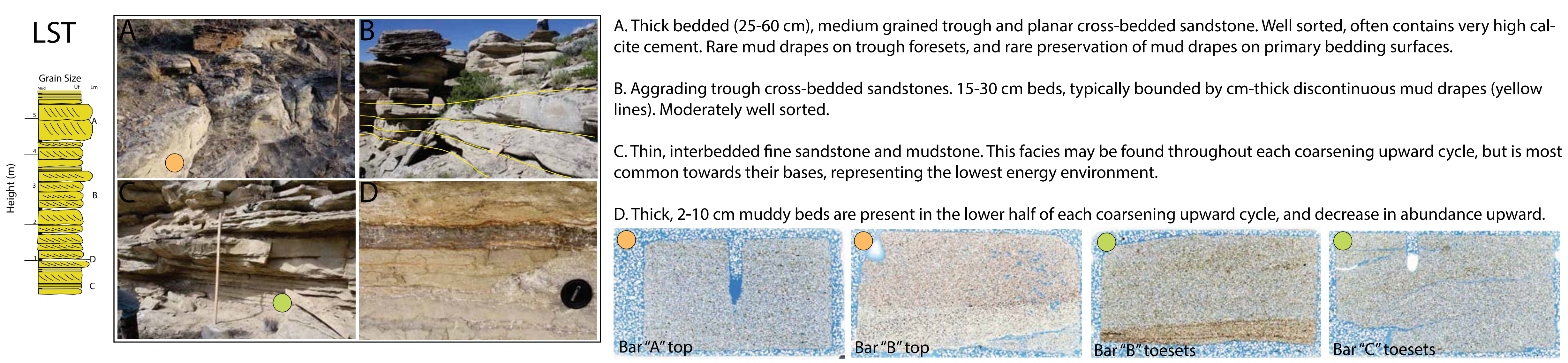
Above: NW-SE cross section parallel to oblique to the sediment transport direction (red line on the location map to the left). Outcrop exposures along this transect are the best preserved in the area, and provide the best constraint of stacking patterns within the LST. Note the regional secondary surfaces in the LST (dashed lines) that are traced along dip.



Interpreted DOM corresponds to the cross section along depositional dip (cross section line is blue line on location map to the left). Regional weathering trends associated with cemented horizons augment field-wide correlation interpretations. Traced horizons match dashed lines of the same color within the upper cross sections.

Facies Characteristics

LST



A. Thick bedded (25-60 cm), medium grained trough and planar cross-bedded sandstone. Well sorted, often contains very high calcite cement. Rare mud drapes on trough foresets, and rare preservation of mud drapes on primary bedding surfaces.

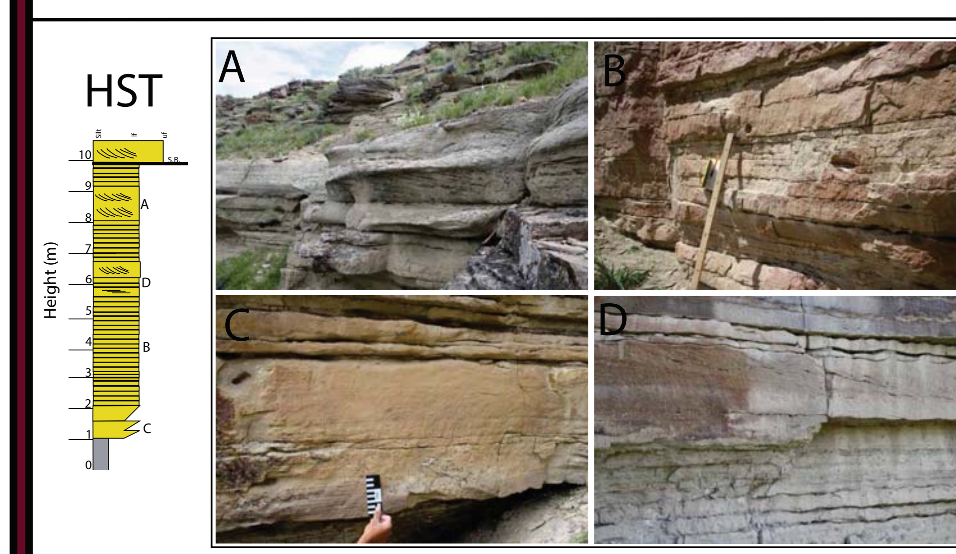
B. Aggrading trough cross-bedded sandstones. 15-30 cm beds, typically bounded by cm-thick discontinuous mud drapes (yellow lines). Moderately well sorted.

C. Thin, interbedded fine sandstone and mudstone. This facies may be found throughout each coarsening upward cycle, but is most common towards their bases, representing the lowest energy environment.

D. Thick, 2-10 cm muddy beds are present in the lower half of each coarsening upward cycle, and decrease in abundance upward.

Representative thin sections of bar top (above left, center left) and toeset facies (above center right, right) within the tidally influenced LST (circles correspond to intervals shown on left). Preliminary observations demonstrate:
- Increased primary porosity in coarser-grained bar tops, which may be partially destroyed by iron and calcite cement.
- Bar toeset facies show 1) a subtle decrease in grain size and sorting quality, and 2) increased secondary porosity due to feldspar hydrolysis.

HST



A. Fine grained, thick bedded (20-30 cm) trough cross bedded sandstone. Most prevalent in the uppermost cycle.

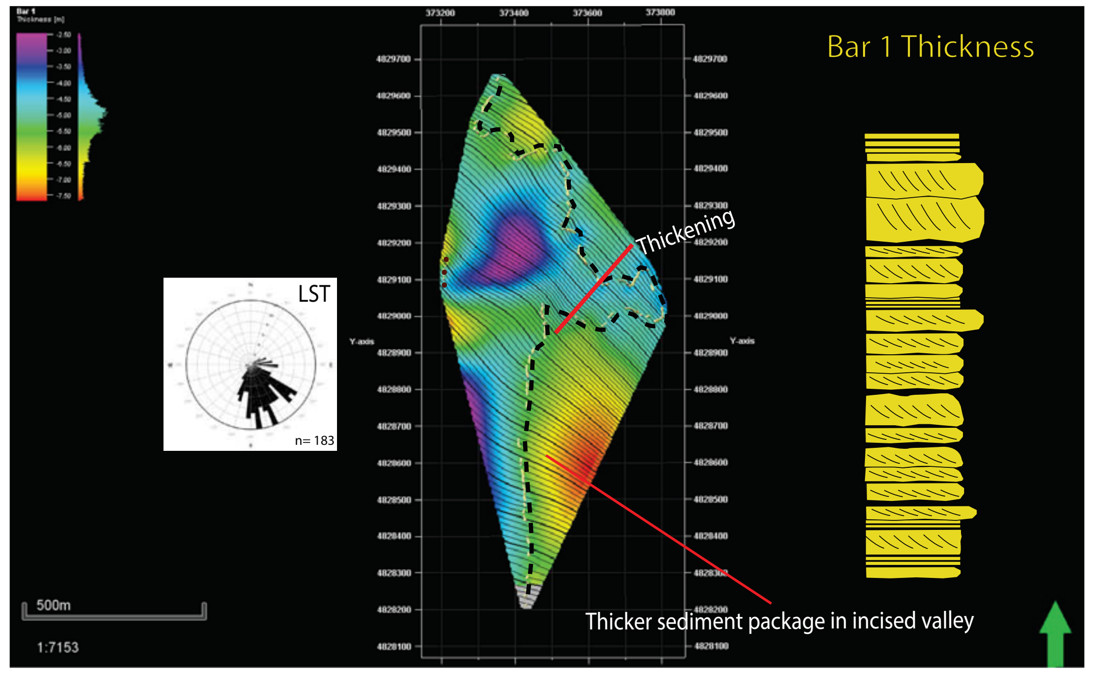
B. Interstratified sandstone and siltstone beds dominate the HST, and are interpreted as delta front turbidite deposits. Beds are thin (~2-5 cm) and extend distances on the order of 100s of meters.

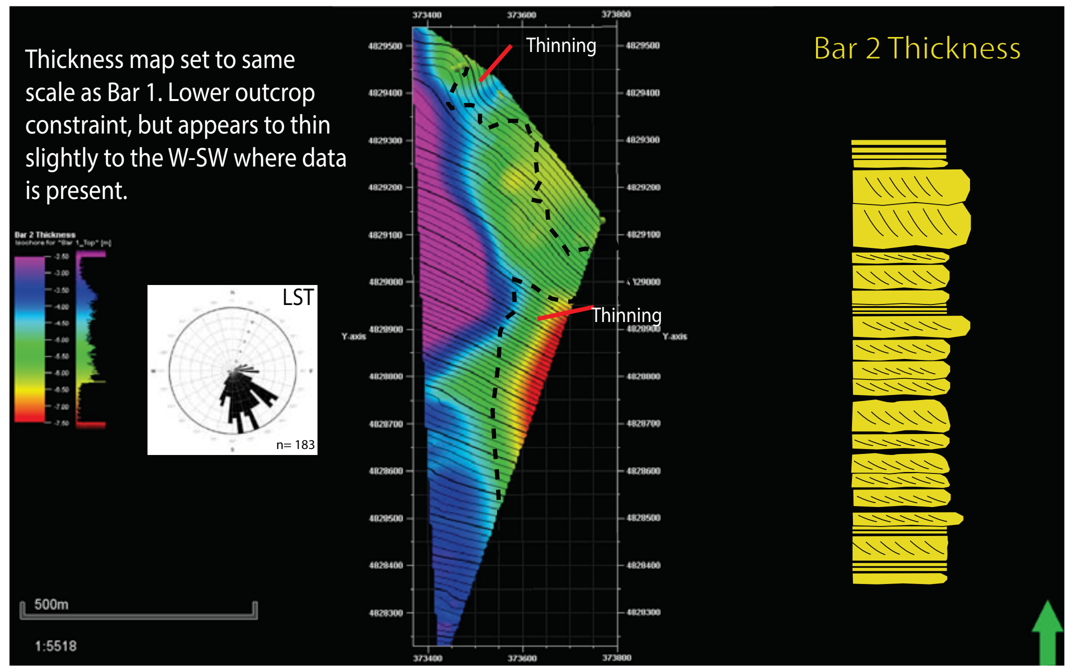
C. Planar low angle stratified beds are often associated with trough cross bedding or storm-induced scour fills. Thicker beds have been interpreted as part of larger hummocky cross stratification deposits.

D. Typical thickening upward stacking of interbedded sandstone and siltstone to thin trough cross bedded sandstone.

Surfaces and cycles (reservoir model framework)

A discrete framework for the high resolution geocellular model is built from regional stratigraphic surfaces that have been identified from sedimentological data and correlated within the digital outcrop model. Note that outcrop exposures become less abundant and lose quality up section within the LST. Thus, the mapped intervals of highest confidence are those of the HST and first barform (cycle) of the LST. The dashed black line delineates the easternmost, best constrained outcrop belt of the WCM. Data points from western outcrops are highlighted by dark red circles.





Lowstand Systems Tract

Above: Thickness map for the lowermost barform (cycle) of the LST.

- Thickness increases to the SW, indicating compensational stacking within the deeper incised shelf on the SW of the field site (see HST isochore below).
- The thin anomaly in the center of the map corresponds to a data gap in which there is no outcrop present, and is likely an artifact of the mapping interpolation.

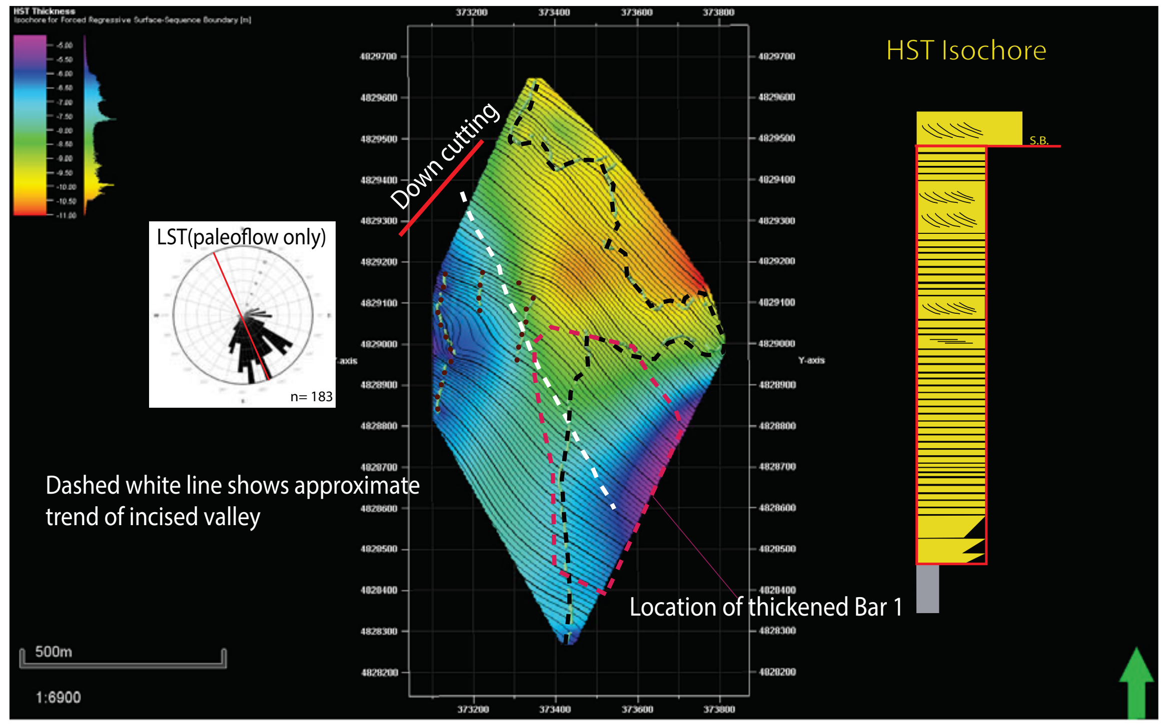
Above: Thickness map for the second observed bar.

- Note the general thickening trend toward the east, indicating compensational stacking between tidal bars.
- The cycle overlaying cycle 2 is poorly constrained due to substantial erosion of sedimentary packages in the western part of the study area.

Highstand Systems Tract

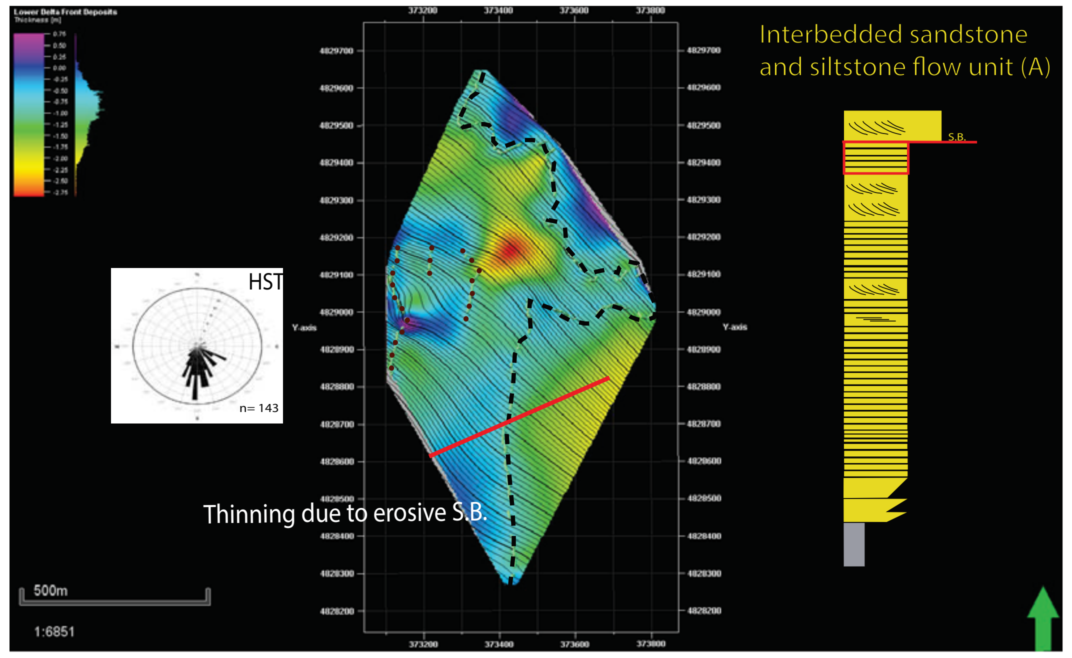
Right: Thickness map of the HST.

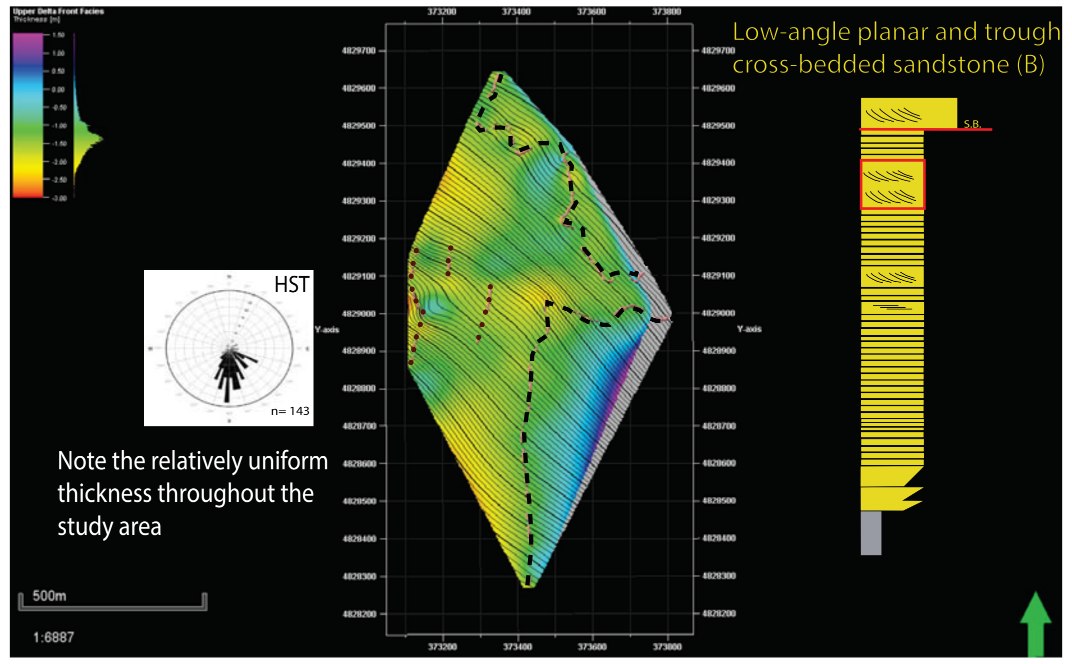
- Interval thins to the south and west.
- Thinning is the result of erosion from a regional lowstand event at the base of the overlying LST, and represents the margins of an incised valley.
- NW-SE trend perpendicular to this incision is consistent with regional paleoflow.



In contrast to the heterolithic LST, the laterally continuous facies of the wave-dominated HST delta deposits make regionally correlative flow units. The maps below are isopach maps of the two continuous bedsets that are separated by a distinct flooding surface. These bedsets are correlative to flow units in the geomodel.

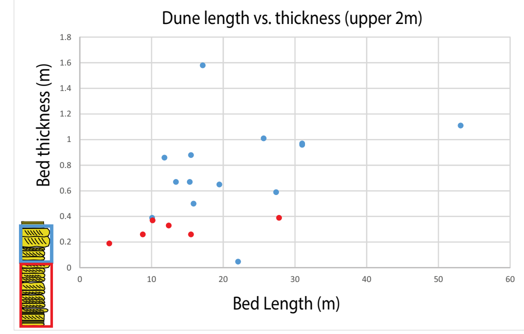
- A) Left figure, interbedded sandstone and siltstone flow unit. Note the gradual westward thinning of this interval resulting in increased erosion to the west along the sequence boundary.
- B) Right figure, low-angle planar and trough cross-bedded sandstone. A slight thinning eastward (basinward) trend is evident, but overall the unit has a very consistent thickness and facies is homogenous across the study area.

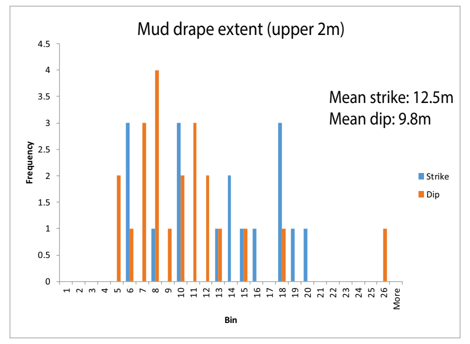




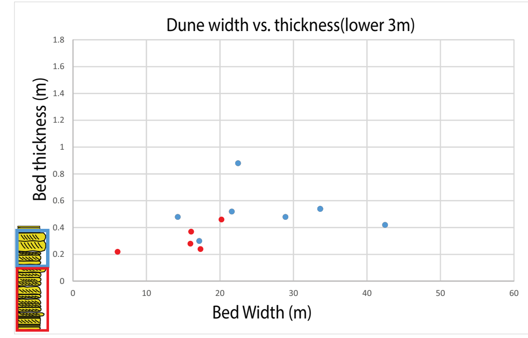
LST Architectural geometries

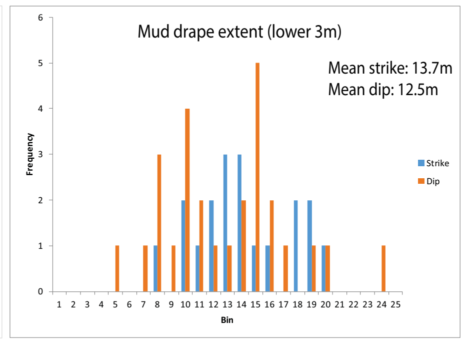
Quantitative input is needed for both the deterministic model building methods used in the fine scale heterolithic facies models, and for geostatistical modelling in future work. LST architectural measurements relevant to the modelling are presented below. Bed dimensions are divided by their stratigraphic location within the lowermost tidal bar (cycle 1 in Surfaces and cycles section to left).





- Far left: Thick bedded trough cross-bedded sandstone and mudstone characteristic of the upper bar facies.
- Middle: length vs. thickness ratios of dunes. Geometries average 25:1 in the thick upper beds, and 35:1 in the lower part of the cycle.
- Right: Measurements of mud drape extents in the upper 2m bar interval.



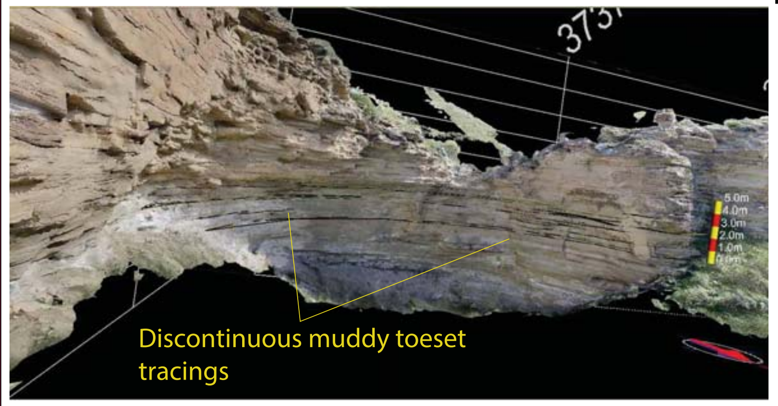


- Far left: thin bedded, trough cross-bedded sandstone and mudstone characteristic of the lower bar facies.
- Center: width vs. thickness ratios. While bed widths increase in the upper part of the cycle, width vs. thickness ratios average 45:1 in both sections.
- Right: Mud drape extent in the lower 3m interval. Note that 1) mean mud drape widths consistently exceed lengths, 2) extents decrease in upper bar, and 3) width:length ratios increase upward.

Heterolithic facies geocellular models

Two detailed models (25m width, 15 m length, <3 cm vertical resolution) were constructed for the the heterolithic, trough cross-bedded facies of barform 1. The first model honors the finer grained, lower 3 meter interval, while the second model honors the upper 2 meters. The primary objective of each model is to accurately represent the geometry and extent of muddy toesets of bed-scale dunes, and their upward character change within a barform. Future, collaborative work with the Montana Tech petroleum engineering group will run fluid simulation for each model, and fluid migration results will provide directional permeability (kx,ky,kz) values for upscaled cells in the regional geocellular model.

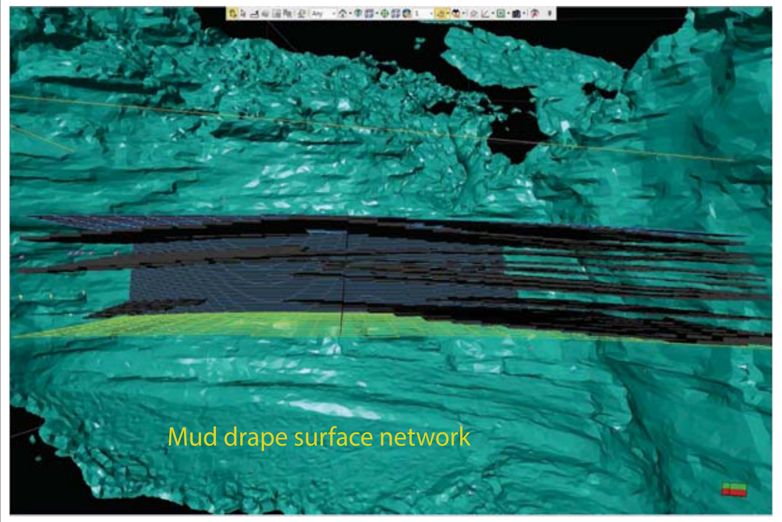
Model building procedure

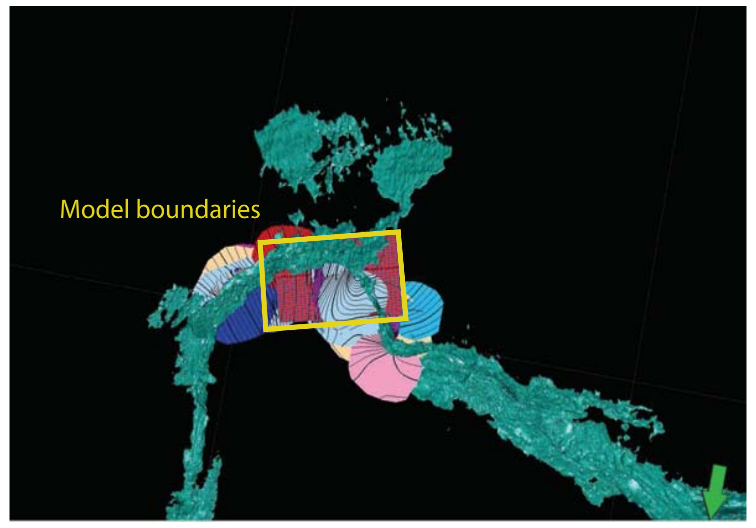


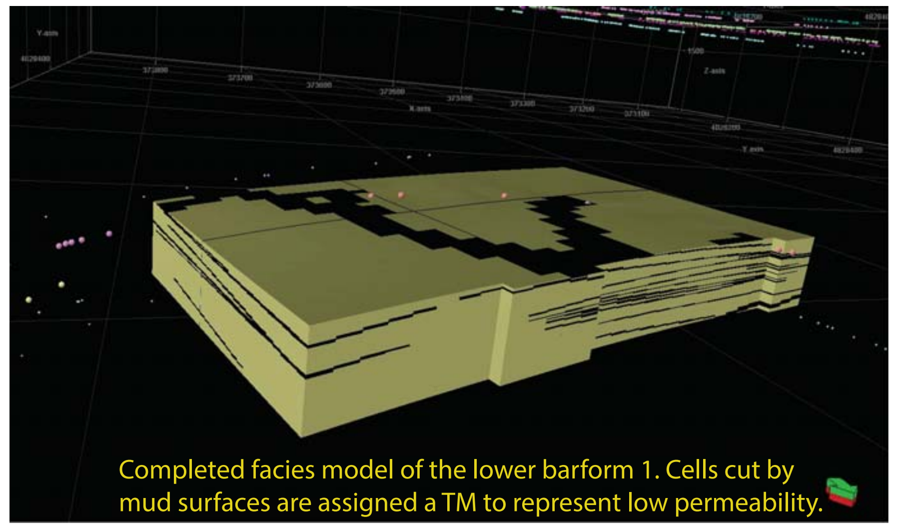
Left: A framework of 1) bedding architecture, and 2) discontinuous mud drapes is interpreted within a three-dimensionally exposed outcrop, in the DOM.

Bottom left and below: Petrel surfaces maintain geological realism by honoring:
- outcrop control points traced in the DOM,
- mean mud drape dimensions (see architectural geometries below)
- geometry conforming to underlying bedding framework

- Geological rules are applied so that younger mud drapes truncate older surfaces, creating an interconnected network of beds.
- Models are oriented parallel to mean depositional strike and dip (see Cross sections). As a result, directional permeability values gathered in this work will readily translate to similar environments in which paleoflow is known.
- Surfaces are given a transmissiblity multiplier value (TM) of <1, while grid cells representing sand remain a constant 1. Future sensitivity analysis will test flow migration through constant architectural models at different TM values, to represent subtle changes in lithology contrasts.







The surface-based approach and vertical model resolution (<3cm) efficiently and accurately captures the impact on flow exerted by thin mud drapes, at a scale that is not resolvable in core-based methods. Fluid simulation between the two models will provide high resolution insight into flow dynamics within tidal barforms, and their variability as a function of stratigraphic height.

Discussion

- Photogrammetry is an effective method to gather a wide range of quantitative stratigraphic architectural information in the WCM.
- A stratigraphic hierarchical system is effectively unravelled by coupling sedimentological data with regional observations (e.g. cemented bar top horizons) and quantitative architectural measurements made in the digital outcrop model.
- Depositional elements vary greatly in size between the LST and HST. In the HST, depositional elements are thin bedded (typically 2-5 cm), and spatially expansive (100s of meters). Cross-bedded and planar bedded facies are an exception, with shorter extents and bed thicknesses typically between 20-30 cm. Reservoir flow units divided by these facies boundaries are regionally correlative in the study area. In the LST, bed thicknesses increase (mean 25.4 cm), but their lateral extent is limited to 10s of meters. Reservoir flow units are defined by the stacking of upward coarsening tidal barforms.
- A surface-based modelling approach is used to create nested geocellular models that effectively represent thin, interwell-scale heterogeneities in the heterolithic facies of the LST. Upward variation in mud drape dimensions, spacing, and connectivity within a barform is captured by two detailed (<3 cm vertical resolution) models.
- Collaborative fluid simulation work with Montana Tech will demonstrate important relationships between bed-scale architecture and preferred fluid migration pathways in ancient tidal settings. I hypothesize that bed-scale barriers will yield a dominant impact on effective reservoir permeability, potentially producing flow anisotropy opposed to the hierarchically higher regional barform geometries. Additionally, sensitivity analysis of deterministic architectural models tested at varying surface transmissibility values will demonstrate the significance of differing lithologies within a constant architectural framework.

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