Research Prospectus:

Quantitative Sedimentology Research Consortium

Dr. Janok P. Bhattacharya
Susan Cunningham Research Chair in Geology
School of Geography and Earth Sciences
McMaster University, 1280 Main St. W
e-mail: bhattaj@mcmaster.ca
Wk: (905)525-9140 Ext. 23528

Website: https://qsl.mcmaster.ca

Introduction

The quantitative sedimentology research consortium is focused on investigating source-to-sink, sequence stratigraphy and 3D facies architecture of shallow marine, paralic, and fluvial depositional systems. Although much industry exploration effort has been focused on deep-water depositional systems, about 50% of global oil production is from shallow marine, paralic and fluvial strata, including shelf mudstones. Ours is one of only a few research programs globally, devoted to this important area.

This prospectus outlines the key thematic problems that we are addressing. It also lists some results of our ongoing research program as well as listing some of the specific projects that we would like to complete using consortium funds. Consortium members are also free to suggest additional research topics and we encourage collaboration, especially in applying our analog studies to actual subsurface reservoirs.

General research interests

- Source-to-sink studies with an emphasis on scaling and sediment budget analysis of ancient systems.
- Clastic facies models with an emphasis on the 3D facies architecture of shallow marine and fluvial depositional systems.
- High-resolution sequence stratigraphy of shallow marine to non-marine systems.
- Quantitative description and modeling of modern and ancient deltas.
- Reservoir architecture and facies characterization of thin-bed and halo plays.
- Origin of shallow-marine shelf mud belts and shelf shales.
- The effects of structure and tectonics on facies architecture and stratigraphy (including syn-sedimentary growth faults).
- Application of Remote sensing, GIS, and GPR techniques to 3D reservoir characterization.

Key Questions

The scientific hypotheses and key questions under investigation in our consortium are myriad, and are specifically addressed in the thesis proposals written by each student (posted on the consortium website), however, key thematic questions are outlined below.

Source-to-Sink:

The source-to-sink (S2S) concept is a basin analysis approach that quantifies sediment fluxes over geological time periods to predict attributes of upstream catchments, including the size, relief and climate of the drainage basin, as well as making predictions about the volumes of sediment in downstream sinks (i.e., the strata in sedimentary basins). My group has pioneered techniques for source-to-sink (S2S) analysis in deep-time systems in which we estimate instantaneous paleodischarge of ancient rivers in Cretaceous systems in North America and integrate these rates over time periods associated with high-frequency sequences deposited over orbital (i.e., Milankovitch) time scales to develop a sediment budget (Bhattacharya and Tye, 2004; Bhattacharya et al., 2016; Lin and Bhattacharya, 2018; Sharma et al., 2018, Table 1). Our techniques include field observations to characterize the paleohydraulics of the rivers, detailed sequence stratigraphic analysis to correlate and map units, and chronometric analysis for temporal constraints. My research team has used the fulcrum method of Holbrook and Wanas (2014) to show that sediment fluxes of Cretaceous trunk rivers incised during falls and lowstands of sea level, match mapped volumes of deltaic sediments in the basin (Lin and Bhattacharya, 2018, Sharma et al., 2018).

Table 1. Paleohydraulic estimates and sediment budgets

	Bankfull Thalweg Depth (m)	Mean Bankfull Depth (m)	Width (m)	Slope	U m/s	Water	Sediment		DA 10^4 m^2	Fulcrum Calculation of Sed. Volume in 20,000 years km^3	Sandstone Isopach Volume km^3	Total Sediment Isopach volume km^3
						Q_w m^3/s	Q_b m^3/s	Q_t m^3/s				
Mississippi	40.0	-	1500	0.00005	1.0	15,000	-	-	320	-	-	300,000
Ferron V1	8.4	4	140	0.0008	2.3	1282	0.70	11.2	50	17.60	20	200
Ferron V2	5.5	3	70	0.0007	1.9	397	0.33	2.8	50	0.83	5	50
Dunvegan	16	-	170	0.0003	1.6	2829	-	-	125	-	20	3000
Dunvegan	20	-	200	0.0003	1.7	4420	-	-	125	-	75	7000
McMurray	40	-	800	-	-	15,000	-	-	~500	-	300	30000
Blackhawk	7.2	-	-	0.0007	-	2200	-	-	-	-	-	-
Paddy	7.0	-	100	-	-	-	-	-	-	-	-	-

We have recently documented high frequency sequences of the Cretaceous Gallup and Crevasse Canyon Formations (Fig. 1) in outcrops along the west side of the San Juan Basin New Mexico (Lin et al., 2019, Lin and Bhattacharya, 2019), and linked this to the fluvial architecture and paleohydraulics of the overlying Torrivio Member. Our stratigraphic analysis has shown that the lithostratigraphically-defined 6 sandstone tongues of the Gallup Formation actually comprise 13 high-frequency 4th and 5th order sequences, containing 61 parasequences (Fig. 1), illustrating a rather more complex sequence stratigraphy than previously interpreted.

Analysis of the shoreline trajectory, with respect to a pair of lower bentonite layers, show vertical sea-level changes ranged from -66 m to + 56 m with horizontal translations of around 50 km (Fig. 1). Chronometric analysis indicate that the sequences are about 92 kyr in duration and parasequences are about 20 kyr, which match orbital climate cycles and support the hypothesis that Cretaceous sea-level changes may have been driven by the growth and decay of ephemeral Antarctic ice sheets. These frequencies match cycles documented in other studies of Cretaceous formations and lend support to the hypothesis that the Turonian-Coniacian age may never have been truly ice free.

Proposed research to follow up these results will be to examine the outcrops along the east side of the San Juan Basin, as well as a major effort in subsurface correlations of well logs in the subsurface San Juan Basin.

Regional Sequence Stratigraphy Correlation Cross-Section in Depositional Dip of the Gallup System

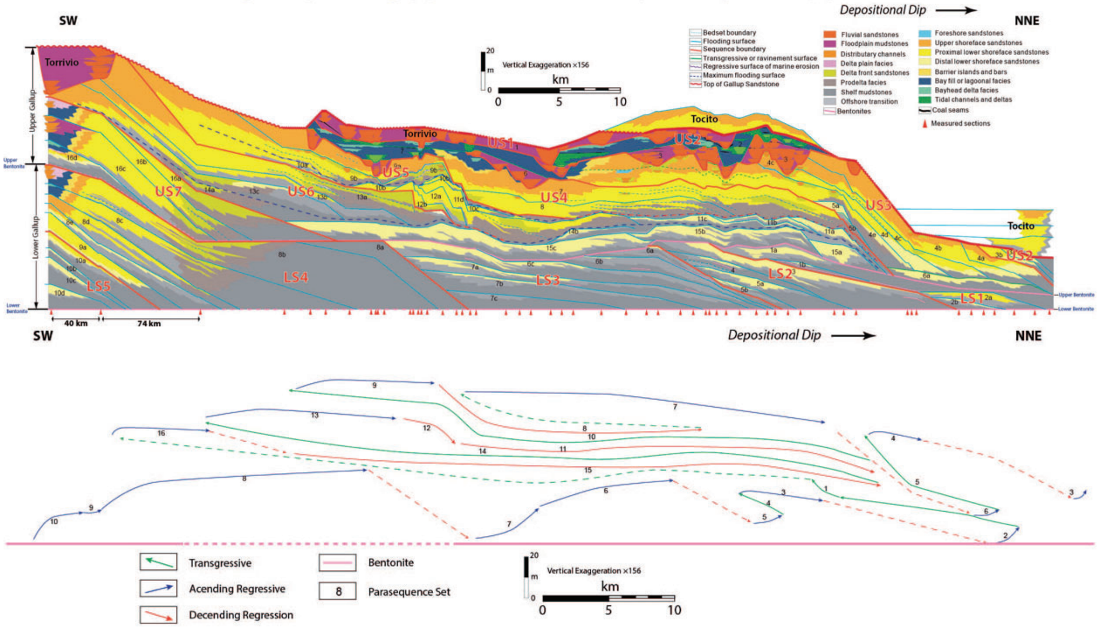


Figure 1. High-resolution dip-direction sequence stratigraphy and shoreline trajectory of the Gallup system. The upper Gallup system comprises seven sequences, subdivided into sixteen parasequence sets and thirty-seven parasequences. The lower Gallup consists of five sequences, ten parasequence sets, and twenty-four parasequences. A regional unconformity lies between the overlying Tocito Sandstone and the Gallup system. The trajectory diagram illustrates magnitudes of lateral and vertical changes in shoreline position (from Lin et al., 2019). We have recently improved on the analysis of changes in relative sea-level by backstripping (Lin et al., in prep.).

Incised valley, degradational landscapes, and diachroneity of sequence boundaries

Strong and Paola (2008) suggested that many so-called sequence boundaries, particularly those at the base of incised valleys, are actually composite, diachronous stratigraphic surfaces that never had any topographic expression. This concurs with studies of Quaternary incised valleys (e.g. Blum, 1993), which also show a prolonged and complex history of numerous cut-and-fills. We have evaluated the chronostratigraphic significance of valley fills (Fig. 2) through detailed facies architecture and sequence stratigraphic analysis integrated with Detrital Zircon (DZ) analysis. The number of erosion surfaces and cyclic fill patterns help to elucidate the genetic relationships and DZ analysis helps us to evaluate how many drainage basins are integrated in the rivers that feed Cretaceous deltaic systems. Chronometric age dating of bentonites and maximum depositional age analysis of DZ's allows us to determine the duration and complexity of long-lived Cretaceous valleys systems and shows that systems like the Ferron and Gallup-Torrivio may be sourced from different areas.

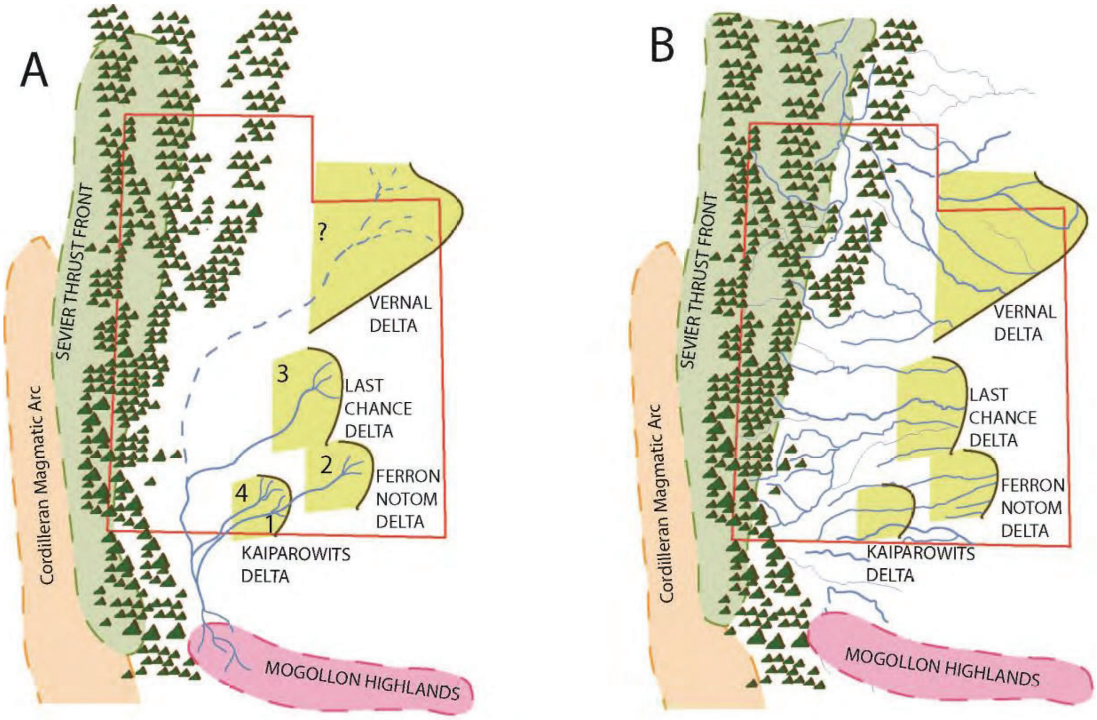


Figure 2. Ferron paleogeography models relative to modern state boundaries, Cordilleran, Sevier Thrust Front and Mogollon Highland terrains (*modified from:* Ryer, 2004). A) Avulsive single trunk drainage model described by Garrison and van den Berg (2004) suggesting a single trunk river that avulsed to form the various Ferron delta complexes (Notom, Last Chance and Vernal. B) Modern Andean eastern drainage in Equator superimposing the Andes on the Sevier Thrust Front in Utah. This figure hypothesizes multiple trunk rivers feeding the various deltaic complexes (Ryer and Lovekin, 1986). Our recent DZ analysis (Kynaston, 2010) suggests that model B is more correct.

Wheeler analysis allows us to evaluate the chronostratigraphic significance of nested erosional surfaces (Fig. 2). Our results to date (Li et al., 2010; Bhattacharya, 2011; Holbrook and Bhattacharya, 2012; Li and Bhattacharya, 2013; Kimmerle and Bhattacharya, 2018) appear to concur with the hypothesis of Strong and Paola (2008) in showing that valleys in the Ferron Notom delta are compound features that record a complex and prolonged history. Analysis of Ferron and Gallup rivers show that two main sources (Sevier and Mogollon) fed these deltas (Ferron, 2019). The Torrivio Member of the Crevasse Canyon Formation in New Mexico is petrographically distinct from the Gallup, and shows a distinct Mogollon DZ signature, and we hypothesize that the Torrivio rivers may have fed the Tocito sandstones. We are proposing to conduct petrographic and DZ analysis of the Tocito to test this hypothesis.

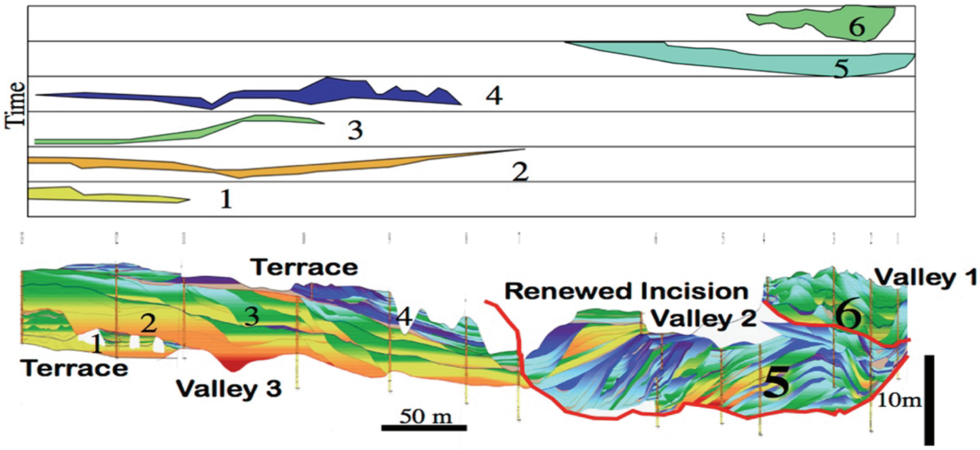


Figure 2. Cross-section of a compound valley in the Ferron Sandstone, showing the detailed facies architecture and well preserved, falling-stage terraces. Accompanying Wheeler diagram (above) emphasizes the diachronous nature of the basal erosion surface (after C. Campbell, 2012). Colors represent grain sizes, with warmer colours representing coarse sandstone, blues very fine sand and brown is mudstones.

What is the control of backwater and baylines on the stratigraphic architecture and facies in paralic systems, especially FMTZ?

The backwater marks the point that the base of a river lies above sea level and is represented by the channel depth divided by the slope (Chantantavet et al., 2012; Fernandes et al., 2016). For continental-scale low slope systems like the Mississippi (D=50m, S=10^{-5}) the backwater is about 500 km landward of the shoreline. At the backwater, the river will feel a drop in shear stress and begin to deposit some component of its bedload. This increase in bedload deposition accelerates bar growth and promotes lateral migration of the river resulting in wide channel belts. Closer to the shoreline, rivers experience greater effects of the sea, including tides, and promotes aggradation of the river and narrower channel belts. The bayline is defined by the tidal range divided by the slope and controls the landward limit of brackish water and associated facies (Fig. 3).

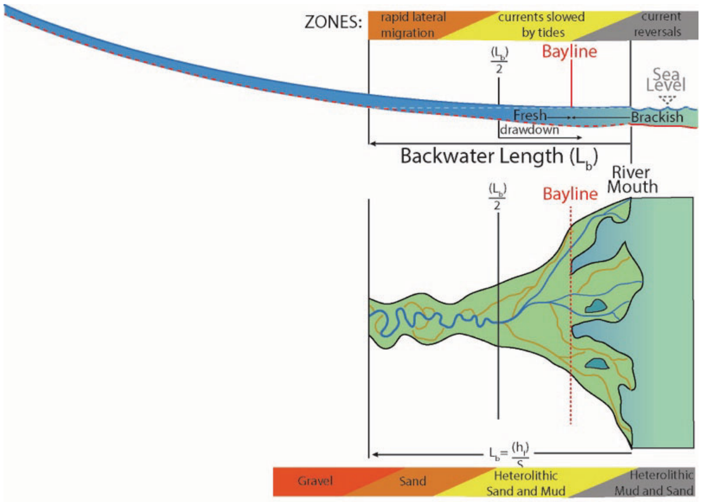


Figure 3. Backwater and bayline limits and its control on facies distribution in the fluvial marine transition zone (from Kynaston in prep, modified after Bhattacharya et al., 2016 and Blum et al., 2013)

Our research group is investigating the role and position of the backwater in a number of ancient systems including the Ferron (Kimmerle and Bhattacharya, 2019; Kynaston, 2019) and Gallup. This work also integrates detailed facies architectural studies to determine the width, depth and slope of formative paleo-rivers. Ferron rivers were on the order of 5-7 m deep, with slopes on the order of 5 x 10^{-4}, resulting in relatively short backwater lengths of less than a few tens of kilometers. This allows coarser fluvial sands to lie closer to the shoreline than the Mississippi example. The bayline limits, assuming a microtidal setting are only a few kilometers, but we do see evidence of tidal modulation of the rivers landward of the bayline. These results may help predict heterogeneity in other systems within the FMTZ, such as the McMurray oil sands in Canada.

What is the relative control of eustasy, climate, and tectonics in controlling Cretaceous sequences and facies?

Bhattacharya (2011) synthesized work on the Cretaceous Seaway suggesting that high frequency tectonic unconformities are angular and commonly show distinct changes in provenance and paleoslope. Holbrook and Bhattacharya (2012) suggested that climate-controlled fluvial erosional surfaces are marked by upstream erosional surfaces (buffer profiles) that correlate downstream to shorelines (i.e. buttresses) that show very little shift. Dip-profiles of the Cretaceous Ferron Notom delta, in central Utah (Fig. 3) show incised valleys that link to downstepping shoreline deposits, requiring a buttress shift, which we believe reflects a eustatic control. However, additional erosion surfaces within the valleys (Fig. 2) suggest higher-frequency perturbation of the fluvial profile, likely reflecting a superimposed climate control (Li et al., 2010; Li and Bhattacharya, 2013). Analysis of Ferron paleosols has helped to evaluate the importance of climate control as indicated by changes in humidity or groundwater levels, and coal types (Akuyuz et al., 2014; Famubode et al., 2016). Geometric analysis of regional stratal relationships (Fig. 4) should show whether erosion surfaces are associated with angular unconformities (i.e. requiring lithospheric deformation), or disconformities, which may be produced by eustatic falls or by regional uniform uplift of an area larger than our study area. The geometry of these wedges may also be used to calculate key paleohydraulic parameters, such as slope, backwater length, and bayline limits (Fig. 3). Geodynamic considerations and modeling will help determine whether large-scale uplift or eustasy is the more likely mechanism. This work is of broad significance in addressing the utility of sequence stratigraphy as a correlation tool and how it applies to the rock record to make predictions about the linkage of depositional systems in time and space. Our new field area is focused on the Gallup Sandstone in the San Juan Basin, New Mexico where both tectonics and eustasy have been proposed to control the origin of high frequency sequences.

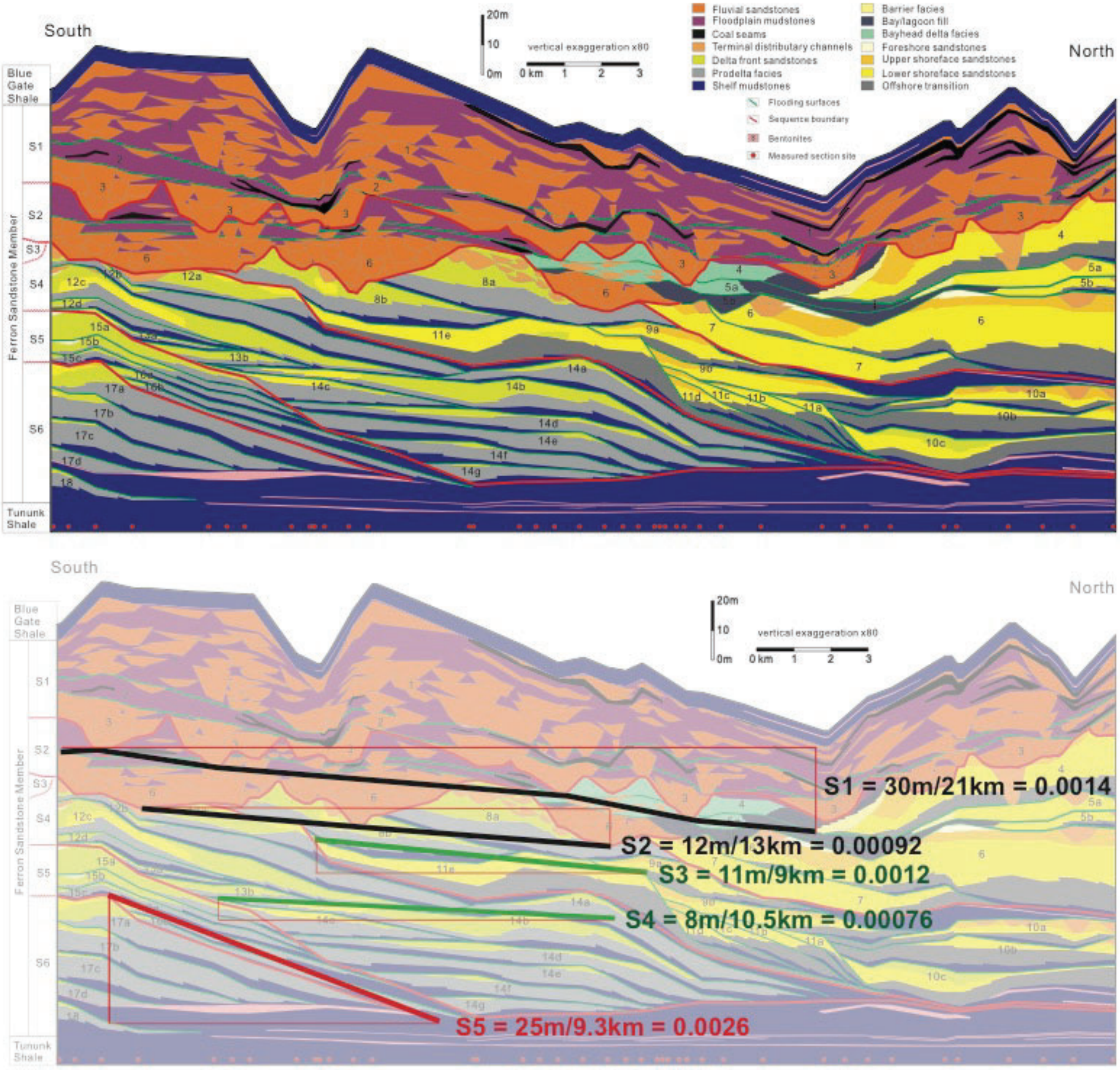


Figure 4. Regional dip cross-section through the Ferron Notom delta system shows 43 parasequences, 18 parasequence sets, and 6 sequences. Upper sequences show well-developed incised valleys. The onlap limits of the base of lowstand (1, top 15a) and top of lowstand wedge (2 - top of 11e) can be used to calculate slope of the respective surfaces. From Zhu, 2010 and Zhu et al., 2012.

What is the 3D heterogeneity of fluvial sequences and systems tracts?

The Ferron outcrops contain both cliff and plan-view exposures of fluvial channel belts and incised valleys, including tributary systems, which can be documented in 3D (Wu et al., 2015; Bhattacharyya et al., 2015). 3D Airborne Lidar scanning and collection of preliminary GPR data across these 3D exposures has been done (Fig. 5). The plan-view exposures allow documentation of the scale of formative rivers, dimensions of channel belts, meander wavelength, as well as grain size variations within meander scrolls. These data are integrated with paleocurrent measurements to document the paleogeographic evolution of each meander-belt, and determine its associated grain size heterogeneity. Plan-view images can also be linked to adjacent cliff exposures, which allows documentation of cross sectional bedding geometry and facies architecture. These plan-view exposures are also amenable to 2D and 3D Ground Penetrating Radar (GPR) surveys to image the 3D architecture of fluvial and mouth bar sandstone bodies.

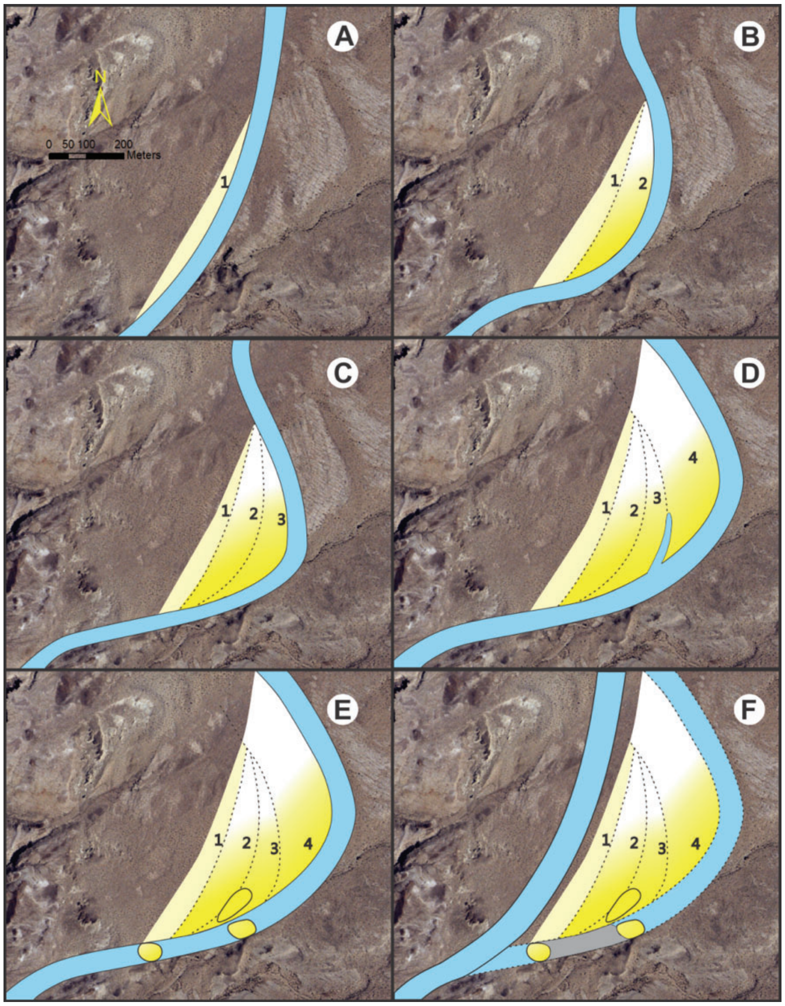


Figure 5. Interpretation of plan-view exposures of a meander belt north of Nielsen Wash, Utah, in highstand fluvial systems tracts of Sequence 1 (see Fig. 2) of the Ferron sandstone. Channels appear to be about 75 to 100 m wide (From Wu et al., 2015).

How is the concept of shoreline trajectory and accommodation successions applied and how can stratigraphic geometry be used to predict facies heterogeneity?

The concept of shoreline trajectory (Helland-Hansen and Gjellberg, 1994) and accommodation successions (Neal and Abreu, 2009) is a geometric approach to facies analysis, analogous to parasequence stacking patterns (Fig. 6). Unfortunately, the concept of parasequence stacking patterns, as originally formulated (Van Wagoner et al., 1990), was insufficient to characterize the full variability of facies stacking and geometry in all likely scenarios. The expression of parasequences during a relative fall of sea level, for example, is now referred to as the falling stage systems tract, but good outcrop examples, tied to an acceptable datum are actually quite rare. In many previous studies, flattening on a datum (and especially flooding surfaces) potentially distorts stratigraphic relationships and makes a quantitative estimate of shoreline trajectory difficult (Bhattacharya, 2011). In our studies, we favor bentonites within underlying condensed-section, which are isochronous and which we believe are relatively flat over the area that we study. The use of bentonite datums allows accurate analysis of trajectory, from which we are able to infer relative sea level fluctuations. Analysis of shoreline trajectory may also be linked to accommodation successions (compare Figs. 1, 4 and 5). Stepped falls of the shoreline may also be linked to fluvial terrace development within the associated valley. Analysis of the geometry of wedges, and particularly the thickness and onlap limits of coastal facies, can be used to predict depositional slopes, backwater length, and bayline limits (Figs. 3 and 4), which can be used to predict limits of key facies, such as the sand-gravel transition in fluvial systems, and the limit of tidal heteroliths (Bhattacharya et al., 2015). This work is of broad significance in addressing the utility of sequence stratigraphy as a correlation tool to define reservoir seal pairs and sub-regional reservoir complexity and heterogeneity.

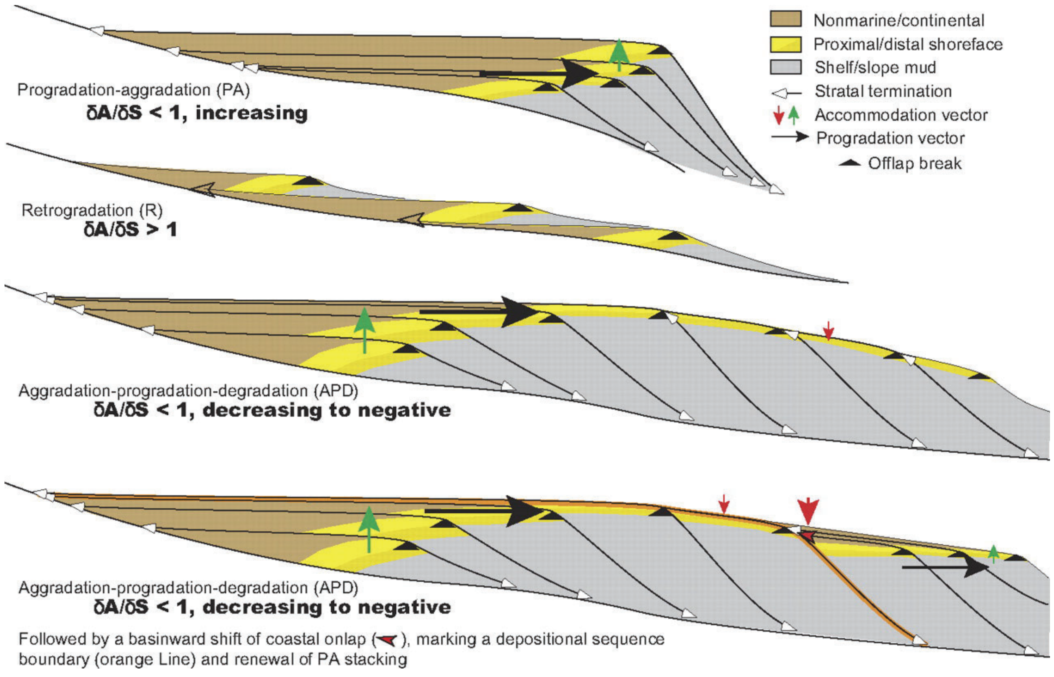


Figure 6. Accommodation successions and shoreline trajectory as a function of changes in Accommodation (**A**) and Sediment Supply (**S**), from Neal and Abreu, 2009.

What are the basic building blocks of deltaic delta fronts and how do they vary with delta type?

Bates (1953) and Wright (1977) suggested that fluvial delta fronts may be buoyancy-dominated (hypopycnal), inertia-dominated (hyperpycnal), or friction-dominated. Orton and Reading (1993) and Postma (1990) classified deltas on the basis of sediment caliber (i.e. grain size) as well as on the nature of the feeder systems (e.g. hypopycnal, hyperpycnal, frictional) and water depth. Although there have been numerous studies that show how these classifications apply to modern delta fronts, there are very few examples that show how these different processes may apply or be recognized in ancient delta systems (Martinsen, 1989; Wellner et al., 2005). A main goal of our research is to use the facies architectural analysis approach (e.g. Miall, 1985) to identify the basic stratigraphic building blocks of deltaic depositional systems in our ancient examples, and to link these to the formative process and it's associated geomorphic element in a modern system (Fig. 7). We have already made some progress in the identification and description of variability of terminal distributary channels and mouth bars in inertial and tide-influenced systems (Olariu and Bhattacharya, 2006; Gani and Bhattacharya, 2005; Lee at el., 2005; 2007; Garza, 2010; Ahmed et al., 2014; Li and Bhattacharya, 2014), however most of our previous studies were in lowstand and forced regressive, highly top-truncated delta systems. The Cretaceous Ferron Sandstone and Gallup Sandstone examples extends this earlier work to higher accommodation settings and provides extensive strike and dip views of key elements (Fig. 8). Because of high sedimentation rates and subsidence, the Ferron and Gallup sandstones preserve much of the paralic and non-marine component. Growth-strata are especially useful because they may preserve fully formed architectural elements (Bhattacharya and Davies, 2004). This work is of broad significance, in that elucidation and interpretation of depositional elements and their stacking relationships provides insights into how deltas actually grow (Fig. 9). The data from these studies also provide abundant dimensional information that may be used in reservoir models.

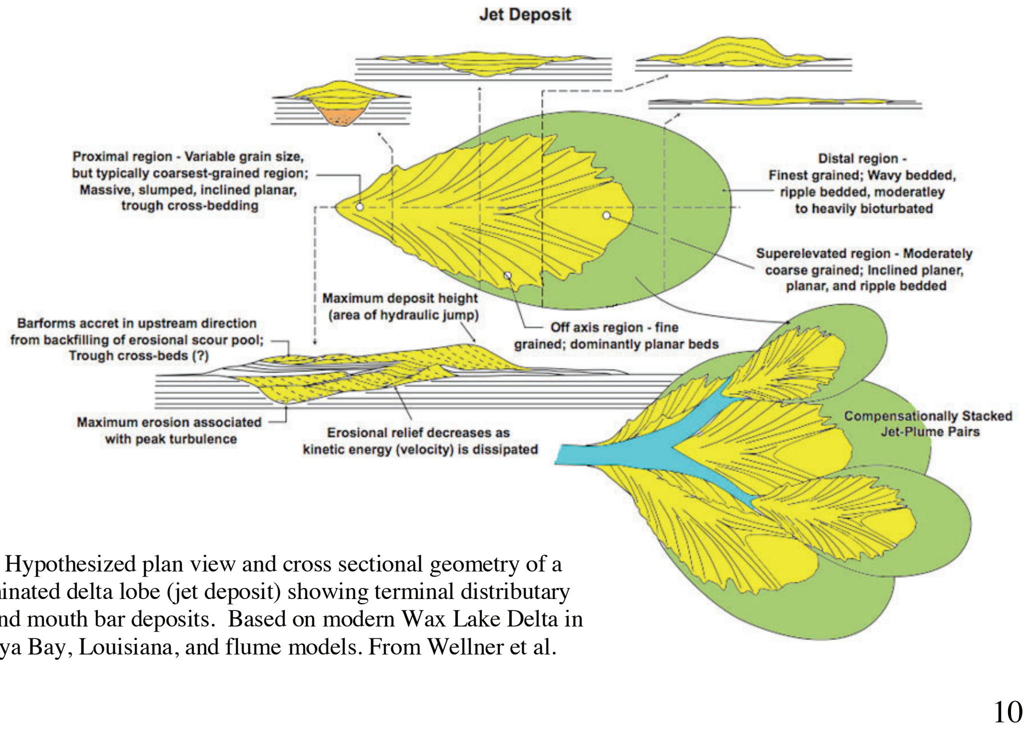


Figure 7. Hypothesized plan view and cross sectional geometry of a river-dominated delta lobe (jet deposit) showing terminal distributary channel and mouth bar deposits. Based on modern Wax Lake Delta in Atchafalaya Bay, Louisiana, and flume models. From Wellner et al. (2005).

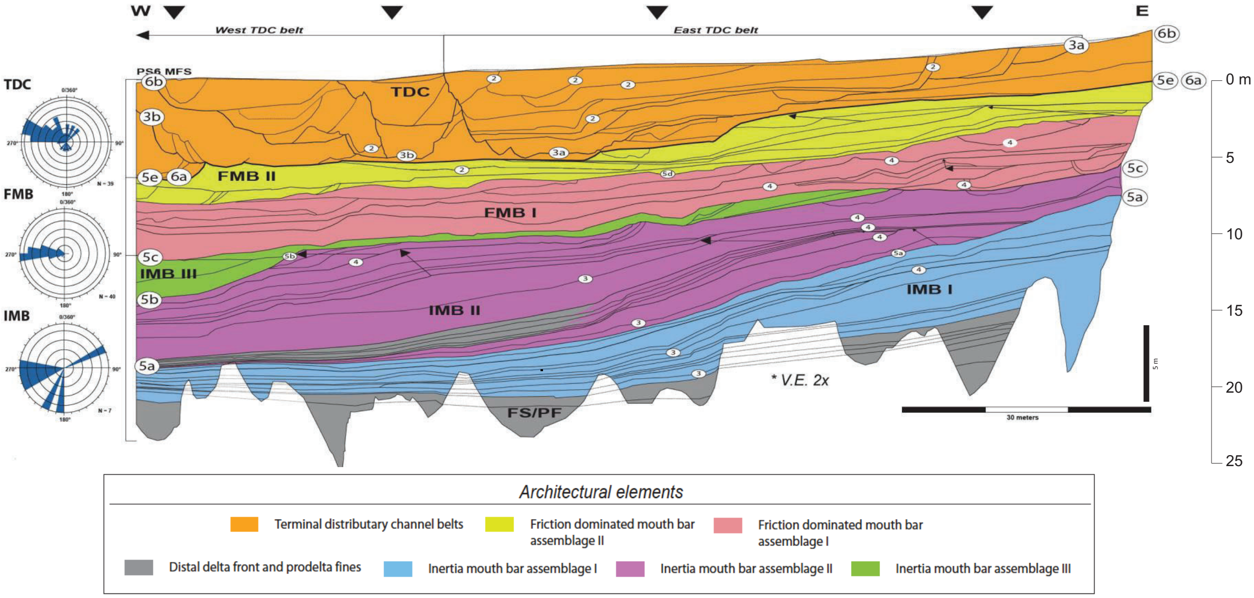


Figure 8. Facies architecture of mouth bar deposits and associated shales, Cretaceous Ferron sandstone, Utah (from Ahmed et al., 2014)

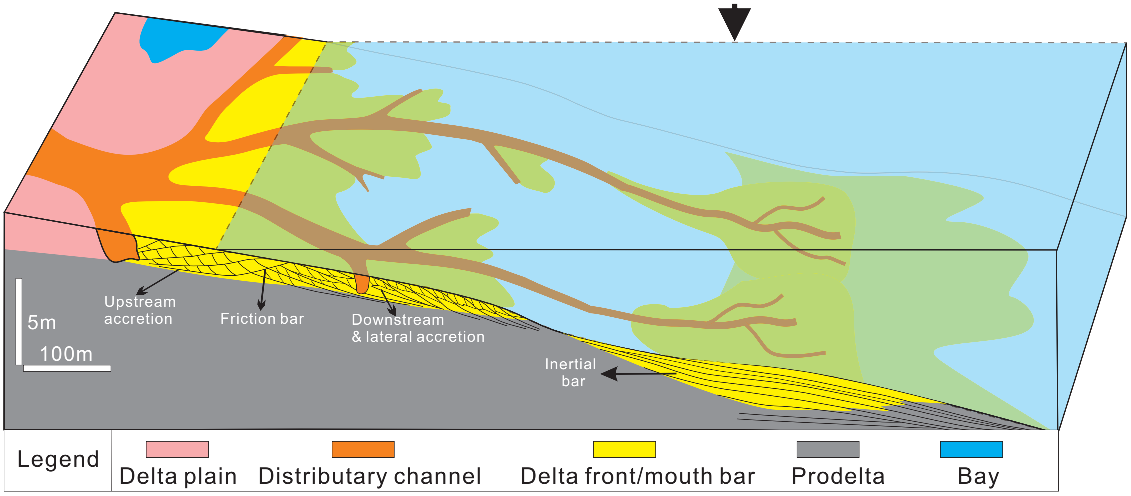


Figure 9. 3D block diagram distributary channels, mouth bar deposits and associated shales, Cretaceous Ferron sandstone, Utah.

What is the along-strike variability within sequences, systems tracts and parasequence?

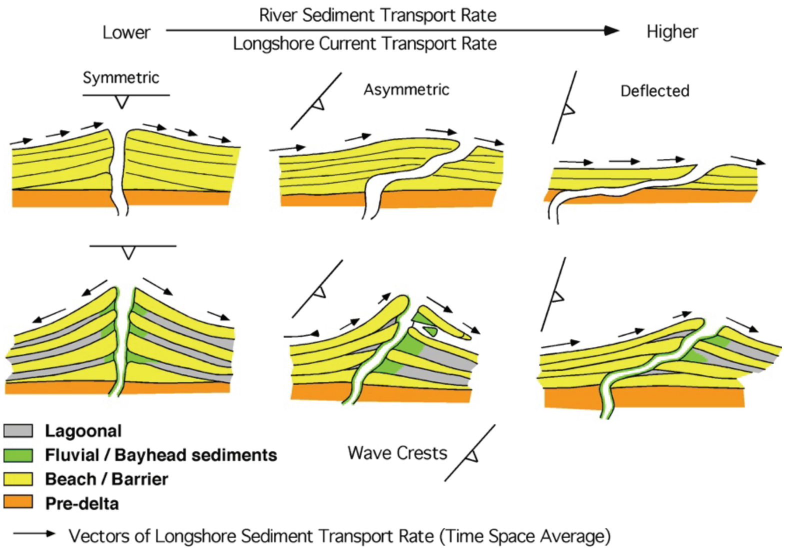


Figure 10. Delta asymmetry as a function of wave-approach. As river discharge decreases relative to alongshore wave-energy, deltas transition from asymmetric to deflected, from Bhattacharya and Giosan (2003).

Bhattacharya and Giosan (2003) suggested that many so-called shoreface deposits, such as are common in the Cretaceous Interior Seaway of North America, are more likely to be components of prograding asymmetric wave-influenced strandplains that have both wave and lesser river-dominated components (Figs. 10 and 11). We are re-evaluating many of these previously interpreted "shoreface" deposits to evaluate the along-strike variability both between parasequences (looking for evidence of autogenic lobe switching) as well as internally to evaluate how river-dominated components pass laterally into wave-dominated shorefaces. Parasequences in the Ferron Sandstone show pronounced asymmetry, with shoreface deposits predominantly to the northwest, and more fluvial influenced, and heterolithic river-dominated deltaic facies to the southeast (Li et al., 2011; Fig. 11). These ideas have been well-tested in the Ferron Sandstone in Utah, but are also important in the Gallup Sandstone in New Mexico (Kreuger, 2009, LoParco, 2011). We are also looking in more detail at the prodelta facies, within these systems, documenting along-strike variability in the muddier facies, which has applications to characterization of thin-bedded, tight, and unconventional reservoirs.

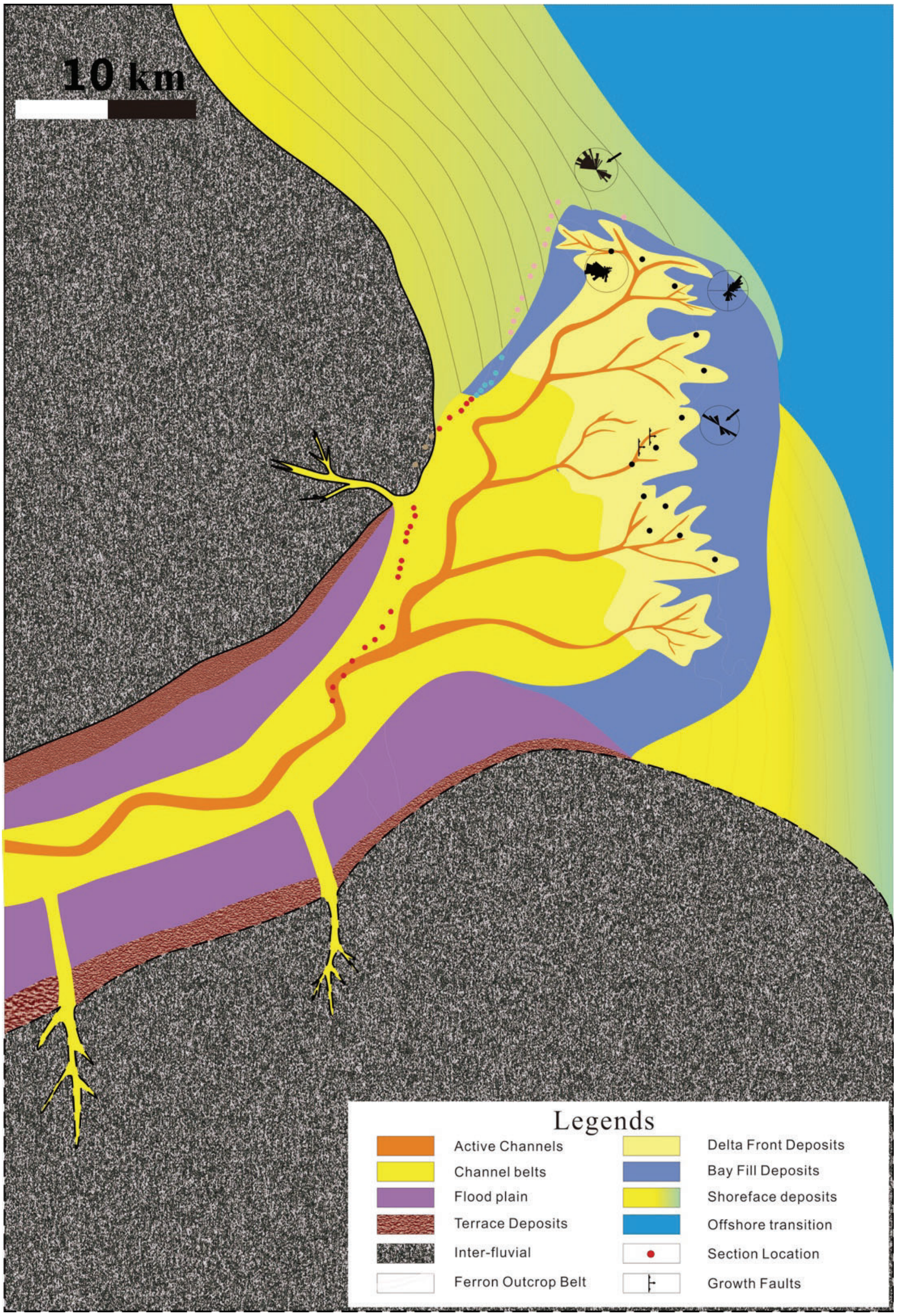


Figure 11. Paleogeographic reconstruction of parasequence 6 in the Cretaceous Ferron Sandstone, Utah. Feeding river is fixed within an incised valley (Sequence 2 in Fig. 3). Note alongshore transition from a wave-dominated shoreface into a river-dominated delta (from Ahmed et al., 2014).

What features are critical in reservoir characterization?

Key controls on fluid flow in conventional siliciclastic oil and gas reservoirs are variations in porosity and permeability. First order controls are typically the extent and proportion of flow-retarding shales versus more permeable sandstones. Shale architecture and distribution is thus critical. However, shale reservoir characterization must be understood to be a component of the overall facies architecture and is best understood if it can be linked to a sandy depositional element. The focus in our group is first to decipher they key sandstone architectural elements and their hierarchy (see above) and then determine the shale architecture and how it may relate to the sandstone elements (Fig. 12, Biber et al., 2017). The largest scale flooding surfaces define the basic reservoir-seal pairs within the clastic wedges, such as the Ferron, in Utah, and the Gallup in New Mexico, although channels and valleys may erode these. Smaller-scale shales may drape bar assemblages or individual bars. Where facies show tide-influence, shales may be found within cross sets. We will also provide data that will allow us to estimate the percentage of a given sandstone element that may be covered or draped by shales. High resolution Lidar scanning with Gigapan photomosiacs provide millimetric-scale imaging of shale drapes in tidally-influenced fluvial sandstone bodies (e.g., Fig. 12).

It is not clear that poro-perm data from the outcrops are required. Poro-perm has been shown to correlate well with grain size in well-sorted facies, although it typically becomes worse in poorly sorted reservoir rock. In general, we are working on relatively well-sorted sandstones and assume that grain-size and facies may be used as a proxy that can be converted into a poro-perm distribution.

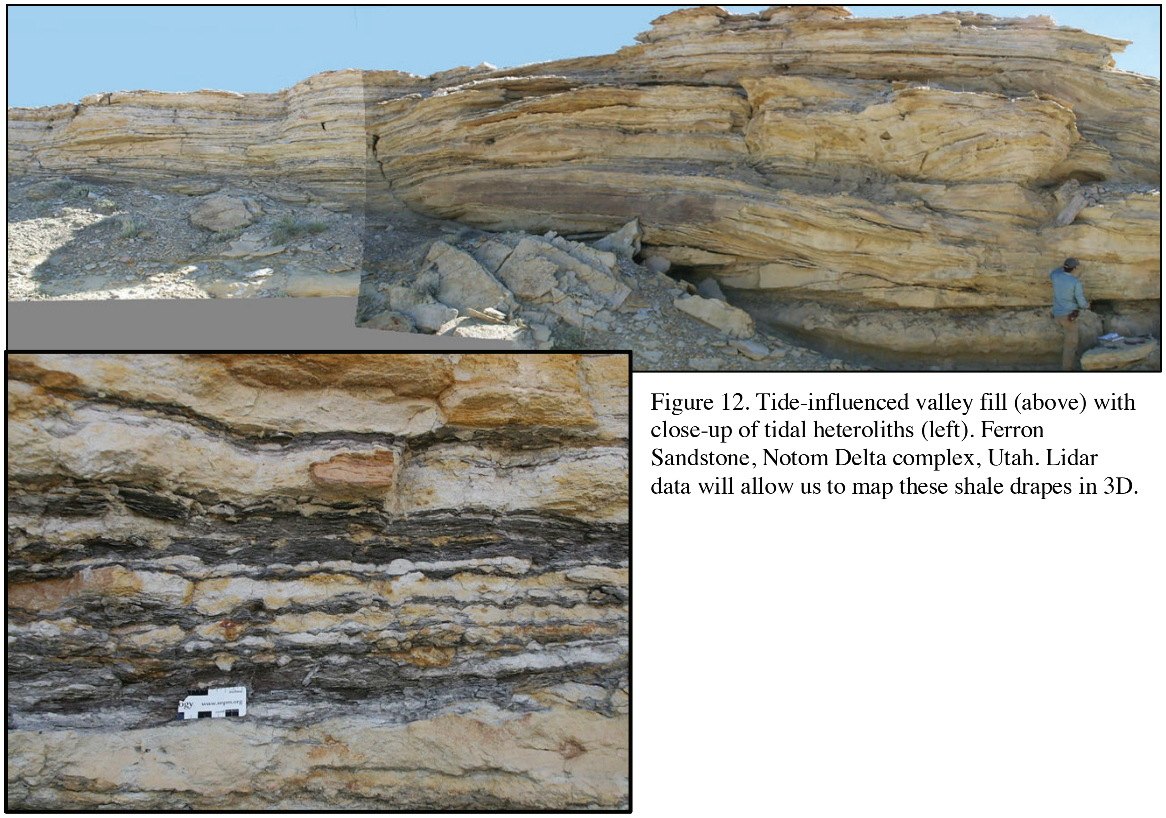


Figure 12. Tide-influenced valley fill (above) with close-up of tidal heteroliths (left). Ferron Sandstone, Notom Delta complex, Utah. Lidar data will allow us to map these shale drapes in 3D.

Sedimentology of thin-bedded reservoirs (halo plays)

Despite the historical assumptions that the bulk of marine “shelf” mud is deposited by gradual fallout from suspension in quiet water, recent studies of modern muddy shelves and their associated rivers show that they are dominated by hyperpycnal fluid mud (Fig. 13; e.g., Allison and Neill, 2003; Bentley 2003; Hill et al. 2007; Liu et al. 2009). Recent flume work shows that bedload transport is critical in the deposition of mud (Schieber et al., 2007), and storm-wave aided hyperpycnal flows are now though to be common on many modern muddy shelves. In addition, muddy coastal deposits remain under-recognized in the ancient record, despite their ubiquity in many modern coastlines (Rine and Ginsburg, 1985; Augustinius, 1989). These ideas are only now being applied to the interpretation of ancient sedimentary fluvio-deltaic systems, such as dominates the mud-rich Cretaceous Western Interior Seaway of North America (Soyinka and Slatt, 2008; Hovikoski et al., 2008; Varban and Plint, 2009; Bhattacharya and MacEachern, 2009). Detailed sequence stratigraphy is required to place the sedimentological studies in a broader framework. To date we have completed work on prodelta systems in the Tununk Shale (Figs. 13-16), which underlies the Ferron Sandstone (Seepersad, 2012, Li et al., 2015), and the Shaftesbury Shale, which underlies the Dunvegan Formation in Canada (Bhattacharya and MacEachern, 2009). We have also completed a screening study to evaluate shale provenance using chemostratigraphic techniques in the Tununk/Ferron system (Wright, 2010). We have also undertaken a preliminary study of the modern Brazos prodelta to determine the relative contribution of Brazos river- derived clay versus along-Mississippi mud, which migrates many hundreds of kilometers along the shelf before it is eventually trapped in the Brazos delta (Rice, 2009). Our current field area, the Gallup Sandstone in New Mexico also overlies a thick prodeltaic and shelf shale section, including the Juana Lopez Member of the Mancos Shale, and is a new focus of our ongoing studies.

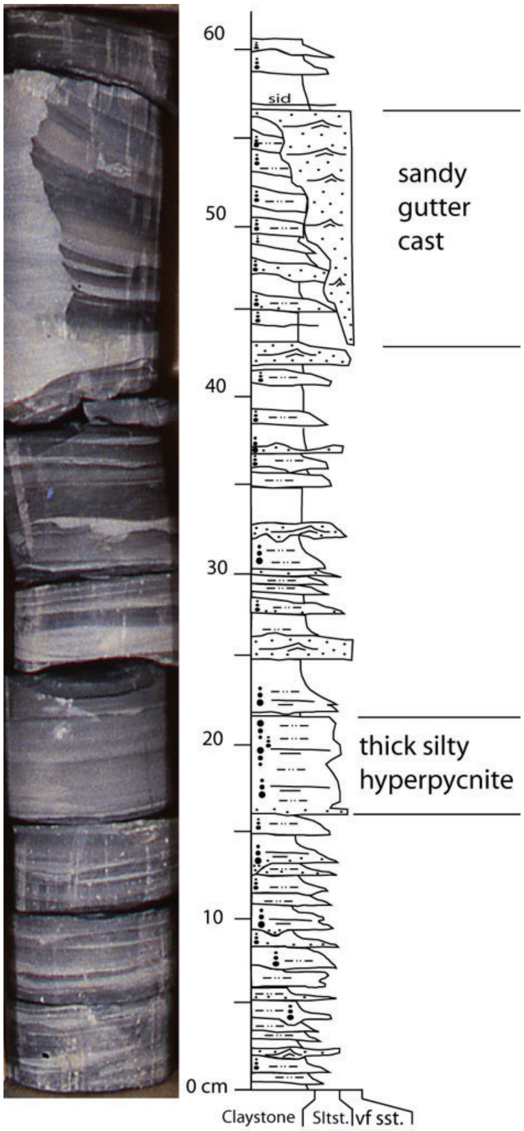


Figure 13. Prodelta facies from the Dunvegan Formation, Canada. Note the lack of burrowing and abundance of inverse graded beds, thought to be diagnostic of hyperpycnal flows (from Bhattacharya and MacEachern, 2009).

Integration of 3D drone images (Fig. 14) may be use to resolve and map thin beds (Snyder et al., 2016). We are particularly interested in understanding the various depositional processes of shelf facies and in particular determining how these reflect the geometry, connectivity and anisotropy. For example, are storm beds better thought of sheets, pods, pancakes, ribbons, or strings? High-resolution photographic and drone images may allow us to determine variations in lateral dimensions of key facies and/or thin beds (Fig. 14).

Remote sensing techniques

Two methods of observations are integrated to map heterolithic thin-bedded facies of the distal delta front in Utah: 1. high resolution, geometrically accurate laser scanning (TLS) using drones (Fig. 14), and 2. traditional sedimentological data such as measured sections, and facies analysis (Snyder et al., 2016). The focus is on prodeltaic and thin-bedded deltaic facies, which are highly variable, ranging from mudstone to interbedded planar-bedded to hummocky cross-stratified sandstone, as well as heterolithic facies deposited within storm-influenced, river-dominated delta fronts (Fig. 14). Remote sensing technologies (i.e., drones) are coupled with facies analysis to provide continuous maps of grain size and lithology, as well as calibration of depositional gradients and facies changes. Typically, these features are interpolated using more traditional field methods, such as linear interpolation between measured sections (control points). The rapid data collection possible with drones allows more efficient and more complete reservoir characterization data sets to be obtained, especially in thin-bedded reservoir analogs, which is a focus of this research. Thinning ratios can used to make maps (Fig. 15) that show the distribution of individual thin beds.

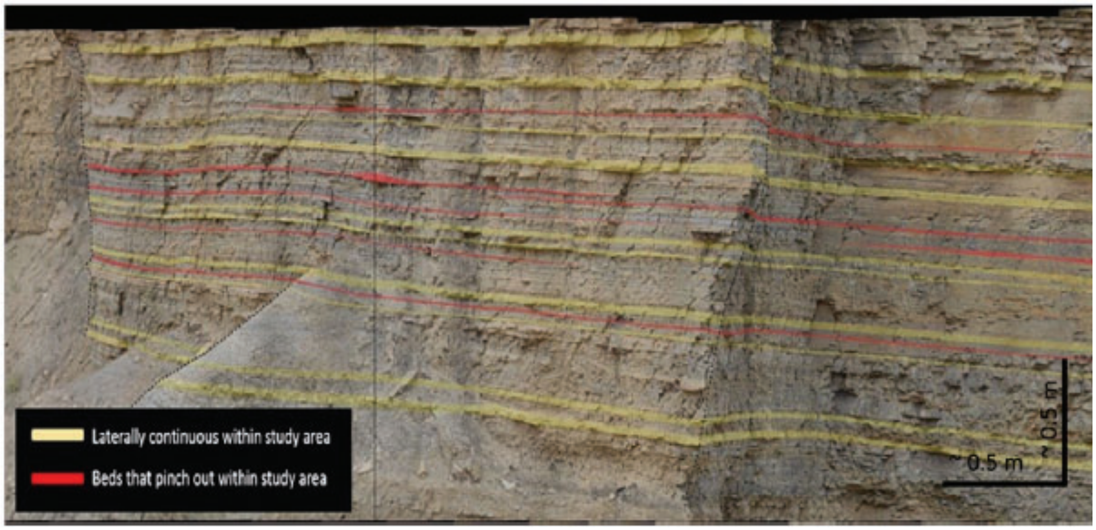


Figure 14. Thin-bedded prodelta facies in the Ferron Sandstone, Utah with mapped beds (from Snyder et al., 2016)

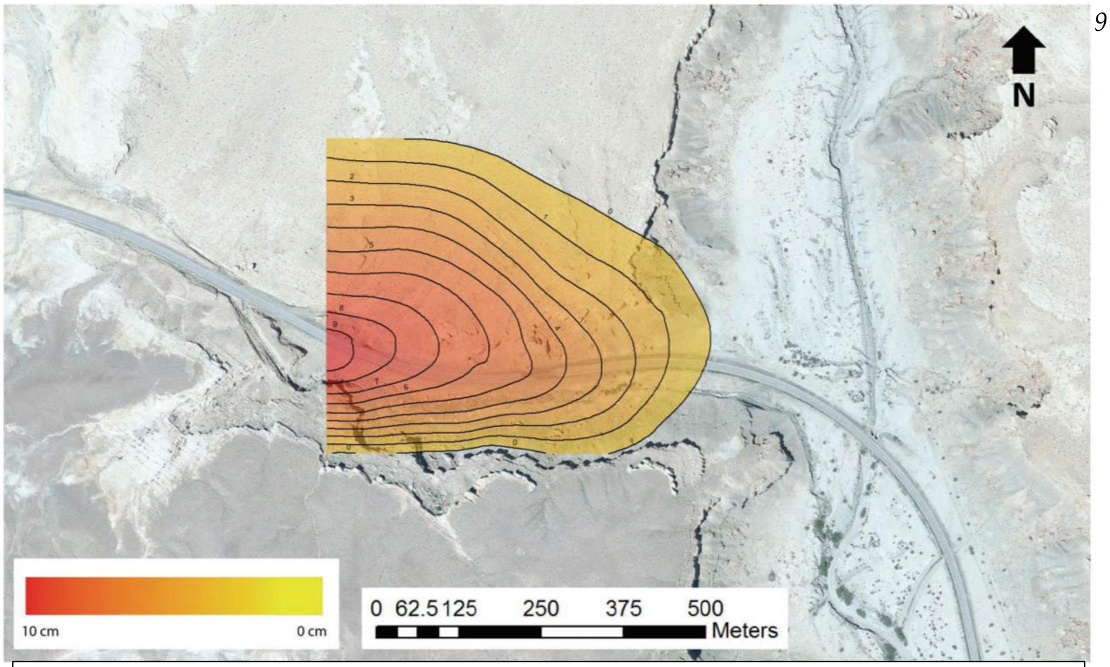
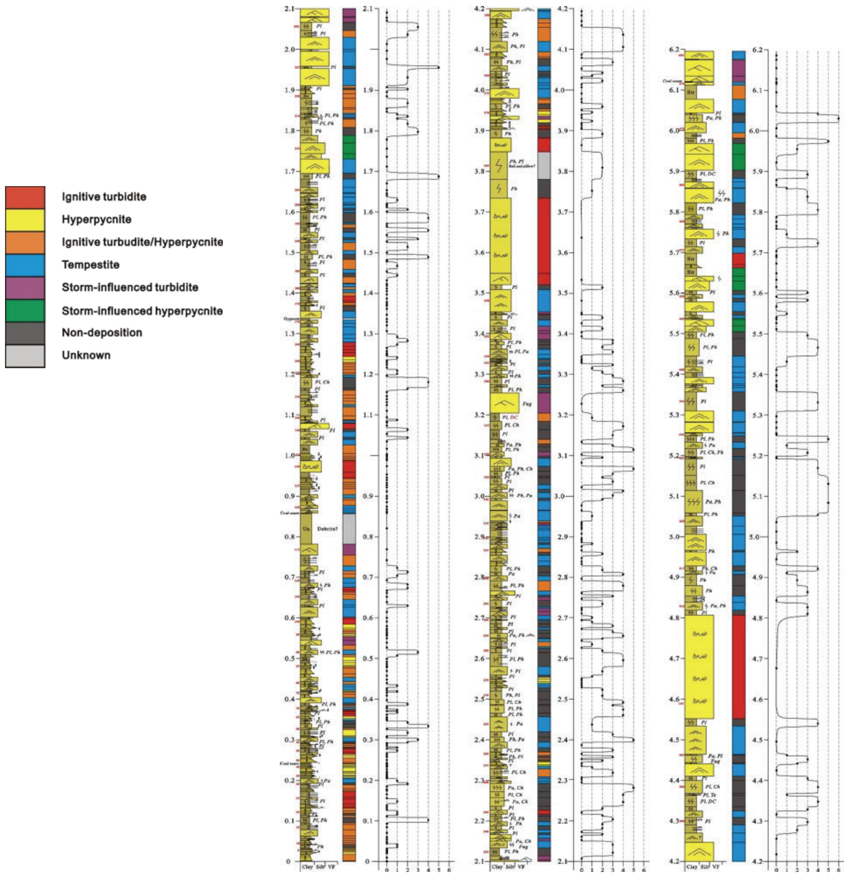


Figure 15: Isopach map of thin bed, showing likely shape and thinning direction (from Snyder et al., 2016).

Extremely detailed measured sections of individual event beds in thin bedded shelf and prodelta facies are required to document the range of formative processes, such as river-fed turbidites and hyperpycnites versus storm-beds (tempestites) or wave-enhanced sediment gravity flows (McQuaker et al., 2010, Lazar et al., 2015) and we have used these data and newer concepts in the literature to document lateral variability of facies and processes in thin-bedded prodelta and shelf facies (Fig. 16).

We are currently conducting a detailed study of the Mancos Shale in the San Juan Basin, including the Juana Lopez Member.



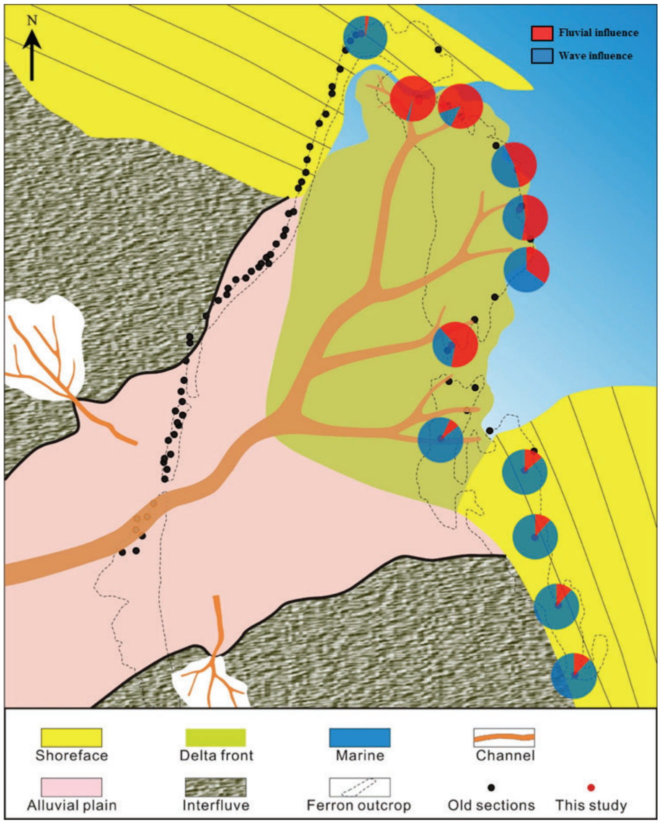


Figure 16. Centimetric-detailed measured section through proximal prodeltaic thin-bedded facies of Parasequence 6 in the Ferron Sandstone. Map shows how thin-bed processes vary regionally in a mixed wave-influenced and river-dominated system (from Li et al., 2015).

Specific Projects

Gallup Sandstone, San Juan Basin, New Mexico

1. High-resolution Sequence stratigraphy, shoreline trajectory, and implications for Cretaceous sea-level changes (Figs. 17).
2. Facies architecture of asymmetrical storm and wave- influenced deltas.
3. Non-marine sequence stratigraphy of the Gallup and Crevasse Canyon formations, New Mexico (Fig. 18).
4. Forced regressions and link between the marine and non-marine expression, Gallup Sandstone, New Mexico
5. Analysis of the origin of thin-beds in prodelta and shelf shales of the Juana Lopez Member of the Mancos Shale, New Mexico (Figs. 19-20).

Ferron Notom Delta Complex, Utah

1. Facies architecture and sequence stratigraphy of wide compound valley systems, Cretaceous Notom Delta complex, Ferron Sandstone, Utah.

More details of these projects can be found on the following website:
https://qsl.mcmaster.ca

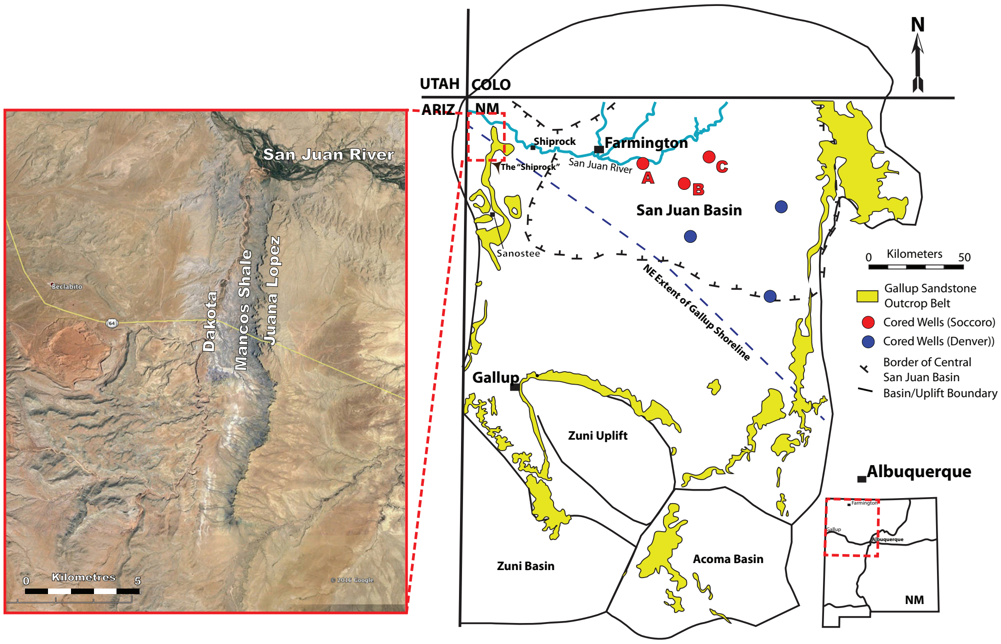


Figure 18. Base map showing outcrop of Mancos Shale (left) and location of cored wells.

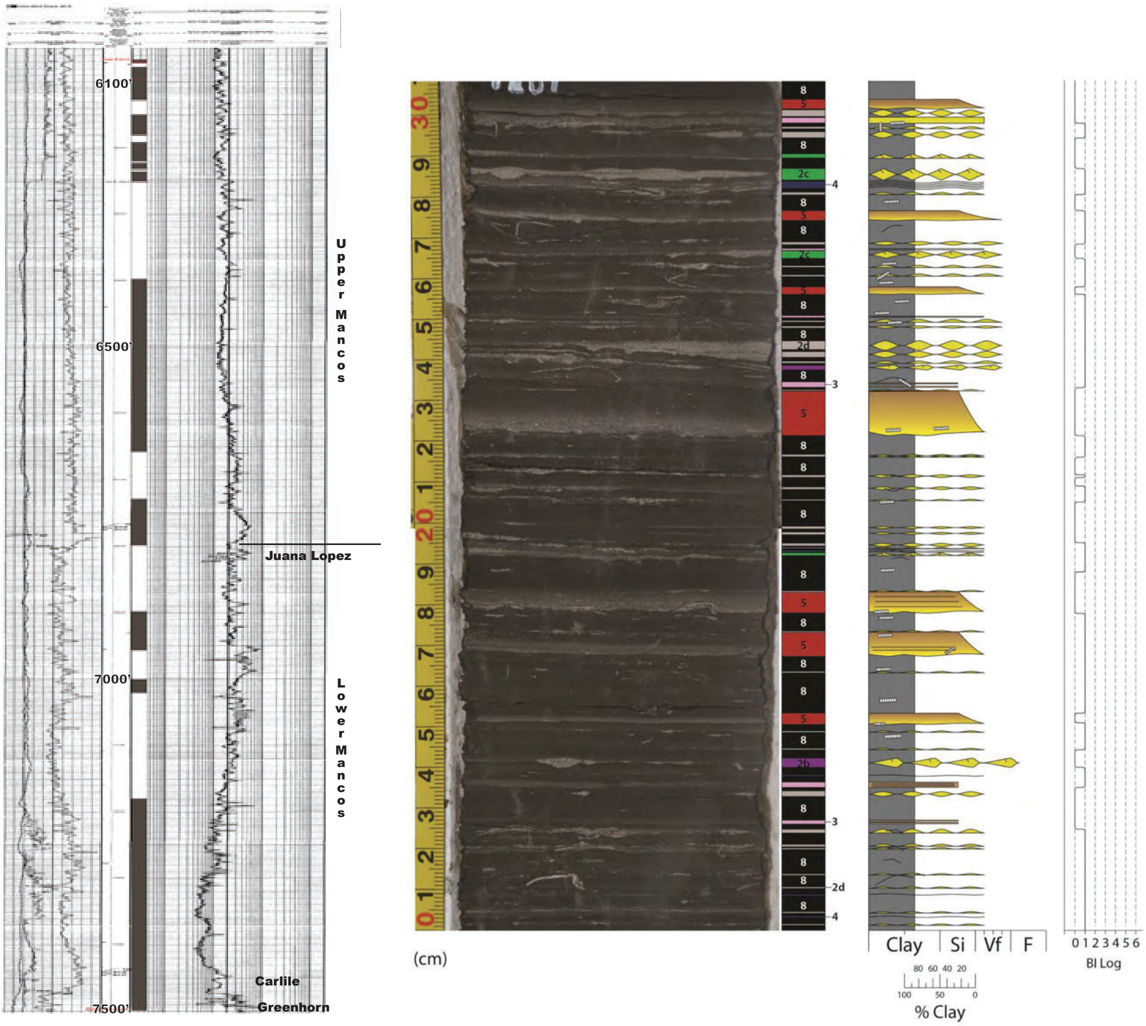


Figure 19. Well log (left) of the Mancos Shale showing cored intervals. This well has nearly 1000' of core. Above - Detailed analysis of thin beds from core of the Mancos Shale.

Costs and Benefits

The consortium-funding fee of $US40,000K per annum is structured to cover all of the costs associated with supporting one graduate student for a year. Funds are also used for PI travel to the field and to conferences. In return for your support, the research group will present a yearly report of activities to the sponsoring company at an annual meeting in the spring. More extensive reports (pre-prints), oral presentations (Powerpoint) and Posters are all provided, via a proprietary web-based format (primarily as pdf files) that can be printed or used internally at your own convenience and discretion. Membership immediately allows you access to the already built websites. These proprietary websites are password protected for the sole use of consortium members. We also run a yearly field trip, usually in mid-August, to illustrate the outcrop examples that we are conducting research on. These field trips are marvelous training opportunities for your staff, and also provide an intimate view of the latest research that we are conducting. Many of our outcrop studies have re-examined classic outcrops used in industry training, and have included the Ferron sandstone, Blackhawk-Castlegate sandstones and Panther Tongue sandstone in central Utah, as well as the Frontier sandstones in Wyoming.

Also, we would be interested to discuss the opportunities of specific projects, cores, or data sets that you have that I could have a student work on as part of their MS or Ph.D. research project. Such ”gifts in kind” would also be encouraged and would give students valuable interaction with industry.

You have access to new ideas and concepts, research breakthroughs, data, PowerPoint visuals, and posters, as they are completed, versus the larger community that only has access to the final published papers, which routinely appear several years after work has been completed. You also have access to PI's and students via in house visits and the annual field trip.

Current McMaster Research Team:

Staff: David Kynaston (PhD), Post-doctoral Research Assistant

PhD Candidates (expected date of completion)

Sandeep Sharma (2020) Sequence stratigraphy and facies architecture of the Torrivio Sandstone, San Juan Basin, New Mexico.
Nick Randazzo (2021) Geochemistry of bentonites and organic shales, Mancos Shale, San Juan Basin, NM
Jeremy Gabriel (2021) Sedimentology and chemostratigraphy of the Mancos Shale, San Juan Basin, NM.
Tuoyu Wu (2022) Subsurface Sequence Stratigraphy of the Gallup Sandstone, NM

MS Candidates (expected date of completion):

Rachel Nelson (2020) Biostratigraphy of the Mancos Shale

BS Candidates (expected date of completion):

Ryan Norris (2020), Jesse Brown (2020), Katrina Fries (2020), Brayden Ralph (2020)

Recent QSL Publications:

Akyuz, I., Warny, S., Famubode, O., Bhattacharya, J.P., 2016, Palynology of the Turonian Ferron-Notom Sandstone, Utah: identification of marine flooding surfaces and Milankovitch cycles in subtropical, ever-wet, paralic to non-marine paleoenvironments. Palynology, v. 40 (1), p. 122-136.

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