Research Prospectus:

Quantitative Sedimentology Research Consortium

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Introduction

The quantitative sedimentology research program is a joint program betwen McMaster University and the University of Houston, focused on investigating the 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 currently from shallow marine, paralic and fluvial strata. Despite the continued importance of these reservoir types, ours is one of only a few research programs 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 additional consortium funds. Consortium members are also free to suggest possible additional research topics and we encourage collaboration, especially in applying our analog studies to actual subsurface reservoirs.

General research interests

- Clastic facies models with an emphasis on the 3D facies architecture of shallow marine and fluvial depositional systems.
- Sequence stratigraphy of shallow marine to non-marine systems.
- The effects of structure and tectonics on facies architecture and stratigraphy.
- Quantitative description and modeling of modern and ancient deltas
- Shale architecture
- Origin of shelf mud belts.

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.

What is the diachroniety and chronostratigraphic significance of incised valleys and sequence boundaries?

Strong and Paola (2008) recently 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 evaluate the chronostratigraphic significance of outcrop2D and 3D facies architecture of valley fills (Fig. 1). The number of erosion surfaces and cyclic fill patterns help to elucidate the genetic relationships. Integrating this with chronometric age dating of bentonites and finally Wheeler analysis allows us to evaluate the chronostratigraphic significance of nested erosional surfaces (Fig. 1). Initial results (Bhattacharya, 2011; Holbrook and Bhattacharya, 2012; Li et al., 2010; Li and Bhattacharya, 2013) appear to concur with the hypothesis of Strong and Paola (2008) in showing that most valleys are compound features that record a complex and prolonged history. We plan to continue analysis of Ferron incised valleys to evaluate the complexity of these chronostratigraphic relationships. We are also initiating work on the floodplain facies to evaluate the level of cyclicity in paleosol evolution and its link to the adjacent incised valleys. New chronometric work on the bentonites provides absolute age control and helps address the rates of variable processes, such as eustasy and tectonics. This is also useful for the next question, outlined below.

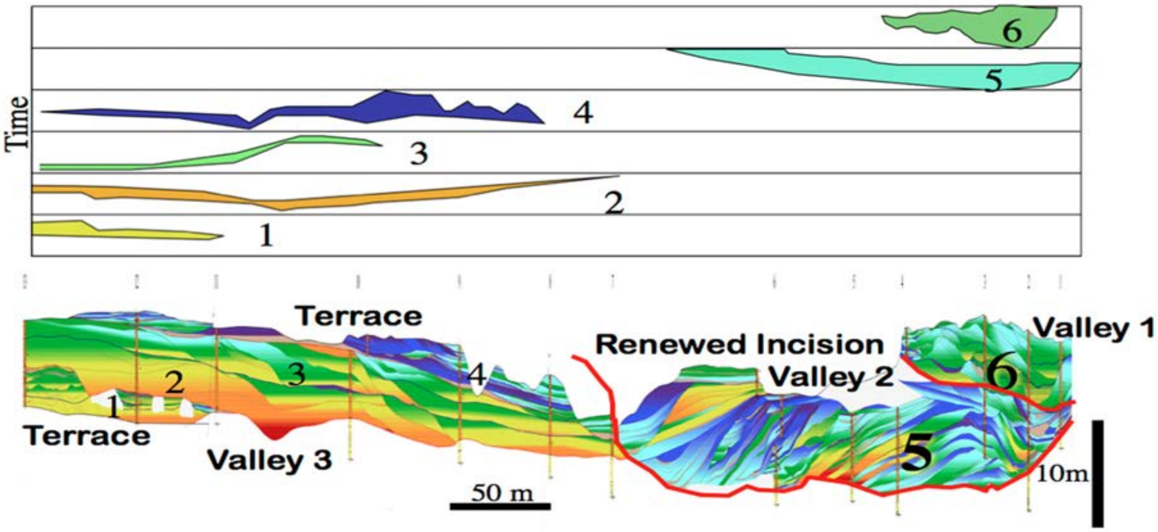

Figure 1. Cross-section of a compound valley in the Ferron Sandstone, with preserved, falling-stage terraces. Accompanying Wheeler diagram (above) emphasizes the diachronous nature of the basal erosion surface (after C. Campbell, *in prep*).

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

Bhattacharya (2011) recently synthesized work on the Cretaceous Seaway that suggests that high frequency tectonic unconformities (i.e. > 500Ka) are angular and commonly show distinct changes in provenance and paleoslope. Holbrook et al. (2006) and Holbrook and Bhattacharya (2012) have suggested that climate-controlled fluvial erosional surfaces typically will be 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. 2) 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. 1) suggest higher-frequency perturbation of the fluvial profile, likely reflecting a superimposed climate control (Li et al., 2010; Li and Bhattacharya, *in press*). Analysis of paleosols may help evaluate the importance of climate control as indicated by changes in humidity or groundwater levels, and coal types. Geometric analysis of regional stratal relationships (Fig. 2) 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. 2; Blum and Tornqvist, 2000). 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.

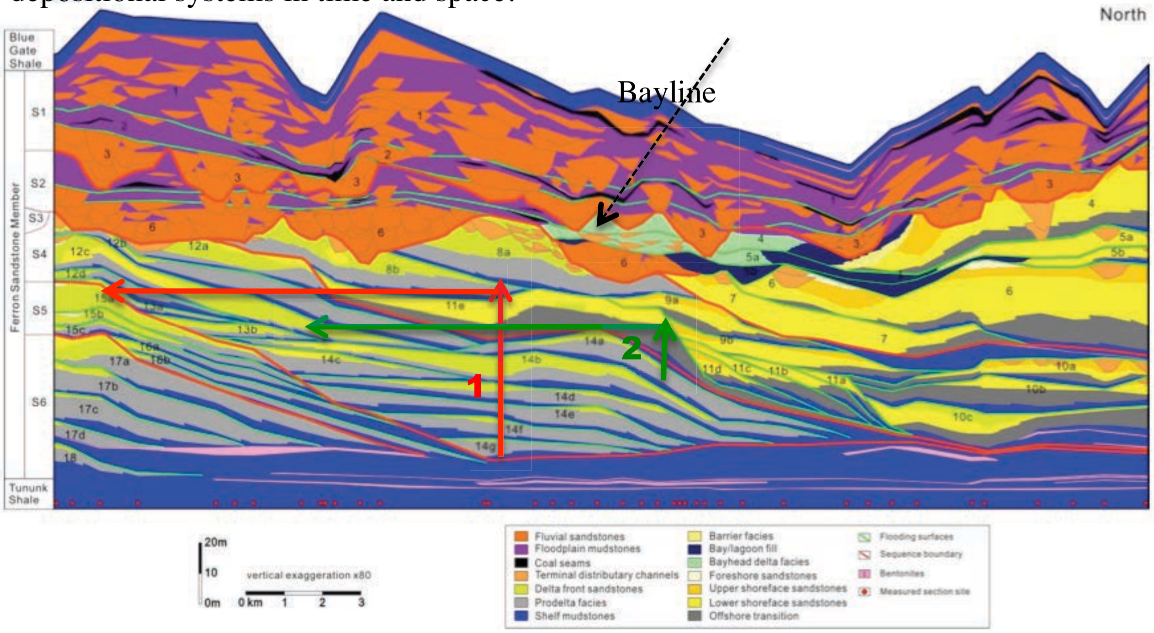

Figure 2. Regional dip cross-section through the Ferron Notom delta system shows 43 parasequences, 18 parasequence sets, and 6 sequences. Upper sequences show well-developed incised valleys. The onlap limits of the base of lowstand (1, top 15a) and top of lowstand wedge (2 - top of 11e) can be used to 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. 3D Airborne Lidar scanning and collection of preliminary GPR data across these 3D exposures has been done (Fig. 3). 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.

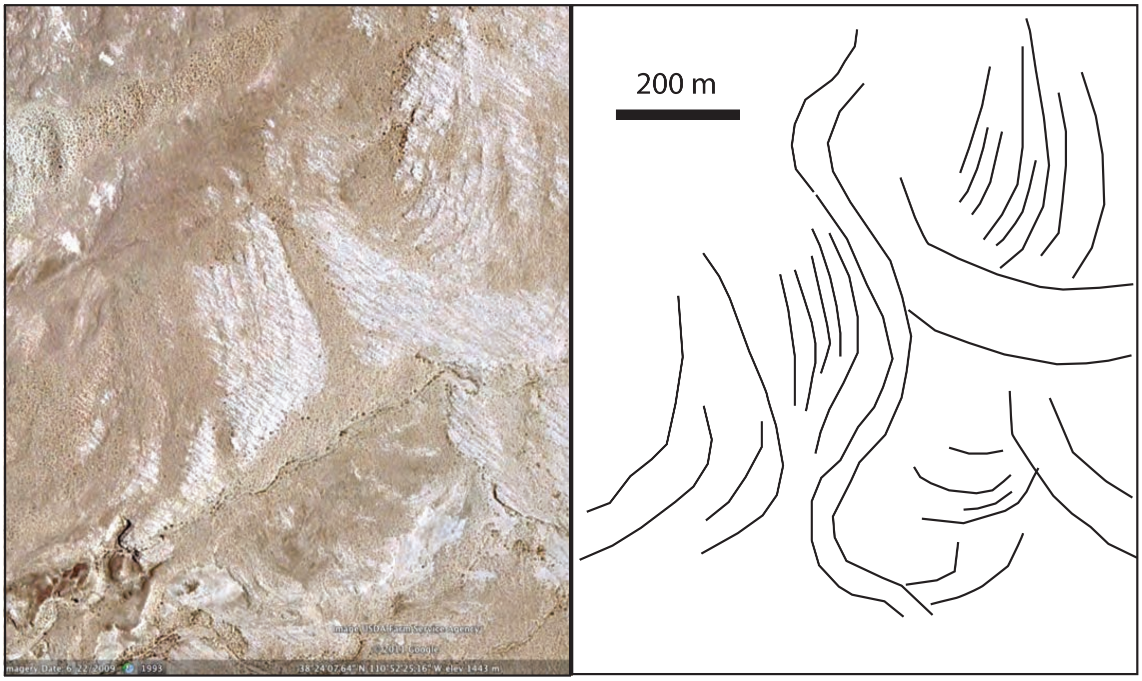

Figure 3. Google earth image and interpretation of meander scroll north of Nielsen Wash, Utah, in highstand fluvial systems tracts of Sequence 1 (see Fig. 2) of the Ferron sandstone. Channels appear to be about 75 to 100 m wide.

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. 4). 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. In this study, 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. 2 and 4). 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 (Fig. 2), 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., 2012). 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.

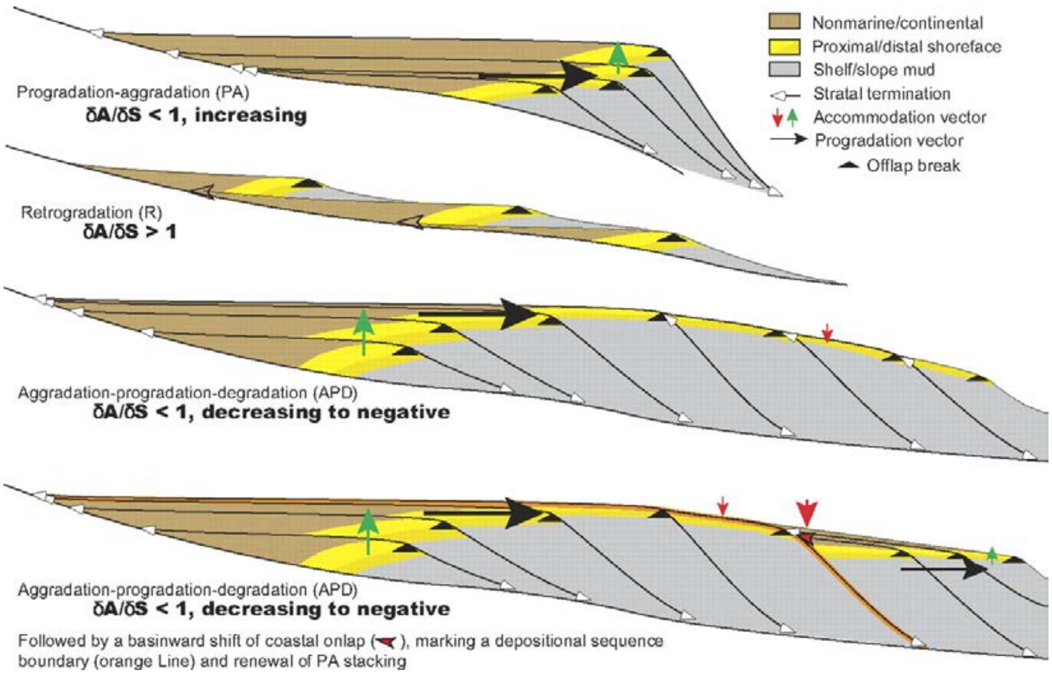

Figure 4. Accommodation successions and shoreline trajectory as a function of changes in Accommodation (**A**) and Sediment Supply (**S**), from Neal and Abreu, 2009.

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. 5). 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, 2011. Li et al., *in press*, Ahmed et al., *in press*), however most of our previous studies were in lowstand and forced regressive, highly top-truncated delta systems. The Cretaceous Ferron Sandstone example extends this earlier work to a higher accommodation setting and provides extensive strike and dip views of key elements (Fig. 6). Because of high sedimentation rates and subsidence, the Ferron Sandstone preserves 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. The data from these studies also provide abundant dimensional information that may be used in reservoir models.

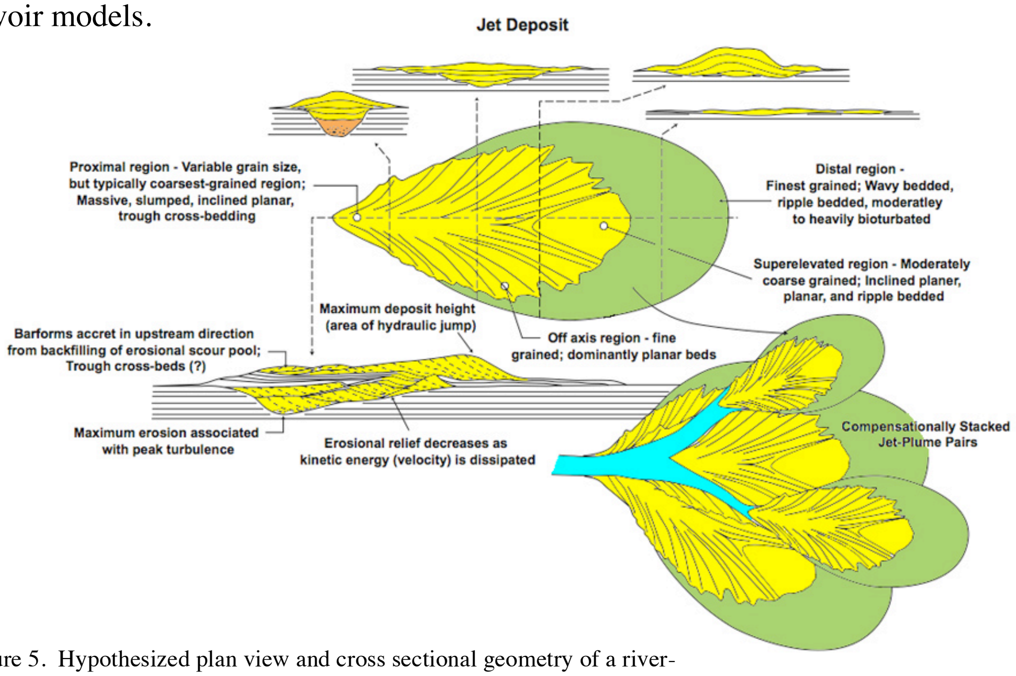

Figure 5. Hypothesized plan view and cross sectional geometry of a river-dominated delta lobe (jet deposit) showing terminal distributary channel and mouth bar deposits. Based on modern Wax Lake Delta in Atchafalaya Bay, Louisiana, and flume models. From Wellner et al. (2005).

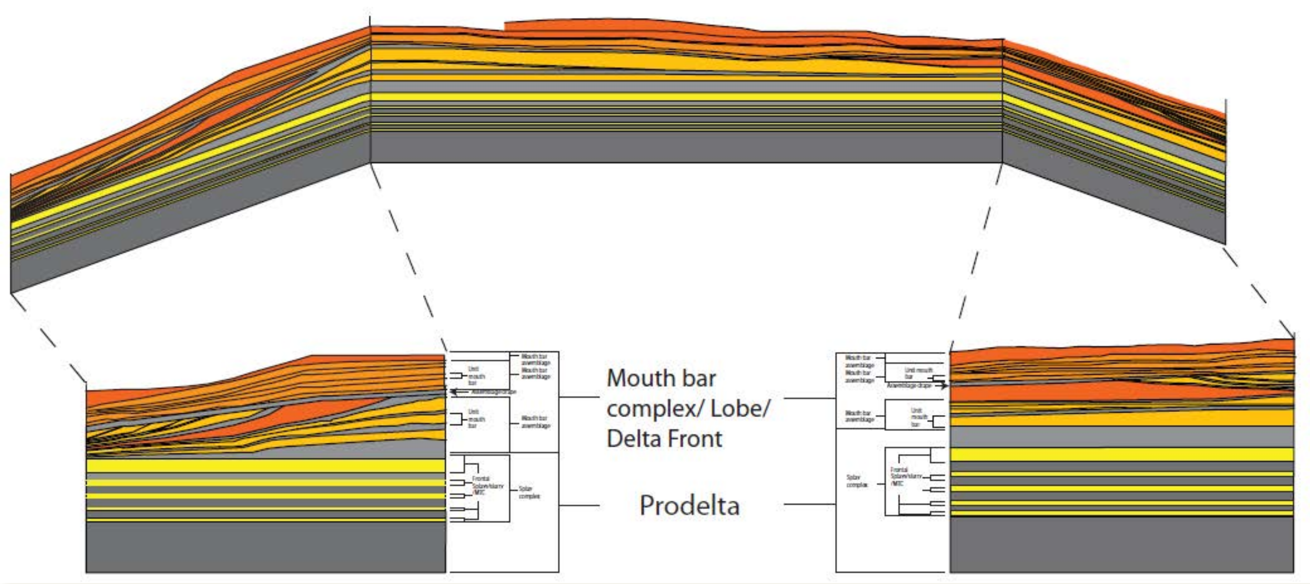

Figure 6. 3D architecture of mouth bar deposits and associated shales, Cretaceous Ferron sandstone, Utah (from Garza, 2010)

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

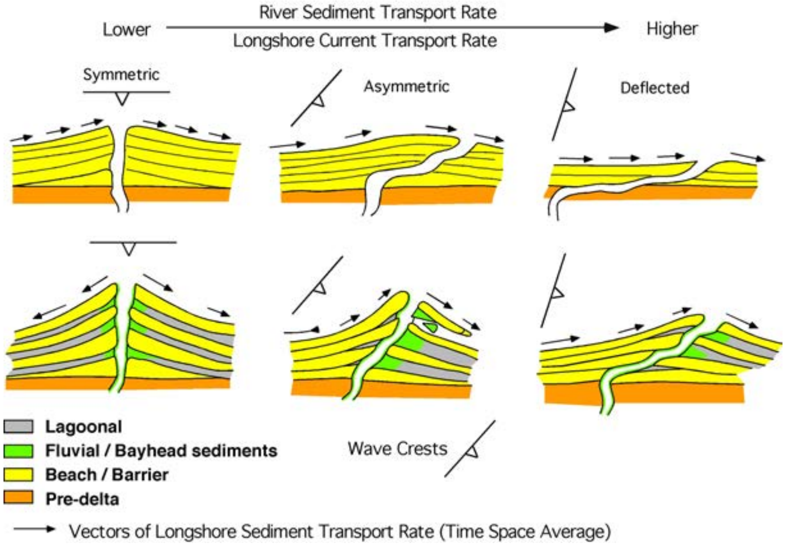

Figure 7. Delta asymmetry as a function of wave-approach. As river discharge decreases relative to alongshore wave-energy, deltas transition from asymmetric to deflected, from Bhattacharya and Giosan (2003).

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 (Fig. 7). 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. 8).

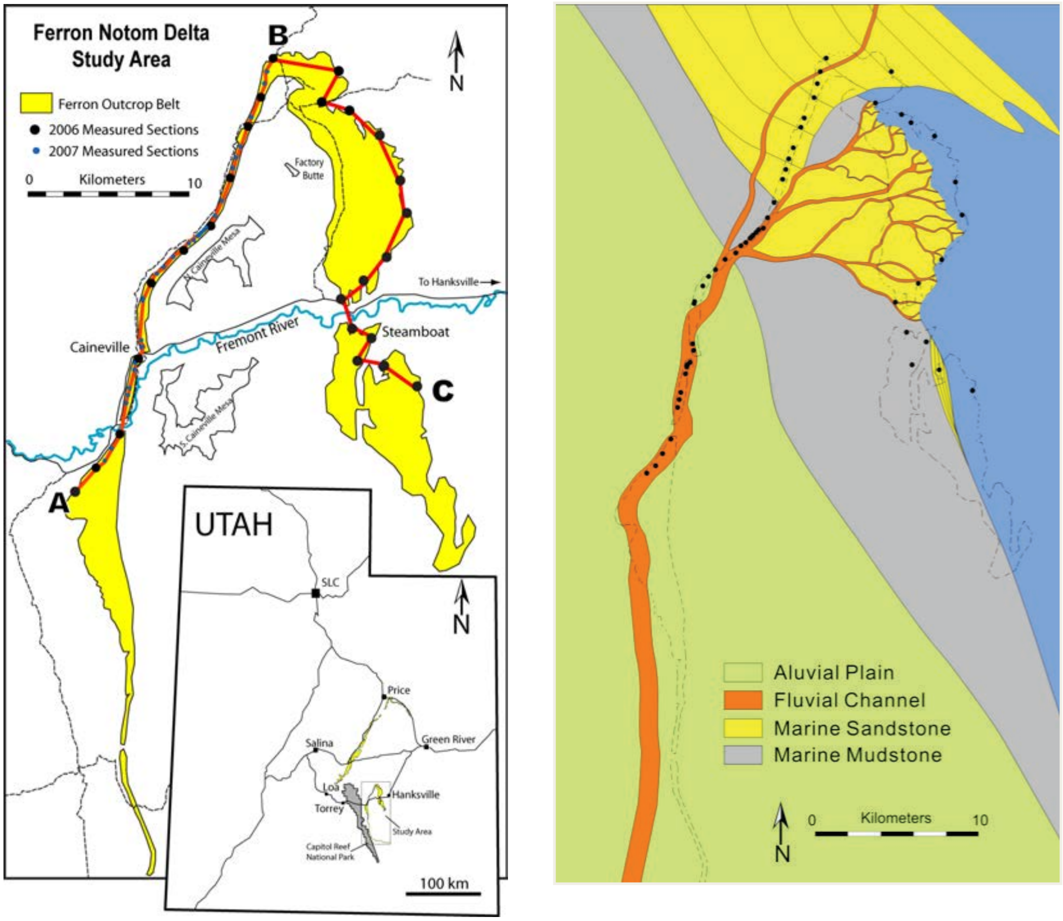

Figure 8. Base map and paleogeographic reconstruction of parasequence 6 in the Cretaceous Ferron Sandstone, Utah. Note alongshore transition from a wave-dominated shoreface into a river-dominated delta (from Zhu, 2010).

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. The largest scale flooding surfaces define the basic reservoir-seal pairs within the Ferron Notom delta, 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.

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. We have also commenced some modeling studies and seismic forward models to address reservoir geophysics and modeling issues.

Sedimentology and Sequence Stratigraphy of Shales

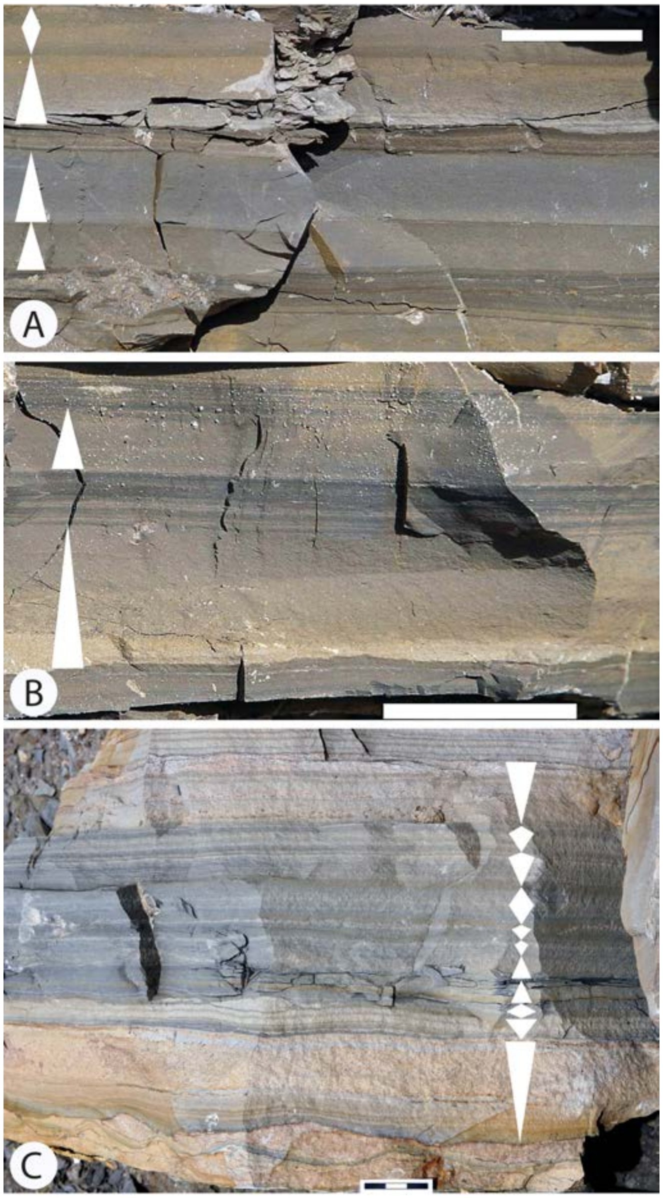

Figure 12. Prodelta and distal delta front facies at the Ferron/Tununk transition. Note the lack of burrowing and abundance of inverse graded beds, thought to be diagnostic of hyperpycnal flows (from Bhattacharya and MacEachern, 2009.

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. 12; 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, which underlies the Ferron Sandstone (Seepersad, 2012), 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-shore Mississippi mud, which migrates many hundreds of kilometers along the shelf before it is eventually trapped in the Brazos delta (Rice, 2009).

Specific Projects:

Ferron Notom Delta Complex, Utah

1. Facies architecture and sequence stratigraphy of wide compound valley systems, Cretaceous Notom Delta complex, Ferron Sandstone, Utah.
2. Facies architecture of storm-flood dominated, hyperpycnal delta-fronts and prodelta deposits in lowstand versus transgressive systems tracts, Cretaceous Notom Delta complex, Ferron Sandstone, Utah.
3. Chemo-stratigraphy of asymmetric deltas and associated shelf mudstone deposits, Cretaceous Notom Delta complex, Ferron Sandstone, Utah.
4. Non-marine sequence stratigraphy of the Ferron Notom delta.
5. Seismic expression and reservoir modeling of the Ferron Notom Delta.
6. Correlation uncertainty in paralic and non-marine systems using sparse data sets.
7. Plan-view mapping, facies architecture, and paleogeographic and paleohydraulic reconstruction of ancient meanderbelts.
8. Analysis of the origin of thin-beds in prodelta shales of the Ferron Notom Delta.

Western Canada

1. Tectono-stratigraphic evolution of clastic wedges and the link to terrane accretion (uses detrital zircons to elucidate tectonic control on major paleogeographic changes).
2. Provenance and paleodrainage reconstruction of ancient fluvio-deltaic systems in the Cretaceous of North America.

Modern Systems

1. Unit braid bars in a meander loop, Red River, Oklahoma/Texas.
2. Sedimentology and facies architecture of the asymmetric, wave-influenced Modern Brazos Delta.
3. Scaling of dunes and unit bars in rivers and deltas.

More details of these projects can be found on the following website:

http://www.qsc.uh

Costs and Benefits

The consortium-funding fee of $35,000K 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, I 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 myself and students via in house visits and the annual field trip.

Current UH Research Team: Theses and Dissertation Topics

PhD Candidates (expected date of completion)

Proma Bhattacharya (2016) - Facies architecture and genesis of compound valleys in sequence 2, Ferron Notom Delta
Oyebode Fambode (2014) – Paleosol evolution and sequence stratigraphy, Ferron Notom Delta, Utah.
Mohammed Ullah (2015)– Facies architecture of high-net-to-gross valley systems and implication for sequence boundary identification.
Benny Wang (2014) - Seismic and reservoir modeling of asymmetric deltas.
Felipe Lozano (2014) – Seismic geomorphology of shelf edge deltas, Gulf of Mexico.
Dan Garza (2016) - Provenance analysis and paleodrainage of the Ferron Sandstone, Utah.

MS Candidates (expected date of completion):

John Ben Browning (2014) - Facies architecture of channel belts within Sequence 1, Ferron Notom Delta, Utah.
Benjamin Richards (2014) - Detailed architecture of compound valley systems in Sequence 2 of the Ferron Sandstone
Zhiyang Li (2014) - Lateral variation in muddy prodelta facies, Parasequence 6, Ferron Notom Delta, Utah
Jordan Mowery (2013) - Facies architecture and sedimentology of the Utica Shale, Ohio.

Current and Prospective McMaster Research Team:

PhD Candidates:

Wen Lin - in application process
Brendan O'Connell - application in progress
Earl Fernandes - application in progress
Sanhita Mukherjee - application in progress
Puloma Chakrabarty - application in progress
Abdulah Wahbi - enquiry
Ninghie Hu - enquiry
Jannatal Ferdous - enquiry
Anto Amboson - enquiry

MS Candidates:

Stephanie Kimmerle - application in progress
David Kynaston (2016) application in progress
Sean Parry - application in progress
Qingyang Liu - enquiry
Dana Howell - enquiry

BS Candidates (expected date of completion):

David Kynaston (2014) - Facies architecture of tidally-influenced point bars in a compound valley fill, Cretaceous Notom Delta, Utah

Harrison Martin - Scaling relationships of dunes and unit bars in rivers using remote sensing

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