3-D Facies Architecture of a Storm-, Flood -Dominated Deltaic system in the Cretaceous Ferron Notom Delta Complex

By

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Proposal submitted to the faculty of the Geosciences Department,
The University of Houston, in partial fulfillment of the
requirements for the degree of:

Masters in Science

Abstract

Three dimensional outcrop studies are essential for developing 3-D quantitative models for present day systems and reservoirs, yet there is a shortage in the literature. The Turonian Ferron Sandstone Member in Utah is ideal for outcrop studies, since multi-intersecting and continuous cliff exposures, arid climate, and sparse vegetation allow for detailed facies architecture mapping and analysis.

The present master's research proposes to apply facies architectural analysis to a fluvial-dominated delta lobe within parasequence 3a of the Ferron Notom Delta complex. Interpretation will require the use of sedimentology, ichnology, paleocurrent data, correlations, and mapping. Preliminary work suggests the environment of deposition as a storm- flood-dominated delta. A subsequent study will apply the concept of 'oceanic floods' to outcrop and to determine the role of storm versus river floods in deltaic facies development. Several measured sections, done by rappelling down cliff faces, and interpretation of photomosaics and bedding diagrams, along with paleoflow, to create a paleogeographic reconstruction of the system will be done. This will also allow a comparison of plan-view morphology versus internal facies to examine if morphology is due to reworking or construction of the complex. Mouth-bar dimensions will also be assessed from the reconstruction and placed in a sequence stratigraphic framework. This study will help with reservoir characterization of mixed-influenced deltas by showing lateral facies variability and bedding complexity and add to the understanding of facies architectural elements in deltaic systems.

Introduction

Three dimensional outcrop facies architectural studies of ancient deltaic systems are sparse in the literature even though they are highly valuable for developing 3-D quantitative models for present day systems and reservoirs (Willis et al., 1999; Gani and Bhattacharya, 2005; Giosan and Bhattacharya, 2005; Lee et al., 2005; Gani and Bhattacharya 2007). Suitably exposed outcrops are very hard to come by, especially those that show sufficient exposure to reconstruct 3-D geometry. Various conditions are required, such as multiple intersecting cliffs that show depositional strike and dip, low vegetation, and accessibility. The Cretaceous Ferron Sandstone Member of the Mancos Shale Formation in Utah is the perfect place for outcrop studies. Multi-intersecting and continuous cliff exposures, arid climate, and sparse vegetation allow for detailed facies architectural mapping and analysis (Fig. 3).

Facies architecture is the study of morphological elements of a depositional environment, such as bedforms, bars, and channels, typically bounded by a hierarchy of surfaces. The formation and preservation of architectural elements typically scales to the formative process (e.g. water depth, flow width, velocity) as well as reworking by post depositional processes (e.g. waves, tides). Facies architecture was first applied to fluvial deposits by several pioneers (e.g. Allen, 1983 and Miall, 1985) and fluvial deposits are far better characterized than deltas (Gani and Bhattacharya, 2007). Miall (1985) suggests that the facies architecture method can also be useful for other clastic environments. Miall (1985) described eight architectural elements that were found in fluvial deposits. The eight elements consisted of channels (Ch), lateral accretion (LA), sediment gravity flow (SG), gravel bar and bedform (GB), sand bedform (SB), forset macroform (FM), laminated sand (LS), and overbank fines (OF). In contrast, in deltaic systems, Gani and Bhattacharya (2007) identified 6 elements or ‘Building Blocks’ within a prograding parasequence and suggest that “these elements are among the basic building blocks of all deltas.” The 6 elements identified are prodelta fines (PF), frontal splays (FS), channel (CH), storm sheets (SS), tidally modulated deposits (TM), and bar accretion (BA). Preliminary work indicates that mass transport complexes (MTC) could also be added to that list. This suggests that with continuing research others elements could also be ‘building blocks’. There are some fundamental differences between fluvial and deltaic systems (i.e. gravel bar and bedform, prodelta fines, frontal splays) but the overall application of facies architecture analysis is the same. Other outcrop facies architectural studies include Soria et al. (2003), who described tectonically produced Gilbert type deltas in Southern Spain and noted beach deposits and sand-marl cycles, and Willis et al. (1999), who examined tide-influenced deltas in the Frontier Formation in central Wyoming. Willis et al. (1999) differentiated between cross-strata formed by dunes and cross-strata formed on seaward-migrating bar-scale bedforms and added those features to their list of ‘building blocks’. Both studies applied the facies architectural analysis method to deltaic deposits.

The importance of delta facies architecture is three fold: (1) developing descriptive parameters that will help in the prediction of delta morphology and growth, (2) defining a geometry and organization of sandbodies that can be incorporated into reservoir characterization, and (3) incorporating complexity of deltas in improved subsurface correlations (Gani and Bhattacharya, 2005a).

The aim of this study is to evaluate and interpret internal facies architecture of an ancient delta lobe, which will allow for a paleogeographic reconstruction. This study will help with reservoir characterization of mixed-influenced deltas by showing lateral facies variability and bedding complexity and add to the understanding of facies architectural elements in delta systems. This study's advantages are: top-preserved delta lobe, high-resolution mapping, and several multi-directional exposed outcrops to gather three dimensional data.

Mouth bars are of particular interest in this study, because they are a fundamental architectural element in building deltas. Most of the active sand deposition occurs in distributary-mouth bars, which can coalesce together to form complex bar assemblages, which then produce regional-scale depositional-, or delta-, lobes (Bhattacharya, 2006). Wellner et al. (2005) examined the Wax Lake Delta and described the process of mouth bar deposition and their grouping into a complex bar assemblage. When a mouth bar' height reaches near mean low sea level it is abandoned and flow from the channel moves to either side of the bar. This creates new mouth bars adjacent and seaward of the previous mouth bar and a second bar forms creating a bar assemblage.

Mouth bar size and shape are controlled by variations in flow conditions (hyperpycnal, homopycnal, or hypopycnal), angle of river plume dispersion, and forces that act on the plume (buoyant, inertial, and frictional forces and basinal processes) (Bates, 1953; Wright 1977;

Bhattacharya, 2006). There are three basic inflows that are characterized by the density of the flow with that of the ambient fluid. Hypopycnal flows occur when the inflow is less dense than the receiving fluid resulting in sediment moving over the surface of the fluid. Hyperpycnal flows occur when the inflow is denser, resulting in sediment moving along the bottom of the basin. Homopycnal flows occur when the density of inflow is equal to the density of the ambient fluid and mixing occurs throughout the basin. Each of these flows has a potentially different style of deposition (Fig.4) (Bates, 1953; Wright, 1977; Bhattacharya, 2006).

Historically, most marine deltas were believed to form from hypopycnal events, even though a river's discharge may change with seasonal climate change or as a result of major floods due to storms, which may then experience hyperpycnal flows (Bhattacharya, 2006). Small "dirty" rivers that drain high-relief small drainage basins, adjacent to tectonically active mountains (Fig. 5) in humid climates, frequently experience hyperpycnal flow conditions (Mulder and Syvitski, 1995; Mutti et al., 2003; Bhattacharya, 2006; Bhattacharya and MacEachern, in press). The question now is differentiating between hyperpycnal deposits of river-floods and the 'Oceanic floods' of Wheatcroft (2000) or storm floods; how would one interpret them in the rock record? Wheatcroft (2000) proposed the concept of "Oceanic Floods", which are short period storm events, usually affecting small rivers, such that the river and the seas respond to the same storm event. These floods are important because of their ability take rivers into a hyperpycnal state which then can bring large quantities of sediment to the shelf slopes or basin (Wheatcroft, 2000). Bhattacharya (2006) descirbes how "…hyperpycnal flows may result in thick, massive beds that typically show inverse grading at the base (associated with increasing flood discharge) followed by normal grading as the flood wanes." Also the flood deposits may display upper flow regime bedforms and indication of high sedimentation rate (i.e.

planar bedding, climbing ripples, and soft sediment deformation) associated with the high river discharge as well as a lack of bioturbation due to those stresses (MacEachern et al., 1995; Bhattacharya, 2006). This can be seen in both river-floods and storm-floods but, the presence of wave induced sedimentary structures, like those created by storm waves (i.e. hummocky cross stratification or oscillatory bedforms) can be key evidence of an association with storms waves.

Preliminary field observations suggest high sedimentation rates, upper flow regime bedforms, and hummocky cross stratification within the delta front and prodelta shelf, this indicates heavy storm influence. This study will attempt to find a link between these observations and apply Wheatcroft's concept to outcrop. This study will test river flood versus storm flood deposits by looking at sedimentary structures with a bar and its associated deposits (e.g. prodelta muds). This study will look for evidence of unidirectional flow (i.e. river input) in the presence of oscillatory flows (i.e. storm waves). This will mean that the system was in flood contemporaneously with waves influential enough to rework the sediment (i.e. storm waves).

After mouth bars are deposited, reworking done by waves and tides can change their morphology. Waves tend to rework post-depositional river deposits in a couple of ways, direct action and longshore drift. Both have a tendency to elongate mouth bars in a direction that is parallel to the shoreline (Fig. 6) (Wright, 1977; Fielding, 2005, Bhattacharya, 2006). Tides, on the other hand, rework and bisect the bars producing linear ridges perpendicular to the shoreline (Fig. 7) (Wright, 1977; Willis et al., 1999; Bhattacharya, 2006).

Reynolds (1999) created a database of widths, lengths, and thickness of ancient paralic sandstones to test sand-body dimensions vs. sequence-stratigraphic settings. Reynolds proposed that distributary mouth bars are, on average, twice as long as they are wide (Fig. 8) (avg. length ~3 km; avg. width ~6 km). Reynolds also states that sand bodies that are deposited in highstand system tracts tend to be twice as wide as those deposited in trangressive system tracts and suggests distributary mouth bars are favored during lowstands sytem tracts, tidal ridges favored during transgression, and shoreline-self sands favored during highstand system tracts. Tye (2004) measured mouth bars of the Mississippi, Atchafalaya deltas and several deltas inthe Alaska North Slope. Modal data was computed and also showed that mouth bars are twice as long as they are wide (e.g. Colville: modal length of .43 km and width of .16 km; Kuparuk: modal length of .61 km and width of .31 km; Achafalaya: modal length of .17 km and average width of .16 km). Although the modern bars described by Tye (2004) were much smaller than the ancient examples compiled by Reynolds (1999), due to the migration of the bar, both studies observed similar results.

This study of the Ferron Sandstone will also add to the various dimensions of an ancient mouth bar and will test Reynolds's suggestion on length to width ratio, by observing if this ancient mouth bar complex is twice as long as it is wide, as well as linking sand-body dimensions to sequence stratigraphic position. This will be done by mapping the mouth bar complex, creating a paleogeographic reconstruction of the plan-view dimensions, and using current sequence stratigraphic work of the Ferron Notom Delta done by Yijie Zhu.

External geometry vs. Internal facies and flood-dominated deltas

Coleman and Wright (1975) intergrated data from 34 modern deltas to develop a classification scheme based on sandbody geometry for deltas and deltaic depositional facies, when cores were available. They suggested 6 delta types that reflect the result of dynamic interacting processes, such as wave energy, climate, longshore current, and tides, which shape these deltas. Galloway (1975) also drafted a triangle diagram that incorporated the different types of deltas based on the dominant processes that controlled delta morphology namely, rivers, waves, and tides (Fig. 9). Bhattacharya and Giosan (2003) introduced a revised wave-influenced delta model, which encompasses the fluvial system versus obliquity of waves and the resulting longshore drift system. The models intent was to allow for a more precise prediction of the three-dimensional facies in wave-influenced deltas. In these mixed influence deltas, the river can act as a barrier to the longshore drift current and one would find updrift-downdrfit changes in facies architecture within a parasequence.

There are a couple of problems with today's delta classification system. People who are studying or working on deltas might have a tendency to match up their case study(ies) with the end-members of the current classification system, when most deltas are more likely to be mixed-influenced. This might cause problems with interpreters who might be looking at only one portion of the whole system, then interpreting the delta incorrectly (Bhattacharya, 2006). Also, recent studies (e.g. Rodriguez, 2000; Lambiase et al., 2003; Bhattacharya, 2006; Gani and Bhattacharya, 2007; Lee et al., 2007) have shown that plan view morphology does not necessarily reflect internal architecture of a delta. Such classification systems will mainly reflect the process responsible for reworking of the delta instead of the primary construction. Rodriguez et al. (2000) suggest a new category of delta which they termed "flood-dominated". This study of the Ferron Sandstone also aims to evaluate delta plan-view morphology vs. internal facies to test if morphology is the result of delta construction or reworking.

Geological Background

The Notom Delta complex of the Ferron Sandstone Member in the Mancos Shale Formation was formed as part of the Western Cordilleran basin associated with the warm, shallow, Cretaceous Western Interior Seaway of North American. The basin began its formation due to tectonic events that began in the Jurassic. The Cretaceous Sevier orogenic event produced fold and thrust belts, thus creating subsidence which eventually developed into a foreland basin (Fig. 10) (DeCelles and Giles, 1996; Ryer and Anderson, 2004).

Drainage of the Sevier belt and a volcanic highland system located in the west, created rivers that flowed in a general northeast direction, transporting sand and mud to the seaway. Sand and mud were then deposited as a series of deltaic complexes including the informally named Notom delta of the Ferron Sandstone Member. The Ferron Sandstone contains 3 deltaic complexes including the better studied Last Chance delta to the west (Ryer and Anderson, 2004) and the less well exposed Vernal deltaic system to the north (Fig. 11).

The formation of these complexes occurred in the Middle Turonian to Late Santonian, during a regressive time period (Hale, 1972; Garrison and Van den Bergh, 2004). Garrison (2004) believes that the Notom Delta is an overall lowstand system. Deposition began around 90.7 Ma then halted about 90.3 Ma due to a regional river avulsion which then formed the younger, backstepping Last Chance and Vernal delta complexes. The Ferron is a fluvial deltaic deposit and was divided into a lower and upper unit by Peterson and Ryder (1975). Conglomerates, sandstones, siltstones, overbank mudstones, carbonaceous shales, and coal, all occupy the upper units of the Ferron Sandstone Member. The lower units consist of fluvial shoreface and delta-front sandstones interfingering with marine shales. General climate of the study area during the Cretaceous was humid to subtropical and within a “greenhouse” cycle. Paleolatitude of the area was about 40 degrees N (Bhattacharaya and Tye, 2004).

Study Area

The outcrop is located within Coalmine Wash (Fig. 12) in southcentral Utah, U.S.A, between the towns of Hanksville and Caineville along Highway 24, and next to Factory Butte (See Fig. 3). The outcrop consists of several oblique cliff exposures varying from 12 m to about 35 m in height.

Regional stratigraphic work of the Ferron Notom Delta by Yijie Zhu (Fig. 13) and Weiguo Li (Fig. 14) recognize 25 fluvial and wave dominated parasequences that are grouped into 9 parasequence sets. This study focuses on parasequence 3a (Fig 13 & 14). They suggest that parasequence 3a is an asymmetric delta, where updrift shorefaces are attached to downdrift, fluvial-dominated heterolithic facies, as in the previously discussed models of Bhattacharya and Giosan (2003). Yijie Zhu's sequence stratigraphy places parasequence 3a in a highstand sytems tract. This research is primarily focused on the fluvial dominated portion of parasequence 3a.

Methodology

Initially seven measured sections were completed on the 3 cliff faces (Fig. 15). Each measured section was done by rappelling down the cliff face by rope. Measured sections were strategically placed in proximal, mid, and distal portions of complete bar deposits. The data collected allowed for the interpretation of a flood-, storm- dominated delta. Tools, such as a rock hammer, a hand lens, a grain size chart, a measuring tape, and a Brunton compass were used when measuring each section.

A camera was used to take pictures of the cliff faces and Adobe Photoshop software was used to merge the individual pictures into a photomosaic. The measured sections were then scanned and digitized, then superimposed on the photomosaic using Adobe Illustrator and finally correlated. Correlations were then used to draft up bedding diagrams.

Several more measured sections will be done with the same strategic positioning, where I am able to safely rappel down, in the proposed study area. Photomosaics and more bedding diagrams will also be created and then assembled together. These diagrams and paleocurrent measurements will allow for a 3-D paleogeographic reconstruction of the delta lobe. Paleocurrents will allow us to possibly differentiate between river, tide, or wave influenced architectural elements. Since the Ferron is noted to have oblique waves hitting the shoreline, paleocurrents could help to infer shoreline from longshore drift currents (Balsey, 1983).

Conclusion

The proposed reaearch will test and add the following:

1. Three dimensional facies architectural studies of ancient outcrop deltaic systems which are sparse in the literature and will add to understanding of facies architectural elements in delta systems.
2. Reservoir characterization of mixed influenced deltas
    a. Lateral facies variability
    b. Bedding complexity
3. This study will test Wheatcroft's 'Oceanic flood' concept by looking for evidence river flood deposits and storm reworking. This will be done by examining facies variation and position within one mouth bar.
4. Will add to the various dimensions of an ancient mouth bar and test Reynolds's suggestion on length to width ratio, by observing if this ancient mouth bar complex is twice as long as it is wide, as well as linking sand-body dimensions to sequence stratigraphic position. This will be done by mapping the mouth bar complex, creating a paleogeographic reconstruction of the plan-view dimensions, and using current sequence stratigraphic work of the Ferron Notom Delta done by Yijie Zhu.
5. This study aims to evaluate delta plan-view morphology vs. internal facies to test if morphology is the result of delta construction or reworking.

References

Allen, J.R.L., 1983, Studies in fluviatile sedimentation: bars, bar complexes and sandstone sheets (low-sinuosity braided streams) in the Brownstones (L. Devonian), Welsh Borders: Sedimentary Geology, v. 33, p. 237–293.

Balsley, J.K., 1982, Cretaceous wave-dominated delta system: Book Cliffs, East Central Utah, Oklahoma City Geological Society Continuing Education Short Course.

Bates, C.D., 1953, Rational theory of delta formation: American Association of Petroleum Geologists, Bulletin, v. 37, p. 2119–2162.

Bhattacharya, J.P. and Giosan, L., 2003, Wave-influenced deltas: geomorphological implications for facies reconstruction, Sedimentology, v. 50, p.187-210.

Bhattacharya, J.P., and Tye, R.S., 2004, Searching for modern Ferron analogs and application to subsurface interpretation, AAPG Studies in Geology, v. 50, p. 39-57.

Bhattacharya, J. P., 2006 Deltas, Facies models revisited., Society for Sedimentary Geology (SEPM) : Tulsa, OK, United States, Special Publication - Society for Sedimentary Geology, September 2006, Vol. 84, pp. 237-292.

Bhattacharya J.P. and MacEachern, J. in press, Hyperpycnal rivers and prodelatic shelves in the Cretaceous Seaway of North America.

Clifton, H.E., 2006, Facies models revisited., Society for Sedimentary Geology (SEPM) : Tulsa, OK, United States, Special Publication - Society for Sedimentary Geology, September 2006, Vol. 84, 293-337.

Coleman, J.M., and Wright, L.D., 1975, Modern river deltas: variability of processes and sand bodies, in Broussard, M.L., ed., Deltas; Models for Exploration: Houston Geological Society: Houston, p. 99–149.

DeCelles, P.G., Lawton, T.F., and Mitra, G., 1995, Thrust timing, growth of structural culminations, and synorogenic sedimentation in the type Sevier orogenic belt, western United States: Geology, v. 23, p. 699-702 .

Galloway, W.E., 1975, Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems in Broussard, M.L., ed., Deltas, Models for Exploration: Houston, Texas, Houston Geological Society, p. 87–98.

Gani, M.R., and Bhattacharya, J.P., 2005a, Lithostratigraphy versus chronostratigraphy in facies correlations of Quaternary deltas: application of bedding correlation, in Giosan, L., and Bhattacharya, J.P., eds., River Deltas: Concepts, Models, and Examples: SEPM, Special Publication 83, p. 31–48.

Gani, M. and Bhattacharya, J. P., 2007, Basic building blocks and process variability of a Cretaceous Delta: internal facies architecture reveals a more dynamic interactions of river, wave, and tidal processes than is indicated by external shape, Journal of Sedimentary Research, v. 77, p. 284- 302.

Garrison, J.R., Jr., The Evolution of the Southern Utah Deltaic Complex, South-Central Utah: a correlation and sequence stratigraphic analysis of the coal-bearing Notom, Last Chance, and “A” Deltas, 2005, submitted.

Garrison, J.R., and van den Bergh, T.C.V., 2004, High-resolution depositional sequence stratigraphy of the upper ferron sandstone last chance delta: an application of coal-zone stratigraphy: AAPG Studies in Geology, v. 50, p. 125-192.

Giosan, Liviu, and Bhattacharya, Janok P., 2005, New directions in deltaic studies, River deltas; concepts, models, and examples., Society for Sedimentary Geology (SEPM) : Tulsa, OK, United States., Special Publication - Society for Sedimentary Geology, August 2005, Vol. 83, pp. 3-10

Hale, L.A., 1972, Depositional history of the Ferron Formation, central Utah, in J.L. Baer and Eugene Callaghan, eds., Plateau-basin and range transition zone: Utah Geological Association Publication No. 2, p. 115-138.

Lambiase, J.J., Damit, A.R., Simmons, M.D., Abdoerrias, R., and Hussin, A., 2003, A depositional model and the stratigraphic development of modern and ancient tide-dominated deltas in NW Borneo, *in* Sidi, F.H., Nummedal, D., Imbert, P., Darman, H., and Posamantier, H.W., eds., Tropical Deltas of Southeast Asia—Sedimentology, Stratigraphy, and Petroleum Geology: SEPM, Special Publication 76, p. 109–123.

Lee, K., Gani, M.R., McMechan, G., Bhattacharya, J.P., Nyman, S., and Zeng X., 2007, Three-dimensional facies architecture and three-dimensional calcite concretion distributions in a tide-influenced delta front, Wall Creek Member, Frontier Formation, Wyoming: American Association of Petroleum Geologists, Bulletin, v. 91, p. 191–214.

Lee, K., Zeng, X., McMechan, G., Howell, C.D., JR., Bhattacharya, J.P., Marcy, F., and Olariu, C., 2005, A ground-penetrating radar survey of a delta-front reservoir analog in the Wall Creek Member, Frontier Formation, Wyoming: American Association of Petroleum Geologists, Bulletin, v. 89, p. 1139–1155.

Maceachern, J.A., Bann, K.L., Bhattacharya, J.P., and Howell, C.D., 2005, Ichnology of deltas: organism responses to the dynamic interplay of rivers, waves, storms, and tides, in Giosan, L., and Bhattacharya, J.P., eds., River Deltas: Concepts, Models, and Examples: SEPM, Special Publication 83, p. 49–85.

Martinsen, R.S., 2003, Depositional remnants, part 1: Common components of the stratigraphic record with important implications for hydrocarbon exploration and production: American Association of Petroleum Geologists, Bulletin, v. 87, p. 1869–1882.

Miall, A.D., 1985, Architectural-element analysis: a new method of facies analysis applied to fluvial deposits: Earth Science Reviews, v. 22, p. 261–308.

Mulder, T., and Syvitski, J.P.M., 1995, Turbidity currents generated at river mouths during exceptional discharge to the world's oceans, Journal of Geology, v. 103, p. 285–298.

Mutti, E. et al., 2003, Deltaic, mixed and turbidite sedimentation of ancient foreland basins, Marine and Petroleum Geology, v. 20, no. 6-8: 755-733.

Peterson, F., and Ryder, R.T., 1975, Cretaceous rocks in the Henry Mountains regions, Utah and their relation to neighboring regions, in Fassett, J.E., and Wengerd, SA., eds., Canyonlands County: Four Corners geological Society Guidebook, 8TH Field Conference, p. 167-189.

Reynolds, A.D., 1999, Dimensions of paralic sandstone bodies, American Association of Petroleum Geologists Bulletin, v. 83, p.211-229.

Rodriguez, A.B., Hamilton, M.D., and Aanderson, J.B., 2000, Facies and evolution of the modern Brazos Delta, Texas: wave versus flood influence: Journal of Sedimentary Research, v. 70, p. 283–295.

Ryer, T.A., and Anderson, P.B., 2004, Facies of the Ferron Sandstone, East-Central Utah, in Chidsey, T.C., Adams. R.D., and Morris, T.H., eds., Regional to Wellbore Analog for Fluvial- Deltaic Reservoir Modeling: The Ferron Sandstone of Utah: American Association of Petroleum Geologists, Studies in Geology, v. 50, p. 59-78

Soria, J.M., Fernandez, J., Garcia, F., and Viseras, C., 2003, Correlative lowstand deltaic and shelf systems in the Gaudix basin (late Miocene, Betic Cordillera, Spain): the stratigraphic record of forced and normal regressions: Journal of Sedimentary Research, v. 73, p. 912–925.

Scruton, P.C., 1960, Delta building and the deltaic sequence, in Shepard, F.P, Phleger, F.B., and Van Andel, T.H., eds., Recent Sediments Nortwest Gulf of Mexico: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 82-102.

Tye, R.S., 2004, Geomorphology: An approach to determining subsurface reservoir dimensions: American Association of Petroleum Geologists, Bulletin, v. 88, p. 1123–1147.

Wellner, R., Beaubouef, R., Van Wagoner, J., Roberts, H. H., and Sun, T., 2005, Jet-plume depositional bodies; the primary building blocks of Wax Lake Delta, Gulf Coast Association of Geological Societies, Vol. 55, pp. 867-909

Wheatcroft, R., 2000, Oceanic flood sedimentation: a new perspective, Continental Shelf Research, v. 20, p. 2059-2066

Willis, B.J., Bhattacharya, J.B., Gabel., S.L., and White, C.D, 1999, Architecture of a tide-influenced delta in the Frontier Formation of Central Wyoming, USA: Sedimentology, v. 46, p. 667–688.

Wright, L.D., 1977, Sediment transport and deposition at river mouths: a synthesis: Geological Society of America, Bulletin, v. 88, p. 857–868.

Figures

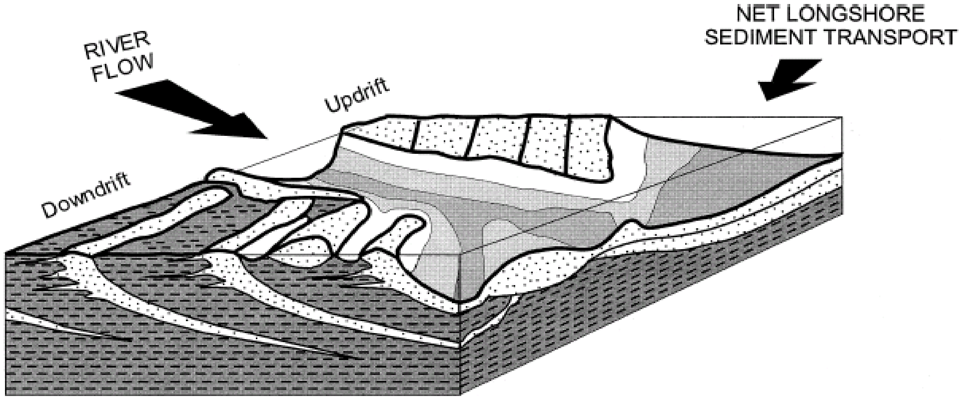
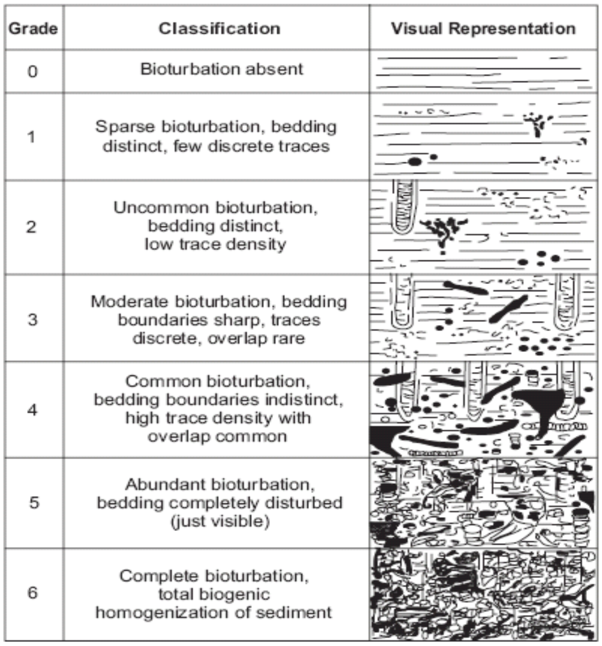


Figure 1. Asymmetric wave-influenced delta model of Bhattacharya and Giosan (2003). Updrift shoreface attached to downdrift heterolithics.



Grade	Classification	Visual Representation
0	Bioturbation absent	
1	Sparse bioturbation, bedding distinct, few discrete traces	
2	Uncommon bioturbation, bedding distinct, low trace density	
3	Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare	
4	Common bioturbation, bedding boundaries indistinct, high trace density with overlap common	
5	Abundant bioturbation, bedding completely disturbed (just visible)	
6	Complete bioturbation, total biogenic homogenization of sediment	

Figure 2. Bioturbation index of MacEachern et al. (2005).

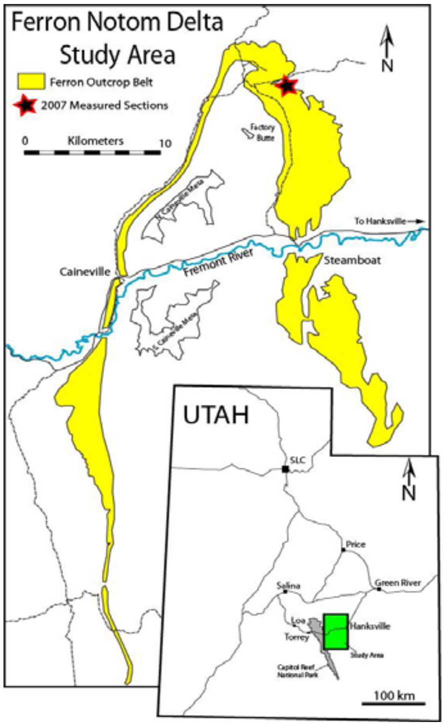


Figure 3. Continous outcrop exposure. Yellow is outcrop.

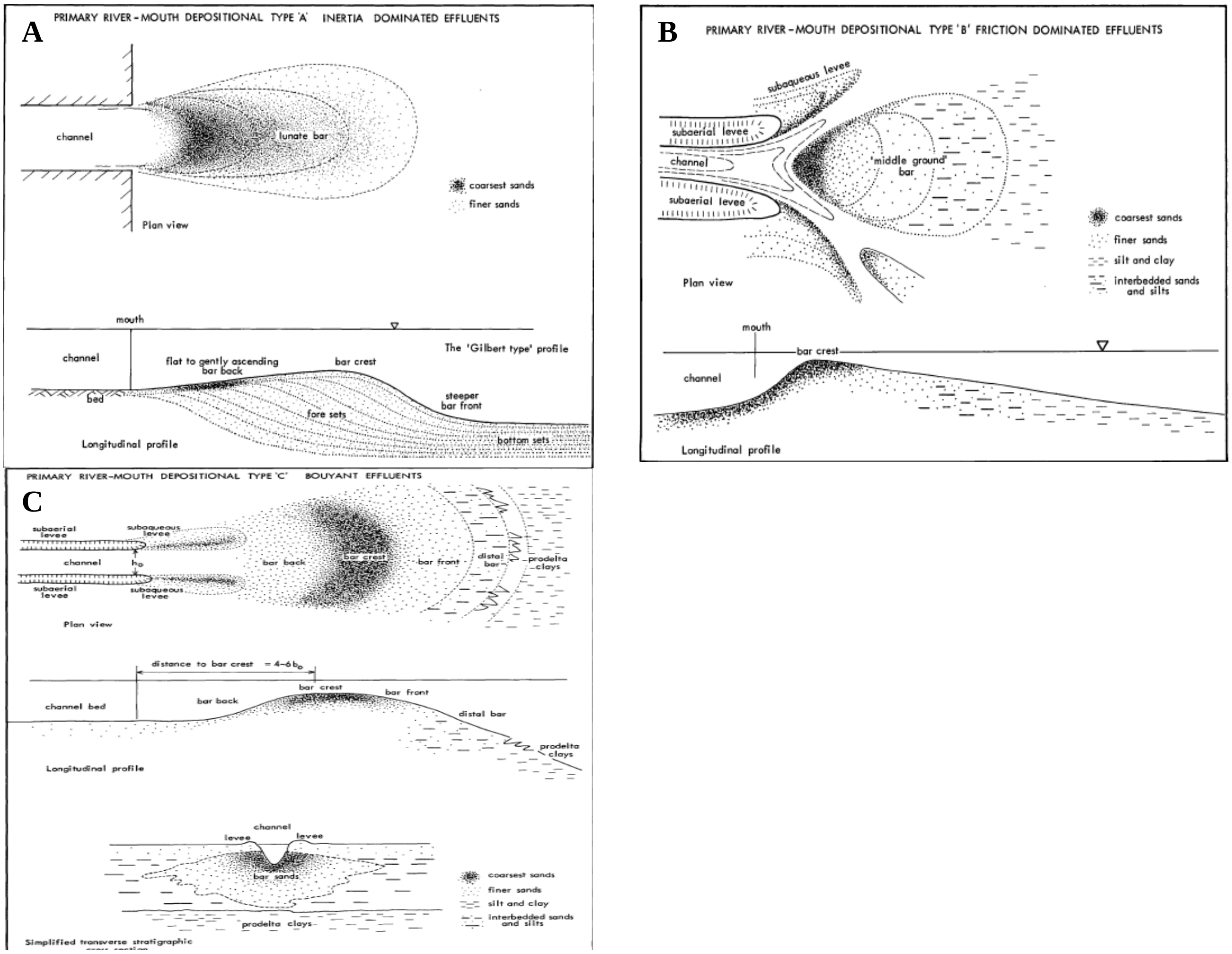


Figure 4. Wright (1977) diagram on different effluents and bar geometry. A) Inertia Effluents B) Friction Effluents C) Bouyant Effluent

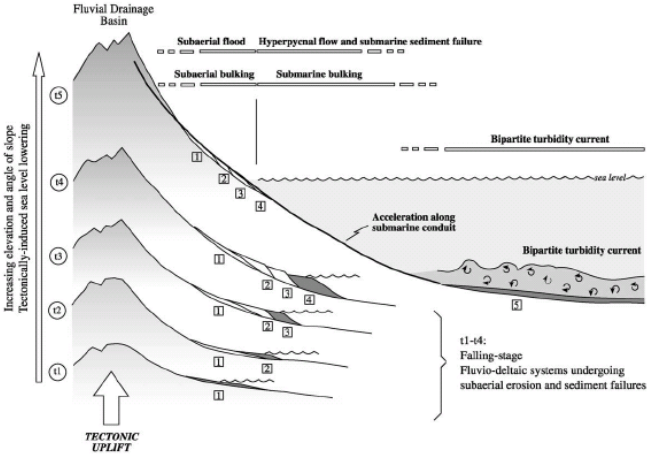


Figure 5. Tectonic and relief. Mutti et al. 2003

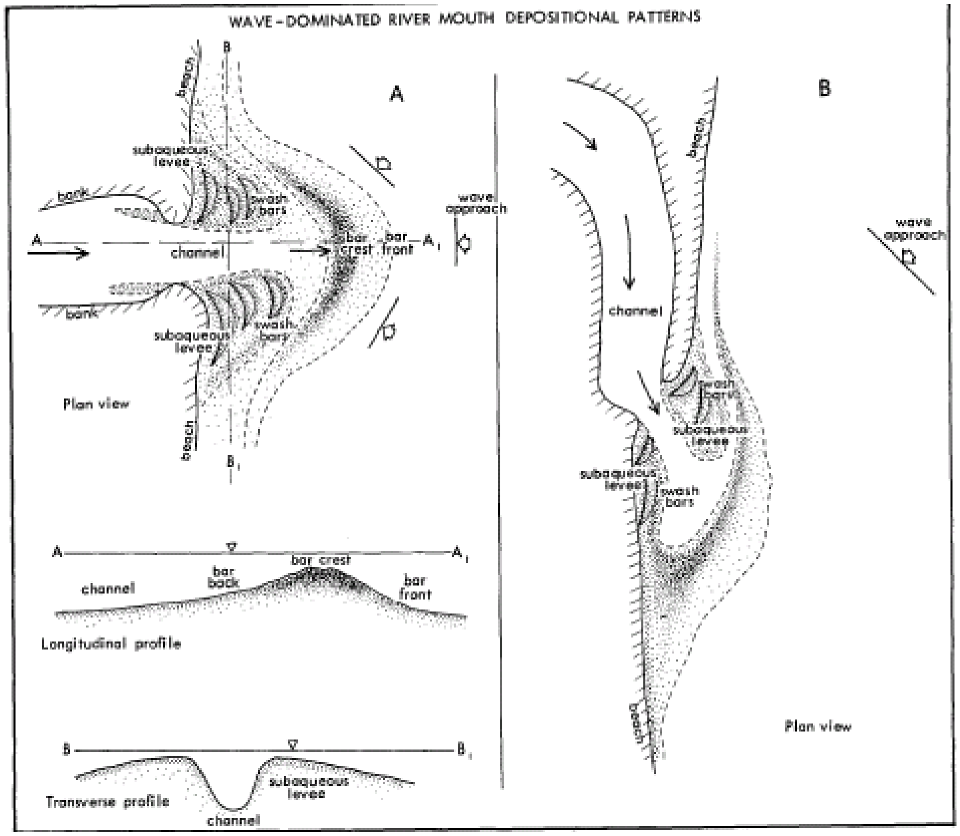


Figure 6. From Wright (1977) illustrated wave influence on mouth bar geometry.

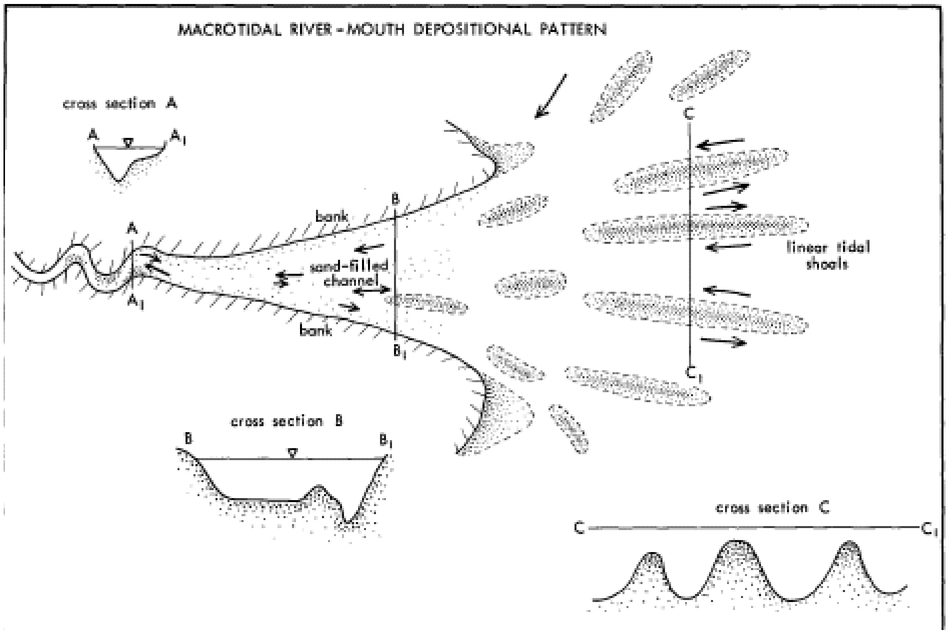


Figure 7. From Wright (1977) illustrating tidal inlfuence onmouth bar geometry.

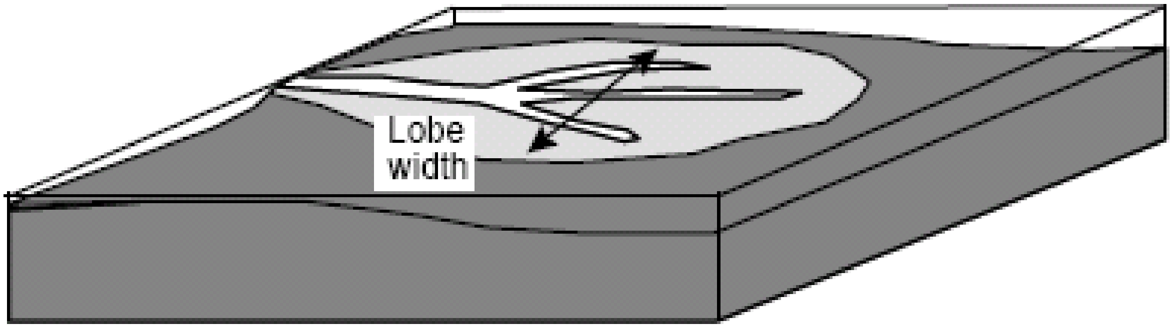


Figure 8. Reynolds (1999) illustration of a distributary mouth bar's dimensions. He suggests mouth bars are twice as long as they are wide.

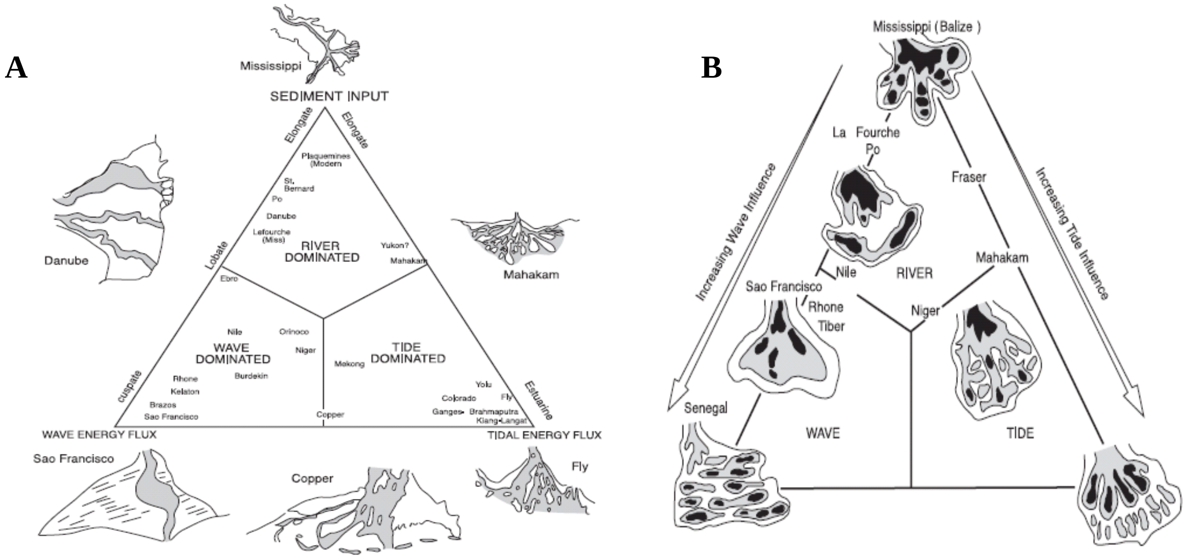


Figure 9. Delta classification A) Galloway (1975) tripartite scheme B) Bhattacharya (2006) Coleman and Wright (1975) on Galloway (1975).

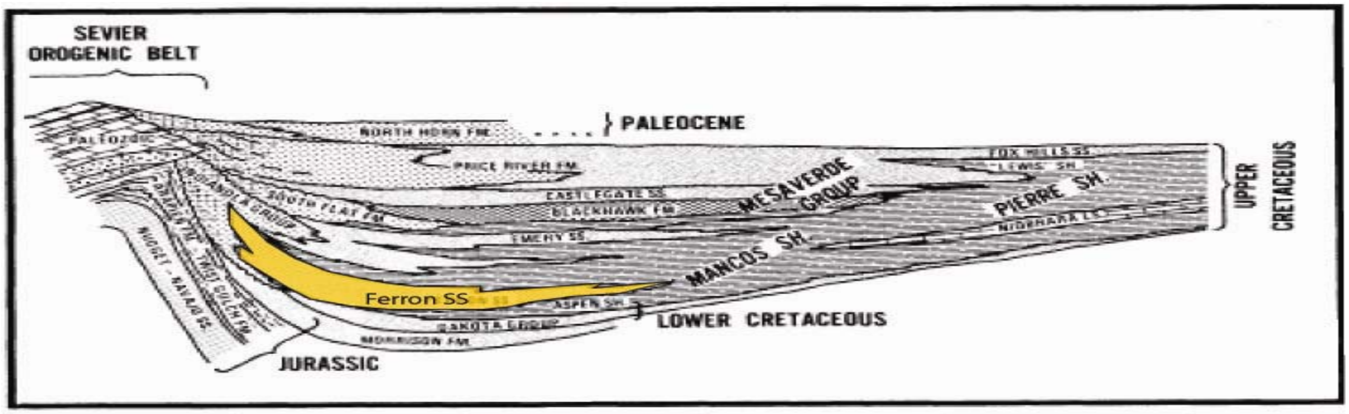


Figure 10. Cross section of the Foreland Basin. Balsey, 1982 Modified after Armstrong, 1968

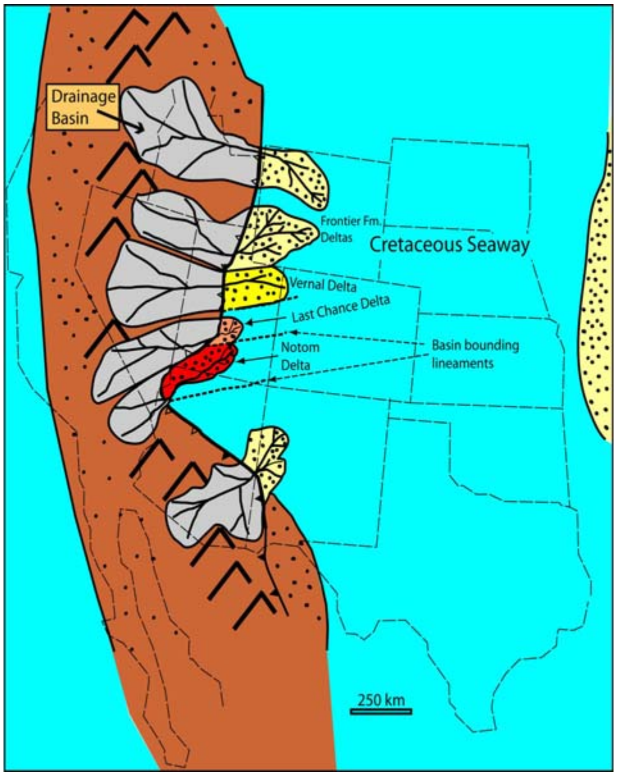


Figure 11. Paleoggeographic reconstruction of the Western Interior Seaway of North America. Bhattacharya and Tye (2004) based on Gardner (1995) and Stelck (1975).

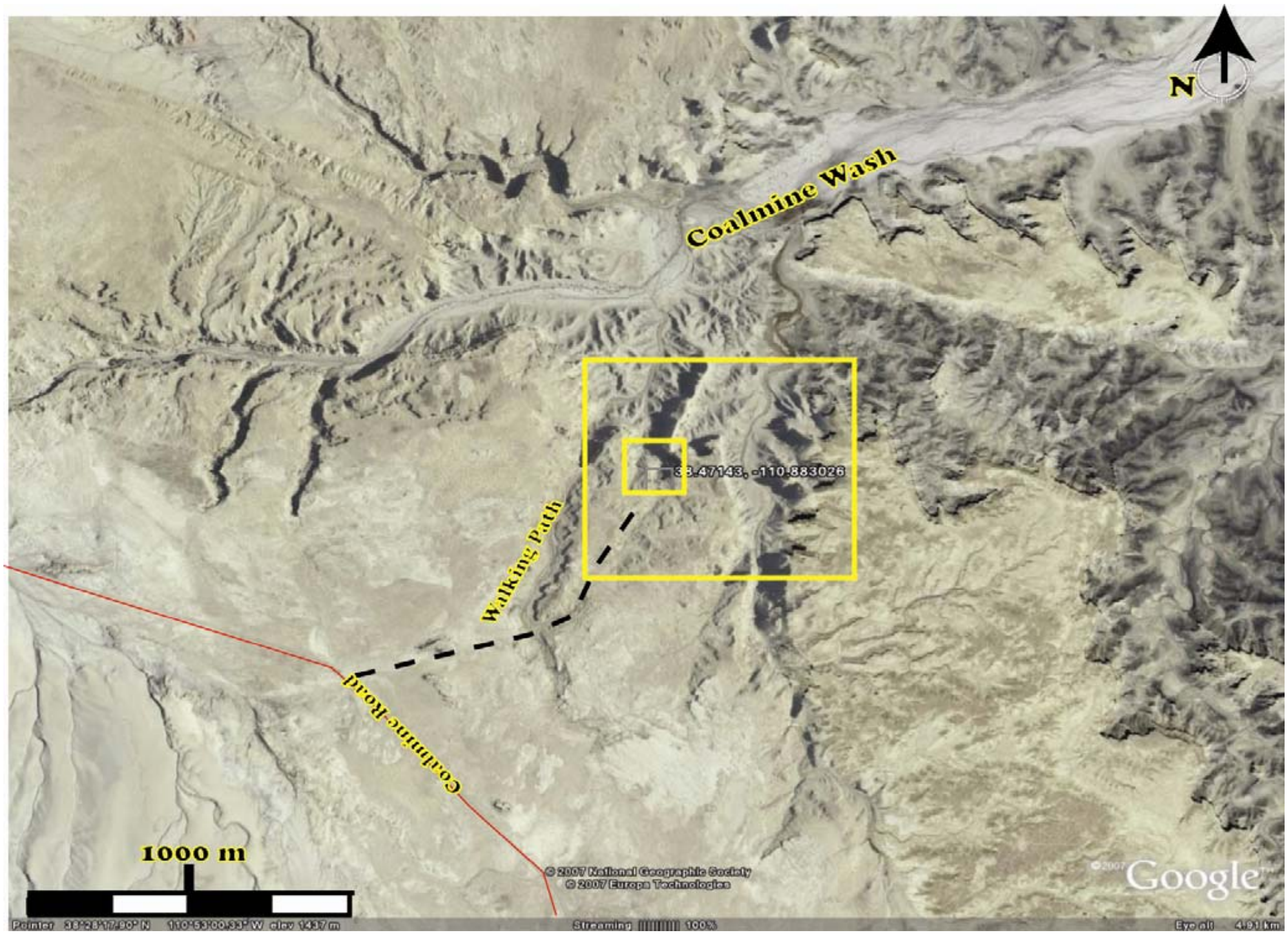


Figure 12. Study area. Small box is location of preliminary work.

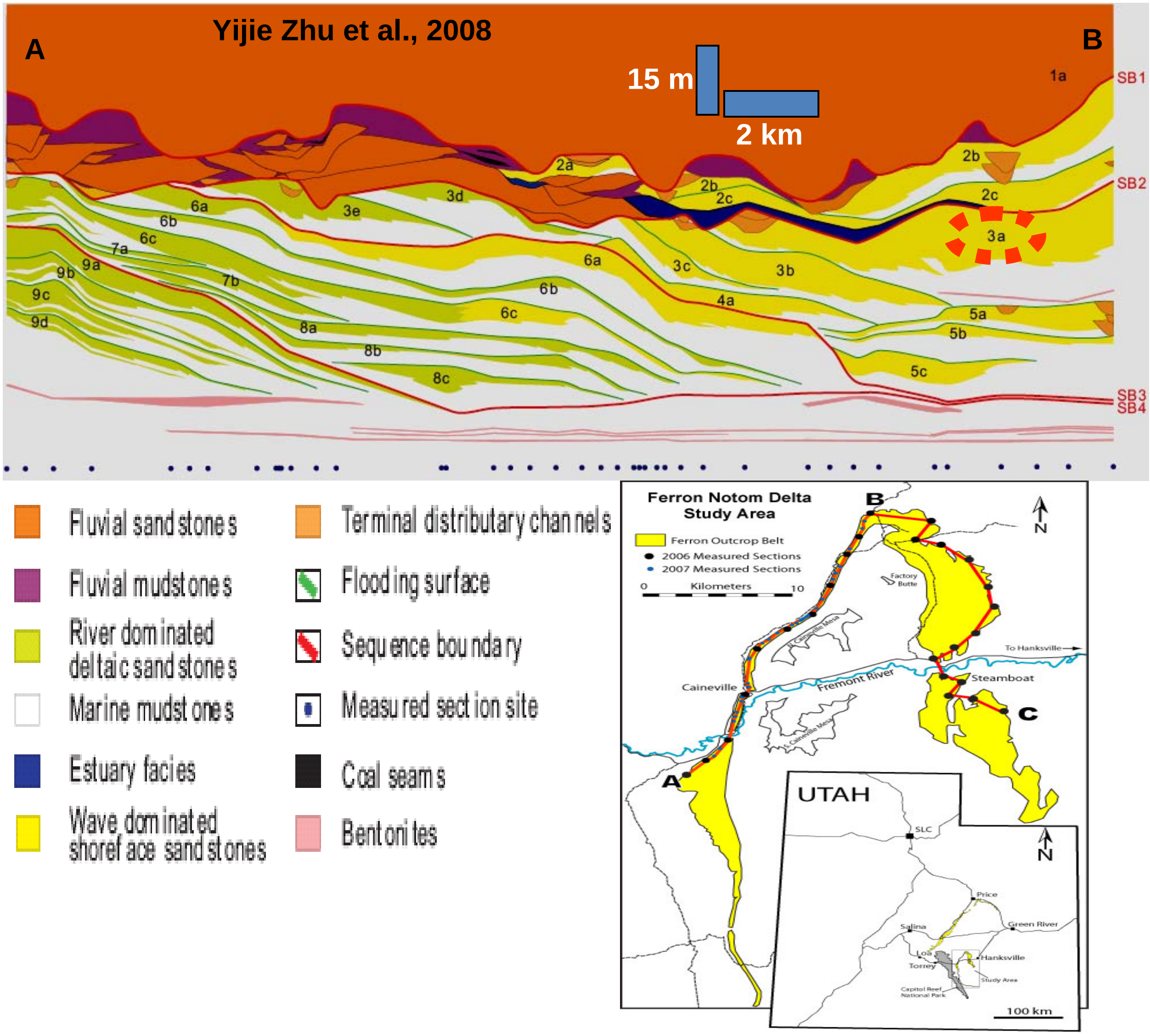


Figure 13. Regional Dip Stratigraphy by Yijie Zhu (2008)

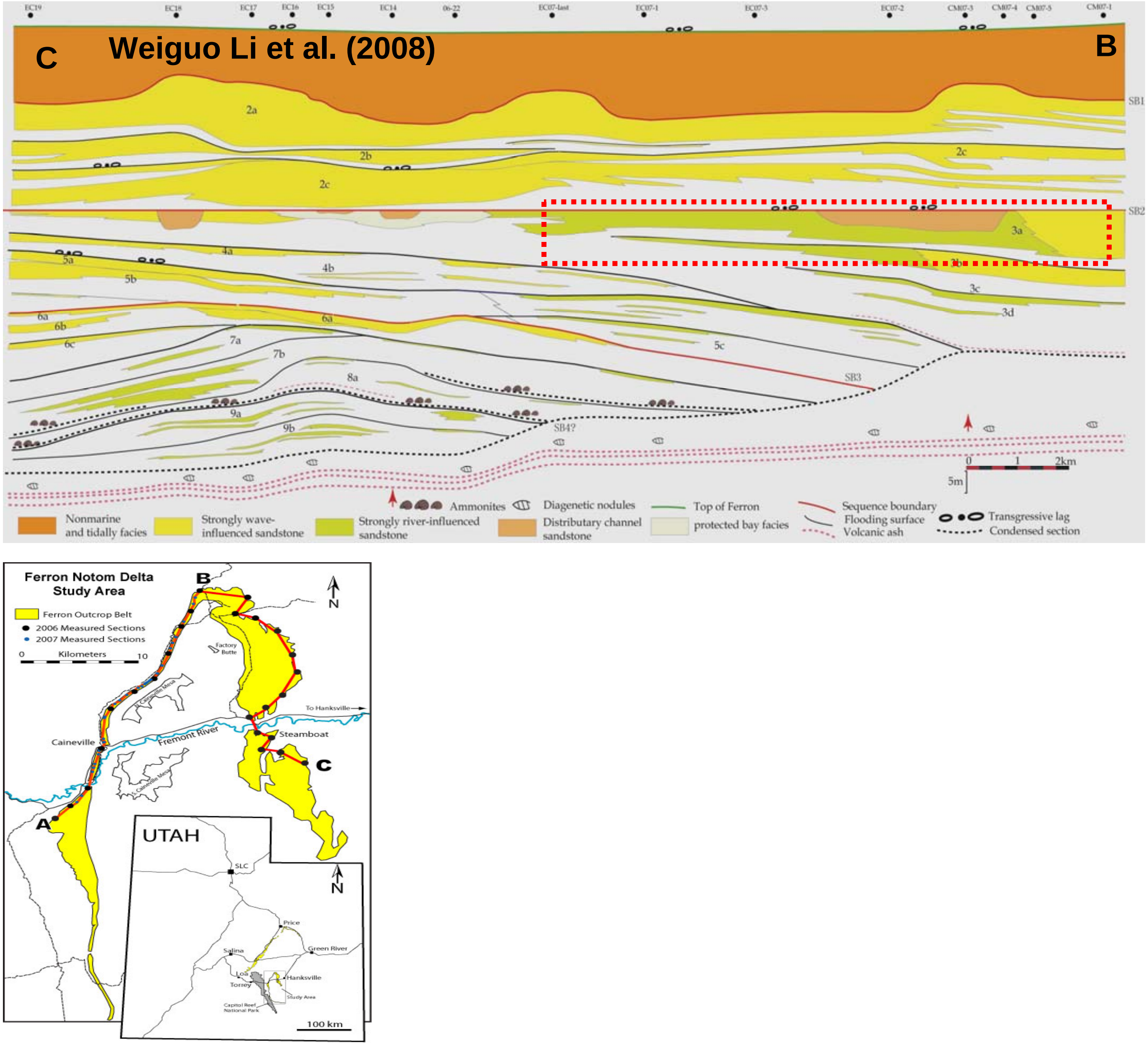


Figure 14. Regional Strike Stratigraphy by Weiguo Li (2008).

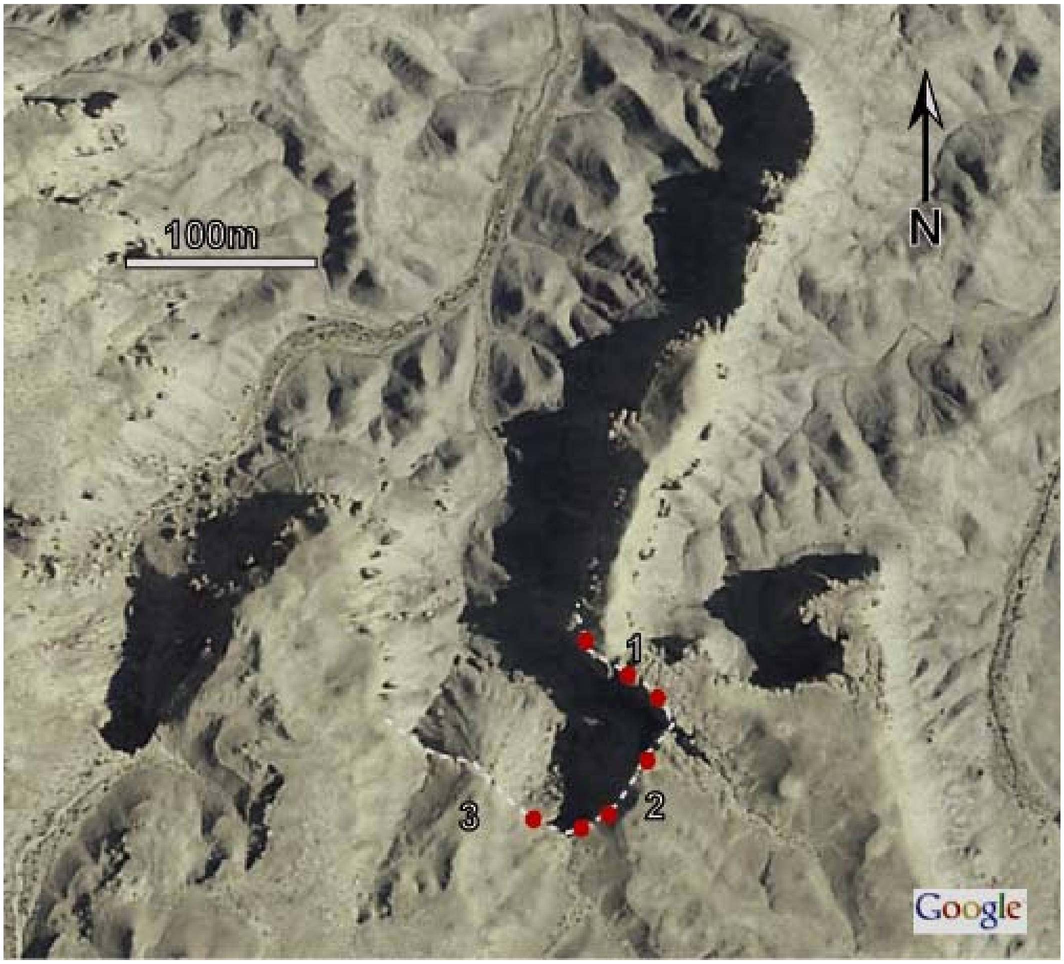


Figure 15 Location of measured sections.