Thin Bed and Sandstone Dike Architecture of Cretaceous Ferron Prodelta Shales, Utah

Proposal

McMaster University
Earth Sc 4MT6
Cristina Genovese
October 3, 2014

Abstract

Most recoverable hydrocarbons in oil and gas reservoirs are located in beds that are thinner than the resolution of common logging tools. These logging tools underestimate the hydrocarbon pore thickness in thin beds, resulting in by-passed pay. Thicknesses of thin beds have been defined differently throughout geological literature. Thin beds occur in all siliciclastic depositional environments, including prodelta areas which are the focus of this study. These beds can be deposited by hyperpycnal flows, ignitive turbidity currents, and tempestites. Exposed sand injectites are studied so that they can be used as models for injectites located below the subsurface. Sand injectites form intrusive traps comprised of dikes, sills, and other irregular features. They are highly porous and permeable, making them conduits for fluid flow within low permeability shales. Sandstone dikes display a variety of geometries including straight and planar, irregular, bulbous and curved. This study aims to look at the facies architecture of thin beds in prodelta shales and compaction factor of a sand dike. This will help determine how the thin beds and dike were deposited. The thin beds were measured on a millimeter to centimeter scale and were recorded in three measured sections. These sections will be digitized in Adobe Illustrator and Rose diagrams will be created from paleocurrent data. Sedimentological and stratigraphical data were obtained from three different outcrop exposures located between Hanksville and Cainville, Utah. This area is located in the Ferron Notom Delta complex which formed in the Cretaceous Western Interior Seaway. From this study, thin bed results will help provide additional information to the interpretation of ancient sedimentary fluvio-deltaic systems in North America. Sand dike results may provide greater interest into how they formed in the area and their relationship with hydrocarbon production, since they have not been studied in the area.

Introduction

Historically, it has been assumed that most shelf mud was deposited out of suspension in quiet waters. However, it is now recognized that many modern shelf muds were accumulated as prodeltaic deposits, and were deposited by hyperpycnal mud plumes (Bhattacharya & MacEachern, 2009). Most studies on hyperpycnal deposits focus on sandstones rather than mudstones, and there have been few studies that look at the origin of prodelta muds on ancient shelves (Bhattacharya & MacEachern, 2009). Hyperpycnal flows, along with ignitive turbidity currents and tempestites, are mechanisms responsible for the formation of thin beds. Hyperpycnal flows form when the density of the river water is greater than that of the marine environment which it is entering (Mulder et al., 2003). Because of this excess density, the flow plunges near the river mouth and continues to move downslope forming turbidites (Zavala et al., 2006). Hyperpycnites can be distinguished from other turbidites by their well-developed inversely graded facies and intrasequence erosional contacts (table 1) (Mulder et al., 2003). Turbidity currents that are generated by ignitive transformation of a submarine slide into turbulent flow are referred to as ignitive turbidites (Soyinka & Slatt, 2008). Ignitive flows are mixtures of seawater and sediments. This allows the flow to be denser than the standing seawater which allows the flow to move rapidly downslope (Soyinka & Slatt, 2008). Figure 1 shows the depositional sequence of a typical turbidite. Tempestites are referred to as storm beds. These deposits have a characteristic signature which allows them to be easily identified in cores and outcrops (Suter, 2006). Tempestites can be identified by an erosional surface that is overlain by low-angle-laminated to hummocky cross-stratified sands which is then overlain by wave oscillation ripples and/or combine-flow ripples (Suter, 2006). The entire sequence is capped by suspension fallout (figure 2) (Suter, 2006).

Most of the Earth's oil and gas reservoirs contain recoverable hydrocarbons in beds that are thinner than the resolution of common logging tools (Passey et al., 2006a). These logging tools underestimate the hydrocarbon pore thickness in thin beds (Passey et al., 2006a). Therefore, it is important to study these bypassed reservoirs. The idea of sand injectites being useful in hydrocarbon exploration has only been around since the 1990s. Geologists study exposed sand injectites in hopes of using them as models for injectites located in the subsurface (Braccini et al., 2008). This study will help improve facies models that are already developed for ancient sedimentary fluvio-deltaic systems located in North America.

Objectives

The first objective of this project is to determine the facies architecture and sequence straitgraphy of thin beds in prodelta shales of the Ferron Notom delta. Studying these thin beds will help determine how they were deposited in the Cretaceous Western Interior Seaway. The second objective of this project is to look at the compaction factor of a sand dike located in the Ferron Notom delta. The compaction factor will help determine the depth of injection, and the cause of the intrusion may be determined.

Background Literature

Geologic Background

The Western Interior Seaway of North America (figure 3) was a vast foreland basin for almost 50 myr during the mid-to late Cretaceous (Sageman & Arthur, 1994). The basin extended from the Gulf of Mexico to the Arctic Ocean and from eastern British Columbia to western Ontario (He et al., 2005). Tethyan waters from the Gulf of Mexico and Boreal waters from the Arctic Ocean both flooded the basin (He et al., 2005). The Ferron Delta complex contains the Vernal delta, which formed in the middle to late Turonian, and the Notom and Last Chance deltas, which formed from the middle Turonian to late Santonian age (Garrison & van de Bergh, 2004). The Ferron Delta complex contains fluvial deltaic rocks that belong to the Ferron Sandstone Member of the Mancos Shale (Garrison & van de Bergh, 2004).

Thin Beds

Thin beds are thin clastic layers of interbedded sandstone and shale. The thicknesses of thin beds have been defined differently throughout geological literature. Bates & Jackson (1984) defined thin beds as sedimentary beds ranging from 5 to 60 cm (2 in. to 2 ft.). Campbell (1967), on the other hand, defined them as beds with thicknesses between 3 and 10 cm (1 to 4 in.). In the petrophysical literature, thin beds are defined as beds that are thinner than the vertical resolution of common logging tools (Eshimokhai et al., 2012). Therefore, each logging tool has its own definition of a thin bed. For example, a thin bed may be 1 m for a gamma ray device whereas for a borehole image log it may be approximately 3 cm (Manescu, 2009). In general, petrophysical thin beds can have thicknesses anywhere between 1 in. and 2 ft. (Passey et al., 2006b).

Thin beds have also been designated as 'shaly sand' throughout the petrophysical literature. A 'shaly sand' is defined as "a sandstone in which quartz is the primary mineral, but clay and other associated minerals may be present in varying amounts, distributions, and particle sizes" (Passey et al., 2006b, p. 30). The type, volume, and distribution of clay minerals found in the sandstone will affect the well log response of that sandstone (Passey et al., 2006b). This can have an impact on the analysis of the hydrocarbons-in-place (Passey et al., 2006b). Because thin beds are thinner than the vertical resolution of log data, they yield a lower resistivity response than a thick hydrocarbon bearing sandstone. If this resistivity response is recognized, they are called low-resistivity pay (Passey et al., 2006b). If the resistivity response is not recognized, then they are referred to as by-passed pay (Passey et al., 2006b).

Thin beds occur in all siliciclastic depositional environments (table 2). This study will take place in the Ferron Notom Delta in Central Utah. The thin beds that will be looked at have been deposited in a prodelta environment. Only a few studies on thin beds have been conducted in this area (Seepersad, 2012; Li, 2014). One of the objectives of this study is to record the thin bed architecture and determine how these thin beds were deposited.

Sand Injectites

Sand injectites form intrusive traps that are comprised of dikes, sills, and other irregular features (figure 4) (Hurst & Cartwright, 2007). Sand injection occurs by the fluidization or liquefaction of sand in response to the catastrophic failure of low permeability fine grained sediment units below, where overpressure has developed (Hurst et al., 2003). Failure of low permeable layers may occur by hydraulic fracturing, differential compaction, polygonal faulting, tectonic faulting and folding, and rapid unloading (Hurst et al., 2003). When sand intrudes low permeability shales, they create seals for the intrusive traps (Hurst & Cartwright, 2007). Because sand injectites are highly porous and permeable, they form conduits for fluid flow within low permeability shales (Hurst et al., 2003). This allows hydrocarbon fluids to migrate through the injectites.

Sandstone dikes are tabular bodies of sandstone that crosscut host strata bedding at low and high angles, defined as $<20^{o}$ and $>20^{o}$ (Hurst et al., 2011). Dikes can display a variety of geometries, and range in height from millimeters to kilometers and width from millimeters to meters. Common geometries include straight and planar, irregular, bulbous and curved (Hurst et al., 2011). Planar dikes form when sand is injected along planar fractures (Hurst et al., 2011). Dikes can also experience ptygmatic folding, which may be caused by the compaction of the host strata after sand injection (Hurst et al., 2011). Discordant marks present along dike margins provide information on how the fluidized sand interacted with the surfaces of the host rock during injection (Hurst et al., 2011). These marks include flutes, grooves, lobate scours, frondescent marks, and gutter marks (Hurst et al., 2011). Internal sedimentary structures, such as laminae and grading, are also common in sandstone dikes (Hurst et al., 2011).

This part of the study will focus on a ptygmatic dike located in the Ferron Notom Delta. Dikes have not been studied in this area, so this study will provide the first information on how the dike may have formed. This part of the study will be modelled after Leckie & Potocki (1988), who determined the compaction factor, which was then used to estimate the injection depth, and to speculate on how the dike formed.

Methods & Analysis

Sedimentological and stratigraphical data were obtained from three different outcrop exposures located between Hanksville and Cainville, Utah (figure 5, figure 6). Thin beds were recorded in three measured sections and were measured on the millimeter to centimeter scale. All measured sections are located in the Tununk shale, and are located well below previous measured sections done in the area (Zhu et al., 2012; Li, 2009). Figures 7 and 8 show where each measured section is located in the stratigraphy. Site 1, containing the sand dike, is not shown in figure 7 since it is located farther North than Zhu et al. (2012) study area. The data obtained from these outcrops consisted of sedimentary structures, grain size information, bed thickness, paleocurrents, ichnofacies, and lithofacies. Data was collected on foot, with the exception of the sand dike measurement, which was collected by rappelling off the rock face. The tools used in the field included a Silva compass, Jacob's staff, measuring tape, rock hammer, hand lens, and grain size chart. The measured sections will be scanned and digitized using Adobe Illustrator. An example of what the digitized measured sections will look like can be seen in figure 9. Sand dike measurements will be compared to the corresponding measured section to determine how much compaction has occurred. Paleocurrents obtained from the thin beds will be displayed as a Rose Diagram to show the dominant direction of flow. Facies will be determined by looking at the sedimentary structures and bioturbation in the thin beds. Looking at the facies, as well as additional literary sources, will help speculate as to what the past depositional environments were.

Expected Outcomes

From this project, the thin bed results will provide additional information to the interpretation of ancient sedimentary fluvio-deltaic systems in North America. Since sand dikes have not been studied in the area, hopefully these results will provide greater interest into how these intrusions form in the area, and their relationship with hydrocarbon production.

Timeline

The tentative timeline for the research project can be seen in table 3. One month of field research, in Utah, was completed in the summer. Once the research proposal is submitted and reviewed, the literature review will be started and will take approximately one month to complete. Following the submission of the literature review, any measured sections that were not digitized in Adobe Illustrator will be, and any diagrams that will be used in the thesis will be created. During this time a draft thesis will be started. Significant progress should be made before the year is over. Once the draft thesis is submitted and reviewed in 2015, changes will be made for the final copy.

Table 1: Differences between turbidites (surge deposits) and hyperpycnites (adapted from Mulder et al., 2003)

Bed Type	**Turbidite Sequence (Bouma-like)**	**Hyperpycnal turbidite sequence (hyperpycnite)**
Flow type	Turbulent surge Unsteady. Mainly waning	Turbidity current Mainly steady. Waxing then waning
Dominant flow regime	Turbulent	Turbulent
Flow duration and time for deposition	Minutes to days	Hours to weeks
Base contact	Erosive to sharp	Gradational
Top contact	Gradational	Gradational
Intrabed contact	Infrequent between facies	Erosive to sharp
Grading	Clear, normal	Clear, inverse then normal
Bioturbation	Absent to intense	Absent to intense
Ichnofacies	Few	Few
Structures	Well-developed parallel and cross bedding, convolutes	Well-developed parallel and cross bedding. Climbing frequent
Fauna/flora	Allochtonous mainly marine	Allochtonous mainly continental. Frequent plant and wood fragment

Table 2: Thin Bed Depositional Environments (adapted from Passey et al., 2006b)

Depositional System	**Thin-bed-prone**	**Not thin-bed-prone**
Deep-water	Overbank/levee deposits Distributary lobe Channel margin Hemipelagic	Channel axis Debrites (sandy or muddy)
Beach/shoreface	Lower shoreface Distal lower shoreface	Foreshore Upper shoreface
Deltaic	Delta front Prodelta	Stream-mouth bar
Tidal/estuarine	Sandy tidal channel Intertidal sand flats	Subtidal
Fluvial	Point bars (meandering stream) Levees Terminal splay (overbank)	Braided streams Channel sands Channel lag deposits Fluvial bars Alluvial Fans
Aeolian	Interdune Wind-rippled deposits	Cross-bedded dunes

Table 3: Thesis Timeline

Task	**Due Date**
Field Research	June to July, 2014
Research Proposal	October 3, 2014
Literature Review	November 7, 2014
Digitize measured sections, complete diagrams	End of December, 2014
Draft Thesis	March 6, 2015
Written Thesis	April 8, 2015
Paper Presentation	April 9, 2015

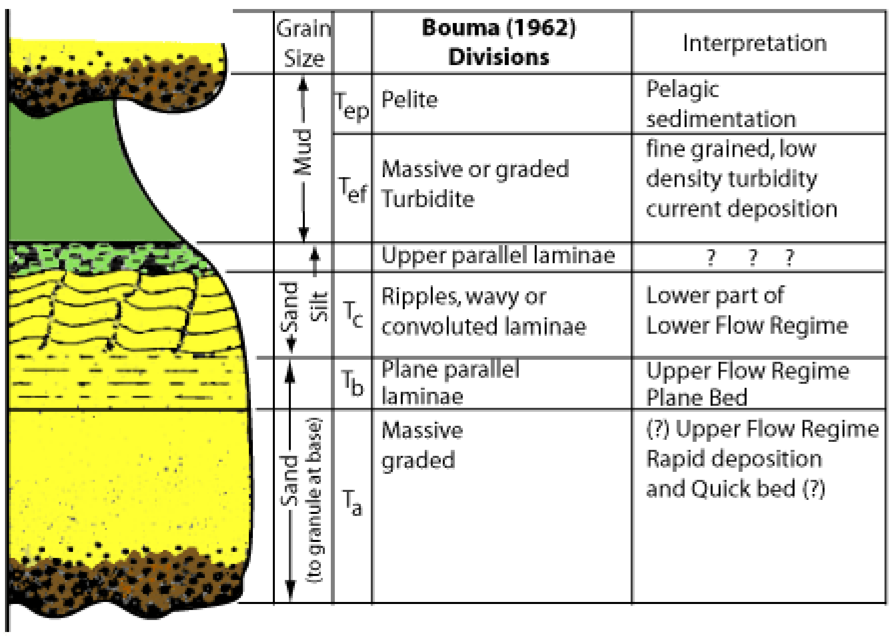

Figure 1: Bouma sequence (http://www.sepmstrata.org/page.aspx?pageid=37)

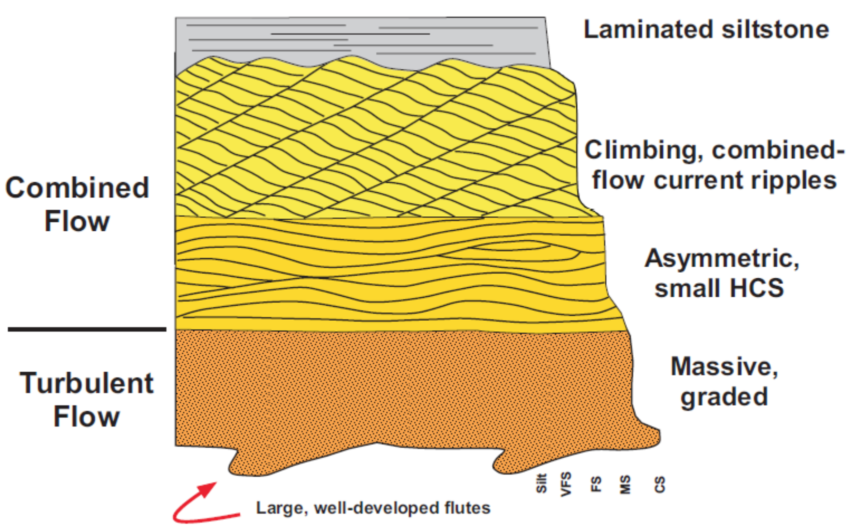

Figure 2: A general model for a tempestite deposited by wave-modified gravity flows (taken from Suter, 2006)

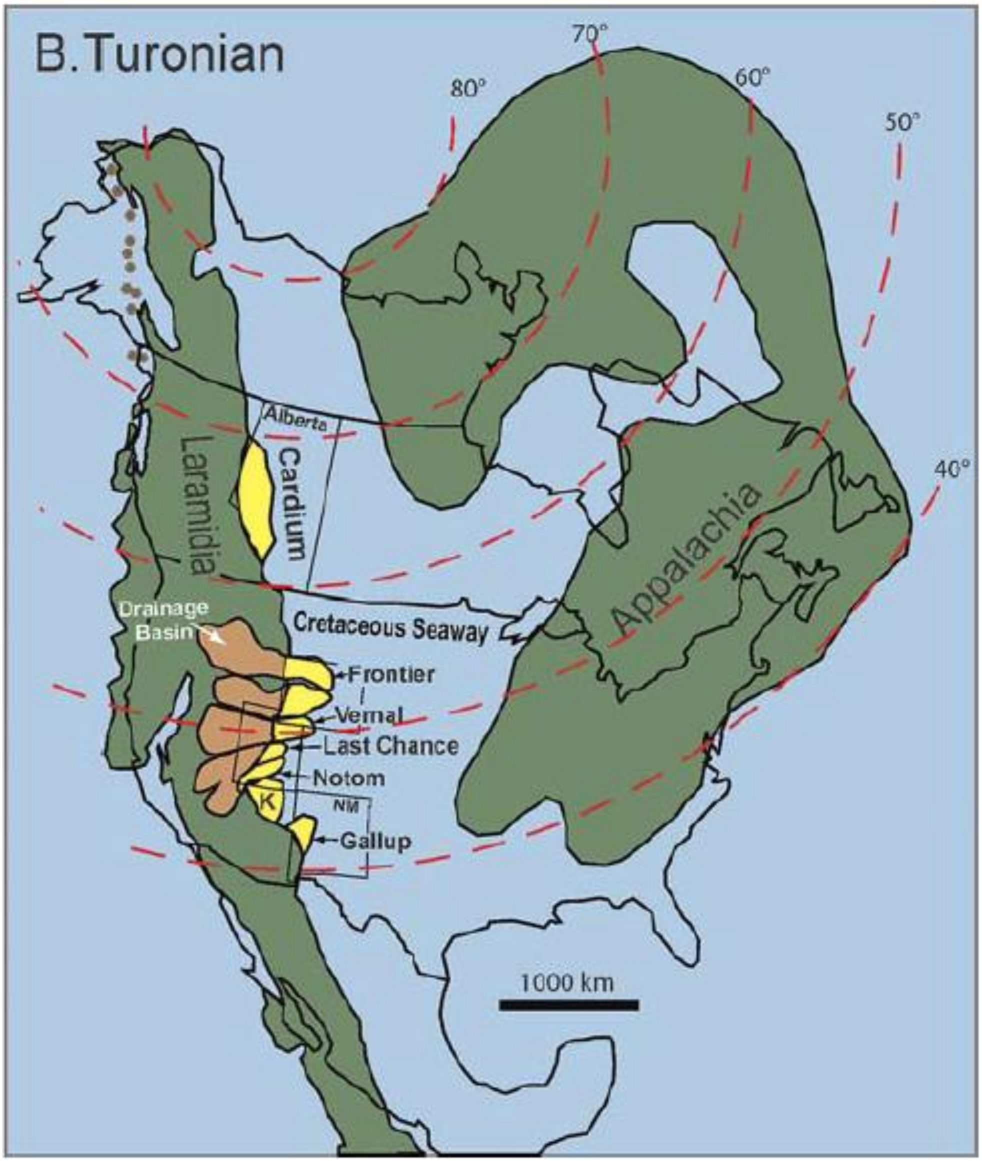

Figure 3: Cretaceous Western Interior Seaway showing the Ferron Delta complex (taken from Bhattacharya & MacEachern, 2009)

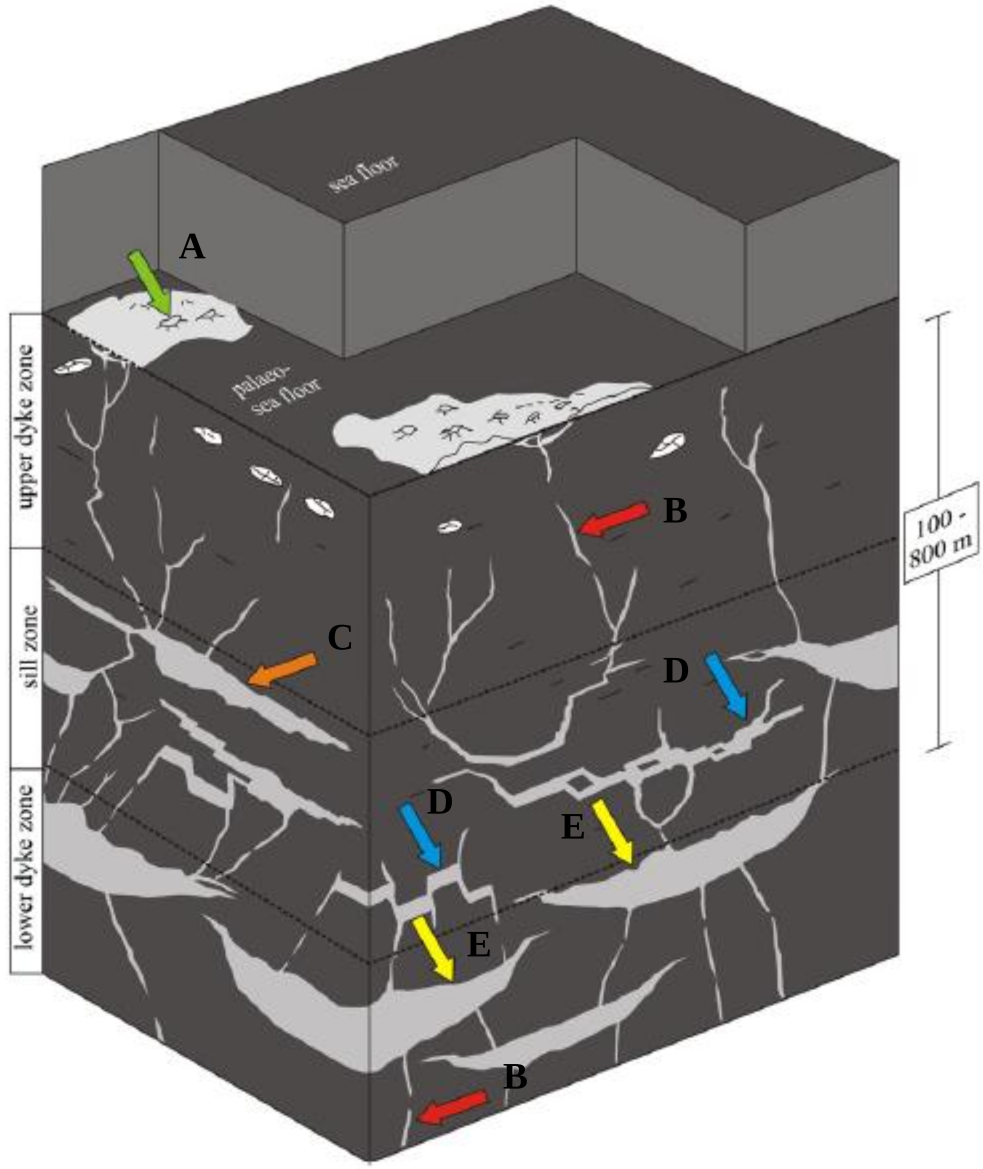

Figure 4: Summary of a sand injectite complex (taken from Hurst et al., 2011). (A) Sandstone extradites; (B) Sandstone dike; (C) Irregular sandstone intrusions; (D) Sills; (E) Remobilized parent sandstone units

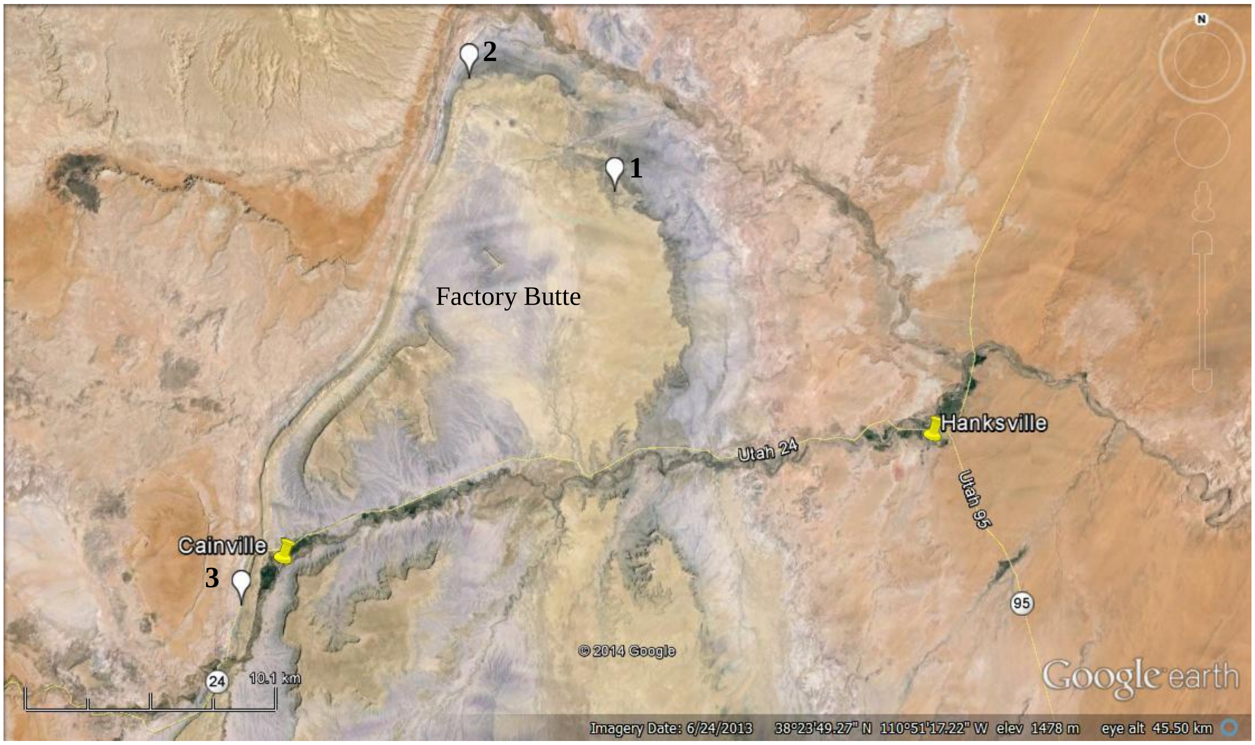

Figure 5: Location of the study area. (2) Location of the sand dike; (1) and (3) Thin bed locations

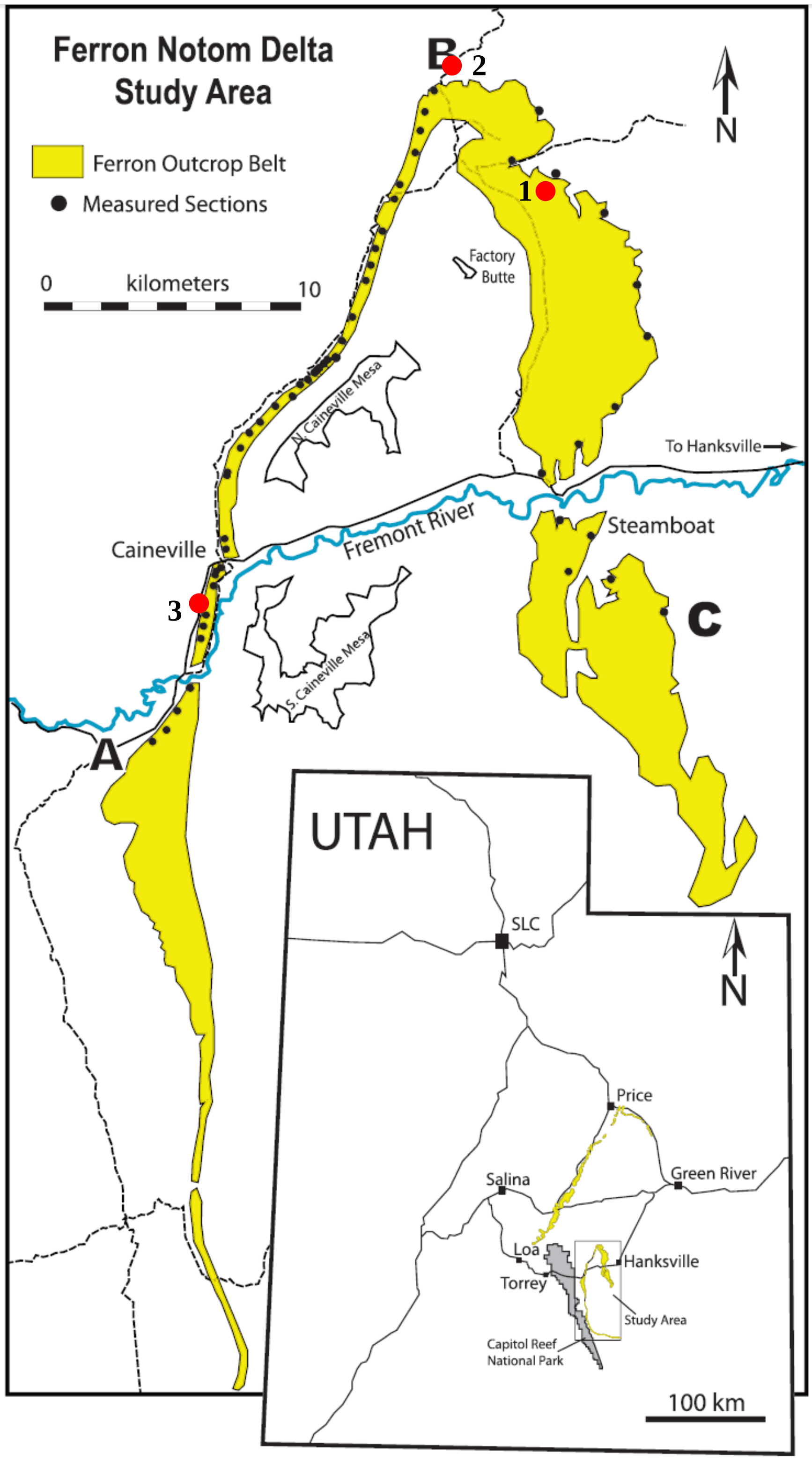

Figure 6: Location of the Ferron Outcrop Belt between Hanksville and Cainville (taken from Zhu et al., 2012). Black dots between A and B represent the locations of all dip sections (Zhu et al., 2012). Black dots between B and C represent locations of all strike sections (Li, 2009). Red dots with numbers represent the measured sections in this project.

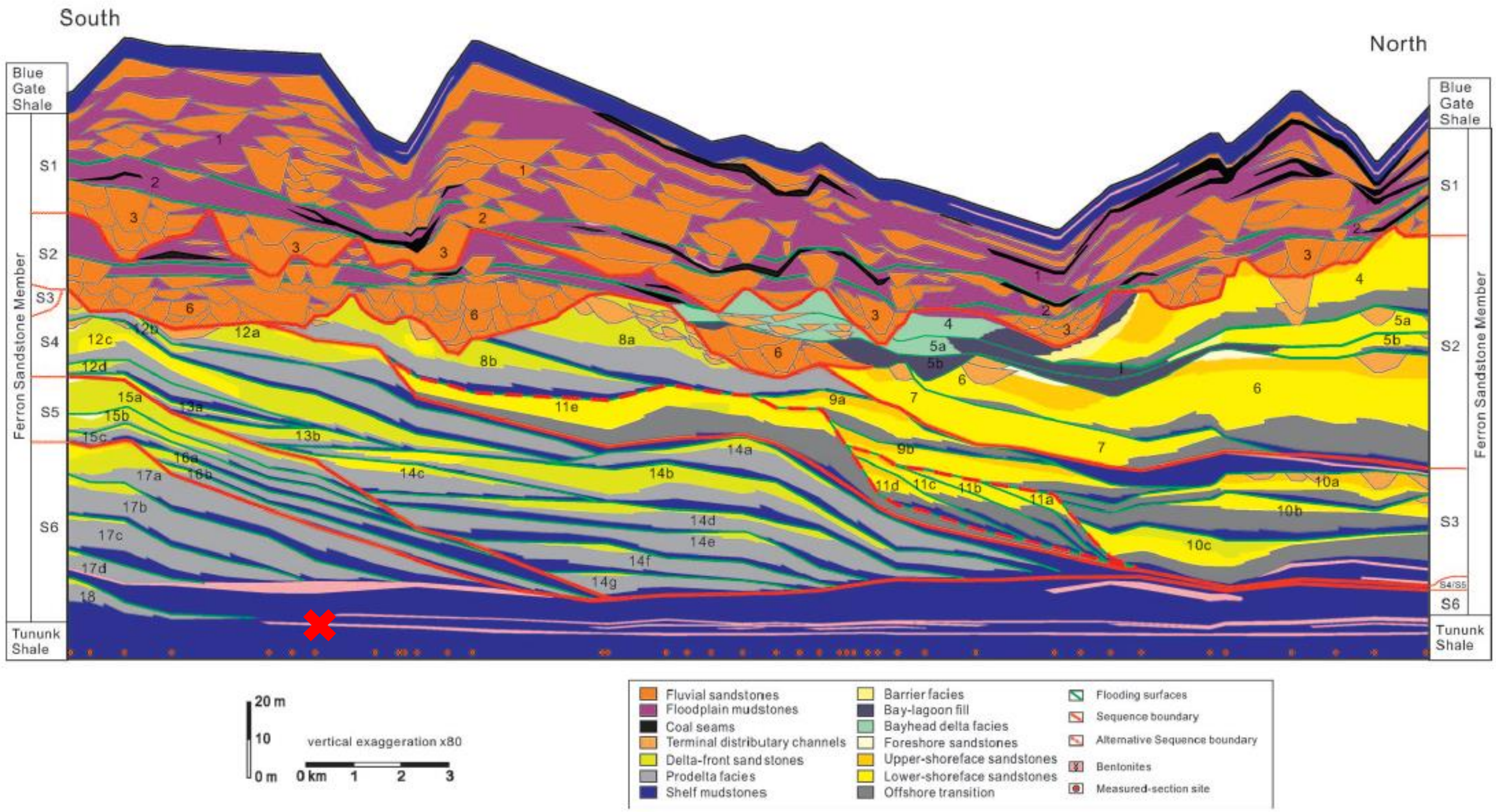

Figure 7: Dip stratigraphy of the Ferron Notom Delta. 43 parasequences, 18 parasequence sets, and 6 depositional sequences are illustrated above. Represents cross-section A-B on figure 4 (taken from Zhu et al., 2012). The red X represents the location of the measured section of site 3 (figure 4) in the stratigraphy.

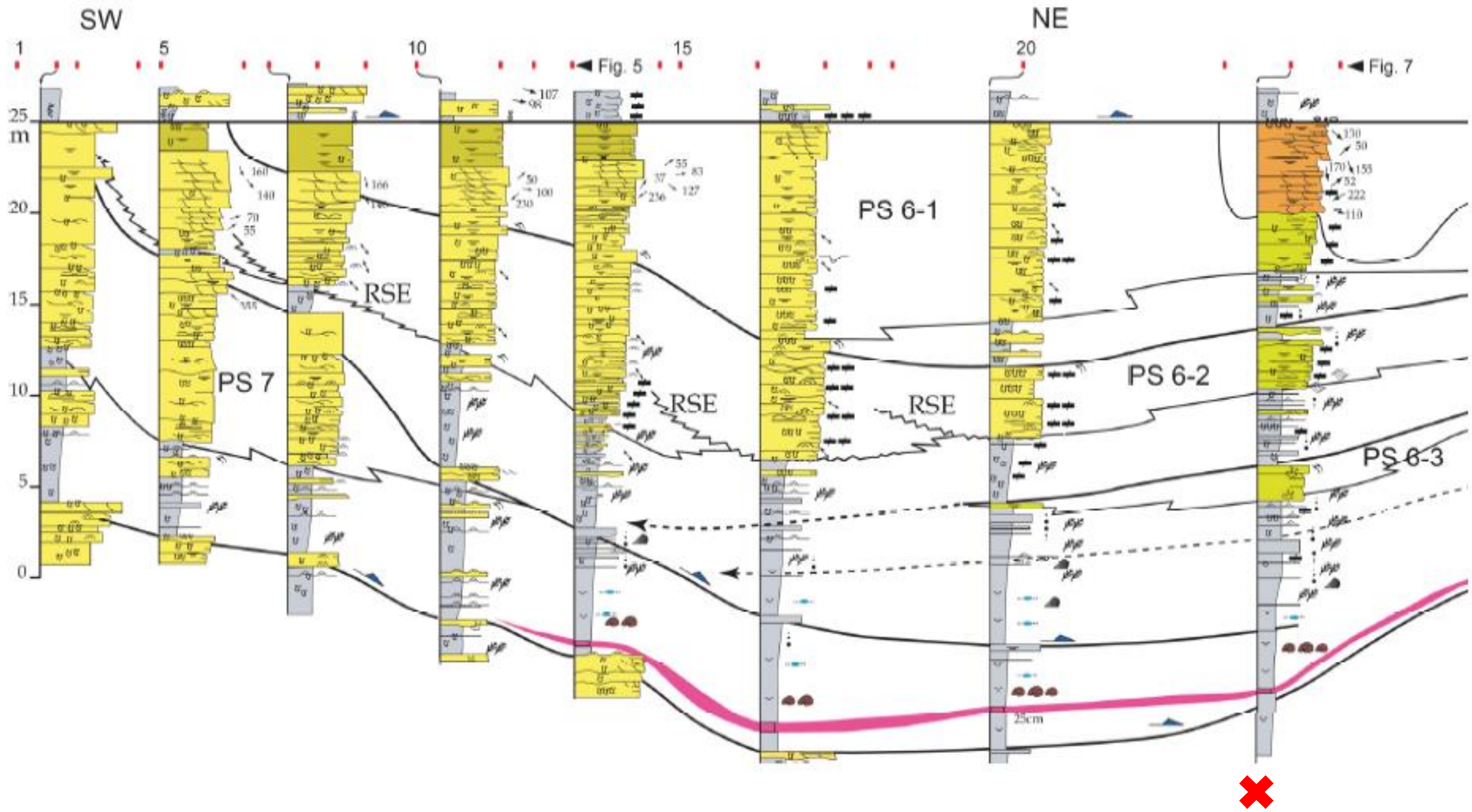

Figure 8: Strike stratigraphy of Ferron Notom Delta. Represents cross-section B-C on figure 4 (taken from Li, 2009). The red X represents the location of the measured section of site 1 (figure 4) in the stratigraphy.

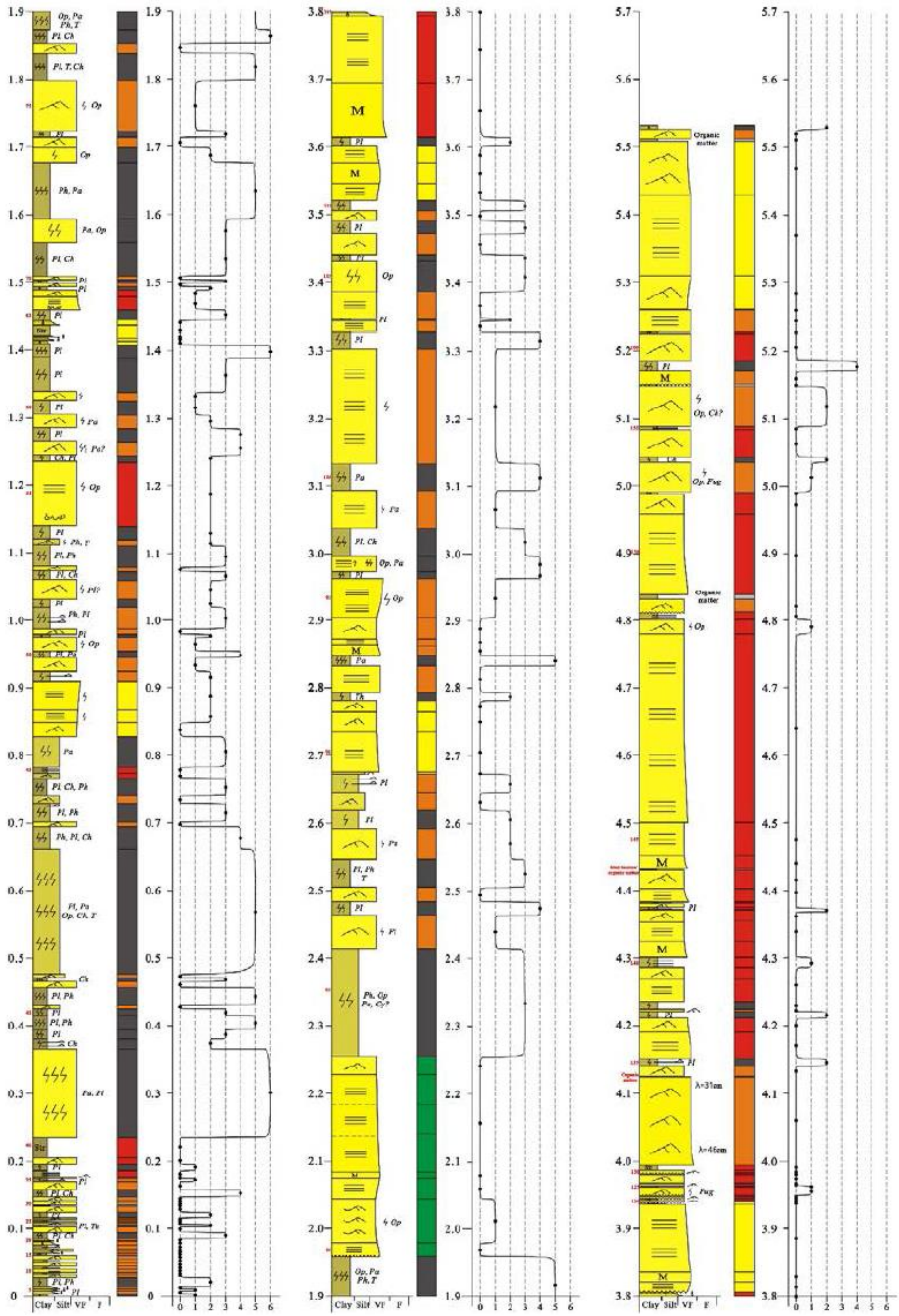

Figure 9: Measured section with interpreted facies associations and BI log (taken from Li, 2014)

References

Bates, R.L., & Jackson, J.A. (1984). *Dictionary of Geological Terms, 3rd Edition*. New York, NY: Anchor Books.

Bhattacharya, J. P., & MacEachern, J. A. (2009). Hyperpycnal rivers and prodeltaic shelves in the cretaceous seaway of north america. *Journal of Sedimentary Research, 79*(4), 184-209.

Braccini, E., De Boer, W., Hurst, A., Huuse, M., Vigorito, M., & Templeton, G. (2008). Sand injectites. *Oilfield Review, 20*(2), 34-49.

Campbell, C.V. (1967). Lamina Set, Bed, and Bedset. *Sedimentology, 8*, 7-26.

Eshimokhai, S., Akhirevbulu, O.E. & Osueni, L. (2012). Evaluation of thin bed using resistivity borehole and NMR imaging techniques. *Ethiopian Journal of Environmental Studies and Management, 4*(4), 96-102.

Garrison, J. R., Jr., & van de 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, 50*, 125-192.

He, S., Kyser, T. K., & Caldwell, W. G. E. (2005). Paleoenvironment of the western interior seaway inferred from δ18O and delta δ13C values of molluscs from the cretaceous bearpaw marine cyclothem. *Palaeogeography, Palaeoclimatology, Palaeoecology, 217*(1-2), 67-85.

Hurst, A., Cartwright, J., Huuse, M., Jonk, R., Schwab, A., Duranti, D., & Cronin, B. (2003). Significance of large-scale sand injectites as long-term fluid conduits: Evidence from seismic data. *Geofluids, 3*(4), 263-274.

Hurst, A., & Cartwright, J. (2007). Relevance of sand injectites to hydrocarbon exploration and production. *AAPG Memoir, 87*, 1-19.

Hurst, A., Scott, A., & Vigorito, M. (2011). Physical characteristics of sand injectites. *Earth-Science Reviews, 106*(3–4), 215-246.

Leckie, D. A., & Potocki, D. J. (1988). Sandstone dikes and an estimate of their depth of injection in the Colorado shales (cretaceous), Alberta. *Memoir - Canadian Society of Petroleum Geologists, 15*, 325-330.

Li, W. (2009). *Valleys, facies, and sequence stratigraphy of the Ferron Notom Delta, Capital Reef, Utah.* Ph.D, Dissertation, University of Houston, Texas, USA.

Li, Z. (2014). *Evaluating along-strike variation using thin-bedded facies analysis, Upper Cretaceous Ferron Notom Delta, Utah.* Master's thesis, University of Houston, Texas, USA.

Manescu, A., Bal, A., Donaldson, I., Ahmad, Z. & Krishnan, R. (2009). Geological and petrophysical evaluation of thin bed laminated shaly sandstones in Peragam Field, offshore Brunei, with NMR and tensor resistivity measurements. Paper presented at the *Indonesia Petroleum Association Thirty-Third Annual Convention & Exhibition.*

Mulder, T., Syvitski, J.P.M., Migeon, S., Faugeres, J. & Savoye, B. (2003). Marine hyperpycnal flows: initiation, behavior and related deposits. A review. *Marine and Petroleum Geology, 20,* 861-882.

Passey, Q.R., Dahlberg, K.E., Sullivan, K., Yin, H., Brackett, B., Xiao, Y. & Guzman-Garcia, A.G. (2006a). Petrophysical Evaluation of Hydrocarbon Pore-Thickness in Thinly Bedded Clastic Reservoirs: The Clastic Thin-bed Problem. *AAPG Archie Series, No. 1,* 1-15.

Passey, Q.R., Dahlberg, K.E., Sullivan, K., Yin, H., Brackett, B., Xiao, Y. & Guzman-Garcia, A.G. (2006b). Petrophysical Evaluation of Hydrocarbon Pore-Thickness in Thinly Bedded Clastic Reservoirs: Definitions and Geologic Occurrence of Thin Beds in Clastics. *AAPG Archie Series, No. 1,* 27-39.

Sageman, B. B. & Arthur, M. A. (1994). Early Turonian paleogeographic/paleobathymetric map, western interior, U.S. Paper presented at the *Mesozoic Systems of the Rocky Mountain Region,* 457-469.

Seepersad, D. (2012). *Thin-bedded facies analysis of a Ferron storm-dominated delta front and prodelta: Cretaceous Ferron Sandstone, Utah.* Master's thesis, University of Houston, Texas, USA.

Soyinka, O.A. & Slatt, R.M. (2008). Identification and micro-stratigraphy of hyperpycnites and turbidites in Cretaceious Lewis Shale, Wyoming. *Sedimentology, 55,* 1117-1133.

Suter, J.R., (2006). Facies models revisited. *Special Publication – Society for Sedimentary Geology, 84,* 1-527.

Zavala, C., Ponce, J.J., Arcuri, M., Drittanti, D., Freije, H. & Asensio, M. (2006). Ancient lacustrine hyperpycnites: a depositional model from a case study in the Rayoso formation (Cretaceous) of west-central Argentina. *Jounral of Sedimentary Research*, *76,* 41-59.

Zhu, Y. (2010). *Sequence stratigraphy and facies architecture of the Cretateous Ferron Notom Delta Complex*, *South-Central Utah, U.S.A.* Ph.D, Dissertation, University of Houston, Texas, USA.