3D Mapping of Vertical and Lateral Facies Heterogeneity of a Tributive Incised Valley System, Turonian Ferron Sandstone, Notom Delta, South-Central Utah

By

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Proposal submitted to the Faculty of the Department of Earth and Atmospheric Sciences,
University of Houston, in partial fulfillment of the requirements for the degree of:

MASTERS IN SCIENCE

November 3, 2011

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Abstract

Incised valley systems are important for sequence stratigraphic and exploration purposes and may inherit complicated plan-view patterns from the self-similar drainage networks that form them. Current depositional models for valleys often exclusively focus on facies within trunk valleys and either ignore or poorly document facies within tributive valleys. The Notom Fluvio-Deltaic complex, a component of, the Turonian Ferron Sandstone Member of the Mancos Shale Formation, outcrops along Nielson Wash, Utah, and provides the opportunity to study the 3D facies heterogeneity of compound incised valley fills, including both trunk and tributive components. This study proposes to: 1. extend previous work through continued vertical and lateral mapping of channel and facies architecture, 2. develop a plan-view map of the orientation and geometry of ancient channel belts (and associated facies) within their respective valleys, and 3. document sedimentological differences between tributive and trunk incised valleys. It is hypothesized that tributary valleys may be finer-grained and may contain smaller-sale fluvial channels compared to trunk valleys. Since there are still too few examples in the literature that document tributive valley facies, a general facies model for this setting has not been developed. This study will contribute to such a model, which may benefit subsurface interpretation and production strategy for incised valley reservoir types.

Introduction

Incised valley systems are vital components of the geologic record. Zaitlin, 1994, defines an incised valley system as a *"fluvially-eroded, elongate topographic low that is* *typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base."* These systems include both the valley and the fill, which may have a complicated interfingering of depositional environments ranging from open marine, to estuarine to fluvial (See Figs 1, 2 and Zaitlin et al., 1994, Posamentier, 2001, Boyd et al., 2006). These fills are not only important for sequence stratigraphic studies, but they have tremendous economic significance; for some of the world's largest hydrocarbon reservoirs are locked within the fluvial/estuarine sandstones contained within them (Peijs-van Hilten et al., 1998, Plint, 2002 and references therein). However, the stratigraphic complexity and internal heterogeneities of these systems often hinder recovery of hydrocarbons, because baffles and facies changes of varying scales control fluid flow patterns (Miall, 1988, Zaitlin et al., 1994, Garrison & van den Bergh, 2006). Understanding the evolution of these systems over time and how different valley fill facies are distributed spatially may be crucial for the future improvement of incised valley facies models.

Boyd et al. (2006) suggest that the current set of depositional models for incised valley systems are in an early classification stage, and that because these systems often have mixed wave/tidal/fluvial influence, current models significantly generalize the natural system complexity (Fig. 2). The body of literature that investigates these systems commonly focuses most attention on the main trunk valley and either ignores or fails to document the fill style of tributary valleys and their channels (Figs. 3, Boyd, 2006 and references therein). Because the fill of trunk valleys will be composed of sediments once part of a tributive system, these valleys ought to be considered in current models.

Tributive valley systems may exhibit complicated plan view morphologies and have more or less impact on trunk fill depending on the sediment yield (Fig. 4, Kvale and Archer, 2007). While some studies address tributary valleys directly, these studies are less common (Kvale and Archer, 2007, Plint and Wadsworth, 2003). Kvale and Archer (2007) use well logs and core data to suggest that muddier fills are characteristic of tributive fills, while sandier, bed-load dominated fills characterize trunk valleys. This suggestion by Kvale and Archer (2007) was based on well log, core and observation in modern valley systems. On the other hand, some studies have seen muddier tributive fills from outcrop data (see Plint and Wadsworth, 2003). Due to the scarcity of examples in the literature, additional details on the nature of tributive valley fills is needed.

Fundamental issues exist in determining the vertical and lateral facies heterogeneity of valley fills, both trunk and tributive valleys. Although expensive (and scarce) 3D seismic data can accurately resolve plan-view geometry of tributive valleys (Posamentier, 2001), seismic cannot resolve in detail the fill heterogeneities. Due to the discontinuous nature of well and core data, studies involving excellent outcrop exposure may be the best way to document fill heterogeneities of ancient tributive valleys. The petroleum industry is interested in gaining more accurate, quantitative and detailed descriptions of sand-body shapes in fluvial/deltaic reservoirs, as well as the distribution of muddier facies.

Numerous well-exposed outcrop belts of the Turonian Ferron Sandstone, member of the Mancos Shale Formation, exist immediately north of Utah’s Henry Mountains region (Fig. 5). This area has long been used as a laboratory for testing sequence stratigraphic concepts (Ryer, 1984, Garrison and van den Bergh, 2004, 2006, Li et al., 2009, 2010, Zhu, 2010, Campbell, in prep, Bhattacharya, 2011 among many others).

A complex incised valley (multiple cut and fill episodes) has been described in detail along Nielson Wash (Li et al., 2010, Campbell, in prep), a modern drainage system that lies north of the Henry Mountains and immediately southeast of Factory Butte (Figs. 5, 6). This study has three objectives: first, to extend previous work through continued vertical and lateral mapping of channel and facies architecture, second, to develop a plan-view map of the orientation and geometry of ancient channel belts (and associated facies) within their respective valleys, and third, to document sedimentological differences between tributive and trunk incised valleys.

Geologic Setting

The Turonian Ferron Sandstone Member of the Cretaceous Mancos Shale Formation comprises several fluvial-deltaic wedges which prograded eastward and north-eastward into the western margin of the Cretaceous Western Interior Seaway (Figs. 7 and 8) (Bhattacharya and Tye, 2004 and others). These mid-late Cretaceous Ferron clastic wedges formed in response to increasing accommodation of the subsiding retroarc foreland basin east of the ancestral Rocky Mountains (Figs. 7 and 8) (Ryer & Anderson, 2004). This Ferron Member is bounded above and below by the Blue Gate Shale and the Tununk Shale Member respectively (Fig. 7). Zhu, 2010, conducted $^{40}Ar/^{39}Ar$ dating of sanidine crystals within bentonites above and below the Notom area Ferron sandstone and interpreted the wedge to have prograded into the seaway between 91.25 Ma and 90.63 Ma (620K years).

Previous Regional Work

The Ferron Sandstone has been divided into three separate clastic wedges called the Vernal Delta, Last Chance Delta and the Notom Delta (north to south respectively, see Fig. 8). The Notom Delta has received far less geologic attention than the more northern Last Chance Delta, regardless of the fact that both deltas have excellent outcrop exposures (Garrison and Van den burgh, 2004).

Zhu, 2010, established a sequence stratigraphic framework of the Ferron Notom Delta Complex, which identified 6 depositional sequences, 18 parasequence sets, and 43 parasequences (Fig. 9, *sensu* Van Wagoner, 1990). While sequences 3 through 6 represent marine sandstones and mudstones, sequence 2 marks a major regional basinward shift in facies (Fig. 9). Sequence 2 includes all facies in the tripartite estuarine sedimentation zonation as described by Boyd et al. (2006) (includes fluvial, estuarine and marine facies, see Fig. 1). Sequence 1 marks an additional basinward shift in facies, whereupon predominantly fluvial sandstones and associated muddy floodplains were deposited. Several compound incised valleys (multiple cut and fill episodes) exist within sequence 1, the base of which is a regional and traceable sequence boundary (SB1a, see Fig. 10). Zhu (2010) showed that each sequence represents about 100K years, while parasequence sets and parasequences represent about 34K and 14K years respectively. The area of focus for this study is where sequence 1 valleys incise into sequence 2 marine sandstones and shales (Figs. 9 and 10). This incision is best seen along outcrops within Nielson Wash.

Previous Work in the Nielson Wash

Previous work by Li et al., (2010) and Campbell (in prep.) show that the Ferron incised valley is compound in nature, with tidal dominated terraces eroded into by a deeper coarser grained trunk valley system (V1 in Fig. 10) and bounded at the base by an 8th order erosional surface (SB1b in Fig. 10). This trunk valley system is well exposed in 3D around the area (Fig. 11). Previous work has focused on the eastern cliff faces of Nielson Wash, which has produced several detailed cross sections (Fig. 6). Although these sections tell much about geometry of these valleys and their fills, additional work is needed to translate their 2D interpretations into a 3D plan-view map of valley and channel orientation.

Li et al., (2010) investigated the temporal evolution of fluvial style within two valleys (V1 and V2 in Fig 10), which outcrop on sheer cliff faces in the NS trending Nielson Wash. These two valley sequences show characteristic onlap and truncation relationships. Li et al., (2010) discovered a complex history of erosion and filling, which indicates high diachroneity within the system. Li et al., (2010) observed a vertical facies transition, which progresses from fluvial, to tidal (and/or tide-influenced fluvial), and back to fluvial facies at the top. They also showed changes in sand-shale ratios. In Campbell's work (in prep), the same vertical facies transition is observed. From these studies, average thickness and width of channel stories was estimated to be approximately 5m and 180m respectively. As shown in Li et al. (2010) V2 facies are truncated by the younger V1 near the northernmost zone of Nielson Wash (Fig. 10). A Wheeler diagram shows the sequence of events within this cross section (Fig. 12).

Since only a small portion of V2 was documented in Li et al. (2010), recent work by Campbell (in prep) has extended facies description in V2. Both studies (Li et al. 2010, Campbell, in prep.) show that the valleys incised into lower shoreface sandstones, indicating a significant and anomalous basinward shift of facies. The tidally influenced channels contain inclined heterolithic facies. The tidal signatures of these channels include: reactivation surfaces/mud-drapes, flaser/wavy/lenticular bedding, sand/mud couplets, and tidal rythmites (see Campbell, in prep, Li et al, 2010). Since both Li et al., (2010) and Campbell (in prep) have described facies heterogeneity of valleys on the eastern side of the area, this study aims to document and interpret outcrops on the western side and extend mapping in 3D where possible.

Problems, Questions and Purpose

This study proposes to investigate a tributary of Li et al., (2010) trunk system. It is expected that fill type will be unique to flow conditions and sediment supply within each segment of the whole valley system.

Heterolithic, tidally influenced strata and overlying units have in large part been completely eroded away in many areas on the interfluves of the modern wash. This differential erosion has exposed the composite valley floor surface of V2 in many areas (Fig. 11). Lateral mapping of the muddy/sandy facies is therefore possible, which will in-turn compliment vertical mapping efforts.

Incision depth of a valley may not be uniform along its length. Best and Ashworth, (2007) explain that it may be much deeper in areas where tributive valleys merge with the main trunk valley (see also Boyd et al., 2006, Schumm and Ethridge, 1994). The development of confluence scours at these junctions may determine fill distribution. The proposed area of study may contain sufficient outcrop information to verify if confluence scours exist.

Another issue may be that it is difficult to differentiate between tributive valleys and regular floodplain channels. Since tributive valleys have smaller streams than trunk valleys, the cross sectional area of the tributive valley may approximate the cross sectional area of a regular channel. This invites several questions that will be addressed with thus study. How does one determine the upstream distance from the trunk valley whereupon a tributary valley becomes a single floodplain channel? How does the fill change upriver? What bedforms and sedimentary structures are characteristic of these environments? How does the mud/sand ratio change with distance upstream?

Because tributive incised valleys may be fractal or self-similar (see Fig. 4), it is assumed that if the study is successful in documenting the valley orientation and style, conclusions can be made on the orientation and style of lower and higher order fractals. Another concept to test involves the tripartite estuarine sedimentation zonation (Fig. 1). Can fill heterogeneities clearly determine the segment the fill belongs to in the overall system?

The overall purpose of this study is thus to document the vertical and lateral facies heterogeneity within tributive incised valley fills of Nielson Wash. The intent of the study is to make interpretations from detailed field work to assess the geometry and orientation of channels (both in plan and cross-section views), compare/contrast differences in fill between trunk and tributive valleys, resolve the distribution of facies types and correlate/enhance findings of previous studies within the Nielson Wash area.

Methodology

First, lateral mapping of facies will be complemented by the creation of two separate DEM (Digital Elevation Model) surfaces, one regional and one local (Fig. 5).

These surfaces will aid in the visualization and interpretation of the area. The regional DEM will be obtained by combining two high-resolution stereo images taken from the satellite QUICKBIRD_1 (www.digitalglobe.com). The purpose of the regional DEM (and associated satellite imagery) is to give high-res elevation details on the Nielson Wash area and to delineate varying valley fill types before fieldwork is initiated. This will also aid in field-activity planning purposes. The local DEM will be obtained by "walking-out" the exposed paleovalley floor using GPS RTK equipment. Data point spacing will increase over areas of complexity and decrease over broader flat areas. Upon creation, both of these DEM's will be shaded by elevation and hill shade in an effort to interpret channel orientations in 3D. It is thought that the ultra-high resolution surface will help define basal tributary channel orientation in plan-view.

Second, vertical facies heterogeneity will be documented using traditional field methods, which include traditional mapping, measuring sections in detail and collecting high-resolution GigaPan images of the outcrop. Bedding diagrams will be constructed from these detailed images. Measured sections will be obtained along the western cliff face and northern reaches of Nielson Wash (Fig. 6). From this field data, 1 or 2 cross sections will be generated (depending on where sections are obtained), which will describe general facies types, stratal bounding surfaces, and major erosional surfaces. Paleocurrent and ichnological data will also be collected with the measured sections to complement interpretations completed by previous workers (Li et al., 2010, Campbell, in prep). Bounding surface hierarchy (8 total) will be assigned to the fluvial succession (valley fill) as described by Miall (1992) in order to make a detailed stratigraphic correlation and calculate bankfull flow depths using the methodology described by

Bhattacharya and Tye, 2004. This study intends to update current 2D interpretations into 3D where possible (Li et al., 2010, Campbell, in prep).

Timeline of Activities

This study will require multiple trips to the field. The first trip will be between Nov 4th and November 11th, 2011. It's purpose is to obtain LIDAR images of the eastern margin of Nielson Wash, test equipment, survey the area/facies near and on top-of the exposed valley floor and to get acquainted to other field methods. The regional DEM will be constructed between November 14th and 25th. The second and main trip to the field will be from March 12th to May 18th 2012. If needed, additional data will be collected during the 2012 Quantitative Sedimentology Lab Research Consortium Field Trip (August 5th - 10th 2012). Once the field data is interpreted, the final thesis report will be drafted, revised and submitted in line with a December 2012 graduation.

Immediate and Broader Scientific Relevance

This study is immediately relevant from a scientific point-of-view because it will document and describe the lateral and vertical facies heterogeneity of an ancient tributive incised valley system. Such a study is rare. Also, as far as the author knows, no-one to date has mapped out a paleovalley floor in 3D using solely outcrop data.

Considering the fact that 3D examples of incised valleys in outcrop are rare, this study may be relevant for the incised valley scientific community. This would be valuable information for petroleum companies, who may be seeking further understanding of fill heterogeneity within incised valley reservoirs. Certain aspects of this study could not only improve industry production strategy but also assess the economic importance of tributive incised valleys and associated facies.

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Figures

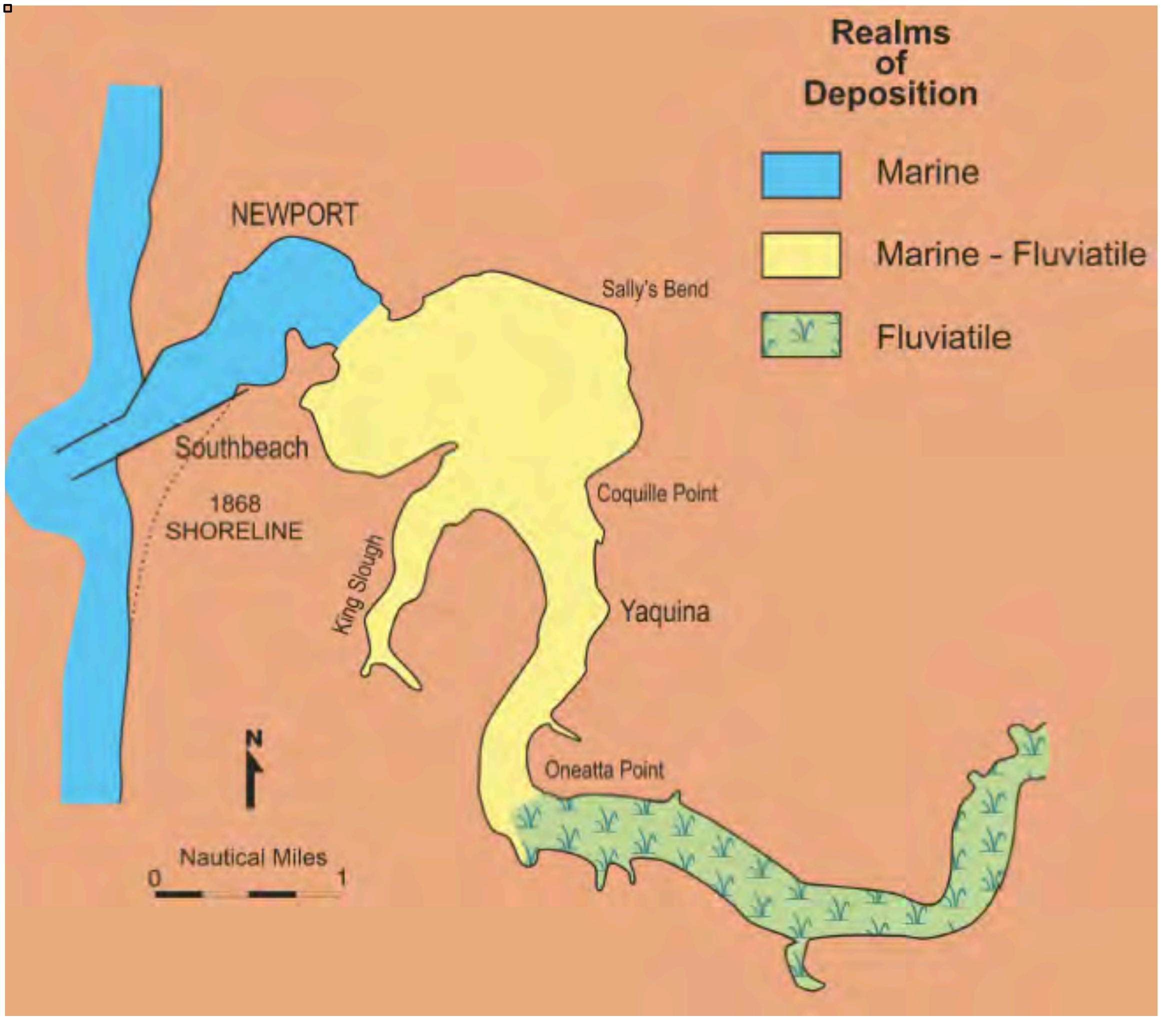

Figure 1: A simplified model showing the tripartite sedimentation zonation commonly observed at the transition between fluvial and marine realms in an incised valley system. Note the lack of detail in the tributary feeder valleys (from Boyd et al., 2006 after Kulm and Byrne, 1967).

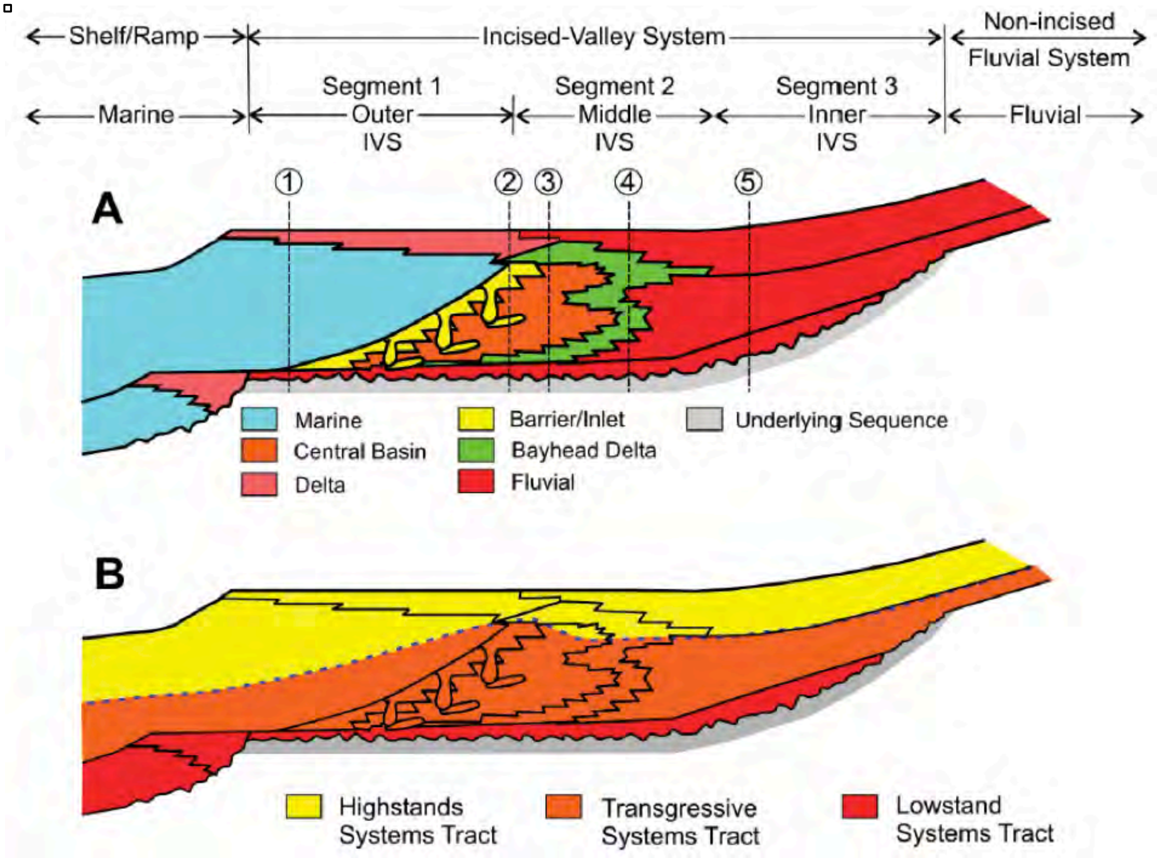

Figure 2. Idealized longitudinal section of a simple incised-valley system showing the distribution of A) depositional environments, B) systems tracts. A wave-dominated estuary has been used in this model. Segments 1 and 3 are typically much longer than segment 2, and are compressed here for presentation purposes. (source: caption words are taken word for word from Boyd et al., 2006 who modified this model from Zaitlin et al., 1994).

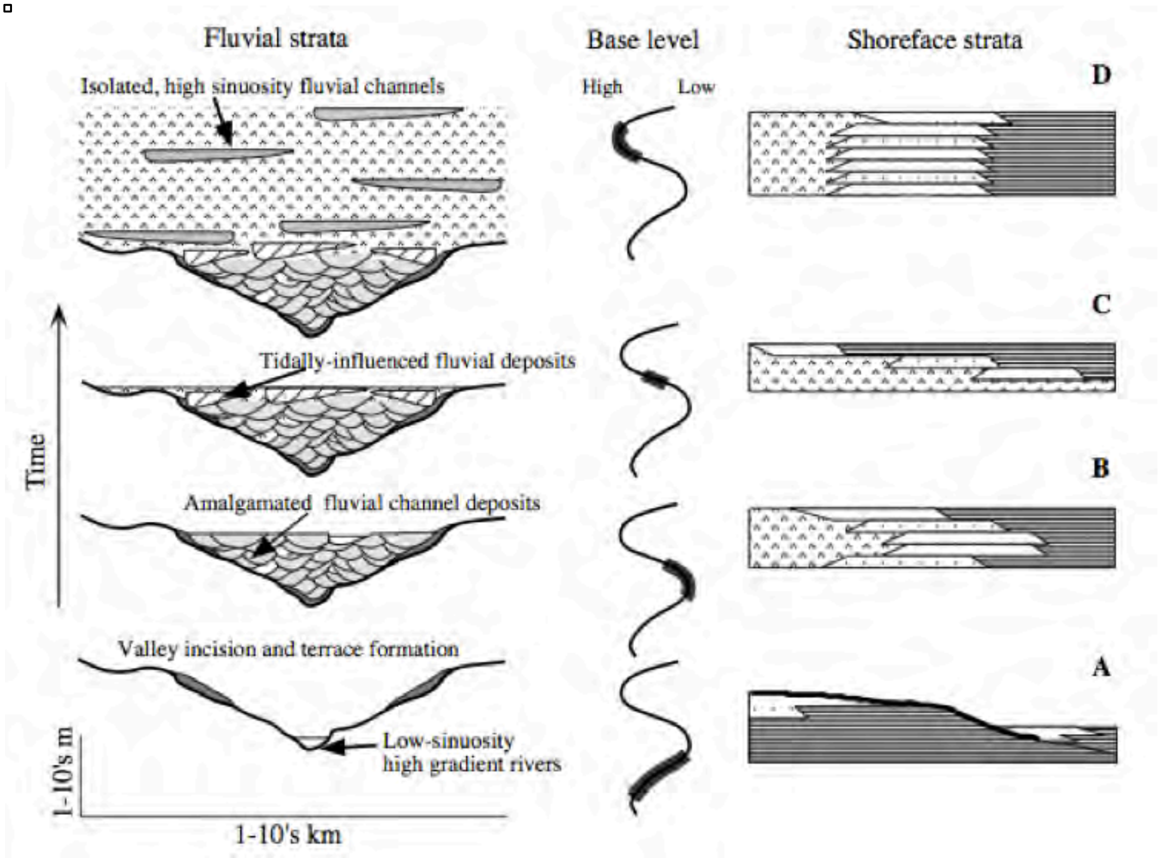

Figure 3. An idealized diagram showing the fluvial architecture of a trunk valley fill and it's relationship to shoreface stacking patterns as a function of base-level change. This commonly accepted model fails to model fill differences in tributary valleys (from Shanley and McCabe, 1994).

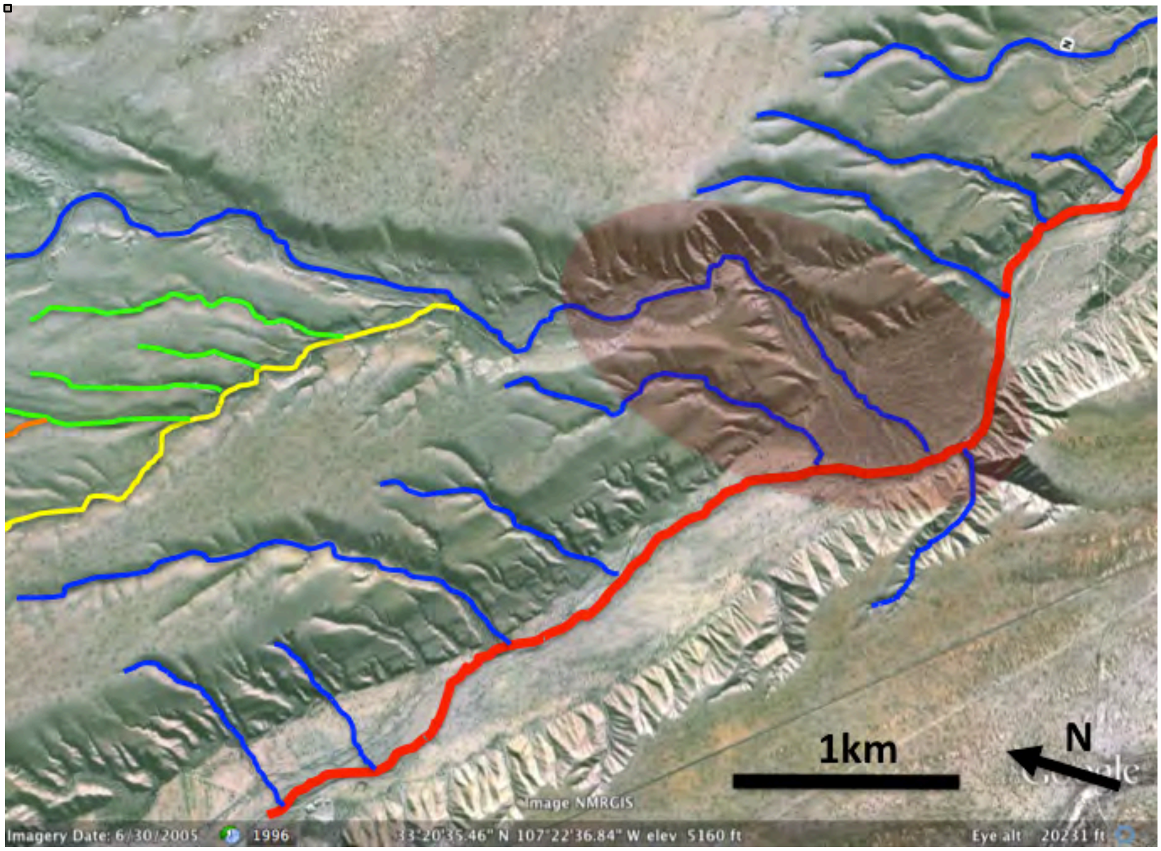

Figure 4. A modern example near Elephant Butte Reservoir that shows plan-view complexity of tributary incised valleys (blue) and their higher order tributaries (yellow, green, orange), which feed into a trunk system (red). Within the study area, the perceived relationship between trunk and tributary valleys is most similar to the shaded region (brown). Source: Google Earth

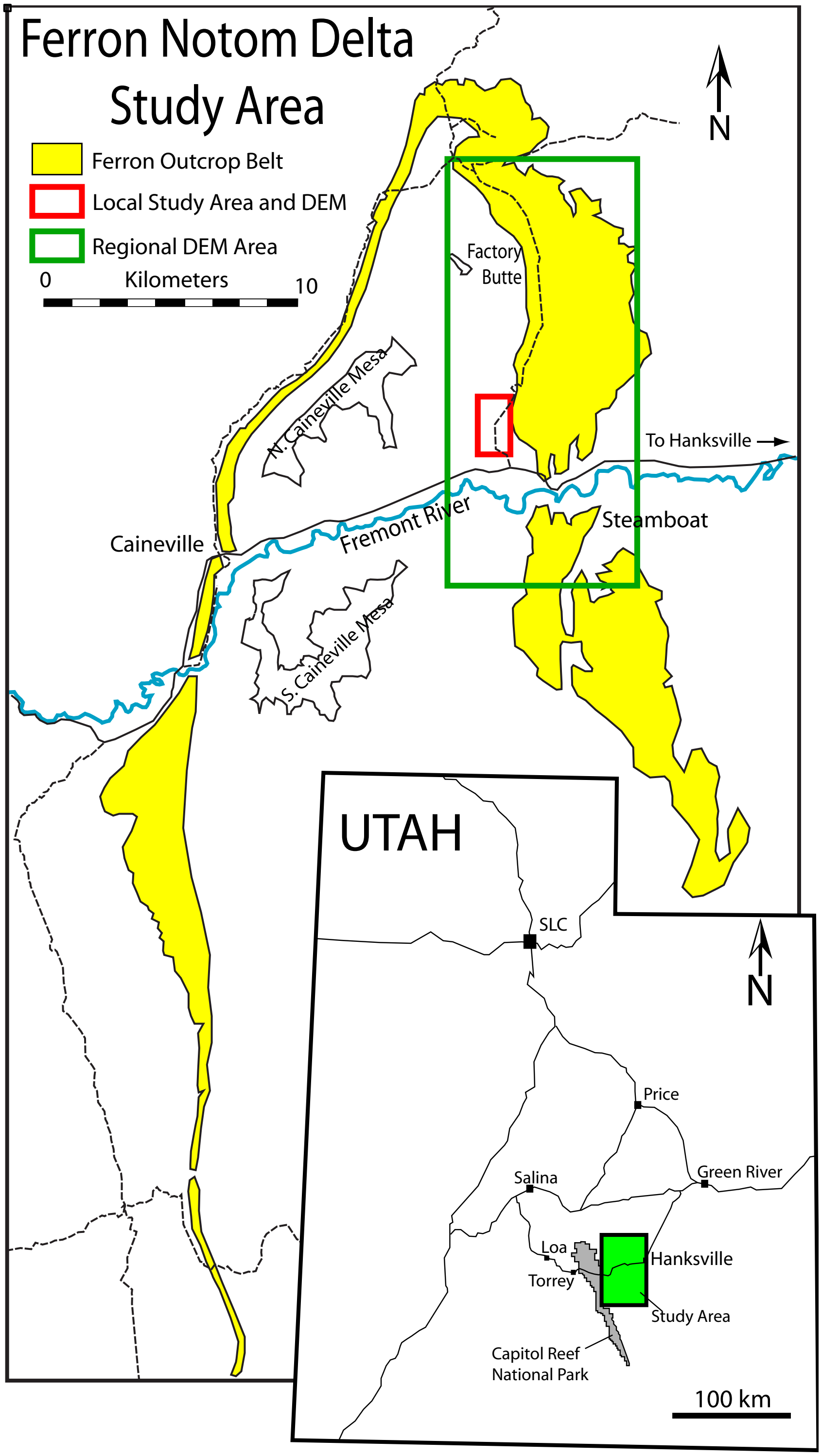

Figure 5. Showing the location of the Ferron Sandstone outcrop (yellow) in South Central Utah, between Hanksville, and Caineville. Nielson wash and the area of greatest interest is outlined in the red rectangle (See Figure 6). Regional DEM and satellite imagery will cover area within the dark green rectangle (Figure modified from Zhu, 2010).

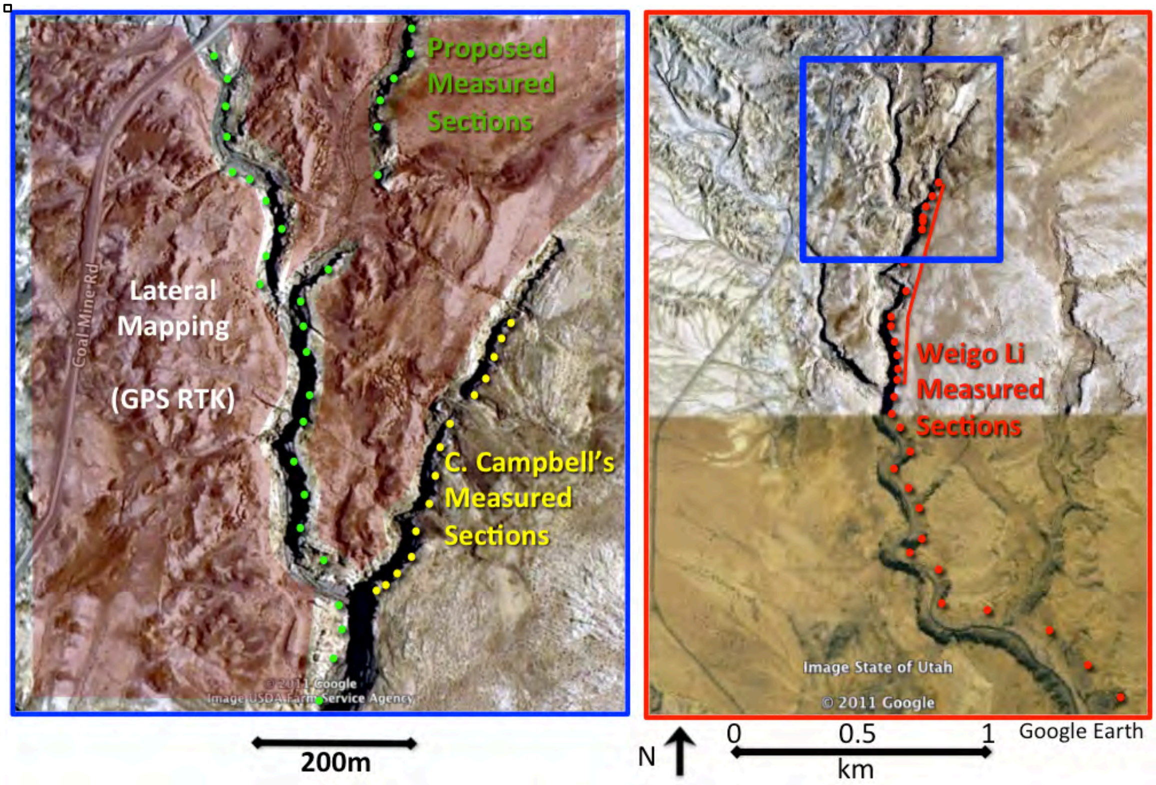

Figure 6. Satellite imagery of Nielson Wash with measured section locations plotted from previous workers (Li et al., 2010, and Campbell, in prep). Proposed measured sections (green points) and area of interest for lateral mapping (dark red area) is also shown. Solid red line adjacent to measured sections in the right image represents what is displayed in Figure 10 (Source Google Earth).

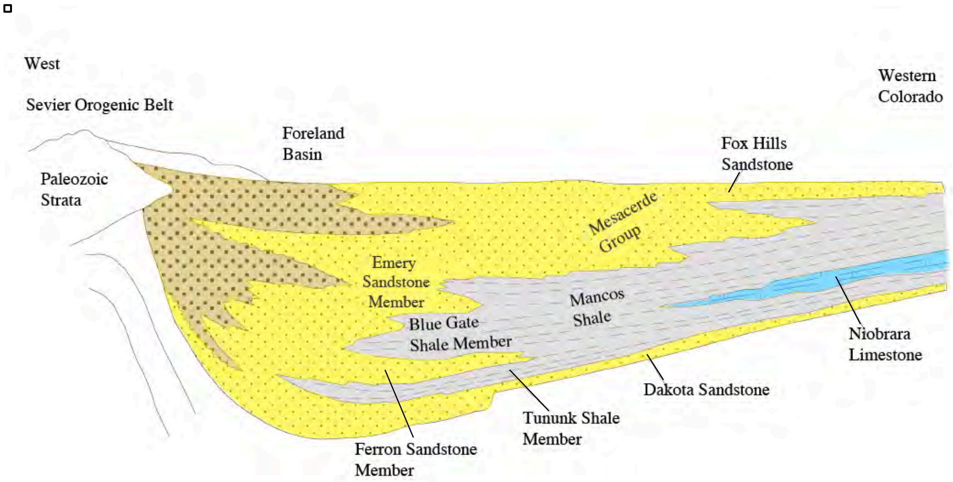

Figure 7. West to east Cretaceous wedge stratigraphy showing the position of the Ferron Sandstone Member (Modified from Barton et al., 2004).

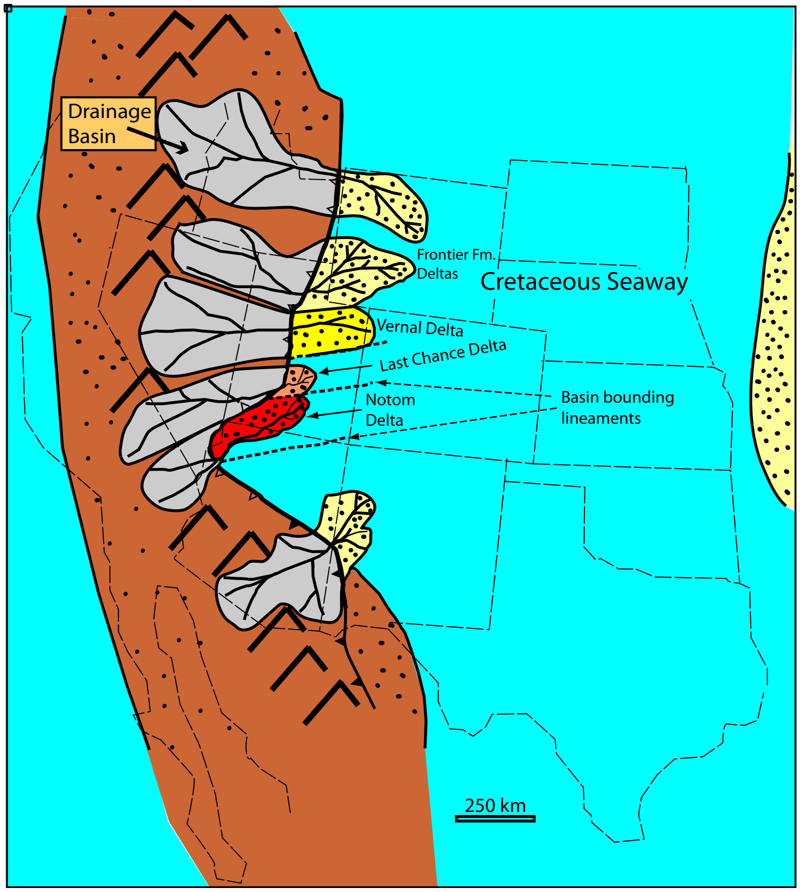

Figure 8. Paleogeographic map of the Cretaceous Interior Seaway during Turonian time showing the orientation and areal extent of the separate prograding fluvio/deltaic clastic wedges. Basin bounding lineaments are shown (from Bhattacharya & Tye, 2004, based on Gardner, 1995).

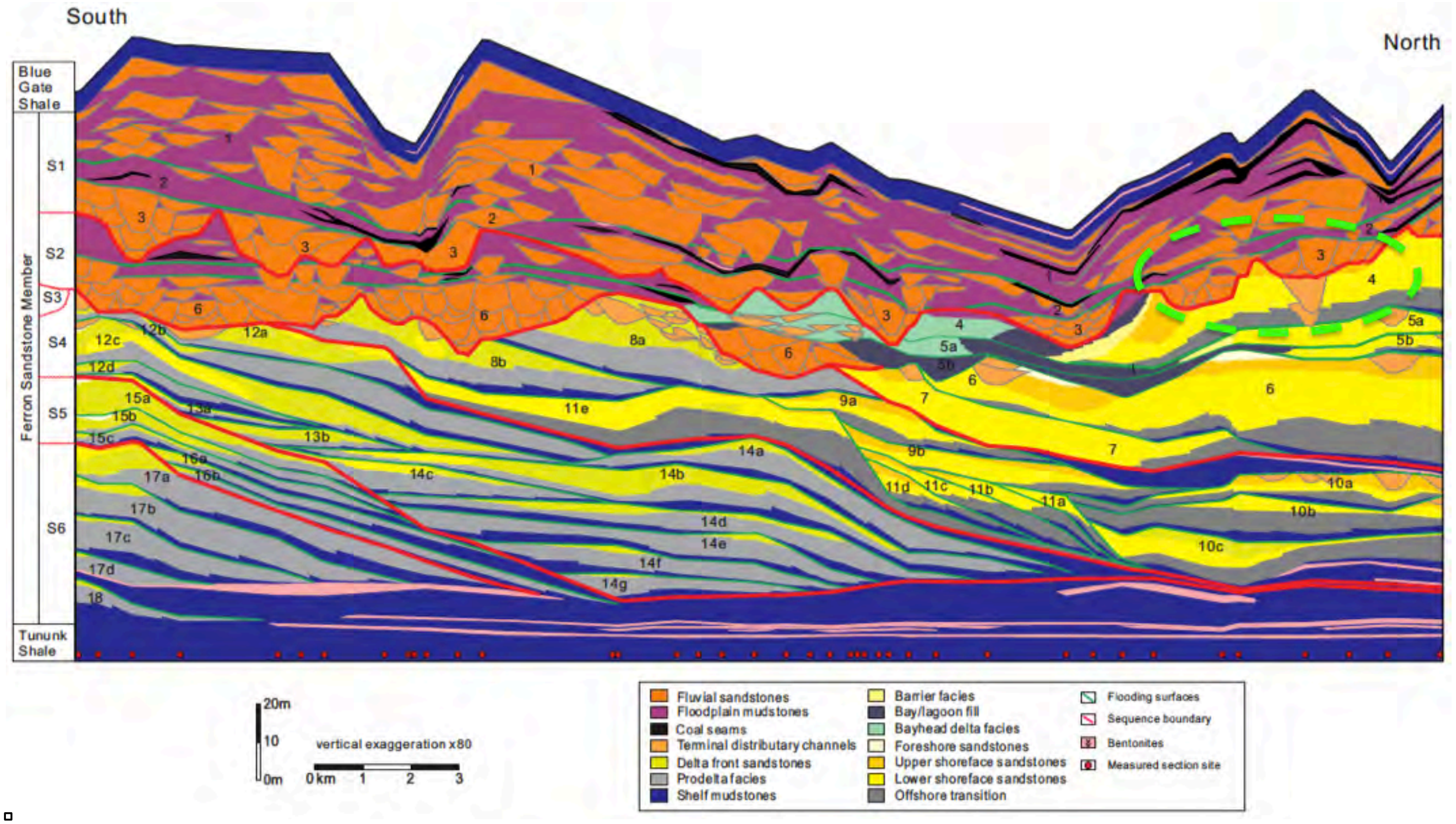

Figure 9. Approximately depositional dip oriented regional stratigraphic cross section through the Ferron Notom delta which shows 6 sequences, 18 parasequence sets and 43 parasequences. The dashed green line at the northern end of this image represents the study area within this sequence stratigraphic framework (Cross section

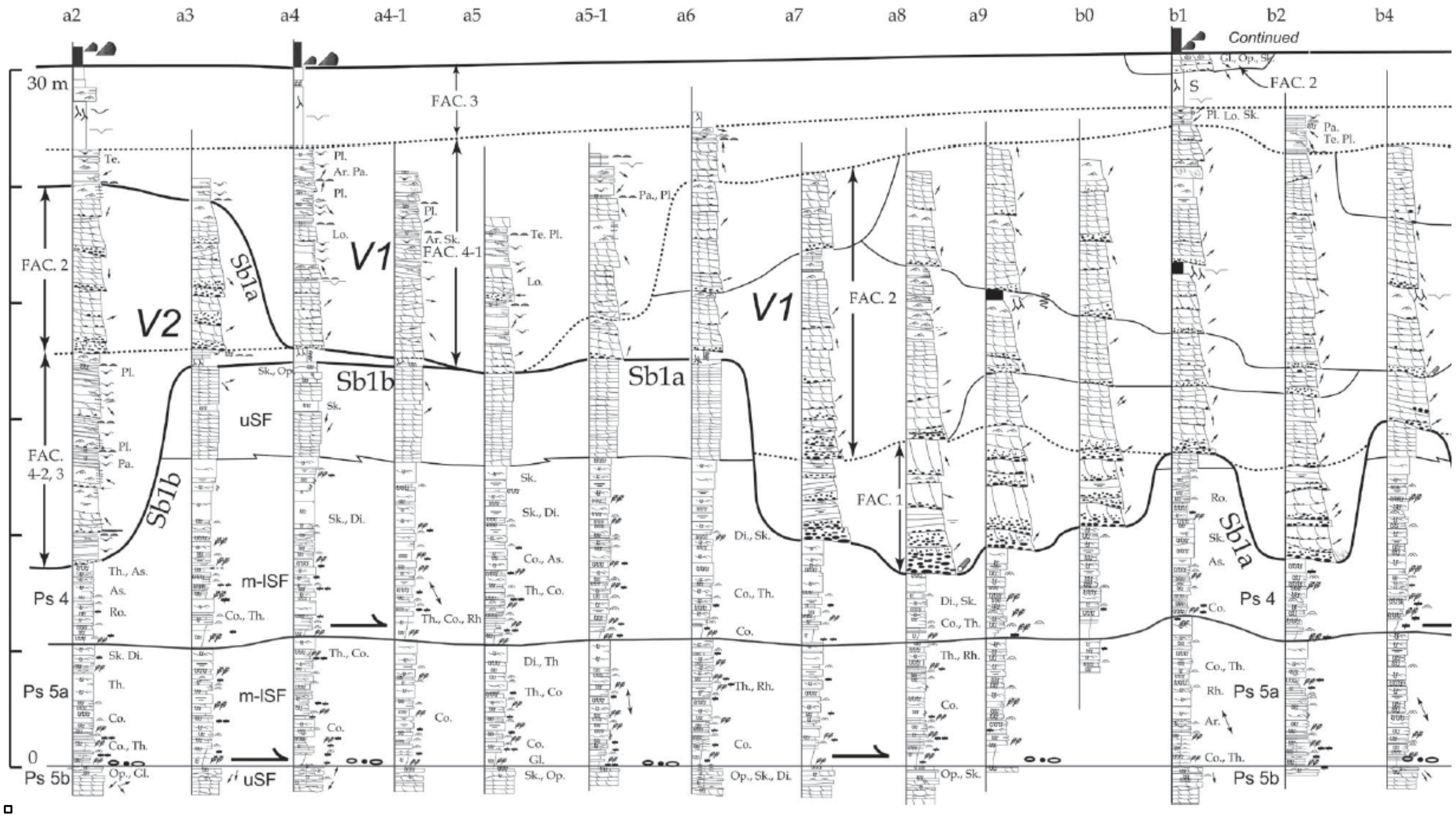

Figure 10. Northern portion of a cross section made by Li et al., (2010) showing measured sections, surfaces and facies boundaries near the transition between a trunk (V1) and tributary valley (V2). Measured sections for this study will be as detailed in order to compare and contrast facies types between trunk and tributive valleys and to transfer the current 2D interpretation into 3D. The data types to be collected will include: grain size, paleocurrent direction, sedimentary structures, trace fossils, strike & dip, dune heights (for water depths) and bed thicknesses.

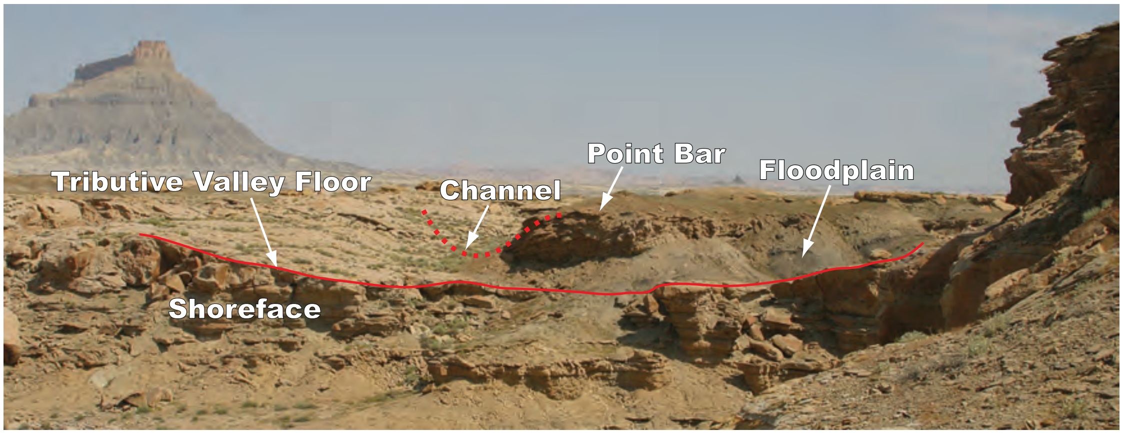

Figure 11. Photograph of exhumed tributary paleovalley floor, which fed a trunk system further to the north (V2A – Campbell, in prep). This incised valley incised into medium and upper shoreface deposits of parasequence 4 and is the surface of interest for the local DEM using GPS RTK equipment. Image is looking northward with Factory Butte in the background (Image/interpretation courtesy: Bhattacharya, 2011).

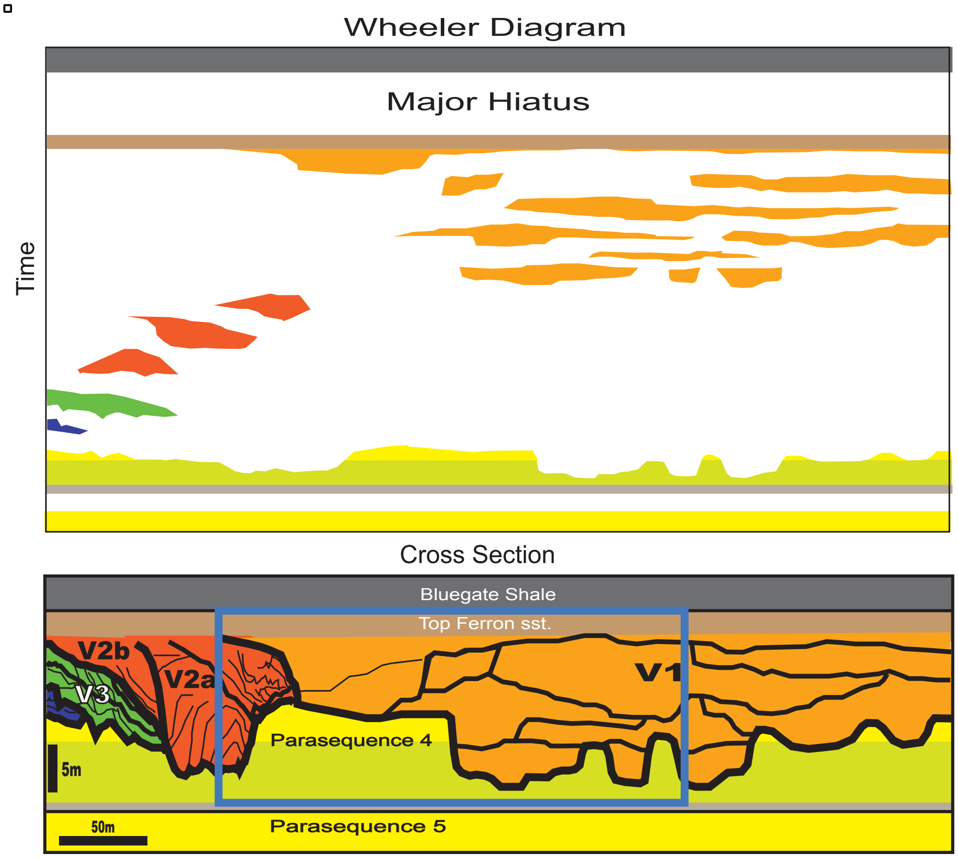

Figure 12. A generalized Wheeler diagram and cross section showing the sequence of deposition and stacking patterns of trunk (orange) and tributive valley (red) components. V3 (green) and the blue valley are actually falling stage terrace deposits. The blue rectangle is what is shown in Figure 10 (Source: Bhattacharya, 2011).