EVIDENCE FOR CLUSTERING OF DELTA-LOBE RESERVOIRS WITHIN FLUVIO-LACUSTRINE SYSTEMS, JURASSIC KAYENTA FORMATION, UTAH

by

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CHAPTER 1

Introduction

The purpose of this investigation is to evaluate reservoir genesis and attributes and to analyze the clustering relationships of channels within fluvio-lacustrine environments. The study will determine if the clustering concept extends into this lesser-understood environmental setting. Many outcrop and subsurface studies in the past have shown that non-marine fluvial strata tend to organize into non-random lateral and vertical succession (Allen, 1978; Shanley and McCabe, 1994; Mclaurin and Steel, 2000; Holbrook, 2001; Hajek, 2010; Hofmann, 2011). The two primary forms of non-random organization are clustering and compensational stacking (Hofmann, 2011). Recognition of clustering within the Kayenta Formation would expand the concept of clustering from strictly fluvial to fluvio-lacustrine systems. Clustering of fluvio-lacustrine deltas, just as in channel belts, is significant in predictive reservoir models in that it impacts connectivity and localization of delta-lobe reservoirs.

Fluvio-Lacustrine

For the purposes of this study fluvio-lacustrine systems are defined as shallow standing bodies of water with low wave and tide influence, are non-marine, and are dominated by fluvial channels penetrating the length of the system. These lakes may be perennial or seasonal, and occur in arid or humid climates. A modern example of a fluvio-lacustrine system is the Hay-Zama Lake system, Alberta, Canada (Figure 1). This is a group of large shallow fresh-water lakes with gently dipping margins. During periods when lake levels are high, which varies seasonally, the margins of the lake stretch out over much larger areas, forming an ephemeral lake region (Wright, 2005). During low lake levels, much of this area is characterized by marshes and poorly drained grassy flood plain areas. Hay-Zama Lake host a notable hierarchy of active and inactive channels including: the main trunk, medium sized distributive channels, and small distal distributive channels (Figure 1.1). There are no major delta forms such as bifurcations,

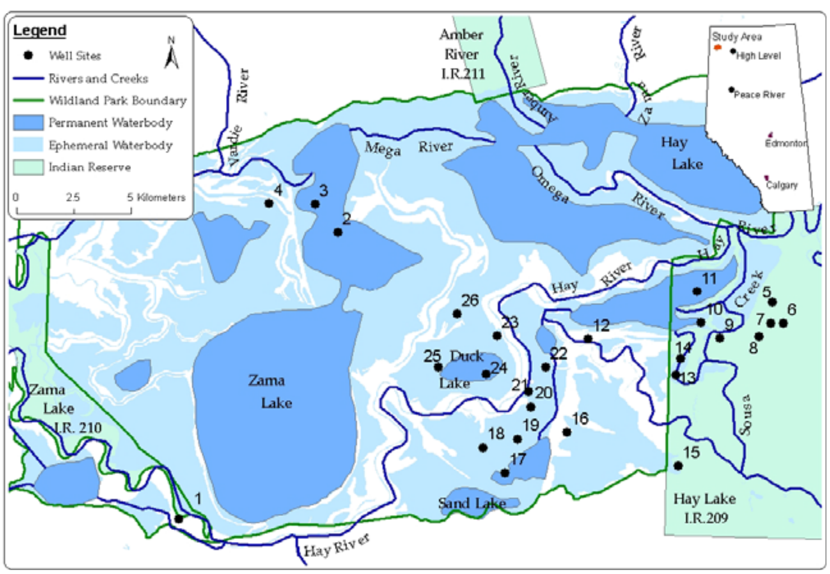


Figure 1.1 Hay-Zama Lake system, Alberta, Canada. There are three shades of blue, dark blue, blue, and light blue representing active channels, permanent lake, and ephemeral lake respectively. The white areas surrounding the active channels and extending out into the ephemeral lake are levies and channel deposits (Wright, 2005).

or bird foots and the primary distributive process appears to be channel avulsion. Channels end abruptly near the middle of the lake where the shallow ephemeral lake ends and the deeper perennial lake begins. The abruptness of the change highlights the importance of a shallow lake system for developing fluvio-lacustrine systems.

Fluvio-lacustrine systems may also occur as flood plain lakes and be a component of a poorly drained flood plain. Modern flood plain lakes are common in the Grijalva River coastal floodplain of Tabasco State, Mexico. While this is a coastal flood plain, not a lake, there are several large flood plain lakes with propagating splay channels (Figure 1.2A and B). Subsidence of the flood plain muds have created a relative sea level rise and forced the water table to rise above the depositional surface forming lakes (Stoner, 2010). The floodplain lakes and propagating splay channels appear to operate very similar to the Hay-Zama Lake system. They are both mostly fresh water systems with shallow standing water, low wave and tide influence.

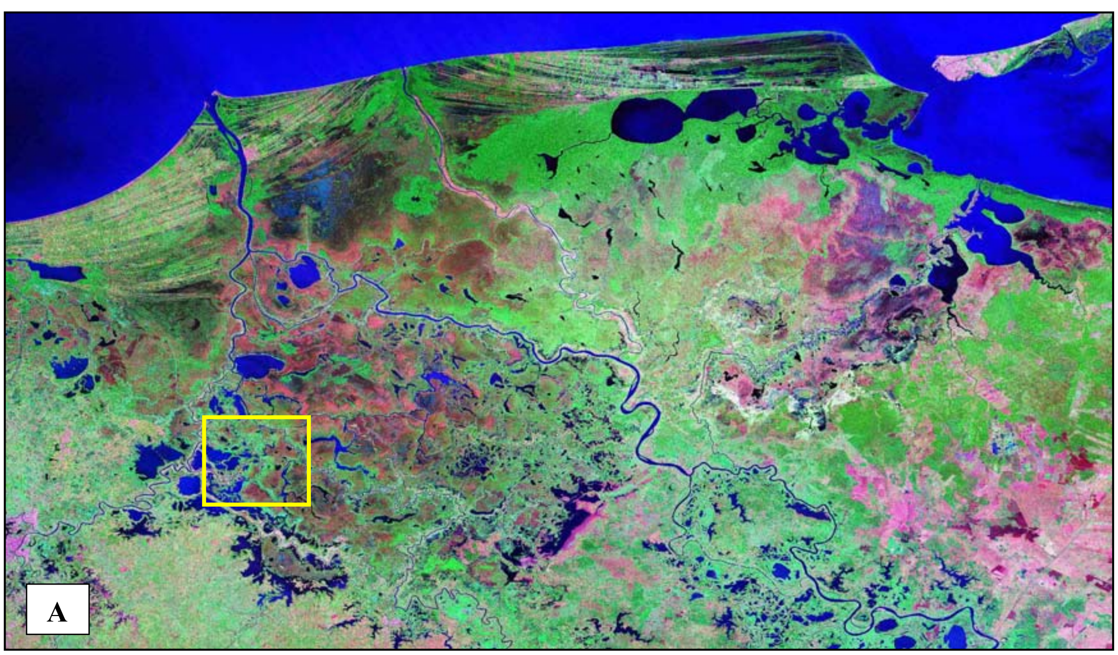
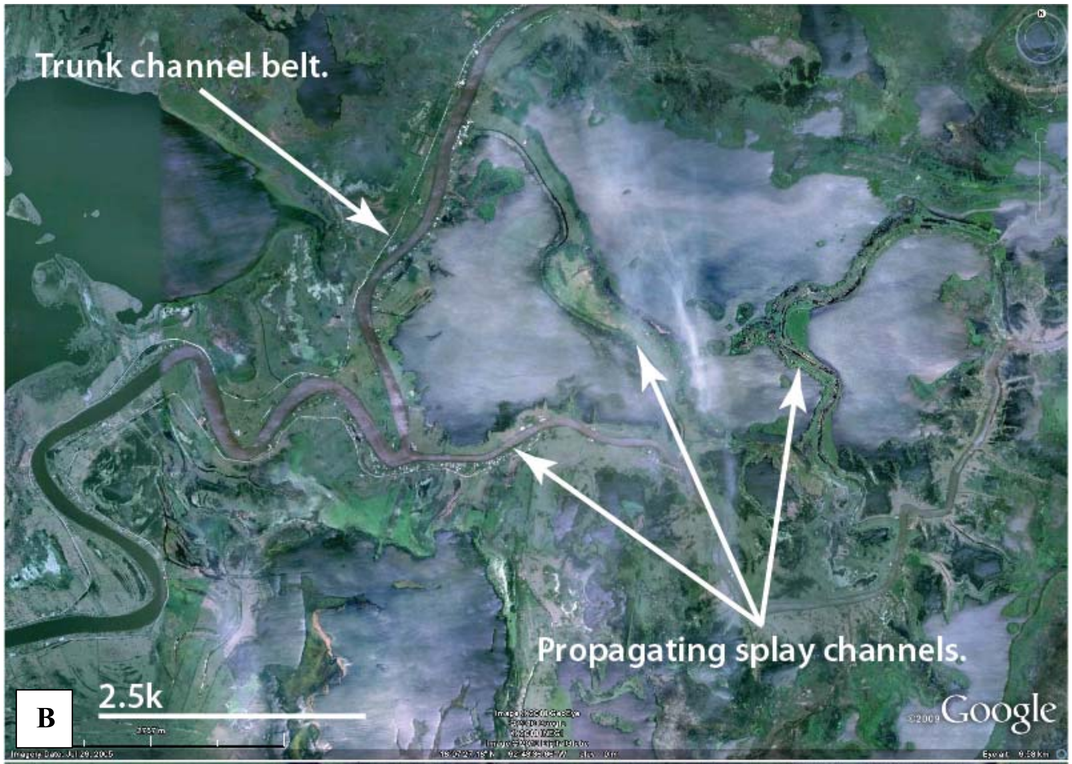


Figure 1.2 A) Grijalva River flood plain Tabasco State, Mexico. Many large floodplain lakes can be seen in blue (from Stoner, 2010). Yellow box indicates close zoomed in area in figure 1.2B.



1.2B) Zoomed in image of Grijalva flood plain lake. The propagating splay channels are building across the floodplain lake (modified from Stoner, 2010).

Delta formation is ultimately dependent on sediment delivery, which is controlled by the energy of the basin processes associated with the delivered sediment, sediment load, sediment size and fluid properties. One theory on the method of sediment delivery is called jet theory. Jet theory was established by Tollmien in 1926 and describes the transfer of energy of a radially symmetric turbulent jet of fluid emitted from an orifice as it enters a still body of similar fluid. As one fluid enters a still body of similar fluid, jet spreading and mixing with the basin water at the margins of the jet causes a Gaussian velocity profile across the jet (Figure 1.3) (Tomanka, 2013).This theory was expanded upon by Wright (1977) where he developed a model explaining elongate non-bifurcating channel deltas. However this model applies to fresh water entering salt water where a hypopycnal jet is supported by the density contrast between fresh and salt water.

However, these elongated deltas also form in fresh-water environments where the density contrast does not exist (Falcini, 2010; Tomanka, 2013).

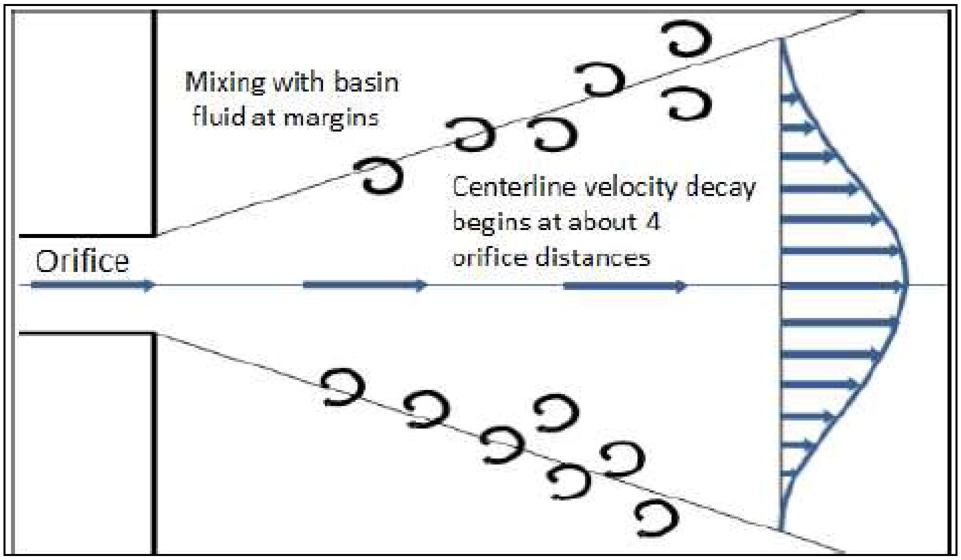


Figure 1.3 Model of Jet theory (Tomanka, 2013, from Bates 1953).

A widely referenced model that categorizes large modern marine deltas is based on three main processes (Galloway, 1975). It incorporates the flux of fluvial sediment input along with the influence of wave and tidal energy. In this model, different modern delta morphologies are explained as either being dominated by one of these processes (end members) or by being the product of any combination of the three processes (Galloway, 1975). Based on this model, the non-bifurcating linear morphology of the Mississippi River is due to river domination (Figure 1.4).

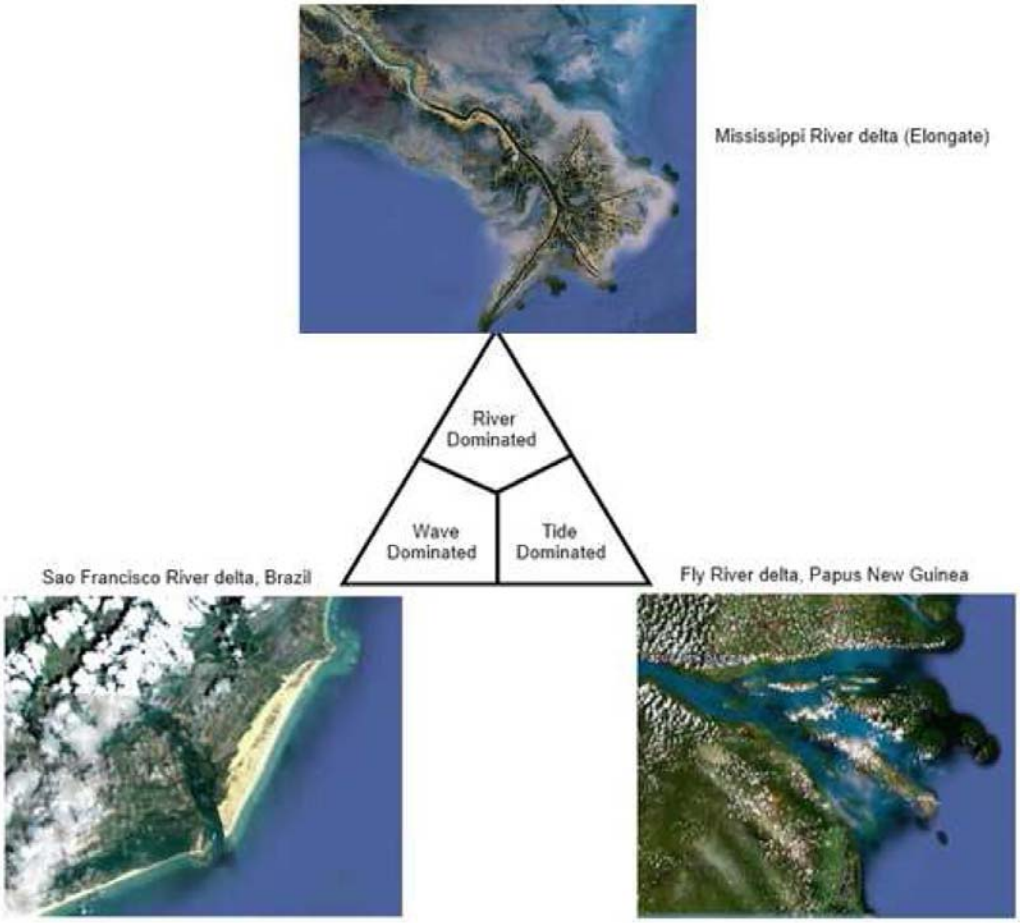


Figure 1.4 Ternary diagram based on Galloway's three primary energy regimes; River Dominated (top), Wave Dominated (lower left), and Tidal Dominated (lower right) (Tomanka, 2013).

Clustering

Channel clusters are stacks of closely spaced channels organized in a preferred spatial position (Leeder 1978; Hajek et al. 2010, Hofmann, 2011). Clustering of fluvial channel belts due to non-random stream avulsion is well documented for aggrading high-accommodation fluvial systems operating in alluvial plains (Hajek, 2010; Hofmann, 2011; Jerolmack, 2007; Kim and Paola, 2007; Sheets et al., 2007). Compensational stacking describes the tendency of fluid-flow deposits to fill topographic lows first, leveling topographic variation, and ''compensating'' for local topographic highs. It is theorized to be a product of reorganization of sediment distribution in order to reach the lowest elevations, thereby lowering the potential energy of the system (Figure 1.5) (Mutti and Normark, 1987; Stow and Johansson, 2000; Mohrig et al. 2000; Straub et al., 2009). Other studies (Burns et al., 1997), assume variation in broad-scale fluvial deposits are largely driven by basin boundary conditions such as tectonically driven changes in subsidence rate or sediment supply (Leeder, 1979; Kraus, 2002). Some field studies and modeling (Allen, 1978; Bridge and Leeder, 1979; Leeder, 1978) assume that during stream avulsion the relocation of the stream is random or that the stream simply moves to the lowest point in the flood plain (compensational stacking).

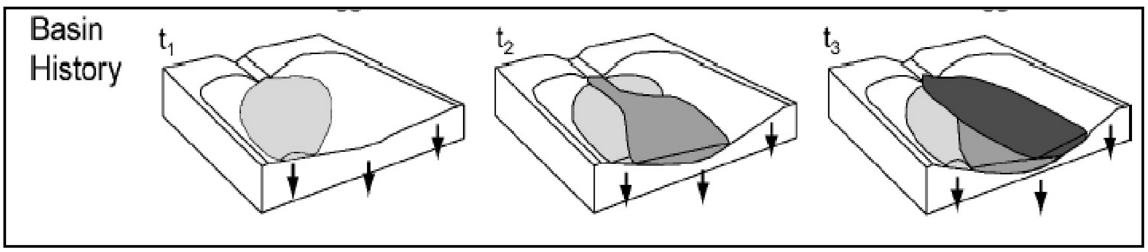


Figure 1.5 Compensational stacking of delta lobes is shown as a progression through time t1, t2, t3 (modified from Straub, 2009).

Channel clustering has long been observed qualitatively (Zaleha, 1997) but has only more recently been shown quantitatively (Jerolmack, 2007; Hajek, 2010; Hofmann, 2011). Sand-body clustering may be present more commonly than reported, but is only readily observed in large-scale fluvial deposits where exposures are sufficiently extensive laterally or vertically to show a sufficient sampling of adjacent channel bodies. Outcrops of the Kayenta Formation in Warner Valley are extensive enough to view these relationships and are the target of this study.

The organization of channel deposits into non-random assemblages occurs in several ways. Adjustments in subsidence rate or sediment supply due to tectonic forces can affect the distribution of channel bodies and other sedimentary deposits within the basin (Figure 1.6A).Valley incision and fill caused by sea-level fluctuation (Wright and

Marriott, 1993; Martinsen, 1994; Shanley and McCabe, 1994; Holbrook, 2001) or changes in discharge (Hall, 1990; Blum and Price 1998; Demko et al., 2004; Holbrook, 2006) can produce zones of closely spaced channel bodies juxtaposed among over-bank deposits (Figure 1.6B). Autocyclic processes of aggradation, subsidence, and channel avulsion can produce clustering shown in the model (Figure 1.6C). The outcrop in Warner Valley most closely resembles the model in 1.6C.

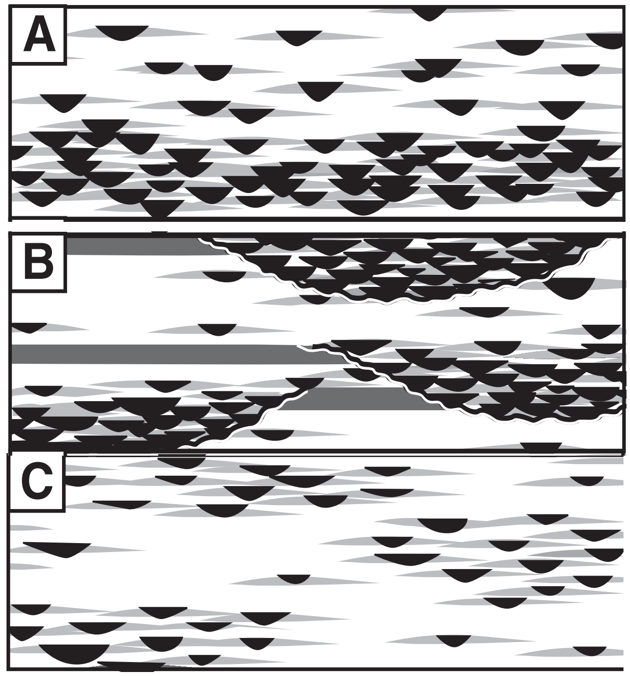


Figure 1.6 Examples of alluvial stratigraphy models, representing basin-scale fluvial deposit (kilometers wide, and hundreds of meters thick). Black lenses are coarse grained channel belts, light gray represents proximal overbank, and white is fine-grained floodplain. A: Early slow aggradation resulted in a higher concentration of channel bodies, and higher aggradation rates later separated the channels creating more isolated channel bodies B: Incised-valley fill from relative sea level change. Wavy black lines are erosional surfaces from valley incision; dark gray is interfluvial deposits with well-developed paleosols. C. Channel clustering formed during basin aggradation by autocyclic channel avulsion. Here the basin depocenter is relatively the same for a period, allowing for closely spaced channel bodies (clusters), and then relocates to a new portion of the basin due to avulsion, forming a new "cluster" of channel deposits (modified from Hajek, 2009).

Autogenic Processes

Autogenic processes refer to the redistribution of sediment within a depositional system as a result of processes inherent to the system such as channel migration, bar development, avulsion, or aggradation (Miall, 1996). An avulsion is presumed to have occurred where individual channel belts are separated by non-channel or other channel-belt deposits (Jones and Hajek, 2007). Jones and Hajek (2007) classify non-channel deposits as either overbank or non-overbank. The non-channel overbank deposits consist of fine-grained material and laminated mudstones from overbank flooding (Perez-Arlucea and Smith, 1999; Mohrig et al., 2000). Non-overbank deposits as outlined by Jones and Hajek "include crevasse splays (e.g., Jorgensen and Fielding, 1996) and crevasse channels formed by breaches in levees, ephemeral flood plain features formed by overland flow (e.g. Taylor, 1999), and/or deposits associated with avulsion; such as heterolithic deposits (Kraus and Wells, 1999), distributary channels and bars (Smith et al., 1989), or small deltas in floodplain lakes (Tye and Coleman, 1989). These non-overbank deposits range from mudstone to sandstone and typically contain ripple and dune-scale tabular cross-beds and planar bedding, and show evidence of intermittent flow" (Jones and Hajek, 2007). In classic moderate to well-drained channel systems both overbank and non-overbank deposits may be altered by typical flood plain processes of bioturbation and paleosol development.

One factor that may account for variation in avulsion stratigraphy is the amount of splay deposits within a given fluvial system (Jones and Hajek, 2007). Floodplains aggrade in two ways: overbank flood sedimentation and crevasse splay deposition (Aslan and Autin, 1999). Systems with relatively high amounts of crevasse splay deposits may be prone to produce stratigraphically transitional channels while other systems are more heavily dominated by overbank deposits (Jones and Hajek, 2007). Periods of active avulsion of the Holocene lower Mississippi River coincide with relatively high amounts of crevasse splay deposition (Aslan and Autin, 1999). The percentage of crevasse splay deposition during the Holocene lower Mississippi River avulsions is similar to the amount Kraus and Wells (1999) attribute to floodplain aggradation by avulsion related non-overbank deposition in the Willwood Formation (Jones and Hajek, 2007).

Multiple scales of avulsions may occur during life of a channel, the avulsions may be full, partial, nodal, local, or regional (Slingerland, 2004). Full avulsions are when all of the flow from one channel is transferred to a new or previously existing inactive channel and lead to the abandonment of the primary channel (Slingerland, 2004). In contrast, partial avulsions occur where portion of the flow from one channel is split between two channels. Partial avulsions may lead to either anastomosing channels or distributary channels. Nodal avulsions have the tendency to occur from a relatively fixed position of the flood plain over time, such as top of an alluvial fan. The opposite of nodal avulsions would be random avulsions occurring anywhere along the length of the channel (Leeder, 1978). Local avulsions divert from the parent channel for only a short distance and then rejoin the parent channel downstream. A regional avulsion is a larger scale event that affects the entire length of the channel downstream from the location of the avulsion (Heller and Paolla, 1996).

Avulsions are typically hierarchical and form in avulsion fairways or belts. An avulsion fairway or belt refers to the entire area of flood plain affected by an avulsion (Smith et al., 1989). The existence of one scale of avulsion within a fairway does not exclude the possibility for another type in a given area. For example, a regional avulsion may contain multiple local avulsions over time as the stream advances, and random avulsions may occur both regionally and locally (Slingerland, 2004).

Within the scales of avulsion multiple styles of avulsion can also occur. Four different styles of avulsions described by Slingerland and Smith (2004) are avulsion by progradation, aggradation, incision, and annexation. Progradation and aggradation have an early period of deposition characterized by crevasse splays and multi-channel distributary networks, which form as an increasing amount of sediment is diverted from the primary channel to the new avulsion (e.g., Smith et al., 1989; Ethridge et al., 1999). Avulsion by incision is brought on by scouring into the floodplain (e.g., Mohrig et al., 2000) and can produce stratigraphically abrupt channels. Avulsion by annexation is when an abandoned channel is reoccupied or an existing tributary is occupied by the primary channel (Slingerland and Smith, 2004).

Field Area

The Kayenta Formation of Warner Valley, UT (Figure 1.7), was chosen as the field site for two primary reasons: it displays the fluvio-lacustrine facies characteristics targeted for this study, and Warner Valley has well exposed extensive outcrops that permit collection of laterally extensive high-resolution photo panoramas for vertical and lateral facies changes to be observed. Mapping of the fluvial architecture in this area gives a more complete view of the fluvio-lacustrine architecture on the basin scale, rather than on a valley or flood plain scale.

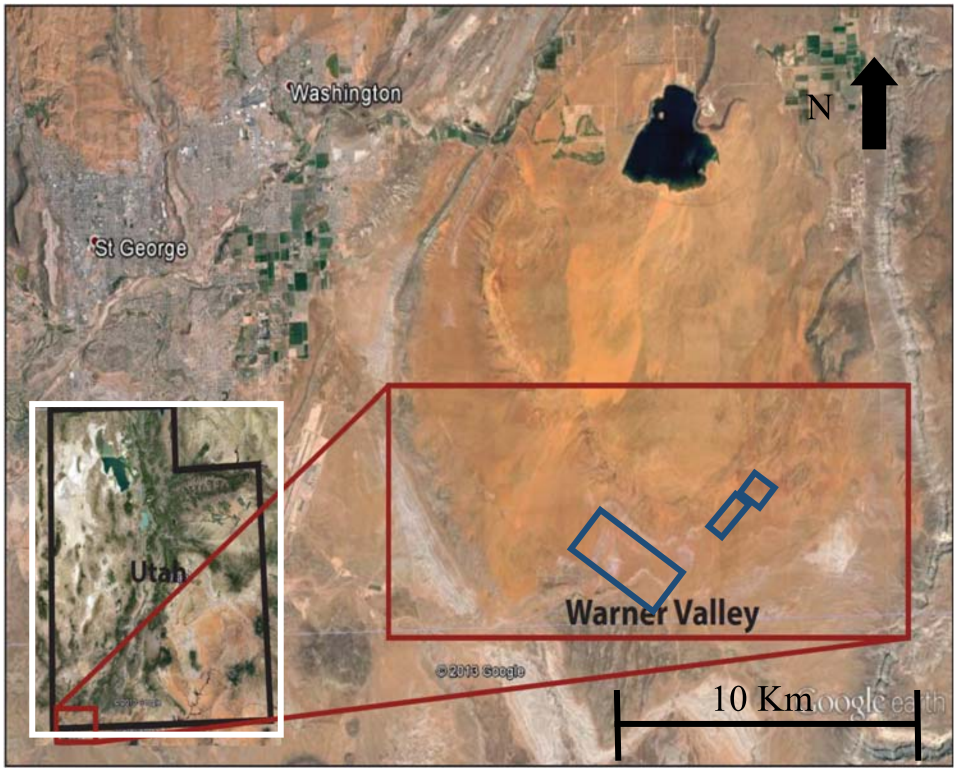


Figure 1.7 Location of Warner Valley, Utah and field area. Location of photo-panoramas are marked by blue boxes (Google Earth, 2013).

The Kayenta Formation is a member of the Glen Canyon Group (figure 1.8B) (Baker et al., 1927; Harshbarger et al., 1957) which includes the Wingate Sandstone, Moenave Formation, Kayenta Formation, and the Navajo Sandstone. The Kayenta Formation is well documented north of Warner Valley in Zion National Park and to the East in Central Utah in, but those outcrops comprise more fluvial-dominated facies compared to outcrops found in Warner Valley (Luttrell, 1992). Warner Valley is dominated by a finer grained silt facies with isolated clusters of fluvial channels (Harshbarger et al., 1957; Luttrell, 1992). During preliminary field work abundant gypsum was found throughout the formation, which suggests intermittent drying and subaerial exposure. The dominant facies present in the Kayenta Formation in Warner Valley is parallel laminated silt and clay, which lacks evidence of well developed paleosols or rooting often found in alluvial plains (Bridge, 2003), and marine indicators, characteristic of shallow lake deposits (Nichols, 2005). Relatively little sedimentological and geochemical work has been done on the Kayenta Formation in Warner Valley, and further analysis would help constrain the details of the lake setting environment.

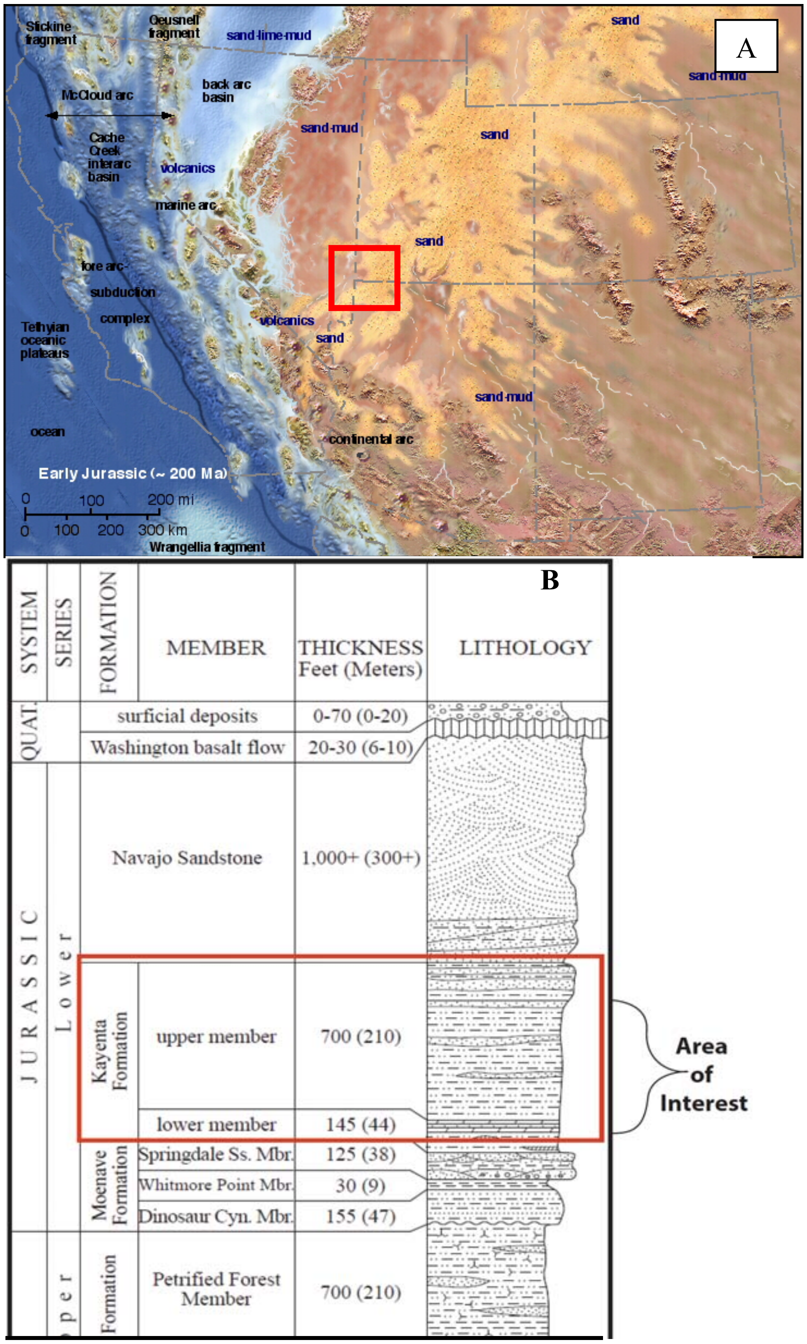


Figure 1.8 A. Paleogeographic map of North America during Early Jurassic (Blakey, 2011). B. Stratigraphic section highlighting the Lower Jurassic Kayenta Formation being studied (Hayden, 2005).

CHAPTER 2

Methods

This research is a combination of field based observations and statistical analysis of clustering relationships mapped on photo panoramas. Three large scale panoramas were taken, and the distribution and interrelationships of lithofacies assemblages were physically identified and mapped on foot using photo panoramas as a base map. Principles of architectural-element analysis (Miall, 1985, 1986, 1988) were used in analyzing the fluvial bounding-surface relationships (Figure 2.1). Bounding surface data were collected from fluvial strata by tracing bedding surfaces on photographs. This work was performed using assumptions considered to apply to primary/depositional bedding that came from principles of superposition and cross-cutting relationships outlined by Holbrook (2001).

"These include: (1) each surface is considered unique and laterally continuous until truncated, or deemed undiscernible; (2) a surface may truncate another, but surfaces my not cross; (3) though surfaces may be diachronous, any location on a surface must be younger than the materials/surfaces it cuts, and older than the materials/surfaces it binds (Miall, 1985; Holbrook, 2001). Surfaces were then assigned rank orders using the following guidelines: (1) bedding surfaces bounding lamina sets are considered 1st-order; (2) lower-order surfaces will be bound by higher-order surfaces; (3) the order of a surface will be one order higher than the highest-order surface it binds, and may be of higher order where guideline 4 should be

Grp	Time scale of process (a)	Examples of processes	Instantaneous sedimentation rate (m/ka)	Fluvial, deltaic depositional units	Rank and characteristics of bounding surfaces
1	10^{-6}	Burst-sweep cycle		Lamina	0th-order, lamination surface
2	10^{-5} -10^{-4}	Bedform migration	10^{5}	Ripple (microform)	1st-order, set bounding surface
3	10^{-3}	Bedform migration	10^{5}	Diurnal dune increment, reactivation surface	1st-order, set bounding surface
4	10^{-2} -10^{-1}	Bedform migration	10^{4}	Dune (mesoform)	2nd-order, coset bounding surface
5	10^{0} -10^{1}	Seasonal events, 10-year flood	10^{2-3}	Macroform growth increment	3rd-order, dipping 5–20° in direction of accretion
6	10^{2} -10^{3}	100-year flood, channel and bar migration	10^{2-3}	Macroform, e.g., point bar, levee, splay immature paleosol	4th-order, convex-up macroform top, minor channel scour, flat surface bounding floodplain elements
7	10^{3} -10^{4}	Long-term geomorphic processes, e.g. channel avulsion	10^{0}–10^{1}	Channel, delta lobe, mature paleosol	5th-order, flat to concave-up channel base
8	10^{4} -10^{5}	5th-order (Milankovitch) cycles, response to fault pulse	10^{-1}	Channel belt, alluvial fan, minor sequence	6th-order, flat, regionally extensive, or base of incised valley
9	10^{5} -10^{6}	4th-order (Milankovitch) cycles, response to fault pulse	10^{-1}–10^{-2}	Major dep. system, fan tract, sequence	7th-order, sequence boundary; flat, regionally extensive, or base of incised valley
10	10^{6} -10^{7}	3rd-order cycles. Tectonic and eustatic processes	10^{-1}–10^{-2}	Basin-fill complex	8th-order, regional disconformity

Figure 2.1 Hierarchies of architectural units (Miall, 1996)

satisfied; (4) surfaces truncate against surfaces of equal or higher rank; (5) similar, but nested, surfaces may be treated as a set of boundaries of equal order, but the set should be ultimately bounded by a surface of higher rank" (Miall 1988, 1996; Holbrook, 2001).

Architectural analysis was used to constrain energy level of the system, water depth, channel size, relative reworking of a channel in a given location, and the hierarchy of deposition processes. Fluvial architecture also is important for identifying the depositional center of each channel element, an integral part of the statistical process.

Along with the three large-scale panoramas, smaller scale photos were taken in order to understand the architectural elements on the bed scale. Stratigraphic sections were measured across the outcrop length. The data from the stratigraphic sections aids in defining and interpreting lithofacies and interpreting depositional processes spatially. Measuring the outcrops also gives scale to the photographs, and permits estimates of the aspect ratios of various elements from the photos.

Statistics

Channel clustering was assessed within the fluvial deposits using spatial-point-process (SPP) statistics. SPP methods can characterize sand-body distributions with the intent of finding information about the spatial distribution of fluvial deltaic lobes. SPPs are datasets of locations (points) representing the products of a process that are assumed stochastic (a spatial point process; Diggle, 2003). In this study, area the points collected are locations of the fluvio-deltaic lobes. A nonrandom pattern may be either aggregated (where occurrences tend to be clustered or clumped together spatially) or regular (where occurrences are more evenly-spaced throughout an area) (Hajek, 2009).

The method for SPP is adapted from Hajek (2009). Hajek (2009) analyzed the fluvial channel-body of the Ferris Formation using SPP and analyzed the clustering relationships using the K-function and nearest neighbor statistics. In order to use the SPP method, the center of the each fluvial deposit must be located and mapped on the panorama (Figure 2.2). Identifying the center allows a single point for each fluvial event, which is necessary for spatial point calculations. In order to identify the center of each lobe large and small scale panoramas of the Kayenta Formation and mapped individual delta splay lobes. The panoramas enabled tracing of the lateral extent of scour surfaces, lapping relationships of delta splays, flooding surfaces, and detailed sedimentary structures. This defined the center of individual deltaic lobes as the mid-point vertically and laterally of discrete channel bodies within the center of discrete deltaic lobes. In many cases, however, only a portion of the lobe is preserved due to erosion and amalgamation of lobes. In these cases a best estimate was made of where the midpoint would be if the lobe had been preserved.

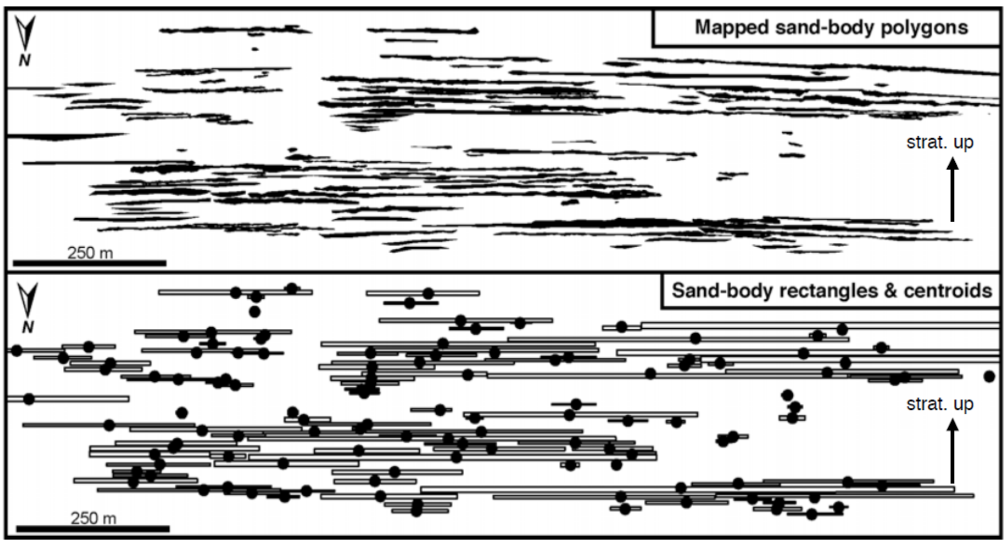


Figure 2.2 The top rectangle shows mapped sand-body polygons from panoramas taken of the Hanna Formation, Wyoming. In the lower rectangle are the same polygons approximated by rectangles, with centroids of each rectangle shown as dots. The panels are oriented so stratigraphic up is at the top (Hajek, 2009).

One advantage of combining large-scale panoramas with SPP is that it allows for the comparison of naturally occurring processes with computer simulations and laboratory experiments. Currently the utility of applying spatial point process methods to stratigraphic data is limited because there are no existing strategies accounting for the finite area occupied by channel deposits; the statistical representations only account for the object centroid (Hajek, 2009). Developing statistics that account for object shape and size would improve the applicability of SPP measures to stratigraphic datasets, particularly in settings with ranges of object shapes and sizes. The spatial relationships in a point process can be analyzed using the K function (Cressie, 1993). *K(h)* is a statistic used to compare the expected number of events (channel bodies for this case) with the average rate of the process λ, within a distance *h* of each event in a study area.

$$K(h) = \lambda^{-1} E(N(h)) \text{ for } h>0 \qquad \text{(Equation 1)}$$

With λ being the number of points within the field location (*N*), divided by the area of the study region and E(*N*(*h*)). This gives the mean number of points within a distance *h* from each point (Hajek, 2009). The *K* function provides a way of testing for complete spatial randomness and characterizing the amount of spatial organization for points over a variety of length scales within a study area (Diggle, 2003; Cressie, 1993).

The using photo pans of the outcrop puts brings all the points into a sin, Ripley's (1977) formula can be used:

$$\hat{K}(h) = \hat{\lambda}^{-1} \sum_{\substack{i=j \\ i \neq j}}^{N} \sum_{j=1}^{N} w(s_i, s_j)^{-1} I(\| s_i - s_j \| \leq h)/N \qquad \text{(Equation 2)}$$

where *si* and *sj* are separate points for a given area, *w(si,sj)* is a weighting factor that is the proportion of the circumference of a circle centered at *si* passing through *sj* that is located within the study area, and *I*(.) is the indicator function, which is 1 when the Euclidian distance between *si* and *sj* < distance *h*, otherwise *I*(.)=0 (Hajek, 2009). Since the K function increases in value with search distance *h,* K is often transformed to make the plots easier to read. The transformation is L:

$$\hat{L}(h) = \sqrt{\{K(h)/\pi\}} - h \qquad \text{(Equation 3)}$$

Hajek (2009) explains that the transformed estimated *K* function for randomly distributed point patterns plots near zero and within the envelope from 99 Monte Carlo simulations (Figure 2.3A). According to Hajek this indicates that “the number of points within *h* of any event in the study area is close to the expected number given the intensity of the point process. When more events are found within a given distance than is expected given the overall intensity of the point process, the transformed *K* function plots positively”, indicating event aggregation (Figure 2.3B). Alternatively, if there are less events than would be expected for a given *h* they are considered to be distributed regularly across the study area and the transformed *K* function is negative (Figure 2.3C). Simply put, the data for the K test is telling us whether the data is random, evenly distributed, or clustered.

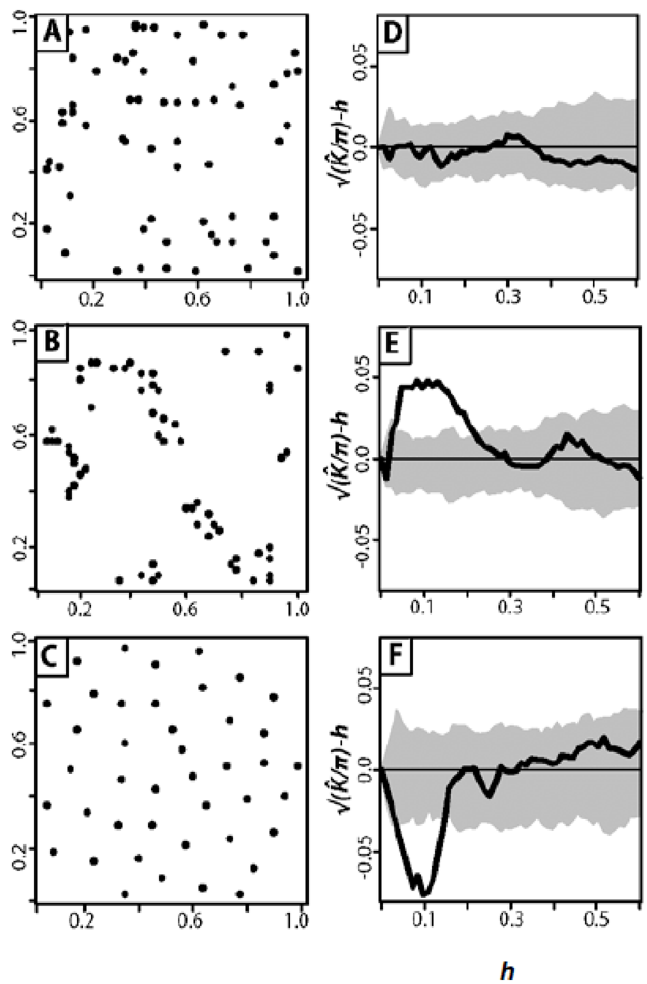


Figure 2.3 Examples of three spatial distributions of point processes A: random B: clustered C: evenly distributed. D-F are the transformed K functions of A-D respectively (Hajek, 2009).

CHAPTER 3

Results

Field Data

Eight facies are identified in the Kayenta Formation within Warner Valley. The facies show distinct depositional environments. The most prominent facies represented is lake muds, followed by cross-bedded and ripple-laminated channel deposits. The lake muds encase all other lithofacies. A description of each is found in Table 3.1.

Table 3.1 Lithofacies descriptions

Assemblage	Lithology	Characteristics	Biota	Environment
Cross laminated sandstone	Silty-fine grain sandstone; medium to thick bedded	Ledge and cliff forming; medium scale trough and planar cross bedding, localized channel scour, soft sediment deformation, ripup clasts	None	Proximal Channel – Main channel trunk-medium size channel
Ripple laminated sandstone	Silty-very fine; localized interbedded lake mudstone and siltstone	Small ripples (centimeters),	None	Channel wings, medium to small channels, or shallow lake
Blocky sandstone (lower portion of formation)	Silt-very fine grained sandstone	Few to no laminations preserved, burrows and rooting (mostly in the lower portion of the Kayetna)	Abundant burrowing	Levee, or other subaerialy exposed channel margin deposits

Thin bedded sandstone	Silt-mud sandstone	Thin isolated beds (centimeters) laterally extensive	None	Distal Fluvial
Paleosol	Bioturbated silt and mud	Localized thin (>.5 m) layers typically scoured into by cross laminated facies	Roots and burrowing	Arid to Semi-arid flood plain with minor soil development
Parallel laminated shale and gypsum	Mudstone, silty mudstone, and crystalline gypsum	Loosely consolidated, slope forming, easily weathered, secondary gray/green sphearoidal chemical alterations throughout, laterally continuous. Gypsum is found mostly in fractures and muddy lake sediment	Minor rooting locally	Open lake to shallow lake - evaporative lake
Limestone	Micrite	Very laterally extensive tabular thin to medium isolated beds, forms thin ledges a few inches thick	Algal	Lake

Lithofacies Descriptions

Channel-Associated Lithofacies

<u>Cross Laminated Sandstone</u>

Characteristics: Cross-bedded, parallel-laminated, ripple and wavy-laminated with mostly silty-to-fine-grained well sorted sandstone with local medium grained sandstone. Basal contact is a sharp scour with mud rip-up clasts. Soft sediment deformation is typical in the channel sand and below in the underlying mudstone. Bedding planes commonly crosscut and truncate each other. The uppermost portion of the deposits have local bioturbation or rooting but are mostly undisturbed ripple or wave laminated sandstone where not truncated by another channel. These units form ledges and cliffs.

Interpretation: These strata record deposition in the primary channel and nearby distributary channels during periods of high energy flow. The scours are cut into the lake muds during periods of high flow and successive pulses of energy lead to frequent truncation, leaving portions of the bedforms to be preserved in the sedimentary record. The mud rip-up clasts are eroded as the thalweg cuts through the underlying sediment and incorporated into the bedload (Bridge, 2000; Stoner, 2010).

<u>Ripple Laminated Sandstone</u>

This facies is found in three different settings within the Kayenta Formation and depending on its spatial relationship to other facies is interpreted to be different environments. All three are ripple laminated silt with varying degrees of mud and very fine grained sediment and are generally well sorted.

Ripple Facies 1: Channel Wings

Characteristics: Ripple laminated sandstone ranging from silt to very fine grained with individual ripples being only a few centimeters tall (Figure 3.1). Ripples are found directly above the cross laminated facies at the top the fluvial deposits. They typically extend laterally across the top the fluvial deposits when not truncated by channels or other ripple laminated strata. The wings scour into the underlying lake deposits proximal to the channel deposits and conformably pinch out as a thin wedge. These wings are usually no more than .5 meters thick as individual wings, but often interfinger with wings from other channels forming ledges up to 2 meters thick when clustered together.

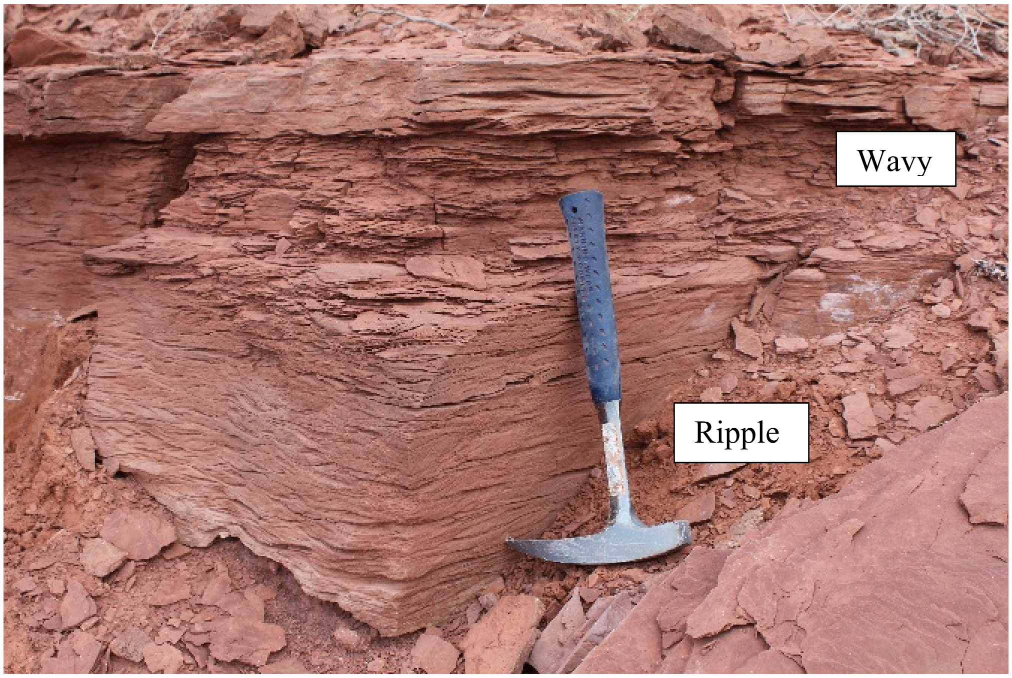


Figure 3.1 Close up of wavy and ripple laminated siltstone from a wing proximal to a channel.

Interpretation: During flooding stages the water levels are high and sediment is flushed down the channel and at times flows over the levees as sheet flows. In this sustained flow event, with rising basin water, the orifice of the turbulent jet and the zone of the jet margin deposition would gradually move upstream contemporaneously resulting in a long linear zone of sedimentation that flanks each side of the channel (Tomanka, 2013).

Ripple Facies 2: Medium to small channels

Characteristics: These ripple laminated deposits are commonly lensoidal deposits without cross laminated facies. They scour into the underlying lake deposits and pinch out laterally but lack the rip-up clasts and soft sediment deformation of the cross laminated sandstone facies. They may form as isolated deposits or in clusters souring and cross cutting into each other, and range in thickness from .5 m to 2 m. These medium to small channels may also have their own ripple laminated wings described in the previous facies.

Interpretation: This is being interpreted as medium to small channels, which may be tie channels or minor distributary channels. Due to the smaller size, lack of cross laminations, and lack of rip up clasts these channels are associated with lower flow regimes than the primary channel, but are still sufficiently channelized to not be considered distal fluvial.

Ripple Facies 3: Shallow Lake

Characteristics: Above the wings, bleached white ripple and wavy laminated silt occur at the top of the upper most channel or channel-fill strata. Open lake sediments are almost always found above in direct contact. White caps may extend over a single channel or cluster of channels, but always at the top, and are bleached white.

Interpretation: The white caps record lake levels fluctuations. As lake levels rose water would flood over the channel fills. Shallow waves would rework the wings and channel deposits creating the ripple and wave laminations. The white color comes from winnowing of the heavier iron oxide minerals and general leaching.

<u>Blocky Sandstone (lower portion of formation)</u>

Characteristics: These are sandstone beds with few to no laminations preserved and contain abundant burrows and rooting. Most of this facies type is located in the lower portion of the formation and outcrops as ledges. The grain size ranges from silt to very-fine-grained sand (Figure 3.2).

Interpretation: These deposits are interpreted to be levee deposits or other subaerially exposed channel margin deposits. As this facies is located mostly in the lower portions of the formation it is possible lake levels remained generally lower during early stages of deposition, allowing for longer durations of subaerial exposure for channels. This would give more opportunity for burrowing and plants.

Non-Channel-Associated Lithofacies

<u>Parallel and Wavy Laminated shale</u>

Characteristics: Parallel laminated with local wavy and small ripple laminated mud to clay size shales. Laminations can be thin to very thin (mm-cm). Rooting is locally found but atypical. Evidence of soil development and marine indicators (e.g. marine fossils, bi-directional flow structures, etc.), or strong current indicators is lacking. Mud rich shale sections may extend laterally for several km or a few meters where truncated by channel scours and can be up to 30m thick. As the dominant facies throughout the formation it weathers into slopes. This facies is typically found directly above ripple laminated wings and white caps with either gradational or sharp contacts. Minor variations in silt content varies episodically in vertical sections. Crystalline gypsum selenite is found throughout this facies within cracks and laminations.

Interpretation: This lithofacies depicts an environment of shallow low-energy/standing water with low wave and tide influence that is penetrated by fluvial channels. The lack of well-developed soils and roots, along with the lateral continuity of the mudstone layers suggest a lacustrine environment. The gypsum lithofacies is also associated with this mudstone lithofacies. Gypsum mostly fills cracks, not found apparent in bedding planes, but was probably deposited and then leached out due to burial and compaction and re-deposited or precipitated in the fractures. The abundant gypsum suggests periods of very low water levels and associated periods of evaporation.

Paleosols

Characteristics: Dominantly mudstone and claystone with almost no primary sedimentation structures preserved. Moderate rooting and bioturbation is present and strata fractures into concoidal nodules. No significant internal soil horizons are present. Where found these sections are <1 m thick, but are typically scoured into by overlying channels, and difficult to follow over intervals more than 75 meters.

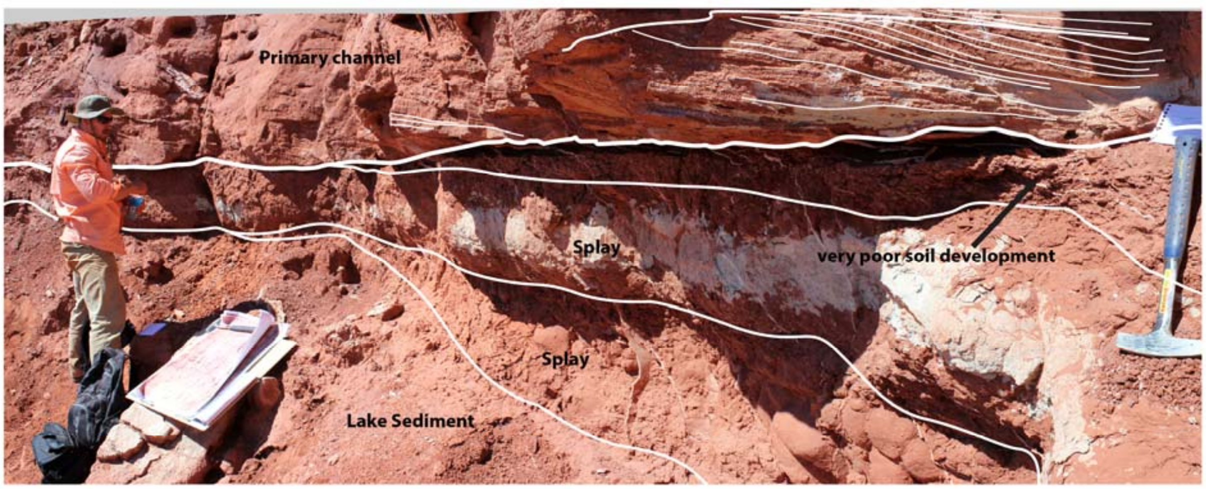


Figure 3.2 Outcrop showing transition from lake sediment to bioturbated blocky facies, paleosol, and cross-laminated facies scouring through into the paleosol.

Interpretation: These immature soils represent temporary emergence of the lake floor and subaerial exposure of portions long enough to begin soil development, but not long enough to establish a strong horizon. It is possible more mature soils evolved locally and were later removed by channel scours. Figure 3.2 shows the presence of an immature soil above a bioturbated blocky siltstone and below a channel fill that locally scours all the way through the soil down into the bioturbated siltstone. The frequent dissection by channels may have isolated small areas from the open lake waters, allowing the isolated areas to dry and develop soils. The presence of the few soils provides a contrast to the parallel laminated shale, enhancing the interpretation of a generally lake dominated system.

<u>Limestone</u>

Characteristics: Isolated and tabular micritic limestone beds are common in the lower portion of the Kayenta Formation. There are sub-parallel laminations and often the laminations appear to be algal and only millimeters thick. These beds are laterally extensive and can be traced the length of the study area (10 km) but are only about 15 cm thick. The layers serve as good correlation markers in the lower portions of the Kayenta Formation. These ledges are encased within open lake muds (Figure 3.3).

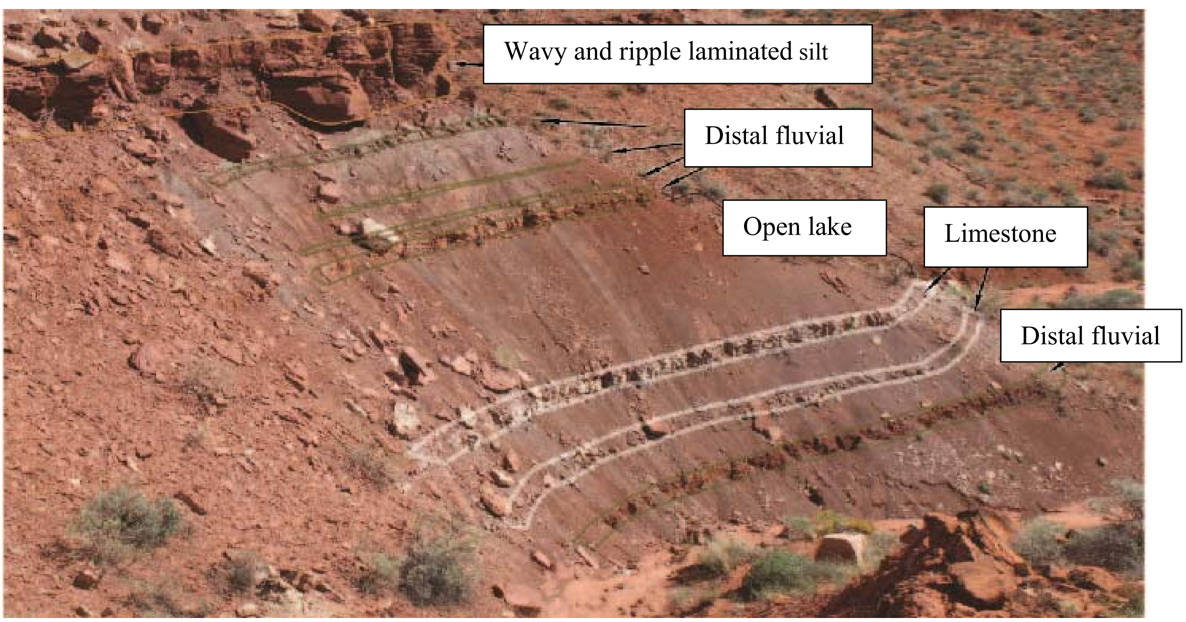


Figure 3.3. Example of distal fluvial, open lake, limestone, and ripple laminated deposits

Interpretation: The limestone is interpreted to be evaporitic or algal deposition in a large shallow lake. No indicators of a marine environment were found. The abundant gypsum found throughout the rest of the formation is consistent with evaporative conditions.

Architectural Analysis

Open Lake Assemblage

A large majority of the Kayenta Formation in Warner Valley is composed of open lake deposits which includes limestone facies, parallel and wavy laminated shale facies, and very distal fluvial deposits. When not truncated by propagating-channel assemblage, described below, the open lake assemblage can be very laterally extensive extending the length of the 10+ km outcrop. The contact between limestone and laminated shale is usually sharp, and the contact between distal fluvial and the laminated shale can be sharp or gradational.

Propagating-Channel Assemblage

The propagating-channel assemblage comprises three elements; bars, channels, and channel wings. The bars and channels amalgamate to form a central lens from which the wings extend. These assemblages are encased in the open lake assemblage and are commonly amalgamated with each other.

<u>Element 1: Bars</u>

Characteristics: This assemblage is dominated by the cross-laminated lithofacies and makes up the majority of channel fills (Figure 3.4). Bars commonly stack on top of each other scouring laterally and vertically into the preceding bar forming bar sets. Bar-set bounding surfaces contain lower order surfaces of laminae, laminae sets, and co-set surfaces. Bounding the bars are scours at the base and a flooding surfaces at the top. The flooding surfaces are ripple laminated facies 3 followed by lacustrine facies and they are typically 0.3-1m thick and 1-15 m wide.

Interpretation: Based on the internal laminae, laminae sets, and co-sets the bars are formed from by bedlaod dunes. Bedload sheets and ripples migrate downstream during waxing and waning high-energy flow events or seasons "smearing" the unit bar onto its associated compound bar (Collinson, 1970; Nanson, 1980; Bridge et al., 1986, 2000; Bridge, 2003; Best et al., 2003). Bars typically build by the accretion of the smaller scale bedforms over the bar face, and reflect the loss of flow regime upwards (Bridge, 2003).

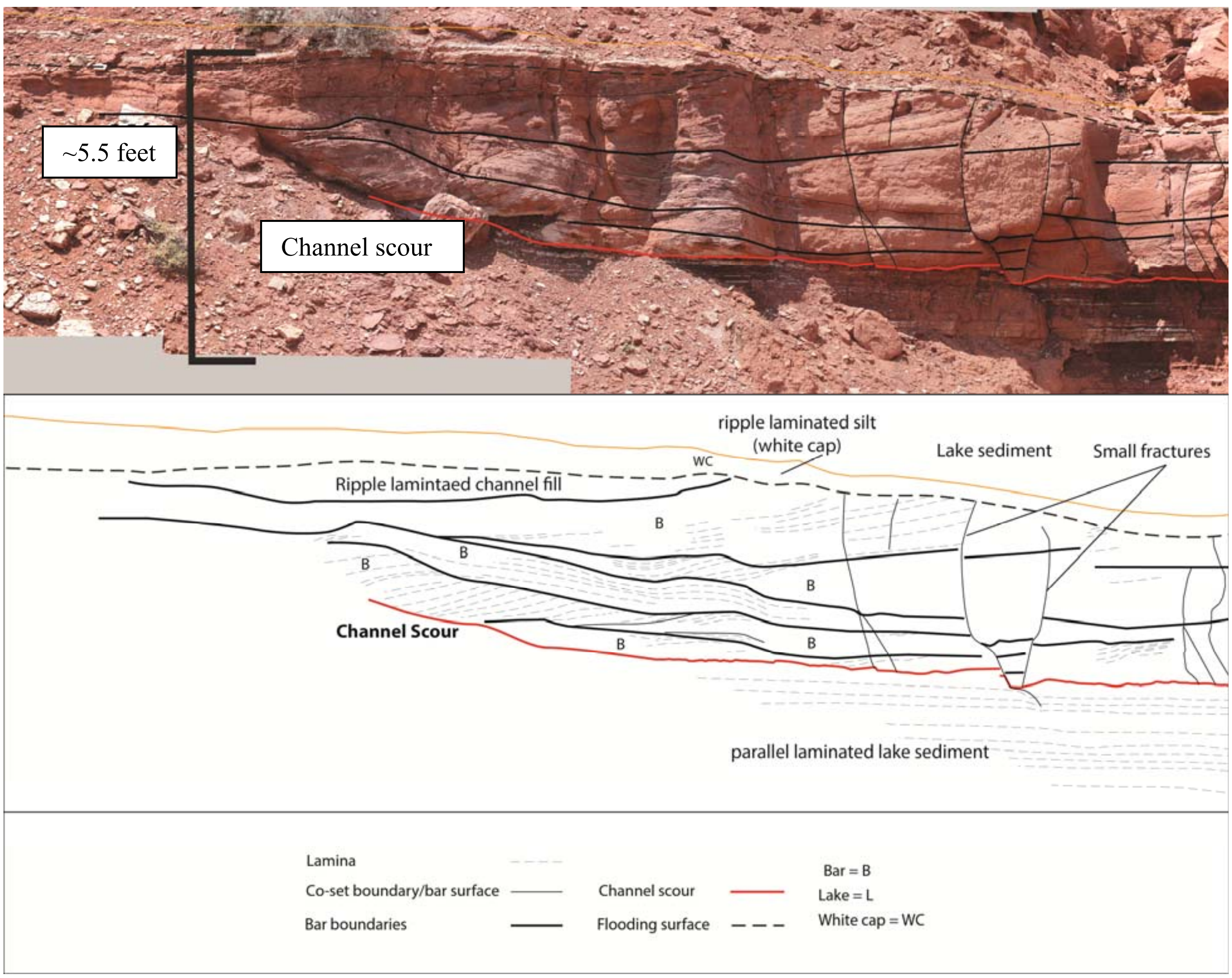


Figure 3.4 Architecture diagram of bar elements stacking and amalgamating with lake sediments below and above.

Element 2: Proximal and Medium Channel Fill

Characteristics: This assemblage incorporates the architecture elements of the bars and the associated bounding surfaces, but adds the basal channel scour and upper bounding surface of ripple laminated facies 3 (Figure 3.4). These channel fills are lense shaped. The lower contact is sharp and the upper contact can be sharp to gradational from cross laminated to ripple laminated shallow lake to parallel laminated open lake facies. Channel fill assemblages are most commonly amalgamated with other channels to form clusters, but occasionally are isolated channels. When clustered they can stack on top of each other and scour vertically (Figure 3.5) or scour laterally and form multilateral channel clusters.

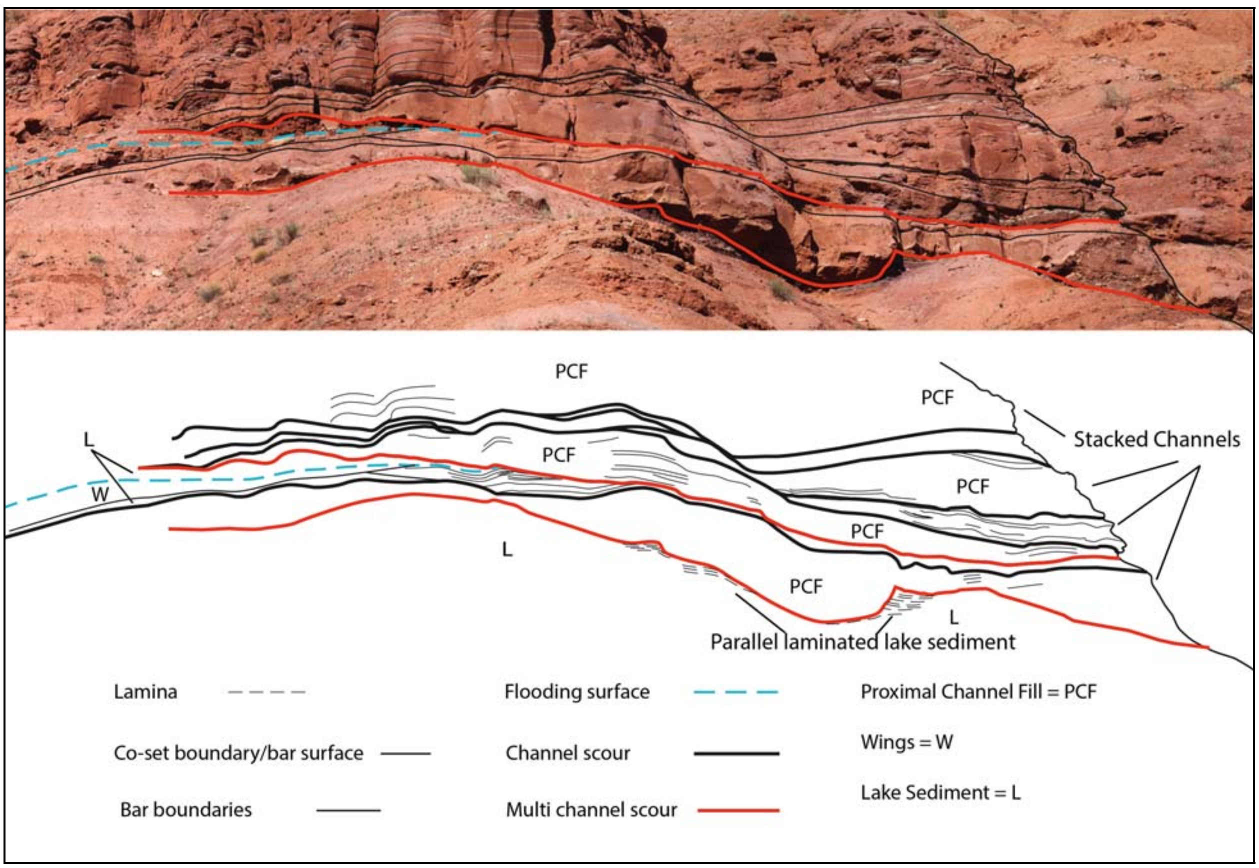


Figure 3.5 Architecture diagram of stacked proximal channel assemblages

Interpretation: Channel-fill elements record filling of major channels during channel avulsion and abandonment cycles. Scours are cut during high flow events over the early life of the channel and then the section fills with bed forms as flow wanes during channel abandonment. Successive pulses of energy lead to frequent truncation of basal-channel fill, leaving portions of the bedforms to be preserved in the sedimentary record (Jones, 2007). The Rippled sandstone assemblages in the upper part of some channel fill elements reflects a decrease in energy during late-stage channel deposition (Jones, 2007) and the parallel laminated muds above indicate a relative rise in lake level.

<u>Element 3: Small Channel</u>

Characteristics: This element is made up of the silty ripple laminated facies and has a sharp basal contact and scour but does not typically contain rip up clasts. The upper contact is also typically sharp but may also be gradational with the lake sediment above. They are thin lensoidal deposits that occur either isolated or in clusters. They occur more frequently as isolated deposits than do the larger channel fill elements but both are common.

Interpretation: This element records the distal progradational reaches of the channels of element 2. They occur as isolated deposits more often than the larger channels because they are further from where the majority of avulsion is occurring, but may occur as clusters if the channel is reoccupied multiple times.

Element 4: Wings

Characteristics: Wings are thin sheets dominated by the ripple facies 1 with local bioturbation and extend laterally from the top of the channels (Figure 3.6). Wings are laterally extensive where not truncated by channel scours either vertically or laterally and can be up to .5m thick near the channel and extend latterally 25m away from the channel before pinching out. They are abundant all throughout the Warner Valley outcrop accompanying large and small channels. Just above the wings occasionally are found the ripple laminated shallow lake deposits and often the two grade into each other and are difficult to distinguish. However, the ripple laminated lake deposits, where present, often span multiple channels whereas the wings are restricted to a given channel. Yet, since channels often cluster, their wings often overlay or interfinger with other wings separated by thin layers of mud (figure 3.6).

Interpretation: As the channels prograde into shallow standing bodies of water, elongated delta lobes can form (Tomanka, 2013). During normal flow periods the elongated delta lobes continue to prograde, advancing the mud dominated delta front and the zone available for wing deposition. Between flooding events the energy of the system would not be great enough to carry the larger grained sediment to the mouth of the channel,

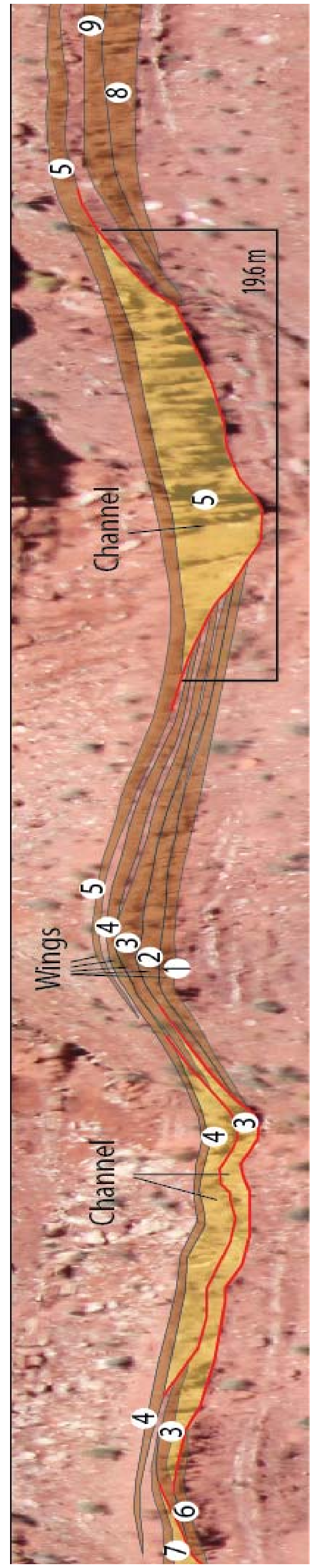


Figure 3.6 Stacked and interfingering small/medium channels with wings. Numbers correspond individual channel and wing deposits not the order in which they were deposited. This photo has a 2.5X vertical exaturation.

but is stored up stream. During flooding events this stored sediment is flushed down stream. The topographically low levees near the delta front are submerged and sediment pulses from flooding events flow over the levees into the lake along the margins of the channel. This over-levee sedimentation is what forms the wings and would extend along the length of the channel. The abundance of these features in outcrop suggests this area was prone to flooding and that when it flooded there was standing water present instead of dry flood plain.

Stages of development

Within the outcrop there is a variety of channel assemblage sizes with internal complexity increasing with size. The range of sizes (Table 3.2) is interpreted to be various stages of development along the length of the prograding delta. The furthest reaches of the delta are the distal fluvial, and the medium to large channels are found further upstream respectively. More about the nature of these various stages is to be addressed later in the discussion but the dimensions are listed below.

Table 3.2 Dimensions of different channel stages

Stage of Development	Width (meters)	Thickness (meters)
Individual distal fluvial deposit	10-55	0.04 - 0.15
Clustered distal fluvial deposits	10-500+	0.10 – 3.00
Individual small channel	15-50	0.30 – 1.50
Clustered small channels	30-200	1.00 – 3.05
Individual proximal to medium channel	30-80	1.00 – 2.50
Clustered proximal to medium channel	30-250	1.50 – 15.00

Statistical Findings

Spatial Distribution of Element Assemblages

The channel fill assemblages for the three outcrops were mapped (Figure 3.7B) and a point placed in the center of the top bounding surface for each channel (Figure 3.7C). These points were recorded then placed on a xy plane using the program Image J (Figure 3.7D), assigning each point a spatial value. K and L statistics were calculated using the program R, downloaded from the www.r-project.org website (Figure 3.8). The red line in the L-plot represents a randomly distributed set of points. Data points plotting above the red line record clustering. Data plotting below the red line are more evenly distributed than random. The gray envelope around the red line represents the range of plots from 500 randomly generated point patterns for each outcrop.

The data from all three outcrops lie well above the envelope for randomly distributed points. Therefore the distribution of points within the data set is not randomly distributed, and since the points are above the line and not below the line they fall in the category of clustered and not evenly distributed. The plot for the Middle section data is closer to the window of random data but still lies completely in the clustered space.

Another pattern noticed in all three outcrops is that there appears to be at least two major periods of clustering separated by large intervals of lake deposition. This can be seen in Figure 3.7D and 3.9 below; moving vertically from the bottom up, there is a lower group of points, followed by a zone of very few channels, and another large group of clusters above that, followed by relatively few clusters. So not only do the individual channels clusters, but the clusters appear to have formed in laterally extensive zones.

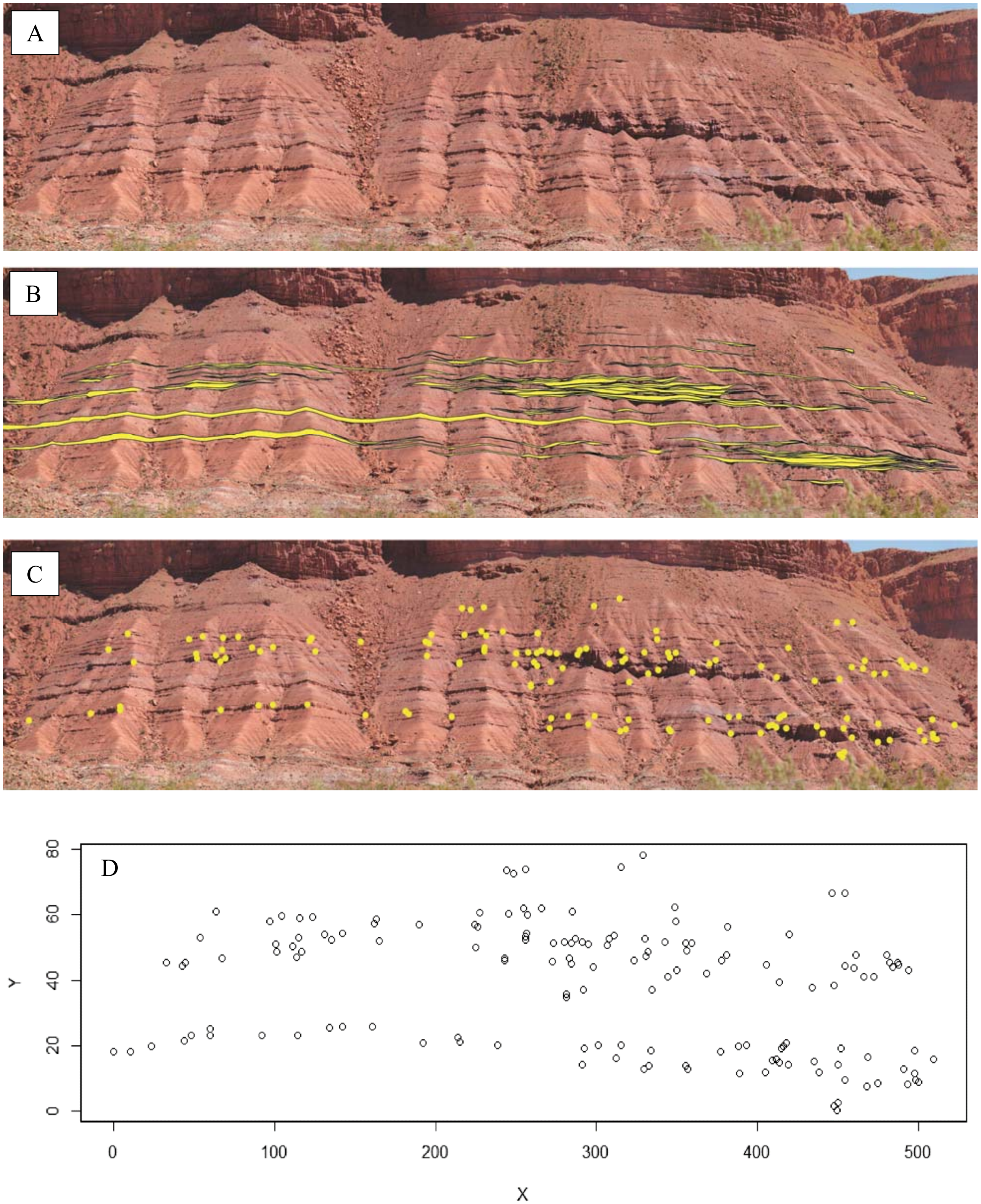
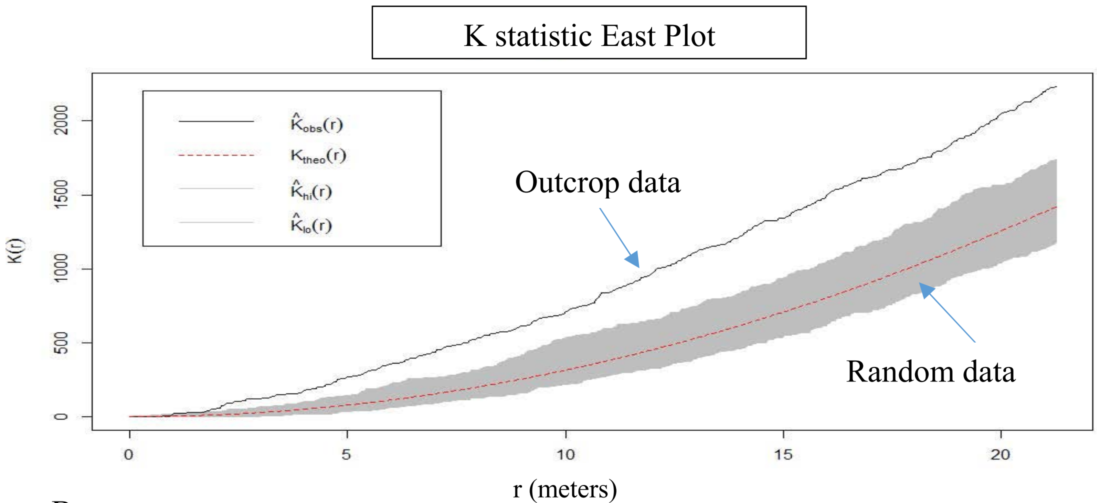
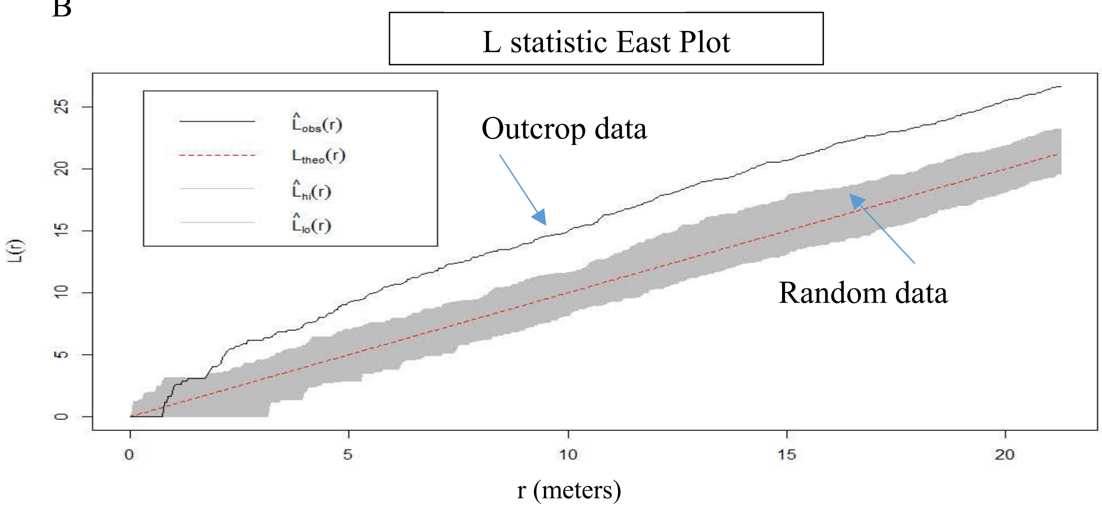


Figure 3.7 A) Photo panorama of east section B) Photo panorama with channel bodies mapped in yellow C) Center points of the mapped channels from B D) Plot of points from C in the xy coordinate system used to run the statistics in *R*.

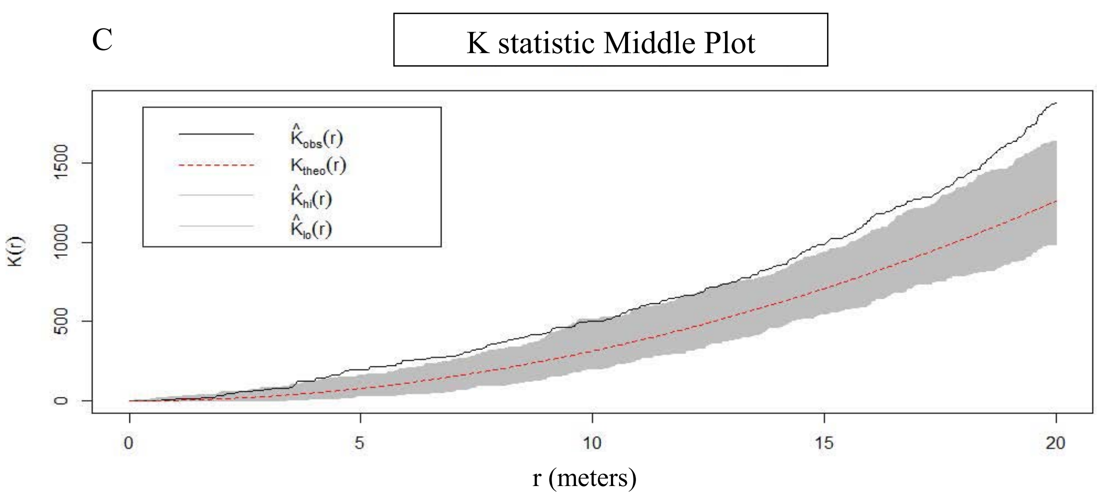
A


K statistic East Plot
$\hat{K}_{obs}(r)$
$K_{theo}(r)$
$\hat{K}_{hi}(r)$
$\hat{K}_{lo}(r)$
Outcrop data
Random data
K(r)
0
500
1000
1500
2000
0
5
10
15
20
r (meters)

B

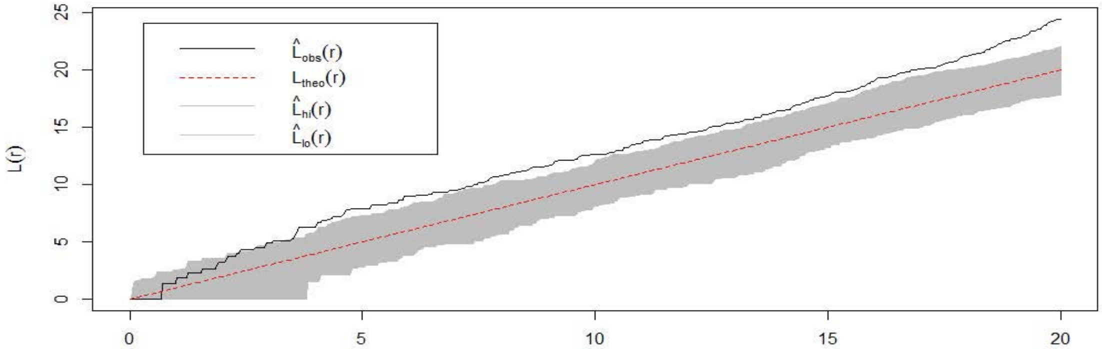

L statistic East Plot
$\hat{L}_{obs}(r)$
$L_{theo}(r)$
$\hat{L}_{hi}(r)$
$\hat{L}_{lo}(r)$
Outcrop data
Random data
L(r)
0
5
10
15
20
25
0
5
10
15
20
r (meters)

C


K statistic Middle Plot
$\hat{K}_{obs}(r)$
$K_{theo}(r)$
$\hat{K}_{hi}(r)$
$\hat{K}_{lo}(r)$
K(r)
0
500
1000
1500
0
5
10
15
20
r (meters)

D

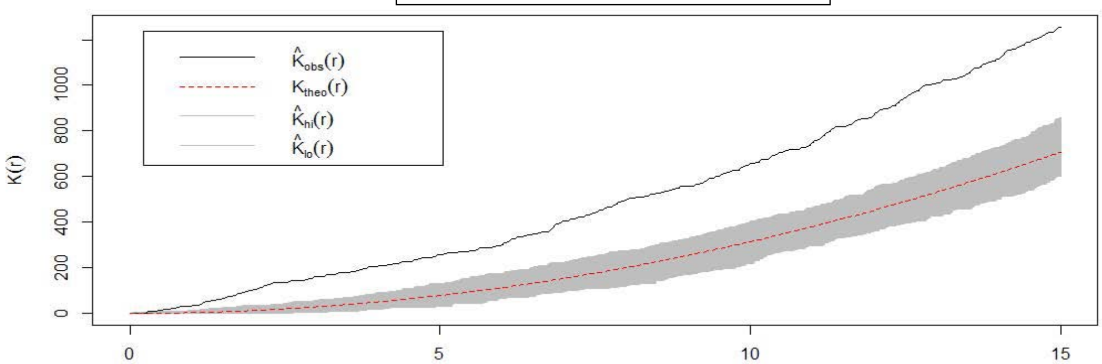
L statistic Middle Plot



r (meters)

E

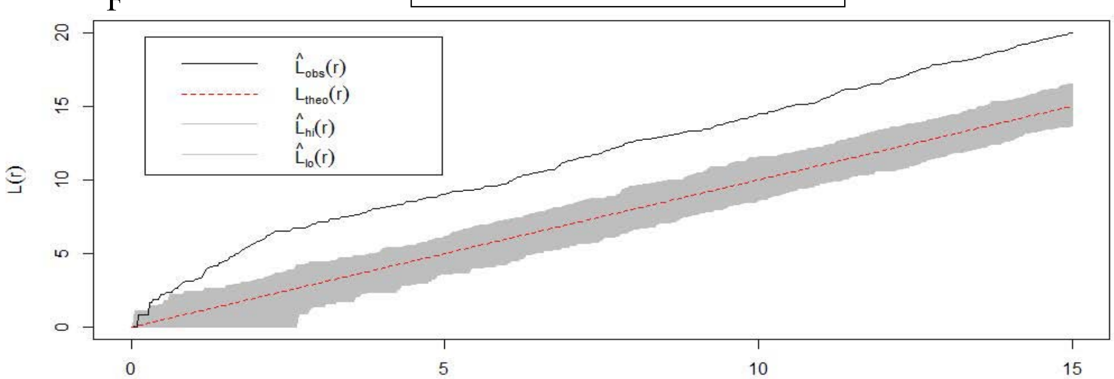
K statistic West Plot



r (meters)

F

L statistic West Plot



r (meters)

Figure 3.8 K statistic (A, C, E) and L statistic (B, D, F) plots from the program R. K plots estimate the whether a group of points is clustered or not. Plots above the red lines indicate clustering, while plots below the red line are uniformly distributed. The L plots show the same thing as the K but have been adjusted for easier visual interpretation. The "r"-axis represents the Pearson's Product Moment Correlation Coefficient. The single dark line represents Warner Valley outcrop data while the grey area represents the plots of 500 random data sets for the given area.

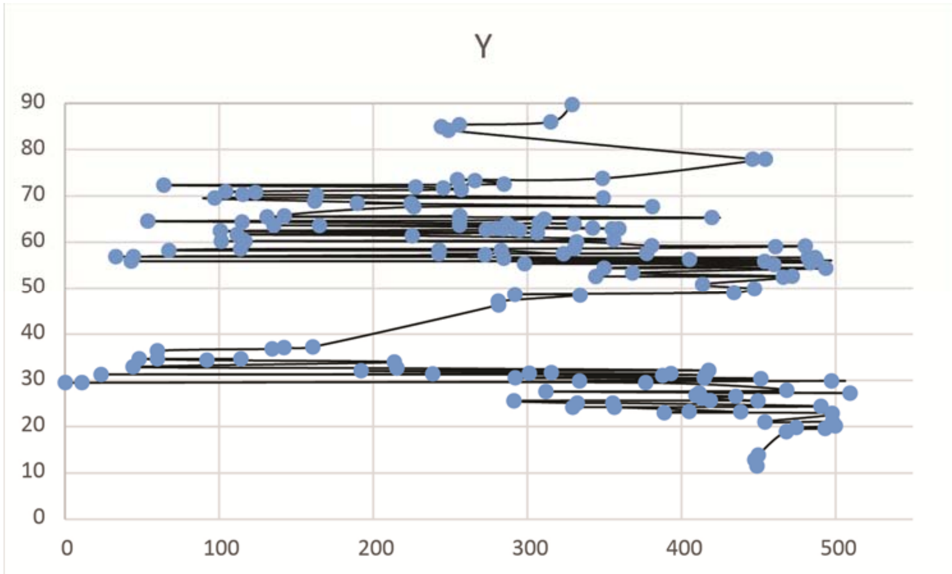


Figure 3.9 Plot of the xy locations of channel deposits. The deposits are connected by a line in the order in which they appear vertically. This would be very similar to the order of deposition except for minor scouring or variations in compaction.

CHAPTER 4

Discusssion

Fluvio-Deltaic Deposition processes for the Kayenta Formation

The Kayenta Formation in Warner Valley is here interpreted to record a fluvio-deltaic system based on the above observations and interpretations. These observations argue this system as a shallow lacustrine environment with low wave and tide influence, in an arid/semi-arid environment, with a shallow broad slope, very little plant and animal life, and dominated by fluvial channels building into the system. The open-lake architectural assemblage with generally non-rooted mudstone and limestone layers with rich gypsum deposits record the open lake component. This lake system was dissected by linear propagating channels.

An unanticipated aspect of the Kayenta Formation is the characteristic dissection by channel assemblage rather than the lobate deltas usually assumed with lacustrine systems. Deltas are typically considered as having lobate geometry because of bifurcation of channels and distribution of sediment through these distributary channels (Miall, 1996). Gilbert originally addressed the process by which deltaic sediment is deposited in a step-wise fashion as driven by grain size as the velocity of a river slows when entering a lake. He addressed the effect of basinward generated energies on deltaic deposits and introduced the precept that deltas coarsen upward in stratigraphic succession (Gilbert, 1885, 1890). However, the Kayenta Formation does not appear to fit the typical coarsening upward bifurcating lobate delta model. These fluvial-deltas do not produce coarsening upward basin deposits as mouth bars and appear to form isolated channels belts maintaining channelized flow crossing lacustrine environments without development of discrete delta lobes or preserving sandy delta-front deposits.

Non-lobate lacustrine deltas appear to be common in shallow freshwater lake environments, though they are poorly studied (Figure 4.1). Tomanka (2013) studied the mechanisms and processes for the formation of non-bifurcating fluvial-deltaic channels in modern fluvio-lacustrine systems, and relates the processes to better-known tie channels. Tie channels typically connect a river with a shallow water-filled basin such as an oxbow or other floodplain lake allowing two-way flow between the river and the reservoir (Rowland, 2007; Rowland, et al., 2009; Tomanka, 2013). Tie channels, like the Kayenta

Figure 4.1 Non-bifurcating, single channel deltas in Texas reservoirs (images A-D). Images A and B are satellite images of Lake Texoma deltas formed by the Red River and Washita River, respectively. Images C and D are images of Lake Lewisville, and Lake Kemp respectively (Tomanka, 2013)

channels, do not follow the classic deltaic processes of mouth bar formation followed by bifurcation (Bates, 1953; Wright, 1977). They do not fill all laterally available basin space, instead they prograde basin-ward as linear channels.

Tie channels pouring into standing lake bodies produce a turbulent jet that forces suspended sediment into the lake and produces large levees flanking the jet at the mouth of the channel. During times when water levels are relatively high the opening of the turbulent jet and the zone of the jet margin deposition would gradually move downstream contemporaneously. This would form a long linear zone of sedimentation that flanks each side of the channel. Over time this process (combined with channel erosion between the levees) would extend the levees down dip and increase the height of the levees up dip. This model creates a self-sustaining process by which levee height is increased, levee taper is maintained, and levee progradation can be sustained by adding of material onto the levee well after the mouth has prograded past a given point (Tomanka, 2013). This process generates a muddy propagating channel that sends minimal sand to the river mouth. High flows cause sand to be deposited over the levees as sheets (Tomanka, 2013). This same process is what could be creating the wings seen throughout the Kayenta Formation.

Continual progradation and basinward decreasing levee height is a shared feature for both tie channels (Rowland, 2007) and for non-bifurcating channels in reservoirs (Tomanka, 2013). The theory of elongated prograding deltas is also documented by flume experiments by Rowland (2007) showing jet margin sedimentation results in longitudinal sediment deposits flanking the channel (Figure 4.2). These deposits taper away from the channel axis at an acute angle in the downstream direction. In a cross sectional profile the highest sediment accumulation is near the channel, thins perpendicular to the channel axis, and is reminiscent of the cross sectional profile of a wing. Similar propagating channels are generated in numerical experiments of Canestrelli (2014) and Edmonds and Slingerland (2010) where mud-dominated delta systems are shown to form few but elongate distributaries as opposed to highly lobate systems with substantial bifurcation.

Figure 4.2 Flume experiment showing levee progradation and the formation of wings (Rowland 2007).

Discrete channel assemblages record channel-belt development between avulsion events. The non-channel component of the Kayenta Formation lacks bioturbation and mature paleosol development and is here interpreted as a lake assemblage without significant subaerial flood plain development. The overall lack of splay deposits or other flood plain elements argues that the avulsion style was progradational (Morozova, 2000; Slingerland, 2004).

Channel-Assemblage Growth by Progradational Avulsion

Avulsions are primarily features of aggrading flood plains (Bridge, 1979; Stouthamer and Berendsen, 2000; Slingerland, 2004), and aggradation is necessary for the continued stacking and clustering of channels. In aggrading systems localized deposition happens near and around the channels, forming an alluvial ridge with levees that slope toward the basin on either side (Allen, 1970; Bridge, 1979, 2003). Prograding avulsions are characterized by deposition of sediment transported out of the parent channel mouth into invaded flood plain or larger lakes (Slingerland and Smith, 2004). According to Slingerland and Smith (2004), prograding avulsions require “standing bodies of water, favored by slow runoff promoted by low floodplain slopes; dense vegetation; and high water tables that encourage ponding, slow drainage, and settling of fine suspended sediment.” The high proportion of lake facies suggests all of these hold true for the Kayenta Formation except for the dense vegetation, as there are very few soil horizons and rooting is not intense and occurs in isolated patches.

Kayenta channels show evidence of guidance of avulsions through reoccupation of earlier channels. Channels tend to flow along the path of least resistance and the path of greatest flow efficiency. During avulsions this can mean that the active channel will reoccupy a previously abandoned channel because there is already an established flow path. This leads to preferential flow paths and stacking of channels on top of and next to each (Jones, 1999; Blum, 2006; Hajek, 2009). Multistory and multilateral channel bodies are good indicators of later reactivation of abandoned channels suggesting successive episodes of reoccupation and widening (Mohrig et al., 2000), both of which are found in the Kayenta Formation. According to Slingerland and Smith (2004) this would indicate an incisional or annexation style of avulsion. However, the continual aggradation and shallow broad regional slope would lend more to the progradation avulsion. It appears that avulsion is indeed progradational, but annexation guides the locations of new channels once initial channels are established.

Changing lake level potentially leads to greater frequency of avulsions. Avulsions are thought by some to occur due to a critical slope differences between channel height and the flood plain (Bridge and Leeder, 1979; Mackey and Bridge, 1995; Mohrig et. Al, 2000; Aslan, 2005). The greater difference between the channel and the flood plain the more likely an avulsion is to occur. During high lake levels the standing water may act as the flood plain base level, since locally that is the lowest point to which the water can drain, but if lake levels drop the relative distance between the base level (the lake) and the levee increases. If the lake completely dries the relative relief between levee and flood plain base level would be at a local maximum and the channel would be more likely to avulse during a rapid flooding event.

Stages of Development

In the outcrop there is a wide variety of fluvial deposits ranging from cm thick distal deposits to large clusters of primary channel cross bedded sands. These are interpreted as different stages of development of single prograding channels (Figure 4.3).

These stages are consistent with the variety of coeval fluvial channels observed in the modern example of Lake Zama, Alberta, Canada (Figure 4.4). In Lake Zama we can see the progression from small distal channels to proximal primary channels. The green highlighted channel shows a relatively recent abandoned channel with multiple avulsion nodes and hierarchy of channel size. In the active channel distal channels extend the larger proximal channel sands, and as the larger channel grows meanders form bars. If this system is allowed to aggrade for prolonged periods of time channels would continue to avulse, forming avulsion fairways and clusters (Figure 4.5).

It is important to note that Lake Zama is a much colder and vegetated environment than what would have existed at the time of deposition for the Kayenta Formation. So the drier climate of the Kayenta formation is not a controlling factor on weather fluvio-lacustrine systems will form.

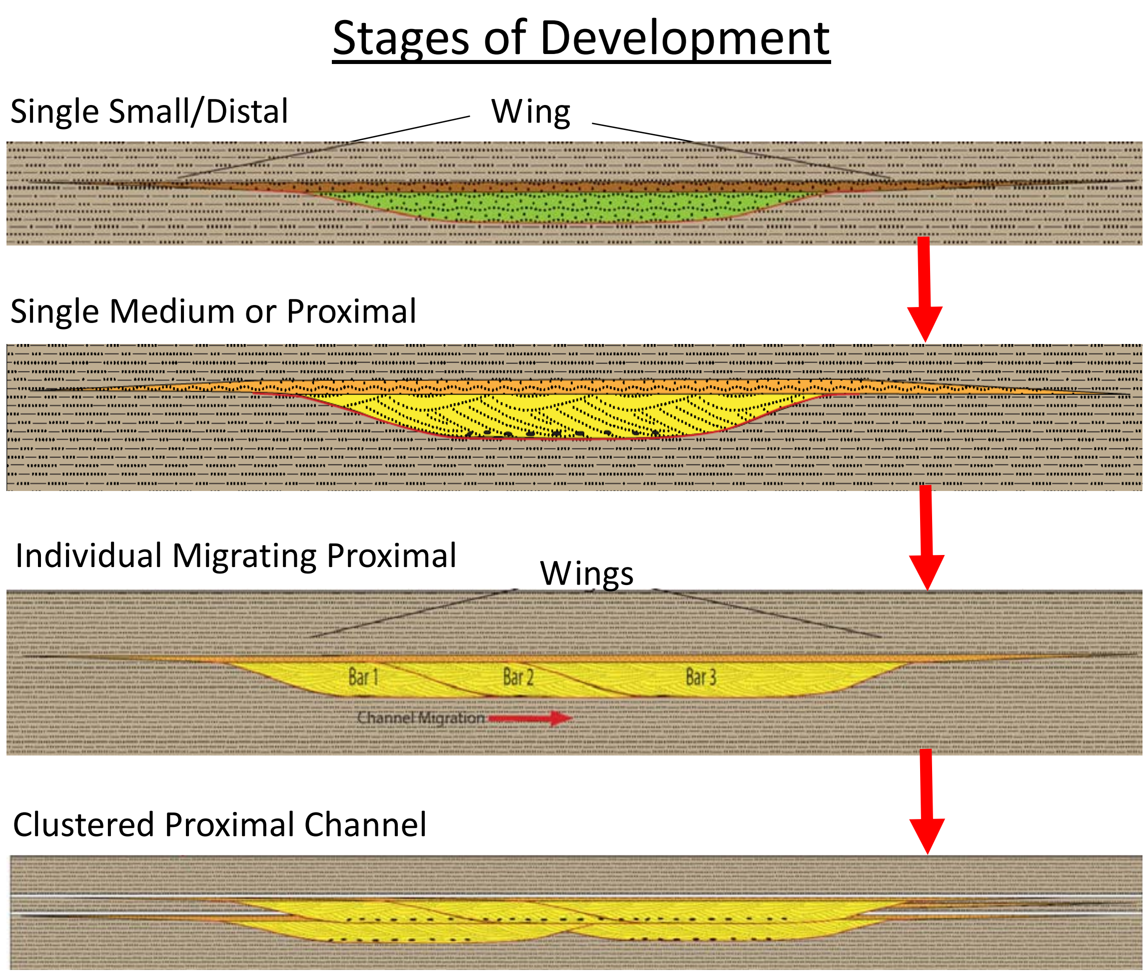


Figure 4.3 There are multiple stages of fluvio-lacustrine development. As the system matures larger channels can prograde on top of the smaller channels and scour away the previous channel or stack on top forming clusters of channels

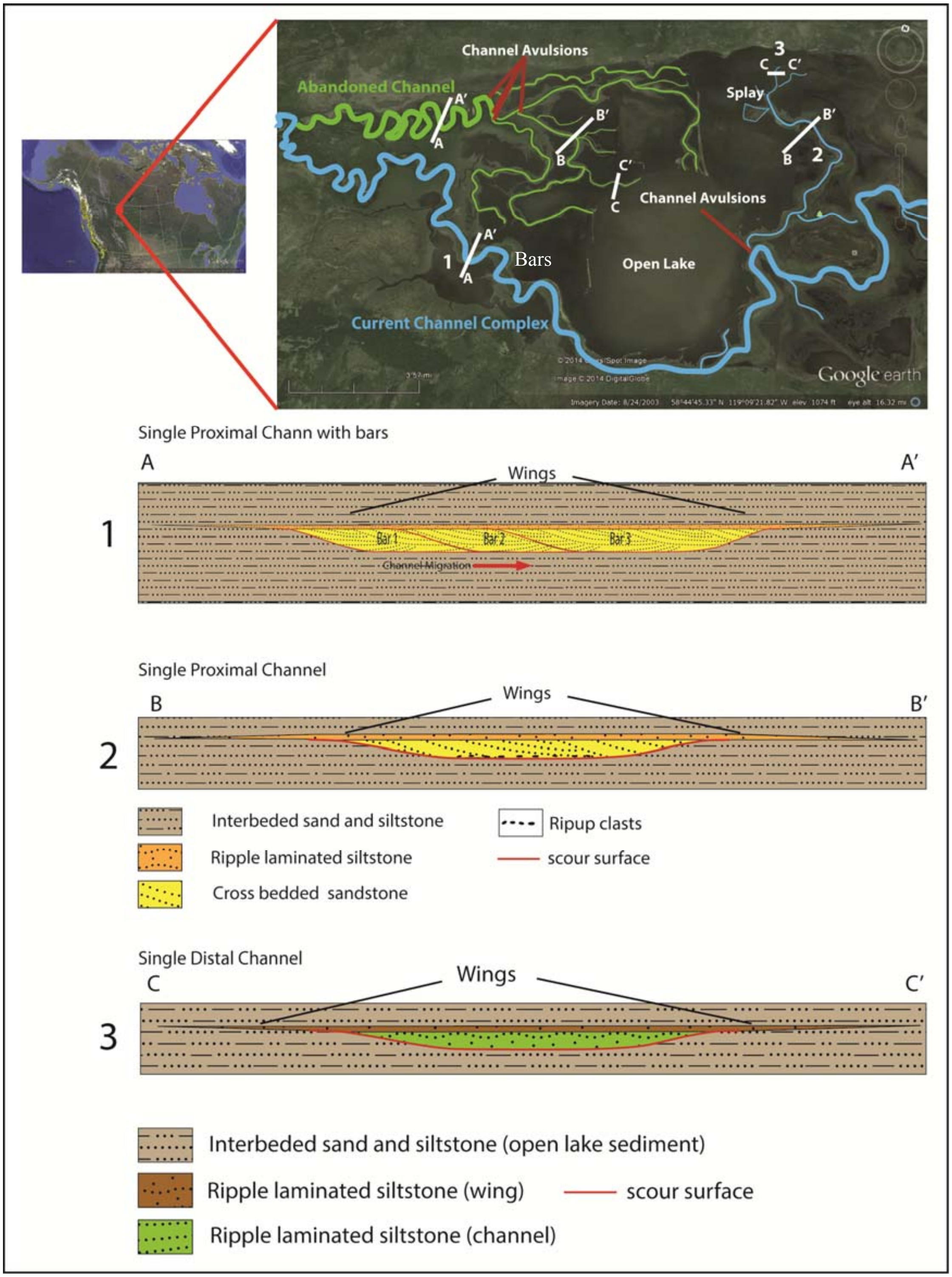


Figure 4.4 The map shows the location of Zama Lake. The main active modern channel shown in blue, and the previous channel in green. The cross sections are models of the hierarchies of channel size observed.

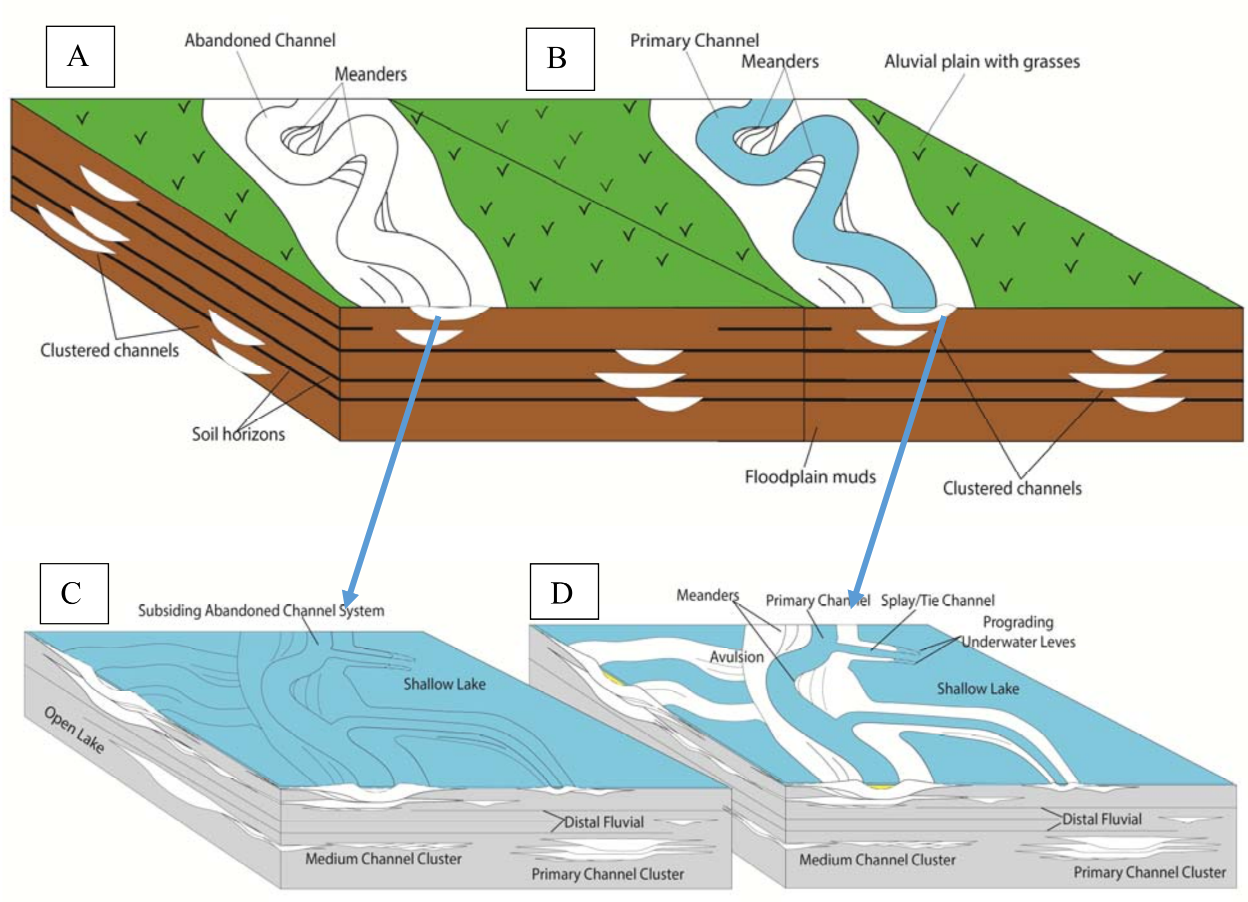


Figure 4.5 3D diagrams of what an active aggrading fluvio-lacustrine environment might look like. (A and B) Abandoned and active channels respectively, operating within typical aggrading floodplain environment. The brown is overbank flood plain muds while the thin horizontal black lines are well developed soil horizons. The white lenses are channel deposits. Note that there is clustering in both due to avulsions. (C and D) Abandoned and active fluvio-lacustrine environments respectively, represent downstream deposition from A and B. Because of a relatively recent avulsion active channel building is not happing in block C but is being buried by shallow lake deposits.

Clustering and Connectivity

K and L statistics show that the Kayenta Formation developed clusters of channel assemblages as it aggraded over time. The primary reason for clustering in the Kayenta Formation is due to the adoption of prograding avulsion fairways. Prior to entering the lacustrine system the fluvial channels would already be clustered and carry this characteristic into the lacustrine, as evidenced by the incision of later channels into old buried channels. Although the older channels are often covered, to some degree by sediment before the new channel progrades over top, the relative low topography of the channel is maintained.

Avulsions are commonly regarded as hierarchical in nature (Slingerland, 2004), and if avulsing channel systems operating in alluvial plains lead to clustering it would make sense that the size of channel assemblage and variation of clusters would also be hierarchical. Avulsions of the primary channel lead to clusters of the larger channel bodies while avulsions of medium and small channels create clusters of medium and small channels. This hierarchy of avulsions can be seen in the modern Lake Zama (Figure 4.4). There are avulsions all along the path of the channels within the lake. Some are proximal and shift the larger and well-developed belts and some effect only the more distal portions of the channel. For instance, the large channel to the east has smaller avulsions down dip within the lake where one path is abandoned for a succeeding channel. The avulsion of the primary channel to the west (green to blue) cut off deposition in the northwestern portion of the lake and relocated the channel to a more southerly portion of the lake. Distal avulsions on this later proximal avulsion happening down-stream are also subject to the avulsions up-stream.

K statistics were not distinguished by channel type in this study, thus this hierarchy of clustering was not tested statistically. Visually, this secondary clustering is apparent. Future work could be done in Warner Valley to distinguish between smaller and larger channel and the tendency of certain channel sizes to cluster.

Connectivity

The amalgamation of channel assemblages due to clustering connects previously isolated channels and creates a larger single reservoir body made up of many connected channels. The connection of channels both vertically and laterally typically happens with a channel scouring into the wings or main channel of a previous channel. Since the channels don't appear to be scouring vertically more than one channel depth, only the top of the channels and the wings are scoured into when the channels are stacked on top of each other. This however joins permeable units of channel assemblages vertically across two or more stories. Some of the multilateral channel belts cluster and extend over 200m along one horizon. Channels however may also be connected because the wings of an assemblage are joined. If at least one channel is scoured into a wing or channel assemblage laterally or vertically, and that wing or channel is connected to other wings or channels the lateral extent of a given connected reservoir could easily extend several hundreds of meters more.

The lateral extent of the relatively unbioturbated well-sorted wings makes the connection of reservoirs more likely than traditional alluvial plains connected mostly by amalgamation of channel belts. Points where wings are pierced and connected to later channel belts are common in Kayenta outcrop (Figure 4.6). The internal connectivity of the clusters by wings is both vertical and lateral. Often wings from neighboring clusters or within a single cluster interfinger. One aspect of the wings is that they do scour into the underlying lake sediment approximately half to three quarters the length of the wing away from the channel. After that they generally no longer scour but lay conformably on

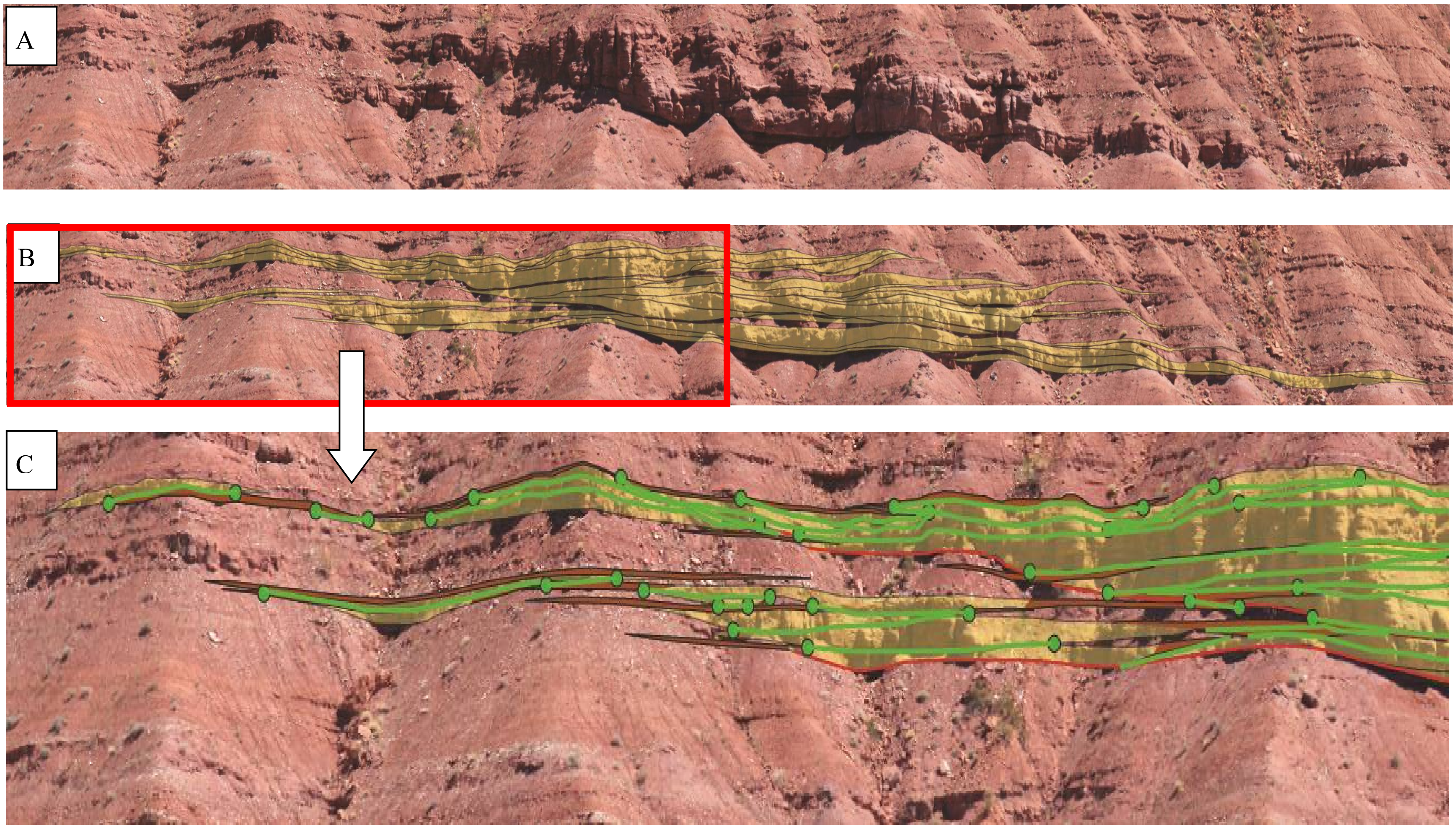


Figure 4.6 A) Photo of fluvial cluster the cluster figure is about 120 m long. B) Individual channels are highlighted in yellow green dots mark the points of connection. C) The wings are brown and the channels are yellow. Points where the channels connect are highlighted by green dots and the length of connection is highlighted by a green line.

top of the lake sediment. Occasionally the scouring is enough to remove the thin layer of lake sediment that would otherwise have isolated wings vertically.

Field observations show that the wings are well sorted and the grain sizes do not vary drastically from sediment found in the middle of the channel. This would allow for similar flow through the wings as well as the channel belt. Therefore, if the wings are connected to any part of an adjacent channel there is possibility for fluid flow. Future lab work on the exact detailed and preserved permeability of these wings would greatly enhance the understanding of fluid flow and connectivity potential through the wings.

Clustering increases the proximity of channels in successive generations and thus increases the probability that the channels will connect by scour. Connectivity is therefore enhanced by amalgamation of channels and fluid flow between channel bodies is more probable. While the sands are thin, they can be laterally extensive, and due to the high connectivity of the clusters it may be possible to drain a large number of channels laterally and vertically from a penetration through a single channel.

Industry Applications

Exploitation of fluvial reservoirs by industry is enhanced by increasing predictability and therefore lowering cost. Due to the variation in sand distribution and lithological changes over short distances fluvial reservoirs can be difficult plays to predict. These variations can limit or enhance pressure communication between two neighboring sand bodies, even within a predicted flow unit (Slingerland and Smith, 2004). The presence of clustering means that poorly drained high-accommodation clay rich floodplain and lake deposits may not always serve as barriers or seals that isolate large channel-belt reservoirs, but instead may provide connecting flow paths and reservoirs composed of thin elongate fluvial-deltaic sands. Better understanding the clustering properties of fluvio-lacustrine settings will help in predicting reservoir properties in fluvial settings.

Flood plain systems with abundant splays and tie channels overlain or scoured into by primary channels could permit enhanced fluid flow and increased pressure communication between fluvial channel-belt sand bodies compared to isolated flood plain channels (Slingerland and Smith, 2004). Reservoirs dominated by propagating channel avulsion stratigraphy may be well connected, and these overall low net-to-gross units may have pockets of higher reservoir potential. This enhanced connectivity may also mean the fluvio-lacustrine channel assemblages may not have the seal necessary to keep the resources contained, and may permit fluid escape to other areas. Fluvio-lacustrine environments may provide a link from source rock to high-quality reservoir rock channels important in reservoir modeling for oil and water (Stoner & Holbrook, 2008). If these channels provide sufficient permeability, they could act as both aquifers and flow conduits, making them important considerations in aquifer management or waste disposal.

Spatial Point Process statistics are good at showing clustering but do not reflect time. Since timing of events is a large part of the depositional process, statistics need to be developed that account for the order in which the channels were deposited. One possible improvement on SPP is the development of an excursion factor statistic. This statistic would measure the distance from one channel to the next but in the order in which they were deposited, and would help give parameters for avulsions; showing the distance between major avulsions, how frequently they occur, and if there is also a hierarchy to avulsions as there is in the clustering shown in this study.

CHAPTER 5

Conclusion

The Kayenta Formation in Warner Valley, Utah is an example of a long-lived aggradational fluvio-lacustrine system. This study represents the first consideration of these strata at this location as a lacustrine depocenter for equivalent Kayenta fluvial deposits. These deposits lack soils and bioturbation features typical of floodplains and do not produce the lobate deltas presumed of lakes. An alternative model for replacement of deltas with propagating channel assemblages (model for fluvio-lacustrine system) is here offered:

1. The system forms in stages as the entrance of a channel or splay enters a standing shallow lake with low wave and tide influence. Jet margin sedimentation allows for the building and progradation of linear non-bifurcating muddy levees and deltas similar to what is seen in modern systems such as Lake Zama, Canada, and the Grijalva River, Mexico.
2. During flooding stages the lower elevation levees near mouth are submerged by rising lake waters. As bedload sediment is flushed down the channel during high-flow events, a portion is pushed out over the top of the now submerged levees forming the wedge shaped wings. If the

channel is allowed to prograde the deposition of longitudinal wings can form along the majority of the channel length on both sides. This forms channel assemblages comprised of central channel belts, bars and channel-fill elements, and lateral wings.

3. As the channel continues to prograde more proximal primary channel deposits build on top of and scour into the previous deposits widening and deepening the channel belt portion of the channel assemblage.
4. Since this is an aggrading fluvial system episodic avulsions occur both up stream away from the lake and among the channels that have built into the lake. This creates avulsion fairways that concentrate the location of prograding channels. This leads to the channels stacking and amalgamating to form clusters

K-statistics for each outcrop showed that channel assemblages cluster. While this study tested for clustering in general, field observations suggest that there is a hierarchy of clustering, whereby large channel assemblages cluster with large channel assemblages and smaller channel assemblages cluster with smaller channel assemblages.

The amalgamation and clustering of channels in predictable patterns leads to higher connectivity between previously isolated sand bodies in a low net to gross system. Better understanding the clustering properties of fluvio-lacustrine settings will help in predicting connectivity between channel-scale sand bodies in fluvial reservoirs. This is critical to maximizing sweep efficiency, but is difficult given the high degree of variability within fluvial systems.

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VITA

Galen Alden Huling was born near Oklahoma City, Oklahoma on October 6, 1984, but grew up in Woodbridge, Virginia. He graduated from Woodbridge Senior High School. He then spent two years in Mendoza, Argentina serving a mission for The Church of Jesus Christ of Latter Day Saints until December 2005 and learned to speak Spanish while he was there.

He moved to Provo, Utah to attend Brigham Young University (BYU) and graduated with a Bachelor of Science in Geology in April, 2012. While attending BYU he met his wife Bonnie Boyd, and they were married August 5, 2008. They now have 2 boys. While in Provo, Galen was employed by Ridgeland Operating, a small oil and gas exploration company and gained experience in well log interpretation, mapping, and the oil industry in general.

In August, 2012, he enrolled in graduate school at Texas Christian University. While a graduate student he was able to present his research at the poster session of the spring 2014 AAPG conference in Houston. Galen also worked as an intern for XTO Energy, a subsidiary of ExxonMobil, beginning October 1, 2014 and was offered a full time position upon the completion of his Master Degree.

ABSTRACT

EVIDENCE FOR CLUSTERING OF DELTA-LOBE RESERVOIRS
WITHIN FLUVIO-LACUSTRINE SYSTEMS,
JURASSIC KAYENTA FORMATION, UTAH

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Xiangyang, Xie, Assistant Professor of Geology

Spatial relationship of fluvial bodies within the Kayenta Formation, Warner Valley, UT, show lateral and vertical clustering of delta-lobe sand bodies within a matrix of fine-grained open-lake deposits. Clustering due to non-random stream avulsion is well documented for high-accommodation fluvial systems operating in alluvial plains, but not well established broadly for lacustrine systems with abundant fluvio-deltaic lobes. Kayenta Formation delta-lobes have similar spatial clustering to those observed in fluvial channel belts, and possibly extend this clustering concept to shallow lacustrine systems.

Lithofacies were mapped on three large photo panoramas and architectural-element analysis was used to identify bounding surfaces of fluvial channels and deltaic

lobes. Clustering of fluvial bodies within shallow lakes is significant in predictive reservoir models because it improves connectivity and localization of delta-lobe reservoirs. The clustering of delta lobes in fluvio-lacustrine systems is theorized to be a basin-ward projection of preferential avulsion fairways observed in fluvial systems.