IMPLICATIONS OF LITHOFACIES ASSOCIATION AND ARCHITECTURE FOR LOW AND HIGH-ACCOMMODATION SYSTEM TRACTS FROM THE SANDSTONE DOMINATED ZONE (THE BARREN SERIES) OF THE CRETACEOUS-PALEOCENE RATON FORMATION, TRINIDAD, COLORADO

by

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I would like to dedicate this dissertation to my beloved family especially my parents (Yousef Alrefaei, Mariam Ali) without whom I could not finished it and whose prayers and encouragement sustained me. Most of all, I wish to thank my dear wife Hanan and children Mariam, Yousef and Hashim for their patience, sacrifices, help and endless support.

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ABSTRACT

IMPLICATIONS OF LITHOFACIES ASSOCIATION AND ARCHITECTURE FOR LOW AND HIGH-ACCOMMODATION SYSTEM TRACTS FROM THE SANDSTONE DOMINATED ZONE (THE BARREN SERIES) OF THE CRETACEOUS-PALEOCENE RATON FORMATION, TRINIDAD, COLORADO

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The Raton Formation is an Upper Cretaceous and Lower Paleocene unit that is interpreted to be deposited in various stages of high-accommodation fluvial systems. High-accommodation flood basin deposits are generally considered poor as reservoir bodies because sand bodies within these basins are considered to be small and disconnected within flood basin mud. Accordingly, they gain less attention in oil and gas exploration and in research. High-accommodation deposits in the Raton Formation contain several sand bodies with different sizes and geometries that could be good candidates for reservoir rocks. These sand bodies are common in outcrops of high-accommodation deposits in the Raton Formation. The size and distribution of these sand bodies reflect a range of processes spanning different stages of accommodation. Six change-overs within low and high accommodation stages are herein proposed. Two fundamental distinctions in process types are native to low-accommodation systems, and

four are native to high-accommodation systems. Low-accommodation systems can be broken into: 1) progressive stacked and 2) iterative stacked end members, whereas high-accommodation systems can be broken into 1) well-drained avulsive distributive, 2) well-drained bifurcating distributive, 3) poorly drained distributive, and 4) fluvio-lacustrine. These subdivisions reflect the progressive intensity of relative accommodation rate against sediment supply. All of these subdivisions have fundamentally different architecture and lithofacies associations, reflecting their differing origins that impact reservoir architecture, particularly in the size arrangement of channel-belts and the connecting units within the flood basin deposits. Careful descriptions of these types of systems will enhance better predictability of reservoir distribution and connectivity and potentially will suggest a new opportunities for oil and gas exploration in high-accommodation systems which otherwise have been overlooked because of low net/gross ratio condition.

CHAPTER 1

INTRODUCTION

The Raton Formation is an Upper Cretaceous and Lower Paleocene unit that has been interpreted to be deposited in various stages of high-accommodation fluvial systems ranging from flood basin, flood basin-lake, crevasse splay, swamp, channel, and lacustrine environments (Johnson et al., 1966; Woodward, 1983; Strum, 1985; Flores, 1987; Pillomore and Flores, 1987). High-accommodation flood basin deposits are generally considered poor as reservoir bodies because sand bodies within these basins are considered to be small, isolated and disconnected within flood basin mud deposits (Bridge and Leeder, 1979; Allen, 1979; Wright and Marriott, 1993; Lagarretta et al., 1993; Shanley and McCabe, 1993; Aitken and Flint, 1994; Shanley and McCabe, 1994; Catuneanu, 2006; Hajek, 2010; Weissmann et al., 2013). The isolation of these small sand bodies within the flood basin deposits is because the aggradation is more than one channel-belt prior to the avulsion return. This aggradation process will lead to the burial of channel-belts by flood basin deposits before the active channel returns, and also is due to sediment grain size loss towards the basin downstream where high-accommodation flood basins are often located (Nicholas and Fisher, 2007; Strong and Paola, 2008; Weissmann et al., 2013).

Understanding the connectivity between the sand bodies units in fluvial systems is essential in oil and gas exploration, particularly in production (Tyler et al., 1984; Tyler and Finely, 1991; Larue and Hovak, 2006). Determining the vertical and lateral connectivity in fluvial system deposits is generally complicated because the sand bodies within fluvial systems (e.g., channel-fills and channel-belts, etc) have different vertical stacking patterns and mainly are separated by flood basin and other fine grained deposits (e.g., lake, levees, and soil deposits, etc). Several factors that can affect sand body connectivity within fluvial system deposits were described by Larue and Friedmann (2005) and Larue and Hovak (2006) in their models for channelized reservoirs (Fig. 1). Based on the Larue and Friedmann (2005) and Larue and Hovak (2006) simulations, crevasse splays can improve connectivity because they have a higher width/depth ratio. Sand sheet deposition during a low-accommodation flood events is also another factor that improves connectivity. However, there are many other natural factors that can reduce reservoir connectivity within high-accommodation fluvial systems. Wide spread regional mudstone intervals can reduce the vertical connectivity between sand body units within high-accommodation deposits. Within channel facies variations related to mud drapes between channel-fills and lateral accretion surfaces can also reduce the connectivity between sand body units. Inclined heterolithic units within sand body units can also reduce the connectivity (e.g., Thomas et al., 1987; Jordan and Pryor, 1992; Reijenstein et al., 2011). Paleosol developments between sand bodies can also reduce connectivity as they form low permeability layers between channels-belts (Kraus, 2002).

Because of all of the previously discussed connectivity issues, high-accommodation fluvial deposits gain less attention in oil and gas exploration and in research. However, high-accommodation deposits in the Sandstone Dominated Zone (informally called the Barren Series) of the Raton Formation contain several sand bodies with different sizes and geometries that could be good candidates for reservoir rocks. Thin wide spread sheets of sandstone beds, amalgamated channels, channel-belts, and buffer valleys are some of the examples of these reservoir rock candidates. These sand bodies are common in outcrop of high-accommodation deposits in the Raton Basin. The size and distribution of these sand bodies reflect a range of processes spanning different stages of accommodation. The forming processes of some of these sand bodies and their role in reservoirs are still poorly known. By understanding the geometries and distributions of these sand bodies in the high-accommodation deposits as exposed in some of the Raton Formation outcrops, will enhance better predictability of reservoir distribution and connectivity, and potentially will suggest opportunities for oil and gas exploration in high-accommodation systems which otherwise have been overlooked because of low net/gross ratio condition.

This study examines the high-accommodation strata in the Sandstone Dominated Zone of the Raton Formation to gain a better understanding of high-accommodation reservoir lithofacies. Particular attention is given to the origin of thin sands beds and their reservoir and connectivity and potential between larger reservoir units. Additionally, this study attempts to develop a generalized architecture across six fundamental accommodation states.

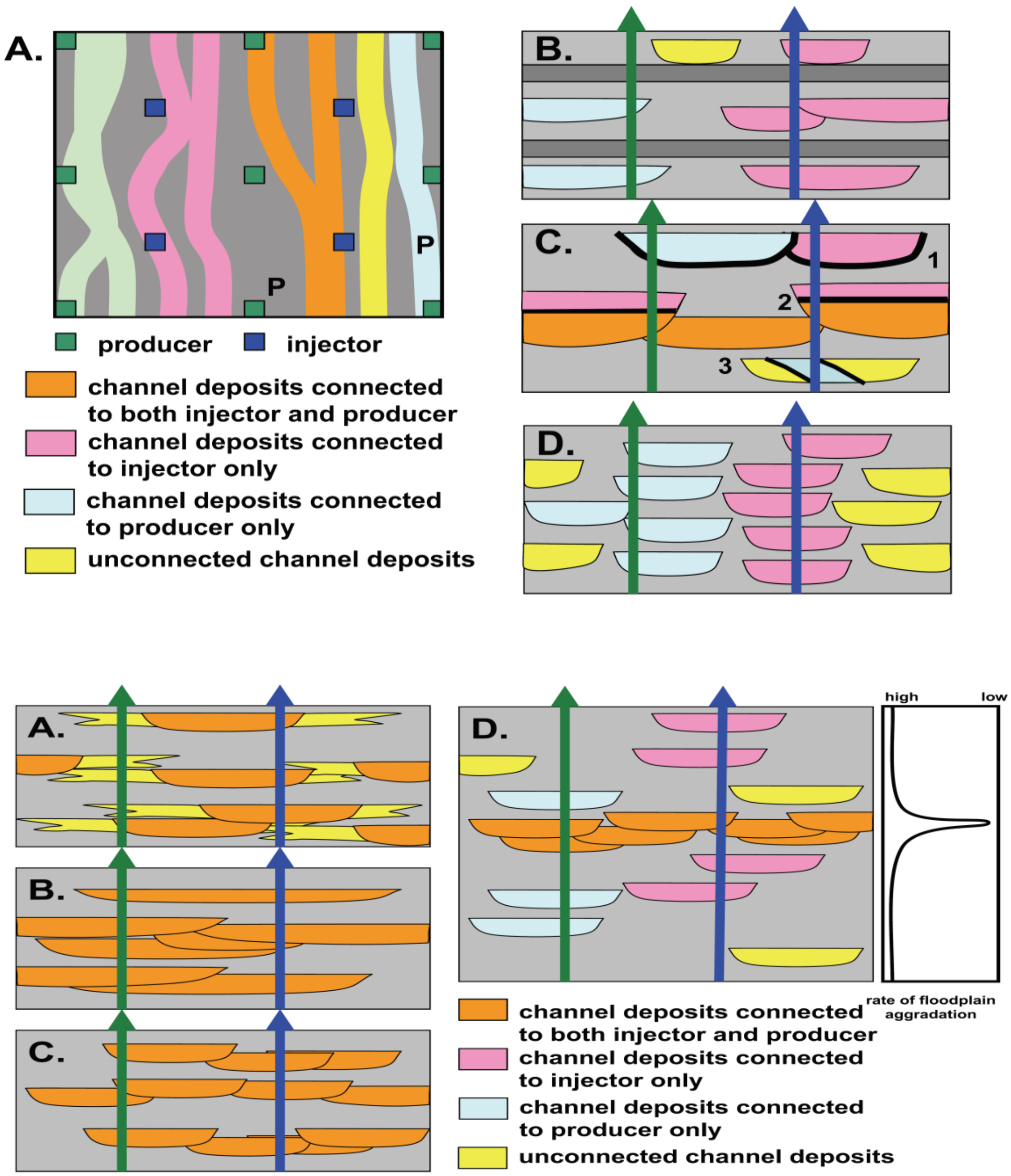


Fig. 1: Models for channelized reservoir shows channel connectivity in high (top) and low (bottom) accommodation systems. (Top figures): High-accommodation: A) 2D connectivity due to parallel channel paths. B) Continuous mudstone units reduces vertical connectivity. C) Local heterogeneous impermeable units are compartmentalized. D) Compensational stacking of channels could in theory result in a poorly connected sand-rich reservoir. (Bottom figures): Low-accommodation: A) Crevasse splays connect channels. B) Channel amalgamation will increase connectivity. C) Genetic clusters of channels (e.g., channel-belts) will increase connectivity. D) Lateral channel amalgamation and formation of complexes will have greater reservoir width/thickness ratios the reservoir. (Larue and Friedmann, 2005; Larue and Hovak, 2006).

1.1 The Raton Basin

1.1.1 Geological settings of the Raton Basin:

The Raton Basin is a Rocky Mountains Laramide intratectonic basin located in the northeastern parts of New Mexico and the south-central parts of Colorado (Baltz, 1965) (Fig.2). Its area is estimated to be about 5698 square kilometers and it extends from the southern parts of Colfax County in New Mexico to north of Huerfano County in Colorado (Stevens et al., 1992a, 1992b). The Raton Basin length is estimated to be about 129 kilometers north to south, whereas it is 80 kilometers east and west wide (Stevens et al., 1992a, 1992b; Lawton, 2008). The axis of the Raton Basin trends towards the east and the north in New Mexico parts of the basin, whereas it trends towards the northwest in Colorado parts of the basin (Johnson et al., 1956; Baltz, 1965; Woodward, 1983). The Raton Basin is asymmetric in shape with the eastern limb dipping gently towards the west, whereas the western limb steeply dips towards the east (Johnson et al., 1956). It is bounded by the Sangre de Cristo Mountains and Culebra Range on the west, the south edge of the Wet Mountains on the north, the Apishapa Arch on the northeast, the Las Animas Uplift on the east, and the Sierra Grande Uplift on the south and southeast (Baltz, 1965). The Raton Basin is considered as a basinal area since Pennsylvanian time (Gabelman, 1956; Baltz, 1965) before being rejuvenated to its current structural settings by the Laramide Orogeny during Late Cretaceous through Eocene time (starting about 67.5 Ma and ending about 50 Ma) (Baltz, 1965; Tweto, 1975; Johnson and Finn, 2001; Lawton, 2008). In the Raton Basin, the Laramide Orogeny started with maximum compressive stress oriented to the east and the northeast during the Late Cretaceous to the

Paleocene time and ended with maximum compression oriented to the northeast during the Eocene time (Chapin and Cather, 1981; Higley, 2007). The north to south and the northwest trending structures of the Raton Basin originated during the early phase of the tectonism, whereas the northwest to east and the west trending compressional structures originated during the late phase of formation (Merin et al., 1988; Higley, 2007).

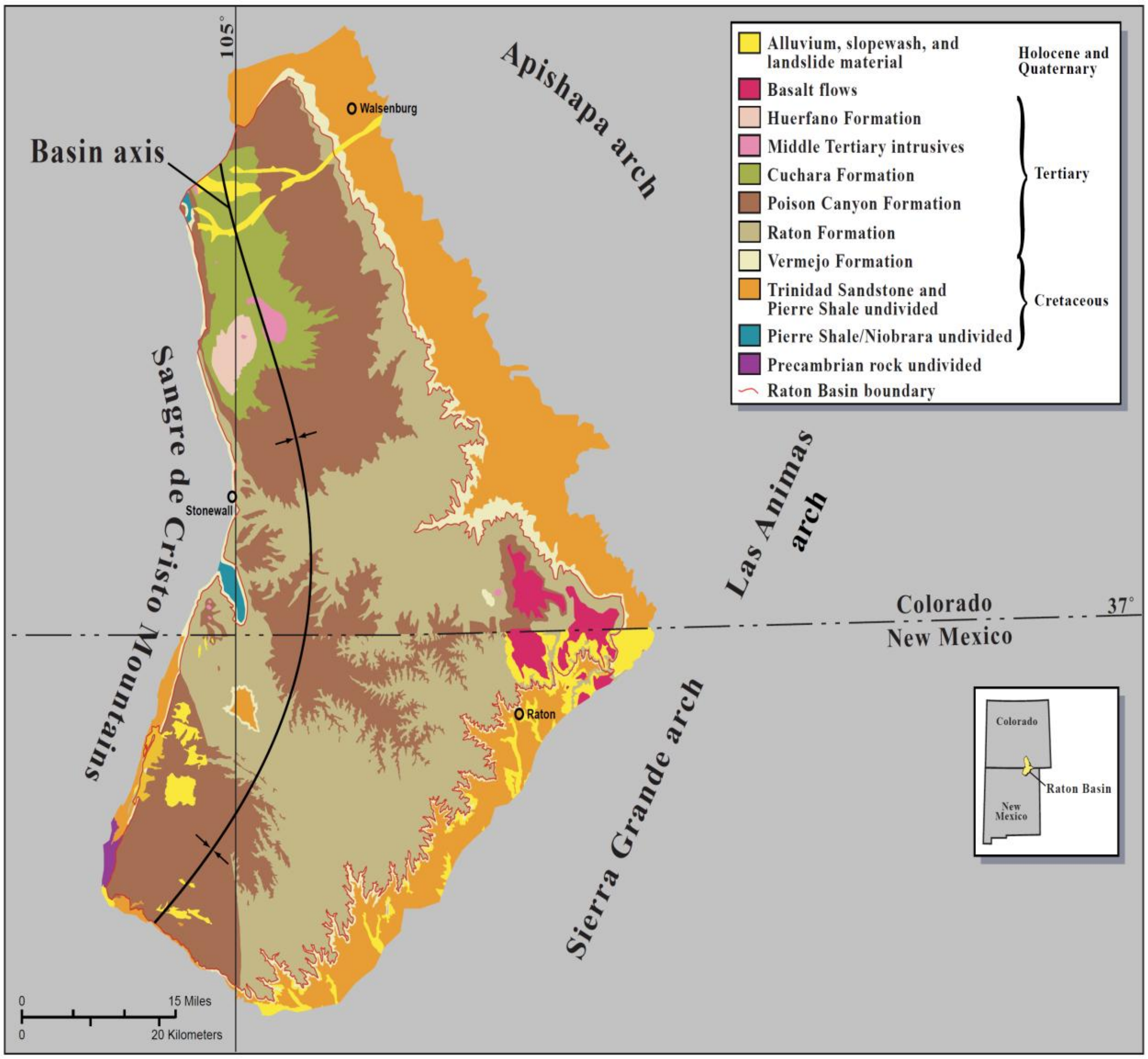


Fig. 2: Generalized geologic map of the Raton Basin, Colorado and New Mexico; modified from Flores and Bader (1999)

1.1.2 Stratigraphic settings and depositional environments of the Upper Cretaceous and Paleocene deposits in the Raton Basin:

The general stratigraphy of the Upper Cretaceous and Lower Paleocene deposits in the Raton Basin is illustrated in Fig. 3. The Pierre Shale is the oldest mapped unit in the Raton Basin (Flores and Bader, 1999) and it consists of dark, silty, non-calcareous, fine-grained, laminated shale beds that coarsen upward to fine sandstone beds with limestone concretions and is interpreted to be deposited in an off shore marine environment within the continental shelf and slope of the Cretaceous interior seaway (Pillomore and Flores, 1987). The formation of the Cretaceous Western Interior Seaway started during Early Cretaceous time and extended from the Arctic to the Gulf of Mexico and from central Utah to eastern Kansas by Late Cretaceous time (Porter and Sonnenberg, 1994) covering a distance of approximately 3,000 kilometers in length (Lawton, 2008). The Pierre Shale is Upper Cretaceous in age and ranges in thickness between 545 to 580 meters.

The Trinidad Sandstone overlies the Pierre Shale and it is composed of buff to gray, slightly arkosic, medium to fine sandstone beds with local thin interbeds of light tan to gray, silty shale that were deposited during the eastward progradation of the Cretaceous interior seaway shoreline (Johnson et al., 1966; Pillomore and Flores, 1987; Flores and Bader, 1999). The Trinidad Sandstone thickness ranges from 0 to 92 meters in the Raton Basin.

The Upper Cretaceous Vermejo Formation conformably overlies the Trinidad Sandstone (Johnson et al., 1966) and it consists of buff gray and dark gray siltstone, gray to green slightly arkosic sandstone, nearly black carbonaceous coaly and silty shale, and numerous coal beds (Johnson and Wood, 1956; Tremain, 1980; Pillomore and Flores, 1987; Tyler et al., 1991) that were deposited within delta, flood plain, and swamp environments as a result of the shoreline retreat of the Cretaceous interior seaway during the Late Cretaceous (Johnson et al., 1966). The Vermejo Formation is between zero to116 meters in thickness in the Raton Basin (Johnson and Wood, 1956).

The Upper Cretaceous and Lower Paleocene Raton Formation overlays the Vermejo Formation. A detail description of lithology, thickness and interpretation of the Raton Formation will be presented separately in the next section because all of the study outcrops are found within this formation.

The Poison Canyon Formation overlies the Raton Formation and it consists of thick, massive, lenticular ledge forming beds of conglomeratic arkosic sandstone intercalated with sandy micaceous mudstone and siltstone (Tremain, 1980; Pillomore and Flores, 1987; Tyler et al., 1991; Flores and Bader, 1999). Generally, the Poison Canyon Formation conformably overlies the Raton Formation, but it intertongues with the Raton Formation at several locations in the west and southwest parts of the Raton Basin (Hills, 1888; Pillomore and Flores, 1987). The Poison Canyon Formation ranges in thickness between 46 to 200+ meters and is interpreted to be deposited in fluvial and deltaic environments (Pillomore and Flores, 1987; Flores and Bader, 1999).

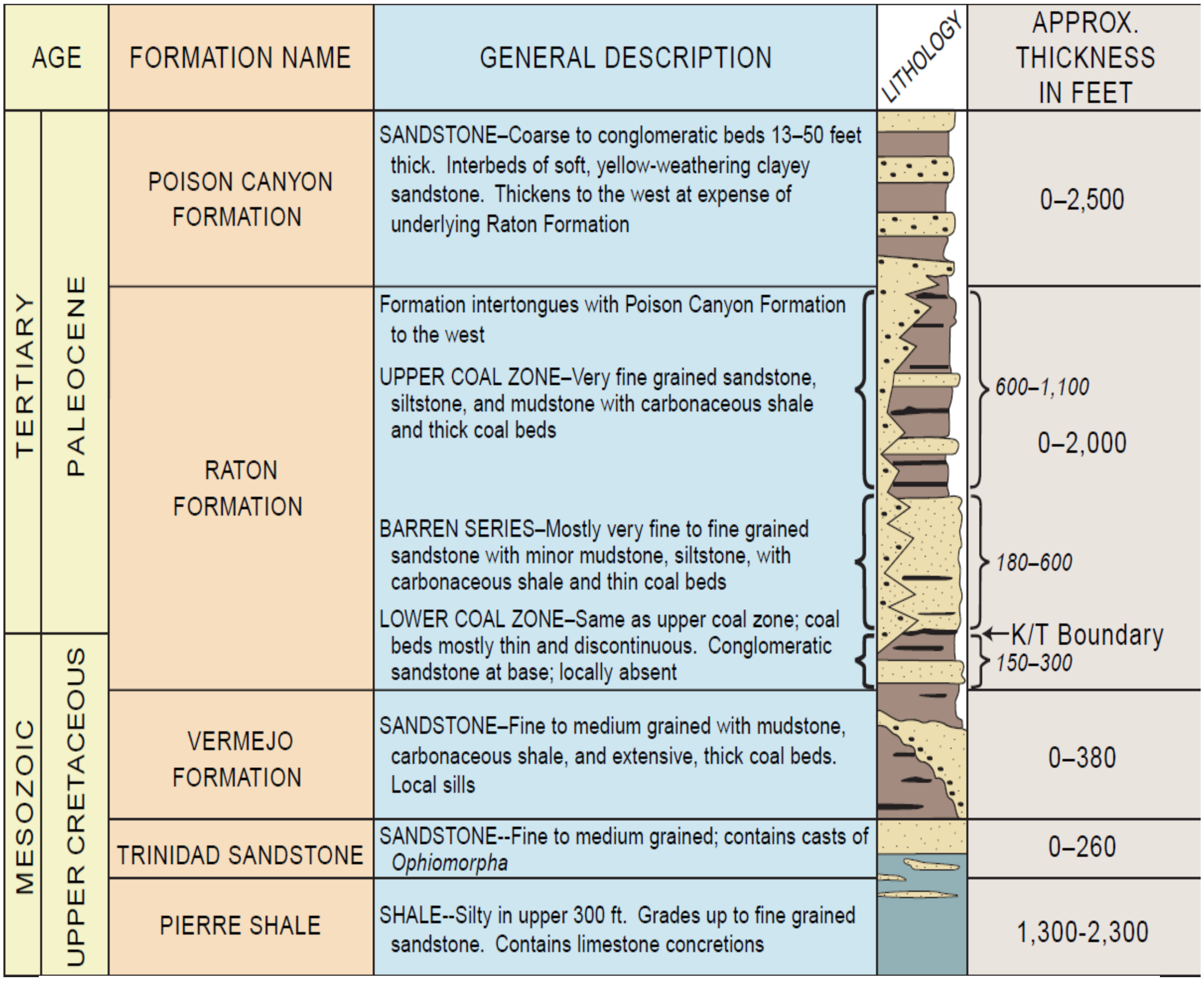


Fig. 3: Generalized stratigraphy of the Upper Cretaceous and Paleocene of the Raton Basin, Colorado (Tremain, 1980; Flores and Bader, 1999)

Fig. 4: The Western Interior Seaway extent during the Late Cretaceous time (Henry and Finn, 2003)

1.1.3 The Raton Formation, Trinidad, Colorado:

The Raton Formation (Lee, 1917) is Upper Cretaceous and Lower Paleocene in age (Johnson et al., 1966), is underlain by the Upper Cretaceous coal-bearing Vermejo Formation and overlain by the Paleocene Poison Canyon Formation. It attains more than 640 meters in thickness in the Colorado parts of the Raton Basin (Pillmore, 1969; Woodward, 1983). The Raton Formation is generally interpreted to be deposited in flood plain, flood plain-lake, crevasse splay, swamp, fluvial, and lacustrine environments (Woodward, 1983; Strum, 1985; Flores, 1987; Pillomore and Flores, 1987). These depositional environments were formed within alluvial plains during the early stages of the Laramide Orogeny when the Cretaceous Western Interior Seaway started to withdraw during Early Tertiary (Flores, 1984; Flores, 1987; Flores and Bader, 1999) (Fig. 4). The Raton Formation is considered as a major coal-derived methane producer in the Raton Basin. Its coal deposits are bituminous in rank and contain around 23 to 193 ft^3/short ton (i.e., 0.72 to 6.07 cm^3/g) of methane gas within the coal beds (Tyler et al., 1995; Higley, 2007).

The Raton Formation was subdivided by Lee (1917) into the Basal Conglomeratic Zone, the Lower Coal-rich Zone, the Sandstone Dominated Zone (informally called the Barren Series), and the Upper Coal-rich Zone. The Basal Conglomeratic Zone consists of interbedded quartzite, chert, gneiss pebble and cobble conglomerate, and granule, quartzose sandstone (Pillomore and Flores, 1987; Flores and Bader, 1999). The Basal Conglomeratic Zone is laterally discontinues and ranges in thickness between 0 and 15 meters (Pillomore and Flores, 1987). The Lower Coal Zone consists of interbedded coal, carbonaceous shale, mudstone, siltstone, and sandstone that ranges in thickness between 30-76 meters (Pillomore and Flores, 1987; Flores and Bader, 1999). The Sandstone Dominated Zone is composed of sandstone and conglomeratic sandstone, subordinate mudstone and siltstone, and sparse coal and carbonaceous shale. It has a thickness of 55 to 183 meters (Pillomore and Flores, 1987; Flores and Bader, 1999). The Lower Coal Zone and the Sandstone Dominated Zone are separated by a very distinctive and important marker, a 1-2 cm claystone bed which is considered the Cretaceous-Tertiary boundary (K/T) (Izett, 1987). This (K/T) boundary is near the top of the Lower Coal-rich Interval below the Sandstone Dominated Zone in the lower part of the Raton Formation (Tschudy et al., 1984, Pillmore and Flores, 1984, Higley, 2007).

The depositional megacycle of the Raton Formation has been described by Pillmore and Flores (1987) and Flores and Bader (1999) (Fig. 5) who attributed the changes in fluvial system architecture within Raton Formation to tectonic uplift of the basin margin and basin subsidence of the Raton Basin. These authors also asserted that the coal-rich lower part of the Raton Formation indicates depositions within meandering and anastomosing fluvial systems to braided and meandering fluvial systems that are largely influenced by basin subsidence (Flores and Bader, 1999). Basin subsidence promotes the vertical aggradation of anastomosing streams and the lateral migration of meandering streams depositing fluvial channel sandstone, crevasse splays, carbonaceous shale, mudstone, siltstone, flood basin fines, and lake mudstone (Flores and Bader, 1999). The Sandstone Dominated Zone is influenced by tectonic uplift in the western margin of the Raton Basin which led to the formation of mountain fronts alluvial fans that acted as point sources of sediments for the basin (Pillmore and Flores, 1987; Flores and Bader, 1999). As a result of alluvial fans formation, more sediments were delivered along the basin margin which led to the development of braided style streams that merged with the pre-exist meandering streams in the basin center (Pillmore and Flores, 1987; Flores and Bader, 1999).

The current study heavily concentrates on the Sandstone Dominated Zone and extends slightly into the lower part of the Upper Coal Zone (about 20 meters above the K/T boundary) of the Raton Formation. The Sandstone Dominated Zone and the lower part of the Upper Coal Zone were chosen for this study because they both have the lithological and architectural sand bodies setting that are needed to accomplish this study objectives.

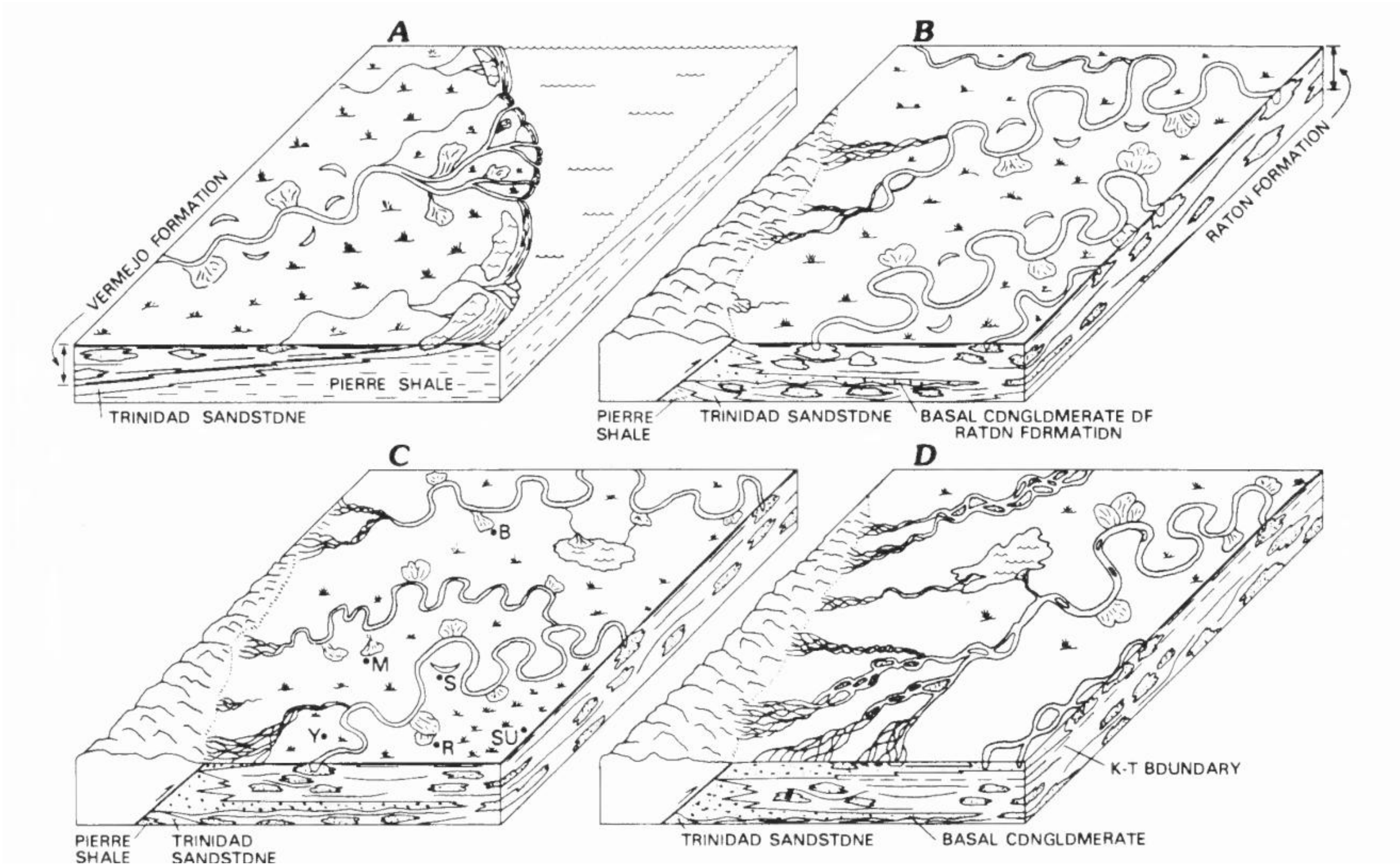


Fig. 5: Block diagram illustrating paleoenvironments of the Cretaceous and Paleocene deposits of the Raton Basin. (Pillmore and Flores, 1987)

1.2 The concept of high and low-accommodation system tracts

Accommodation is the available space for potential sediment accumulation below a base level (Payton, 1977; Jervy, 1988) which is defined as the lowest level to which rivers can erode (derived from Powell, 1875). The concept of accommodation was first applied for marine basins where the accommodation space is confined between sea level and the sea floor (Payton, 1977; Jervy, 1988; Schumm, 1993; Miall, 2014).

Accommodation can be formed in both marine and fluvial environments under the effects of climate, tectonism, and sea level change (Catuneanu, 2006). In fluvial systems, the base level is the level of any body of water into which the river debouches such as sea level, lake level, water table level or another river level (Posamentier and Allen, 1999; Catuneanu, 2006).

The idea of fluvial accommodation systems was derived from sequence stratigraphy as proposed for the shallow marine environment deposits (Vail, 1977). These concepts of sequence stratigraphy were later used to explain coastal fluvial deposits (Posamentier and Vail, 1988). The early models for alluvial system deposits were proposed by Bridge and Leeder (1979) (Fig. 6) as what are now considered as the LAB models, named after the authors Leeder, Allen and Bridge (Allen, 1978, 1979; Leeder, 1978; Bridge and Leeder, 1979; Bridge and Mackey, 1993a; Mackey and Bridge, 1995). Other models have been proposed by Wright and Marriott (1993) (Fig. 7), and Shanley and McCabe (1994) (Fig. 8). The Bridge and Leeder (1979) models are quantitative computer models that were developed to simulate the development of a two-dimensional alluvial sedimentary succession beneath a flood plain traversed by a single major river. This model illustrates how channel-belt connectivity decreases with increasing the flood plain width, mean avulsion period, and channel-belt aggradation rate (Bridge and Leeder, 1979). The Bridge and Leeder (1979) models also stressed that a channel-belt showing off-lap tendencies tends to cluster closer to the active flood plain margin, whereas the fine grain deposits are concentrated in the inactive side of the flood plain. The Bridge and Leeder (1979) models also show that the channel-belt thickness increases during aggradation periods. The LAB models were generated from the previous work of the three authors (Allen, 1978, 1979; Leeder, 1978; Bridge and Leeder, 1979; Bridge and Mackey, 1993a; Mackey and Bridge, 1995) to illustrate the link between channel stacking pattern and sedimentation rate.

Wright and Marriott (1993) and the Shanley and McCabe (1994) (Fig. 8) proposed the first two sequence models developed for non-marine deposits (Miall, 2014). In the Wright and Marriott (1993) model, an erosional sequence boundary formed at the base of the section during the falling stage and was characterized by the deposition of amalgamated channel facies. As sea level rose, a transgressive stage occurs and channels are isolated within the fine grained flood basin deposits. Then sea level rise slows down forming high-stand stages where accommodation generation decreases, and channel avulsion and point bar formation increases. The Shanley and McCabe (1994) model is very similar to the Wright and Marriott (1993) model which illustrates the relationship of base level change, shoreline and fluvial architecture. In the Shanley and McCabe (1994) model, the erosional sequence boundary (i.e., incised valley) forms during the falling stage and deposition of an amalgamated channel occurs during the low-stand stage. The deposition of the isolated channels within the fine-grained flood basin deposits occur during the transgressive stage, followed by high-stand stage deposits similar to the ones in the Wright and Marriott (1993) model.

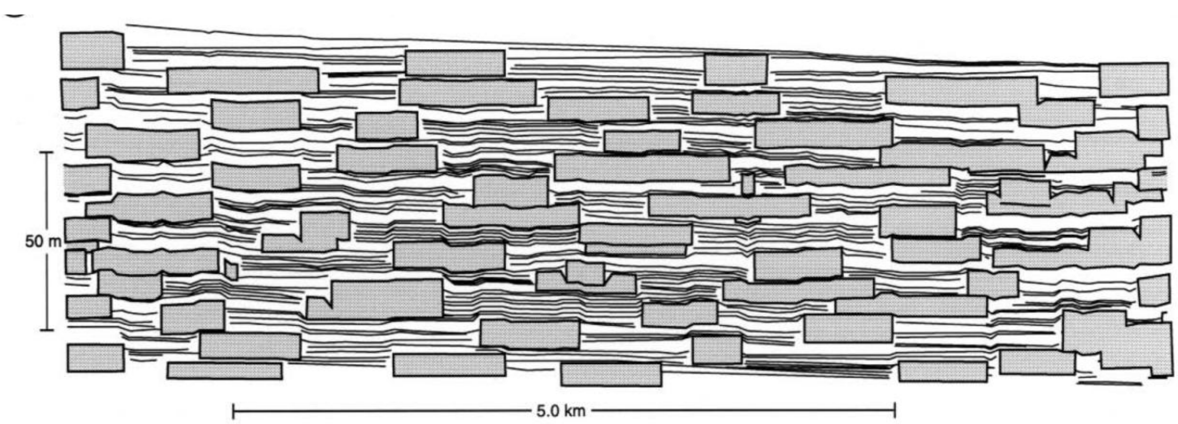


Fig. 6: An example of a simulated cross section constructed by using the Bridge and Ledeer (1979) numerical model. (Davies et al., 1993)

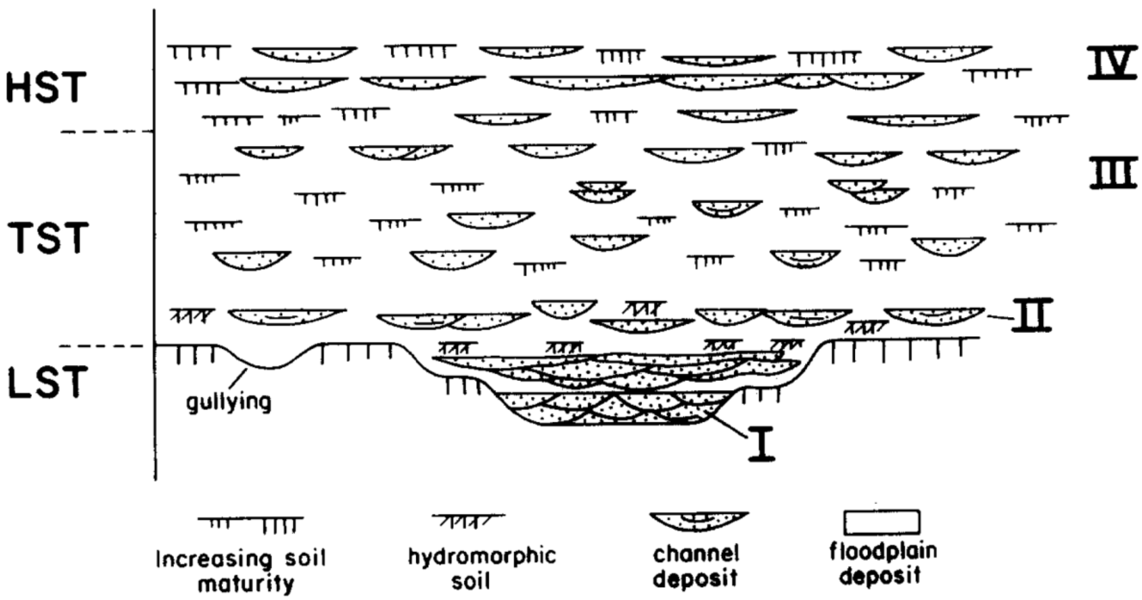


Fig. 7: The Wright and Marriott (1993) model shows the relationship between fluvial deposits architecture as a function of base level change.

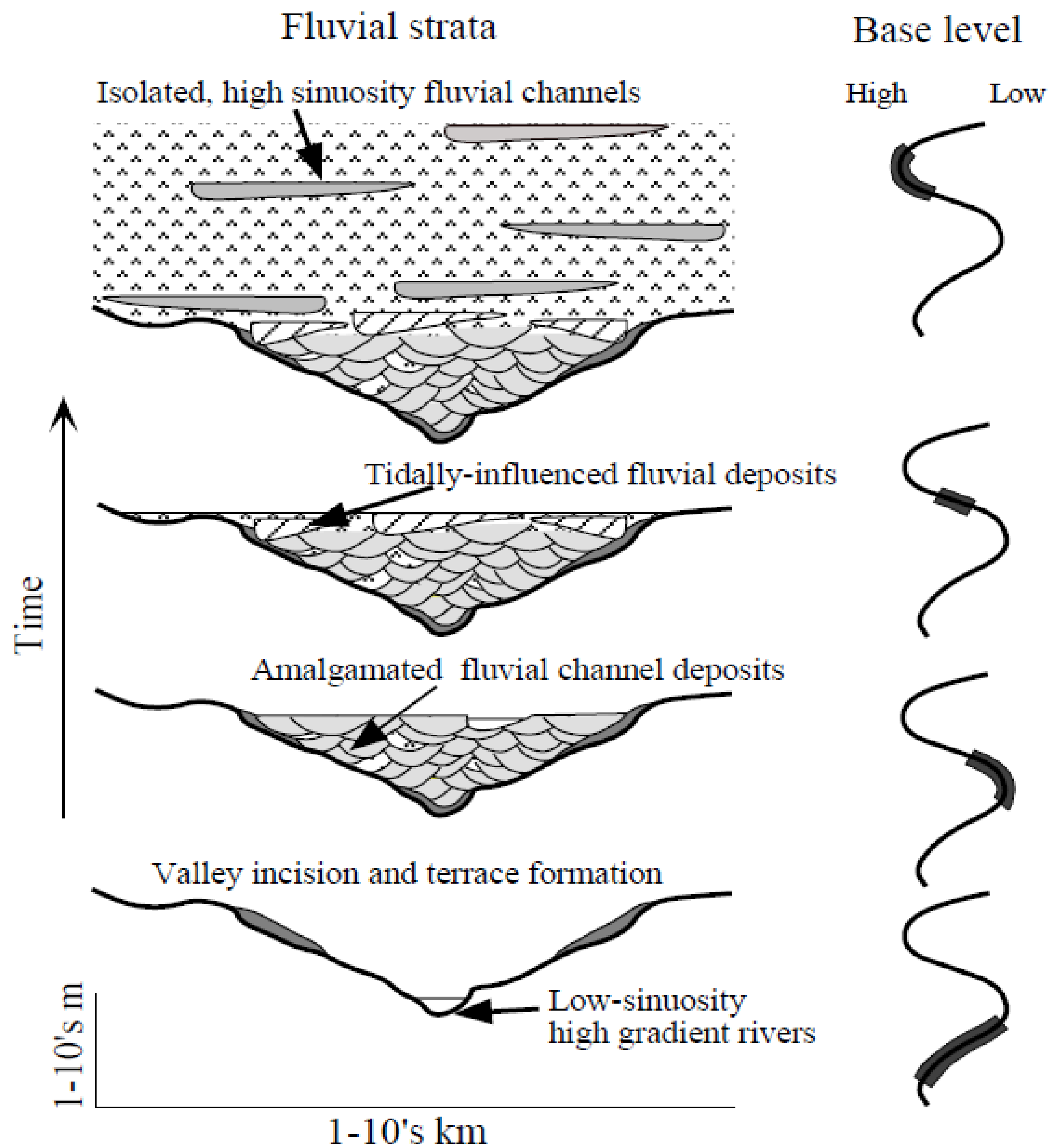


Fig. 8: The Shanley and McCabe (1994) stratigraphic model shows the relationship between fluvial architecture as a function of base level change.

All of the previous models were constructed based on studies of modern river processes (e.g., the LAB model). These models also are dependent on sea level changes, and sedimentation being isolated from any correlative marine deposits, and/or are highly tied to a shoreline shift which make their applicability very limited when applied to ancient fluvial deposits (Catuneanu, 2006; Miall, 2014; Colombera et al., 2015). The inapplicability of using traditional marine based sequence stratigraphy nomenclature for fluvial system stratigraphy in non-marine basins that show no evidence of shoreline transgression and regression, has led to a proposal of a new nomenclature more applicable to fluvial system deposits (Dahle et al., 1997).

In fluvial systems, accommodation can be subdivided into two categories based on the channel stacking pattern (i.e., the degree of channel amalgamation due to sedimentation rate and avulsion) (Martinsen et al., 1994; Catuneanu, 2006).These two categories are the low-accommodation system tracts, and the high-accommodation system tracts (Olsen et al., 1995; Dahle et al., 1997). Another opinion regarding the distinction between low-and-high accommodation was recently proposed by Colombera et al. (2015) who proposed that the distinction between low-and-high accommodation by only channel stacking pattern is not justified, as they discovered that high mud content within the high-accommodation system reflects phases of short and rapid aggradation within a longer term pattern. Colombera et al. (2015) also noted that high-accommodation systems do not aggrade fast enough to make high-accommodation deposits.

A low-accommodation system tract is characterized by highly amalgamated channel-belts. These channel belts are vertically stacked and the upper channel stories scour into the lower channel stories forming one unit of a laterally extensive sand body that consists of amalgamated smaller channel-belts (Lagarretta et al., 1993; Shanley and McCabe, 1993; Aitken and Flint, 1994) .These amalgamated bodies are formed when the flood basin fails to aggrade more than one channel-belt prior to its avulsion return to the same spot, allowing active channels to cut through its own deposits forming the amalgamated sand bodies (Miall, 1996; Holbrook, 2001; Straub, 2009). Deposition within the low-accommodation system tract is still progradational with a low rate of aggradation and is often influenced by the underlying incised topography (Boyd et. al., 1999; Catuneanu, 2006). Low-accommodation system deposits are mainly deposited subaerially above water level and consist of coarse-grained sediments such as sand and silt with a low percentage of fine sediments and coal (Catuneanu, 2006). The coarse-grained sediment content could be due the presence of the higher energy fluvial system that usually occupies the lower portion of the sequence or possibly due to sediment source rejuvenation (Catuneanu, 2006).

In a high-accommodation system tract, channel-belts are vertically isolated in the fine-grained flood basin mud deposits in the form of isolated sand ribbons (Lagarretta et al., 1993; Shanley and McCabe, 1993; Aitken and Flint, 1994, Catuneanu, 2006). Within a high-accommodation system tract, aggradation is more than one channel-belt prior to avulsion return which causes the burial of channel-belts by flood basin deposits before the active channel returns to the previous location (Bridge and Leeder, 1979; Shanley and McCabe, 1994; Holbrook, 2001). The high-accommodation system tract depositional style is aggradational with a lower influence from the underlying topography (Boyd et. al, 1999; Catuneanu, 2006) and also is characterized by a high water level (i.e., water table or lake level) and a high proportion of fine-grained mud and clay deposits due to declining depositional energy (Catuneanu, 2006). The high-accommodation system tract is also distinguished by the presence of peat, well developed coal (in a poorly-drained flood basin), and organic rich mud deposits (Catuneanu, 2006).

1.3 Distributive fluvial systems (DSF)

Distributive fluvial systems (DSF) are defined as the depositional pattern of channels and flood basin deposits that radiated in a fan-like shape from an apex point where the river enters the sedimentary basin (Hartley et al., 2010; Weissmann et al., 2011). Friend (1978) in his study of fluvial systems in the Ebro Basin in Spain was the first to notice the difference between some ancient axial fluvial deposits and modern axial fluvial systems. Friend (1978) recognized that some ancient axial fluvial systems have a downstream decrease in river depth, absence of alluvial incision, and convex-up and lobate topography that are not present in modern axial fluvial systems (Nichols and Fisher, 2007). Based on previous findings, Friend (1978) suggested that these ancient axial fluvial deposits could be deposited as a 'terminal fan' in a distributive river system (Friend, 1978; Nichols and Fisher, 2007). Several studies followed Friend (1978) that led to the establishment of better and more detailed fluvial distributary systems models (e.g., Hirst and Nichols, 1986; Friend, 1989; Kelly and Olsen, 1993; Nicholas and Fisher , 2007; Hartley et al., 2010; Weissmann et al., 2011; Weissmann et al., 2013).

The most recent models for DFS have been proposed by Nicholas and Fisher (2007), Hartley et al. (2010) and, in more detail, by Weissmann et al. (2013) (Figs. 9, 10). This last DFS model was established based on previous work in both modern and ancient distributive fluvial systems and from earlier conceptual models (e.g., Friend, 1978;

Graham, 1983; Nichols, 1987; McCarthy, 1990; Kelly and Olsen, 1993; Sadler and Kelly, 1993; McCarthy et al., 1999; Nichols, 2004). According to Nicholas and Fisher (2007), the DFS radial distance from the apex to the distal parts of the system is estimated to be in the order of tens of kilometers based on observations in ancient DFS deposits (e.g., Hirst and Nichols, 1986). Nicholas and Fisher (2007) also noted that the extent of the DFS is determined by the water supply and the water loss by evaporation, which imply that the extent of the DFS might be larger than what can be preserved in ancient DFS deposits. Several types of DFS have been described in modern and the ancient fluvial systems which include: alluvial fans, fluvial fans, humid alluvial fans, and megafans (Weissmann et al., 2010, 2013). DFS channel morphology varies due to climate changes and sediment supply (Hartley et al., 2010; Weissmann et al., 2010, 2013). Despite the channel morphology variation, DFS channels might have common characteristics such as those described by Hartley et al. (2010) as: the DFS has a radial pattern of channels away from the apex, channels are commonly decreasing in size downstream, grain size also commonly decreases towards the DFS downstream, and the DFS channels may lack lateral channel confinement. A DFS can be divided into three depositional zones, proximal, medial, and distal, based on changes in stratigraphic architecture (Hirst and Nichols, 1986).

The proximal zone is located near the apex where the DFS exits from the confined river and spreads across a low laying alluvial plain (Weissmann et al., 2013). The proximal zone is relatively narrow and extends only for a few kilometers (Nicholas and Fisher, 2007; Weissmann et al., 2013). The fluvial deposits of the proximal zone are mainly coarse-grained, sandy and conglomeratic, and cross bedded deposits with minor fine flood basin deposits (Nicholas and Fisher, 2007; Weissmann et al., 2013) The presence of coarse size deposits in the proximal zone is due to the loss in flow energy when the river loses confinement (Weissmann et al., 2013). Channel-belts within the proximal zone are amalgamated with bars and they have very low fine deposit content (Nicholas and Fisher, 2007; Weissmann et al., 2013). The limited preservation of fine flood basin deposits is due to the mobility and laterally migration of channels within the narrow proximal zone (Weissmann et al., 2013). The avulsion/sedimentation ratio in the proximal zone is relatively low due to the high sediment supply and the high sediment bypass (Nicholas and Fisher, 2007; Weissmann et al., 2013). As a result of the presence of coarser grains in the proximal zone deposits, the permeability of layers below the river is high and the flow will lose energy due to high infiltration rate (i.e., lower accommodation space) and the system would have a well-drained condition (Weissmann et al., 2013).

The medial zone is the transitional zone between the proximal and the distal zones, and covers a larger and wider spread area compared to the proximal zone (Nicholas and Fisher, 2007). The medial zone deposits show an increase in the flood basin fine deposits, and a decrease in channel belt size and thickness (McCarthy, 1990; Hirst, 1991). In the medial zone, channel-belts are enclosed within the fine flood basin deposits and show evidence of soil formation within the fine deposits which indicates well-drained flood basin conditions (Nicholas and Fisher, 2007; Weissmann et al., 2013). The preservation of the flood basin fine deposits is due to the high avulsion/sedimentation ratio (higher than in the proximal zone) which leads to a better preservation of flood basin fine deposits as a result of the low sediment supply in the medial zone (Weissmann et al., 2013). Channel-belt scours in the medial zone are not deeply incised into the flood basin deposits and are characterized by levee development (Sadler and Kelly, 1993; Nicholas and Fisher, 2007; Weissmann et al., 2013).

The distal zone is the farthest downstream extent of the DFS and is characterized by its high flood basin fine sediment content with a very low percentage of coarse sediment (Nicholas and Fisher, 2007; Weissmann et al., 2013). The fine-grained flood basin sediments are organic rich, grey in color, and were deposited in a relatively shallow water table and commonly in standing water (i.e., poorly drained flood basin conditions) (Weissmann et al., 2013). In the distal zone, channel-belts decrease in size downstream and experience additional bifurcation, with some channels terminating in splays and wetlands. The flood basin that surrounds these channel-belts mainly consists of wet soil and wetlands (Nicholas and Fisher, 2007; Weissmann et al., 2013). Avulsions are very common in the distal zone of the DFS and most of the deposits occur as avulsion-type deposits (Weissmann et al., 2013). The sand bodies in the distal zones of the DFS are thin, sheet-like, and laterally extensive with a sharp and erosive base due to the localized channelization of flow in certain areas in the DFS distal zone (Graham, 1983).

1.4 Well-drained vs. poorly-drained flood-basins

The degree of flood basin drainage is measured by the relation between sedimentation rate and water table rise (i.e., accommodation rate) (Van Wagoner et al., 1990; Posamentier and Allen, 1999). The permeability of flood basin deposits also has a major effect in the degree of drainage (Kraus, 2002). Kraus (2002) investigated paleosol development in the Willwood Formation in the northern parts of Wyoming. She proposed an architectural model that shows how floodplain paleosols vary in response to changes in basin subsidence, water table level, and to variations in the relationship between avulsion frequency and sedimentation rate. Kraus (2002) in her architectural model indicated that flood basins with finer deposits have a low permeability which prevents the water from infiltrating into the lower layers, leaving the deposition to occur either below or very close to water level. In contrast, in coarser flood basin deposits, water can infiltrate through the pore spaces into the lower layers leaving the paleosol sediments exposed above the water level.

Generally, flood basins can be divided into two categories, well-drained and poorly-drained. The aggradation variation within well-drained and poorly-drained flood basins occurs because of the variation of accommodation rise rates. Well-drained and poorly-drained flood basins can also be characterized by the fluvial distributive models that were discussed in the previous section (e.g., Nicholas and Fisher, 2007; Hartley et al., 2010; Weissmann et al., 2013) in contrast to sequence stratigraphic models.

In well-drained flood basins, the sedimentation rate exceeds the water table rise (Van Wagoner et al., 1990; Posamentier and Allen, 1999). As result of the higher sedimentation rate, well-drained flood basins are usually exposed and allow the sediment to develop a better soil horizons on the flood basin floors (Kraus, 1999; Kraus, 2002; Weissmann et al., 2013). Well-drained flood basin deposits are also characterized by their low organic content, rare coal development, and the common presence of rooting on top of these deposits. Well-drained flood basins are represented as the proximal zone deposits in the Weissmann et al. (2013) (Fig. 9) and Nichols and Fisher (2007) (Fig. 10) DFS model.

In poorly-drained flood basins, the water table rise is equal or higher than the sedimentation rate, and the flood basin is either very close to or below the water table, which permits the formation of standing water environments such as wetlands, swamps, and lakes (Van Wagoner et al., 1990; Posamentier and Allen, 1999; Aslan and Autin, 1999; Nicholas and Fisher, 2007). Poorly-drained flood basin deposits mainly consist of organic-rich sediments, peat, coal and fine muddy deposits. According to Kraus's (2002) architectural model, one of the reasons for the high water level within poorly-drained flood basins is the low permeability of the flood basin fine sediments, which prevents the water from infiltrating into the lower layers and promotes water retention near or above the surface. Poorly-drained flood basins are at the distal zone of the distributive fluvial system of the Weissmann et al (2013) DFS geometric model and Nicholas and Fisher (2007) fluvial distributary system model.

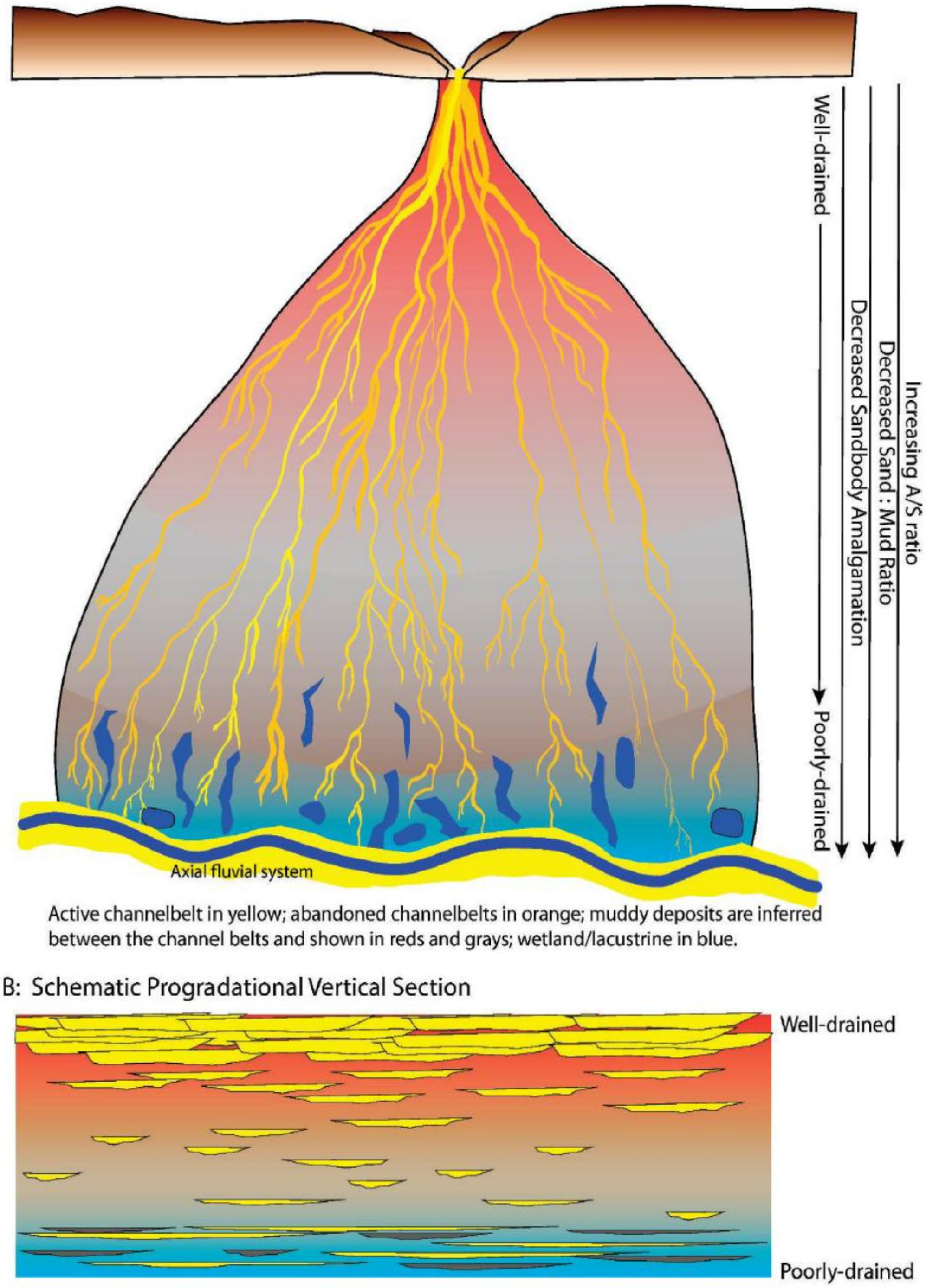
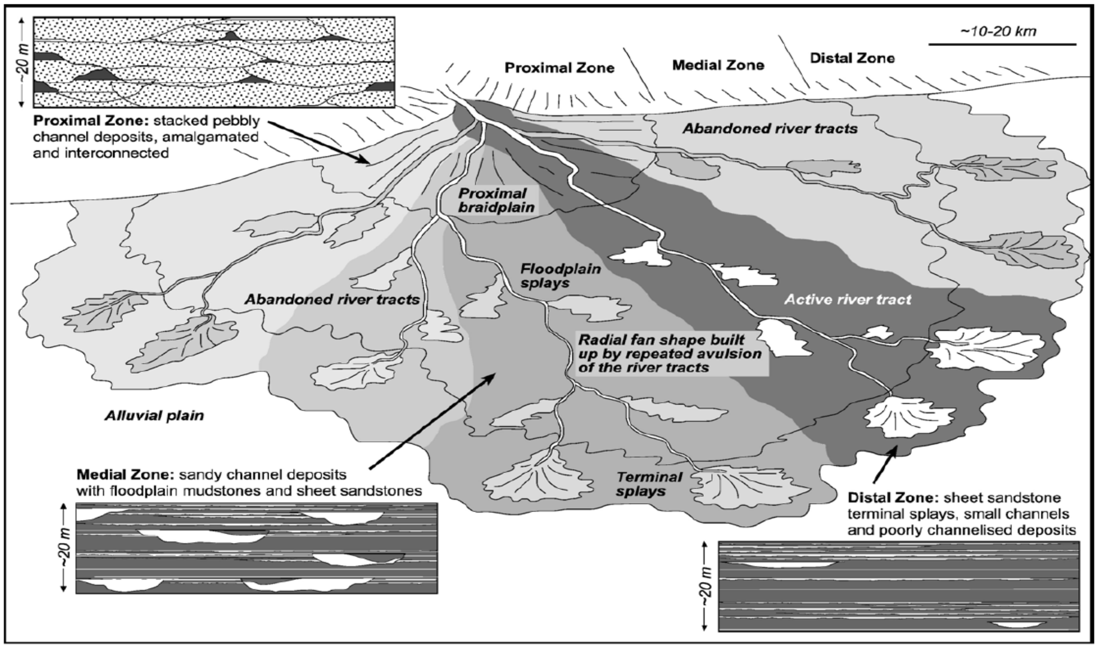


Fig. 9: Schematic diagram of the distributive fluvial system model showing the range of depositional zones and degree of flood plain drainage (Weissmann et al., 2013)



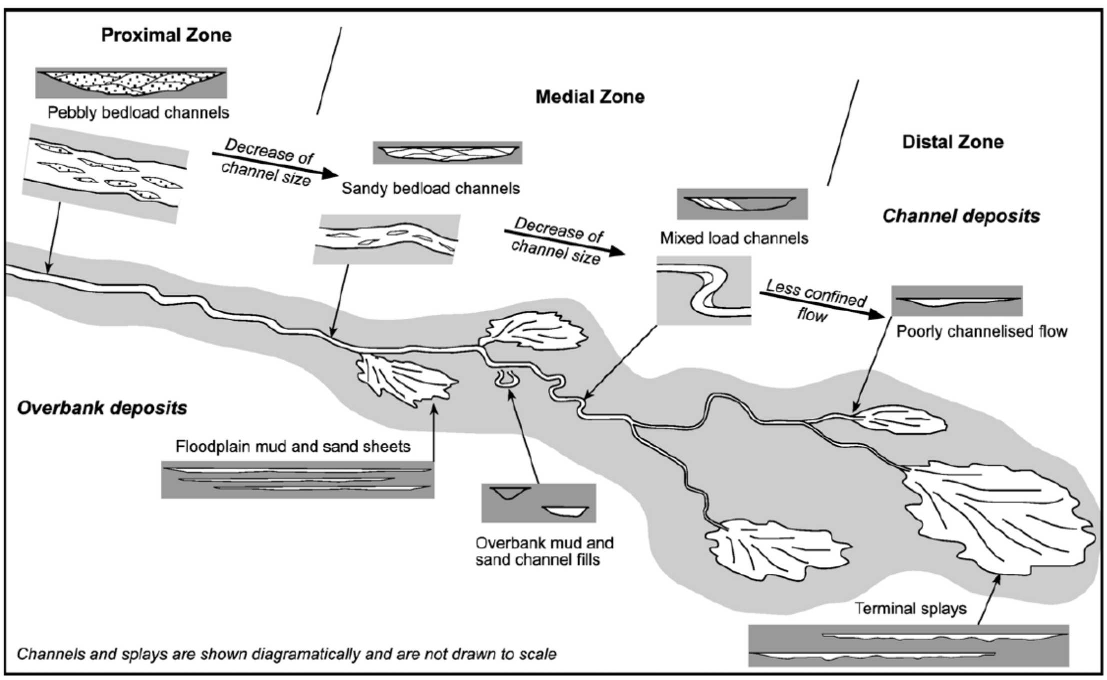


Fig. 10: Nichols and Fisher (2007) fluvial distributary systems models to illustrate changes in channel architecture at the proximal, medial and the distal zones.

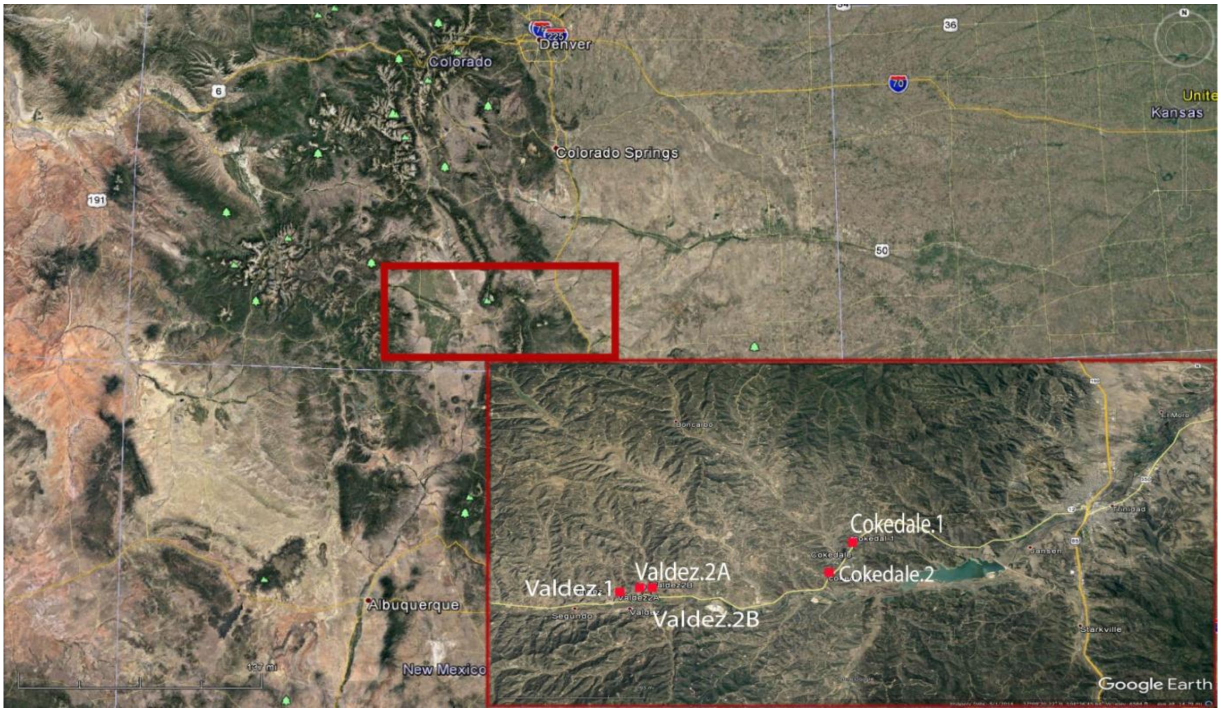


Fig. 11: Location map for the study area and outcrops locations.

1.5 The study area

The study area is located to the west of the City of Trinidad near the southern border of Colorado and close to the northern border with New Mexico in the Raton Basin (Fig. 11). Five outcrops were selected along highway 12 between the towns of Cokedale and Segundo to be examined in this study: Cokedale.1, Cokedale.2, Valdez.1, Valdez.2A, and Valdez.2B. The main criteria that were used to choose these outcrops are that they are laterally extensive and high enough to observe the lateral and vertical variations, and lithofacies distribution within the high-accommodation deposits that these outcrops contain. Another criterion was the presence of sand bodies of different sizes and geometries which aided in illustrating the changes in sand body geometry, and their size and connectivity in the different accommodation stages.

The Cokedale.1 outcrop is located about 565 meter west of Cokedale, Las Animas County, Colorado. The Cokedale.1 outcrop is about 350 meters long and 32 meters high. The Cokedale.2 outcrop is about 965 meters west of Cokedale and 480 meters west of the Cokedale.1 outcrop. The Cokedale.2 outcrop is about 305 meters long and 21meters high. Both of the Cokedale.1 and Cokedale.2 outcrops exhibit high-accommodation and poorly-drained flood basins conditions, and are dominated by fine grained sediments. The Valdez.1 outcrop is about 1610 meters east of the town of Segundo, Las Animas County. The Valdez.1 outcrop is about 670 meters long and 20 meters in height. The Valdez.2A outcrop is 2414 meters away from Segundo, and approximately 805 meters east of the Valdez.1 outcrop. The Valdez.2A outcrop is about 286 meters in length and 17 meters in height. The Valdez.2B outcrop is about 2415 meters east of Segundo and only 80.5 meters away from Valdez.2A. The Valdez.2B outcrop is about 213 meters long and 12 meters high. All of the three Valdez outcrops deposits have high-accommodation well-drained flood basin settings.

CHAPTER 2

METHODS

Detailed identifications of lithofacies were recorded in all of the five outcrops of the Raton Formation in the study area. The lithofacies identification characteristics include: detailed examination of lithology, unit thickness, color, composition, grain size and grain size changes (i.e., fining upward or coarsening upward), texture, bedding type (e.g., lamination, cross-bedding, graded bedding, etc), sedimentary structures, contact nature between lithofacies (sharp, gradual), fossils and trace fossils content, and lithofacies extent (e.g., isolated, extensive, pinching-out).

Several measured sections were constructed at each outcrop to constrain the vertical and lateral variation of the previously identified lithofacies assemblages (example shown in Fig. 12). Locations of measured sections within the study area outcrops were assigned with equal spacing and they vary in numbers from one outcrop to another. The number of measured sections in each outcrop depends on the length and the height of each particular outcrop. There are three measured sections at the Cokedale.1, Cokedale.2, and Valdez.2B outcrops, whereas there are four measured sections at the Valdez.1 and Valdez.2A.

Each outcrop of the Raton Formation at the study area was photographed in a series of overlapped pictures that were taken from the same elevation and with equal spacing distances. The photographs were taken by a Canon EOS Rebel t2i - high resolution digital SLR camera (18 megapixel)-with a 18-55mm lenses to provide the maximum fluvial architectural details that are presented in the study area outcrops. The photographs were taken during morning light (8-10 am) from 50 feet across the highway. All photographs were taken from the same 50 feet distance and with 10 feet spacing intervals between each two consecutive photographs. The 10 feet spacing intervals were chosen to assure a 30 to 40% overlap between each consecutive pair of photographs. Then the photographs were stitched into one large panorama panel. Due to outcrops curvature, photographs were made into a photo mosaic using Adobe Photoshop CS6 software. These stitched photographs were added to another by using stitching software called Panoedit to construct one large high resolution outcrop panorama panel. The measured sections that were previously constructed were used to constrain the scale of each panel. The panels were later printed and used as a base map for mapping lithofacies distribution, sand body geometry and any other sedimentary structures that were observed within the study area outcrops in the field. The lithofacies that were previously identified in the measured sections were sketched on top of the photograph panels using Adobe Illustrator CS6 software to make lithofacies maps. These lithofacies maps illustrate the lithofacies distribution and lateral and vertical interrelationships in the study area outcrops. These lithofacies maps also illustrate sand body distribution, geometry and connectivity within the study area outcrops.

Fig. 12: Measured section example of the Sand Dominated Zone (i.e., the Barren Series) of the Raton Formation from the Cokedale 1 section 2 outcrop. Legends are in Appendix A.

2.1 Architecture element analysis

After mapping the lithofacies on the panorama base maps, architecture element analysis techniques were applied to the previously mapped sand body lithofacies. These architecture element techniques follow the principles of architectural element analysis that were proposed by Miall (1985; 1988; 1996) which were defined by the surface orders, surface shape, geometry, size, and lithofacies type within the bounding surfaces (Table 1). These architecture element techniques were applied by tracing all bedding surfaces on the base map and assigning to them a proper hierarchial order. These assigned orders follow the proposed guidelines of Holbrook (2001): 1) 1st order is assigned for bedding surface lamina; 2) lower order surfaces will be bounded by a higher order surface; 3) the bounding surface should be one order higher than the surface that it binds; 4) surfaces only truncate against surfaces with the same or higher order; 5) nested surfaces can be treated as a set of boundaries of the same order only if they are bounded by a higher order surface.

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

Table 1: Architectural elements hierarchy proposed by Miall (1985, 1988, 1996)

CHAPTER 3

DATA AND RESUALTS

3.1 Lithofacies assemblages description

Ten lithofacies assemblages were identified and described within the Sandstone Dominated Zone of the Raton Formation at Trinidad, Colorado. Each of these lithofacies assemblages contains specific depositional characteristics that record the environment in which they were deposited. The mudshale and clayshale lithofacies are the most dominant in the study area outcrops, followed by poorly developed paleosol, siltstone, laminated thinly-bedded sandstone and cross bedded sandstone lithofacies, respectively. Lithofacies assemblage descriptions and characteristics are illustrated in Table 2.

No.	Assemblage	Lithology	Characteristics	Biota	Environment
F1	Cross bedded sandstone	Medium to fine-grained sandstone	Medium to fine-scale trough and planar cross bedding, channel scours with mud rip-up	Leaves, stems and plants debris; top is rooted	Channel fill and bar
F2	Laminated sandstone	Medium to fine-grained sandstone interbedded with thin beds of mudshale	Medium to thin beds, laminated, tubular, rare scours (localized) to no scours; separated by very thin beds of mudshale		Terminal splays
F3	Laminated thinly bedded sandstone	Very fine sandstone interbedded with mudshale and clayshale	Thin, sheet, small ripples, extensive and widely spread.	Roots common	Channel wings
F4	Blocky siltstone	Dark grey to reddish color muddy siltstone interbedded with mud/clayshale	Siltstone: Reddish color, iron-rich (oxidized), blocky, structureless, lenticular bedding, pinching out Mud/clay shale: thinly laminated coarsening upward to siltstone	Heavily rooted	Crevasse splays, splay delta
F5	Laminated siltstone	Grey, interbedded with thinly laminated clay shale	Fine, thin bedded laminated, small ripples, pinching out	Heavily rooted	Distal delta, shallow lake deposits
F6	Poorly developed paleosol	Grey to yellow siltstone, mudshale and clayshale	Thin, poorly developed soil, oxidized; abundant concretions	Heavily rooted	Exposed splay deltas and lake deposits

Table 2: Lithofacies assemblage descriptions of the Barren Series of the Raton Formation at the Raton Basin.

Continued Table 2: Lithofacies assemblage descriptions of the Barren Series of the Raton Formation at the Raton Basin.

F7	Laminated clayshale	Grey to dark grey clayshale	Very fine-grained, thinly laminated, carbonaceous in some locations, generally thin	Rooting, small plant debris	Shallow lake deposits
F8	Laminated mudshale	Dark grey mudshale	Fine-grained, slightly thick laminated, varies in thickness, generally thick	Rooting, small plant debris	Lake deposits
F9	Carbonaceous mudshale	Dark grey to black mudshale	Carbonaceous (lignitic) with small coal chunks, slightly laminated to no lamination, very thin, extensive	Small plant debris	Shallow wetlands
F10	Coal	Black, bituminous to anthracitic coal	Generally very thin, thick in one location		Wetlands and swamps

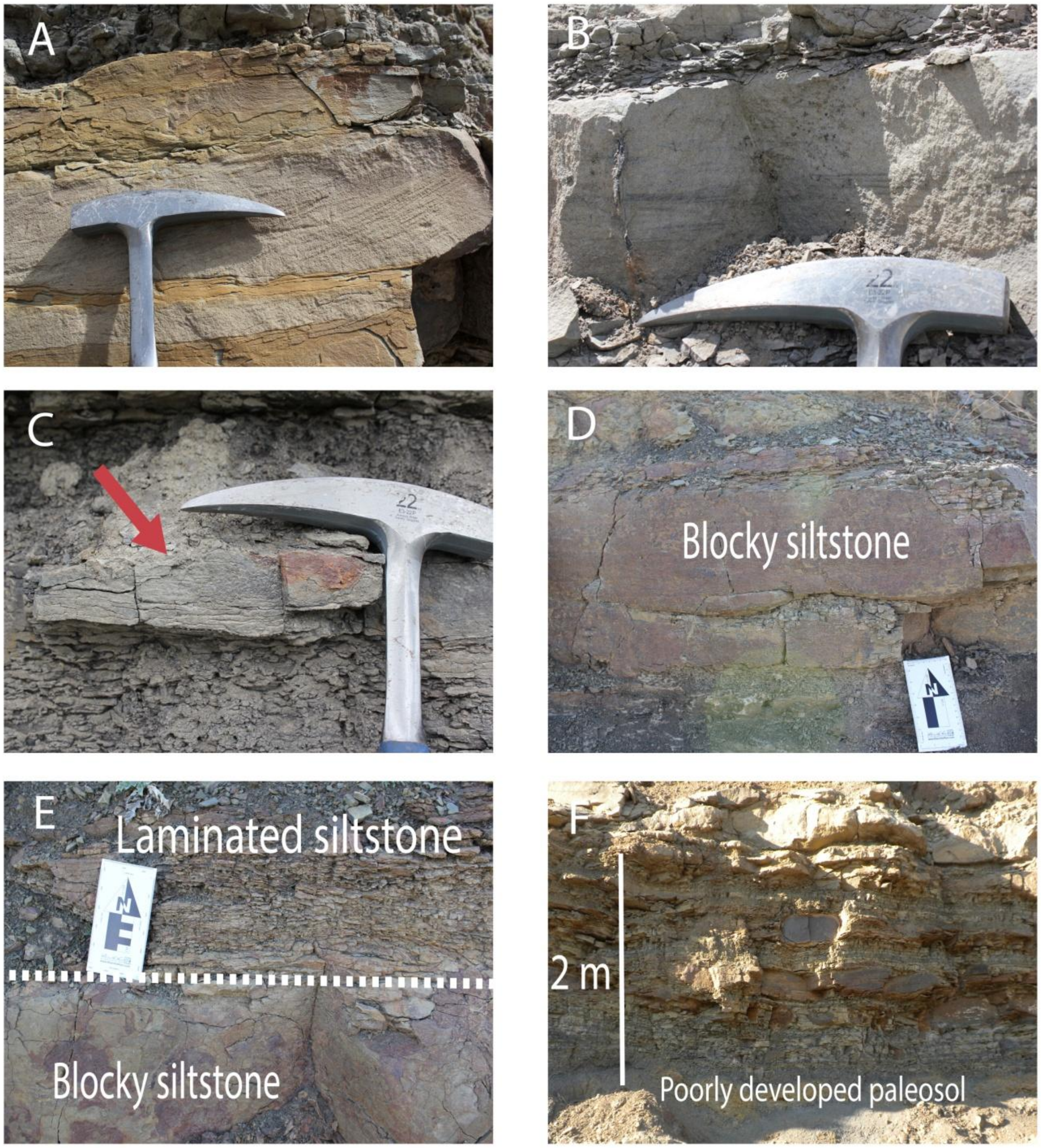
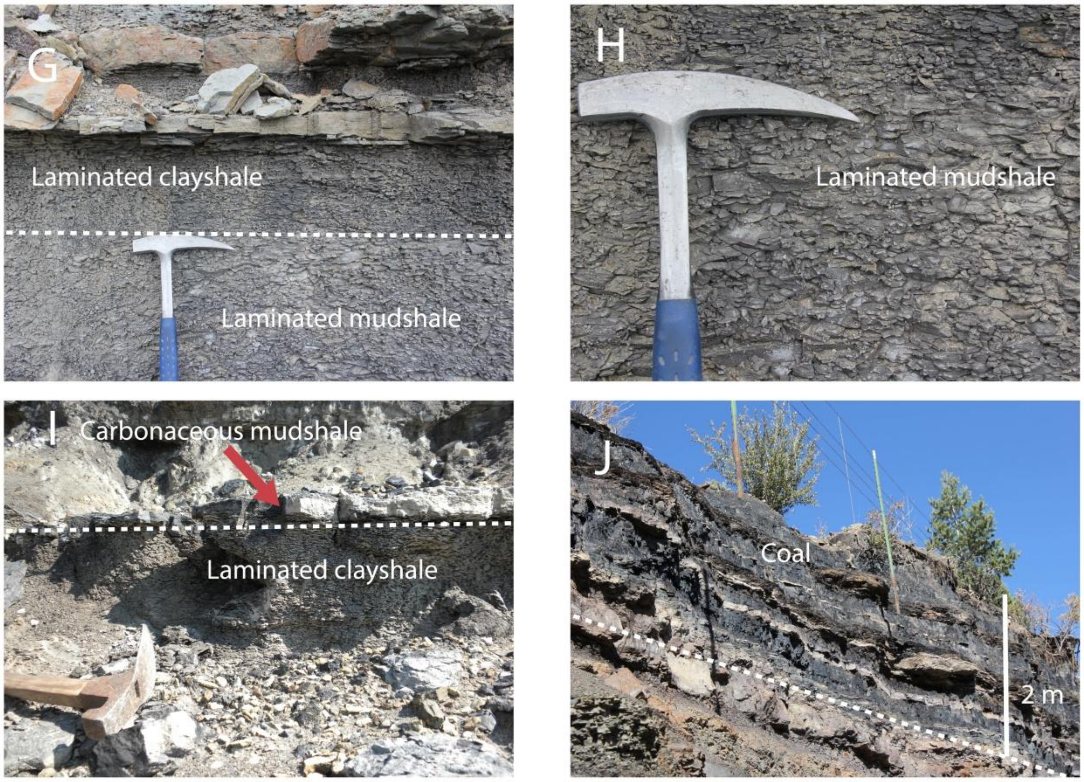


Fig. 13: Lithofacies assemblages in the Barren Series of the Raton Formation: A. Cross bedded sandstone. B. Laminated sandstone. C. Laminated thinly bedded sandstone. D. Blocky siltstone. E. Laminated siltstone. F. Poorly developed paleosol.



Continued Fig. 13: G. Laminated clayshale above the hammer. H. Laminated mudshale. I. Carbonaceous mudshale. J. Coal.

3.1.1 Cross bedded sandstone lithofacies assemblage (F1):

Description: The cross bedded sandstone lithofacies is trough cross-bedded, yellow to buff color, with medium to fine and medium to well-sorted quartz arenite beds. The cross-beds are trough and planar, and are medium to fine-scale. The base of the cross bedded sandstone lithofacies is incised into the underlying fine mudshale and clayshale deposits and contains mud rip-ups along the scour surface. Leaves, stems, upright tree stumps, wood, and plants debris are some of the commonly found fossils within the cross bedded sandstone lithofacies (Fig. 15). Leaves ranges in size from between a few centimeters to about 50 centimeters long, stems and plant debris are 2-5 centimeters only, whereas upright tree stumps and wood debris range between 30-120 centimeters. Rooting is very common in the cross bedded sandstone lithofacies and is mainly found at the top of beds. The vertical size of the rooting interval ranges from a few centimeters to a meter at some locations (e.g., Cokedale.1 and Cokedale.2) (Fig. 14). Bioturbation is not present in the cross bedded sandstone lithofacies and there are no evidence of any marine influence within the cross bedded sandstone lithofacies.

Interpretation: The cross bedded sandstone lithofacies is interpreted as an active channel fill and bar system. The presence of cross-bedding and the basal scours indicate high energy, lower regime flow conditions. The scours occur as a result of the inherited tendency of the fluvial system to concentrate the erosion processes at the river thalweg (Holbrook, 2001). The rip-up mud clasts at the channel thalweg represents the portion of the underlying fine deposits that were eroded during the channel incision. The presence of rooting and other plant fossils, and the lack of marine fossils within the cross bedded sandstone lithofacies, imply that this lithofacies was deposited in a terrestrial environment.

Fig. 14: Rooting in the cross bedded sandstone lithofacies at the Cokedale.2 outcrop.

Fig. 15: Floras in the Barren Series of the Raton Formation: wood logs, upright tree stumps, and leaves.

3.1.2 Laminated sandstone lithofacies (F2):

Description: The laminated sandstone lithofacies is a medium to fine-grained, well-sorted, parallel laminated, quartz arenite, interbedded with thin beds of thickly laminated mudshale. The beds of the laminated sandstone lithofacies are tubular and medium to thin in thickness. The laminated sandstone lithofacies is mainly found at the Valdez.1, Valdez.2A, and Valdez.2B outcrops. The thin beds of mudshale are rooted, oxidized, and contain small to medium size concretions. Impressions of leaves, stems, upright tree stumps, wood logs, and plant debris are very common within the laminated sandstone lithofacies (Fig. 15). There is no evidence of bioturbation or marine influence within the laminated sandstone lithofacies.

Interpretation: The laminated sandstone lithofacies is interpreted as terminal splays, generally defined as ephemeral fluvial deposits that terminate as a fan shape near the distal zone of the fluvial system (Lang et al., 2004; Amos et al., 2010). The terminal splays are divided into two categories: confined and unconfined terminal splays (Lang et al., 2004). Confined terminal splays consists of a well-established channelized system in the upstream part of fluvial systems and consist of sheeted-like splay lobes in the downstream distal areas. Unconfined terminal splays are similar to the distal part of confined terminal splays, which are dominated by sheeted-like splay lobes (Lang et al., 2004). Laminated sandstone lithofacies were deposited as a part of the unconfined terminal splays in the downstream parts of an axial fluvial system. The presence of concretions and oxidation within the mudshale deposits indicates that these deposits were exposed to soil formation processes, but not for long enough to form a mature paleosol.

The presence of leave remains, tree stumps and rooting indicates a terrestrial depositional environment. Alternation between the tubular sandstone beds and the mudshale beds record repeated cycles of flooding events that transported the coarser-grained sand further downstream. The coarser-grained sand was later deposited in the upper flow regime as tubular planar sandstone beds on top of the flood basin fine deposits (Harms and Fahnestock, 1960; Harms et al., 1963; Rigby and Hamblin, 1972; Bridge et al., 2000)

3.1.3 Laminated thinly bedded sandstone lithofacies assemblage (F3):

Description: The laminated thinly bedded sandstone lithofacies assemblage consists of very fine-grained, clean, well-sorted, thin tubular planar, quartz arenite beds interbedded with laminated mudshale and clayshale beds. The tubular planar beds of the laminated thinly bedded sandstone lithofacies are slightly parallel laminated with the presence of small size ripples at the top of the beds. Rootings are very small in size and uncommon within the laminated thinly bedded sandstone lithofacies. The presence of other fossils within the laminated thinly bedded sandstone lithofacies is very limited. The laminated thinly bedded sandstone lithofacies in the study area outcrops extends from both sides of the channel-fill bodies and spreads away as sheeted-like sand bodies over the flood basin deposits (i.e., the mudshale and clayshale deposits). Despite being thin, these tubular planar beds are very extensive and widely spread, and reach more than 10 times their main channel width. It is difficult to determine the actual extent of these tubular planar beds in the study area as they intertongue with other sandstone sheets, are incised by other channels, and pinch-out into flood basin deposits, and/or extend beyond the outcrop limit. The laminated thinly bedded sandstone lithofacies is mainly found at the Cokedale.1 and Cokedale.2 outcrops.

Interpretation: The laminated thinly bedded sandstone lithofacies is interpreted as channel wing deposits which are thin, wedge-shaped, fine sheeted sand beds that extend laterally from the main channel sides to the top of levees and flood basin. Wings may represent the wide topmost part of the channel story (Friend et al., 1979; Friend, 1989; Hirst, 1991; Gibling, 2006) or may represent splays from the main channel to the levees during high water stages (Bridge et al., 2000; Gibling, 2006). The presence of parallel lamination and small sized-ripples within the channel wings indicate that these wings were deposited in the lower flow regime. The lack of soil development, and rooting within the laminated thinly bedded sandstone lithofacies indicate that the water level was at or slightly higher than the ground level during deposition (i.e., a high-accommodation, poorly-drained flood basin condition).

3.1.4 Blocky siltstone lithofacies (F4):

Description: The blocky siltstone lithofacies is fine-grained, dark grey to reddish color, muddy lenticular siltstone interbedded with thickly laminated mudshale and thinly laminated clayshale. The blocky siltstone lithofacies is structureless, iron-rich (oxidized) and heavily rooted. The rootings are large in size and abundant in the blocky siltstone lithofacies. The beddings in the blocky siltstone lithofacies are lenticular, onlapping and, pinching-out into the flood basin fine deposits. The contact between the siltstone and the mudshale and the clayshale is gradual and coarsens upward from thinly laminated clay shale to mudshale to siltstone. The blocky siltstone lithofacies is predominantly found at the Cokedale.1 and Cokedale.2 outcrops.

Interpretation: The blocky siltstone lithofacies is interpreted as a crevasse-splays or levees environment. The rich iron oxides content within the blocky siltstone lithofacies indicates that deposition occurred during a wet season in high-accommodation, medium to poorly drained flood basin conditions. During these conditions, the water table was high and vegetation helped in leaching iron from the soil, forming the iron oxides (Zaleha, 1997; Bridge et al., 2000). The depth of rooting into the entire thickness of the blocky siltstone lithofacies indicates subaerial exposure after the lithofacies deposition, which allowed plants with large roots to grow on top of the deposits. The geometry, hetrolithic lithology, and affiliation with mudflat deposits argue for coarser overbank deposition and splay development.

3.1.5 Laminated siltstone lithofacies (F5):

Description: Medium to fine-grained, thinly laminated, slightly rippled, light grey siltstone beds interbedded with thinly laminated clayshale beds. The lamination within the laminated siltstone lithofacies is thin with barely visible small ripples. The laminated siltstone lithofacies beds are thin, lenticular, and pinching-out into the flood basin deposits. Rooting is uncommon within the laminated siltstone lithofacies and upper and lower contacts are gradational. The laminated siltstone lithofacies mainly overlies lithofacies (F4) and is gradually fining-upward to thinly laminated clayshale.

Interpretation: The laminated siltstone lithofacies is interpreted to be deposited within a shallow lake or distal delta environment. The presence of silt size sediments, the thin lamination within the siltstone, and the small ripple size imply that water current during deposition was weak and water level was relatively shallow. The presence of the clayshale lamination, and the lack of rooting and bioturbation indicate that the laminated siltstone lithofacies beds were deposited subaqueously into a flood basin lake. The interbedding between the siltstone and the thinly laminated clayshale deposits indicates a progradation of crevasse-splays into the flood basin lake.

3.1.6 Poorly developed compound paleosol (F6):

Description: Grey to yellow, weakly developed, oxidized beds that consists of reworked siltstone, mudshale and clayshale. Sedimentary structures within the poorly developed compound paleosol are absent and only a small portion of the old original deposits sedimentary structures are preserved. The thickness of the poorly developed compound paleosol varies from one outcrop to another and ranges from 20 centimeters to more than 2.5 meters. The poorly developed compound paleosol is thicker at the Valdez.1, Valdez.2A, and Valdez.2B outcrops, whereas it is thinner and uncommon at Cokedale.1, Cokedale.2. Rooting is very abundant within the poorly developed compound paleosol and upright tree stumps and wood debris are very common. Concretions are also found in the poorly developed compound paleosol and vary in diameter from 10 centimeters to 1 meter. The poorly developed compound paleosol is found as bands in the topmost part of crevasse splays, terminal splays and the fine-grained lake deposits.

Interpretation: This lithofacies is interpreted as a poorly developed compound paleosol. The presence of a poorly developed compound paleosol on the top of the crevasse splay and lake deposits indicates a dropping in the lake water level that led to exposure of these deposits to soil-forming processes. The presence of rooting indicates that these deposits were subaerially exposed allowing vegetation to grow on top. The presence of iron oxides and concretion development indicates a shifting between the wet and dry seasons. The presence of iron oxides represents a wet season (Zaleha, 1997; Bridge et al., 2000), whereas concretions form when ground water evaporates during the dry season (Zaleha, 1997). The lack of well-defined soil horizons indicates that deposits of the poorly developed compound paleosol were exposed to soil-forming processes for a short period of time, which prevented the mature development of the paleosol.

3.1.7 Laminated clayshale lithofacies (F7):

Description: Very fine-grained, grey to dark grey, thinly parallel laminated clayshale. The laminations are barely visible and poorly developed. The presence of rooting and small plant debris is very common within the laminated clayshale lithofacies, especially at the Cokedale.1 and, Cokedale.2 outcrops. The thickness of the laminated clayshale lithofacies varies and ranges from 13 to 30 centimeters.

Interpretation: The laminated clayshale lithofacies is interpreted as deposits formed in a shallow lake environment. The fine-grained size and the thin laminations indicate deposition within a low energy water flow that allowed the fine clay size sediments to settle out from suspension. The sparse presence of roots and plant debris indicate a periodic shallow water level during or directly after deposition.

3.1.8 Laminated mudshale lithofacies (F8):

Description: The laminated mudshale lithofacies consists of fine-grained, dark grey, thickly laminated mudshale fining upward and gradually changing to the thinly laminated clayshale lithofacies (F7). The thickness of the laminated mudshale lithofacies ranges from 5 centimeters to 3 meters. In general, the laminated mudshale lithofacies is thicker at the Cokedale.1 and, Cokedale.2 outcrops and thinner at the Valdez.1, Valdez 2A, and Valdez.2 B outcrops. Rootings and plant debris are rare within the laminated mudshale lithofacies and are mainly found in the topmost of the beds.

Interpretation: The laminated mudshale lithofacies deposits are also interpreted as formed in a lake environment. The difference between the laminated mudshale lithofacies and the previous laminated clayshale lithofacies is that the laminated mudshale lithofacies is deposited in relatively more distal waters. The gradual change from laminated mudshale lithofacies to the previous facies (F6) is due to lake level drop during the time of deposition.

3.1.9 Carbonaceous mudshale lithofacies (F9):

Description: The carbonaceous mudshale lithofacies is fine-grained, very dark grey to black color, slightly thinly laminated, carbon-rich (lignitic), mudshale. The laminations are very thin and can only be seen by using a magnifying lenses. The carbon content within the carbonaceous mudshale lithofacies is mainly lignite with small chucks of anthracitic coal. The carbonaceous mudshale lithofacies beds are very thin but very extensive and wide spread, especially at the Cokedale.1 and Cokedale.2 outcrops.

Interpretation: The carbonaceous mudshale lithofacies is interpreted to be deposited in a wetland environment. The high percentage of carbon content within the carbonaceous mudshale lithofacies beds implies that the water table level stayed high for a period of time long enough to form high-accommodation, poorly drained flood basin conditions. The presence of mudshale deposits within the carbonaceous mudshale lithofacies beds indicates that the high-accommodation, poorly drained system had fine-grained sediment input during deposition, which mixed with the carbonaceous material. The lack of thickness of the carbonaceous mudshale lithofacies beds indicates that these conditions did not last for a sufficient time to form thicker carbon-rich deposits.

3.1.10 Coal lithofacies (F10):

Description: The coal lithofacies consists of black color, compacted, bituminous to anthracitic coal beds whose thickness varies from a few centimeters to three meters. The thickest coal beds are at the Valdez.1 outcrop.

Interpretation: The coal lithofacies was deposited in a high-accommodation, poorly drained flood basin environment such as found in swamps and wetlands and where the water table level stayed high enough above the ground level for a period of time long enough to allow coal to be deposited.

3.2 Architectural element analysis

The Sandstone Dominated Zone of The Raton Formation at Trinidad, Colorado represents two architectural assemblages and one architectural association of assemblages which are: the flood basin assemblage, the channel-belt assemblage, and the valley-fill association, respectively. The flood basin assemblage is divided into two categories based on the drainage conditions which are: the well-drained and the poorly-drained flood basins. The well-drained flood basin category is more abundant at Valdez.1, Valdez.2A, and Valdez.2B. The poorly-drained flood basin category is mainly found at the Cokedale.1 and Cokedale.2 outcrops. The characteristics and distinction between well-drained and poorly-drained flood basins were previously discussed in this study.

3.2.1 The flood basin assemblage:

3.2.1.1The poorly-drained flood basin:

3.2.1.1.1 The laminated fines element:

Description: The laminated fines element is the most dominant in the study area outcrops, especially at Cokedale.1 and Cokedale.2 where it covers about 75% of the outcrop areas. The laminated fines element is composed of laminated clayshale (F7), and laminated mudshale (F8) lithofacies. The laminated fines element is very extensive and widely spread in the study area outcrops. At Cokedale.1 and Cokedale.2, the thickness of this element varies from 13 centimeters to 3 meters. At Valdes.1, Valdez.2A, and Valdez.2B, the thickness of the laminated fines element is between 25 centimeters to 1.3 meters. The laminated fines element contains bands of poorly developed compound soil horizons. At Valdes.1, Valdez.2A, and Valdez.2B, these poorly developed compound soil horizons are more abundant and thicker, whereas they are less abundant and thinner at Cokedale.1 and Cokedale.2. The contact between the laminated fines element and the surrounding elements varies from gradual to sharp. At the Cokedale 1 and Cokedale.2 outcrops, the contact gradually changes from laminated clayshale (F7) and laminated mudshale (F8), to carbonaceous mudshale (F9) and coal (F10) lithofacies, whereas it gradually changes to a poorly developed compound paleosol at Valdez.1, Valdez.2A, and Valdez.2B. The sharp contacts at both the Cokedale and Valdez outcrops are with the cross bedded sandstone (F1), laminated sandstone (F2) and, laminated thin bedded sandstone (F3) lithofacies.

Interpretation: The laminated fines element records deposition in a relatively shallow lake environment, alternating to a poorly-drained flood basin mudflat that is located in a generally poorly-drained flood basin. Lamination within the fine-grained deposits indicates that the water level was high for a long period of time and the system lacked a supply of coarse sediments. The lack of a coarse sediment supply allowed the fine laminated deposits to settle out freely from suspension and be deposited in the shallow lake environment. The variation in thickness, the gradual facies change, and the lamination within the laminated fines element indicate a fluctuation in lake level and a periodic change in drainage conditions. The orientation and the increase in lamination size within the laminated fines element deposits indicate a rising in lake level and more poorly-drained conditions during deposition (i.e., at Cokedale.1 and Cokedale.2). The presence of compounded paleosol horizons and rooting on top of the previous poorly-drained deposits indicate a lowering in lake level and more well-drainage conditions occurring during deposition (i.e., at Valdez.1, Valdez.2A, and Valdez.2B).

3.2.1.1.2 The carbonaceous flood plain fines element:

Description: The carbonaceous flood basin fine element (FF element of Miall, 1985; 1996) is composed of the carbonaceous mudshale (F9) and coal (F10) lithofacies. The carbonaceous flood basin fine element is found in both the Cokedale and Valdez outcrops. The carbonaceous flood basin fine element is very extensive and spread throughout the extent of the outcrops. The thickness of the carbonaceous flood basin fine element is very thin at the Cokedale.1, Cokedale.2, Valdez 2A, and Valdez.2B outcrops. The contact between the carbonaceous flood basin fine element and the underlying elements at the Cokedale.1, Cokedale.2, Valdez 2A, and Valdez.2B outcrops gradually changes from laminated clayshale (F7) and laminated mudshle (F8) lithofacies to carbonaceous mudshale (F9) lithofacies. The thickness of the carbonaceous flood basin fine element at Valdez.1 is thicker than the element at Cokedale.1, Cokedale.2, Valdez 2A, and Valdez.2B and ranges from 1.3 to more than 2.5 meters. The carbonaceous flood basin fine element at Valdez.1 overlies the blocky siltstone (F4) lithofacies with a sharp contact.

Interpretation: The carbonaceous flood basin fine element represents deposition in a higher degree of drainage within a poorly-drained flood basin setting compared to the previous elements (i.e., the laminated fines element). The high organic content in the carbonaceous flood basin fine element (e.g., peat and coal) indicates a long period of standing water conditions environments such as swamps or ponds (Miall, 2006) that are found in a poorly-drained flood basin. The gradual change of the lithofacies and thickness in the carbonaceous flood basin fine element indicates a fluctuation in drainage degree during deposition, but retention within high-accommodation poorly-drained conditions. Similar characteristics of the wide extensive carbonaceous flood basin fine element have been noted in several other studies (e.g., Willis and Behrensmeyer, 1994, 1995).

3.2.1.1.3 The crevasse splays/splay delta element:

Description: The crevasse splays/splay delta element (CS of Miall, 1996) consists of a blocky siltstone (F4) and, laminated siltstone (F5) lithofacies. The crevasse splays/splay delta element is predominantly found at the Cokedale.1 and Cokedale.2 outcrops. The crevasse splays/splay delta element bounds the lamina sets (1st, 2nd and 3rd order) by a 4th order bounding surfaces (Miall, 1996; Currie et al., 2009). The crevasse splays/splay delta element is formed of beds that are lobate, lenticular sheeted-like and that onlap each other and pinch-out in the flood basin and lake deposits (Miall, 1996). The crevasse splays/splay delta element ranges in thickness from between 20 to 50 centimeters. The width of the crevasse splays/splay delta element is very difficult to determine due to the lapping and interfingering relationship between each splay unit. Generally in the study area outcrops, the crevasse splays/splay delta element width is estimated to be at least 20 times its own unit thickness. The crevasse splays/splay delta element is more abundant at the Cokedale.1 outcrop where at least 50 of these crevasse splays were recorded. At Cokedale.2, only 20 crevasse splays units were recorded in the topmost part of the outcrop. The crevasse splays/splay delta element is generally associated with the laminated fines element with a gradationally and coarsening-upward contact (Fig. 16).

Interpretation: The crevasse splays/splay delta element represents delta-like deposits that are found near the main channel margins (Miall, 1996). These deltas-like deposits were flushed into the flood basin and/or the flood basin lake by crevasse channels and laid down as sheeted-like deposits (e.g., Farrell, 1987; Platt and Keller, 1992). The distinction between crevasse splays and a lacustrine splay delta are very difficult to determine (Miall, 1996) due to their similar characteristics, which led to considering them as one element in this study. The lack of basal incision into the underlying fine deposits, and the presence of parallel laminations within these deposits, indicate that the crevasse splays/splay delta element is deposited by low energy flow when the flow loses its power once it has left the confinement of the main channel. The gradual change in the crevasse splays/splay delta element lithofacies indicates a relative increase in water level and a decrease in the flow strength during deposition which permits fine flood basin/lake deposits to overlie the crevasse splays/splay delta element deposits.

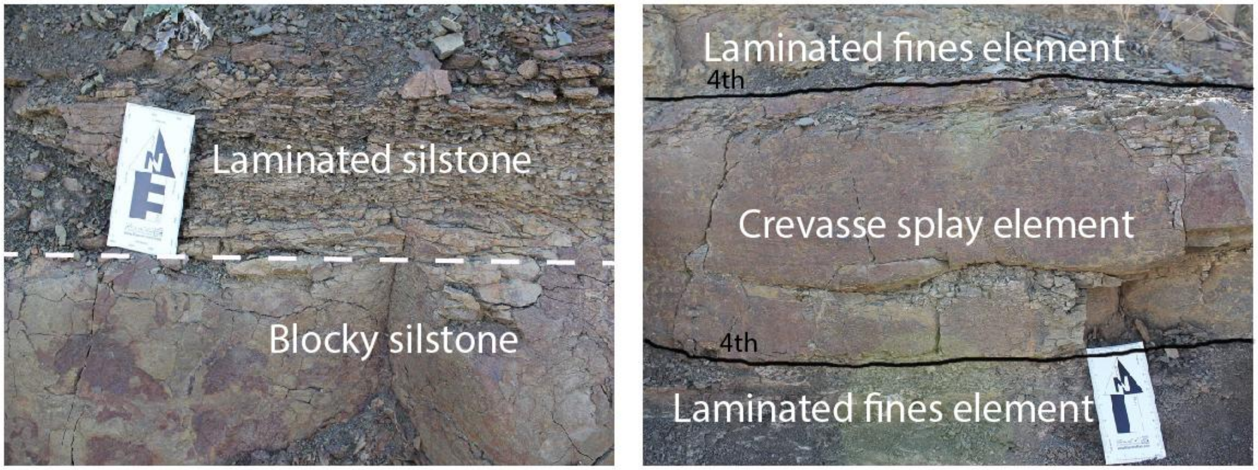


Fig. 16: The crevasse splay/delta splay element deposits at Cokedale.1.

3.2.1.2 The well-drained flood basin:

3.2.1.2.1 The laminated sand sheet element (LS):

Description: The laminated sand sheet element (LS of Miall, 1985) (Fig. 17 and Fig. 18) are mainly composed of the laminated sandstone lithofacies (F2). The laminated sand sheet element is found only at the Valdez.1, Valdez.2A, and Valdez.2B outcrops where they occupy about 70% of the outcrops cross sectional area. The laminated sand sheet element is a 4th order bounding surface, bounding 1st, 2nd and 3rd order surfaces within it (Miall, 1996). The laminated sand sheet element beds are tubular planar, and range in thickness from 16 to 60 centimeters. These tubular planar beds are amalgamated in several locations at the study area outcrops to form extensive composite sheeted-like beds that extend beyond the length of the outcrops. The basal bounding surface (i.e. the 4th order bounding surface) is relatively flat with no to very minimal scouring. The laminated sand sheet element is mainly associated with poorly-developed paleosol deposits, and the laminated fines element (i.e., (F7) and (F8) lithofacies).

Interpretation: The laminated sand sheet element represent deposition within a terminal splay delta environment at the distal and near distal zones of a DFS system (e.g., Sneh, 1983; Tunbridge, 1984; Amos et al., 2010).The presence of parallel laminations within the laminated sand sheet element beds, and the lack of basal scouring indicates that the deposition occurred by an ephemeral stream in the upper flow regime (Miall, 1977; Sneh, 1983; Tunbridge, 1984). The association of the laminated sand sheet element beds with a poorly-developed paleosol, and laminated fines element deposits implies a waning flow condition at the end of an ephemeral flood event (Miall, 1996; Bridge, 2003). The thickness change in the laminated sand sheet element beds represents the distance from which each beds were deposited away from the main splay channel. The further the propagation of the deposits towards downstream, the thinner the beds will be. The characteristics of the laminated sand sheet element is well documented in the literature and many similar examples have been observed in ancient and modern fluvial systems deposits (e.g., Hurbert and Hyde, 1983; Tunbridge, 1984; Olsen, 1987).

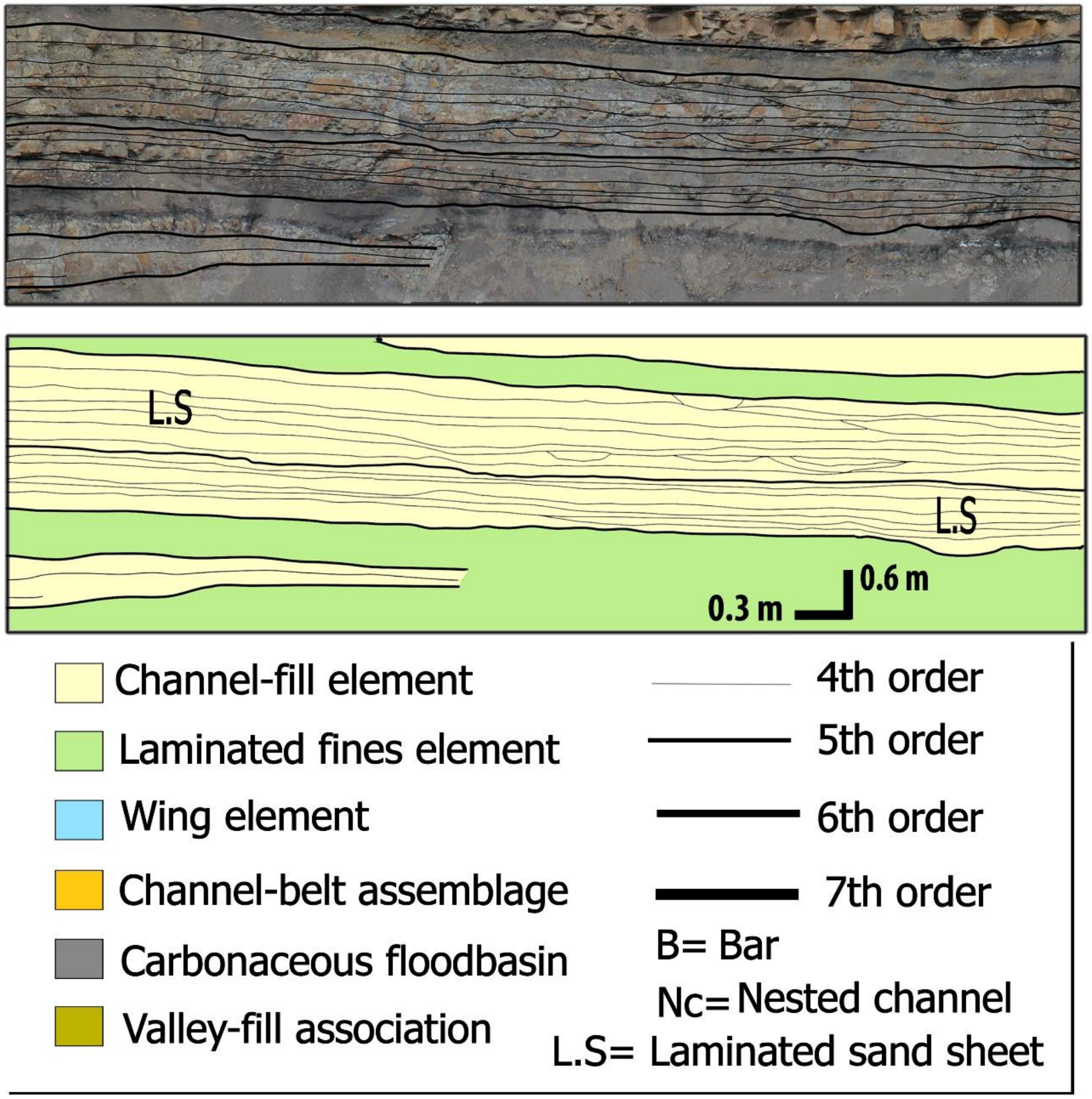


Fig. 17: Channel-fill element bounding laminated sand sheet element, Valdez.2A.

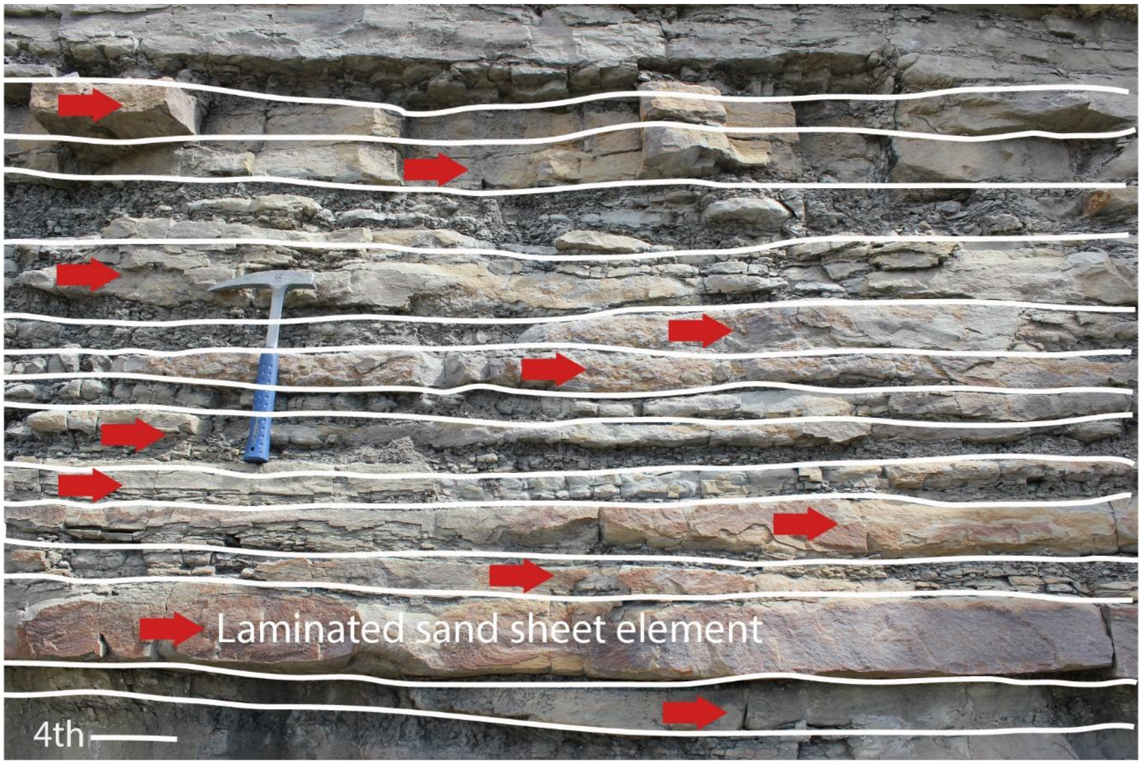


Fig. 18: The laminated sand sheet element deposits, Valdez.2A

3.2.2 The channel-belt assemblage:

The channel-belt assemblage (Fig. 19) includes channel-fill elements, nested channel cuts elements, bar elements, and wing elements. In study area, the channel-belt assemblage is bound by a 6th order bounding surface, with 5th order bounding surfaces of a channel-fill element (Miall, 1996). The channel-belt assemblage consists of 3-8 channel-fill elements amalgamated into one large and widely extensive sand body bed. These channel-fill elements are vertically stacked where the upper channel stories scour into the lower channel stories forming a channel-belt element (e.g., Holbrook, 2001).These amalgamated sand bodies beds are formed when the flood basin fails to aggrade more than one channel-belt prior to avulsion return to the same spot (Miall, 1996; Holbrook, 2001). The channel-belt assemblage is interpreted to be deposited during low-accommodation conditions where deposition occurs above water level. Channel-belt assemblage deposits are characterized by an abundance of coarse-grained sediments with a significantly lesser quantity of fine sediments and coal (Catuneanu, 2006). The lower bounding surface of a channel-belt assemblage is an erosional surface which is incised into the underlying fine flood basin deposits. Five channel-belt assemblages were identified in the study area outcrops: at the top of Cokedale.1, at the base and the top of Cokedale.2, at the tops of Valdez.2A and Valdez.2B. The exact thickness and width of these channel-belt assemblages are difficult to determine as they are buried under the outcrop exposure, eroded and/or extend laterally beyond the outcrops limits. The thickness of the channel-belt assemblage is estimated to be between two to more than three meters, whereas the width can reach more than 10's of meters beyond the study area outcrops. The internal architecture of channel-belts assemblages is difficult to determine due to the outcrops condition especially near the base and the top (e.g., heavily weathered, rock fall, sediment slumps, talus) and because only a few partial surfaces of the channel-fill element were preserved.

Fig. 19: Channel-belt assemblage containing channel-fill elements, Cokedale.1

3.2.2.1 The nested channel cuts element:

Description: The nested channel cuts element (Holbrook, 1996a; Holbrook, 2001) consists of several small size amalgamated scours within the channel-fill element. The nested channel cuts element is composed of the cross-bedded sandstone (F1) and laminated sandstone (F2) lithofacies (Fig. 19). The nested channel cuts element is very common in the channel-fill element. The nested channel cuts element bounds 1st, 2nd and 3rd order bounding surfaces by a 4th order bounding surface (Holbrook, 2001). The 4th order bounding surfaces are convex-upward and cross-cut each other within the channel-fill element. The nested channel cuts element ranges in thickness from between 15 to 45 centimeters. The nested channel cuts element is found only at Valdez.1 and Valdez.2A. At Valdez.1, these small scours are very scarce (less than 15 scours) and isolated, whereas they are more clustered and amalgamated in several spots at Valdez.2A (Fig. 19).

Interpretation: The shape and orientation of the bounding surfaces indicate that the nested scours were formed as a result of a series of cut and fill stages due to discharge fluctuation. The cutting happens during the high discharge and deposition occurs during the waning flow periods (Hopkins, 1985; Kirschbaum and McCabe, 1992; Hoorn, 1994; Holbrook, 1996a; Martinsen et al., 1999; Holbrook, 2001). The nested channel cuts element is very common in channel-fills and represents low-accommodation system deposits (e.g., Hopkins, 1985, Hoorn, 1994, Martinsen et al., 1999; Holbrook, 2001). The dipping surfaces within the nested channel cuts element indicate the direction of bars migration. Bars within the nested channel cuts element are partially preserved due to the episodes of cutting and filling during discharge fluctuation and only the bar base is preserved within the nested channel cuts element. Similar characteristics have been observed by Holbrook (2001) in Middle Cretaceous strata in Colorado.

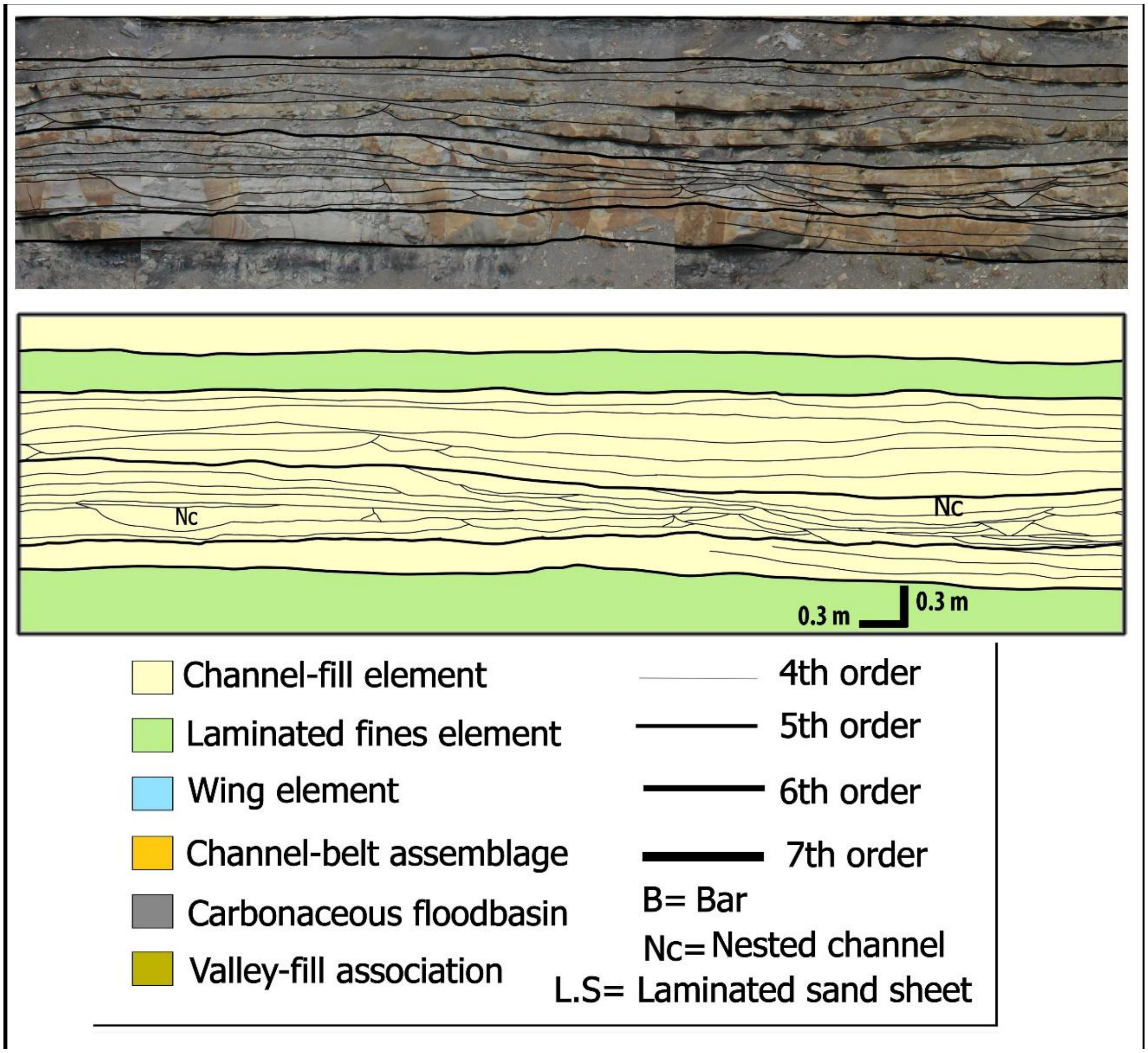


Fig. 20: Channel-fill element bounding nested channel scours element, Valdez.2A.

3.2.2.2 The bar element:

Description: The bar element is composed of the cross-bedded sandstone (F1) and laminated sandstone (F2) lithofacies (Fig. 20). The bar element bounds 1st, 2nd and 3rd order surfaces of laminae, laminae sets, and co-set, respectively, by a 4th order bounding surface (Miall, 1996). These bounding surfaces within the bar element are dipping towards the channel migration direction. The lower bounding surface of the bar element is erosional and cuts into the top of the underlying older bar. Due to the previous erosional process, only the base of the bars will be preserved and form a composite bar unit that consists of three or more stacked partially preserved bars. The bar element is found within channel-fill elements at both the Cokedale and Valdez outcrops. At Cokedale.1 and Cokedale.2, unit bars range in thickness between 22 to 32 centimeters. The composite bar in Cokedale.1 and Cokedale.2 consists of 3-4 stacked unit bars which range in thickness between 61 to 123 centimeters. There are two composite bars at Cokedale.1 and four at Cokedale.2. At the Cokedale.1 and Cokedale.2 outcrops, the bar element is overlain and underlain by a flood basin fine element (i.e., laminated clayshale (F7) and laminated mudshale (F8)). At Valdez.1 and Valdez.2A, the bar element ranges from 31 to 95 centimeters. The composite bar unit at Valdez.1 and Valdez.2A ranges in thickness from 1.5 to 2 meters. The bar element at Valdez.1 and Valdez.2A is overlain and underlain by a poorly-developed compound paleosol facies (F6). There are three composite bar units at Valdez.1 and only one at Valdez.2A.

Interpretation: The bar element consists of sets of large scale inclined strata that formed due to the downstream migration of dunes and ripples during high energy flow periods (Smith, 1970, 1972; Collinson, 1970; Cant and Walker, 1978; Bridge, 1993; Bridge and Tye, 2000; Lunt et al. 2004). The presence of laminae, laminae sets, and a co-set within the bar element bounding surfaces, the dipping of bounding surfaces along with the bar basal erosional scour indicate bar building by accretion processes due to energy loss in the flow regime (Bridge et al., 2000; Bridge, 2003).

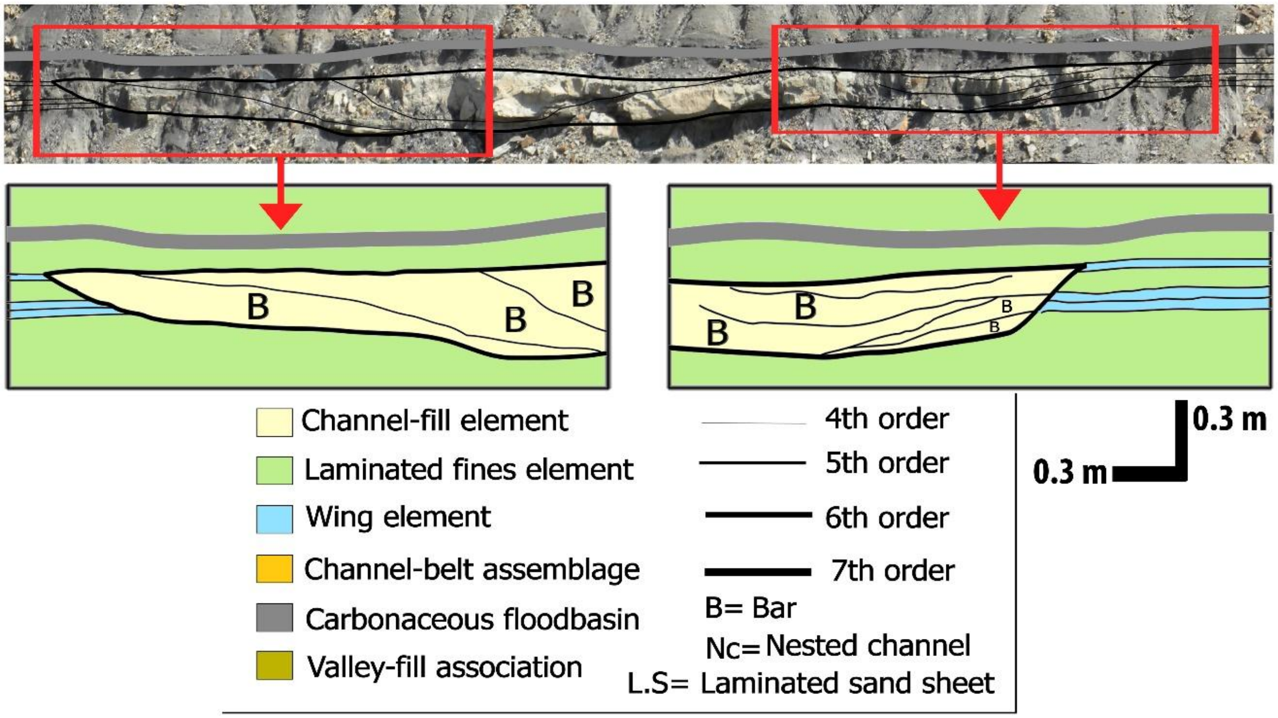


Fig. 21: Channel-fill element bounding the bar elements, Cokedale.2.

3.2.2.3 The wings element:

The wings element is a sheeted-like ribbon of sandstone beds (Eberth and Miall, 1991; Currie et al. 2009; Ghazi and Mountney, 2009). In the study area, the wings element consists of laminated thin bedded sandstone (F3) lithofacies. The wings element ranges in thickness between 10 to 26 centimeters. The wings element bounds the 1st, 2nd and 3rd order surfaces by a 4th order bounding surface. The basal bounding surface is relatively flat and non-erosive. The width of each individual wing element is very difficult to determine due to their tendency to interfinger with each other forming a sheet that consists of two to four interfingered wings. The wing element is mainly associated with the channel-fill and flood basin fines elements. At Cokedale.2, there are at least 25 bands of channel wings that vary in width from three to 16 meters. These wing elements extend at least 10 times their own channel width and extend beyond the outcrop limits. Many of these wings elements have been incised by thin channel-fill elements (four to five channel-fills at Cokedale.2).

Interpretation: The wings element is composed of thin, wedge shaped, fine sheeted sand beds that extend laterally from the wide topmost level of the main channel sides into the top of channel levees and the flood basin during the main channel high water stages (Friend et al., 1979; Friend, 1983; Hirst, 1991; Reading, 1996 Gibling, 2006) (Fig. 22 and Fig. 23). During high water stages (e.g., flooding) when water level exceeds channel capacity, sediments will splay out from the main channel over the low relief levees, flood basin, and flood basin lakes forming the wings element deposits (Bridge et al., 2000; Gibling, 2006). The lack of sedimentary structures and the lack of soil development in the underlying fine deposits indicate that the wings element was splayed over a flood basin shallow lake where the water level was slightly higher than the water table level within high-accommodation, poorly-drained flood basin conditions. The traces of rooting at the top of the wings element also backs the presence of shallow water conditions during deposition. The wings element can be easily confused with the crevasse splays/splay delta element because of their similar characteristics. Despite their similarities, the differences between the wings element and the crevasse splays/splay delta element can be distinguished because the wings element consists mainly of clean, well-sorted sandstone beds, whereas the crevasse splays/splay delta element consists of deposits of more silt and fine sediment. Rooting are rare and very small within the wings element, whereas the crevasse splays/splay delta element is characterized by the abundant presence of rooting. The contact between the underlying fine-grained deposits and the wing element is sharp, whereas the contact between the crevasse splays/splay delta element with the underlying deposits is gradual. Also, the wings element is more extensive and wide spread than the crevasse splays/splay delta element.

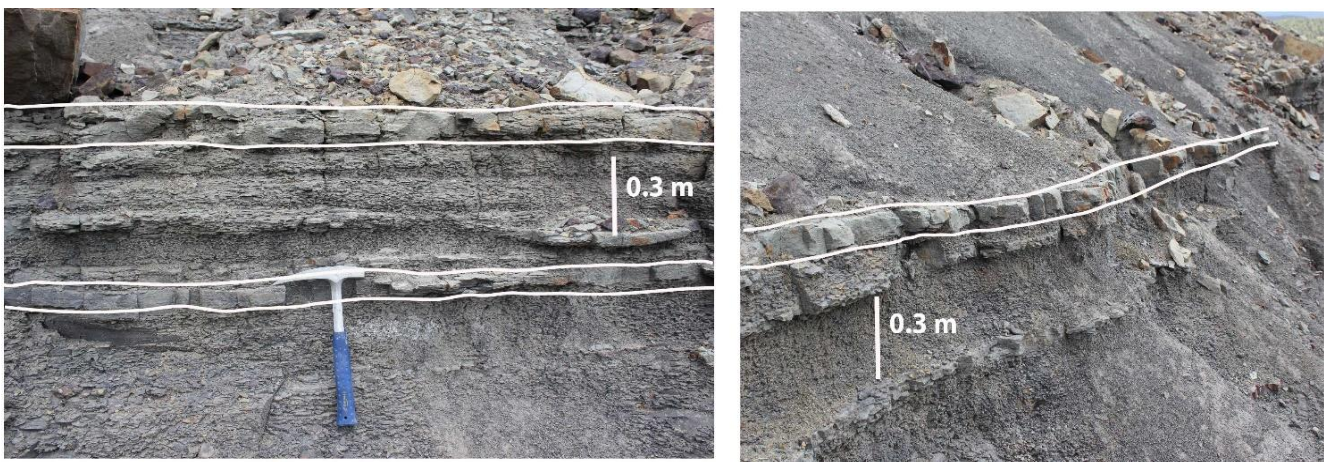


Fig. 22: The wings element deposits, Cokedale.2.

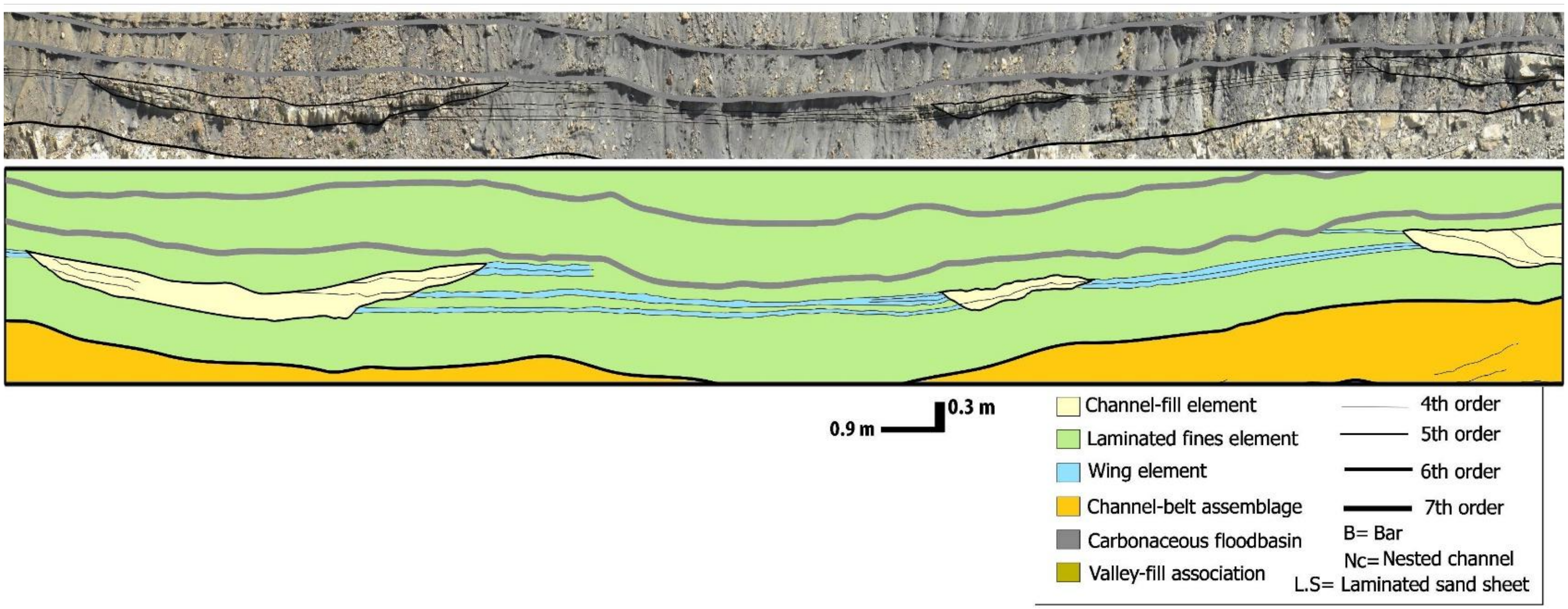


Fig. 23: Architecture of the wings element, Cokedale.2. Figure has been vertically exaggerated to illustrate wings geometry.

3.2.2.4 The channel-fill elements:

Description: The channel-fill element (Miall, 1985; Miall, 1996) consists of smaller scale elements of the bar element, nested channel cuts element, and laminated sand sheet element. The channel-fill element is composed of cross-bedded sandstone (F1) and laminated sandstone (F2) lithofacies, is characterized by a concave-up erosional base, and is generally fining upward (Miall, 1985, Miall, 1996). In the study area outcrops, the erosional base is incised into flood basin fines and into other channel-fill elements. The channel-fill element bounds the 4th order surfaces of bar element, nested channel cuts element, and laminated sand sheet element by a 5th order bounding surface (Miall, 1996). In the study area outcrops, the fining upward within the channel-fill element was not seen and only the coarser portions of the channel fills were preserved.

Interpretation: The channel-fill element is referred to the filling of the channel without any changes in its perimeters during the avulsion and abandonment events (Holbrook, 2001; Gibling, 2006). The basal concave-up erosional surface is formed during a high energy flow event (Bluck and Kelling, 1963; Readning, 1996; Miall, 2014). Channel scours filled during the abandonment events where the water flow was low in energy. The preservation of only the coarser portion deposits within the channel-fill element indicates that several cycles of high energy flows occurred during the deposition of the channel-fills that led to the erosion of the top-most, finer grains deposits within the channel-fill element.

3.2.2.4.1 Channel-fill examples from the study area:

The channel-fill element size and geometry vary in study area outcrops due to the variation in accommodation and drainage level (more information in the discussion section).

At Cokedale.1 and Cokedale.2 where the accommodation is high and the system is poorly-drained, channel-fill elements ranged between 26 to 65 centimeters. Despite their lack in thickness, the channel-fill elements at Cokedale.1 and Cokedale.2 are very wide (Fig. 23). The width of the channel-fill element is about 3.7 to 16.5 meters at Cokedale.1 and Cokedale.2. Channels of the channel-fill element are isolated and they are all at the same stratigraphic level within the flood basin deposits. The channel-fill scours are nearly flat and filled with about two to four bar elements per each channel-fill. Two channel-fill elements were identified at Cokedale.1, whereas there are four channel-fill elements at the Cokedale.2 outcrop. The channel-fill element is fining upward in to siltstone deposits at limited locations (e.g., Cokedale.2) and is underlain and overlain by a flood basin fine element. The presence of rooting at the topmost and through some of the thin channel-fill elements indicates that water level was shallow and/or lowered during channel-fill element deposition.

At Valdez.1, Valdez.2A and Valdez.2B, the accommodation is slightly less than at Cokedale.1 and Cokedale.2 and the drainage settings are better drained than at Cokedale.1 and Cokedale.2. The channel-fill elements at Valdez.1, Valdez.2A and Valdez.2B are thicker than the ones at Cokedale.1 and Cokedale.2. The presence of poorly-developed paleosols above and below the channel-fill elements at Valdez.1, Valdez.2A and Valdez.2B implies that the sedimentation rate exceeded water level rise during deposition, leaving these deposits either below or very close to the water level, giving the soil developing processes and rooting the chance to rework the previous high-accommodation deposits. The channel-fill elements differ in size and geometry at Valdez.1, Valdez.2A, and Valdez.2B.

At Valdez.1, two channel-fill elements were identified. Channel element.1a is located at the bottom east side of the Valdez.1 outcrop. The channel element.1a is 2.2 meters thick and 45+ meters wide (Fig. 24). The actual extent of the channel element.1a is unknown as the full extent is not exposed and is buried by a large slump/minor fault at the west side of the outcrop. The channel element.1a scour is relatively flat and consists of several lateral amalgamated small scours incising into poorly-developed paleosol fine deposits and forming one laterally extensive composite scour. The channel element.1a is filled with terminal splay deposits (i.e., laminated sand sheet element) that are separated by very thin poorly-developed paleosol deposits.

The channel-fill element.1b is 1.6 meters thick and 40+ meters wide (Fig. 24). The full extent of the channel element.1b is also hard to determine for the same reasons that were noted for the channel-fill element 1.a. The channel-fill element.1b scour incised into terminal splays, a poorly-developed paleosol, and the top of the channel-fill element.1a with a slightly concave-up composite scour. The channel-fill element.1b is filled with thicker terminal splays deposits (i.e., laminated sand sheet element) that are separated by thin layers of poorly-developed paleosols.

Two channel-fill elements were recognized at Valdez.2A and Valdez.2B. The channel-fill element.2a (Fig. 25) is located at the base of the Valdaz.2A outcrop and is mainly filled with bar elements with a minor presence of nested channel scour elements. The channel-fill element.2a is incised into poorly-developed paleosol and terminal splays deposits. Two channel-fills that fall into the channel element.2a category were identified at Valdez.2A and Valdez2B (Fig. 25). Both of these channel-fills have one concave-up scour and are filled with two to five bar elements. Both channel-fills are around 1.7 meters thick and 25 meters wide.

The channel-fill element.2b is located in the middle section of the Valdaz.2A and Valdez.2B outcrops. The channel-fill element.2b is predominantly filled with nested channel-fill scour element and has a thickness between 1.8 meters and 100+ meters in width (Fig. 20). Its full extent is unknown because larger sand bodies (i.e., valley fill and channel-belt) are incised into the channel-fill element.2b at both Valdaz.2A and Valdez.2B. The channel-fill element.2b scour is localized, relatively flat, and incised into terminal splays deposits. The scour also consists of amalgamated smaller scours that cut across each other and form one long composite scour.

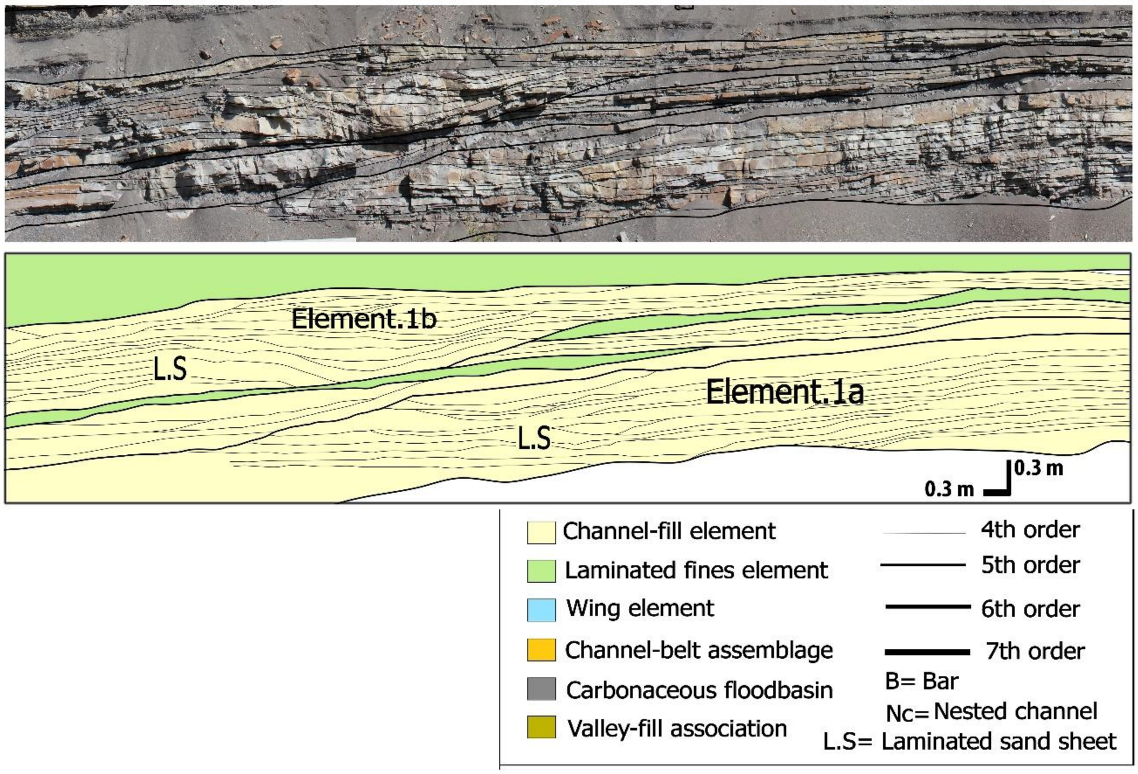


Fig. 24: Channel-fill element1.a and channel-fill element1.b, Valdez.1.

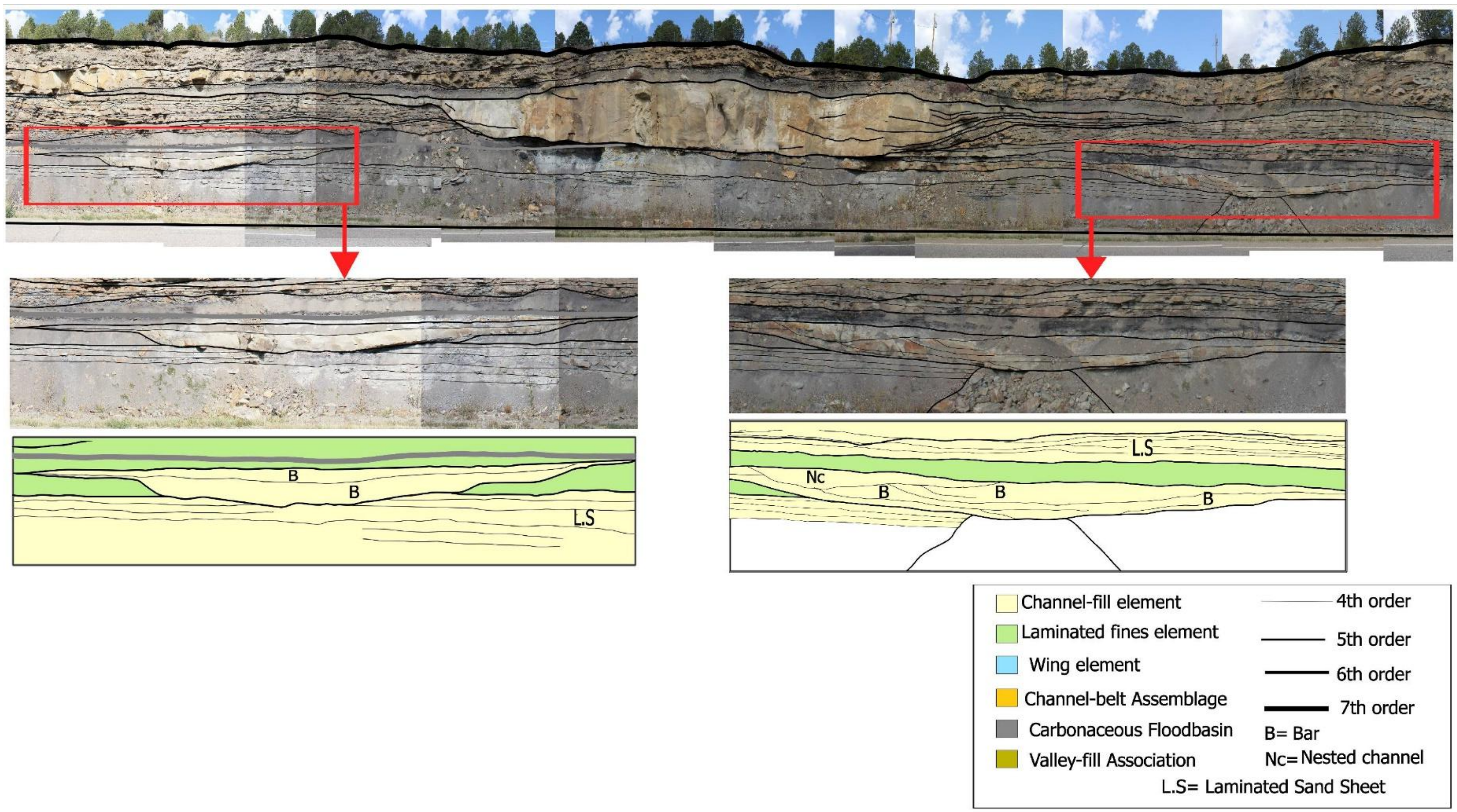


Fig. 25: Channel-fill element.2a, Valdez.2A.

3.2.3 The valley-fill association:

Description: The valley-fill association bounds several 6th order bounding surfaces of channel-belt assemblages with a 7th order bounding surface. Only one isolated valley-fill association was identified in the study area at the Valdez.2A outcrop (Fig. 26). Several other incomplete valley-fill associations were observed around and within the study area. Those valley-fill association around the study area were not included in this study because they could not be traced back to the one at the Valdez.2A outcrop. At the Valdez.2A outcrop, the valley-fill association is filled with at least eight partially preserved channel-belt assemblages ranging in thickness between 0.7-1.8 meters per each channel-belt assemblage. The valley-fill association is approximately six meters thick and 50 meters wide. The scour of the valley-fill association is broad, concave-upward and incised into a sand sheet element, poorly-developed paleosol deposits, and a carbonaceous flood basin fine element.

Interpretation: The interpretation of this association as valley-fill was determined by the criteria of Van Wagoner et al. (1990), Zaitlin et al. (1994), and Posamentier (2001): the valley-fill association is thicker than one channel-thick, has traceable scour, and bounds 6th order bounding surfaces. The formation of the valley-fill association indicate a local lowering in base level and low-accommodation conditions that led to the deep incision of the valley to adjust to the new base level. The valley then later was filled by aggradational stacking of channel-belts (Shanley and McCabe, 1994; Holbrook, 2001).

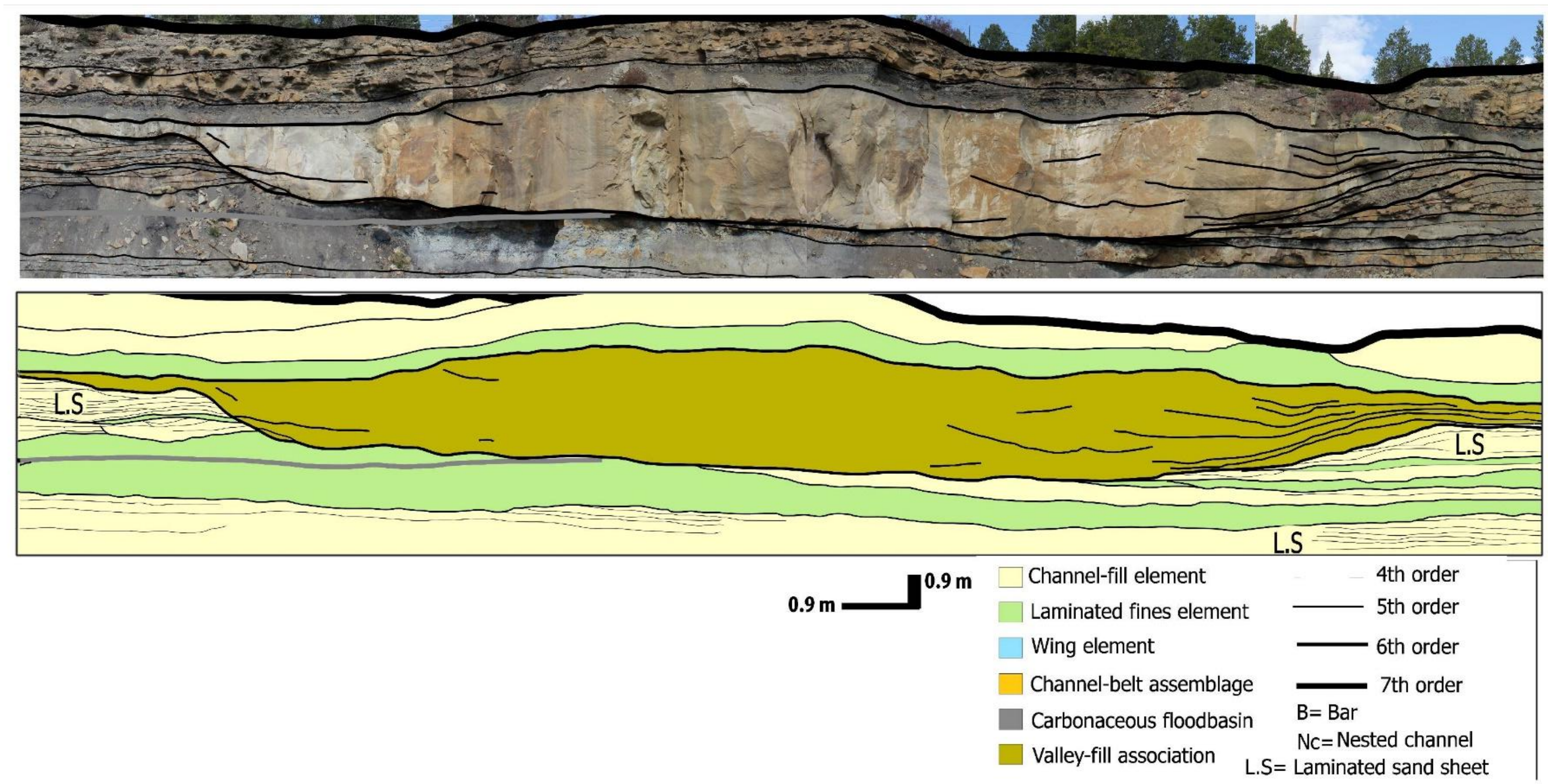


Fig. 26: Valley-fill association bounding channel-belt assemblage, Valdez.2A.

Chapter.4

DISCUSSION:

4.1 Fluvial facies association in the Sandstone Dominated Zone of the Raton Formation

A fluvial facies association is a collection of multiple, genetically related lithofacies that were deposited under the same condition in one depositional system (Walker, 1992). Closer examination of the lithofacies and the architectural element assemblages in the Sandstone Dominated Zone of the Raton Formation reveal that distinct lithofacies and architectural element assemblages are associated with certain levels of drainage and accommodation conditions. Three lithofacies associations have been identified within the Sandstone Dominated Zone of the Raton Formation based on facies changes due to a change in balance of accommodation and sediment supply. These three facies associations are: the channel-belt dominated low-accommodation valley-fill association, the distributive-dominated high-accommodation well-drained association, and the fluvio-lacustrine high-accommodation poorly-drained association.

4.1.1 The channel-belt dominated low-accommodation valley-fill association:

The channel-belt dominated low-accommodation valley-fill association consists mainly of sandstone lithofacies with a very limited amount of flood basin fine sediments (Fig. 26). The channel-belt dominated low-accommodation valley-fill association is dominated by several amalgamated channel-belts assemblages that are concentrated near the base of valley-fill scour. The flood basin fine deposits are mainly found at the top of the valley-fill. The presence of flood basin fine deposits at the topmost part of valley-fills indicates a loss in flow energy which allowed the fine sediments to be deposited from suspension and fill the remaining accommodation space at the top of the valley-fill. Rootings are common in the topmost deposits of this association. The presence of rooting and a compound paleosol at the top of the valley-fill imply that these fine deposits were exposed to weathering and soil forming processes for a short period of time. The valley-fill scour is into the laminated sand sheet element (i.e., terminal splays), and the carbonaceous flood basin fine element which indicates a lowering in the base level at the downstream part of the system. The channel-belt dominated low-accommodation valley-fill association is well-described and several examples of a similar interpretation can be found in the literature (e.g., Allen and Posamentier, 1993, Blum, 1993; Willis, 1997; Plint et al., 2001, 2003).

4.1.2 The distributive high-accommodation well-drained association:

The distributive high-accommodation well-drained association is composed of the laminated mudshale and clayshale lithofacies (i.e., laminated fines element) that were deposits in well-drained flood basin. A poorly-developed paleosol with rooting is very common in this association and indicates that these deposits were exposed for a short period of time between terminal splay formation events. Sand bodies in the distributive high-accommodation well-drained association are common and are represented by laminated sand sheet elements (i.e., a terminal splays complex) (Figs. 17, 18). The laminated sand sheet element splayed over flood basin deposits in the distal reach of distributive fluvial system during seasonal flooding events (see the DFS section). The abundance of laminated sand sheet elements indicates that periods of high energy flow was very common during the deposition of this association. Local lowering in the base level may occur within a distributive high-accommodation well-drained association where scours cut into the flood basin fine deposits and into the laminated sand sheet element, and then are filled again with a laminated sand sheet element. This association changes abruptly to the low-accommodation valley-fill association when channel-belts are incised into the section. Examples similar to the distributive high-accommodation well-drained association are well-documented in the literature (e.g., Hirst and Nichols, 1986; Olsen, 1987; Friend, 1989, Kelly and; Lang et al., 2005; Nicholas and Fisher, 2007; Hartley et al., 2010; Amos et al., 2010; Weissmann et al., 2010; Weissmann et al., 2013).

4.1.3 The fluvio-lacustrine high-accommodation poorly-drained association:

The fluvio-lacustrine dominated high-accommodation poorly-drained association is characterized by a high content of laminated mudshale and clayshale, and carbonaceous shale lithofacies (i.e., carbonaceous flood basin fines and laminated fines elements) that were deposited in a poorly-drained lake environment (Figs. 22, 23). Sand bodies within this association are common and are represented by thin, wide channels with laterally extensive wings (i.e., channel-fill and wings elements). Poorly-developed paleosols and rootings are rare in this association and only can be found in few locations in the topmost strata of the lake deposits, and in the top most part of the channel-fill element. The presence of poorly-developed paleosols and rootings indicate that lake water level was high during most of the depositional process with a few periodic shallowings when plants grew in the top part of the lake and channel-fill deposits. This association is often found at top and at the base of the low-accommodation valley-fill association which indicates an abrupt change from low to high accommodation and vice versa with a rhythmic depositional cycle repetition. The fluvio-lacustrine dominated high-accommodation poorly-drained association is poorly-documented in the literature and very few example have been found (e.g., Carrol and Bohacs, 1999; McCarthy et al., 1999; Hampson et al., 1999; Huling, 2014).

4.2 Six degrees of separation across the low-to-high-accommodation continuum in fluvial systems and their distinct facies associations

The fluvial systems -as has been previously discussed - are subdivided into low- and high-accommodation systems based upon the degree to which the channel belts are amalgamated. In low-accommodation systems tracts, channels vertically scour into lower stories and form larger sand-bodies that consist of many truncated and amalgamated channel-belts, whereas in high-accommodation systems, these sand bodies are vertically separated by fine flood basin deposits. These two distinctions are presumed to record a change in the balance between the sedimentation rate and the rate of accommodation increase. In modern fluvial systems, rivers can switch from a low-accommodation system, whereby flood basins fail to aggrade more than a one channel-belt thickness prior to an avulsive return of a channel to the same site, to a high-accommodation system, whereby they aggrade more than one channel belt prior to avulsive return (Lagarretta et al., 1993; Shanley and McCabe, 1993; Aitken and Flint, 1994; Catuneanu, 2006;

Holbrook, 2001). This binary description of fluvial system accommodation states has served well for general interpretations and mapping of fluvial strata. Within these two accommodation stages, however, are important change-overs in the fundamental processes that alter the preserved architecture of the fluvial section in significant ways and that are not captured by the simpler binary model.

In this study, six change-overs within low and high accommodation stages are proposed. Two fundamental distinctions in the processes are native to the low-accommodation system, and four are native to high-accommodation systems. The low-accommodation systems may be broken into: 1) progressively stacking and 2) iteratively stacking end members, whereas the high-accommodation systems can be broken into 1) well-drained avulsive distributive, 2) well-drained bifurcating distributive, 3) poorly drained distributive, and 4) fluviolacustrine systems. These subdivisions reflect progressing intensity of relative accommodation rate against sediment supply. These subdivisions have fundamentally different architecture and facies association, reflecting their differing origin that impacts reservoir architecture, particularly in the size arrangement of channel-belts and the connecting units within the flood basin deposits. Most importantly, the genetic associations of processes and related reservoir elements within each of these systems means that an encounter with a succession of some part of one of these associations implies that the other elements in the system are also present. The breakdown of lithofacies by these accommodation states infers a common set of depositional conditions that govern the reservoir elements that may be preserved. This interpretation provides a valuable predictive tool for assessing potential reservoir elements in basins where knowledge of the reservoirs present is limited to just a few cores. The progressively stacked and well-drained avulsive distributary models are the most commonly used and are likely well over-subscribed for lack of consideration of the other four subdivisions, and value of lithofacies analysis from one-dimensional data is probably underutilized.

The following sections lay out the processes and products expected under each accommodation state and examples from the Raton and other formations. The six accommodation states provide a continuum of responses to increasing accommodation conditions in fluvial systems from the lowest to the highest accommodation state.

4.2.1 Low accommodation systems:

4.2.1.1 Progressive stacking:

In progressive stacking, the aggradations of channel-belts is in response to a linear and non-reversing rise of base level (Bridge and Leeder, 1979; Shanley and McCabe, 1994; Holbrook, 2006). Channel-belts in progressive stacking are vertically stacked and the upper channel stories scour into lower channel stories forming one unit of a laterally extensive sand body that consists of amalgamated smaller channel-belts (Lagarretta et al., 1993; Shanley and McCabe, 1993; Aitken and Flint, 1994).These amalgamated sand bodies are formed as result of the failure of the flood basin to aggrade more than one channel-belt prior to the avulsion return to the same spot, which allows an active channel to cut through its own deposits forming amalgamated channel-belts (Miall, 1996; Holbrook, 2001; Straub, 2009). Re-incision would be considered as unrelated to a later and separate base level/accommodation cycle (Holbrook, 2006). This style is over inferred, however, largely because any vertical section of low-accommodation strata will appear to record only a section of the amalgamated channel stories in a single column, which is consistent with this linear model (Holbrook, 2001). This subdivision is commonly established downstream near a base level buttress (sensu Holbrook, 2006) like sea or water table level where movement of the buttress directly controls the stacking of channel-belts (Fig. 28) (Holbrook, 2006). In progressive stacking, deposition and other processes occur above the water level (i.e., subaerially) and are dominated by sandstone deposits with no to very limited flood basin fine deposits.

Progressive stacking is very common in ancient fluvial systems and well-documented in the literature. In the study area, two examples were identified that fall within the progressive stacking category. They are found at the base and the top of the Cokedale.2 outcrop and are a part of the channel-belt dominated low-accommodation valley-fill association (see previous sections for details) (Fig. 27). Several authors have described progressive stacking in the literature. One good example is the Cretaceous lower part of the Mesa Rica Sandstone Formation of the Dakota Group in New Mexico and Colorado (Holbrook, 2001; Holbrook et al., 2006) (Fig. 28). Holbrook (2001) and Holbrook et al. (2006) noted that down-dip in the Dry Cimarron Canyon area the lower part of the Mesa Rica Sandstone channels are laterally amalgamated forming a sheeted-like body that extends for about 84 km with vertical progressive stacking (Holbrook, 1996). A similar example has been documented by Plint et al. (2001) for the Cenomanian Dungvegan Formation in Alberta Foreland Basin, Canada. Plint et al. (2001) documented a low-accommodation system of multi-story, vertically stacked and laterally accreted channel-belts that were deposited within valley-fills. There are many other examples from the literature that represent and/or are assumed to be progressive stacking (e.g., Lagarretta et al., 1993; Shanley and McCabe, 1993; Blum, 1993; Aitken and Flint, 1994; Willis, 1997; Hampson et al., 2013; Straub et al., 2014).

Fig. 27: Progressive stacking example from the Cokedale.1 outcrop, Trinidad, Colorado: two vertically stacked and laterally extensive channel-belts.

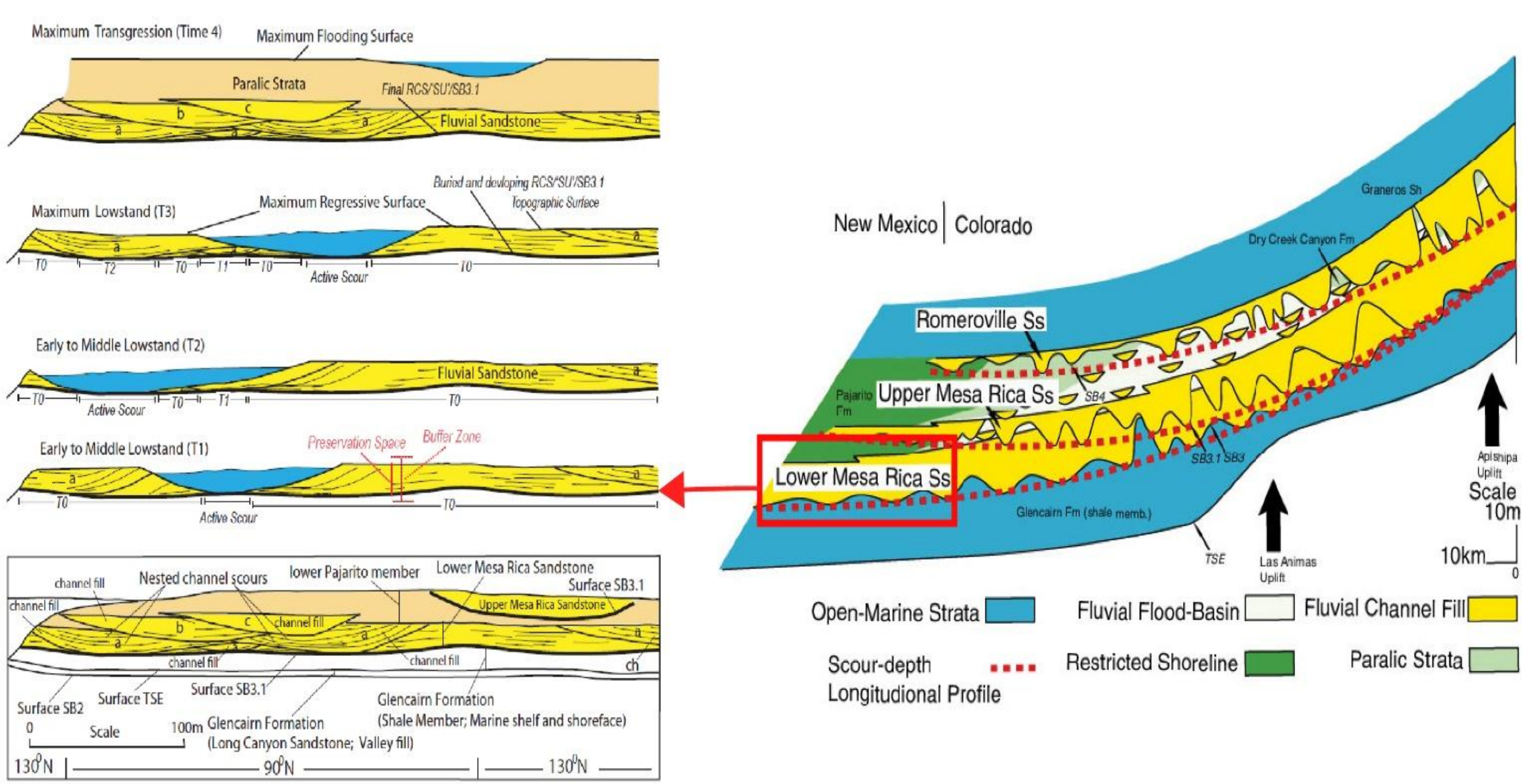


Fig. 28: Progressive stacking example from the literature: The lower part of the Mesa Rica Sandstone, New Mexico and Colorado (Holbrook, 2001).

4.2.1.2 Iterative stacking:

In iterative stacking, amalgamation of channel-belts at low accommodation proceeds by multiple phases of incision and aggradation within a thin vertical buffer zone that itself may rise or fall with the regional base level (Holbrook, 2006). This process can result in laterally amalgamated multi-valleys and terrace systems within the low-accommodation sheet so that each contain their own progressively stacked fluvial sections (Holbrook, 2006). These multi-valley sheets (sensu Holbrook, 2001) occur because of drainage-specific and repeated shifts in the sedimentation and water supply that cause related cycles of aggradation and valley/terrace incision that can be unique to each river and are not part of a larger basin accommodation trend (Holbrook, 2006) (Fig. 29). These multi-valley sheets will occur up dip of the shoreline or other base level buttress where sediment and water cycles can result in incision and aggradation cycles (Holbrook, 2006) by thin multi-story stacked channel-belts that are laterally amalgamated into one laterally extensive multi-story channel-belt downstream (Holbrook, 2001; Holbrook et al., 2006). Iterative stacking is mainly up-dip where changes in the buttress are negligible. Progressive stacking and iterative stacking are very similar. The main difference between these two subdivisions is that in iterative stacking, re-incision is very common which leads to an increase in the erosional area, which will increase the accommodation for new amalgamated channel-belts to be preserved.

Iterative stacking is poorly documented in the literature and only few authors have described it in their research. Holbrook (2001) and Holbrook et al. (2006) reported similar settings in the upper part of the Mesa Rica and the Romeoville Sandstones in eastern Colorado. Holbrook (2001) and Holbrook et al.(2006) stated that channel-fills with channel-belts of the Mesa Rica and the Romeoville Sandstones are intensively laterally and vertically amalgamated up-dip within multi-valley sheets due to cycles of aggradation and incision at the valley-fill scale which were confined within discrete, long lasting and extensive upper and lower limits, resulting in freely vertical and lateral migration of channels within these limits, forming one amalgamated multi-story channel-belt (Fig. 29). Hampson et al. (2013) also recognized similar settings in the Upper Cretaceous of the Black Hawk Formation, Utah. In his model, Hampson et al. (2013) described many channelized fluvial sand bodies in the Blackhawk Formation that have a multilateral and multistory internal characters. Hampson et al. (2013) also noted that these multistory channels generally increase in size and abundance from the base to the top of the formation.

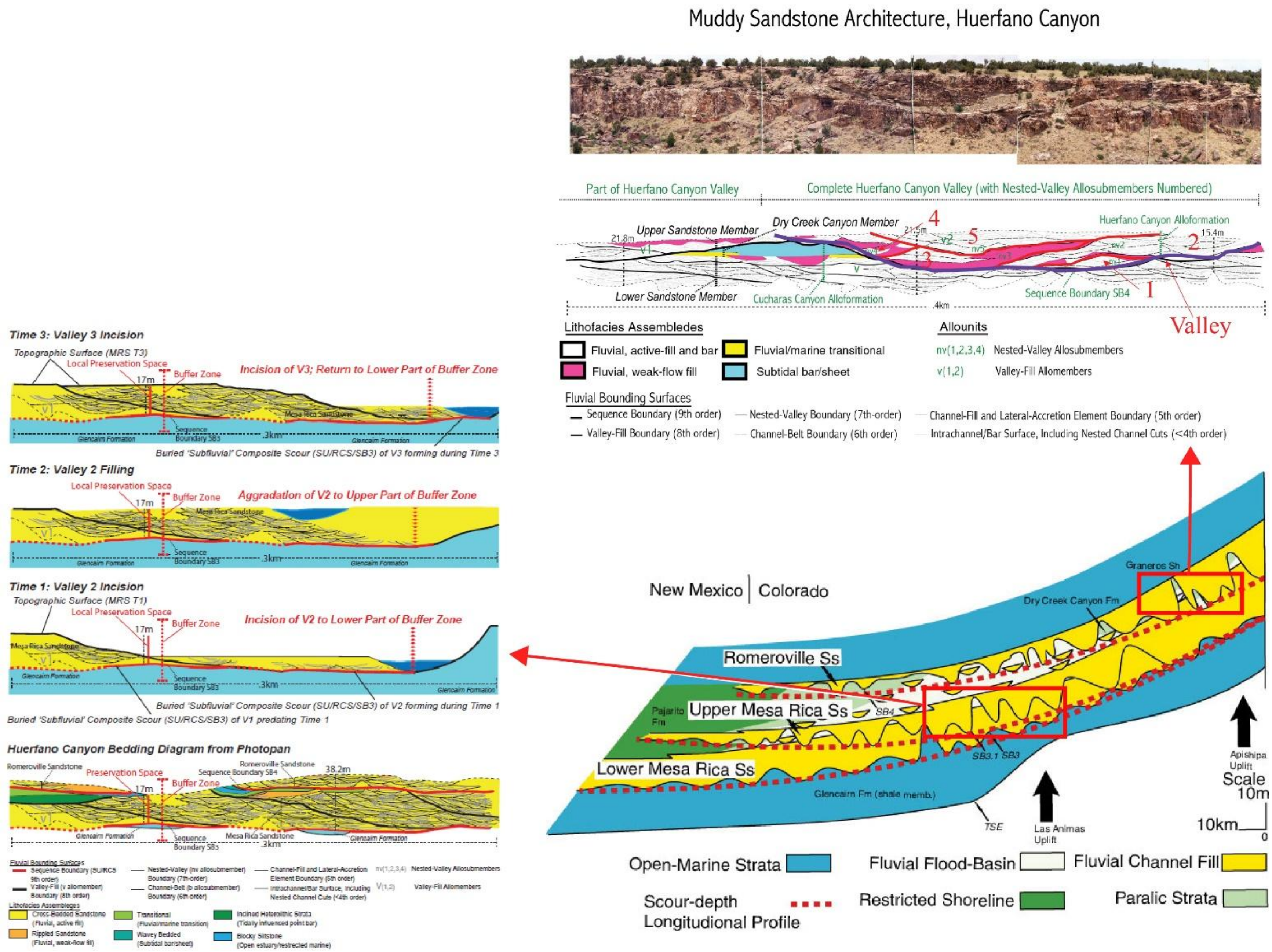


Fig. 29: Iterative stacking example from the literature: The up-dip parts of the lower and upper parts of the Mesa Rica and the Romeroville sandstones (Holbrook, 2001).

4.2.2 High accommodation systems:

High-accommodation systems can be broken into 1) well-drained avulsive distributive, 2) well-drained bifurcating distributive, 3) poorly drained distributive, and 4) fluviolacustrine systems, reflecting the progressing intensity of the relative accommodation rate. In this stage, aggradation of fluvial systems will result in the separation of channel-belts by flood basin deposits where the system first becomes high-accommodation.

4.2.2.1 Well-drained avulsive distributive and well-drained bifurcative distributive:

In both of the well-drained avulsive distributive and well-drained bifurcative distributive stages, the sedimentation rate exceeds the rate of the water table rise, and the land surface remains above the regional water table (i.e., subaerial) allowing soil forming processes to rework the newly exposed sediments and which results in well-drained flood basins.

In both of the well-drained avulsive distributive and well-drained bifurcative distributive stages, channels will avulse from nodes developing an avulsive distributive system of channels that are active largely in succession and producing channel-belts consistent in size with the full river flow and separated by soil zones (Bridge and Leeder, 1979). When the accommodation increases, the bifurcation rate will exceed the avulsion rate and channels will no longer endure at a location for a sufficient time to capture the full flow and the system will become bifurcative distributive. Channel-belts in this case may become more numerous, but will be generally smaller within the flood basin fine sediments.

The well-drained avulsive distributive and the well-drained bifurcative distributive are very similar in characteristics. The main difference between the two is that a well-drained avulsive distributive has a lower degree of drainage conditions, and channel-belts are isolated within paleosol fine deposits, whereas in a well-drained bifurcative distributive, aggradation is higher, which increase the bifurcation tendency due to the slope increment (Murray and Paola, 2003). Also channel-belts show minor lateral and vertical localized amalgamation within and have a better degree of drainage conditions in a well-drained bifurcative distributive.

Examples of the well-drained avulsive distributive are well covered in the literature. A good example of well-drained avulsive distributive systems in the literature is the Palaeogene Willwood Formation in the Bighorn Basin, northern Wyoming (Kraus and Wells, 1999; Kraus, 2002) (Fig. 30). Kraus and Wells (1999) and Kraus (2002) illustrated that sand channels and thin sheets are found within mudrocks with weakly developed paleosols and show an avulsive distributive pattern in the Willwood Formation. These sand bodies are found isolated within the flood basin deposits and are connected by several bands of both poorly and well developed paleosols (Kraus and Wells, 1999) (Fig. 30).

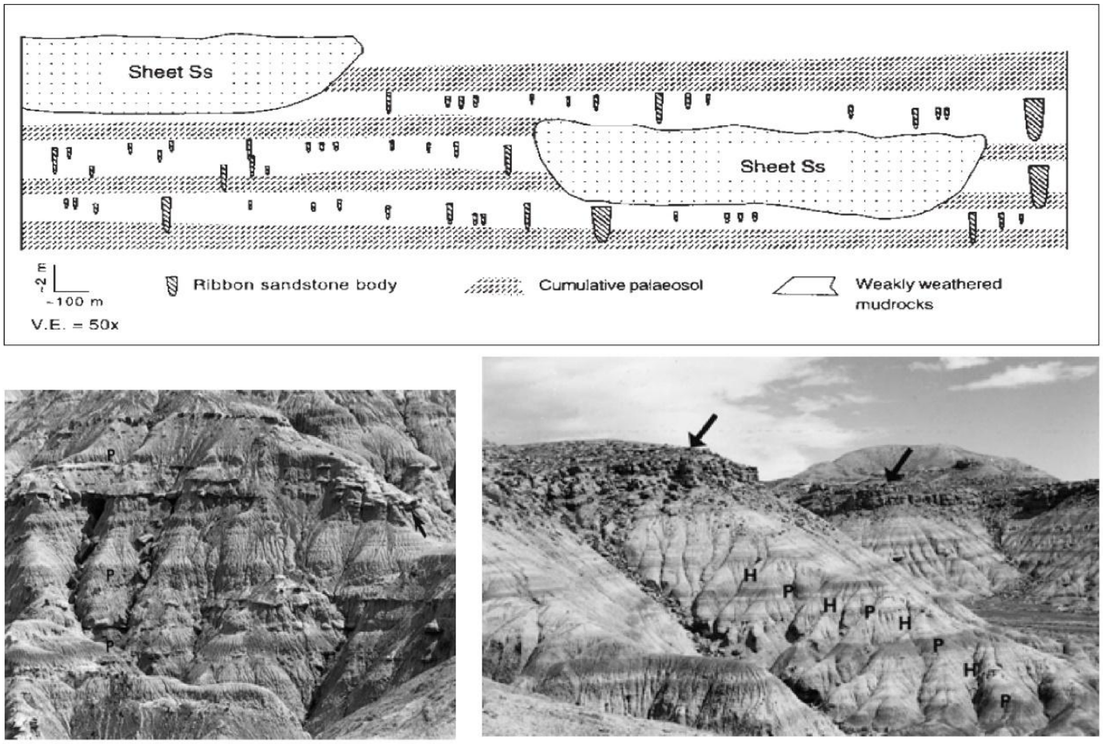


Fig. 30: The Willwood Formation in the Bighorn Basin, northern Wyoming as a well-drained avulsive distributive example. Arrows show location of sandstone sheets. (Kraus and Wells, 1999; Kraus, 2002)

Examples of well-drained bifurcative distributive systems are also well-documented. In the study area and particularly at Valdez.2A (Fig. 20), there is lateral amalgamation of small size scours with some localized vertically amalgamation due to bifurcation forming sheeted-like channel-fills and channel-belts. Both of these channel-fills/channel-belts were incised by a valley-fill. They are both laterally extensive and extend beyond the outcrop limit. Another example of a well-drained bifurcative distributive in the literature is in the medial zone of the Luna and Huesca Miocene depositional system in the Ebro Basin, Spain (Nichols and Fisher, 2007; Fisher and Nichols, 2013) (Fig. 31). Nichols and Fisher (2007) illustrated that sand bodies of the Luna and Huesca depositional system are laterally extensive for over tens of meters and have sharp, vertical and lateral amalgamation with a distributive characteristic in the medial zone of the DFS (Fisher and Nichols, 2013). Nichols and Fisher (2007) also noted that these sand bodies are formed in a well-drained fluvial system due to the presence of a paleosol between these sand bodies. (Weissmann et al., 2013).

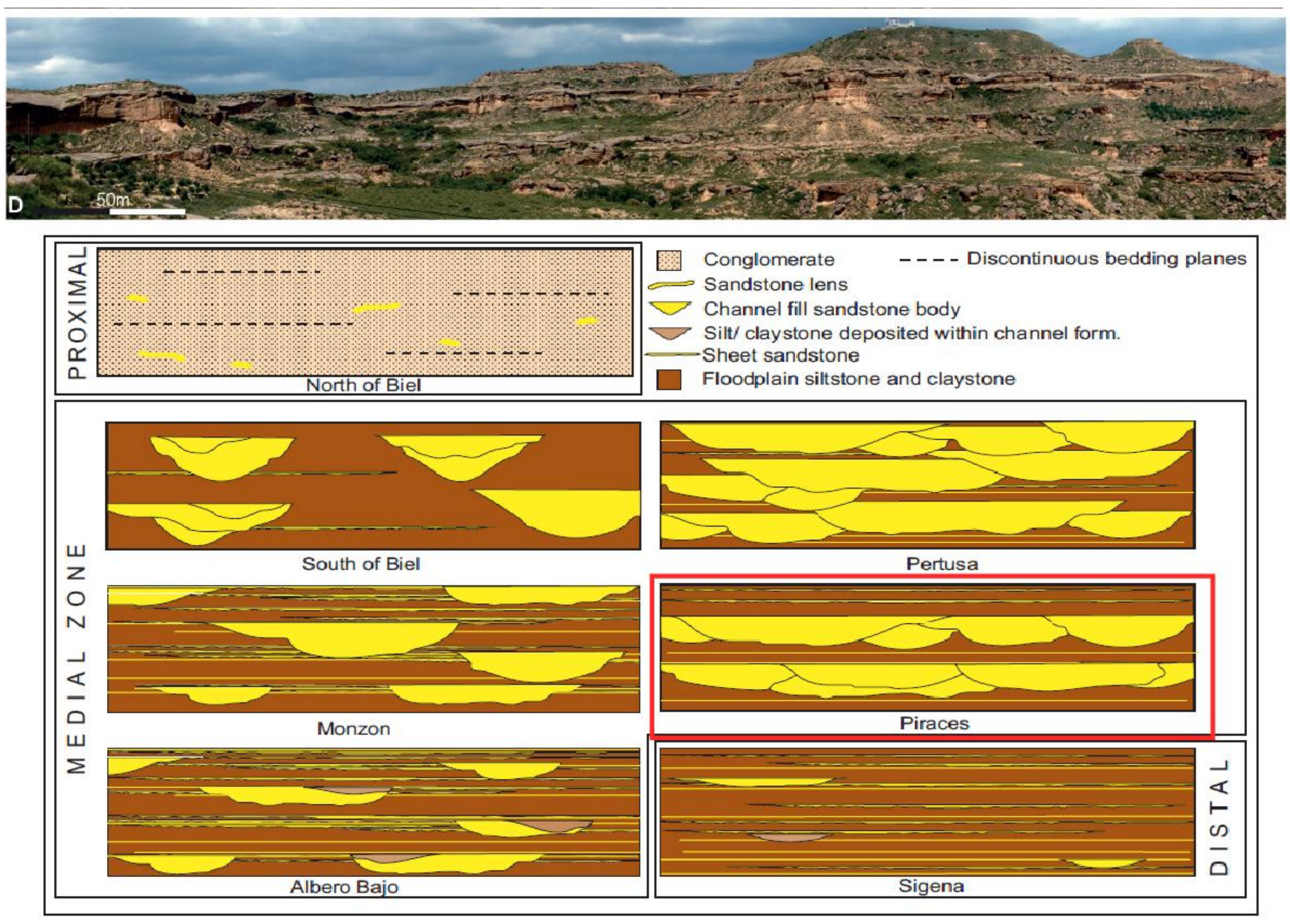


Fig. 31: The medial zone deposits of the Luna and Huesca Miocene depositional system deposits in the Ebro Basin, Piraces, Spain: Laterally amalgamated channel-fill and thick flood basin siltstone. (Nichols and Fisher, 2007; Fisher and Nichols, 2013).

4.2.2.2 Poorly-drained bifurcative distributive:

In poorly drained bifurcative distributive systems, the flood basin becomes poorly-drained when accommodation is increased further to where the average sedimentation rate of the basin is roughly equal to or surpassed by the rate of water table rise. In poorly drained bifurcative distributive systems, the sedimentation rate is roughly equal to the rate of water-table rise and the flood basin is transformed into numerous lakes that record where sedimentation is locally low and into subaerial alluvial ridges, splays, and mudflats where sedimentation is high. Channels continue to maintain distributive patterns, but the primary process of bifurcation and distributary growth now becomes progradation of linear deltas through flood basin lakes, with subdominant splay-driven avulsion. Channels in a poorly drained bifurcative distributive are generally thin, narrow to medium, and show little lateral migration with wide extensive sandy wings. These wings from various channels are likely to interfinger and/or overlap each other and also act as connectors between channels within the same flood basin.

Very few studies have been conducted to better understand the poorly drained bifurcative distributive and examples in the literature are very rare. In the study area, the Cokedale.2 outcrop is a good example of a poorly drained bifurcative distributive (Fig. 32). At Cokedale.2, channels are thin and wide (Fig. 23) with low lateral migration and widely extensive wings that interfinger into one band of thinly bedded sandstones.

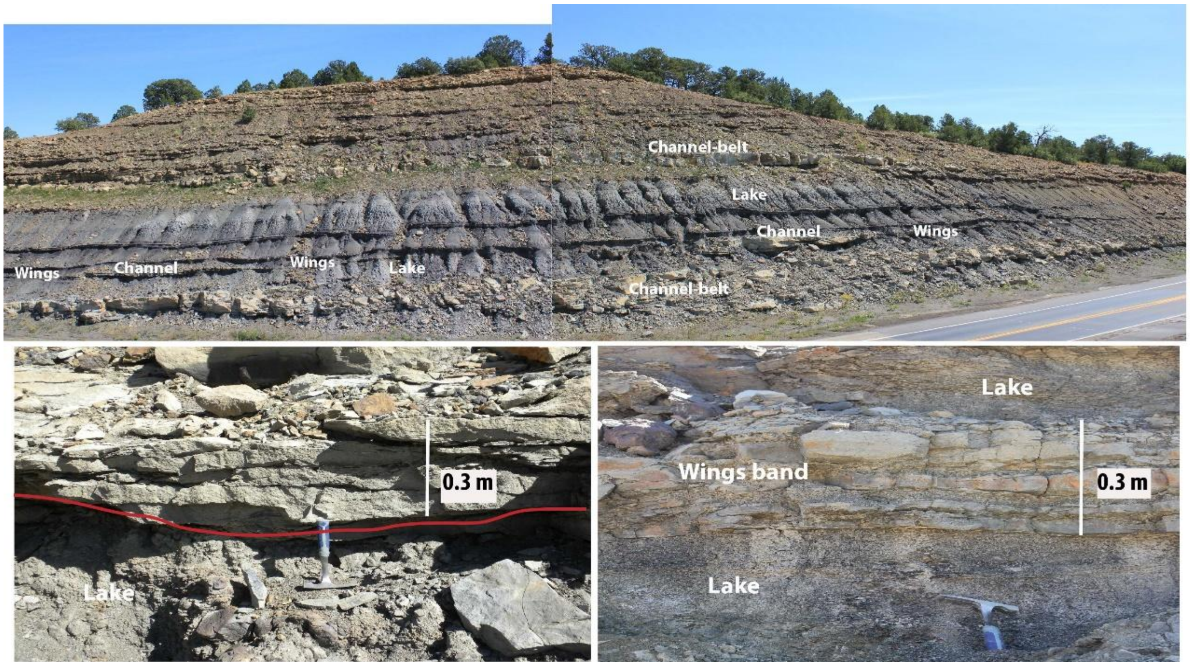


Fig. 32: Characteristics of poorly drained bifurcative deposits, Cokedale.2: Chennels are narrow with wide extensive wings.

The distal zone of the Luna and Huesca Miocene depositional system in the Ebro Basin, Spain is another good example that illustrates a poorly drained bifurcative distributive (Nichols and Fisher, 2007; Fisher and Nichols, 2013) (Fig. 33). Channels within the distal zone of the Huesca depositional system are thin with shallow scour surfaces and are sheet-like with the presence of some sand ribbons (Hirst and Nichols, 1986; Fisher and Nichols, 2013). Sheeted sandstone intervals are a few centimeters thick consisting of parallel lamination or current ripples, but are generally structureless (Nichols and Fisher, 2007; Fisher and Nichols, 2013). These sand sheets (i.e., wings) are often amalgamated into a macro-sheet that can continue laterally for tens to hundreds of meters (Nichols and Fisher, 2007; Fisher and Nichols, 2013). Other examples are from the work of Atkins (2016) and Ney (2015) in the Upper Pennsylvanian Breathitt Group and lower part of the Conemaugh Group at the Central Appalachian Basin at Louisa, Kentucky. Atkins (2016) and Ney (2015) documented thin and wide spread channels with wings that connected these channels through incision within the high-accommodation flood basin deposits (Fig. 34).

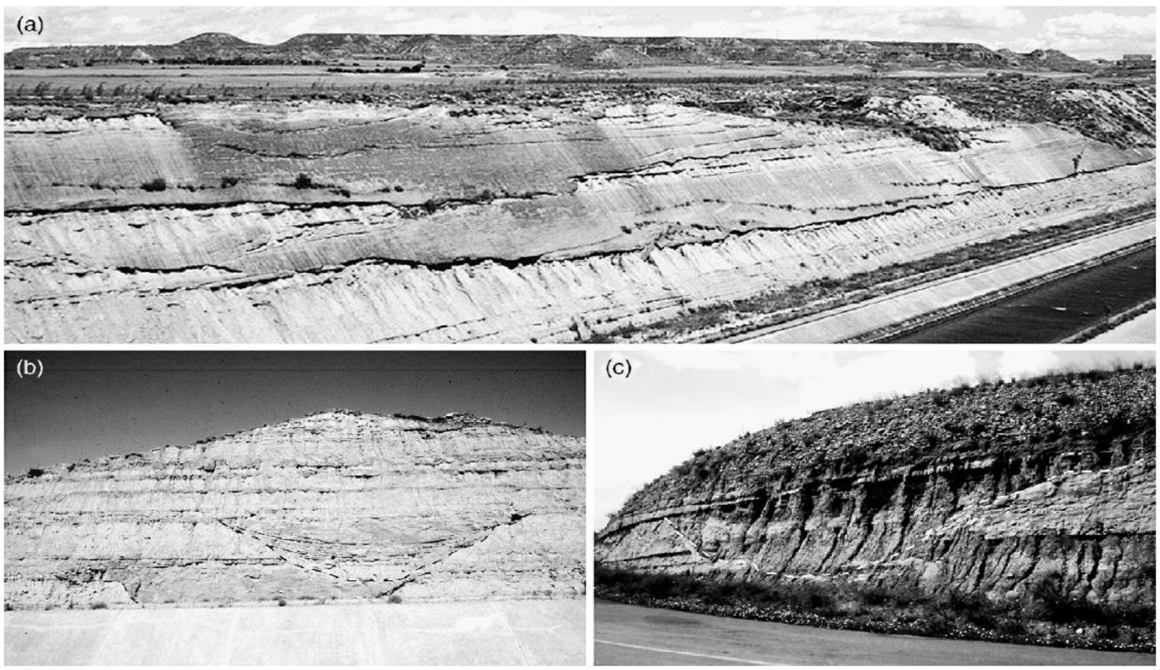
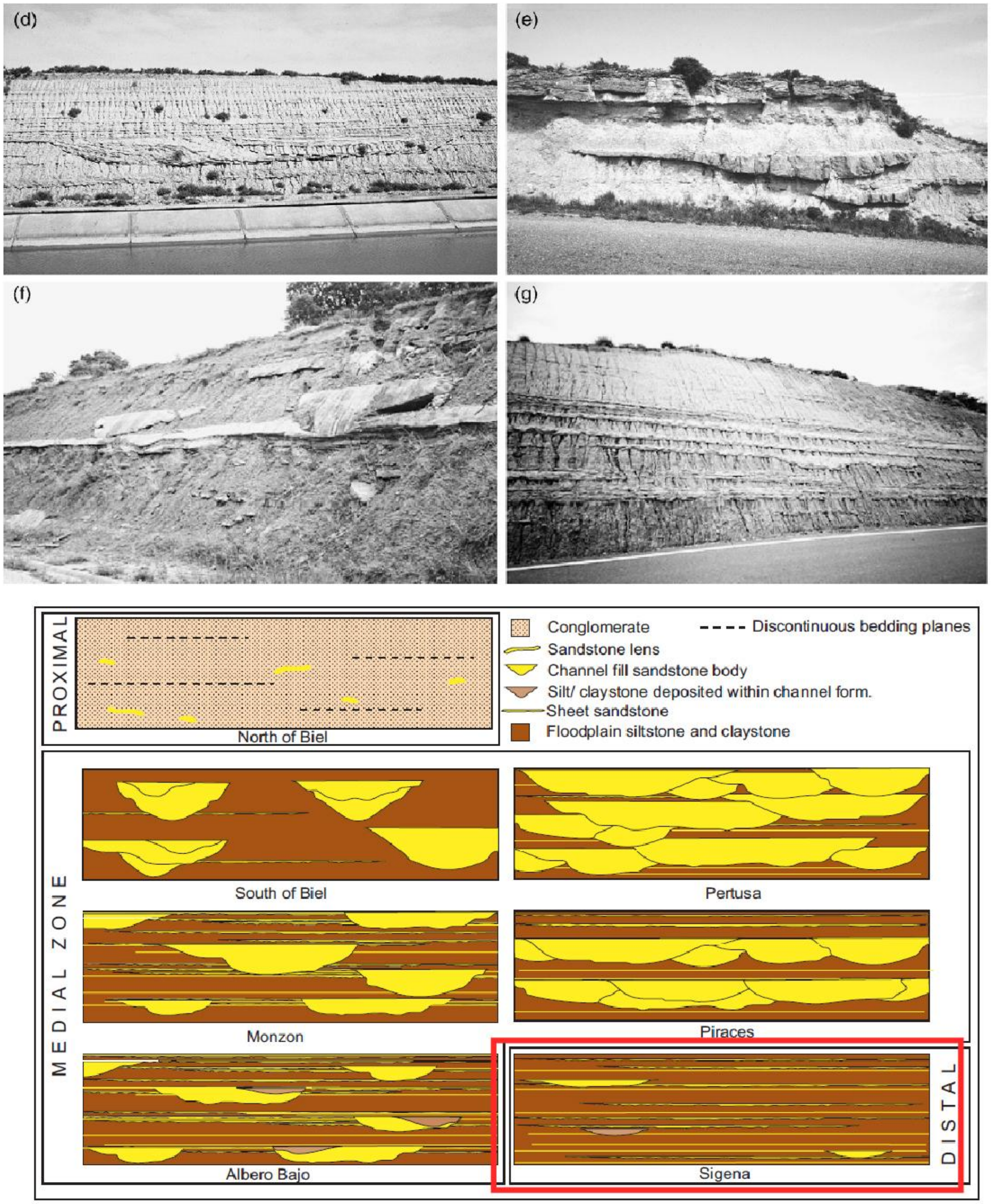


Fig. 33: Distal deposits of the Luna and Huesca Miocene depositional system in Ebro the Basin, Piraces, Spain (Nichols and Finsher, 2007; Fisher and Nichols, 2013).



Cont-Fig. 33: Distal deposits of the Luna and Huesca Miocene depositional system in the Ebro Basin, Piraces, Spain (Nichols and Fisher, 2007; Fisher and Nichols, 2013)

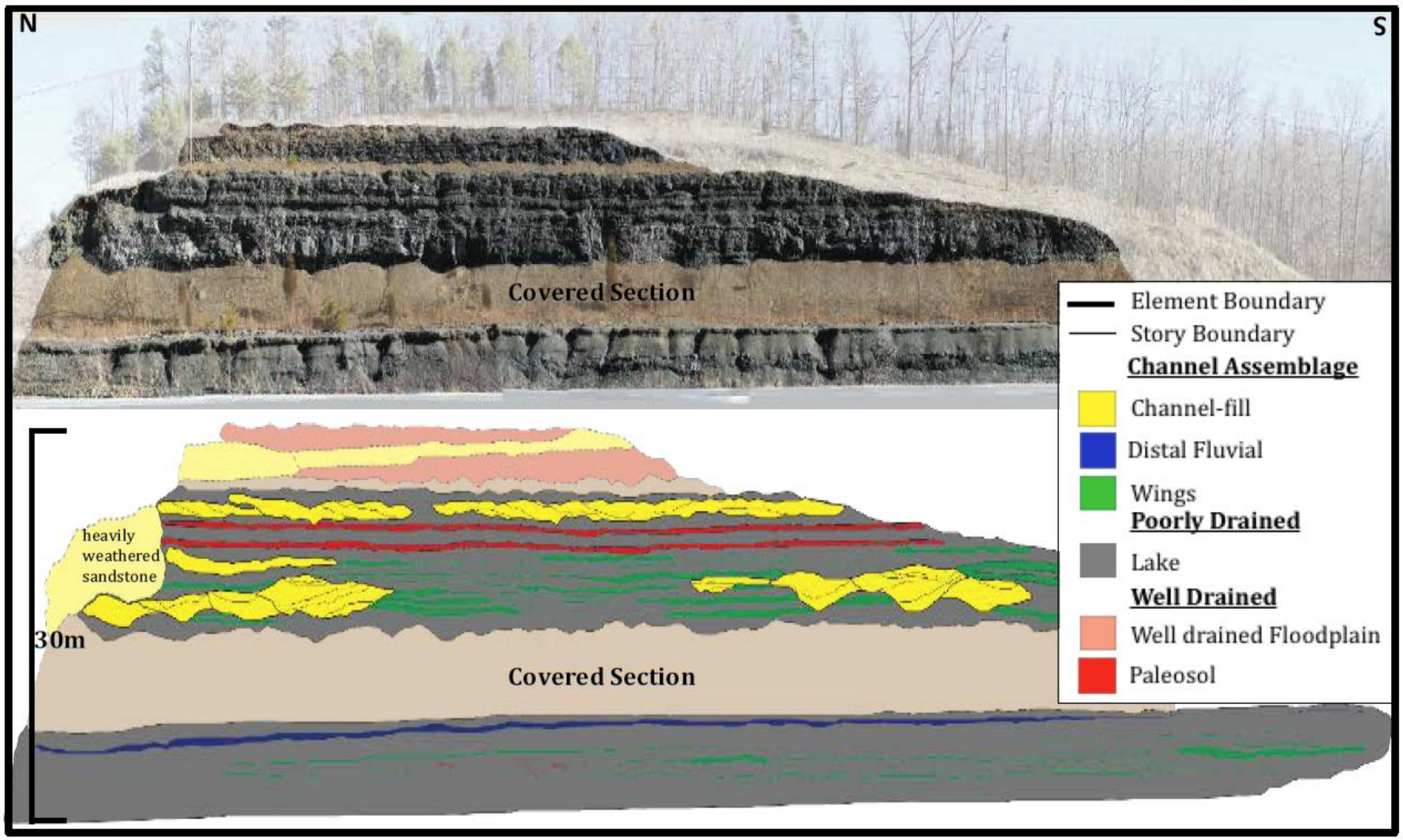


Fig. 34: Poorly-drained bifurcative deposits at the Upper Pennsylvanian Breathitt Group and the lower part of the Conemaugh, Central Appalachian Basin in Louisa, Kentucky. (Atkins, 2016)

Another example of a poorly drained bifurcative distributive was illustrated as a case study by Weissmann et al. (2013) for the distal zone of their proposed prograding distributive fluvial systems model which can be seen in the Late Triassic Blue Mesa and Sonsela Members in Petrified Forest Natural Park, Arizona (Fig. 35). Channel-fill elements within the Chinle Formation are isolated, very thin and are encased within fine-grained flood basin deposits (Weissmann et al., 2013).

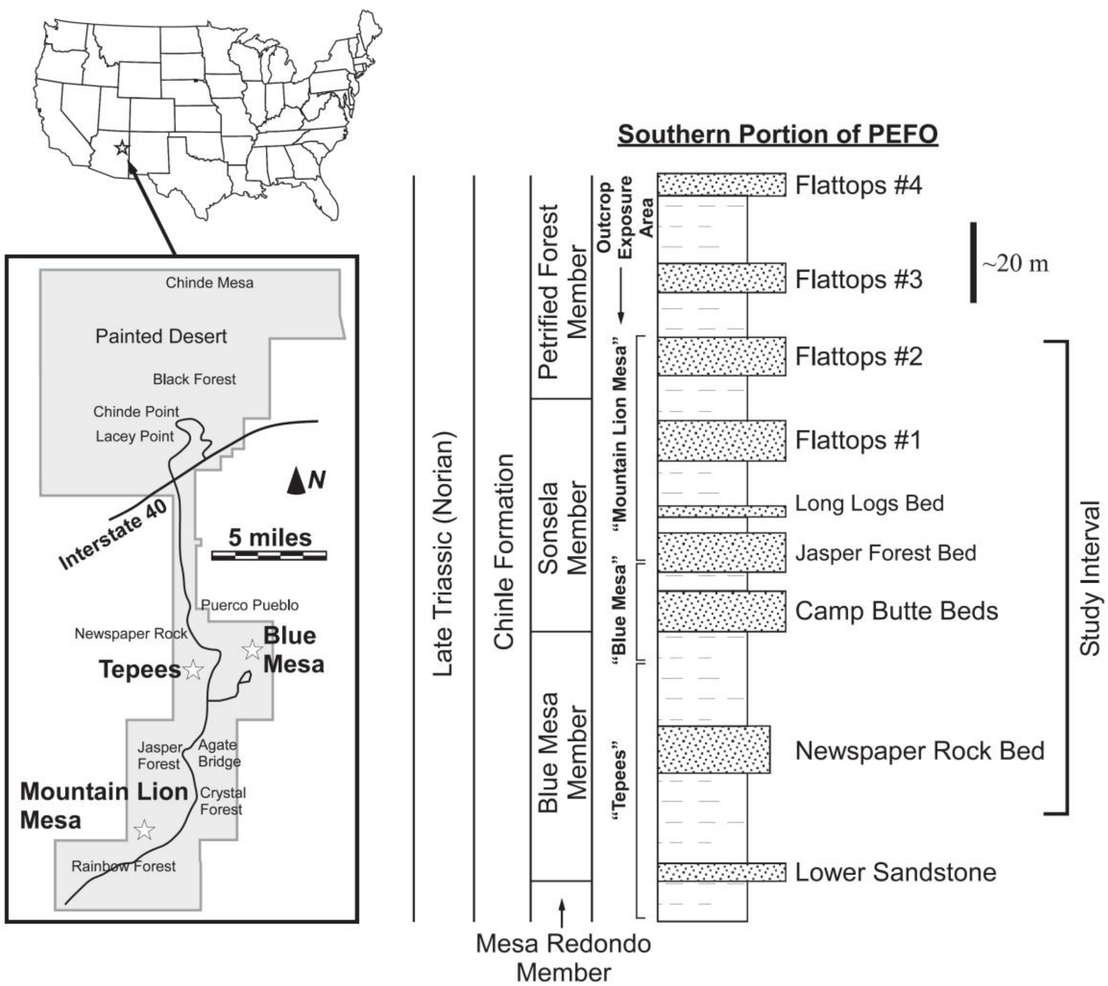


Fig. 35: Poorly drained bifurcative example: The Chinle Formation of the Late Triassic Blue Mesa and Sonsela Members in Petrified Forest Natural Park, Arizona (Weissmann et al., 2013).

4.2.2.3 Fluvio-Lacustrine:

The fluvio-lacustrine state occurs when the sedimentation rate is lower than water the table rise and the entire flood basin becomes a shallow standing water and/or lake system. In this stage, fluvial systems will deliver sediment to the lake margins, however, the low accommodation of the shallow lake promotes rapid progradation of fluvial deltas. If the lake lacks strong wave/tide energy and is generally fresh water, the fluvial system will develop linear deltas. These linear deltas will generate long fluvial channel systems propagating through the shallow water in networks of channels separating lake basins. The resulting deposit will be dominantly lake strata, with ribbons of fluvial systems cutting commonly through a grittier delta-front section. The fluvio-lacustrine division has the highest degree of poor drainage and the lowest sediment rate compared to the previous subdivisions.

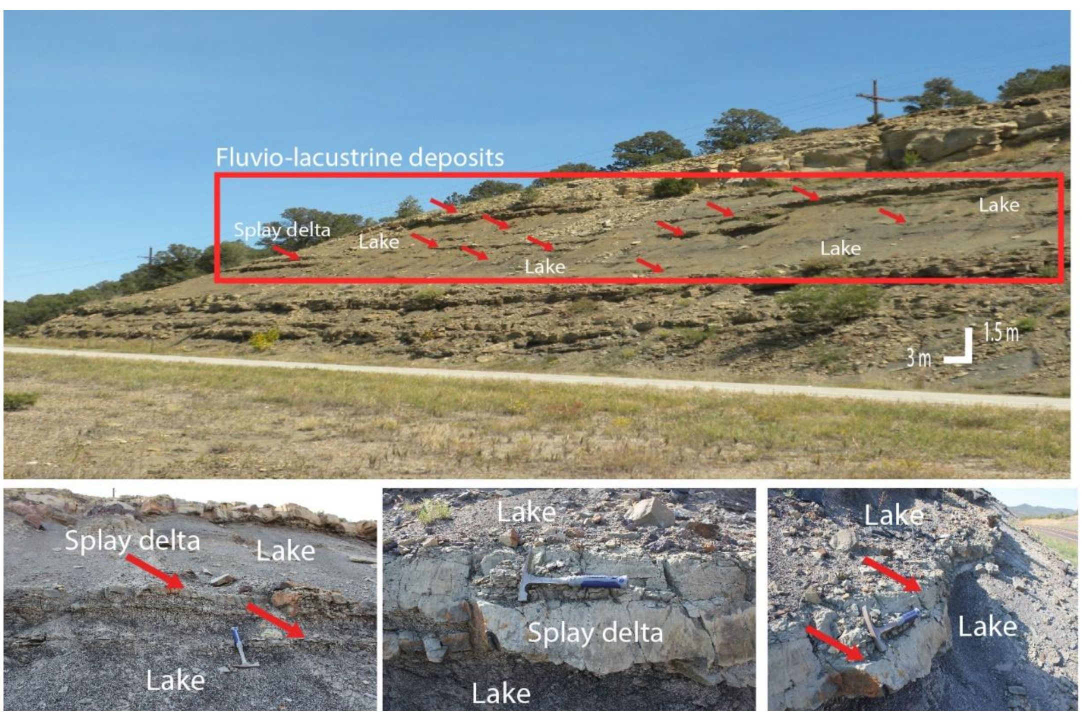


Fig. 36: The fluvio-lacustrine deposits, Cokedale.1: splay delta deposits within fine-grained lake deposits

The fluvio-lacustrine subdivision has received the least attention in the literature of all of the six subdivisions as it lacks the presence of thick sand bodies and reservoir rocks. In the study area, the middle section of both Cokedale.1 and Cokedale.2 are good examples of the fluvio-lacustrine subdivision. These sections are dominated by splay deltas that are relatively thin, fining upward and prograding intoe lake deposits. They are either onlapping older splay deltas forming a band of interfingering splay deltas or are pinching-out into the lake deposits fines. A good and rare example from the literature is the Lumen Tongue of the Green River Formation, Wyoming (Roehler, 1993; Carroll and Bohas, 1999). The Lumen Tongue (Fig. 37) facies has a repetitive grading upward depositional cycle around 10 meters thick starting at the base with a calcareous mudstone or siltstone that grades into a small fine sand delta, coquina, and then a thin coal (Horsfield et al., 1994) that prograde into the hydrologically open lake (Carroll and Bohas, 1999). Another good example is the study of Huling (2014) in a fluvio-lacustrine system in the Jurassic Kayenta Formation, Utah. Huling (2014) reported that deltas within Kayenta fluvio-lacustrine deposits propagate linearly into lake and flood basin deposits without producing the lobate deltas presumed of lakes.

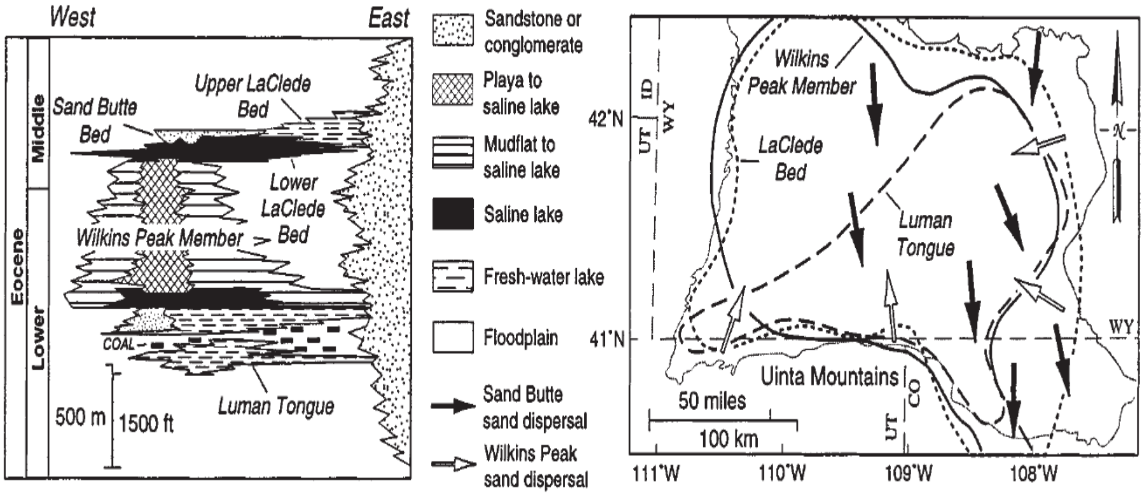


Fig. 37: The Luma tongue of the Green River Formation as an example of fluvio-lacustrine deposits. (Carroll and Bohas, 1999; Roehler, 1992)

4.3 Sand bodies connectivity as potential reservoir rocks in the high-accommodation deposits of the Sandstone Dominated Zone of Raton Formation and their potential application in oil and gas exploration:

Although sand bodies within high-accommodation system deposits are considered poor as reservoir bodies, examination of sand body geometry, architecture, distribution and lithofacies associations in the Sandstone Dominated Zone of Raton formation show that there are several potential sand bodies that could be considered as reservoir rocks in various drainage and high-accommodation stages. Channel-fill, channel-belt and valleys-fill elements are examples of good potential reservoir rocks, whereas the sandy terminal splays and channel wings could be considered as good potential "connectors" between the previous potential reservoir rocks (Fig. 38).

At Cokedale.1 and Cokedale.2 where high-accommodation poorly-drained conditions are present, channel-belts which are found at the top and the base of these outcrops are laterally amalgamated to form one wide, extensive, thick, sandstone unit that spreads for more than tens of meters throughout and beyond the outcrops and which could be a good candidate for reservoir rock (Figs. 19, 27). The presence of two channel-belts at the top and base of Cokedale.2 separated by the poorly-drained high-accommodation deposits indicates that they might be a part of a repetitive depositional cycle and that more channel-belts could be predicted to be below and above these channel-belts. Also, the thin narrow channels with their extensive wings that are found within the high-accommodation poorly-drained system could be candidates for unconventional reservoirs as they have high porosity and permeability (Figs. 21, 22, 23). Channel wings could also be crucial as connectors between sand bodies which could help in increasing the net/gross ratio of the reservoir (Fig. 23). These thin beds of sands could connect several channel bodies with their main channel by incision by other channels, channel-belt, and valley-.

At Valdez.1, Valdez.2A, and Valdez.2B, where the strata record better drainage, sand bodies are more abundant and better connected. The channel-belts are similar to the ones at Cokedale.1 and Cokedale.2. Channel-fills are thicker and are connected by incision into terminal splays and/or other channel wings within the same depositional level (Figs. 17, 20, 24). Channel-fills that incised into terminal splays and poorly-developed paleosol sections are incised into another sandy channel-fill which increases the reservoir rocks size and connectivity. Isolated thick buffer valley-fills are common within these deposits based on the examination of outcrops within and surrounding the study area (Fig. 26). Unfortunately, the full extent of these valley-fills are not preserved and cannot be traced and correlated to the valley-fill in the study area outcrops. At Valdez.1, Valdez.2A, and Valdez.2B, the sandy terminal splays can be potential good connectors between the previous possible reservoir rocks as they are very extensive and consist of sandstone lithofacies with high porosity and permeability.

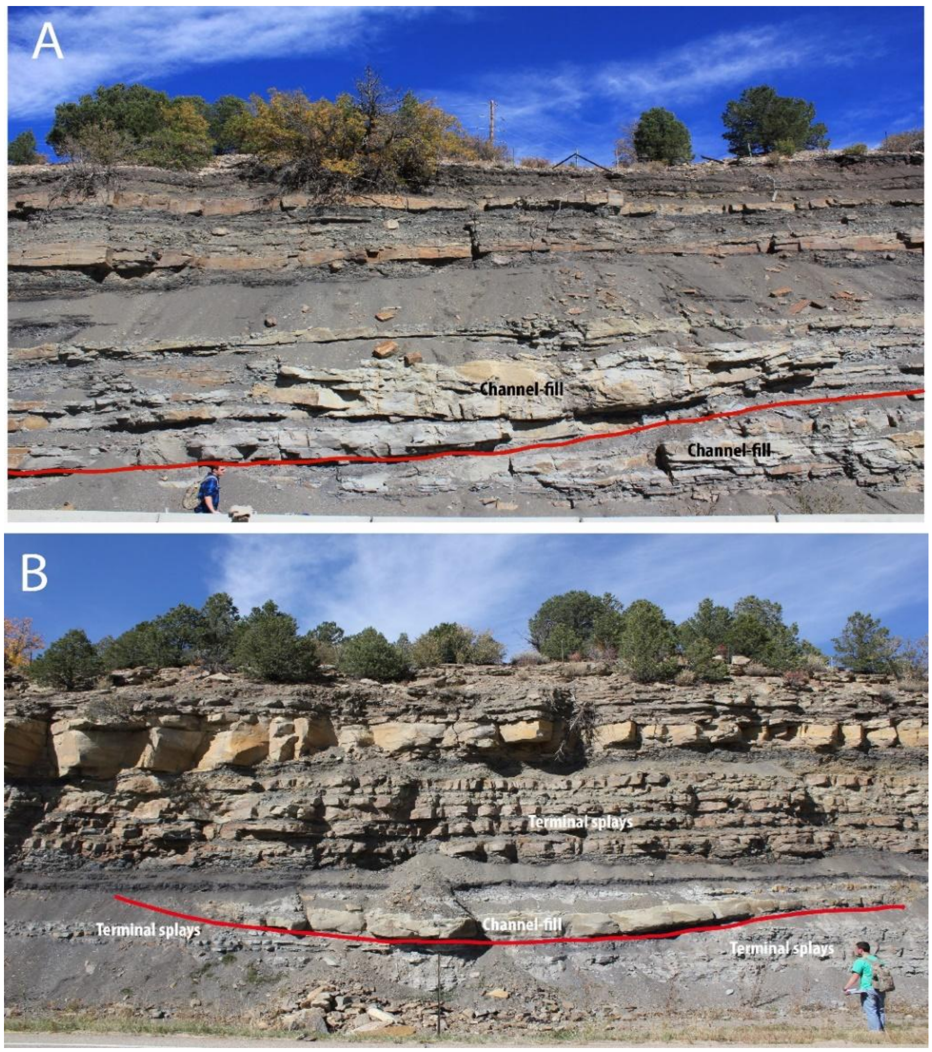


Fig. 38: Sand bodies connectivity in the Barren Series deposits of the Raton Basin: A. Channel-fill incised into another channel-fill. B. Channel-fill incised into terminal splays.

Continued Fig. 38: C. Valley-fill incised into terminal splays.

CHAPTER 5

CONCLUSIONS

1. Closer examination of lithofacies and architectural element assemblages in the Sandstone Dominated Zone of Raton Formation has revealed that distinct lithofacies and architectural element assemblages are associated with different levels of drainage and accommodation conditions.

2. Facies associations that were identified in the Sandstone Dominated Zone of the Raton Formation can be used to predict the lateral and vertical variation at different stages of high-accommodation fluvial systems.

3. Three lithofacies associations were identified within the Sandstone Dominated Zone of the Raton Formation based on lithofacies changes because of the changes in balance of accommodation and sediment supply which are: (1 channel-belt dominated low-accommodation valley-fill association (2 distributive dominated high-accommodation well-drained association, (3 fluvio-lacustrine high-accommodation poorly-drained association.

4. Six change-overs within low and high accommodation stages are proposed. Low-accommodation systems may be broken into 1) progressively stacked and 2) iteratively

stacked end members. High-accommodation systems can be broken into 1) well-drained avulsive distributive, 2) well-drained bifurcating distributive, 3) poorly drained distributive, and 4) fluvio-lacustrine systems.

5. High accommodation fluvial deposits in the Sandstone Dominated Zone of the Raton Formation contain several sand bodies with geometry and size capable to be potential reservoir rocks such as channel-belts, valley-fill, and channel-fills.

6. Connectivity between the sand bodies in the Sandstone Dominated Zone can be seen and were the result of the incision of sand bodies (e.g., channel-belt and valley-fill) into other sand bodies or through thin sand sheets (e.g., terminal splays and wings).

7. The thin sand sheets beds of terminal splays and channel wings are very common in the high-accommodation fluvial deposits at the Sandstone Dominated Zone of the Raton Formation and can act as connectors between larger sand bodies by incision.

References

Aitken, J.F., and S.S. Flint, 1994, High-frequency sequences and the nature of incised-valley fills in fluvial systems of the Breathitt Group (Pennsylvanian), Appalachian Foreland Basin, Eastern Kentucky, *in* R.W. Dalrymple, R. Boyd, and B.A. Zaitlin, eds., Incised Valley Systems: Origin and Sedimentary Sequences, Society of Economic Paleontologists and Mineralogists Special Publication 51, p. 353-368.

Allen, J.R.L., 1978, Studies in fluviatile sedimentation: An exploratory quantitative model for the architecture of avulsion-controlled alluvial sites: Sedimentary Geology, v. 21, p. 129–147.

Allen, J.R.L. 1979. Studies in fluviatile sedimentation: An elementary model for the connectedness of avulsion-related channel sand bodies: Sedimentary Geology, v. 24, p. 253–267.

Allen, G., and W. Posamentier, 1993, Sequence stratigraphy and facies model of an incised valley-fill: The Gironde estuary, France: Journal of Sedimentary Petrology, v. 63, no. 3, p. 378-391.

Amos, K., S. Gupta, K. Goddard, J. Kim, and J. Muller, 2010, Where Ephemeral Fluvial Systems Terminate onto a Playa: The Terminal Splay Complex of Lake Eyre, Australia. Earth Analogues for Martian Deltas? Abstract, First International Conference on Mars Sedimentology and Stratigraphy, El Paso, Texas. LPI Contribution No. 1547, p. 2.

Aslan, A., and W.J. Autin, 1999, Evolution of the Holocene Mississippi River floodplain, Ferriday, Louisiana: Insights on the origin of fine-grained floodplains: Journal of Sedimentary Research, v. 69, no 4, p. 800–815.

Atkins, S., 2016, Fluvial-deltaic deposition in high-accommodation floodplain lakes, Pennsylvanian Appalachian Basin, Eastern Kentucky, M.S. thesis, Texas Christian University, Fort Worth, Texas, 68 p.

Baltz, E.H., 1965, Stratigraphy and history of Raton Basin and notes on San Luis Basin, Colorado–New Mexico: American Association of Petroleum Geologists Bulletin, v. 49, p. 2041–2075.

Bluck, B., and G. Kelling, 1963, Channels from Upper Carboniferous coal measures in South Wales: Sedimentology, no. 2, p. 29-53.

Blum, M.D., 1993, Genesis and architecture of incised valley fill sequences: a Late Quaternary example from the Colorado River, Gulf Coastal Plain of Texas, *in* P. Weimer and H.W. Posamentier, eds, Siliciclastic Sequence Stratigraphy: Recent Developments and Applications: American Association of Petroleum Geologists Memoir, no. 58, p. 259-283.

Bridge, J.S., 1993, Description and interpretation of fluvial deposits: A critical perspective: Sedimentology, v. 40, p. 801–810.

Bridge, J.S., 2003, Rivers and Floodplains; Forms, Processes, and Sedimentary Record: Oxford, U.K., Blackwell, 491 p.

Bridge, J.S., and M.R. Leeder, 1979, A simulation model of alluvial stratigraphy: Sedimentology, v. 26, p. 617–644.

Bridge, J.S., and, S.D. Mackey, 1993, A revisited alluvial stratigraphy model, *in* M. Marzo, C. Puigdéfabregas, eds, Alluvial sedimentation: International Association of Sedimentologists Special Publication 17. p. 319-336.

Bridge, J.S., and R.S. Tye, 2000, Interpreting the dimensions of ancient fluvial channel bars, channels, and channel belts from wireline-logs and cores: American Association of Petroleum Geologists Bulletin, v. 84, p. 1205–1228.

Bridge, J.S., G. Jalfin, and S. Georgieff, 2000, Geometry, lithofacies, and spatial distribution of Cretaceous Fluvial sandstone bodies, San Jorge Basin, Argentina: Outcrop analog for the hydro-carbon bearing Chubut Group: Journal of Sedimentary Research, v. 70, no. 2, p. 341–359.

Boyd, R., C. Diessel, J. Wadsworth, G. Chalmers, M. Little, D. Leckie, and B. Zaitlin, 1999, Development of a nonmarine sequence stratigraphy model: American Association of Petroleum Geologists Annual Meeting, San Antonio, Texas, USA. Official Program, p. A15.

Cant, D.J. and R.G. Walker, 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology, v. 25, p. 625-648.

Carlton, D.R., 2006, Discovery and development of a giant coalbed methane resource, Raton Basin, Las Animas County, Southeast Colorado, *in* S.A. Sonnenberg and E.D. Dolly, eds., Rocky Mountain gas reservoirs revisited: The Mountain Geologist, v. 43, no. 3, p. 231–236.

Carrol, A., and K. Bohacs, 1999, Stratigraphic classification of ancient lakes: Balancing tectonic and climate controls: Geology, v. 27; no. 2; p. 99–102.

Catuneanu, O., 2006, Principles of Sequence Stratigraphy, Elsevier, Oxford, UK., 386 p.

Chapin, C.E., and S.M. Cather, 1981, Eocene tectonics and sedimentation in the Colorado Plateau–Rocky Mountains area, *in* W.R. Dickson, and W.D. Payne, eds., Relations of tectonics to ore deposits in the southern Cordillera: Arizona Geological Society Digest, v. 14, p. 173–198.

Collinson J., 1970, Bedforms of the Tana River, Norway: Geografiska Annaler, Series A, Physical Geography, v. 52, p. 31-56.

Colombera, L., N.P. Mountney, and W.D. McCaffrey, 2015, A meta-study of relationships between fluvial channel-body stacking pattern and aggradation rate: implications for sequence stratigraphy: Geology, v. 43, no. 4, p. 283-286.

Currie, B.S., C.E. Colombi, N.J. Tabor, T.C., Shipman, and I.P. Montañez, 2009, Stratigraphy and architecture of the Upper Triassic Ischigualasto Formation, Ischigualasto Provincial Park, San Juan, Argentina: Journal of South American Earth Sciences, v. 27, p. 74-87.

Dahle, K., K. Flesja, M.R. Talbot, and T. Dreyer, 1997, Correlation of fluvial deposits by the use of Sm-Nd isotope analysis and mapping of sedimentary architecture in the Escanilla Formation (Ainsa Basin, Spain) and the Statfjord Formation (Norwegian North Sea), Abstracts: Sixth International Conference on Fluvial Sedimentology, Cape Town, South Africa, p. 46.

Davies, D.K., B.P.J. Williams, and R.K. Vessell, 1993, Dimensions and quality of reservoirs originating in low and high sinuosity channel systems, Lower Cretaceous Travis Peak Formation, east Texas, USA, *in* C.P. North and D.J. Prosser, eds., Characterization of fluvial and aeolian reservoirs: London Geological Society Special Publication 73, p. 95–121.

Eberth, D.A., and A.D. Miall, 1991, Stratigraphy, sedimentology, and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico: Sedimentary Geology, v. 72, p. 225-252.

Farrell, K.M., 1987, Sedimentology and facies architecture of overbank deposits of the Mississippi River, False River Region, Louisiana, *in* F.G. Ethridge, R.M. Flores, and M.D. Harvey, eds, Recent Developments in Fluvial Sedimentology: Special Publication Society Economic Paleontologists and Mineralogists, Tulsa, v. 39, p. 111–120.

Fisher, J.A., and G.J. Nichols, 2013, Interpreting the stratigraphic architecture of fluvial system in internally drained basins: Journal of Geological Society, v. 170, p 57-65.

Flores, R.M., 1984, Comparative analysis of coal accumulation in Cretaceous alluvial deposits, southern United States Rocky Mountain basins, *in* D.F. Stout, and D. Glass, eds, The Mesozoic of Middle North America: Canadian Society of Petroleum Geologists, Memoir 9, p. 373-385.

Flores, R.M, 1987, Sedimentology of Upper Cretaceous and Tertiary siliciclastics and coals in the Raton Basin, New Mexico and Colorado: New Mexico Geological Society Guidebook, 38th Field Conference, Northeastern New Mexico, p. 255-264.

Flores, R.M., and L.R. Bader, 1999, A summary of Tertiary coal resources of the Raton Basin, Colorado and New Mexico, *in* Resource assessment of selected Tertiary coal beds and zones in the Northern Rocky Mountains and Great Plains Region: U.S. Geological Survey Professional Paper,1625–A, p. 38.

Friend, P.F., 1978, Distinctive features of some ancient river systems, *in* A.D. Miall, ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir, v. 5, p. 531–542.

Friend, P.F., 1989. Space and time analysis of river systems, illustrated by Miocene systems of the northern Ebro Basin in Aragon, Spain: Revista de la Sociedad Geológica de España, v. 2, p. 55–64.

Friend, P.F., M.J. Slater, and R.C. Williams, 1979, Vertical and lateral building of river sandstone bodies, Ebro Basin, Spain: Journal of the Geological Society of London, v. 136, Part 1, p. 39-46.

Gableman, J.V., 1956, Tectonic history of the Kalun Vasin, *in* Guidebook to the geology of the Kalun basin, Colorado: Rocky Mountain Association of Geologists, p. 35-39.

Ghazi, S., and N.P. Mountney, 2009, Facies architectural element analysis of a meandering fluvial succession: The Permian Warchha Sandstone, Salt Range, Pakistan: Sedimentary Geology, v. 221, p. 99-126.

Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record; a literature compilation and classification: Journal of Sedimentary Research, v. 76, p. 731-770

Graham, J.R., 1983, Analysis of the Upper Devonian Munster Basin, an example of a fluvial distributary system, *in* J.D. Collinson, J. Lewin, eds, Modern and Ancient Fluvial Systems: International Association of Sedimentologists, Special Publication, v. 6, p. 473–484.

Hajek, A.E., 2010, Significance of channel–belt clustering in alluvial basins: Geology, v. 38; p.535-538.

Hampson, G.J., S.J. Davies, T. Elliot, S.S. Flint, and H .Stollhofen, 1999, Incised valley fill sandstone bodies in Upper Carboniferous fluvio-deltaic strata: recognition and reservoir characterization of Southern North Sea analogues, Petroleum Geology of Northwest Europe: Proceedings of the 5th conference, Geological Society of London, p. 771-788.

Hampson, G.J., T.O. Jewell, N. Irfan, M.R. Gani, and B. Bracken, 2013, Modest change in Fluvial Style with Varying Accommodation in Regressive Alluvial-to-Coastal-Plain Wedge, Upper Cretaceous Blackhawk Formation, Wasatch Plateau, Central Utah, U.S.A: Journal of Sedimentary Research, v. 83, p. 145-169.

Harms, J, and R. Fahnestock, 1960, Stratification, bed forms, and flow phenomena (with an example from Rio Grande), *in* G. Middleton, ed., Primary sedimentary structures and their hydrodynamic interpretation: Society of Economic Paleontologists and Mineralogists Special Publication 12, p. 84-115.

Harms, J., D. Mackenzie, and D. McCubbin, 1963, Stratification in modern sands of the Red River, Louisiana: Journal of Geology, v. 71, p. 566-580.

Hartley, A.J., G.S. Weissmann, G.J. Nichols, and G.L. Warwick, 2010, Large distributive fluvial systems: Characteristics, distribution, and controls on development: Journal of Sedimentary Research, v. 80, p. 167-183.

Henry, M., and T. Finn, T., 2003, Evaluation of undiscovered natural gas in the Upper Cretaceous Ferron Coal/Wasatch Plateau Total Petroleum System, Wasatch Plateau and Castle Valley, Utah: International Journal of Coal Geology, v. 56, p. 3– 37.

Higley, D.K., 2007, Petroleum systems and assessment of undiscovered oil and gas in the Raton Basin–Sierra Grande Uplift Province, Colorado and New Mexico, *in* D.K. Higley, Petroleum systems and assessment of undiscovered oil and gas in the

Raton Basin–Sierra Grande Uplift Province, Colorado and New Mexico-USGS Province 41: U.S. Geological Survey Digital Data Series DDS–69–N, ch. 2, p.124

Hills, R.C., 1888, The recently discovered Tertiary beds of the Huerfano River basin, Colorado: Colorado Scientific Society, Proceedings, v. 3, p. 148-164.

Hirst, J.P.P., 1991, Variations in alluvial architecture across the Oligo-Miocene Huesca Fluvial System, Ebro Basin, Spain, *in* A.D. Miall, and N. Tyler, eds, The three-dimensional facies architecture of terrigenous clastic sediments and its implications for hydrocarbon discovery and recovery: Society for Sedimentary Geology, Concepts in Sedimentology and Paleontology, v. 3, p. 111–121.

Hirst, J.P.P., and G.J. Nichols, 1986, Thrust Tectonic Controls on the Miocene Alluvial Distribution Patterns, Southern Pyrenees, *in* P.A Allen, and P. Homewood, eds, Foreland Basins: International Association of Sedimentologists, Special Publications, v. 8, p. 247–258.

Holbrook, J., 1996, Complex fluvial response to low gradient at maximum regression: A genetic link between smooth sequence boundary morphology and architecture of overlying sheet sandstone: Journal of Sedimentary Research, v. 66, no. 4, p. 713-722.

Holbrook, J., 2001, Origin, genetic interrelationship, and stratigraphy over the continuum of fluvial channel-form bounding surface: An illustration from middle Cretaceous strata, Southeastern Colorado, Sedimentary Research, v. 144, p. 179-222.

Holbrook, J., R.W. Scott, and F. Oboh-Ikuenobe, 2006, Base-level buffers and buttresses: A model for upstream versus downstream control on fluvial geometry and architecture within sequences: Journal of Sedimentary Research, v. 76, no. 1, p. 162-174.

Hoorn, C., 1994, Fluvial Palaeoenvironments in the Intracratonic Amazonian Basin (Early Miocene to Early Middle Miocene, Colombia): Palaeogeography, Palaeoclimatology, Palaeoecology, v. 109, p. 1-55.

Hopkins, J., 1985, Channel-fill deposits formed by aggradation in deeply scoured, superimposed distributaries of the Lower Kootenai Formation: Journal of Sedimentary Petrology, v. 55, p. 42-52.

Horsfield, B., D.J. Curry, K. Bohacs, R. Littke, J. Rullkötter, H.J. Schenk, M. Radke, R.G. Schaefer, A.R. Carroll, G. Isaksen, E.G. Witte, 1994, Organic geochemistry of freshwater and alkaline lacustrine sediments in the Green River Formation of the Washakie Basin, Wyoming, U.S.A.: Organic Geochemistry, v. 22, p. 415–440.

Huling, G.A., 2014, Evidence for Clustering of Delta-lobe Reservoirs within Fluvio-lacustrine Systems, Jurassic Kayenta Formation, Utah, M.S. thesis, Texas Christian University, Fort Worth, Texas, 73 p.

Hurbert, J., and M. Hyde, 1983, Sheet flow deposits of graded beds and mudstones on an alluvial sandflat-playa system: Upper Triassic Blomidon redbeds, St. Mary's Bay, Nova Scotia: Sedimentology, v. 29, p. 457-474.

Izett, G.A., 1987, The Cretaceous-Tertiary (K-T) boundary interval, Raton Basin, Colorado and New Mexico, and its content of shock-metamorphosed minerals; implication concerning the K-T boundary impact-extinction theory: U. S. Geological Survey Open-File Report 87-606. 125 p.

Jervey, M.T., 1988, Quantitative geological modeling of siliciclastic rock sequences and their seismic expression, *in* C.K. Wilgus, B.S. Hastings, C.G.S.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, eds., Sea-Level Changes: an Integrated Approach: Society of Economic Paleontologists and Mineralogists, Special Publications, v. 42, p. 47–69.

Johnson, R.B., and G.H. Wood Jr., 1956, Stratigraphy of Upper Cretaceous and Tertiary rocks of Raton Basin, Colorado and New Mexico: American Association of Petroleum Geologists Bulletin, v. 40, no. 4, p. 707–721.

Johnson. R.B., G.H. Dixon, and A.A. Wanek, 1966, Late Cretaceous and Tertiary stratigraphy of the Raton Basin in New Mexico and Colorado: New Mexico Geological Society, Guidebook, p. 88-98.

Johnson, R.C., and T.M. Finn, 2001, Potential for a basin-centered gas accumulation in the Raton Basin, Colorado and New Mexico, *in* V.F. Nuccio, and T.S. Dyman, eds., Geologic studies of basin-centered gas systems: U.S. Geological Survey Bulletin 2184B, 18 p.

Jordan, D.W., and W.A. Pryor, 1992, Hierarchical Levels of Hetrogeneity in a Mississippi River Meander Belt and Application to Revervoir Systems: American Association of Petroleum Geologists Bulletin, v. 76, no. 10, p. 1601-1624.

Kelly, S.B., and H. Olsen, 1993, Terminal fans: A review with references to Devonian examples: Sedimentary Geology, v. 85, p. 339–374.

Kirschbaum, M., and P. McCabe, 1992, Controls on the accumulation of coal and on the development of anastomosed fluvial system in the Cretaceous Dakota Formation of southern Utah: Sedimentology. v. 39, p. 581-598.

Kraus, M., 1999, Paleosols in clastic sedimentary rocks: their geologic applications. Earth-Science Reviews, v. 47, p. 41–70.

Kraus, M., 2002, Basin-scale changes in floodplain paleosols: implications for interpreting alluvial architecture. Journal of Sedimentary Research, v. 72, no. 4, p. 500–509.

Kraus, M., and, T. Wells, 1999, Recognizing avulsion deposits in ancient stratigraphical record: Special Publications International Association of Sedimentology, v. 28, p. 251–268.

Lang, S.C., T.H.D. Payenberg, M.R.W. Reilly, T. Hicks, J. Benson, and J. Kassan, 2004, Modern analogues for dryland sandy fluvial-lacustrine deltas and terminal splay reservoirs: Australian Petroleum Production Exploration Association Journal, v. 44, p. 329–356.

Larue, D.K. and F. Friedmann, 2005, The controversy concerning stratigraphic architecture of channelized reservoirs and recovery by water flooding: Petroleum Geosciences, v. 11, p. 131–146.

Larue, D.K., and J. Hovadik, 2006, Connectivity of channelized reservoirs: a modeling approach: Petroleum Geoscience, v. 12, p. 291–308.

Lee, W.T., 1917, Geology of the Raton Mesa and other regions in Colorado and New Mexico, *in* W.T. Lee, and F.H. Knowlton, eds., Geology and Paleontology of Raton Mesa and other regions in Colorado and New Mexico: U.S. Geological Survey Professional Paper 101, p. 450.

Leeder, M.R., 1978, A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness: Canadian Society of Petroleum Geologists Memoir 5, p. 587–596.

Legarreta, L., M. A. Uliana, C. A. Larotonda, and G. R. Meconi, 1993, Approaches to nonmarine sequence stratigraphy: theoretical models and examples from Argentine basins, *in* R. Eschard and B. Doligez, eds., Subsurface reservoir characterization from outcrop observations: Collection Colloques et Seminaires, Institut Fracais du Petrole, v. 51, p. 125-143.

Lawton, T.F., 2008, Laramide Sedimentary Basin, *in* K.J. Hsu and A.D. Miall, eds, The Sedimentary Basins of the World: The Sedementary Basins of the United States and Canada, v. 5, p. 429-446.

Lunt, I., J.S Bridge, R.S. Tye, 2004, A quantitative three-dimensional depositional model of Gravelly braided rivers: Sedimentology, v. 51, p. 377-414.

MacCarthy, I.A.J., 1990, Alluvial sedimentation patterns in the Munster Basin, Ireland: Sedimentology, v. 37, p. 685–712.

Mackey, S.D., and J.S. Bridge, 1995, Three-dimensional model of alluvial stratigraphy: Theory and applications: Journal of Sedimentary Research, Section B: Stratigraphy and Global Studies, v. 65, p. 7-31.

Martinsen, O. J., W. Helland-Hansen, G. P. Allen, and H.W. Posamentier, 1994, Sequence stratigraphy and facies model of an incised valley fill: The Gironde estuary, France; discussion and reply: Journal of Sedimentary Research, Section B: Stratigraphy and Global Studies, v. 64, no. 1, p. 78-84.

Martinsen, O.J., A., Ryseth, W. Helland-Hansen, H. Flesche, G. Torkildsen, and S. Idil, 1999, Stratigraphic base level and fluvial architecture, Ericson Sandstone (Campanian), Rock Springs Uplift, SW. Wyoming, U.S.A.: Sedimentology, v. 46, p. 235–259.

McCarthy, P.J., U.F. Faccini, and A.G. Plint, 1999, Evolution of an ancient coastal plain: paleosols, interfluves and alluvial architecture in a sequence stratigraphic framework, Cenomanian Dunvegan Formation, NE British Columbia, Canada: Sedimentology, v. 46, p. 861-891.

Merin, I.S., J.R. Everett, and P.R. Rose, 1988, Tectonic evolution and structural geology of the Raton Basin, Colorado and New Mexico, and Huerfano Park, Colorado, *in*: L.L. Sloss, ed., Sedimentary Cover - North American Craton: Geological Society of America, Decade of North American Geology, v. D–2, p. 170–179.

Miall, A.D., 1977, A review of braided river depositional environment: Earth-Science Reviews, p. 13:1-62.

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

Miall, A.D., 1988, Reservoir heterogeneities in fluvial sandstones: lessons from outcrop studies: American Association of Petroleum Geologists Bulletin, v. 72, p. 682-697.

Miall, A.D., 1996, The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology. Springer, Berlin, 524 p.

Miall, A.D., 2014, Fluvial Depositional Systems. Berlin, Springer, 316 p.

Murray, A., and C. Paola, 2003, Modeling the effect of vegetation on channel pattern in bedload rivers: Earth Surface Processes Landforms, v. 28, p. 131–143.

Ney, J.M., 2015, Testing the distributary channel model against predicted changes in fluvial reservoir geometry during transitions from low to high accommodation settings: Upper Pennsylvanian of the central Appalachian Basin. M.S. thesis, Texas Christian University, Fort Worth, Texas, 74 p.

Nichols, G.J., and J.A. Fisher, 2007, Processes, facies and architecture of fluvial distributary system deposits: Sedimentary Geology, v. 195, p. 75-90.

Nichols, G.J., 1987. Structural controls on fluvial distributary systems–the Luna System, Northern Spain, in F.G. Ethridge, R.M. Florez, and M.D. Harvey, eds., Recent Developments in Fluvial Sedimentology: Society of Economic Paleontologists and Mineralogists, Special Publication, vol. 39, pp. 269–277.

Olsen, T., R. Steel, K. Høgseth, T. Skar, and S-L. Roe, 1995, Sequential architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesa Verde Group, Price Canyon, Utah: Journal of Sedimentary Research B65, p. 265-280.

Olsen, H., 1987, Ancient ephemeral stream deposits: A local terminal fan model from Bunter Sandstone Formation (L. Triassic) in the Tronder -3, -4 and -5 wells, Denmark, *in* L. Frostick, and I. Reid, eds, Desert sediments: Ancient and modern: Special Publication Geological Society of London. P. 69-89.

Payton, C.E., 1977, Seismic Stratigraphy Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists, Memoirs, 26.

Pillmore, C.L., 1969, Geologic map of the Casa Grande quadrangle, Colfax County, New Mexico, and Las Animas County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-823, scale 1:62,500.

Pillmore, C.L., and R.M Flores, 1987, Stratigraphy and depositional environments of the Cretaceous-Tertiary boundary clay and associated rocks, Raton Basin, New Mexico and Colorado, *in* J.E. Fassett, and, J.K. Rigby Jr., eds., The Cretaceous-

Tertiary Boundary in the San Juan and Raton Basins, New Mexico and Colorado: Geological Society of America, Special Paper 209, p. 111-130.

Platt, N., and B. Keller, 1992, Distal alluvial deposits in a foreland basin setting- the lower fresh water Molasse (lower Miocene), Switzerland: Sedimentology, architecture and paleosols: Sedimentology, v. 39, p. 545-565.

Plint, A.G., and J. Wadsworth, 2003, Sedimentary and paleogeomorphology of four large valley systems incising delta plains, western Canada Foreland Basin: Implications for mid-Cretaceous sea-level changes: Sedimentology, v. 50, p. 1147-1186.

Plint, A.G., P. McCarthy, and U. Faccini, 2001, Non-marine sequence stratigraphy: Updip expression of sequence boundaries and system tract in high-resolution framework, Cenomanian Dunvegan Formation, Alberta Foreland Basin, Canada, American Association of Petroleum Geologists Bulletin, v. 11, p. 1967-2001.

Porter, K., and S. Sonnenberg, 1994, Overview of criteria for recognition and mapping valley fills and associated surface: Lower Cretaceous Muddy sandstone, Rocky Mountain Region: Rocky Mountain Association of Geologists, Unconformity controls symposium, p. 157-166.

Posamentier, H.W., 2001, Lowstand alluvial bypass systems: incised vs. unincised: American Association of Petroleum Geologists Bulletin, v. 85, no. 10, p. 1771-1793.

Posamentier, H.W., and P.R. Vail, 1988, Eustatic controls on clastic deposition II sequence and systems tract models, *in* C.K. Wilgus, B.S. Hastings, C.G.S.C. Kendall, H.W. Posamentier, C.A. Ross, and J.C. Van Wagoner, eds., Sea-Level Changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publications 42, 125–154.

Posamentier H.W., and G.P. Allen, 1999, Siliciclastic Sequence Stratigraphy Concepts and Applications, Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology 7, 204 p.

Powell, J.W., 1875, Exploration of the Colorado River of the West and its Tributaries. Explored in 1869, 1870, 1871, and 1872, under the direction of the Secretary of the Smithsonian Institution, Government Printing Office, Washington, D. C., 291 p.

Reading, H., 1996, Sedimentary environments: processes, facies and stratigraphy. Madeline: Wiley-Blackwell Publishing. 3rd ed, 704 p.

Reijenstein, H.M., H.W. Posamentier, and J.P. Bhattacharya, 2011, Seismic geomorphology and high-resolution seismic stratigraphy of inner-shelf fluvial, estuarine, deltaic, and marine sequences, Gulf of Thailand: American Association of Petroleum Geologists Bulletin, v. 95, no. 11, p. 1959-1990.

Rigby, J.K. and W.K. Hamblin, eds., 1972, Recognition of ancient sedimentary environments: Society of Economic Paleontologists and Mineralogists Special Publication 16, 340 p.

Roehler, H.W, 1992, Correlation, composition, areal distribution, and thickness of Eocene stratigraphic units, greater Green River basin, Wyoming, Utah, and Colorado: U.S. Geological Survey Professional Paper 1506-E, p. 49.

Sadler, S.P., and S.B. Kelly, 1993, Fluvial processes and cyclicity in terminal fan deposits: an example from the Late Devonian of Southwest Ireland: Sedimentary Geology, v. 85, p. 375-386.

Schumm, S.A., 1993, River response to base level change; implications for sequence stratigraphy: Journal of Geology, v. 101, p. 279-294.

Shanley, K.W., and, P.J. McCabe, 1994, Perspectives on the sequence stratigraphy of continental strata: American Association of Petroleum Geologists Bulletin, v. 78, no. 4, p. 544-568.

Shanley, K.W. and P.J. McCabe, 1993, Alluvial architecture in a sequence stratigraphic framework: A case history from the Upper Cretaceous of southern Utah, USA, *in* S.S. Flint and I.D. Bryant, eds, The Geologic Modeling of Hydrocarbon Reservoirs and Outcrop Analogues: International Association of Sedimentology Special Publication, v. 15, p. 21–56.

Smith, N.D., 1970, The braided stream depositional environment: comparision of the Platte River with some Silurian clastic rocks, north-central Appalachians: Bulletin of the Geological Society of America, v. 81, p. 2993-3014.

Smith, N., 1972, Some sedimentological aspects of planar cross-stratification in sandy braided river: Journal of Sedimentary Petrology, v. 42, p. 624-634.

Sneh, A., 1983, Desert stream sequences in the Sinai Peninsula: Journal of Sedimentary Petrology v. 53, p. 1271-1280.

Stevens, S.H., T.E. Lombardi, B.S. Kelso, and J.M. Coates, 1992a, A geologic assessment of natural gas from coal seams in the Raton and Vermejo Formations, Raton Basin: Gas Research Institute (GTI), 1700 South Mount Prospect Road, Des Plaines, IL, 60018, GRI Report no. 5091–214–2316, p. 91.

Stevens, S.H., T.E. Lombardi, B.S. Kelso, and J.M. Coates, 1992b, Geological assessment of natural gas from coal seams in the Raton and Vermejo Formations, Raton Basin, Gas Research Institute Topical Report January 1991–June 1992, GRI-92/0345, p. 87.

Straub, J., J. Hill, R. Viso, R. Peterson, and M. Carter, 2014, Fluvial Morphology and Bedform in Ebb Tidal Dominated Duplin River, Georgia. American Geophysical Union, Fall Meeting 2014, San Francisco, abstract EP31B-3545.

Straub, K.M., C. Paola, D. Mohrig, M.A. Wolinsky, and T. George, 2009, Compensational Stacking of Channelized Sedimentary Deposits: Journal of Sedimentary Research, v. 79, p. 673-688.

Strong, N., and C. Paola, 2008, Valleys that never were: Time surfaces versus stratigraphic surfaces: Journal of Sedimentary Research, v. 78, p. 579-593.

Strum, S., 1985, Lithofacies and depositional environments of the Raton Formation (Upper Cretaceous-Paleocene) of northeastern New Mexico: North Carolina State University, M.S. thesis, North Carolina State University, Raleigh, North Carolina. 81 p.

Thomas, R., D. Smith, J. Wood, J. Visser, E. Calverly, E. Koster, 1987, Inclined heterolithic stratification-terminology, description, interpretation and significance: Sedimentary Geology, v. 53: p. 123-179.

Tremain, C.M., 1980, The coal bed methane potential of the Raton Mesa coal region, Raton Basin, Colorado: Colorado Geological Survey Open–File 80-4, 48 p., 2 pls.

Tschudy, R.H., C.L. Pillmore, C.J. Orth, J.S. Gilmore, and J.D. Knight, 1984, Disruptions of the terrestrial plant ecosystem at the Cretaceous-Tertiary boundary, Western Interior: Science, v. 225, no. 4666, p. 1030-1034.

Tunbridge, I.P., 1984, Facies models for a sandy ephemeral stream and clay playa complex, the Middle Devonian Trentishoe Formation of North Devon, UK: Sedimentology, v. 31, p. 697-716.

Tweto, Ogden, 1975, Laramide (Late Cretaceous–early Tertiary) orogeny in the southern Rocky Mountains, *in* B. Curtis, ed., Cenozoic Geology of the Southern Rocky Mountains: Geologic Society of America Memoir 144, p. 1–44.

Tyler, K., A. Henriquez, and T. Svanes, 1995, Modeling heterogeneities in fluvial domains: A review on the influence on production profile, *in* J.M. Yarus, and R.L. Chambers, eds., Stochastic Modeling and Geostatistics: Principles, Methods, and Case Studies: AAPG Computer Applications in Geology, v. 3, p. 77–89.

Tyler, N., and R. Finley, 1991, Architecture controls on the recovery of hydrocarbons from sandstone reservoirs, *in* D. Miall, and N. Tyler, eds., The three dimensional facies architecture of terrigenous clastic sediments and its implication for hydrocarbon discovery and recovery: Society of Economic Paleontologists and Mineralogists Concepts in Sedimentology and Paleontology, v. 3, p. 1-5.

Tyler, N., W.E. Galloway, C.M Garrett, Jr, and T.E. Ewing, 1984, Oil Accumulation, Production Characteristics, and Targets for Additional Recovery in Major Reservoirs of Texas: The University of Texas, Bureau of Economic Geology, Geological Circular, 84 2, 31 p.

Vail, P.R., R.M. Mitchum, and S. Thompson, 1977, Seismic Stratigraphy and Global Changes of Sea Level, Part III. Relative Changes of Seal Level From Coastal Onlap, *in* C.E. Payton, eds., Seismic Stratigraphy Applications to Hydrocarbon Exploration, American Association of Petroleum Geologists, Memoir 26, p. 63-82.

Van Wagoner J.C., R.M. Mitchum, K.M. Campion, V.D. Rahmanian, 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores and Outcrops, Methods in Exploration 7: American Association of Petroleum Geologists, Tulsa, Oklahoma.

Walker, R., 1992, Facies, facies models and modern stratigraphic concepts, *in* R. Walker, and N. James, eds., Facies models: response to sea level change: Geological Association of Canada, St John's, Newfoundland, p. 1-14.

Weissmann, G.S., A. Hartley, G. Nichols, L. Scuderi, M. Olson, H. Buehier, and R. Banteah, 2010, Fluvial form in modern continental sedimentary basins: Distributive fluvial systems: Geology, v. 38, p. 39–42.

Weissmann, G.S., A. Hartley, G. Nichols, L. Scuderi, M. Olson, H. Buehler, and L. Massengill, 2011, Alluvial facies distributions in continental sedimentary basins distributive fluvial systems, *in* S. Davidson, S. Leleu, and C. North, eds, From River to Rock Record: The Preservation of Fluvial Sediments and their Subsequent Interpretation: Society of Economic Paleontologists and Mineralogists Special Publication 97: Tulsa, Oklahoma. p. 327–355

Weissmann, G.S., A. Hartley, L. Scuderi, G. Nichols, S. Davidson, A. Owen, P. Bhattacharyya, T. Chakbraborty, P. Ghosh, L. Nordt, L. Michel, and N. Tabor, 2013, Prograding distributive fluvial systems- geomorphic models and ancient examples: Society of Economic Paleontologists and Mineralogists Special Publication 104, p. 131-147.

Willis, B., 1997, Architecture of fluvial-dominated valley-fill deposits in the Cretaceous Fall Formation: Sedimentology, v. 44, p. 735-57.

Willis, B.J., and A.K. Behrensmeyer, 1994, Architecture of Miocene overbank deposits in northern Pakistan: Journal of Sedimentary Research, B64, p. 60–67.

Willis, B.J., and A.K. Behrensmeyer, 1995, Reply to Comment by J. S. Bridge on Architecture of Miocene overbank deposits in northern Pakistan: Journal of Sedimentary Research B65, p. 403-407.

Wright, V.P., and S.B. Marriott, 1993, The sequence stratigraphy of fluvial depositional systems: The role of floodplain storage: Sedimentary Geology, v. 86, p. 203–210.

Woodward, L., 1983, Geology and Hydrocarbon Potential of the Raton Basin, New Mexico: Four Corners Geological Society, v. III, p. 789-798.

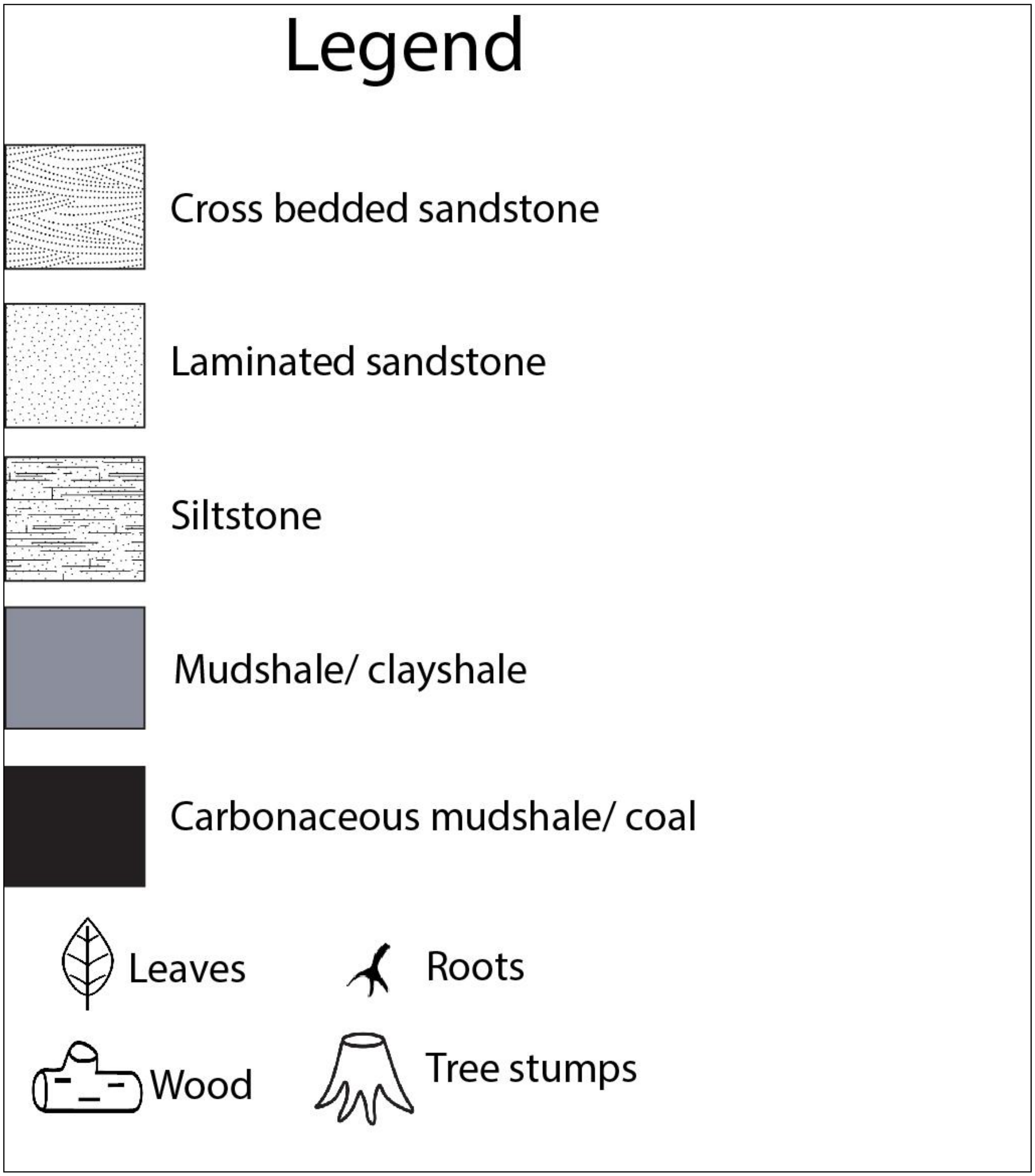
Zaitlin, B., R. Dalrymple, and R. Boyd, 1994, The stratigraphic organization of incised valley systems associated with sea level changes, *in* R. Dalrymple, R. Boyd., and B. Zaitlin, eds., Incised valley systems: Origin and sedimentary sequences: Society of Economic Paleontologists and Mineralogists Special Publication 51, p. 45-60.

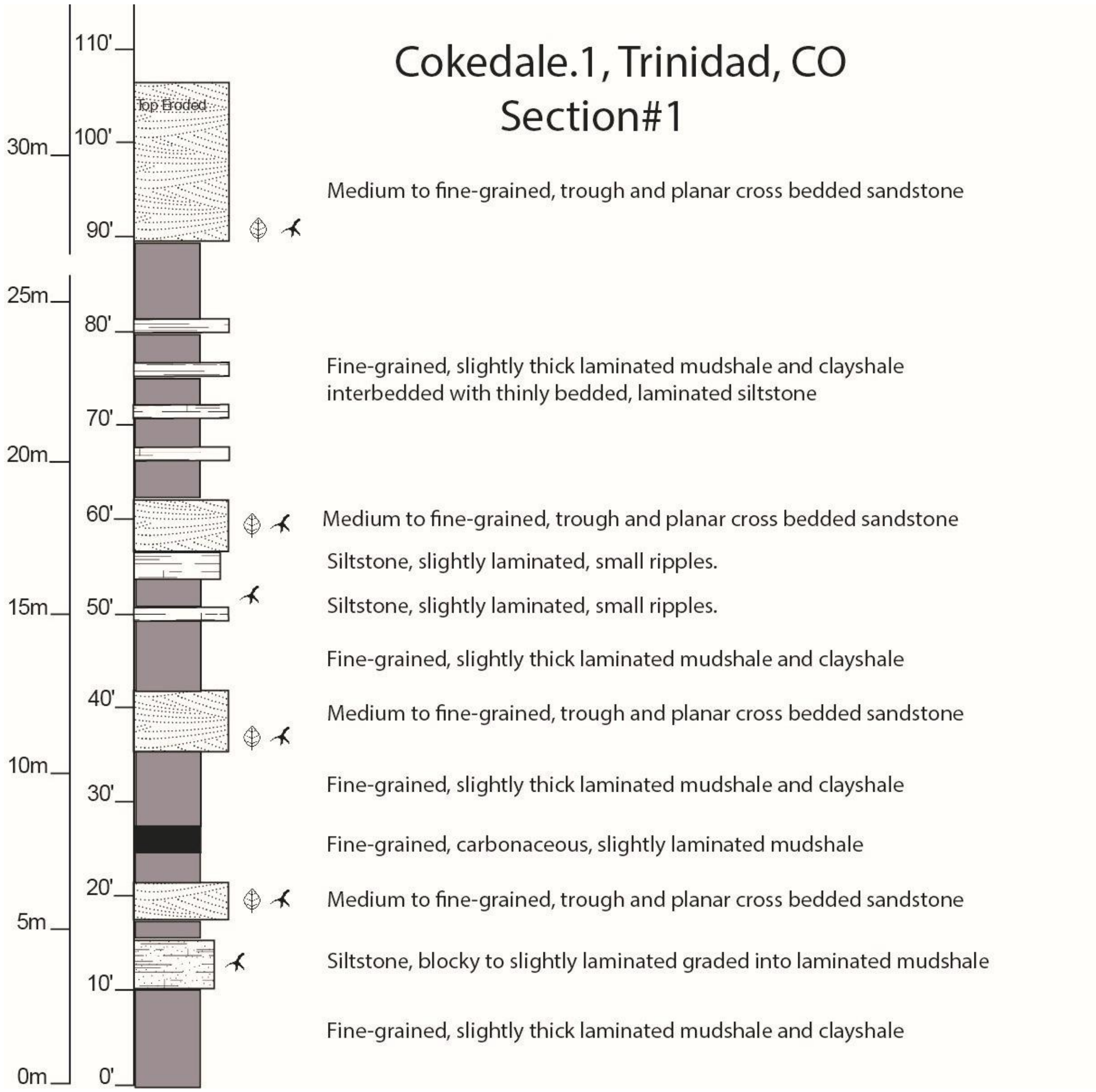
Zaleha, M.J., 1997, Fluvial and lacustrine palaeoenvironments of the Miocene Siwalik Group, Khaur area, northern Pakistan: Sedimentology, v. 44, p. 349-368.

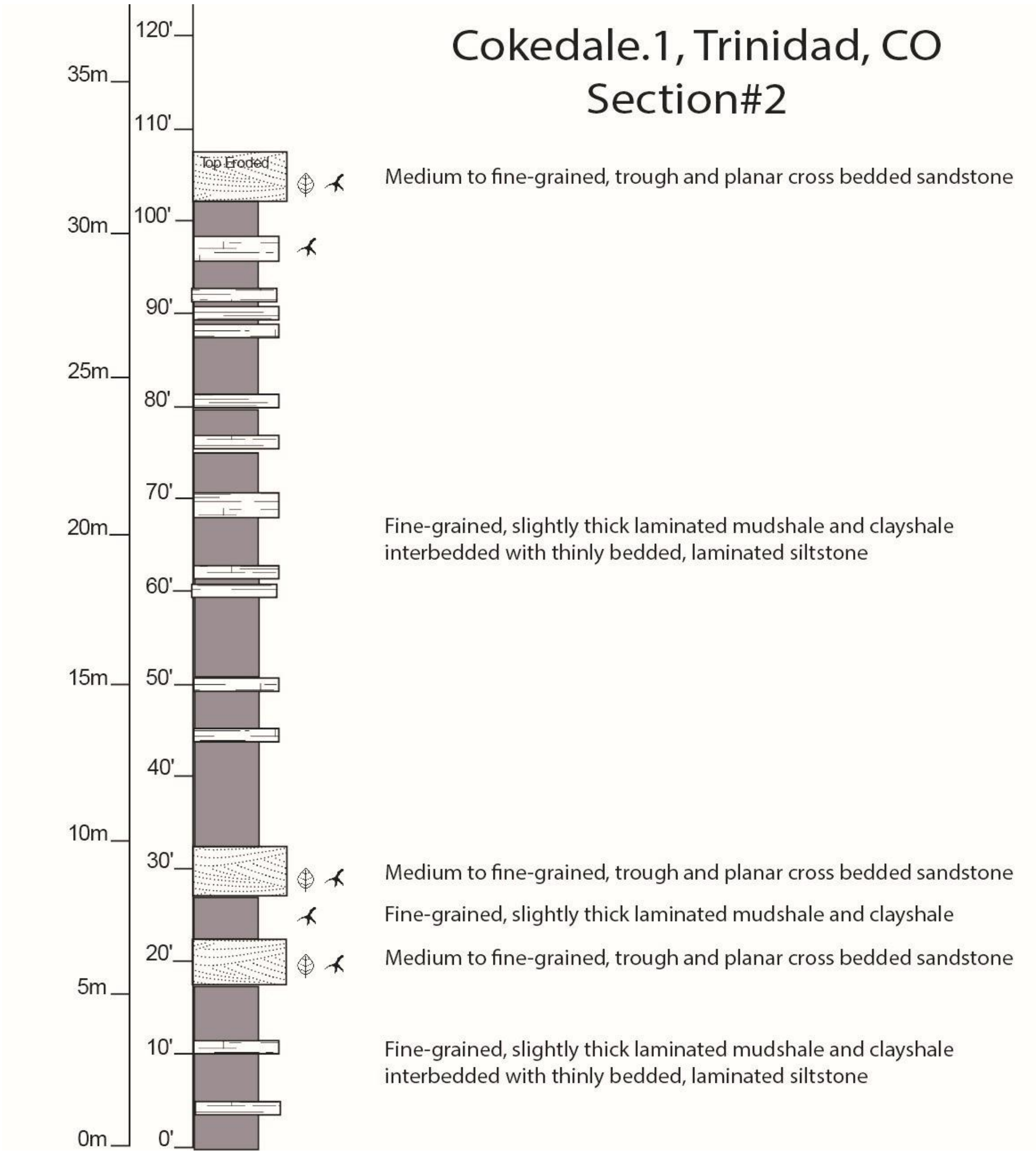
Appendix A

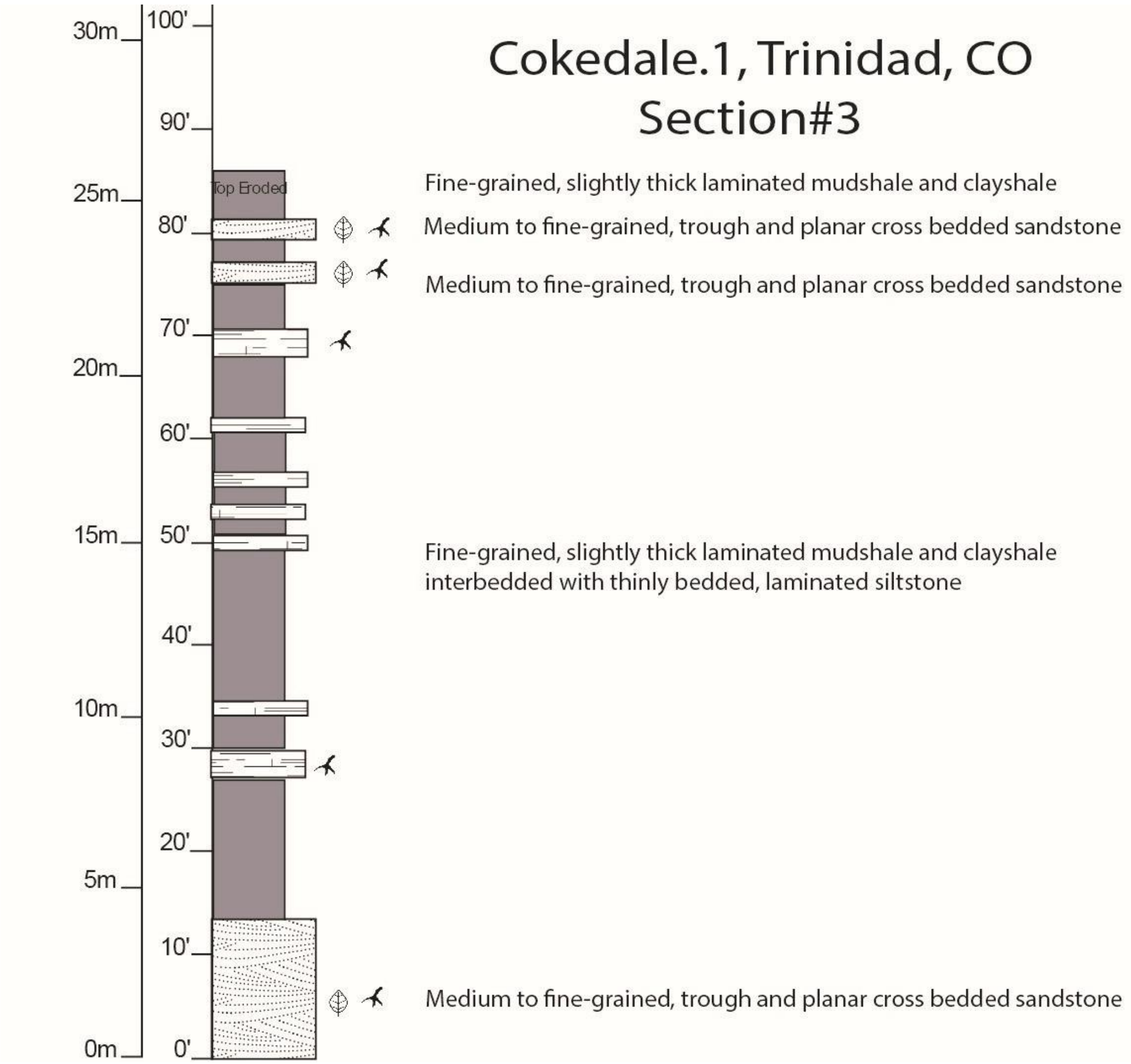
Measured sections

Description: Detailed measured sections that were constructed for the five study area outcrops. Location of each measured sections is marked on the study area outcrop photographs in the supplementary files Cokedale.1_sections.jpg, Cokedale.2_sections.jpg, Valdez.1_sections.jpg, Valdez.2A_sections.jpg, and Valdez.2B_sections.jpg

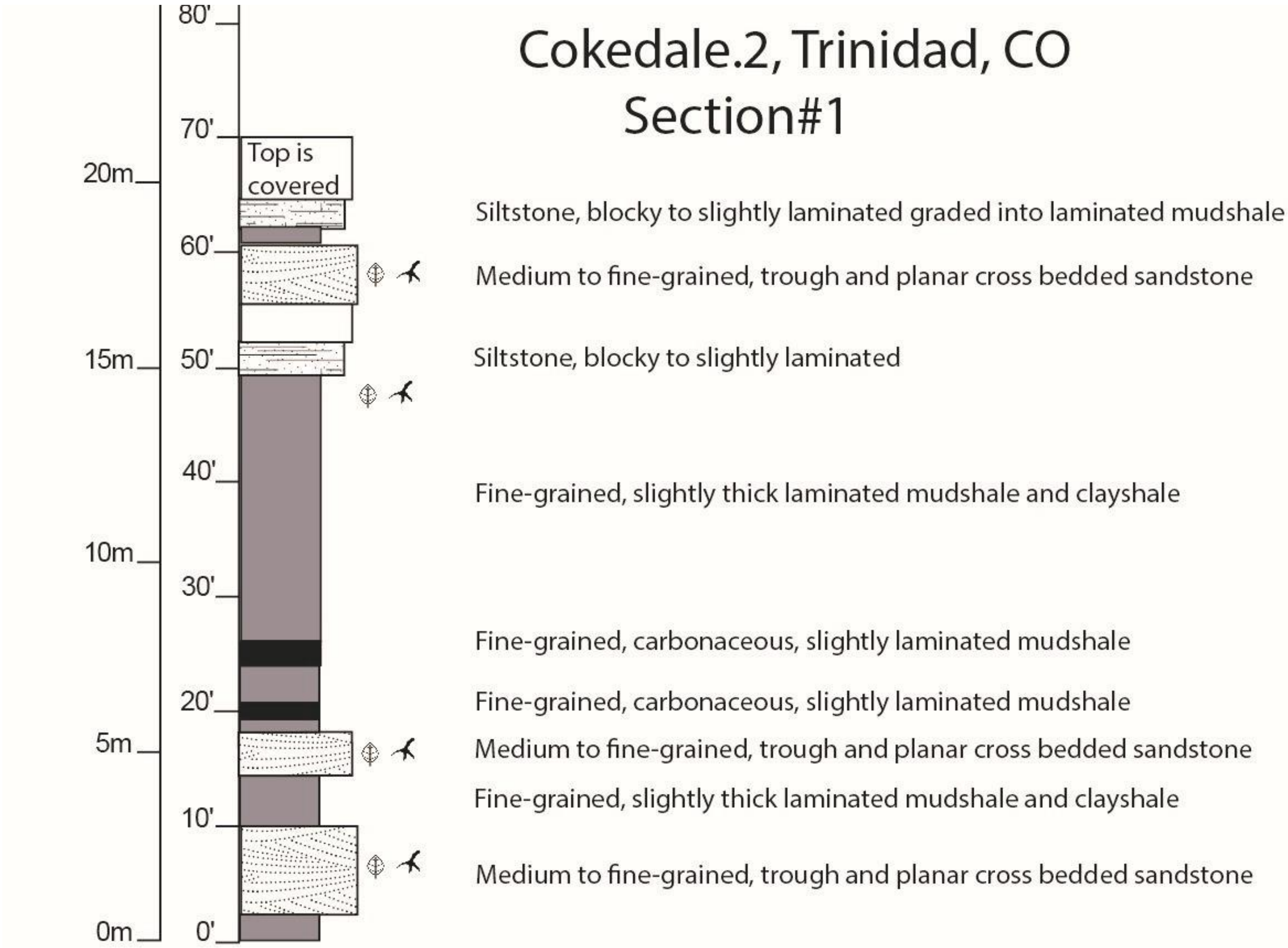

Legend
Cross bedded sandstone
Laminated sandstone
Siltstone
Mudshale/ clayshale
Carbonaceous mudshale/ coal
Leaves
Roots
Wood
Tree stumps


Cokedale.1, Trinidad, CO
Section#1
110'
100'
90'
80'
70'
60'
50'
40'
30'
20'
10'
0'
30m
25m
20m
15m
10m
5m
0m
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with thinly bedded, laminated siltstone
Medium to fine-grained, trough and planar cross bedded sandstone
Siltstone, slightly laminated, small ripples.
Siltstone, slightly laminated, small ripples.
Fine-grained, slightly thick laminated mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale
Fine-grained, carbonaceous, slightly laminated mudshale
Medium to fine-grained, trough and planar cross bedded sandstone
Siltstone, blocky to slightly laminated graded into laminated mudshale
Fine-grained, slightly thick laminated mudshale and clayshale

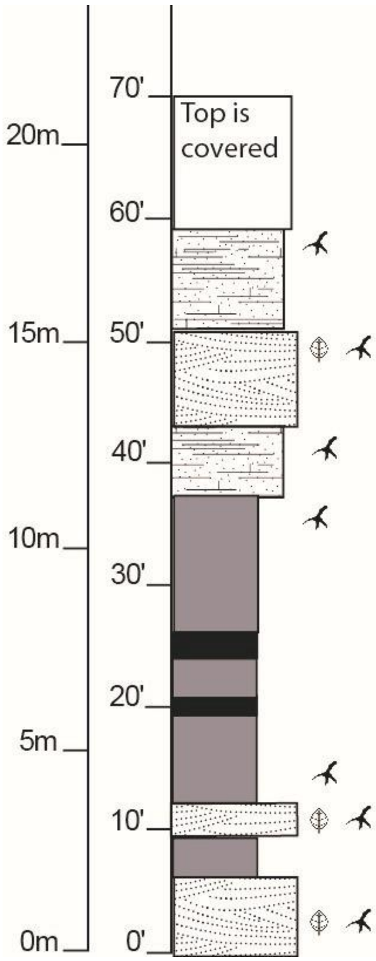

Cokedale.1, Trinidad, CO
Section#2
35m
30m
25m
20m
15m
10m
5m
0m
120'
110'
100'
90'
80'
70'
60'
50'
40'
30'
20'
10'
0'
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with thinly bedded, laminated siltstone
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with thinly bedded, laminated siltstone



Cokedale.1, Trinidad, CO
Section#3
30m
25m
20m
15m
10m
5m
0m
100'
90'
80'
70'
60'
50'
40'
30'
20'
10'
0'
Top Eroded
Fine-grained, slightly thick laminated mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with thinly bedded, laminated siltstone
Medium to fine-grained, trough and planar cross bedded sandstone


Cokedale.2, Trinidad, CO
Section#1
80'
70'
Top is covered
20m
Siltstone, blocky to slightly laminated graded into laminated mudshale
60'
Medium to fine-grained, trough and planar cross bedded sandstone
15m
50'
Siltstone, blocky to slightly laminated
40'
Fine-grained, slightly thick laminated mudshale and clayshale
10m
30'
Fine-grained, carbonaceous, slightly laminated mudshale
20'
Fine-grained, carbonaceous, slightly laminated mudshale
5m
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale
10'
Medium to fine-grained, trough and planar cross bedded sandstone
0m
0'

Cokedale.2, Trinidad, CO
Section#2



Siltstone, blocky to slightly laminated graded into laminated mudshale

Medium to fine-grained, trough and planar cross bedded sandstone

Siltstone, blocky to slightly laminated graded into laminated mudshale

Fine-grained, slightly thick laminated mudshale and clayshale

Fine-grained, carbonaceous, slightly laminated mudshale

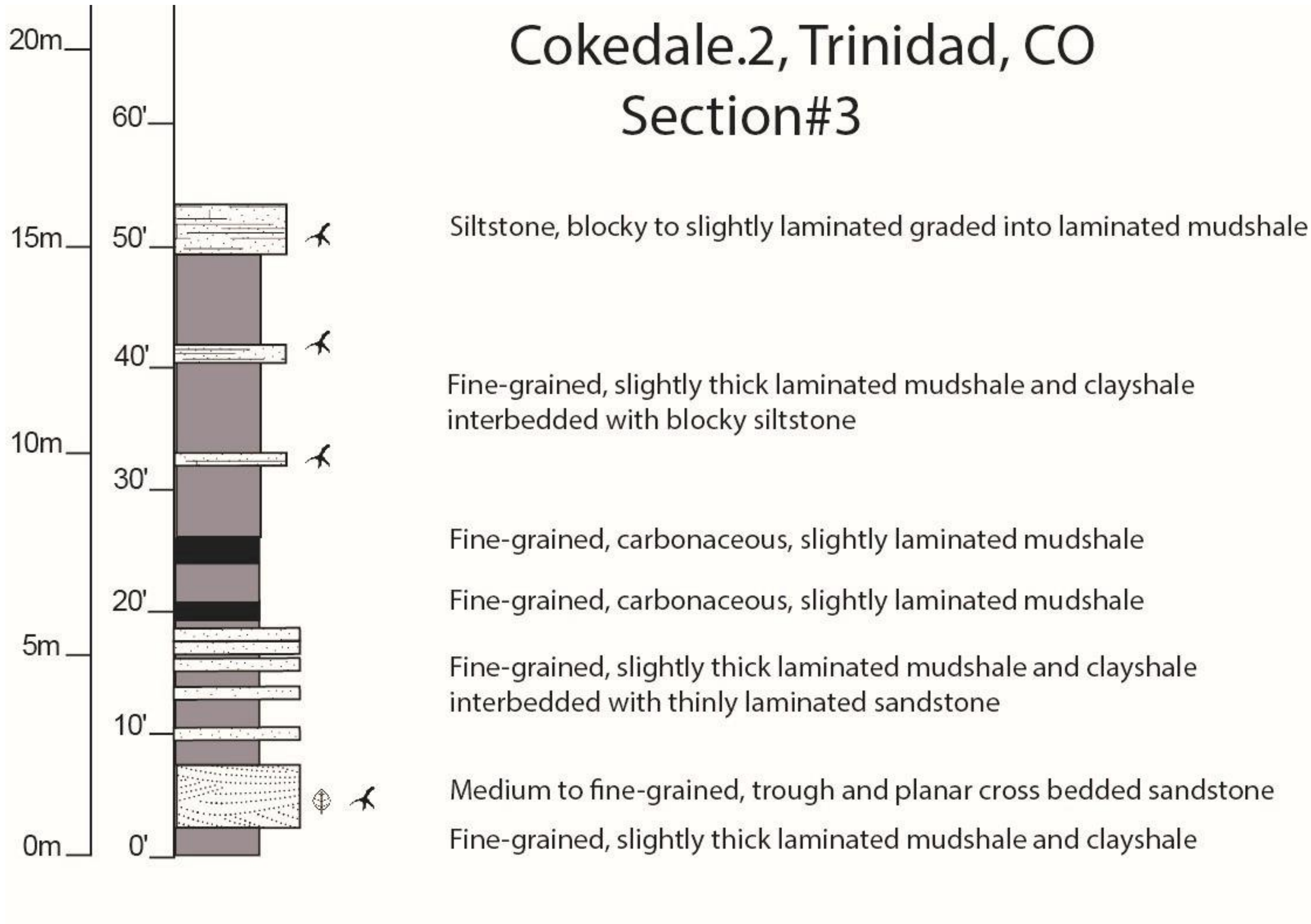
Fine-grained, carbonaceous, slightly laminated mudshale

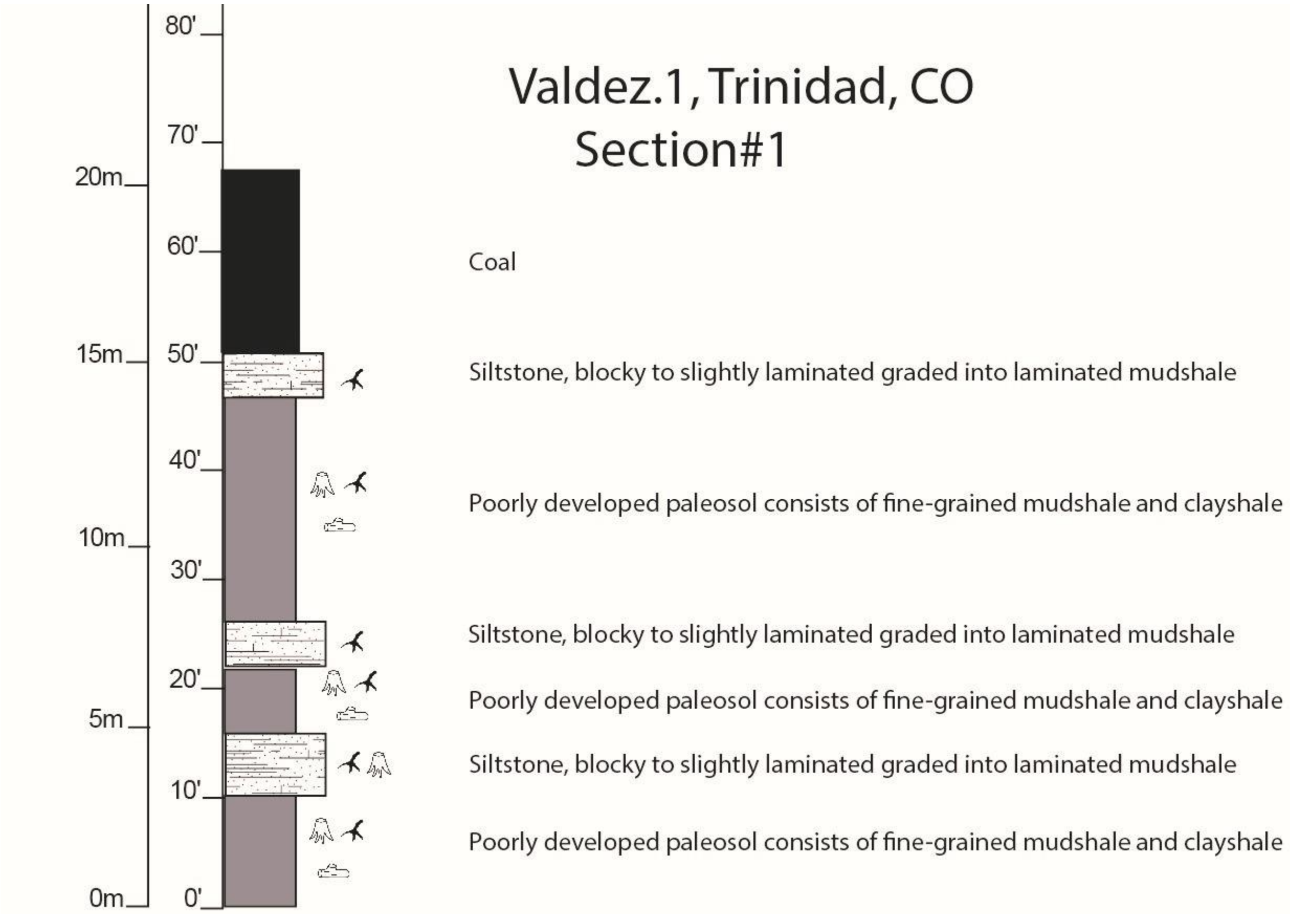
Fine-grained, slightly thick laminated mudshale and clayshale

Medium to fine-grained, trough and planar cross bedded sandstone

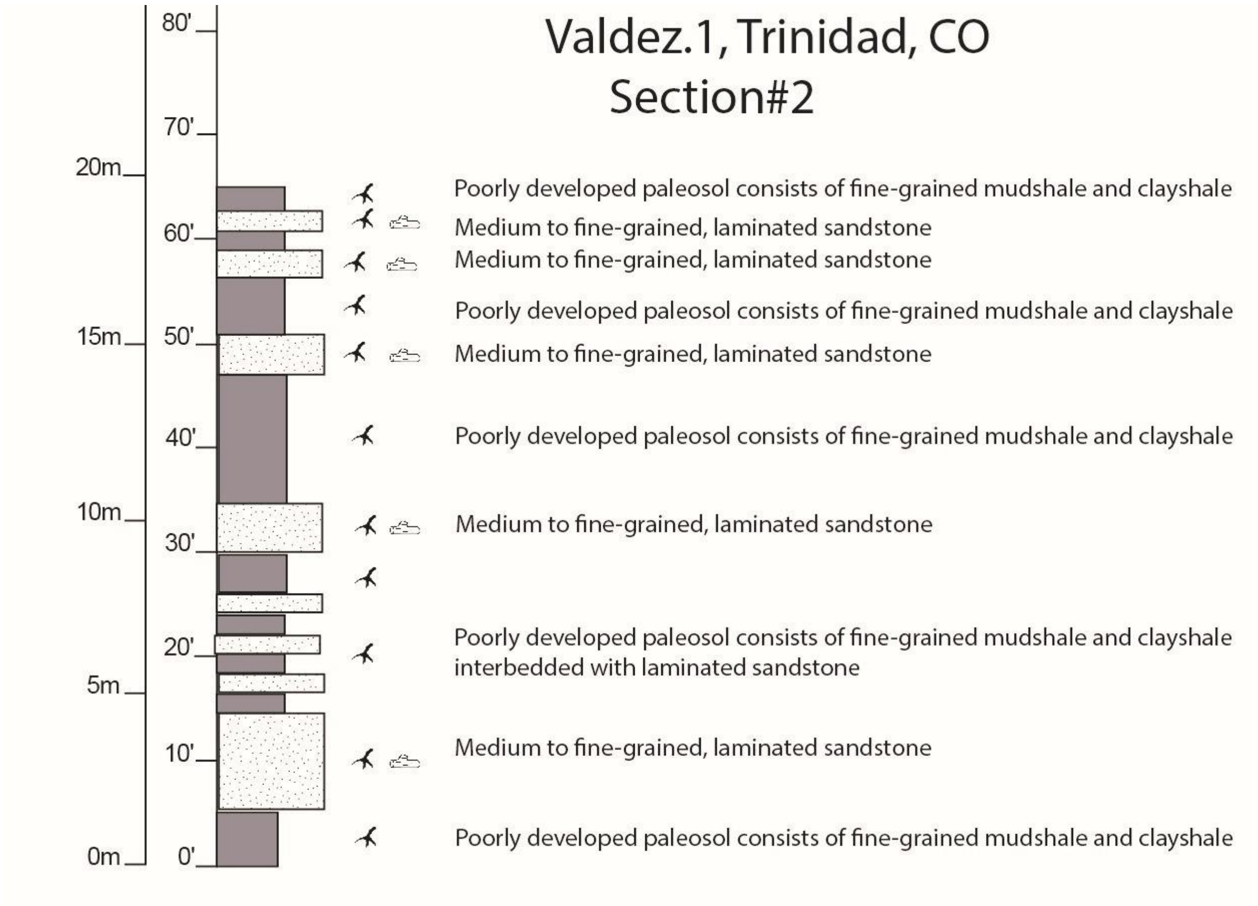
Fine-grained, slightly thick laminated mudshale and clayshale

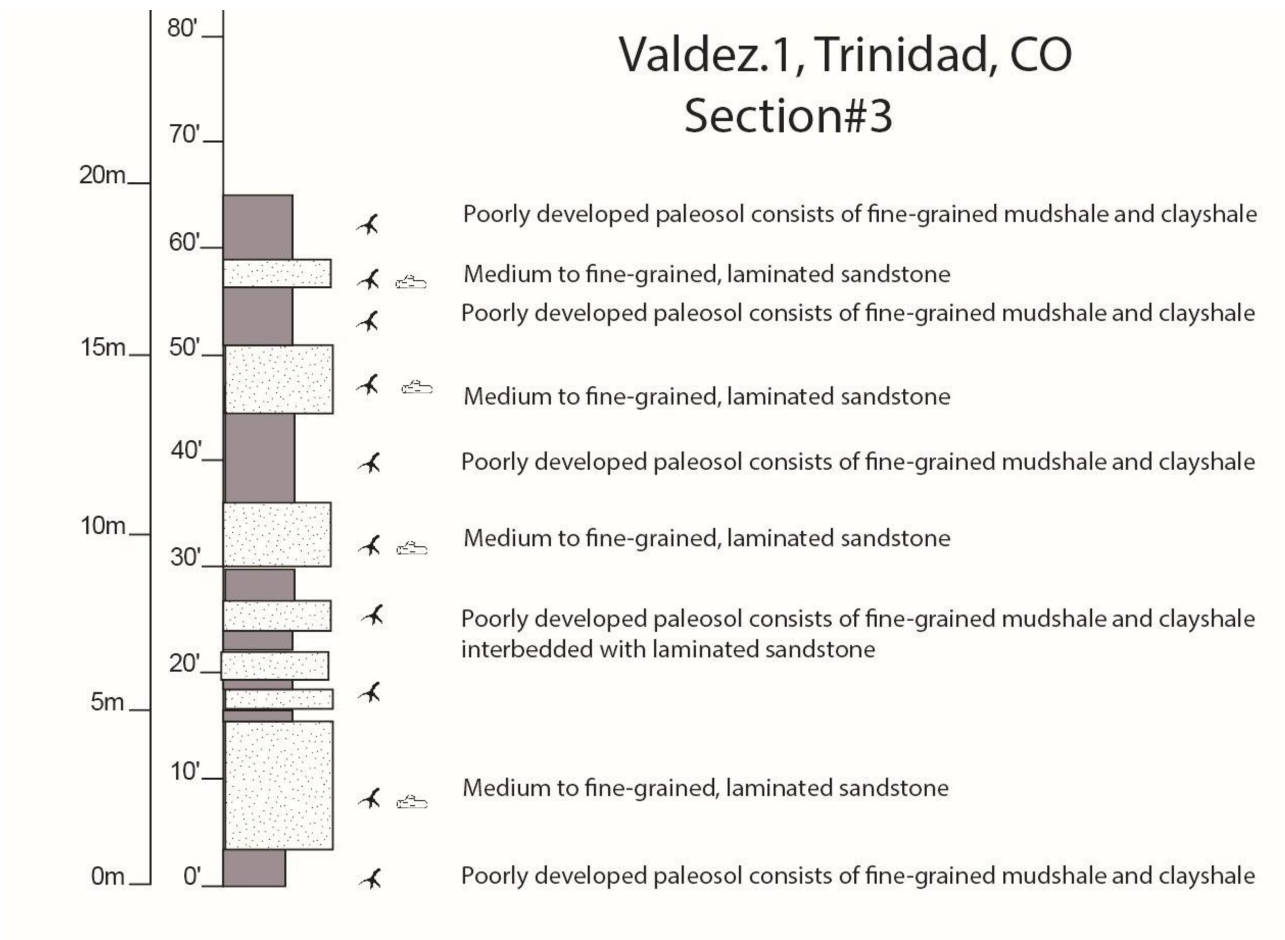
Medium to fine-grained, trough and planar cross bedded sandstone

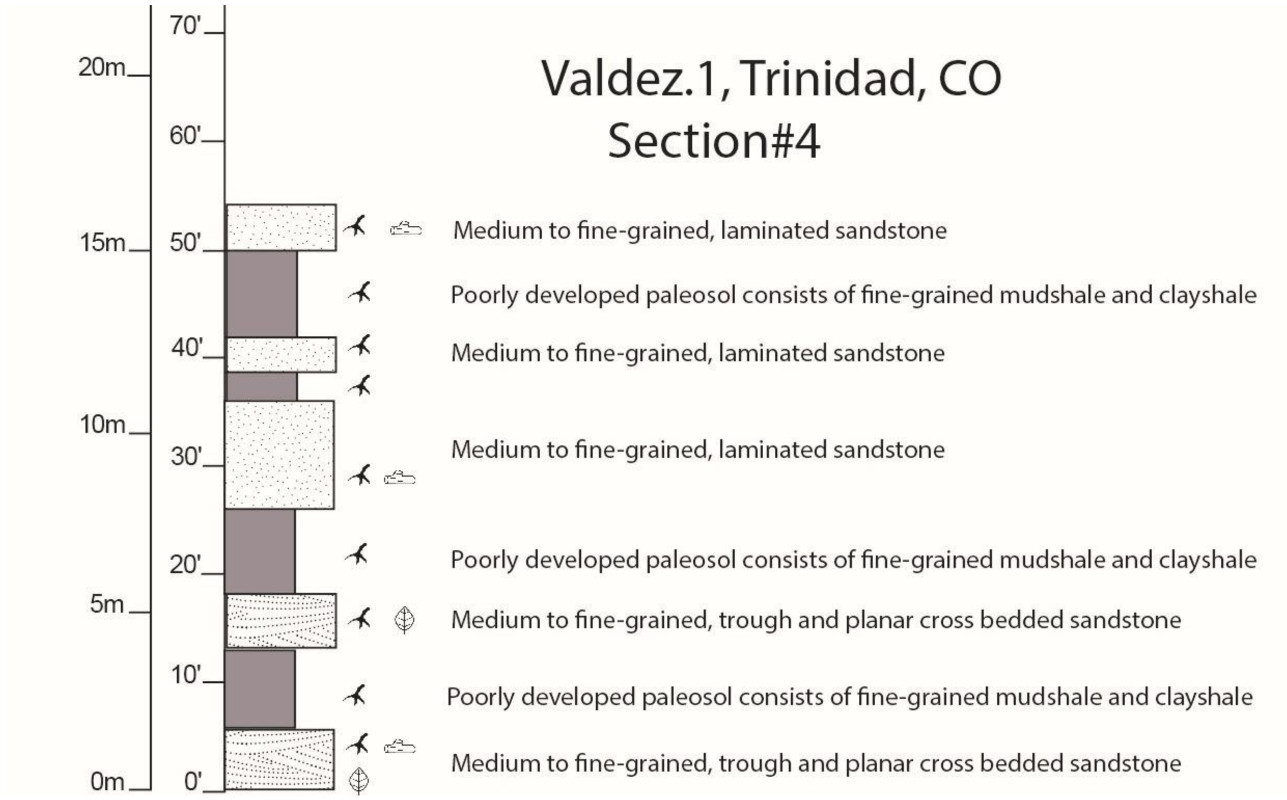

Cokedale.2, Trinidad, CO
Section#3
20m
60'
15m
50'
40'
10m
30'
20'
5m
10'
0m
0'
Siltstone, blocky to slightly laminated graded into laminated mudshale
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with blocky siltstone
Fine-grained, carbonaceous, slightly laminated mudshale
Fine-grained, carbonaceous, slightly laminated mudshale
Fine-grained, slightly thick laminated mudshale and clayshale interbedded with thinly laminated sandstone
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, slightly thick laminated mudshale and clayshale



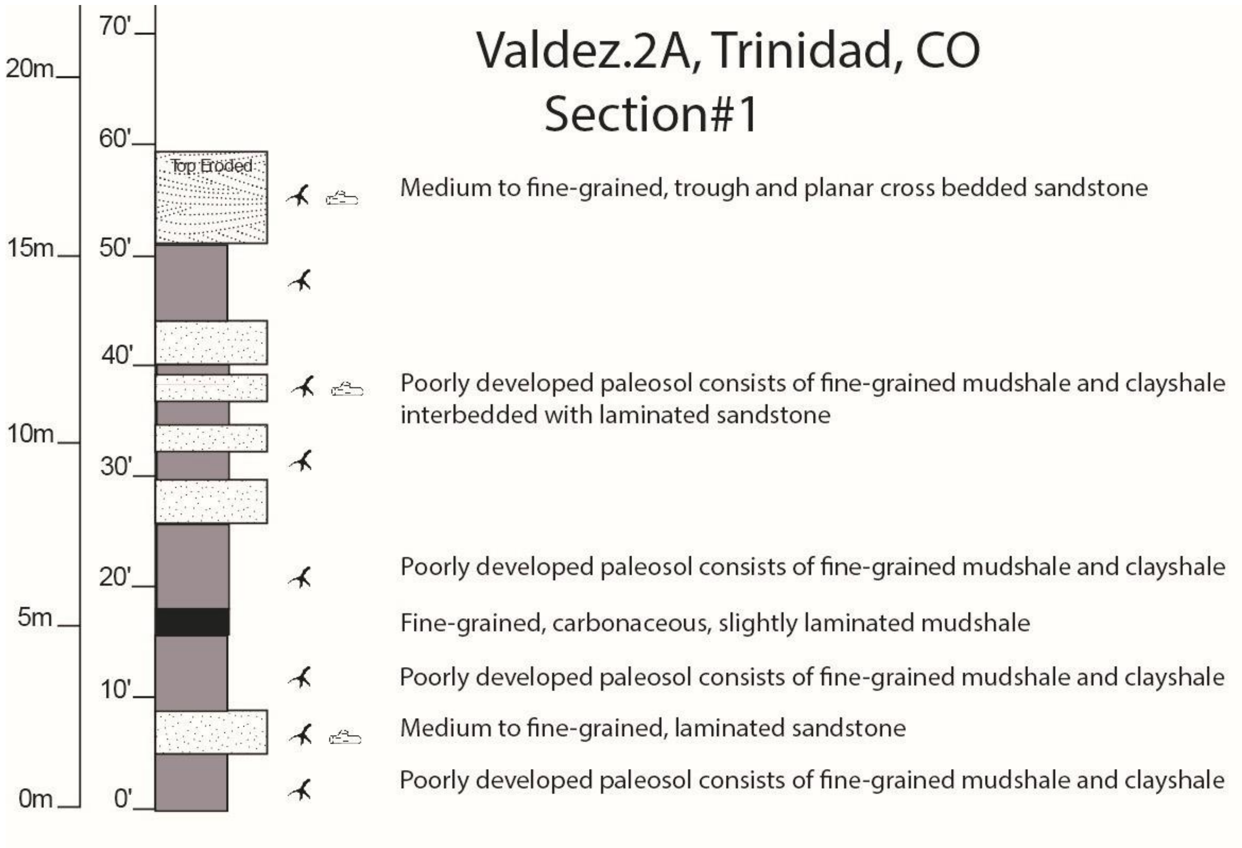
Valdez.1, Trinidad, CO
Section#1
80'
70'
60'
50'
40'
30'
20'
10'
0'
20m
15m
10m
5m
0m
Coal
Siltstone, blocky to slightly laminated graded into laminated mudshale
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Siltstone, blocky to slightly laminated graded into laminated mudshale
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Siltstone, blocky to slightly laminated graded into laminated mudshale
Poorly developed paleosol consists of fine-grained mudshale and clayshale

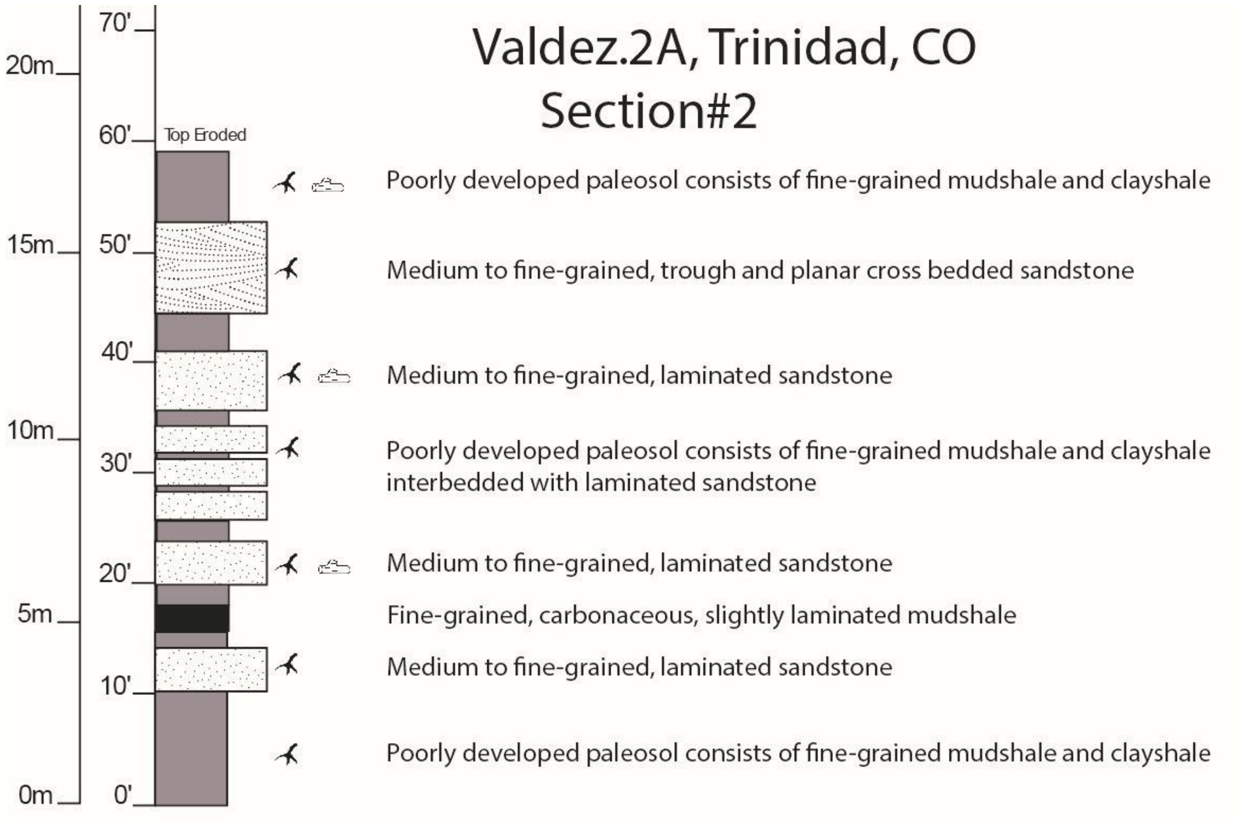

Valdez.1, Trinidad, CO
Section#2
20m
15m
10m
5m
0m
80'
70'
60'
50'
40'
30'
20'
10'
0'
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale interbedded with laminated sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale

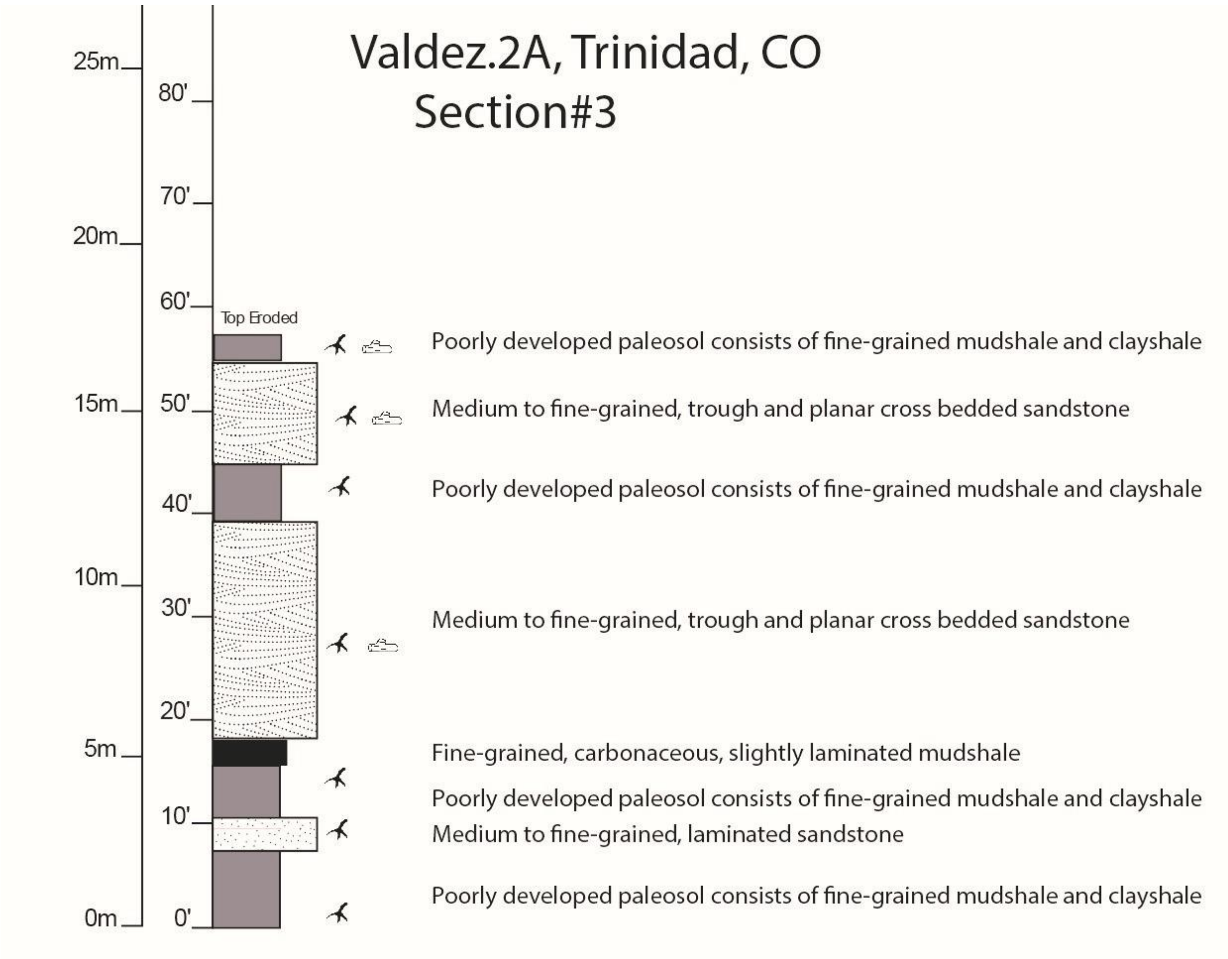

Valdez.1, Trinidad, CO
Section#3
80'
70'
20m
60'
15m
50'
40'
10m
30'
20'
5m
10'
0m
0'
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale interbedded with laminated sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale

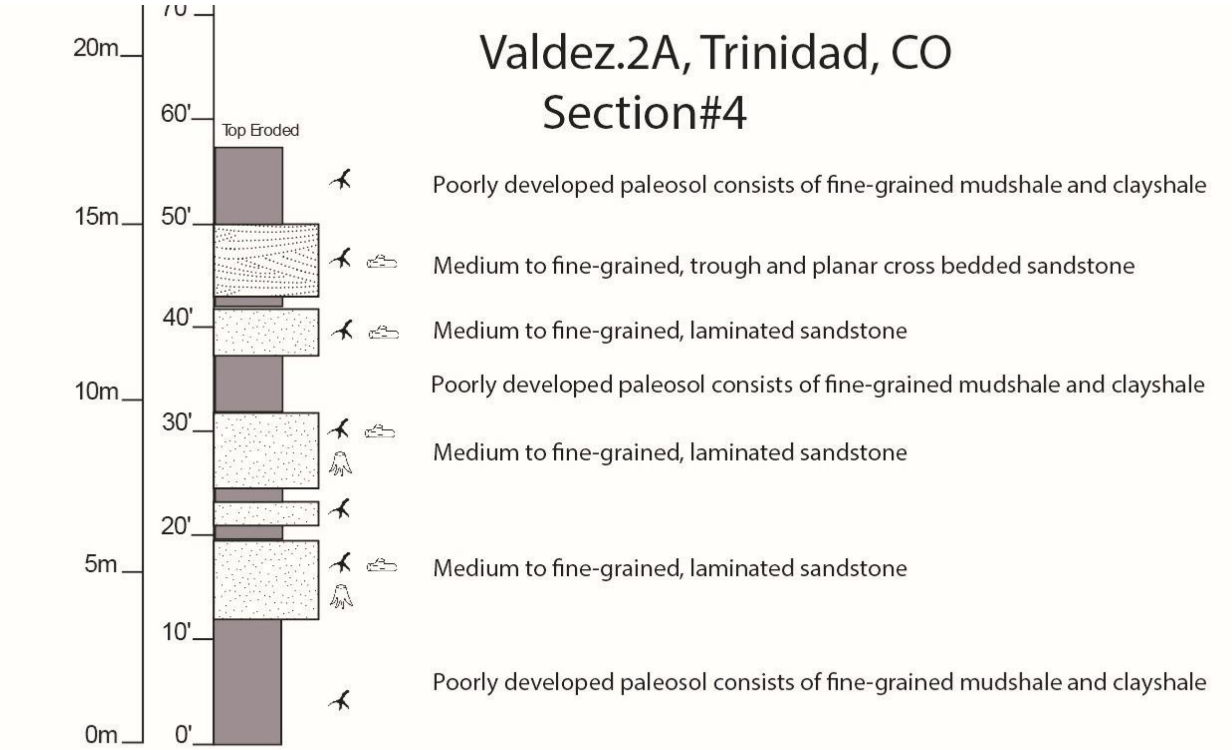


Valdez.1, Trinidad, CO
Section#4
70'
20m
60'
Medium to fine-grained, laminated sandstone
15m
50'
Poorly developed paleosol consists of fine-grained mudshale and clayshale
40'
Medium to fine-grained, laminated sandstone
10m
30'
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
20'
5m
Medium to fine-grained, trough and planar cross bedded sandstone
10'
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
0m
0'


Valdez.2A, Trinidad, CO
Section#1
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale interbedded with laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Fine-grained, carbonaceous, slightly laminated mudshale
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
20m
15m
10m
5m
0m
70'
60'
50'
40'
30'
20'
10'
0'


Valdez.2A, Trinidad, CO
Section#2
20m
15m
10m
5m
0m
70'
60'
50'
40'
30'
20'
10'
0'
Top Eroded
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale interbedded with laminated sandstone
Medium to fine-grained, laminated sandstone
Fine-grained, carbonaceous, slightly laminated mudshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale


Valdez.2A, Trinidad, CO
Section#3
25m
20m
15m
10m
5m
0m
80'
70'
60'
50'
40'
30'
20'
10'
0'
Top Eroded
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Fine-grained, carbonaceous, slightly laminated mudshale
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale


Valdez.2A, Trinidad, CO
Section#4
Top Eroded
20m
15m
10m
5m
0m
70'
60'
50'
40'
30'
20'
10'
0'
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale


Valdez.2B, Trinidad, CO
Section#1
15m
10m
5m
0m
50'
40'
30'
20'
10'
0'
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale


Valdez.2B, Trinidad, CO
Section#2
15m
10m
5m
0m
50'
40'
30'
20'
10'
0'
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, laminated sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale


15m
10m
5m
0m
50'
40'
30'
20'
10'
0'
Valdez.2B, Trinidad, CO
Section#3
Top Eroded
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale
Medium to fine-grained, trough and planar cross bedded sandstone
Medium to fine-grained, trough and planar cross bedded sandstone
Poorly developed paleosol consists of fine-grained mudshale and clayshale

Appendix B

Supplementary data files

Description: The accompanying JPEG files contain measured section locations at the study area outcrops and, the architectural element analysis of the study area outcrops. File names and descriptions are listed in the folowing tables:

Measured section location on the study area outcrops

File name	Description
Cokedale.1_sections.jpg	Locations of measured section at Cokedale.1 outcrop
Cokedale.2_sections.jpg	Locations of measured section at Cokedale.2 outcrop
Valdez.1_sections.jpg	Locations of measured section at Valdez.1 outcrop
Valdez.2A_sections.jpg	Locations of measured section at Valdez.2A outcrop
Valdez.2B_sections.jpg	Locations of measured section at Valdez.2B outcrop

Architecture element analysis of study area outcrops

File name	Description
Legend.jpg	Legend for architectural element
Cokedale.2_arch.jpg	Architecture element analysis at Cokedale.2 outcrop
Cokedale.2_arch_interp.jpg	Architecture element analysis with interpretation at Cokedale.2 outcrop
Valdez.1_arch.jpg	Architecture element analysis at Valdez.1 outcrop
Valdez.1_arch_interp.jpg	Architecture element analysis with interpretation at Valdez.1 outcrop
Valdez.2A_arch.jpg	Architecture element analysis at Valdez.2A outcrop
Valdez.2A_arch_interp.jpg	Architecture element analysis with interpretation at Valdez.2A outcrop

BIOGRAPHICAL INFORMATION

Yaqoub Yousef Alrefaei is from the State of Kuwait. He received his B.S in Geology from Kuwait University in 2006 and his Master's degree in Geology from University of Texas at Arlington in 2011. He worked at the Kuwait Institute for Scientific Research in the Petroleum Research and Studies Center (PRSC) as a research assistant for two years. He earned a scholarship from Kuwait University to pursue a Master's and a Ph.D. in the United State of America where he has been a graduate student at University of Texas at Arlington.