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The Fluvial Muddy Creek Formation Near Overton, Nevada

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THE FLUVIAL MUDDY CREEK FORMATION
NEAR OVERTON, NEVADA

By

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Bachelor of Science
University of Nevada, Las Vegas
2009

A thesis submitted in partial fulfillment of
The requirements for the

Master of Science in Geology
Department of Geoscience
College of Science
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ABSTRACT

The Muddy Creek Formation (MCF) may represent an ancestral Colorado River deposit. To test this hypothesis, I mapped exposures of the MCF within the Virgin River Depression (VRD), a rift basin in the central Basin and Range. This is the first study to analyze fluvial MCF facies and test their viability as ancestral Colorado River deposits.

Mapping, paleocurrent analysis, conglomerate provenance, and architectural elements analysis were used in order to characterize the fluvial MCF near Overton NV. Architectural elements analysis revealed that MCF fluvial facies are most closely associated with those of a high-energy sand-bed braided river system. These results do not resemble definitive Colorado River deposits. In light of these findings, fluvial facies of the MCF may be attributed to a Miocene Virgin River and permit a revised depositional model for the MCF within the VRD. Additionally, these findings inform models of dryland fluvial systems in rift basins.

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TABLE OF CONTENTS

ABSTRACT	iii
ACKNOWLEDGMENTS	iv
LIST OF TABLES	vii
LIST OF FIGURES	viii
CHAPTER 1 INTRODUCTION	1
CHAPTER 2 BACKGROUND	5
2.1 Geologic Background	5
2.2 Previous Work	7
2.3 Architectural Elements Analysis	9
CHAPTER 3 METHODOLOGY	11
3.1 Field Mapping	11
3.2 Architectural Elements Analysis	11
CHAPTER 4 RESULTS	13
4.1 Clast Counts	13
4.2 Mapping	13
4.2 Paleocurrents	14
4.3 Architectural Elements study	15
4.3.1 Study Site 1	15
4.3.2 Study Site 2	17
4.4 Study Site 1 Measured Section Results	19
CHAPTER 5 INTERPRETATIONS	20
5.1 Revised Depositional Model	21
CHAPTER 6 CONCLUSIONS	26
APPENDIX A	28
BIBLIOGRAPHY	56
VITA	60

LIST OF TABLES

Table 1 Architectural Elements Classification	28
Table 2 Facies Classifications	29
Table 3 Bounding Surface Classifications.....	30

LIST OF FIGURES

Figure 1 Structural Provinces of North America	31
Figure 2 Extent of Muddy Creek Formation	32
Figure 3 Virgin River Depression Location Map	33
Figure 4 Half Graben Depositional Model	34
Figure 5 Ancestral Colorado River Hypotheses	35
Figure 6 Structural Domains of the Central Basin and Range	36
Figure 7 Cross Section of the Virgin River Depression	37
Figure 8 Virgin River Depression Sub-Basins	38
Figure 9 Previous Studies Map	39
Figure 10 Architectural Elements Example	40
Figure 11 Hierarchy of Scale in Architectural Elements Analysis	41
Figure 12 Clast Count Results	42
Figure 13 Field Area Photograph Showing Key Facies Change	43
Figure 14 Paleocurrent Results	44
Figure 15 Summed Paleocurrent Results	45
Figure 16 Channel Elements Explanation	46
Figure 17 Site 1 Measured Section Results	47
Figure 18 Mobil 1A Well Results and Correlated Stratigraphic Section	48
Figure 19 Depositional Model for Internally Drained Half Graben	49
Figure 20 Platte Type Fluvial Model	50
Figure 21 S. Saskatchewan Type Fluvial Model	50
Figure 22 High Energy Sand-Bed Braided Fluvial Model	51
Figure 23 Vertical Profile Models of Low-Sinuosity Fluvial Systems	52
Figure 24 Example of an Ancient Platte Type Fluvial System: Devonian Brownstones	53
Figure 25 Example of Element Formation from the Modern Platte River	54
Figure 26 Plot Showing Stability Fields for Sedimentary Bedforms	55

CHAPTER 1

INTRODUCTION

Sedimentary rocks deposited in rift basins are vital to understanding both the development of the rift basin as well as the geologic history of the region. Rifts are one phase of the Wilson cycle and rifts can form in most plate tectonic settings, even in regions of overall compression (Miall, 2002). The Basin and Range physiographic province (Fig. 1) is one such rift and it offers an opportunity to study rift rocks exposed at the surface. The Muddy Creek Formation (MCF) was deposited over a wide area of the central Basin and Range (Fig. 2) during the late Miocene and early Pliocene (8.5 – 4.1 Ma) (i.e. during the latest stages of Basin and Range extension) (Fig. 3). It has been described differently in separate study locations (Dicke, 1990; Schmidt, 2000; Pederson, 2008; Forrester, 2009). This study analyzes MCF stratigraphy within the southern portion of the Virgin River Depression (VRD), which is a rift basin within the central Basin and Range near Overton, NV (Fig. 3). Within the study area the MCF is ~850 meters thick, elsewhere in the VRD the stratigraphic thickness of the MCF exceeds 2.0 km and is relatively undeformed (Bohannon et al., 1993).

Although the structure, thickness, and age of the MCF are fairly well known, different and even conflicting models describe MCF deposition. Localized studies have yielded interpretations that support dissimilar and even conflicting models for the deposition of the MCF and contribute to the stratigraphic discrepancy known as the “Muddy Creek Problem”. Previously proposed models are that, 1) that the MCF was deposited in a clastic wedge setting (Fig. 4) until fluvial rocks were deposited by a late Miocene Virgin River (Williams, 1996; Pederson 2008; Forrester, 2009), and 2) that the MCF may represent the ancestral Colorado River (Lucchita, 1990; Schmidt, 2000). To test these models, MCF stratigraphy was mapped and characterized near Overton, NV.

The study area near Overton was chosen for several reasons. First, it includes the basin bounding fault; a likely site of the main fluvial channel bringing sediment to the basin during the Miocene. Second, the MCF in this area is capped by previously described conglomerates which are commonly associated with fluvial deposits (Bohannon, 1984; Williams, 1996). Finally, because it contains the late Miocene fluvial strata, the study location is central to The “Muddy Creek Problem” and hypotheses regarding the pre-Grand Canyon Colorado River (Pederson, 2008).

The pre-Grand Canyon or ancestral Colorado River refers to a long-standing geologic problem. There is consensus that the modern Colorado River started flowing from the mouth of the Grand Canyon and into the central Basin and Range via the Grand Wash Trough between 5.5 Ma and 4.4 Ma (House et al., 2005). However, intense debate still exists about the course of the ancestral Colorado River before 5.5 Ma (Pederson, 2008; Polyak et al., 2008; Wernicke, 2011). The river before this time is known to have flowed onto the northeastern Colorado Plateau, but the river’s course from that location remains unknown. Competing models (Fig. 5) describe the river’s course off the central plateau, including that the river flowed 1) southeast towards the region of the Little Colorado River; 2) southwest and infiltrated into the Colorado Plateau; and 3) northwest and into the central Basin and Range (as described in Pederson, 2008). A new model 4) proposed by Wernicke (2011) hypothesizes that the Colorado River was actually a “California River” flowing northeast towards the Rockies as the Laramide uplifted the western U.S.

Recent provenance studies have attempted to test hypothesis 3; that the ancestral Colorado River flowed into the VRD. Pederson (2008) conducted a provenance study within the MCF using sandstone petrography from samples collected from the uppermost MCF in the northern VRD. Pederson (2008) concluded that the MCF was predominantly sourced from local sources. In his conclusion, Pederson (2008)

used these data to rule out the MCF as an ancestral Colorado River deposit, and agreed with Williams (1996) who concluded that the fluvial MCF represented an ancestral Virgin River. Forrester (2009) conducted a similar provenance study in the VRD along a north-south transect and found mixing of local and Colorado Plateau derived sediments. Additionally this study showed that moving farther south, the MCF is increasingly Colorado Plateau derived.

These findings are important, but they do not rule out an ancestral Colorado River in the VRD, they only indicate that the VRD was a site of mixing for local and Colorado Plateau sourced sediment. No previous studies of the MCF addressed the following key questions: If a Miocene river flowed through the VRD then what was its size? What was its fluvial style? Do the size and style support an ancestral Colorado River hypothesis?

The MCF near Overton, NV was deposited in the central Basin and Range from ~8.5 – 4.1 Ma (Lamb et al., 2005; Williams, 1996). This age, along with a Colorado Plateau provenance and the presence of fluvial sediments provides stratigraphy that can be analyzed in order to test the validity of the hypothesis that an ancestral Colorado River flowed off the northern Colorado Plateau and into the central Basin and Range. The goal of this study was to test the ancestral Colorado hypothesis by characterizing the type and size of the Miocene VRD fluvial system.

A further result of this characterization is a better understanding of dryland river systems in rift basins. The MCF is a well exposed proxy for fluvial rocks that serve as hydrocarbon reservoirs in prospective and producing basins across the world. Examples include the North Sea Triassic Skagerrak Fm. (McKie et al., 2010), and central Australian Jurassic Hutton Sandstone (Cotton et al., 2006). To address these issues I mapped the western half of the Overton SE quadrangle. In addition, two architectural elements maps were completed and four vertical stratigraphic sections were measured

in one of the architectural elements study sites. The purpose of these measurements was to gather data regarding grain size and bed thickness which, along with probable architectural element areal extent, allow estimation of paleo fluvial hydraulics and approximate reservoir size and porosity/permeability. Quantified data regarding reservoir architecture aids exploration geologists in interpreting subsurface data sets.

CHAPTER 2

BACKGROUND

Geologic Background

In the Lake Mead region of the central Basin and Range, east directed thrusting (Sevier aged, ~155 – 55 Ma) in the late Mesozoic-early Cenozoic placed Paleozoic marine carbonate and clastic rocks onto cratonic units (DeCelles, 2004; Anderson and Beard, 2010). The eastern limit of this thrusting near the study area is the north Muddy Mountains which are located ~15 km west of the study area (Anderson and Barnhard, 1993). Following the contractional events of the Sevier and Laramide orogenies, rifting initiated in the extreme north and south of the Basin and Range Province. In general, extension across domains of the Basin and Range swept southward and northward toward the central Basin and Range. The first sedimentary evidence of extension in the central Basin and Range are rocks of the Horse Spring Formation (Axen et al., 1993; Sonder and Jones, 1999; Anderson and Beard, 2010). Lamb et al. (2010) describe three major structural domains along a north-south axis (Fig. 6); the Mormon Mountain domain in the north, the Lake Mead domain in the center, and the Whipple domain in the south. With some overlap, the initiation of extension varied in each domain. The study area is located in the Lake Mead domain, which underwent major extension from 16 – 8 Ma (Lamb et al., 2010). The study area lies within a structurally complex extensional feature termed the VRD. The VRD is a normal-fault bound basin that contains two sub-basins, the Mesquite basin in the northwest and the Mormon basin in the south. Their internal structure is a series of half grabens composed of west dipping faults bounding east dipping blocks (Fig. 7). As the fault blocks dropped down, they rotated along the fault plane and accommodation was created in fault hanging walls.

The Mesquite and Mormon sub-basins are separated by a buried ridge and reflect the evolution of the VRD and sedimentation within it. Axial basins along faults

were sites of localized deposition until depocenters became linked. Thus, the Mesquite and Mormon basins were filled independently until the buried ridge was overtopped and the VRD became one connected depocenter (Bohannon et al., 1993). This project is located within the Mormon sub-basin (Fig. 8). After deposition ceased in the Mormon basin the landscape stabilized and a petrocalcic soil developed across the VRD. Today, this petrocalcic surface controls much of the geomorphology of the VRD and large mesas (Mormon Mesa and Flat Top Mesa) armoring the underlying Miocene MCF and Pliocene units from erosion. There is debate regarding the age of this petrocalcic surface; the upper constraint is defined by a 4.1 ± 0.6 Ma basalt flow in the upper MCF (Williams, 1996). Brock and Buck (2009) described a series of pedogenic processes initiating immediately following deposition of the MCF.

The oldest Tertiary rocks in the region are the pre-24 Ma conglomerates of the Rainbow Gardens Member of the Horse Spring Formation. The Horse Spring Formation (24 - 12 Ma) records the major pulses of extension in the Lake Mead Region and unconformably overlies Paleozoic and Mesozoic rocks.

Unconformably overlying the Horse Spring Fm. is the Red Sandstone unit (12 – 8.5 Ma). Above the Red Sandstone lies the Muddy Creek Formation. Ages for the MCF vary depending on location within the central Basin and Range; near the Mormon basin, recent geochronology constrains the age of deposition from 8.5 Ma to $<4.1 \pm 0.6$ Ma (Williams, 1996; Lamb et al., 2005). Where exposed in the field area, the MCF is composed of massive, planar laminated, and cross bedded sandstones capped by pebble and cobble conglomerates. Elsewhere in the VRD the MCF crops out as sandstone, mudstone, gypsiferous mudstone, and minor evaporites. Following deposition of the MCF the land surface stabilized and over much of the VRD a petrocalcic soil started to form as early as 4 Ma (Brock and Buck, 2009). The Pliocene

integration of the VRD with the modern Colorado River drainage system led to at least 4 major downcutting events and incised MCF strata (Gardner, 1968; 1972a).

The depositional environment of the MCF has previously been interpreted as a “clastic wedge” (Bohannon, 1984; Longwell, 1928, 1946; Hunt et al., 1942; Hunt, 1956; Lucchitta, 1972; Kowallis and Everett, 1986; Dicke, 1990) wherein the basin is internally drained and alluvial fans carry sediment from eroding mountains into the basin, progressively fining towards lacustrine or playa environments. This type of depositional system produces rocks that fine basinward and matches what is observed in the field in the lower, non-fluvial portions of the MCF. Williams (1996) mapped north of this study near Mesquite, NV (Fig. 3) and in general agreed with previous interpretations noting a lack of coarse sediment in the non-fluvial units of the MCF. Williams (1996) interpreted this field evidence as further proof that no major streams ran through the VRD prior to late Muddy Creek time. Finally, Williams (1996) interpreted the upper fluvial and conglomerate facies as the arrival of the Virgin River in the late Miocene/early Pliocene and the beginning of the last phase of aggradation within the basin.

Previous Work

The Muddy Creek Fm. was first described by Stock (1921) in the Meadow Valley near Overton, NV. Between Stock’s (1921) naming of the MCF and 1970s, Longwell (1928; 1946), and Lucchitta (1972) described the major Tertiary rock units present in the central Basin and Range. Tertiary rocks described by these workers include the four members of the Horse Spring Fm., the Red sandstone unit, and the Muddy Creek Fm. The MCF initially included two other units, the Hualapai Limestone which caps the MCF and the rocks of the Grand Wash Trough (GWT), both of which are exposed in the Grand Wash. The modern Colorado River flows off the Colorado Plateau and into the Grand Wash Trough and therefore rocks of the GWT and the Hualapai Limestone are

critical pieces of stratigraphic evidence for dating the appearance of the modern Colorado River into the central Basin and Range (House et al., 2005).

Any discussion of the ancestral Colorado River or the MCF must eventually deal with the “Muddy Creek Problem”. The Muddy Creek problem is multifaceted and means different things to different researchers. The heart of the problem is stratigraphic; the focus of early workers was to understand the timing and geometry of major structures and not the stratigraphy of the relatively undeformed MCF basin-fill. The widespread extent of the MCF and isolated study areas led early workers to combine time equivalent units that would later be separated. Another factor adding to the confusion has to do with the depositional history of Muddy Creek basins which were filled separately until aggradation overtopped basin margins. Thus, lower parts of the MCF may be stratigraphically separated in separate basins whereas the upper MCF may be stratigraphically connected. The 1980’s brought the first attempts to clarify MCF stratigraphy. In 1984, Bohannon proposed new stratigraphic nomenclature that consolidated previous work and established the stratigraphic conventions that were used by this study. Bohannon (1984) restricted the term MCF to describe the rocks clearly connected to the MCF type-section near Glendale, NV. The result of this restriction is that the Hualapai Limestone and rocks of the GWT were formally excluded from the MCF. While most subsequent studies (Fig. 9) have followed the Bohannon (1984) conventions, Wernicke (2011) overlooked them, typifying the Muddy Creek problem. A second stratigraphic facet of the Muddy Creek problem is that the MCF was initially described and separated from the Red sandstone because of an angular discordance observed in some locations. In localities without this angular discordance undeformed red sandstone (the MCF) is deposited conformably on another undeformed red sandstone (the Red sandstone unit). Lithologically they are very difficult to separate. A third facet of the Muddy Creek Problem is that Powell (1875) hypothesized that the

Grand Canyon was carved by the Colorado River via antecedence. Early on, the MCF was hypothesized to be a Colorado River deposit but the mapped MCF did not offer any evidence of a major fluvial system. As shown in Figure 2, the MCF was deposited in basins adjacent to the Colorado Plateau, basins likely to receive the ancestral Colorado River. Because no evidence of the Colorado River was found in these rocks, the stratigraphy required the Grand Canyon to have been carved since ~5.5 Ma. This age relationship appeared to rule out the antecedence hypothesis of Powell (1875) and created the mystery of the ancestral Colorado River described by Pederson (2008). A modification of Powell's (1875) hypothesis was recently put forth by Wernicke (2011), who posited that Laramide-aged uplifts caused a northeast flowing "California River" carving the Grand Canyon via antecedence.

Architectural Elements Analysis

Drawing on the work of previous sedimentologists and stratigraphers, Miall (1985) combined facies analysis techniques and models of fluvial sedimentary processes into a new, more complete and quantitative approach. This approach is called architectural elements analysis and can be applied to fluvial sediments across all scales and fluvial styles. One of the results of this approach is the generation of new facies models and a better understanding of river systems. Previous techniques relied on vertical profiles and invoked end-member models for ancient rivers. However, architectural elements studies use two and three-dimensional maps of favorable outcrops in order to characterize an ancient river system and compare them with modern fluvial systems (Fig. 10). This application of uniformitarianism allows for a more accurate interpretation of the ancient flow regime, sediment load, paleoenvironment, and areal extent of the fluvial sediments. Additionally, information regarding reservoir size, connectivity, and compartmentalization is gained. Ultimately, interpretations are made

with more resolution than over simplified, end-member models such as “braided” or “meandering”.

As outlined in Miall (1985) architectural elements analysis relies on two key features found within fluvial rocks. These features are present in all types and sizes of fluvial system. The first key analysis feature is the architectural element, also called a macroform. Macroforms (Table 1) are composed of meso- and microforms which are in turn composed of various lithofacies types. Lithofacies are defined by their grain size and sedimentary structures. Lithofacies (Table 2) are the smallest identifiable part of an outcrop map or architectural elements study. Micro-, meso-, and macroforms (architectural elements) are separated by the second key feature, bounding surfaces. Bounding surfaces differ in scale according to the hierarchy shown in Table 3 and are described as being first through eighth order (Fig. 11). For example, a first order surface boundary marks very minor changes within a micro- or mesoform such as the change from climbing ripples into planar laminations of the same grain size and are centimeters to meters in scale. A sixth order surface marks groups of channels or the base of a paleovalley and may be several km wide. Typically macroforms are bounded by third, fourth, and fifth order surfaces. These examples illustrate that a bounding surface implies a fluvial process that altered the pattern of sedimentation. It is worth reemphasizing that the value of this method is that these features are present in all types and sizes of fluvial system.

CHAPTER 3
METHODOLOGY
Field Mapping

The western half of the Overton SE 7.5' quadrangle, NV was mapped at 1:24,000 scale using standard techniques from Compton (1985). This area was chosen because it includes critical exposures of the MCF and has not been previously mapped at this scale. In addition to mapping bedrock units, Quaternary units were mapped using the classifications outlined by Peterson (1981).

Tuff beds exposed within upper MCF stratigraphy were collected in order to attempt to constrain the age of the uppermost MCF using tephrochronology (Alloway et al., 2006). Samples were crushed to fine sand size and flushed with a 10% hydrofluoric acid solution. The crushed sample was then analyzed using a binocular microscope to determine if glass was present.

Paleocurrent data were gathered from upper MCF and Quaternary conglomerates which contained imbricated clasts as well as sandy downstream and laterally accreting foresets. These were measured using a Brunton pocket transit and plotted onto a rose diagram (north oriented circular histogram) using Stereowin 1.2, a stereonet program developed by Allmendinger (2002). Conglomerate clast counts were also taken within upper MCF conglomerates as well as within mapped Quaternary units. Clasts were identified and counted along a horizontal line using a tape measure and a 3 cm interval. The target at each site was to identify 100 clasts. The results were entered into a spreadsheet and plotted as pie charts showing the relative abundance of sedimentary, volcanic, and metamorphic clasts.

Architectural Elements Analysis

For this study, a series of photographs was taken in order to stitch a panoramic photo of the outcrop. For the first architectural elements study (site 1), photos were

taken approximately 5 meters from the outcrop face at a constant height of 3 meters. Site 1 is a large, man-made trench called “Double Negative”. Double Negative is a land art project completed by the artist Michael Heizer. The second study site (site 2) was photographed ~200 meters away from the outcrop. Using the criteria of Miall (1985; 1996), lithofacies, architectural elements, and bounding surfaces were mapped onto the photograph. In order to minimize distortion, photos were taken as high as possible and at a uniform height regardless of ground surface topography. At site 1, the best stitching results were obtained by making lateral offsets every two-thirds of the camera’s field of view. Lateral offset was not required when taking photographs for site 2 because of the increased distance at which the photos were taken. Stitching was accomplished with the “Panorama Tools Graphical User Interface” (PTGUI) offered from <http://www.ptgui.com/>. PTGUI’s algorithm identifies similar points within overlapping images and stitches them into a single panoramic photo. The resulting image was imported into a graphics program, studied in detail, and overlaid with interpreted bounding surfaces and architectural elements.

CHAPTER 4

RESULTS

Clast Counts

In order to determine compositional changes along a north-south transect, six conglomerate clast counts were taken from the upper MCF at locations A-F (Fig. 12). Clast counts taken in the upper MCF reveal that MCF conglomerates are homogenous across the studied transect. The dominant clast type is sedimentary and the clasts are generally orange-yellow sandstones, grey quartz arenites, and black cherts. Light grey limestones were less common. The proportion of sedimentary rocks ranged from 71% to 87%, averaging 81.3%. The volcanic rock portion ranged from 8% to 21%, averaging 13.2%. The metamorphic rock portion ranged from 3% to 8%, and averaged 5.5%.

Mapping

The western half of the Overton 7.5 minute quadrangle was mapped at 1:24,000 scale (Plate 4.1). Mapping identified 15 stratigraphic units including 10 Quaternary units in addition to the Pliocene/Quaternary Mormon Mesa Petrocalcic surface (QTkm). Of major interest to this study was the identification and separation of the exposed MCF into two informal members, the upper and lower MCF. The contact between these two units is identified by the presence of a limonite horizon as well as local angular discordance. As shown in the map, the lower MCF crops out in the southern end of the field area. The angular discordance is only evident beyond the southern map boundary. A key outcrop was photographed (Fig. 13) showing east dipping beds of alluvium and capped by the upper MCF. The alluvium is conglomerate with angular clasts with a red sandy matrix and is sited along the basin bounding normal fault that runs along the west side of Black Ridge (Fig. 3). The capping conglomerate contains rounded clasts of a provenance identical to the upper MCF conglomerate underlying the Mormon Mesa. Interpretation of these relationships will be described in the following chapter.

Four tuff beds were discovered during mapping. Inspection of these tuff beds in the field revealed that 2 were completely reworked, while 2 others appeared to be viable candidates for geochronologic analysis. Unfortunately, these samples were also reworked and did not contain minerals of sufficient size or abundance for $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology. An attempt was made at a tephrochronologic correlation, but upon crushing these samples and flushing them with acid, no glass was present in the sample. The tuff was completely devitrified and no other data were discovered that helped constrain the age of the MCF within the VRD.

Paleocurrents

Paleocurrent data within the MCF were gathered at the same stratigraphic interval as the architectural elements studies. Measurements were taken at locations A-F (Fig. 14) along a north-south transect from preserved paleocurrent indicators including imbricated clasts, laterally accreting sets, and downstream accreting foresets. Measurements were plotted on rose diagrams using the Stereowin 1.2 stereonet program designed by Allmendinger (2002). At sample location A, two sets of measurements were taken. The first set measured imbricated clasts and the recorded paleoflow was south-southeast directed. The second set measured downstream accreting foresets in sandy beds and recorded south-southwest directed paleoflow. At sample location B imbricated clasts recorded south-southwest directed paleoflow. Imbricated clasts at sample location C showed south-southeast paleoflow. At sample location D both imbricated clasts and laterally accreting sets in sandy beds were measured. The measured paleocurrent indicators record southerly flow. Finally, at location E downstream accreting sets recorded west-southwest paleoflow. When all imbricated clast measurements along the transect are summed, the overall paleocurrent direction is 174° (Fig. 15).

Architectural Elements Study

The architectural elements study of site 1 (Plate 4.2) and site 2 (Plate 4.3) within the upper MCF revealed macroforms bounded between fourth and fifth order bounding surfaces. The completed architectural elements studies show complex patterns of sedimentation that are not seen in vertical stratigraphic sections. The scale and presence or absence of architectural elements and their overall vertical succession were used to document the style of the system. Mapped macroform elements included downstream accreting sets (DA), fine grained overbank deposits (FF), sediment gravity flows (SG), and sandy bedforms (SB), and channel fill deposits (CH) (Table 1). Element CH is used when further refinement is not possible. Thus, CH may include other macroforms as depicted in Figure 16. Lithofacies were identified using the nomenclature described by Miall (1985; 1996), which is shown in Table 2. Mapped lithofacies include low angle cross-bedded sands (Sl), shallow scour sands (Ss), grouped planar cross-bedded sands (Sp), as well as horizontally bedded and imbricated clast supported conglomerates (Gh), and matrix supported pebbly debris flow facies (Gmg). The nomenclature for this study is derived from Miall (1985; 1996) and uses letters for major (5th order and above) bounding surfaces (Table 3). Within the zones defined by letters the architectural elements are labeled first by number showing chronologic relationship, which may be further specified by a letter indicating stratigraphic relationships or equivalence. Finally, the architectural element is identified. For example, elements 4A-SB and 4B-SB precede 5-SG which itself precedes 6-SB, etc. (Plate 4.2).

Study Site 1

Downstream Accreting (DA) elements (named Foreset Macroforms FM in Miall, 1985) are similar and related to laterally accreting (LA) macroforms. They are both the result of accretionary sand bodies within the fluvial channel and DA elements may grade into LA elements at channel bar margins. The basis for classification of DA elements in

this study is the very low angle cross bedded sands that are inclined in the paleo-downstream direction. The size of the outcrop in this study does not allow for accurate interpretation of the areal extent of the mapped DA macroform (8-DA; Plate 4.2). However, the mapped exposure is 22 meters in downstream length, approximately 1.5 m thick, and continuous beyond the photographed area. Macroform 8-DA is inferred to have a lateral extent of several 10's of meters is inferred, it is bounded by 5th order surfaces (labeled B and C), and is dominated by SI lithofacies with minor lag gravels of facies Gh.

The mapped FF element (1-FF; Plate 4.2) (described as Overbank Fines OF in Miall, 1985) is thin and truncated by later LA deposits. It contains facies FI and is dominantly thin planar laminated muds. Additionally, a thin interbedded tuff horizon partially caps 1-FF. Samples were collected from this tuff but the samples were reworked and devitrified so no dating or tephrochronology was possible. The exposure of 1-FF is not complete but is 0.5 meters thick and at least 15 meters wide as mapped.

Sediment Gravity flow (SG) elements record flood events. I mapped SG elements containing cobble and small boulder-sized mud rip ups along with a sandy and pebbly conglomeratic matrix. Element 3-SG has a non-erosive basal contact with the underlying 2-LA element. 5-SG partially eroded and scoured 4-SB creating the exposed 4A and 4B elements. While separated in 2-D outcrop exposure, I interpret them to be continuous in 3 dimensions.

Sandy Bedform (SB) elements I observed lack structure and features indicative of cyclicity. This lack of cyclicity is key to this study's interpretation of MCF fluvial style. In general, SB elements document the aggradation of several types of sand bodies including fields of dunes (St) linguoid and transverse bars (Sp), upper flow regime beds (Sh), and ripples (Sr). Elements 4A; 4B; and 4C-SB are bounded by 4th order surfaces except where truncated by element 7-CH. They are underlain by debris flow facies of

element 3-SG and eroded by 5-SG (Plate 4.2). It is likely that 4-SB elements and 6-SB are related and were deposited in succession following the debris flow event marked by 5-SG. Taken together, these SB elements are approximately 1 meter thick where not truncated and are exposed beyond the 22 meter long study area. Element 9-SB is at least 2 meters thick and is more homogenous than SB elements lower in site 1 stratigraphy. All mapped SB elements are massive sandstones with minor planar laminated sandstone. 9-SB is capped by several meters of the Mormon Mesa petrocalcic horizon (map unit QTkm; Plate 4.1).

Scour hollows (HO) were not described by Miall (1985) and initially HO elements were classified as Channels (CH). Cowan (1991) identified hollows, which are characterized by concave-up 4th order basal surfaces. The main differentiation between HO and CH elements rests in their shape; channels are cylindrical whereas hollows are scoop-shaped (Miall, 1996). Element 7-HO is 8.5 meters wide and 1 meter thick, containing lag gravels of facies GH and sandstone of facies SI.

Study Site 2

The architectural elements study of site 2 (Plate 4.3) includes more MCF fluvial stratigraphy than site 1 and consists of similar architecture. At site 2 paleoflow is coming out of the plane of the picture. The outcrop is oriented east-west and the photo is taken from the south. Within the upper 85 meters of the MCF I identified 8 architectural elements and their associated lithofacies. All of the macroforms mapped at site 2 are bound by 4th and 5th order surfaces, with the exception of the Mormon Mesa Petrocalcic Soil which is floored by a 6th order surface.

Element 1-SB is 50+ meters thick and composed of fine and medium sandstones, lithofacies Sm. The upper bounding surface is well defined while the lower surface is covered by alluvial deposits. The only sedimentary structures observed in this interval are planar bedding within the sandstone.

The classification of element 2-CH as a channel rests on 1) the concave-up basal contact seen on the left of the macroform (Plate 4.3) and 2) the presence of lag gravel within the concave-up portion. This macroform is filled by white, aphanitic tuff. Based on the geometry of the macroform and the tuff that comprises it, I interpret this to be a small, possibly ephemeral channel that was filled by air fall deposits at which point the channel was filled and flow diverted. The significance of this CH element and its size will be discussed in the interpretations section.

Stacked sand and gravel lenses make up element 3-GB. The east-west exposure of southerly flowing fluvial rocks allows for a cross-sectional view of the linguoid sand and gravel bars that are classified as lithofacies Sp. Several lenses are truncated by the 5th order bounding surface that forms the basal contact with element 4-CH above.

Element 4-CH is the largest channel identified in the study area. Because most of the basal contact is covered an accurate channel width/depth ratio is unattainable. The channel is predominantly filled with massive sandstone as well as minor imbricated conglomerate.

A thin, continuous layer of planar laminated overbank fines (5-FF) lies above 4-CH. Prolonged exposure and the migration of the channel away from its location during 4-CH time lead to the classification of the 5-FF basal contact as a 5th order surface.

Mapped element 6-DA is predominantly composed of low angle cross bedded sandstones. Within 6-DA lies a small sediment gravity flow (SG) macroform, element 6-SG. The sedimentary texture and outcrop character of element 6-SG, along with visible mud rip-ups lead to the classification of 6-SG as a flood deposit. I classified 6-DA as downstream accreting because of the presence of variable geometries within 6-DA sedimentary structures. Several portions of downstream accreting sandbars and dunes

are recorded in this interval. This interpretation admits planar and concave-down strata, angular cross bedding, and the observed scoop-shaped fill.

In contrast to element 6-DA element 7-LA contains uniformly dipping cross bedding indicative of lateral accretion surfaces. Element 7-LA is bounded on its upper surface by the 6th order boundary that marks the base of the Mormon Mesa Petrocalcic soil. This boundary is very widespread and present across the VRD.

Site 1 (Double Negative) Vertical Profile Results

Four vertical stratigraphic sections were measured at the site of the architectural elements study (Fig. 17). These measurements were taken in order to inform a qualitative assessment of reservoir size, quality, and connectivity. This assessment may then be used as an analog for similar ancient fluvial systems at depth. Stratigraphic data were also gathered to aid in the identification and description of both the upper Muddy Creek Fm. and the mapped architectural elements.

Measured section 1 is composed of ~84% sandstone, ~11% conglomerate, and 5% mudstone. Section 2 is ~76% sandstone, ~17% conglomerate, and 7% mudstone. Section 3 is ~69% sandstone, ~29% conglomerate, and 2% mudstone. Finally, section 4 is composed of ~83% sandstone, 17% conglomerate, and no mudstone.

CHAPTER 5

INTERPRETATIONS

The geologic map, field data, and architectural elements maps represent data sets going from gross observations to detailed analysis of the MCF depositional model in the VRD. With that in mind, my interpretations are presented by working from the broadest applicability, to the most detailed.

MCF Fluvial Strata

A central challenge in any attempt to characterize the MCF as a whole lies in the small amount of MCF exposed. I mapped the upper 200 meters, approximately 20% of the total MCF stratigraphy based on the Mobil Virgin River 1 A test well interpreted by Bohannon et al. (1993) (Fig. 18). Therefore, the characterization of fluvial MCF stratigraphy in this study relies on key assumptions. First, that the tectonic regime was similar throughout the deposition of the MCF. Within the VRD the major extensional phase was from 16 – 8 Ma (Lamb et al., 2010) as recorded by the Horse Spring Fm. and Red Sandstone unit underlying the MCF. Relative tectonic quiescence since 8 Ma is shown in the relatively undeformed MCF strata documented in the seismic study by Bohannon et al. (1993). A second assumption is that the climate was regionally homogenous throughout the latest Miocene and early Pliocene. River flow characteristics are mainly driven by climate and gradient (Ashley, 1990). A similar climate in the catchments of both the Virgin and Colorado Rivers would permit me to compare their size and fluvial style. A third assumption lies in the siting of the study location. The study location includes the VRD and Mormon sub-basin bounding fault and lies downstream of the zone of mixing of Colorado Plateau and Caliente Caldera Complex derived sediments (Forrester, 2009; Pederson, 2008). As shown in Bohannon et al. (1993) the geometry of the VRD is such that it contains west dipping faults which bound east dipping fault blocks. These structures create topographic lows along the

eastern edge of each rotating fault block. Thus, at any given time, the depocenter of the MCF within the VRD was most likely on the basin's eastern margin. The western half of the Overton SE quad is located at the eastern margin of the VRD along the basin bounding fault and at the southern end of the Mormon sub-basin. A final assumption is that the MCF exposed in the study area may represent ancestral Colorado River age rocks. Local age control in the upper MCF is a whole rock K/Ar date of 4.1 ± 0.6 Ma taken from a small basalt flow. Two samples from this outcrop were dated with overlapping results, however thin section analysis revealed that the groundmass was altered, possibly affecting the geochronology results (Williams, 1996). The lower age control is taken from the upper Tertiary Red sandstone unit dated at 8.5 Ma (Lamb et al., 2005). Recent work by Muntean (personal communication) yielded new age controls from tuff beds in the middle MCF; a tephrochronologic correlation of 6.62 ± 0.03 Ma, and a detrital sanidine $^{40}\text{Ar}/^{39}\text{Ar}$ 7.09 ± 0.20 Ma. Thus, without better age resolution it is impossible to know how much time is represented by the upper 200 meters of MCF exposed in the field area.

Revised Depositional Model

Detailed mapping revealed thick (~150 m) and continuous fluvial rocks forming the upper MCF. Previous workers mapping elsewhere in the MCF or lower in the stratigraphy have interpreted the MCF as post-tectonic basin fill in clastic wedge geometry as depicted in Figure 4 (Bohannon, 1984; Lucchitta, 1972, 1979; Kowallis and Everett, 1986; Dicke, 1990). Observations made in this study in the lowest mappable strata and outside the map area support these previous interpretations. The photograph shown in Figure 13 is further evidence of this relationship; alluvial conglomerates extend basinward, and these are overlain by fluvial facies of the MCF. I further interpret the presence of extensive upper MCF fluvial strata mapped by Williams (1996) and this study as the arrival of a significant through-going fluvial system into the VRD. This study

sought evidence constraining the timing of this event, but all attempts at dating the upper MCF were unsuccessful. Paleocurrent measurements indicate a southerly flowing axial drainage, changing the late Miocene depositional model of the MCF to the one depicted in Figure 19. In this study, the mapped stratigraphy, paleocurrent indicators, conglomerate clast counts, and stacked architectural elements were used to interpret the fluvial facies of the MCF.

The uniformity of measured paleocurrents (Fig. 14) provides evidence of the sinuosity of the ancient fluvial system. Paleocurrent data record southerly flowing current matching the modern Virgin River. Due to the broad area encompassed by these measurements, I interpret the paleocurrent data as representative of low sinuosity within the ancient fluvial system.

Analysis of mapped lithofacies goes hand-in-glove with the analysis of each mapped architectural element. Based on the mapped architectural elements, I interpret the fluvial MCF as an example of a “High-Energy, Sand-Bed braided river”, (HESB) following the nomenclature of Miall (1996). In this type of fluvial system common macroforms include downstream accreting (DA), sandy bedform (SB), scour hollow (HO), and minor overbank fines (FF). As stated in chapter 2, channel elements (CH) are used where other in-channel macroforms cannot be reliably identified. These macroform elements are present in one or both sites; however the rigorous assignment of a fluvial model is difficult because these same elements are commonly present in other low sinuosity braided systems. These systems are described below in order to form a basis for comparison of HESB systems with similar fluvial models.

Initial study and interpretation of mapped architectural elements identified three possible models as viable explanations of the mapped fluvial stratigraphy. All three models are types of sand-dominated, low sinuosity rivers as described in Miall (1985; 1996). They are 1) the shallow perennial braided “Platte-type” (Fig. 20); 2) the deep

perennial braided “S. Saskatchewan-type” (Fig. 21); and 3) the high-energy sand-bed braided (Fig. 22). An example of likely vertical profiles for each of the above systems is shown in Figure 23.

Macroforms develop in Platte-type rivers in two main hydrologic regimes, high-stage and low-stage. These fluvial systems are only braided in the low stage while the characteristic mid-channel bars are active at high stage. 2-D and 3-D dunes are formed in the active channels (Miall, 1996). Examples of this type of system include the Devonian Brownstones (Fig. 24) (Allen, 1983), and the modern Platte River (Fig. 25), described by Blodgett and Stanley (1980). Common macroforms include sandy bedforms (SB) and associated lithofacies as shown in Table 1.

Deep perennial braided streams of the S. Saskatchewan-type are similar to the Platte model except that they are bigger in scale and river depth. Deeper channels and more complex flow fluctuations create more varied facies. Fluctuations in flow can vary between low, medium, and high stage (Miall, 1985). Thus, mid-channel bars may remain partially exposed during medium stage water levels. This process allows for accretion and sedimentation/erosion to take place on mid-channel bar flanks, but not on bar tops. Common macroforms in these fluvial systems include DA, LA, SB, and FF. Miall (1985) emphasizes that the differentiation of these systems from Platte type fluvial systems is strictly an interpretation. This interpretation is based on the fact that no single sedimentation event or macroform can be thicker (deeper) than the depth of the channel. Therefore, while S. Saskatchewan-type macroforms may compare favorably with Platte-type rivers, they contrast in their respective stratigraphic thicknesses. The deep channels produce thicker macroforms of more complexity. An ancient example is described by Kirk (1983) and the modern S. Saskatchewan River is described by Cant and Walker (1978) and Lane et al. (2010).

As stated above, I determined that the ancient fluvial system was a high-energy sand-bed braided system. This classification is made based on my interpretation of the following data sets: Fluvial architecture, lithofacies, and sedimentary structures. Site 1 and site 2 fluvial architecture contains macroforms characteristic of an HESB system; elements DA, SB, HO, and minor FF (Plates 4.2, 4.3). Although not characteristic, the presence of Sediment Gravity flows (SG) is evidence of a high energy fluvial system. The dominant lithofacies present within each element is gravelly sand, also indicative of high energy depositional environments. Where measured, sand and gravel comprise at least 93% of the stratigraphic section (Fig. 17). Lithofacies within the SG elements are clast supported gravels with large rip-ups. Sedimentary structures within each macroform are also indicative of high energy and rapid sedimentation. Horizontally bedded sand (Sh) and low-angle cross-bedded sand (Sl) were mapped throughout both study sites, most common in DA, LA, and SB elements. Lithofacies Sh are deposited in the upper plane bed flow regime (Fig. 26) and may be deposited to several meters thickness in a single flood event (Ashley 1990; Miall, 1996). Lithofacies Sl may be deposited in similar flow regimes to Sh, or they may be deposited at the boundary between subcritical and supercritical flow (Miall, 1996). While any single macroform mapped in this study might be logically assigned to a Platte-type or S. Saskatchewan-type fluvial architecture, the presence and abundance of coarse, high-energy facies and the absence of lower energy trough cross-bedding and ripple lamination and bioturbation supports the classification of MCF fluvial rocks as the result of a high-energy sand-bed braided river system. Cowan (1991) described similar features from the Westwater Canyon Member of the Morrison Fm.

Once characterization of fluvial style is made, the size and character of subsurface strata can be inferred. The inference(s) gained represent very valuable information to geologists searching for natural resources such as water and

hydrocarbons. If buried relatively intact, a high-energy sand-bed braided system may offer very good reservoir qualities. Very high sand/shale ratios in the measured sections provide good porosity/permeability properties and there is evidence that fine grained aquitards observed at site 1 (Plate 4.2) are discontinuous. Therefore, compartmentalization is less likely in MCF strata than in other reservoirs. Furthermore, there is reason to infer that dynamic high-energy events scour underlying bedforms during deposition. This process increases connectivity. Larue and Hovadik (2006) used computer modeling of 11 fluvial models to determine connectivity in clastic reservoirs. These models were applied to lower-energy, less connected systems of channel sands within overbank fines. The results of the modeling were that ~90% reservoir connectivity was achieved whenever the sand/shale (net-to-gross, NTG) ratio was higher than 50%. These models are a very conservative proxy, describing a reservoir architecture that is much less favorable than that of the fluvial MCF.

CHAPTER 6

CONCLUSIONS

Objectives of this study included 1) describe the stratigraphy of the Muddy Creek Formation; 2) refine MCF depositional models; and 3) test a hypothesis relating to the “Muddy Creek Problem” and the ancestral Colorado River. Previous studies tackling these problems have mainly utilized provenance studies (Kowallis and Everett, 1986; Scott, 1988; Dicke, 1990; Pederson, 2008; Forrester 2009), while other studies have used mapping (Bohannon, 1984; Williams, 1996). Provenance studies have variously concluded that the MCF was sourced both locally and from the Colorado Plateau and interpreted that the MCF did not represent an ancestral Colorado River.

Previous studies did not rigorously rule out an ancestral Colorado River in the VRD; however they did generate evidence pointing toward that conclusion. To the extent that the MCF was a possible ancestral Colorado River deposit this study sought to characterize the fluvial MCF. The study area is located at the depositional center of the VRD along the basin bounding fault and contains fluvial lithofacies that were deposited in the Miocene. I combined detailed mapping with conglomerate provenance and architectural elements analysis to characterize the fluvial portion of the MCF. These analyses provided insight into the style of the fluvial system that deposited the upper MCF and confirmed a previous depositional model.

When combined with previous work my study concludes that in the latest Miocene the MCF was deposited in an internally drained basin. After an undefined period of time, the ancestral Virgin River overtopped its barrier and flowed into the VRD. This conclusion concurs with Williams (1996), Pederson (2008), and Forrester (2009) who have concluded that the fluvial MCF represents the arrival of the Virgin River into the Virgin River Depression and not the ancestral Colorado River. The fluvial attributes in the MCF in the study area bear little resemblance to the known “Colorado River

Gravels” near Sandy Cove at the upper reaches of Lake Mead. Repeated provenance studies have shown a Colorado Plateau influence in VRD sediments which are permissively attributed to an ancestral Virgin River. Paleocurrents indicate southerly flow along the axial Mesquite and Mormon basins, essentially where the Virgin River flows today. The ancient river system was a high-energy sand-bed braided system as evinced by the stacked architectural elements, high-energy lithofacies, sedimentary structures, and absence of bioturbation.

The Virgin River brought a rapid phase of aggradation before it was integrated into the Colorado River and incision began. Previous work shows that the Colorado River reached the central Basin and Range between 5.5 and 4.4 Ma, and that deposition of the MCF within the VRD lasted until at least 4.1 Ma. This age relationship places an age limit of approximately 4.0 Ma on the capture of the Virgin River by the Colorado River. An enclosed Virgin River Depression is one model that may explain the time elapsed between development of the through-going Colorado River and the end of MCF deposition. In this model, the Virgin River aggrades until the VRD is overtopped, the river reaches a new base level, and down-cutting begins. In addition to this new depositional model, this study also provides surface mapping at higher detail than previous maps, refines the Quaternary history of the area, and confirms the 4 incision events described by Gardner (1968; 1972b). Additionally, this study informs rift basin reservoir models.

Tables

Architectural Elements Classification

Element Symbol	Element	Principal lithofacies assemblage (see Table 2)
CH	Channels	Any combination
DA	Downstream accretion macroforms	St, Sp, Sh, Sl, Sr, Ss
LA	Lateral accretion macroforms	St, Sp, Sh, Sl, Ss, less commonly Gmm, Gmg, Gp, Gt
FF	Overbank fines	Fm, Fl
SB	Sandy bedforms	St, Sp, Sh, Sl, Sr, Ss
GB	Gravel bars and bedforms	Gmm, Gmg, Gp, Gt
HO	Scour hollows	Gh, Gt, St, Sl
SG	Sediment gravity flows	Gmm, Gmg, Gci, Gcm

Table 1. Table shows architectural elements as defined by Miall (1985; 1988; 1996) along with scour hollows (HO) as defined by Cowan (1991) (Table modified from Miall 1996).

Facies Classifications

Symbol	Facies	Sed structures	Interpretation
Gmm	Massive, matrix supported gravel	Weak grading	Plastic debris-flow (high strength, viscous)
Gmg	Matrix supported gravel	Inverse to normal grading	Pseudoplastic debris flow (low strength, viscous)
Gci	Clast-supported gravel	-	Pseudoplastic debris flow (turbulent flow)
Gcm	Clast-supported massive gravel	Massive	Pseudoplastic debris flow (inertial bedload, turbulent flow)
Gh	Clast supported, crudely bedded gravel	Horizontal bedding, imbrication	Longitudinal bedforms, lag deposits, sieve deposits
Gt	Gravel, stratified	Trough cross-beds	Minor channel fills
Gp	Gravel, stratified	Planar cross-beds	Transverse bedforms, deltaic growths from older bar remnants
St	Sand, very fine to coarse, may be pebbly	Solitary or grouped trough cross-beds	Sinuuous crested and linguoid (3-D) dunes
Sp	Sand, very fine to coarse, may be pebbly	Solitary or grouped planar cross-beds	Transverse and linguoid bedforms (2-D dunes)
Sr	Sand, very fine to coarse, may be pebbly	Ripple cross-lamination	Ripples (lower flow regime)
Sh	Sand, very fine to coarse, may be pebbly	Horizontal lamination, parting current lineations	Plane-bed flow (critical flow)
Sl	Sand, very fine to coarse, may be pebbly	Low angle (< 15°) cross-beds	Scour fills, humpback or washed-out dunes, antidunes
Ss	Sand, very fine to coarse, may be pebbly	Broad, shallow scours	Scour fill
Sm	Sand, fine to coarse	Massive, or faint lamination	Sediment-gravity flow deposits
Fl	Sand, silt, mud	Fine laminations, very small ripples	Overbank, abandoned channel, or waning flood deposits
Fm	Mud, silt	Massive, desiccation cracks	Overbank, abandoned channel, or drape deposits
P	Paleosol carbonate	Pedogenic features, pisoliths	Soil with chemical precipitation

Table 2. Table shows lithofacies as defined by Miall (1985; 1988; 1996) (Table modified from Miall 1996).

Bounding Surfaces Classification

Order	Fluvial depositional unit	Rank and characteristics of bounding surfaces
0	Lamina	Lamination surface
1	Microform (e.g. ripples)	Set bounding surface
2	Diurnal dune increment, reactivation surface	Coset bounding surface
3	Macroform growth increment	Dipping 5-20° in direction of accretion
4	Macroform	Convex-up macroform top, minor channel, minor channel scour, flat surface bounding floodplain elements
5	Channel	Flat to concave-up channel base
6	Channel belt, alluvial fan, minor sequence	Flat, regionally extensive or base of incised valley
7	Major dep. system, fan tract, sequence	Sequence boundary; flat, regionally extensive, or base of incised valley
8	Basin-fill complex	Regional disconformity

Table 3. Table shows bounding surface hierarchy as defined by Miall (1985; 1988; 1996) (Table modified from Miall 1996).

Figures

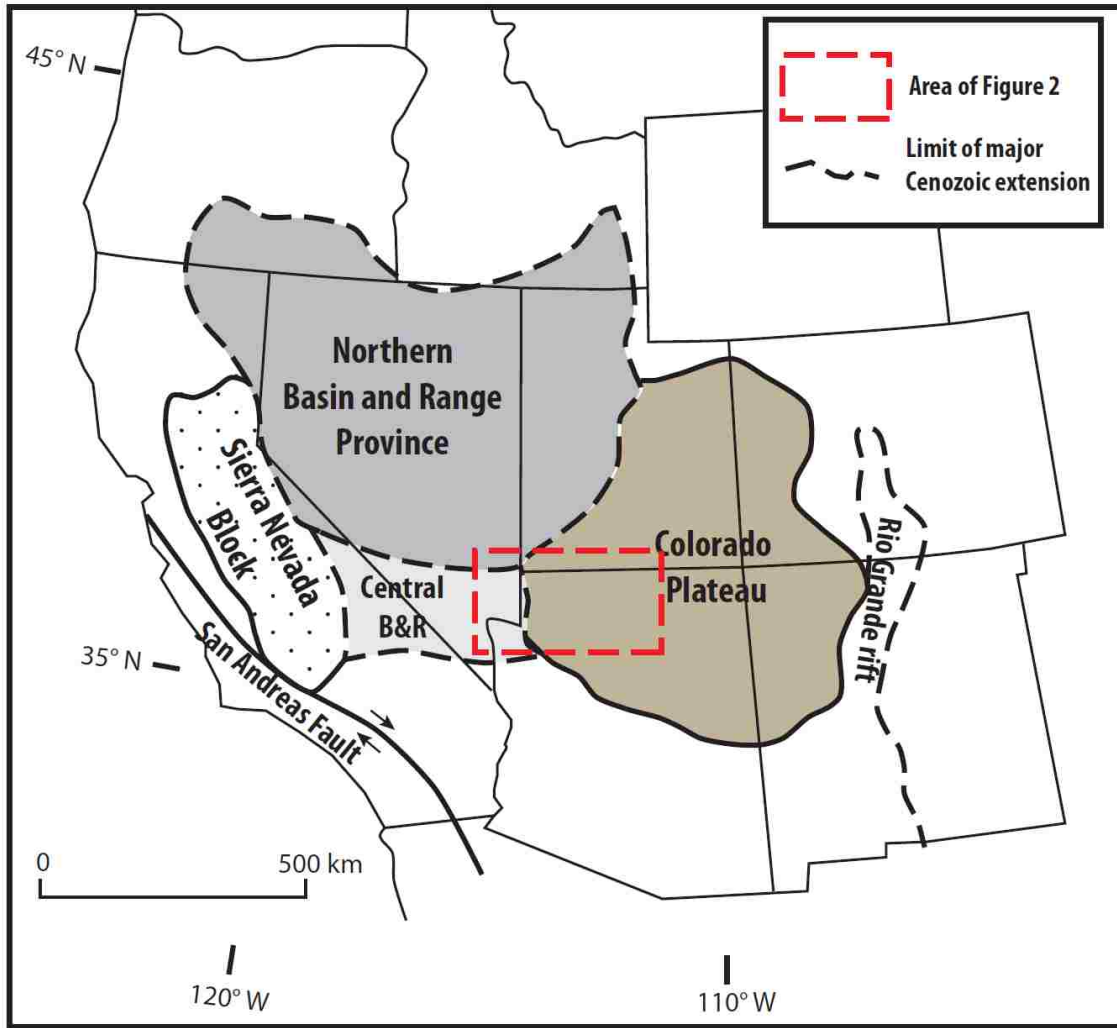


Figure 1. Structural provinces of western North America (modified from Faulds et al., 2001).

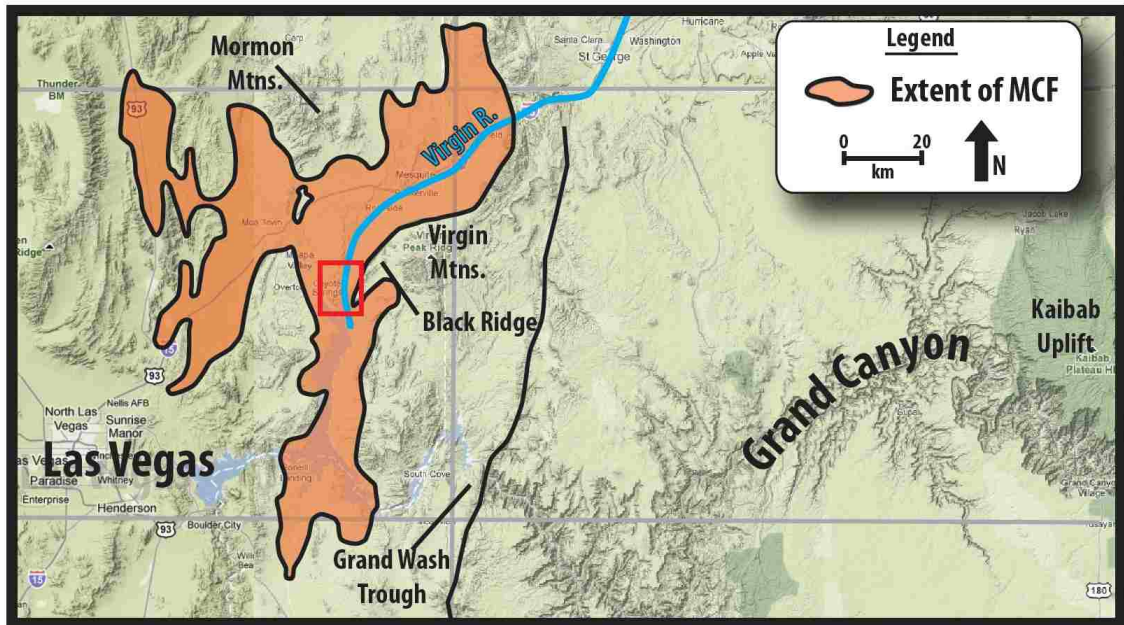


Figure 2. Map modified from Pederson (2008) shows the extent of Muddy Creek Fm. throughout the central Basin and Range.

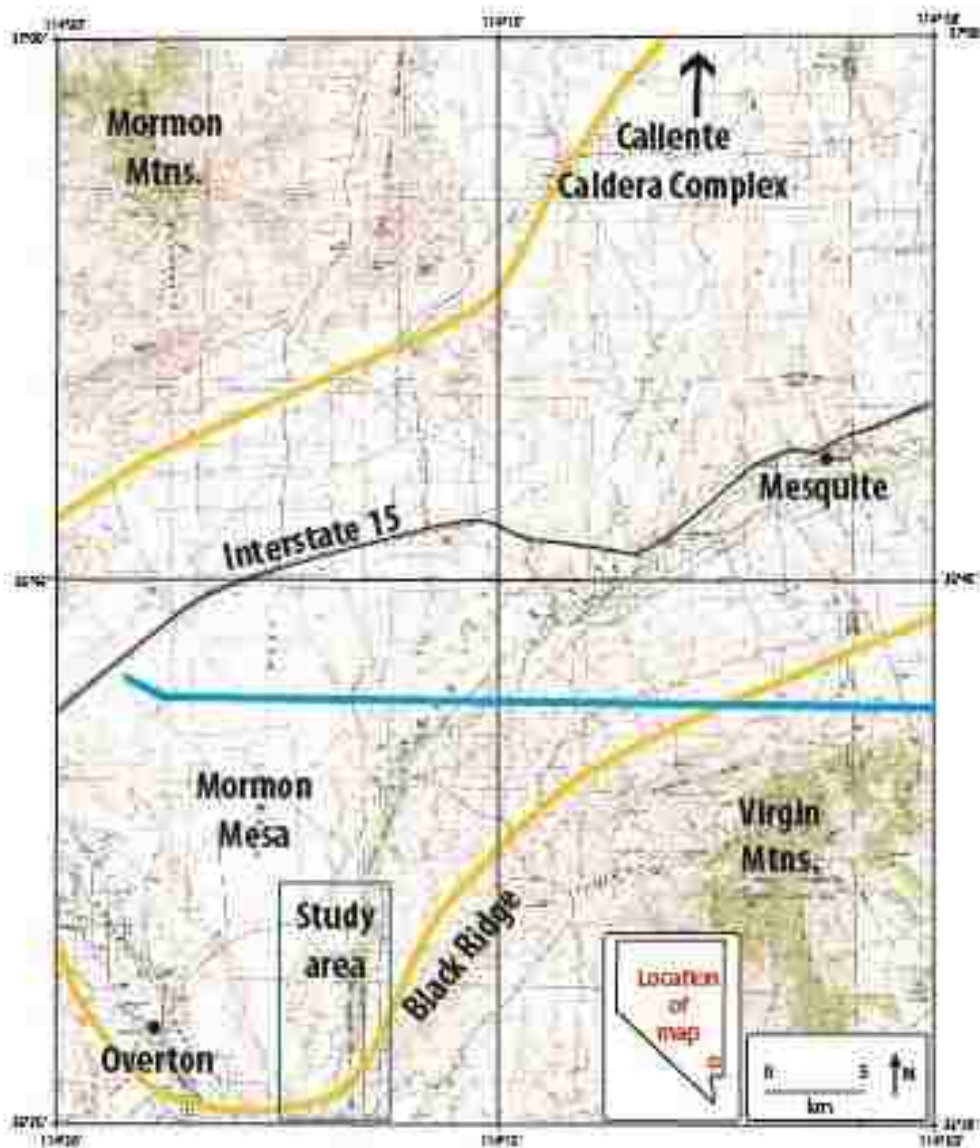


Figure 3. Location map showing key locations within the Virgin River Depression (outlined in yellow). The study area outlined in blue is the western half of the Overton SE Quadrangle. The thick blue line is the location of the seismic transect interpreted by Bohannon et al. (1993) (Fig. 7).

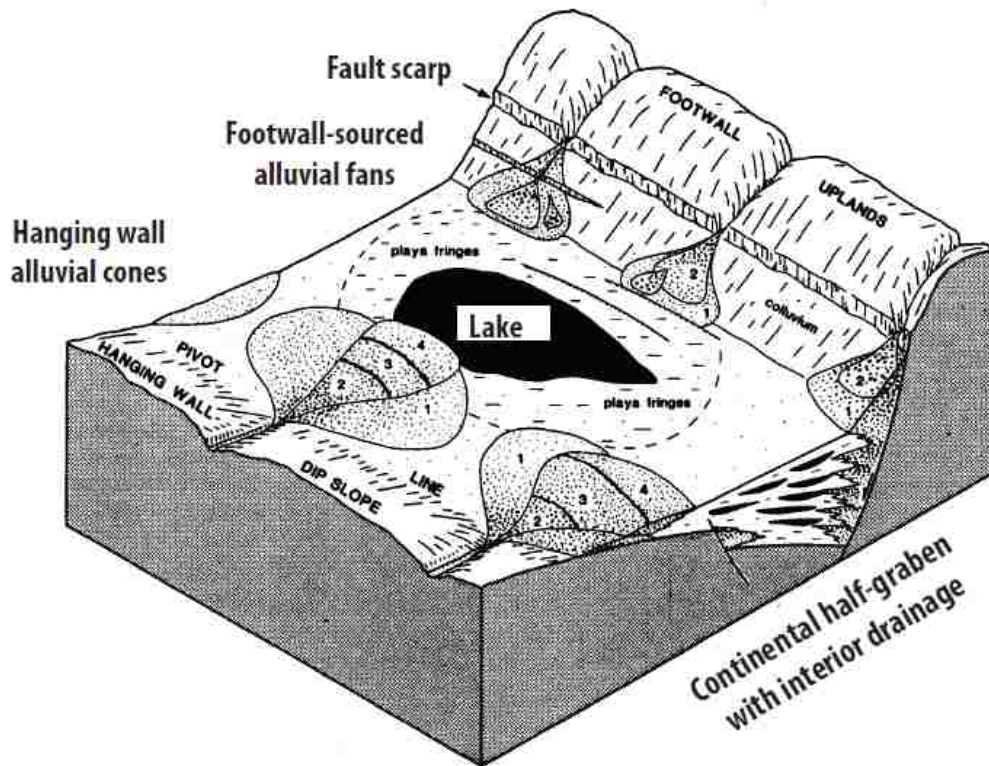


Figure 4. Depositional model for an internally drained half-graben rift basin (modified from Leeder and Gawthorpe, 1987).

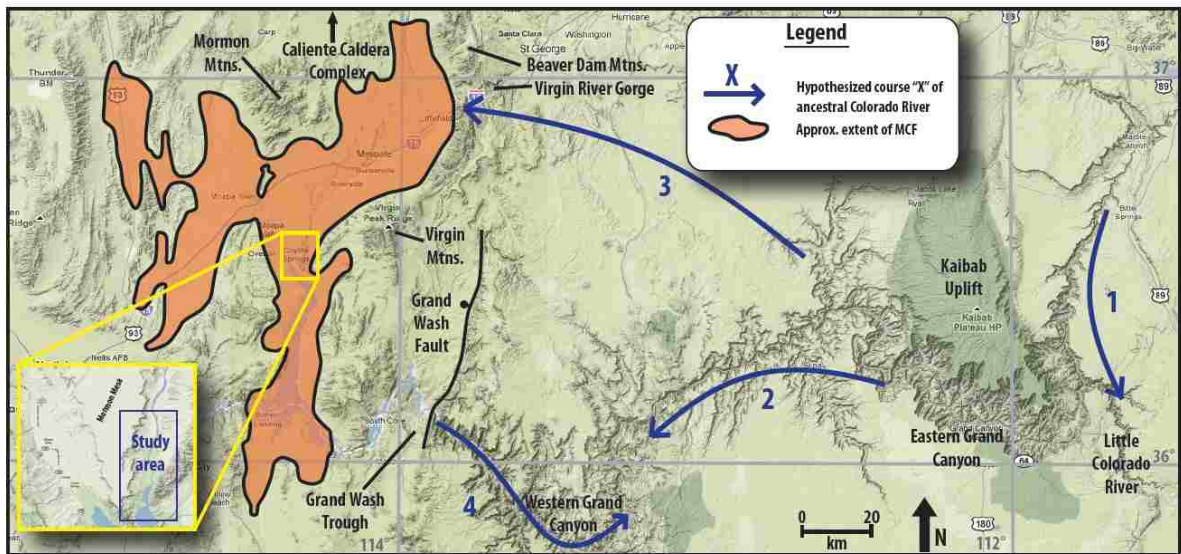


Figure 5. Map modified from Pederson (2008) shows Colorado and central Basin and Range regions, extent of Muddy Creek Formation, and location of study area. Hypothesized ancestral river courses: 1) Southeast (McKee et al., 1967) 2) West and infiltrating/terminating (Hunt, 1969) 3) Northwest (Lucchitta, 1990) and 4) “California River” hypothesis (Wernicke, 2011).

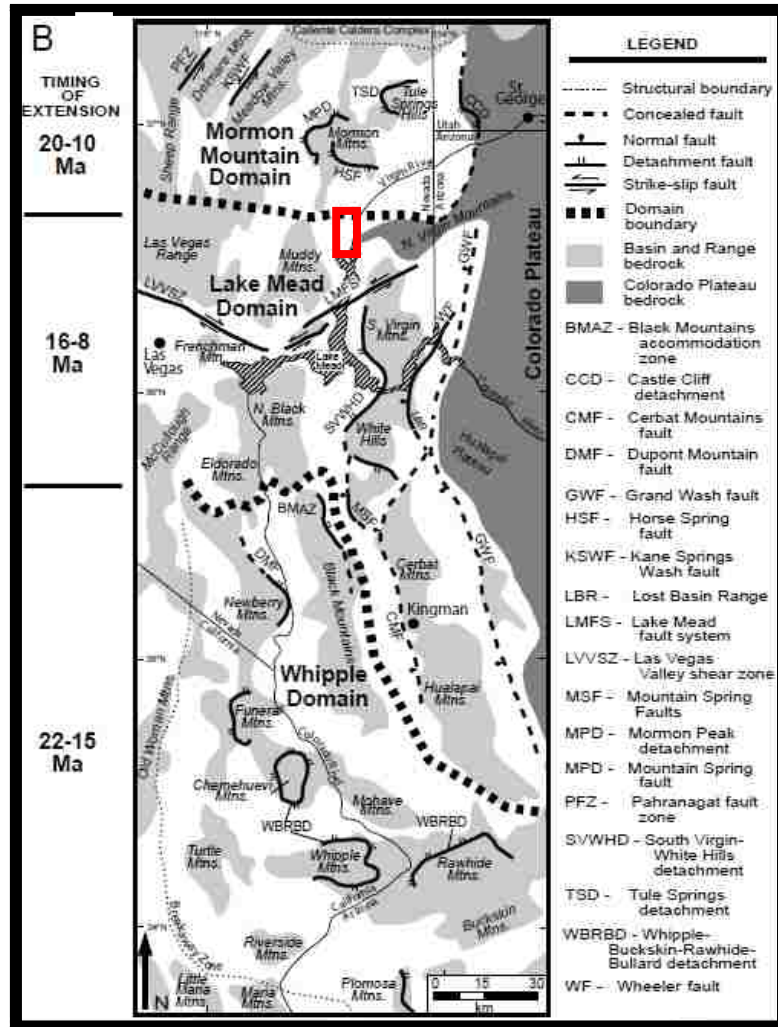


Figure 6. Map shows Lake Mead area structural domains and their respective timing of extension. Location of study area is outlined in red (modified from Lamb et al., 2010).

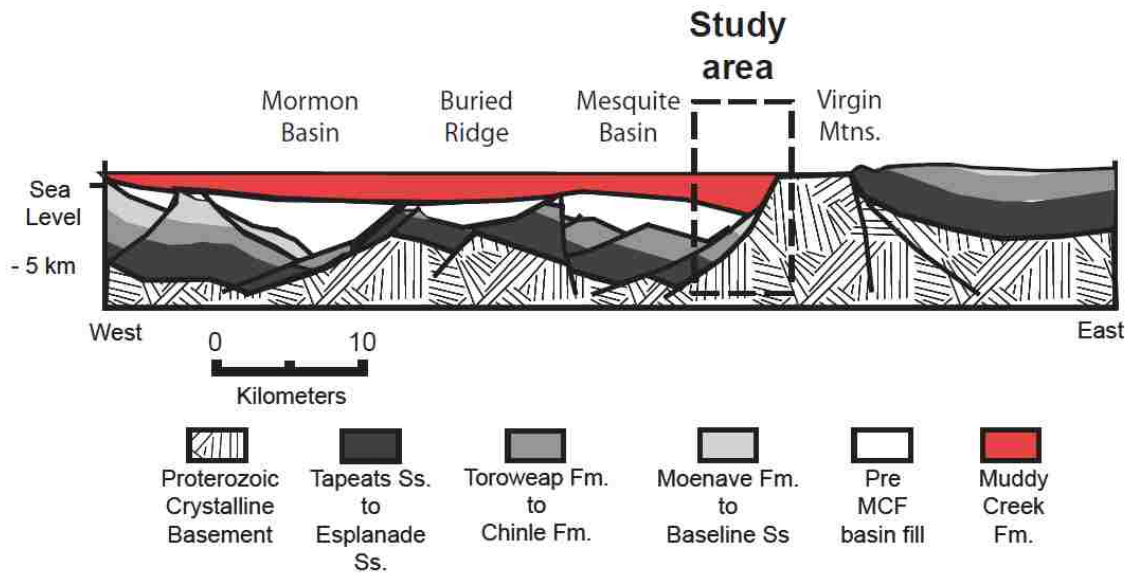


Figure 7. Cross section of Mormon and Mesquite basins (VRD) showing west dipping faults offsetting east dipping half grabens. Cross section is an east-west transect across the VRD ~12 km north of study location. Although the study location does not include the transect, the study area is shown because the structural regime is identical; the basin bounding fault lies within the study area. Structural interpretation by Bohannon et al. (1993) was derived from seismic data and Mobil 1A test well drilled on Mormon Mesa.

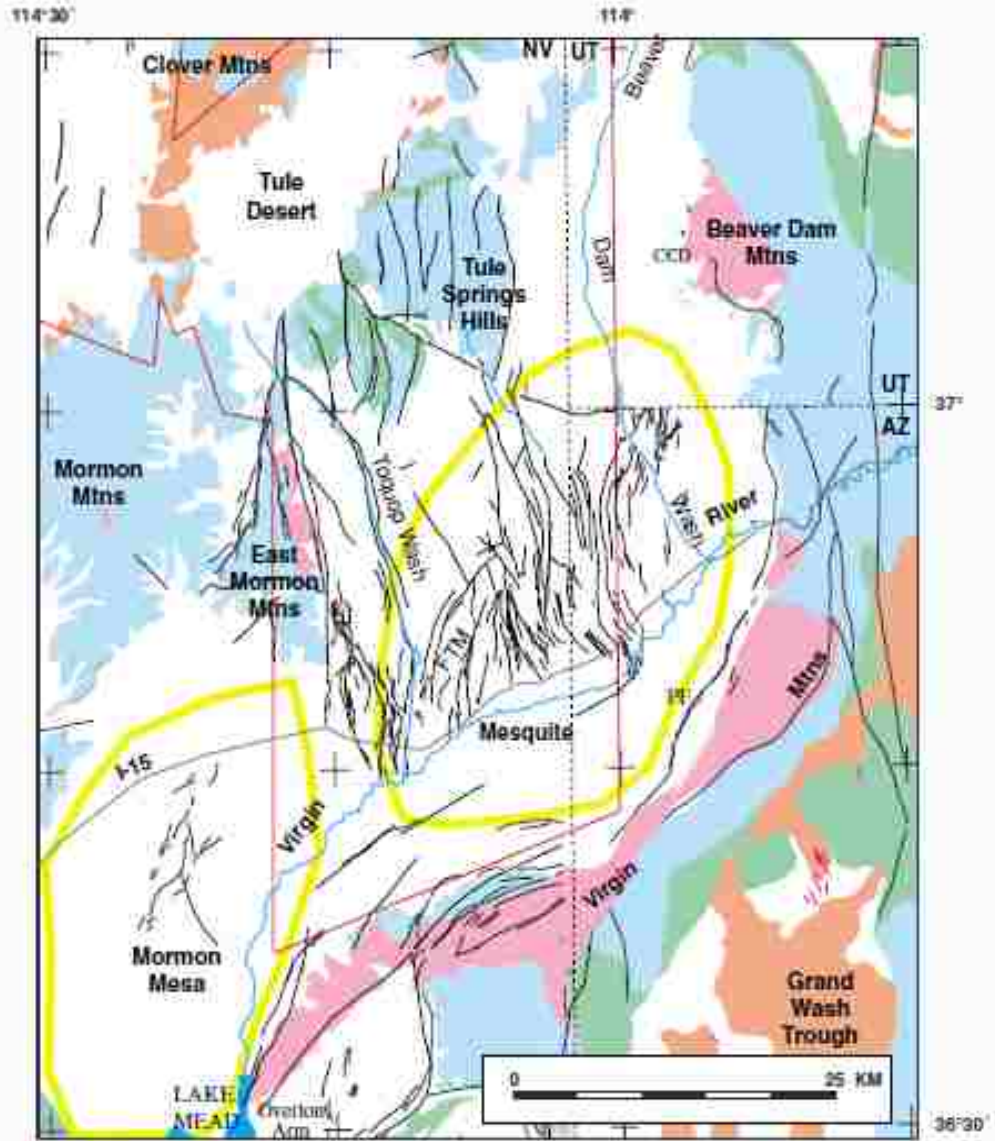


Figure 8. Map from Langenheim et al. (2000) showing the outlines (yellow) of the Mesquite sub-basin in the northwest and the Mormon sub-basin to the southwest.

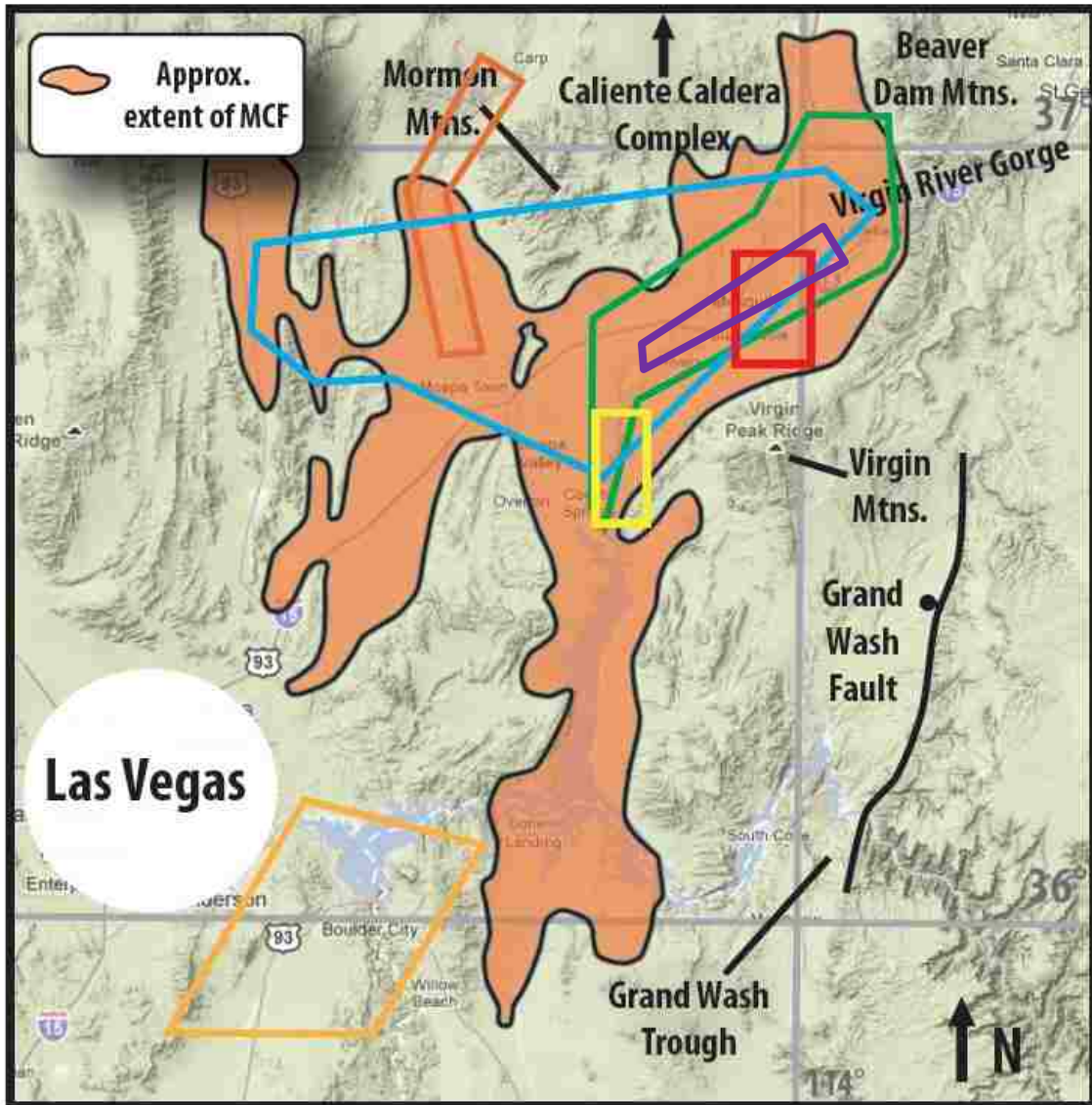


Figure 9. Map modified from Pederson (2008) showing the locations of previous studies. The purple polygon is the outline of the study for Kowallis and Everett (1986). The light orange polygon is the outline of the study area for Scott (1988). The dark orange polygon is the outline of the study area for Dicke (1990). The blue polygon is the outline of the study area for Pederson (2008). The green polygon is the outline of the study area for Forrester (2009). The red polygon is the outline of the study area for Williams (1996). The yellow polygon is the outline of the study area for this project.

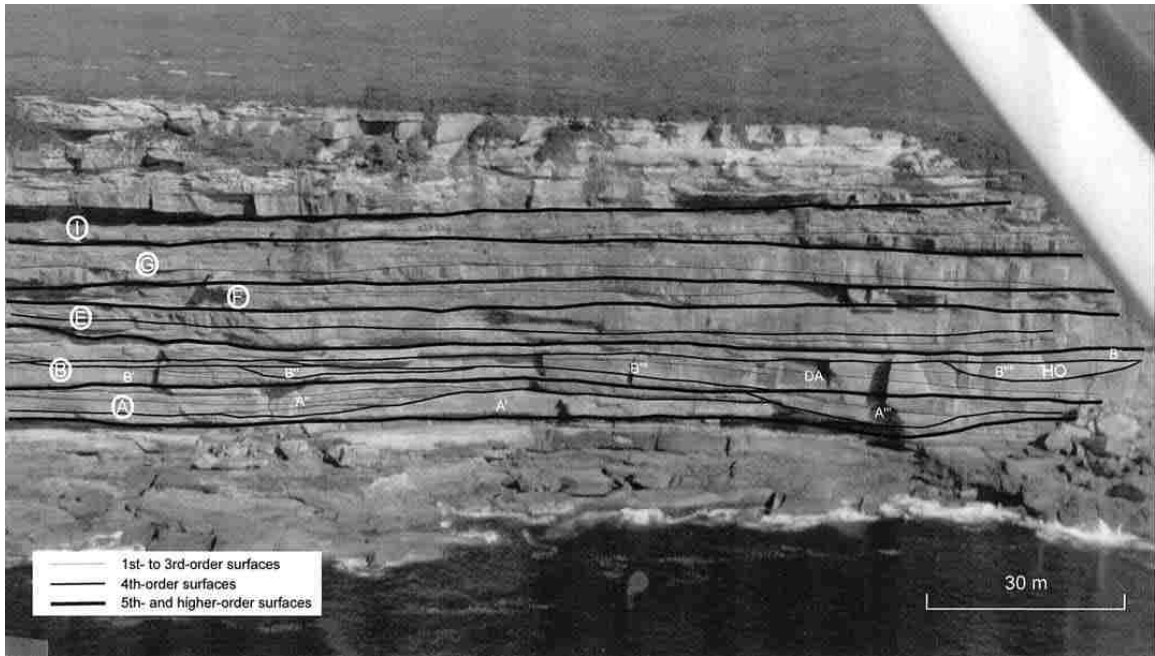


Figure 10. Example of architectural elements analysis of the Hawkesbury Sandstone by Miall and Jones (2003). In this example one photo is overlaid with a map of identified architectural elements. A more detailed alternative is to map architectural elements onto a photomosaic of the outcrop.

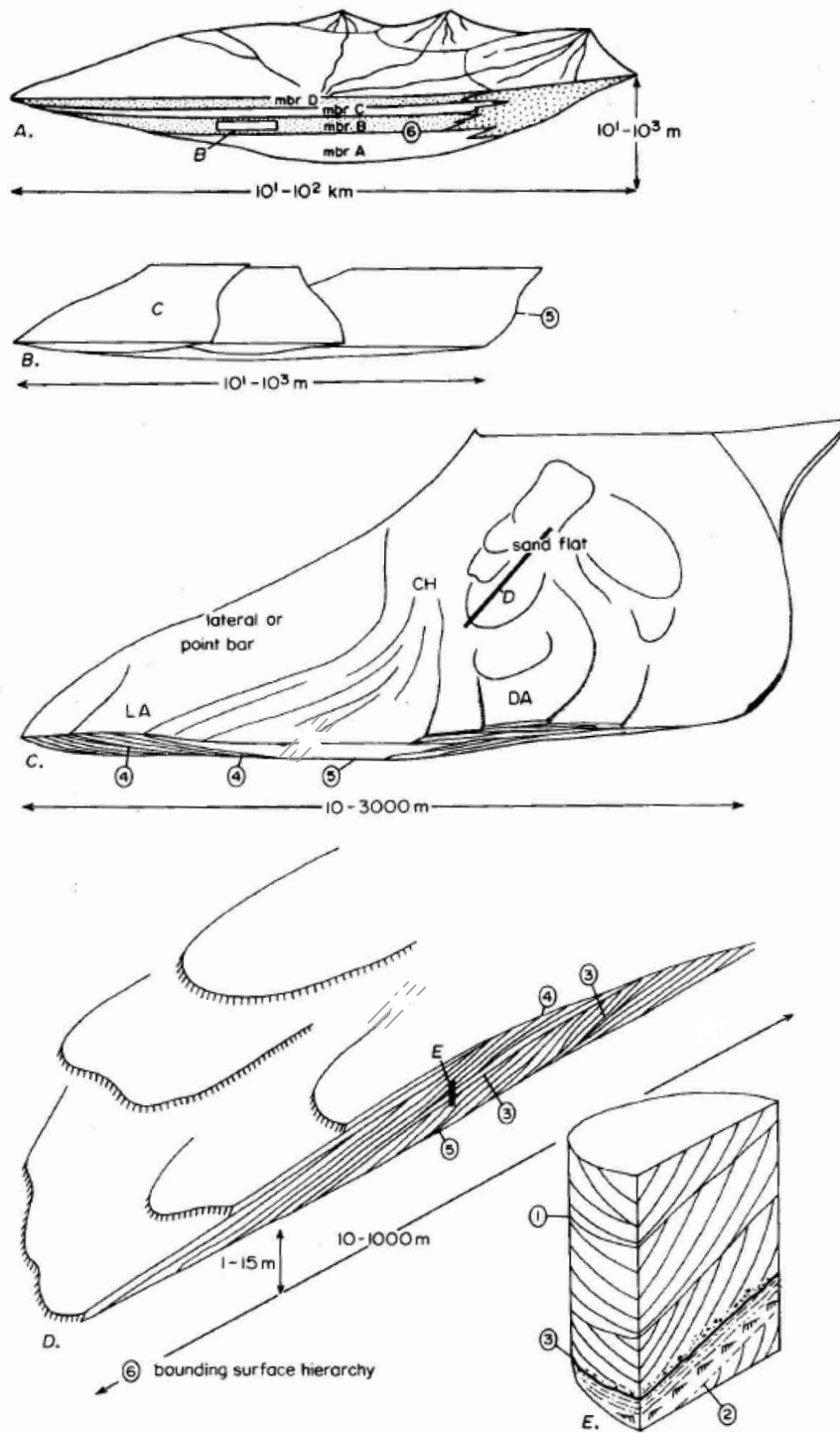


Figure 11. This diagram shows the various scales present in fluvial systems. Bounding surface hierarchy is shown in the circled numbers; the diagram shows ranks 1 – 6. Starting in C., two-letter architectural element codes label the macroforms (from Miall, 1988).

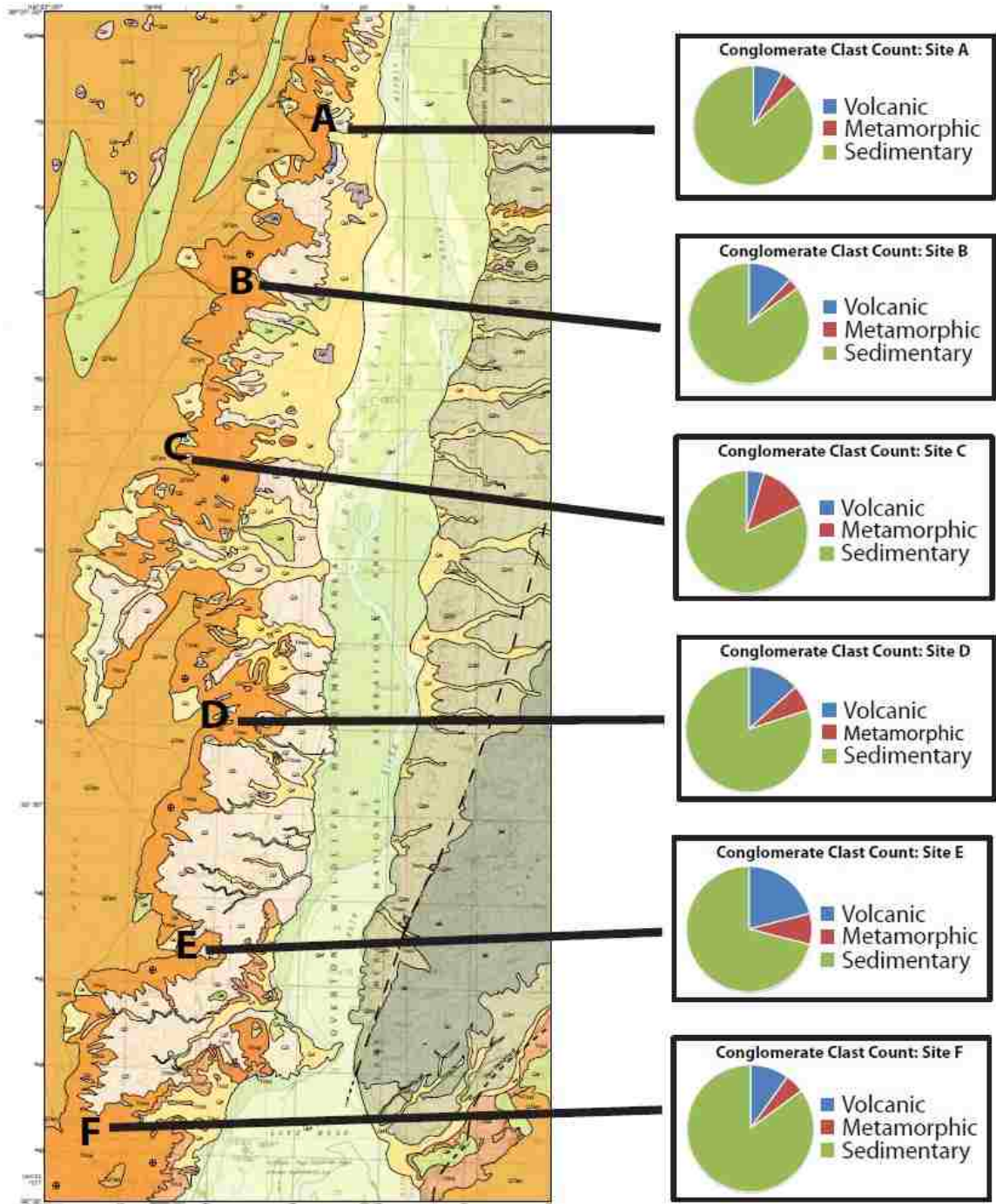


Figure 12. Geologic map of the Overton SE quadrangle (this study) showing site A – F clast count results. See Plate 4.1 for map key.

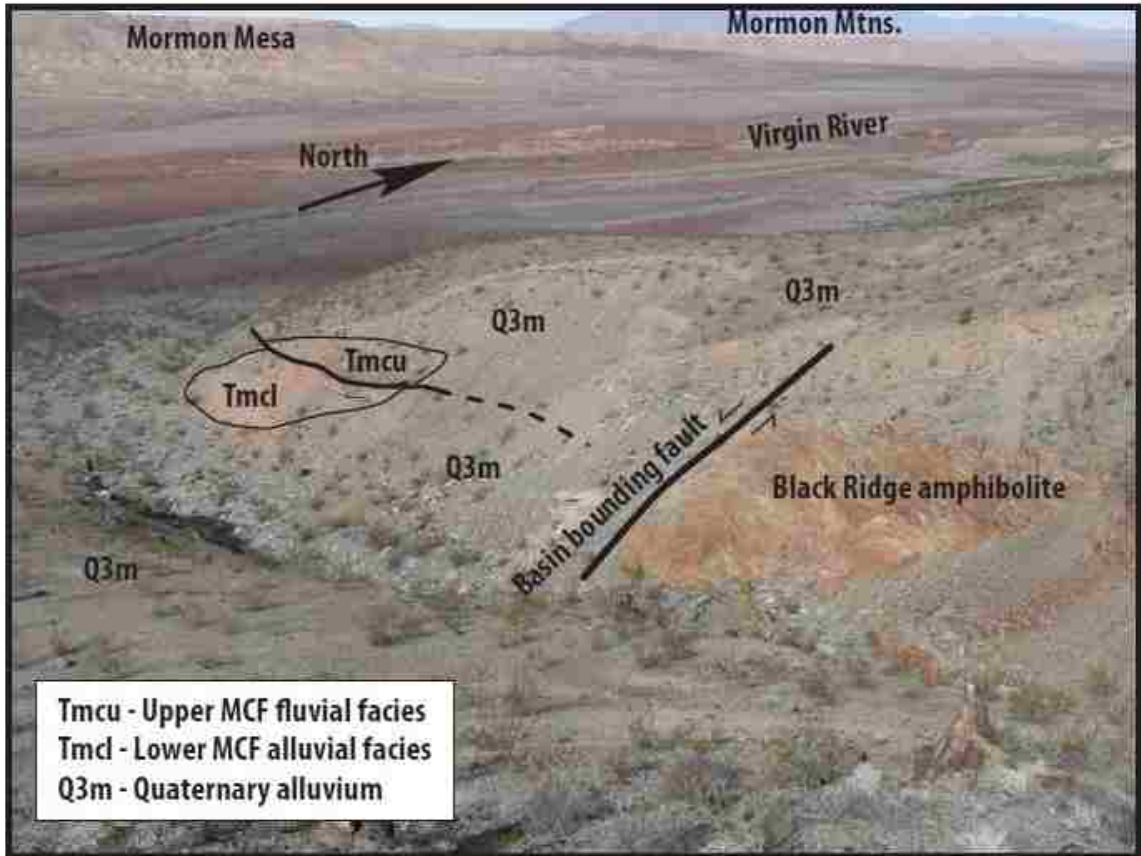


Figure 13. This photograph was taken near the southeastern portion of the field area on the western slope of Black Ridge. The photo shows the contact between lower MCF alluvial facies overlain by fluvial facies. This area is proximal to Black Ridge and mantled by modern Quaternary alluvium.

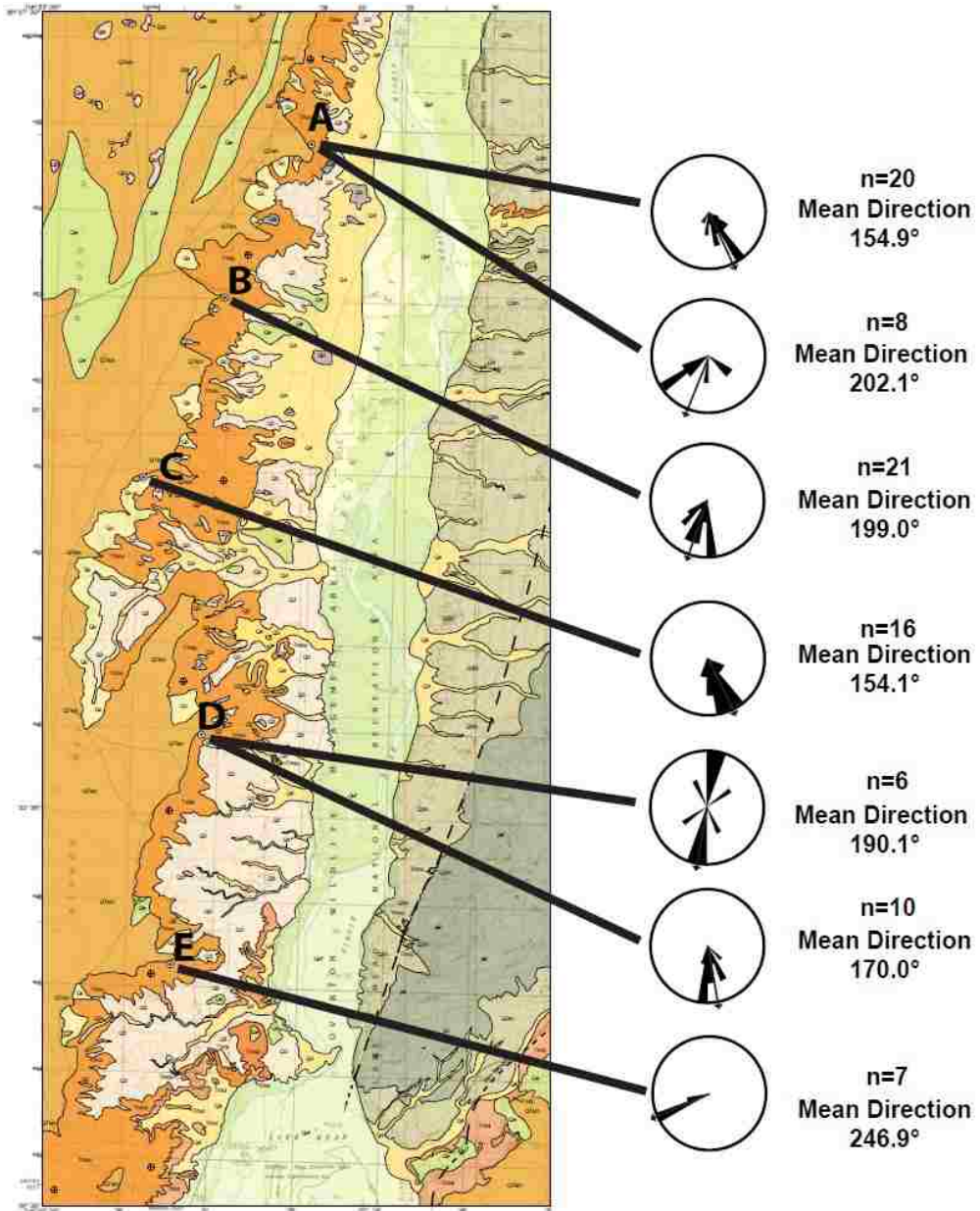


Figure 14. Geologic map of the Overton SE quadrangle (this study) showing site A – F paleocurrent measurement results. See Plate 4.1 for map key.

Equal Area

n=77

**Mean direction
174.0**

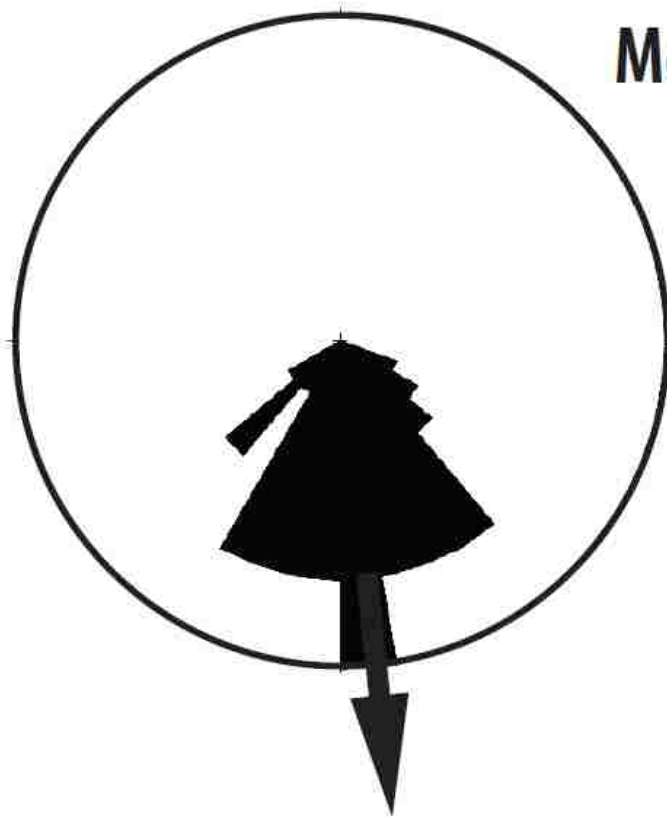


Figure 15. Rose diagram shows all paleocurrent measurements from sites A – E summed.

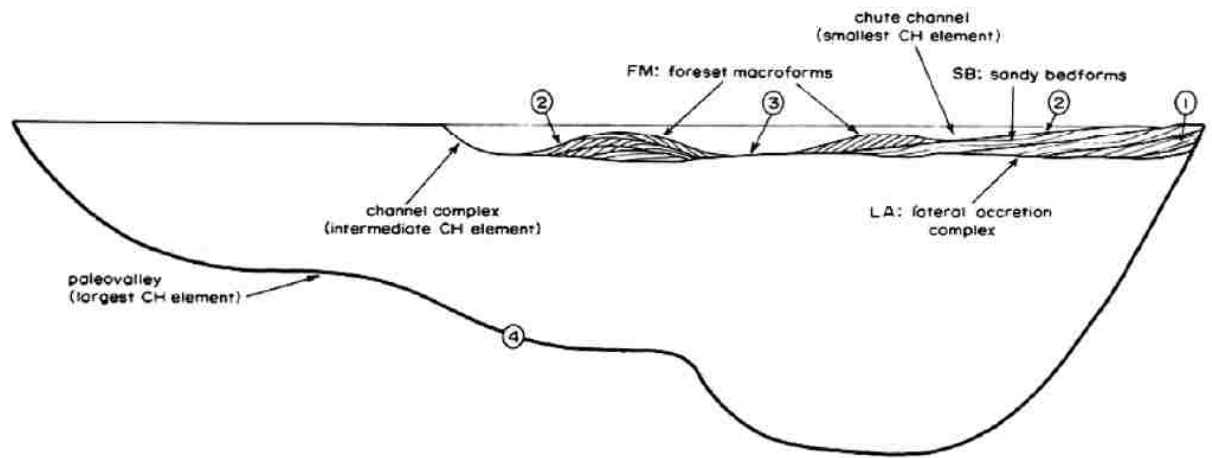


Figure 16. Channel (CH) elements contain smaller constituent architectural elements or are used to classify concave up geometries where a genetic relationship cannot be determined. As shown in Figure 11, channels can be used to classify large, 6th order channel complexes or minor channels just meters wide (from Miall 1985).

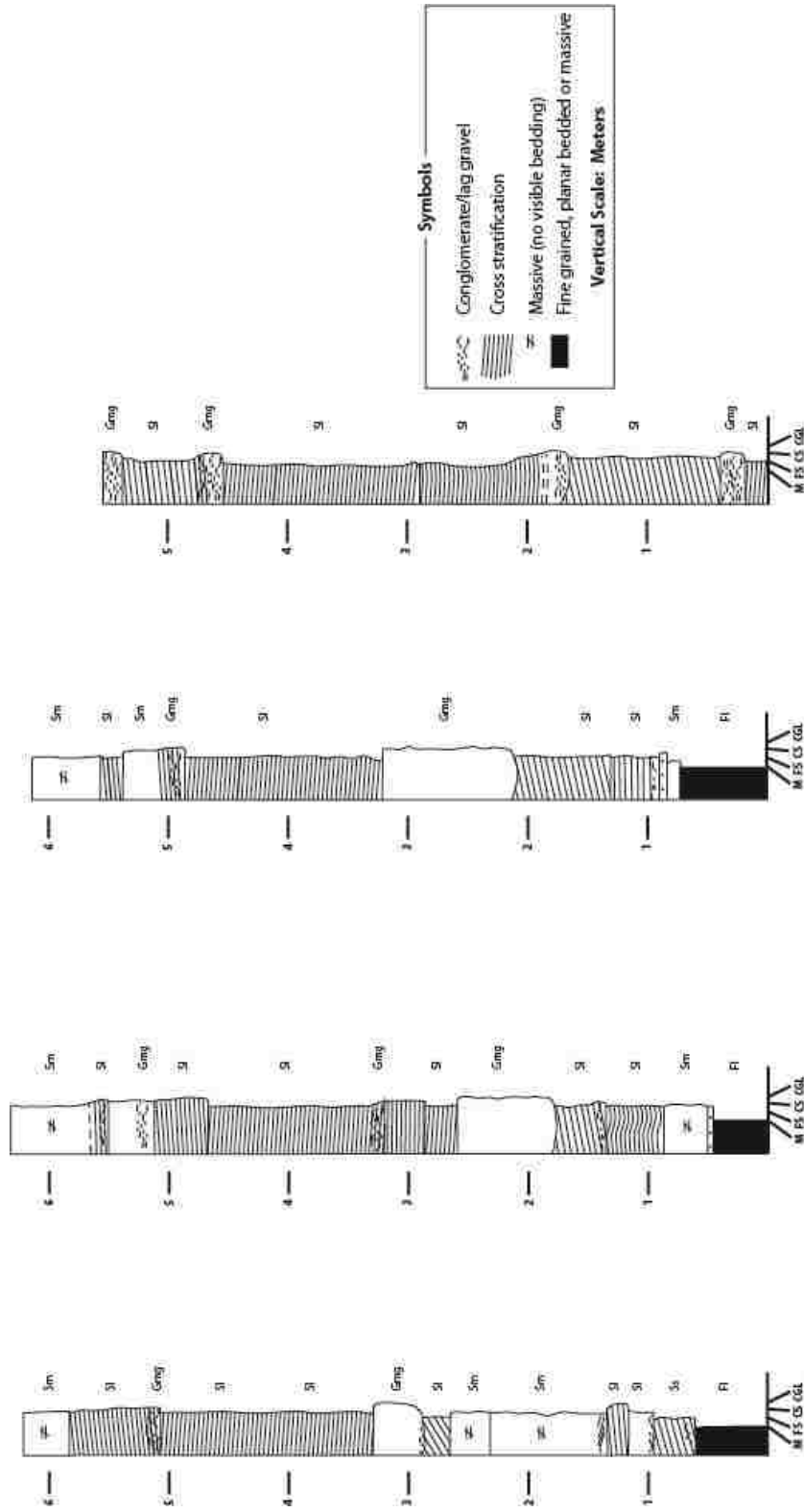
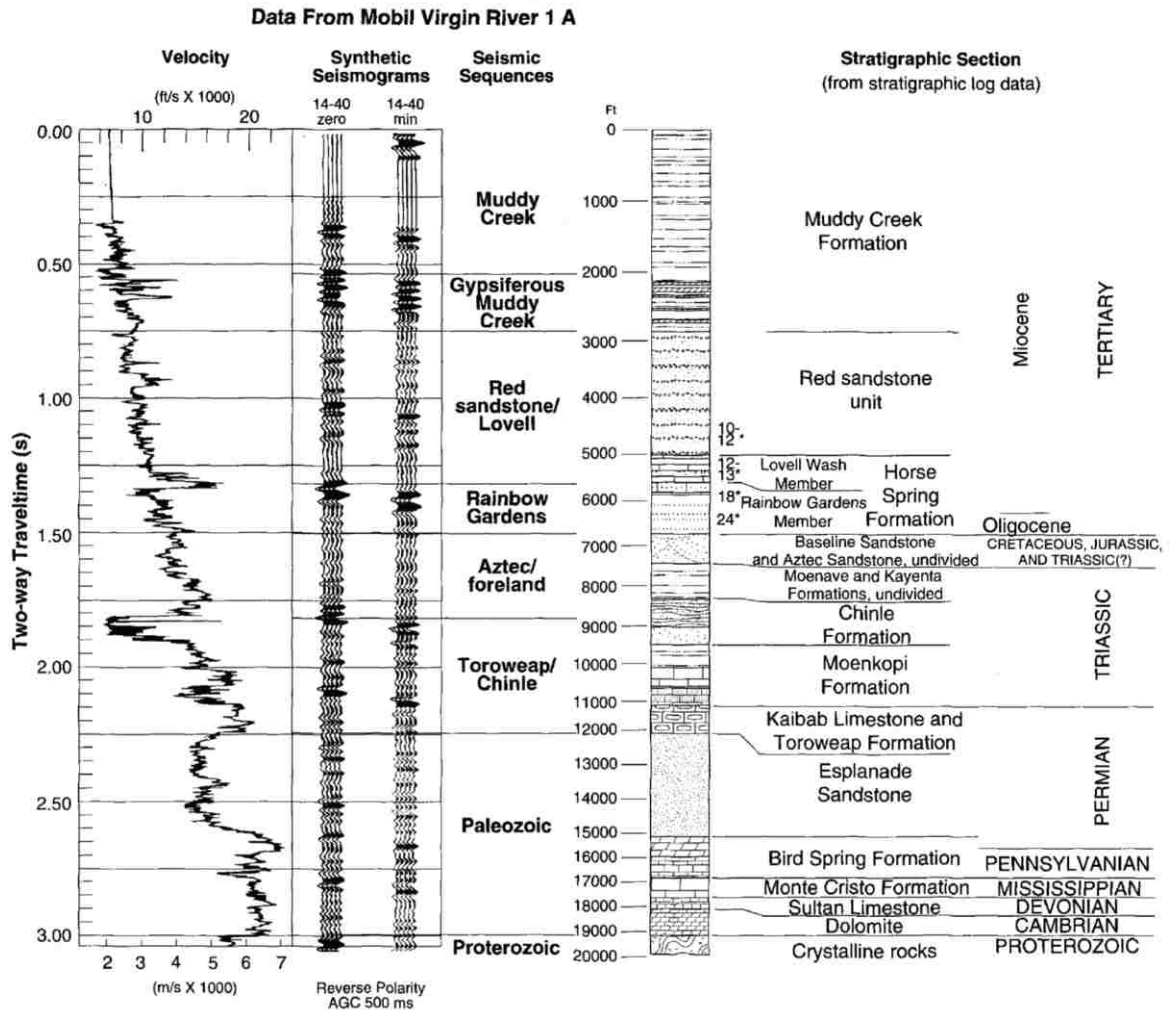


Figure 17. Measured sections from architectural elements site 1 (Plate 4.2). Each column was measured in order to determine sand/shale ratios. The predominant grain size is medium to fine sand with pebbly intervals at the base of macroforms. Inclined strata shown within beds are diagrammatic and do not necessarily reflect the true inclination of sedimentary structures. Lithofacies classifications are shown at the right of each measured section. For lithofacies definitions see plat 4.2 or Table 2



* Approximate ages in millions of years; based on regional fission-track studies conducted on regionally distributed surface rocks (Bohannon, 1984; Carpenter and others, 1989)

Figure 18. Interpretation of Mobil 1A well and seismic correlation by Bohannon et al. (1993). The Mobil 1A well was drilled on Mormon Mesa just outside the study area and offers a good approximation of unit thicknesses within the study area. Facies within the MCF coarsen upward from evaporites and distal fines to sandstone, and fluvial conglomerate.

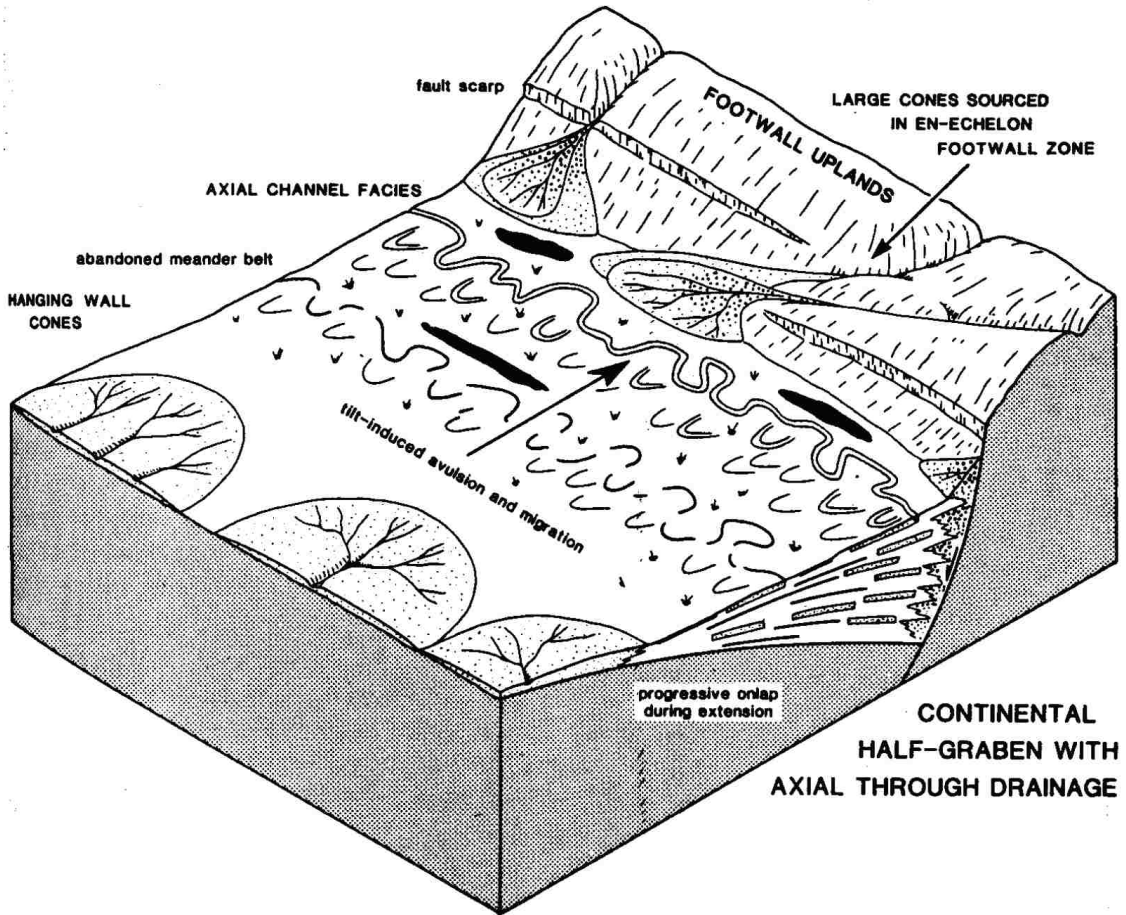


Figure 19. Block diagram from Leeder and Gawthorpe (1987) shows a basin geometry similar to that of an internally drained half-graben basin. The tectonic processes are identical but the change from internal drainage to a through-going axial drainage produces a dramatic change in sedimentation. The fluvial upper MCF overlies clastic wedge-type rocks (lower MCF) and represents the arrival of a through-going river system, the Virgin River.

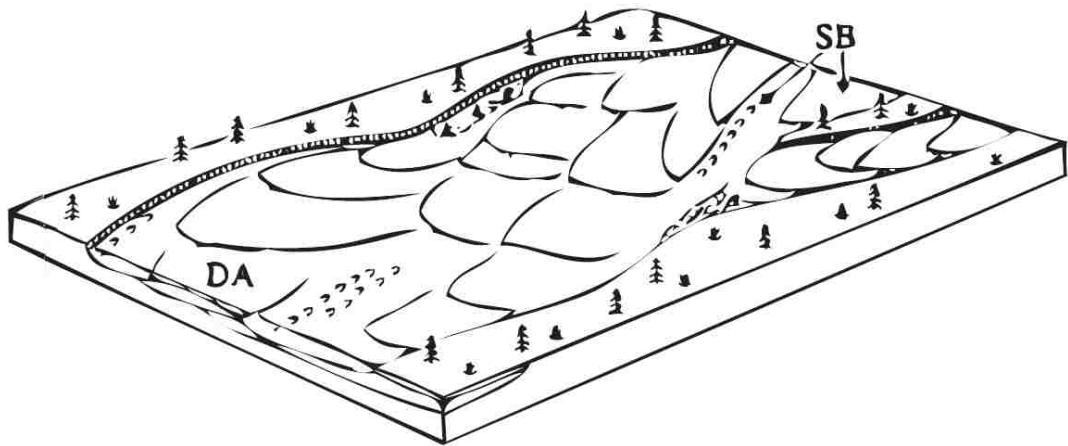


Figure 20. Architectural model for the shallow, perennial, sand-bed braided “Platte-type” river (from Miall, 1985).

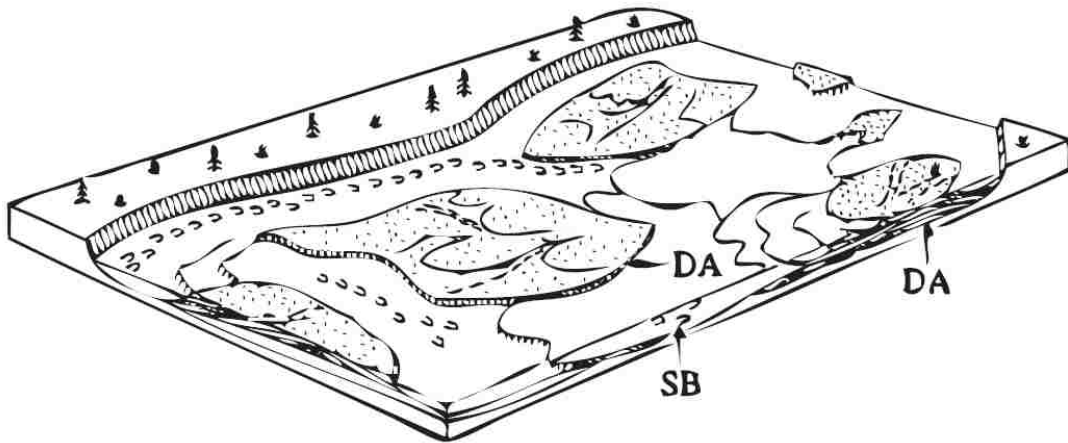


Figure 21. Architectural model for the deep, perennial, sand-bed braided “S. Saskatchewan-type” river (from Miall, 1985).

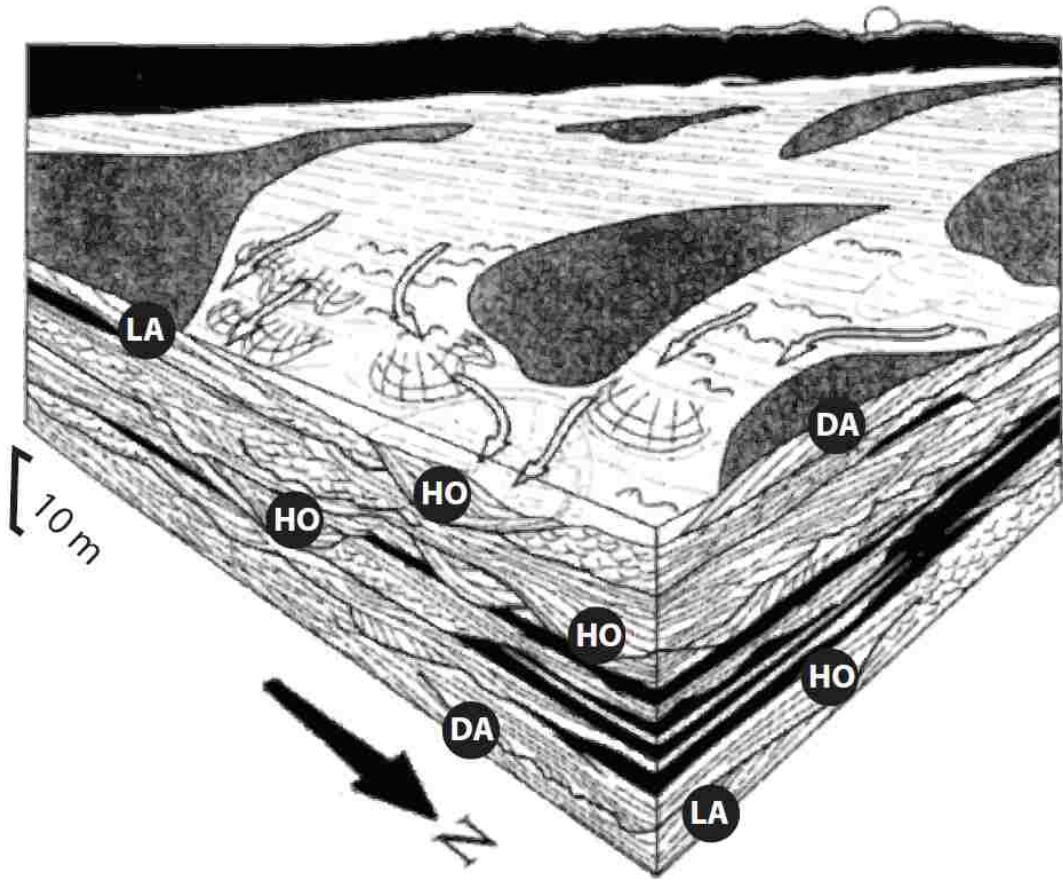


Figure 22. Architectural model of the high-energy sand-bed braided river described by Cowan (1991) in the Morrison Fm in northern New Mexico. Diagnostic scour hollows (HO) are prevalent in this type of fluvial system, as are lithofacies Sh, which represent deposition in the upper plane-bed flow regime (modified from Cowan, 1991).

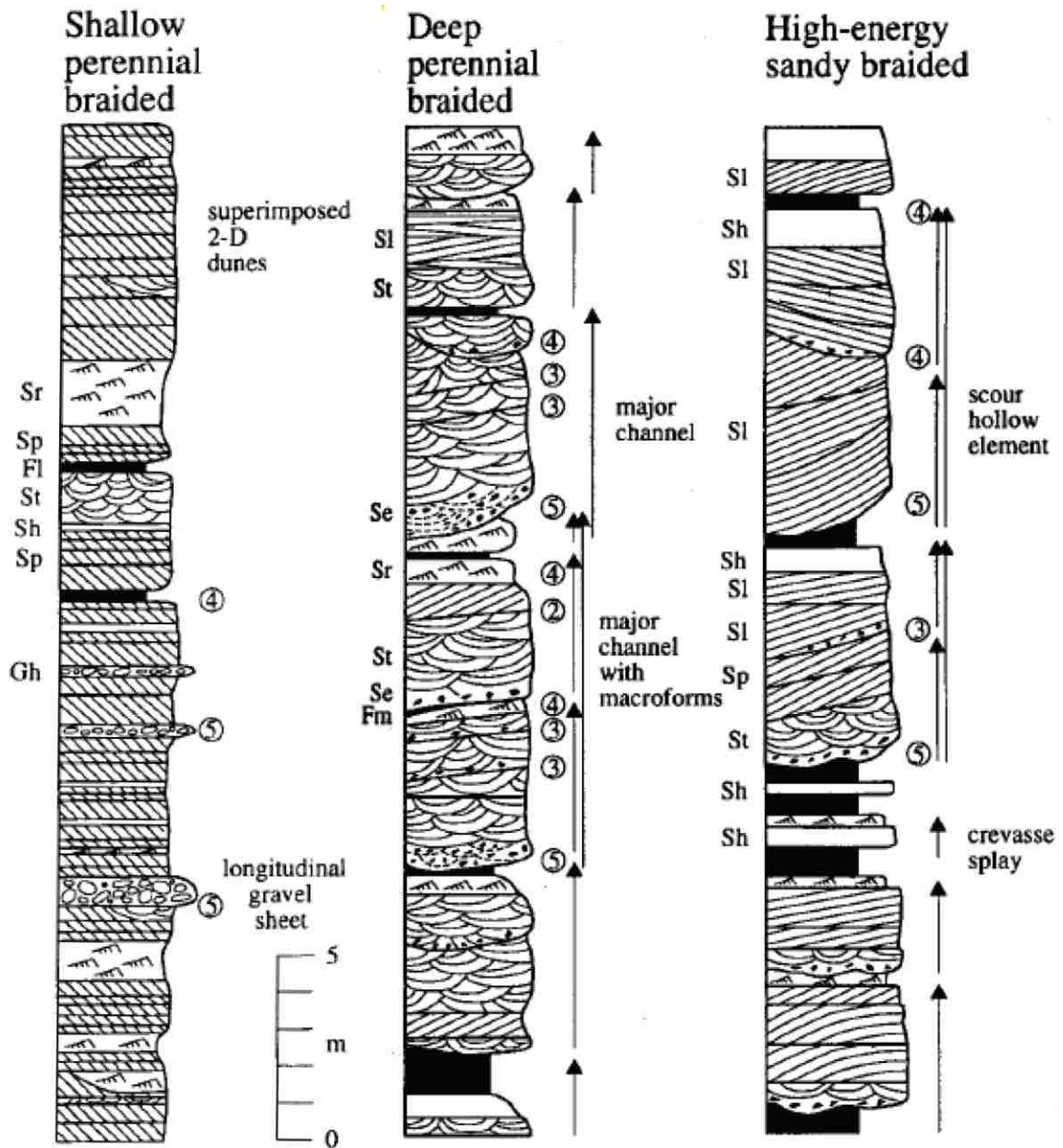


Figure 23. Figure shows example of typical vertical profiles from the 3 models considered. Note the abundance of low angle cross-bedding and lack of trough cross-bedding in the high-energy sand-bed braided system. Another key distinction between other models is the presence of repeated overbank fines (modified from Miall, 1996).

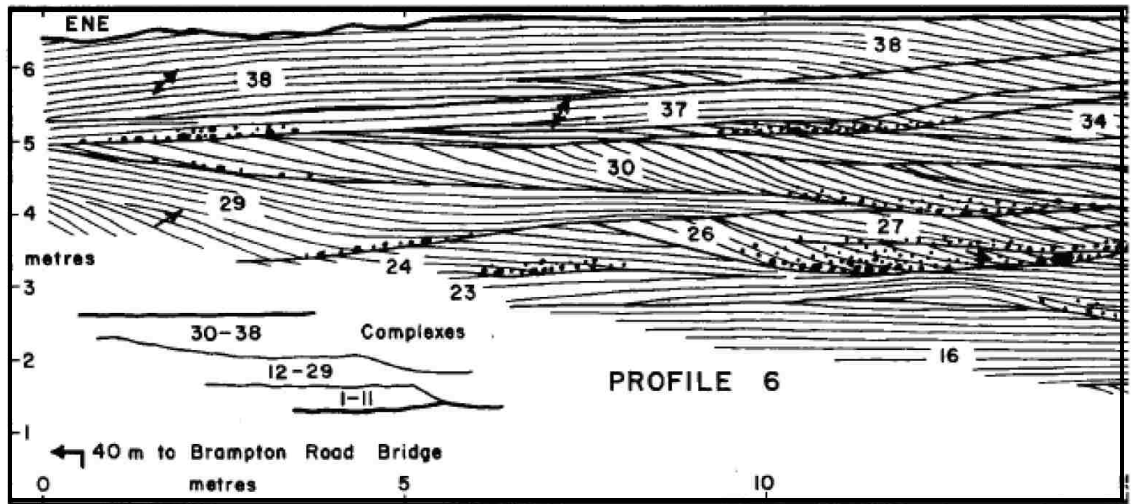


Figure 24. This figure shows an architectural elements map from the Devonian Brownstones, an ancient “Platte-type” fluvial system described by Allen (1983). Although low angle cross-bedding is abundant, overbank deposits, scour hollows, and flood deposits are absent.

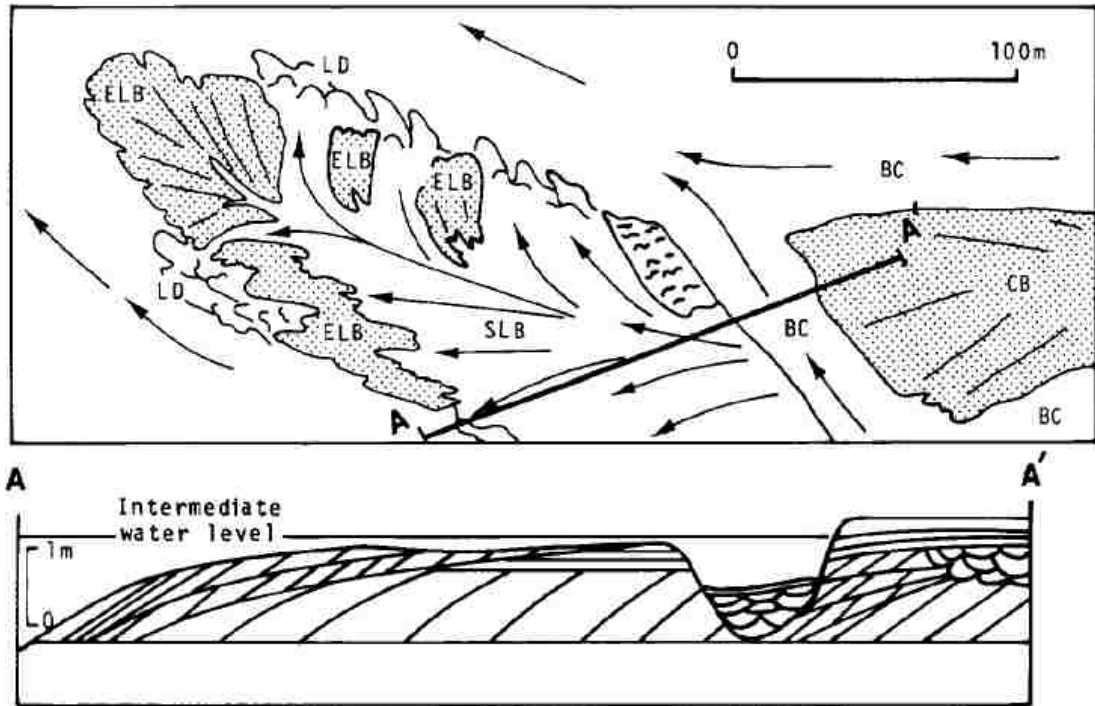


Figure 25. Map and cross-section illustrate the modification of bedforms deposited during high and low-stage flows in the modern Platte River in Nebraska. A-A' shows a composite sequence where low-stage beds are truncated and high-stage deposits onlap. Incision of low-stage bedforms may also occur where channels flow in high-stage conditions. Channel features include: SLB – Submerged portion of the dissected linguoid bar top. ELB – Exposed and dissected linguoid bar top. LD – Lobate microdeltas. BC – Braid Channel. CB – Composite bar. (from Blodgett and Stanley, 1983).

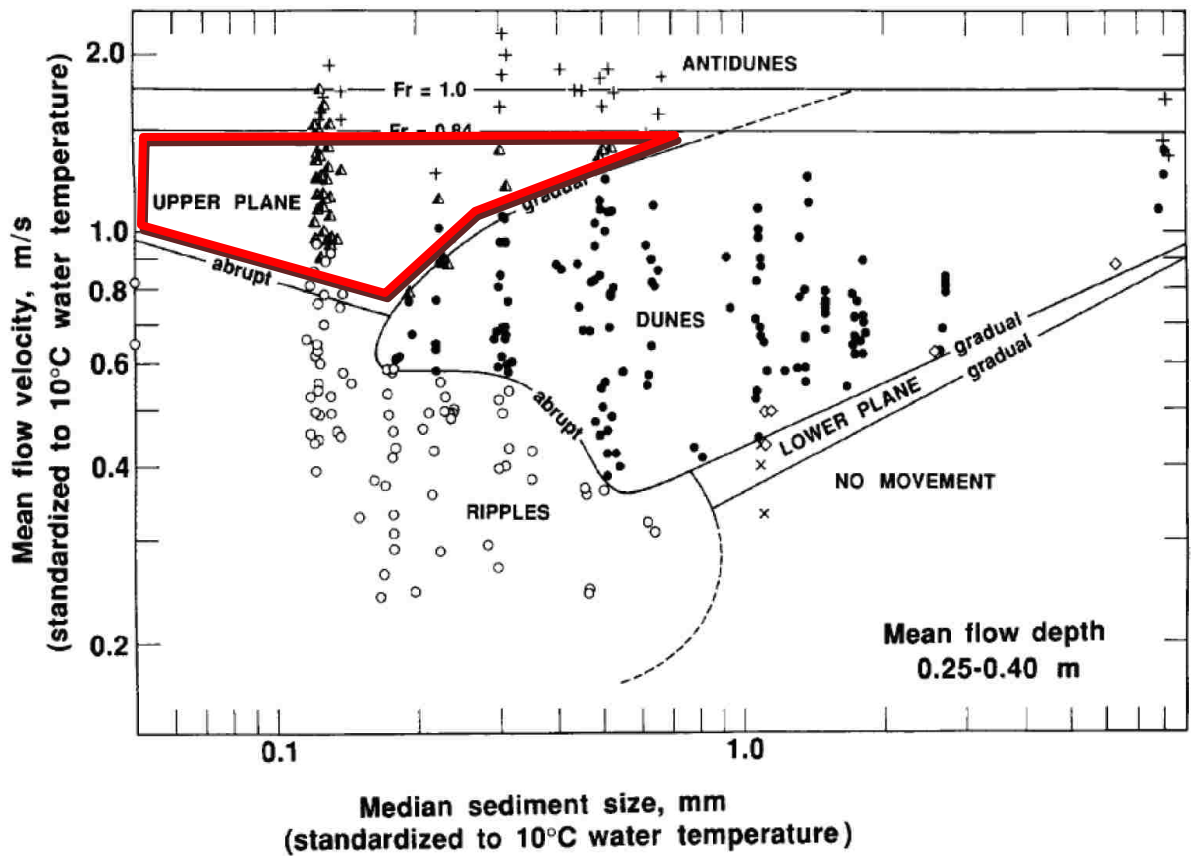


Figure 26. Plot of sediment grain size vs. mean flow velocity shows fields of stability for sedimentary bedforms. Lithofacies Sh are deposited in the upper plane bed flow regime which is highlighted in red (modified from Ashley, 1990).

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