Depositional development in a dryland basin: The Morrison Formation, Eastern Utah, USA

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Thesis submitted for the degree of
Master of Science in Geology
60 credits

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Abstract

The study comprises the Morrison Formation with the three members, Tidwell, Salt Wash, and Brushy Basin members, Upper Jurassic, Utah, USA. The Tidwell Member represents floodplain, lacustrine and fluvial environments. The Salt Wash Member is fluvial dominated, and the Brushy Basin Member is mainly lacustrine. In eastern Utah, the deposits are well exposed both in cross section and planar view. Sedimentological data are collected together with Google Earth-images, used to establish the depositional development through the Morrison Formation.

Dryland climate of the region in late Jurassic time affected the hydrology, pattern of sediment transport, sediment distribution and character of depositional environment in the Morrison Basin. The Morrison Basin was created as a back-bulge basin of the Cordilleran Orogeny, with the rate of subduction governing the rate of creation and destruction of accommodation. This is reflected and recorded by vertical sedimentary trend in the Morrison Formation in the study area, including paleosols and unconformities.

The fluvial system in the Tidwell and Salt Wash members was earlier believed to be a prograding braided system within a large alluvial fan. Google Earth-images and palaeocurrent measurements reveals that the fluvial system are of a more sinuous character, as part of a major distributary low-gradient fluvial system, termed the Salt Wash distributary fluvial system by Owen et al. (2015b).

Keywords: Sedimentology, fluvial, lacustrine, depositional environment, distributary fluvial system, dryland system, North American Cordillera, palaeoenvironment, palaeoclimate, Jurassic, Morrison Formation, Colorado Plateau, Utah

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I would like to officially apologise to all my family and friends for my isolation and depression the last months. Thanks for the support and thoughtfulness through the work with this thesis. Special thanks go out to my wife Ingrid Hagen-Kristiansen for understanding and comfort and to have endured with me.

To all my colleagues at Rom 219, thanks for lunch breaks, quiz, shearing of frustration and help. You have made the work with the thesis a little bit more fun.

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Contents

1 Introduction

The Morrison Formation in the Western Interior of North America (Figure 1.1) is famous for holding more dinosaur bones than any other formation in the world. Most findings are made from quarries at Como Bluff in central Wyoming, Dry Mesa near Grand Junction, Colorado, and Dinosaur National Monument in eastern Utah (Hintze and Kowallis, 2009). Despite the abundance of dinosaur fossils, this Thesis will emphasise the development of the depositional environment and the controlling mechanisms of sedimentation in the Morrison Basin, with main attention to fluvial channel systems and overall controlling mechanisms for deposition in a continental basin during arid to semiarid climate conditions.

The climate in Utah in the late Jurassic is believed to have varied from arid to seasonal arid to semi-humid. The dominant arid climate is reflected in the fluvial deposits. Such deposits in areas of dry and arid climate is generally characterised by coarse and poorly sorted sediments

Figure 1.1: Map over the USA, with Utah State in red and the study area outlined in black.

(Tooth, 2000).

The data set in this Master Thesis is limited to four logs (Figure 1.2) with little lateral extent, due to short time in the field. A study of architectural elements of the Morrison Formation has therefore been difficult, similarly lateral correlation. With sedimentary logs through the Morrison Formation, except the lowermost Tidwell Member, and photos from Google Earth-maps of channel segments in the Salt Wash Member, the thesis has been concentrated to definition of facies, facies associations and mechanisms of deposition and depositional environment in a dryland setting. In this connection, the generally accepted sedimentological criteria for distinguishing braided and sinuous stream deposits (Miall, 1977) has been discussed. The particular problem of how creation and destruction of accommodation is formed in a continental basin during arid conditions have been analysed from vertical and lateral trends recorded in the Morrison Formation in the present study, in combination with published data from other studies in the Morrison Formation.

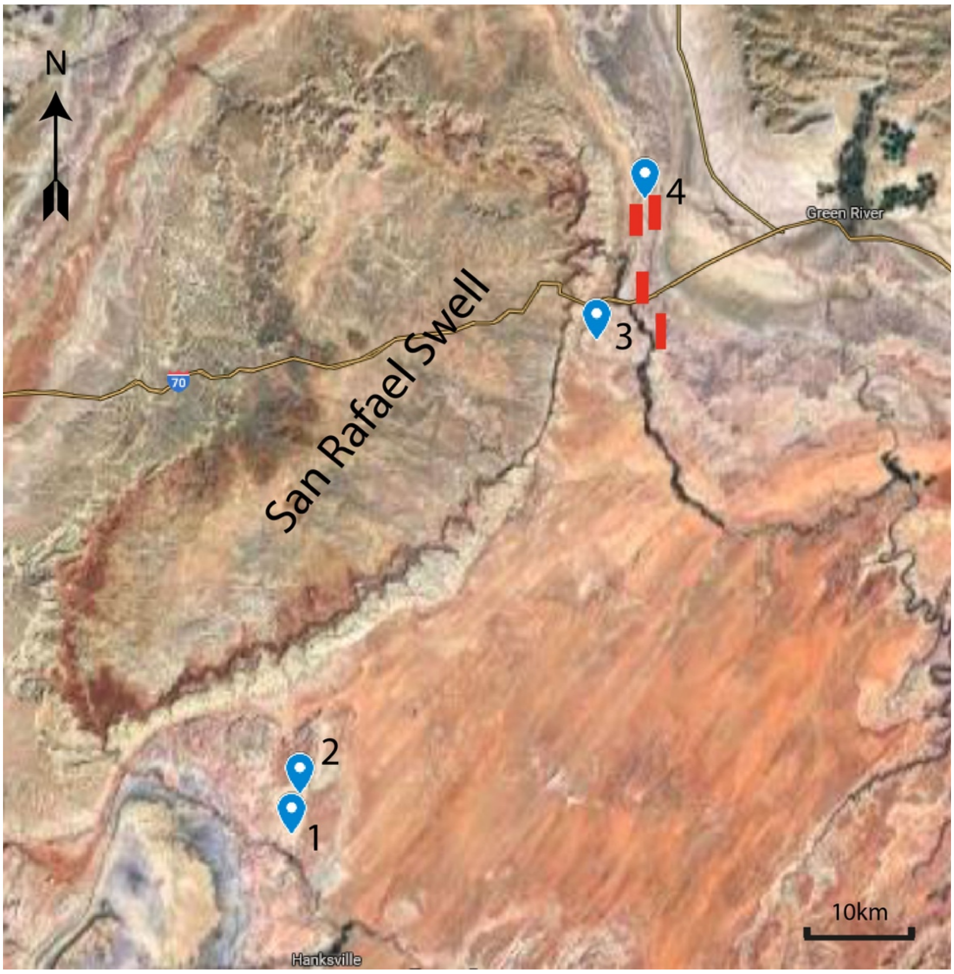


Figure 1.2: Map B showing Mid-East Utah with the location of Google Earth-images marked in blue. Log locations marked in red and location names from south to north Jessies Twist, 4 corner mine/I70 intersection, Tidwell Bottoms and Buckmaster Draw North.

2 Method

2.1 Sedimentological field work

Methods regarding the data collected, presented in this thesis, are geological field work conducted in a two-week period in June-July of 2016. Data collected during the field work consist of sedimentary logs recorded on paper in scale of 1:50, 1:100 and 1:200, and photos taken at log-sites. Palaeocurrent measurements were collected at log sites when possible, to establish a main transport direction. Additional photos were extracted from Google Earth to strengthen the data set and are used for morphological studies.

2.2 Sinuosity

Photos from Google Earth are extracted and used to measure sinuosity of the channels in the Salt Wash Member. Leopold and Wolman (1957) computed the sinuosity of a reach as the ratio of thalweg length to valley length (figure 2.1). Sinuosity, SI, is defined as the ratio of channel length/downvalley length. From the extracted photos of the channel infill, stream lengths are measured and divided on the measured valley lengths (fig. 2.1). When only one

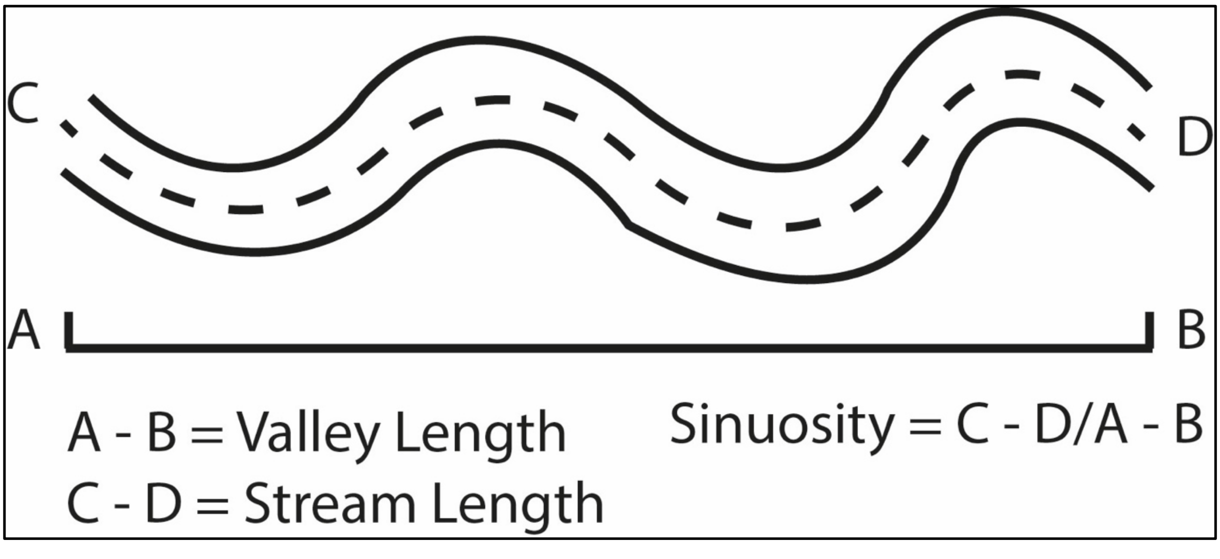


Figure 2.1: Diagram representing calculation of sinuosity for a channel.

single bed is exposed the measured sinuosity value is of restricted representativeness for a longer segment of the river, but nevertheless it is supposed to give an impression of the character of the stream system. According to Leopold and Wolman (1957), the classes of sinuosity for rivers are: $SI < 1.05$: almost straight; $1.05 \leq SI < 1.25$: winding; $1.25 \leq SI < 1.50$: twisty; $1.50 \leq SI$: meandering (Chapter 5).

3 Geological setting

3.1 Mesozoic era

During the Triassic the super continent Pangea started to break up, and the rifting between Laurasia and Gondwana ultimately formed the Atlantic Ocean. In the Triassic, a steeply dipping subduction zone developed on the west margin of North America, as the North American collided with the Farallon plate (Figure 3.1). This plate interaction produced large volumes of intrusive and extrusive igneous rock and has been a major controlling factor in Cordilleran tectonics since then (Hintze and Kowallis, 2009). In three phases the orogenic activity moved eastward across Utah; (1) In Late Jurassic to Early Cretaceous the Nevadan

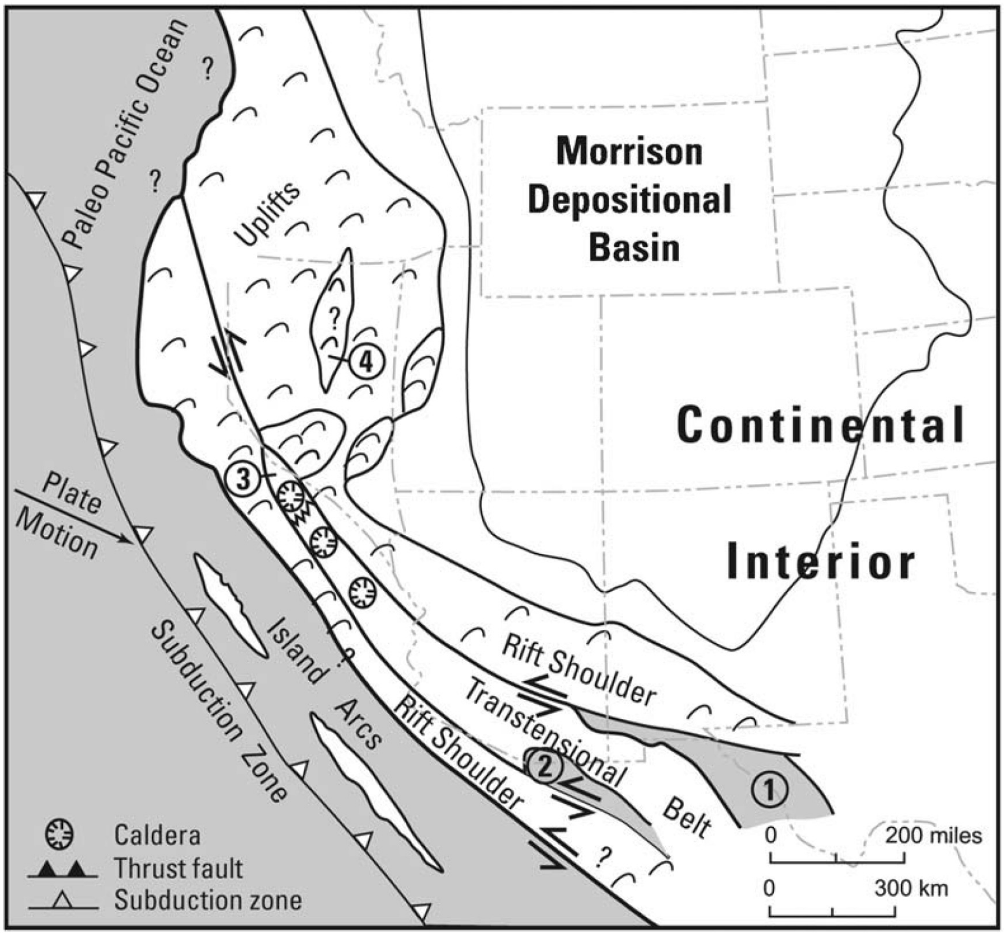
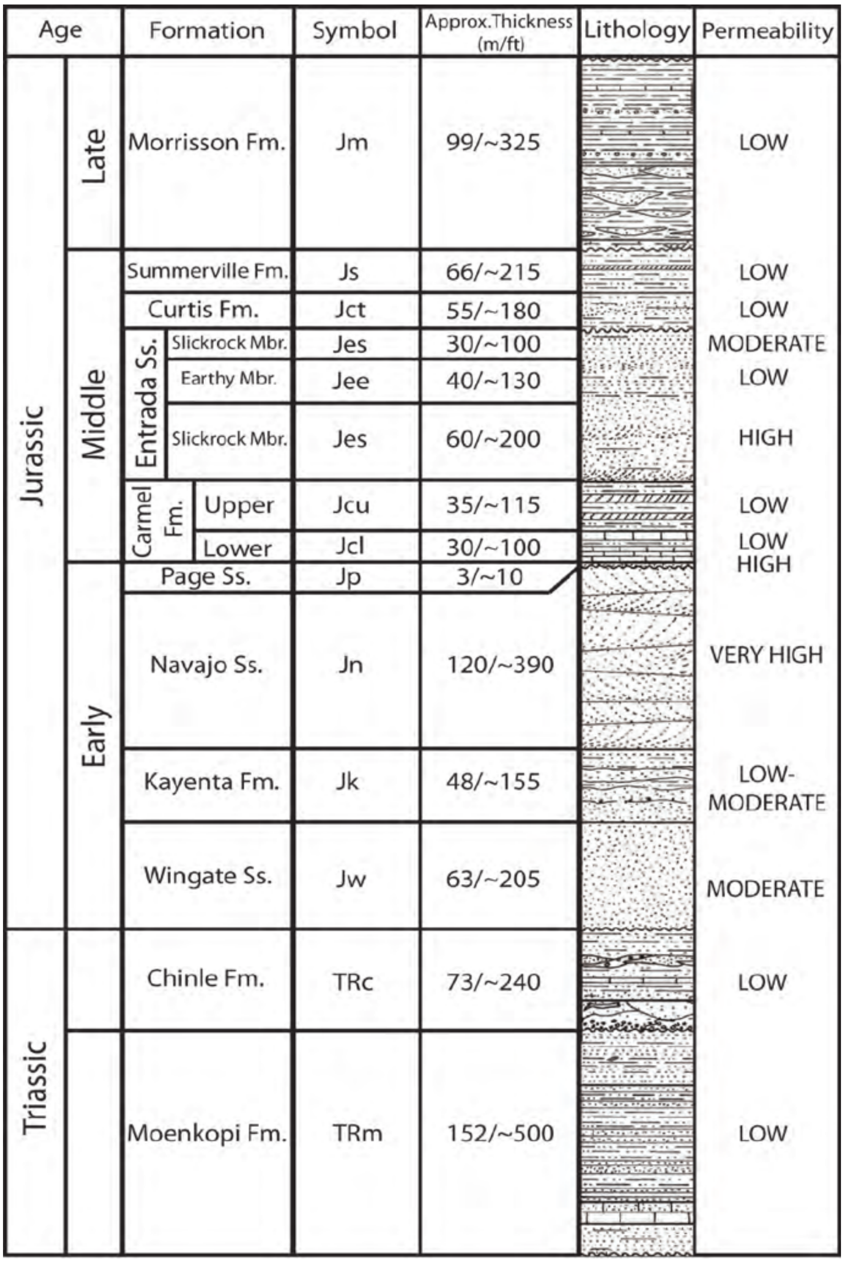


Figure 3.1: Map of western US showing the tectonic setting of the Morrison Formation during Late Jurassic time. 1, Chihuahua trough, 2, Mar Mexicano; 3, Remnant of Middle Jurassic arc graben depression; 4. Remnant of Middle Jurassic Toiyabe uplift. From Turner and Peterson (2004).

Orogeny as evidenced by granitic intrusions along the Utah-Nevada border; (2) Throughout Cretaceous and Paleocene time the Sevier Orogeny occurred, evidenced in Utah by multiple eastward-moving thrust sheets and concurrent deposition of thick Cretaceous sediments in eastern Utah; (3) In Early Cenozoic the Laramide Orogeny occurred, evidenced by multiple upwarps and downwarps principally the Uinta Mountain, Uinta Basin, Monument Upwarp, San Rafael Swell and Waterpocket fold (Hintze and Kowallis, 2009).



Age		Formation		Symbol	Approx.Thickness (m/ft)	Lithology	Permeability
Jurassic	Late	Morrisson Fm.		Jm	99/~325		LOW
	Middle	Summerville Fm.		Js	66/~215		LOW
		Curtis Fm.		Jct	55/~180		LOW
		Entrada Ss.	Slickrock Mbr.	Jes	30/~100		MODERATE
			Earthy Mbr.	Jee	40/~130		LOW
			Slickrock Mbr.	Jes	60/~200		HIGH
		Carmel Fm.	Upper	Jcu	35/~115		LOW
			Lower	Jcl	30/~100		LOW
	Early	Page Ss.		Jp	3/~10		HIGH
		Navajo Ss.		Jn	120/~390		VERY HIGH
		Kayenta Fm.		Jk	48/~155		LOW-MODERATE
		Wingate Ss.		Jw	63/~205		MODERATE
Triassic		Chinle Fm.		TRc	73/~240		LOW
		Moenkopi Fm.		TRm	152/~500		LOW

Figure 3.2: Stratigraphic column Jurassic and Triassic rocks (Richey and Evans, 2013)

3.1.1 Triassic

The Triassic strata found in Utah are the Early Triassic marine sediments and the continental Late Jurassic (Figure 3.2). Middle Jurassic fossil bearing rocks are absent in Utah. The Early Triassic Moenkopi Formation is predominantly a mudstone deposit on a broad and flat coastal plain that gently dipped to the west in southern Nevada (Hintze and Kowallis, 2009). The depositional environment of the formation is interpreted to include stream channels, flood plains, fresh and brackish ponds, playas, and shallow seas (Hintze and Kowallis, 2009).

The Chinle Formation of Late Triassic contains a large amount of petrified wood fragments, in some of which the wood fragments are replaced by silica. This silica is believed to have originated from bentonitic ash beds from aerial fallout. The ash occurrence, derived from volcanic eruption in the west, marked the onset of eastward subduction on the western continental margin; it has been argued that this is the reason of the change from marine to continental environments in Late Triassic in the study area (Hintze and Kowallis, 2009). Blakey and Gubitosa (1983) concluded that Chinle sedimentation occurred in an enclosed continental basin and represents alternating fluvial and lacustrine depositional systems.

3.1.2 Jurassic tectonic setting

During the Middle to Early Late Jurassic, most of Utah was a broad and shallow basin (Figure 3.3). This broad and shallow basin has been recognized as a back-bulge basin in the Sevier Thrust System (Willis, 1999). It is debated whether or not the Sevier Thrust System should be included in the Jurassic tectonism (Hintze, 1988). Heller et al. (1986) excludes the Sevier Orogeny from the Jurassic tectonism and Armstrong (1968) argues for a slight overlapping between the Sevier and the Nevadan Orogeny. In east-central and southern Utah the back-bulge basin was first covered by a shallow ocean, tidal flats, sabkha, or coastal sand dunes in Carmel, Entrada, Curtis and Summerville formations. Later, the basin was covered by broad low-angle river floodplains, represented by the deposits in the Morrison Formation. As the thrust system migrated eastward the back-bulge basin migrated east of Utah and the former basin in Utah turned mostly into a forebulge high. The gentle, broad uplift resulted in highs with enough elevation to undergo erosion or slow sporadic deposition. This resulted in an extensive unconformity between the Late Jurassic Morrison Formation and the Early Cretaceous Cedar Mountain Formation (Willis, 1999).

3.1.3 Jurassic

In Utah, the Jurassic strata can be divided into three packages. Early Jurassic rocks are mostly non-marine sandstones, then an epicontinental seaway advanced from Canada in the Middle Jurassic and then retreated, and finally in the Late Jurassic, the non-marine Morrison Formation was deposited (Hintze and Kowallis, 2009).

3.1.4 Early Jurassic

The three aeolian sandstone formations Wingate Sandstone, Kayenta Formation and Navajo Sandstone make up the Early Jurassic deposits (Figure 3.2). They thicken to the west and passes beneath over-thrust plates along Utah´s hingeline. Navajo sandstones are believed to represent a costal to inland dune field, interrupted at two stratigraphic levels by widespread interdune lake deposits along the eastern edge. Dip directions of Navajo cross-bed indicate wind directions from the northwest (Hintze and Kowallis, 2009).

3.1.5 Middle Jurassic

Marine fossil-bearing shales and limestone of Twin Creek and Carmel formations are an indication of a shallow seaway that extended from Canada in the north to Carmel Junction in the south (Hintze and Kowallis, 2009). When the Entrada Sandstone was deposited, the marine waters had retreated northward out of Utah. A marine invasion is again recorded as marine fossils are found in the Curtis Formation (Hintze and Kowallis, 2009). This time the marine invasion only penetrated to the San Rafael Swell and Capitol Reef area in the central Utah (Hintze and Kowallis, 2009). The Sevier thrust system created the back-bulge depression which lead to the continental seaway (Willis, 1999).

3.1.6 Late Jurassic

The Late Jurassic is characterized by the deposition of the Morrison Formation. The Morrison Formation got its name in 1914, named after the town of Morrison in Colorado where the first fossils in the unit were found in the last part of the 19th century (Mook, 1916). The Morrison Formation has for a long time been known world-wide for its dinosaurs remains, in particular for the large herbivorous sauropod fossils excavated at several sites in Colorado, Utah and Wyoming. The Morrison Formation is also known for its content of uranium (Lee and Brookins, 1978, Turner-Peterson and Fishman, 1986). The Morrison Formation has a wide regional extent in western North America from New Mexico to Canada (Parrish et al., 2004).

In the study area in Utah, the Morrison Formation is 180-200 meters thick and consists of three members-Tidwell, Salt Wash and Brushy Basin members. The sediments in the Morrison Formation were deposited in a variety of environments including both fresh water and saline-alkaline wetlands and lakes, flood plains and riparian systems (Hintze and Kowallis, 2009).

Tidwell Member strata are dominated by varicoloured mudstones interbedded with sandstones, limestone and gypsum beds (Peterson, 1988). These sediments are interpreted to be deposited in lacustrine, evaporative mudflat, minor aeolian, and fluvial environments (Peterson, 1988).

The Salt Wash Member is dominated of fluvial channel deposits interbedded with flood-plain and crevasse splay deposits, interpreted to be of alluvial origin as a fan shaped fluvial system (Craig, 1955, Mullens and Freeman, 1957). The alluvial sediments of the Morrison Formation have recently been interpreted as being dominated by distributary fluvial systems (DFS) (Owen et al., 2015b). The depositional system will be discussed further in Chapter 6.

Brushy Basin Member consists of varicoloured mudstone with some channel sandstone and conglomerate beds in between. These deposits are interpreted to be of lacustrine origin (Peterson, 1988). There are several horizons of reworked volcanic ash in the Morrison Formation. Radiometric age determination of the volcanic beds show that the Morrison Formation ranges in age from 155 to 147 million years old (Kowallis et al., 1997).

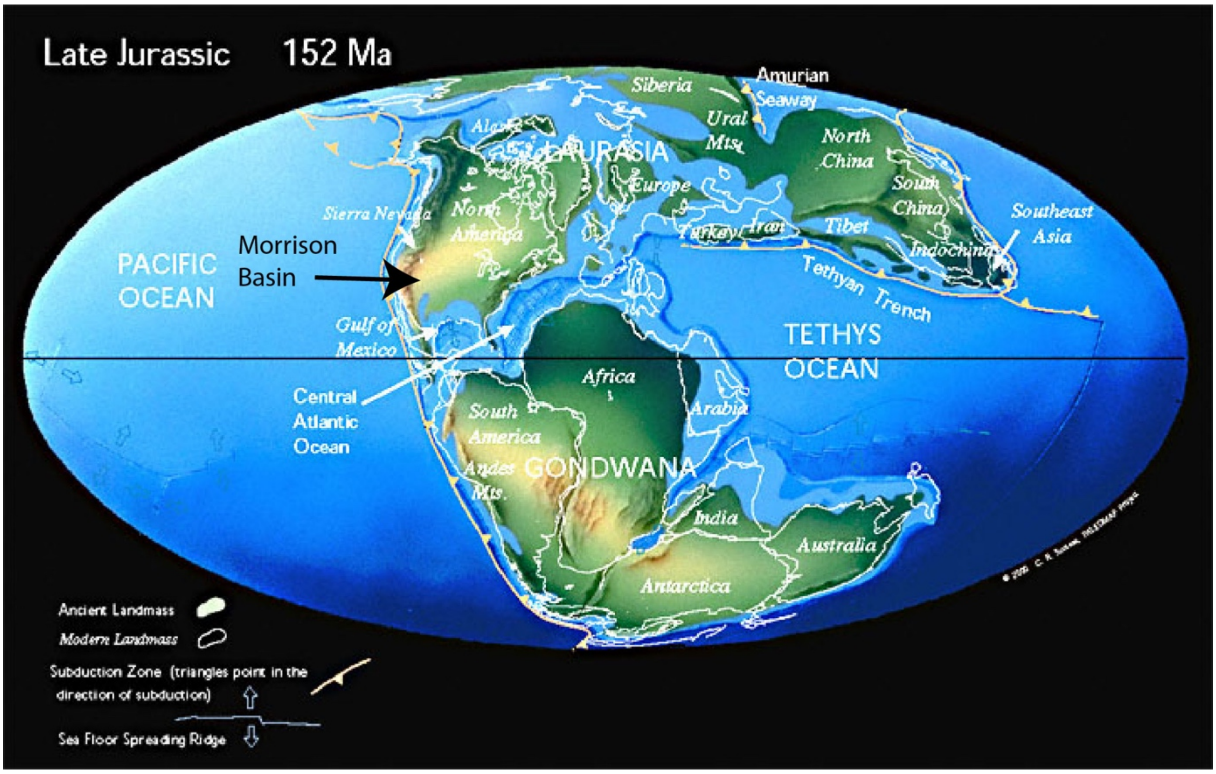


Figure 3.3: Late Jurassic palaeogeographic reconstruction showing position of the Morrison basin. Modified from (Scotese).

3.2 Paleoclimate in Late Jurassic

In the Late Jurassic, due to the breakup of Pangea the climate shifted from megamonsoonal atmospheric circulation patterns to more zonal patterns (Demko and Parrish, 1998). The climate in the Morrison Basin was believed to be hot (summer temperatures of abut 40°C, winter temperatures 10°C) and semi-arid with some seasonal rainfalls. The region was under influence of subtropical westerly winds and the western Cordillera worked as a shield against the maritime air masses. The rain shadow created by the Cordillera supports the interpretation of low annual rainfall (Demko and Parrish, 1998). Certain types of rocks have the potential to reflect the climate in which they were formed and deposited, and the Morrison Formation houses several of these sedimentary palaeoclimatic indicators. Continental aeolian dunes form mainly in regions of arid and semi-arid climate. Such aeolian deposits occur in several places in the lower half of the Morrison Formation (Demko and Parrish, 1998). Palaeowind directions found in the aeolian sandstone units correlate well with previous suggested directions. Sedimentary facies containing evaporate minerals have to be deposited in climate regions where evaporation exceeds precipitation, runoff, and groundwater input. In the Brushy Basin Member, the ancient Lake T´oo´dichi deposits show signs of repeated wetting and drying. It has hence been deposited under booth playa and lacustrine conditions (Bell, 1986).

3.3 Petrography

Petrographic analyses have not been done in this research, due to time and resources. The mineralogy of the lithofacies is extracted from a work of Bilbey et al. (1974). They found that the channel sandstones in the Morrison Formation consist of approximately 70-85% quartz, 10% feldspar and the last 5-20% are clay minerals and rock fragments (Bilbey et al., 1974).

4 Fluvial systems

Rivers constitute the biggest agent of transportation of sediments from continents into seas and oceans. When continental landmasses are uplifted, relief is getting higher, running water develops drainage systems that erodes the landmasses and transport sediments. All processes and landforms created by running water can be termed fluvial. A complete fluvial system contains a catchment area, a transport or routing system of water and sediments in channels and a depositional system where sediments are delivered to a basin. Various controlling factors affect different parts of the fluvial system. Autogenic controls comprise processes that occur within the fluvial system itself, e.g. evolution of meanders, braiding and delta lobe switching. Allogenic controls describe the external forces controlling the river system, primarily tectonics and climate.

4.1 Fluvial style

Four different styles of fluvial channels are commonly recognized; braided, meandering, anastomosing and straight (Figure 4.1). These styles are again controlled by total discharge, runoff pattern, sediment supply, grain size of sediment load and by river gradient (Bridge, 2003). Changes between the fluvial styles are commonly gradational and similar depositional morphological elements, or bedforms, can develop within channels of different styles (Schumm, 2005).

4.1.1 Straight and anastomosing

Straight rivers have well defined single channel courses with stable banks flanked by levees (See right side in Figure 4.1). The turbulence in water often creates sinuous thalwegs with alternate bars on the inside of the bends in straight rivers. Anastomosing rivers have also stable banks but they are often vegetated and composed of fine-grained silt and clay. The river channels form interconnected networks at low gradient, are relatively deep and narrow and with variable sinuosity (Emery and Myers, 1996). Due to the fine-grained and vegetated banks anastomosing rivers show limited lateral channel migration. This channel type may be developed during rapidly base level rise, where an increase in accommodation space leads to a vertical accretion deposit (Smith and Smith, 1980). The deposits of these channels therefore show isolated sand bodies, separated by levee-overbank, crevasse splay and flood-plain fines (Friend, 1983).

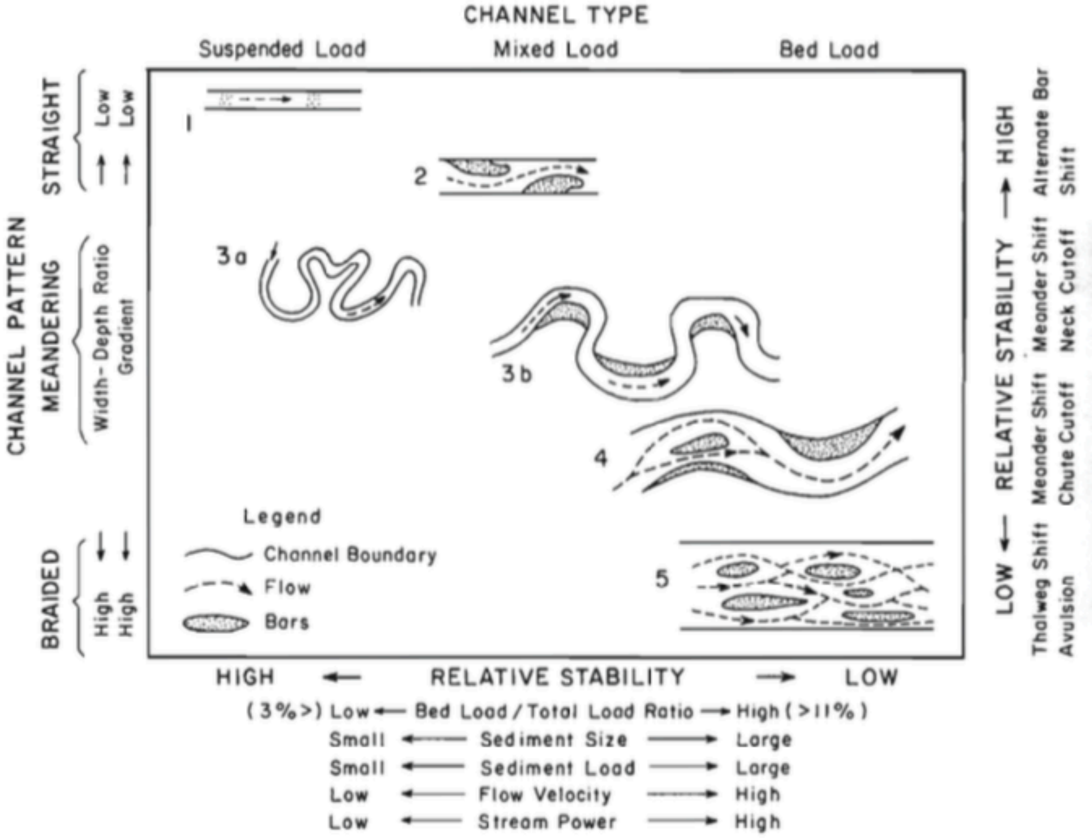


Figure 4.1: Channel classification based on pattern and type of sediment load. (Schumm, 1981)

4.1.2 High-sinuosity systems

High-sinuosity channels develop in drainage areas with low-gradient slopes. They have a high range in sediment load and grain-size and generally a high suspended load to bedload ratio (Figure 4.1)(Rosgen, 1994). A high-sinuosity river deposits primarily point bars, levees and crevasse splays and crevasse channel infill. Individual channels are commonly forming meander belts consisting of active channels and abandoned channels as oxbow lakes. Fluvial successions of stacked deposits formed in high-sinuous rivers typically form tabular to sheet-like sandstone bodies separated by overbank and flood-plain material (Emery and Myers, 1996). During deposition within a basin with rising base level, such tabular sandstone bodies tend to be separated by flood plain mudstone, whereas in a basin with base level fall the sandstone bodies have great potential to be amalgamated.

4.1.3 Low-sinuosity systems

Low-sinuosity or braided channel systems have a bedload with coarse grain-size. Due to low cohesive bank material, the channels are extremely mobile (Figure 4.1). The mobile channels are separated by temporary bars and islands. Braided rivers are characterized by high discharge variability. Environments with seasonally high discharge variability tend to be braided, like ephemeral rivers in arid regions. Due to these factors, low-sinuosity fluvial systems give rise to a stratigraphic record dominated by lenticular, concave-upwards sand bodies characterized by variable scale cross stratification, lateral accretion and in-channel deposits and a lack of channel margin facies (Emery and Myers, 1996).

4.2 Tectonics

Tectonics generates relief that drives the erosional mechanisms. It generates earthquakes, providing vast amounts of sediments to a river by mass wasting processes, and furthermore causes avulsion and gradient changes. All the above affects river type and behaviour. Steep, high relief drainage basins will produce more sediment and influence river type. Tectonically active areas will provide large amounts of sediment, much of which can be the result of mass movements, depending on climate and slope gradients. Earthquakes can modify landforms by landsliding and hence they can significantly affect river morphology and hydrology both temporarily or permanently by triggering an avulsion (Schumm, 2005).

In mountainous areas, huge catastrophic events often influence the hydraulic behaviour of rivers. High relief is a necessity, but a triggering mechanism is required. Triggering mechanisms may include heavy rainfall or large earthquakes (Schumm, 2005). Hicks et al. (1996) suggested that the highest rates of sediment transport tend to cluster along tectonic plate boundaries, ultimately relating to the rates of tectonic uplift and relief creation.

Rivers tend to follow structural lows or major geofracture systems. Melton (1959) estimated that between 25 and 75 percent of all continental drainage in unglaciated regions has been tectonically influenced or controlled. Potter (1978) concluded that some large rivers have persisted in essentially their present location for hundreds of millions of years, because they occupy major tectonic zones. Earthquakes that occur a considerable distance upstream may affect the downstream river channel. Fluvial response to active tectonics and climate is well illustrated by the Ganges-Brahmaputra system in front of Himalaya (Schumm, 2005).

In Bangladesh in 1950 an earthquake caused massive landslides in the Himalayas. This lead to significant aggradation in the upper reaches of the Brahmaputra River (Schumm, 2005). The long-term effects can be considerable, as the sediments are being transported downstream. Coleman (1969) noted that the oldest courses of the Brahmaputra River were of sinuous type. It is likely that increased sediment load, as a result of earthquakes, have altered the dimensions and pattern of the rivers during the past 200 years.

Alluvial plains of the Brahmaputra-Ganges delta actively deform under complex stress caused by tectonic plate collision. Warping and faulting elevate some areas and depress others. Elevation differences are critical in controlling the pattern of inundation during seasonal flooding. The distribution, flow direction, depth, and persistence of floodwater on the alluvial plain are also indications of Holocene subsidence and uplift.

4.3 Hydrology

Climate is a controlling factor in determining river hydrology and type. Depending upon the amount of precipitation, rivers will be either ephemeral, intermittent, or perennial, and as the hydraulic geometry relations then indicate, the more the water-the larger the channel. Scientists concluded that in artificially made adjustable channels, the changes in sediment load and discharge would result in adjustments of channel width, depth, gradient and pattern. Lane (1955) summarized these relations by presenting a qualitative relation, including bed load (Qs) and sediment size (d50) as follows:

$Qs * d50 = Q,S$

A change in sediment character requires a change in Q and/or S to compensate. This equation covers only one aspect of river morphology, gradient. Obviously, as discharge or sediment load changes, other aspects of the channel will be affected. Channel width (b), depth (d), and meander wavelength (l) are directly related to discharge (Q) whereas gradient (S) is inversely related to discharge. From this, the following general relation is obtained:

$Q=b,d,l/S$

Schumm (1968) showed when other parameters are constant, the bed-material load is directly related to width, meander wavelength and slope, and inversely to depth and sinuosity:

$Qs=b,l,S/d,P$

With an increase of flow, channel width and depth will increase in a downstream direction, but if a river is exotic, the reverse will pertain. Downstream discharge will decrease and so should channel dimensions.

4.3.1 Sediment yield

Natural erosion rates vary greatly with rock type and relief within one climatic region They are however also closely related to climatic controls. The relationship between erosion and mean precipitation in continental climates reveal that maximum natural erosion rates for drainage basins between 26 and 130 km^2 tend to occur in semiarid regions (Schumm, 2005). In humid conditions vegetation protects the soil from erosion, but in arid regions there is insufficient rainfall and runoff to move large amount of sediment. Therefore, at an intermediate rate of precipitation the vegetation is low, yet there is enough runoff to move sediment out of the drainage basin.

Humid and tropical regions are dominated by chemical weathering, whereas semiarid and arid regions are characterized by physical weathering. In humid and tropical regions, suspended sediment loads of silt and clay will dominate and in semiarid and arid regions, sand and gravel bed loads will dominate. This suggests that braided rivers will be common in semiarid and arid regions and meandering and straight rivers will be common in humid and tropical climates.

The nature of discharge is very influential and the variable peak or maximum discharge can have a significant effect on channels. Wohl (2000) lists a variety of channel changes caused by floods; bed erosion, bank erosion, deposition within the channel, growth of bars and islands, floodplain accretion, channel lateral shift and pattern change. Rivers with high ratios of peak to mean discharge are morphologically different from rivers with low ratios.

4.4 River classification

All rivers can be divided into two major categories determined by their freedom to adjust the channels shape and gradient. Bedrock-controlled channels are confined with fixed position controlled by lithology and structural grain of the rock type, which the river channel has formed. In such rivers, the material forming bed load and bank deposits determines the morphology of the channel. The other major category is the alluvial channels, where dimensions, shape, pattern and gradients adjust as a response to change in hydrology. Bed and bank deposits are composed of material transported by the river under flow conditions that are free to vary laterally and downstream in accordance to changing flow conditions. The morphology of alluvial channels is controlled by the two independent variables, discharge and sediment load (Schumm, 1977).

Discharge determines the size of the stream channels and the amplitude and wavelength of meanders. Discharge can be used for qualitative distinction among stream channels.

Sediment load comprises grain size and grain size distribution of the material being transported through the channel. The character of the sediment load influence upon channel morphology and can be applied for classification of alluvial channels, based on both the nature of the sediment load and the predominant mode of sediment transport, suspended load or bed load and the ratio bed load to suspended load. Considering the grain size in general, silt and clay are transported as suspension and sand and coarser sediments are transported on or near the stream bed. Alluvial channels can be classified according to the type of sediment load as bed-load, mixed-load, and suspended-load channels (Figure 4.1).

Alluvial channels can be divided into two types of river channels, single-channel and multiple-channel systems. Within the single-channel category, straight channels are bed-load channels, and meandering channels are mixed- or suspended-load channels. Exceptions do occur, and where valley gradient is very low, even a suspended-load channel can be straight. Braided channels are single-channel or multiple channels forming braid plains. Braided single channels are bed-load rivers that, at low water, have islands or braid bars exposed within the channel.

A second division of alluvial channels can be made, considering the sediment load and the rivers ability to erode or deposit sediments. A channel with an excess of total load relative to the transporting capacity of the stream flow causes deposition, a deficiency in bed load versus total transport capacity may cause erosion; between the two extremes channels with high degree of stability is located. To determine the channel stability of rivers is not always straight forward, but it is possible to think of all rivers as falling into one of these classes. The stabile channel shows no progressive change in gradient, dimension or shape. Flood and other events can make temporary changes to the channel, but the stabile channel can be seen as a graded stream profile where sediment influx to the system equals sediment volume out of the system. The eroding channel is being progressively degraded and/or widened by bank erosion, and the depositing channel is being aggraded and/or having sediment deposited on its banks.

In summary, alluvial-stream channels have been classified based on one of the two independent variables influencing the channel morphology. Discharge controls mainly the size of the channel and is more appropriate for a hydrological classification than a sedimentological classification. Sediment load, including mode of transport as bed-load, mixed-load or suspended load, is a major factor determining the character of the channel; hence sedimentological classifications of alluvial streams is primarily based in this variable. The classification only applies on segments of a river system. A channel can change significantly over a short distance and the classification is of channels rather than of river systems. Discharge as a factor for river classification is relevant in regard to the overall fluvial environment as being controlled by climate. Total annual precipitation as rain or snow or both, besides run off pattern, perennial or ephemeral, are of great importance to the sediment load and sedimentological character of fluvial deposits. In this respect, there are some principal differences of fluvial systems developed in humid regions and dryland regions. The continental basin of the Morrison Formation was characterized by arid to semiarid climate (see below), and for this reason emphasis is here put on dryland river system.

4.5 Dryland rivers

Warm drylands are characterized by arid climate, low ratios between precipitation and potential evapotranspiration, and by sparse, unevenly distributed, or temporally variable vegetation cover. Dryland regions cover over one third of the present global area. Arid zones are where evapotranspiration exceeds precipitation. Drylands are created where climatic, topographic or oceanographic factors prevent moisture-bearing weather systems from reaching these zones (Tooth, 2000).

4.5.1 Global atmospheric patterns and position of dryland regions

The sub-tropical regions are dominated by dry high-pressure air. At the equator, solar heating is at its highest, making air rise, which in turn causes it to cool, producing water condensation and creating a cloudy zone with equatorial belts of rain (Aguado and Burt, 2010). The now dry air spreads out at high altitude towards the poles and descends in the subtropics at around

30 degrees north and south. The now dry air warms as it descends, creating a stabile warm and dry region.

Increased distance from marine or other sources of moisture encourage aridity, thus drylands are often situated in the center of large landmasses. Another locality depending variable is topography. Mountain ranges create rain shadows as the landmasses forces the air to rise, which makes it cool and causes the water to condense and precipitate.

4.5.2 Solute and sediment transport

Sand-bed rivers are dominated by excess shear stresses and suspended sediment transport. Gravel-bed rivers are dominated by low shear excess stresses and bedload transport. Rivers draining areas of low precipitation are frequently distinctive in terms of high suspended sediments concentrations. Hyperconcentrations of suspended sediment (defined as those over 400,000 ppm) is a frequent occurrence in many dryland rivers (Powell, 2009).

4.5.3 Hydrology

Four types of flood in dryland rivers have been defined (Graf, 1988); seasonal floods, multiple-peak floods, single-peak floods and flash floods, of which the latter has come to be regarded as typical for dryland rivers (Nanson et al., 2002).

Characteristics that are more common in dryland river environments are the importance of large floods as a control on channel morphology, extreme temporal and spatial variability of rainfall, interaction of aeolian systems and tendencies for downstream decreases in discharge and channel size (Nanson et al., 2002).

4.5.4 Sediments

Discussing sediments of dryland rivers, most sediments are sands and gravelly sands deposits in characteristically thin beds (0,1-0,3 m thick) with a predominance of horizontal lamination.

Ephemeral gravel-bed channels often lack armor layers, which is a contrast to the very common coarse surfaces (armor layers) for most gravel-bed rivers (Powell, 2009). The processes of armoring are often explained by flow shear stress that are too small to move the largest grain sizes and large enough to transport fine grain sizes, causing selective erosion and grading. Dietrich et al. (1989) explains that the armoring occurs when the sediments supply in the river is lower than the capacity of the flow. They argue that the lack of coarse surfaces reflects rates of sediment supply exceeding transport rates in the river. The high rates of sediment supply relative to transport rates forces the deposition of finer friction and limits the degree of selective erosion.

Drylands rivers transport large quantities of sediment both as bedload and as suspended load. Total sediment yield measurements have indicated significant spatial and temporal variability, but despite their limited periods of flow, ephemeral rivers are thought to transport more sediments over time than perennial rivers (Powell, 2009).

Bed sediments in dryland rivers become finer downstream because of the competence of the flow is decreasing. Coarse bedload is most common with high total sediment yield in small dryland rivers, whereas in large rivers fine-grained sediment appears to be the dominant component (Nanson and Tooth, 1999).

4.5.5 Channel morphology and pattern

Dryland rivers can be represented by a wide variety of channel morphology and floodplain types. In arid zones braided channels are most common (Graf, 1988) but in semi-arid to sub-humid Africa, meandering channels are abundant (Tooth et al., 2002). Single-channel and anabraching channels are most common in the arid Australia (Nanson et al., 2002) Ephemeral meandering channels are uncommon and have been rarely reported (Li et al., 2015).

5 Description

5.1 Facies description

The sedimentary facies are presented from the dominating grain size, from coarsest to finest.

5.1.1 *Cross-stratified conglomerate – Facies A*

Description:

This facies consists of cross-stratified poorly sorted medium to granule sandstone. Unit thickness varies from 2 to 5 meters with internal layers of 0,25 to 1,00 meter thick (Figure 5.1). The amalgamated cross-stratified conglomerate facies occurs both in Salt Wash and Brushy Basin members of the Morrison Formation and in the overlaying Cedar Formation. The conglomerate is matrix supported with clasts up to 30 mm in grainsize. Clasts are angular to subangular and show no signs of imbrication or internal grading. The height of the cross-stratified conglomerate varies from 10 to 30 cm. The upper boundaries of Facies A appear abrupt and not gradational. In the field, many of the upper surfaces of the conglomerate beds were exposed, forming the uppermost part of the bedrock beneath the topographic surface and the overlaying sediments were thus eroded away. The lower boundary of the Facies A units is erosional; water flow has cut down into underlying strata.

Interpretation:

The cross-stratified conglomerate facies indicate that the beds were deposited during flow in the upper flow regime. The grain size and sorting thus indicate deposition from high energy processes in ephemeral rivers during flood events. The roundness of the clasts can be interpreted to be the product of multiple repetitions of short-lived events of a periodically river flooding and material transport, reworking and recycling, typical for dryland river systems (Tooth, 2000) see Chapter 4. The lower erosional boundary of the conglomerate units shows that the water flow of the stream during flood was high enough for scouring and creating a channel floor for the river.

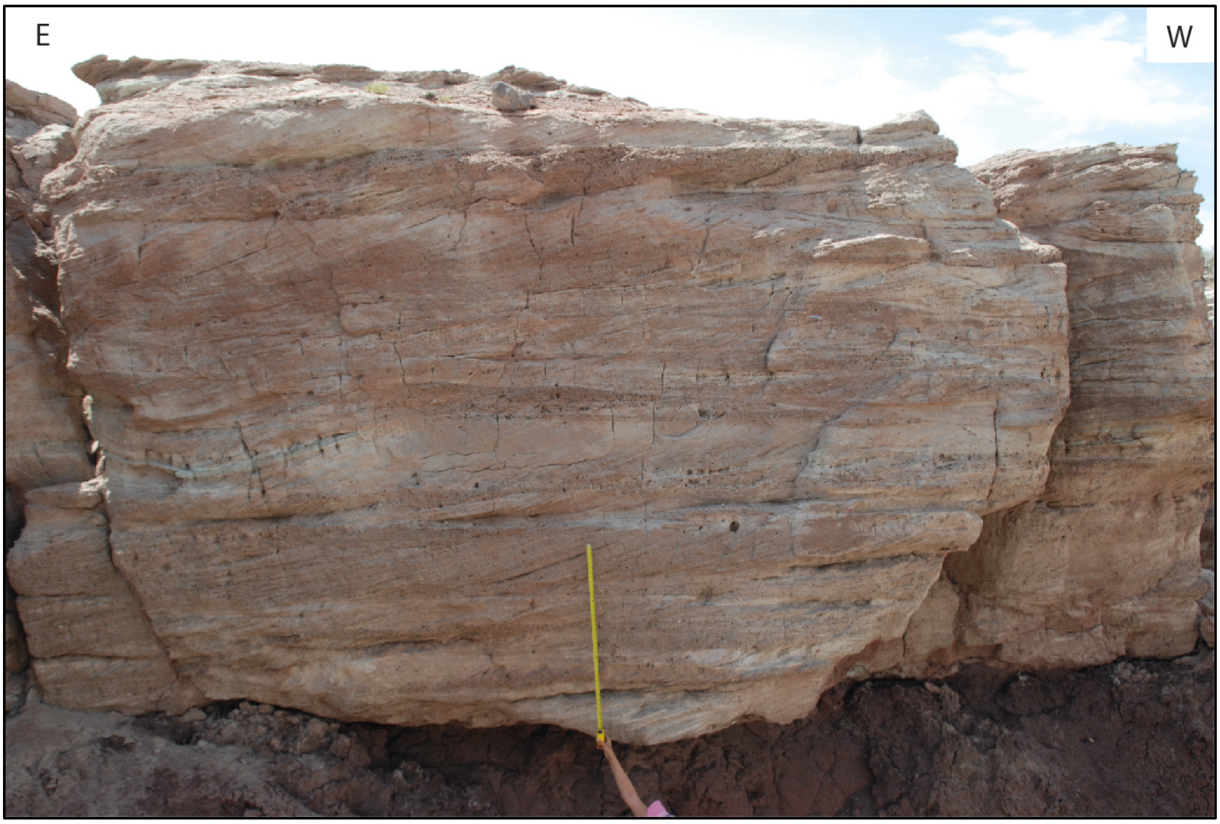


Figure 5.1: Cross-stratified conglomerate at locality 4 corner Mine I70 intersection (Figure 1.2).

5.1.2 Trough cross-stratified sandstone – Facies B

Description:

This facies consists of fine to medium well-sorted sandstone. The beds vary in thickness from 0,2 to 0,5 m. Trough cross-stratification is common with the lower boundary of bottom sets being erosional, cutting down into the underlying sediment. The trough cross-stratified sandstones are most common in the Salt Wash Member but also occur in Brushy Basin Member. The sandstone shows a rusty red colour. Palaeocurrent directions measured on the cross-stratification in the Salt Wash Member indicate flow and sediment transport directions to the north-east. The height of the trough cross-stratifications are measured to be around 10 cm. The beds show little to no sign of grading with almost constant grain size from base to top of individual beds.

Interpretation:

The fine to medium grain size and the cross-stratification of this sandstone facies indicates that these sandstone beds were deposited as 3D dunes with sinuous crest lines in a river characterised by the lower flow regime (Hjulstrom, 1939, Ashley, 1990). The bases of the cross-beds are marked by undulating erosion surface in front of lee slope avalanching of migrating dunes (Nichols, 2009). Lower flow regime trough cross-stratified sandstone beds in the Tidwell and Salt Wash member in the Morrison Formation were by Kjemperud et al. (2008) interpreted as channel deposits and more specifically as bedforms of the channel thalweg.

5.1.3 Plain-Parallel-Stratified Sandstone – Facies C

Description:

This facies consists of upwards coarsening fine to medium well-sorted sandstone (Figure 5.2). The beds vary in thickness from 0,2 to 1,0 m and show plain-parallel lamination. Plain-parallel-stratified sandstone is registered in the Salt Wash Member and in Brushy Basin Member. In the Salt Wash Member, the sandstone beds of this facies change upwards and laterally from wavy lamination over to the plain-parallel-stratification. Cross stratified conglomerate beds are observed on top of the plain-parallel-stratified sandstone in Salt Wash

Member. In the Brushy Basin Member, sandstone beds with the plain-parallel-stratification are embedded in structurless mudstone.

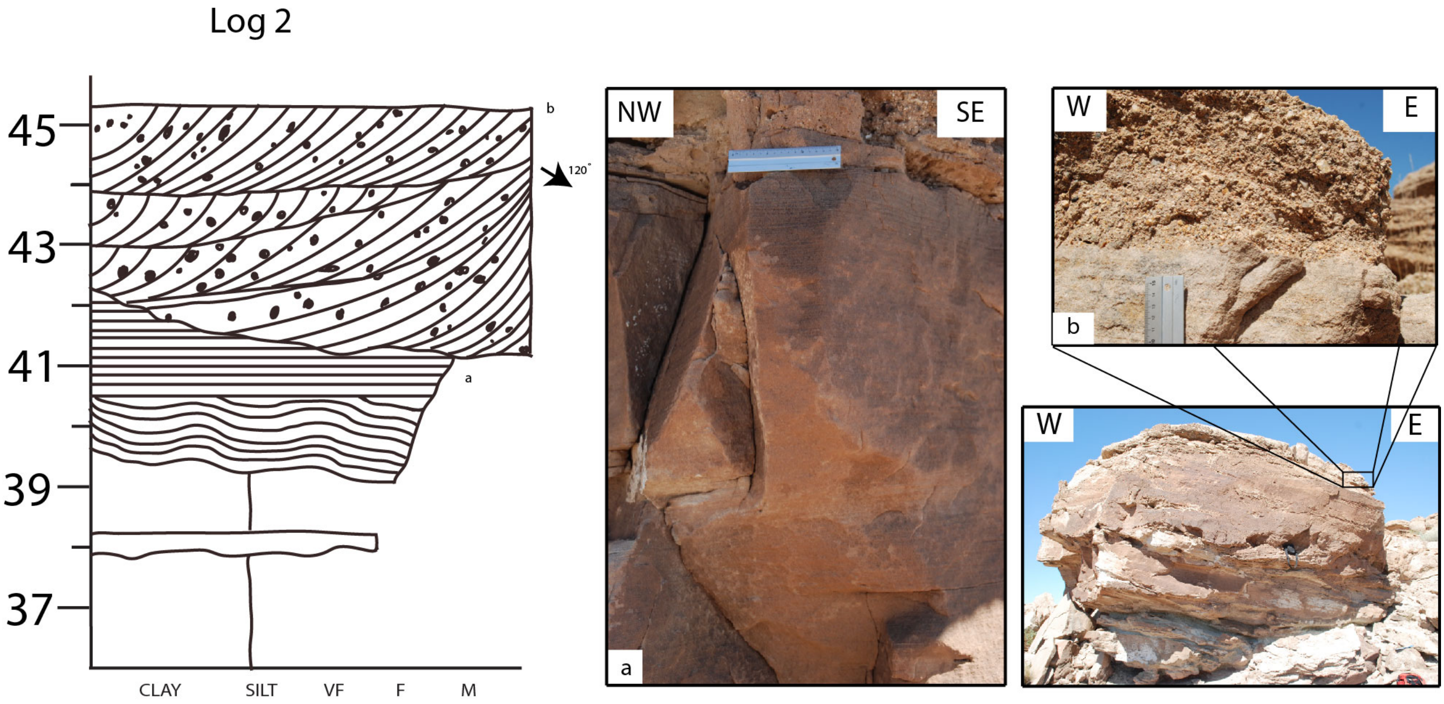


Figure 5.2: Illustration showing Facies C underlying Facies A at Tidwell Bottoms (See figure 1.2 for location).

Interpretation:

Plain-parallel-stratified layers are interpreted to have formed as upper flow regime flat beds (Hjulstrom, 1939, Harms, 1975). In the Brushy Basin Member, where the plain-parallel-stratified sandstone is embedded in structureless mudstone, beds of this facies can be interpreted as crevasse splay deposits. The lateral facies transition in Salt Wash Member is interpreted as a transition from shallow-water, upper flow regime deposits, to deeper water, lower flow regime channel deposits, as also interpreted by Kjemperud et al. (2008).

5.1.4 Crevasse splay – Facies D

Description:

This facies has fine to medium sand grain size. Layers and depositional units are from 0,2 to 1,0 m thick. The facies show some cross-stratification, but structureless units are also abundant. Facies D beds occur as interspersed sandstone beds in otherwise mudstone-dominated successions. Facies D beds are most common in the Salt Wash Member but also occur in Brushy Basin Member. Their lower and upper bed boundaries appear as sharp contacts to the aforementioned mudstone succession (Facies E, described below).

Interpretation:

These 0,2 to 1 meter thick sandstone layers are interpreted to represent crevasse splays. A crevasse splay forms when a channel levee breaks and sediments from the river are fed directly onto the floodplain through a crevasse channel (North and Davidson, 2012). The medium grain size and cross-stratification of the crevasse splay indicate sediments being deposited in the lower flow regime. The little to some cross-stratification indicates low flow velocities.

5.1.5 Structureless Mudstone – Facies E

Description:

Facies E is composed of mudstone with no structures and grain size ranging from silt clay to very fine sand. For brevity, the descriptive name of the Facies unit omits the full range of included grain sizes. The facies occur in laterally continuous layers in stratigraphic units varying in thickness from 0,5 to 25 m. The thickness of these mudstone layers increase drastically from the Salt Wash Member, where the maximum thickness is 2,5 meters, and into the Brushy Basin Member where maximum thickness is 25 m. Facies E varies in colour, from mostly grey mudstone in the Salt Wash Member, with some red layers beneath thicker channel sandstones (FA 1, described below), to strikingly varicoloured mudstone in the Brushy Basin Member (Figure 5.3). Here it is ranging from different shades of grey to red and purple. The mudstone facies appear structureless in both Salt Wash and Brushy Basin

Member. The mudstone successions are generally poorly consolidated and friable, making the identification of detailed structures difficult due to their appearance as scree slopes in field.

Figure 5.3: Varicolored mudstone seen in Brushy Basin Member, at the 4 Corner Mine I70 Intersection, note the camera bag as scale (23cm).

Interpretation:

The silty mudstone is interpreted as formed as overbank, abandoned channel or floodplain deposits. Red colour indicates oxidising conditions by subaerial exposures or/and well drained conditions (Boggs, 2006). Floodplain deposits occur when the floodplain is invaded by water with suspended sediment and bed load during overbank floods and topping and breaching of levees. In the Brushy Basin Member, the structureless mudstones are much greater in thickens and due to red colour interpreted to be lacustrine deposits.

Table 5.1: Facies table for the Salt Wash and Brushy Basin members in the Morrison Formation.

Facies	Description	Grain size	Interpretation
A	Cross-stratified conglomerate	M-P	High energy regime, fluvial channel fill
B	Cross-stratified sandstone	F-M	Fluvial channel fill
C	Plain-parallel-stratified sandstone	M	Fluvial channel fill
D	Thin sandstone beds	F-M	Crevasse splay
E	Structureless mudstone	Si	Flood plain/Lacustrine

5.2 Facies associations

5.2.1 Facies association 1 – Fluvial channel fill

Description:

The Fluvial channel fill facies association consists of Facies A (Cross stratified conglomerate), Facies B (Cross stratified sandstone) and Facies C (Plain-parallel-laminated sandstone). The Facies B appear as units with both amalgamated (Figure 5.4) and isolated sandstone units. Facies A and Facies C occur together; a transition from Facies C to Facies A is shown in Figure 5.2. As also seen in Figure 5.2, the Facies A, B and C occur in beds with erosional contact to the underlying Facies E. The facies association is seen through the Salt Wash Member with an overall upwards increasing thickness of depositional units represented by this facies association (Figure 5.18). In the Brushy Basin Member the FA 1 is less dominating with only 1 to 3 channel units observed. Figure 5.5 shows a cross section of a large channel infill in the Brushy Basin Member. Note the clear asymmetrical shape of the channel infill with a pinching out to the north. At the Shadscale Mesa locality the fluvial channel infill show channel sinuosity also backed up by palaeocurrent measurements (Figure 5.4 and Table 5.2).

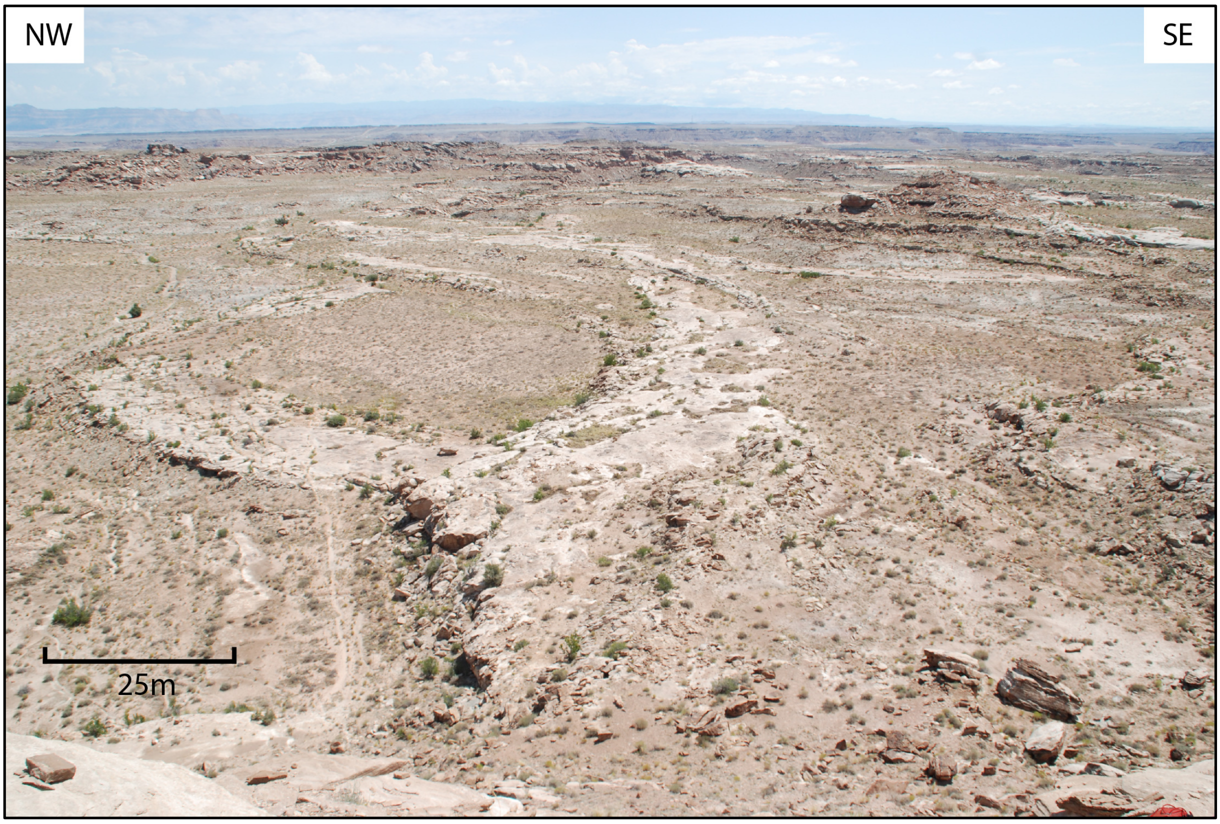


Figure 5.4: Vertically amalgamated multistory channel infill shows sinuosity of the palaeochannels at Shadscale Mesa (Figure 1.2 for position) (Figure 5.14 for overview photo).

Figure 5.5: Cross section of isolated steer-head channel infill in Brushy Basin (Kjemperud et al., 2008). Note the clear asymmetrical shape of the infill.

5.2.2 Channel morphology

To strengthen the dataset, photos of the extraordinarily good exposure of channel infill sandstones of the Salt Wash Member in the Morrison Formation is extracted from Google Earth (Figure 5.6 for positions). The photos show channel infills with various sinuosity ranging from 1,00 in channel bend 3.2 (Figure 5.14) to 1,24 in the south channel bend 1.1 (Figure 5.12). At location 1 (Figure 5.7 and 5.8) the north bend (channel bend no. 1-1) and the south bend (channel bend 1.2) show clearly prograding point bar deposits with scroll-bar relief, with the sinuosity of the south channel bend is measured to 1,24 and the north bend to 1,23 (Table 5.2). At location 2 (Figure 5.9 and 5.10; channel bend 2.1) the sinuosity is measured to 1,10. At location 3 (Figure 5.11 and 5.12) multiple generations of channels are observed (channel bend 3.1, 3.2, 3.3, 3.4). At location 4 (Figure 5.13 and 5.14; channel bend 4.1) the channel lobe shows a low sinuosity, measured to 1,09, and varying from the main depositional direction.

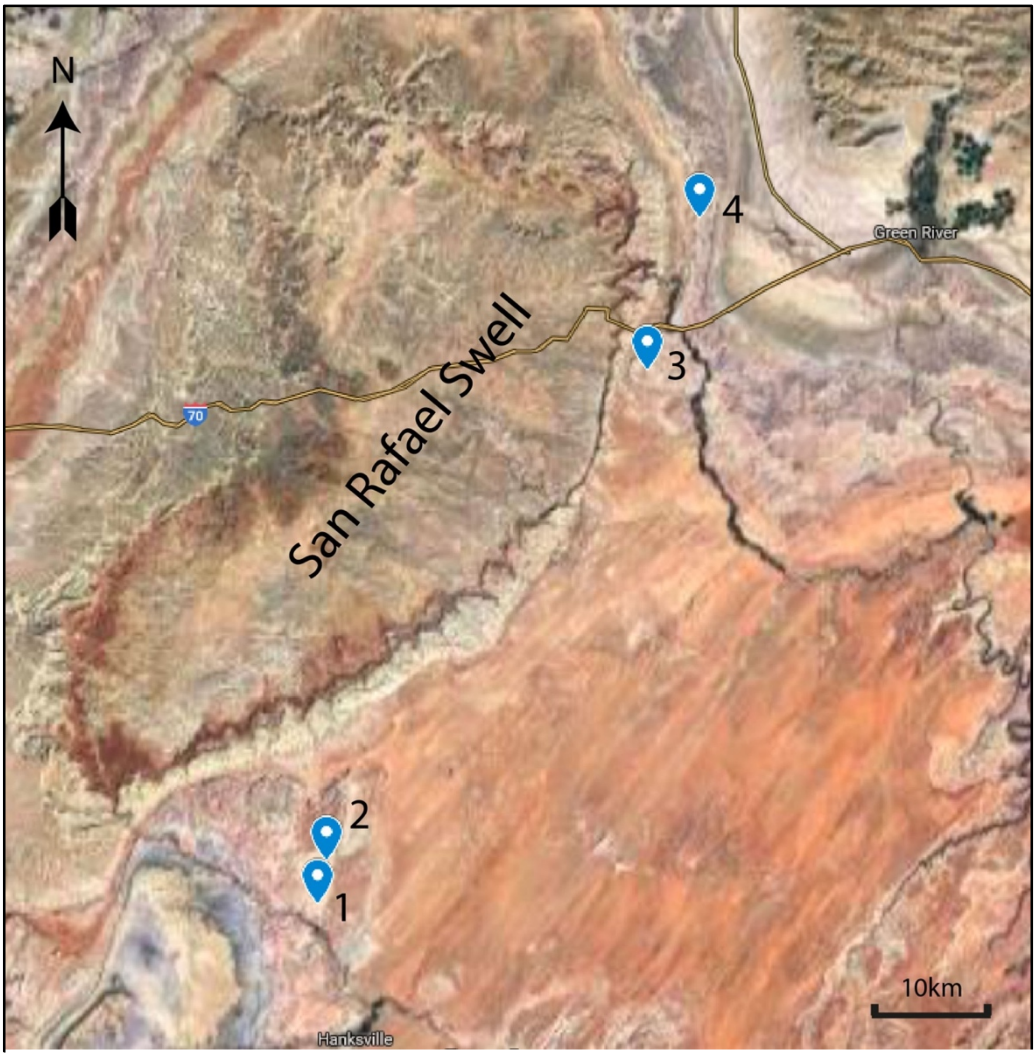


Figure 5.6: Map showing the locations of the channels.

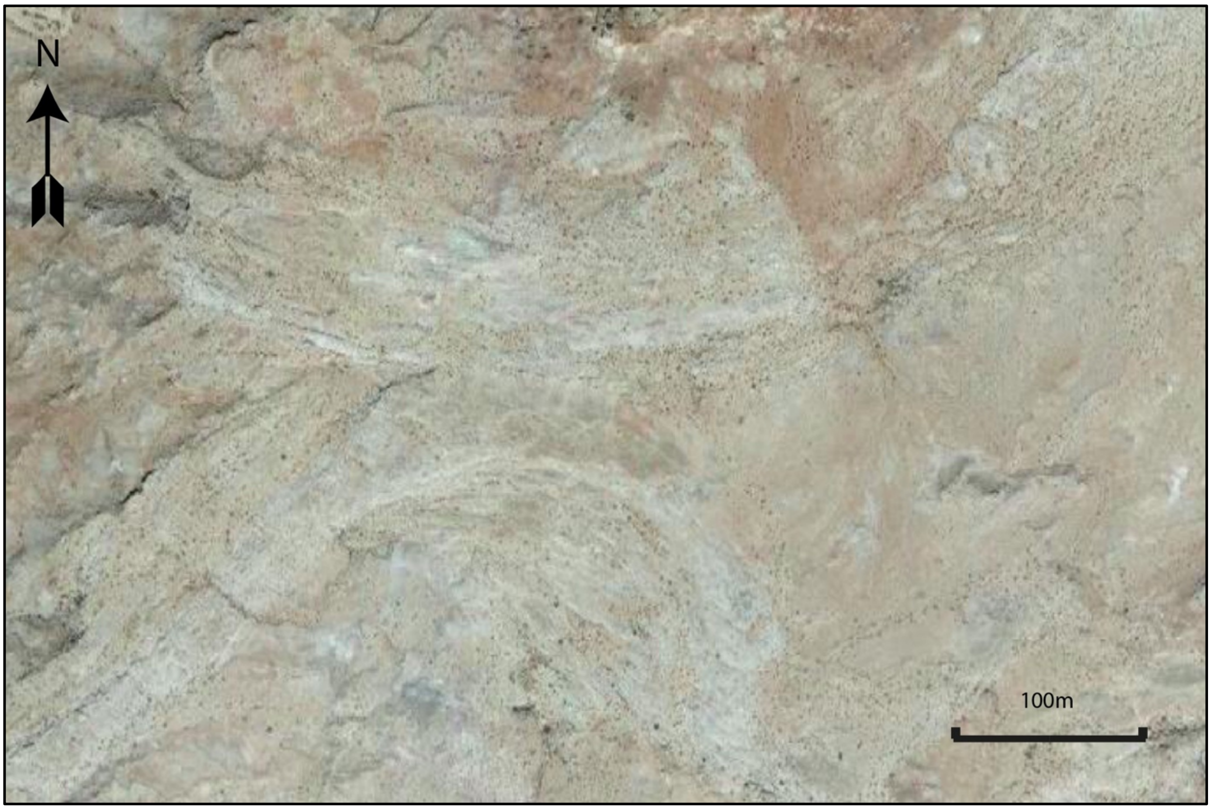


Figure 5.7: Location number 1 showing two channel lobe bends (Channel bend 1.1 and 1.2).

Figure 5.8: Location number 1 with two channel lobes (1.1 and 1.2). Both bends showing scroll bars, indicated with dashed lines. Channel bend 1.1 has a sinuosity of 1,24, and channel bend 1.2 have a sinuosity of 1,23.

Figure 5.9: Location number 2 showing a sinuous channel bend (2.1).

Figure 5.10: Location number 2 with channel bend 2.1 with a sinuosity of 1.10.

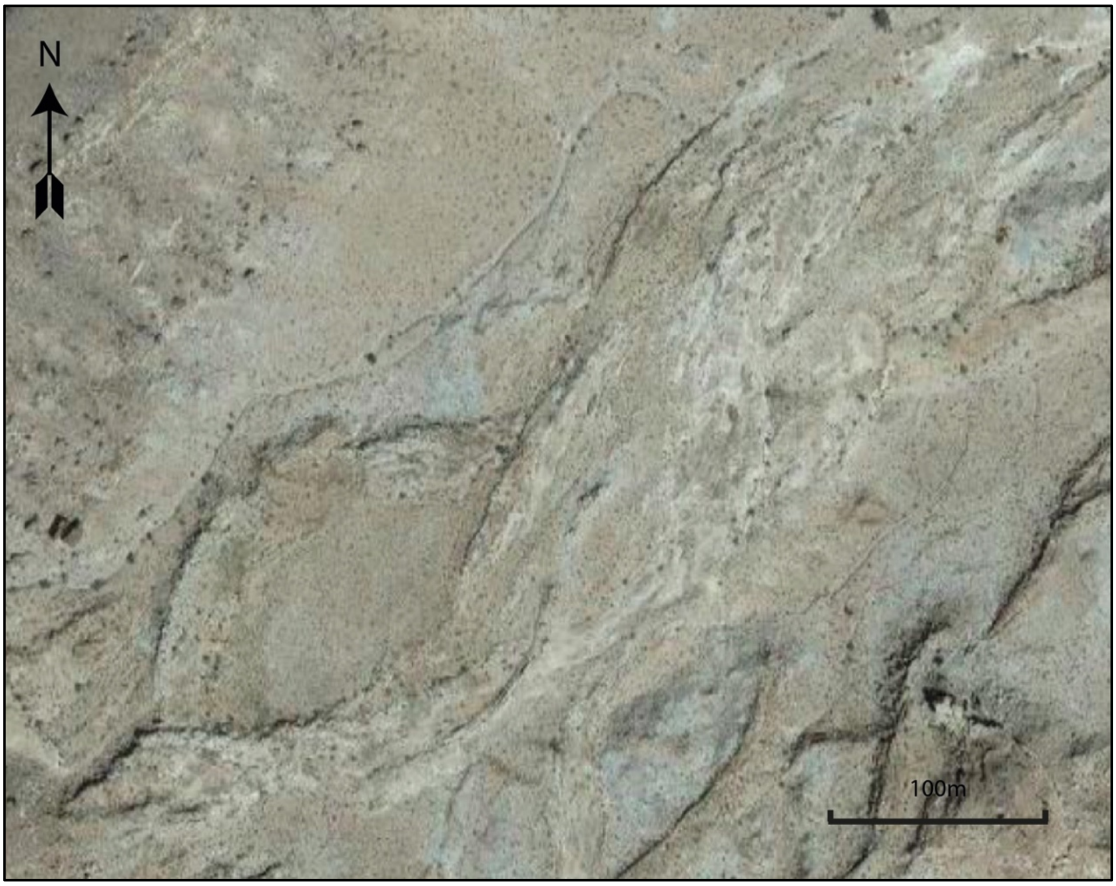


Figure 5.11: Location number 3 showing multiple sinuous channel lobes.

Figure 5.12: Location number 3 shows four different channel lobes from four channel generations (See Figure 5.4). They are numbered from relatively oldest to youngest.

Figure 5.13: Location number 4 showing a low sinuous channel bend (Channel bend 4.1).

Figure 5.14: Location number 4 with channel bend 4.1 with a sinuosity of 1.09.

Tabell 5.2: Sinuosity measurements and sinuosity class of the studied channel beds

Locality	Channel bend no.	Sinuosity SI	Sinuosity class
1	1-1	1.24	Winding
1	1-2	1.23	Winding
2	2-1	1.10	Winding
3	3-1	1.18	Winding
3	3-2	1.00	Almost straight
3	3-3	1.14	Winding
3	3-4	1.05	Winding
4	4-1	1.09	Winding

Interpretation:

Coarse grained, poorly sorted channel infill indicates high energy rivers. The observed scroll bars in figure 5.8 indicate deposition by prograding lateral-accretion point bars. The palaeocurrent measurements strengthen the already established hypothesis about a basin with fluvial streams draining in northeast direction (Owen et al., 2015b). Upwards thickening trend of the channel infill indicates a relatively decreasing A/S (see discussion below). The sinuosity of the channels bends is measured (Table 5.2) and the majority is in the sinuosity class winding (Chapter 2). Only one channel bend is in the sinuosity class of almost straight (Figure 5.13; 5.14).

5.2.3 Facies association 2 – Floodplain

Description:

Facies association 2 consists of Facies D (Crevasse splay) and Facies E (Structureless mudstone). Thick units of Facies E are interrupted by thin layers of Facies D. In Salt Wash Member, Facies association 2 dominates with Facies association 1 in between. Three to four crevasse splays are embedded in the mudstone between each channel infill (FA 1), and there are no signs of change in crevasse splays frequency.

Interpretation:

Mudstone deposits with crevasse splays embedded indicate floodplain environment. The mudstone deposits are the normal floodplain sedimentation and the crevasse splays are created where the rivers are breaking their levees.

5.2.4 Facies association 3 – Lacustrine deposits

Description:

Facies association 3 consists of Facies E (Structureless monotonous Mudstone; Figure. 5.15; 5.3). Units of Facies E range in thickness from 2 to 25 meters of thickness and have been traced laterally for distances within the dimensions of wide escarpment outcrops. The colours of the Facies E in Brushy Basin, ranges from different shades of grey, to red and purple.

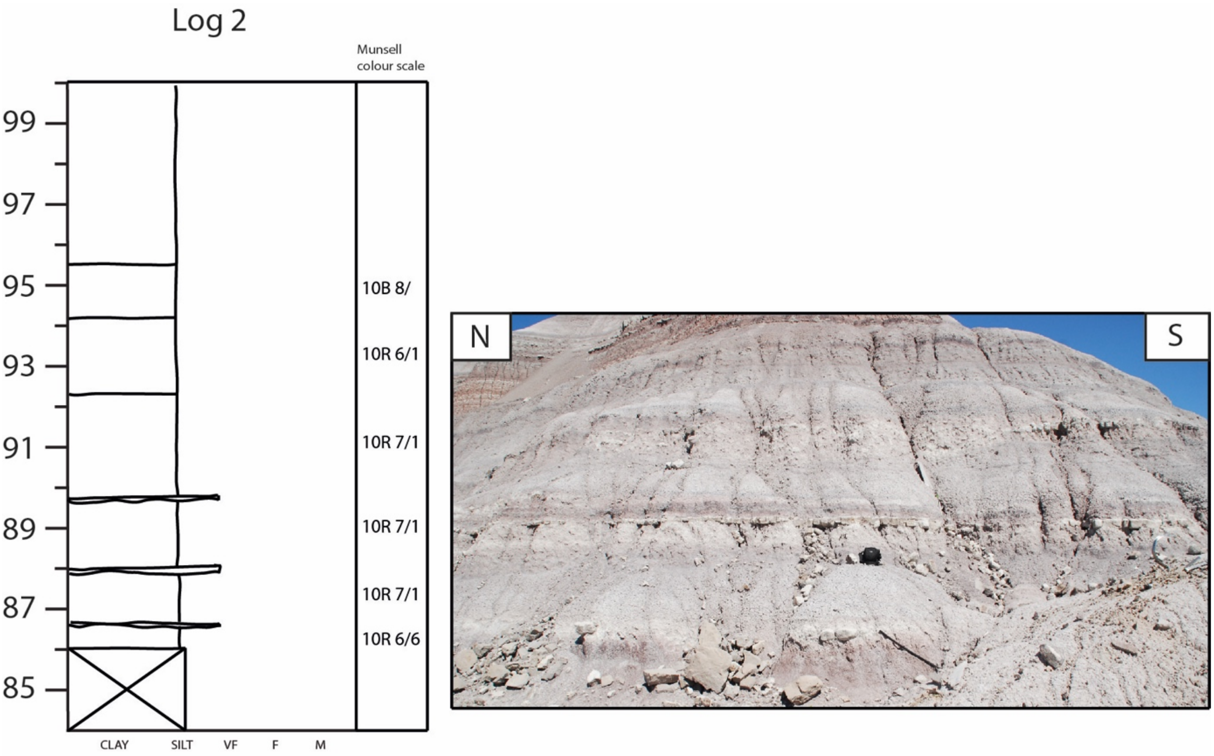


Figure 5.15: Log section from Log 2 at Tidwell Bottoms, and picture from log site showing FA 3 with mudstone beds of varying colours (note camera bag for scale).

Interpretation:

The presence of lacustrine mudstone indicates periods of relative high precipitation or/and ground water level within depressions on the floodplain. The observed data do not give any information of whether the lacustrine basins have been permanent filled with water over the time period they have existed, or if they were cyclically filled with water during ephemeral flood events. The alternation of colour from shades of grey to red and purple is interpreted to reflect subaerial exposure of the deposits. Deposition of grey mudstone occurred during periods of ephemeral flood events filling the lacustrine basin. The red and purple deposits reflect times with low precipitation and water supply to the lacustrine basin, which caused oxidising conditions.

5.3 Paleosol and the Salt Wash Member/Brushy Basin Member boundary

Through the Salt Wash Member the channel fill sandstones are upwards thickening and coarsening and is terminated by a mudstone bed (Figure 5.18). This mudstone is in the top dark red to brownish red (Figure 5.16, 5.17). In this red bed, white spots are observed (Figure 5.17). Some of these light-coloured features are long and vertically oriented and are interpreted as bleached spots and areas around roots and rootlets. The red colour of the mudstone bed and the white spots indicate that the uppermost part of the Salt Wash Member is transformed into a paleosol, developed by a strong oxidation of a land surface exposed for weathering and pedogenic processes for a rather long time period. The mudstone with the paleosol in the top has been eroded beneath the overlaying fluvial sandstone which in this area defines the lower boundary of the Brushy Basin Member.

Similar paleosols have been described in several other areas in the Morrison Formation (Jennings et al., 2011), and were by Demko et al. (2004) characterised as vertic paleosol. Demko et al. (2004) showed that the boundary between the Salt Wash Member and the Brushy Basin Member, defined by the vertic deep red paleosol and an erosional boundary, is a prominent regional correlation surface in the Morrison Formation and called the surface the Mid-Morrison unconformity. The implication of this surface is discussed below.

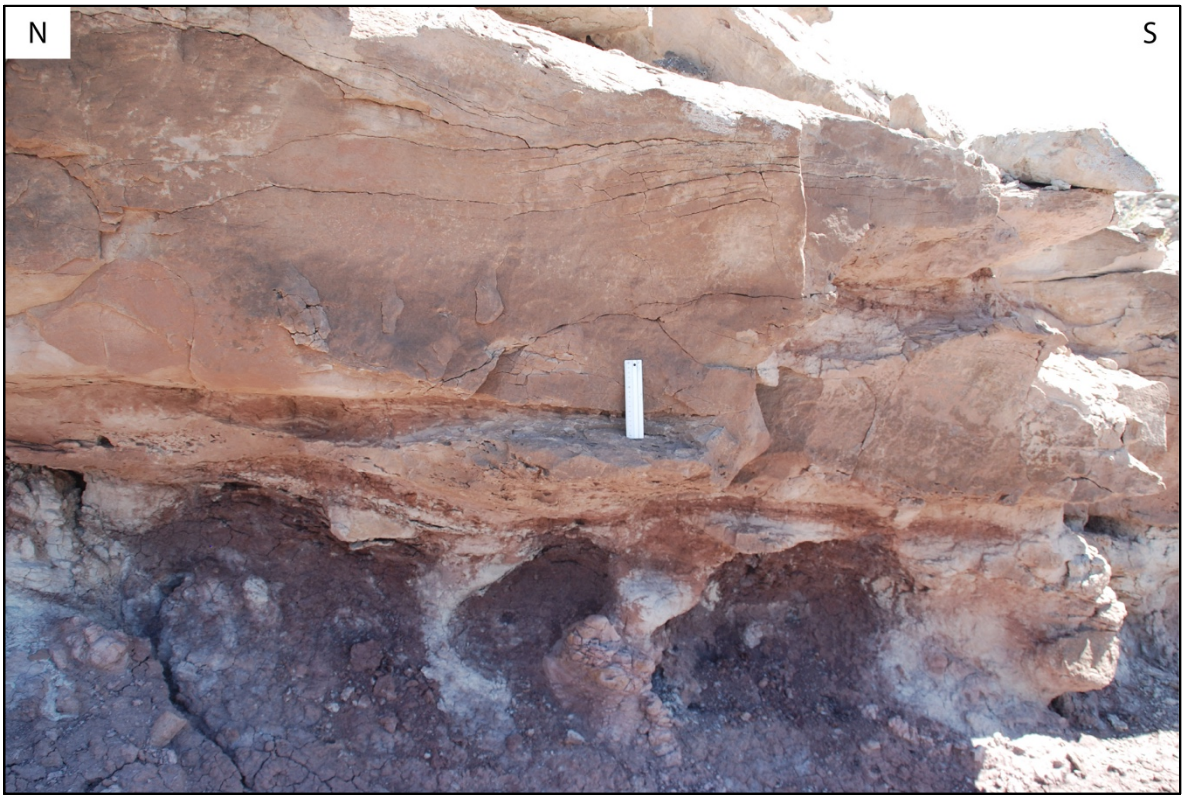


Figure 5.16: Paleosol bed between the Salt Wash Member and Brushy Basin Member (note the ruler for scale, 15cm).

Figure 5.17: Paleosol bed, note the white spots in the red paleosol (note the ruler for scale, 15cm).

5.4 Summary log – Salt Wash Member and Brushy Basin Member

Due to log site topography, the sedimentary log starts in the Salt Wash Member (Figure 5.18). However, a simplified photo-log is prepared from the uppermost part of the Tidwell Member. The FA 1 and 2 dominate through all of the Salt Wash Member. The FA 1 shows an upward increase in both thickness and grain size, with the topmost channel infill clearly amalgamated. At the boundary between the Salt Wash Member and the Brushy Basin Member, a red paleosol is seen beneath an unconformity that was interpreted to be the regional Mid-Morrison unconformity by Demko et al. (2004) (Chapter 5.3).

Through the Brushy Basin Member FA 3 is the dominating facies association. In the lower parts of the Member some minor channel infills are observed. These beds are succeeded by a thick succession of FA 3, whereas in the upper part of the member, thicker units of channel infill are present.

The Brushy Basin Member is truncated by a marked erosional unconformity that is overlain by very coarse to gravelly sandstone unit. This is the Buckhorn Formation, also called the Buckhorn Conglomerate, forming the lowermost lithostratigraphic unit of the Lower Cretaceous on the Colorado Plateau (Hintze, 1988).

The logged section through Morrison Formation at the site of this study reveals prominent vertical trends as regards mud:sand ratio and frequency and thickness of fluvial sandstone beds or bed sets. These trends are thought to reflect changes in rate of accommodation (see discussion below).

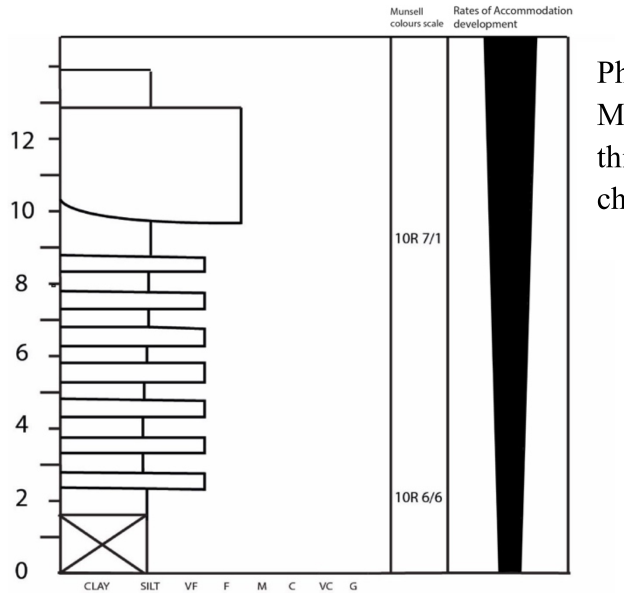
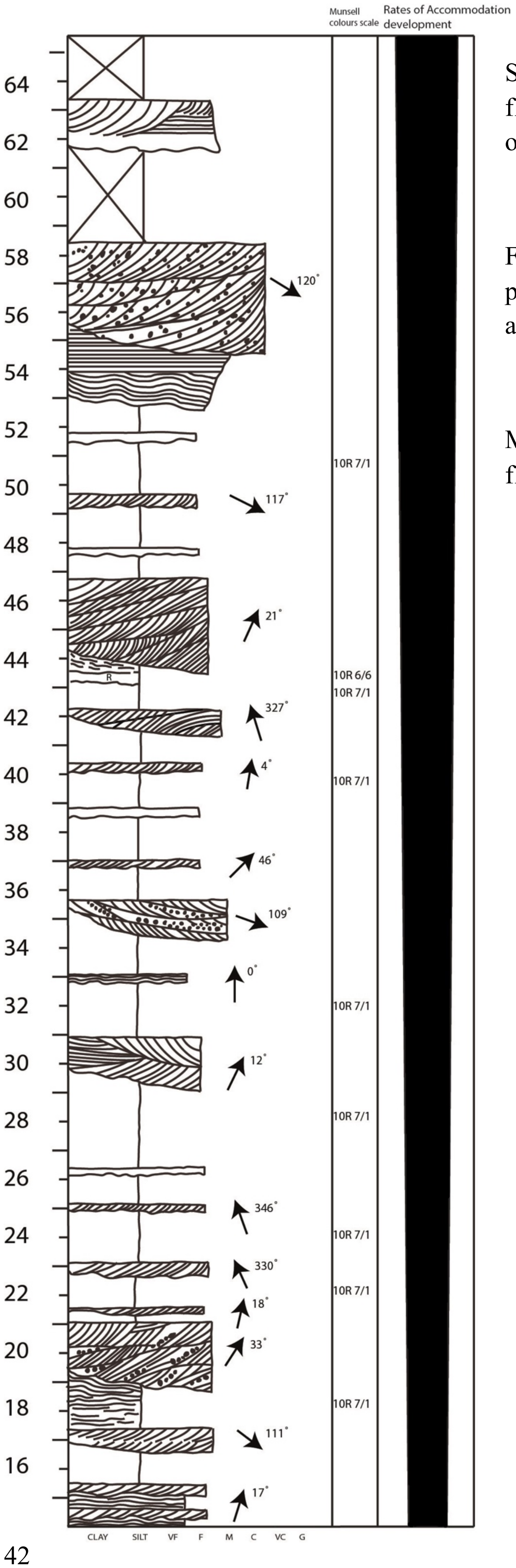


Photo log of the uppermost part of the Tidwell Member showing floodplain mudstone with thin overbank sandstone beds and a fluvial channel sandstone in the upper part

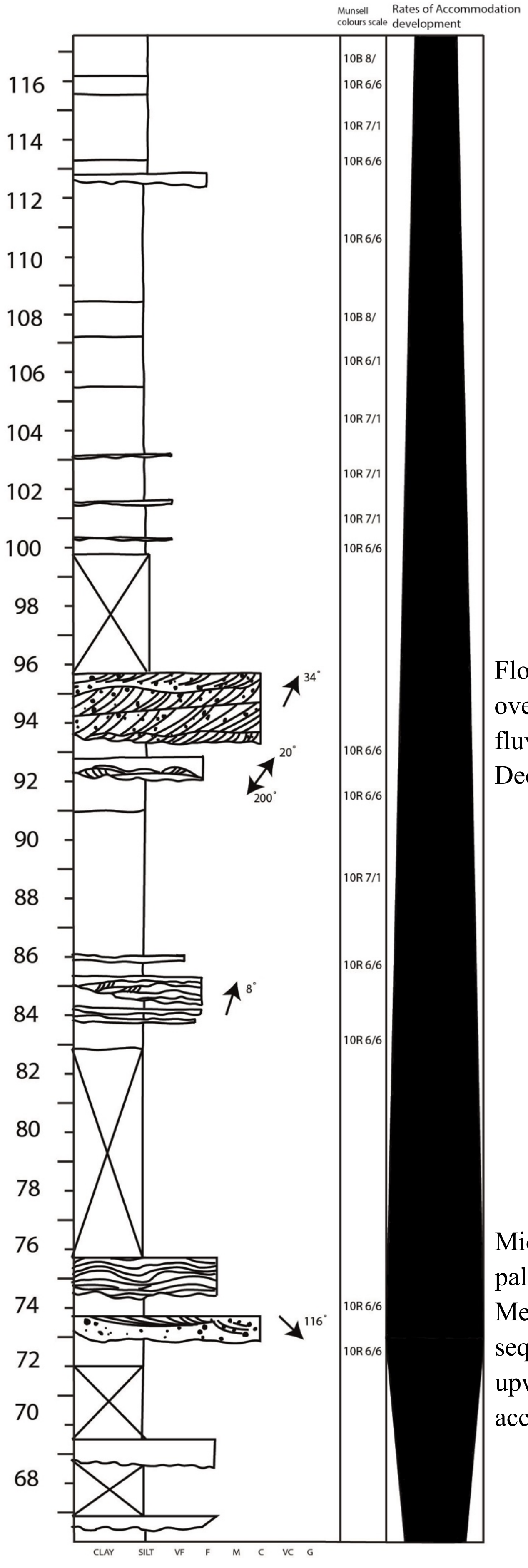
Figure 5.18: Sedimentological log, and following three pages. Through the Morrison Formation, starting with Tidwell Member and the Brushy Basin Member at the end of the figure (Vertical axis given in meters). The black arrow points in the direction of increasing accommodation space.



Salt Wash Member with fluvial mudstone, fluvial channel sandstone infill units and thin overbank or crevasse splay sandstone bed

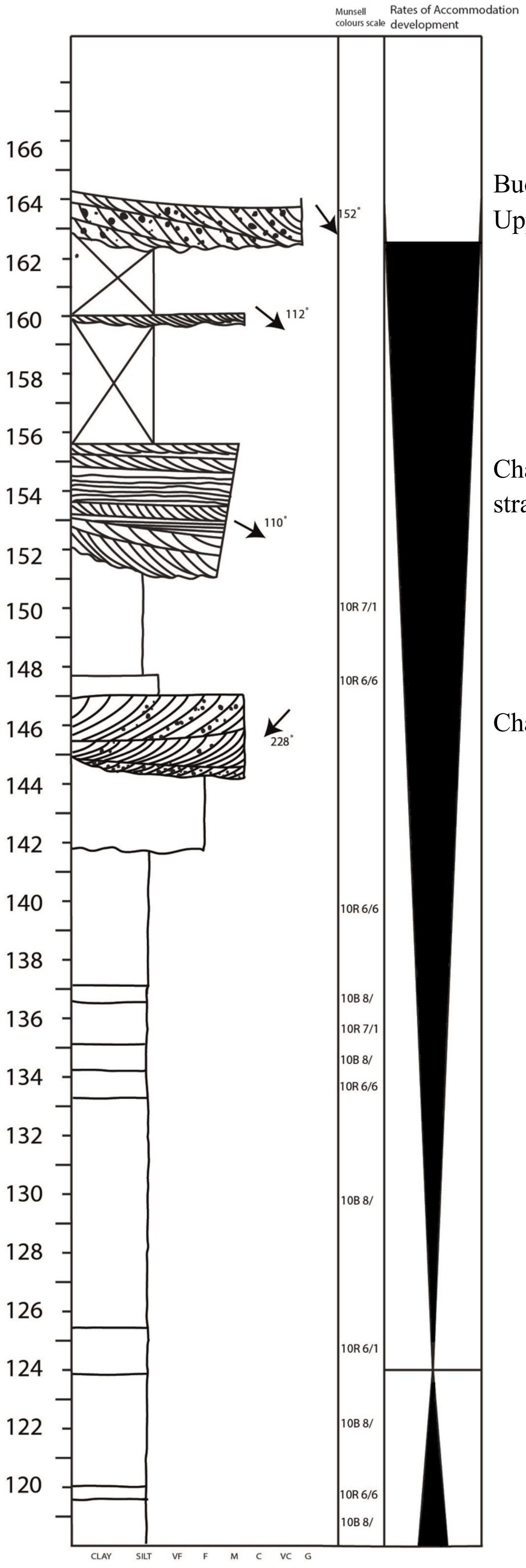
Fluvial channel sandstone units consists of planar cross stratified sandstone beds/bedsets and planar stratified sandstone as main facies

Measured directions indicate palaeocurrent flow direction



Floodplain and lacustrine mudstone with thin overbank sandstone beds and singlestorey fluvial channel infill sandstone units. Decreasing influx of sand

Mid-Morrison unconformity overlying red paleosol: Boundary between the Salt Wash Member and the Brushy Basin Member, sequence boundary and turnaround from upward decreasing to upward increasing accommodation



Buckhorn Conglomerate above the Uppermost Morrison unconformity

Channel sandstone with cross-bedded and planar stratified sandstone

Channel sandstone with planar cross-bedded sandstone

6 Discussion

6.1 Depositional environment and geological development: an overview

The *Tidwell Member* represents a variety of depositional environments. Deposits of mudstone are interbedded with isolated small fluvial channel sandstone and thin overbank sandstone beds and reflect a distal floodplain environment, whereas limestone and gypsum beds reflect a lacustrine to evaporitic mudflat environment (Peterson, 1988). The interfingering and overlaying more proximal Salt Wash Member consists of large-scale fluvial systems and associated floodplain deposits (see below). As the Tidwell Member is poorly or not at all exposed in the sections studied in this master thesis project, the Tidwell Member will not be discussed further, except for its regional and stratigraphic association with the Salt Wash Member.

The *Salt Wash Member* extends across central Utah, Western Colorado, northeastern Arizona, and northwestern New Mexico (Mullens and Freeman, 1957). The Salt Wash Member was deposited in a fully fluvial regime, consisting of fluvial channels interbedded with floodplain mudstone and local lacustrine beds. Rivers were draining in northeast directions (Chapter 5). The dry and hot climate with few or heavy seasonal periods of rainfall, gave rise to dryland rivers; ephemeral rivers that during flash floods transported and deposited gravel and coarse-grained sand in channels of various geometry (Chapter 4). The channels were distributed in a fan-shaped pattern (Craig, 1955, Mullens and Freeman, 1957). Kjemperud et al. (2008) suggested that the Salt Wash fluvial system prograded into the basin from the southwest to northeast. The fan-shaped distributary pattern, with proximal development in the southwest and distal facies in the northeast, has recently been characterized as a *distributary fluvial system* (DFS) by Owen et al. (2015b). The DFS system of the Morrison Formation comprises both the Tidwell and the Salt Wash members, but was by (Owen et al., 2015b) termed the *Salt Wash DFS*.

Distributive fluvial systems are defined by (1) a channel pattern that radiates away from an apex; (2) a decrease in channel size and abundance downstream; (3) an increase in preservation of floodplain deposits relative to channel deposits downstream; (4) a decrease in grain size downstream; and (5) a change from amalgamated channel deposits in proximal regions to smaller fixed channels in the distal regions (Hartley et al., 2010, Weissmann et al., 2013).

Owen et al. (2015a)predicted the apex of the Salt Wash DFS by using statistical projection of palaeocurrent data and found the apex to have been located in north-eastern Arizona (Figure 6.1) and suggested that the source of the Salt Wash DFS was located in the Mogollon-Sevier Highlands formed by collision between the North-American plate and the Farallon plate, or solely from the western part of the Mogollon Highland in the north-central Arizona (Dickinson and Gehrels, 2008) (Chapter 3).

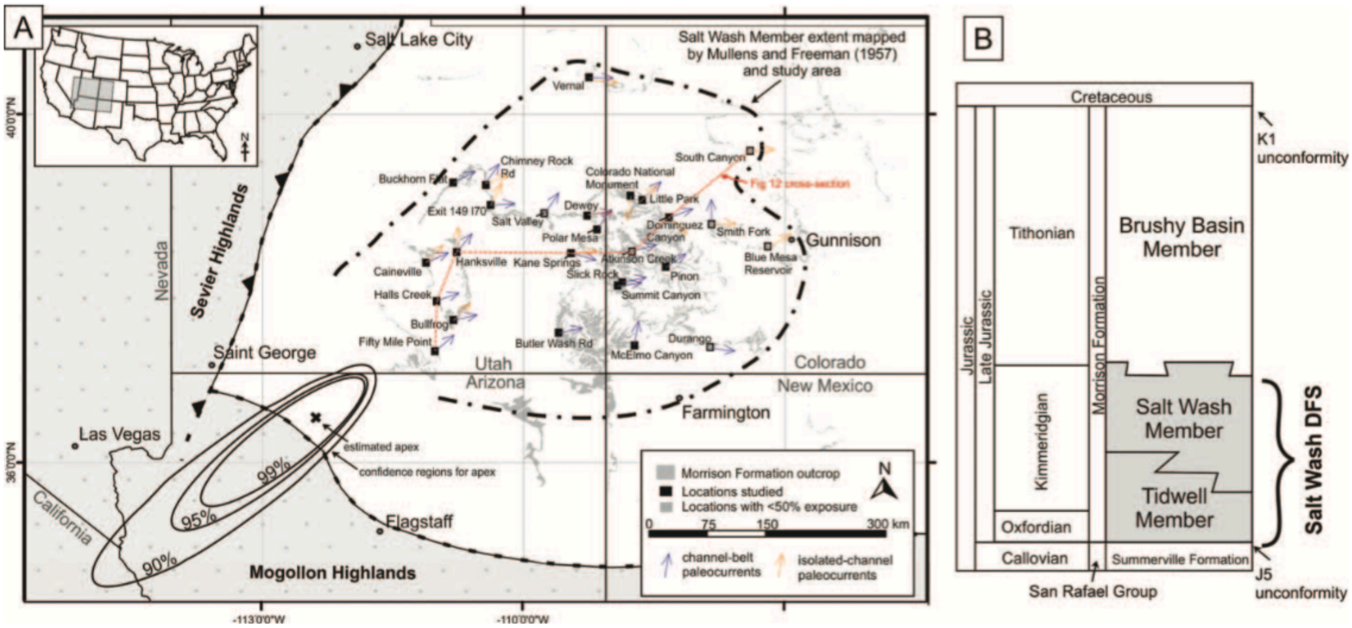


Figure 6.1: Location map of the Salt Wash fluvial system. Apex position defined by Owen et al. (2015a).

The amalgamated channel sandstone bodies of the Salt Wash Member are typically multistorey and multilateral, with a series of channel segments amalgamated, resulting in type of sandstone bodies of potential high reservoir quality (Kjemperud et al., 2008).

The *Brushy Basin Member* was deposited in a dominantly lacustrine environment. The fluvial environment of the Salt Wash DFS was altered to a more lacustrine environment with deposition of mud and some thin sand beds (Chapters 3 and 5). Dunagan and Turner (2004) explained the change of the fluvial Salt Wash basin to a lacustrine/wetland basin, irrespective of the dry to semi-humid climate, due to a regional groundwater flow towards the east and northeast, from the Mogollon-Sevier Highland in the west and southwest. Increase in rate of basin subsidence caused the groundwater to rise to surface, thus forming lakes and wetlands. Due to high evaporation, the lake water evolved during deposition of the Upper Brushy Member to be alkaline and saline in a lake that covered northeastern Arizona, northwestern New Mexico, southwestern Colorado and southeastern Utah (Turner-Peterson, 1986, Turner and Fishman, 1991). This combined lacustrine and wetland system is the largest and oldest alkaline-saline wetland/lake in the geological record and has been named Lake T'oo'dichi (Navajo for "bitter water") (Turner-Peterson, 1986, Turner and Fishman, 1991, Dunagan and Turner, 2004).

The major depositional elements, recorded as facies associations in the present study (Chapter 5), will be discussed below before a closing discussion of major controlling factors of the vertical and lateral trends recorded.

6.2 Channels

As shown in Chapter 5, the channel infill successions of the Salt Wash Member are composed of multilateral and multistorey composite fluvial sandstone bodies, representing *amalgamated channels*, and singlestorey channel successions, interpreted as formed as *isolated channels.*

6.2.1 Amalgamated channels

Bar deposits, defined by accretion surfaces, are often found above erosional surfaces developed in underlying floodplain mudstone units (Chapter 5). Downstream accretion bars are inferred when the dip of downstream accretion surfaces corresponds to the dip of cross-bedding within the bedform deposit, and lateral-accretion bars are inferred when cross-bedding dips obliquely to the overall downstream palaeocurrent direction. The general poor sorting, coupled with horizontal stratification and irregular cross-bedding (Chapter 5) implies that this facies association was deposited from rivers that experienced seasonally flashy discharge with high and fluctuating energy, as also previously suggested by Miall (1977) Lorenz and Nadon (2002), an interpretation backed up by Robinson and Mccabe (1998) and Turner and Peterson (2004).

Many authors have earlier suggested that the amalgamated Salt Wash DFS channel deposits were deposited from mainly braided fluvial streams (Craig, 1955, Mullens and Freeman, 1957, Peterson, 1977); this interpretation has been based largely on the sand rich, highly reworked nature of the deposits and the braid bar appearance of the coarse-grained sandstone units. Thus, Kjemperud et al. (2008), from a study of the Salt Wash Member in southern part of the Capitol Reef National Park, in a more proximal position than the area of the present study, interpreted the amalgamated channel sandstone bodies as formed in braided streams. The fluvial sandstone facies and facies associations of the present study, in concert with the plane view Google Earth images, demonstrate that most of the amalgamated channels with coarse-clastic debris were formed in channel belts with varying sinuosity (Table 5.2). This is discussed further below.

The sandy characteristics and multilateral and multistorey architectural style of the amalgamated sandstone bodies of the Salt Wash Member is interpreted to be a function of the low accommodation/sediment supply (A/S) regime (Kjemperud et al., 2008, Owen et al., 2015b) and low slope gradient of the basin and of the streams (Owen et al., 2015b). See discussion below.

6.2.2 Isolated channels

These channel types are lens-shaped sandstone bodies with clear channel morphology in cross section and sandy wings in the overbank successions. The channel bodies are embedded in floodplain mudstone. They are singlestorey sandy fills that range in grain size from fine to granules (Chapter 5). These characteristics indicate deposition in a fixed fluvial channel with little lateral migration (Friend et al., 1979, Owen et al., 2015b). Both asymmetric and symmetric channel morphology, as seen in cross section, are observed (Chapter 5). An asymmetric channel form does according to Miall (2016) reflect a sinuous channel, whereas symmetric channel cross sections reflect relatively straight and fixed channels (Pyles et al., 2010). However, asymmetric channels can also be deposited in straight rivers (Bridge, 2003).

Kjemperud et al. (2008) termed these deposits in the Tidwell Member and Salt Wash Member “steer-head channels” and interpreted them as being distributary channels feeding the distal floodplain and lacustrine environments (in the Tidwell Member). Owen et al. (2015b) also found isolated channels all throughout the Salt Wash DFS succession with no apparent relation to lacustrine deposits, even though being commonly associated with floodplain deposits. These isolated-channel-fills are not considered to be part of anastomosing channels because of the lack of more than one channel within each stratigraphic horizon (Owen et al., 2015b).

6.2.3 Braided vs sinuous coarse-grained channel infill

Associations of channel bed conglomerate, conglomeratic and poorly sorted coarse-grained sandstone, cross stratified and planar to low-angle stratified sandstone beds are generally considered to be typical facies associations for braided stream deposits (Rust, 1978, Schumm, 1981, Miall, 1977). In the present study area of the Salt Wash Member this “typical” braided stream facies assemblage is also accompanied by sandstone units, revealing lateral accretion (Chapter 5). The association of both downstream accretion- and lateral-accretion elements, the last one with scroll bar deposits as demonstrated in Google Earth plan view pictures (Chapter 5), indicate that the amalgamated channel fill successions represent mixed, almost straight to winding multi-channel river systems with braid bars, downstream accretionary bars, as well as lateral accretionary channel bars. Conglomeratic and coarse-grained fluvial sandstone bars, formed by lateral accretion in sinuous streams have been identified elsewhere from corresponding settings in semiarid climate (Nijman and Puigdefabregas, 1977).

The reason for formation of sinuous channels with successions of apparent braided stream facies may be ascribed to the coincident of very low depositional gradient and low rate of creation of accommodation. This is then triggering lateral accretion in sinuous stream, combined with typical dryland hydrology with seasonal strong flooding and supply of coarse-grained clastic debris from highland areas.

6.3 Floodplain environment

The floodplain environment of the Salt Wash Member is represented by thick mudstone units with thin crevasse splay sandstone beds (Chapter 5). As discussed above, the isolated channel sandstone bodies are also elements of the floodplain. The crevasse splay sandstone beds are likely to be representing distal facies of splays formed during overbank flooding in isolated channels. Red-coloured horizons, inferred to be paleosols (Chapter 5), represent time intervals with moderate to very low rate of sedimentation, as generally considered for formation of paleosols (Retallack, 2008). Detailed studies of paleosols in the Morrison Formation have revealed various types of pedogenic development, indicating local to regional variations in climate from dry to tropical seasonal wet-dry climate, fluctuating groundwater level and trace fossils showing the presence of opportunistic flora and fauna (Demko et al., 2004, Parrish et al., 2004, Jennings et al., 2011, Owen et al., 2017).

The nearly plane parallel and flat stratification of the floodplain facies association deposits are in favour of the very low-sloping gradient of the depositional basin.

Through the Salt Wash DFS the distal region show a relatively higher mud:sand ratio than the proximal region (Owen et al., 2015b).

6.4 Lacustrine environment

The lacustrine environment is represented by varicoloured mudstone, isolated single channel infill and related thin fine-grained overbank sandstone beds (Chapter 5). As discussed above the depositional environment altered to lacustrine due to a rise in groundwater above the surface, thus forming lakes and wetlands (Dunagan and Turner, 2004). The semi-arid to arid climate in the Late Jurassic led to limited surface water and few perennial stream, furthermore meteoric water was also limited and probably seasonal in nature (Turner and Peterson, 2004, Parrish et al., 2004). No deltaic or shoreline deposits were recorded in the log (Chapter 5). The variation of greenish grey and pink to red-coloured mudstone units in the otherwise overall homogenous lacustrine mudstone may have been caused by changes in water circulation and thereby oxidation. Changes in water depth in the lacustrine part of the

Morrison Basin may have been related to a fluctuating groundwater level (Dunagan and Turner, 2004).

6.5 Vertical and lateral trends: controlling factors of deposition

As shown by Kjemperud et al. (2008) and Owen et al. (2015b) there are marked vertical trends in grain size, mud:sand ratio, sandstone bed thickness and frequency of amalgamated channel fill sandstone units through the Morrison Formation. This is particularly within the Salt Wash DFS, including the Tidwell and the Salt Wash members. Such trends are also revealed in the present study, as shown by the logs (Figure 5.18).

Kjemperud et al. (2008) defined stratigraphic cycles in the Salt Wash Member. Some vertical trends, characterized by upward fining, upward thinning of sandstone beds and upward decrease in frequency of fluvial channel sandstone bodies, were ascribed to rising base level (increasing accommodation). Other trends, with upward coarsening and upward thickening of sandstone beds and upward increase in frequency of fluvial channel sandstone bodies were interpreted as formed during fall in base level (decreasing accommodation).

The succession shown by the log in Figure 5.18 reveals variation in trend, starting from below in the Tidwell Member with (A) a general upwards increase in grain size and frequency of sandstone beds, terminating with an amalgamated thick channel sandstone on top of the trend at the lower boundary of the Brushy Basin Member. From the base of the Brushy Basin Member and up to the central part of the mudstone-dominated lacustrine facies association, the overall upward fining trend (B) is interpreted to represent an increase in rate of creation of accommodation, whereas from this level and up to the boundary beneath the Buckhorn Formation another trend (C) of decreasing rate in creation of accommodation is suggested.

6.5.1 Trend A

Trend (A) is inferred to be the result of progradation of the alluvial plain with its distributary channels, as a result of decreasing rate in creation of accommodation. As pointed out by Owen et al. (2017) there are numerous detail variations in this lower progradational trend in the Morrison Formation, reflecting local variation in accommodation and sedimentation.

Owen et al. (2015b) demonstrated that an overall progradational pattern, revealed by vertical facies trends from distal to proximal positions, can be traced through the Salt Wash DFS from the apex in the southwest to the distal parts of the fan-shaped distributary

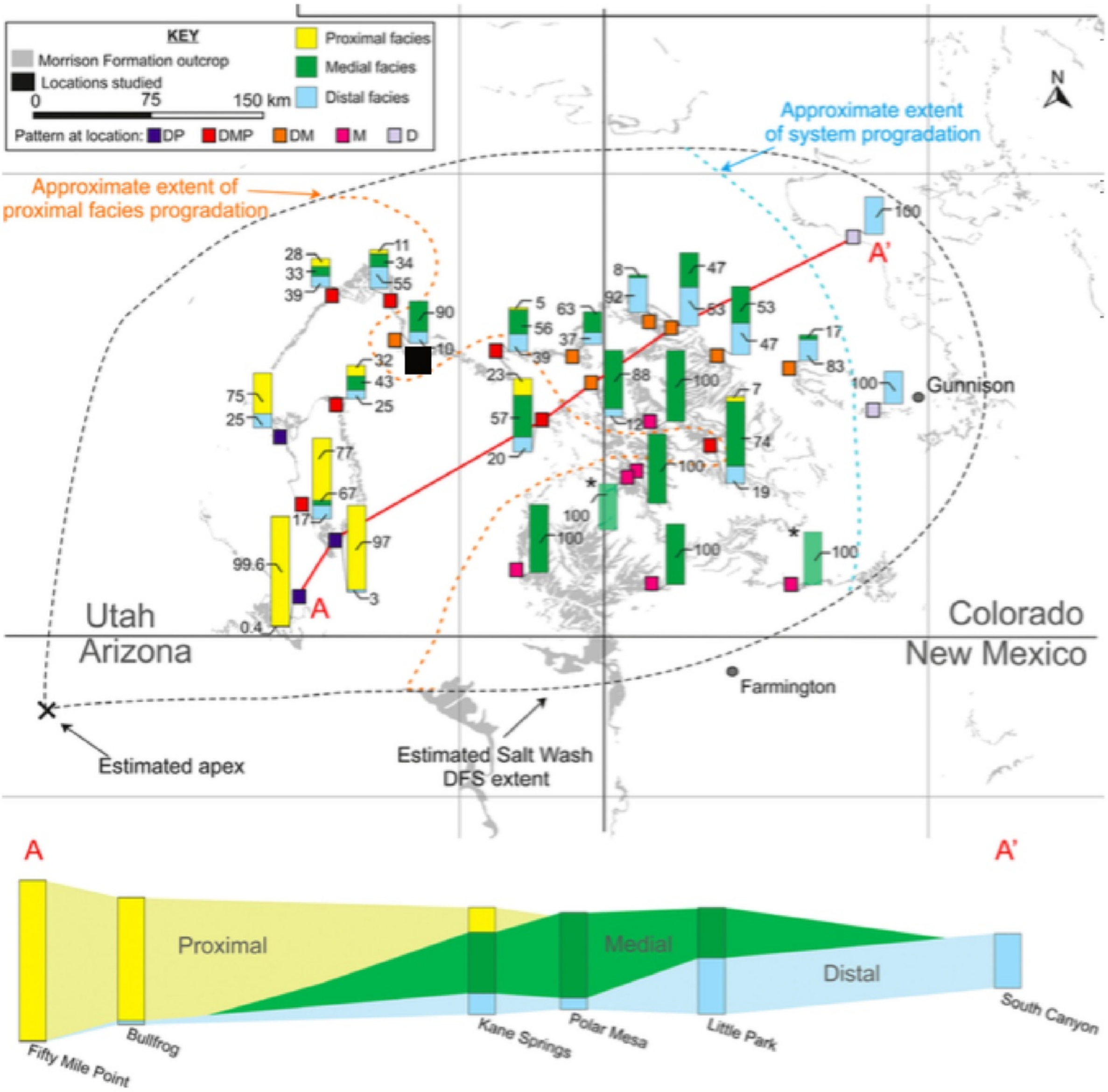


Figure 6.2: Lateral and vertical stacking patterns of proximal, medial and distal facies in the Salt Wash Member, Morrison Formation. From Owen et al. (2017). Numbers represent percentage that each facies comprises each sedimentary log. Approximate position of present study area is shown with the black square.

depositional system in the northeast (Figures 6.1 and 6.2).

The thickness of the Salt Wash DFS decreases from the proximal regions in the southwest to the distal regions in the northeast. In the relatively proximal region the thickness is measured to 174 m and in the most distal region to 40 m. Within this depositional system, the sandstone percentages show a clear downstream decrease, from 70% to 75% in the proximal regions to 8% to 26% in the most distal regions of the DFS (Owen et al., 2015b). The proximal section of the Salt Wash DFS are composed of laterally extensive highly amalgamated channel sheet sandstones, where 80% - 90% of channel bodies are amalgamated and connected (Owen et al., 2015b). This indicates a regime with a low ratio of accommodation to sediment supply in an environment with mobile channels (Weissmann et al., 2013, Owen et al., 2015b).

In the medial portion of the Salt Wash DFS, where this thesis study area is located (Figure 6.2), the channel sandstone bodies are less amalgamated and less connected, being separated by floodplain deposits (Chapter 5). Owen et al. (2015b) showed that 20% of the channel complexes are amalgamated and connected in the medial region, implying a high grade of connectedness. The ratio of accommodation to sediment supply is increasing in the medial section of the DFS, with channels with lower mobility; allowing floodplain deposits to be better preserved (Weissmann et al., 2013, Owen et al., 2015b).

The distal portion of the Salt Wash DFS is characterized by isolated channel sandstone bodies embedded in floodplain material, with no amalgamation or connectivity between the sandstone beds observed (Owen et al., 2015b). A regime with relatively high ratio of accommodation to sediment supply is inferred, with isolated and immobile channels.

6.5.2 Trend B

This trend starts at the Mid-Morrison Unconformity, forming the lithostratigraphic boundary between the Salt Wash and Brushy Basin members (Figure 5.18). The general increase in mud:sand ratio and decrease in sandstone beds can be explained by a general increase in lake depth and thereby distance to lake shoreline and reduction in supply and settling of sand in the actual site of the lake basin. Considering the ratio of creation of accommodation, it has increased in this trend.

6.5.3 Trend C

The uppermost recorded trend marks the change to increasing influx and sedimentation of sand versus mud. The trend may represent an upward shallowing of the lake and again a prograding system entering the Morrison Basin. This trend of decrease in rate of creation of accommodation culminated with the regional erosional surface below the Lower Cretaceous Buckhorn Formation.

6.6 Regional factors in control of depositional trends

As pointed out by Kjemperud et al. (2008) and Owen et al. (2015b) depositional style, stratigraphically and laterally, is controlled by rate in creation of accommodation versus rate of sedimentation (A/S). A/S ratio is on basin-scale generally controlled by the allogenic factors tectonics, character of source rocks, climate and sea-level changes, whereas autogenic factors like stream avulsion, bar migration and local changes in topography control smaller-scale variation in depositional pattern, as summed up by Owen et al. (2017).

As the Morrison Basin was a continental basin, sea level changes can be excluded from the list of allogenic control factors. The overall dry-land climate, with or without seasonal variations and variations locally (Chapter 4), controlled water discharge and sediment flux. Tectonic movements in the mountain chain in the west (Chapter 3) influenced rate of weathering and sediment production.

The rate of creation and destruction in accommodation in the backbulge basin of the Morrison Formation (Chapter 3) was likely controlled by crustal dynamics forced by rate in subduction of the Farallon plate beneath the North-American plate in the west, according to the model of evolution of retroarc forland system by Catuneanu (2004). Rate in aggradation of thrust sheets and amount of tectonic loading in the orogenic wedge and eastward propagation of the foreland bulge might have contributed to the relief of the source area for clastic material to the Morrison Basin (Chapter 3).

Demko et al. (2004) illustrated the development of accommodation through late Jurassic time in the Morrison Basin and subdivided the formation in two depositional sequences (Figure 6.3).

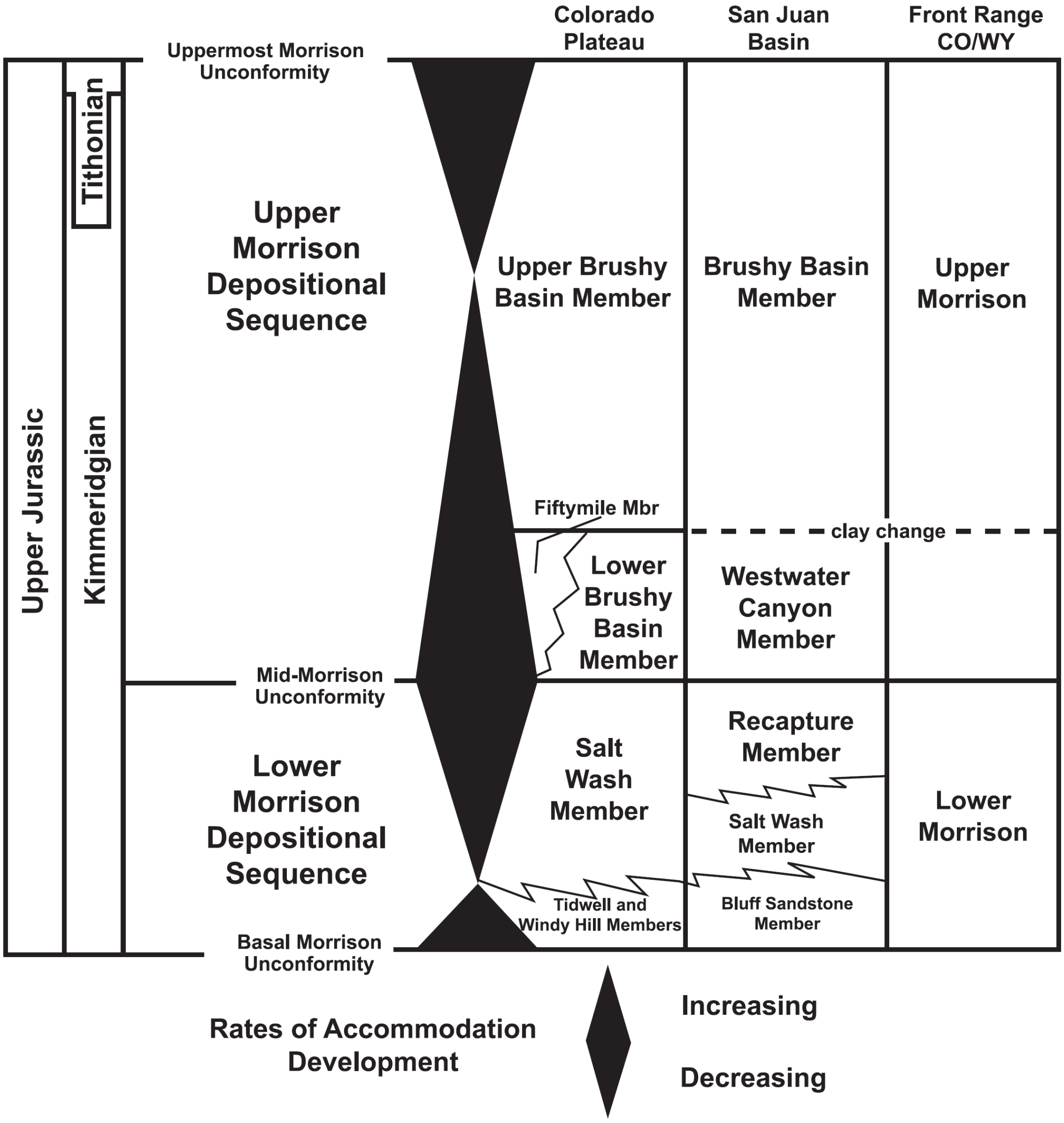


Figure 6.3: Diagram showing development of accommodation during deposition of the Morrison Formation, according to Demko et al. (2004).

The trend pattern of Demko et al. (2004) coincides with that recorded in the present study, except for the lowermost increasing trend above the Basal Morrison Unconformity. This part of the Morrison Formation was not available for inspection in the present study area. The Lower Morrison Depositional Sequence was defined by its sequence boundary located at the Basal Morrison Unconformity, and the Upper Morrison Depositional Sequence with sequence boundary at the Mid-Morrison Unconformity, the boundary between the Salt Wash Member and the Brushy Basin Member.

The A/S changed drastically between the Salt Wash and Brushy Basin Member. The depositional environment shifted from being fluvial dominated in the Salt Wash Member to lacustrine dominated in the Brushy Basin Member. The accommodation space has increased and led to a decrease in energy in the depositional environment. Flow of water in Salt Wash Member is altered to quiet conditions in Brushy Basin. This boundary is in many places recorded as a marked subaerial unconformity with a marked paleosol (Demko et al., 2004, Kjemperud et al., 2008, Owen et al., 2017). The Uppermost Morrison Unconformity (Figure 6.3) is succeeded by the Cretaceous Buckhorn Conglomerate Formation before marine transgressive strata.

Demko et al. (2004) explained the formation of the regional unconformities mentioned above as the result of changes in dynamic subsidence within the back-bulge basin of the Morrison Formation (Figure 6.4). The unconformities were formed at stages when the creation of accommodation was negative; the basin was eroded and acted as a bypass area for rivers flowing from the highlands in the southwest to lowlands in the northeast. Between these events, the creation of accommodation was positive and the continental basin accumulated sediments. The rate in creation of accommodation was highest at the boundary between the Tidwell and Salt Wash Member and in the upper part of the Brushy Basin Member, when the lakes and wetland areas had their largest regional extent.

7 Conclusion

- Facies and facies associations show that the Morrison Formation was deposited in fluvial, floodplain and lacustrine environments within the study area in southeastern Utah. The study area was part of a low relief distributary fluvial system that during its final stage turned to a lake and wetland system due to rising groundwater.
- The lower part of the Morrison Formation, the Tidwell and Salt Wash members, previously described as a fan-shaped prograding braided stream system, is by Owen et al. (2015b) termed the Salt Wash DFS (distributary fluvial system); the studied section is located in the central northern part of this large distributary system that drained form the SW to the NE.
- Google Earth-photos, lateral accretionary bars and palaeocurrent measurements of the channel fill in the Salt Wash Member show that active amalgamated channels of coarse-grained, apparent braided stream facies associations were formed in channels varying from almost straight to winding sinuous channels.
- Sinuous channel morphology in the Salt Wash Member is interpreted to have resulted from the combination of very low depositional gradient, supply of coarse material, ephemeral dryland river drainage and low rate of creation of accommodation.
- The Morrison Formation reveal in the study area vertical trends of upward increase and decrease in rate of creation/destruction of accommodation. This corresponds to similar trends recorded elsewhere in the Morrison Formation.
- Main controlling mechanisms of the Morrison Formation are climate and tectonics. Climate contributed to coarse-grained material transported in deposition by ephemeral rivers during heavy floods and to autogenic changes in deposition from avulsion and changes in bedform morphology. The rate of subduction in the Cordilleran Orogeny in the west was the main allogenic factor that affected rate of creation of accommodation in the Morrison Basin.

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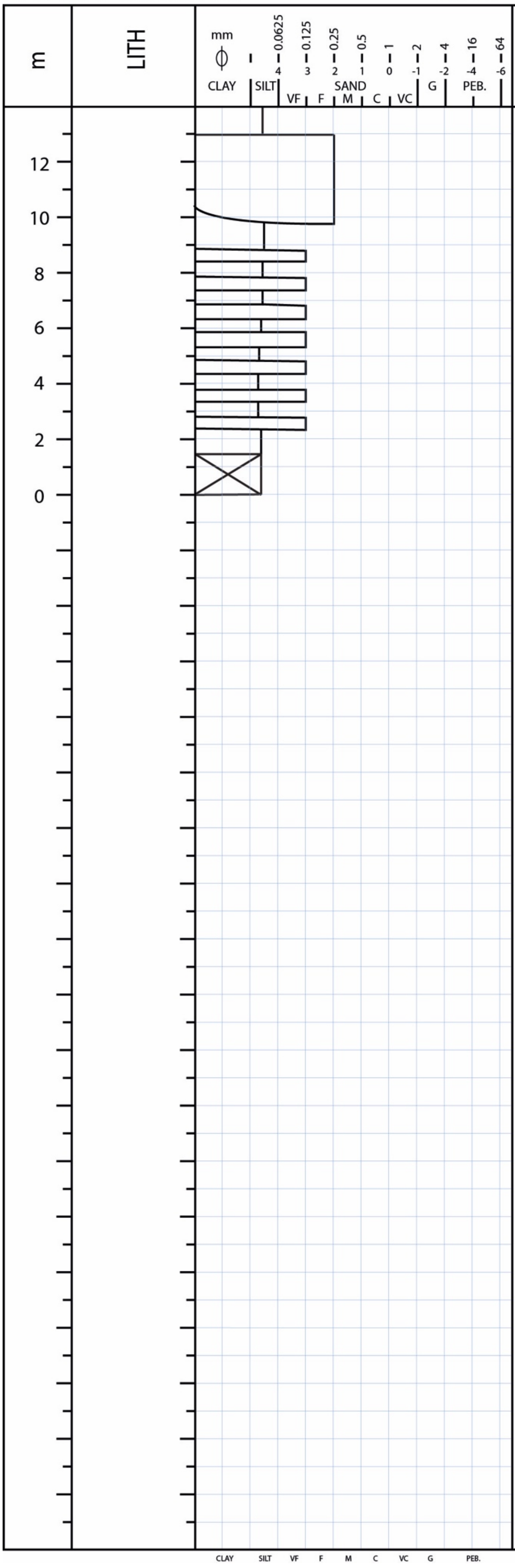
Appendix

Appendix A – Log from Tidwell Bottoms

LOCALITY Log 2, Foto log **SHEET** 1 **OF** 4 **DATE:** 26.01.17 **SCALE:** 1:200

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison and Summerville
AGE: Late Jurassic



Munsell color scale

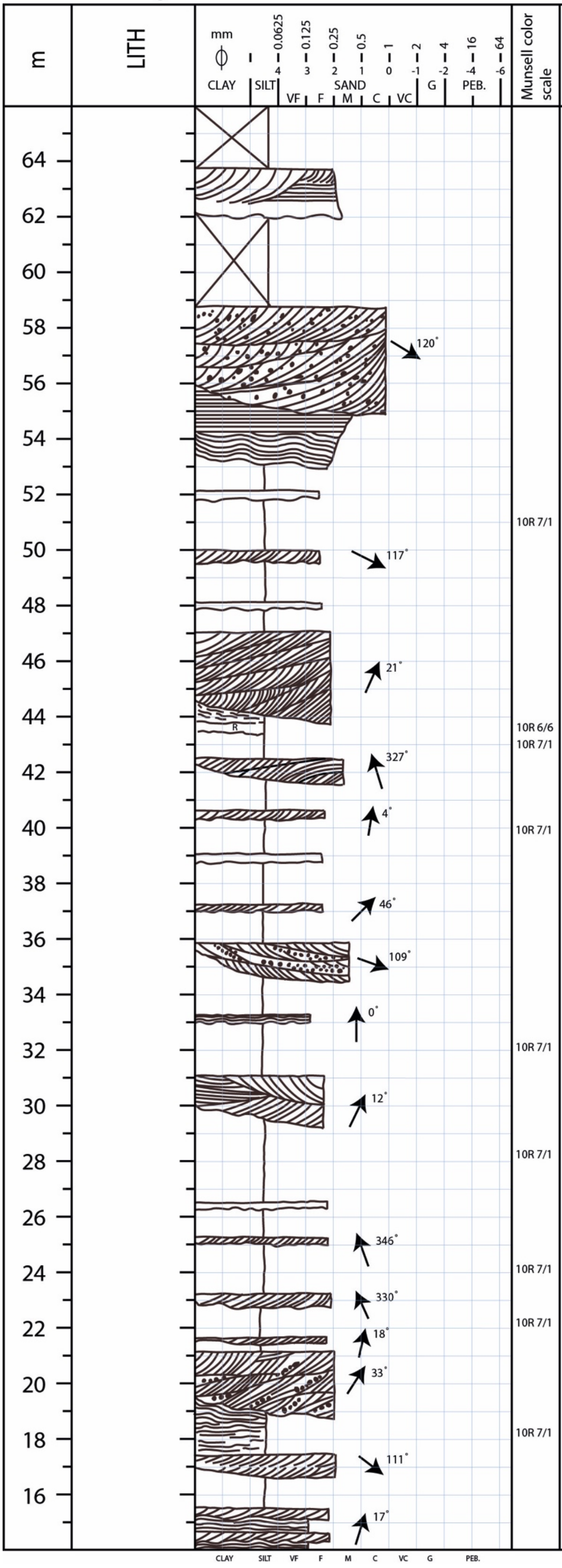
10R 7/1

10R 6/6

The silt is changing in color. From red to grey

LOCALITY Log 2 SHEET 2 OF 4 DATE: 05.07.16 SCALE: 1:200

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic



Impossible to log.

Conglomerate, with porly sorted and angular grains
Sample 10

Plain parallell lamination, upwards coarsening.

Wavy lamination. Sample 11

Well sorted. Sample 12

Sample 13

Sample 14

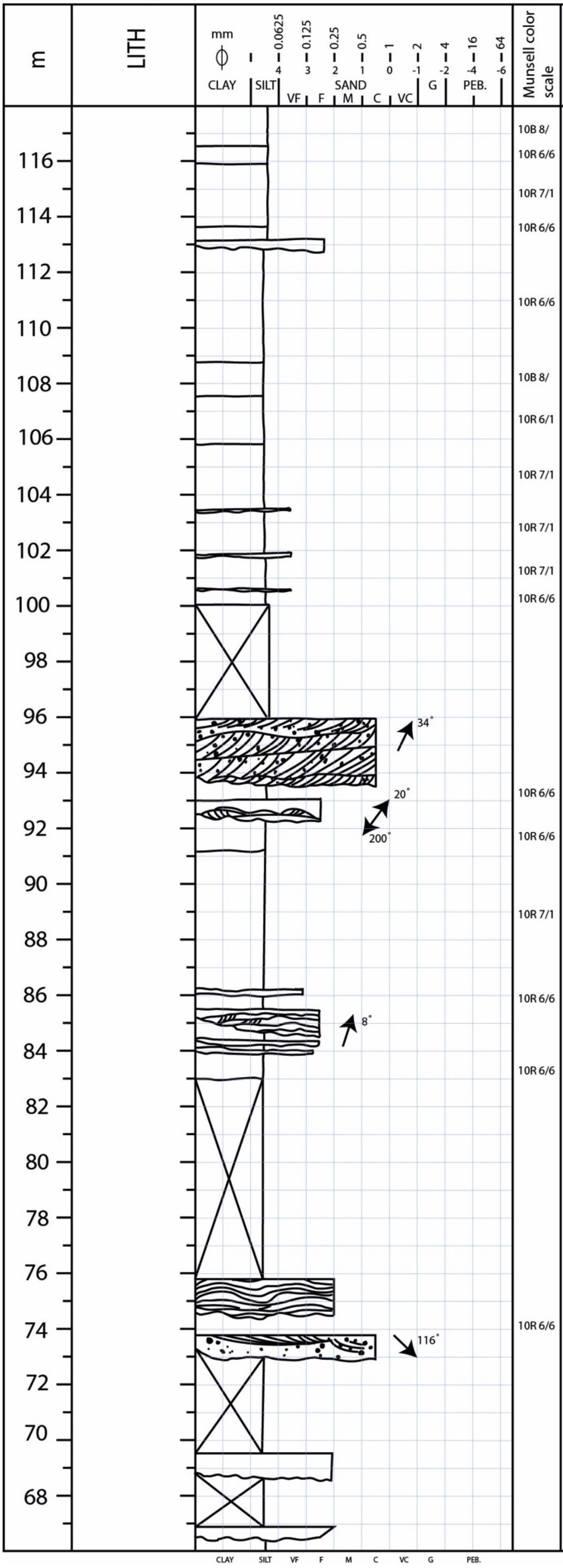
Moderately sorted, with subangular grains. Sample 15

Sample 16

Moderately sorted, with subangular.

LOCALITY Log 2 SHEET 3 OF 4 DATE: 06.07.16 SCALE: 1:200

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic



Conglomerate, with poorly sorted subrounded grains

Wavy lamination. Ripples on two directions

Wavy lamination, with small ripples

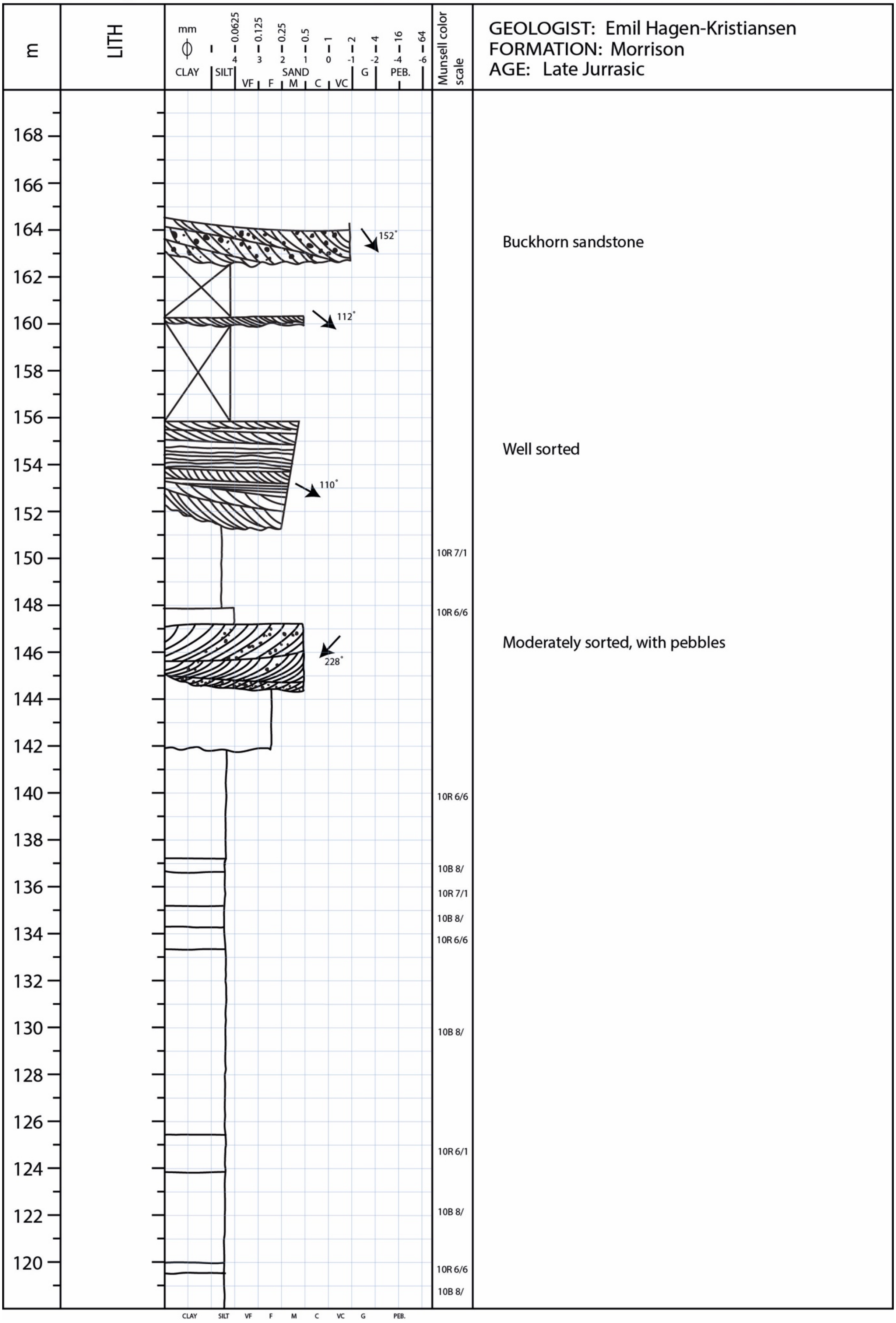
Impossible to log, ca. 6-8 m
Most likely silt, no large channels

Wavy lamination

Poorly sorted sediments with subangular grains

LOCALITY Log 2 SHEET 4 OF 4 DATE:07.07.16 SCALE: 1:200

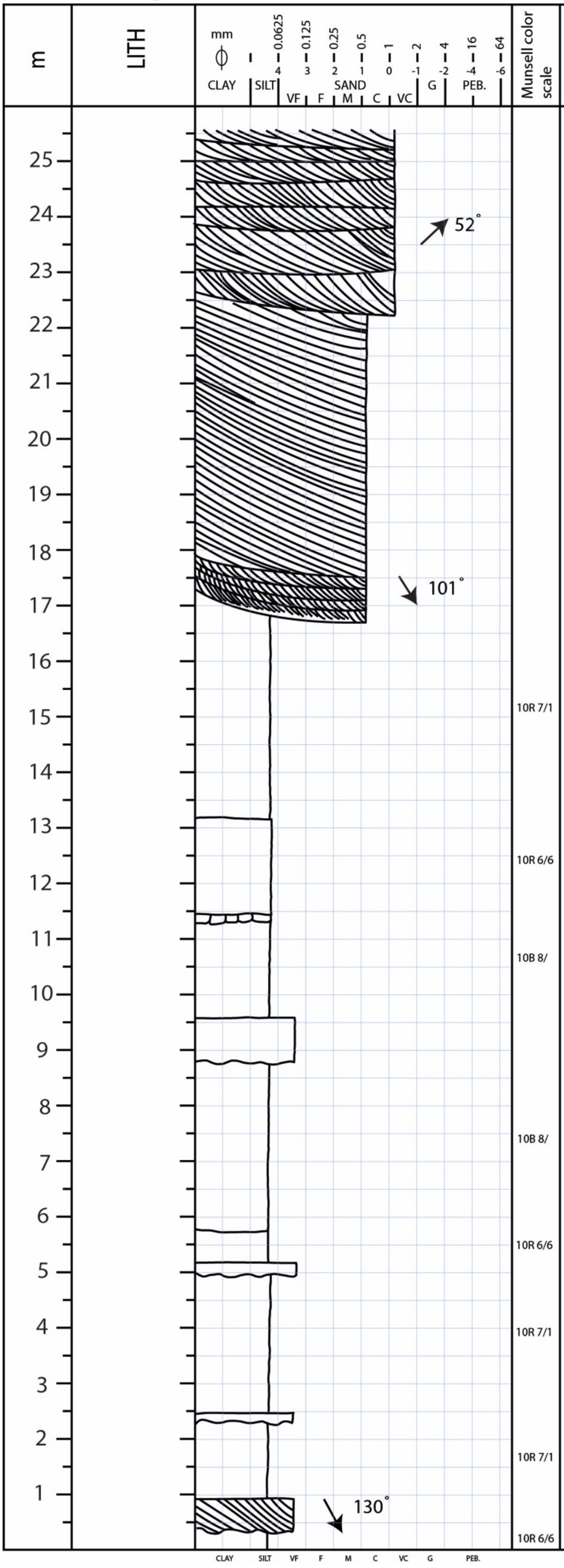
GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurrasic



Appendix B – Log from Buckmaster Draw North

LOCALITY Log 3 SHEET 1 OF 2 DATE: 11.07.16 SCALE: 1:100

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic

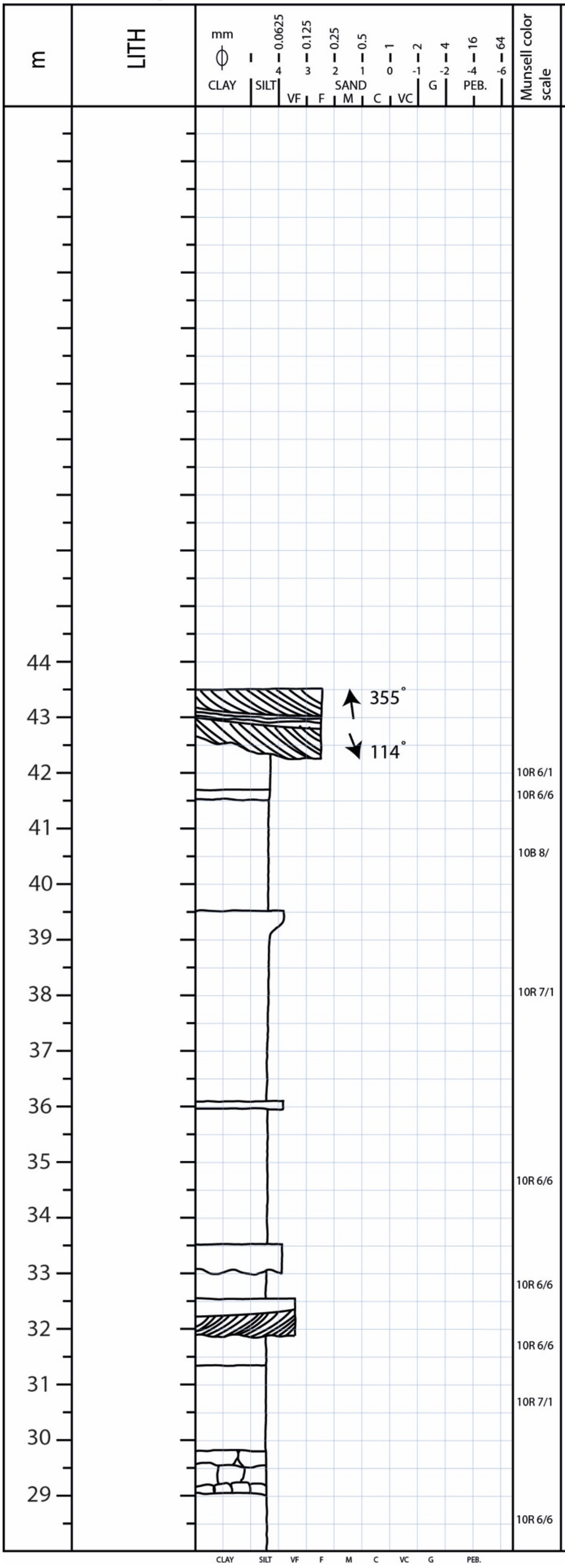


Good sorting

Thin black drops in base

LOCALITY Log 3 SHEET 2 OF 2 DATE: 11.07.16 SCALE: 1:100

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic

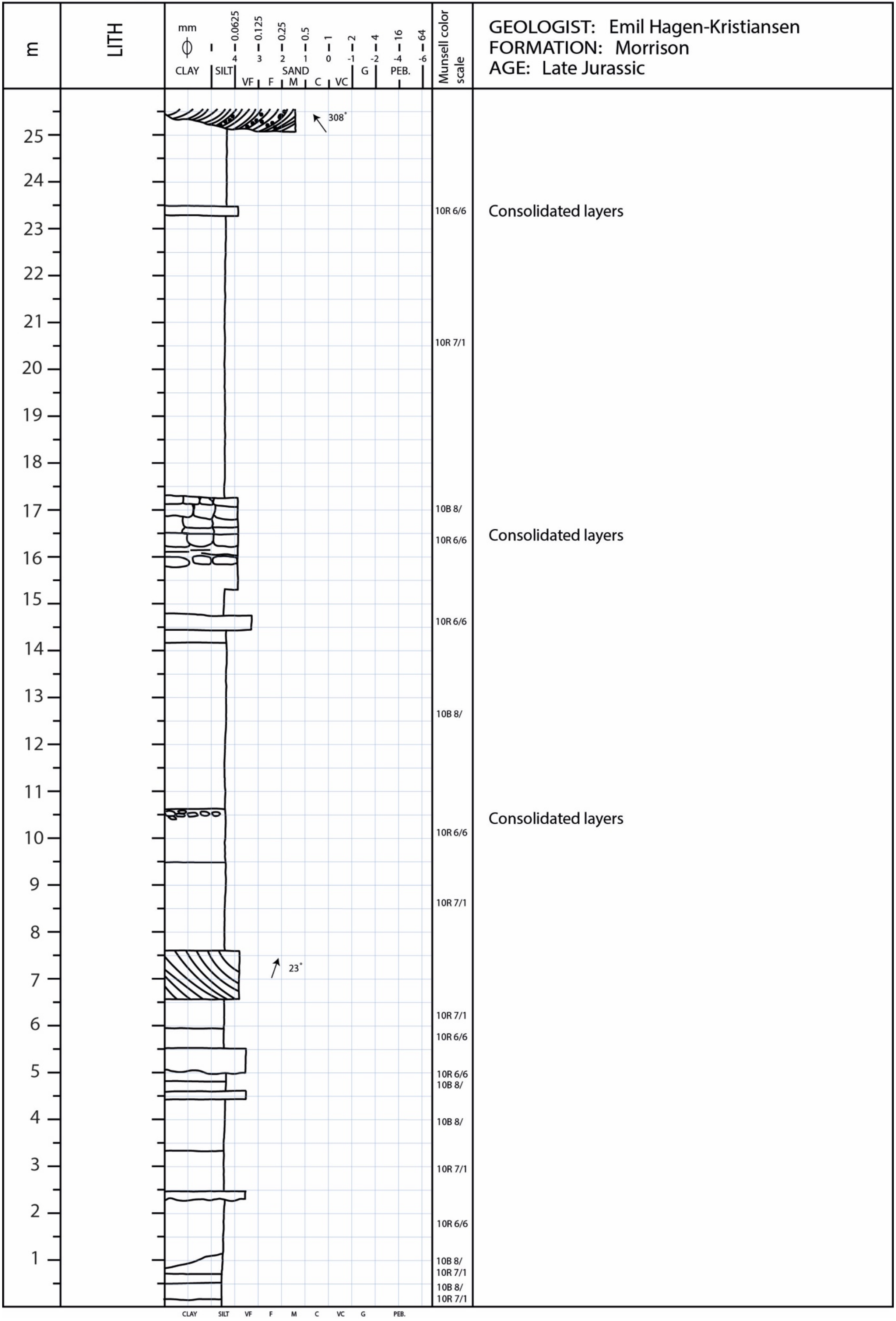


Solemarks

Appendix C – Jessies Twist

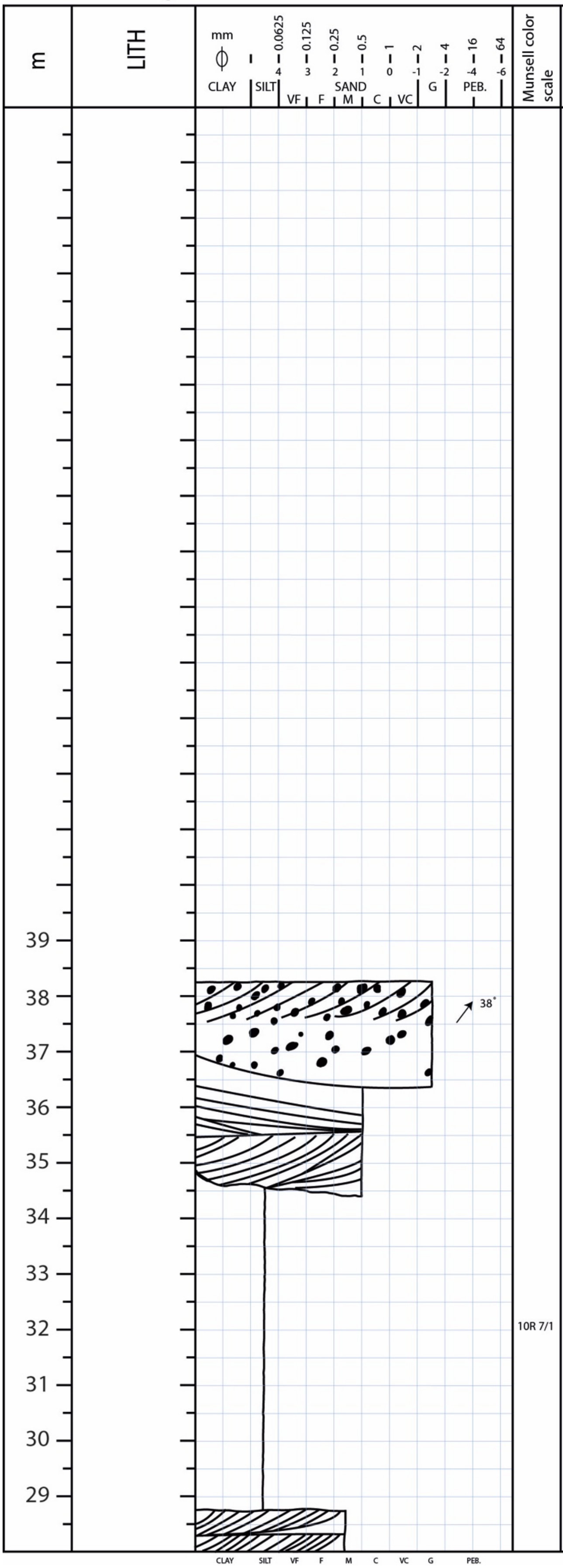
LOCALITY Log 4 SHEET 1 OF 2 DATE: 11.07.16 SCALE: 1:100

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic



LOCALITY Log 4 SHEET 2 OF 2 DATE: 11.07.16 SCALE: 1:100

GEOLOGIST: Emil Hagen-Kristiansen
FORMATION: Morrison
AGE: Late Jurassic



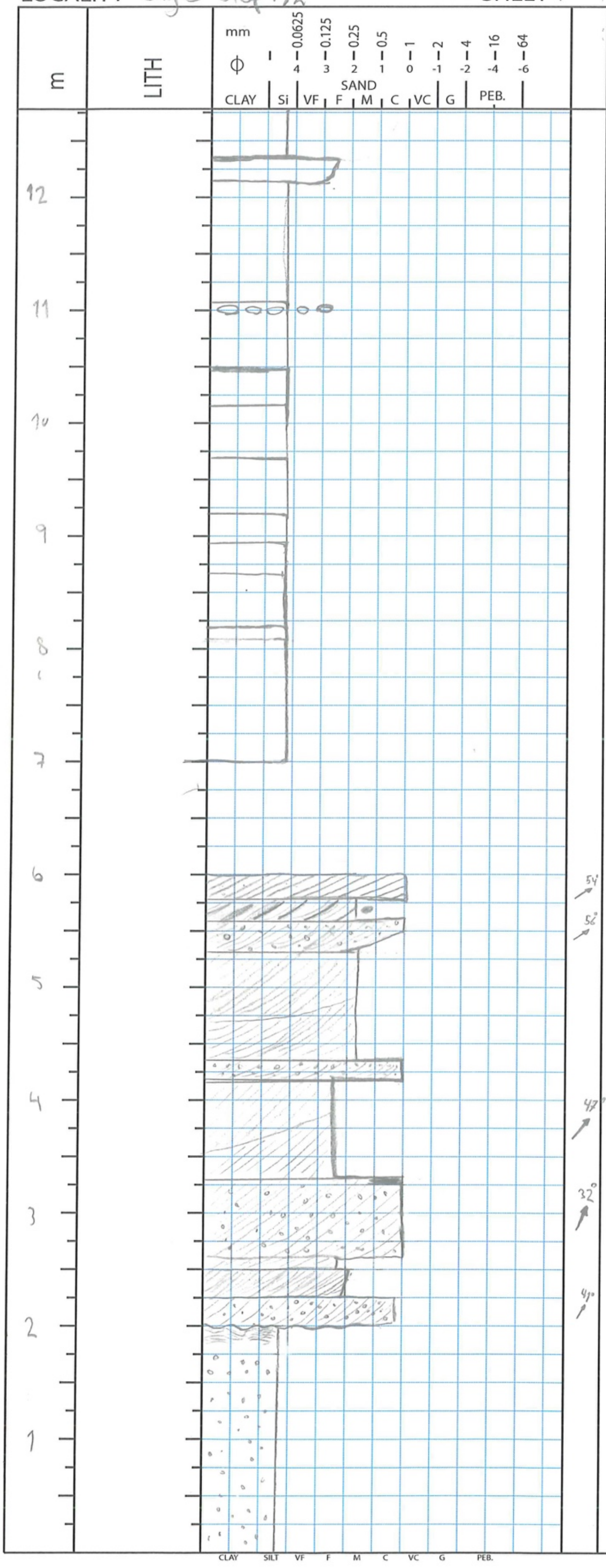
Very poorly sorted, with subrounded grains

Moderately sorted

Appendix D – Log from 4 corner mine I70 intersection

LOCALITY Day 3 stop 1,2 SHEET 1 OF 5 DATE: 29.06.16 SCALE: 1:50

GEOLOGIST: Emil
FORMATION: Morrison
AGE:



Dark grey

red/purple ligth grey clasts < 50cm

ligth grey

Red/purple

Grey

~~Red/purple~~ dark grey

grey

Dark grey

Red/purple weathered

Weathered
Grey

Poorlysorted pebbels: 5mm s.rounded

black draping Pebbels: 15mm s.rounded

Pebbels: 15mm s.rounded

Poorly sorted

Pebbels: 15mm s.rounded

Pebbels: 10mm s.rounded

skifrig i kontakten med overliggende sediment

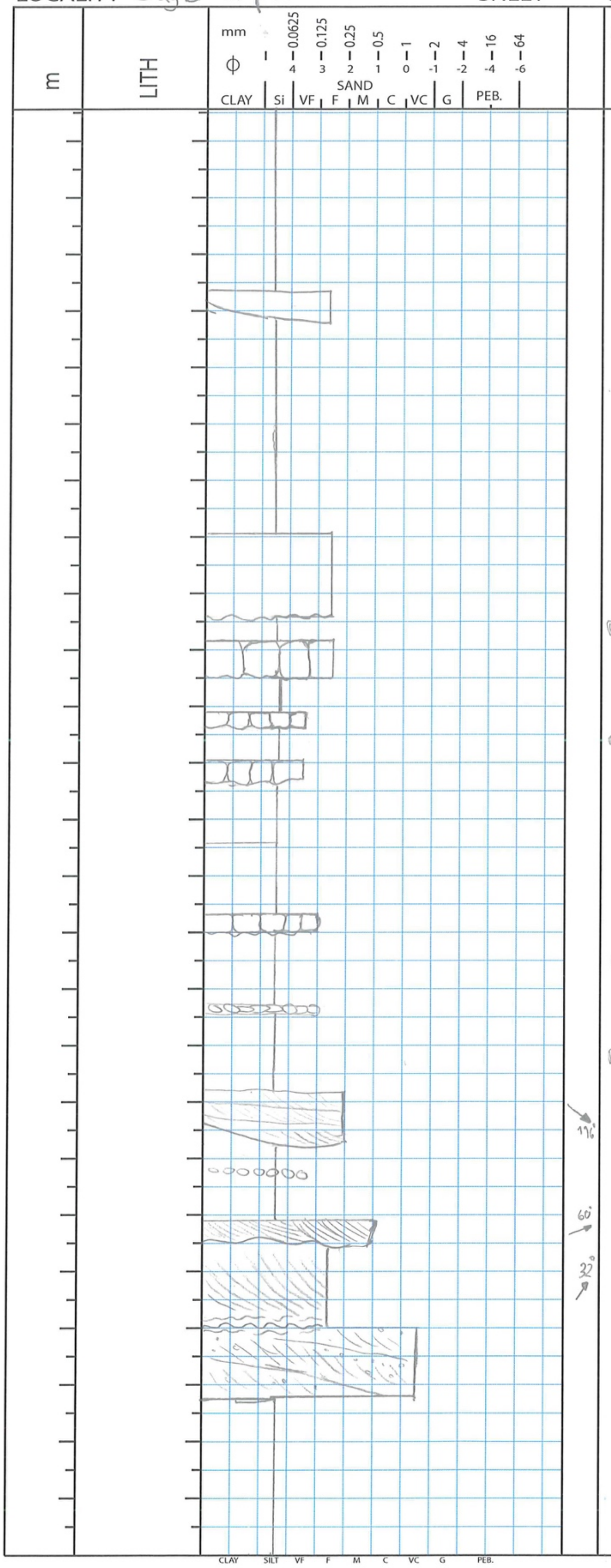
pebbels of 2mm weathered
poorly consolidatet
dark purple

P: 0142-0148

Photo: 0139-0141

LOCALITY Day 3 Stop 2 SHEET 2 OF 5 DATE: 29.06.16 SCALE: 1:50

GEOLOGIST: Emil
FORMATION: Morrison
AGE:



Light grey

Ligth grey

Red/purple

Red/purple

Light grey

Red/purple

Red/purple

Poorly sorted. Pebbly

Dark grey

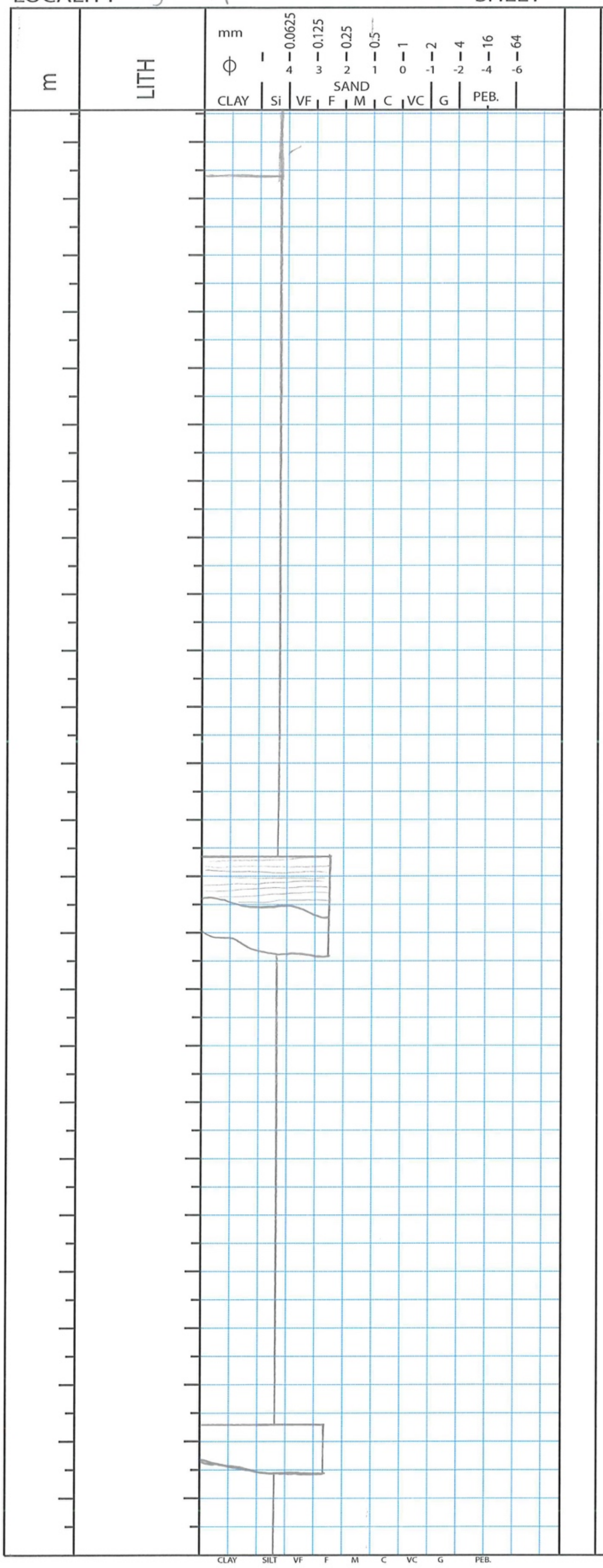
P:0176-0178

P:0171-0175

P: 0162-0170

LOCALITY Day 3 stop 2 SHEET 3 OF 5 DATE: 30.06.16 SCALE: 1:50

GEOLOGIST: Emil
FORMATION: Morrison
AGE:



Dark grey

Few structures
Some paraleld laminting

Ligth grey

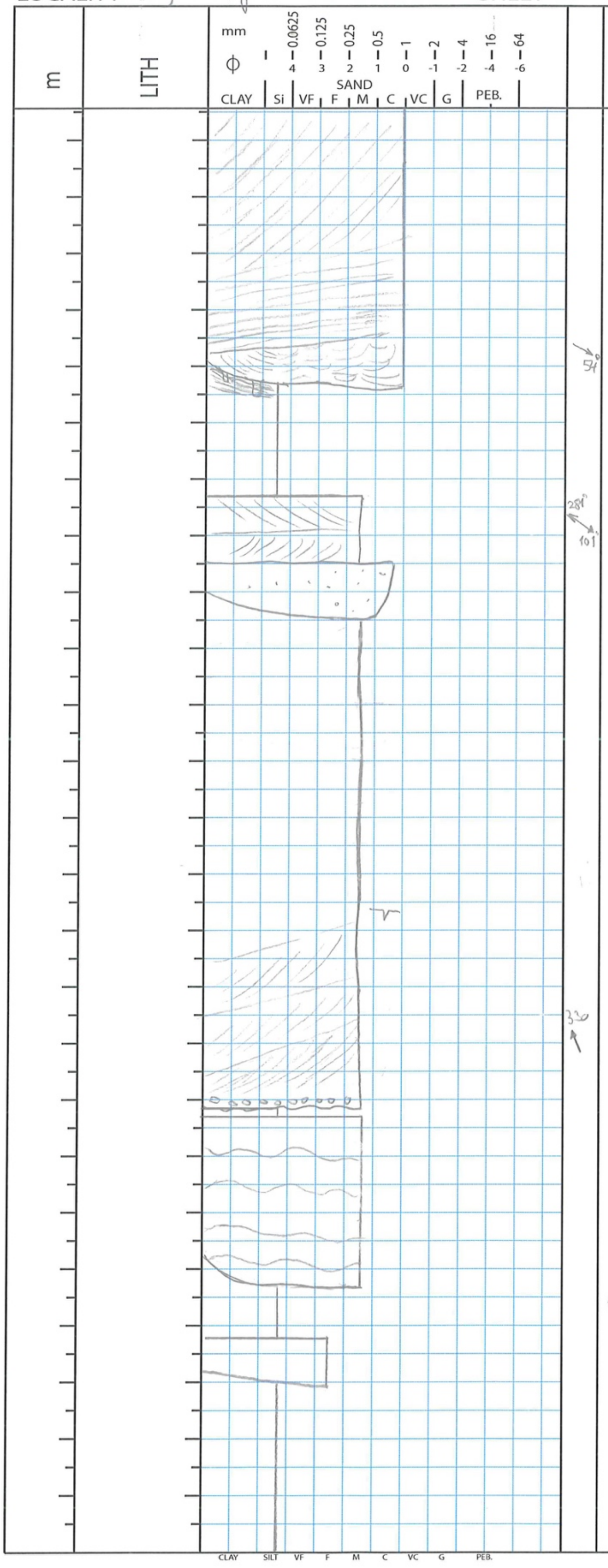
Ligth grey

P: 0192 - 0194

P: 0188 - 0191

P: 0184 - 0187

LOCALITY Day 3 Stop 2 SHEET 4 OF 5 DATE: 30.06.16 SCALE: 1:50



GEOLOGIST:
FORMATION:
AGE:

P: 0213-0214

Poorly sorted Bioturbation. P:0210-0212

P:0208-0209

pebbly

Poorly sorted

Dry cracks? P 0205-0207

Rip up clasts

Poorly sorted

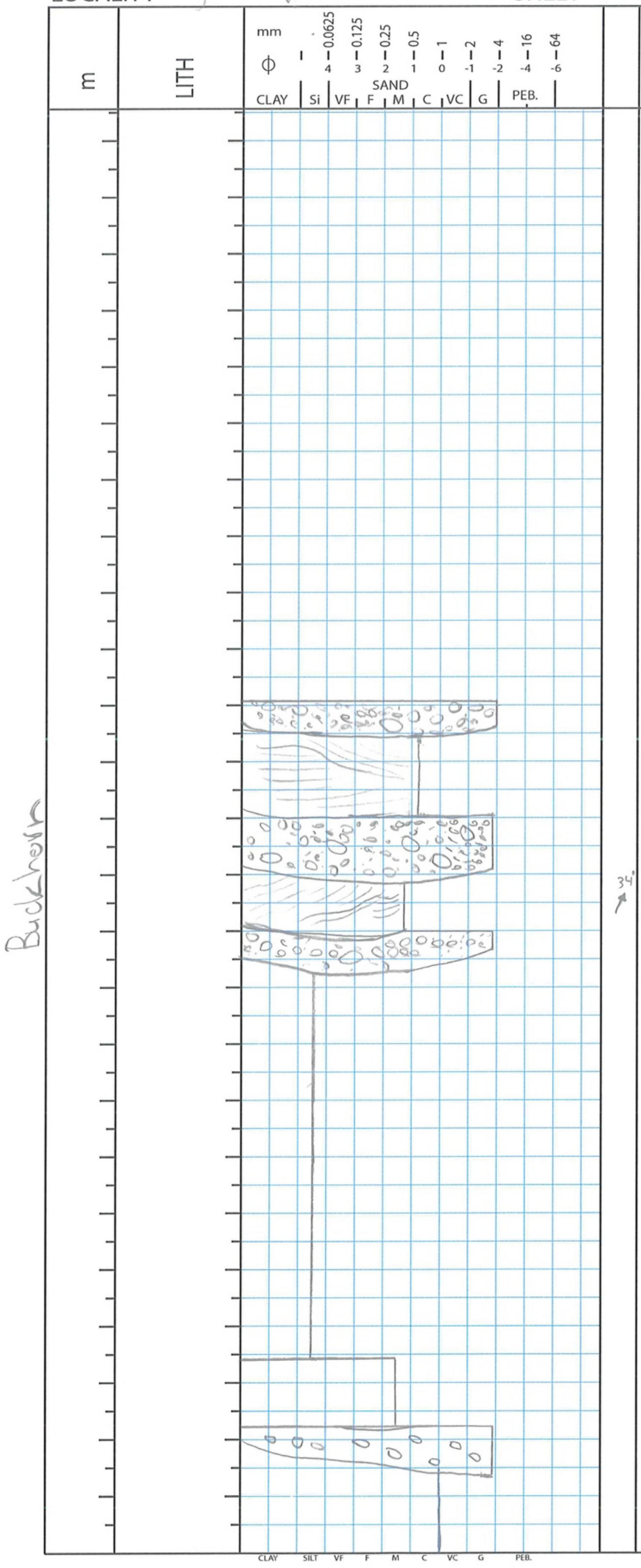
Red/purple

P:020-0204

Red/purple

LOCALITY Day 3 Stop 2 SHEET 5 OF 5 DATE: 30.06.16 SCALE: 1:50

GEOLOGIST: Emil
FORMATION: Morrison
AGE:



Poorly sorted, sub rounded, clast supported

Poorly sorted, subrounded, clast supported Pebbels 64mm

Poorly sorted, subrounded, clast supported

Pebbels < 30mm

P: 0215 – 0218