

RUNNING TITLE: QUANTIFICATION OF THE SALT WASH DFS

**QUANTIFICATION OF A DISTRIBUTIVE FLUVIAL SYSTEM; THE SALT WASH DFS OF THE MORRISON  
FORMATION, SW USA**

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**ABSTRACT**

Recent analysis of modern aggradational continental sedimentary basins reveals that sedimentation patterns are dominated by distributive fluvial systems (DFSs). The Salt Wash Member of the Late Jurassic Morrison Formation has previously been described as a fan-shaped fluvial system. This study characterizes facies variations across the Salt Wash DFS to qualitatively test predicted trends in

conceptual DFS models. Notable proximal-to-distal trends include a change in total thickness of the fluvial succession from 174 m to 40 m, and in average grain size from coarse sand to silt, while the percentage of sand decreased from 70% in the proximal region to 8% in the distal region. The proportion of amalgamated channel-belt deposits decreased from 67% to 0%, while floodplain facies and lacustrine deposits increase (38% to 94% and 0.1% to 7% respectively). A downstream decrease in average channel belt thickness (15 m to 3.8 m, from thickest to thinnest) and average story thickness (7.7 m to 2.3 m, from thickest to thinnest) is also recorded. Significant downstream changes in deposit architecture were also noted, with proximal regions dominated by stacked channel belt deposits with a high degree of amalgamation. Distal deposits are dominated by floodplain muds and sheet sandstones and sparse ribbon channels, with little to no amalgamation of channel deposits. This study provides quantified information for an ancient DFS with the aim of providing a dataset that can be used for objective comparison between different DFSs, as well as providing numerical data to aid resource exploration and modelling efforts.

## **INTRODUCTION**

Non-aggrading rivers and their associated floodplain deposits have limited preservation potential (Bristow et al. 1999). It is therefore imperative that correct modern analogues be used when applying observations from modern geomorphic studies to the geologic record. A remote-sensing study on over 700 modern aggrading continental sedimentary basins (Weissmann et al. 2010, 2011) reveals that fluvial sedimentation patterns are dominated by distributive fluvial systems (DFS), thus deposits of DFSs are consequently expected to constitute a substantial part of the continental geologic record. It is therefore important that facies models for DFS be tested and defined.

Descriptions of modern and ancient DFSs exist. Modern examples include the Okavango DFS (Stanistreet and McCarthy 1993), the Taquari DFS (Assine 2005; Buehler et al. 2011), systems in the Himalayan foredeep (Shukla et al. 2001), systems in the Andean foreland basin (Horton and Decelles 2001), and others discussed in Hartley et al. (2010) and Davidson et al. (2013). Ancient examples

include the Permian Organ Rock Formation, Utah (Cain and Mountney 2009; 2011), Devonian systems of Greenland and Ireland (Kelly and Olsen 1993) and Spitsbergen (Friend and Moody-Stuart 1972), the Permo-Triassic Beaufort Group (Gulliford et al. 2014), the Late Jurassic Salt Wash Member of the Morrison Formation (Craig et al. 1955; Mullens and Freeman 1957), Cenozoic deposits of the Andes (Horton and Decelles 2001), Oligocene to Miocene Huesca and Luna DFSs in Spain (Hirst and Nichols 1986; Nichols 1987; Nichols and Fisher 2007), and Miocene deposits of Siwalik Group in northern Pakistan (Willis 1993a, 1993b).

However, as noted by Colombera et al. (2013), most traditional facies models lack quantitative information about deposit variations, particularly across an entire depositional system. Exceptions include Hirst (1983, 1991), who measured facies association ratios and channel-body thicknesses across the Huesca DFS, and Cain and Mountney (2011), who measured facies and facies association trends across the Organ Rock Formation.

DFSs have been shown to contain important petroleum and gas reservoirs (e.g., Moscariello 2005; Kukulski et al. 2013), to host significant mineral deposits (e.g. Peterson 1977; Turner-Peterson 1986), and to constitute major aquifers (e.g., Weissmann et al. 1999, 2002, 2004). Therefore, gaining a better understanding of spatial variations across DFSs, particularly information on system-wide quantitative trends, will facilitate resource exploration. Such analysis also permits objective comparisons between different systems to refine conceptual DFS models.

This paper documents lateral trends across the Salt Wash fluvial system of the Morrison Formation. Excellent vertical and lateral exposure across this fluvial system enables a detailed system-wide study to be conducted. Recent work on apex estimation conducted by Owen et al. (2015) allows outcrops to be more precisely located within proximal, medial, and distal domains. Detailed documentation of vertical trends in the Salt Wash DFS have been documented in Weissmann et al. (2013), thus we focus instead on observed proximal-to-distal trends in this work.

### *Salt Wash DFS*

The Morrison Formation was deposited across the western interior of the United States and southern Canada during the Late Jurassic (Turner and Peterson 2004), when the eastward-dipping paleo-Pacific oceanic plate was subducting beneath the continental northwestward-propagating North American plate (Decelles 2004; Turner and Peterson 2004). An orthogonal compressional regime was present in the northern portion of the margin, resulting in crustal shortening and formation of the Sevier Highlands (Decelles 2004). A nearly parallel compressional regime was present in the southwest portion of the margin which resulted in the formation of a sinistral strike-slip intracontinental rift, the Bisbee-McCoy Basin (Dickinson and Lawton 2001b; Spencer et al. 2011), and the formation of elevated rift shoulders, including the Mogollon Highlands, which bounded the southern edge of the Morrison depositional basin (Dickinson and Lawton 2001b; Decelles 2004; Turner and Peterson 2004).

The timing of thrusting is debated (Turner and Peterson 2004). It has been argued (Decelles and Burden 1991; Decelles and Currie 1996; Currie 1997, 1998), that deposition occurred in a foreland basin or in the back-bulge of an overfilled foreland basin. The latter requires the presence of a foredeep, which cross sections in Royse (1993) demonstrate as plausible. Forebulge migration and flexural and regional dynamic subsidence are drivers for subsidence and accommodation in this case (Currie, 1997, 1998; Decelles, 2004). Heller et al. (1986), Lawton (1994), and Decelles et al. (1995) argue that significant thrusting, and therefore foreland-basin development, did not occur until the Early Cretaceous. Heller et al. (1986) suggest that accommodation for Morrison deposits was created through regional tectonothermal subsidence and hypothesize that this was the result of a Middle Jurassic thermal metamorphic event and/or thrusting to the west of the Sevier thrust sheet. Dickinson and Lawton (2001a) argue that the subduction of the Farallon Plate could have played a far-field role in creating subsidence for Morrison deposits.

The Salt Wash Member of the Morrison Formation extends across central Utah, west-central Colorado, northeast Arizona, and northwestern New Mexico (Fig. 1) (Craig et al. 1955; Mullens and Freeman 1957). It is composed of fluvial channel deposits interbedded with floodplain deposits (Craig et al. 1955; Mullens and Freeman 1957; Tyler and Ethridge 1983; Peterson 1980, 1984, 1988; Robinson and McCabe 1997, 1998; Turner and Peterson 2004; Kjemperud et al. 2008; Weissmann et al. 2013). It has been described as a fan-shaped fluvial deposit (Craig et al. 1955; Mullens and Freeman 1957), which data from this study support (Fig. 1), which helps define proximal, medial, and distal domains. We use the lithostratigraphic definition of Mullens and Freeman (1957) to define the areal limits of the Salt Wash Member in this study (Fig. 1).

Peterson (1980, 1984), Kjemperud et al. (2008), and Weissmann et al. (2013) suggest that the Salt Wash fluvial system prograded into its sedimentary basin. Distal facies of the Tidwell Member (composed of minor fluvial, mudflat, and lacustrine facies), typically underlie the more proximal facies of the Salt Wash Member (composed of large-scale fluvial channels and associated floodplain deposits). These two members together comprise the "Salt Wash DFS" defined in this study (Fig. 1), representing deposition from a single fluvial system. A genetic rather than a lithostratigraphic approach is taken to ensure that the focus is on the distribution of facies across a single depositional system as opposed to a lithostratigraphic unit which may contain several different individual systems or represent only part of a system.

The regionally extensive J5 unconformity of Piringos and O'Sullivan (1978) defines the contact between the base of the Morrison and formations below (Fig. 1). The J5 is both a conformable and an unconformable contact (Cadigan, 1967) and has a relatively low relief (Piringos and O'Sullivan, 1978). In areas where a conformable contact is present, depicting the boundary between the Summerville (topmost stratigraphic unit in the San Rafael Group) and Morrison Formation is difficult due to the gradational contact. The Summerville Formation (Fig. 1), was deposited in a shallow-water hypersaline environment as the Western Interior Seaway retreated (Peterson 1988). The base

of the Salt Wash DFS in this study is therefore defined as the first point at which true fluvial deposits are recognized. Peterson (1980) defines the top of the Salt Wash Member as the topmost appreciable sandstone body in which a significant amount of mudstone was not present beneath channel deposits. The transition from the Salt Wash to the overlying Brushy Basin Member can be ambiguous (Peterson 1988), particularly in the distal portions. The identification of Demko (2004) mid-Morrison paleosol unconformity (which separates the Salt Wash and Brushy Basin Members), and a change in mudstone color from red to green-gray between the Salt Wash and Brushy Basin Members (Fig. 2), helps define the top of Salt Wash deposits. However, Salt Wash facies can be above Demko's paleosol, making the contact diachronous in places (Kjemperud et al 2008). We speculate that the Brushy Basin Member may also be a DFS; but a regional study is needed to test this hypothesis and is thus beyond the scope of this work. Material that can be radiometrically dated is largely absent in the Salt Wash Member. However, dates obtained from the base of the Tidwell ( $154.75 \pm 0.54$  Ma,  $154.82 \pm 0.58$  Ma,  $154 \pm 1.4$  Ma) and the top of the Brushy Basin ( $148.1 \pm 0.5$  Ma) by Kowallis et al. (1998) indicate seven million years of deposition for the Morrison Formation. Unfortunately, sections studied are unable to be tied together due to the lack of marker beds. The Salt Wash DFS is therefore considered as one depositional unit, but it is not implied that deposits were coeval within the system, and it is more likely that deposition took place within a series of DFS lobes through time.

The apex for the Salt Wash DFS has been predicted using a statistical projection of paleocurrent data (Fig. 1; Owen et al, 2015). Owen et al. (2015) use a methodology based on the von Mises distribution and the method of maximum likelihood to obtain an estimated apex and associated confidence regions for the system. The authors determined that the apex of this DFS was located in northeastern Arizona (Fig. 1) and suggest the Salt Wash DFS was likely sourced from the Mogollon-Sevier Highlands syntaxis or solely from the western portion of Mogollon Highlands, within north-central Arizona. This is supported by provenance studies conducted by Dickinson and Gehrels (2008),

who use U-Pb detrital zircon data to show that the Salt Wash could have been either partly or wholly sourced from the Mogollon Highlands.

The termination type (Hartley et al. 2010) for the Salt Wash DFS is not fully understood due to exposure limitations; however, Dunagan and Turner (2004) state that the Salt Wash DFS eventually grades laterally into a wetland environment. Hartley et al. (2010) define the toe of a DFS as the most distal point at which a fluvial planform is defined. Distal characteristics displayed at South Canyon (Fig. 1 for location), correspond to the criteria given by Hartley et al. (2010) due to the scarcity of simple, small-scale fluvial channel bodies (documented below). South Canyon is tentatively considered to be the toe of the DFS, as we assume that substantial facies variations do not occur beyond this point. This is considered to be a reasonable assumption based on the downstream trends documented in this paper. This gives the Salt Wash DFS a potential apex-to-toe length of approximately 550 km and an areal extent of approximately 100,000 km<sup>2</sup>.

## **DATA AND METHODS**

Distributive fluvial systems are defined by: 1) channel patterns that radiate 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 areas to smaller fixed channels in distal areas (Friend and Moody-Stuart 1972; Friend 1978; Nichols 1987; Hirst 1991; Stanistreet and McCarthy 1993; Nichols and Fisher 2007; Cain and Mountney 2009; Hartley et al. 2010; Weissmann et al. 2010; 2013).

In this study these parameters are calculated from sedimentary logs measured in 26 locations. Sites were selected based on exposure quality and to ensure a good areal coverage across the exposed DFS (Fig. 1). The overall thickness of the DFS deposit, sand-to-mud ratio, grain size, and average bed thickness of each facies association are measured at each locality. When calculating the sand-to-mud

ratio, covered sections are assumed to be mud, and therefore presented statistics are underestimates. This is a reasonable assumption, in as much as the exposure style causes mud-dominated intervals to be less well exposed than sandier intervals. Cited trends for isolated channels may also be underestimated due to exposure style, whereas channel belt elements are considered to be accurate because they form distinct ledges at outcrop. Sites with less than 50% exposure (6 out of 26 locations) are shown in gray on all maps. This is not envisaged to affect trends cited within this paper, in that the vast majority of sites have exposure that is considered to be representative of the fluvial system.

Calculations of average bed thickness and grain size calculations were conducted only on beds that were exposed, because it is not possible to specify a grain size or bed thickness for covered sections. For the amalgamated channel-belt facies association the mean thickness of channel belts and stories were calculated. Datasets for the channel belt, isolated channel-fill, and lacustrine facies do not show any trends in a distribution analysis. However, floodplain datasets do show a negative skew, and it should be noted that the derived bed thickness means are less meaningful when concerned with floodplain analysis. Average grain size is calculated by converting Wentworth class nomenclature to phi ( $\phi$ ). Averages are then calculated and weighted according to thickness within each succession to ensure a fair statistical representation. Architectural style is documented in a qualitative manner because a suitable quantified methodology was not established. Facies associations, as defined by Collinson (1969), as opposed to lithofacies (Reading and Lovell 1996), were analyzed because they were deemed to be the most appropriate for a system-scale study, and are more comparable to modern datasets. A study on differential compaction conducted by Peterson (1984), estimated from contorted sandstone-filled desiccation cracks in mudstone beds, shows that approximately 23% compaction of mudstone with respect to sandstone occurred. Although significant, this amount is not considered to affect general trends within the data presented here; statistics stated here therefore do not take compaction into consideration and are calculated from outcrop data directly.



Measured parameters were plotted onto graphs and maps for a quantified spatial analysis. Because the positions of the apex and toe are approximately constrained, the distance downstream, both in absolute distance and percentage downstream, can be calculated. These two criteria form the horizontal axis on the graphs and allow the position of locations to be put into a system-scale context.

Regression analysis of each parameter relative to position on the DFS refines the significance of observed trends. Because none of the datasets showed evidence for autocorrelation, i.e., whether the values were dependent on one another (also known as serial correlation and autocovariance), the Spearman's rank correlation coefficient for monotonic trends ( $\rho$ ) (Davis 2002) was used to indicate the presence and strength of observed trends. A critical value (CV) was calculated to define a correlation coefficient value, indicating the likelihood of results occurring by chance (Davis 2002). Results that have a CV value less than 0.05 indicate a less than 5% chance that the trends occurred by chance.

Parameter trends with less statistical significance in some cases still appeared to have defined spatial patterns on graphs and maps. In some of these cases we infer these patterns to be significant even though they did not change in a linear way with distance along the DFS. Contour maps were drawn manually, because computer-generated contour maps were found to be geologically unrealistic and varied depending on the algorithm used. Original data are held in the supplementary material.

## RESULTS

### *Descriptions of Facies Associations*

Four broad facies associations were identified from sedimentary logs 1) amalgamated channel-belt, 2) isolated channel-fill, 3) floodplain, and 4) shallow ephemeral lake facies associations.

**Amalgamated Channel-belt Facies Association.**--- The amalgamated channel-belt facies association is composed of fine-grained to pebbly, cross-bedded sandstones. The presence of trough and planar

cross bedding, current ripples, trace fossils that are indicative of terrestrial fluvial environments (sauropod tracks, *Camborygma*, and *Staphylinidae* burrows amongst others (Hasiotis, 2004)), and paleosols, above and below the deposits, collectively imply deposition in a fluvial channel environment (e.g., Miall 1978; Walker and Cant 1984; Robinson and McCabe 1998; Nichols and Cantrill, 2002; Bridge 2003; Cain and Mountney, 2009;). Accretion surfaces, which define deposits of bar features, are present and range in thickness from 1 to 2.5 m, dip between 5 and 30 degrees, and often lie above erosional surfaces that are not laterally persistent. Downstream accretion surfaces are inferred when cross-bedding dips in the same orientation as the accretion surfaces, and lateral accretion surfaces are inferred when cross-bedding dips obliquely to accretion surfaces.

The deposits form large-scale sheet complexes (up to 26 m thick and greater than 10 km wide) (Fig. 3A) within which one to four stories are observed (see Fig. 5 for example log). Story surfaces represent erosion events where the once-active river has eroded into previous channel deposits. A high degree of paleocurrent variability (up to 100°) is sometimes observed between stories, and in such cases when lateral accretion deposits are also observed, a sinuous planform can be inferred. When the edge of the sheet complex could be observed, a gradual thinning is noted. The deposits are generally poorly sorted and often have mud- and pebble-size clasts lining the base of story, bar, and trough set surfaces (Figs 3, 5). These characteristics, coupled with the presence of horizontal lamination, mud and sand drapes, and irregular cross-bedding thickness collectively imply that this facies was deposited from rivers that experienced a seasonally flashy discharge (Miall 1977; 1978; Stear 1985; Lorenz and Nadon 2002), a view mirrored by Robinson and McCabe (1998), Good (2004), and Turner and Peterson (2004). The lateral and vertical amalgamation of stories records the lateral migration of rivers and juxtaposition of their deposits over time (Friend et al. 1979; Gibling 2006). The juxtaposition of deposits appears to be random in most cases, with only isolated cases showing a systematic migration in one direction. Paleocurrents from the amalgamated channel-belt facies association demonstrate a radial pattern in a northeast to east direction (Fig. 1).

Many have suggested that the Salt Wash DFS was deposited from a dominantly braided fluvial system (Peterson 1977; Tyler and Ethridge 1983; Peterson 1984; Robinson and McCabe 1998), an interpretation that has been based largely on the sand-rich, highly reworked nature of the deposits. Our system-wide study has identified both downstream accretion and lateral accretion elements throughout the system, as well as scroll bars in planform, and example of which can be seen in Figure 3A from the proximal to medial portion of the system. This implies that a mixed meandering to braided planform existed. Meandering elements, either minor or large, have been previously noted in various parts of the system by Fischer and Hilpert (1952) Stokes (1954), Peterson (1977), LeBaron (1980), Peterson (1984), and more recently Holzweber (2013) and Owen (2014). We suggest that the previous emphasis on interpretations as braided stream deposits is misplaced, a viewpoint shared by Ethridge et al. (1980), and we interpret the sandy characteristics to be a function of the low accommodation/sediment supply (A/S) regime that persisted in the basin, a view echoed by Kjemperud et al. (2008). Amalgamated channel-belt deposits constitute 37% of all sections logged.

**Isolated channel-fill Facies Association.**--- These are simple lens-shaped sandstones, with a clear channel geometry in cross section and sandy wings in the adjacent overbank successions (Fig. 3B). Erosional bases and simple, single-story sandy fills that range in grain size from fine sand to granules are common. Occasional mud plug fills are also observed (Fig. 3B). These characteristics suggest deposition from a fixed fluvial channel in which little lateral migration occurred (Friend et al. 1979; Friend 1983; Hirst 1991; Gibling 2006). Such deposits are alternatively referred to as ribbon or fixed channels (Friend et al. 1979; Friend 1983; Gibling 2006). This facies association ranges from 5 cm to 4.7 m thick and can extend laterally for up to 400 m. Either asymmetric (Fig. 3B) or symmetric channel forms are observed. Asymmetric channels are generally regarded to represent deposition within a fixed sinuous channel (e.g., Leopold and Wolman, 1960; Miall, 1996; Jobe et al., 2010), whereas symmetric channels are considered to represent relatively straight reaches of a fixed channel (Pyles et al 2010), although asymmetric channels can also form in straight reaches (Bridge 2003).

Ribbon-shaped channel-fill bodies have already been noted by Kjemperud et al (2008) in Salt Wash deposits around Capitol Reef National Park, Utah. Kjemperud et al (2008) term the deposits “steer-head channels” and interpret them as being distributary channels that drain into floodplain lakes and wetland systems. In this study, isolated channel-fill deposits are found throughout vertical successions across the whole system with no apparent relation to lacustrine deposits, but they are more commonly associated with floodplain deposits (Fig. 5). The isolated channel-fill facies association has a less consistent paleocurrent pattern than the channel belt facies association (Fig. 1), but a broad northeasterly flow direction can still be seen. When data are available for both facies associations, four out of eleven locations have a paleocurrent direction that is within 10 degrees of each other. Those that are not within 10 degrees of the channel belt facies deviate away from the main trunk channel. These data suggests that the isolated channel-fill facies association are splay and/or smaller distributary channels (relationship conceptualised in Fig. 3C), but differ in that they are fixed channels that show no evidence for lateral migration. The deposits are not considered to be from anastomosing channels, because no more than one isolated channel-fill was found within each stratigraphic horizon when extensive (1 km) exposure was available. Isolated channel-fill deposits constitute 4% the Salt Wash DFS deposits.

**Floodplain Facies Association.**--- The floodplain facies association is composed of interbedded sandstones and mudstones. The beds are commonly tabular but can often have an undulating form (Fig. 4A). Packages of floodplain deposits can be either mud- or sand-dominated (Fig. 4A). This can be related to proximity to a channel (Pizzuto 1987; Guccione 1993), to flood magnitude, or to sediment supply. Root traces, rhizoliths (rhizoconcretions), nodules, and color mottling help determine the presence of paleosols. Two broad types of paleosols are observed in the succession; red, to red-brown well-drained argillic calcisols and green-gray poorly drained protosols (Fig. 4). Burrows, dinoturbation, rootlets, and tree stumps were observed in the deposits. Collectively these features indicate deposition in a vegetated floodplain environment. Comprehensive reviews of paleosols and ichnofossils found in Salt Wash deposits are found in Demko et al. (2004) and Hasiotis

(2004). Floodplain deposits constitute 57% of the Salt Wash DFS deposits logged. This calculation includes sections that are inferred to be floodplain based on outcrop style, and therefore may overestimate the actual percentage.

**Shallow Ephemeral Lake Facies Association.**--- All beds of this facies association have a tabular to undulating geometry, are no thicker than 2.9 m, and do not exceed 1 km in lateral extent, indicating they were minor elements on the Salt Wash landscape (constituting 3% of the Salt Wash DFS deposits). Three different types of ephemeral lake deposits are present in the Salt Wash DFS. Gypsiferous lake deposits consists solely of gypsum deposits that have an enterolithic or bladed texture (Fig. 4B) (Warren 1999), and represent periods in which evaporation rates exceeded water recharge rates. Carbonate lake deposits are generally fine grained (wackestone) and have good preservation of gastropods and charophytes indicating a low-energy fresh-water environment. Clastic ephemeral lake deposits are composed predominantly of horizontally laminated muds and wave-rippled sandstones (Fig. 4B). This, coupled with the presence of *Steinichnus* and *Cochlinus* burrows, indicates deposition in a shallow lacustrine environment in which there was clastic input (Hesse and Reading 1978; Talbot and Allen 1996, Hasiotis 2004).

This facies association is commonly interbedded with the floodplain facies association (Fig. 5). This relationship, along with the presence of mudcracks in some beds, indicates that the lakes were not permanent features on the landscape, appearing only during wetter periods (Rogers and Astin 1991). It is likely that the standing bodies of water formed within depressions on the floodplain in which floodwaters collected and ponded before subsequently drying out. This, coupled with a flashy discharge regime, suggests the Salt Wash DFS was deposited under a semiarid climate that had seasonal precipitation. Turner and Peterson (2004) share this view and state that the Morrison Formation had a climate that is similar to a modern African savannah. Deposits are found primarily at the bases of successions in the Tidwell Member, and only rarely in the overlying more proximal

Salt Wash Member. Lacustrine deposits within the Salt Wash are also noted by Peterson (1980, 1984), Tyler and Ethridge (1983), and Kjemperud et al (2008).

### *Architecture*

The architecture of the Salt Wash DFS varies greatly across the system. In the most proximal sections studied, such as Bullfrog (Fig. 6A), the outcrops are composed of laterally extensive highly amalgamated channel sheet sandstones. The sandstone complexes can be traced > 10 km laterally and display a high degree of amalgamation. Connectivity between the sandstone bodies is clear, where approximately 80 to 90% of channel bodies amalgamate and connect, with floodplain deposits forming only intermittent pockets due to crosscutting fluvial channels. These characteristics suggest a regime with low ratio of accommodation to sediment supply in an environment in which channels were mobile (Weissmann et al. 2013).

In the medial portion of the system, channel sandstone bodies are less amalgamated and organized into distinct channel belt packages, separated by floodplain deposits (Fig. 6B). Channel complexes are laterally extensive (> 1 km lateral extent) and connect and amalgamate in places (approximately 20% of channels amalgamate and connect) (Fig. 6B), implying that a degree of connectivity is still present between the sandstone bodies. A regime with a higher ratio of accommodation to sediment supply is inferred in the medial domain (Weissmann et al. 2013), where the channel deposits are less mobile, allowing floodplain deposits to be better preserved (Fig. 6).

Deposits exposed in the distal domain, (e.g., Smith Fork, Fig. 6C), are characterized by isolated channel deposits in a floodplain-dominated succession. No apparent amalgamation or connectivity was observed between sandstone bodies. A regime with high ratio of accommodation to sediment supply is inferred, with little evidence of lateral migration or reworking by the channels.

### *Salt Wash DFS Sand:Mud Ratio*

A clear downstream and radial decrease in sandstone proportion is observed (Fig. 7A, B). Highest sandstone percentages occur in the most proximal regions, such as at Fifty Mile Point (70%) and Bullfrog (75%). The lowest sand percentages are present in the most distal area, such as at Blue Mesa Reservoir (8%) and South Canyon (26%). Slick Rock has a higher sand percentage (71%) than surrounding sites (Fig. 7A), making it anomalous to the general trend. Vernal (50%) is also anomalous to the general trend.

#### *Thickness of the Salt Wash DFS*

The thickest portion of the Salt Wash DFS (174 m thick at Fifty Mile Point), defined as the observed thickness from the J5 unconformity to the top of the Salt Wash Sandstone, is in the relatively proximal southwestern part of the system. The system thins to the northeast, with the thinnest succession exposed at South Canyon (40 m thick), the most distal section studied (Fig. 7C). If a relatively flat basal topography and uniform subsidence is assumed, it can be inferred that the Salt Wash DFS had a convex-upward profile. Alternatively, an area of depression or increased subsidence rate can be assumed in the center and proximal portion of the system (alternatives that are not mutually exclusive). Compaction is deemed to have a relatively minor influence on the deposits, based on a study by Peterson (1984), who noted that isopach thickness maps do not change significantly when compaction is taken into consideration.

A relatively abrupt thinning is recognized laterally across the system from the southeast to the northwestern portion (Fig. 7C). For example, the fluvial section is 51 m thick at Dewey, yet 22 km away at Polar Mesa the system it is 105 m thick. The fluvial system thickens from Colorado National Monument (59 m thick) to Little Park (115 m thick), 11 km away (Fig. 7C). The weak negative relationship between DFS thickness and distance downstream (Fig. 7D), despite obvious mapped thickness patterns (Fig. 7C), reflects pronounced lateral thickness variability, particularly in the medial sections (i.e., jagged pattern circled in Fig. 7D). A more significant  $\rho$  value of -0.56, calculated when data points from the northwest are removed, indicates a stronger downstream correlation.

Possible causes for the thickness variation are discussed later. The thickness divide is also observed in maps presented in Craig et al. (1955) for the Dewey to Grand Junction area, but it is not found on maps in Mullens and Freeman (1957), where a coarser contour interval of 100 ft (approximately equal to 30 m) masks this variation. Vernal is again anomalous to the general trend.

#### *Salt Wash DFS Grain Size*

The average grain size generally decreases down DFS, with the coarsest successions commonly found in the most proximal regions and the finest in the distal region (Fig. 7E, F). A few exceptions fall off this trend; Smith Fork has slightly coarser deposits (medium sand) in an area in which deposits average very fine sand. We speculate that sediment bypass to Smith Fork may have resulted in the coarser average grain size. Halls Creek has a finer grain size (fine sand) in an area dominated by coarse sand, which might be attributed to a higher degree of reworking, or delivery of finer sediment at this location. Downstream fining is also evident with distance along the DFS (Fig. 7F), despite local anomalies. This is interpreted to reflect a decrease in transport capacity downstream as a result of lateral expansion of the river into the sedimentary basin. Channel bifurcation, infiltration, and evaporation may have further contributed to a decrease in transport capacity (Nichols and Fisher 2007; Weissmann et al. 2010; 2013).

#### *Analysis of Facies Associations*

**Analysis of Facies Percentage.**--- Strong downstream trends and radial contour patterns are observed in the relative abundance of amalgamated channel-belt (Fig. 8A), floodplain (Fig. 8C), and shallow ephemeral lake (Fig. 8D) facies associations. Vernal is anomalous in all criteria evaluated.

The statistically strongest downstream trend is observed in the amalgamated channel-belt facies association dataset, with the highest percentages observed in the most proximal areas, e.g., Bullfrog (67%) and Fifty Mile Point (61%) (Fig. 8A). Downstream, the amalgamated channel-belt facies association becomes less dominant, constituting only 17% of the succession at Smith Fork, 16% of



the succession at Colorado National Monument, and is entirely absent at the most distal localities (South Canyon and Blue Mesa Reservoir) (Fig. 8A). A strong negative correlation is evident when the data are plotted onto a scatter graph (Fig. 8E). A downstream decrease in energy, infiltration of water and channel bifurcation are considered to be the causal mechanisms behind the trends observed.

A strong positive correlation is observed for the floodplain facies association (Fig. 8E). The lowest values are present in the most proximal areas (30% at Bullfrog, 33% at Caineville, and 38% at Fifty Mile Point), with the floodplain facies association dominating successions farther downstream (78% at Colorado National Monument; 82% at South Canyon and 94% at Blue Mesa Reservoir) (Fig. 8C).

A downstream increase is also observed in the shallow ephemeral lake facies association dataset (Fig. 8D), but to a lesser degree. No lacustrine deposits are observed in the center of the medial area, but towards the periphery of the system an increase is observed in all directions, i.e., 4.% at Buckhorn Flat, 7% at South Canyon, 3% at Durango, and 3% at Halls Creek. Overprinting this trend is a general downstream increase in values, with higher percentages generally present in the distal area (i.e., 22% at Dominguez Canyon and 6% at Smith Fork) and relatively low percentages in the most proximal area studied (i.e. < 1% at Fifty Mile Point and 2% at Bullfrog). The combination of the two patterns has resulted in a relatively flat positive trend line (Fig. 8E).

The low proportion of floodplain and ephemeral lake facies associations in the proximal area is largely a function of preservation potential coupled with a decrease in energy downstream. It is evident from satellite imagery of modern DFSs that low-energy geomorphic elements (i.e., floodplain deposits) are not absent from proximal regions. However, they are not commonly observed in proximal deposits in the geologic record due to the high degree of channel migration and reworking (Cain and Mountney 2011; Weissmann et al. 2013). Downstream, a decrease in energy as a result of channel bifurcation, infiltration, and evapotranspiration, along with the increasing depositional area due to increasing width of the DFS downfan, and an increase in the A/S regime, allows lower-energy

environments to be better preserved. We speculate that the lack of lacustrine deposits in the medial portion of the system may be a function of the convex-upwards profile of the fan or a function of a low A/S regime in the center of the DFS.

The isolated channel-fill facies association displays the weakest statistical trends. A weak downstream increase may be present because a cluster of lower values is present in the relatively proximal and medial areas (0.8% at Fifty Mile Point, 1.8% at Bullfrog, 0.6% at Salt Valley, and 1.8% at Atkinson Creek) and a cluster of higher values in the distal area (18.1% at Smith Fork, 9.9% at Little Park, and 10.8% at South Canyon) (Fig. 8B). However, high, or low, values are not exclusive to any particular area of the system, as is evident by a relatively flat linear trendline in Figure 8E. These data suggest no downstream controls on the presence of the isolated channel-fill facies association. It is possible that the isolated channel form appears to be more prevalent downstream on DFS due to it becoming the dominant fluvial form, as opposed to actually increasing in presence, since amalgamated channel-belts diminish downstream. This is evident in data presented in Hirst (1991) from the Huesca DFS, with the proportion of ribbon sandstone relative to the total number of channel sandstone bodies increasing significantly beyond 45 km downstream (approximately equal to 65% downstream).

**Analysis of average thickness.**--- Only moderate to weak trends are observed when the average thickness of each facies association is plotted against distance downstream (Fig. 9). Statistically the strongest trend is observed in the amalgamated channel-belt facies association dataset. Broadly speaking, a crude downstream decrease in average thickness is observed when analyzing both the average belt and story thickness, with thinner averages generally, although not exclusively, observed in distal areas. Importantly, thin channels are also present in the proximal region, as is evident in the range of thickness recorded (Fig. 9A). The range of thicknesses recorded for the amalgamated channel-belt facies association does not substantially differ downstream, with only a weak decrease observed as large ranges are absent > 350 km downstream (Fig. 9A).

The data suggest that the Salt Wash channels decrease in size downstream, but maybe not as strongly as one might have expected, in that it is commonly cited to be a key characteristic feature of DFSs (Friend 1978; Kelly and Olsen 1993; Nichols and Fisher 2007; Hartley et al. 2010; Weissmann et al. 2010; Cain and Mountney 2011; Davidson et al. 2013; Weissmann et al. 2013). Preservation of story thickness and degree of amalgamation may be causing a weaker-than-expected trend to occur. However, it must be noted that little data from modern studies are present on channel depth down DFSs, and therefore until such data are available it remains contentious. The indication that the Salt Wash system is a prograding system (documented in Weissmann et al 2013) may also explain why a stronger statistical trend is not observed, as more proximal facies are present farther basinwards as a result of progradation. This may have important implications for reservoir characterization and modelling efforts, as it is important to factor in the presence of small as well as large channels in proximal regions.

The average thickness of the floodplain facies association changes only moderately downstream (Fig. 9C). Large ranges in recorded thicknesses for the floodplain facies association appear to be more prevalent in the distal regions but are not absent from proximal regions (Fig. 9C). A similar trend is observed for the shallow ephemeral lake facies association, with thicker averages generally present farther downstream, particularly beyond 400 km. The ranges of thicknesses recorded also do not differ substantially downstream. A decrease in stream capacity coupled with a better preservation potential is interpreted to have produced the trends observed.

The statistically weakest downstream trend for the average-thickness data was from the isolated channel-fill facies association (Fig. 9B). Thick and thin examples are found across the whole system, with the range of recorded thicknesses also present across the whole system (Fig. 9B). This suggests that there are no downstream controls on the thickness of these channel deposits.

**Analysis of average grain size.**--- A strong downstream change in average grain size was not identified for any of the facies associations. The floodplain facies association has the strongest

downstream trend; however, no grain size dominates a particular area of the system (Fig. 10C). This suggests that the calibre of sediment entering floodplain environments was relatively uniform across the system.

Though expected initially, the amalgamated channel-belt facies association does not show a downstream decrease in calibre of channel sediment (Fig. 10A). Coarser grain sizes are generally found in the most proximal areas studied (i.e., coarse sand at Fifty Mile Point, Caineville, and Hanksville), with the grain size generally decreasing to medium sand in medial areas (Fig. 10A). However, in the distal domain, relatively coarse grain sizes are also present (Fig. 10A). Turner and Peterson (2004) noted that the Ancestral Rockies, located in central Colorado, provided distinct angular chert to the Morrison Basin in the eastern Front Range foothills. Paleocurrent data presented in this study (Fig. 1) and Owen et al. (2015) do not support this in as much as paleoflow is shown to be going east towards the ancestral Rockies, as opposed to west and away from them. A petrographic analysis conducted by Owen (2014) also discounts this view, in that a change in composition was not found.

As noted by Shukla et al. (2001), flow competency and sediment supply control the distribution of grain sizes in a channel. A decrease in flow competency and deposition of coarse sediment in proximal areas explains the initial downstream decrease. A hypothesis of sediment bypass has been used by other authors (Evoy et al. 1997; Nemec and Postma 1993; Parsons et al. 2012) to explain sediment distribution patterns in a range of environments, and is a favorable explanation for the unusual grain-size trends observed in the Salt Wash DFS.

Mixtures of medium and fine sand are found across the system for the isolated channel-fill dataset (Fig. 10D), suggesting that grain size varied within the fixed channel environments.

## **DISCUSSION**

### *Paleogeographic Implications for the Salt Wash System*

Due to the lack of correlative markers it cannot be proved that channels measured are coeval. However, the described down-system trends suggest that the Salt Wash fluvial system was a distributive fluvial system. A radial paleocurrent (Fig. 1), downstream decrease in sand percentage and overall system grain size, decrease in thickness of amalgamated channel bodies, and increase in the percentage of floodplain relative to amalgamated channel facies associations is evident, and consistent with the DFS model proposed by Weissman et al. (2010). These combined characteristics suggest a downstream decrease in energy, which is attributed to channel bifurcation, infiltration, evapotranspiration, and deceleration of flow as the system radiates outwards from the apex (Kelly and Olsen 1993; Nichols and Fisher 2007; Weissmann et al. 2010; Hartley et al. 2010; Davidson et al. 2013).

Robinson and McCabe (1998) speculated that vertical trends observed in the Salt Wash reflect base-level changes associated with shrinking and expanding lacustrine systems. Our study, however, takes an alternative viewpoint in as much as the lakes are documented to be minor features on the distal fringes of the system. It is unlikely that such small intermittent bodies of water could control a system the size of the Salt Wash. In this respect, the Salt Wash fluvial system is deemed to be an upstream fluvial system (Kukulski et al. 2013), in that it is controlled primarily by upstream influences (i.e., sedimentation rate and discharge). Currie (1998) also interpreted patterns observed in Salt Wash sediments to be related to interactions between basin accommodation development and sediment supply, but additionally interpreted migration of the flexural components of the foreland basin system to be a key factor. Marine base-level influences are discounted, because the western interior shoreline is reported to be in southern Canada, over 1000 km away, at the time of Salt Wash deposition (Turner and Peterson 2004).

Vernal is consistently anomalous to the general trend when analyzing architecture, percentage of sand, grain size, and facies percentages. Based on trends on the Salt Wash DFS, we hypothesize that deposits at Vernal represent medial deposits of a different DFS. For this reason Vernal was excluded

from any graphical analyses. We therefore postulate that thickness variations presented in Figure 11 represent other individual fluvial systems in the northern portion of the basin. Detailed mapping of these sediments is needed to confirm whether there are a series of multiple DFSs draining from the west into the basin. The identification of multiple fluvial systems in what is regarded as Salt Wash Member deposits, or undifferentiated Morrison Formation, highlights the importance of taking a systems rather than a lithostratigraphic approach to the study of continental basin fills.

The cause of the northeast to southwest-trending thickness divide identified in the Salt Wash DFS is not clear. The divide is not considered to be a function of gradual DFS thinning towards the peripheries, because it is a relatively abrupt thickness variation along a relatively straight line. We also discount erosion from later systems, because there is no evidence for significant erosion from the overlying mud-dominated Brushy Basin Member, which also buffers the Salt Wash from later Cretaceous erosion at the sites studied (Craig et al. 1955). It is possible that the divide represents a pre-existing topographic variation within the basin or represents differential subsidence across the basin. The only structure identified with the same orientation is a Precambrian shear zone and crustal boundary identified by Decelles (2004), because structures that were active during the Late Jurassic mapped by Peterson (1984) and Turner and Peterson (2004) are in an opposing northwest-to-southeast orientation. We therefore postulate that subtle syndepositional differential subsidence across the basin caused the thickness variations observed, potentially related to a Precambrian shear zone. We further speculate that the differential subsidence is only subtle, as indicated by the lack of an extensive paleosol horizon or erosional remnants that would be expected to be present if there had been a topographic variation across the basin. However, whatever the cause of the divide, it is clear that sediments were still distributed evenly across the system, as indicated by the percentage datasets for all but the isolated channel-fill facies association.

#### **A Generic Quantified Model of the Salt Wash DFS**

A quantified model of the Salt Wash DFS is presented in Figure 12. Although many more elements were quantified, only the percentage of amalgamated channel-belt and floodplain facies associations and the sand:mud ratio have been incorporated into the model. Because these trends are shown to be statistically strongest and are ratios, they are perceived to be most favorable to be incorporated into a quantified DFS model. This is, however, only hypothesized, and comparison with other systems will reveal which trends can be statistically incorporated into a generic model. Further comparison with other systems may reveal that none of the trends can be statistically added to a generic model. However, there is a clear need for statistical analyses of sedimentary systems, and even having quoted ranges is still a step forward.

Other criteria are perceived to more likely change from DFS to DFS depending on local variations. For example, mean grain size may vary considerably depending on catchment lithology. Channel size is also expected to vary considerable depending on DFS size and discharge. For example, the maximum average thickness of fluvial channels on the Huesca DFS is 5.1 m with a maximum thickness of 11.5 m measured (Hirst 1991), which is different to those from the Salt Wash DFS (15.2 m and 26.9 m for amalgamated channel thickness, 8 m and 13.5 m for individual story thicknesses, and 3.7 m and 4.7 m for isolated channel-fill facies) (Fig. 9). Therefore the total thickness, average, and range of thicknesses of channel deposits cannot be appropriately statistically included into a generic model, despite observed downstream trends. It is also inappropriate to add quantified information about the isolated channel-fill facies associations, because no statistically robust trends were identified (Figs. 7, 8, 9, 10). We stress that although the statistics from these criteria are not deemed appropriate to be incorporated into a generic DFS model; their importance is not discounted, in as much as vital information on the system was gained, such as insights into the identification of sediment bypass, basin topography, and climate.

The facies model presented in Figure 12 is considered to be an improvement on previously published conceptual models (Friend and Moody-Stuart 1972; Friend 1978; Hirst 1991; Stanistreet

and McCarthy 1993; Nichols and Fisher 2007; Cain and Mountney 2009; Weissmann et al. 2010; 2013). The trends have been statistically tested and quantified parameters have been added to trends that are considered to be potentially common to most DFSs. Those that have been tested statistically, but are not considered as common features of most DFSs, are qualitatively present in the model. The model provides a basis for objective comparisons to be made. We view this to be a starting point and a framework to build upon as more system-scale studies are conducted. We hope that through further comparison of the data from different DFSs present under different conditions, insights into key controls on DFS can be gained. Although there may be a degree of variation from the model presented depending on local conditions, it has potential in aiding subsurface exploration of resources because it provides quantified criteria for DFS which will aid reservoir modelling, characterization, and prediction at the system scale. The provision of statistical parameters also allows reservoir analogues to be more readily constructed and ensures geological realism.

## **CONCLUSIONS**

This study illustrates and statistically tests proximal-to-distal trends across the Salt Wash DFS. We document that downdip the total fluvial thickness changes from 174 m to 40 m, the grain size of the whole fluvial system changes from coarse sand to silt, and the percentage of sand decreases from 70% to 8%. The percentage of amalgamated channel-belt facies association decreases downstream from 67% to 0%. Alternatively the floodplain facies association becomes increasingly dominant (from 38% to 94%), as does the lacustrine facies association, but to a lesser degree (0.1% to 7%). When present, the average thickness of the channel belts and individual stories decreased downstream from at its thickest 15 m to 3.8 m at its thinnest, and 7.7 m to 2.3 m respectively. The architectural style of the deposits distinctively changed, with proximal regions dominated by deposits of stacked channel belts with a high degree of amalgamation, and distal regions dominated by floodplain muds



and sheet sandstones and sparse ribbon channels, with little to no amalgamation of channel deposits.

Weaker trends were present in all grain-size datasets for each facies association and average-thickness datasets for the floodplain and shallow ephemeral lake facies associations. The isolated channel-fill facies association displayed the weakest trends out of all facies analyzed. Trends that may be generic in a quantified state (sand:mud ratio and percentage of channels present) have been added to the Salt Wash facies model, and it is hoped that the model will provide a platform for later comparisons. Those trends that are not quantified (e.g., grain-size and thickness datasets and architectural style) are included in a qualitative state and are still deemed to be of value because important insights into character and controls on the system have been gained. A decrease in energy downstream, related to flow expansion as the river enters a sedimentary basin, channel bifurcation, and infiltration, are interpreted to be key controls

Measured downstream facies trends provide a basis for objective comparison with other DFSs deposited under differing conditions, which may lead to better predictions of variations across distributive fluvial systems. Such data may aid resource exploration and reservoir characterization within these systems.

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### Figures

Figure 1 – A) Location map of the Salt Wash fluvial system. Apex position defined by Owen et al. (2015). B) Stratigraphy of the study area.

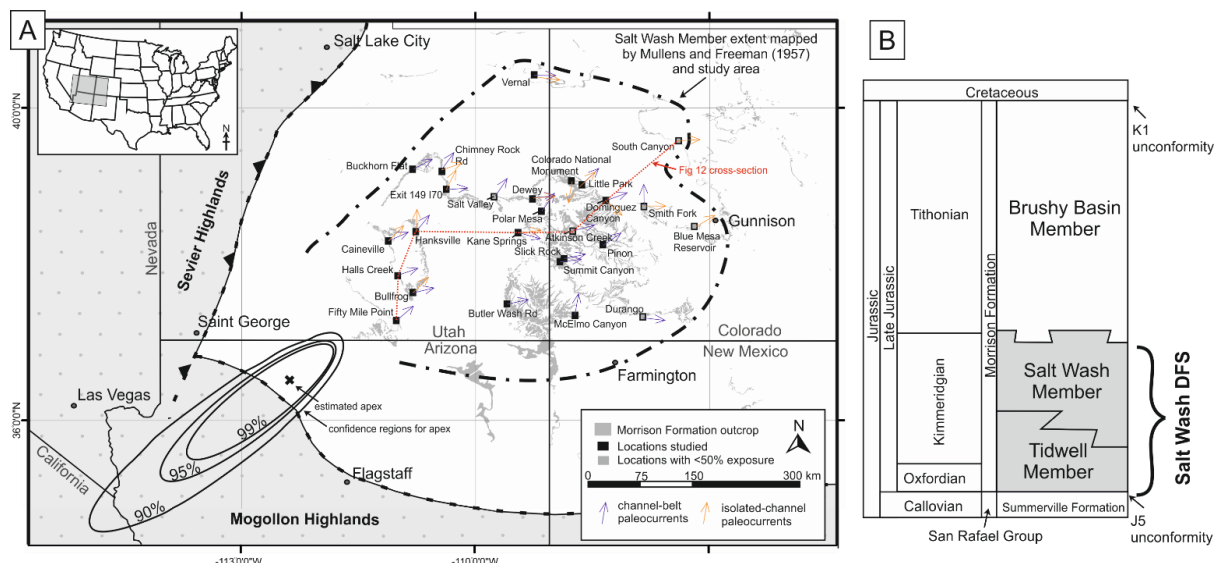


Figure 2 – Outcrop photo of Little Park (distal DFS) demonstrating the color change between the Salt Wash and Brushy Basin Members.

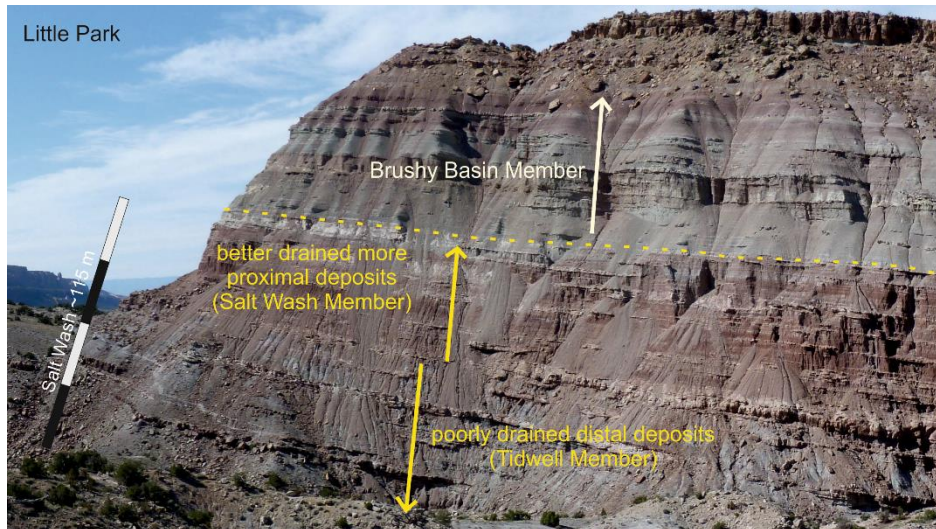


Figure 3 – Example images. A) Amalgamated channel-belt facies association. Various images show the characteristics of the channel belt deposits at a variety of scales. Scroll-bar deposit shown in satellite imagery is located in the proximal to medial portion of the system and is typical of scroll-bar deposits in the Salt Wash. Story thickness in the scroll bars typically ranges from 4 to 7 m B) Isolated channel-fill facies association. Example image of an isolated channel-fill taken from Hanksville (proximal to medial DFS). C) Schematic representation of isolated channel deposits to channel belt deposits. Satellite image from the Gilbert DFS, Australia. Satellite images taken from Google Earth (2014).

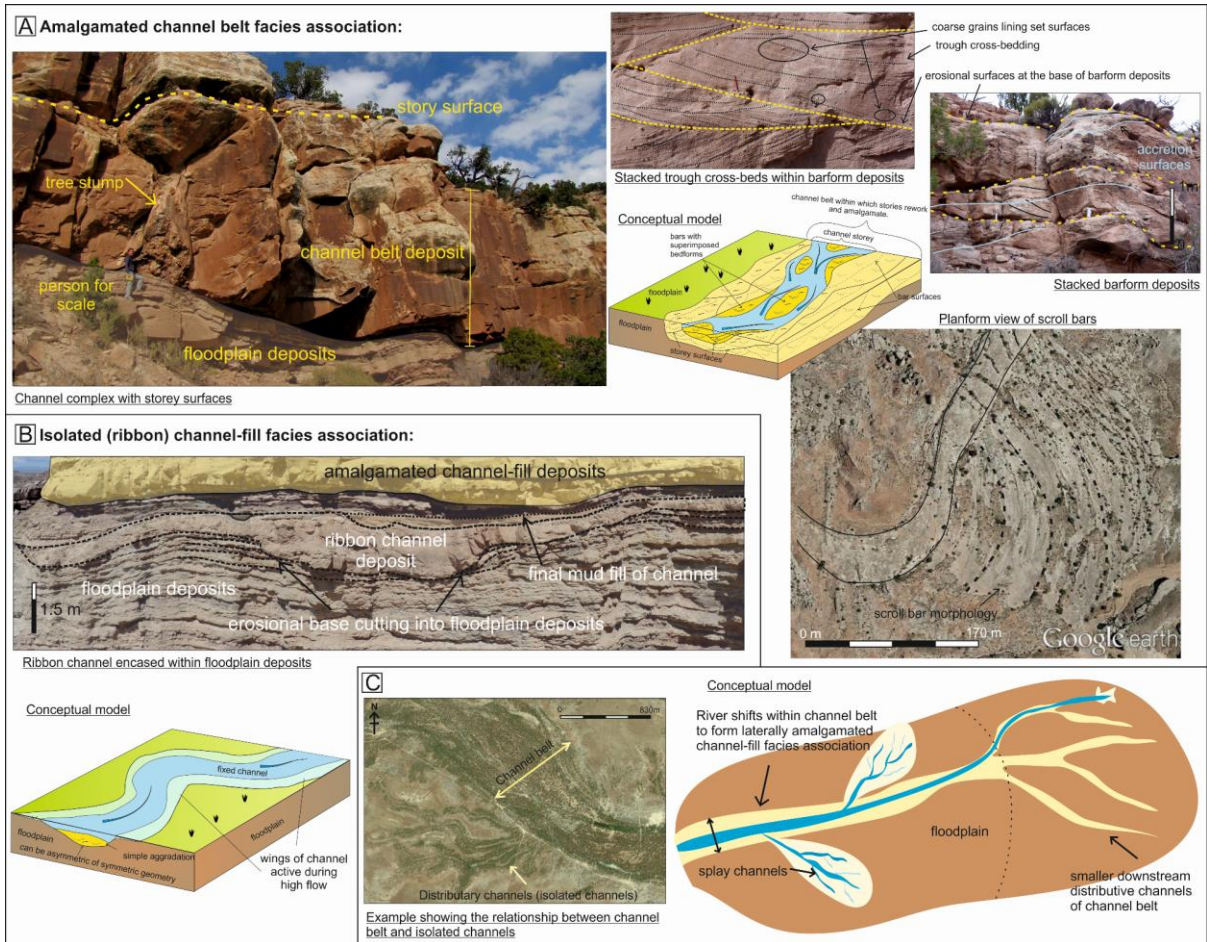


Figure 4- Example images of A) floodplain facies association. Example of a sand-dominated floodplain succession can be seen on the left, and a mud-dominated succession to the right. Note that the difference in colour demonstrates whether the deposits are well drained (left) and poorly drained (right), and B) shallow ephemeral lake facies association. Gypsiferous deposits (right) and wave-rippled sand deposits (left) are shown.

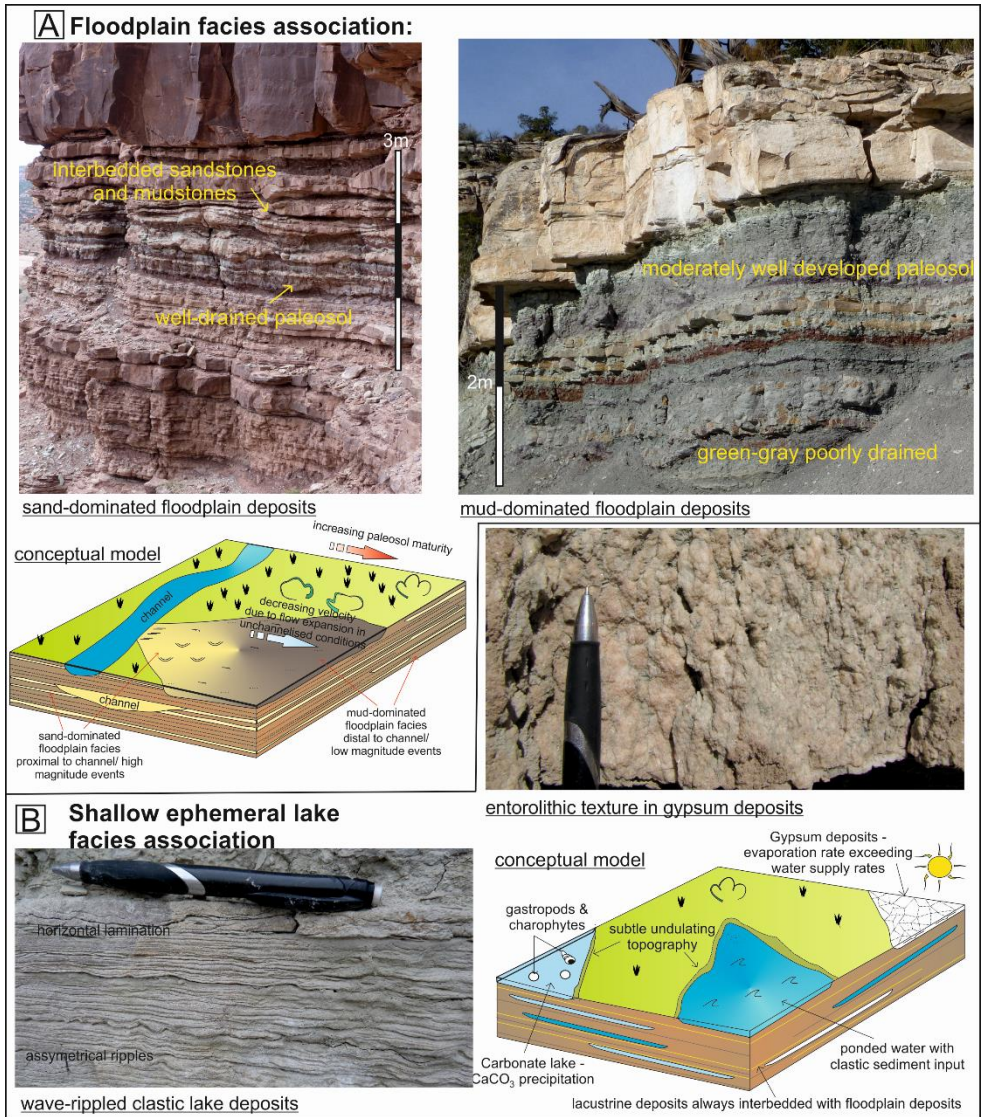


Figure 5 – Example sedimentary log from Atkinson Creek demonstrating typical relationships between each facies association.



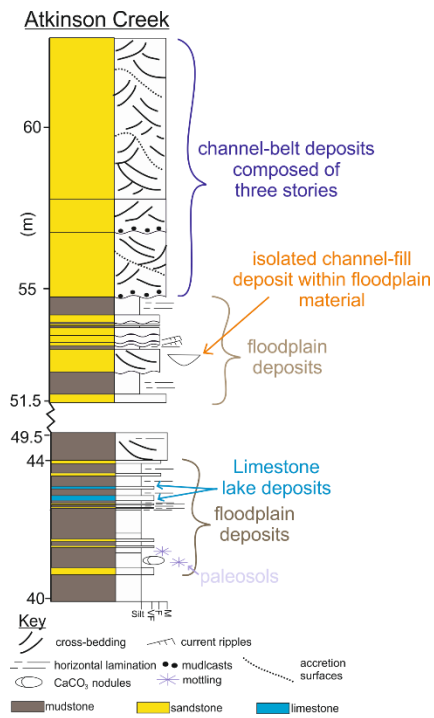


Figure 6 – Architecture panels of three locations across the DFS. Note the change in architecture downstream from amalgamated channel sheet deposits to isolated channel deposits in a mud-dominated succession. A) Panel of Bullfrog. B) Panel of Atkinson Creek. C) Panel of Smith Fork. D) Location map highlighting the position of panels A-C on the DFS. See text for explanation of key characteristics of each site.

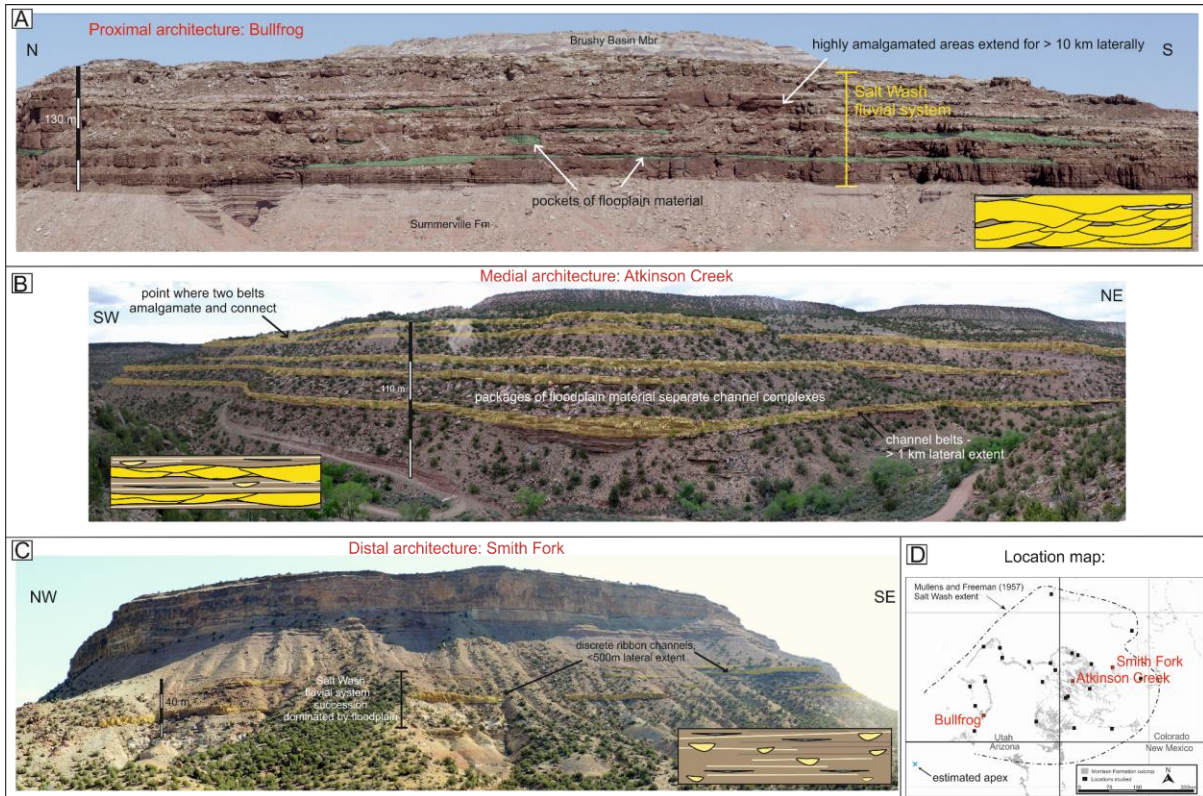


Figure 7 – A) Contour map of sand % at each section. B) Graph of sand % against distance downstream. C) Contour map showing the total thickness at each section (circled sites highlight abrupt thickness variation). D) Graph of total fluvial thickness against distance downstream (% and km). E) Contour map of average grain size for the whole fluvial system. F) Graph of average grain size of the whole fluvial system against distance downstream (% and km).  $\rho$  value for each facies association and critical value (CV) are indicated on each graph.

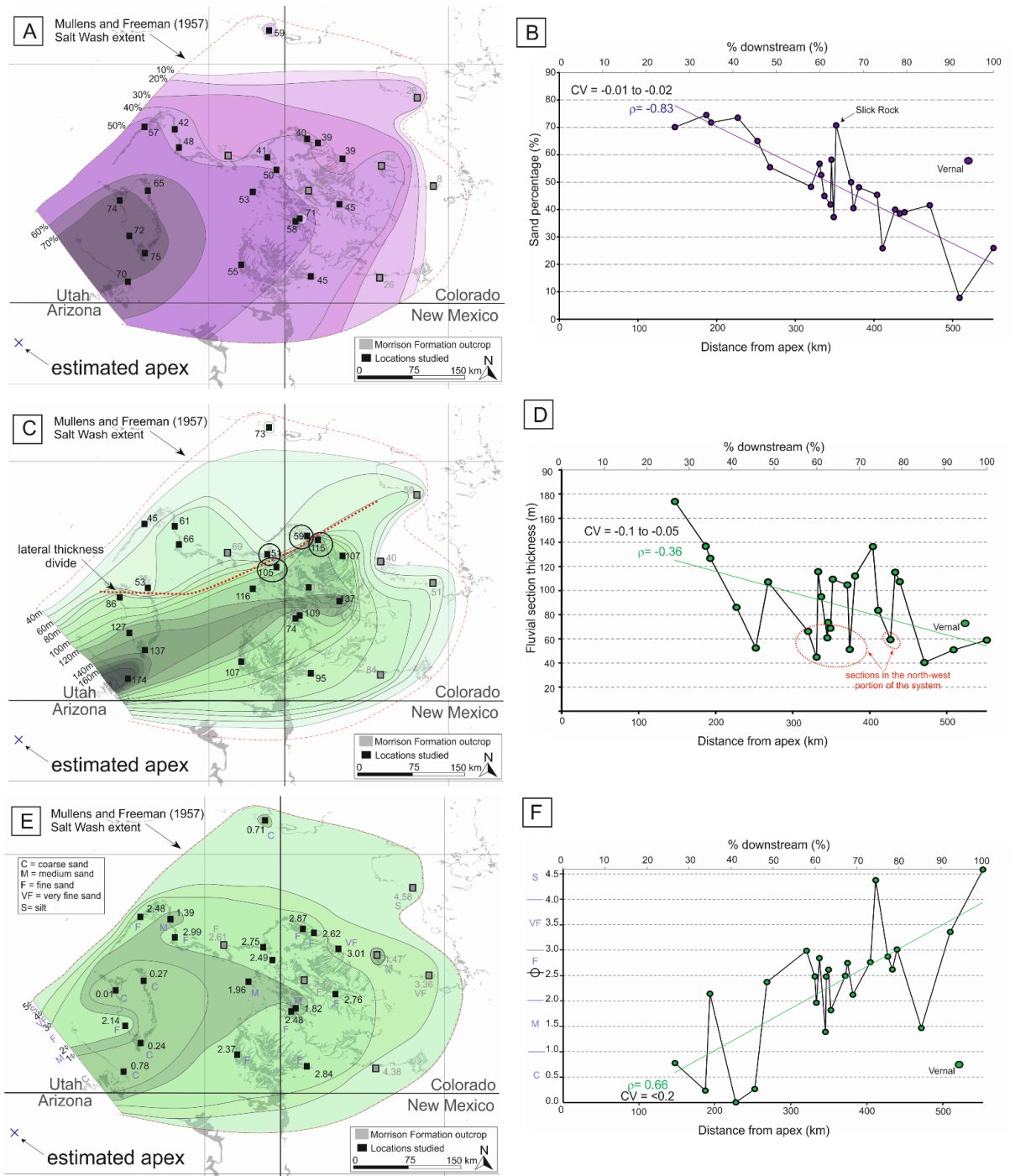


Figure 8 – Contour maps showing the percentage that each facies constitutes the whole fluvial section at each locality. A) Amalgamated channel-belt facies association. B) Isolated channel-fill facies association. C) Floodplain facies association. D) Shallow ephemeral lake facies association. E) Graph of facies percentage against distance downstream (% and km).  $\rho$  value for each facies association and critical value (CV) are indicated on the graph.

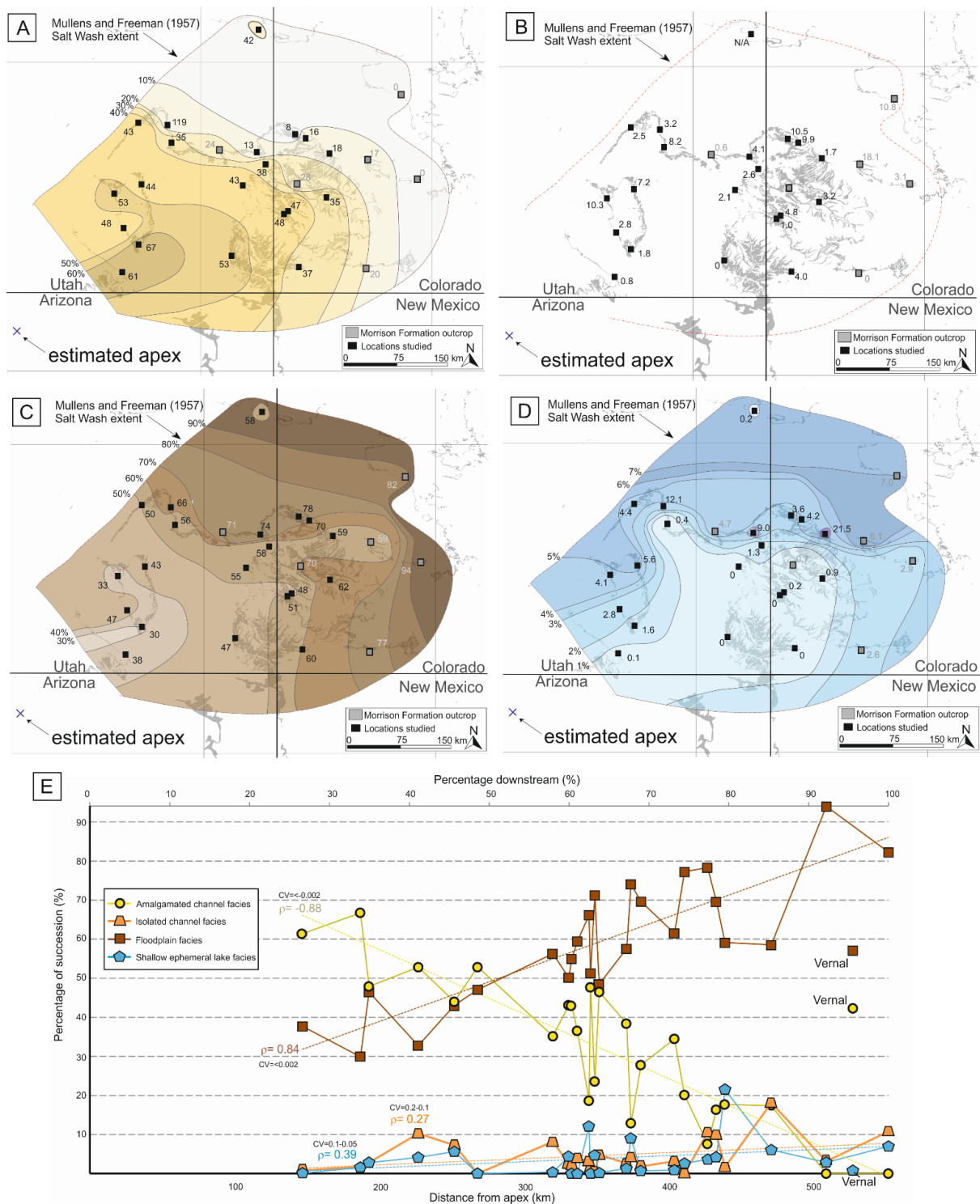


Figure 9 - Graphs showing the average and range of thickness recorded for each facies association plotted against distance downstream (% and km). A) Amalgamated channel-belt facies association. B) Isolated channel-fill facies association. C) Floodplain facies association. D) Shallow ephemeral lake

facies association.  $\rho$  value for each facies association and critical value (CV) are indicated on the graph.

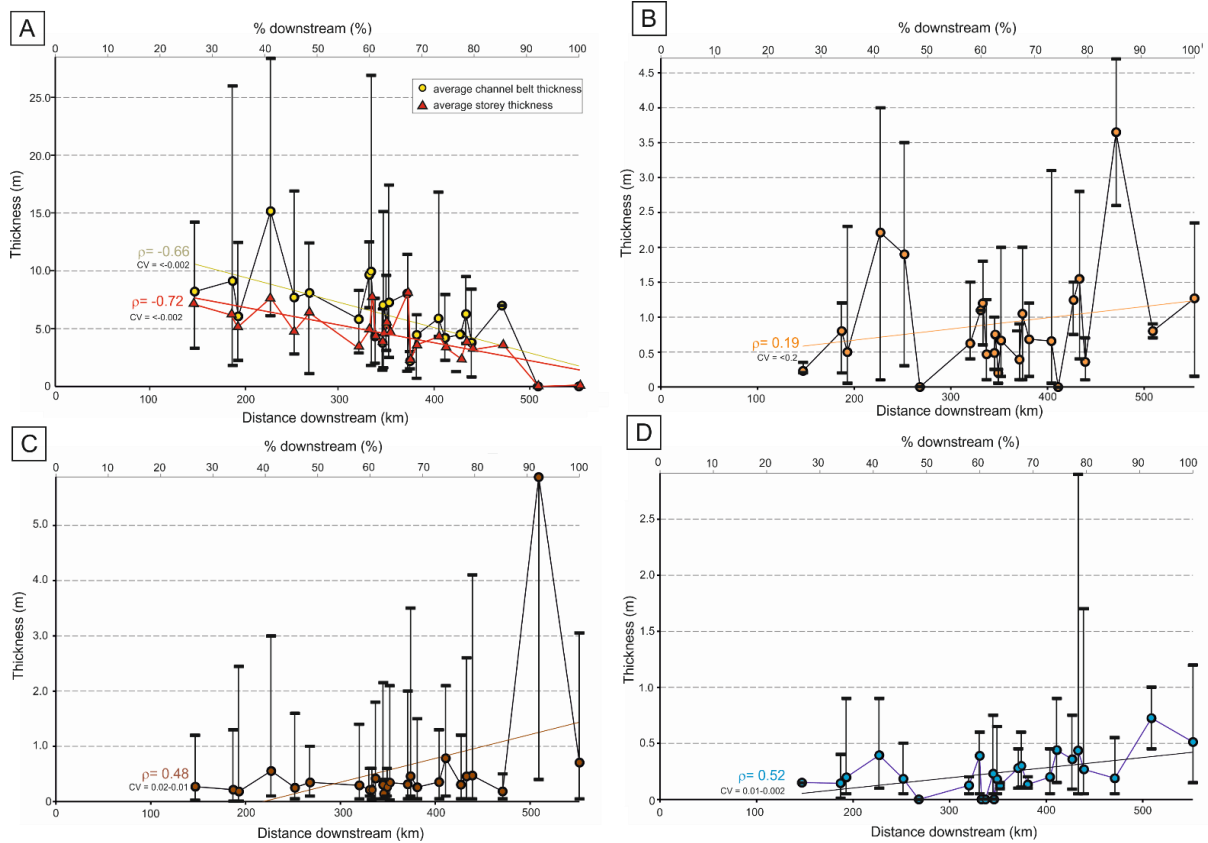


Figure 10 – Average grain size for each facies association. A) Amalgamated channel-belt facies association. B) Isolated channel-fill facies association. C) Floodplain facies association. D) Graph of average grain size for each facies association plotted against distance downstream (% and km).  $\rho$  value for each facies association and critical value (CV) are indicated on each graph.

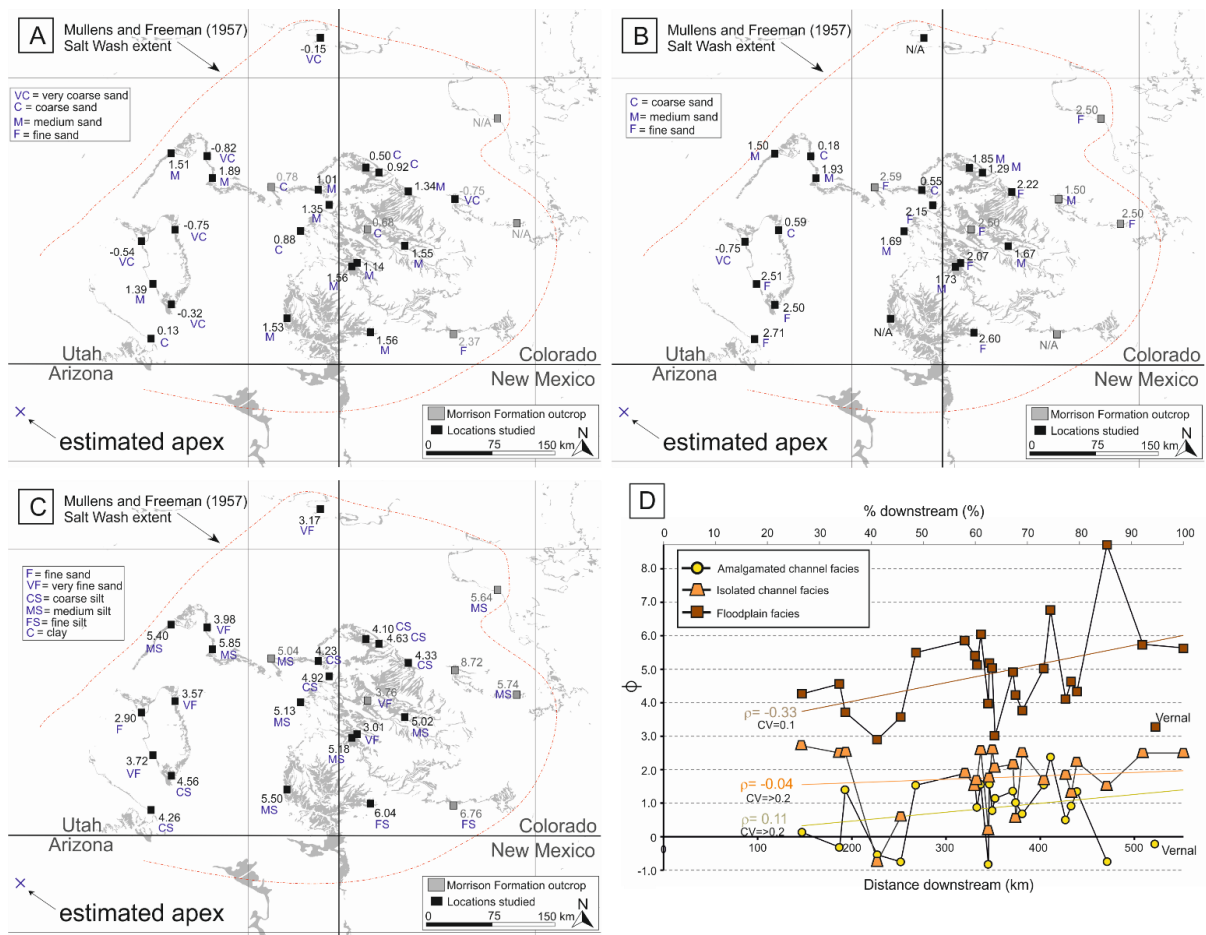


Figure 11 –A) Interpreted Morrison thickness map from Decelles (2004). Depocenters are interpreted to be different fluvial systems. B) Thickness map of the Salt Wash Member from Craig et al. (1955). Two separate depositional systems are interpreted to be present in the Salt Wash Member in Utah, based on field observations and results presented in this paper.

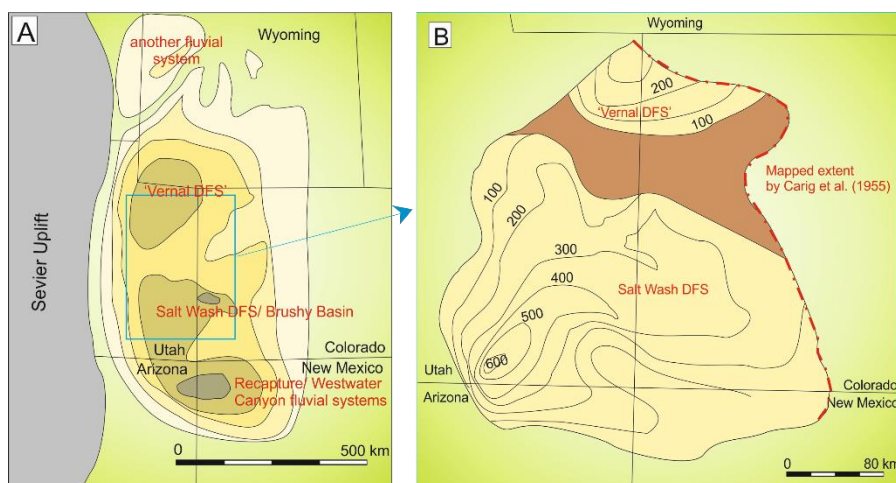


Figure 12 – A depositional model for the Salt Wash DFS.

