Received Date : 09-Feb-2015

Revised Date : 12-Oct-2015

Accepted Date : 16-Oct-2015

Article type : Original Article

Title: Vertical trends within the prograding Salt Wash distributive fluvial system, SW USA.

Running title: Vertical trends within the Salt Wash DFS

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Keywords: Progradation, fluvial, distributive fluvial system, Morrison Formation, Salt Wash Member

(A) Abstract

Progradation is an important mechanism through which sedimentary systems fill sedimentary basins. Whilst a general progradational pattern is recognised in many basins, few studies have quantified system scale spatial changes in vertical trends that record fluvial system progradation. Here we provide an assessment of the spatial distribution of vertical trends across the Salt Wash distributive fluvial system (DFS), in the Morrison Formation SW, USA. The vertical distribution of proximal, medial, and distal facies, and channel belt proportion and thickness, are analysed at 25 sections across approximately 80,000 km^2 of a DFS that spanned approximately 100,000 km^2. The stratigraphic signature of facies stacking patterns that record progradation varies depending on location within the basin. An abrupt and incomplete progradation succession dominates the proximal region, whereby proximal deposits directly overlie distal deposits. A more complete succession is preserved in the medial region of the DFS. The medial to distal region of the DFS are either simple aggradational successions, or display progradation of medial over distal facies. Spatial variations in facies successions patterns reflects preservation changes down the DFS. A spatial change in vertical trends of channel belt thickness and proportion is not observed. Vertical trends in channel belt proportion and thickness are locally highly variable, such that systematic up-section increases in these properties are observed only at a few select sites. Progradation can only be inferred once local trends are averaged out across the entire succession. Possible key controls on trends are discussed at both allocyclic and autocyclic scales including climate, tectonics, eustasy and avulsion. Eustatic controls are discounted, and it is suggested that progradation of the Salt Wash DFS is driven by up-stream controls within the catchment.

(A) **Introduction**

Vertical successions provide valuable insights into temporal changes in fluvial basin fills at a specific location, allowing an understanding of how sedimentary systems fill a basin to be gained. Prograding sequences are common stratigraphic signatures in continental basins: examples include the Salt Wash fluvial system, Utah and Colorado (Peterson, 1980; 1984; Currie, 1998; Kjemperud *et al*., 2008; Weissmann *et al*., 2013), Permian to Palaeogene aged sediments in Argentina (Legarreta, *et al*., 1993; Legarreta & Uliana, 1998), the Organ Rock Formation, Utah (Cain & Mountney, 2009), the Upper Carboniferous foreland basin succession of South Wales (Kelling, 1988; Hartley, 1993), Neogene foreland basin deposits in Bolivia (Uba *et al.,* 2005*),* the Chinle Formation, Arizona (Trendell *et al*., 2013) and the Blackhawk Formation, Utah (Rittersbacher *et al*., 2014). However, few studies have documented quantified changes in three-dimensions across an entire fluvial system, which is required to understand changes in basin filling processes through time and the controls exerted on them.

There are a variety of variables that can affect whether a succession is prograding, retrograding, or aggrading, including changes in source area and basin climate, subsidence rates, sediment supply, and base level (Shanley & McCabe, 1994; Posamentier & Allen, 1999; Holbrook *et al.,* 2006), all of which can occur on a range of scales (Cecil, 2003). Deciphering key controlling mechanisms is challenging because these variables are intrinsically linked across a variety of scales. This can be particularly true of spatially limited datasets, where it is difficult to assess the scale of controls. It is therefore important to recognise the spatial coverage of studies to avoid false, or biased, reconstructions of depositional architecture and controls from local to basin scale (Kukulski *et al*., 2013). A system scale study is therefore needed in order to decipher autocyclic from allocyclic controls.

A recent analysis of modern sedimentary basins by Weissmann *et al.*, (2010) showed that distributive fluvial systems (DFS), are the dominant fluvial form, and should therefore comprise a significant portion of the continental geologic record. DFS have predictable downstream characterisitcs, described by Nichols & Fisher (2007); Weissmann *et al*., (2011), Trendell *et al*., (2013), and recently quantified by Owen *et al.*, (2015b). As the spatial characteristics of a DFS are predictable, Weissmann *et al.,* (2013) postulate a system-scale conceptual model for prograding DFSs, based on observations from modern systems and outcrop data from the Blue Mesa and Sonsela members of the Chinle Formation, Arizona; the Salt Wash DFS of the Morrison Formation in southwestern USA; and the Pennsylvanian–Permian Lodéve Basin in southern France. The authors propose that a vertical succession through a prograding DFS will have:

- Distal facies at the base and progressively more proximal facies higher in the succession.
- An increase in channel density, channel amalgamation, and channel thickness up-section.
- A change from poorly drained distal palaeosols to well-drained proximal soils through the succession. However, the authors stress that local climate conditions within a basin may affect the presence of wet and dry palaeosols.

The aim of this paper is to quantitatively document changes in vertical successions across 80,000 km^2 of the Salt Wash DFS, a system that is previously considered to be progradational (e.g. Weissmann *et al.*, 2013), to test the proposed conceptual model put forward by Weissmann *et al.*, (2013) for prograding systems.

(B) **The Salt Wash DFS**

The Late Jurassic Salt Wash fluvial system was deposited during the early stages of foreland basin development. During this time there was subduction of the palaeo-Pacific oceanic plate beneath the continental North American plate (Decelles, 2004; Turner & Peterson, 2004). A broadly parallel compressional regime on the southern portion of the plate margin resulted in the formation of elevated rift shoulders across central Arizona and New Mexico, called the Mogollon Highlands (Fig. 1) (Dickinson & Lawton, 2001; Decelles, 2004; Turner & Peterson, 2004). On the northern portion of the plate margin an orthogonal compressional regime persisted, resulting in crustal shortening and formation of the Sevier Highlands (Fig. 1) These highlands spanned the western limits of Arizona and Utah, through Nevada, extending northwards to southern Canada (Decelles, 2004). This complex tectonic regime is likely to have resulted in variable subsidence rates in the basin. Morrison thickness maps published in Decelles (2004) suggest the fluvial systems to the south of the basin (i.e. the Salt Wash and Westwater Canyon Members, Craig *et al.,*1955) were more extensive than those coming from the Sevier Highlands.

The Salt Wash fluvial system is lithostratigraphically divided into the Tidwell and Salt Wash Members of the Morrison Formation (Fig 1). The Salt Wash Member contains channel belt deposits that become increasingly separated by floodplain deposits downstream. These characteristics, coupled with a dispersive paleocurrent pattern, led authors Craig *et al.* (1955); and Owen *et al.*(2015b), to conclude that the Salt Wash is a DFS. The Tidwell Member is composed of floodplain, minor fluvial channel and lacustrine facies. The Salt Wash Member comprises the more proximal facies of the fluvial system that prograded over distal facies of the Tidwell Member, in a semi-arid environment with seasonal precipitation (Peterson 1980; Peterson 1984; Turner and Peterson 2004; Kjemperud *et al*., 2008; Weissmann *et al*., 2013; Owen *et al*., 2015a,b). We include both members into the term "Salt Wash DFS", to emphasize that the two members are a single depositional system. Owen *et al*., (2015a) used a statistics-based approach to predict the position of the apex using palaeocurrent data from across the system. This study showed the Salt Wash DFS to be sourced from the southwest, either from the Mogollon-Sevier highlands syntaxis, or solely from the western portion of the Mogollon Highlands proper (Fig. 1), which is consistent with estimates from previous studies (Craig *et al*., 1955; Dickinson & Gehrels, 2008). Flow dispersed from this point in a north to northeast direction over 100, 000 km^2 of the southwestern portion of the Colorado Plateau (Fig. 1) (Craig *et al*., 1955; Mullens & Freeman, 1957; Owen *et al.,* 2015b). The system is relatively thin for its size (Owen *et al*. 2015b), and had low overall accumulation rates. At its thickest at Fifty Mile Point, the Salt Wash DFS is 180 m thick and it thins from there to 40 m at Smith Fork (Fig. 1). Relatively slow basin subsidence rates have been suggested by Robinson and McCabe (1998), who calculated a 6.2m/My (0.0062mm/yr) in the Notom area based on fission-track ages from bentonites by Kowallis and Heaton (1987) and 22m/My (0.22mm/yr) in Bullfrog. Detailed descriptions of facies associations and quantified spatial trends from the Salt Wash can be found in Owen *et al*., (2015b), and are summarised in Table 1.

Peterson (1977, 1978, 1980, 1984), Tyler & Ethridge (1983), Robinson & McCabe (1998), and Kjemperud *et al*., (2008), have previously documented vertical trends in the Salt Wash Member. Peterson (1977, 1978, 1980, 1984), divided the Salt Wash Member in the Henry Mountains and Kaiparowitz basin (proximal to medial part of this DFS) into three informal sequences using stratification ratios and the cross-bedding dip-vectors. Smith (1970), originally states that using the assumption that transverse bars are more prevalent downstream as a result of stream fractionation, the ratio between planar- and cross-stratification and horizontal stratification can give a rough estimate of the relative proportion of transverse bars to longitudinal bars. Through this an idea of proximity, as deposits with low ratios are generally found in proximal area and high ratios in more distal areas, is argued to be gained. Peterson (1986) states that the lowest sequence is characterised by high stratification ratios and northeastward palaeoflow directions; the middle by lower stratification ratios and east to southeast palaeocurrent directions; and the uppermost sequence by intermediate stratification ratios and northeast or southeast palaeocurrent directions. The sequences were reported to interfinger with one another and to not extend across the Colorado Plateau. However, there is some doubt about the use of the 'stratification ratio' as it is difficult to justify the use of this ratio due to assumptions based on the formation and preservation of horizontal and planar cross-sets and extrapolation of bedforms across the entire fluvial system. A particular issue lies with how much of a set is preserved, as it cannot be assumed that the preserved thickness is representative of the original depositional thickness (e.g. Leclair and Bridge, 2001). It appears that the stratification ratio has not been tested sufficiently and thus care should be taken before applying it. Robinson & McCabe (1997) subdivided the Salt Wash Member into two parts in the Henry Mountains region, Utah (proximal to medial DFS); a lower interval that is composed of greater than 80% cliff-forming amalgamated sands with thin mudstone intervals, and an upper interval that consists of less than 80% recessive sandstone and thicker mudstone packages. Robinson & McCabe (1997) suggest that the difference in weathering is due to differing mud content. Kjemperud *et al*. (2008) suggest there is cyclicity within an overall prograding pattern from outcrop studies in the southern portion of Capitol Reef National Park, west of the Henry Mountains. Tyler & Ethridge (1983) subdivided the Salt Wash of the Slick Rock district, Colorado (medial DFS), into three units based on sandstone proportion. Their basal interval is sandstone-dominated, middle interval has a variable mudstone content that is interbedded with three to seven sandstone bodies, and upper interval that is again sandstone dominated. Currie (1998) stated that the Salt Wash Member of the Uinta Mountains, northern Utah, can be divided into two units within an overall prograding sequence. He described a lower unit consisting of interbedded sandstone, mudstone and limestone, and an upper interval that consists of sandstone and conglomerates. Extensive mapping by Owen *et al*., (2015b), however, showed that deposits in the Uinta Mountains area are part of a different fluvial system to the Salt Wash DFS and informally referred to this system as the "Vernal DFS".

Lack of agreement between these previous studies suggests local variability in the stratigraphic succession in different parts of the Salt Wash DFS. A system scale study, that also takes into account the distal Tidwell Member, is therefore needed.

(B) Methods

To test the criteria cited in Weissmann *et al*., (2013), vertical trends were measured from sedimentary logs at 25 locations across the Salt Wash DFS (Fig. 1). To quantitatively test the vertical arrangement of strata, successions within each log were assigned a facies domain (proximal, medial, or distal), based on grain size, architecture of the deposits and sandstone percentage (see Table 1). The percentage of facies domains at each location is show in Figure 2.

At a smaller scale, channel belt proportion and thickness are also analysed, to investigate how the channel belt deposits are arranged internally within the facies domains and vertically through the successions. To maintain a system scale overview the percentage and average thickness of channel belt deposits was calculated for the bottom, middle and top third of each measured succession, which spans the entire vertical section of the DFS. This approach allowed varying channel thicknesses, and presence, to be appropriately recognised in proximal, medial and distal domains. Comparison statistics between each third allowed quantification of up-section trends. Individual channel belt thicknesses were plotted alongside average thickness within each third to document internal variations (Fig. 3).

This study focused on channel belts and floodplain development as they represent key facies and the majority of the Salt Wash DFS (Owen *et al*., 2015b). Analysis of the distribution of palaeosols within each section has been addressed previously by Weissmann *et al*., (2013). These authors documented a change in paleosol type in vertical succession (Fifty Mile Point, Pinon and Dominguez Canyon - see Fig.1 for locations). In the lower part of the successions poorly drained green-gray paleosols are the dominant paleosol type, whereas up-section red and brown argillic paleosols become more abundant. Isolated channels, otherwise known as fixed channels (Gibling, 2006), are not included within the analyses as Owen *et al*., (2015b), demonstrated that they are distributed uniformly across the DFS. Therefore, their distribution within a prograding system is not expected to change.

(A) Facies domain distribution analysis

(B) Description

Five distinct vertical succession types are recognised in the Salt Wash DFS (Fig. 2, types DP, DMP, DM, M and D).

A Distal-Proximal succession (DP) has basal facies of lacustrine and/or thin (less than 1 m thick) isolated channel fill deposits encased within floodplain deposits (distal deposits). This facies is overlain abruptly by thick, well-developed channel belt deposits separated locally by minor, discontinuous beds of floodplain deposits (proximal DFS deposits). This succession records an abrupt upward shift from distal to more proximal DFS deposits. Distal deposits comprise only a small percentage of the overall succession (0.4-25%), whereas proximal deposits dominate (75-99.6%). The abrupt transition is defined by an erosion surface, which can on occasion reach several metres of relief, and is laterally extensive (over several kilometres). Example images and sedimentary logs of pattern DP are given in Figure. 3.

Succession type Distal-Medial-Proximal (DMP) is characterised by the presence of medial deposits (channel belt deposits separated by laterally extensive floodplain packages), in the middle of the succession, with distal facies comprising the bottom of the succession, and proximal deposits the top. The transition between distal and medial deposits remains relatively abrupt however, scour surfaces at the base of medial channel belt deposits generally have a much lower relief (1m or less). The transition between medial and proximal facies is gradational. Distal deposits can comprise 17-55% of a succession, medial from 6-74%, and proximal 7-77%. Stacking pattern DMP is present at 7/25 localities across the system (Fig. 2). Example images and logs of pattern DMP are shown in Fig. 4.

Succession type Distal-Medial (DM) is present at 7/25 localities (Fig. 2), and is characterised by the presence of distal deposits at the base, which are overlain by medial facies. An apparently abrupt contact is observed; however relief of the erosion surface is minimal (less than 0.5m) (Fig. 5). Distal deposits comprise 12-72% of the succession, and medial deposits 28-88% of the succession.

Successions that contain only Medial (M) and Distal (D) are uniform in character. This type of succession is present at 6/25 localities, however, it is worth noting that the base of successions at Slick Rock and Durango (asterisked logs in Fig. 2), are poorly exposed, and therefore it could be possible that distal deposits may be present. Succession type D is rare (2/25 localities), and only found in the furthest downstream end of the system in western Colorado (Fig. 2). A summary of the facies domains can be found in Table 1.

(B) **Interpretation of facies domain distribution analysis**

The successive change from distal facies to relatively more proximal facies (i.e. successions DP, DMP and DM), suggests there was progradation of the system, as deposits become increasingly more proximal up-section, suggesting a basinward shift of facies domains. These successions therefore quantitatively support the conceptual model put forward by Weissmann *et al.*, (2013). Succession M and D are interpreted to represent aggradational conditions, as there is no basinward shift, or back-stepping, in facies types up-section, and therefore locally fit the conceptual model put forward by Weissmann *et al.*, (2013).

A spatial pattern is evident when analysing the presence of different successions across the system (Fig. 2). Succession DP is only found at the most proximal sites studied; succession DMP in the proximal to medial portion of the system; M in the medial, DM in the medial to distal and D in the most distal portion of the system. Interestingly, the progradation model proposed by Weissmann *et al*., (2013), where distal facies are overlain by medial facies, which are in-turn overlain by proximal deposits, is only present in the centre of the system (Fig. 2).

This distribution is interpreted to be the result of preservation potential down DFS. As reported by Nichols & Fisher (2007) and Weissmann *et al*., (2013), the proximal region of a DFS is characterised by high sedimentation rates due to proximity to the source area and a high degree of reworking as channels migrate across a limited DFS surface. A decrease in stream power and channel reworking is experienced downstream as a result of channel bifurcation, infiltration, and evapotranspiration. With increasing distance from the apex accumulation space increases laterally, and, dependent on subsidence rates, accumulation and vertical aggradation rates may also increase vertically. All of these factors combined allow a more complete progradation signature to be better preserved further into the basin, to the point at which the system no longer progrades. Therefore the conceptual model proposed by Weissmann *et al.*, (2013) is only fully applicable in certain areas of the Salt Wash, which we relate to preservation potential and progradation extent.

(A) Channel belt analysis

The amalgamated channel belt deposits are predominately composed of poorly sorted, fine to pebbly cross-bedded sandstones, which contain downstream and lateral accretion bar forms. The deposits amalgamate to form large scale (up to 26 m thick, 10 km lateral extent) sheet sandstones that are composed of multilateral and multi-storey deposits, representing the lateral migration and juxtaposition of channel deposits (Gibling, 2006; Hartley *et al.*, 2015). A more extensive description of the channel belt deposits can be found in Owen *et al*.(2015b).

Six different patterns were recognised at twenty-three locations when analysing the vertical trends of channel belt presence and average thickness of the channel belt deposits. Blue Mesa Reservoir and South Canyon are exempt from analysis as no channel belt deposits are present at these locations. A summary and graphic representation of the different vertical patterns is shown in Table 2.

(B) Up-section change in channel belt proportion

(C) Description

Four of the six different vertical patterns are recognised when analysing channel belt proportion up-section. Pattern 1 is present at 15/23 localities, making it the most prevalent pattern across the system (Fig. 6). It records a progressive increase in channel belt presence from the bottom to top third.

Pattern 2a is present at 6/23 localities and is again distributed uniformly across the system (Fig. 6). An increase in channel belt presence up-section is only observed from the bottom to middle third, followed by a decrease from the middle to top third.

Pattern 3a is only present at Bullfrog (Fig. 6) and is characterised by a decrease in channel belt presence from the bottom to middle third, with the final third of the succession containing the highest percentage of channel belt deposits.

Pattern 4 is present at Summit Canyon (Fig. 6), and demonstrates a progressive decrease in channel belt presence from the bottom to the top third.

(C) Discussion of channel belt presence

Weissmann *et al*., (2013) suggested that a progressive increase in channel belt development would be expected up-section within a prograding DFS succession. Pattern 1 is the only pattern that is consistent with this hypothesis. Some form of progradation is evident in patterns 2a (demonstrated by an increase from the bottom to middle third), and 3a (demonstrated by an increase from middle to top third). Progradation is not prevalent throughout Salt Wash deposition as a decrease in channel belt proportion is observed from the middle to top third in pattern 2a, and from the bottom to middle third in pattern 3a. However, at localities at which pattern 2a is found, the differences in percentages between the middle and top third are often minimal. Data in Table 3 shows that a 10% or less difference is observed at all localities at which pattern 2a is present, with the exception of McElmo Canyon, where a 29% difference is observed, and at Caineville, where a 14% difference is observed. Therefore the differences between pattern 1 and 2a are considered in the most part to be minimal, suggesting only subtle local variations within the basin and overall progradation of the system.

The different patterns appear to be randomly distributed across the system, suggesting no apparent spatial trends on channel belt pattern presence, unlike trends displayed in the facies domain analysis. We relate this to differences in scale as channel belt deposits are the internal constituents of the facies domains, and therefore are highlighting the internal complexities at a smaller scale. Possible controls at a variety of scales are discussed later in the discussion section.

(B) Up-section change in average channel belt thickness

(C) Description

All six patterns are recognised when analysing the up-section change in average thickness of channel belt deposits (Fig. 7). A successive increase in channel belt thickness (Pattern 1) is observed at 11/23 localities, making it the most prevalent pattern across the system.

Patterns 2a and 2b illustrate an initial increase followed by a decrease in the average channel belt thickness from the bottom to top third. Pattern 2a is the only pattern that is spatially restricted as it is found only in the northeastern portion of the DFS in the medial to distal zone. Pattern 2b differs from pattern 2a in that a significant decrease in average thickness is observed from the middle to top third.

An initial decrease in average thickness from the bottom to middle third, followed by an increase from the middle to top third (Patterns 3a and 3b) is present at 3/23 localities across the system (Fig. 7). A smaller jump in average thickness from the middle to top third is observed in pattern 3b compared to 3a. Pattern 4 is present only at Fifty Mile point and Summit Canyon, and illustrates a successive decrease in average channel belt thickness up-section.

(C) Discussion of up section changes in channel belt thickness

Weissmann *et al*., (2013) postulated that an up-section increase in channel thickness would be expected within a prograding DFS sequence. Again, pattern 1 is the only pattern that supports the notion of a complete and systematic progradation through time. However, this is only evident when analysing the average thickness of the deposits in each third. When individual channel belt thicknesses are plotted against height in the succession, a very scattered pattern is present within an overall increasing trend (Fig. 7). Hanksville is the only locality that shows a progressive increase in individual channel belt thickness up-section. Evidence for partial progradation within the successions is seen in patterns 2a, 2b, 3a and 3c, through an increase in average thickness either from the bottom to middle third (patterns 2a,b), or from the middle to top third (patterns 3a,b). However, evidence suggesting retrogradation is also present in these successions as a decrease in average thickness is observed from the middle to top third (patterns 2a,b), or bottom to middle third (patterns 3a,b). As a progressive decrease in average channel belt thickness is present in pattern 4, this suggests that within these successions retrogradation is occurring. Again when individual channel belt thickness are plotted (Fig. 7), very scattered results are present. The patterns are distributed randomly across the system, suggesting there is no spatial trend on pattern distribution at a system scale.

(A) Discussion

From the above analyses, sufficient evidence exists to support the notion that the Salt Wash DFS prograded into the basin through time, with 22/25 localities demonstrating some form of progradation. The basinward shift in facies domains is considered to provide conclusive evidence of progradation, which coupled with a general increase in channel belt proportion and average thickness in the majority of successions supporting this interpretation. However the patterns produced in channel thickness and proportion data can also be the result of mechanisms other than progradation (or retrogradation). For example, an increase or decrease in channel belt thickness may simply reflect differences in proximity to an actively migrating channel (e.g. Bridge and Tye, 2000). An increase, or decrease, in channel proportion can also be the function of topography. For example, Venus *et al.*, (2015), in the Permian Cutler Group, Utah, showed that the channel belt density and thickness can vary in response to halokinesis. Therefore, although Weissmann *et al.*, (2013) state an increase in channel density and proportion is expected in a prograding DFS sequences, it is also important to note that such successions can be produced by other factors. However, in the case of the Salt Wash DFS, we are confident that a progradation interpretation is correct as we are able to document the overall basinwards shift in facies domains at the basin scale.

The overall extent of progradation can be constrained with proximal facies prograding as far east as the Utah-Colorado border, and medial facies as far east as Smith Fork and Durango (Fig. 2). The same extent is inferred when analysing the proportion and thickness of channel belt deposits up-section. The extent of progradation of the system can therefore be confidently inferred as being in the region of 30 km west of Gunnison, Colorado.

(B) Comparison between criteria tested

A comparison was conducted to assess whether the same trends could be identified in all three criteria assessed. As can be seen in Table 4, only 6 localities (Halls Creek, Hanksville, Buckhorn Flat, Kane Springs and Pinon) show trends expected for a successive progradation of the system. Evidence for a partial progradation of the system across all three criteria is observed at three localities (Bullfrog, Caineville and Little Park). Summit Canyon is the only locality that suggests a retrogradation of the system. Therefore, only 10/25 localities studied show the same trends across the three criteria analysed.

When a comparison is made between the two criteria that analyse the channel belt deposits, 18/23 localities have the same vertical pattern, eleven of which suggest progradation of the system. Therefore, in the case of the Salt Wash DFS, it can be inferred that the channel belt thickness and presence change concurrently up-section. Five localities (Fifty Mile Point, Butler Wash Rd, Slick Rock, Polar Mesa and Dewey), do not show the same vertical pattern when analysing the channel belt deposits. At Fifty Mile Point an initial increase followed by a decrease in channel belt presence is observed (pattern 2), while the mean channel belt thickness decreases progressively (pattern 4), suggesting varying amalgamation of decreasing channel thickness through time. Butler Wash Rd, Slick Rock, Polar Mesa and Dewey all show an increase in channel belt presence (pattern 1), and varying mean channel belt thickness up section (patterns 2 and 3), demonstrating an increasing channel belt amalgamation of varying channel thicknesses. As can be seen in Table 4, localities that show concurrent changes up-section are present across the system, while those that do not, appear to be randomly distributed across the system, suggesting localised controls on channel belt development.

The discrepancy across the criteria tested highlights the complex nature of fluvial systems, demonstrating that not all areas of the Salt Wash system behaved in the same way through time. In addition to the inhomogeneity of fluvial systems, the apparent spatial control in facies succession will also influence the co-occurrence of patterns. As discussed, certain facies successions are only expressed in certain areas of the system, yet there is no apparent spatial trend in channel belt stacking patterns. As a result, it is only possible to get the co-occurrence of complete progradation signatures in a small area of the system. For example, pattern DMP is expressed only in the centre of the system, therefore restricting the number of localities that can have a complete progradation signature in facies stacking and channel belt analyses.

(B) **Controls**

The concept of trends being developed within sedimentary successions at both allocyclic and autocyclic scale has provided a powerful method to deduce controls on stratigraphic signatures within the geologic record. Climate, tectonics and eustacy are considered to be important allocyclic controls, whereas smaller scale controls, such as bar migration, avulsions and local changes in topography are considered to occur at an autocyclic scale (Cecil, 2003; Allen, 1971; Miall, 2000, Ethridge *et al*., 1998). However, as noted by Ethridge *et al*., (1998), deciphering key controlling factors for sedimentary successions can be challenging as different factors may produce the same signature, or indeed it may be the case that several controlling factors could be responsible for any observed variations. It is also important to recognise that allocyclic and autocyclic scale processes overlap. For example, as is described by Cecil (2003), a change in climate may change the discharge of a fluvial system, which may affect bar dynamics. Due to the intrinsic interplay between different factors, all of the various controls need to be taken into consideration when interpreting deposits. For this reason key controls are speculative as it is not possible to constrain all possible variables, particular those concerned with processes within the paleo-catchment.

As described by Cecil (2013) the sedimentary response to autocyclic processes is often localised, with trends commonly unable to be mapped on a regional scale. High local variability within the channel belt analyses cannot be mapped regionally until averaged in the succession, suggesting that the channel belt deposits in the Salt Wash were influenced by both autocyclic and allocyclic controls, as small scale patterns cannot be mapped across the system, but yet an overall trend can be determined. DFS are constructed through the repeated avulsion of channel belts across a sedimentary basin (Nichols & Fisher, 2007; Weissmann *et al*., 2010; Buehler *et al*., 2011). Therefore avulsion processes are a key autocyclic process in the formation of DFS architecture. As the DFS builds through time, the placement of an avulsion cycle will be affected by previous avulsion deposits by creating subtle topographic variations, with new avulsions commonly filling topographic lows, eventually smoothing out any topographic relief (compensational stacking) (Straub *et al.* 2009). This means that there will be self-driven topographic variations across the system. As avulsions occur over long time scales (at a system or channel belt scale), it is highly unlikely that other variables, such as sediment supply and climate, will remain constant throughout the deposition of an entire DFS. For example, seasonality through time will produce slight variations in sediment supply and discharge, which will affect the morphology of the resultant deposits. The result of these variations across time and space will mean the deposits of a DFS are inherently heterogeneous. The high local variability is therefore interpreted to be a combined function of channel belt avulsion and local variations in other factors such as accumulation space and sediment supply (the effects of which are subsequently discussed), within an overall prograding sequence. Similarly, Rittersbacher et al., (2014), also demonstrated high local variability in up-section channel belt thickness within the Blackhawk Formation, Utah, and interpreted this to be related to autocyclic controls on the system, with the overall up-section trends to be related to allocyclic controls. It is clear when analysing channel belt data that progradation is not as succinct as proposed by Weissmann *et al.*, (2013). Although the model holds true when averaged over the succession it is important to note that, as with all models, internal variations may mean that the overall trends are more difficult to determine.

As substantial long term change is needed to push facies tracts, and the overall system either backwards or forwards, it can be inferred that regionally mapped facies domains (Fig.2) are under the influence of allocyclic scale. For example, sites at which succession M is identified (i.e. stable deposition) but an up-section change in channel belt occurrence or thickness is identified, it can be inferred that alterations to the system are not substantial enough, in strength or time, to cause a facies tracts to move basinward, but locally they are sufficient enough to result in increased channel deposit thickness, or amalgamation, up-section. Alternatively, long term allocyclic controls may result in the basinwards movement of facies (i.e. succession DMP at Pinon), but internally the deposits are affected by smaller scale allocyclic processes that result in a scattered channel belt thickness distribution up-section, such as local subsidence variations, and small-scale changes in sediment supply and climate. This highlights the fact that although the overall trends may be influenced by allocyclic controls, internally they are composed of deposits influenced by local autocyclic controls.

Eustacy, tectonics, and climate are considered to be allocyclic controls (Allen, 1971; Ethridge *et al.*, 1998; Miall, 2000; Cecil, 2003). At the approximate time of Salt Wash deposition, the Western Interior Seaway was regressing, and by the end of the Late Jurassic it was 500 miles north of the study area close to the present U.S.A – Canada border (Turner & Peterson, 2004). Therefore a eustatic sea-level control is not envisaged to be a key factor. Based on work around the Henry Mountains and regional stratigraphic cross-sections by Peterson (1994), Robinson & McCabe (1998) deduce that tectonics and fluctuating lake levels were key controlling factors on the architecture of the Salt Wash fluvial system. A more recent system scale study by Owen *et al*., (2015b) show lake deposits to be minor constituents of the fluvial system, comprising less than 3% of total deposits, being less than 2.9 m in thickness and less than 1 km in lateral extent. It is difficult therefore, to envisage how such small scale and sparse bodies of water are likely to have controlled a system the size of the Salt Wash DFS, although aggradation rates may need to be considered. A lack of large-scale channel incision and decrease in grain size (Owen *et al*., 2015b) further supports this. Downstream base level controls are therefore not considered to be a key factor and the Salt Wash fluvial system is considered to be, influenced by up-stream controls (e.g. Holbrook *et al*., 2006; Kukulski *et al*., 2013), such as discharge and sediment supply related to the source area of the system.

Tectonic processes are important in creating the initial framework for Salt Wash deposition by creating a source area and space for the system to accumulate. Variable subsidence rates, both spatially and temporally could have affected the architecture of the Salt Wash fluvial system, which could explain the variable internal trends observed in channel belt datasets. Unfortunately no reliable datum can be defined internally within the system, thus inferring how smaller scale patterns relate to one another is challenging. Decreasing overall subsidence rates could have caused the system to prograde due to a decrease in basin accommodation. Relatively slow subsidence rates were calculated by Robinson and McCabe (1998) for the basin, such that if sediment supply was held constant or increased, then this could force the system to prograde. Propagation of the apex basinwards, as a result of a migrating thrust system, provides an alternative causal mechanism for progradation of a system. DeCelles *et al*., (2011) reported that within Cenozoic strata in Argentina, a basinwards migration of the apex occurred as a result of the propagation of the thrust system into the foreland. This is another plausible scenario for the Salt Wash fluvial system as both Currie (1998) and Decelles (2004) have argued that the Cordilleran thrust belt propagated basinwards during Late-Jurassic through to Cretaceous times.

Climate could also have influenced the architecture of the Salt Wash DFS as it affects the rate of discharge and sediment supply into the basin (Blum & Törnqvist, 2000). However, despite its importance climate has received less attention compared to other allocyclic controls (Allen *et al*., 2015). Sedimentation rates are interpreted to be of importance in the development of patterns observed within the Salt Wash DFS. Without sustained, or increased, sediment input, the fluvial system would not have been able to prograde basinwards. Grain size data from channel deposits imply that an increase in discharge may have occurred since channel belt deposits towards the top of logs in the distal domain are composed of coarse sand (Owen *et al*., 2015b). However, it is important to note that an increase in the sediment supply and discharge can also occur through the expansion of the source area, regardless of climate, or by increasing the size of the sediment load entering the basin. Mather (2000) documents the contraction and expansion of systems related to changes in river catchment size in the Sorbas area of SE Spain. Field observations and limited provenance studies by Owen (2014) do not indicate substantial changes in composition within the Salt Wash, which is supported by data presented in a U-Pb study by Dickinson & Gehrels (2008). However, a detailed petrographic study at various intervals within Salt Wash deposits is needed before any firm conclusions can be made. Although a change in provenance is not observed, this possibility cannot be ruled out as a causal mechanism for the progradation of the Salt Wash DFS, as expansion of the source area may be occurring in similar bedrock geology. Good (2004) concluded from a study on growth bands in bivalves that a change in seasonality occurred during the deposition of the Salt Wash fluvial system. Growth band studies in the Tidwell Member (distal DFS deposits), near Green River, Utah, showed no continuous annual banding, suggesting that changes in discharge and climate did not vary substantially during the year at this location. Bivalves from the Salt Wash Member at Colorado National Monument, Colorado, tell a different story as bivalves possessed light and dark annual banding, suggesting seasonal cyclicity. This work illustrates how intrinsically complicated the deposits are likely to be, and it is possible that the difference in seasonality may occur through time, or space during different avulsion cycles. Demko *et al*., (2004), through the study of palaeosols, demonstrated that climate conditions within the Morrison basin became steadily more humid through time. For the Salt Wash specifically, these authors identify simple gypsic Protosols, marginal-lacustrine to, palustrine Calcisols and weakly developed floodplain argillic

Calcisols in the Tidwell Member, whereas the Salt Wash is dominated by floodplain argillic Calcisols. The loss of evaporitic soils suggests the climate became wetter through time. However, it must also be noted that such changes in paleosol characteristics may also have occurred as a result of prograding better drained more proximal soils into the basin (e.g. Hartley *et al.*, 2013). The combined findings from Good (2004) and Demko *et al*., (2004) suggest a change in basin climate is plausible during Salt Wash deposition. However, these studies are concerned with climate in the basin. Gaining insights into climatic changes in the paleo-catchment are difficult, however, it is speculated that an increase in grain size up-section in several logs in the medial to distal domain (Owen *et al.*, 2015b) could indicate that the climate in the catchment got wetter through time.

Kjemperud *et al*., (2008) noted cyclicity within an overall decreasing accommodation to sediment supply (A/S) regime from a study on the Salt Wash fluvial system along the Waterpocket Fold, in Capitol Reef National Park, Utah. These authors described four stratigraphic cycles within the Salt Wash and attribute changes to the A/S regime related to stratigraphic base level changes as a causal mechanism. This interpretation differs from those made within this study, as the stratigraphic cycles cannot be extrapolated across the system. It is hypothesised therefore that the stratigraphic cycles represent channel belt avulsions or DFS lobe switching. The authors also note that superimposed onto the four cycles is a basinwards progradation of the system related to a decrease in accommodation, an interpretation that is supported by this paper. Upwards coarsening trends within the Salt Wash are interpreted by Currie (1998) to reflect a decrease in the rate of basin accommodation.

(A) **Conclusions**

We present a detailed analysis of vertical trends within the prograding Salt Wash distributive fluvial system (DFS). A spatial control is evident when analysing the distribution of facies domain successions vertically, which we relate to changing preservation potential from proximal to distal areas of the DFS. Increasing grain size, channel size, and channel belt amalgamation vertically up-section was predicted by Weissmann *et al.,* (2013) to occur in prograding DFS deposits. This study implies that location in the basin is important as to whether such stratigraphic signatures may be present. It is speculated that in settings where higher amounts of accumulation space are available a more complete signature may be preserved in the proximal region, however, further study in such settings is needed to test this hypothesis. A spatial control is not observed when analysing the up-section trends in channel belt presence and thickness. When averaged an increase in channel belt density and thickness is observed, as predicted by Weissmann *et al.,* (2013). In most cases, however, when data are not averaged over the system, complex patterns are observed, suggesting local variations in key controls, such as accumulation rates or climate, resulting from variable conditions during avulsion cycles as the system developed. Subtleties observed highlight the inherent inhomogeneity within fluvial sequences, illustrating the dangers of extrapolating trends across sedimentary basins from localised studies. However, all three analyses combined do indicate progradation. The system scale analysis conducted within this study has enabled the distinction between allocyclic and autocyclic trends to be recognised, allowing unique insights to be gained into how fluvial systems fill continental sedimentary basins to be gained. The Salt Wash DFS is interpreted to be an up-stream controlled fluvial system as it appears to be disconnected from sea-level, and not under the influence of any large scale down-dip lacustrine systems. Influence of other potential variables on Salt Wash architecture are discussed such as climate and tectonics but no firm conclusions could be made as to whether they are key controlling mechanisms since many of the controls are interrelated.

(A) Acknowledgements

This work has been supported by the Fluvial Systems Research Group Consortium Phase 1, supported by BG, Chevron, ConocoPhilips, and Total. Discussions with John Howell on prograding sequences are greatly appreciated. The authors would also like to thank Anna Kulikova, Guy Prince, Kelsey McNamara and Karen Oud for assistance in the field. We thank reviewer Brian Willis, an anomalous reviewer and Editor Sébastien Castelltort for constructive comments that improved this manuscript.

(A) Conflict of Interest

No conflict of interest to declare.

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(A) **Figure list**

Fig. 1- Location maps and stratigraphic framework of the Salt Wash DFS. (a) Tectonic framework of the Late Jurassic during the deposition of the Salt Wash DFS. Modified from Turner & Peterson (2004)and Blakey (2013) . (b) Location map of the study area. Blue arrows indicate mean palaeocurrent direction at each locality. Estimated apex location taken from Owen *et al.,* (2015a). (c) Stratigraphic framework of the Salt Wash DFS.

Fig. 2 – Spatial distribution of facies stacking patterns. Coloured markers depict pattern observed (see key), see text for detailed description of the succession. Numbers represent the percentage that each facies comprises each sedimentary log. The height of each log represents the relative thickness of each succession. Asterisked logs possess poor exposure. Cross-section is hung from a theoretical maximum progradation datum due to the lack of stratigraphic markers within the Salt Wash.

Fig. 3 – Example of Pattern DP from Caineville. Note the sharp and abrupt contact of proximal facies onto distal deposits.

Fig. 4 – Example of Pattern DMP from Kane Springs. Note the thickening upward succession from distal, to medial to proximal facies.

Fig. 5 – Example of Pattern DM from Colorado National Monument. Note the low relief on the erosional base of the channel sandstone.

Fig. 6 – Spatial distribution of channel belt percentage vertical patterns. Coloured markers depict pattern observed, see text for detailed explanation of patterns. On each graph the Y axis represents section thickness (m), and the X axis percentage of succession (%).

Fig. 7 – Spatial distribution of channel belt thickness vertical patters. Coloured markers depict pattern observed, see text for detailed explanation of patterns. On each graph the Y axis represents section thickness (m), and the X axis channel belt thickness (in metres).

(A) **Table list**

Table 1 – Characteristics of facies associations and facies domains. Facies association applies specifically to the Salt Wash (taken from Owen *et al.* 2015b). Description of facies domains sourced from Nichols & Fisher (2007); Weissmann *et al*., (2011); Trendell *et al*., (2013); and Weissmann *et al*., (2013). Sand percentages taken from Owen *et al*., (2015b).

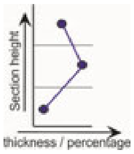
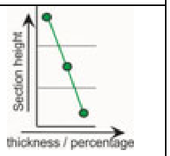
Table 2 – Description of the different patterns observed in the vertical analysis of channel belt presence and thickness.

Table 3 – Percentage of channel belts present within the lower, middle and top third of each succession. Pattern relates to patterns described within text and observed in Fig. 6.

Table 4 – A comparison between the different criteria analysed. ✓= a successive progradation through a succession, - = partial progradation expressed within a succession, ✗ = no evidence for

progradation. Locations are listed in decreasing distance from the estimated apex from top to bottom.

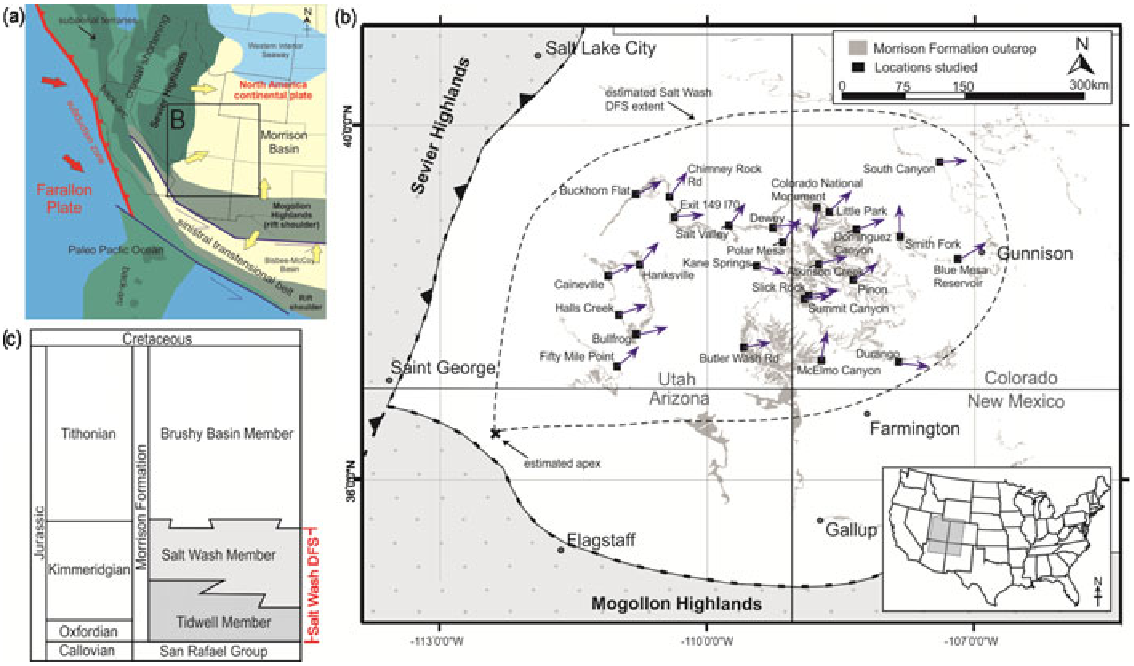
Facies Associations	**Characteristics**
Amalgamated channel belt	• Fine to pebbly sandstones. • Trough cross-bedding, current ripples, planar cross-bedding, horizontal lamination, and accretion surfaces (downstream and lateral) present. • One to four stories observed. • Form large scale tabular sheet sandstones (26 thick and 10's Km wide). • Compose 37% of the system.
Isolated channel	• Fine sand to granular sandstones. • Trough cross-bedding, current ripples, planar cross-bedding, horizontal lamination, and lateral accretion surfaces present. • Range in thickness from 5 cm to 4.7 m, and extend laterally up to 400 m. • Simple lens-shaped sandstones with a clear channel geometry. • Compose 4% of the system.
Floodplain	• Composed of interbedded sandstones (up to coarse sandstone) and mudstones. • Tabular to undulating form. • Paleosols present. 1) Red-brown well-drained argillic calcisols. 2) Green-gray poorly-drained protocols. Burrows, rootlets and dinoturbation most prolific in well-drained paleosol, but still present in poorly-drained paleosols. • Compose 57% of the system.
Lacustrine	• Composed of gypsum deposits, fresh-water carbonate deposits and wave-rippled sandstones and horizontally laminated mudstones and sandstones. • Tabular geometries. • Maximum thickness of 2.9m and 1 km lateral extent. • Compose 3% of the system.
Facies domain	**Characteristics**
Proximal	• Coarsest grain size (i.e. where coarse sands and gravels are present). • Dominated by amalgamated channel belt deposits. • Limited preservation of fine material. • High sand percentage (100-70% on the Salt Wash DFS).
Medial	• Channel belt deposits are separated by distinctive packages of fine material. • Moderate sand percentage (70-40% on the Salt Wash DFS).
Distal	• Channel belt deposits largely absent with sparse ribbon channels present. • Succession dominated by fine-grained material (floodplain/ lacustrine deposits). • Low sand percentage (<40% on the Salt Wash DFS).

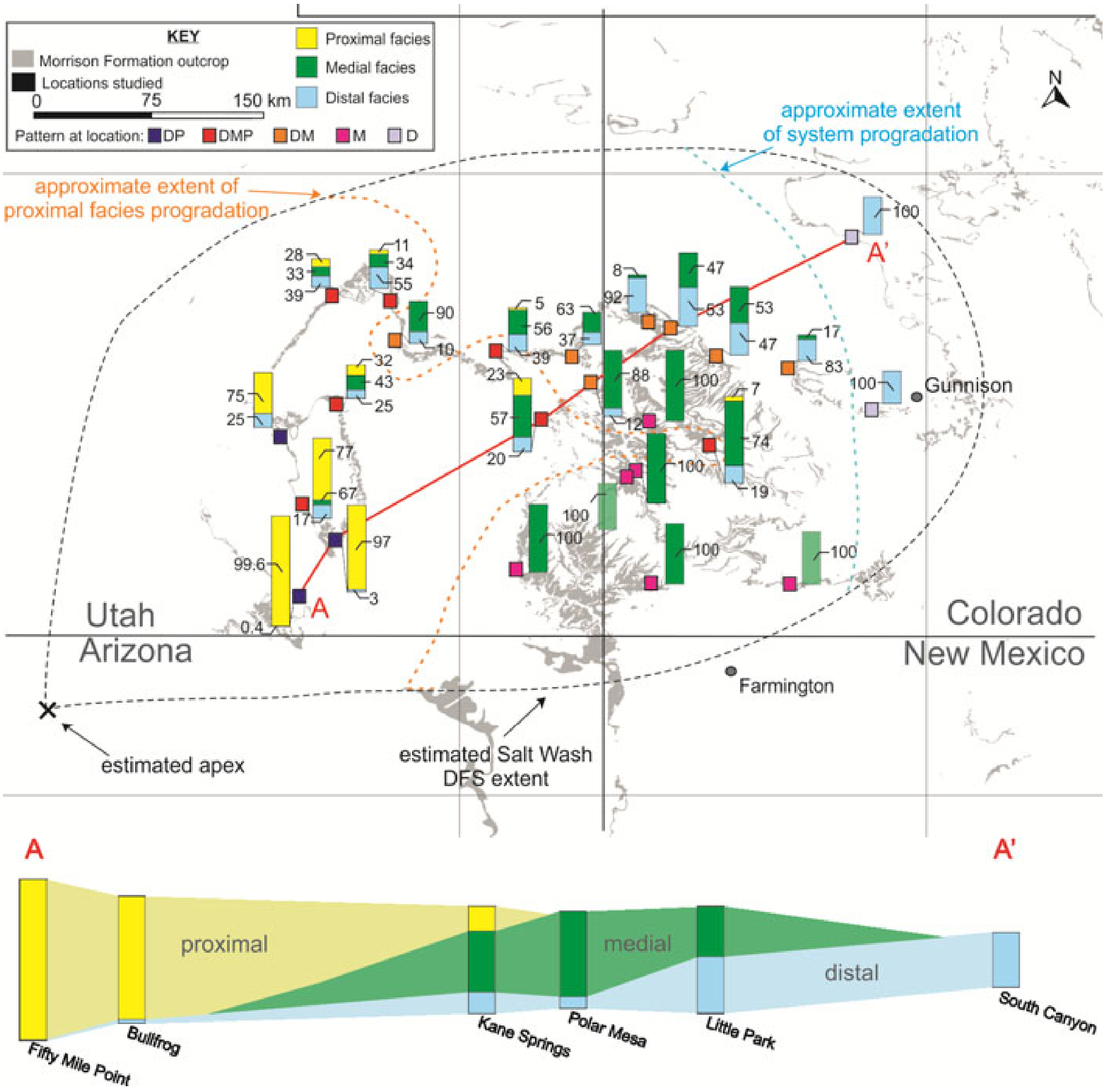
Pattern	Description	Example
1	A successive increase in values is observed from the bottom, to middle to top third of the succession.	
2a	An initial increase in value from the bottom to middle third of the succession. A decrease in from the middle to top third follows. The value in the top third is higher than that of the bottom third.	
2b	An initial increase in from the bottom to middle third of the succession. A decrease in value is present from the middle to top third. The value in the top third is however lower than that in the bottom third.	
3a	A decrease in value from the bottom to middle third. An increase in values from the middle to top third is present, with the top third being higher in value than the bottom third.	
3b	A decrease in value is from the bottom to middle third. An increase in values from the middle to top third is present, with the top third being lower in value than the bottom third.	
4	A successive decrease in values from the bottom to top third.	

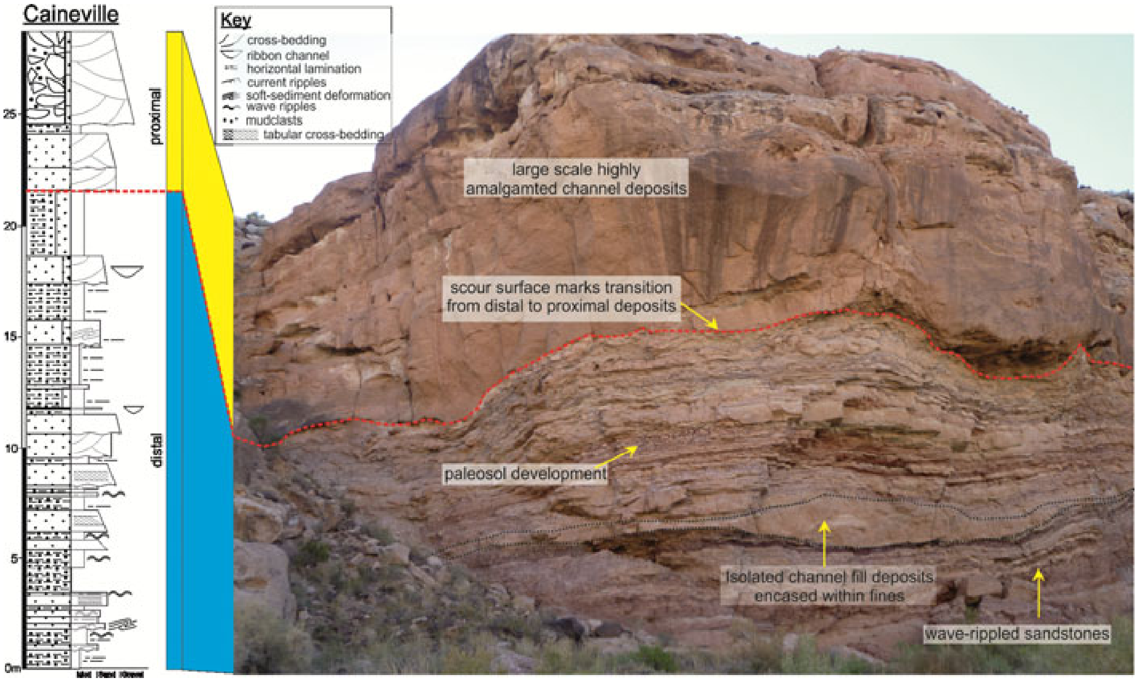
Locality	Channel belt percentage			Pattern
	Lower third	Middle third	Upper third	
Fifty Mile Point	56	66	63	2
Bullfrog	67	54	79	3
Halls Creek	23	49	72	1
Caineville	25	74	60	2
Hanksville	16	20	97	1
Butler Wash Rd	34	62	63	1
McElmo Canyon	21	59	30	2
Exit 149 I70	13	44	49	1
Buckhorn Flat	0	46	84	1
Chimney Rock Rd	0	16	40	1
Salt Valley	0	37	34	2
Kane Springs	22	23	85	1
Summit Canyon	62	52	30	4
Slick Rock	32	53	56	1
Durango	0	24	37	1
Pinon	10	34	59	1
Atkinson Creek	22	36	26	2
Polar Mesa	5	52	57	1
Dewey	0	18	33	1
Colorado National Monument	0	0	23	1
Little Park	0	30	20	2
Dominguez Canyon	0	20	33	1
Smith Fork	0	0	52	1

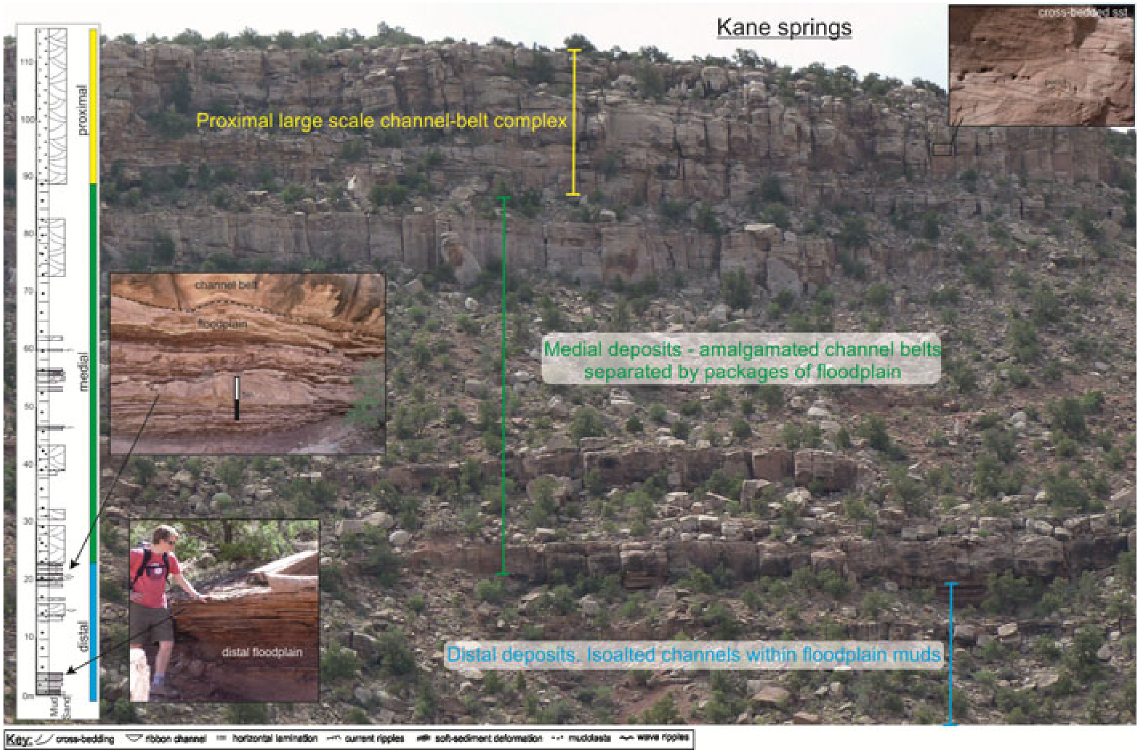
Location	Facies stacking pattern		Channel belt % pattern		Mean channel belt thickness pattern	
Fifty Mile Point	DP	-	2	-	4	×
Bullfrog	DP	-	3	-	3	-
Halls Creek	DMP	✓	1	✓	1	✓
Caineville	DP	-	2	-	2b	-
Hanksville	DMP	✓	1	✓	1	✓
Butler Wash Rd	M	×	1	✓	3b	-
McElmo Canyon	M	×	2	-	2b	-
Exit 149 I70	DM	-	1	✓	1	✓
Buckhorn Flat	DMP	✓	1	✓	1	✓
Chimney Rock Rd	DMP	✓	1	✓	1	✓
Salt Valley	DMP	✓	2	-	2	-
Kane Springs	DMP	✓	1	✓	1	✓
Summit Canyon	M	×	4	×	4	×
Slick Rock	M	×	1	✓	3	-
Durango	M	×	1	✓	1	✓
Pinon	DMP	✓	1	✓	1	✓
Atkinson Creek	M	×	2	-	2	-
Polar Mesa	DM	-	1	✓	2	-
Dewey	DM	-	1	✓	2	-
Colorado National Monument	DM	-	1	✓	1	✓
Little Park	DM	-	2	-	2	-
Dominguez Canyon	DM	-	1	✓	1	✓
Smith Fork	DM	-	1	✓	1	✓

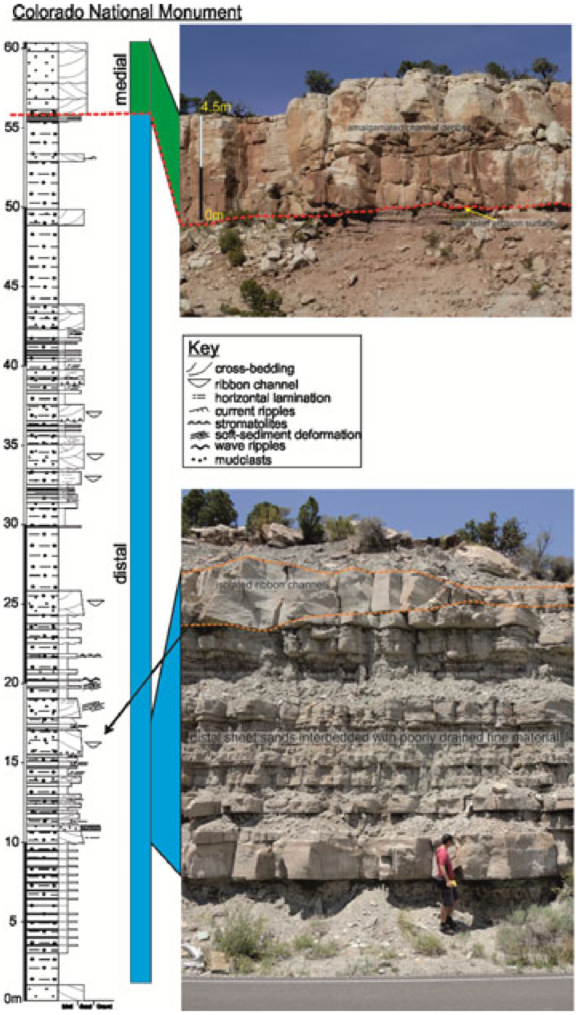
Blue Mesa Reservoir	D	×	N/A	N/A
South Canyon	D	×	N/A	N/A

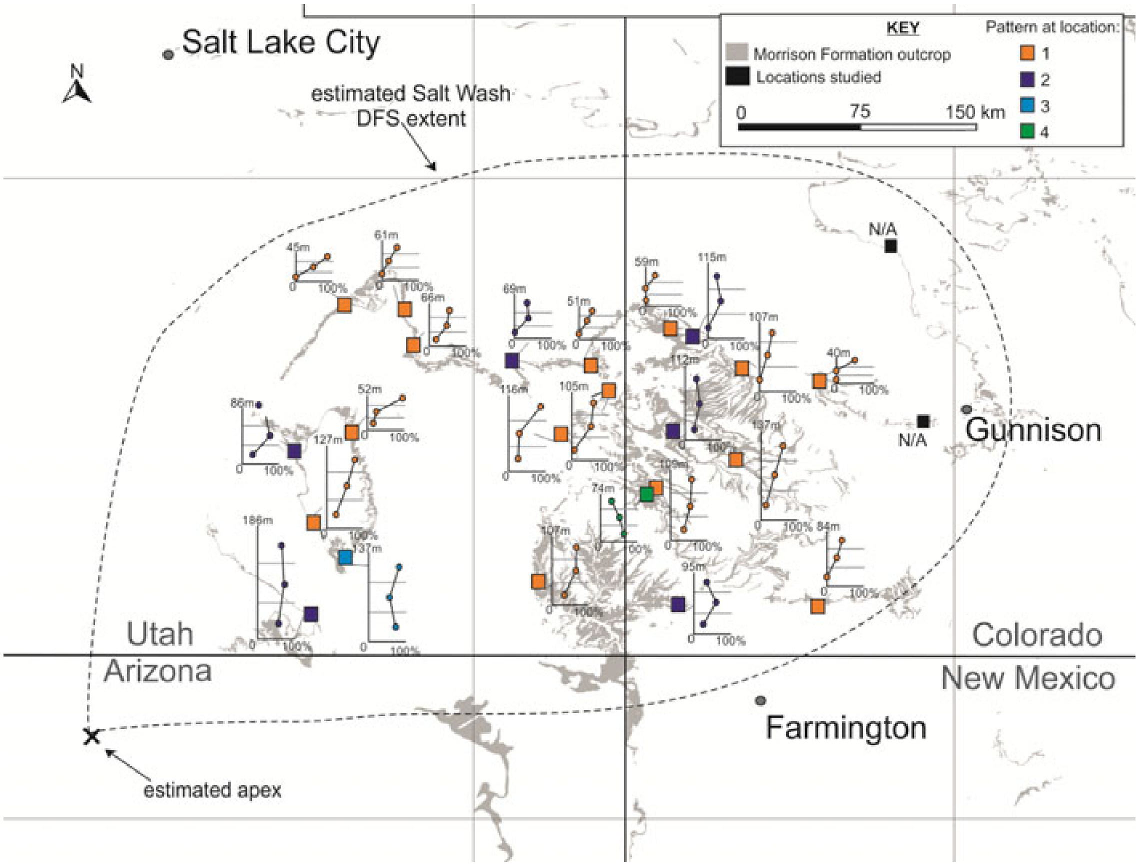


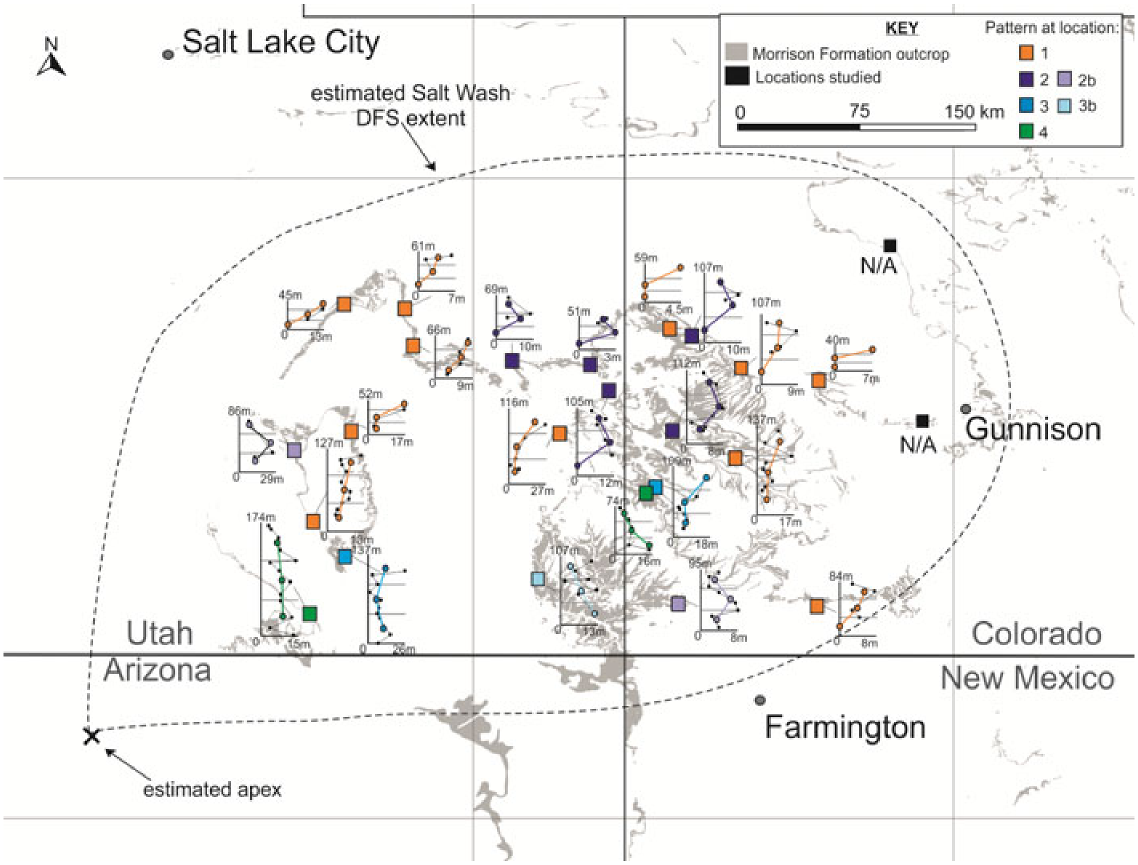

KEY
Morrison Formation outcrop
Locations studied
0
75
150 km
Proximal facies
Medial facies
Distal facies
Pattern at location: DP DMP DM M D
N
approximate extent of system progradation
approximate extent of proximal facies progradation
28
33
39
11
34
55
90
10
5
56
39
63
37
92
8
47
53
53
47
17
83
100
Gunnison
32
43
25
75
25
23
57
20
88
12
100
7
74
19
77
67
17
97
3
99.6
0.4
100
100
100
100
A
A'
Utah
Arizona
Colorado
New Mexico
Farmington
estimated apex
estimated Salt Wash DFS extent
A
A'
proximal
medial
distal
Fifty Mile Point
Bullfrog
Kane Springs
Polar Mesa
Little Park
South Canyon


Caineville
Key
cross-bedding
ribbon channel
horizontal lamination
current ripples
soft-sediment deformation
wave ripples
mudclasts
tabular cross-bedding
proximal
distal
0m
5
10
15
20
25
Mud
Sand
Gravel
large scale highly amalgamted channel deposits
scour surface marks transition from distal to proximal deposits
paleosol development
Isolated channel fill deposits encased within fines
wave-rippled sandstones


Kane springs
cross-bedded sst.
Proximal large scale channel-belt complex
Medial deposits - amalgamated channel belts separated by packages of floodplain
Distal deposits. Isoalted channels within floodplain muds
channel belt
floodplain
distal floodplain
proximal
medial
distal
0m
10
20
30
40
50
60
70
80
90
100
110
Mud
Sand
Key: cross-bedding
ribbon channel
horizontal lamination
current ripples
soft-sediment deformation
mudclasts
wave ripples


Colorado National Monument
60
55
50
45
40
35
30
25
20
15
10
5
0m
medial
distal
4.5m
0m
amalgamated channel deposits
Key
cross-bedding
ribbon channel
horizontal lamination
current ripples
stromatolites
soft-sediment deformation
wave ripples
mudclasts
isolated ribbon channels
distal sheet sands interbedded with poorly drained fine material


Salt Lake City
N
estimated Salt Wash DFS extent
KEY
Morrison Formation outcrop
Locations studied
0
75
150 km
Pattern at location:
1
2
3
4
N/A
N/A
Gunnison
Utah
Arizona
Colorado
New Mexico
Farmington
estimated apex
45m
61m
66m
69m
51m
59m
115m
107m
40m
112m
116m
105m
52m
86m
127m
137m
100m
74m
107m
186m
137m
95m
84m
0
100%


N
Salt Lake City
estimated Salt Wash DFS extent
KEY
Morrison Formation outcrop
Locations studied
0
75
150 km
Pattern at location:
🟧 1
■ 2
■ 2b
■ 3
■ 3b
🟩 4
N/A
N/A
Gunnison
61m
7m
45m
15m
66m
9m
69m
10m
51m
3m
59m
4.5m
107m
10m
107m
9m
40m
7m
112m
8m
137m
17m
86m
29m
52m
17m
127m
10m
116m
27m
105m
12m
109m
18m
74m
16m
174m
15m
137m
26m
107m
13m
95m
8m
84m
8m
Utah
Arizona
Colorado
New Mexico
Farmington
estimated apex