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# Syn-sedimentary salt diapirs as a control on fluvial system evolution: an example from the proximal Permian Cutler Group, SE Utah, U.S.A.

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## Abstract

Loading of subsurface salt during accumulation of fluvial strata can result in halokinesis and the formation of salt pillows, walls and diapirs. Such movement may eventually result in the formation of salt-walled mini-basins, whose style of architectural infill may be used to infer both the relative rates of salt-wall growth and sedimentation, and the nature of the fluvial system response to salt movement. The Salt Anticline Region of the Paradox Basin of SE Utah comprises a series of elongate salt-walled mini-basins, arranged in a NW-trending array. The bulk of salt movement occurred during deposition of the Permian Cutler Group, a NE-derived, SW-prograding wedge of predominantly quartzo-feldspathic clastic strata. The sedimentary architecture of selected mini-basin fills has been determined at high resolution through outcrop study. Mini-basin centres are characterized by multi-storey fluvial channel elements arranged into stacked channel complexes, with only limited preservation of overbank elements. At mini-basin margins, thick successions of fluvial overbank and sheet-like elements dominate in rim-syncline depocentres adjacent to salt walls; many such accumulations are unconformably overlain by single-storey fluvial channel elements that accumulated during episodes of salt-wall breaching. The absence of gypsum clasts suggests that sediment influx was high, preventing syn-sedimentary surface exposure of salt. Instead, fluvial breaching of salt-generated topography reworked previously deposited Cutler Group sediments atop growing salt walls. Palaeocurrent data indicate that southwesterly fluvial dispersal early in the history of basin infill was subsequently diverted to a westerly and ultimately northwesterly direction as the salt walls grew to form topographic barriers. Late-stage retreat of the Cutler fluvial system coincided with construction and accumulation of an aeolian system, recording a period of heightened climatic aridity. Aeolian sediments are preserved in the lees of some salt walls demonstrating that halokinesis played a complex role in the differential trapping of sediment.

**Keywords: halokinesis, fluvial; aeolian; architecture, depositional model; mini-basin; salt**

## Introduction

Salt-walled mini-basins evolve via the halokinetic movement of subsurface salt layers in response to salt withdrawal and salt-wall growth, driven by progressive contemporaneous in-basin sedimentation and associated sediment loading. Mini-basins are common in the geological record, with documented occurrences recorded, for example, from the Central North Sea (Hodgson *et al*., 1992; McKie & Audretsch, 2005; Mckie *et al*.,2010), the Gulf of Mexico (Rowan & Weimer, 1998; Sinclair &Tomasso, 2002), the La Popa Basin, northeast Mexico (Giles & Lawton, 2002; Rowan, *et al*., 2003; Andrie, *et al*., 2012; Rowan *et al*., 2012; Giles & Rowan, 2012) and the Salt Anticline Region of the Paradox Basin of SE Utah (Trudgill *et al*., 2004;Paz, 2006; Lawton & Buck, 2006; Trudgill& Paz, 2009; Kluth & DuChene, 2009; Rasmussen & Rasmussen, 2009; Trudgill, 2011).

The growth of salt diapirs typically exerts a significant influence on the development of contemporaneously active fluvial systems and their preserved stratigraphy and architecture. Although the mechanics of salt movement in response to sediment loading are now relatively well understood from a structural perspective (e.g., Talbot & Jackson, 1987; Ge *et al*., 1997; Hudec & Jackson, 2007), less is known about the detailed sedimentological response to syn-sedimentary salt movement (Aschoff & Giles, 2005; Madof *et al*., 2009). Whilst some studies have been concerned with the style of development and preservation of fluvial architecture in salt-walled mini-basins (e.g., Bromley, 1991; Barde *et al*., 2002; Lawton & Buck, 2006; Mathews *et al*., 2007; Andrie *et al*., 2012; Giles& Rowan, 2012; Banham& Mountney, in press),much remains to be understood about the relationship between sedimentation and halokinesis. Previous studies demonstrate that the preserved thickness of sediment infill typically exhibits significant variation across individual salt-walled mini-basins: the thickness of the basin-fill succession commonly increases significantly adjacent to salt diapirs where so-called rim synclines have developed in response to localized enhanced salt withdrawal at depth (Lehner, 1969; Trudgill *et al*., 2004; Trudgill, 2011). Whilst the general term ‘salt mini-basin’ refers to the area between two salt structures, across which accommodation may vary, the term ‘rim syncline’ refers specifically to localized depocentres adjacent to salt structures where accommodation is locally enhanced. Both passive folding of sediments adjacent to salt walls and the partial reworking of previously deposited strata can assist in discerning the relative timing of sedimentation and deformation of stratal packages (Jackson & Talbot 1986; Trudgill *et al*., 2004; Vendeville, 2005; Trudgill& Paz, 2009; Trudgill 2011;Fuschs*et al*., 2011).

Syn-sedimentary movement of salt to generate a surface topographic expression can impact fluvial flow pathways and has been demonstrated to divert or even reverse fluvial systems that are captured within the confines of evolving salt mini-basins. This influence is demonstrated in both modern examples, such as the Zagros Basin of Iran (Jahani *et al*., 2007), and in ancient examples, such as Triassic and Permian systems, including those in SE Utah (Mathews *et al*., 2007; Trudgill& Paz, 2009; Trudgill, 2011).and the East Texas Diapir Province (Seni & Jackson, 1983)

Salt movement can cause dramatic variations in the rate of accommodation space creation, whereas fluvial processes dictate how that space is filled as sedimentation proceeds; individual lithofacies and the larger-scale fluvial elements composed of these facies typically undergo significant lateral changes over relatively short distances in salt mini-basins and packages of elements tend to vary temporally as salt basins evolve (Seni & Jackson, 1983; Mohr *et al*., 2005; Trudgill & Paz, 2009; Mathews *et al*., 2007; Trudgill, 2011; Fuchs *et al*., 2011; Andrie, *et al*., 2012; Giles & Rowan, 2012). Thus, syn-sedimentary salt mini-basin evolution plays a significant role in governing resultant preserved fluvial stratigraphy. Larger-scale halokinetic sedimentary packages are commonly recognisable in both seismic and in outcrop (e.g., Giles & Lawton, 2002; Trudgill *et al*., 2004; Kluth & DuChene, 2009; Giles & Rowan, 2012), and generally record both the history of progradation of sedimentary systems into a mini-basin area and the sedimentary response to syn-sedimentary salt-movement. Actively evolving salt basins influence the development of fluvial systems in many climatic regimes and sedimentary settings (Rowan & Weimer 1998; Ray, 1988; Mohr *et al*., 2005; Mathews *et al*., 2007; Madof *et al*., 2009), such that mini-basin sedimentary fills represent a complex record of both the history of salt-basin evolution and also the climatic setting in which the fluvial system developed.

This paper presents results of an outcrop-based sedimentological study of the proximal, predominantly fluvial Permian Cutler Group (undifferentiated) in the Salt Anticline Region of the Paradox Basin. The aim of this study is to propose a high-resolution tectono-stratigraphic model for the evolution of salt-walled mini-basins by demonstrating the detailed response of fluvial systems to ongoing salt-wall growth and associated salt mini-basin subsidence. Specific objectives are: (i) to determine the extent to which syn-sedimentary salt movement resulted in fluvial diversion around salt-generated topography, versus breaching of that topography; (ii) to propose a generic model with which to predict and account for architectural variations within and between salt-walled mini-basins; (iii) to consider the implications for applied subsurface reservoir analysis. This research is significant because laterally continuous and extensive outcrop exposure has enabled a detailed, high-resolution study of sediment architecture and sandbody distribution. The study has direct implications for subsurface interpretation of sandbodies present around salt structures, and wider implications for understanding fluvial response to salt-induced generation of topography. More broadly, patterns of fluvial network development continue to be a topical focus of research (e.g., Hartley *et al*., 2010; Cain & Mountney, 2011); this study demonstrates that the morphology and stratigraphy of distributive fluvial systems and their preserved successions can be highly complex in response to a range of external controls that operate over a range of spatial and temporal scales, including macro-scale responses to tectonically driven regional subsidence and sediment input, meso-scale response to halokinetic effects(e.g., rates of salt withdrawal from beneath subsiding mini-basins and associated rates of salt-wall uplift), meso-scale climatic controls that might be manifested as localised changes in the style of sedimentation within evolving mini-basins (Banham& Mountney, 2013 a,b,c).

## Sedimentary response to salt diapirism

The impact of salt movement has long been studied from a structural standpoint. Trusheim (1960) described styles of salt-structure developed under varying conditions of loading by overburden, recognising salt pillows (relatively low-amplitude swells), stocks (towers or pillars of salt) and walls (elongate and relatively laterally continuous features). The style of deformation of salt at depth is dependent on the type and orientation of stresses placed upon them (Jackson & Talbot, 1986; Hudec & Jackson, 2007; Fuchs *et al*., 2011) and on variations in rates of sedimentation of adjacent and overlying strata. These variables give rise to different shapes of diapir wall.

Much prior work has been undertaken to define the large scale fill geometries of salt-walled mini-basins (e.g., Trudgill *et al*., 2004; Trudgill& Paz, 2009; Kluth & DuChene, 2009; Trudgill, 2011; Giles & Rowan, 2012). Sedimentary packages recognized in seismic and in outcrop can be shown to record discrete accumulations formed in response to temporally discrete episodes of salt movement. Such packages are recognized in the subsurface (seismic & well data) in various basins, including in the Cutler Group of the Paradox Basin(e.g., Trudgill *et al*., 2004; Banbury, 2006;Kluth&DuChene, 2009), in outcropping sections of the La Popa Basin of northeast Mexico (Giles & Rowan, 2012; Andrie *et al*., 2012), and in outcrop sections of the Salt Anticline Region of Utah (e.g., Trudgill, *et al*., 2004; Mathews, *et al*., 2007; Trudgill& Paz, 2009; Kluth & DuChene, 2009; Giles & Rowan, 2012). Halokinetic sequences are typically represented by discrete packages of strata that are commonly bounded by a local basal unconformity in the vicinity of nearby salt structures and recognized by onlap relationships of overlying strata onto underlying strata; halokinetic packages generally thin toward salt structures (e.g., Giles & Lawton 2002; Trudgill *et al*., 2004; Banbury, 2006; Giles & Rowan, 2012).

Kluth & DuChene (2009) present examples from the Cutler Group to demonstrate a characteristic mini-basin fill-geometry comprising a series of seismically resolvable packages, and they propose a ‘heel-and-toe’ model to describe the geometrical make-up of the salt mini-basins: sediments deposited prior to salt movement at the side of the mini-basin proximal to the sediment source are later rotated basinward in response to partial salt withdrawal to forma ‘heel’ geometry. Subsequent sedimentation preferentially occurs at the basinward edge (the thinnest part) of the 'heel' wedge, where accommodation is greatest due to salt-withdrawal, thereby creating a 'toe' geometry. This style of salt-sediment interaction is also recognized by Trudgill *et al*., (2004), Trudgill& Paz (2009) and Trudgill(2011) who demonstrate a systematic basinward migration of depocentres through time.

However, relatively few detailed outcrop studies have been undertaken previously to characterise the sedimentary architecture and sand-body distribution in fluvially infilled, salt-walled mini-basins. Matthews *et al*., (2007) demonstrate a positive feedback loop between sediment loading and salt movement in the fluvial Chinle Formation (Triassic) of the Salt Anticline Region of SE Utah, whereby increased sediment loading promoted enhanced rates of salt withdrawal. This salt withdrawal locally increased accommodation and enabled further sediment accumulation, which itself drove additional loading (Doelling, 1982; Lawton & Buck, 2006). Other outcrop based studies undertaken in the Salt Anticline Region (e.g., Banbury, 2006; Bullar, 2009; Lawton & Buck, 2009; Shock, 2012; Banham& Mountney, in press) are discussed below.

## Study location and geological setting

The sedimentology and stratigraphy of a series of salt-walled mini-basins have been examined in the Salt Anticline Region, also known as the Salt Mini-Basin region (*sensu* Shoemaker *et al.*, 1958), of the proximal part of the Paradox foreland basin of southeast Utah and southwest Colorado, a region of the Paradox fold-and-fault belt (Kelley, 1968). The study area is located ~20 km NE of the town of Moab in the region between Richardson Amphitheater and Fisher Towers in the north, and Castle Valley and Big Bend in the south (Figs. 1& Fig. 2). Previous studies of structural salt mini-basin development in this region have included work by Trudgill *et al*., (2004), Lawton & Buck (2006), Mathews *et al*., (2007)Kluth & DuChene (2009), Rasmussen & Rasmussen (2009), Trudgill& Paz (2009), Trudgill (2011), Giles& Rowan (2012) and Banham& Mountney (in press).

The Paradox Basin is located in the Four Corners Region of the southwest USA (Fig. 1). The foreland basin is an elongate NW-trending feature that developed adjacent to the Uncompahgre Uplift, one of a series of blocks that formed the Ancestral Rocky Mountains (Baker *at al*., 1933; Mallory, 1972; Baars, 1979; Barbeau, 2003). During Pennsylvanian and Permian times, a 4,000 m-thick clastic wedge accumulated in a foredeep adjacent to the SW flank of the Uncompahgre Uplift. There is ongoing debate as to the source of the thick succession of Permian strata that is preserved; the succession is likely too thick to have been solely derived from the Uncompahgre Uplift and other Ancestral Rocky Mountain blocks may have contributed (Kluth & DuChene, 2009;

Blakey, 2009). Recent work (e.g., Dickinson &Gehrels, 2003; Gehrels *et al*., 2011) suggests that rivers likely traversed the continent in Permian times, bringing sediments from further afield, possibly including a catchment that drained the Appalachians (Kluth & DuChene, 2009; Blakey, 2009; Gehrels *et al*., 2011).However, the work by Blakey (2009)Gehrels *et al*., (2011) and additionally by Thomas (2011) and Parr (2012) argue that the Cutler Group (undifferentiated) sediments in the proximal Paradox Basin were predominantly sourced from the Uncompahgre Uplift and associated progradation of the large alluvial fans dominated over sediment supplied by axial rivers along strike of the orogen front.

Over time, the basin accumulated a thick succession of carbonate, halite, potash and clastic sediments of mixed shallow-marine, fluvial and aeolian affinity. Nonmarine clastic sedimentation became dominant in the latter stages of the basin filling, and such deposits are represented by the upper part of the Cutler Group (Fig. 3). By contrast, lower units of basin fill are represented by the Hermosa Group, which underlies the Cutler Group. These lower units comprise the Paradox Formation, a succession of mixed evaporites (halite, gypsum, anhydrite and potash), black shales and carbonates (Baker *et al*., 1933; Hite & Buckner, 1961; Baars *et al*., 1967), and the Honaker Trail Formation, a succession of limestone, sandstone and siltstone of mixed fluvial and shallow-marine affinity (Elston *et al*., 1962; Condon, 1997; Williams, 2009).

In the easternmost part of the basin, east of Moab, deposition of clastic material, throughout deposition of the Cutler Group was influenced by diapirism of previously deposited salt layers of the older Paradox Formation (Trudgill, 2011); a variety of salt-related deformation structures are present as a series of salt-walled mini-basins in this region (Fig. 4).The Salt Anticline Region comprises 8 discrete NW-trending salt diapirs and walls, which separate a series of 6 mini-basins (Figs. 1&4). Of these salt structures, the Onion Creek, Fisher Valley, Cache Valley, Castle Valley and Moab Valley salt-wall structures, and the Fisher, Parriott and Big Bend mini-basins have been the focus of this study. Each salt wall is2 to 5 km wide and 15 to 40 km long (Figs.1&4); the mini-basins present between salt walls are each 10 to 15 km wide. Sediment transfer zones are present in the form of linking mini-basins that extend between the noses of the salt-diapirs, one such example being the Big Bend mini-basin, which was an important conduit for fluvial sedimentation in the Permian and a local depocentre in the late Triassic (Mathews *et al*., 2007).

The salt structures in the Salt Anticline Region grew by down-building (Kluth & DuChene, 2009), which required the structures to have been at or near the surface throughout their growth history, and which resulted in several types of syn-sedimentary interaction (Trudgill, *et al*., 2004; Banbury, 2006; Lawton& Buck, 2006, Trudgill, 2011). Sediment folding likely occurred passively as the salt rose relative to surrounding sediments resulting in folding of sediments above the roof of, and drape folding adjacent to the salt structure in a style similar to that observed in sediments in the La Popa Basin of northeast Mexico (Rowan, *et al*., 2003; Giles & Rowan, 2012).

The Cutler Group comprises intercalated packages of shallow marine (carbonate), aeolian and fluvial strata (Campbell 1977, 1979; Stanesco & Campbell, 1989; Stanesco *et al*., 2000; Dubiel *et al*., 2009), with sediments of nonmarine origin sourced principally from the eroding Uncompahgre Uplift (Mack & Rasmussen 1984; Doelling *et al*., 1988; Condon, 1997). In distal parts of the Paradox Basin, the Cutler Group stratigraphy is divided into the lower Cutler beds, a succession of mixed shallow-marine, aeolian and fluvial affinity (Loope *et al*., 1990; Williams, 2009; Jordan & Mountney, 2010, 2012), the Cedar Mesa Sandstone, which is of predominantly aeolian affinity (Loope, 1984; Mountney &Jagger, 2004; Mountney, 2006, 2012; Langford *et al*., 2008), and the uppermost Organ Rock Formation, which is of predominantly fluvial origin but with subordinate aeolian influence (Cain & Mountney, 2009, 2011). The Permian Cutler Group succession is capped in medial and distal parts of the Paradox Basin by the White Rim Sandstone, a predominantly aeolian succession with some evidence of marine and fluvial activity (Chan &Huntoon, 1984; Huntoon& Chan, 1987; Komola & Chan, 1988); the White Rim Sandstone is mostly absent from more proximal parts of the basin having been removed by erosion associated with the generation of the base Triassic unconformity. In the study area this unconformity is located at the base of the Moenkopi Formation that overlies the Cutler Group (Banham & Mountney, 2013b).

In proximal parts of the basin, including the study area, the Cutler Group is undivided (undifferentiated), though it is possible to recognize locally both aeolian- and fluvial-dominated parts of the succession that correspond informally to stratigraphic levels approximately equivalent to the Cedar Mesa Sandstone, the Organ Rock Formation and the White Rim in more distal parts of the basin (Condon, 1997). Although some authors (e.g., Rasmussen & Rasmussen, 2009) have used the name ‘Organ Rock Formation’ to describe the fluvially dominated Undifferentiated Cutler Group succession in the proximal part of the basin, this is potentially confusing since this is the formal name reserved for the tongue of fluvial strata lying above the Cedar Mesa Sandstone in more medial parts of the basin. Similarly, the names White Rim Sandstone and “White Rim Sandstone equivalent” have been used by Rasmussen & Rasmussen (2009) to describe both aeolian and mixed aeolian-fluvial successions in the uppermost part of the Undifferentiated Cutler Group succession in proximal parts of the basin. In this study we use the term ‘Undifferentiated Cutler Group’ – as coined by Newberry(1861),used subsequently by Dane (1935) and Doelling ( 2002a) and Doelling et al., (2002) –to refer to the thick package of clastic strata that encompasses the entire Cutler Group succession in proximal parts of the Paradox Basin.

## Overview of previous work in the Salt Anticline Region

Numerous studies have been undertaken on both the sedimentology and stratigraphy of the Undifferentiated Cutler Group (and younger successions), and on the structural development of the salt-walled mini-basins in the study area (e.g., Elston et al., 1962; Mack & Rasmussen, 1984; Hazel, 1994;Trudgill *et al*., 2004; Lawton & Buck, 2007; Rasmussen & Rasmussen 2009, Trudgill and Paz, 2009; Kluth & DuChene 2009; Cain & Mountney, 2009, 2011; Trudgill, 2011; Giles & Rowan, 2012). Although previous workers have documented and mapped the deformation structures associated with salt-diapir growth and collapse in detail – particularly the Onion Creek diapir (e.g., Doelling, 2002b; Trudgill, 2011) –hitherto there has been little detailed evaluation of the sedimentological response to salt-walled mini-basin evolution.

Salt movement in the Paradox Basin was conventionally thought to have begun during the late Pennsylvanian, in response to loading following progradation and accumulation of the Honaker Trail Formation (Elston *et al*., 1962; Condon, 1997; Williams, 2009). However, Kluth & DuChene (2009) use geometrical and architectural relationships between the Uncompahgre thrust zone and the sediments in the proximal part of the basin to demonstrate that the Honaker Trail sediments were deposited after salt deposition but prior to the onset of orogenesis (i.e., pre-Uncompahgre Uplift), whereas the Undifferentiated Cutler Group sediments were deposited syn-orogenically, at least in the part of the Salt Anticline Region studied here, though not across the entire of the Uncompahgre Front, some of which extended beyond the limit of salt accumulation and influence (Trudgill, 2011).Cross sections constructed from analyses of well and seismic data across the Salt Anticline Region by Rasmussen & Rasmussen (2009) and Kluth & DuChene (2009) demonstrate that sediment accumulated in a proximal trough area adjacent to the Uncompahgre Uplift with the Undifferentiated Cutler Group thickening toward the proximal salt walls in a manner indicative of syn-orogenic and syn-halokinetic sedimentation (Kluth & DuChene, 2009). Within the mini-basin area, notable thickness variations in the Cutler and overlying Moenkopi and Chinle formations occur over <5 km distances and the mini-basins have asymmetric cross-sections (e.g., Trudgill *et al*., 2004; Kluth & DuChene,2009; Banham & Mountney, 2013a).

During Cutler accumulation, progressive syn-sedimentary movement of salt coupled with coeval mini-basin infilling resulted in gradual migration of depocentres to the SW as the location of maximum salt withdrawal shifted (e.g., Trudgill *et al*., 2004; Trudgill, 2011). Paz, (2006), Trudgill and Paz (2009) and Trudgill (2011) used isopach maps to demonstrate episodic fluvial progradation during the accumulation of a stratal packages present both within the study area and farther east (Fig. 1).Thickness variations *within* packages arose as a consequence of differential salt withdrawal and progressive infilling of rim synclines adjacent to salt-walls.

At a broad scale, mini-basin infill is characterized by several seismically resolvable packages of SW-dipping strata; these packages also thin onto the flanks of salt-walls as a result of salt withdrawal and diapirism (Doelling *et al*., 1988; Trudgill *et al*., 2004; Trudgill& Paz, 2009; Rasmussen & Rasmussen, 2009; Trudgill, 2011). Sediment packages are thickest in depocentres to the NE side of salt-walls where salt withdrawal generated the greatest accommodation; this is most notable to the north of the Onion Creek salt diapir (Fig. 4). Preserved sediment packages experienced variable amounts of both syn- and post-depositional passive folding due to ongoing salt diapirism (Kluth & DuChene, 2009). Immediately adjacent to the salt-walls, at least 3 local unconformities are present and multiple stratal packages onlap and thin onto the flanks of the salt walls and onto the margins of older, tilted sediment packages (Banbury, 2006; Trudgill& Paz, 2009; Trudgill, 2011).

Although previous studies provide useful insight into the halokinetic packages preserved in the Undifferentiated Cutler Group succession(e.g., Kluth & DuChene, 2009; Trudgill, 2011), they do not detail the distribution of individual groups of sand bodies, nor consider palaeocurrent variations; neither do they attempt to distinguish or determine the distribution of architectural elements and lithofacies, though arrangements of such packages may have important implications for understanding sediment and salt movement and interaction. Such elements may include both channel complexes, as well as non-channelized fine-grained overbank elements that can compartmentalise or separate sand-bodies.

Combined sedimentological and tectono-stratigraphic studies of the Triassic Moenkopi and Chinle formations in the Salt Anticline Region demonstrate that salt-generated topography played an important role in influencing styles of fluvial sedimentation and preserved architecture within the salt mini-basins via diversion of fluvial flow and generation of localized depocentres (Lawton & Buck, 2006; Mathews *et al*., 2007; Banham& Mountney, 2013 a,b,c); this study assesses the role of salt-generated topography in influencing fluvial distribution pathways in the deposits of the Cutler Group.

## Methodology

This study is an outcrop based evaluation of the exposed part of the Undifferentiated Cutler Group. Seventy-four vertical sedimentological sections were measured across three mini basins, in locations ranging from adjacent to salt walls to the centres of mini-basins (see Fig. 2 for locations). In addition, architectural panels and photomontages representing a total of 5 km and 10 km of outcrop belt, respectively, have been collected to constrain lateral changes in architectural relationships. Architectural panels were recorded as scaled diagrams of near-vertical outcrops, and are used to demonstrate the two- and pseudo three-dimensional relationships between architectural elements, and changes in architectural style across the study area. Palaeocurrent data (1854 readings) were determined from the orientations of channel bases and trough axes, as well as from cross-bedding foreset dip-azimuths using the methods described by DeCelles et al., (1983) and Dasgupta (2002).

Vertical sedimentological sections, architectural panels, photomontages and palaeocurrent data were compiled and used to determine lateral and vertical variations in preserved fluvial and aeolian architecture, both within individual salt-walled mini-basins and between adjacent basins. Analyses of tectono-stratigraphic relationships evident in the preserved sedimentary architecture have enabled a series of depositional models to be devised that describe the spatio-temporal evolution of the Undifferentiated Cutler Group in relation to contemporaneous salt-walled mini-basin development. Statistical analyses of facies thicknesses and palaeocurrent data have allowed important trends to be quantified in terms of relationships between locations in each mini-basin.

The regional structural dip of the Undifferentiated Cutler Group stratigraphy, together with its unconformable relationship to the overlying Moenkopi Formation, means that no reliable and regionally identifiable datum exists from which to hang sedimentary-log profiles. A series of trigonometric calculations have been performed using differential GPS positioning, topographic heights, distances between logs, and the attitude (dip and strike) of local stratigraphy to determine the relative positioning of sedimentary sections, thereby enabling their placement on cross sections in a correct stratigraphic position within the mini-basins. This procedure has not been undertaken across the crests of the salt diapirs because the presence of zones of salt collapse in these areas has resulted in differential movement of originally adjacent packages of stratigraphy; this is not considered problematic since few substantial outcrops of the Undifferentiated Cutler Group exist directly over the crests of collapsed salt walls.

## Stratigraphy of salt-walled mini-basins

The following descriptions are based on fieldwork carried out in the study area depicted in Figures 1 and 2; facies and architectural-element descriptions relate to the exposed succession of the Undifferentiated Cutler Group. Twenty-two distinctive lithofacies are recognized in the Undifferentiated Cutler Group in the Salt Anticline Region. The principal facies types have been documented previously (e.g.,Doelling, 1981; Mack & Rasmussen, 1984; Langford & Chan, 1989; Condon, 1997; Cain & Mountney, 2009) and only summary descriptions and interpretations are provided here of the main facies associations (Table i, Fig. A in online supporting information) and architectural elements (Table ii, online supporting information Fig. A in online supporting information) in which these associations occur. Four distinctive architectural-element-groups (multi-storey channelized fluvial, single-storey channelized fluvial, non-channelized fluvial and aeolian) are recognized (Figs5a & b).The stratigraphy present in each of the salt mini-basins and associated with each of the salt walls in the study area is described in turn.Table1, Figure5and Figure B (in online supporting material)depict the variations in grain size, facies occurrence and architecture across the mini-basin area, and are compiled from data recorded in the 74 measured vertical sections.

## Fisher mini-basin

The Fisher mini-basin is the most northerly salt mini-basin in the area (Figs.1 & 4) and lies within the Fisher Towers 7.5' quadrangle (Doelling, 2002b). It is bounded on its southern side by the Onion Creek salt diapir structure and to the north by the Uncompahgre frontal thrust that defines the proximal limit of the Paradox Basin. The Undifferentiated Cutler Group attains a maximum thickness of ~2,500 m thick in this mini-basin (Doelling, 1981, 1988; Condon, 1997; Doelling *et al*., 2000; Trudgill& Paz, 2009; Kluth & DuChene, 2009; Trudgill, 2011). The exposed section ranges from ~1,000 m at Fisher Towers to zero just north of Richardson Amphitheater, where the gently dipping succession plunges into the subsurface.

*Description of basin-fill.* In excess of 95% of the succession in the Fisher mini-basin is of fluvial origin. Poorly sorted and texturally immature conglomerate and pebbly-sandstone lithofacies are characteristic of the basal fill of channel elements and, where not reworked or cut out by overlying erosively-based channelized elements, these pass upward into sets of trough cross-bedded sandstone (Fig. B in online supporting information). Pebble-grade clasts are common throughout the succession, the majority being extraformational clasts of quartz and various basement lithologies (dominantly clasts of quartz, igneous intrusive rocks and schist); derived from Uncompahgre basement rocks. Although present, siltstone and mudstone facies are very rare, though intraformational mudstone and siltstone pebble-grade clasts are relatively common in the basal parts of erosively-based channel infills. Fluvially-reworked gypsum clasts have not been observed in this mini-basin. Burrow- and root-mottling is generally rare in this area, except in overbank elements. Table 1depicts the relative abundance of facies observed at Fisher Towers and Richardson Amphitheater.

Mean trough-axis palaeocurrents are to the west ($285^0$; ang. dev. = $136^0$; n = 129), whereas channel-axis palaeocurrent orientations show a more southwesterly direction ($253^0$; ang. dev. = $23^0$; n = 8); considerable variation is noted in palaeocurrent data derived from overbank and minor channel elements.

Major channel elements tend to be laterally extensive over several hundred metres (mean = 500 m) and are commonly vertically stacked (F1; multi-storey and multi-lateral), with most examples preserving only the lowermost, clast-rich parts of the channel fills. Fine-grained non-channelized elements (F5) are only rarely preserved and where present typically extend laterally for less than 100 m to a point where they are cut out by erosional channel bases (Fig. 6). On the western side of the Colorado River, near the outcrop base, intensely burrowed overbank elements laterally interfinger with aeolian dune (A1) and interdune elements (A2). Fine-grained, non-channelized (F5) and sheet-like non-channelized (F6) elements become increasingly common adjacent to the Onion Creek salt diapir. Aeolian elements (A1, A2 & A3) are laterally restricted in this basin (<10 m) and are laterally cut out by fluvial elements, with the exception of the areas around the nose of the Onion Creek diapir where such aeolian elements can be traced continuously for over 1 km around the nose of the anticline (Fig. 1).

*Interpretation.* The abundance of extraformational clasts of igneous, metamorphic and other extraformational lithologies is consistent with a location proximal to the Uncompahgre frontal thrust to the NE. The abundance of multi-storey and multi-lateral channel elements (F1), in which only the basalmost parts of the channel-fill successions tend to be routinely preserved, suggests that the mini-basin was in an over-filled state whereby sediment input exceeded the available accommodation. Locations within the mini-basins, where non-channelized elements and aeolian elements accumulated likely represent zones of reduced fluvial activity, where potential for erosion via repeated channel incision was reduced.

Variations in palaeocurrents between non-channelized elements (F5 & F6) and channelized elements (F1, F2, F3 & F4) likely reflect differences between downstream-migrating bedforms and processes operating away from the main channels in overbank areas.

The lateral persistence of elements around the western end of the Onion Creek diapir suggests that sedimentation was not restricted by the salt diapir where it plunged into the subsurface. The occurrence of laterally extensive aeolian elements (A1, A2 & A3) indicates episodes during which aeolian processes dominated, probably in zones of slightly elevated (growing?) topography where fluvial flow was inhibited.

## Parriott mini-basin

The Parriott mini-basin is located between the Onion Creek salt diapir to the NE and the Castle Valley salt wall to the SW (Fig. 1) and is located within the Fisher Towers 7.5' quadrangle (Doelling, 2002b). The maximum thickness of Undifferentiated Cutler Group preserved in this basin exceeds 3,000 m (Trudgill, 2011), with the thickest exposed part of the succession being ~1,000 m, in the centre of the Parriott mini-basin area (Fig. 1 & 4).The Undifferentiated Cutler Group is exposed across the majority of the mini-basin (Doelling, 2002b).

*Description of basin-fill.* In the centre of the basin, the exposed succession is dominated by multi-storey and multi-lateral fluvial channel elements (F1; 55%) separated by thin, laterally restricted overbank (F5) and sheet-like fluvial (F6) elements (40%), the remainder of the fill is composed of aeolian elements (A1-3; 5%). Overbank and sheet-like elements become thicker and increasingly amalgamated towards the lateral margins of the basin to locations within 500 m of the salt walls where they represent in excess of 50% of the succession (Fig. 5).

The basin fill is especially pebble-rich towards the top of the succession, though distinctly less so than in the Fisher Towers mini-basin further north. Intraformational clasts (sand and mud balls up to 0.3 m in diameter) are very common and occur both as <0.5 m-thick lags in the basal parts of channel infills, and as metre-thick sets of pebbly sandstone and conglomerate that fill entire channel elements (Fig 7a). Pebble-rich facies are more common towards the peripheries of the mini-basin. Quartz-pebble conglomerate (Gm-a) is notably limited in all locations with the exception of sections directly adjacent to the south side of the Onion Creek salt wall (Figs 6 & 7a). Sets of conglomerate of mixed clast affinity (Gm-b) decrease in abundance across the mini-basin from north to south, before increasing again adjacent to the north side of the Castle Valley salt wall (Fig. B, in online supporting information).. Sets of intraformational conglomerate (Gm-c) are present across the study area, though are notably more abundant closer to the sat walls. Sets of ripple-laminated siltstone (Fl-a) and interlaminated fine sandstone and siltstone (Fl-b) decrease in abundance towards the centre of the mini-basin; sets of ripple-laminated sandstone (Sr) are absent on the south side of the Onion Creek salt-diapir. Sets of interbedded fine-grained sandstone and siltstone (Fl-b) are present across the area, but are most common to the south of the Onion Creek salt diapir. The occurrence of nodular facies(N) exhibits an inverse relationship with that of interbedded fine sandstone and siltstone (Fl-b). Laterally discontinuous grey-green limestone beds that lack fossils and weather with a pitted surface texture are present at some horizons, and are notably more abundant on the south side of the mini-basin. (Fig. B, in online supporting information).

Palaeocurrent data demonstrate a variety of flow directions, with most channelized fluvial elements dominantly recording SW-directed flow (mean = $243^0$; ang.dev. = $31^0$; n= 63) across the salt walls. Current ripple-lamination and primary current-lineation in facies of overbank elements exhibit palaeocurrent directions ranging from $206^0$ to $314^0$ (mean = $228^0$; ang.dev. = $52^0$; n = 4).

*Interpretation*. The variation in facies across the basin must be interpreted with care given that three of the six measured log profiles for this mini-basin(FM 3, 4 and 5) are restricted in vertical extent due to the inaccessible nature of the outcrop. The relative concentration of quartz pebbles (Gm-a) on the south side of the Onion Creek diapir compared to the rest of the basin, combined with a dominant SW-directed palaeoflow, suggest that these sediments may have originated from rapid deposition of Uncompahgre-sourced detritus during an episode of breaching of the topographic salt high of the Onion Creek salt diapir by the fluvial system. Polymictite conglomerate(Gm-b) deposits were likely predominantly sourced from the Uncompahgre Uplift. The abundance of intraformational clasts(Gm-c) within elements adjacent to the salt structures at the basin peripheries, and their relative absence elsewhere in the mini-basins, suggests that reworking of sediments was common as fluvial systems onlapped, or breached the salt-generated topography (where accommodation was limited). The abundance of nodular horizons (N) are indicative of weak calcisol palaeosol development; their presence indicates locations where fluvial systems did not traverse the mini-basin floor for protracted episodes, though the reworking of these nodules and their incorporation as clasts in some fluvial channel deposits indicates their ultimate fate via fluvial reworking. The occurrence of siltstone of fluvial overbank origin (Fl-a) and aeolian facies on the southern periphery of the mini-basin supports the inference that the presence of increased local accommodation (during episodes of salt-wall growth and fluvial diversion) promoted preservation of fine-grained overbank and aeolian facies. The occurrence of laterally discontinuous limestone of apparent nonmarine origin on the southern periphery of the mini-basin (adjacent to the Castle Valley salt wall), where there is also an abundance of siltstone facies (Fl-a), suggests that ponds may have formed in overbank areas adjacent to topography generated by the Castle Valley salt wall.

The range of palaeoflow directions might be attributed to flows breaching the confines of channels at times when bankfull discharge was exceeded, leading to flow out-of and away-from channel confines (cf. Cain & Mountney, 2009). Vertical variations in palaeocurrent data in the exposed succession from locations across the study area demonstrate episodic changes in dominant fluvial flow direction between axial and transverse to the elongate basin axis, further supported by corresponding vertical variations in the preserved stratigraphy whereby fluvial non-channelized elements adjacent to salt structures generally demonstrate transverse flow and are characterized byabundant intra-formational clasts of older Cutler Group detritus apparently derived from localized reworking of former fluvial deposits.

### Big Bend mini-basin

The Big Bend mini-basin is bounded to the NE by the Castle Valley salt diapir and to the SW by the Moab salt wall. The Big-Bend mini-basin is located on four7.5' quadrangles: Warner Lake (Ross, 2006), Fisher Towers (Doelling, 2002c), Big Bend (Doelling& Ross, 1998) and Moab (Doelling, 2002a, b). Only limited work has been carried out in the Big Bend mini-basin; the Cutler Group is not exposed extensively across this area as it is mainly present in the subsurface, where it attains a maximum thickness of 1,500 m (Trudgill& Paz, 2009; Trudgill, 2011).

*Description of basin-fill*. At the northern margin of the Big Bend mini-basin an aeolian dune (A1) succession in the uppermost 100 m of the Undifferentiated Cutler Group is exposed on the southern flank of the Castle Valley salt diapir at a similar stratigraphic level to the aeolian White Rim Sandstone exposed in more distal areas of the Paradox Basin. This unit has subordinate minor fluvial channelized deposits embedded within it, and numerous horizons characterized by calcified rhizoliths are present. The Cutler succession in the centre of the mini-basin is not exposed.

*Interpretation*. The limited thickness of preserved Cutler Group at the margins of this mini-basin suggests that accommodation was reduced on the flanks of the growing salt structure (e.g., the Moab Salt Wall). In recent work Parr (2012) suggested that the exposed aeolianite is likely of equivalent age to the White Rim Sandstone found in more distal locations within the Paradox Basin. However, the presence of numerous fluvial channel elements and plant-root (rhizolith) horizons preserved between aeolian dune elements in the Big Bend area suggests that this aeolian-dominated unit could have accumulated during a relatively, or intermittently, humid episode (cf. Cain & Mountney, 2011).

## Sedimentology of the Cutler Group adjacent to salt structures

### Onion Creek salt diapir

Subsurface correlation of well-log data (Trudgill *et al*., 2004; Banbury, 2006; Trudgill and Paz, 2009; Kluth & DuChene 2009 and Trudgill, 2011) demonstrates that the movement of salt to initiate the development of the Onion Creek salt diapir commenced at the same time as a clastic wedge of fluvial sediment of the Undifferentiated Cutler Group prograded from the developing Uncompahgre Uplift. The Onion Creek salt diapir and its along-strike extensions, the Fisher Valley salt wall to the SE and the Sinbad Valley salt wall to the NW, comprise the most proximal and youngest of the salt walls in the area (Kluth and DuChene, 2009).

*Description*. Across the wall, the thickness of Cutler sediments varies from ~2,500 m on the immediate NE side to only 266 m on the immediate SW side (Trudgill, 2011;also see Dane, 1935, Condon, 1997, Doelling, 2002a and Doelling *et al*., 2002,c). Up to 1000 m Cutler sediments are exposed on the NE side of the salt wall, although the uppermost 200 m of the succession is inaccessible in many locations where it forms vertical cliffs. A complete section (266 m) of the Undifferentiated Cutler Group is exposed along the southern side of the Onion Creek salt diapir (Fig.2), along with the uppermost part of the underlying Pennsylvanian Honaker Trail Formation (cf. Rasmussen & Rasmussen, 2009; Trudgill, 2011).

The facies vary in occurrence across the salt wall; sections measured directly adjacent to the northern margin of the salt diapir (Fig. B in online supporting information; Fig.5a) have a notably different facies distribution both to the northern regional measured log section (RA RL, Fig.5a) and also to sedimentary log sections measured on the south side of the diapir (Fig. B in online supporting information).Conglomeratic facies (Gm-a, Gm-b and Gm-c) vary across the salt wall: the quartz-pebble-dominated facies (Gm-a) is notably more abundant on the south side of the salt wall, whereas polymictic extraformational-clast facies (Gm-b) are less abundant in sections measured directly adjacent to the salt wall, and facies characterized by abundant intraformational clasts are rare on the north side of the salt wall. Ripple-laminated siltstone (Fl-a) and interbedded fine sandstone and siltstone (Fl-b) facies are more common in the sections adjacent to the salt wall (Fig. 5c). Other notable trends include the presence of nodular (N) facies on the south side of the salt wall and an increase in the presence of horizontally laminated sandstone (Sh) adjacent to the salt-wall.

Much of the succession directly adjacent to the currently exposed salt diapir is not *in situ,* having been significantly affected by diapir collapse. However, in unaffected parts of the succession, such as in the area NE of the Onion Creek salt wall, the exposed section is dominated by vertically stacked and laterally overlapping fluvial overbank elements (F5 & F6), each ~10m thick, and by erosively-based channel elements (F2, F3 & F4). Juxtaposed with the salt contact on the northern edge of the salt diapir, interbedded non-channelized elements (F5 & F6) and single-storey channel elements (F2, F3 & F4) are present (Fig. 5c) These interbedded packages are absent from locations distal to the salt wall, such as Richardson Amphitheater where they are replaced by multi-storey channel (F1) and fluvial non-channelized sheet-like elements (F6 ).

Adjacent to the salt wall, in fault blocks that formed during late-stage post-depositional salt-wall collapse (cf. Hudec 1995), fanning of sediment packages away from the salt high is observed (Trudgill, 2011 – his Figure 12). This fanning is important: structural dips decrease up-section from 30 degrees to 22 degrees over a 60 m-thick part of the succession. Additionally, structural dips decrease away from the contact with the salt wall to near-horizontal over a distance of 200 m from the diapir (Fig. 7 and Fig. D in online supporting information. Convoluted, distorted and overturned beds and structures are present in architectural elements adjacent to the diapir: flame structures are present near the nose of the diapir structure and distorted laminations and bedding are present throughout this part of the stratigraphy.

At least three low-angle-inclined, intrabasinal unconformities are present in the Cutler succession directly adjacent to the northern margin of the Onion Creek salt wall. Each of these unconformities bounds sediment packages of poorly sorted, blue-purple, pebble-rich, erosively-based channel elements (F2) and fine-grained, orange-brown, highly burrowed, mica-rich overbank elements (F6). These unconformities can only be traced locally for distances of ~100 m and they are not imaged on published seismic sections (Trudgill, 2011). The unconformities pass laterally into a conformable succession 200 m away from the salt diapir (Fig. 7; Fig. D in online supporting information).

Palaeocurrent measurements from sets of trough cross-bedding in larger channel-element fills are variable, though a dominant southwesterly palaeoflow is recorded (mean = $237^0$; ang.dev. = $36^0$; n = 107), indicating that the fluvial systems passed directly over the growing salt high (Fig. C in online supporting information). In sheet-like non-channelized fluvial elements (F5 & F6)and finer-grained minor channel elements, palaeocurrent data are more variable than those measured in fluvial channelized elements (mean = $256^0$; ang. dev. = $53^0$; n = 35). By contrast, small-scale sandstone-filled channel elements show a mean direction towards $325^0$, which is close to parallel to the trend of the salt wall.

Although the succession on the SW side of the salt wall is not generally well exposed, the complete Cutler Group is exposed in a few locations and at the SE end of the salt wall (Figs. 1& 3), and the uppermost part of the underlying Honaker Trail Formation is also exposed. Four unconformities in the Cutler Group can be observed above the contact with the underlying Hermosa Group SW of the Onion Creek salt wall. However, the discontinuous nature of the outcrop precludes detailed analysis of their spatial extent. The unconformities separate packages of fluvial channel elements (see Trudgill, 2011); indeed, the overall succession in this area is dominated by multi-storey and multi-lateral fluvial channel elements (F1) with relatively few overbank (F5) and sheet-like (F6) elements present. Intraformational clasts of sandstone and siltstone are common throughout the succession, though no gypsum clasts are observed.

The stratigraphy changes significantly around the western nose of the Onion Creek salt diapir structure, where this feature dies out (Fig. 1). Significantly, the succession is correlatable in this region and architectural elements can be traced over many hundreds of metres. The preserved stratigraphy is characterized by intercalated fluvial overbank (F5) and multi-storey and multi-lateral channel elements (F1), with at least two aeolian packages additionally present, which are themselves laterally continuous over distances of up to 500 metres. Individual architectural elements and groups of related architectural elements (e.g., multi-storey and multi-lateral channel complexes) can be traced over several hundred metres until they pinch out or are truncated by larger, erosively-based channel elements (Fig. 5d).

Palaeocurrent data vary between architectural elements: mean flow direction inferred from channel axes is $231^0$ (ang. dev. = $21^0$; n = 3);foresets of planar cross-bedded sandstone sets record palaeoflow toward $265^0$ (n = 55); measurements from trough axis record palaeoflow towards $221^0$ (ang. dev. =$21^0$; n =29). The upper part of the succession is not preserved in this area but ~2 km to the west, on the north bank of the Colorado River, the uppermost Cutler succession is dominated by stacked fluvial channel elements (Fig. 6).

Aeolian elements south of the salt diapir that are characterized by cross-bedded sets record a NE direction of bedform migration ($013^o$; ang.dev. =$29^o$; n = 5).

*Interpretation*. The distinctive and unique succession on the north side of the Onion Creek diapir suggests that a variety of fluvial processes operated in this localized area. Strata dipping away from the salt wall are overturned in some locations, suggesting that passive folding (cf. Giles & Rowan, 2012) was very active throughout the development of the diapir. The relatively shallow dips (outside the zone of collapse) and laterally discontinuous unconformities (Fig.7; D in online supporting information) support an interpretation of wedge-halokinetic sequences rather than hook types (Giles & Lawton, 2002; Giles & Rowan, 2012).These two end members of halokinetic packages have characteristic geometries: hook sequences are typified by drape folding 50-200 m from the diapir, $\leq 90^o$ angular unconformities and abrupt near-diapir facies changes; wedge sequences have a much wider zone of drape folding (300-1000 m from diapir), much shallower ($\leq 30^o$) angular unconformities and a broad zone of gradational facies changes (Giles & Rowan 2012).

The occurrence of fine-grained non-channelized elements (F5) that are commonly abundant in mica and burrow-mottling suggest that the rate of generation of accommodation was sufficiently high in this area to allow the preservation of non-channelized elements despite the proximal location and generally over-filled state of the basin. The abundance of mica in very fine-grained sandstone and siltstone facies, suggests sluggish or static flows that likely represent ponding of the fluvial systems, possibly behind salt-generated topography during episodes when the rate of sedimentation was exceeded by the rate of salt rise, thereby demonstrating the growth and subtle surface expression of topography.

Channel elements (F2, F3 & F4) that overly unconformities, and which demonstrate palaeoflow to the SW (i.e., across salt structures), record episodes of breaching of salt-generated topography by fluvial systems. The abundance of multi-storey and multi-lateral fluvial channels in the upper part of the succession suggests that in the latter stages of accumulation of the Cutler Group, available accommodation was low, probably indicating the formation of a salt weld and the filling of any remaining accommodation. At this time, the fluvial system was able to breach the salt diapir in some locations, reworking previously deposited fine-grained facies within non-channelized elements (F5 & F6), a hypothesis supported by the abundance of intraformational clasts adjacent to the south side of the salt wall. The dominance of multi-storey and multi-lateral channel elements suggests that deposition was dominated by high energy fluvial events that were able to breach salt-wall topography at certain times, whereas, at other times, reworking of previously deposited sediments may have occurred along the salt wall during episodes when fluvial systems flowed axially (i.e., parallel to the salt walls).

Movement of the Onion Creek salt diapir continued throughout the Triassic, influencing sedimentation and deposition of both the Moenkopi and Chinle formations (Mathews *et al*., 2007; Banham & Mountney, 2013 a,b,c). A final stage of movement of the diapir occurred at between 2-3 and 0.25 Ma resulting in the diversion of the Fisher Creek fluvial system to a course that it maintains today (Colman, 1983).

## Castle Valley salt wall

The Castle Valley salt wall now forms a valley feature owing to its partial collapse, though Cutler outcrops are well exposed adjacent to the flank of the relic salt wall where remnant salt-induced topography remains at the far SE end of the valley (Figs. 1& 2).

*Description*. Directly adjacent to the former position of the diapir on the north side of the salt wall, Cutler strata dip away from the diapir at an inclination of $12^0$ toward $308^0$. This dip reduces gradually to approach horizontal at a distance of 1,000 m from the diapir. This geometry has been described by Giles & Rowan (2012) as wedge type where the sediment packages thicken away from the salt structure (cf. Banham & Mountney, 2013a). Some minor growth structures are present on the north side of the salt wall, including small growth faults with associated subtle changes in bed thickness. The variation in dip and thickening occur both spatially and up-section in a manner similar to that observed on the north side of the Onion Creek diapir (Fig. 7).

The preserved sedimentary architecture adjacent to the NE side of the Castle Valley salt wall is less well organised than, for example, that on the NE side of Onion Creek (Fig. 5a, b).Near the base of the exposed section (on the NE side of the Castle Valley Salt Wall), overbank elements

(F5) are interbedded with aeolian dune, interdune and aeolian sandsheet elements (A1, A2 & A3). Aeolian sandsheet elements (A3) are distinguished from interdune elements by virtue of their greater lateral extent: sandsheet elements typically extend for distances > 10 m, whereas interdune elements (A2) are commonly lense shaped bodies of restricted extent that are commonly encased completely within, or interfinger laterally with aeolian dune elements (A1).Conglomerate units with abundant intraformational clasts(Gm-c) are more abundant on the north side of the diapir, as are ripple-laminated siltstone beds (Fl-a) and interbedded fine-grained sandstone and siltstone (Fl-b) (Fig. B in online supporting information).

Erosive-based, single-storey channel elements (F2, F3 & F4) are interbedded with non-channelized fluvial elements (F5 & F6). Slumping and dewatering structures are common in sheet-like and channelized elements; in particular flame structures, distorted bedding and lamination, and pebble lags are common. The upper part of the Cutler succession is characterized by intensely bioturbated, fine-grained, orange-brown, non-channelized fluvial elements (F5 & F6).

Channel elements on the north side of the Castle Valley salt wall contain fewer pebbly intervals than those observed adjacent to the Onion Creek salt diapir, though intraformational clasts are very common in the basal parts of some sets in the lower parts of erosionally-based channel elements. The style of channel-element infill is variable: although pebbly basal lags and trough cross-bedded sets and cosets are common, planar bedded and massive sandstone fills of channel elements are also present. Overbank elements are commonly planar laminated with current ripple-lamination present in the uppermost parts of bed sets. Palaeocurrent data measured from trough axes in channel complexes on the northern side of the salt wall indicate a mean palaeoflow towards $301^0$ (ang. dev. = $53^0$; n = 93).

Aeolian elements (A1, A2& A3) occur at the base of the exposed succession immediately north of the Castle Valley salt diapir and are horizontally laterally extensive over several tens of metres but are relatively thin (< 2.5 m) and typically represent aeolian sand-sheet elements rather than aeolian dune elements with intervening interdune elements. Measurements taken from the foresets of aeolian dunes demonstrate a wide radial distribution and a resultant direction of $172^o$ (ang.dev. = $38^o$; n = 5).

The Undifferentiated Cutler Group is not extensively exposed on the south side of the Castle Valley salt wall, the uppermost part of the succession having been progressively removed by the overlying angular unconformity at the Permo-Triassic boundary. However, an exception is the western end of the SW side of the valley (Fig. 5b). Here, fluvial channel elements (F2, F3),each 2 to 3 m thick, are interbedded with aeolian dune elements (A1) that are themselves ~2 m thick. Most fluvial channel elements have pebble lags at their bases, many examples of which are composed of abundant intraformational clasts of locally reworked sandstone and siltstone. Conglomerate facies with mixed clast populations (Gm-b) are more abundant on the south side of the wall compared to the north side. The Cutler is overlain in this area by a bleached white unit that is up to 50 m thick and which has previously been described as an aeolianite of equivalent age to the White Rim Sandstone (Lawton &Buck, 2006; Parr, 2012). This unit rests apparently conformably on the underlying fluvial strata of the Cutler Group and lies directly beneath the Permo-Triassic unconformity (Doelling& Ross, 1998). It is composed almost entirely of cross-bedded sandstone, typically with individual cross bedded sets up to 4.5 m thick, many containing abundant calcified rhizolith structures (cf. Loope, 1988).

At the SE end of Castle Valley, the Honaker Trail Formation is exposed in a sliver (Ross, 2006). In the field it appears as an isolated outcrop separated from the main Cutler succession on the south side of Castle Valley by an area of non-exposure. This is significant as the sliver also exposes the lower Cutler succession and its contact with the underlying Honaker Trail Formation; in this locality the contact appears to be gradational. Several small faults are present in this area and the beds have been rotated to near vertical.

Palaeocurrent data from fluvial elements are of low variability on the south side of the valley and record a mean direction of fluvial flow towards $270^0$ (ang. dev. $33^o$; n = 67); palaeocurrent data measured form aeolian dune foreset azimuths in the overlying White Rim Sandstone record a unimodal distribution (vector mean = $207^0$; ang.dev. = $15^o$; n =7).

*Interpretation*. The succession adjacent to the Castle Valley salt wall differs from that adjacent to the Onion Creek salt diapir and therefore indicates differing styles of salt-sediment interaction. The mixed succession on the north side of the diapir indicates that fluvial processes did not continuously operate adjacent to the Castle Valley salt wall. Episodes of fluvial quiescence allowed aeolian elements to accumulate and their preservation indicates that accommodation remained available. The presence of growth faults and fanning strata (Fig.7) suggests that sedimentation and salt movement were penecontemporaneous; salt movement did not occur episodically as the absence of unconformities in the succession supports the interpretation of relatively continuous sedimentation during salt movement.

The mean palaeoflow suggests that the fluvial systems were orientated parallel to the trend of the salt wall, although there is sufficient variation to suggest that episodic breaching of the salt-topography might have occurred at certain times. The abundance of intraformational clasts on the northern side of the diapir, and their relative absence from the southern side, indicates that fluvial flow was dominantly axial to salt structures with episodic transverse flow, whereby fluvial channels reworked previously deposited non-channelized elements as they migrated into the mini-basin depocentre, or rim syncline, generated by salt-withdrawal.

Using a range of forward modelling approaches Trudgill *et al.*(2004), Banbury (2006),Trudgill& Paz (2009) ,Kluth & DuChene (2009) and Trudgill (2011) have demonstrated that the Cutler Group deposits exposed in Castle Valley post-date the first topographic expression of the salt wall. Therefore the succession documented here records the response to a gradually rising salt structure and onlap of the Cutler system onto the flanks of that structure.

Buller (2009) undertook a localized sedimentological study of the Undifferentiated Cutler Group in two locations directly south of the Onion Creek and Castle Valley salt walls and demonstrated that salt movement significantly impacted sedimentation where growing surface topography above developing salt walls deflected sediment flow and restricted sediment supply to more distal parts of the Paradox Basin. Buller (2009) suggested that repeated uplift of Cutler sediments above growing salt walls prevented their reworking via fluvial streams and therefore encouraged the development of palaeosols, the recognition of which might serve to allow the identification of halokinetic ‘cycles’. Subsequent work by Shock (2012) has demonstrated that these ‘palaeosols’ are likely carbonates that formed as a cap rock on the exposed salt-wall due to the action of sulphur-reducing bacteria; the implications of this are discussed below. Palaeocurrent data collected by Shock (2012) suggest both axial and transverse fluvial activity on the south side of the Castle Valley salt wall.

## Moab Valley salt wall

The Moab Valley salt wall is the most southwestern salt wall in the studied mini-basin area. The Cutler succession is not exposed between the SW side of the Castle Valley salt wall and the southernmost part of the Arches National Park boundary, to the north of the Moab salt wall, because it dips into the subsurface. Also, the presence of the Moab Fault adjacent to the Moab Valley salt wall complicates the stratigraphy considerably. At this location the Cutler Group is divided into the lower and upper Cutler units on published geological maps (e.g. Doelling, 2002a).

*Description.* Four sections were measured along the limb of the salt wall; these, together with photomontages, demonstrate significant thinning of the succession, with over 100 m of exposed strata 5 km north of Moab thinning to zero near the entrance to the Arches National Park, 1 km north of Moab (Fig. E& F in online supporting information).

Fluvial elements (F2, F3 & F4) are composed of fine- to medium-grained sandstone with few (< 10%) clasts of pebble grade; both the mean and mode grain size are significantly finer than their equivalents at the same stratigraphic level in more proximal locations. Fine-grained non-channelized (F5) and sheet-like (F6) fluvial elements represent 50% of the succession in this area;

single-storey channel elements (F2, F3 & F4) represent only 20%; multi-storey channel elements are absent; 30% of the succession comprises aeolian elements. Significantly, unlike much of the Undifferentiated Cutler Group studied to the north of the Moab salt wall, laterally extensive aeolian elements (some traceable continuously for distances over 8 km) are present at the top of the succession in this locality.

*Interpretation.* The succession associated with the Moab salt wall is interesting due to its similarity to the succession in the Shafer Basin (Fig. 1) developed at an equivalent stratigraphic level to the Cedar-Mesa Sandstone present in more distal parts of the basin. This suggests that aeolian elements of substantial size and considerable lateral continuity in the lower Cutler Group (as observed south of the study area) extend only as far north as the first major salt structure. Further, it suggests that the deposition of sediments that are time-equivalent to the Cedar Mesa Sandstone and Organ Rock Formations post-date the formation of most of the salt structures in the Salt Anticline Region but are penecontemporaneous with the formation of the Moab Salt Wall (as indicated by the onlapping relationship). The presence of an aeolian-dominated succession adjacent to the Moab Salt wall suggests one or more of the following: (i) that a previously deposited fluvial-dominated part of the succession was removed by erosion; (ii) that the Moab Salt Wall acted a topographic high throughout much of the Cutler accumulation, thereby inhibiting sediment transport to and accumulation in this vicinity; (iii)that sediment bypassed the area and was deposited in the more distal Shafer Basin; (iv) that salt-generated topography may have shielded an aeolian accumulation at this location from being reworked by fluvial processes, thereby allowing localized aeolian accumulation in an otherwise fluvial-dominated setting. The aeolian accumulation adjacent to this salt wall may be correlative with aeolian elements preserved in the Shafer Basin SW of the Moab salt wall.

## Sedimentary response to salt movement

Accumulation of the Undifferentiated Cutler Group was intrinsically linked to the history of salt movement via a positive feedback loop between sedimentation and generation of load-induced accommodation due to salt withdrawal (Trudgill& Paz, 2009; Kluth & DuChene, 2009; Trudgill, 2011). Large-scale variations in the preserved thickness of the predominantly fluvial stratigraphic succession and regional changes in stratigraphic architectural relationships both within and between mini-basins (cf. Kluth & DuChene 2009; Trudgill, 2011) serve as a framework on which to build more detailed observations regarding the sedimentological response to salt movement. Diversion of fluvial drainage pathways in response to growth of salt structures at depth and associated creation of a surface topographic expression can be demonstrated by both temporal and spatial changes in dominant fluvial flow pathways whereby such systems alternated between flow that was axial and transverse to the trend of the elongate salt walls. Palaeocurrent data from Cutler fluvial deposits beyond the immediate vicinity of the Salt Anticline Region (e.g., Mack & Rasmussen, 1984; Condon, 1997; Cain & Mountney, 2009&2011) demonstrate that the Cutler fluvial system generally flowed to the SW. The presence of fluvial successions indicative of major fluvial fairways that flowed to the NW, parallel to the trend of the elongate salt walls within the Salt Anticline Region, likely represents major fluvial diversion by growing salt topography. The abundance of conglomerate facies with abundant intra-formational clasts(Gm-c) adjacent to salt structures indicates reworking of previously deposited fluvial sediments exposed by passive folding.

The growing salt walls were likely at or near the surface for much of their history (Lawton & Buck, 2006), though the scarcity of gypsum clasts indicates that exposure of salt at the surface and its erosion and reworking by Cutler fluvial systems was not widespread, a situation that is unexpected. Furthermore, the tectono-stratigraphic relationships are unusual, compared with those seen in other salt basins, such as La Popa Basin (northeast Mexico; e.g., Andrie *et al*., 2012): no salt cusps or flares can be discerned from seismic sections (e.g., Trudgill 2011). The presence of growth strata and localized unconformities, together with the absence of gypsum clasts, suggests that the relative rate of salt rise did not exceed the rate of infill of accommodation by ongoing sedimentation, supporting the interpretation that there was a high rate of sediment delivery into the Paradox Basin throughout much of its evolution in the Permian, as typified by the abundance of multi-storey and multi-lateral channel elements (F1).

The absence of correlatable surfaces over salt walls, the presence of substantial and significant sediment thickness variations over short distances, and the fluctuations in interpreted palaeocurrent direction collectively indicate a sedimentary response to the salt movement. Stratigraphic correlation panels and schematic cross-sections across the study area (Figs. 9 & 14) demonstrate predictable spatial variations in fluvial and aeolian architecture and architectural-element distribution, both within the mini-basins and across the salt walls. The following observations regarding detailed response to salt movement, both in terms of the resultant sedimentary architecture (and hence sand-body preservation) and the effect of syn-sedimentary salt movement on developing fluvial systems, are derived from the outcrop-based observations arising from this study; individual observations collectively allow the fluvial response to be reconstructed as discussed below.

1. The presence of growth unconformities in parts of the succession adjacent to salt walls demonstrates that salt movement was contemporaneous with sedimentation (see Trudgill, 2011, his Figure 12). Individual unconformities are neither laterally persistent nor traceable

over distances in excess of 500 m away from salt walls. Within unconformity-bound stratal packages, fanning of sediment layers away from the salt walls is observed at several localities, particularly in the area directly north of the Onion Creek salt wall (Fig. D, in online supporting information). This demonstrates that the response of the fluvial systems to salt-wall growth and associated mini-basin subsidence was progressive; the geometries of these packages are comparable to the 'wedge' style of Giles & Lawton (2002), as suggested by Giles & Rowan (2012).

2. The abundance of convoluted and dewatered facies in elements adjacent to salt walls likely arose in response to passive folding of previously deposited sediments, which led to slumping away from salt-generated topographic highs and dewatering of underlying water-saturated sediments; these relationships are similar to those in the models for passive-folding of sediments adjacent to salt walls proposed by Giles & Rowan (2012). Both slumping and dewatering could alternatively have occurred in response to more regional climatic or tectonic events (such as earthquakes or a shift to a more humid climate), whereby flooding was characterized by a rapid rate of rise to peak discharge at times when the infiltration capacity of the substrate was exceeded – a common behaviour in dryland fluvial systems (e.g., Tooth, 2000) – inducing the generation of dewatering structures (Schwan, 1987). However, the occurrence of extensive slumping structures solely in locations adjacent to salt walls suggests that the origin of these features was at least partially controlled by salt movement: had they been generated by a widespread regional climatic or environmental change, they would be distributed across the study area.

3. There exists a predictable distribution of fluvial architectural elements in the exposed succession across the mini-basins. In particular multi-storey and multi-lateral channel complexes in mini-basin centres pass laterally into non-channelized and single-storey channel elements close to salt walls. Episodes when the rate of salt-wall uplift exceeded the rate at which the fluvial systems could fill newly-generated accommodation would favour passive folding of previously deposited sediments and diversion of fluvial flow around topographic expressions developed above the growing salt walls, with the loci of fluvial-system activity (expressed as major channel fairways) likely confined to the central parts of the mini-basins. This would have encouraged the accumulation of finer-grained overbank-dominated successions in areas adjacent to the salt diapirs, with the location of maximum accommodation and the stacking of multi-storey and multi-lateral channel elements away from the salt diapirs (Fig. 8). Progressive infilling of mini-basin depocentres at times when the rate of sediment input exceeded the rate of topography generation allowed the fluvial systems to episodically breach the salt topography, with channels delivering sediment to the SW. This finding differs from

studies of other fluvial systems (e.g., Andrie, *et al*., 2012; Banham& Mountney, *in press*) where localized accommodation facilitates the preservation of channel bodies; in the proximal part of the Undifferentiated Cutler Group, the generation of accommodation in mini-basins led to the preservation of non-channelized elements. This has important implications for subsurface study because such non-channelized elements are typically composed of finer-grained facies assemblages and may compartmentalise coarser-grained sandbodies. Furthermore, episodic breaching of the salt-generated topography without reworking of the salt (as indicated by the absence of gypsum clasts in the preserved stratigraphy), is also unusual and suggests that there was always a 'buffer' layer of earlier-deposited Cutler sediments atop the growing salt structures that was available for episodic reworking and renewal.

4. Temporal (i.e., up-succession) changes in palaeocurrent data demonstrate that successive episodes of salt movement resulted in repeated diversion of the fluvial systems from their preferred, regional-gradient-driven NE-to-SE flow path, as demonstrated, for example, by dip-meter data from wells penetrating the base of the Undifferentiated Cutler Group (Fig. C in online supporting information; see also Cain and Mountney, 2009, 2011), to a path directed along the axis of the evolving salt mini-basins to the NW. This observation is supported by the repeated switching in the preserved fluvial succession from packages of channel-element dominance to packages of overbank-element dominance adjacent to the salt diapirs (Fig. C in online supporting information). This contradicts current models of palaeoflow, which suggest that the Cutler fluvial system gradually evolved from an axial to transverse pattern (e.g., Trudgill 2011) and also indicates that sedimentation was not confined to one mini-basin at a time, as implied by Kluth & DuChene (2009).

5. Palaeocurrent data collected for this study demonstrate that the Big Bend mini-basin formed a corridor (Fig. 1) that was an important route of bypass for fluvial systems during the Cutler accumulation (Fig. C in online supporting information), through which fluvial flow was directed to the SW. A long-lived and well established fluvial drainage system traversed this area until late in the episode of Cutler accumulation, after which mean palaeoflow migrated towards a more westerly direction (Fig. C in online supporting information and Trudgill *et al*., 2004; Trudgill& Paz, 2009; Trudgill, 2011).This zone of bypass has not been previously recognized and likely formed an important conduit of sediment into more medial parts of the basin, as well as into other mini-basins.

6. The presence of highly micaceous facies, together with climbing ripple-stratification and parallel lamination, in overbank elements located adjacent to salt walls demonstrates that the flows responsible for generating these deposits were sluggish, with evidence for suspension settling

as velocities waned(Allen, 1973). The significant thickness of these overbank depositional elements (up to 5 m) suggests that ponding may have occurred behind salt walls, in rim synclines, at times when the rate of generation of surface topography due to salt rise exceeded the rate at which that topography could be filled by the ongoing fluvial sedimentation process, whereby fluvial channels were diverted around salt highs.

7. The abundance of intraformational clasts present as thick lag deposits in the basal parts of channel-fill elements and the preferential preservation of only the basal parts of erosively-based channel elements adjacent to the salt diapirs suggests repeated episodes of reworking of sediment across or around salt highs. This, combined with the general absence of gypsum clasts derived from reworked salt layers of the Paradox Formation, suggests that previously deposited sediments acted as a buffer that inhibited the exposure and erosion of the Paradox Formation. This also suggests that fluvial flow aligned transverse to the salt walls was occurring not only to maintain accumulation on the flanks of the salt structures but also to rework sediments being passively uplifted by diapir rise. Recent work by Shock (2012) demonstrates that at least one layer of carbonate cap-rock (composed of microcrystalline dolomite) formed on the Castle Valley salt diapir, and this subsequently became incorporated into the sediments on the south side of the diapir. These carbonates, and their detritus in the form of reworked carbonate clasts, are restricted in the study area to one location on the south side of the Castle Valley Salt Wall within the zone of diapir collapse. It is therefore not possible to place them within the stratigraphy, although they do appear to overlie the Paradox Formation exposed in the remnant salt wall (Shock, 2012). Their occurrence is significant as it suggests that the Castle Valley salt wall did breach the surface on at least one occasion; however, rapid carbonate formation prevented the salt itself from being exposed (Shock, 2012).

8. Aeolian elements are most prevalent in the lee (downstream) side of salt walls, particularly on the south side of the Castle Valley salt diapir (Fig. 8). Aeolian facies in the Cedar Mesa Sandstone and in the Undifferentiated Cutler Group outside the Salt Anticline Region record a consistent bedform migration direction to the SE. Aeolianites preserved in the lee of the Castle Valley salt diapir record the accumulation and partial preservation of an aeolian dune field that developed during the final retreat of the Cutler fluvial system (cf. Cain & Mountney, 2009). Aeolianites observed elsewhere in the study area are less extensive and commonly interfinger with, or are encased in fluvial elements, suggesting penecontemporaneous deposition. As such, these aeolianites might not necessarily record protracted episodes of heightened climatic aridity. Aeolian elements were able to develop in the Big-Bend mini-basin corridor (e.g., at Hitle Bottom) during episodes when fluvial systems were able to breach topography generated by the rise of the Onion Creek diapir, when the main fluvial-flow pathways were being directed

over the buried salt walls, rather than being diverted into the Big-Bend mini-basin corridor. It nevertheless remains possible that episodes of heightened climatic aridity promoted aeolian system construction and accumulation when fluvial activity was diminished.

## Discussion

The evolution of the Cutler fluvial system in the Salt Anticline Region underwent a complex relationship with movement of salt layers of the underlying Paradox Formation. Successive phases of progradation resulted in the systematic generation of a series of salt-walls that progressively young basinwards (Trudgill *et al*., 2004; Trudgill& Paz, 2009; Kluth & DuChene, 2009; Trudgill, 2011). This study has contributed to the understanding of the relationship between diapir rise and coeval sedimentation by identifying the distribution of facies and architectural elements around salt structures and by determining the relationship between diapir-rise and element preservation.

The preserved sedimentary architecture of the Undifferentiated Cutler Group highlights three key observations: (i) repeated diversion of the fluvial system, resulting in alternations of flow direction over and around salt-generated topography (Fig. 9); (ii) the preservation of sedimentological and stratigraphical relationships that demonstrate how the presence of surface topographic expression arising from halokinesis influenced fluvial flow pathways, resulting in partial reworking of previously deposited fluvial strata but without widespread surface-breaching of salt; (iii) accumulation and preservation of aeolian elements in the lee of salt diapirs, for example SE of the Castle Valley salt wall (Fig. 9).

The Cutler succession exposed in the Salt Anticline Region differs from outcrops studies of other salt-influenced successions because it does not contain strata of marine origin and because it is a succession dominated by channelized elements; correlation between mini-basins is therefore difficult. The salt structures in the Paradox Basin show no evidence of either flaring or expansion of the salt diapirs, unlike those observed in La Popa Basin, northeast Mexico (Giles & Lawton, 2002; Rowan *et al*., 2003). This likely arose due a combination of factors: (i) the over-filled state of the mini-basins prevented salt-movement outpacing sediment accumulation and (ii) the lack of shortening (compression) of the salt-structures during Permian times (Trudgill, 2011), a process known to contribute to flaring or expansion of salt structures (Giles& Lawton, 2002; Rowan *et al*., 2003).

The interaction between salt movement, sediment delivery and sediment accumulation was complex and the filling of accommodation in each mini-basin was chiefly via a ‘fill-and-spill’ mechanism, whereby fluvial channel complexes delivered sediment across salt structures and into the next mini-basin downstream. Syn-sedimentary salt movement episodically re-established topographic highs, at which times fluvial systems were diverted along the axis of mini-basins and sediment was delivered to more distal mini-basins via pathways around the plunging noses of the diapirs. Over time a salt weld occurred on the northern side of the Onion Creek salt wall and sediment bypassed the Fisher mini-basin, whilst accumulation continued in the Parriott and Big Bend mini-basins. Salt welds apparently did not occur in the Permian in the Parriott or Big Bend mini-basins (Trudgill, 2011), and it is likely that sediments were able to prograde into the more distal parts of the basin during episodes when rates of sediment influx outpaced rates of salt movement. The abundance of extraformational clasts adjacent to the Onion Creek salt diapir and on the south side of the Castle Valley salt diapir, together with the relative abundance of intraformational clasts at the margins of the Parriott basin (i.e., adjacent to the Onion Creek Salt Diapir and Castle Valley Salt Wall), support the hypothesis of sediment by-pass and reworking in the Fisher mini-basin, after the formation of a salt weld adjacent to the Onion Creek Diapir. Avulsion across the surface of the prograding fan may also have been partly responsible for the stratigraphic complexity present in the part of the accumulation indicative of a component of along-axis drainage in the Parriott and Big Bend mini-basins.

Indicators of high sedimentation rates (including the presence of sediment buffers over salt highs, repeated breaching of salt highs and an abundance of multi-storey and multi-lateral channel-elements) suggest that accommodation was rapidly filled as fluvial sediments of the Undifferentiated Cutler Group were delivered into the basin.. It is possible that avulsion frequency may have increased during episodes of high rates of sediment influx and low rates of accommodation generation, and such processes may have encouraged movement of channelized fluvial sedimentation away from the margins of mini-basins, thereby allowing aeolian accumulation during episodes of heightened aridity or the accumulation of non-channelized fluvial facies and palaeosols during less arid episodes.

The models proposed by Trudgill *et al*., (2004), Kluth & DuChene (2009) and Trudgill (2011) suggest that progressive progradation of the fluvial system occurred across the study area, resulting in the preservation of a series of halokinetically controlled sediment packages or sequences. Based on these models, results from this study can be placed within a larger stratigraphic framework. The proposed 'heel-and-toe' basin in-fill geometry (Kluth & DuChene, 2009), favours a southerly migration of the basin depocentre through time as individual mini-basins changed from a 'heel-type' to a 'toe-type 'depositional system; in later stages of mini-basin in-filling (toe infilling) an accommodation setting such as that hypothesised for the exposed part of the Cutler Group in the Parriott mini-basin would be generated, whereby multi-storey and multi-lateral channel elements (F1) accumulated over the heel-wedge of previously deposited strata. Interbedded channel elements (F2, F3 & F4) and non-channelized elements (F5 & F6) are preferentially preserved in the rim syncline accommodation zone generated by salt withdrawal in the more distal part of the mini-basin (correlating with 'toe' style of geometry proposed by Kluth & DuChene, 2009).

Kluth & DuChene's (2009) model of systematic and sequential mini-basin development, including welding of the pre- and post-salt sediments before the mini-basin was abandoned, suggests that synchronous multi-basin occupancy by fluvial systems was unlikely and that therefore correlation between the mini-basins should not be possible. However, based on their correlation of units between mini-basins, Rasmussen & Rasmussen (2009) interpret coeval sedimentation across several mini-basins. Through analysis of the distribution of architectural elements, palaeocurrents and tectono-stratigraphic relationships, this study demonstrates that coeval sedimentation in several multi-basins did occur. Furthermore, studies of the Triassic Moenkopi and Chinle formations (Banham& Mountney, 2013a,b,Prochnow*et al*., Mathews *et al*., 2007, respectively) clearly demonstrate that there was sufficient syn-sedimentary salt movement to influence the development of the Triassic sedimentary systems and this further supports the hypothesis of multiple-phases of mini-basin development and repeated occupancy by long-lived fluvial systems.

## Architectural element distribution in salt mini-basins

Detailed sedimentological data in the form of graphic sections and correlation panels have enabled a series of three-dimensional evolutionary models of the studied mini-basins to be proposed (Figs. 9, 10 & Fig. G in online supporting information), which demonstrates the preferred location and style of juxtaposition of collections of genetically related architectural elements during both episodes of fluvial diversion and episodes of breaching of the salt-walls. The exposed part of the Undifferentiated Cutler Group demonstrates significant variations in element distribution relative to positions within mini-basins. These models can be applied as generalized predictive tools for the analysis of salt-walled mini-basins and their infills.

1. Sedimentological evidence to demonstrate syn-sedimentary salt movement includes dramatic thickness variations across salt walls, the development of growth unconformities adjacent to salt walls, the fanning of stratal packages and the presence of facies characterized by convoluted bedding and dewatering structures (Fig. 10). The development of local unconformities indicates that salt movement was likely episodic rather than continuous, and the greatest influence on sedimentology localized.

2. Sedimentological evidence to demonstrate diversion of fluvial flow includes up-section (i.e. temporal) changes in palaeocurrent indicators. The preferred southwesterly drainage direction (as indicated by the broader context of the Undifferentiated Cutler Group in the Paradox Basin)

is expressed in the study area as drainage that was perpendicular to salt walls. However, palaeocurrent data may fluctuate between directions aligned perpendicular and parallel to the salt walls (Fig. 10g & h), the latter being indicative of local drainage diversion. Localized reworking of previously deposited sediments due to fluvial breaching of topographic highs is indicated by an abundance of intraformational clasts(Fig. 10 b, g & h) and the preferred preservation of multiple stacked elements composed of channel-lag deposits in areas where available accommodation was restricted (e.g., salt-wall crests). Ponding of non-channelized fluvial deposits behind salt-generated topography in areas of salt generated accommodation, as demonstrated by the presence of mica-rich fine-grained sandstone and siltstone facies exhibiting an abundance of planar lamination or ripple cross-lamination as fining-upward depositional cycles, further demonstrates the impact of salt-induced topography on fluvial drainage.

3. This study demonstrates that it is possible to predict the distribution of fluvial and aeolian architectural elements across mini-basins. This has important implications for the interpretation of subsurface successions for which seismic resolution is typically poor in areas adjacent to salt walls. Multi-storey and multi-lateral channel elements are typically confined to areas of lower accommodation away from rim-syncline depocentres; such elements comprise predictable facies associations (Fig. 10 a, b & d). Single-storey channel elements and non-channelized elements dominate in areas close to salt walls (Fig. 10a, c & e) but pass abruptly laterally into multi-storey and multi-lateral channel elements. In semi-arid, fluvial-dominated settings, aeolian elements may preferentially accumulate in the lee of salt walls (e.g., Castle Valley) where they are protected from fluvial reworking (Fig. 10f).

## Syn-sedimentary salt movement as an influence on fluvial-aeolian interaction

Beyond the confines of the Salt Anticline Region, the Cutler Group is characterized by interfingering and interbedding of packages of aeolian and fluvial strata, especially in the lowermost part of the succession, which is stratigraphically equivalent to the aeolian Cedar Mesa Sandstone in more distal parts of the Paradox Basin. In the exposed part of the succession in the Salt Anticline Region, aeolian packages are of restricted lateral and vertical extent and they form less than 10% of the exposed succession.

Observations presented herein can be used to make three general statements about the nature of the fluvial-aeolian interactions and the resultant preserved stratigraphy in the Salt Anticline Region.

1. *Preferential preservation of aeolian elements in the fluvial- lee of salt walls* (Fig. 10. a & f). In settings where preferred fluvial flow direction was perpendicular to the salt walls, diversion of

fluvial flow promoted preservation of aeolian elements on the downstream (lee) side of the salt walls (e.g., Castle Valley). In systems where fluvial palaeo flow was oblique to the salt walls, the pattern of aeolian accumulation is more complex, with such deposits being restricted in extent, for example, to one end of the downstream side of a salt wall. Where preferred palaeoflow was parallel to salt walls, aeolian element preservation potential was less since fluvial systems dominated the basin floors for protracted episodes.

2. *Preservation of aeolian elements around the noses of salt walls and between adjoining salt walls*. Where preferred fluvial flow was perpendicular to salt walls, aeolian elements may have preferentially accumulated around the noses of salt walls and in corridors between adjoining salt walls during episodes when the fluvial systems were able to breach salt-wall crests. The diversion of fluvial flow by salt movement likely restricted accumulation of these aeolian elements to the edges of salt-generated topographic highs (e.g., as seen around the nose of the Onion Creek diapir). Where fluvial palaeo flow was oblique or parallel to a salt wall, aeolian elements may have preferentially accumulated on the flanks of salt-generated topographic highs where fluvial activity was limited.

3. *Preservation of aeolian elements in other locations in mini-basins*. Extrinsic influences, such as climatic or tectonic cyclicity, together with intrinsic processes such as avulsion, likely resulted in the temporary localized retreat of the fluvial system in parts of some mini-basins, thereby allowing localized aeolian accumulation. The preservation potential of such aeolian elements was likely greatest in areas of higher accommodation(such as in rim synclines adjacent to salt walls). This would account for the presence of laterally discontinuous aeolian elements throughout the Cutler succession, and their notable preservation adjacent to the Castle Valley salt wall.

## Conclusions

Syn-sedimentary movement of salt significantly influences the development of fluvial systems and any resultant stratigraphic architecture. Variations observed across salt-walled mini-basins in SE Utah demonstrate that the rate of creation of accommodation in mini-basin depocentres increased in response to salt withdrawal. Uplift occurred across the crests of the salt walls, with the greatest accommodation created immediately adjacent to these walls as rim synclines. In the resulting depocentres, preserved fluvial architecture is characterized by intercalations of channel and overbank elements. Away from depocentres, in areas subject to reduced rates of accommodation creation, the stratigraphic architecture is characterized by the accumulation of multi-storey stacked channel elements, many possessing evidence for the reworking of older fluvial deposits, as demonstrated by the widespread occurrence of fills composed of lags of intraformational clasts.

This study demonstrates that episodes of single- and multi- mini-basin occupancy occurred during accumulation of the Undifferentiated Cutler Group. Accumulation of fluvial strata was restricted across topographic highs, which developed as a surface expression of salt wall growth, chiefly due to the limited availability of accommodation. This led to substantial sediment reworking as erosively-based channel bodies combed these areas, generating abundant intraformational clasts, especially on the downstream SW side of salt walls due to extensive sediment reworking as the fluvial systems flowed over salt-cored uplifts.

Aeolian elements are preserved either during episodes of limited fluvial activity (possibly driven by a switch to a more arid climate), or in response to diversion of fluvial systems around growing salt walls, creating under-filled accommodation in which wind-blown sediments could accumulate. Some aeolian elements are laterally extensive where developed in basin depocentres but more typically they tend to be discontinuous and of restricted lateral extent, especially where they were subject to fluvial reworking, for example in areas adjacent to salt walls or between salt-diapirs.

Tectono-stratigraphic models (Fig. 10) from this outcrop-based study can be used as an aid for subsurface interpretation of salt-walled mini-basins, especially those known only from the subsurface such as the Triassic Skagerrak Formation of the Central North Sea and the Saigak Field, Precaspian Basin, Kazakhstan (Barde *et al*., 2002). The characteristic architectural associations described from this study have important implications for predicting architectural relationships from subsurface well-log- and seismic-based studies, for predicting facies occurrence, and for constraining likely architectural-element dimensions and relationships.

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## Table Caption

Table 1: Summary data describing the distribution of facies across the Salt Anticline Region.

## Figure Captions

Figure 1: Map of the study area showing: (i) the main salt diapirs: OC, Onion Creek salt diapir; FV, Fisher Valley salt structure; CV, Castle Valley salt wall; MV, Moab salt wall; CcV, Cache Valley salt structure; SV, Salt Valley salt wall;(ii) salt-walled mini-basins: FiT, Fisher mini-basin; P, Parriott mini-basin; PB, Porcupine mini-basin; BB, Big Bend mini-basin;(iii) notable field localities: FT, Fisher Towers; RA, Richardson Amphitheater; HB, Hitle Bottom; SB, Shafer Basin, DP, Dome Plateau;(iv) locations of subsequent figures.

Figure 2: Geological map depicting the outcrop extent of the geological units in the study area and the locations of measured sedimentary sections used in this study. Dashed black line denotes logs used in construction of Fig. 5a, dashed red line denotes correlation panel Fig. 5c. All measured sections are shown on this figure and may be used as a location reference for subsequent figures.

Figure 3: Schematic stratigraphic cross section of the Paradox Basin showing relative stratigraphic positions and ages of units of the basin fill (modified after Condon, 1997). The Needles District, Corral Pocket, Indian Creek and Lockhart Canyon are all within, or adjacent to, the boundary of Canyonlands National Park SE of the study area. Stated ages are from Gradstein *et al.*(2012). The White Rim Sandstone is of probable Leonardian age; limestone present in the lower Cutler beds is of shallow-marine origin; the undifferentiated Cutler Group has a thickness of up to 4,000 m in the foredeep of the Paradox Basin. The symbol *marks the timing of commencement of significant salt movement.

Figure 4: Cross-section across the Salt Anticline Region illustrating large-scale thickness variations. Particularly dramatic thickness variations occur between the north and south sides of the Onion Creek salt diapir. Modified after Trudgill & Paz (2009).

Figure 5: Examples of stratigraphic architecture at various scales. (a) Regional correlation panel constructed using representative sedimentary logs (sections) measured across the study area; correlation panel depicts variations in architectural-element distribution. Locations of sedimentary logs (sections) are shown on the inset map, and in detail on Fig. 2. Grey bodies represent fluvial

channel packages, yellow package represents aeolian element on the south side of the Castle Valley Salt Wall. Brown unit at top of figure is the Moenkopi Formation. Vertical exaggeration is approximately 100:1. (b) Architectural panel depicting relationships between architectural elements present adjacent to the Castle Valley Salt Wall. Note how channel fill is dominated by trough cross-bedded sandstone (Facies St); channel elements (F2, F3 & F4) are separated by laterally extensive fluvial non-channelized elements (F5 & F6). (c) Sedimentary logs measured adjacent to the north side of the Onion Creek salt diapir depicting the abundance of fluvial non-channelized elements (F5 & F6) in this region; locations of sedimentary logs are shown on Fig. 2.(d) Correlation panel constructed using sedimentary logs measured around the nose of the Onion Creek salt diapir. Note the presence of aeolian elements (A1, A3) of limited lateral extent and the abundance of fluvial non-channelized elements (F5 & F6). Fluvial channelized elements are both single-storey and multi-storey (F1, F2, F3& F4).Line of section is denoted by black line on Fig. 2.

Figure6 :Examples of architectural relationships adjacent to the Onion Creek salt diapir. (a) The photomontage (view toward 045$^{o}$).(b)Architecture at Fisher Towers, a location close but not directly adjacent to the salt wall. Here, bounding surfaces between elements are close to parallel to each other. (c) Architecture at a location close to the nose of the Onion Creek salt diapir; here, bounding surfaces delineating architectural elements exhibit onlapping relationships. Palaeocurrent rose diagrams represent data collected from multiple elements, than single sets. See Figure 1 for location within the regional study area. Key to figure can be found on Fig. 5.

Figure 7: Correlation panel across the studied part of the Salt Anticline Region. This panel was constructed using key sedimentary profiles, aided by lateral tracing and correlation of distinctive channel elements and laterally extensive sheet-like elements. Note the abundance of multi-storey and multi-lateral (F1) channel elements towards the centres of the mini-basins and increased preservation of non-channelized elements (F5 & F6) adjacent to salt walls.

Figure 8: Schematic cross section across study area illustrating the style of distribution of genetically related groups of architectural elements. Key features are highlighted. This section was constructed from correlation panels (e.g., Fig. 7) and from field observations.

Figure 9: Models depicting the distribution of architectural elements in response to episodes of fluvial diversion along the axes of mini-basins and episodes of fluvial flow over the top of the salt walls. (a) Episode of diversion of fluvial channel systems. Subsurface movement of salt layers of the Paradox Formation resulted in the generation of accommodation adjacent to salt walls and the diversion of fluvial flow around topographically-elevated salt-cored highs. Thick successions of

non-channelized elements (F5 & F6) accumulated adjacent to the salt walls, whereas multi-storey and multi-lateral channel elements (F1) were chiefly confined to the centres of the mini-basins. (b) Episode of breaching of the salt walls and re-equilibration of fluvial system. Progressive infilling of available mini-basin accommodation enabled the fluvial system to eventually breach the salt highs and single-storey channel elements (F2, F3 & F4) were preserved over the crest of the salt wall. These elements typically unconformably overlie non-channelized (F5 & F6) elements. This process likely occurred a number of times following repeated episodes of salt movement and uplift and subsequent infilling of the generated space during tectonically quiescent episodes. During episodes of diversion of fluvial flow, aeolian accumulation occurred on the downstream side of the topographic highs.

Figure 10: Generic model depicting the expected architectural-element locations within salt-walled mini-basins. Depiction of fluvial pathways during an episode of diversion around salt walls (a); some breaching of the salt wall is likely across topographic lows; multi-storey and multi-lateral channel elements are located primarily in the centres of mini-basins (b & d), whereas non-channelized and single-storey channel-elements are located towards the edges of mini basins (c & e). Aeolian elements may accumulate in the lee of salt walls (f). Schematic logs taken through a multi-storey channel complex (g) and an overbank and single-storey channel element (h). Palaeocurrent vectors are used to illustrate the influence episodic fluvial diversion by salt-generated topography.

Supplementary Information

Table ii: Lithofacies and facies associations in deposits of the Undifferentiated Cutler Group in the Salt Anticline Region.

Table iii: Architectural elements of the Undifferentiated Cutler Group in the Salt Anticline Region.

Figure A: Principal fluvial (a) and aeolian (b) architectural associations of the Cutler Group. Genetically related architectural elements are assigned to one of four groups: multi-storey and multi-lateral channel elements, single-storey channel elements, non-channelized fluvial elements and aeolian elements. The facies key of this figure is applicable to subsequent figures.

Figure B: Changes in the distribution of facies across the study area (NE to SW). (a) Graph showing facies distribution by location, facies are represented as a percentage of the exposed outcrop. (b) Enlargement of part of graph shown in (a) depicting the distribution of less abundant facies.(c)The variable distribution of granule, pebble and cobble grade clasts across the study area; note the decrease in proportion of all clasts across the study area. The spikes in the incidence of granule-grade clasts in the River localities and pebble- and cobble-grade clasts in Castle Valley are largely due to localized occurrences of reworked detritus of intraformational origin. The graph shows percentage of exposed outcrop and the data have been compiled from measured sections at named locations. See Figure 5 for explanation of facies codes. See Figure 2 for location of sedimentary sections.

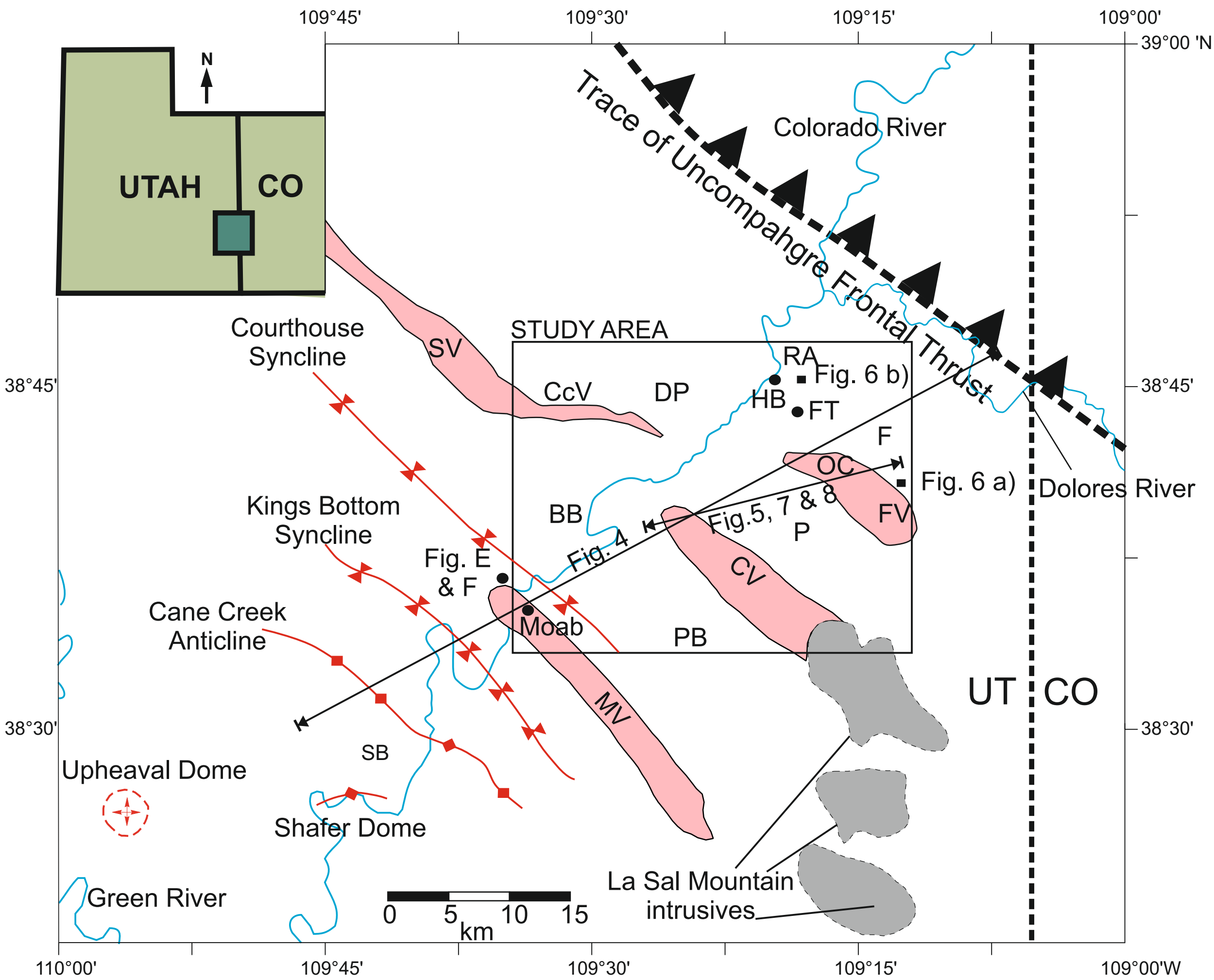
Figure C: Palaeoflow reconstruction for the Cutler fluvial system at a stratigraphic level approximately equivalent to the P6 stage of Trudgill (2011). (a) Representative reconstruction of the subsurface part of the Cutler Group showing a general SW-directed palaeoflow. (b to d) Representative reconstructions for three stratigraphic levels in the exposed part of the Cutler Group, with (d) representing the uppermost part of the exposed succession. These models demonstrate episodes of fluvial flow over and around the salt walls. Palaeocurrent data are presented on the maps as vector mean arrows (black arrows) derived from the rose diagrams shown in the lower part of the figure.

Figure D: a) Sketch depicting the relationship between the Onion Creek salt diapir and the adjacent succession, note the presence of an unconformity adjacent to the salt structure, key fluvial channelized elements are labelled. This sketch depicts the geometrical arrangement of sedimentary packages adjacent to the salt structure and not the detailed arrangement of architectural elements. Figure is not to scale; b) Annotated photograph of the Onion Creek salt diapir depicting the positions of two of the main unconformities present on the northern side of the salt structure; c) Schematic sketch depicting the localized nature of the unconformities with respect to the Onion Creek salt diapir, note how the succession becomes conformable within a short distance from the diapir.

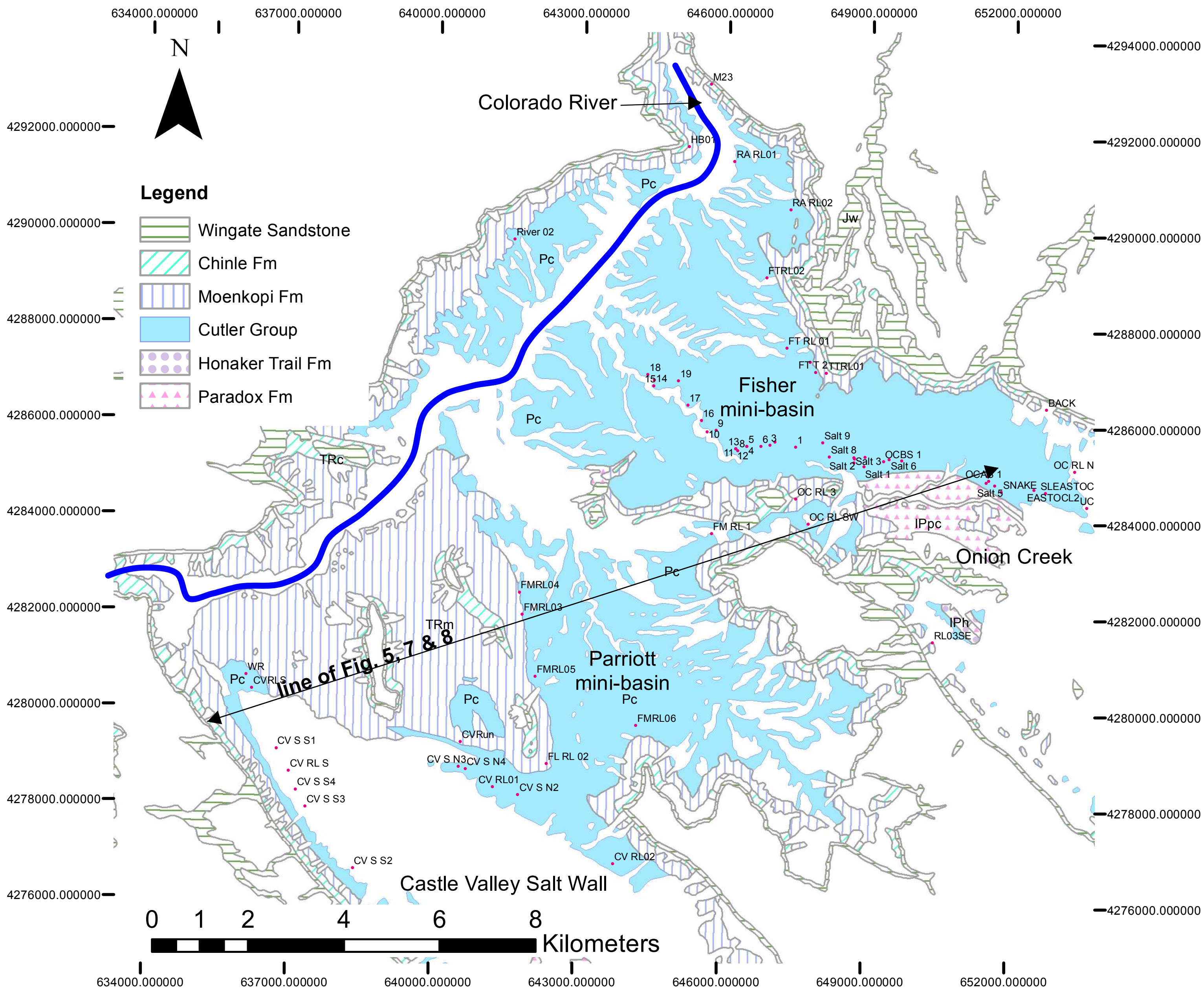
Figure E: Annotated photographs showing the thinning of deposits of the Cutler Group onto the Moab salt wall. Both photographs face southwest; bearings are not indicated on the photographs because the photographs have been rotated as part of the montaging process. The direction of thinning is illustrated by the arrow on figure E b. The field of view is approximately 7 km in (a) and 3 km in (b). The cliffs have a maximum vertical height of ~400 m. Figure location is shown on Figure 1

Figure F: Representative sedimentary section showing the relative abundance of aeolian elements preserved adjacent to the Moab salt wall. Figure location is shown on Figure 1

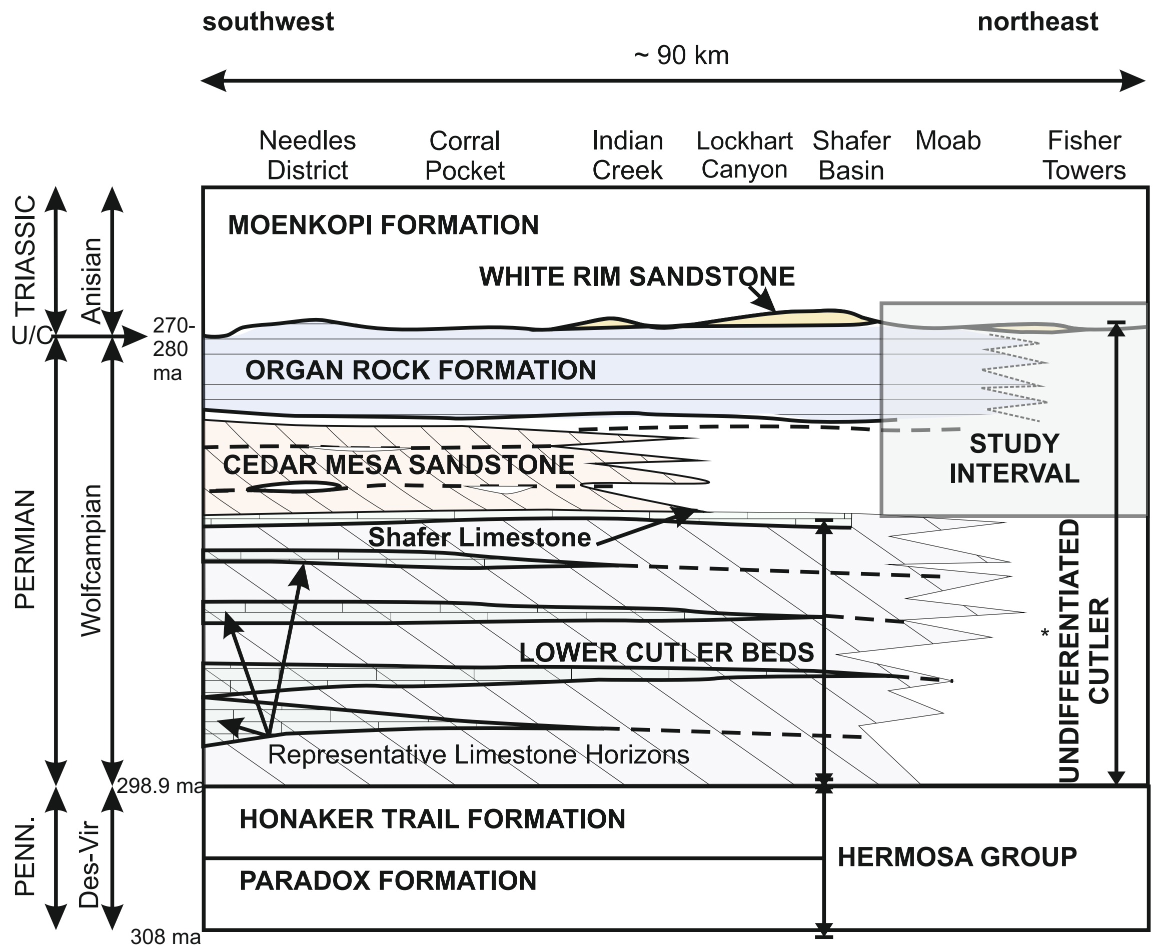
Figure G: Depositional model for the Undifferentiated Cutler Group in the Salt Anticline Region, highlighting diversion of fluvial flow. (a) Diversion of fluvial flow around topographic highs enabled aeolian accumulation in the lee of salt highs and aeolian sandsheet construction at basin margins and in locations away from the main fairways of fluvial activity. (b) Breaching of salt walls occurred after infilling of salt-generated accommodation. This model is based on analysis of exposed successions where correlation has been possible through lateral outcrop tracing of key stratal surfaces. Architectural elements are coloured according to the key on Figure 9.

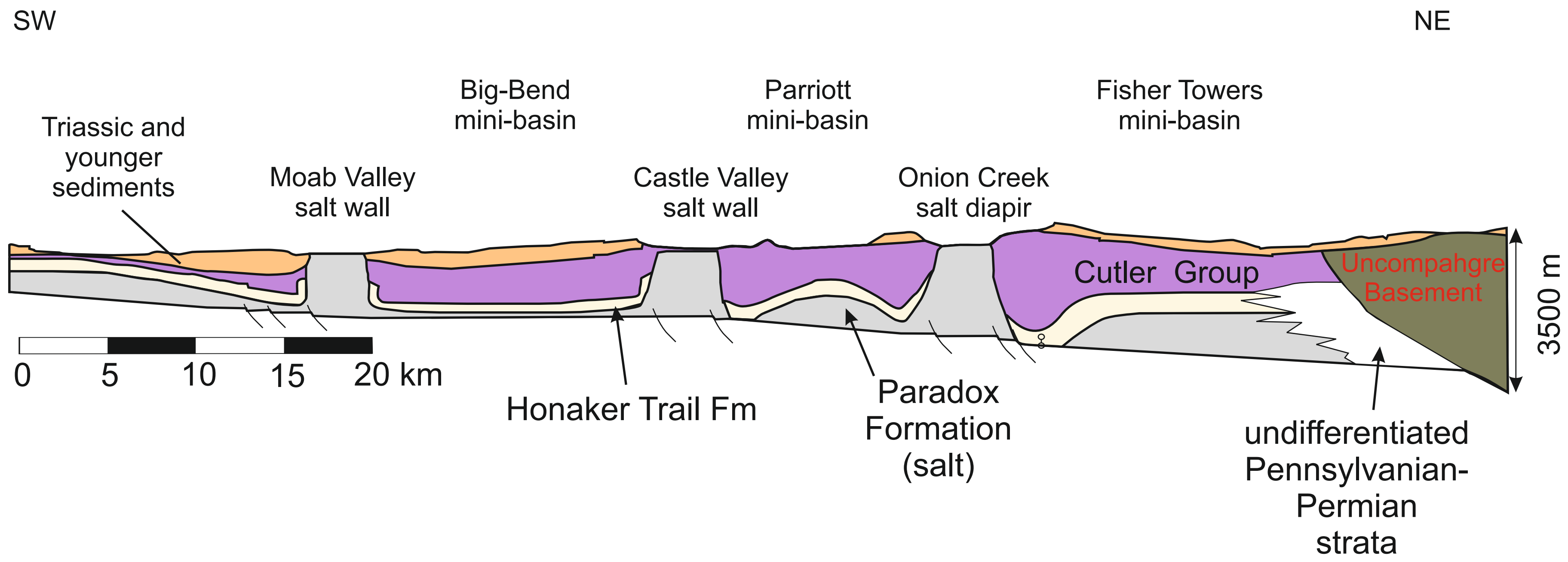


109°45'
109°30'
109°15'
109°00'
39°00 'N
38°45'
38°30'
110°00'
109°00'W
N
UTAH
CO
Trace of Uncompahgre Frontal Thrust
Colorado River
Dolores River
Courthouse Syncline
Kings Bottom Syncline
Cane Creek Anticline
Upheaval Dome
Shafer Dome
Green River
STUDY AREA
SV
CcV
DP
RA
HB
FT
Fig. 6 b)
F
OC
FV
Fig. 6 a)
BB
Fig.5, 7 & 8
P
Fig. 4
CV
Fig. E & F
Moab
PB
MV
SB
UT
CO
La Sal Mountain intrusives
0 5 10 15
km

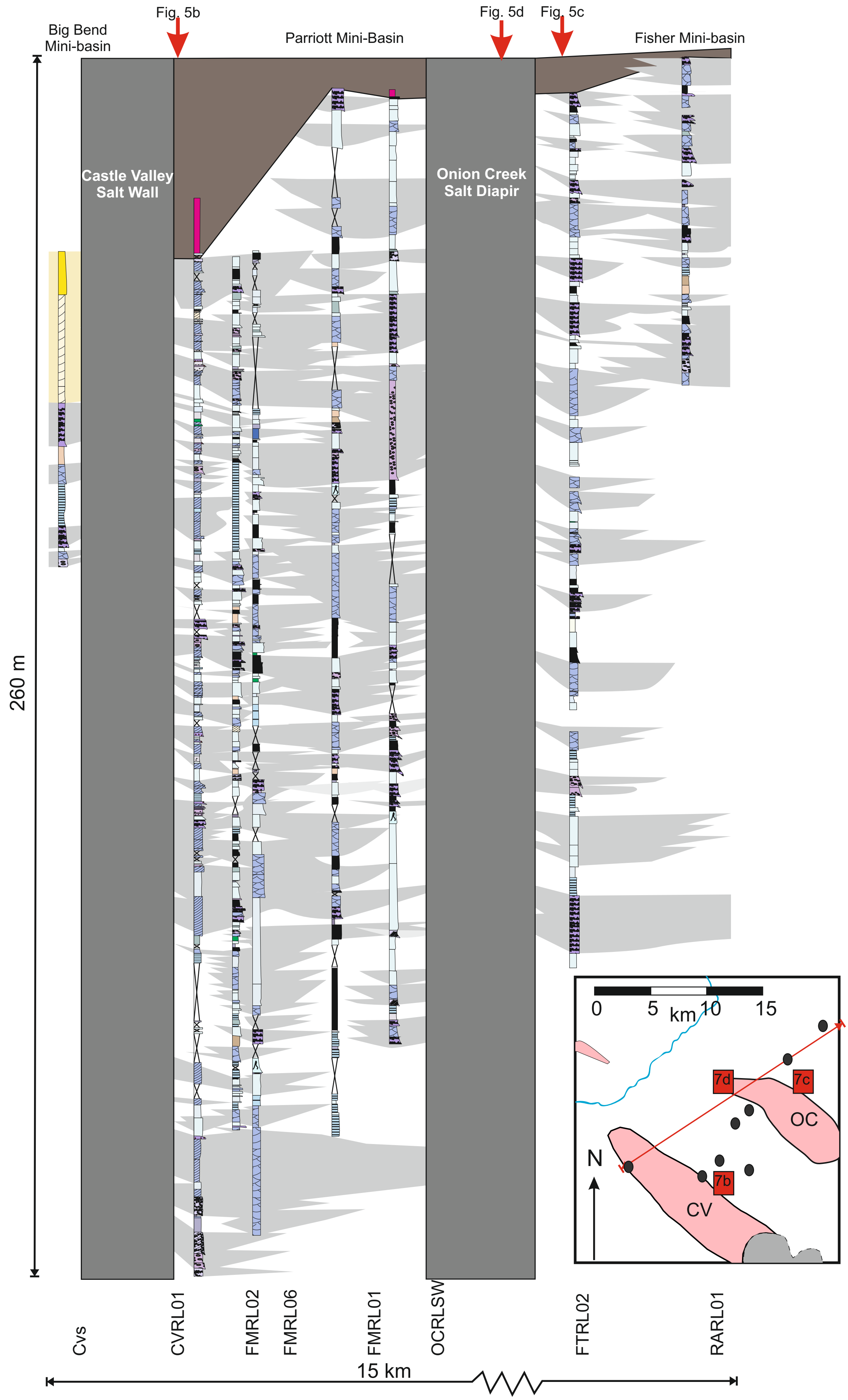


N
Legend
Wingate Sandstone
Chinle Fm
Moenkopi Fm
Cutler Group
Honaker Trail Fm
Paradox Fm
Colorado River
Fisher mini-basin
Parriott mini-basin
Onion Creek
Castle Valley Salt Wall
line of Fig. 5, 7 & 8
0 1 2 4 6 8 Kilometers
634000.000000
637000.000000
640000.000000
643000.000000
646000.000000
649000.000000
652000.000000
4294000.000000
4292000.000000
4290000.000000
4288000.000000
4286000.000000
4284000.000000
4282000.000000
4280000.000000
4278000.000000
4276000.000000

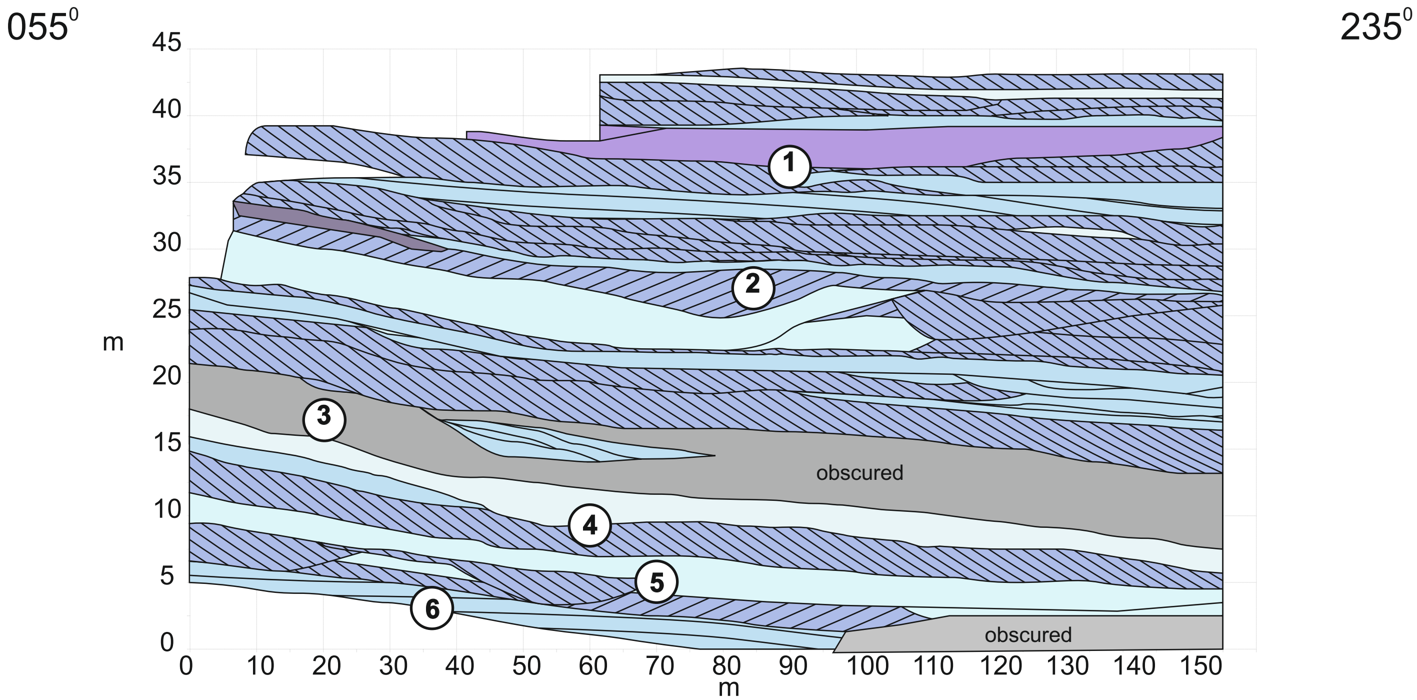

southwest
northeast
~ 90 km
Needles District
Corral Pocket
Indian Creek
Lockhart Canyon
Shafer Basin
Moab
Fisher Towers
TRIASSIC
Anisian
U/C
270-280 ma
PERMIAN
Wolfcampian
298.9 ma
PENN.
Des-Vir
308 ma
MOENKOPI FORMATION
WHITE RIM SANDSTONE
ORGAN ROCK FORMATION
CEDAR MESA SANDSTONE
STUDY INTERVAL
Shafer Limestone
LOWER CUTLER BEDS
Representative Limestone Horizons
UNDIFFERENTIATED CUTLER
*
HONAKER TRAIL FORMATION
PARADOX FORMATION
HERMOSA GROUP



SW
NE
Big-Bend mini-basin
Parriott mini-basin
Fisher Towers mini-basin
Triassic and younger sediments
Moab Valley salt wall
Castle Valley salt wall
Onion Creek salt diapir
Cutler Group
Uncompahgre Basement
3500 m
0 5 10 15 20 km
Honaker Trail Fm
Paradox Formation (salt)
undifferentiated Pennsylvanian-Permian strata



Big Bend
Mini-basin
Fig. 5b
Parriott Mini-Basin
Fig. 5d
Fig. 5c
Fisher Mini-basin
Castle Valley
Salt Wall
Onion Creek
Salt Diapir
260 m
0
5
km
10
15
7d
7c
OC
N
7b
CV
Cvs
CVRL01
FMRL02
FMRL06
FMRL01
OCRLSW
FTRL02
RARL01
15 km




## Panel Information

| | |
|---|---|
| Name | SAR: Castle Valley Track 1 |
| Facing | northwest |
| Orientation | 055⁰ - 235⁰ |
| Location | SAR: Castle Valley, See Appendix 1 |
| Facies | Gm-c,St, Sm-a, Sm-b; |
| Elements | Fluvial channel elements (F1,F2, F3 & F4); Non-channelized elements (F5 & F6) |

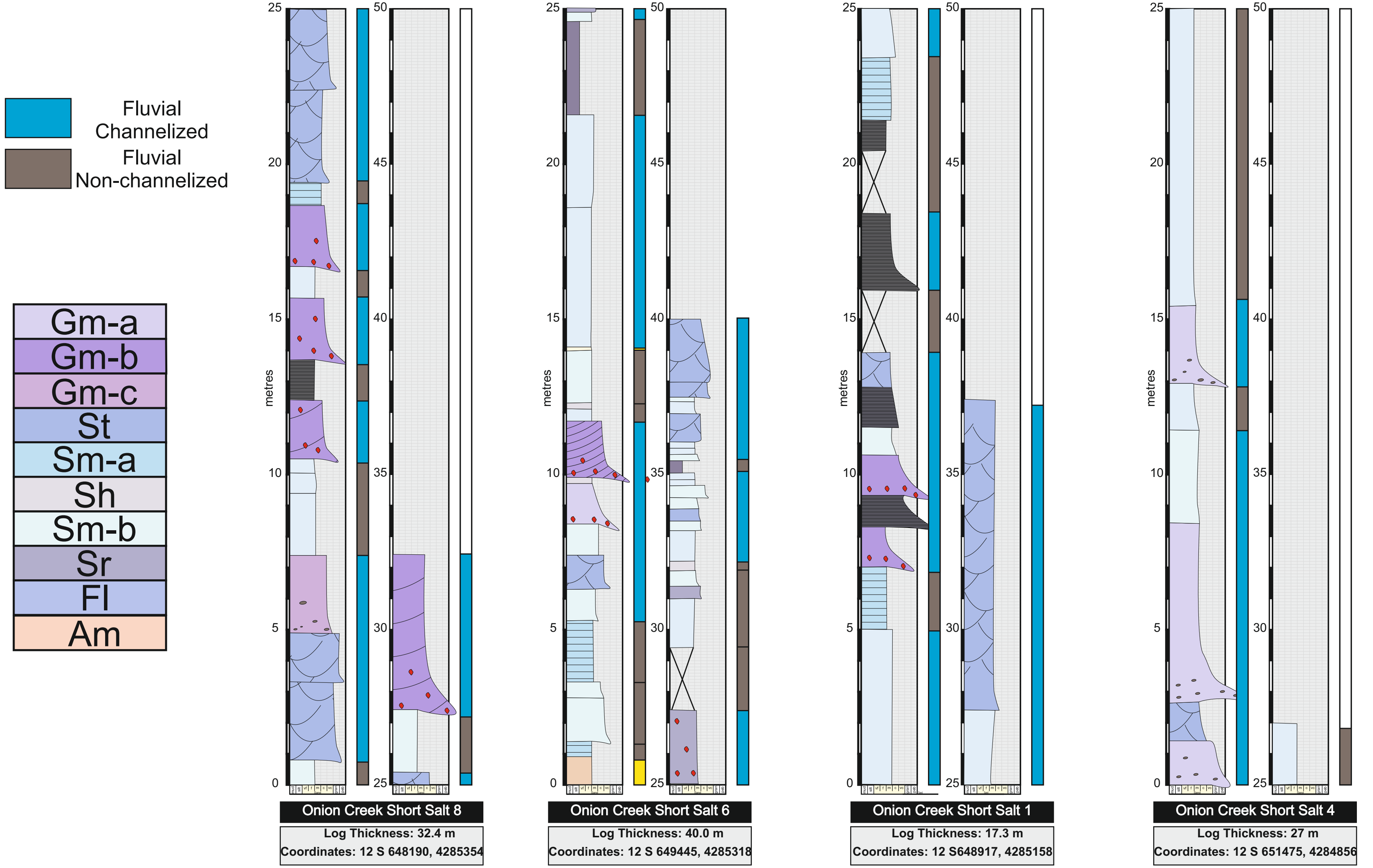
## Key Features

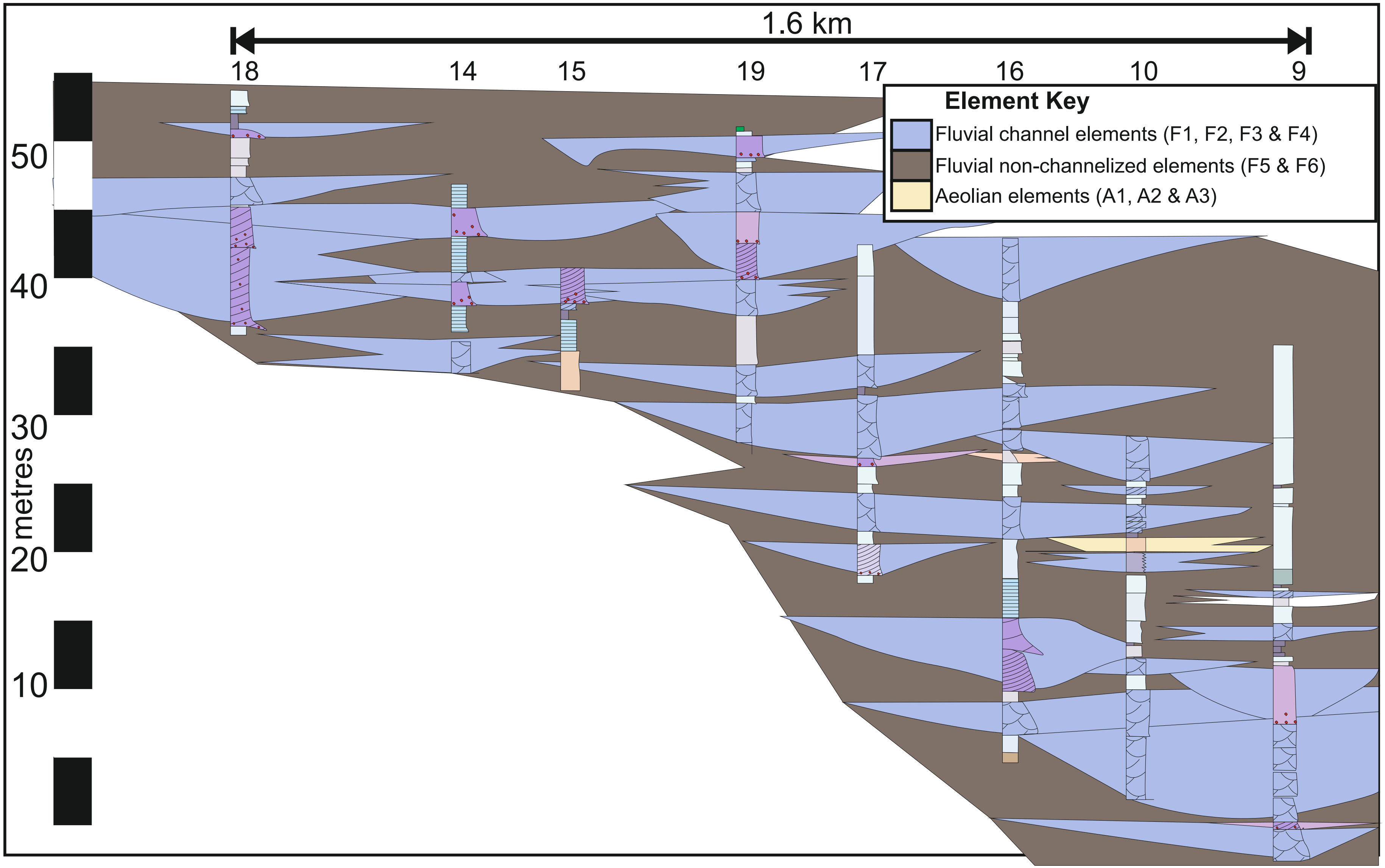
1. Laterally amalgamated fluvial channelized element (F2, F3 or F4) in upper part of the succession,
2. Fluvial channel element, incising into non-channelized fluvial elements (F6) below.
3. Area of obscured stratigraphy; likely representing prefered weathering on non-channelized elements (F5 & F6)
4. Multi-storey and multi-lateral fluvial channel elements (F1)
5. Massive sandstone facies, contained within laterally extensive sheet-like non-channelized fluvial elements (F6)
6. Laterally extensive sheet-like non-channelized fluvial elements (F6)

## Facies Key

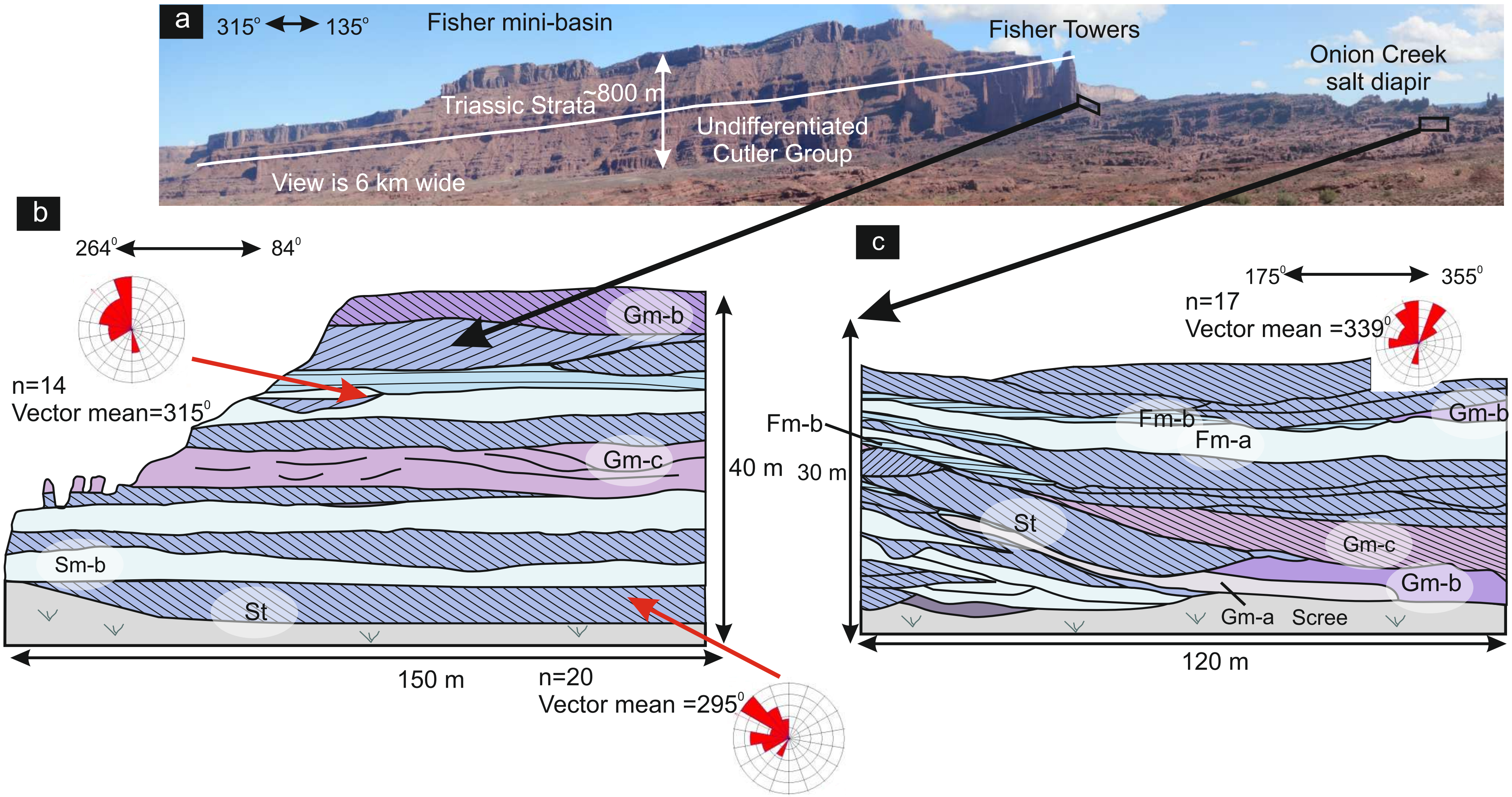
Fluvial Facies

- Trough cross-bedded sdst (St)
- Massive sandstone (Sm-b)
- Horizontally bedded sdst (Sm-a)

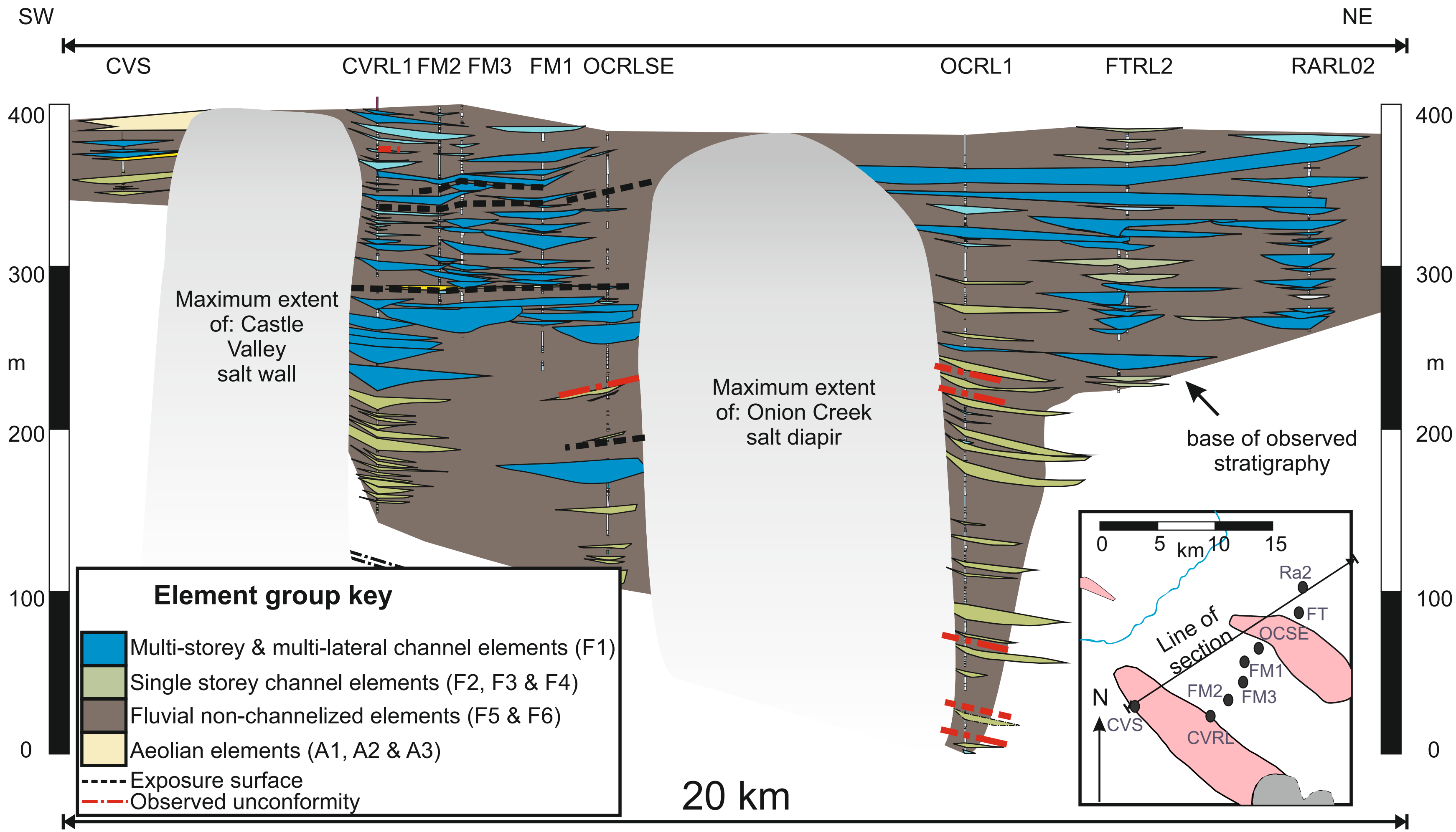

Fluvial Channelized
Fluvial Non-channelized
Gm-a
Gm-b
Gm-c
St
Sm-a
Sh
Sm-b
Sr
Fl
Am
metres
Onion Creek Short Salt 8
Log Thickness: 32.4 m
Coordinates: 12 S 648190, 4285354
Onion Creek Short Salt 6
Log Thickness: 40.0 m
Coordinates: 12 S 649445, 4285318
Onion Creek Short Salt 1
Log Thickness: 17.3 m
Coordinates: 12 S648917, 4285158
Onion Creek Short Salt 4
Log Thickness: 27 m
Coordinates: 12 S 651475, 4284856

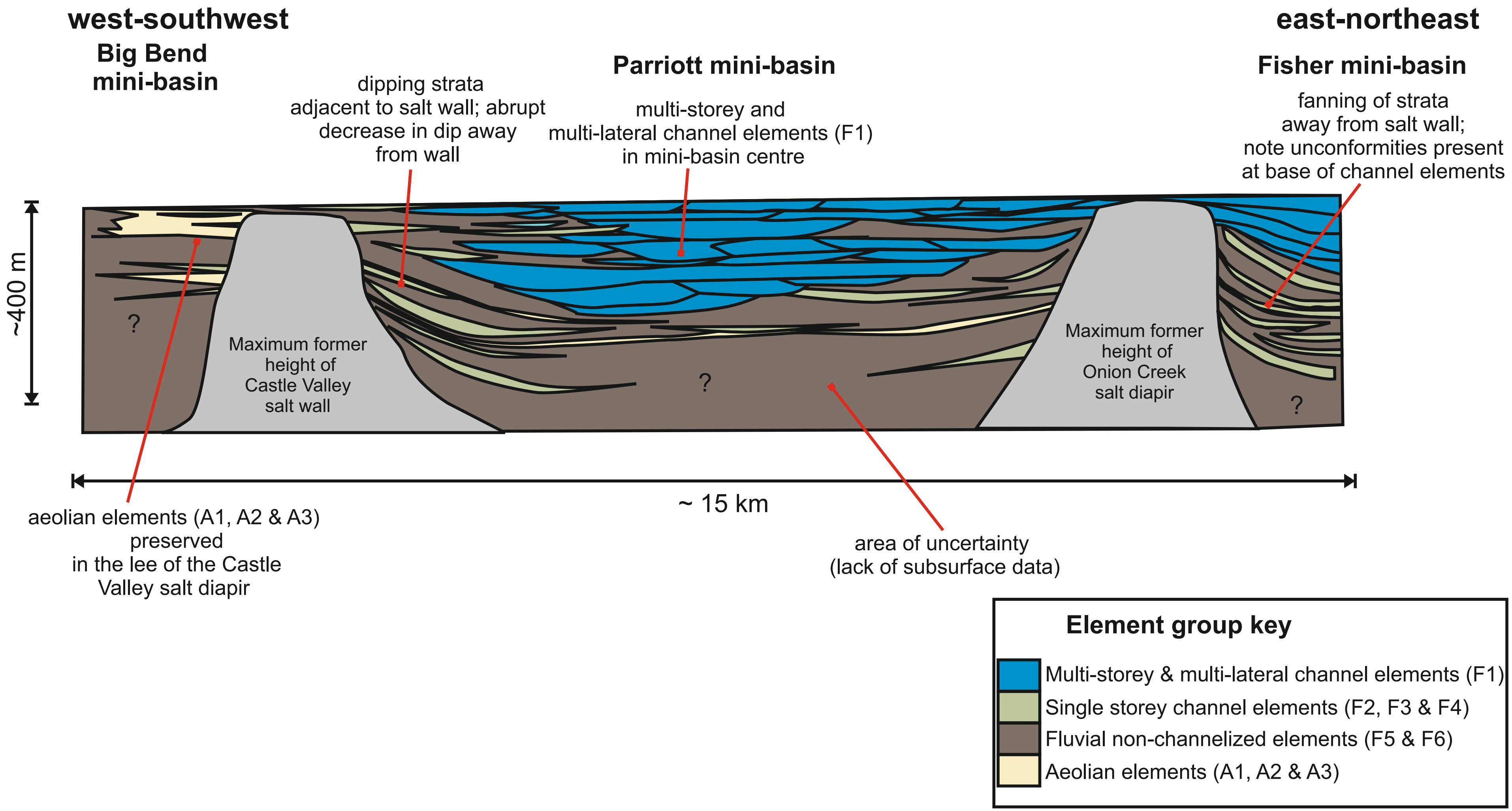


1.6 km
18
14
15
19
17
16
10
9
Element Key
Fluvial channel elements (F1, F2, F3 & F4)
Fluvial non-channelized elements (F5 & F6)
Aeolian elements (A1, A2 & A3)
50
40
30
20
10
metres

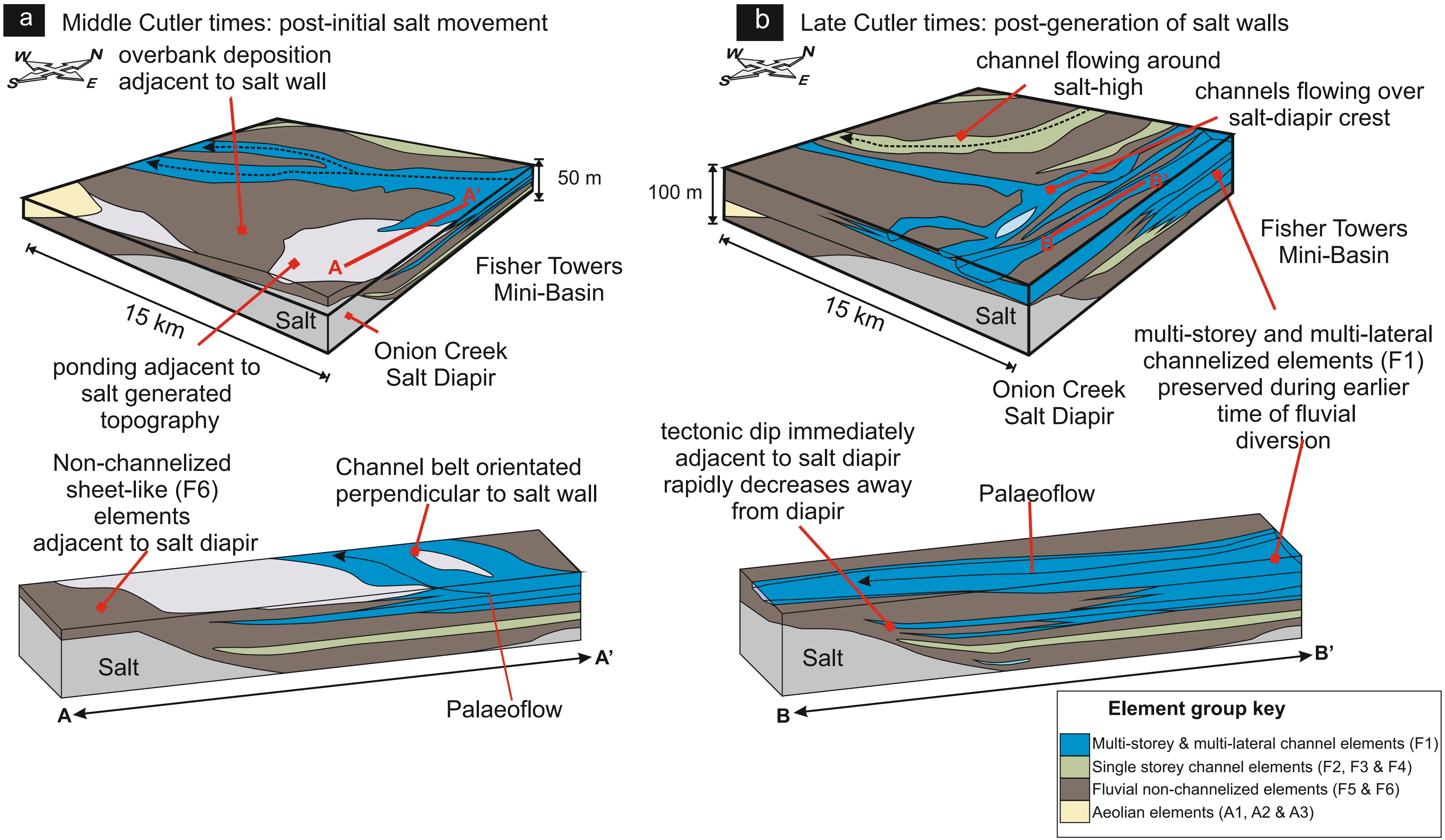


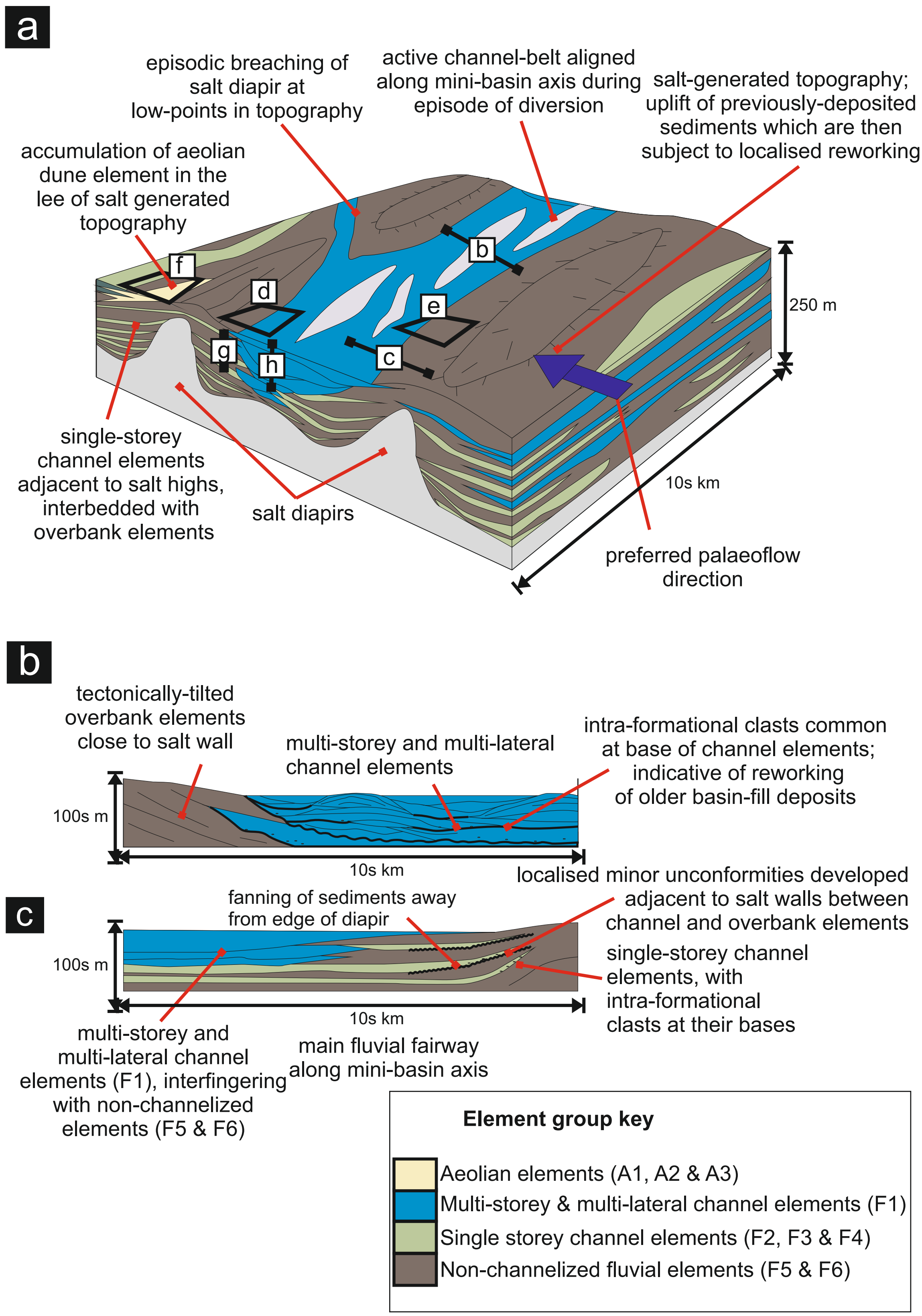
a
315° 135°
Fisher mini-basin
Fisher Towers
Onion Creek
salt diapir
Triassic Strata
~800 m
Undifferentiated
Cutler Group
View is 6 km wide
b
264° 84°
n=14
Vector mean=315°
Gm-b
Gm-c
Sm-b
St
40 m
150 m
n=20
Vector mean =295°
c
175° 355°
n=17
Vector mean =339°
Fm-b
Fm-a
Gm-b
St
Gm-c
Gm-a
Scree
30 m
120 m

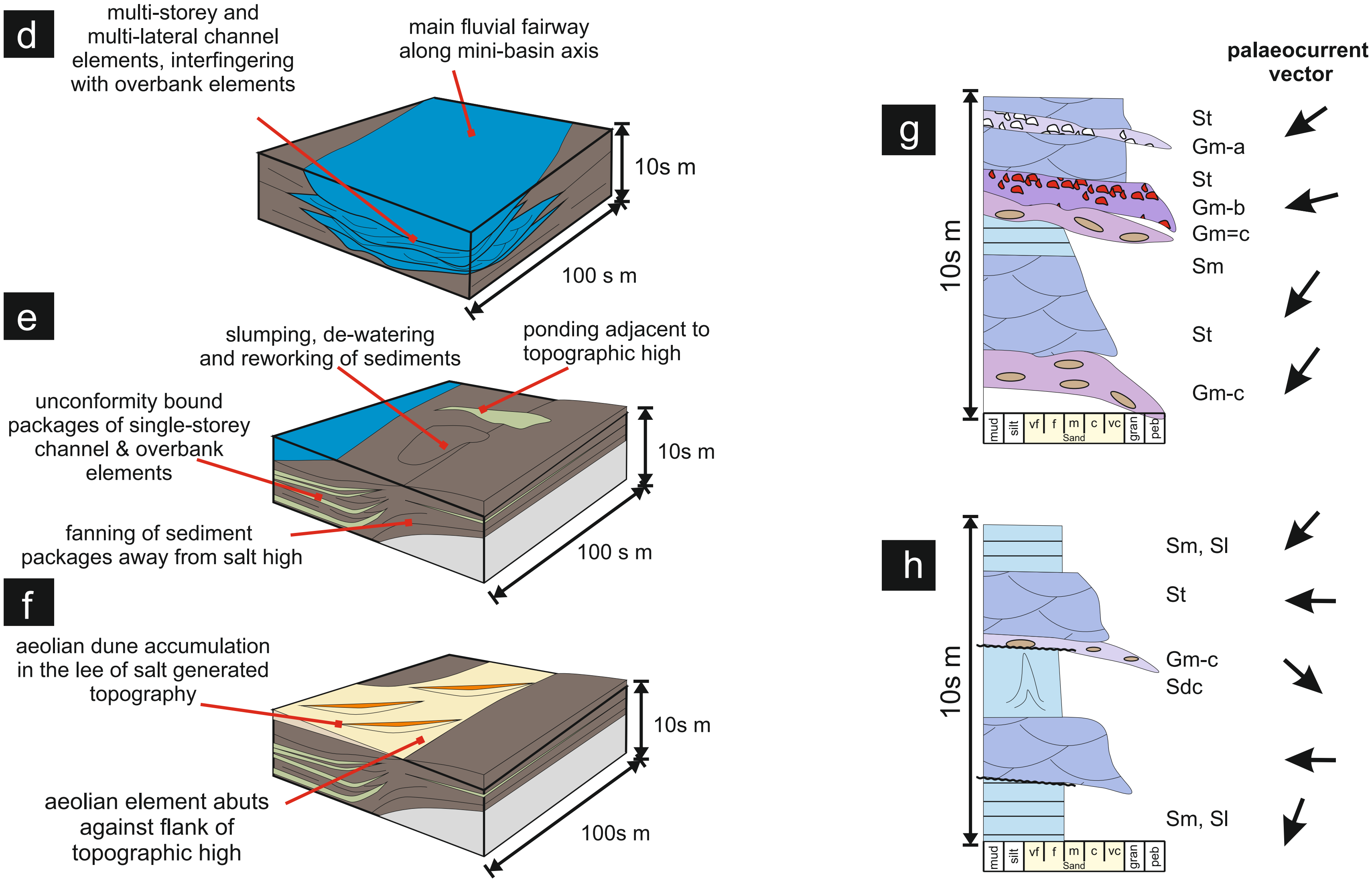

SW
NE
CVS
CVRL1 FM2 FM3
FM1 OCRLSE
OCRL1
FTRL2
RARL02
400
300
m
200
100
0
Maximum extent of: Castle Valley salt wall
Maximum extent of: Onion Creek salt diapir
base of observed stratigraphy
Element group key
Multi-storey & multi-lateral channel elements (F1)
Single storey channel elements (F2, F3 & F4)
Fluvial non-channelized elements (F5 & F6)
Aeolian elements (A1, A2 & A3)
Exposure surface
Observed unconformity
20 km
0 5 km 10 15
Ra2
FT
OCSE
FM1
FM2
FM3
CVS
CVRL
N
Line of section

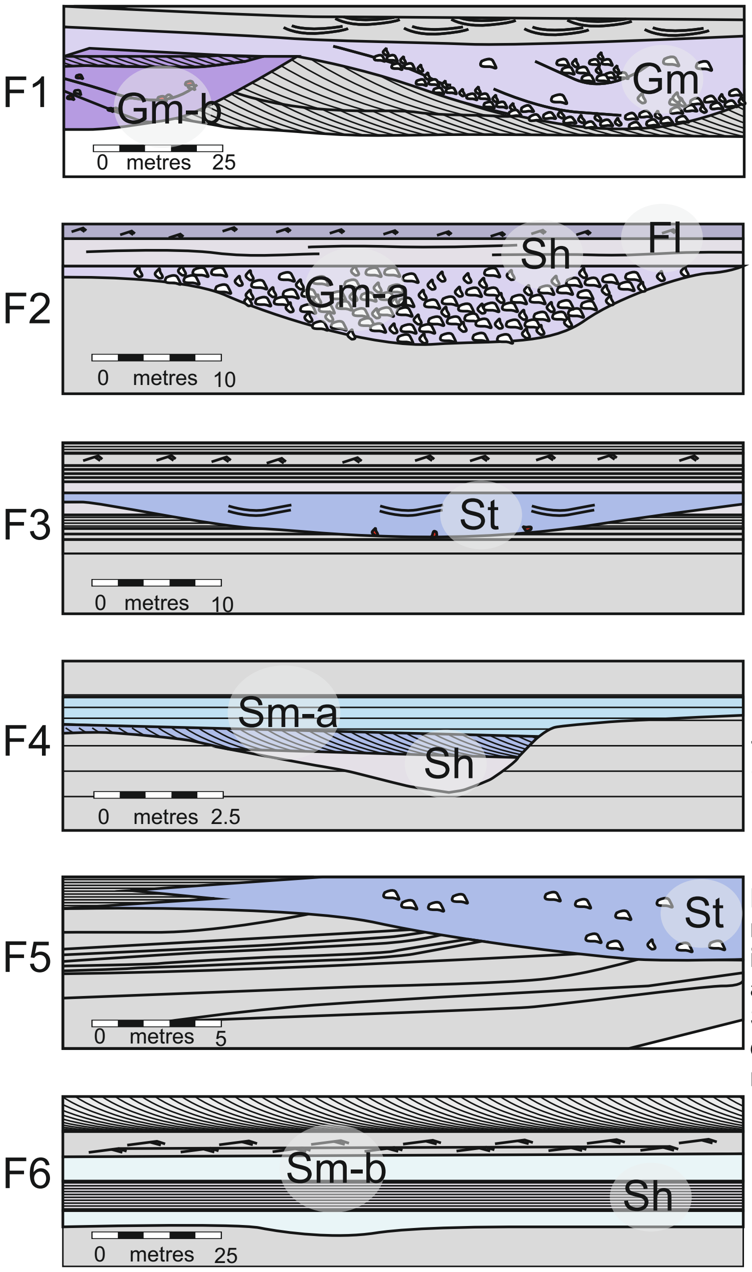


west-southwest
Big Bend mini-basin
dipping strata adjacent to salt wall; abrupt decrease in dip away from wall
Parriott mini-basin
multi-storey and multi-lateral channel elements (F1) in mini-basin centre
east-northeast
Fisher mini-basin
fanning of strata away from salt wall; note unconformities present at base of channel elements
~400 m
?
Maximum former height of Castle Valley salt wall
?
Maximum former height of Onion Creek salt diapir
?
~ 15 km
aeolian elements (A1, A2 & A3) preserved in the lee of the Castle Valley salt diapir
area of uncertainty (lack of subsurface data)
Element group key
Multi-storey & multi-lateral channel elements (F1)
Single storey channel elements (F2, F3 & F4)
Fluvial non-channelized elements (F5 & F6)
Aeolian elements (A1, A2 & A3)


a
Middle Cutler times: post-initial salt movement
W N S E
overbank deposition adjacent to salt wall
50 m
A'
A
Fisher Towers Mini-Basin
15 km
Salt
Onion Creek Salt Diapir
ponding adjacent to salt generated topography
Non-channelized sheet-like (F6) elements adjacent to salt diapir
Channel belt orientated perpendicular to salt wall
Salt
A'
A
Palaeoflow
b
Late Cutler times: post-generation of salt walls
W N S E
channel flowing around salt-high
channels flowing over salt-diapir crest
100 m
B'
B
Fisher Towers Mini-Basin
15 km
Salt
Onion Creek Salt Diapir
multi-storey and multi-lateral channelized elements (F1) preserved during earlier time of fluvial diversion
tectonic dip immediately adjacent to salt diapir rapidly decreases away from diapir
Palaeoflow
Salt
B'
B
Element group key
Multi-storey & multi-lateral channel elements (F1)
Single storey channel elements (F2, F3 & F4)
Fluvial non-channelized elements (F5 & F6)
Aeolian elements (A1, A2 & A3)


a
episodic breaching of salt diapir at low-points in topography
active channel-belt aligned along mini-basin axis during episode of diversion
salt-generated topography; uplift of previously-deposited sediments which are then subject to localised reworking
accumulation of aeolian dune element in the lee of salt generated topography
f
d
b
e
g
h
c
250 m
single-storey channel elements adjacent to salt highs, interbedded with overbank elements
salt diapirs
10s km
preferred palaeoflow direction
b
tectonically-tilted overbank elements close to salt wall
multi-storey and multi-lateral channel elements
intra-formational clasts common at base of channel elements; indicative of reworking of older basin-fill deposits
100s m
10s km
localised minor unconformities developed adjacent to salt walls between channel and overbank elements
c
fanning of sediments away from edge of diapir
100s m
single-storey channel elements, with intra-formational clasts at their bases
10s km
multi-storey and multi-lateral channel elements (F1), interfingering with non-channelized elements (F5 & F6)
main fluvial fairway along mini-basin axis
Element group key
Aeolian elements (A1, A2 & A3)
Multi-storey & multi-lateral channel elements (F1)
Single storey channel elements (F2, F3 & F4)
Non-channelized fluvial elements (F5 & F6)


d
multi-storey and multi-lateral channel elements, interfingering with overbank elements
main fluvial fairway along mini-basin axis
10s m
100 s m
e
slumping, de-watering and reworking of sediments
ponding adjacent to topographic high
unconformity bound packages of single-storey channel & overbank elements
10s m
fanning of sediment packages away from salt high
100 s m
f
aeolian dune accumulation in the lee of salt generated topography
10s m
aeolian element abuts against flank of topographic high
100s m
palaeocurrent vector
g
10s m
St
Gm-a
St
Gm-b
Gm=c
Sm
St
Gm-c
mud silt vf f m c vc gran peb
Sand
h
10s m
Sm, Sl
St
Gm-c
Sdc
Sm, Sl
mud silt vf f m c vc gran peb
Sand




**Multi-Storey and Multi-Lateral Channel Elements**
Laterally extensive over 100-5000 m, vertically stacked 10-50 m; composed of Gm, St, Sm.

**Laterally Isolated, Single-Storey Channel Element**
5- 20 m wide and ~5 m deep; composed of Gm, Sh, Sr and Sm; basal lags of Gm; fining upward cycles common.

**Homogenous Channel-Fill Element**
Laterally restricted 1-20 m in width and 0.5-5 m deep; channel fill either Sm, St, Sr or fl.

**Interbedded Channel-Fill Element**
Small channels 1-25m wide, <1 m -5m deep; incision steep (>30°) composed of Sh, St, Sm-a and Sm-b; commonly associated with F6.

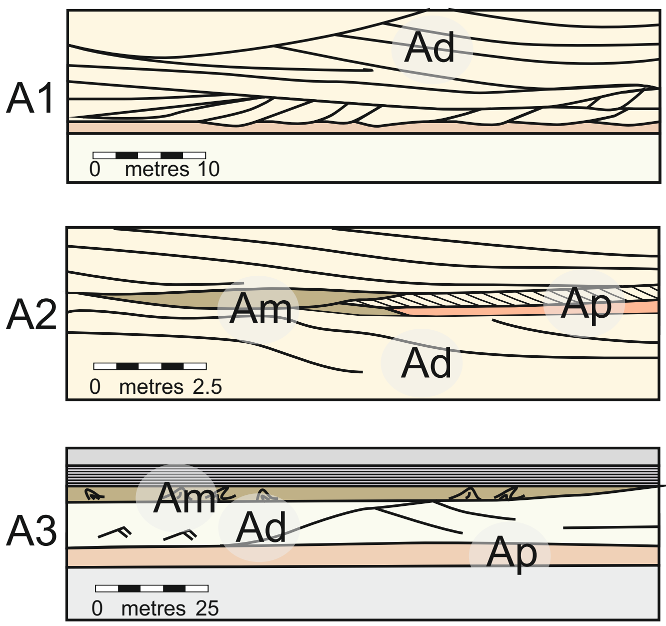
**Overbank Element**
Laterally extensive to locally restricted; 0.5-10 m thick; interfingers with channelized and aeolian elements; composed of Sh, Sr and Fl; burrowing, desiccation cracks calcrete nodules are common.

**Unconfined Sheet-Like Element**
Laterally extensive over 10-500 m; interfingers with aeolian and channelized fluvial elements; composed of Sm-b, Sh, Sr and St; some small (0.2-5m) scours at base.

Multi-Storey Multi-Lateral

Single-Storey Fluvial -Channelized

Fluvial - Non-Channelized




**Aeolian Dune Element**
Major bounding surfaces are sub-horizontal; sets cross stratified with curved reactivation bounding surfaces; composed of Ad; bleaching on foresets common.

**Interdune Element**
Lense shaped and <1m thick; interfinger with A1 and Sl & Sp; composed of Aw, Ap and Am; root and burrow mottling common.

**Aeolian Sheet-like Element**
Sheet-like geometry; laterally interfingers with Ad, Am, Sl and Sp elements; composed of Ami and Ad; root and burrow mottling common.

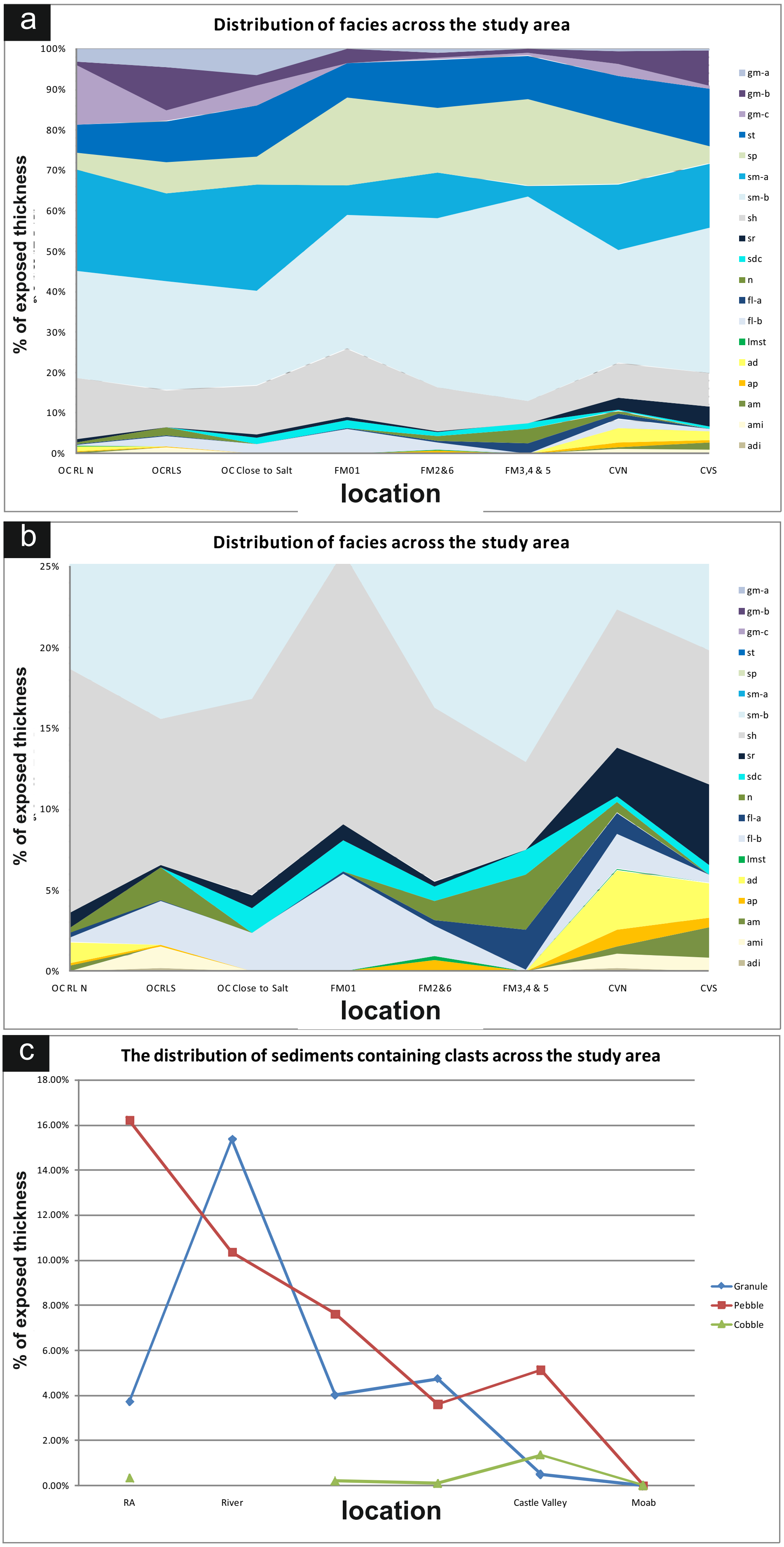
Aeolian

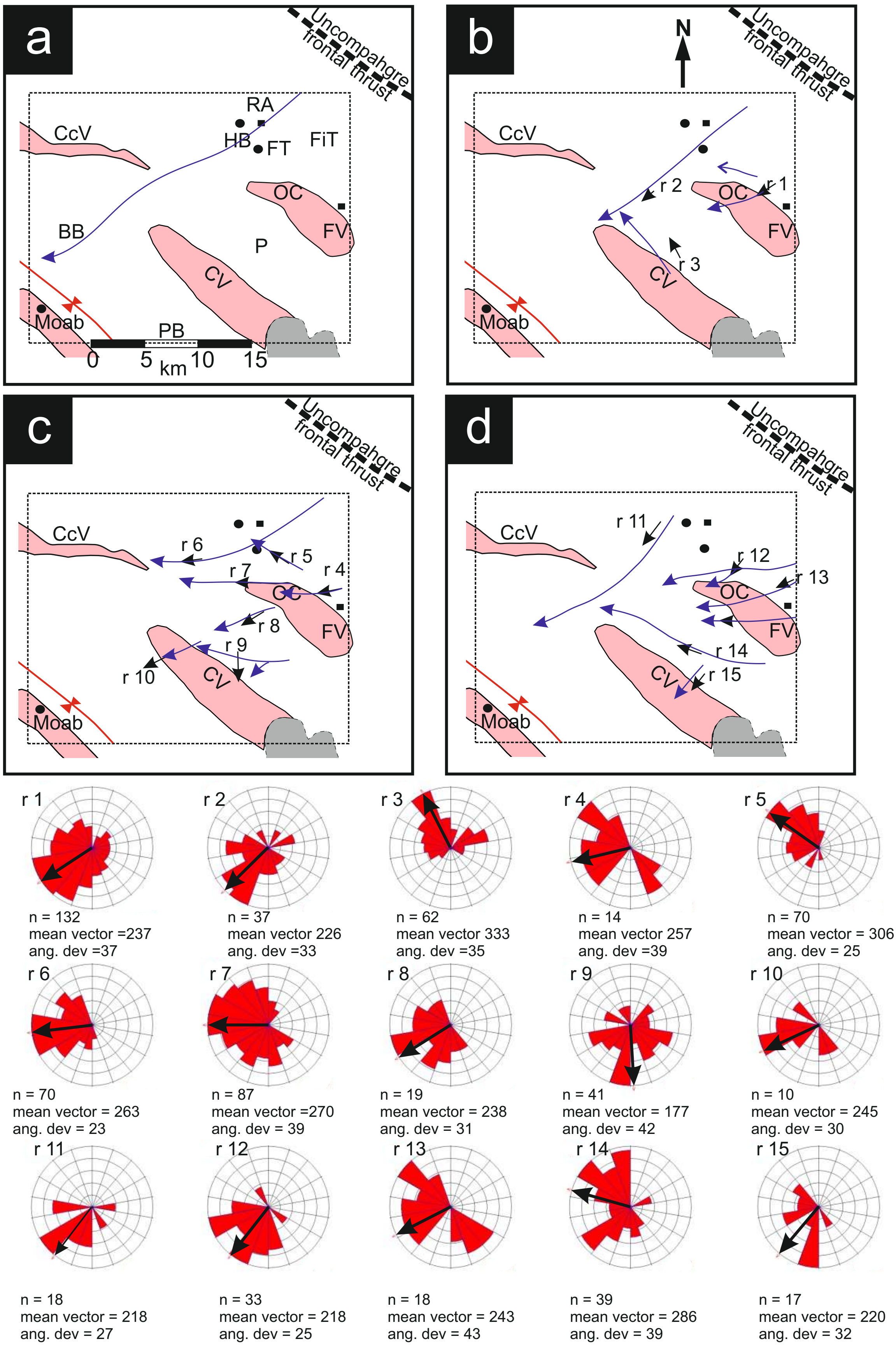
## Fluvial Facies

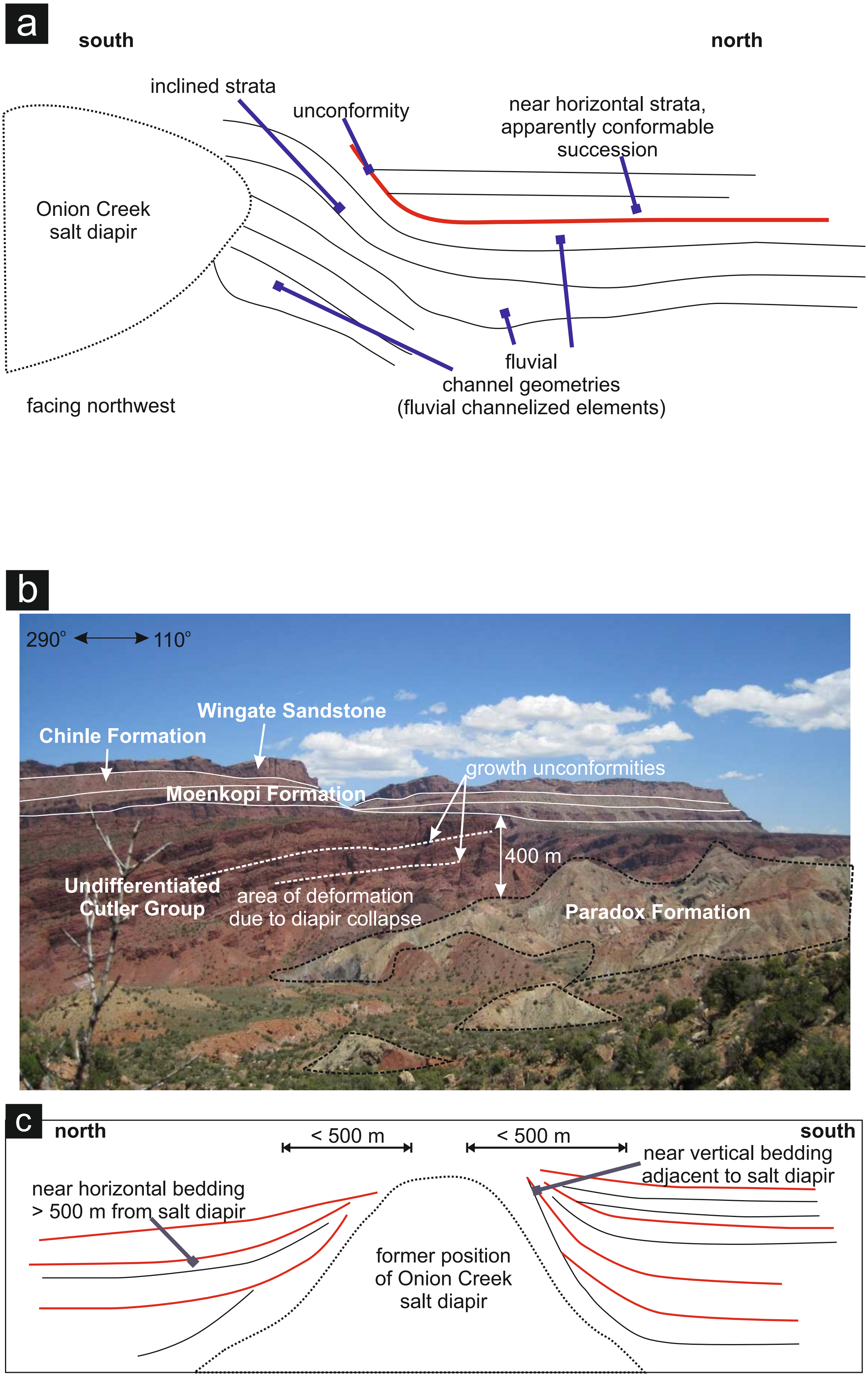
| | | |
|---|---|---|
| conglomerate – extra-formational | quartz-dominated | Gm-a |
| conglomerate – extra-formational | polymictite | Gm-b |
| conglomerate – intra-formational | mixed clast | Gm-c |
| trough cross-bedded sdst | high-angle | St |
| trough cross-bedded sdst | low-angle | Sl |
| planar bedded sdst | | Sp |
| massive sdst- horizontally bedded | | Sm-a |
| planar laminated sandstones | | Sh |
| massive sandstone | | Sm-b |
| de-watered & convoluted sdst | | Sdc |
| current-ripple bedded sdst | | Sr |
| laminated mudstone | | Fl |
| nodular calcrete | | N |
| ripple-laminated siltstone | | Fl-a |
| interbedded silt and fine sand | | Fl-b |

## Aeolian Facies

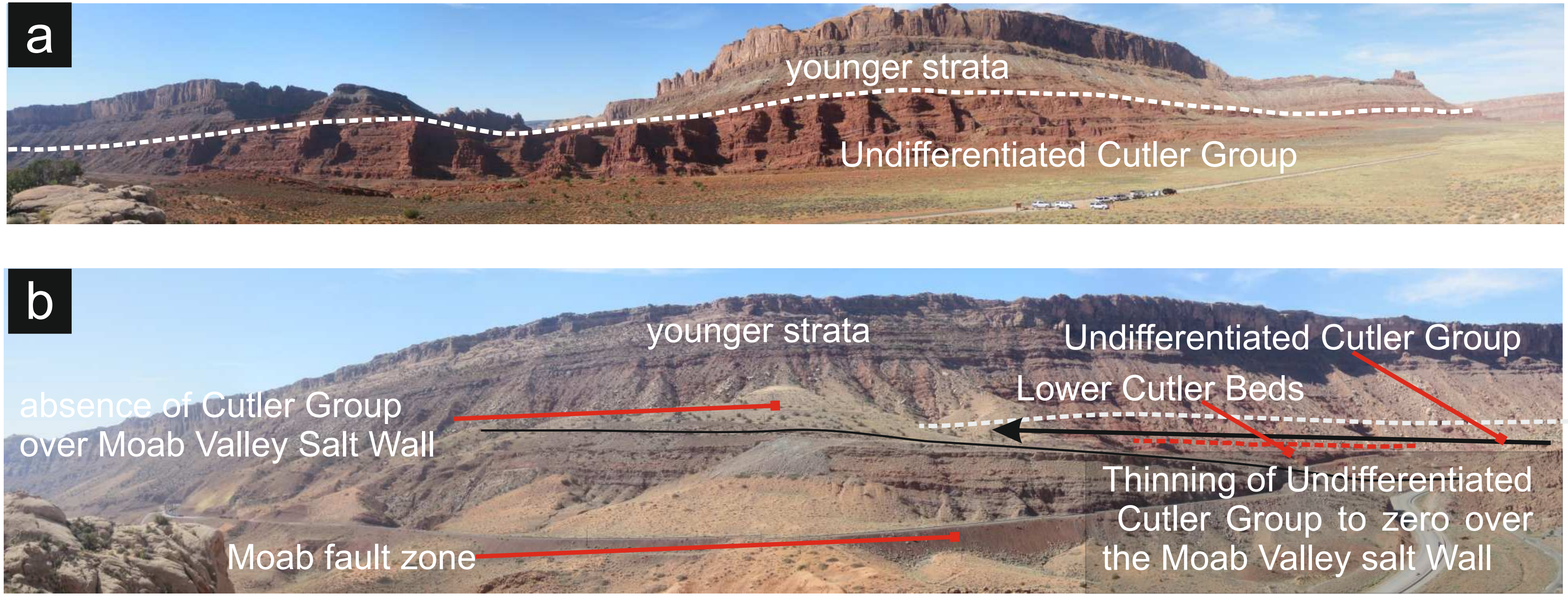
| | | |
|---|---|---|
| aeolian dune | cross bedded sdst | Ad |
| aeolian dune | massive sdst | Am |
| interdune | wavy laminated sdst | Aw |
| interdune | planar laminated sdst | Ap |
| interdune | inter-laminated sdst muds and sdst | Amd |
| sandsheet | mixed horizontal & cross laminated sdst | Ami |
| sandsheet | convoluted sdst | Adi |


a
Distribution of facies across the study area
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
% of exposed thickness
OC RL N
OCRLS
OC Close to Salt
FM01
FM2&6
FM3,4 & 5
CVN
CVS
location
gm-a
gm-b
gm-c
st
sp
sm-a
sm-b
sh
sr
sdc
n
fl-a
fl-b
lmst
ad
ap
am
ami
adi
b
Distribution of facies across the study area
25%
20%
15%
10%
5%
0%
% of exposed thickness
OC RL N
OCRLS
OC Close to Salt
FM01
FM2&6
FM3,4 & 5
CVN
CVS
location
gm-a
gm-b
gm-c
st
sp
sm-a
sm-b
sh
sr
sdc
n
fl-a
fl-b
lmst
ad
ap
am
ami
adi
c
The distribution of sediments containing clasts across the study area
18.00%
16.00%
14.00%
12.00%
10.00%
8.00%
6.00%
4.00%
2.00%
0.00%
% of exposed thickness
RA
River
Castle Valley
Moab
location
Granule
Pebble
Cobble


a
b
c
d
N
Uncompahgre frontal thrust
CcV
RA
HB
FT
FiT
OC
FV
BB
P
CV
Moab
PB
0
5
10
15
km
r 1
r 2
r 3
r 4
r 5
r 6
r 7
r 8
r 9
r 10
r 11
r 12
r 13
r 14
r 15
n = 132
mean vector =237
ang. dev =37
n = 37
mean vector 226
ang. dev =33
n = 62
mean vector 333
ang. dev =35
n = 14
mean vector 257
ang. dev =39
n = 70
mean vector = 306
ang. dev = 25
n = 70
mean vector = 263
ang. dev = 23
n = 87
mean vector =270
ang. dev = 39
n = 19
mean vector = 238
ang. dev = 31
n = 41
mean vector = 177
ang. dev = 42
n = 10
mean vector = 245
ang. dev = 30
n = 18
mean vector = 218
ang. dev = 27
n = 33
mean vector = 218
ang. dev = 25
n = 18
mean vector = 243
ang. dev = 43
n = 39
mean vector = 286
ang. dev = 39
n = 17
mean vector = 220
ang. dev = 32



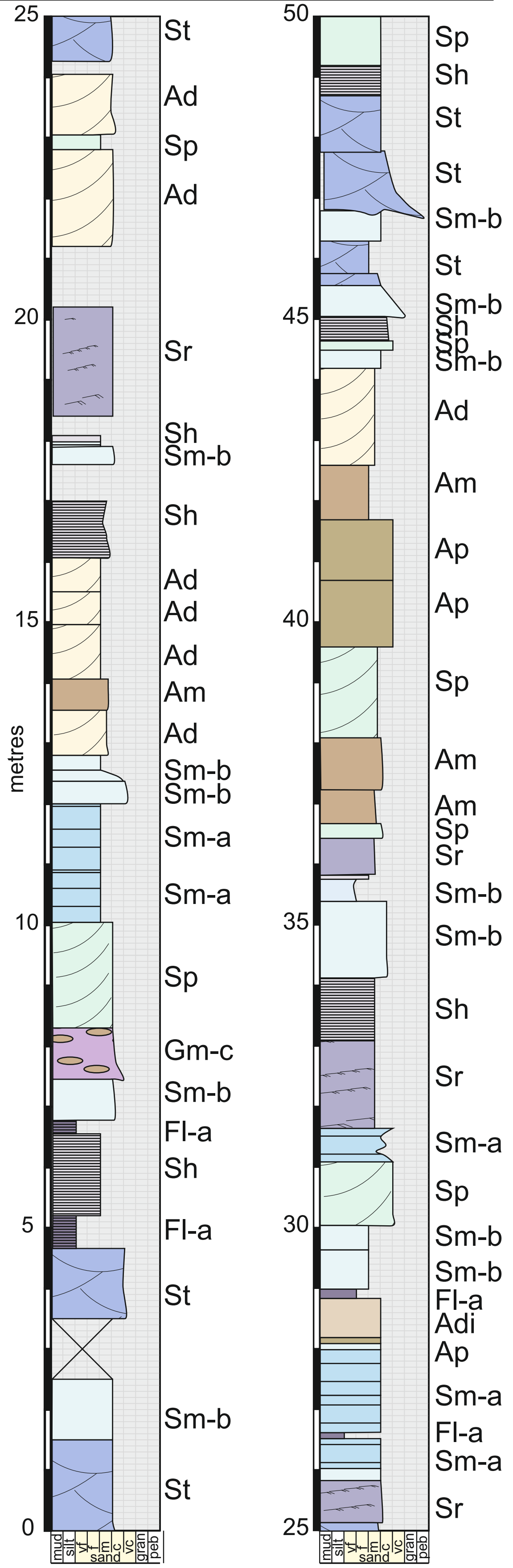
a
south
north
inclined strata
unconformity
near horizontal strata,
apparently conformable
succession
Onion Creek
salt diapir
fluvial
channel geometries
(fluvial channelized elements)
facing northwest
b
290° 110°
Wingate Sandstone
Chinle Formation
growth unconformities
Moenkopi Formation
400 m
Undifferentiated
Cutler Group
area of deformation
due to diapir collapse
Paradox Formation
c
north
south
< 500 m
< 500 m
near vertical bedding
adjacent to salt diapir
near horizontal bedding
> 500 m from salt diapir
former position
of Onion Creek
salt diapir

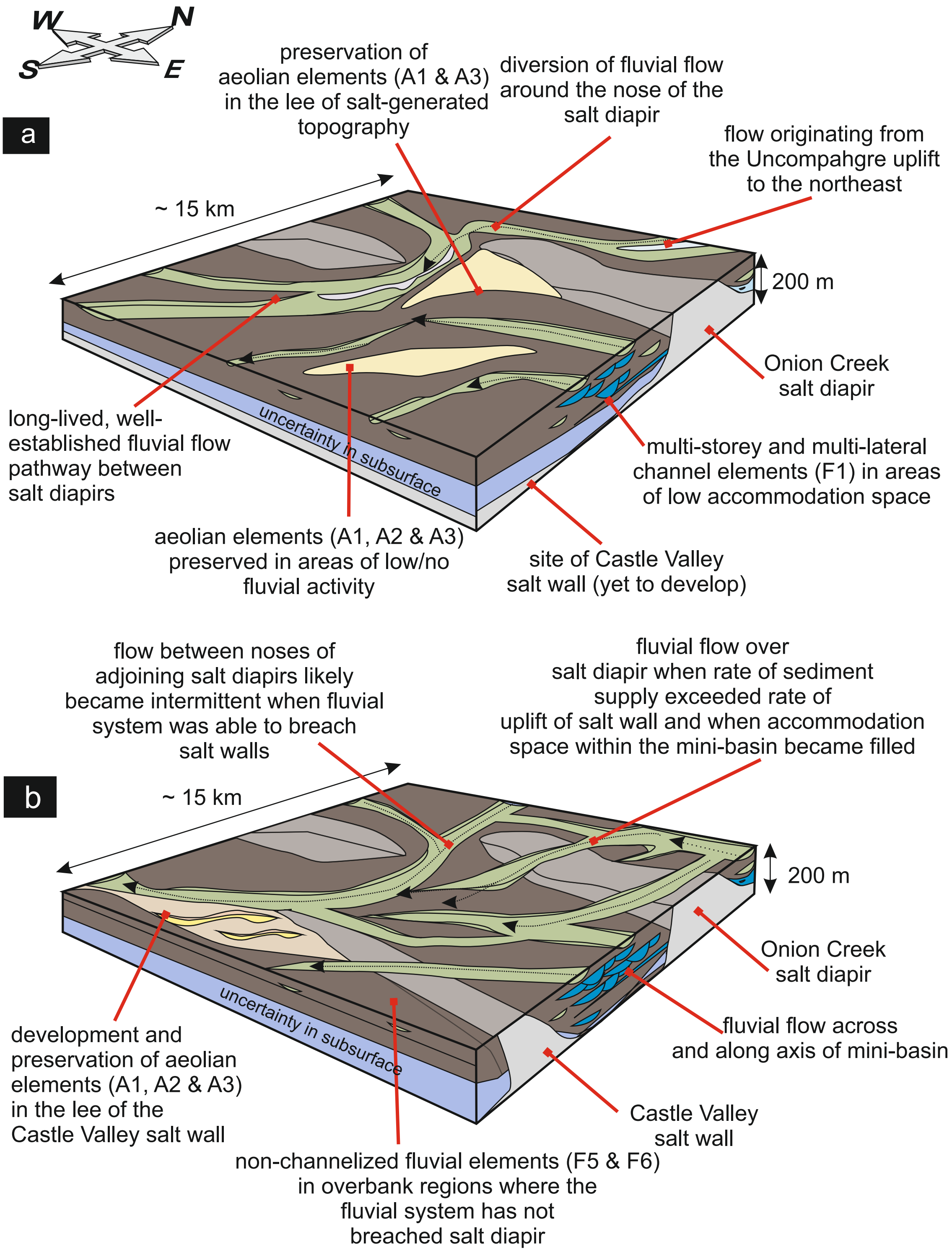

a
younger strata
Undifferentiated Cutler Group
b
younger strata
Undifferentiated Cutler Group
Lower Cutler Beds
absence of Cutler Group
over Moab Valley Salt Wall
Thinning of Undifferentiated
Cutler Group to zero over
the Moab Valley salt Wall
Moab fault zone

# Moab Salt Wall 2

**Log Thickness: 53.5m**

**Coordinates: 12 S 615384, 4277673**





W
N
S
E
a
preservation of aeolian elements (A1 & A3) in the lee of salt-generated topography
diversion of fluvial flow around the nose of the salt diapir
flow originating from the Uncompahgre uplift to the northeast
~ 15 km
200 m
Onion Creek salt diapir
long-lived, well-established fluvial flow pathway between salt diapirs
uncertainty in subsurface
multi-storey and multi-lateral channel elements (F1) in areas of low accommodation space
aeolian elements (A1, A2 & A3) preserved in areas of low/no fluvial activity
site of Castle Valley salt wall (yet to develop)
flow between noses of adjoining salt diapirs likely became intermittent when fluvial system was able to breach salt walls
fluvial flow over salt diapir when rate of sediment supply exceeded rate of uplift of salt wall and when accommodation space within the mini-basin became filled
b
~ 15 km
200 m
Onion Creek salt diapir
fluvial flow across and along axis of mini-basin
uncertainty in subsurface
development and preservation of aeolian elements (A1, A2 & A3) in the lee of the Castle Valley salt wall
Castle Valley salt wall
non-channelized fluvial elements (F5 & F6) in overbank regions where the fluvial system has not breached salt diapir