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Sedimentological control on the reservoir and caprock properties of a bleached palaeoreservoir in the Entrada Formation at Salt Wash Graben, Green River, Utah

Environmental Modelling Programme

Open Report OR/15/005

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Sedimentological control on the reservoir and caprock properties of a bleached palaeoreservoir in the Entrada Formation at Salt Wash Graben, Green River, Utah

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Summary

The stratigraphy and sedimentology of the Entrada Formation are central to understanding the origin of the bleached palaeoreservoir exposed at Salt Wash Graben. Aeolian sandstones of the Slick Rock Member formed high-permeability carrier beds which distributed reducing fluids laterally within the formation. The overlying Earthy Member is a massively-bedded succession of low permeability mudflat/sabkha deposits which acted as a caprock: albeit one that formed an imperfect seal and allowed the upward diffusion of reducing fluids for a distance of up to 4 m above the top of the reservoir. The Salt Wash Graben is located on the crest of the Green River Anticline and was filled by buoyant fluids that may have migrated updip along this north plunging fold; alternatively these fluids may have entered via the northern fault of the Salt Wash Graben. The role of this structure in forming an updip seal during the filling of the reservoir is uncertain. The reservoir was probably filled in the early Cretaceous at a depth of around 1 km or less, during the subsidence phase of the Paradox Basin. The fluids are likely to have been an admixture of H_2S, CO_2 and CH_4. The reservoir was later breached by NNW-trending fractures related to extension across the crest of the Green River Anticline.

1 Introduction

1.1 BACKGROUND

Subsurface reservoirs and aquifers are by their nature difficult to study and an understanding of the structural, stratigraphic and diagenetic controls on fluid movement is generally based on remotely-sensed geophysical data such as seismic, limited sampling of the rock matrix by boreholes, and numerical modelling. Though not replacing such work, outcrop analogues provide a cost-effective means of gaining additional insight into the range of possible geological controls on fluid movement (Howell et al. 2014). An outcrop analogue is an exhumed reservoir or aquifer which, through the action of tectonic uplift and erosion, is no longer deeply buried but is exposed at surface. While it is highly unlikely that such exhumed reservoirs will contain the actual fluids (e.g. brines or hydrocarbons) which were present in the subsurface, a fingerprint of their former presence and migration path may be preserved through chemical alteration of the rock matrix. Many well-documented examples of this phenomenon occur on the Colorado Plateau where the bleaching of red-bed continental sandstones shows the former flow path of reducing fluids, such as hydrocarbons, through permeable reservoirs and along fractures (Chan et al. 2000; Haszeldine et al. 2005) (Figure 1). At outcrop it is possible to study the relationship between rock properties and former fluid migration paths at low cost and in three dimensions. Knowledge gained from outcrop can be usefully applied in analogous subsurface reservoirs and aquifers where data availability and sampling are typically much reduced. Outcrop analogue data have been applied across multiple areas of rock-fluid interaction including hydrocarbons, groundwater, and subsurface carbon storage (Howell et al. 2014).

Figure 1 Bleaching of red sandstones leaves evidence for the movement of reducing fluids along this fracture zone in the Entrada Formation of south central Utah.

1.2 THE SALT WASH GRABEN PALAEORESERVOIR

The Colorado Plateau is an area of exceptional rock exposure due to high rates of tectonic uplift and erosion under a semi-arid climate. Moreover many of the exhumed sedimentary basins of the Colorado Plateau have seen multiple episodes of fluid flow involving hydrocarbons, CO_2 and H_2S which have left an indelible mark in the stratigraphy, most notably in the form of spectacular bleached palaeoreservoirs within terrestrial red-bed deposits (Beitler et al. 2003; Haszeldine et al. 2005). In some areas, such as around Green River in south-central Utah, bleached red-bed palaeoreservoirs are closely associated with modern CO_2 springs and these phenomena have been the subject of much research over the past five years as analogues for the types of rock-fluid interaction which might occur when CO2 is injected into the subsurface as part of Carbon Capture and Storage (CCS) projects (Burnside et al. 2013; Kampman et al. 2013; Pearce et al. 2011; Wigley et al. 2013; Wigley et al. 2012). Most of this work has had a strong emphasis on geochemistry and structural geology and relatively little attention has been paid to other aspects of the bleached palaeoreservoirs, such as establishing whether a relationship exists between heterogeneity and permeability variation related to lithofacies and the migration and trapping of fluids. This aspect is explored in this work by re-visiting one of the well-studied bleached sandstone reservoirs in the Middle Jurassic Entrada Formation near Green River, Utah.

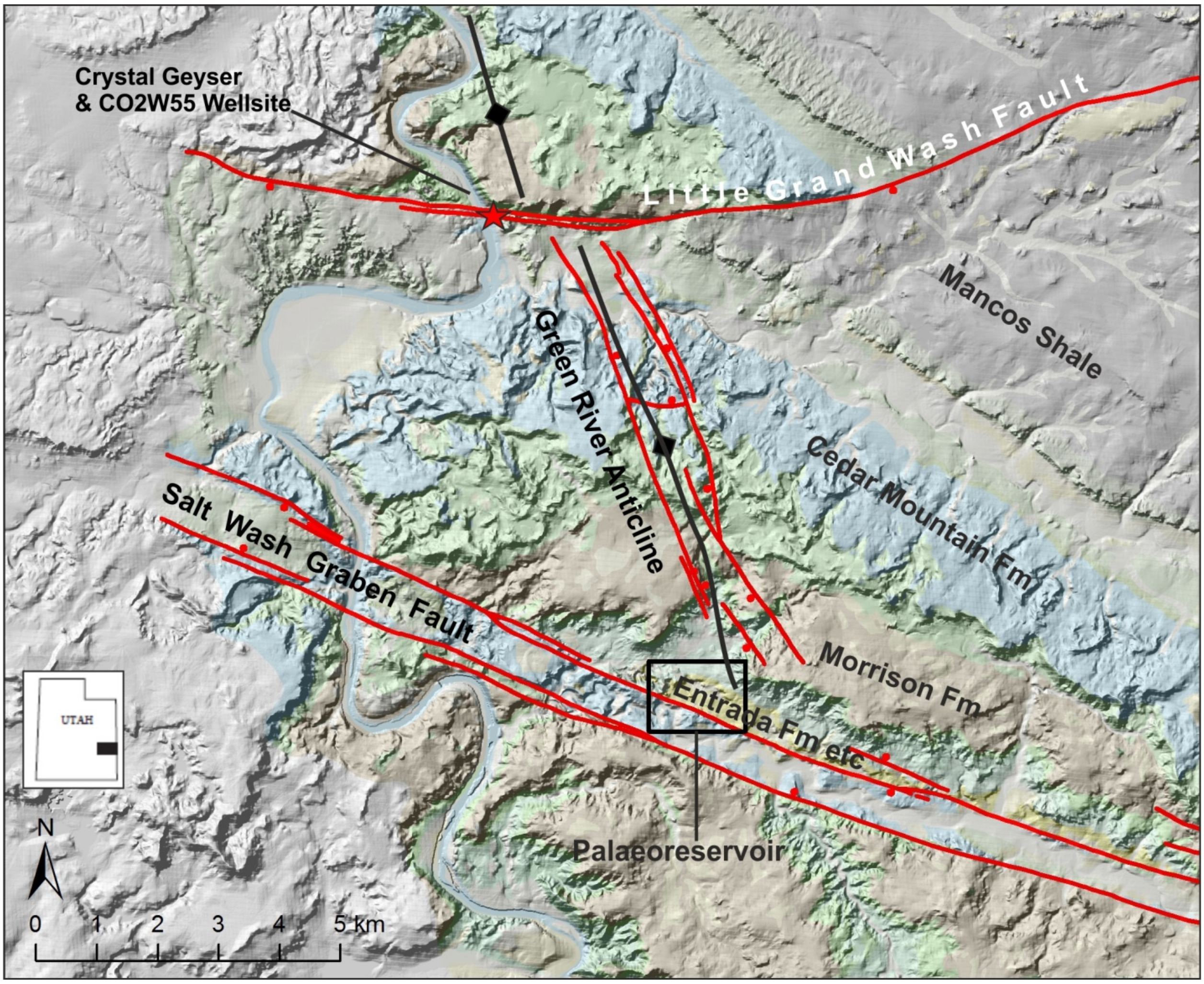


Figure 2 Site location (black rectangle) adjacent to the Salt Wash Graben (major faults are shown in red). The town of Green River is just to the north of the map and the Green River itself meanders from north to south. The site is located on Middle Jurassic Entrada Formation, which crops as a small sliver on the northern footwall of the Salt Wash Graben. To the northeast of the site, the Entrada Formation passes upwards through a stepped series of scarps and dip slopes into the younger Morrison, Cedar Mountain and Mancos Shale formations. The southwest deflection of the outcrop trace in the western half of the

map results from the development of the Green River Anticline which plunges to the north and is truncated by the Little Grand Wash Fault. Geology and fault patterns are from the digital version of the Utah Geological Survey Map 180 (Doelling 2001).

The site is located 13 km south of the town of Green River in east central Utah (Figure 2, please also see Enclosure 1 at rear of report). The palaeoreservoir is located along a WNW-ESE trending fault structure which in most recent published literature is called the Salt Wash Graben (Ogata et al. 2014; Pearce et al. 2011; Wigley et al. 2013); although note that on Utah Geological Survey Map 180 this structure is labelled the Tenmile Graben (Doelling 2001). The term Salt Wash Graben is used throughout this report.

The palaeoreservoir lies 9 km south of the well-known 'Crystal Geyser' where natural and drilling-induced CO_2 springs and associated travertine deposits occur along the Little Grand Wash Fault (Burnside et al. 2013; Han et al. 2013). Springs and travertines also occur along the Salt Wash Graben and there has been a great deal of recent interest in both fault structures as natural geochemical analogues for carbon dioxide storage in deep geological porous reservoirs (Burnside et al. 2013; Pearce et al. 2011; Wigley et al. 2013).

1.3 METHODS

The conclusions presented in this report are based primarily on a six-day field study which started on the 13th October 2014. Weather conditions were dry, cool and ideal for fieldwork. A range of activities were undertaken in the field including:

1. Structural and stratigraphic mapping of the bleached palaeoreservoir zone in an area covering approximately 1.2 km^2 (Figure 3) Mapping was undertaken using the BGS ArcGIS SIGMAMobile2012 system running on a Panasonic Toughbook CF-19. A Garmin Edge 510 was used for mapping the location of bleached fracture zones. High quality basemaps were obtained from internet sources and included one metre resolution aerial photography (http://gis.utah.gov/data/aerial-photography/), NED 10 m digital terrain model (http://ned.usgs.gov/) and 1:100000 and 1:500000 geological maps (http://geology.utah.gov/maps/gis/index.htm). Data were collected on geological boundaries, dip and strike of bedding, locations of major faults and fractures and the extent of bleaching throughout the reservoir. All data were assembled in ArcGIS using the projection UTM Zone 12N with NAD 1983.

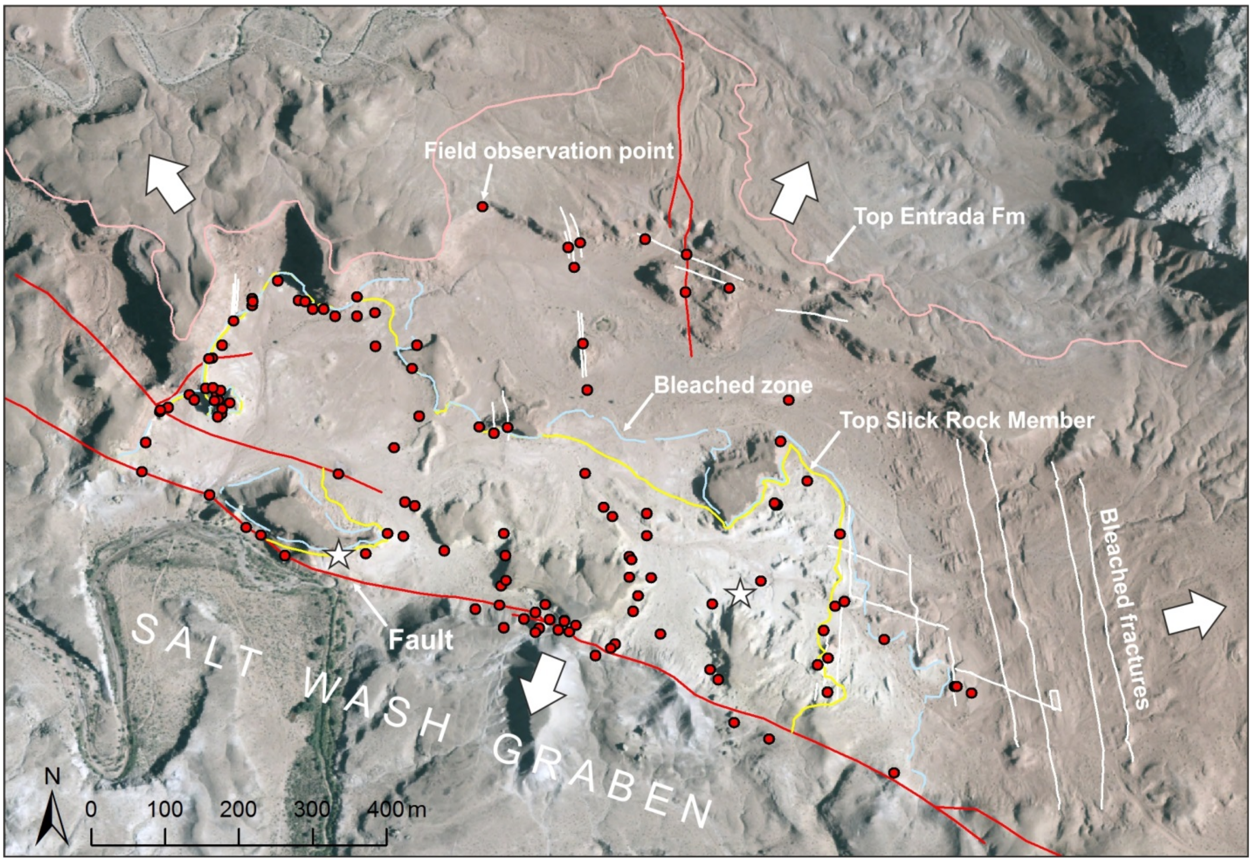


Figure 3 Map showing the extent of data capture and some of the key geological features. Thick white arrows indicate the general dip direction, note the four way structural closure around the bleached (pale grey) palaeoreservoir. White stars indicate the location of the west (left) and east (right) logged sections.

2. Two sedimentary logs were measured in the Entrada Formation at the western and eastern end of the palaeoreservoir (Figure 3). Logging started in the lowest part of the Entrada Formation (Slick Rock Member) that was exposed and continued into the lower part of the Earthy Member. The logs show the range of lithofacies that occur with this part of the Entrada Formation and their vertical stacking pattern. The accurate field determination of grain-size and sorting was a priority (because of their importance to permeability) so a conventional hand-lens was replaced with a high-resolution USB microscope (Dino-Lite AM4113T) attached to the Panasonic Toughbook (see Enclosure 2). Grain-size and sorting were determined from digital images both by measuring individual grains using Dinocapture 2.0 software and by automated image-analysis using a transferable wavelet transform method (Buscombe 2013). A Python framework released by the USGS to undertake this task is downloadable from https://pypi.python.org/pypi/pyDGS.

3. Field measurements of sandstone permeability were taken using a portable hand-held air permeameter (TinyPerm from NER, see http://www.ner.com/site/systems/tinyperm.html for specifications). Permeametry was undertaken in tandem with sedimentary logging with multiple measurements taken from each bed or lithofacies interval (see Enclosure 2). For rock matrix, the permeability measurement range of the TinyPerm is from approximately 10 millidarcys to 10 darcys. Rock faces were brushed or chipped with a hammer were necessary to remove weathered surface crusts.

Post-fieldwork analysis has included the laboratory determination of porosity, permeability and pore throat size on a small number of samples. Selected samples were taken for thin section, SEM and other analysis: the results of this work will be reported separately.

2 Geological background

2.1 THE PARADOX BASIN

The Salt Wash Graben site is located in the Paradox Basin, an asymmetric foreland basin located mostly in southeast Utah and southwest Colorado. The basin is elongate northwest to southeast and bordered on the east by the Uncompahgre Plateau (see Enclosure 3). The combined Carboniferous to Tertiary basin fill reaches 4600 m thick in parts of the basin (Nuccio and Condon 1996). Permian to Tertiary strata was deposited on thick layer of ductile Pennsylvanian salt and halokinesis played a major role in the post-Pennsylvania stratigraphic and structural evolution of the basin (Baars and Doelling 1987). Reconstructions of the burial history of the Green River area (Figure 4) show that the Middle Triassic Entrada Formation was probably buried to depths approaching 2.5 km, before being rapidly exhumed and brought back to the surface from around the Oligocene onwards (Nuccio and Condon 1996). Given the relatively weakly-deformed state of the Colorado Plateau, the driving forces behind its high-magnitude uplift and erosion have been a long standing enigma (Flowers 2010), although recent evidence suggests a link to deep lithospheric processes (Levander et al. 2011), probably coupled with isostatic rebound in response to erosion (Pederson et al. 2013).

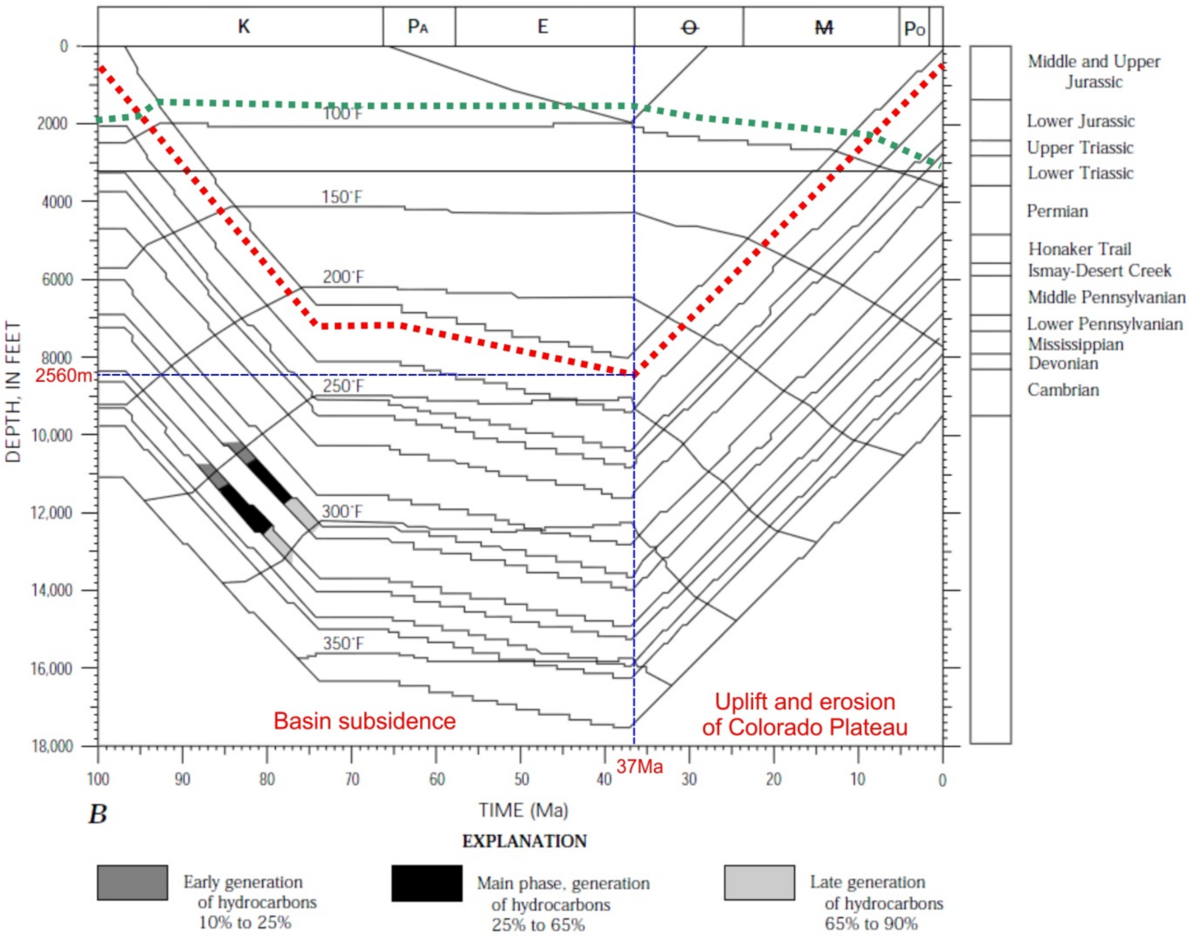


Figure 4 Burial and thermal history of the Paradox Basin since the end Jurassic at Green River, Utah (Nuccio and Condon 1996). Red dashed line indicates the approximate burial path of the Entrada Formation. Note the rapid exhumation of the formation from 37Ma onwards associated with uplift and erosion of the Colorado Plateau. Green dashed line indicates the temperature of the fluids thought to have caused the bleaching of the Entrada Formation.

2.2 STUCTURAL SETTING OF THE SALT WASH GRABEN PALAEORESERVOIR

The Salt Wash Graben palaeoreservoir is located on the crest of the Green River Anticline, an open, NNW plunging structure that is one of a number of similarly trending salt-cored anticlines in the Paradox Basin (Pederson et al. 2013) (see Enclosure 5). Most of the anticlines are characterised by faults which occur parallel to the fold axis (Figure 5) and it is likely that these developed in response to salt dissolution at shallow levels (Baars and Doelling 1987), local stretching across the tops of drape anticlines, or the thinning of salt walls during regional extension (Ge and Jackson 1998). The Green River Anticline is notable in that the two major faults zones of Salt Wash Graben and the Little Grand Wash Fault are not parallel to the fold axis but cut it at a high angle (Figure 2). Pederson et al. (1993) suggest that these broadly NW-SE trending structures may have formed in response to SW-NE regional extension in the Pliocene, driven by a combination of Basin and Range rifting along the margins of the Colorado Plateau and isostatic rebound and doming related to the late Cenozoic exhumation. Faults parallel to the Green River Anticline also occur, forming a north-south linkage between the Salt Wash Graben and Little Grand Wash Faults (Figure 2). The palaeoreservoir under discussion thus occurs at the intersection of three major structural features which were fundamental to both the formation of the reservoir and its subsequent breaching.

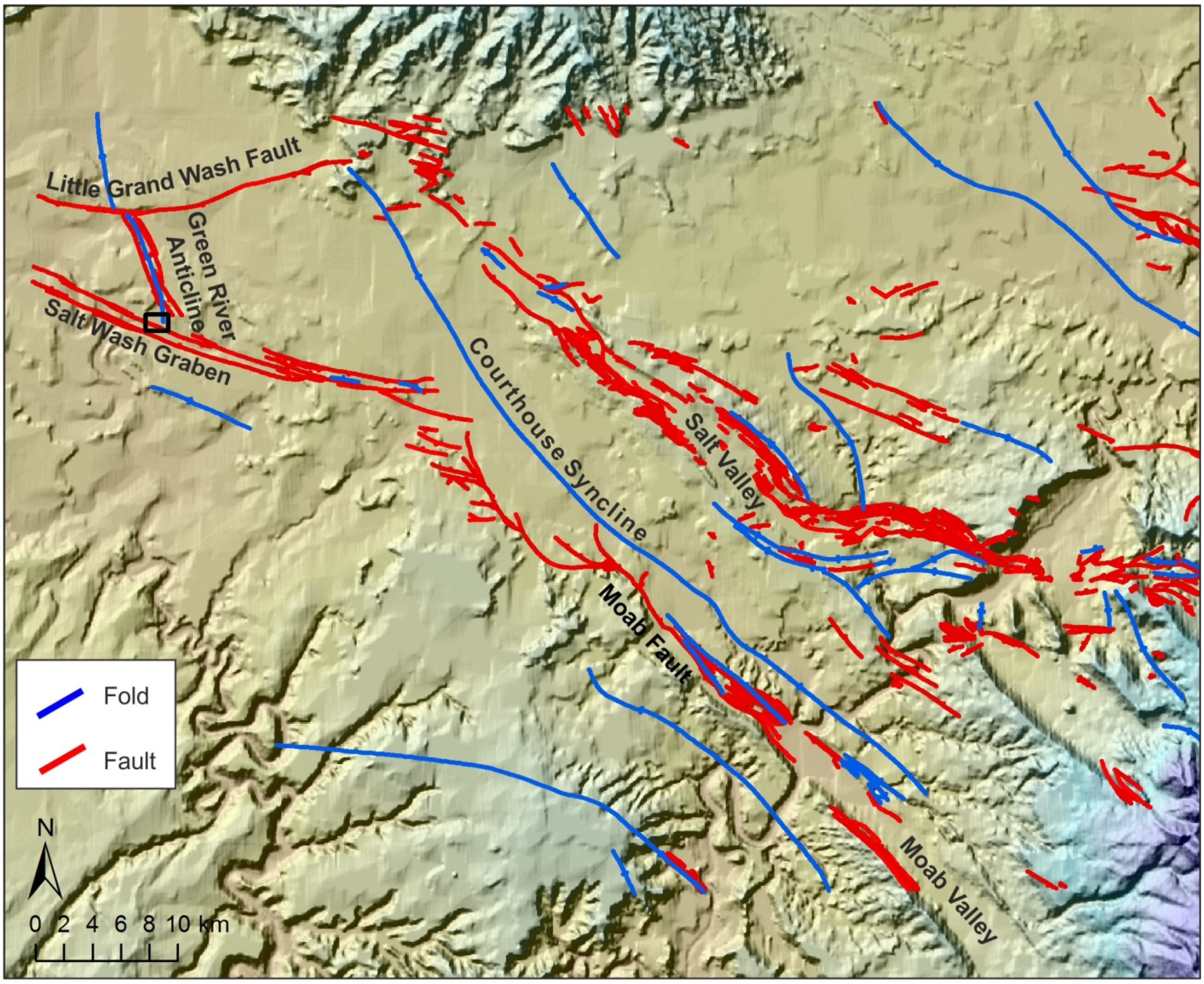


Figure 5 Map showing the location of major fold (blue) and fault (red) structures. Note the coalignment of the majority of faults and folds, with the Salt Wash Graben and Little Grand Wash Faults being notable exceptions. The Salt Wash Graben forms a northwestern extension of the Moab Fault Zone. Geological structures are from Utah Geological Survey Map 180 (Doelling 2001).

The bleached palaeoreservoir is located within Middle Jurassic Entrada Formation which crops in a narrow zone on the northern footwall of the Salt Wash Graben (Figure 6). This fault downthrows Cretaceous Cedar Mountain (and possibly Morrison) Formation into the central part of the graben, indicating an offset of around 200 m (Figure 6). Immediately south of the fault, the Cretaceous strata within the graben dip at relatively high angles (10-15 degrees) to the south, probably as a consequence of normal fault drag (Figure 6). To the north of the fault, on the footwall, the Entrada Formation dips at around 4 degrees toward the north, northwest and northeast thus forming a dome-like structure, with a three-way closure against the southern bounding fault (see Figure 3).

Bleaching in the Entrada Formation does not appear to continue across the fault into the adjacent Morrison/Cedar Mountain formation. Grey-coloured mudstones are present but these reflect the development of gleyed palaeosols at the time of deposition (Figure 6). There are a number of possible explanations for why the bleaching does not extend across the fault:

- The Cretaceous Morrison and Cedar Mountain formations are much less haematite-rich than the Entrada red-beds so may not have reacted in the same way to the reducing fluids.
- The fault acted as a lateral seal, preventing the movement of reducing fluids from the Entrada Formation into hanging-wall strata.
- Movement on the Salt Wash Graben fault has been ongoing since bleaching occurred and any rocks in the hanging wall which may (or may not) have been bleached are now located deep within the graben.

A lack of borehole information on the concealed strata within the graben precludes a definitive answer, however given the evidence for recent (Quaternary) movements on the Salt Wash Graben (Hecker 1993) it is likely that any strata juxtaposed against the Entrada Formation at the time of bleaching are now buried within the Salt Wash Graben.

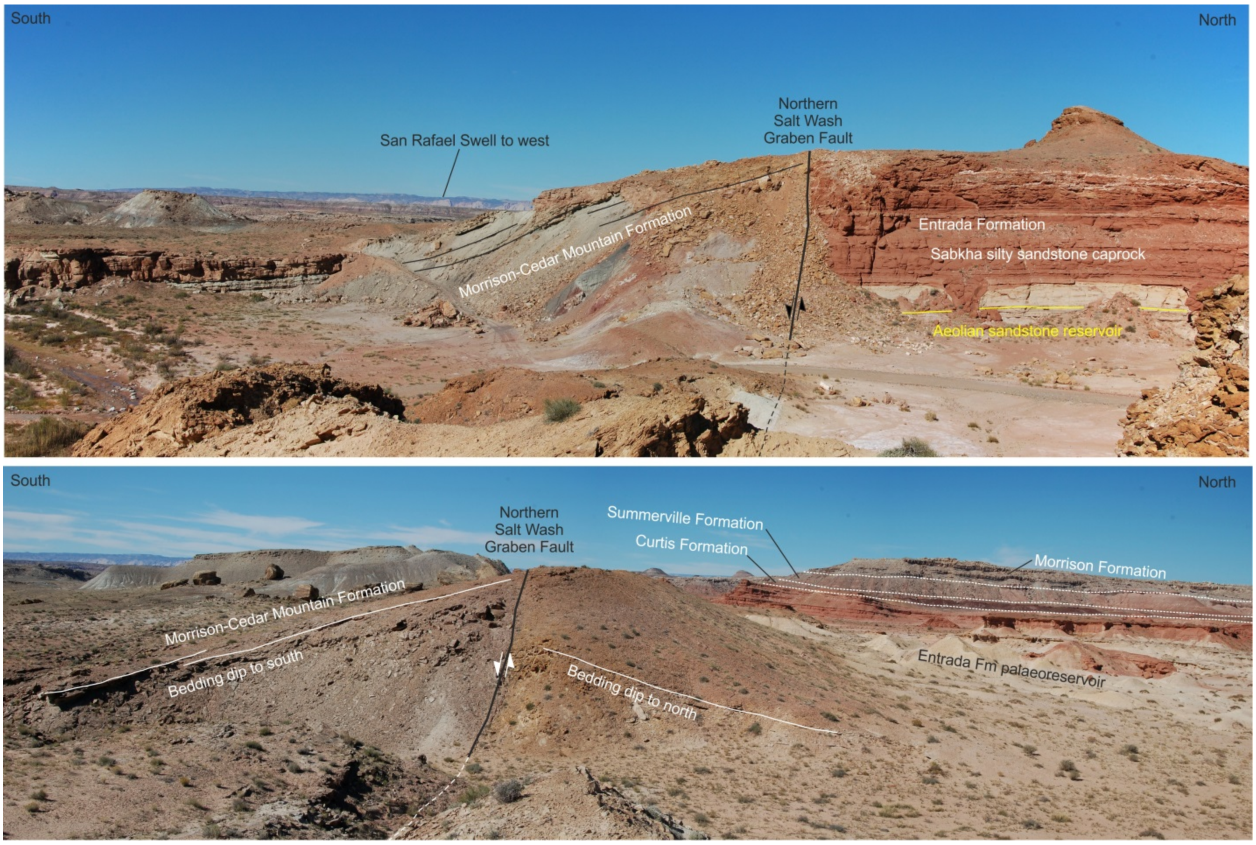


Figure 6 Two views of the northern bounding fault of the Salt Wash Graben Fault along the southern perimeter of the palaeoreservoir. The fault juxtaposes south-dipping Cretaceous Morrison/Cedar Mountain Formation in the hanging wall against north-dipping, partially bleached, Jurassic Entrada Formation on the footwall.

2.3 ENTRADA FORMATION STRATIGRAPHY

The palaeoreservoir occurs within the Middle Jurassic Entrada Formation, which overlies the Upper Carmel Formation and is unconformably overlain by the Curtis Formation (see Enclosure 4 for a full lithostratigraphical context). In the Moab region, the Entrada Formation ranges from 43 to 170 m thick and can be subdivided into two members, the Slick Rock Member and the Earthy Member (Doelling 2001). The Slick Rock Member is typically an alternation of clean, pale brown cross-bedded sandstone, and finer-grained intervals of horizontally or wavy-laminated silty sandstone or sandy siltstone (Figure 7). Units alternate on a 1-10 m scale (see Enclosure 6). The Earthy Member sharply overlies the Slick Rock Member and comprises dark reddish brown clayey silty sandstones with a massive or discontinuous wavy bedding fabric. At outcrop the Earthy Member erodes and weathers to form large spheroidal boulders: an indicator of the lack of anisotropic bedding fabric within what is a remarkably monotonous lithology. The Earthy Member is typically around 20-30 m thick in the area of Salt Wash Graben.

Figure 7 Sharp contact (dotted line) between the pale red/grey/brown sandstones of the Slick Rock Member and the dark reddish brown silty sandstones of the Earthy Member. The Slick Rock Member shows well-developed cross-bedding dipping from left to right. Note the characteristic rounded boulders of Earthy Member resting on the outcrop.

To the southeast of the Salt Wash Graben, toward Moab, the Earthy Member of the Entrada Formation thins and it is not present to the east of White Wash, where the Slick Rock Member is directly overlain by the Curtis Formation (McKnight 1940) (Figure 8). Further to the southeast, toward Bartlett Wash, the Entrada Slick Rock Member is overlain by the Moab Member, an aeolian sandstone tongue within the Curtis Formation (Doelling 2001). To the west of the Green River the Earthy Member thickens at the expense of the Slick Rock Member and it forms the bulk of the Entrada Formation (and equivalents) in the San Rafael Swell (see Enclosure 7).

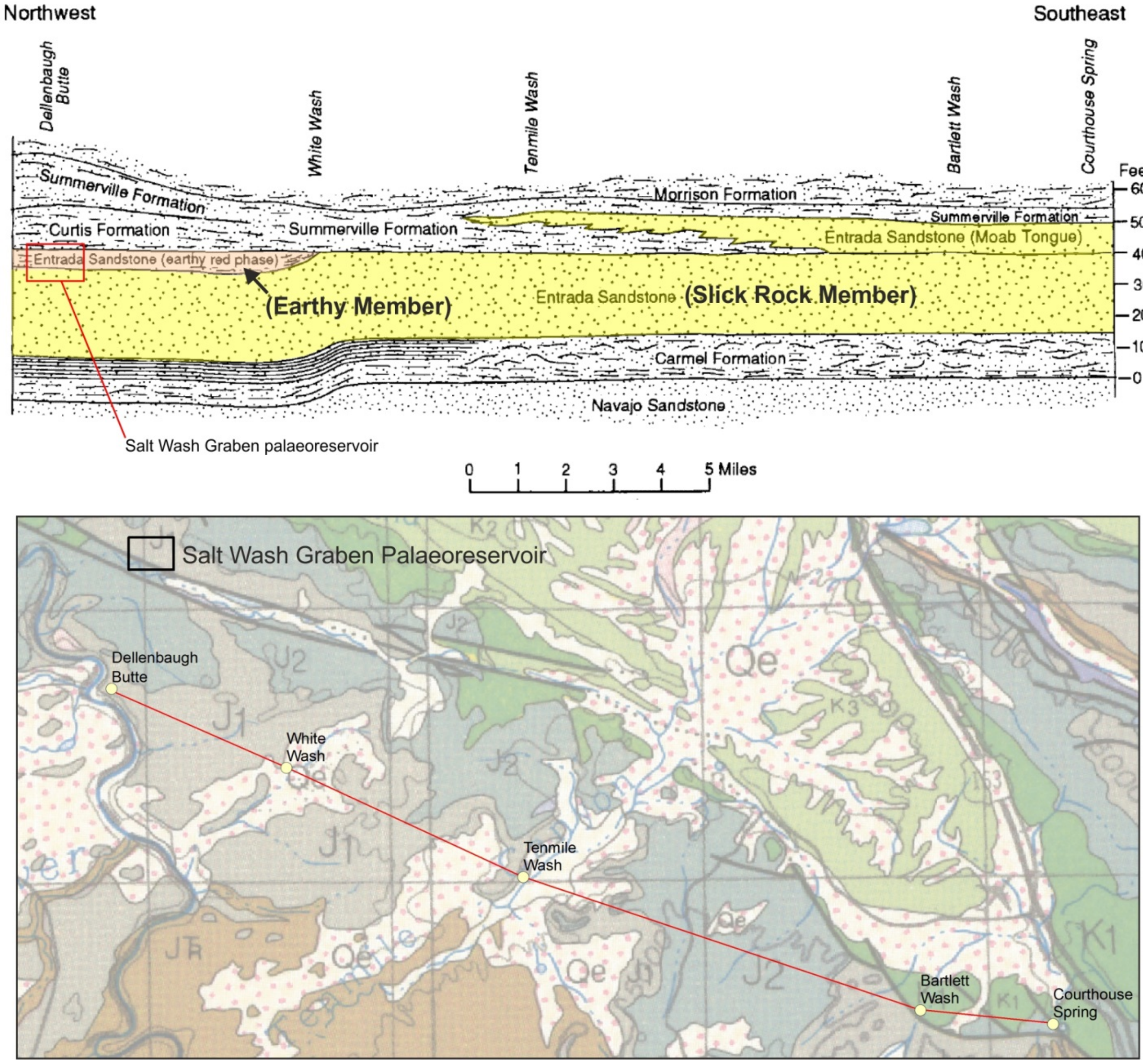


Figure 8 Lateral changes in the stratigraphy of the Entrada Formation along a 20 km transect from Dellenbaugh Butte (located just south of the study area) toward Courthouse Spring (McKnight 1940)

2.4 DEPOSITIONAL SYSTEM

Around Green River, and in areas to the southeast, the Entrada Formation is predominantly a continental sandstone sandwiched between the marine-influenced Carmel and Curtis formations. This 'Slick-Rock' facies of the Entrada Formation shows good evidence for having been deposited within a large aeolian sand-sea (erg) including the presence of wind-ripple lamination, aeolian trough cross-bedding and a quartz-dominated mineralogy, with many well-rounded and frosted grains (Kocurek 1981). Cross-bed dip directions indicate prevailing winds to the southeast and southwest (Tanner 1965). The clean aeolian dune sandstones are intercalated with muddier sandstones ('earthy facies') which commonly show a disrupted, irregular lamination suggesting deposition within low-lying wet interdune areas, or on more extensive mudflats or salt-encrusted sabkhas adjacent to the dune field (Kocurek 1981). The Entrada Formation is considered a classic example of a 'wet aeolian dune system' where interdune depressions were frequently flooded by rises in a shallow water table (Crabaugh and Kocurek 1993). The erg was flanked to the west by mudflats and sabkhas which bordered a shallow epicontinental sea within the Utah-Idaho trough (see Enclosure 7 for a palaeogeographic map).

3 Palaeoreservoir sedimentology

3.1 LOGGED SECTIONS

Two sedimentary logs were measured at a western and eastern location within the bleached palaeoreservoir (see Figure 3 for locations) (Figure 6). The western logged section is 26 m in length and includes the uppermost 6 m of the predominantly aeolian sandstone Slick Rock Member, sharply overlain by around 20 m of the massive silty sandstones of the Earthy Member (Figure 7). The eastern logged section is shorter (19 m), but includes a greater thickness of the Slick Rock Member (12 m) and approximately 7 m of the overlying Earthy Member; the base of this log is at the lowest stratigraphic level of the Entrada Formation that was exposed within the area of the palaeoreservoir. Based on evidence from the CO2W55 research borehole, located at Crystal Geyser 9 km to the NNW (Kampman et al. 2013), it is possible that a further 113 m of Entrada Formation is concealed at Salt Wash Graben down to its basal contact with the Carmel Formation (see Enclosure 6 for the CO2W55 borehole log). The Earthy Member was not measured in full up to its contact with the overlying Curtis Formation, but there is probably approximately 20-30 m in total. As noted elsewhere, although the top of the Entrada Formation represents a major Jurassic unconformity (J3) it is often difficult to pick at outcrop (McKnight 1940; Wright et al. 1962).

The twofold subdivision of the Entrada Formation into Slick Rock and Earthy members is fundamental to understanding the behaviour of the bleached palaeoreservoir but has not been discussed by some previous work (Wigley et al. 2012). Where the Entrada Formation is unbleached or only weakly bleached, the sharp contact between the two units is generally very obvious at outcrop, not least because of the colour change (Figure 7). However, where the Entrada Formation is bleached the contact is more difficult to identify because the pale grey bleaching extends throughout most of the Slick Rock Member and into the Earthy Member for a distance of several metres (Figure 9). The facies boundary within the palaeoreservoir is still present and sharp but concealed by the bleaching.

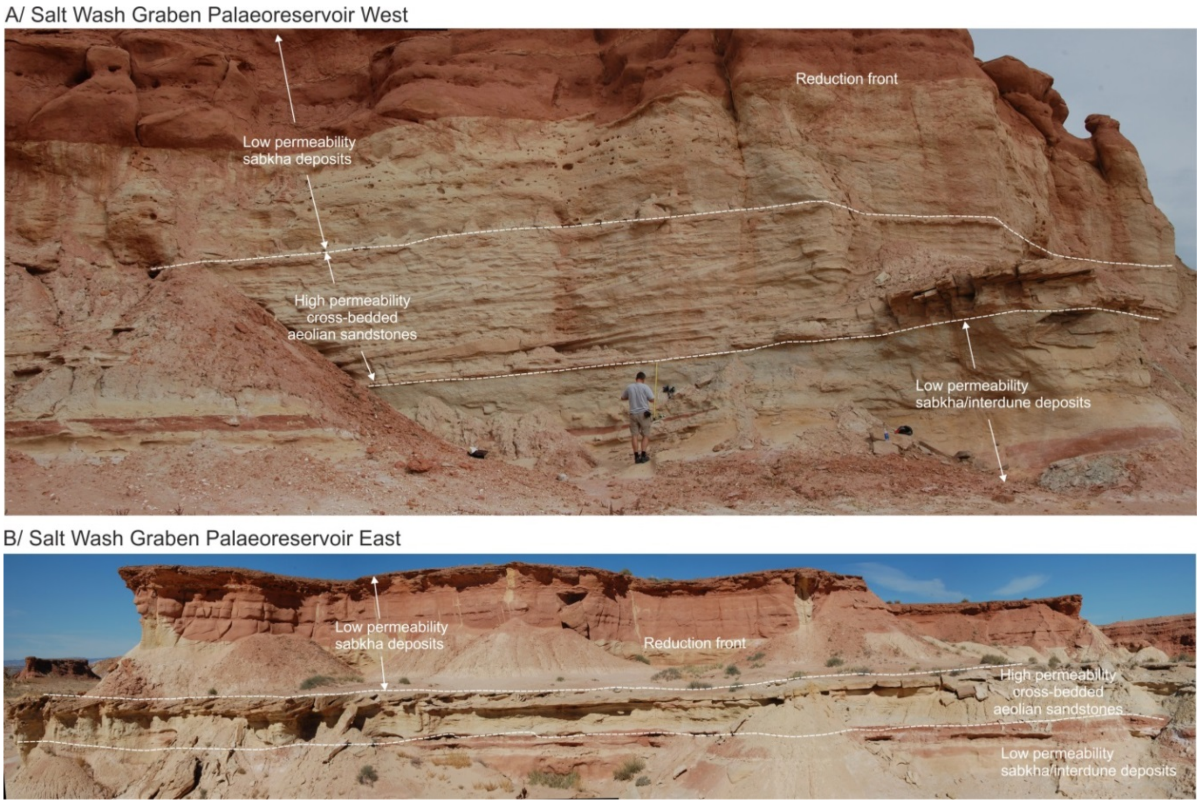


Figure 9 The Slick Rock/Earthy Member contact at the site of the two logged sections. Note that, particularly in the upper photograph, the bleaching crosses (and conceals) the sharp lithological boundary.

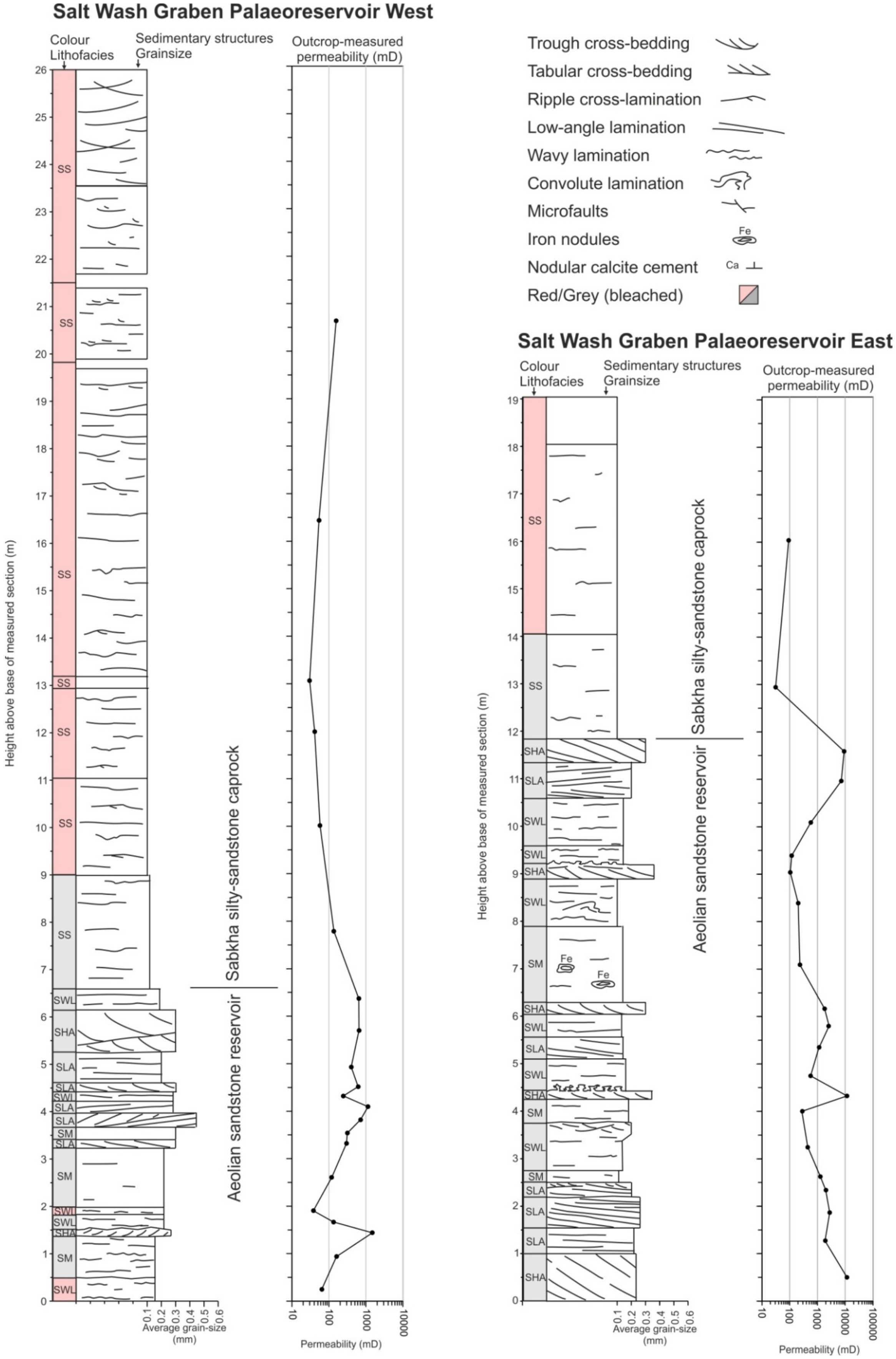


Figure 10 Logged sections showing vertical stacking of lithofacies (Table 1), mean grain size in mm, and the position of grey-red colour changes. Typical field-derived permeability values for each bed/lithofacies are shown in millidarcies (mD) plotted on a log scale.

3.2 LITHOFACIES OF THE SLICK ROCK MEMBER – RESERVOIR SANDSTONE

The Slick Rock Member is a sandstone-dominated unit composed of a number of different lithofacies whose key characteristics are shown in Table 1.

Table 1 Lithofacies of the Slick Rock Member

Code	Description	Interpretation	Typical permeability
SHA	Sandstone, high-angle cross-bedded. Tough or tabular cross-bedded with foresets reaching a maximum angle of around 28 degrees. Wedge-shaped or parallel laminated foresets. Composed of fine-medium grained sand, moderately to well-sorted, quartz-rich.	Mobile aeolian dunes with curved or straight crests. Lamination results from grain-flow and grain fall on dune avalanche faces.	10000mD
SLA	Sandstone, low-angle lamination. Typically displays well-developed pin-stripe lamination with alternation of cm-thick, fine-medium sand laminate and mm-thick fine-very fine sand. Quartz-rich, bimodal grain-size distribution.	Migration of wind-ripples on low relief sand sheets or dune aprons	5000-10000mD
SM	Sandstone, massive. Structureless sandstone, or one showing only occasional faint lamination. Very fine to medium grained, sorting generally poor.	Sand accretion in damp interdune areas	100-1000mD
SWL	Sandstone, wavy laminated. Irregular wavy discontinuous lamination, occasionally convolute lamination. Poorly sorted with common silty and very fine-grained sand laminae.	Sand accretion in damp to wet, water saturated, interdune areas	100-1000mD
SMC	Massive or faintly bedded sandstone with ferruginous concretions and wavy lamination, undulating erosion surfaces and channel fills.	Channel fills	100-1000mD
SS	Silty sandstone, discontinuous wavy lamination, massive, occasionally convolute. Very poorly sorted admixture of sand, silt and clay	Deposition on sandflats and sabkha, salt crusts probably important in trapping sediment	10-100 mD

The sandstones of the Slick Rock Member were deposited in a range of aeolian environments from those that were almost entirely dry, and wind could sculpt loose sand into dunes and ripples, to those that were damp or wet resulting in silty sandstones with an irregular lamination. Figure 11 illustrates the spectrum of sandstone types which in terms of reservoir properties represent a variation in permeability that extends over at least three orders of magnitude.

Aeolian dune sandstones are typically comprised of quartz-dominated, rounded grains with a mean diameter of around 0.4 mm (Figure 12A). Wind-ripple laminated sandstones have a similar maximum grain-size but are distinctly bi-modal with finer-grained sand concentrated in pin-stripe laminae (Figure 11B). Both types of sandstone are ‘clean’ with little clay and silt within the pore spaces: permeability is thus high with field-measured values reaching 10000 mD.

Sandstones or silty sandstones showing wavy or convolute lamination were deposited on damp or wet substrates within low-lying interdune areas, or on more extensive sandflats or sabkha environments which may have flanked aeolian dune-fields. Wind-blown sand, silt and clay may have been deposited within these areas by adhering to the damp surface. Salt crusts precipitated from shallow saline groundwaters may also have been important in trapping irregular patches of wind-blown sediment. The subsequent dissolution of salt may account for some of the highly disturbed lamination. Due to their fine grain-size and poor sorting these silty sandstones have lower permeabilities typically in the order of 100-1000 mD. Muddy sandstones may have a permeability of a few 10s of millidarcies or less.

Wet and dry aeolian lithofacies typically alternate on a scale of around one metre. Often the facies are arranged in ‘drying-upward cycles’ where muddy wet interdune deposits pass upwards, through wavy laminated sandstones and wind-ripple laminated sandstones, into cross-bedded aeolian dune sandstones. Dune sandstones are capped by a flooding surface marked by a nodular texture which in some cases may represent bioturbation.

The aeolian dune sandstones have a high lateral continuity and can be mapped and correlated across the full extent of the palaeoreservoir. These high-permeability beds might be expected to form preferential flow paths for reducing fluids entering the formation, a view supported by their strong uniform bleaching. In contrast, low permeability muddy wet interdune and sabkha deposits are likely to form flow baffles, a point illustrated by the common absence of bleaching within this facies which often retains its reddish brown colouration (Figure 6).

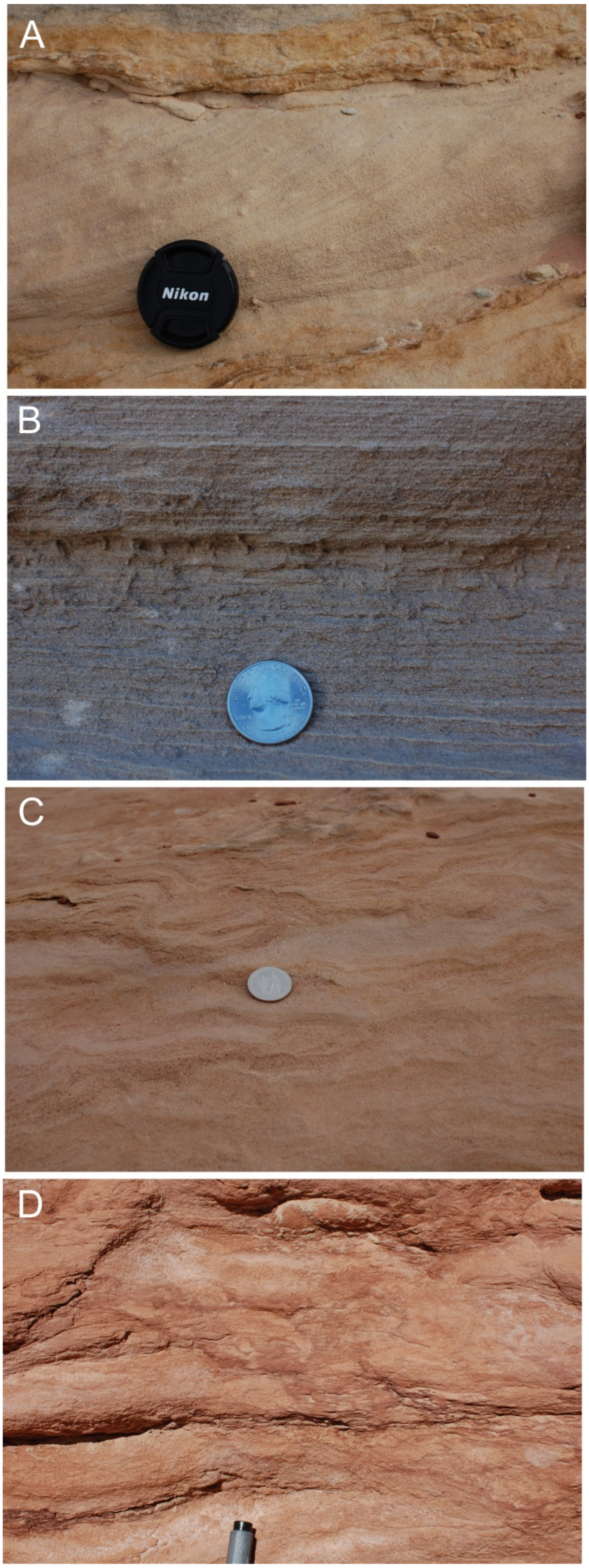


Figure 11 Spectrum of sandstone lithofacies within the Slick Rock Member, from; (A) high angle cross-bedded dune sandstones, to (B) low-angle wind-ripple laminated sandstone, to (C) wavy and convolute laminated sandstone wet interdune deposits and (D) massive and muddy sabkha sandstones. Reservoir quality decreases from A-D.

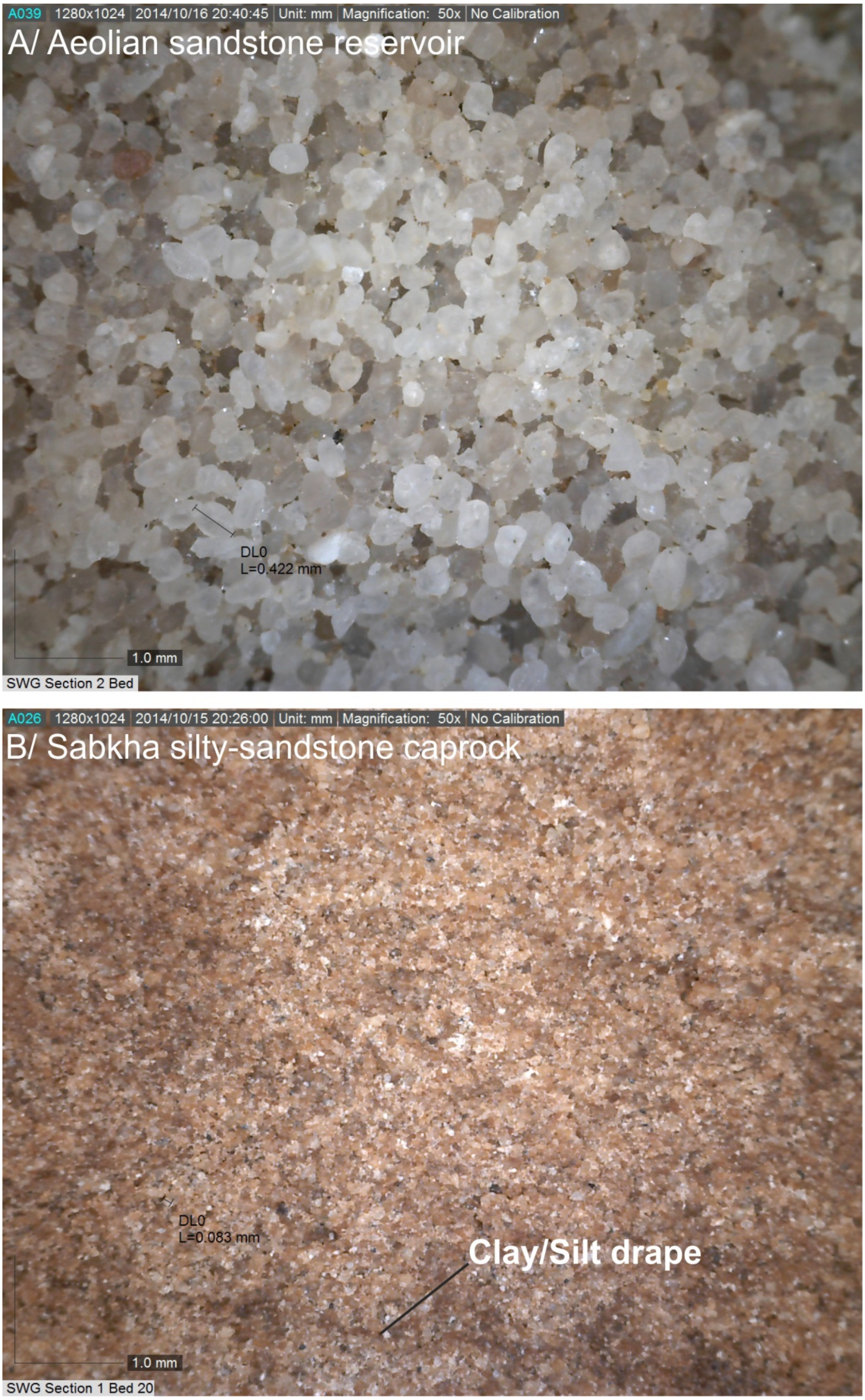


Figure 12 Images taken in the field using a Dino-Lite USB microscope which contrast the typical grain-size and textures of, (A) aeolian dune sandstones in the Slick Rock Member (reservoir) and (B) Sabkha deposits of the Earthy Member (topseal). Both photographs at x50 magnification , 1mm scale bar is shown in lower left corner.

3.3 LITHOFACIES OF THE EARTHY MEMBER – THE TOPSEAL

The Earthy Member is a massive bedded unit sharply overlying the Slick Rock Member. It is predominantly an admixture of sand, silt and clay with a highly disturbed fabric consisting of irregular pods and lenses of sand separated by laminated silts and clays (Figure 13).

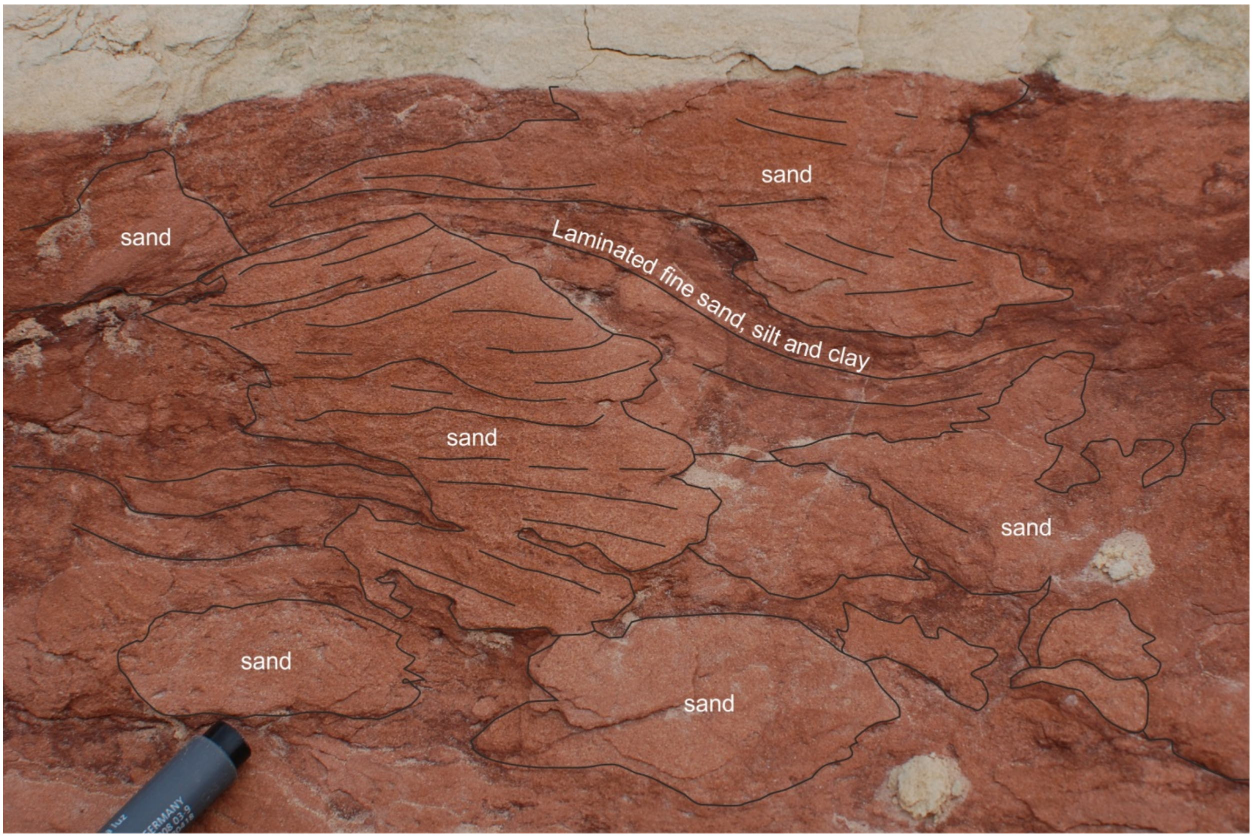


Figure 13 Example of the chaotic bedding fabric with the Earthy Member with irregular pods of sand separated by laminated clays and silts.

Individual sand pods show an infinite range of geometries but are usually less than 10 cm across. They are generally composed of fine-medium grained sand that is relatively clean and field measurements show that they can have a permeability in excess of 1000 mD. These are values typical of a good reservoir rock, however, the transmissive properties of this lithofacies will be severely reduced by the poor connectively of individual sand pods, which are separated by poorly-sorted admixtures of very fine- to fine-grained sand, silt and clay (Figure 12B). This poorly sorted, fine-grained lithology has a low permeability of 100mD or much less. Considering the Earthy Member at the reservoir scale it would be expected to behave as a barrier to fluid migration, even if isolated sand pods are present which have a relatively high permeability.

The Earthy Facies is generally interpreted as the product of a sabkha or mudflat environment in an arid marginal marine setting (Kocurek 1981). The chaotic bedding fabric is thought to indicate the former presence of salt crusts that precipitated from temporary bodies of saline water (from marine or groundwater flooding) covering the mudflats. As the saline waters evaporate salt crusts form blisters and plates with upturned edges which play an important part in trapping pods of wind-blown silt and sand on featureless mudflats (Goodall et al. 2000). Subsequent dissolution of the salt crusts and sediment compaction produces a chaotic siliciclastic deposit which may show no physical evidence for the former presence of salt.

While clean sandstones mostly occur as small centimetre-scale pods and lenses, very occasionally thin sheets of aeolian sandstone are encapsulated within the Earthy Facies (Figure 14). These sandstones are generally less than 0.5 m thick and composed of wind-rippled sandstone. They represent small, localised, and discontinuous mounds of windblown sand building up on the mudflat. Such sands are highly permeable and are bleached where they are connected to a source of reducing fluid via faults and fractures.

Figure 14 Minor aeolian sandsheet enclosed within the Earthy Member. Note the bleached fault zone which cuts the right margin of the aeolian sandstone and may have supplied reducing fluids to the bleached aeolian sandstone (dotted arrow). This aeolian sandstone represents a small-scale analogue for the main Slick Rock reservoir where a highly permeable bed acts as a lateral feeder for reducing fluids ascending a fault.

4 Evidence for fluid flow

4.1 DISTRIBUTION OF THE BLEACHING

Bleaching is seen within a broadly semi-circular area that is 1150 m across (parallel to the Salt Wash Graben Fault) and 408 m wide (perpendicular to the Salt Wash Graben Fault) (Figure 15). Vertically, the zone of bleaching is at least 13 m thick, but its base is not seen and bleached sandstones are likely to extend into the concealed Slick Rock Member bedrock for an unknown depth. Neither is the full lateral extent of the bleaching known, because to the north it disappears into the subsurface beneath a cover of unbleached younger strata.

The upper contact between bleached (grey) with unbleached (red-brown) Entrada Formation is well exposed along the western and eastern exposed margins of the palaeoreservoir (Figure 16). Along the western margin, the grey-red contact is seen dipping toward the north from an elevation of around 1276 m to 1265 m (Figure 17). In the eastern part of the palaeoreservoir the contact climbs to an elevation of 1282 m toward the crest of the Green River Anticline (Figure 15).

The grey-red contact is undulating, irregular and locally cross-cuts the poorly-defined bedding within the Earthy Member. However, on the scale of the palaeoreservoir it is broadly conformable to the stratigraphy of the Entrada Formation, always occurring at a level just above the contact between the Slick Rock Member (permeable reservoir) and the Earthy Member (low permeability caprock). Figure 15 shows the close correspondence between the mapped extents of the stratigraphic contact and the grey-red reduction front; as the top of the Slick Rock Member dips and disappears into the subsurface toward the north so does the bleached zone. The vertical separation of the grey-red reduction front from the top of the Slick Rock Member typically ranges from 2 m to a maximum of 4 m (Figure 16). Changes in the thickness of the reduced zone are mostly smooth and undulating, but locally sharp where the boundary is offset by a fault or where the palaeoreservoir has been cut by secondary fractures (described below) and the reducing fluids have escaped vertically.

The bleaching is not uniformly and ubiquitously developed throughout the Slick Rock Member which can contain patches of originally-reddened strata below the main reduction front (e.g. see Figure 9). Such reddened strata are invariably muddy sandstones whose low permeability has inhibited the ingress of reducing fluids.

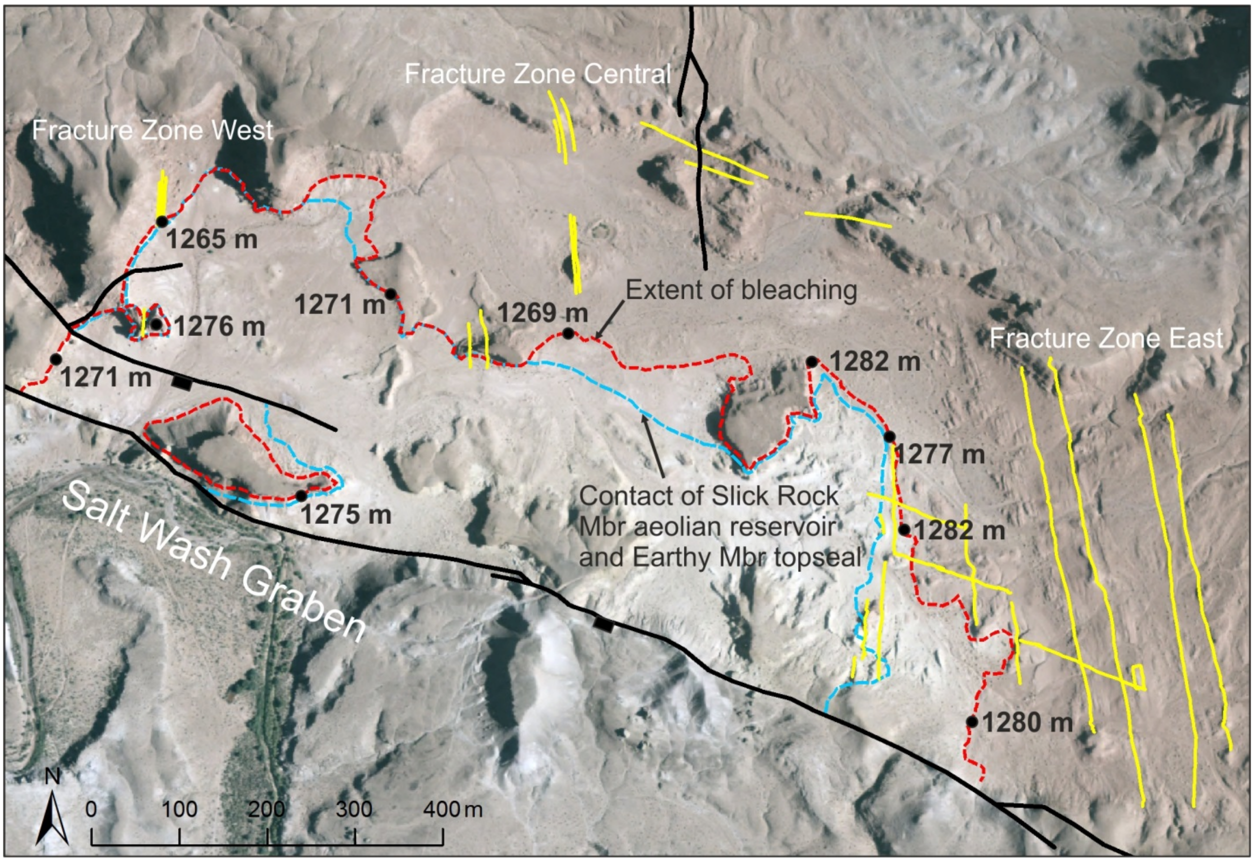


Figure 15 Map showing the boundary of the bleached reservoir zone (red line) and the location of major bleached fractures (yellow line). Four digit numbers are the elevation of the grey-red contact in metres. Note the bleached reservoir zone is broadly coincident with the boundary (blue line) between the Slick Rock Member (reservoir) and the Earthy Member (topseal). Major faults as black line with downthrown side indicated.

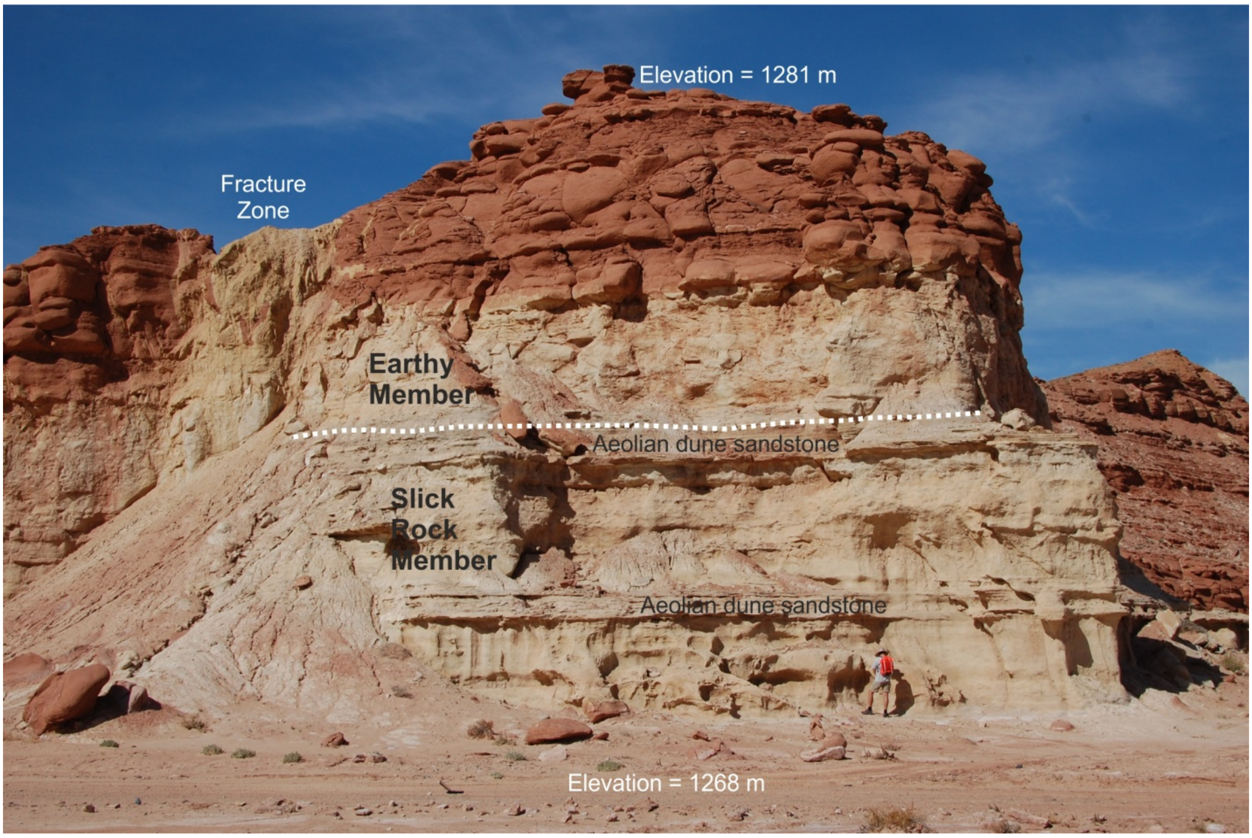


Figure 16 Bleached zone extending for around 4 m into the Earthy Member caprock above the top (dotted white line) of the Slick Rock Member. The horizontal grey-red contact is concordant to the stratigraphy. Note fracture zone to the left with a vertical zone of bleaching parallel to the fractures.

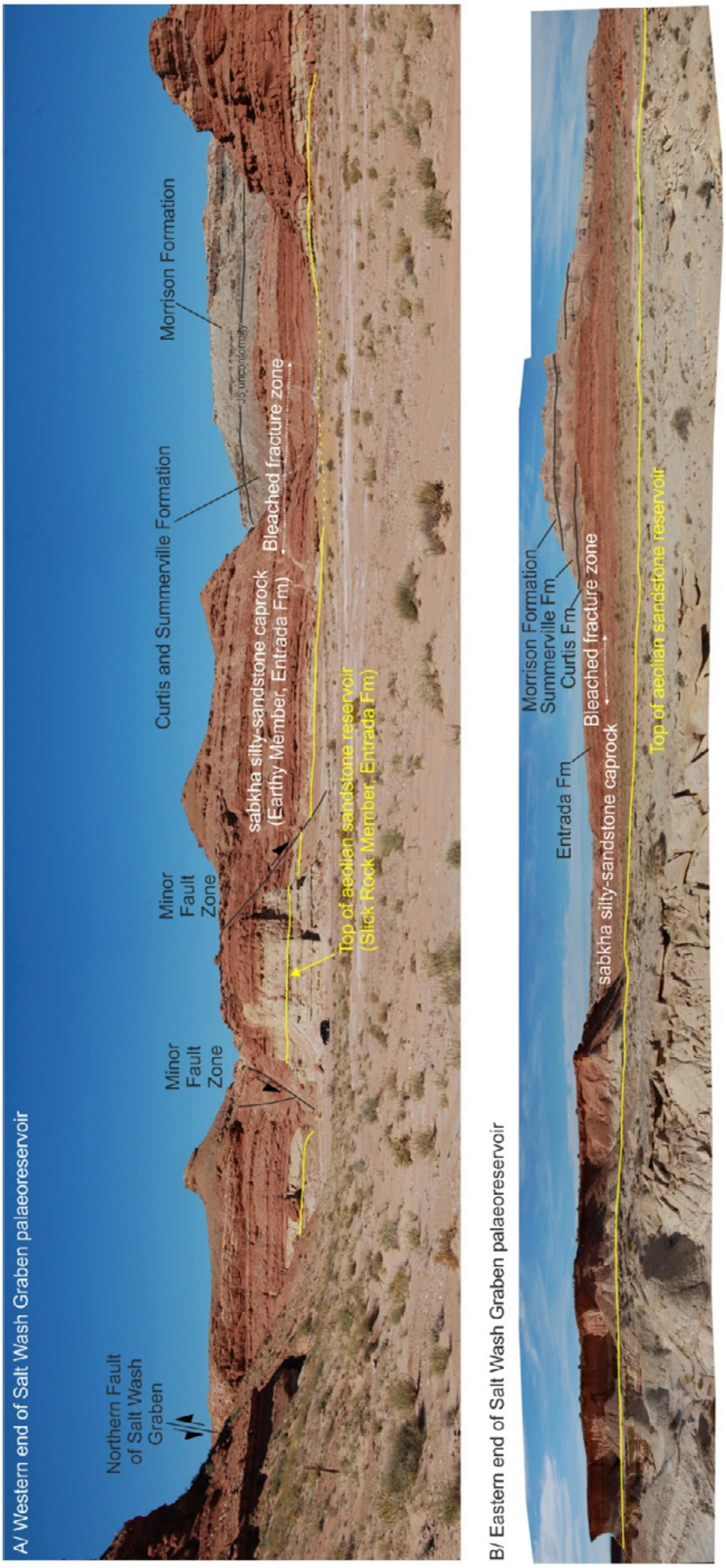


Figure 17 Distribution of the bleaching relative to the top of the aeolian sandstone reservoir at the (a) western and (b) eastern parts of the site.

4.2 NATURE OF THE REDUCING FLUIDS

Bleaching of red beds occurs whenever acidic or reducing fluids remove oxidised iron, usually present in rocks as fine-grained haematite. Haematite (Fe_2O_3) is a common early diagenetic grain coating developed in sediments deposited under humid but well-drained terrestrial conditions (Sheldon 2005; Walker et al. 1978). Ferric (Fe^{3+}) iron is relatively insoluble but reduction to the more soluble ferrous (Fe^{2+}) iron allows its removal and sandstone decolouration. There are a range of possible reducing agents in sedimentary basins which include hydrocarbons, H_2S and CO_2 (Schumacher 1996), and there is evidence for the presence of all three of these in the Paradox Basin around Green River.

Productive oil wells prove the generation and migration of hydrocarbons in the Paradox Basin around Green River, with the most likely source rocks being organic-rich shales from the Pennsylvanian Paradox Formation (Nuccio and Condon 1996). Adjacent to the Little Grand Wash Fault oil residues were observed in core from the Entrada Formation at the CO2W55 research borehole (Kampman et al. 2013) and at surface, hydrocarbon seeps were seen in the overlying Curtis and Morrison formations (Dockrill and Shipton 2010). It is unsurprising then that bleaching of red beds on the Colorado Plateau is often linked directly to hydrocarbons (Beitler et al. 2003; Chan et al. 2000; Garden et al. 2001).

At Salt Wash Graben, no evidence for the former presence of hydrocarbons was seen during this study. Dockrill and Shipman (2010) also report the absence of hydrocarbon residues in the area, although fluid inclusions from the Entrada Formation showed the presence of minor methane in gas phases dominated by CO_2 (Wigley et al. 2013). There is a possibility that hydrocarbon residues could have been removed by powerful organic solvents such as CO_2 rich fluids (Haszeldine et al. 2005). However, it could also indicate that hydrocarbons were not the bleaching agent at Salt Wash Graben. Haszeldine et al. (2005) cast doubt on whether the bleaching of sandstone palaeoreservoirs across the Colorado is solely the result of hydrocarbons, because in other basins, such as the North Sea, there are many analogous red-bed sandstone oil and gas reservoirs that do not show any bleaching.

The Colorado Plateau is anomalous in hosting very large natural accumulations of CO_2 (Allis et al.), probably generated by magmatic activity (Haszeldine et al. 2005). Evidence for the migration and surface leakage of CO_2 (together with minor N_2, Ar, He and H_2S) is very well documented around Green River (Burnside et al. 2013; Han et al. 2013; Kampman et al. 2012; Kampman et al. 2013; Pearce et al. 2011). Surface emissions typically occur as cool, saline-water springs preferentially located along faults and fractures where they are associated with the build-up of travertine mounds (Figure 18). There is a long history of CO_2 emission in this part of the Paradox Basin with a sequence of travertine deposits dating back to at least 400,000 years (Dockrill and Shipton 2010; Kampman et al. 2012; Wigley et al. 2012). Wigley et al. (2012) argue that bleaching of the Entrada Formation at Salt Wash Graben results from inputs of CO_2-charged brines along the Salt Wash Fault. The bleaching capacity of CO_2 charged brines has been questioned (Milodowski personal communication) and following the suggestion of Hazeldine et al. (2005) it is possible that H_2S, commonly associated with CO_2 in many of the spring discharges, was an important reducing agent. Organic acids or CO could also be added to the list of feasible reductants (Haszeldine et al. 2005).

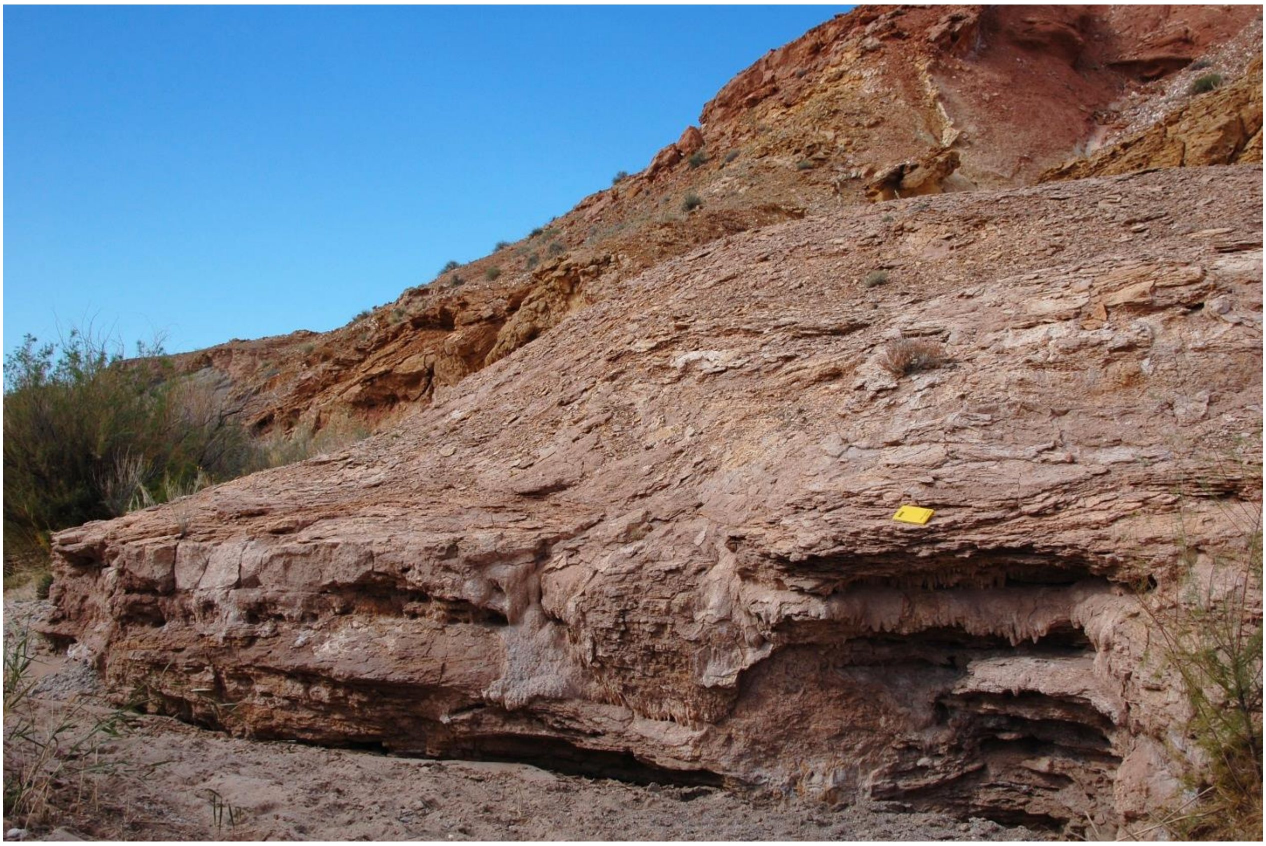


Figure 18 Travertine mound adjacent to the Salt Wash Graben Fault. The mound is location on the hanging wall side of the fault (which is located immediately behind the mound).

4.3 DENSITY OF THE REDUCING FLUIDS

Most bleached palaeoreservoirs on the Colorado Plateau occur on structural highs, such as the crests of anticlines, and at the top of permeable formations sealed beneath caprocks (Beitler et al. 2003). This indicates that the reducing fluids were buoyant relative to the formation pore fluids. However, at Salt Wash Graben, Wigley et al. (2012, 2013) haved argued that the reducing fluids were dense brines and entered the Entrada Formation as a density current. The stratigraphic position of the bleaching would tend not to support this hypothesis. The bleaching does not occur at the base of the Entrada Formation aquifer as suggested by Wigley et al. (2012, 2013) but at the top, where the high-permeability Slick Rock Member is overlain by the low permeability Earthy Member. This would favour bouyant fluids trapped beneath a caprock. Rather than a density current, it seems more likely that reducing fluids moved laterally into the formation along high-permeability carrier beds formed by aeolian dune sandstones in the Slick Rock Member before vertical diffusion into the low-permeability caprock formed by the Earthy Member (Figure 19).

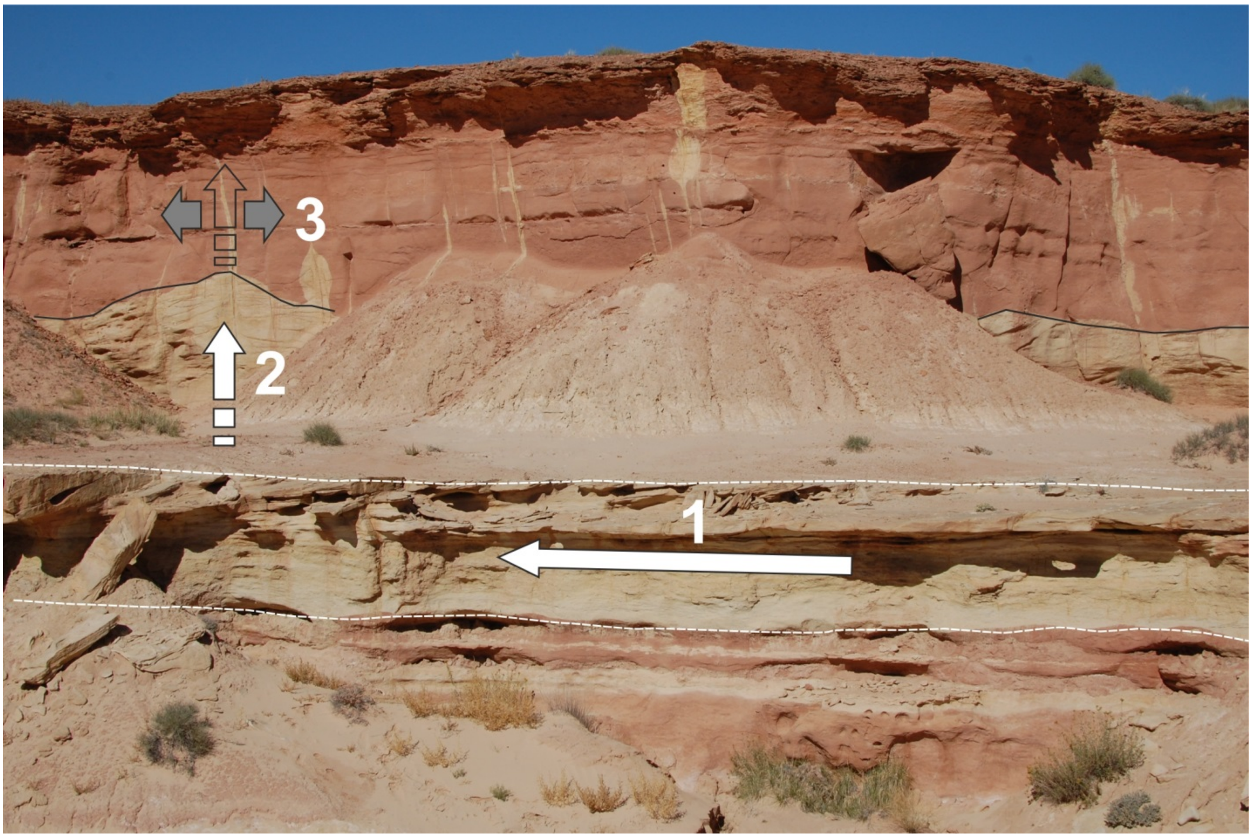


Figure 19 An illustration of the proposed flow pathway: (1) Reducing fluids travel laterally through carrier beds formed by high-permeability aeolian dune sandstones, note that unbleached muddy sandstones occur above and below the bleached aeolian sandstone, (2) Reducing flow diffuse into low-permeability caprock formed by the Earthy Member, (3) Reducing fluids escape through vertical fractures following breaching of the caprock.

The structural setting of the Salt Wash Graben reservoir supports the view that the reducing fluids were buoyant because it is located on a structural high along the crest of the north plunging Green River Anticline where it intersects the Salt Wash Graben (Figure 20). The faults bounding this graben could have acted as an updip seal, stopping the migration of bouyant fluids up the plunging anticline through either the development of a clayey fault gouge or shale smear, or by juxaposing low permeabilty strata on the updip side of the against the Entrada Formation on the footwall (Figure 20). Alternatively by causing rotation of strata toward the south, the faults may have created a four-way structural closure with the reservoir extending into the graben.

4.4 REGIONAL FLOW PATHWAYS

The heavy oxygen isotope composition of secondary carbonates in the bleached zone suggests that the parent fluid contained a significant fraction of basinal brine derived from depth (Wigley et al. 2012). However the fluid pathway into the bleached palaeoreservoir is uncertain. The Salt Wash Graben Fault is clearly a strong candidate given that it currently forms the southern boundary of the bleached zone and is a proven conduit for fluid flow with modern CO_2 springs and ancient travertine located along its trace (Pearce et al. 2011). Although the development of fault gouge and shale smear within a fault zone may impede fluid flow across a fault the enhanced fracturing of rocks in an envelope adjacent to the fault may form a pathway for vertical flow parallel to the fault plane. Sandstones of the Morrison Formation and Entrada Formation adjacent to the Salt Wash Graben Fault both show a high density of fracturing in the damage zone adjacent to the fault (Figure 21).

Alternatively the fluids could have migrated into the reservoir up the north-plunging Green River anticline, with the Salt Wash Graben Fault acting as a barrier to further southward migration.

This migration path would be broadly consistent with the current south directed regional groundwater flow (Hood and Patterson, 1984). Reducing fluids from depth could gave entered the Entrada aquifer via the Little Grand Wash Fault.

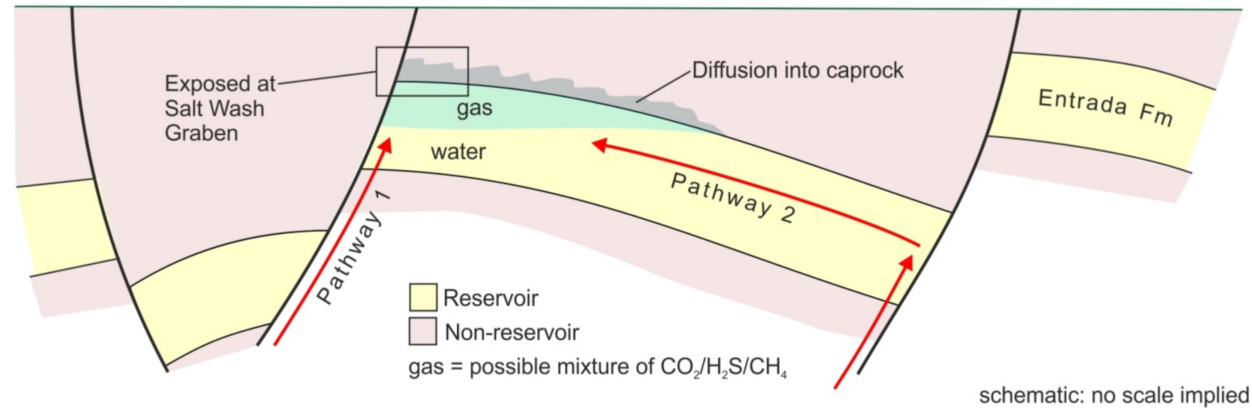


Figure 20 Schematic configuration of the Salt Wash Graben Palaeoreservoir showing two possible pathways for buoyant fluids to enter the crest of the Green River Anticline, (1) via the northern fault of the Salt Wash Graben, or (2) updip through the aquifer from the Little Grand Wash Fault. Box indicates the part of the reservoir which can be seen in outcrop at Salt Wash Graben. The height and precise composition of the gas column are unknown.

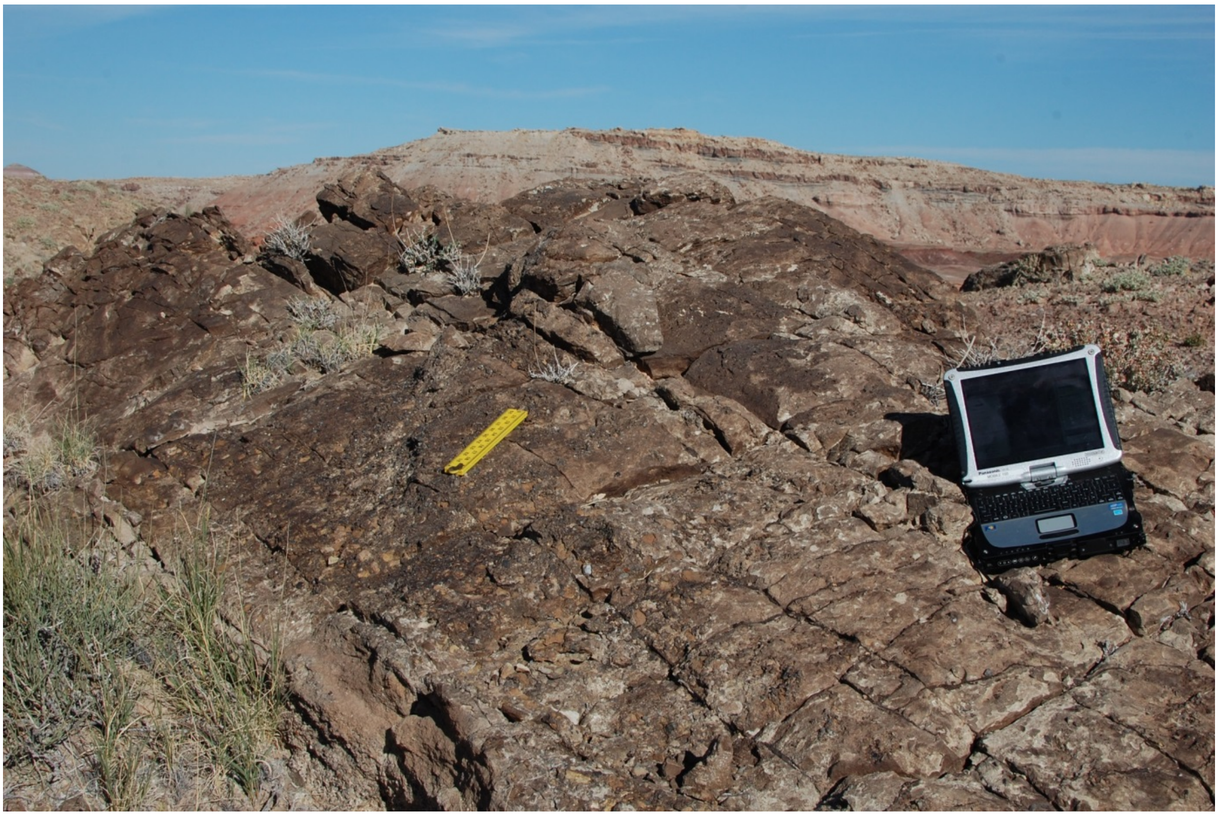


Figure 21 Strongly jointed pebbly sandstones of the Cedar Mountain Formation (or possibly Morrison Formation) adjacent to the Salt Wash Graben fault

4.5 DEPTH, TEMPERATURE AND AGE OF BLEACHING

The Entrada Formation which today sits as surface outcrop on the northern footwall of the Salt Wash Graben has had a long and complex burial and thermal history since deposition (Nuccio and Condon 1996). Following its deposition in the Middle Jurassic, subsidence of the Paradox Basin took it down to a maximum depth of 2.5 km at around the Eocene-Oligocene boundary (Figure 4). Subsequent uplift of the Colorado Plateau coupled with the rapid (around 100 m/ma) erosion of the Colorado River drainage basin (Summerfield and Hulton 1994) has subsequently brought it back to surface. The only evidence for the timing of the bleaching probably comes from the microthermometry of fluid inclusions hosted in quartz overgrowths and gypsum which are petrographically linked to the bleaching (Wigley et al. 2012). These indicate that the bleaching fluid was a low temperature (27°C) brine with a salinity of around 2.5–7 wt% (Wigley et al. 2012). It is therefore likely that bleaching occurred at a depth that was shallow relative to the maximum burial depth. Present-day temperature-depth profiles for the Green River Desert Region indicate relatively low geothermal gradients of around 10°C per 1 km with mean near surface temperatures of around 15°C (Bodell and Chapman 1982). Used as a general guide (surface temperatures and gradient will vary through geological time and circulating fluids may disrupt normal geothermal regimes) this would suggest that the bleaching occurred when the Entrada Formation aquifer was at a depth of around 1 km. The burial and thermal curves of Nuccio and Condon (1996) for the Green River area indicate that temperatures of 27°C occurred at around 500-900 m depth since the start of the Cretaceous (Figure 4). Depths of 500-1000 m could have been attained either during the initial basin subsidence phase in the early to mid-Cretaceous (just prior to the main phase of hydrocarbon generation) or during exhumation in the mid Miocene (Nuccio and Condon 1996). In either the relative antiquity of the bleaching event is consistent with the observation that the bleaching front has been deformed by later fault movements at Salt Wash Graben which may be Quaternary and younger (Dockrill and Shipton 2010).

4.6 CO_2 PHASE

At the pressures typically associated with burial depths of 800 m or more CO_2 normally exists in a supercritical state with a density like that of a liquid. If the bleached reservoir was filled primarily with CO_2 (Wigley et al. 2012) and if that CO_2 was supercritical it is interesting to speculate on the possible effect of volume increases within the reservoir as the Colorado Plateau was progressively uplifted and eroded, passing the threshold for the phase change from supercritical fluid to gas. Has uplift, exhumation and gas expansion been an important driver for the expulsion of CO_2 from subsurface reservoirs?

4.7 RESERVOIR FRACTURING AND THE ESCAPE OF REDUCING FLUIDS

Much of the interest surrounding the Salt Wash Graben site has been on the secondary fracturing which allowed the escape of reducing fluids contained within the palaeoreservoir (Ogata et al. 2014; Pearce et al. 2011). The movement of reducing fluids through the fractured caprock is clearly shown by the development of bleached margins adjacent to the fractures (Figure 22). The bleached margins are symmetrical either side of the vertical or sub-vertical fractures and a few centimetres to tens of centimetres wide (Figure 22). Wider bleached areas occur where fractures form zones of many closely spaced fractures (e.g. Figure 1) or where there are local increases in the permeability of the host rock. Where the vertical bleached margins of fractures intersect the horizontal bleached margin of the main reservoir (Figure 22A) a funnel shaped pattern is commonly developed (e.g. Figure 19). The relatively narrow width of the vertical bleached zones adjacent to fractures relative to the thick horizontal bleached zone adjacent to the sandstone reservoir presumably reflects factors such as the exposure time and the height of the gas column or gas pressure driving the ingress of the reducing fluid into the low-permeability caprock. The fractures are open, or have a partial infill of carbonate or gypsum which may have precipitated from later phases of fluid flow.

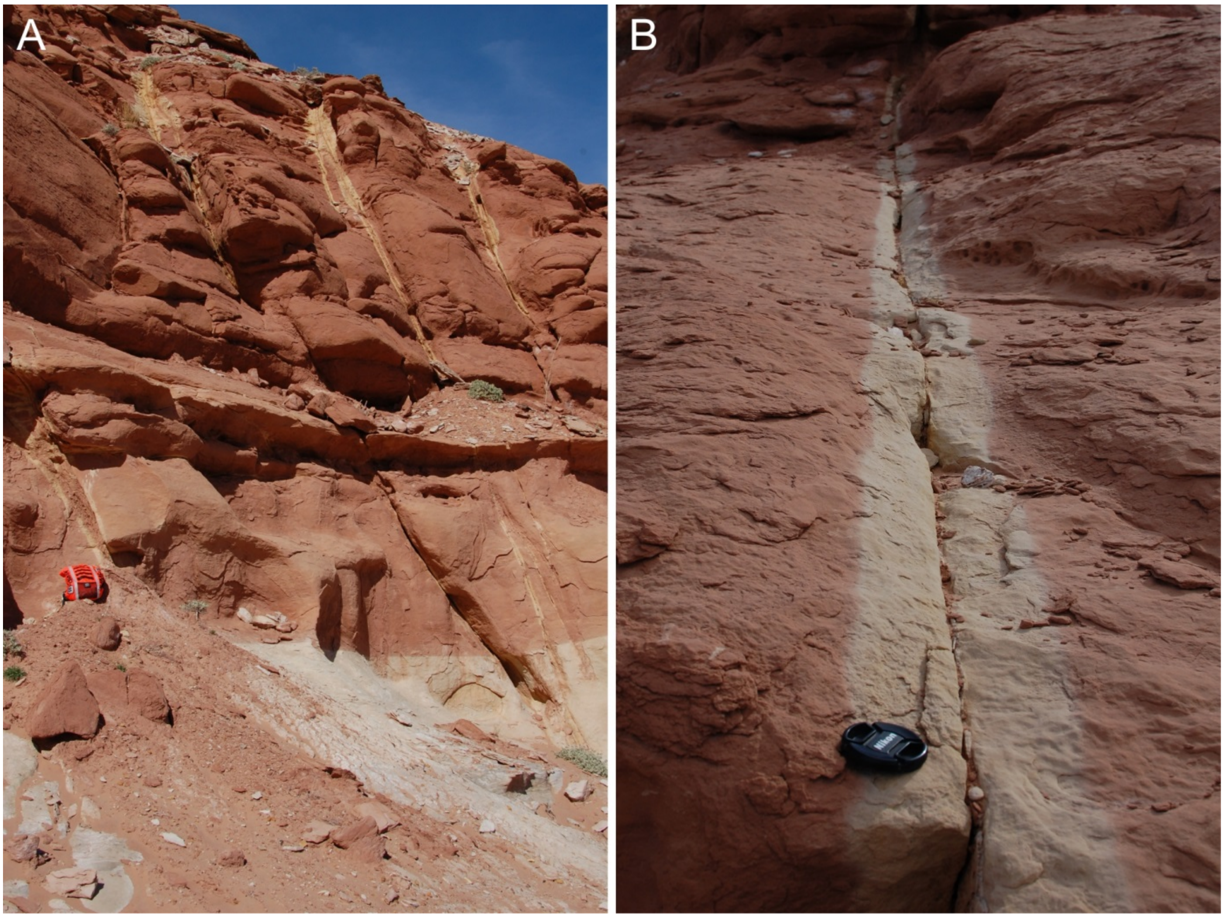


Figure 22 (A) Bleached fracture set in the Earthy Member, note that the vertical bleached fractures extend upwards from a horizontal bleached zone representing the diffusion front from the underlying reservoir, (B) Single bleached fracture with partial carbonate infill.

A detailed analysis of the bleached fractures was not attempted during this study but would be a worthy future extension of this work. Mapping showed the bleached fractures are mostly orientated approximately NNW-SSE and occur in three main corridors in the western, central and eastern part of the palaeoreservoir (Figure 15). Fracture zones can be traced for 500 m or more with the longest and highest density of bleached fractures occurring on the eastern margin of the palaeoreservoir, close to the crest of the Green River Anticline. A conjugate set of WNW-ESE fractures occurs in the eastern part of the reservoir.

The NNW-trending bleached fractures at Salt wash Graben are clearly an extension of a major NNW-trending fault zone which lies along the crest of the Green River Anticline to the north (Doelling 2001) (Figure 23). By analogy to similar structures in the northern Paradox Basin it is likely that the Green River Anticline is cored by salt (Dockrill and Shipton 2010). The development of faults parallel to the axis of salt-cored folds is common and may result from local stretching related to diapir growth, buckling of the drape anticline or in response to regional extension and subsidence of the underlying diapir (Ge and Jackson 1998).

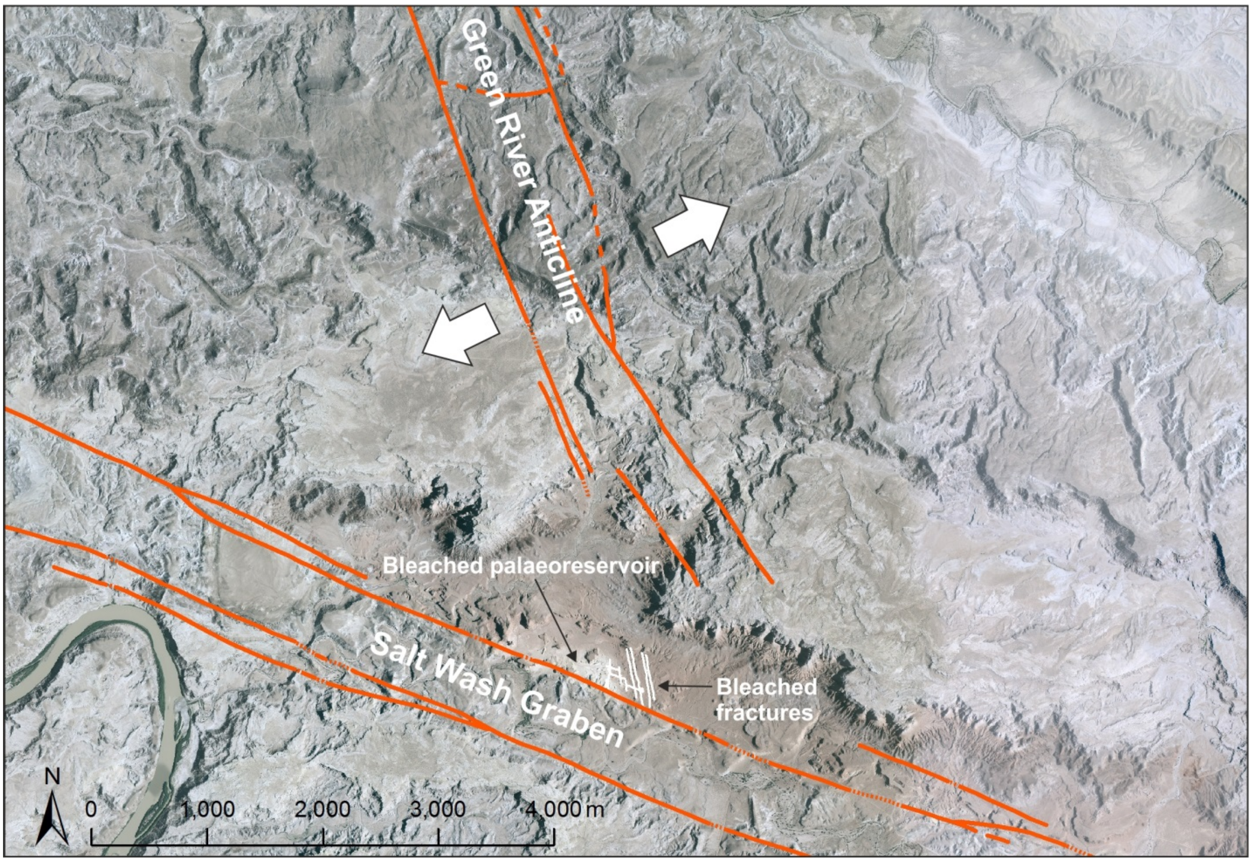
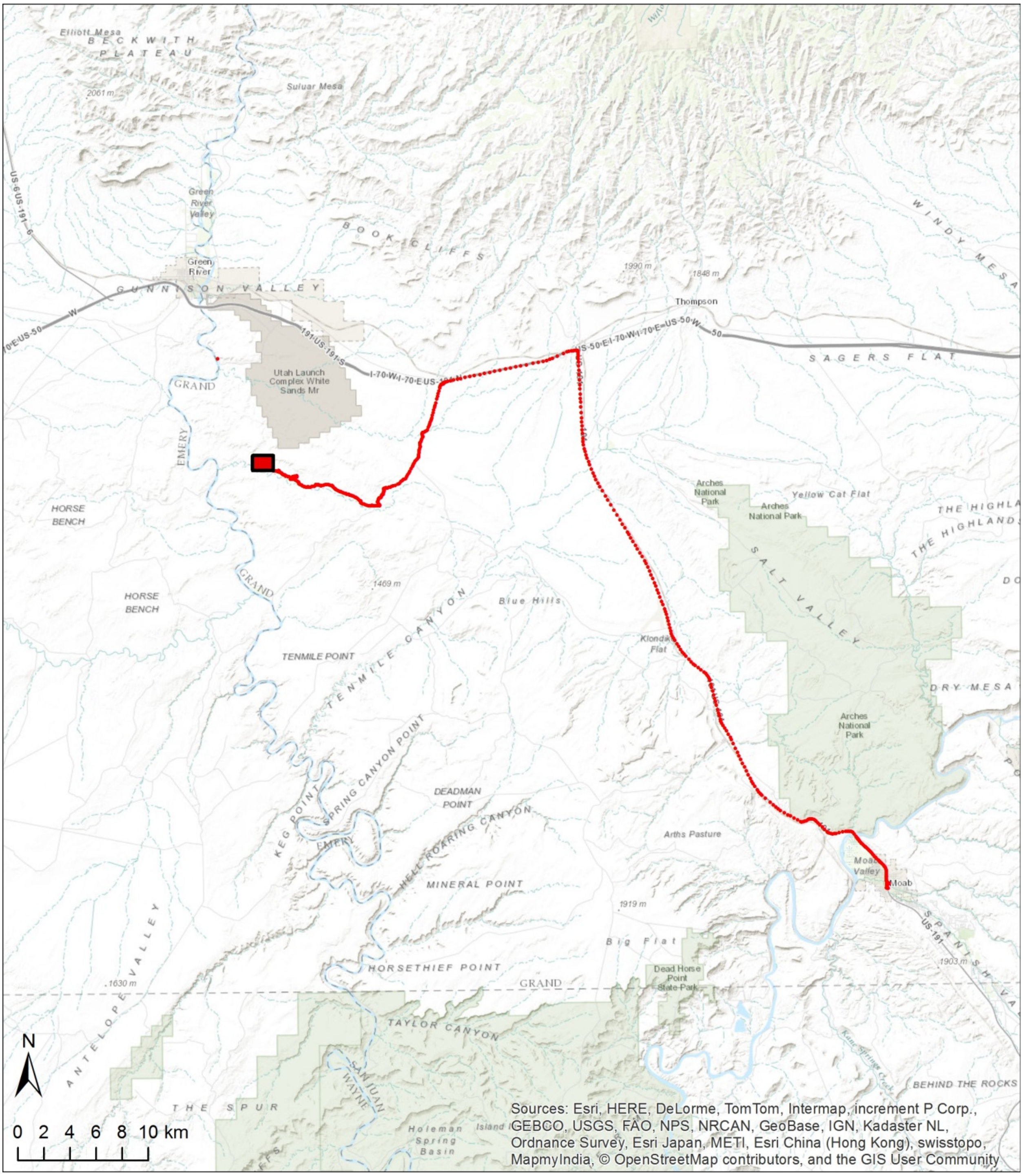


Figure 23 Map showing how the major NNW trending set of bleached fractures at the eastern end of the palaeoreservoir is a southern extension of the fault zone which is parallel to the Green River Anticline. Structures in red from Utah Geological Map 180 (Doelling 2001). Structures in white mapped during this study.

5 Conclusions

The stratigraphy and sedimentology of the Entrada Formation are central to understanding the origin of the bleached palaeoreservoir exposed at Salt Wash Graben. Aeolian sandstones of the Slick Rock Member formed high-permeability carrier beds which distributed reducing fluids laterally within the formation. The overlying Earthy Member is a massively-bedded succession of low permeability mudflat/sabkha deposits which acted as a caprock: albeit one that formed an imperfect seal and allowed the upward diffusion of reducing fluids for a distance of up to 4 m above the top of the reservoir. The Salt Wash Graben is located on the crest of the Green River Anticline and was filled by buoyant fluids that may have migrated updip along this north plunging fold; alternatively these fluids may have entered via the northern fault of the Salt Wash Graben. The role of this structure in forming an updip seal during the filling of the reservoir is uncertain. The reservoir was probably filled in the early Cretaceous at a depth of around 1 km or less, during the subsidence phase of the Paradox Basin. The fluids are likely to have been an admixture of H_2S, CO_2 and CH_4. The reservoir was later breached by NNW-trending fractures related to extension across the crest of the Green River Anticline.

Enclosure 1

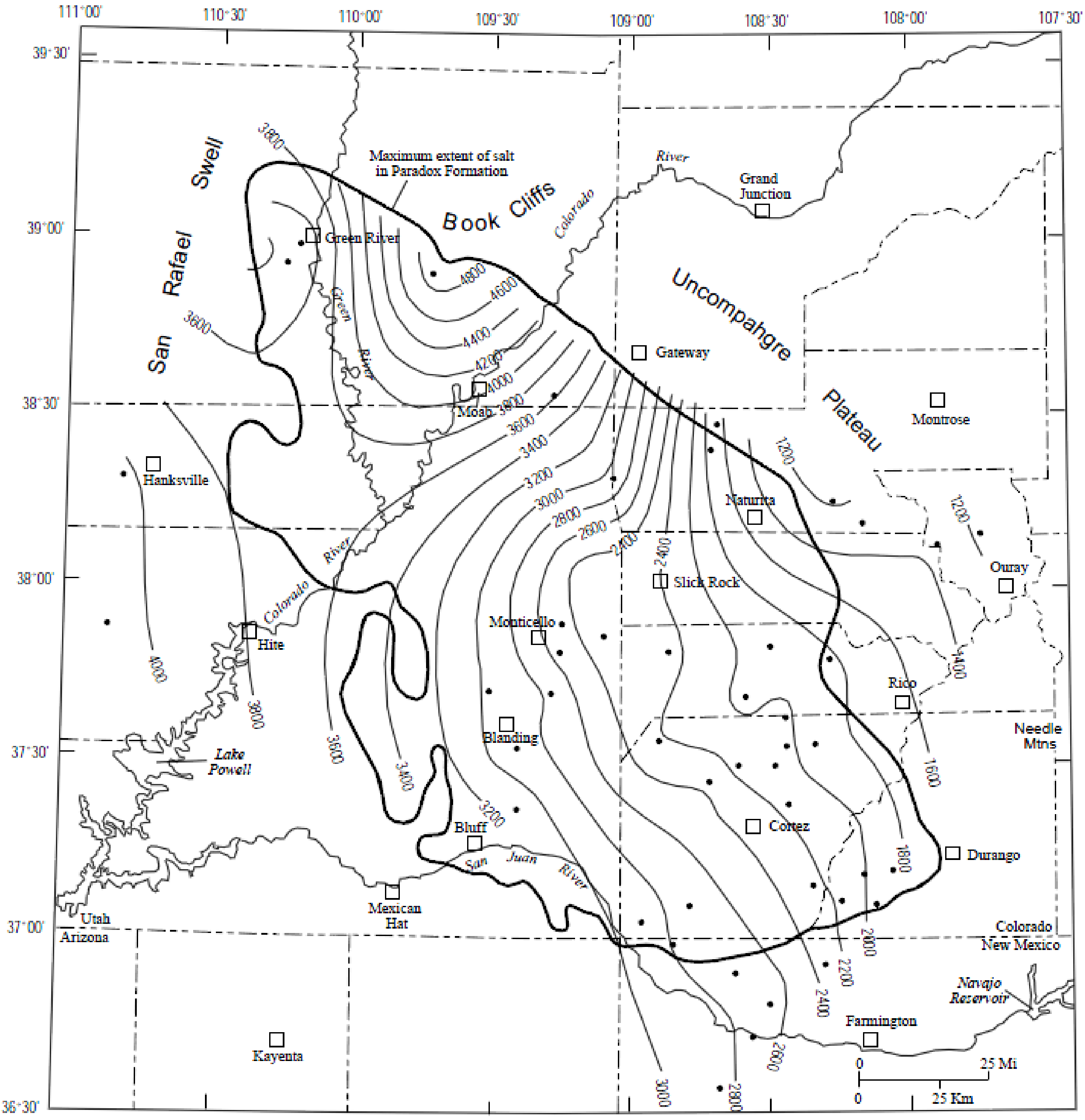


Location of the site (red rectangle) and the most efficient route to reach it from Moab leaving Interstate 70 at the Floy Wash Junction and travelling onward via gravel roads and unsurfaced but clearly designated tracks.

Enclosure 2

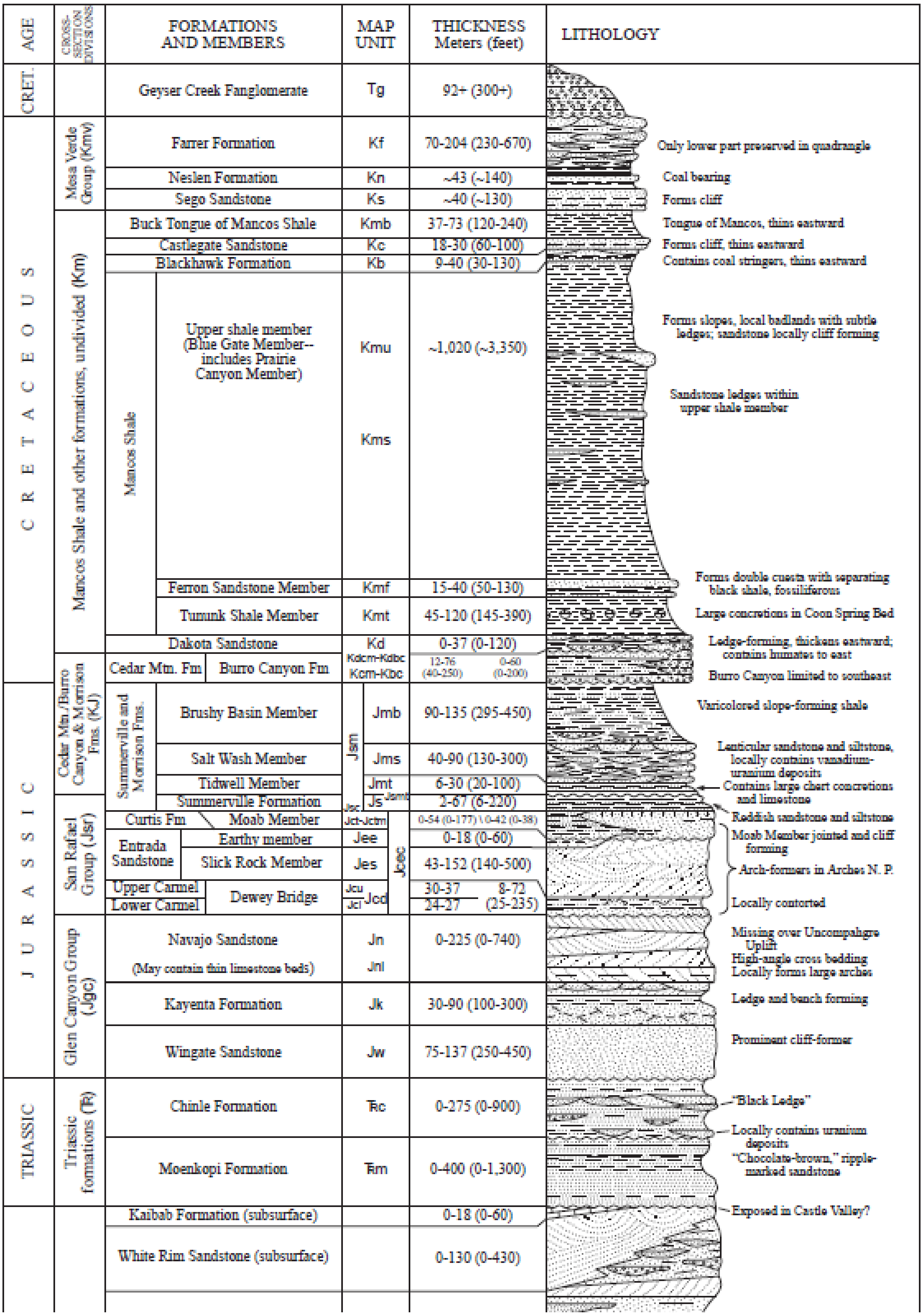
Fieldwork tools included a TinyPerm portable probe permeameter and a DINO-LITE usb microscope for accurate capturing of grainsize and sorting data

Enclosure 3



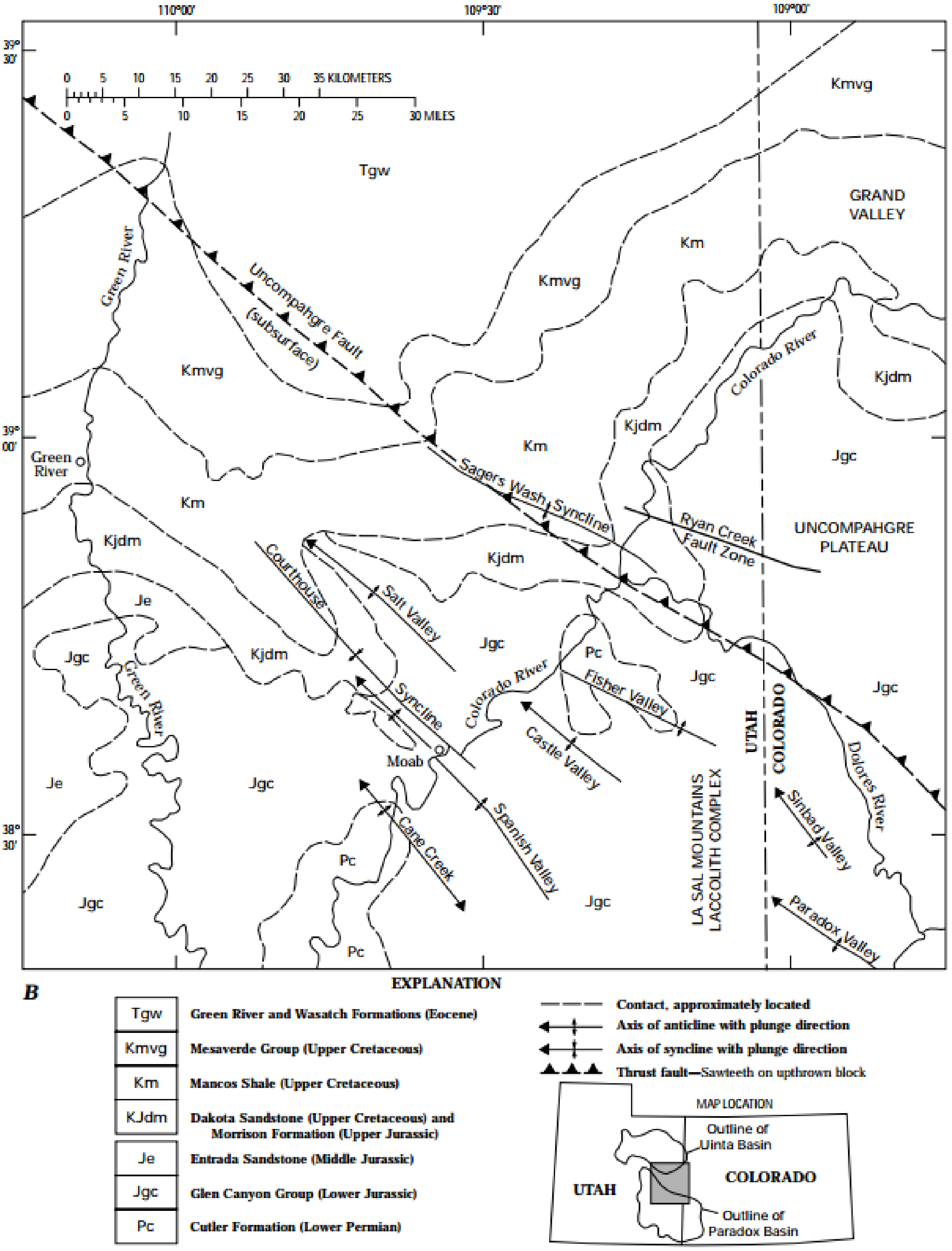
Isopach map of Triassic and Jurassic stratigraphic units in the Paradox Basin. Contour interval 200 feet (Nuccio and Condon 1996).

Enclosure 4



Triassic, Jurassic and Cretaceous stratigraphy of the Moab area (from Doelling 2001).

Enclosure 5



Generalised geology of the northern part of the Paradox valley showing strong NW trending structural trend of salt-cored anticlines (LIVO et al. 1998)

Enclosure 6

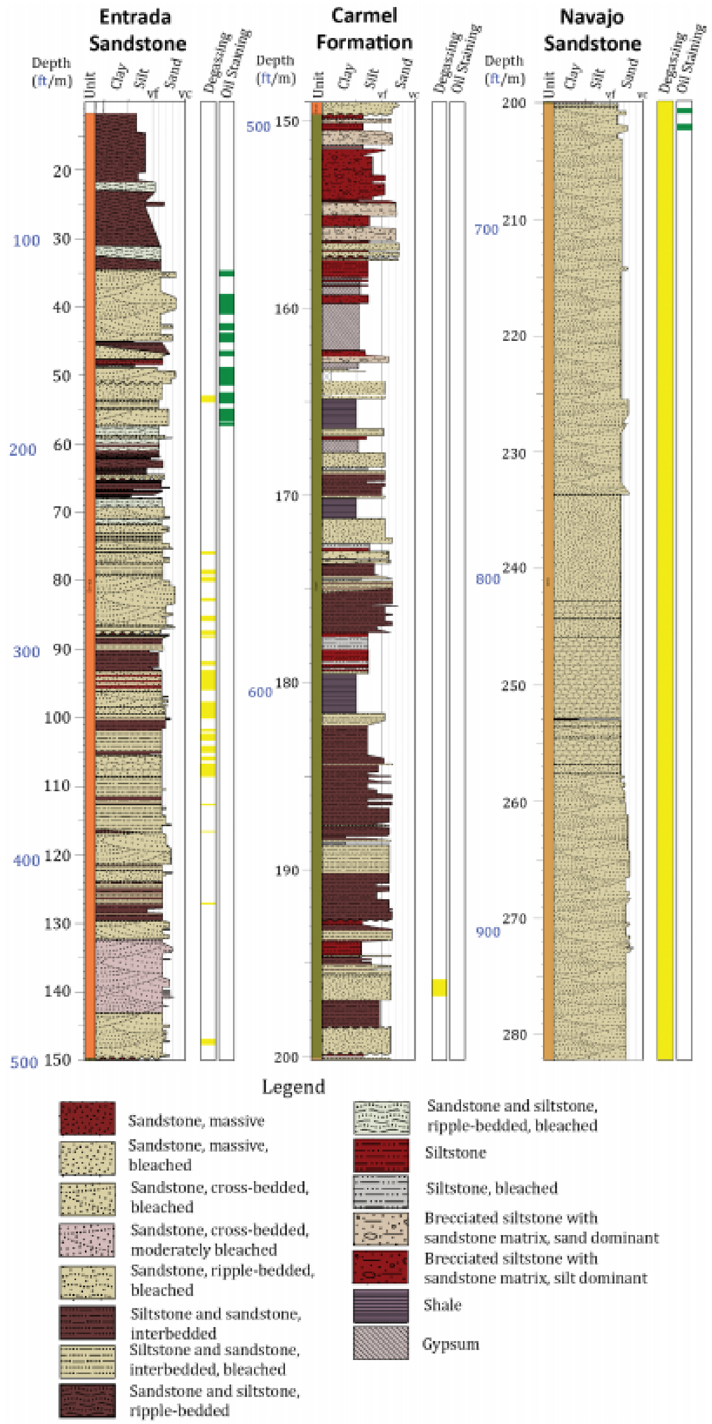
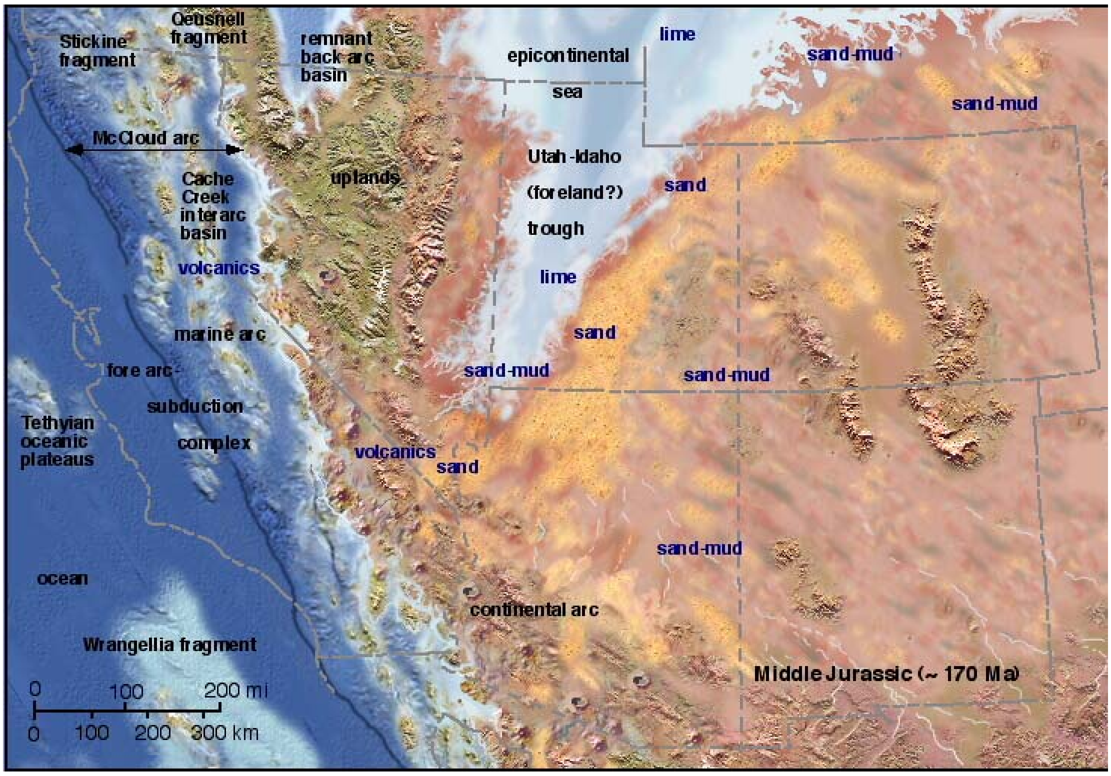
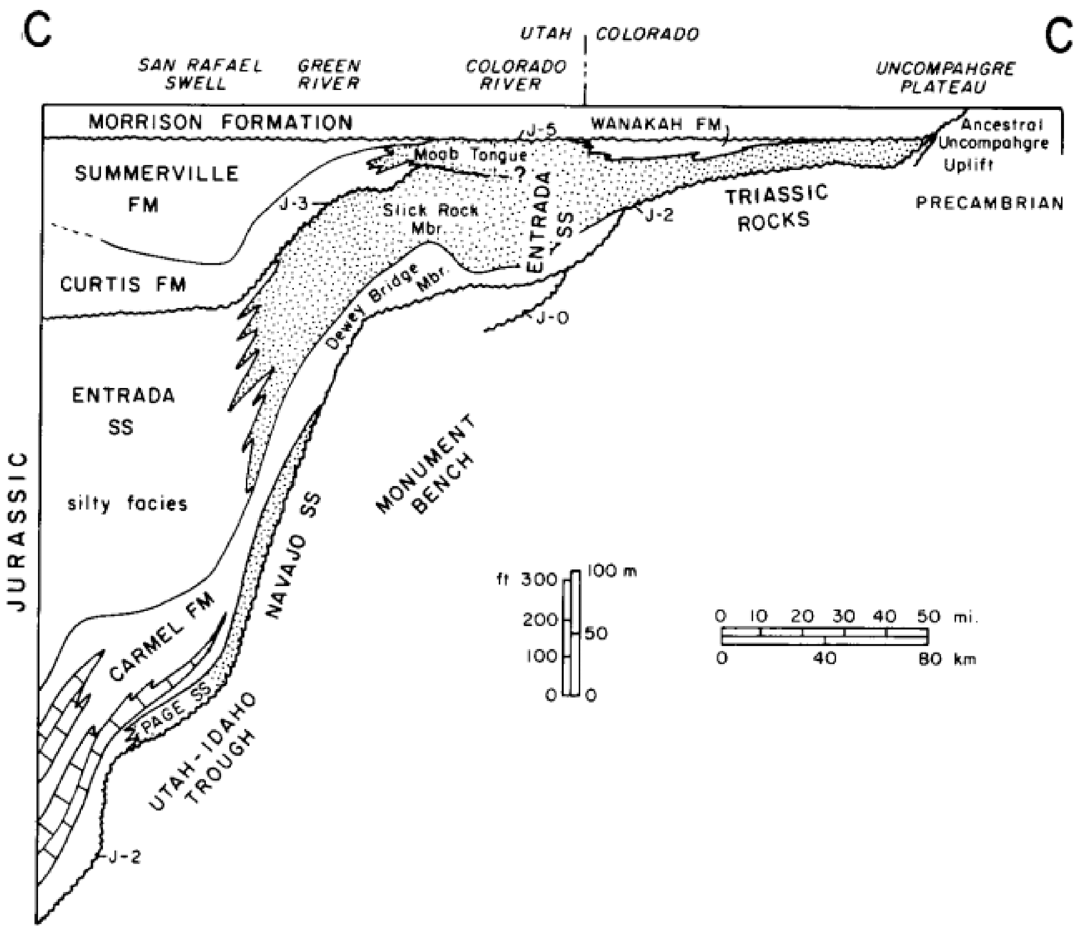


Figure 5. Sedimentary log of the core recovered from drill hole CO2W55 showing the main geological features of the three units, the Entrada Sandstone, Carmel Formation and Navajo Sandstone, transacted by the drill hole. Zones of CO_2-degassing core and hydrocarbon bearing zones are also shown.

Stratigraphy of the Entrada Formation at Crystal Geyser (Kampman et al. 2013)

Enclosure 7





Middle Jurassic palaeogeography and west-east stratigraphic section (Blakey et al. 1988)

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