PS Fluvial-Aeolian-Evaporitic Interactions in Arid Continental Basins: Implications for Basin-Scale Migration and Reservoir Characterisation*

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Abstract

The sedimentary fill of arid continental basins may comprise deposits of aeolian, fluvial, and evaporitic environments. While the distribution and preservation of different facies associations within each environment are reasonably constrained from comprehensive past studies, the relationships between deposits of coeval environments, and the temporal evolution of sediment through environments, have received comparatively little attention despite their potential to affect both basin-scale fluid migration and reservoir quality. We present results of studies of sedimentary interactions between arid environments of the Paradox Basin, USA, along with analysis of the allocyclic-controls upon them. The studies are based upon extensive regional fieldwork to examine the sedimentology, and 3D photogrammetry techniques to examine geometries and interactions. Fluvial-aeolian sediments of the Kayenta Formation preserve associations of varied reservoir quality. Relationships between them are spatially predictable, governed by one system's dominance. A dominant aeolian system limits fluvial sediments to interdune corridors and controls localised sediment supply, resulting in flash-flood and debris facies of moderate reservoir quality comprising sediments of aeolian calibre and texture. Dominance of the fluvial system restricts aeolian bedforms and preserves extensive ephemeral fluvial sediments of poor reservoir quality with fluvial textures dominated by extraformational sediment. The temporal evolution between systems preserves unique facies, but a switch in dominant system takes place quickly, severely limiting the vertical extent of interactions and potentially isolating reservoir intervals of basin fill. The margin of the Cedar Mesa erg preserves aeolian-evaporitic sediments. Interactions suggest a dominance of the evaporitic system, even during drier times, with extensive reworking of aeolian sediments into sabkha-related associations of poor reservoir quality. Interactions can be extensive, but sporadic, in space and time, preserving complexly interbedded relationships of clean aeolian and evaporitic strata that can both compartmentalise and provide migration pathways to connect reservoir intervals. Our studies provide evolutionary models that we apply to subsurface data from the arid Permian basins of the North Sea, UK – an active hydrocarbon province – in order to better characterise basin-scale migration and reservoir quality in terms of the evolving basin fill.

Fluvial-Aeolian-Evaporitic Interactions in Arid Continental Basins: Implications for Basin-Scale Migration and Reservoir Characterisation

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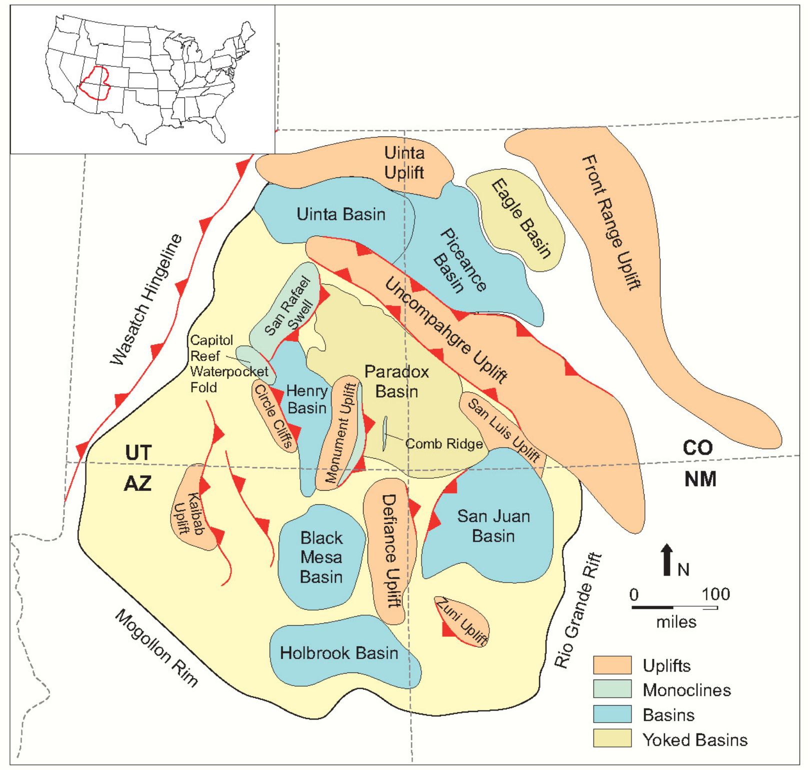
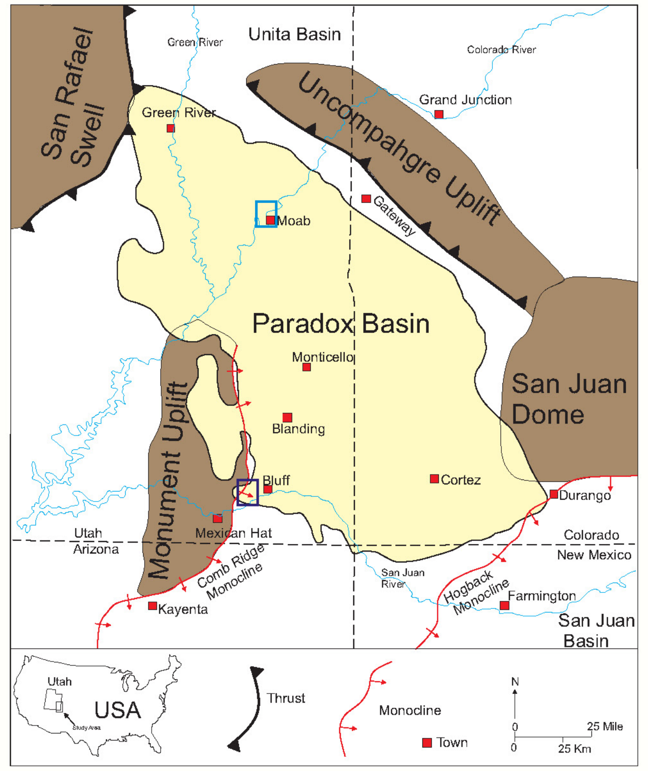
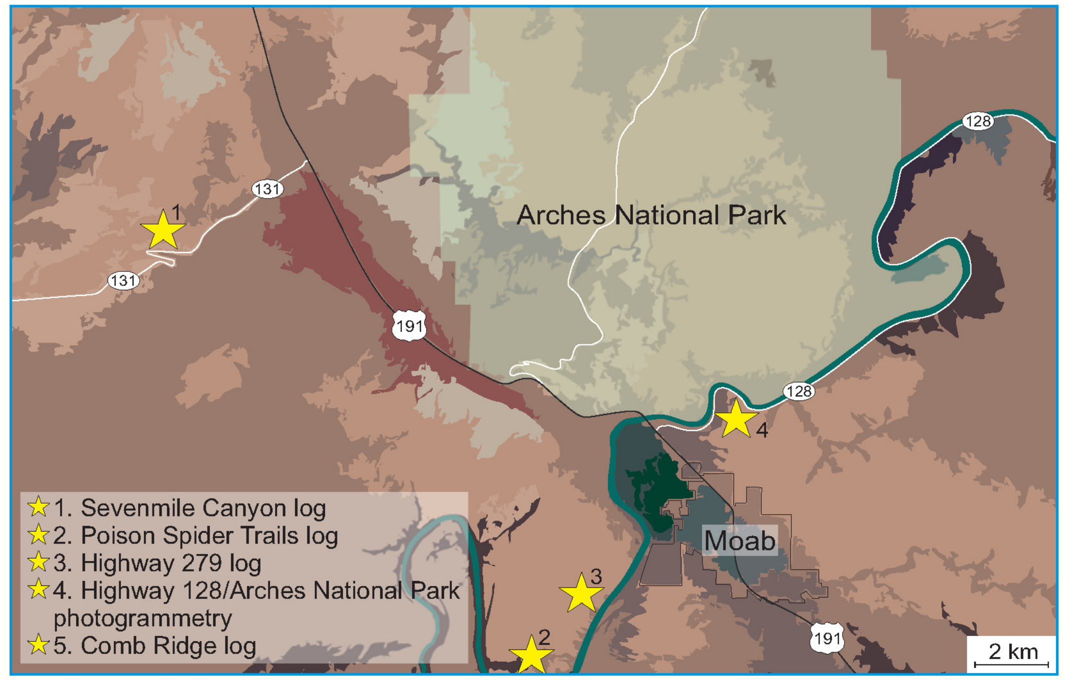
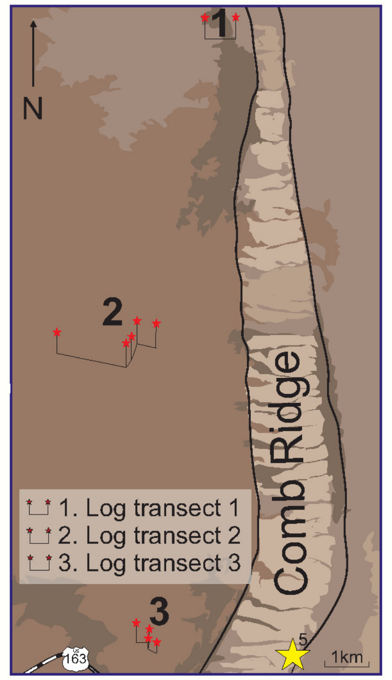
Geological Setting

The sedimentary fill of arid continental basins may comprise deposits of aeolian, fluvial, and evaporitic environments. While the distribution and preservation of different facies associations within each environment are reasonably constrained from comprehensive past studies, the relationships between deposits of coeval environments, and the temporal evolution of sediment through environments, have received comparatively little attention despite their potential to affect both basin-scale fluid migration and reservoir quality. We present results of studies of sedimentary interactions between arid environments of the Paradox Basin and Colorado Plateau, USA, along with analysis of the allocyclic-controls upon them. The studies are based upon extensive regional fieldwork to examine the sedimentology, and 3D photogrammetry techniques to examine geometries and interactions.





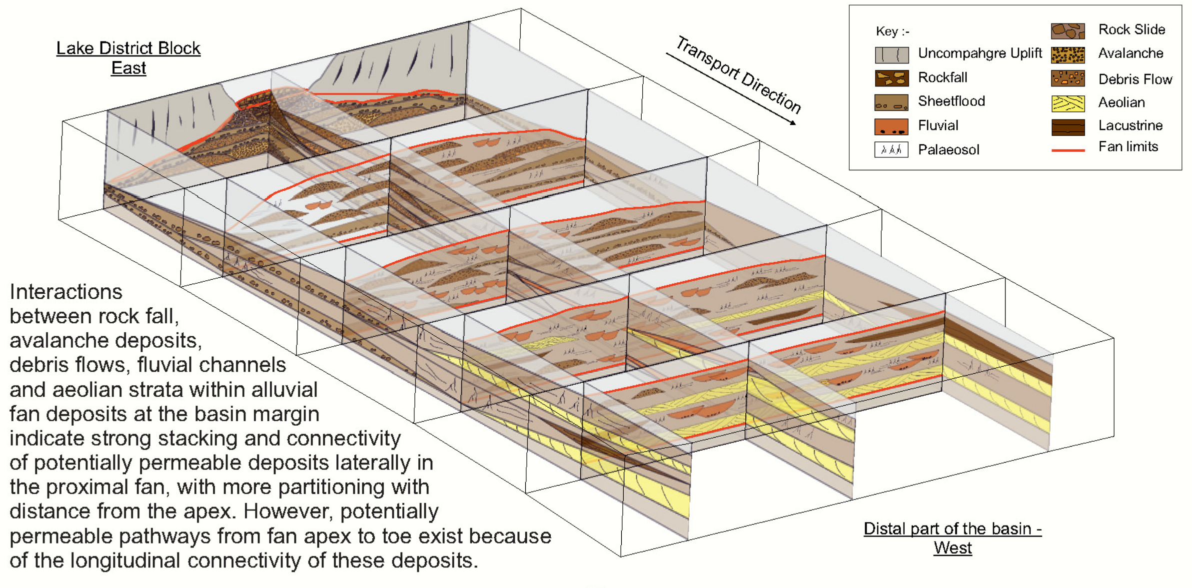




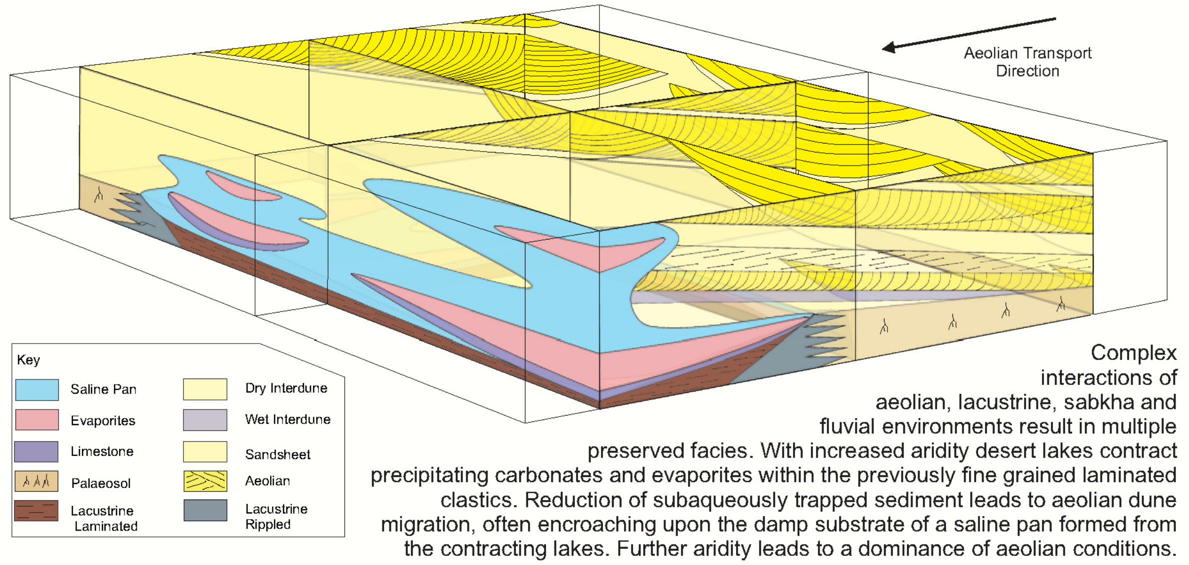
(Top left) *Location of the Colorado Plateau with positions of basins and uplifts within the Plateau, including the Paradox Basin, and structures that define the edges of the Plateau.* **(Top right)** *Location of the Paradox Basin, including structures and uplifts and locations of field studies.* **(Bottom left)** *Field locations for Case Study 1: Fluvial-aeolian Interactions of the Kayenta Fm.* **(Bottom right)** *Field locations for Case Study 2: Aeolian-evaporitic Interactions of the Cedar Mesa Sandstone*

Interactions & Fluid Migration

Interactions between architectural elements and facies assemblages in different arid environments have the potential to connect permeable and non-permeable pathways through those environments, effecting both reservoir quality at the smaller scale and fluid migration pathways at the basin scale.

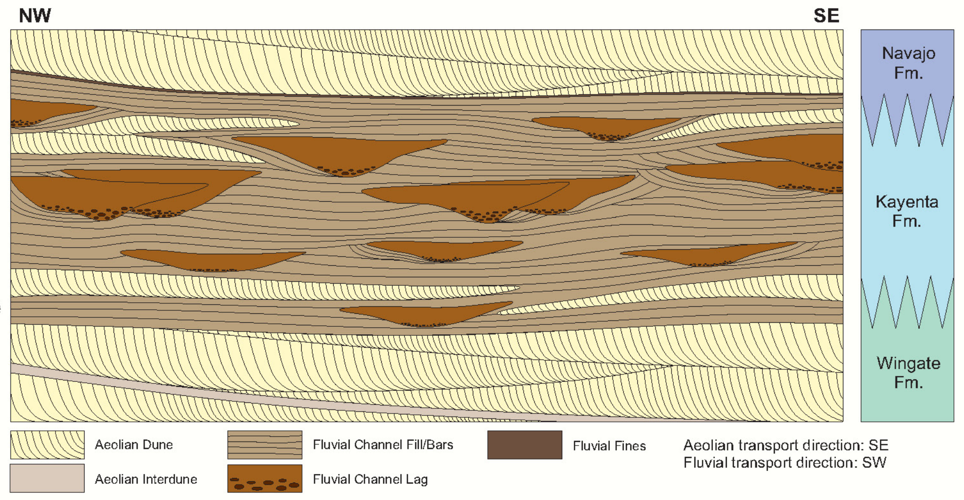


Interactions between rock fall, avalanche deposits, debris flows, fluvial channels and aeolian strata within alluvial fan deposits at the basin margin indicate strong stacking and connectivity of potentially permeable deposits laterally in the proximal fan, with more partitioning with distance from the apex. However, potentially permeable pathways from fan apex to toe exist because of the longitudinal connectivity of these deposits.



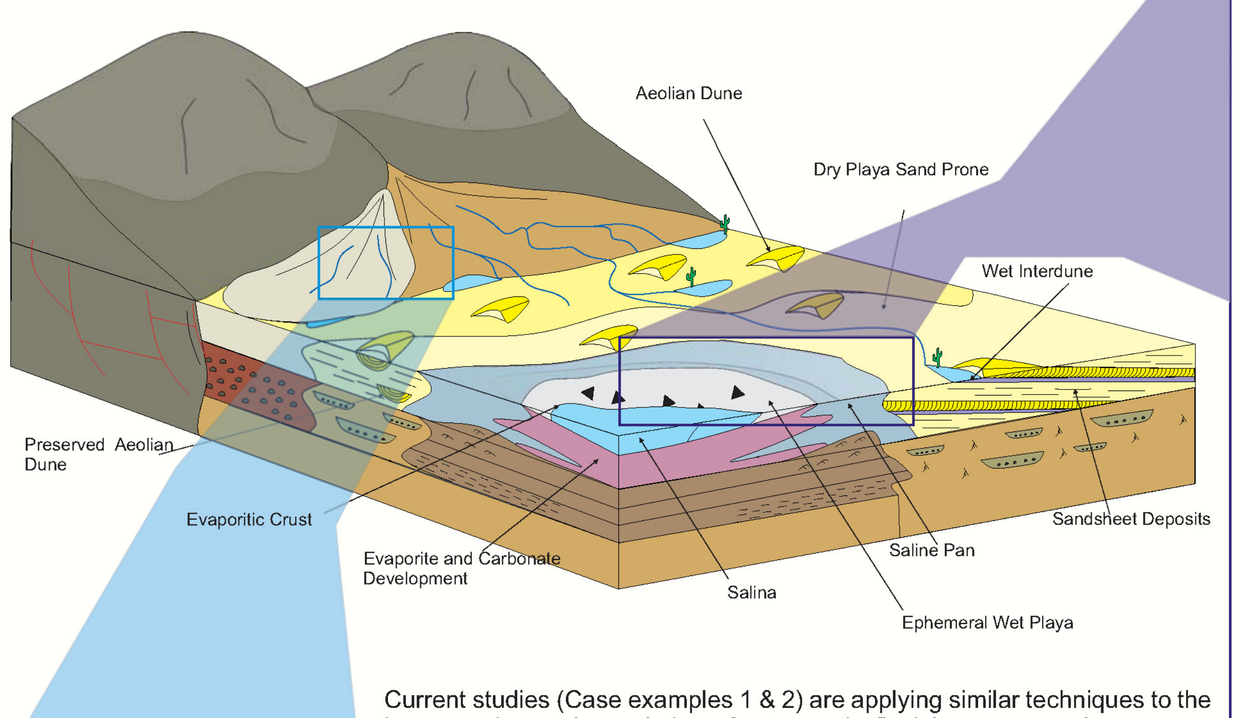
Complex interactions of aeolian, lacustrine, sabkha and fluvial environments result in multiple preserved facies. With increased aridity desert lakes contract precipitating carbonates and evaporites within the previously fine grained laminated clastics. Reduction of subaqueously trapped sediment leads to aeolian dune migration, often encroaching upon the damp substrate of a saline pan formed from the contracting lakes. Further aridity leads to a dominance of aeolian conditions.

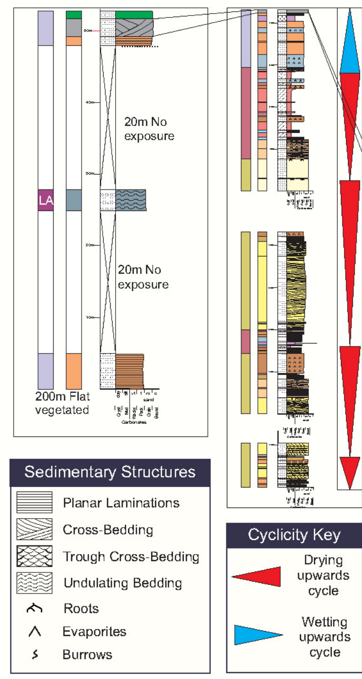
Interactions between the fluvial Kayenta Formation and the underlying and overlying aeolian Wingate and Navajo formations are one system's dominance. A switch in the dominant system takes place quickly and severely limits the vertical extent of interactions. For example, a thin band of fluvial fines of the Kayenta below the well-developed dunes of the Navajo.



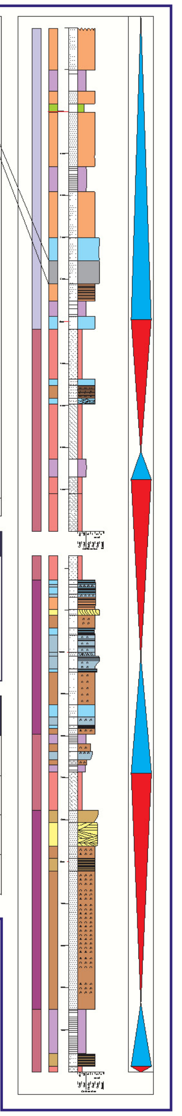
Basin-Scale Relationships

Climatic cyclicity in arid aeolian systems can be used as a correlation tool by identifying wet and drying cycles and correlating on the points of maximum aridity or humidity. This technique has proved valuable in correlating deposits with the wet desert system of the Cedar Mesa Sandstone of the Paradox Basin, Utah (Jagger and Mountney, 1999-2002), and has been extended into the contemporaneous alluvial fan deposits of the Culter Group (Gough and Clarke, 2011—2014).



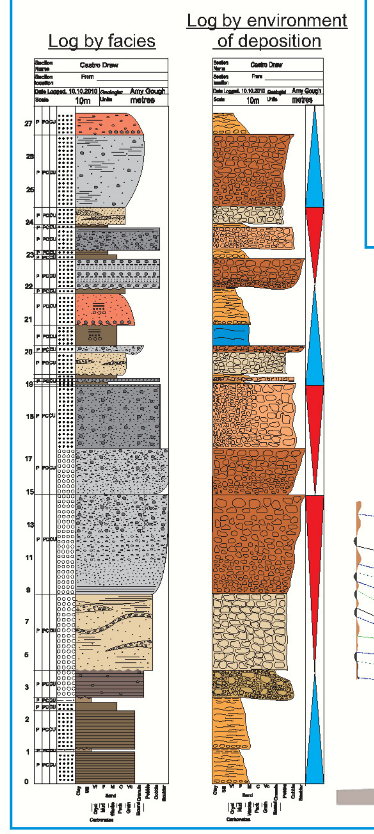


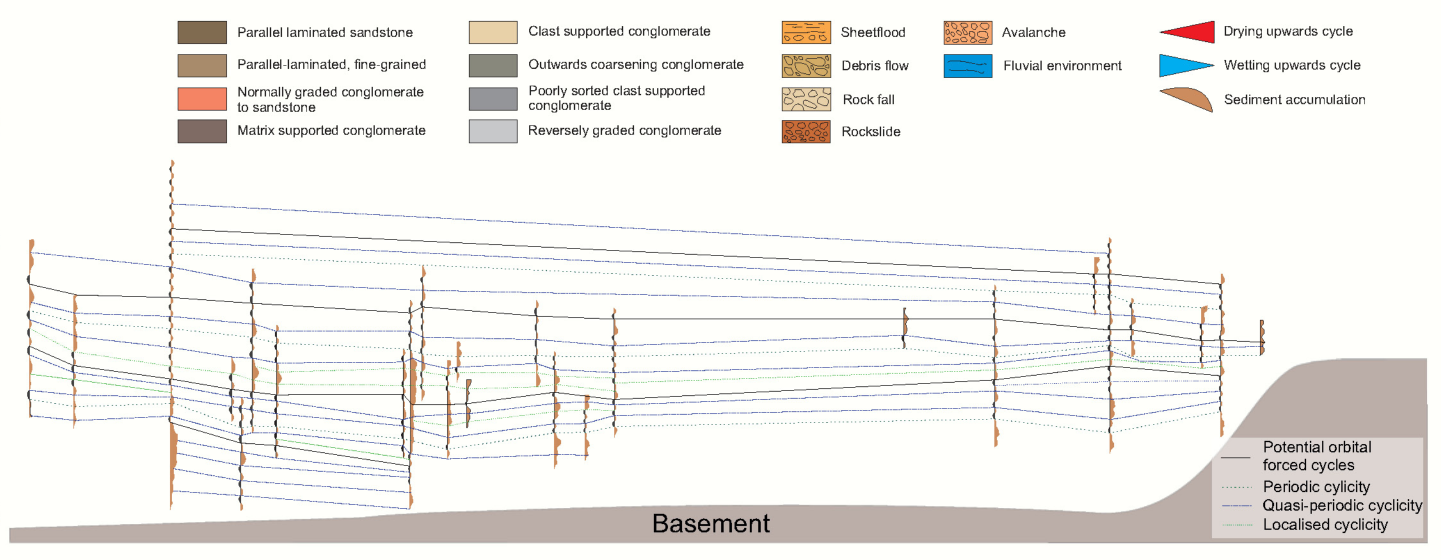
Assoc.	Facies Codes	Environments
AL	Sl,Sr,Sx,Sxe, Lm, Sb, Sbe	Aeolian
SH	G, Lm, Sb, Sbe, Sg, Sge, Sxe	Sabkha
LA	Sb,Sbe, Sg, Sge, Sx, Sl, Su	Lacustrine
FI	Sl, Mm, Sxr, Srr, Lm, Sg, Sge,	Fluvial



Current studies (Case examples 1 & 2) are applying similar techniques to the interpretation and correlation of erg-margin fluvial systems and erg-centre sabkha systems.

Climatic cyclicity occurs on a variety of scales and provides a means of correlating locally and regionally. Larger scale cycles identifiable in the proximal alluvial fans of the Culter Group can be correlated to the erg centre and probably relate to allocyclic controls, but smaller scale cycles are local to the fan and may, in part, result from auto-cyclicity. Further work will investigate correlation from the erg to desert sabkha and the erg to erg-margin fluvial settings.





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Case Study 1: Fluvial-Aeolian Interactions of the Kayenta Formation, Paradox Basin, Utah, USA

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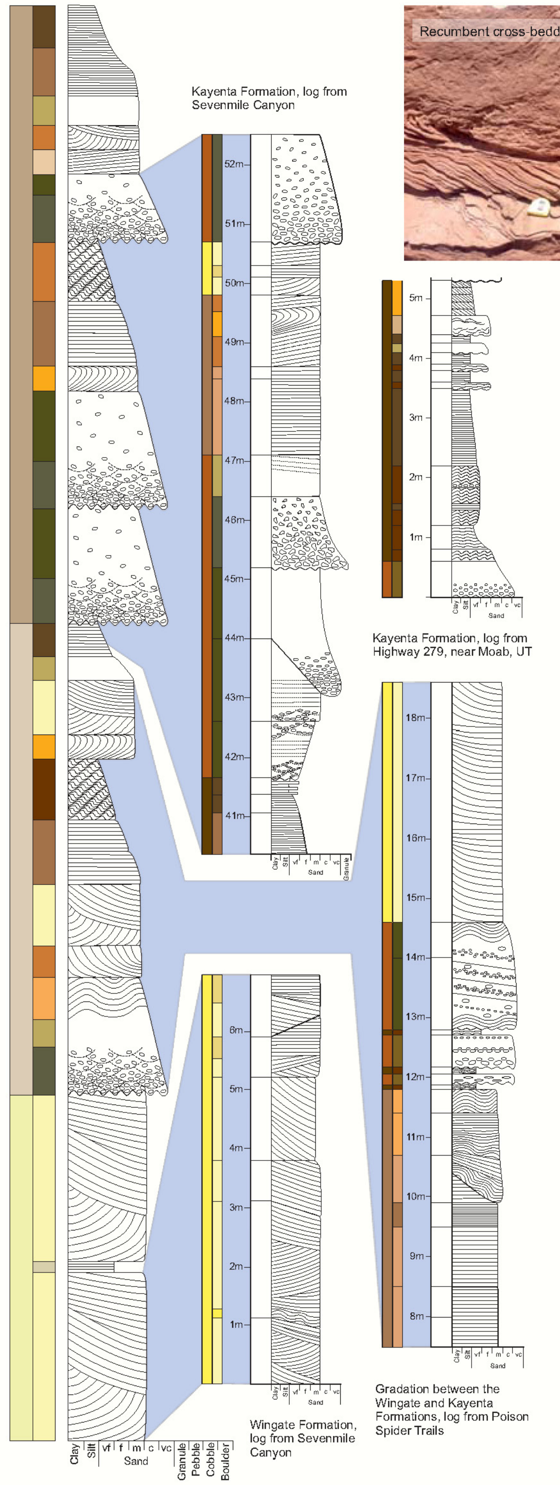
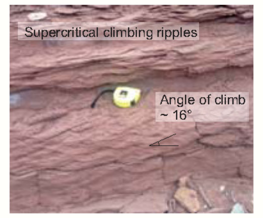
Introduction

The lower Jurassic Kayenta Formation consists of complex interactions between aeolian and ephemeral fluvial sediments. The underlying Wingate, and overlying Navajo formations, of aeolian origin, have gradational, conformable contacts with the Kayenta. Preliminary results and interpretations are presented in the form of sedimentary logs, facies schemes and associations, three-dimensional photogrammetry and facies models, representing the evolution, interactions and dominance of the environments in space and through time as the environment evolves from aeolian to ephemeral fluvial, and back to aeolian.

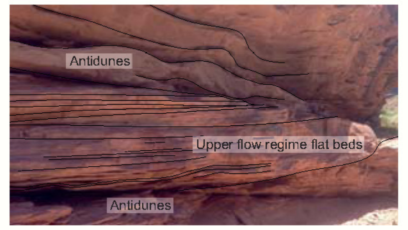
Results

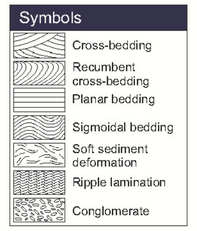




Facies Assoc.	Facies Codes	Interpretation
AD	Smxb, Smwb, Smpb, Sm	Aeolian Dunes
AI	Lm, Sm	Interdunes
FF	Spl, Stpl, Sfrl	Fluvial fines
FCF	Sm, Scb, Spb, Sma, Spl, Srb, Sxb	Fluvial channel fill/bars
FCL	Cms, Ccs, Cm, Sm, Spl	Fluvial channel lag
FO	Spl, Stpl	Fluvial overbank

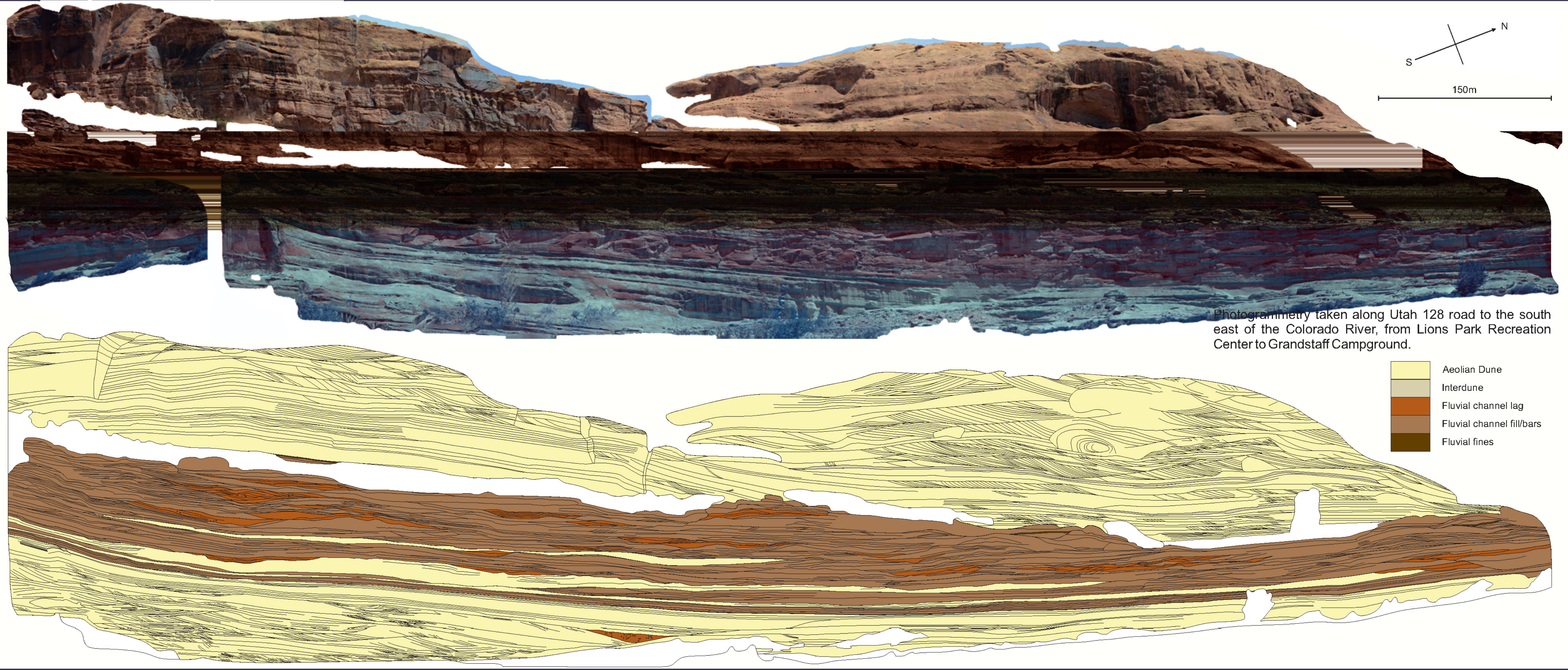
Distinct boundary between the Kayenta and Navajo formations within the gradational system.





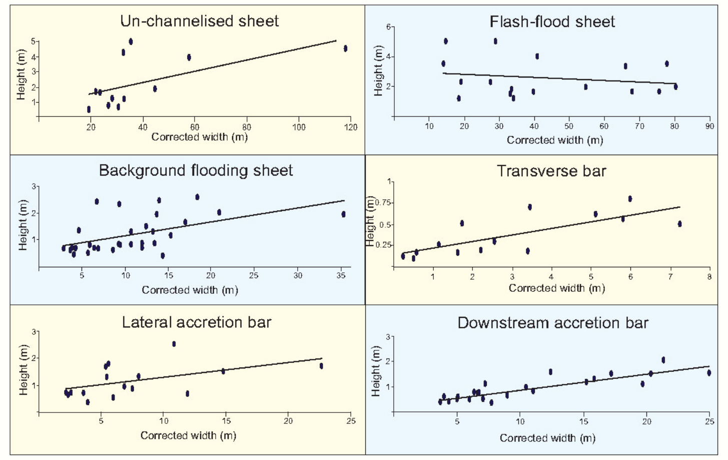
Code	Lithology & Texture	Sed. Structures	Interpretation
Smxb	Orange medium sdst, well sorted, well rounded	Cross-bedding	Wind blown
Smpb	Orange medium sdst, well sorted, well rounded	Planar-bedding	Wind blown
Smwb	Orange medium sdst, well sorted, well rounded	Undulating-bedding	Wind blown
Sm	Orange medium sdst, well sorted. well rounded	Massive	
Sxb	Brown medium sdst, well sorted, well rounded	Cross-bedding - occasional clasts	Lower flow regime
Spb	Brown medium sdst, well sorted, well rounded	Planar-bedding - occasional clasts	Upper or lower flow regime flat beds
Spl	Brown medium sdst, well sorted, well rounded	Parallel laminations	Upper or lower flow regime flat beds
Sfrl	Brown fine/medium sdst, well sorted, well rounded	Ripple laminations	Lower flow regime - migrating current
Stpl	Dark brown siltstone	Parallel laminations	Lower flow regime - suspension fall out
Sma	Orange medium sdst, well sorted, well rounded	Sigmoidal bedding	Upper flow regime - antidunes
Srb	Orange/grey medium sdst, well sorted, well rounded	Recumbent cross-bedding	Lower flow regime - change in current
Cms	Grey medium/v. coarse, poorly sorted, sub-rounded	Mainly massive, crude trough cross-bedding, clasts	High energy flow - non Newtonian (matrix support)
Ccs	Brown v. coarse, poorly sorted, sub-rounded	Massive, abundant clasts	High energy flow

Photogrammetry



Photogrammetry taken along Utah 128 road to the south east of the Colorado River, from Lions Park Recreation Center to Grandstaff Campground.

Discussion



In order to provide representative measurements of architectural elements from the photo-panels, the facing direction of the outcrop (θ), palaeocurrent direction (α) and the stacking/erosion of these elements need to be taken into account (Visser & Chessa, 2000). $C = l(\cos\alpha - \theta)$ can be used to correct measurements of obliquely cut architectural elements, where C is the corrected length, and l is the incorrect measured lengths of the obliquely cut elements.

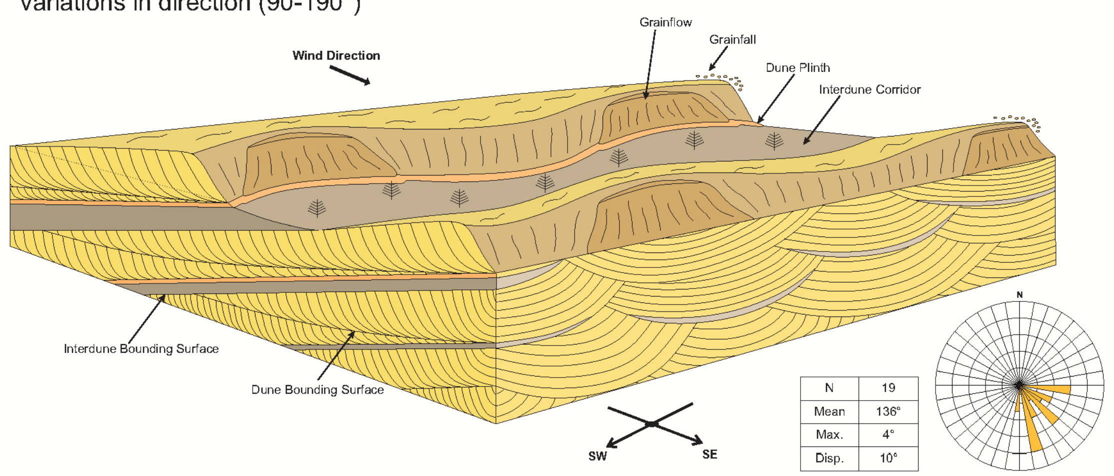
Conclusions and Future Work

The relationships between the fluvial-aeolian sediments of the Kayenta Formation are spatially predictable, and are governed by one system's dominance. A dominant aeolian system limits fluvial sediments to interdune corridors whereas a dominance of the fluvial system restricts aeolian bedforms and preserves extensive ephemeral fluvial sediments. A switch in the dominant system takes place quickly and severely limits the vertical extent of interactions. Future work includes a more regional study of the interactions within the Kayenta Fm., to establish their extent, their relationship to climatic cyclicity, and how they affect reservoir quality.

Interpretation

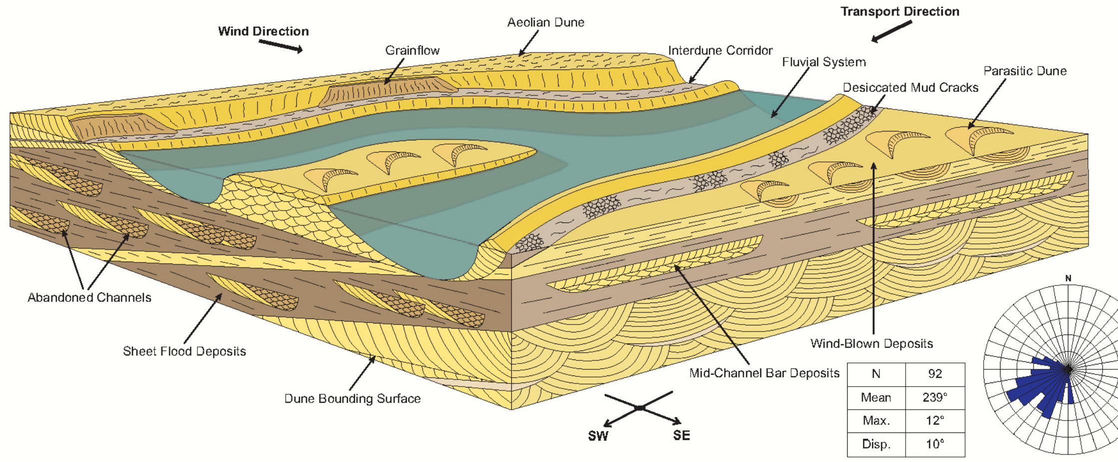
1) Mature Aeolian System

Palaeocurrent values indicate a dominant wind direction towards the southeast, with small variations in direction (90-190°)



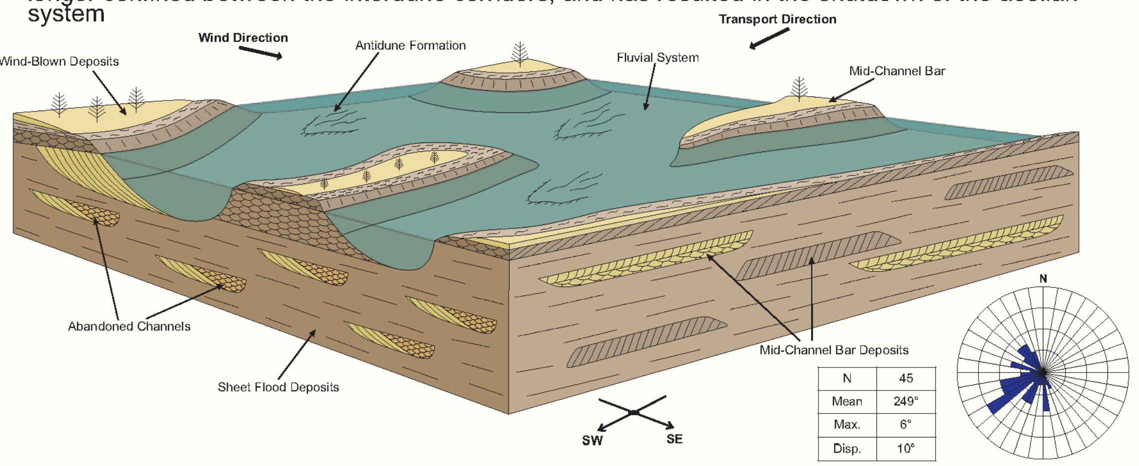
2) Mixed Aeolian and Ephemeral Fluvial System

Immature ephemeral fluvial system confined to interdune corridors, with dominant palaeocurrent towards the southwest



3) Mature Ephemeral Fluvial System

Palaeocurrent is a lot more dispersed due to the dominance of the fluvial system, which is now no longer confined between the interdune corridors, and has resulted in the shutdown of the aeolian system



References:
Visser, C.A., Chessa, A.G., 2000. A new method for estimating lengths for partially exposed features. Mathematical Geology, 32, 1, 109-126
Visser, C.A., Chessa, A.G., 2000. Estimation of length distributions from outcrop datasets – application to the Upper Permian Cutler Formation, Utah. Petroleum Geoscience, 6, 29-36

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Case Study 2: Aeolian-Evaporitic Interactions of the Cedar Mesa Sandstone, Paradox Basin, Utah, USA

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Basin Dynamics Research Group

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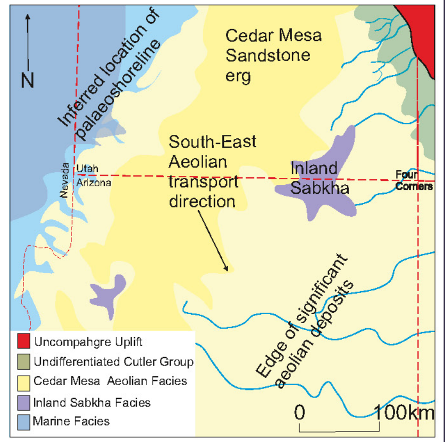
Geological Setting

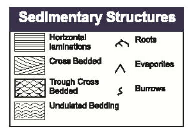
The interactions between coeval clastic and evaporitic systems are poorly understood despite the fact that these environments form important components within many major petroleum systems. Whilst individual elements of the system are well defined, the relationships between environments, and the governing controls upon them, have received little attention. This work presents initial results taken from seven logs across three transects through the Cedar Mesa Sandstone, a predominantly aeolian succession of the Paradox Basin exposed across southern Utah and northern Arizona. In the south-eastern corner of Utah, the aeolian sediments grade into sabkha deposits, which are the main focus of this study.



Data & Results

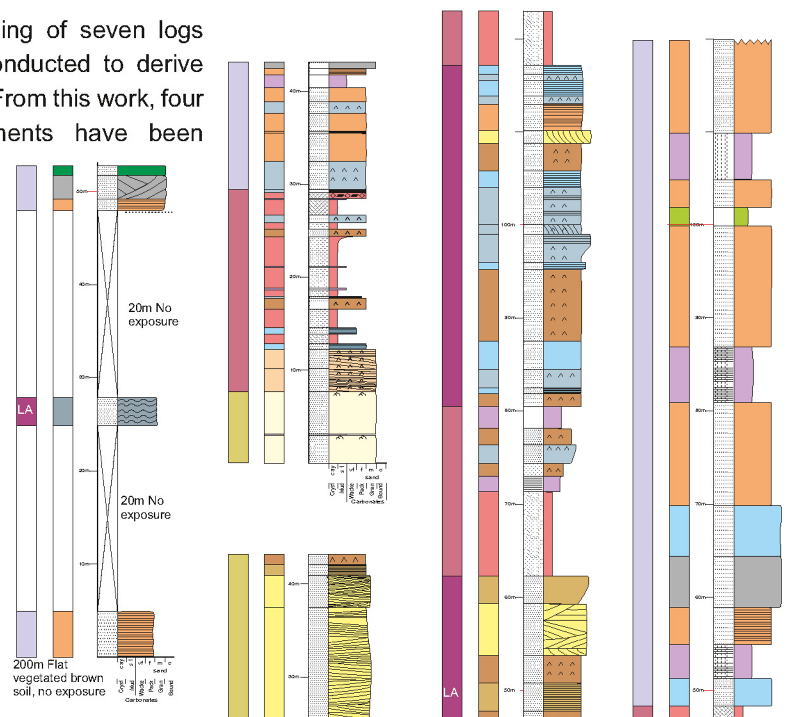
Detailed sedimentological logging of seven logs across three transects was conducted to derive facies and facies associations. From this work, four distinct depositional environments have been determined:

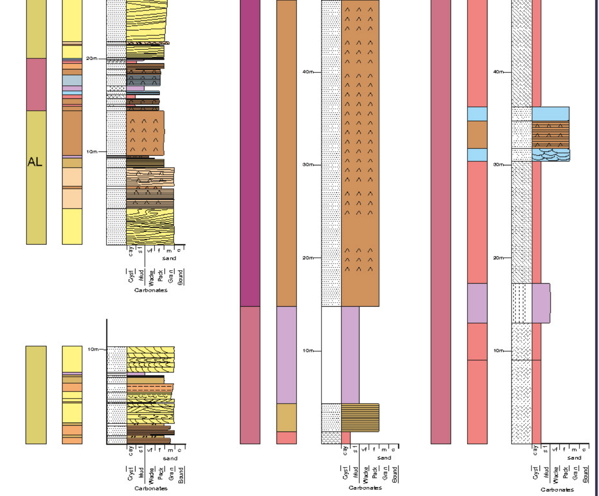
- Lacustrine
- Sabkha
- Fluvial
- Aeolian



Assoc.	Facies Codes	Environments
AL	Sl,Sr,Sx,Sxe, Lm, Sb, Sbe	Aeolian
SH	G, Lm, Sb, Sbe, Sg, Sge, Sxe	Sabkha
LA	Sb,Sbe, Sg, Sge, Sx, Sl, Su	Lacustrine
Fl	Sl, Mm, Sxr, Sm, Lm, Sg, Sge,	Fluvial

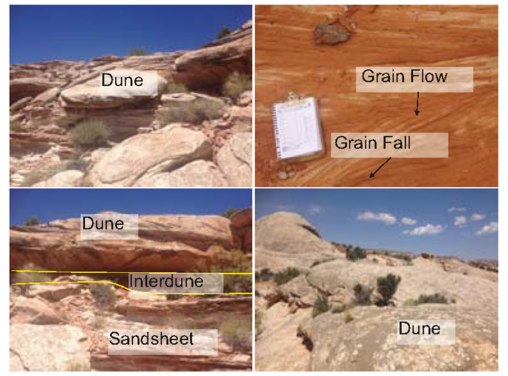
Facies	Texture	Structure
Sl	Fine-medium-grained SANDSTONE. Well rounded and sorted. Mica and quartz rich	Parallel laminated, occasionally massive.
Sr	Medium-grained SANDSTONE. Mottled grey, white and purple bands. Well sorted.	Roots and rhizoliths. Flat mound like profiles.
Sx	Fine-medium-grained orange SANDSTONE. Well sorted and rounded.	Cross-bedded. Large foresets. Grain fall and flow. Soft sediment deformation.
Sxe	Medium-grained SANDSTONE. Highly weathered in places.	Gypsum along cross beds & bounding surfaces. Cross-cutting gypsum veins.
Sxr	Medium-grained, light grey SANDSTONE. Quartz rich, high calcite content	Cross-laminated. Blocky and forms as prominent ridge.
Sm	Medium-grained blue green SANDSTONE. Quartz rich, high calcite content	Massive
Su	Fine-grained brown orange, rounded and well sorted SANDSTONE	Undulated laminations
Sb	Fine-very-fine-grained . Mottled dark brown purple SANDSTONE.	Bioturbated/rooted. Often thinly laminated.
Sbe	Fine-very-fine-grained SANDSTONE. Gypsum veins, crystals, crusts and clasts	Occasionally thinly laminated
Sg	Fine-very-fine-grained white grey blue green SANDSTONE. Mottled	Often thinly laminated once crude trough cross bedding present
Sge	Fine-very-fine-grained SANDSTONE. Mottled. Gypsum veins, crusts, clasts & crystals.	Occasionally laminated
G	GYPSUM, occasional fine-grained sediment or clasts. Fiberous. White fresh surface	Euhedral to subhedral under microscope. Crystal regrowth.
Lm	Dark grey purple blue micritic LIMESTONE. Occasional marl bands.	Blocky and massive. No macro fossils, ostracods in thin section.
Mm	Light orange brown MUDSTONE.	Micaceous



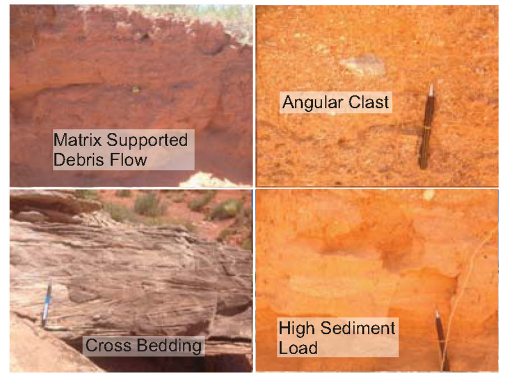


Facies

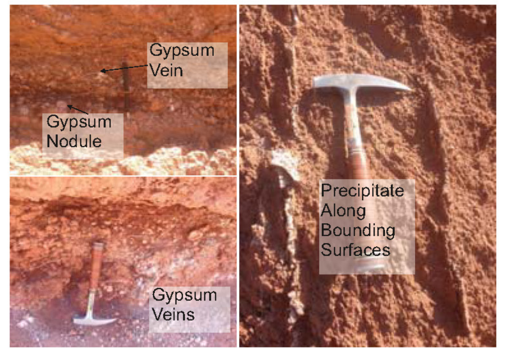
Aeolian



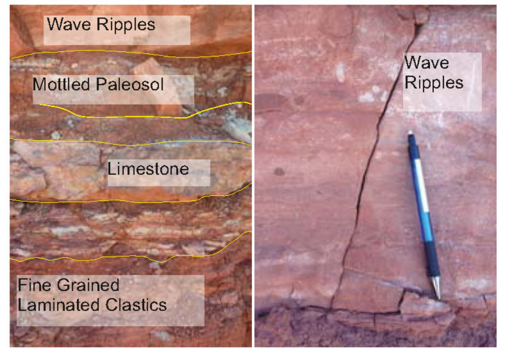
Fluvial



Sabkha

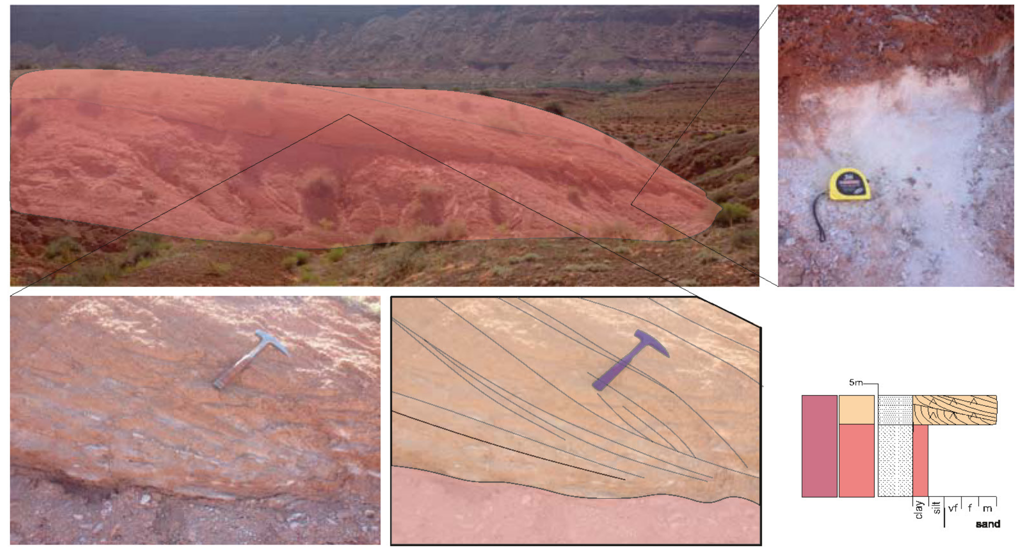


Lacustrine



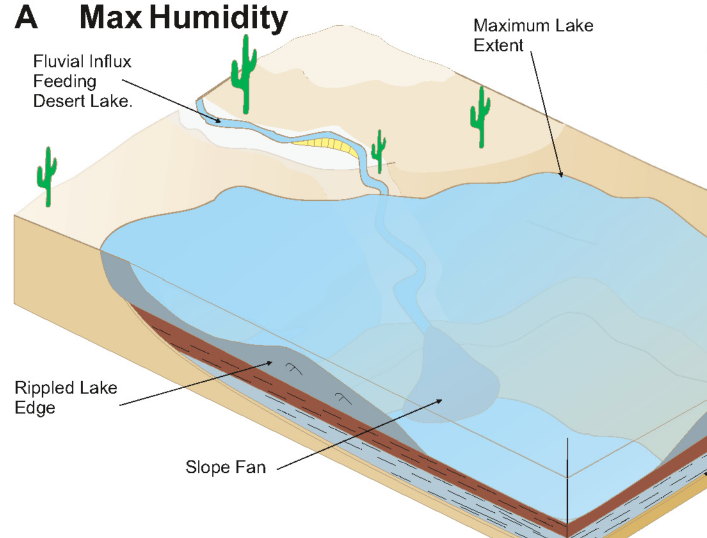
Interactions

Complex interactions of aeolian, lacustrine, sabkha and fluvial environments are present throughout the study area. For example, below shows a medium-grained, cross-bedded sandstone unit on top of a large gypsum bedform. This suggests the sandstone dune has migrated across a damp, solute rich substrate, resulting in concentrated brine being drawn up the bounding surfaces and precipitated. Cross-cutting horizontal lineaments suggest subsequent changes in water level after deposition, demonstrating the complex temporal interactions between aeolian and sabkha facies.



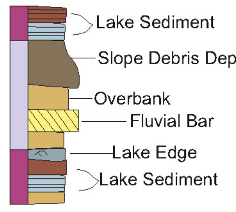
Interpretation

A Max Humidity

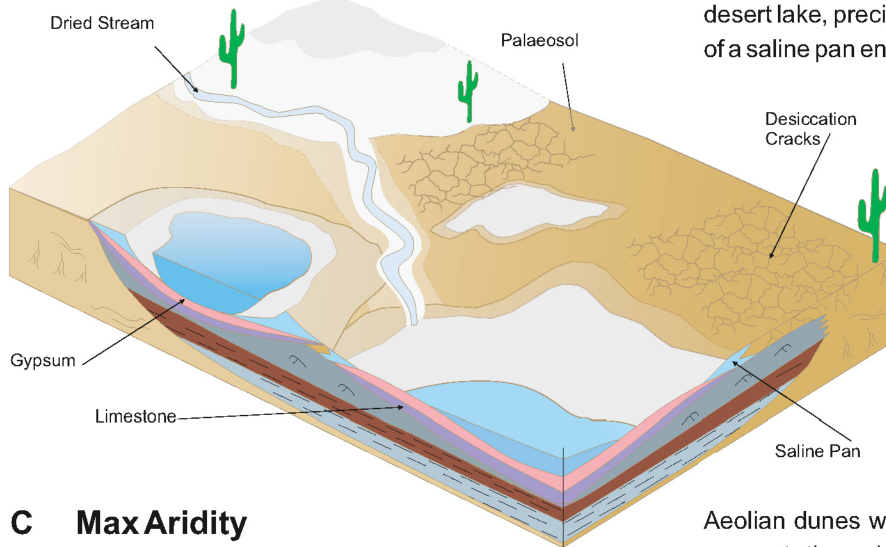


Desert lake environment, long-standing calm waters, enabling laminated sediment to settle out of suspension.

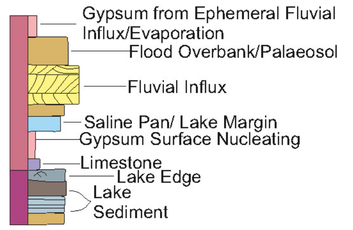
Idealised Logs



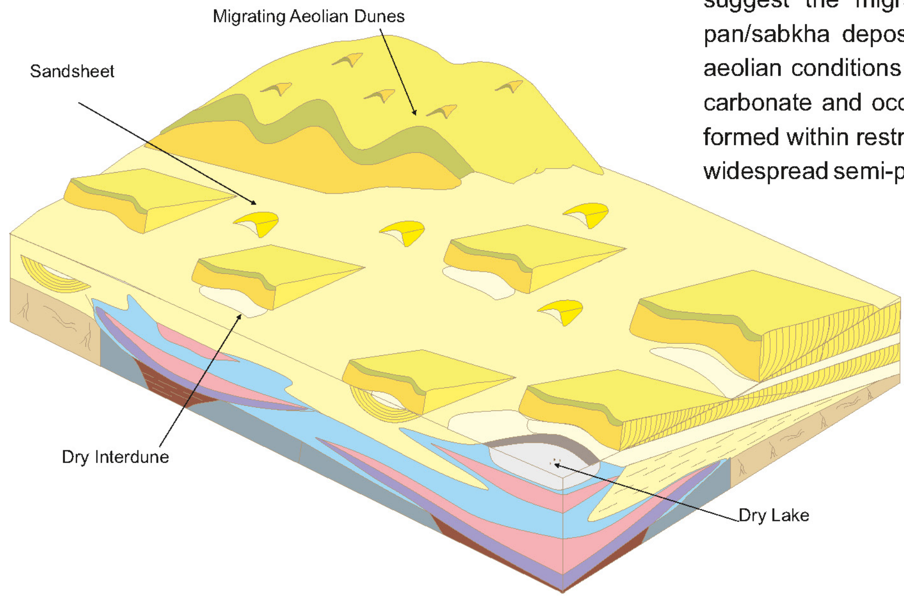
B Drying



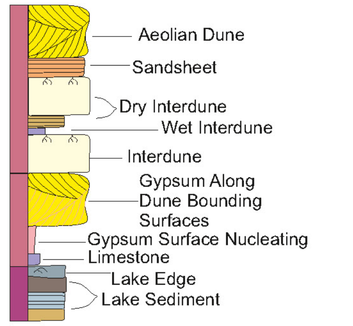
Increased climatic aridity leads to contraction of the desert lake, precipitation of gypsum and development of a saline pan environment.



C Max Aridity

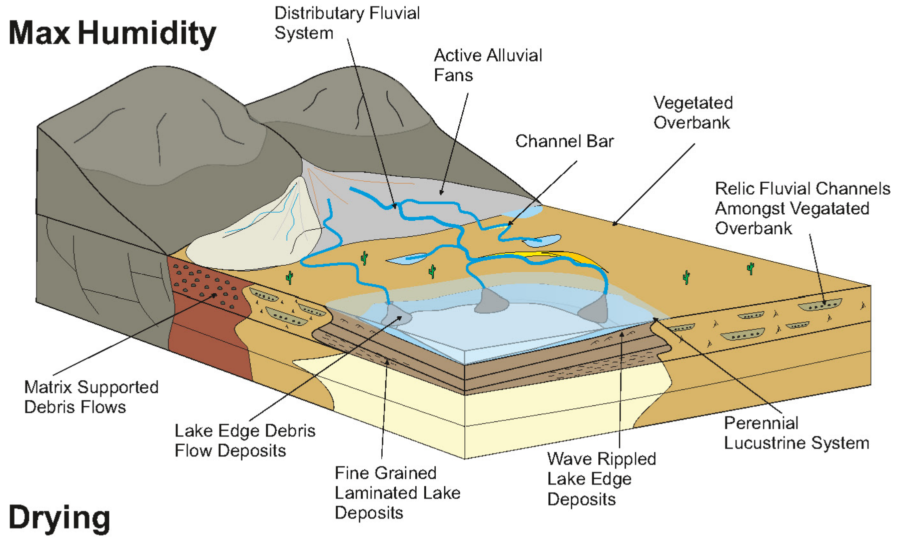


Aeolian dunes with gypsum along bounding surface suggest the migration of dunes over this saline pan/sabkha depositional setting. In other locations aeolian conditions dominate, accompanied by small carbonate and occasional evaporitic deposits, likely formed within restricted interdune ponds, rather than widespread semi-perennial lakes.

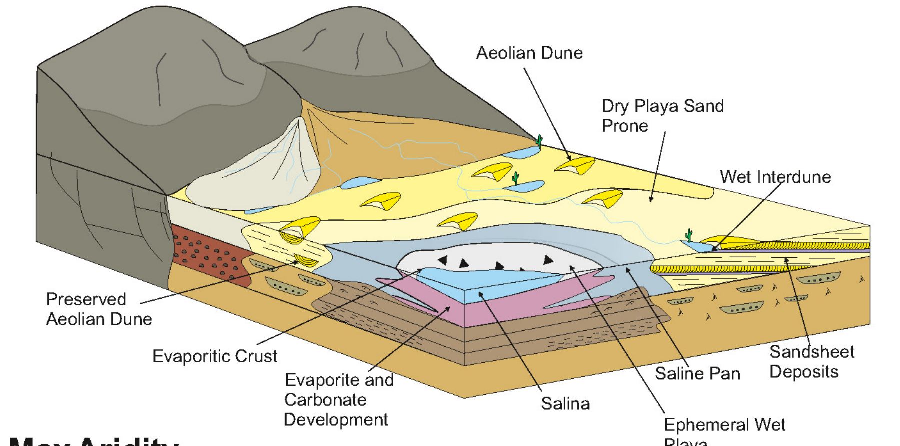


Discussion & Conclusions

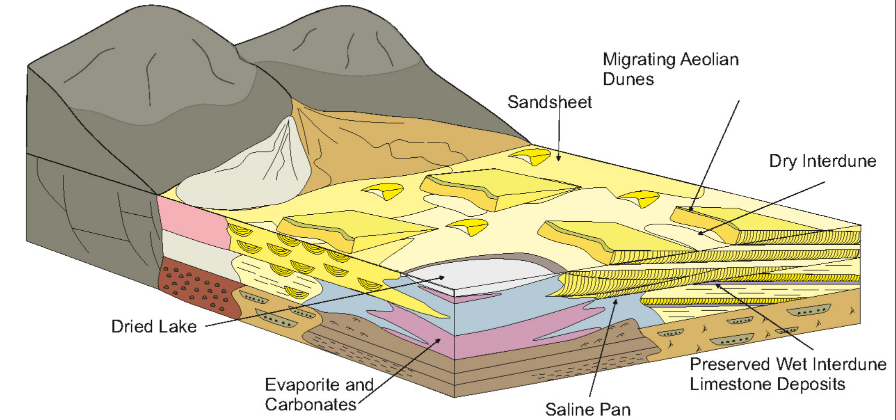
Max Humidity



Drying



Max Aridity



Climatic variation appears to be the dominant control on depositional environment. Increased aridity leads to contraction of desert lakes and sabkha development. Influxes of aeolian facies occur as groundwater levels drop and subaqueously trapped sediment becomes available for transport and deposition. Further work will fully characterise and evaluate the complex interactions between the clastic and sabkha facies. Climatic variations and cyclicity will be determined from detailed study of outcrop and core, allowing for the prediction of facies and interactions when applied to subsurface data.

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