Alluvial Fan Interactions with Adjacent and Contemporaneous Arid Continental Environments: Implications for Basin-Scale Fluid Migration and Charge*

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Abstract

The Cutler Group sediments of the Paradox Basin, western USA, provide unparalleled exposure of the proximal alluvial fan environments through to the environments that dominated the distal extent of the basin. This allows for a comprehensive analysis of the deposits that form the zone of interaction between the proximal and distal parts of the basin. Detailed analysis of the zone of interaction demonstrates that where the alluvial fan is dominated by debris-driven depositional mechanisms, winnowing through interactions with wind-blown or fluid-driven processes of the distal environments results in a relative increase in the permeability of the deposits. Influx of debris-rich flows can also affect small-scale ponds, leading to the development of secondary subaqueous fans that display an elevated permeability. Proximal fan-related fluid-driven systems can also interact with distal aeolian environments. Periodic flooding within the zone of interaction leads to an isolation of the aeolian deposits between fine-grained baffles. Stochastic facies modelling of these interactions outlines the effect they have upon latter-stage fluid flow throughout the basin system. The complex relationships affect potential reservoirs by: 1) interconnecting isolated reservoirs of the distal basin, 2) creating ‘thief zones’ that impact stratigraphic trapping potential of distal reservoirs, 3) providing a bypass route to charge the reservoirs, and 4) introducing baffles into an otherwise productive system. Generic facies models and stochastic simulations derived from this work are applied to the sediments of the Brockram Facies, northern England: a poorly exposed arid continental depositional system dominated by alluvial fan sediments at the basin margin. The application provides significant insight into facies, geometry, and connectivity of the zone of interaction and subsequent implications for fluid migration within this basin

Introduction

Proximal continental deposition is dominated by alluvial fan environments, which are prominent throughout basin development. Towards the distal extent of the basin, the alluvial fan interdigitates with contemporaneous arid environments of deposition. The unique petrophysical properties of the deposits that form this ‘zone of interaction’ have the potential to significantly impact upon the basin-scale hydrocarbon migration pathways. This work considers the Cutler Group sediments of the Paradox Basin, western USA ; they provide unparalleled exposure from the proximal to distal extent of the basin and allow a comprehensive analysis of the deposits that form the zone of interaction between the proximal and distal parts of the basin.

The models derived from these data are used as analogues for the deposits of the Brockram Facies, Eden Valley Basin and East Irish Sea Basin, northern England. The Brockram Facies comprises a Permian-aged basin margin alluvial fan and related fan environments. The deposits of the Brockram Facies are poorly exposed, and the analogue derived from the interpretation of the Cutler Group aids in the interpretation of individual facies, geometry, and flow zone connectivity in the Brockram Facies.

Permian Cutler Group

This work focuses on the Permian sediments exposed within the Paradox Basin, Utah. The Paradox Basin is an intracratonic foreland basin (Trudgill, 2009) located in the Four Corners area (Figure 1). During the Permian Period, the Paradox Basin was positioned on the western margin of equatorial Pangea, resulting in an arid to semiarid palaeoclimate (Blakey and Ranney 2008). The Cutler Group evolves laterally across the basin from the alluvial fan deposits that are exposed around the proximal part of the basin into the segregated depositional packages throughout the distal extent of the basin; these represent a range of contemporaneous arid continental environments

The distal deposits have been divided into four distinct units: the lower Cutler beds, the Cedar Mesa Sandstone, the Organ Rock Formation and the White Rim Sandstone. The lower Cutler beds formed from shallow-marine and coastal deposits (Jordan, 2006). The Cedar Mesa Sandstone represents an intermittently flooded aeolian erg system (Mountney and Jagger, 2004). The overlying Organ Rock Formation represents the deposits of a large-scale terminal fluvial fan environment (Cain and Mountney, 2009). The White Rim Sandstone represents deposition within an aeolian erg. The deposits of the White Rim Sandstone are restricted to the Canyonlands National Park area, with a potentially related outlier around the Castle Valley area of Utah (Kamola and Chan, 1988). The proximal alluvial fan deposits of the Cutler Group are not divided into formations; they grade transitionally into the distal deposits through a zone of interaction, which is referred to informally as the Arkosic Facies.

Cutler Group, Undivided

The proximal deposits of the Cutler Group form a homogenous clastic wedge sourced from the Uncompahgre Plateau; it progrades towards the medial extent of the basin, around the town of Moab, Utah. The deposits represent both fluid-driven and debris-driven depositional mechanisms. The fluid-driven and debris-driven environments evolve throughout the alluvial fan system. The fluvial systems grade into progressively more mature fluvial units. The deposits of these fluvial and debris-driven systems occur intermittently with those of aeolian, lacustrine and marine environments in the distal extent of the basin (Doelling, 2001; Campbell, 1980; Mack and Rasmussen, 1984).

Styles of Interaction

This work has identified the depositional environments from the exposures of the Cutler Group (Figure 2). The work has examined exposures that span from the proximal Cutler Group, Undivided to the subdivided deposits of the distal basin. Multiple and competing depositional environments occurred throughout the deposition of the Arkosic Facies; the dominance of these environments depended on which individual environments dominated in the proximal and distal extents of the basin at the time of deposition. The styles of depositional interaction between these competing environments resulted in the deposition of varied facies assemblages

When the climate was predominantly more humid, there is evidence of an increased amount of debris-driven deposits controlling the alluvial fan system. The debris-dominated environments often interacted with distal aeolian depositional systems; this results in a degree of wind-driven winnowing of the clast-rich deposits (Figure 3a). The process of wind winnowing resulted in the removal of the fine-grained matrix, superimposing a clast-supported architecture throughout the deposits. Within the proximal Cutler Group sediments the palaeocurrent data indicate a southwest trend of these debris-driven flows. The palaeowind of the aeolian sediments is perpendicular to the debris-driven flows. As a result of this, the winnowing is extensive along the debris-driven flow front and the sides of the debris-flow system. As the top of the debris-driven flow was exposed for an extended period of time, it was also often winnowed.

The debris flows also interacted with fluvial systems within the distal part of the basin (Figure 3b). This interaction led to a degree of infiltration of the fluvial waters into the coarse-grained flow front, resulting in water-driven winnowing of these debris-rich deposits. This process removed a proportion of the matrix sediments. However, this infiltration of water resulted in an increase in the hydrostatic pore pressure of the mud-grade component of the matrix. As a result of this, the energy of the fluvial systems was not high enough to facilitate the removal of the mud-grade portion of the matrix which left a residue between the clasts. The observed palaeocurrent of the fluvial system was again perpendicular to the southwest- trending debris-driven alluvial fan system. The cross-cutting effect of the fluvial system also resulted in the restricted growth of the fan environment.

Where the alluvial fan system interacted with distal lacustrine-ponds, which developed within depressions on the basin floor, coarse-grained subaqueous fans were deposited along the margin of the lacustrine body (Figure 3c). The reworking of the debris-rich sediments by lacustrine processes resulted in reverse grading of the deposits, with a coarser grained flow front. The coarse-grained subaqueous fans occur intermittently within the parallel-bedded deposits that dominated deposition in the distal extent of the lacustrine-pond environments.

During relatively more arid climatic conditions, and mainly throughout the wetting upwards or drying upwards stages of the absolute climatic cycle, fluvial systems began to dominate the fan system. These systems interacted with the environments of the distal extent of the basin. Where the distal part of the basin was dominated by an aeolian system, that area was commonly flooded, rapidly and ephemeral, by the proximally sourced fluvial deposits (Figure 3d). This flooding caused an increase in the amount of fine-grained deposits throughout the dominantly aeolian sandstones. The intermittent flood events also fed long-standing wet interdunes within the system.

In a similar fashion to the infiltration of debris-driven flows into lacustrine-pond settings, the fluvial systems also intermittently fed these standing water bodies (Figure 3e). As the sediment-rich flows entered the lacustrine ponds, they deposited small-scale subaqueous fans. The coarse-grained component of the sediment-rich flow was reworked and deposited in proximity to the lacustrine-margin. The deposits fine with distance from the lacustrine system edge. As the system developed, it led to a temporal build-up of the lake-margin fans.

When the climate reached the point of maximum aridity within the absolute climate cycle, the alluvial fan was forced into a state of retrogradation. This resulted in a stunting of the flows that fed the alluvial fan system and consequently promoted the development of aeolian systems throughout the proximal extent of the basin.

Aeolian systems often provide a sediment source for lacustrine environments that occur within the distal extent of the basin. As a result of this, the lacustrine deposits are relatively more sand-grade than the typical mud-grade lacustrine deposits (Figure 3f).

Throughout the deposits of the Early Permian Period, there is evidence of several marine incursions into the Paradox Basin. As a whole, these shallow-marine incursions dominated the distal extent of the basin, but there was occasional flooding throughout the alluvial fan and fan-related depositional system.

Fluid Flow in the Zone of Interaction

Complex sedimentary relationships occur within the zone of interaction between the proximal alluvial fan environment and the deposits of the distal extent of the basin. Where the proximal debris-driven alluvial fan environment becomes winnowed by the aeolian systems of the distal extent of the basin, there is an increase in overall permeability throughout both the snout and top of the debris-rich deposits (Figure 4). As the debris flows stand proud against the basin floor, the winnowed zone is often juxtaposed against younger basin fill. As a result of this, the effect of the winnowed horizon on fluid flow persists temporally. This increase in permeability around the fan edge and on the top of the debris-rich deposits leads to the development of outwards migration pathways and a potential bypass to charge distal reservoirs.

Where the debris-rich deposits interact with distal fluvial deposits, the water-driven winnowing reduces the degree of matrix within the deposits and superimposes a clast-supported architecture throughout the debris flow snout (Figure 4). By contrast to the wind-driven winnowing, the top-extent of the flow has a reduced amount of winnowing. This leads to an elevated permeability throughout the snout architectures and the potential development of flow pathways between the proximal and distal parts of the basin. As these debris flows stack through time, this can lead to an outwards migration pathway away from otherwise permissible reservoirs in the distal part of the basin.

Where these debris-rich deposits influx lacustrine systems, they lead to a reworking of the debris-rich flows (Figure 4). This reworking leads to the initial deposition of the coarser-grade component of the flow. After this initial deposition, the finer-component of the flow is held in suspension within the standing water of the lacustrine system, and subsequently it settles out gravitationally on top of the coarser deposits. This results in a basal increase in permeability around the edge of the lacustrine system. This increase in permeability can persist as the coarse subaqueous fans build temporally, leading to a potential outwards migration pathway, or the ability to charge potential reservoirs formed in the distal extent of the basin.

Aeolian deposits form known reservoirs within continental basins. The depositional interaction of these aeolian environments with proximally-derived flashy, braided fluvial systems can reduce the efficiency of these reservoirs by increasing the proportion of fine-grained sediment throughout the system (Figure 4). The fluvial systems are often ephemeral, and, therefore, the aeolian systems are flooded on a seasonal basis. This introduction of fine-grained baffles throughout the system causes limitations in otherwise productive fluid flow systems.

Where these fluvial systems influx distal lacustrine-pond environments, small-scale subaqueous fan systems are formed. The fine-grained component of these flows is stunted but is held in suspension within the water body and subsequently settles gravitationally throughout the development of the system. As these fluvial systems are ephemerally-driven, the lacustrine bodies are recharged on an annual basis, leading to a stacking of the subaqueous fans. The fans are relatively permeable but are separated by thin baffles created by the settling of the fine-grained component of the flow (Figure 4).

Where the lacustrine-ponds occur towards the edge of the aeolian erg, they are fed by the sediment carried within the aeolian system. This generates an overprint of a relatively decent reservoir network within the gravitationally settled deposits (Figure 4). Where these interlink with the distal aeolian ergs, it can create an extension of the pre-exiting reservoir. However, the interaction between aeolian and lacustrine environments commonly has little effect on the basin-scale, fluid-flow system.

Periodic marine incursions often flood the environments of the proximal extent of the basin. The marine incursions facilitate the deposition of carbonate lithologies, which create a baffle between otherwise potentially permeable deposits (Figure 4). During the subsequent retreat of these marine systems, fluvial systems begin to dominate, reworking the carbonate material and depositing calcarenite lithologies. Secondary alteration of these calcareous deposits leads to a mass reduction of potential permeability.

Application to the Brockram Facies

The Brockram Facies is a Permian-aged alluvial fan system that was deposited throughout the Permo-Triassic Eden Valley and East Irish Sea basins of northern England during a time of relatively high aridity (Burgess, 1965). This work combines limited data collected from outcrop with subsurface study. The model constructed from the data collected from the Cutler Group of the Paradox Basin can be applied to these poorly exposed deposits in England to assess the effects of fluid flow on the basin system as a whole. The model allows for flow zones to be predicted across the Brockram Facies deposits, especially along potentially winnowed horizons. The analysis of core data from the Brockram Facies has led to the development of a preliminary facies scheme, which fits the scheme that has been developed for the Cutler Group. The interpretation of the depositional system of the Brockram Facies is ongoing.

Conclusion

The Permian-aged deposits of the Paradox Basin, western USA, are formed from a proximal, undivided clastic wedge and distal, segregated depositional packages. The proximal deposits have been interpreted as a large-scale, arid alluvial mega-fan, whereas the distal depositional systems grade between shallow-marine, aeolian, and fluvial environments. The deposits of the transitional zone between the proximal and distal extent in the Paradox Basin is informally termed the Arkosic Facies, and the interacting sedimentary environments within this zone led to the formation of unique sedimentary architectures. When the alluvial was dominated by debris-rich flows, the deposits often became winnowed by contemporaneous depositional environments in the distal extent of the basin. The process of both wind- and fluvial-driven winnowing resulted in the removal of the fine-grained component of the matrix of the debris-rich deposits. When the alluvial fan was dominated by fluid-driven flows, the fluvial systems often flooded the distal depositional environments, leading to the shut-off of sediment supply and environment development. When lacustrine systems developed throughout the distal portion of the basin, in-fluxing flow events led to the development of subaqueous fans.

The deposits of the zone of interaction can have an effect on basin-wide fluid flow. The relationships affect potential reservoirs by: 1) interconnecting isolated reservoirs of the distal basin, 2) creating ‘thief zones’ that impact basins, 3) providing a bypass route to charge the reservoirs, and 4) introducing baffles into an otherwise productive system. Understanding the conditions under which these relationships occur can aid in the interpretation of flow dynamics in poorly-exposed proximal continental basins such as the East Irish Sea basin in northern England.

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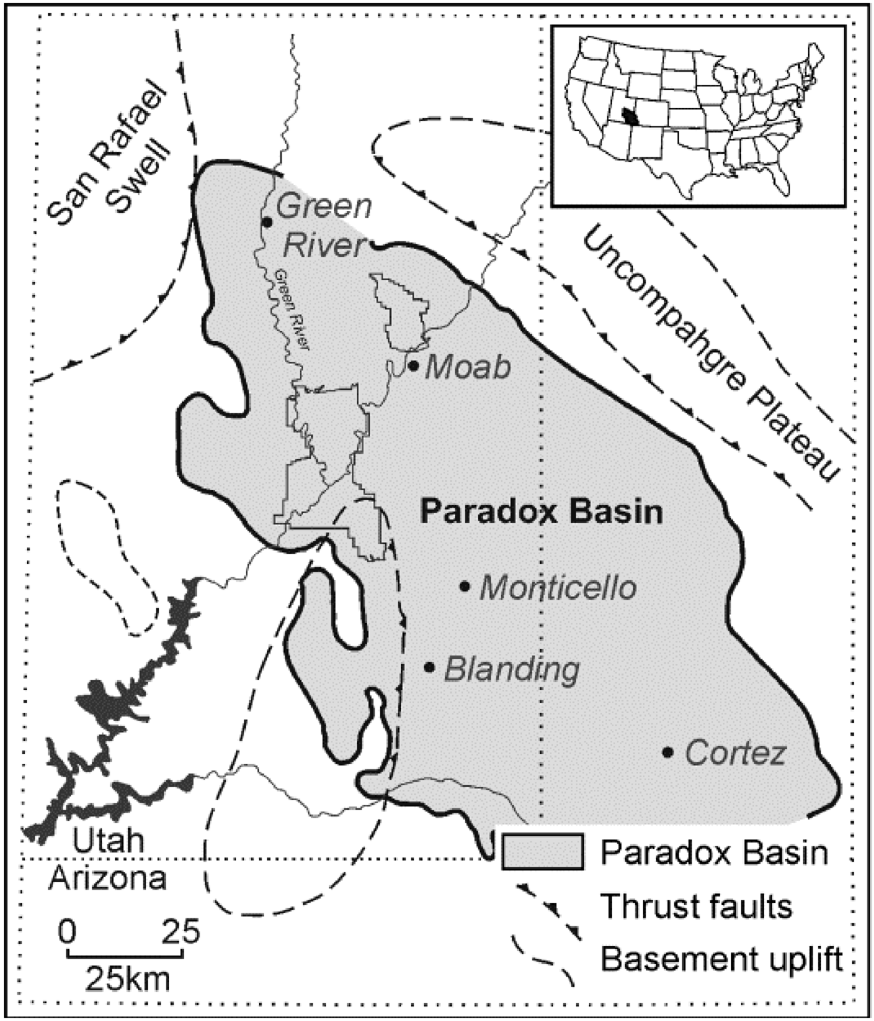
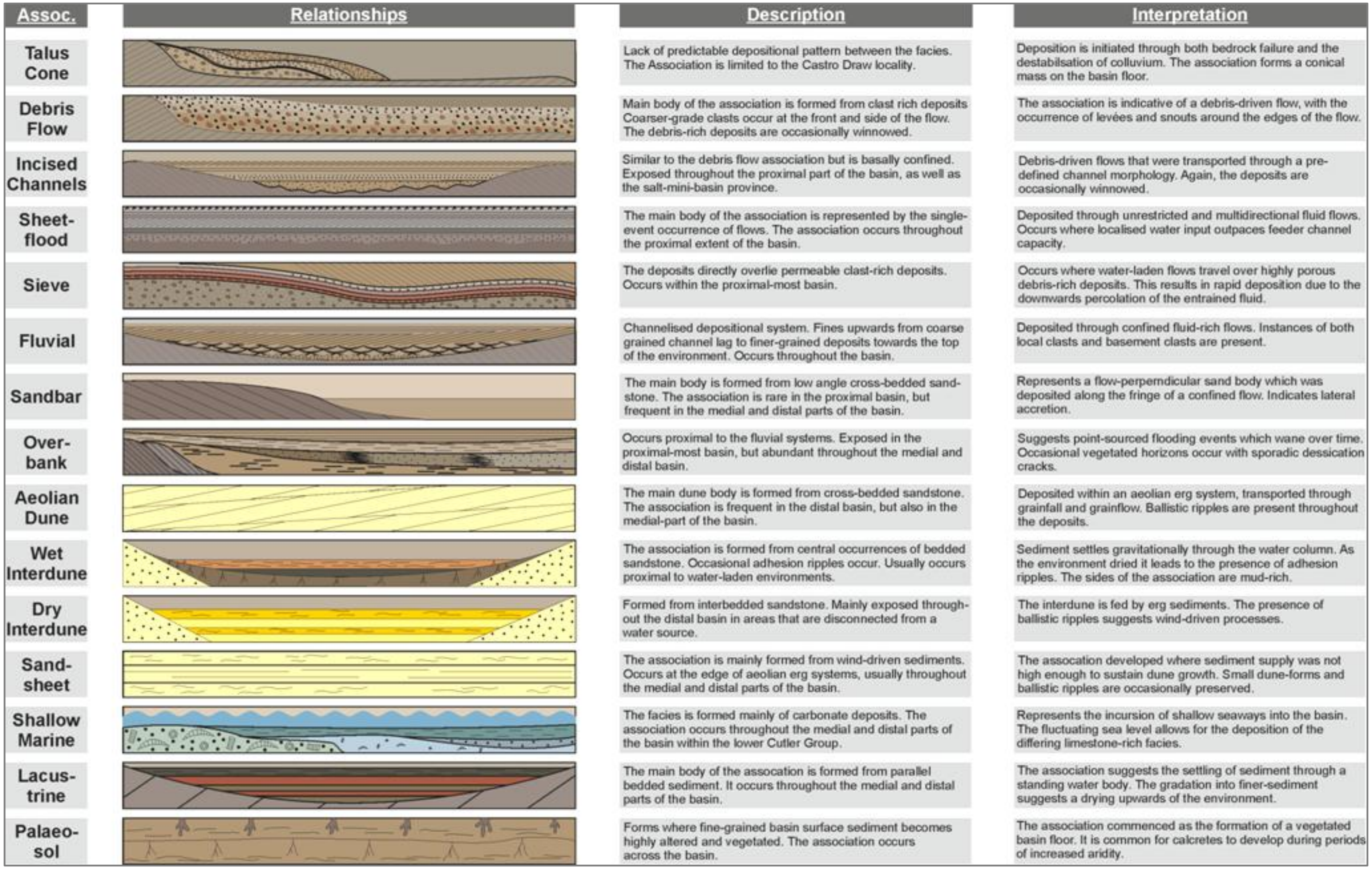


Figure 1. Location map of the Paradox Basin, western USA (after Nuccio and Condon, 1996).



Assoc.	Relationships	Description	Interpretation
Talus Cone		Lack of predictable depositional pattern between the facies. The Association is limited to the Castro Draw locality.	Deposition is initiated through both bedrock failure and the destabilsation of colluvium. The association forms a conical mass on the basin floor.
Debris Flow		Main body of the association is formed from clast rich deposits Coarser-grade clasts occur at the front and side of the flow. The debris-rich deposits are occasionally winnowed.	The association is indicative of a debris-driven flow, with the occurrence of levées and snouts around the edges of the flow.
Incised Channels		Similar to the debris flow association but is basally confined. Exposed throughout the proximal part of the basin, as well as the salt-mini-basin province.	Debris-driven flows that were transported through a pre-defined channel morphology. Again, the deposits are occasionally winnowed.
Sheet-flood		The main body of the association is represented by the single-event occurrence of flows. The association occurs throughout the proximal extent of the basin.	Deposited through unrestricted and multidirectional fluid flows. Occurs where localised water input outpaces feeder channel capacity.
Sieve		The deposits directly overlie permeable clast-rich deposits. Occurs within the proximal-most basin.	Occurs where water-laden flows travel over highly porous debris-rich deposits. This results in rapid deposition due to the downwards percolation of the entrained fluid.
Fluvial		Channelised depositional system. Fines upwards from coarse grained channel lag to finer-grained deposits towards the top of the environment. Occurs throughout the basin.	Deposited through confined fluid-rich flows. Instances of both local clasts and basement clasts are present.
Sandbar		The main body is formed from low angle cross-bedded sandstone. The association is rare in the proximal basin, but frequent in the medial and distal parts of the basin.	Represents a flow-perperndicular sand body which was deposited along the fringe of a confined flow. Indicates lateral accretion.
Over-bank		Occurs proximal to the fluvial systems. Exposed in the proximal-most basin, but abundant throughout the medial and distal basin.	Suggests point-sourced flooding events which wane over time. Occasional vegetated horizons occur with sporadic dessication cracks.
Aeolian Dune		The main dune body is formed from cross-bedded sandstone. The association is frequent in the distal basin, but also in the medial-part of the basin.	Deposited within an aeolian erg system, transported through grainfall and grainflow. Ballistic ripples are present throughout the deposits.
Wet Interdune		The association is formed from central occurrences of bedded sandstone. Occasional adhesion ripples occur. Usually occurs proximal to water-laden environments.	Sediment settles gravitationally through the water column. As the environment dried it leads to the presence of adhesion ripples. The sides of the association are mud-rich.
Dry Interdune		Formed from interbedded sandstone. Mainly exposed throughout the distal basin in areas that are disconnected from a water source.	The interdune is fed by erg sediments. The presence of ballistic ripples suggests wind-driven processes.
Sand-sheet		The association is mainly formed from wind-driven sediments. Occurs at the edge of aeolian erg systems, usually throughout the medial and distal parts of the basin.	The assocation developed where sediment supply was not high enough to sustain dune growth. Small dune-forms and ballistic ripples are occasionally preserved.
Shallow Marine		The facies is formed mainly of carbonate deposits. The association occurs throughout the medial and distal parts of the basin within the lower Cutler Group.	Represents the incursion of shallow seaways into the basin. The fluctuating sea level allows for the deposition of the differing limestone-rich facies.
Lacus-trine		The main body of the assocation is formed from parallel bedded sediment. It occurs throughout the medial and distal parts of the basin.	The association suggests the settling of sediment through a standing water body. The gradation into finer-sediment suggests a drying upwards of the environment.
Palaeo-sol		Forms where fine-grained basin surface sediment becomes highly altered and vegetated. The association occurs across the basin.	The association commenced as the formation of a vegetated basin floor. It is common for calcretes to develop during periods of increased aridity.

Figure 2. Facies associations indicating the varying environments of the Cutler Group, Undivided deposits, grading from debris-driven and fluid-driven flows within the proximal fan environment to aeolian, lacustrine, marine and basin surface deposits within the distal extent of the fan system. The facies associations have been interpreted from facies data.

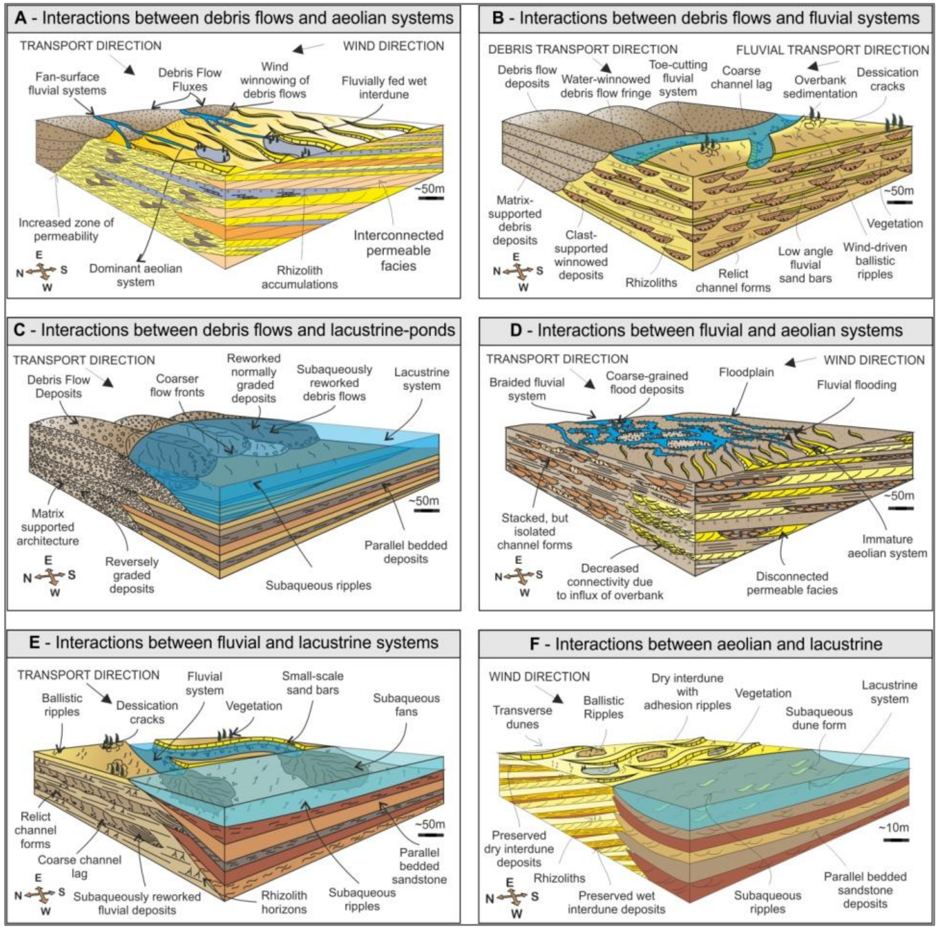


Figure 3. The depositional architectures observed throughout the zone of interaction between the proximal and distal extent of the basin. A) The interactions between proximal debris-driven environments and distal aeolian settings. B) The interactions between proximal debris-driven environments and distal fluvial settings. C) The interactions between proximal debris-driven environments and distal lacustrine bodies. D) The interactions between fluvial and aeolian settings. E) The interactions between fluvial and lacustrine systems. E) The interactions between aeolian and lacustrine systems.

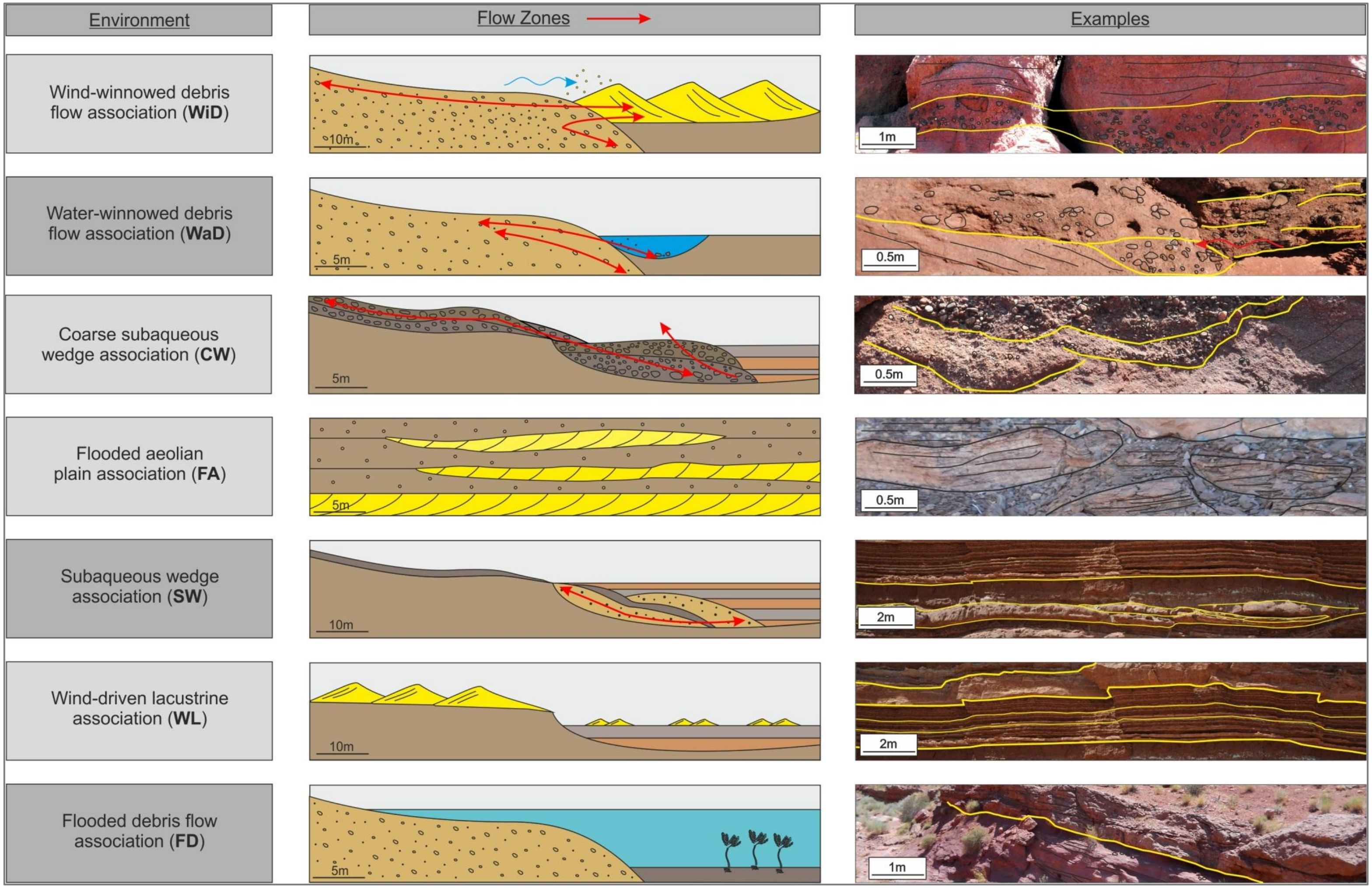


Figure 4. The effect of the depositional systems within the zone of interaction between the Cutler Group, Undivided and the segregated deposits of the distal extent of the basin. The diagram displays how the interaction can affect fluid flow throughout the basin; it also displays examples from outcrop.