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

R. Pettigrew¹, C. Priddy¹, A. Elson¹, K. Johnson², A. Gough¹, S.M. Clarke¹, and P. Richards¹

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

Pettigrew, R.1, Priddey, C.1, Elson, A.1, Johnson, K.1, Gough, A.1, Clarke, S.M.1 & Richards, P.1

1 Basin Dynamics Research Group, Earth Observation & Geoscience, Keele University, Keele, Staffordshire, ST5 5BG, UK. 2 British Geological Survey, The Key Centre, Keyworth, Nottingham, NG12 5GG

Summary

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 petrographic studies, the relationships between deposits of general 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 on sedimentary interactions 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 distribution and preservation of different facies associations within each environment and correlated with both allocyclic and alloeconomic factors.

The sedimentary fill of arid continental basins may comprise deposits of aeolian, fluvial, and evaporitic environments. While the present results of studies of sedimentary interactions between arid environments of the Paradox Basin and Colorado Plateau, USA, have received comparatively little attention despite their potential to affect both basin-scale fluid migration and reservoir quality. We present results of studies on sedimentary interactions 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 distribution and preservation of different facies associations within each environment and correlated with both allocyclic and alloeconomic factors.

Interactions & Fluid Migration

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

Geological Setting

The Paradox Basin, including structures and uplifts and locations of field studies, was examined. The studies are based upon extensive regional fieldwork to examine the distribution and preservation of different facies associations within each environment and correlated with both allocyclic and alloeconomic factors.

Basin-Scale Relationships

Climatic cyclicity in arid and semiarid systems can be used as a correlation tool to identify 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, and correlating those deposits into the contemporaneous alluvial deposits of the Gallup Group (Gough and Clarke, 2011–2014).

Interactions between the fluvial Kayenta Formation and the underlying Wingate Sandstone result in multiple preserved basins. With increased aridity, these basins contain precipitating carbonates and evaporites within the fluvial facies. The fluvial sedimentary systems are the proximal fan, with more partitioning with distance from the apex. Further aridity leads to a dominance of aeolian conditions.
Case Study 1: Fluvial-Aeolian Interactions of the Kayenta Formation, Paradox Basin, Utah, USA

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 Facies Codes Interpretation

<table>
<thead>
<tr>
<th>Facies Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smxhr, Smwh</td>
<td>Orange medium sand, well planar-bedding, sorted, well rounded</td>
</tr>
<tr>
<td>Smhp, Sm</td>
<td>Orange medium sand, well trough cross-bedding, sorted, well rounded</td>
</tr>
<tr>
<td>Smpb, Sm</td>
<td>Orange medium sand, well massive, sorted, well rounded</td>
</tr>
<tr>
<td>Brmp, Br</td>
<td>Brown medium sand, well planar-bedding, occasional sorted, well rounded clasts</td>
</tr>
</tbody>
</table>

Symbols

- Cross-bedding
- Plane bedding
- Sigmoidal bedding
- Soft sediment deformation
- Parallel laminae
- Recumbent cross-bedding

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 & Chesa, 2000). C = I(α - θ) can be used to correct measurements of obliquely cut architectural elements, where C is the corrected lengths, and I is the incorrect measured lengths of the obliquely cut elements.

Interpretation

1) Mature Aeolian System

Aeolian systems exhibit a dominant wind direction towards the southeast, with small variations in direction (239° ± 12°).

2) Mixed Aeolian and Ephemeral Fluvial System

Aeolian-ephemeral fluvial system continued to interdune corridors, with dominant palaeocurrent towards the southwest.

3) Mature Ephemeral Fluvial System

Aeolian-ephemeral fluvial system is to the dominance of the fluvial system, which is now no longer confined between the fluvial corridors, and has resulted in the shutdown of the aeolian system.

Conclusions and Future Work

The environments between the fluvial and 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 windward and leeward excursions of depositional elements. Place and time limits the vertical extent of interactions involved and, as the climate changes, so too does the relationship between the aeolian and fluvial systems, influencing the overall preservation of the facies associations and the resulting sedimentary record.
Case Study 2: Aeolian-Evaporitic Interactions of the Cedar Mesa Sandstone, Paradox Basin, Utah, USA

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. While 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-western corner of Utah, the aeolian sediments grade into sabkha deposits, which is the main focus of this study.

Data & Results

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

- **Aeolian**
- **Fluvial**
- **Lacustrine**
- **Sabkha**

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

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

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

Asian dunes with gypsum along bounding surface suggest the migration of dunes over this saline pan as environmental conditions change. In other localities carbonate and occasional evaporitic deposits, likely formed within restricted inter-dune ponds, rather than widespread semi-perennial lakes.

Discussion & Conclusions

Climate variation appears to be the dominant control on depositional environment. Increased aridity leads to contraction of desert lakes and sabkha development. Influences of aeolian facies occur as groundwetted levels drop and subsequently 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 variation 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.