PS A Quantitative Approach to the Characterization of Sedimentary Architecture in Mixed Eolian-Fluvial Reservoir Successions*

Mohammed A. Al-Masrahy[1] and Nigel P. Mountney[2]

Search and Discovery Article #41669 (2015)**
Posted August 24, 2015

*Adapted from poster presentation given at AAPG 2015 Annual Convention and Exhibition, Denver, Colorado, May 31 – June 3, 2015

[1]Reservoir Characterization, Saudi Aramco, Dhahran, Eastern province, Saudi Arabia (eemaa@leeds.ac.uk)
[2]Earth and Environment, University of Leeds, Leeds, West Yorkshire, United Kingdom

Abstract

Eolian and fluvial processes operate coevally in most desert-margin settings to generate a range of styles of sedimentary interaction that are documented from both modern arid systems and analogous ancient preserved outcrop and subsurface successions. Such styles of system interaction give rise to considerable complexity in terms of sedimentology and preserved stratigraphy. The physical boundary between geomorphic systems in hot deserts is dynamic such that facies belts undertake considerable lateral shift over time with the result that preserved sequence architectures exhibit complexity arising from system interactions that operate at a range of spatial and temporal scales from local to regional. An improved understanding of factors that govern these multiple scales of interaction is important for prediction of preserved stratigraphic architecture and therefore for assessment of fluid-flow properties and for development of well placement strategy in mixed eolian-fluvial reservoir prospects. A database has been developed to record the temporal and spatial scales over which eolian and fluvial events operate and interact in a range of modern and ancient desert-margin settings. Data have been collated using high-resolution satellite imagery, field observation and subsurface data. Ten distinct styles of eolian-fluvial interaction are recognized: fluvial incursions aligned parallel to the trend of linear chains of eolian dune forms; fluvial incursions oriented perpendicular to the trend of eolian dunes; bifurcation of fluvial systems around eolian dunes; through-going fluvial channel networks that cross entire eolian dune-fields; flooding of dune-fields due to regionally elevated water-table levels associated with fluvial floods; fluvial incursions emanating from a single point source into dune-fields; incursions emanating from multiple sheet sources; cessation of the encroachment of entire eolian dune-fields by fluvial systems; termination of fluvial channel networks into playas within eolian dunefields; long-lived versus short-lived styles of fluvial incursion. The database of case-study examples is employed to develop a series of quantitative facies models with which to account for dynamic spatial and temporal aspects of eolian-fluvial system behavior. Models can be used to predict the arrangement of architectural elements that define gross-scale system architecture in a variety of mixed eolian-fluvial reservoirs.

FRG ERG

UNIVERSITY OF LEEDS

1

A Quantitative Approach to the Characterization of Sedimentary Architecture in Mixed Aeolian-Fluvial Reservoir Successions

Mohammed Al-Masrahy[1] and Nigel P. Mountney[1]

1. Fluvial Research Group, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.

Abstract

Aeolian and fluvial processes operate coevally in most desert-margin settings to generate a range of styles of sedimentary interaction that are documented from both modern arid systems and analogous ancient preserved outcrop and subsurface successions. Such styles of system interaction give rise to considerable complexity in terms of sedimentology and preserved stratigraphy. The physical boundary between geomorphic systems in climatic deserts is dynamic such that facies belts undertake considerable lateral shift over time with the result that preserved sequence architectures exhibit complexity arising from system interactions that operate at a range of spatial and temporal scales from local to regional. An improved understanding of factors that govern these multiple scales of interaction is important for prediction of preserved stratigraphic architecture and therefore for assessment of fluid-flow properties and for development of well placement strategy in mixed aeolian-fluvial reservoir prospects. A database has been developed to record the temporal and spatial scales over which aeolian and fluvial events operate and interact in a range of modern and ancient desert-margin settings. Data have been collated using high-resolution satellite imagery, field observation and subsurface data. Ten distinct styles of aeolian-fluvial interaction are recognized: fluvial incursions aligned parallel to the trend of linear chains of aeolian dune forms; fluvial incursions oriented perpendicular to the trend of aeolian dunes; bifurcation of fluvial systems around aeolian dunes; through-going fluvial channel networks that cross entire aeolian dune fields; flooding of dune fields due to regionally elevated water-table levels associated with fluvial floods; fluvial incursions emanating from a single point source into dune fields; incursions emanating from multiple sheet sources; cessation of the encroachment of entire aeolian dune fields by fluvial systems; termination of fluvial channel networks into playas within aeolian dune fields; long-lived versus short-lived styles of fluvial incursion. The database of case-study examples is employed to develop a series of quantitative facies models with which to account for dynamic spatial and temporal aspects of aeolian-fluvial system behaviour. Models can be used to predict the arrangement of architectural elements that define gross-scale system architecture in a variety of mixed aeolian-fluvial reservoirs.

Aim and Objectives

This study comprises three parts. **First,** to quantify the form of geomorphic relationships between dune and interdune sub-environments in both the central and marginal parts of four modern dune fields using the Rub' Al-Khali desert of Saudi Arabia as an example, with overall aim to document how and explain why dune- and draa-scale aeolian bedforms and their adjoining interdunes systematically change form from central to marginal dune-field areas in terms of their morphology, geometry (scale), orientation and style of bedform linkage (i.e. the extent to which interconnected and amalgamated aeolian bedform complexes are developed). Specific objectives of this research are as follows: (i) to assess the geomorphic complexity and variety of dune types present in the Rub' Al-Khali desert; (ii) to demonstrate and quantify types of spatial variation in dune and interdune type and geometry for a series of major dune fields; (iii) to consider how a series of external factors that collectively define the sediment state of the system act to dictate spatial changes in dune and interdune morphology and geometry. **Second,** to propose a generalized framework with which to account for the diverse styles of interaction known to exist between coevally active aeolian-fluvial depositional systems, and to discuss the significance of these interactions for the geomorphological and sedimentological evolution of mixed aeolian-fluvial systems. Specific objectives of this work are as follows: (i) to illustrate the principal types of aeolian-fluvial interaction documented from the world's major dryland systems and to propose a framework for their classification; (ii) to demonstrate how the orientation of fluvial systems relative to the trend of aeolian bed forms present at the leading edge of dune fields controls the nature of aeolian-fluvial system interaction; (iii) to consider the role of open versus closed interdune corridors in controlling the style and distance of incursion of fluvial systems into aeolian dune fields; (iv) to consider how different styles of aeolian-fluvial interaction give rise to complex geomorphic arrangements of landforms and to consider the implications of such arrangements for the paleoenvironmental reconstruction of ancient preserved counterparts. **Third,** to document a case study from an ancient outcropping succession to show the preserved expression of aeolian-fluvial system interactions. This research is significant because the temporal and spatial scales over which processes related to aeolian-fluvial interactions occur are highly varied and complex. Understanding the different interaction styles between the two systems is important in the development of generic facies models to explain the rock record in terms of geomorphic landscape evolution and formative paleoenvironment, and for predicting heterogeneity in preserved subsurface reservoir successions.

Introduction

Significant advances in our understanding of the spatial arrangement of aeolian dune patterns have been made possible through the increasing availability of high-resolution satellite imagery in recent years. Aeolian dune-field patterns are a product of self-organizing systems in which the development of simple or complex distributions of genetically related groups of aeolian bedforms and their adjoining interdunes is characterized by systematic and predictable changes in dune type, size, morphology, orientation and spacing from dune-field centre to dune-field margin settings. Several previous studies have documented spatial variation in bedform type and associated spatial changes in aeolian lithofacies distributions in desert dune fields. However, relatively few studies have attempted to quantitatively document the form of spatial variability of dune and interdune morphology from the centres of aeolian dune-field systems to their margins. Dune fields are not necessarily continuously covered with active aeolian sand dunes and most additionally include other morphological bodies of aeolian-derived or aeolian-related sediment deposits, including interdunes, sand sheets (which lack distinctly recognizable larger bedforms), areas of soil cover, lacustrine systems (e.g. playa lakes), and fluvial systems (typically ephemeral), some developed between active aeolian dunes. Thus, dunes in sand seas, including those in the Rub' Al-Khali, are commonly separated from each other by geomorphic elements whose well-defined shapes are, in part, dictated by the shapes of adjoining dune bedforms of different types. The construction of aeolian dune-field systems and the spatial variation in the form of interdunes and components (e.g. dunes and interdunes) is governed by numerous controlling parameters that dictate sediment state. At a regional scale, the sediment state of aeolian dune fields is defined by separate components of sediment supply, sediment availability and transport capacity of the wind, and together these factors govern where and when aeolian system construction via the growth of dunes occurs. At dune field margins, the physical boundary between geomorphic systems in hot desert is dynamic such that facies belts undertake considerable lateral shift over time with the result that preserved sequence architectures exhibit complexity arising from system interactions that operate at a range of spatial and temporal scales from local to regional. Aeolian and fluvial processes operate coevally in most desert-margin settings to generate a range of styles of sedimentary interaction that are documented from both modern arid and semi-arid environments and analogous ancient preserved outcrop successions.

Data and Methods

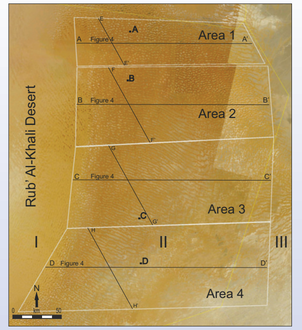
1) Aeolian dune field geomorphology: This study has entailed work in four distinct geographic areas of the Rub' Al-Khali, which collectively cover an area of 73,200 km². These areas were selected for study according to the following specific criteria: (i) chosen locations document spatial changes in the morphology of dunes and interdunes from the central part of a dune field to its outer margin; (ii) public-release satellite imagery used for examination of the dune forms is available for these areas at a resolution that is sufficiently high to enable detailed quantitative measurements to be made regarding various morphological attributes of dunes and interdunes. **Morphological and geometrical attributes relating to 555 dunes and 1415 interdunes** from the 4 selected study areas were collected through examination of satellite imagery provided by Google Earth Pro software and datasets, a business- and scientific-oriented mapping service.

2) Aeolian-fluvial system interaction in modern dune-field margins: This study has analysed the morphological expression and areal distribution of **130 examples** of fluvial–aeolian interaction that have been mapped using high-resolution satellite imagery from **60** desert dune fields around the world. Case study examples have been classified to propose **a framework of ten distinct types of system interaction**. Studied desert systems include the Namib Desert and Skeleton Coast (Namibia), Taklamakan Desert (northwest China), Rigestan Desert (southwestern Afghanistan), Sahara Desert (North Africa), Algodones (southeastern California), White Sands (New Mexico), Rub' Al-Khali and An Nafud sand seas (Saudi Arabia), and Wahiba Sands (Oman), Great Sandy, Great Victoria, and Simpson Deserts (Australia).

3) Ancient preserved aeolian-fluvial system interactions: Outcrop analysis of the upper part of the Wilmslow Sandstone and the lower part of the overlying Helsby Sandstone formations of the Triassic Sherwood Sandstone Group, Cheshire Basin, UK has revealed the preserved stratigraphic expression of several types of ancient fluvial-aeolian interactions.

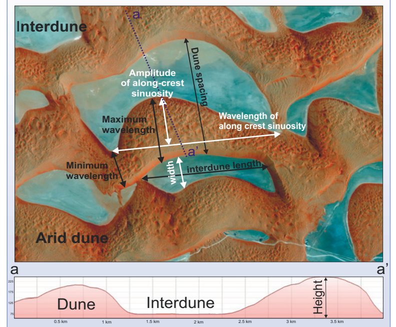
Rub' Al-Khali: Location of Study Area

Map of the Arabian Peninsula showing the location of the Rub'Al-Khali sand sea, dune fields within which are the focus of study.



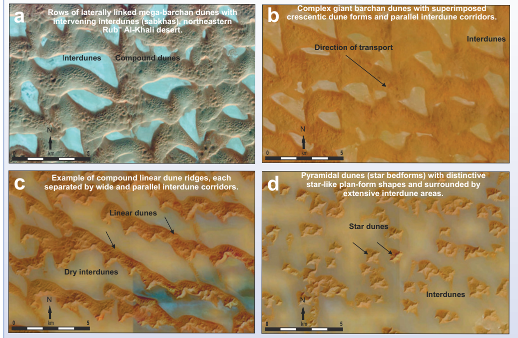
Morphological and geometrical attributes relating to 555 dunes and 1415 interdunes from the 4 selected study areas were collected through examination of satellite imagery provided by Google Earth Pro software and datasets.

Terminology Definitions

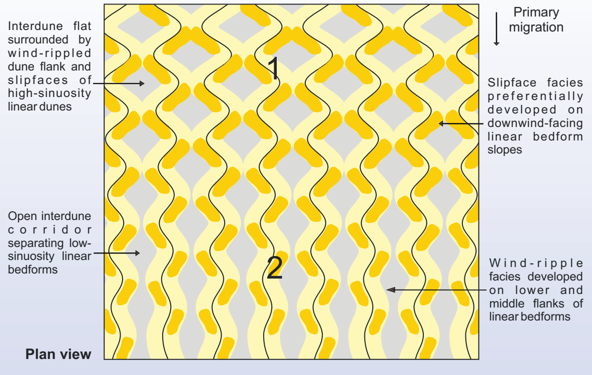


Example of dunes and interdunes of the Rub' Al-Khali, together with an example of the application of measures used in this study to quantitatively define dune and interdune morphology and geometry. Data were tabulated in a relational database to determine common trends that describe spatial change in morphology across the dune field.

Variation of Dune and Interdune Morphology

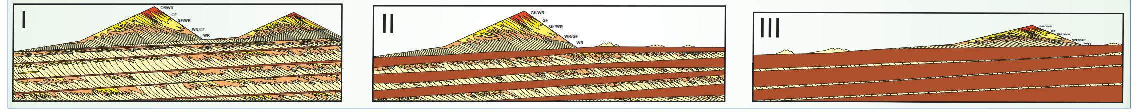


Satellite images from different locations across the Rub' Al-Khali desert depicting typical variations in dune and interdune morphology. Note the contrast in dune form and size between each image (all images have the same scale; see study area maps for locations). (a) Image from the northern part of Study Area 1 showing rows of laterally linked mega-barchan dunes with intervening interdunes (sabkhas); (b) Image from Area 2, showing a region dominated by complex giant barchan dunes with superimposed by crescentic dune forms and parallel interdune corridors. (c) Image from Area 3, showing example of compound linear dune ridges, each separated by wide and parallel interdune corridors. (d) Image from Area 4, characterized by pyramidal dunes (star bedforms) with distinctive star-like plan-form shapes and surrounded by extensive interdune areas.

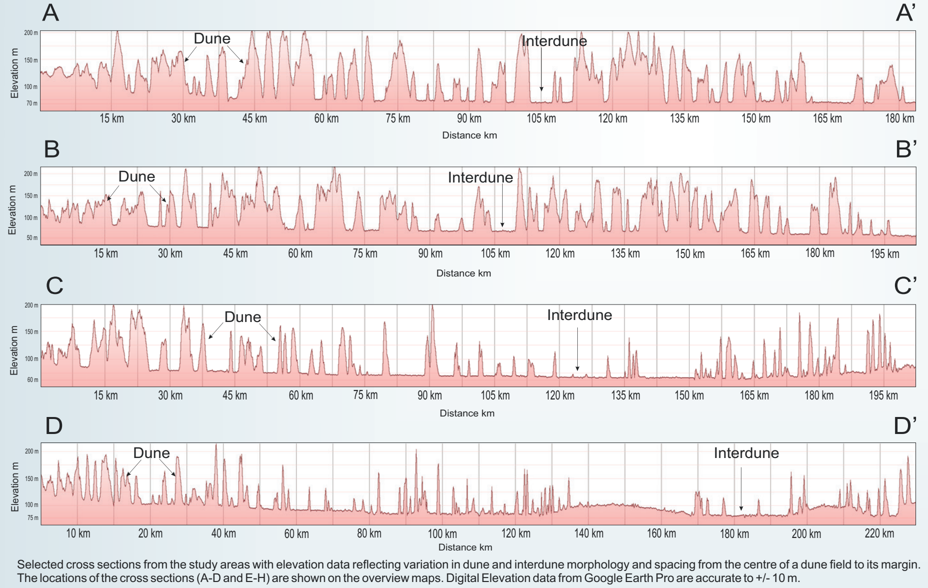


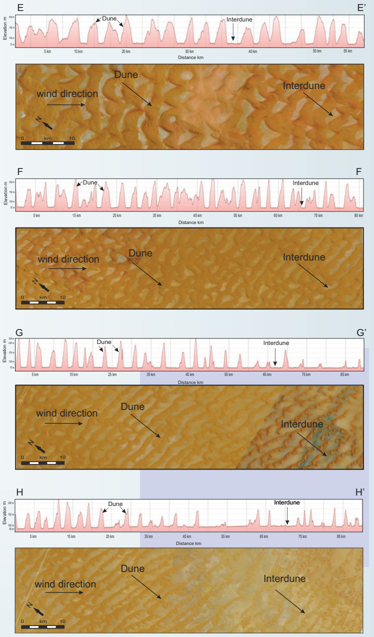
Schematic plan-view illustration of longitudinal dunes that undergo a downwind decrease in crestline sinuosity. Note the change in dune geomorphology in the direction of transport toward the dune-field margin, and the increase in the amount of inter-connectivity of the interdune flats (grey). 1: an area of enclosed interdune flats surrounded by wind-rippled dune flank and slipface facies of high-sinuosity linear dunes (improved likelihood of inter-connectivity of dune slipface architectural elements). 2: an area of open interdune corridors separating low-sinuosity linear bedforms (reduced likelihood of inter-connectivity of dune slipface architectural elements).

Temporal and Spatial Variations in Original Dune and Interdune Morphology Act as a Primary Control on Resultant Preserved Set Architecture.



Digital Elevation Data





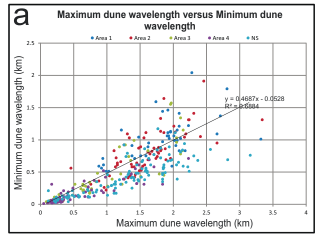
Selected cross sections from the study areas with elevation data reflecting variation in dune and interdune morphology and spacing from the centre of a dune field to its margin. The locations of the cross sections (A-D and E-H) are shown on the overview maps. Digital Elevation data from Google Earth Pro are accurate to +/- 10 m.

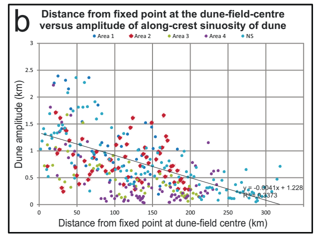
Dunes in the Rub' Al-Khali desert exist in great variety of morphologic types that change systematically across the dune field. Variation in dune form is the primary control on the morphology of adjacent interdunes, especially in dune-field centre regions where the shape and extent of each interdune form is governed and defined by the geometry and spacing of surrounding dune forms. Spatial variation in the arrangement of dune patterns in the Rub' Al-Khali takes the form of gradational transitions from complex to simple bedform types, and a decrease in dune size and an associated increase in interdune size from the centre to the outer-margin areas of dune fields. Such changes reflect the interaction between sediment supply and transport capacity. The availability of sand for dune construction has long been recognized as a primary control on dune morphology, whereby simple barchan dunes tend to evolve in systems where sand supply is limited and therefore are the main bedform type in marginal areas of many dune fields including the eastern part of the Rub' Al-Khali studied here. By contrast, the central and northern part of the studied dune field is dominated by barchanoid dune types, whose presence records a greater sand supply.

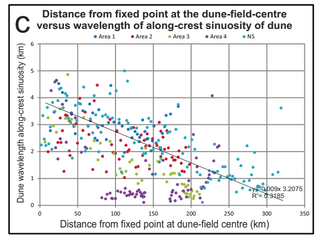
Summary

- The collection of data relating to primary desert dune-field landform morphology has enabled an improved understanding of the sediment system state of the modern Rub' Al-Khali Desert sedimentary system. Observed trends arise as a function of spatial changes in the sediment state of the system whereby sediment supply, the availability of that supply for transport and the sediment transporting capacity of the wind each combine to dictate the geomorphology of dune and interdune forms, which vary from thick accumulations of sands in the form of coalesced compound and complex barchanoid bedforms in dune-field centre settings, to spatially discrete star dunes and small, spatially isolated barchan dunes separated by extensive water-table-controlled interdune flats in dune-field margin settings.
- Observations from this modern dune-field system have enabled the spatial rate of change of morphology of aeolian sub-environments to be characterized and described through a series of empirical relationships.
- Results of this study have implications for developing an improved understanding of the likely controls on the detailed sedimentary architecture of preserved aeolian successions by enabling the proposition and development of a range of dynamic facies models for aeolian systems. This has wider applied implications and significance: for example, the morphological changes in the distribution of aeolian bedforms and interdunes across dune-field systems provides important information with which to improve our understanding of the likely arrangement of architectural elements in ancient aeolian preserved successions, several of which form important reservoirs for hydrocarbons. This work is therefore an important step in the development of improved models for the characterization of stratigraphic complexity and heterogeneity in aeolian reservoirs.

Morphological & Geometrical Relationships Between Dunes

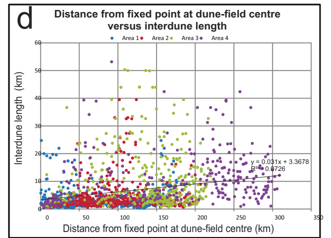


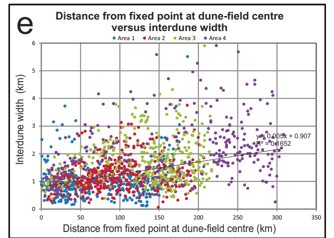




Dune bedform wavelength is a simple measure of bedform size, herein defined as the extent of a dune bedform in an orientation perpendicular to its crestline. In this study both maximum and minimum dune wavelengths are recorded for individual dune segments as a measure of size. The difference between maximum and minimum wavelength for a single dune segment is also a measure of along-crest crest variability, with similar values representing relatively straight-crested bedforms and values with greater differences reflecting increasing bedform crestline sinuosity. A strong positive correlation exists between maximum and minimum dune wavelength (a). Dune spacing is the distance between successive dunes in a train (measured between successive bedform crests), and includes both the wavelength of a dune bedform plus the width of the adjoining interdune. Wavelength and amplitude of along-crest plan-form sinuosities are together a simple measure of bedform crestline sinuosity. For each of the 4 study areas, over a distance of 300 km, mean amplitude of along-crest sinuosity decreases from 2.5 km at the centre of dune field to less than 0.5 km at the outer margin where the dunes become smaller (b). Mean wavelength of along-crest sinuosity decreases from 5 km at the dunefield centre to 0.2 km at the dune-field margin (c).

Morphological & Geometrical Relationships Between Interdunes





Interdunes have a tendency to become longer and wider with increasing distance from a fixed point in the dune-field centre towards the eastern dune-field margin (d and e), though considerable variability exists. For the data from Area 3, as interdune lengths become very large (>40 km) their widths stabilize at 1.5–3.5 km in the dune-field margin areas (e). In these marginal areas, interdunes become the dominant landform type and they effectively partition the dune field with the dune bedforms being subordinate and in some cases spatially isolated landforms. The spatially isolated interdune depressions present between bedforms in the central dune-field region are elevated up to 25 m above the regional level and this demonstrates that bedforms in these central regions are climbing over one another to generate an accumulation.

FRG ERG

UNIVERSITY OF LEEDS

A Quantitative Approach to the Characterization of Sedimentary Architecture in Mixed Aeolian-Fluvial Reservoir Successions

Mohammed Al-Masrahy[1] and Nigel Mountney[1]

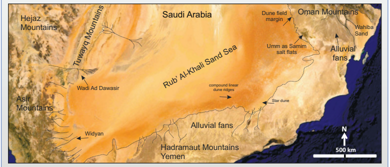
1. Fluvial Research Group, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.

Types of Fluvial Activity in Aeolian Dune Fields

Fluvial systems are present at a variety of scales in desert-margin settings. For both exogenous and endogenous dryland rivers, a diverse range of fluvial system types are known from a range of settings. Where such fluvial systems pass into aeolian dune fields a variety of types of system interaction occur. Rivers in such settings undertake a range of downstream changes in channel morphology and floodouts at channel termini. Although most (but not all) fluvial systems in desert dune-field margin settings are ephemeral, they play a significant role in landscape evolution and dictate regional geomorphology. Floods associated with dryland rivers can generally be assigned to one of four types: flash floods, single peak events, multiple peak events and seasonal floods. In dryland settings there also exist a relatively small number of large and permanent river courses (e.g. the Nile) and such rivers exert their own set of controls on neighbouring aeolian environments across which they flow. This study presents a novel classification scheme for the description of types of interaction between fluvial systems and adjoining aeolian dune systems and their marginal areas into which flood events episodically extend. **Ten distinct styles of interaction are recorded and illustrated by a set of case-study examples from around the world.**

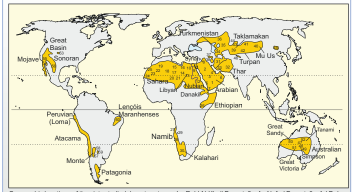
Fluvial-Aeolian Processes

Many ephemeral fluvial or alluvial systems emerge from steep-gradient mountain catchments onto low-gradient basin plains. Preferred flow pathways are commonly hindered by the presence of aeolian sand dunes constructed on the basin floor and this typically induces an abrupt decrease in stream power due to the combined effects of a sudden decrease in surface gradient and the presence of topographic obstacles.

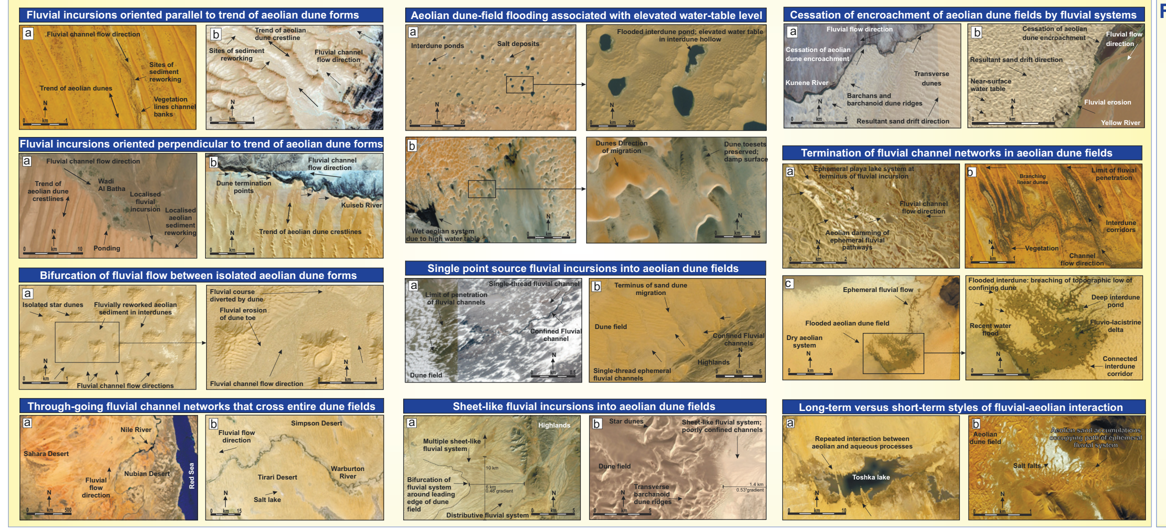


Google Earth image from southern Arabian Peninsula showing the location of the Rub' Al-Khali sand sea and surrounding mountains. Note the alluvial systems surrounding the dune fields.

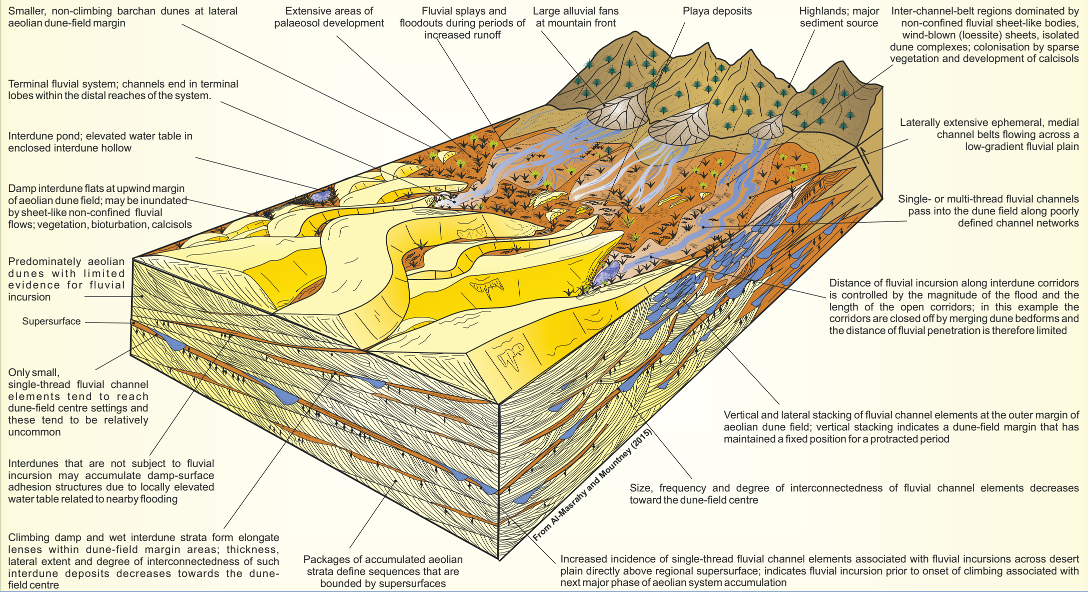
Studied Deserts



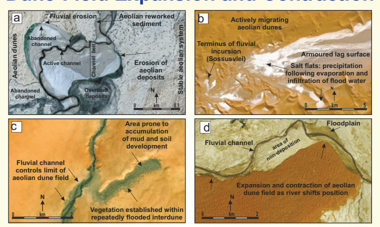
Aeolian-Fluvial interaction: Modern Examples



Depositional Processes at Dune-Field Margins

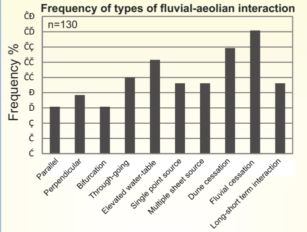


Fluvial Flooding as a Control on Aeolian Dune-Field Expansion and Contraction

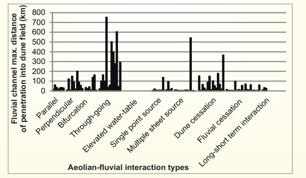


Although climatic aridity is a dominant factor that controls the distribution and extent of many sandy deserts, aeolian dune fields are present not just in arid and semi-arid settings but also in a range of humid, non-climatic desert settings where sediment supply, sediment availability for transport, and the potential sediment transport capacity of the wind are sufficient to enable aeolian bedform construction. Climate exerts a fundamental control on the relative dominance of fluvial versus aeolian processes and plays a primary role in governing how aeolian dune-field margins expand or contract over time.

Increases in either the frequency or magnitude of fluvial flood events in dune-field margin areas in response to climate change will impact continued aeolian dune-field construction in a number of ways. Increased fluvial discharge and stream power will promote erosion of older aeolian deposits. Fluvial reworking of aeolian sediment, its transport downstream and its ultimate re-deposition in areas where floods terminate will influence the supply and availability of sediment of a calibre suitable for later aeolian construction. Increased fluvial flood activity will limit the potential for aeolian dune migration. The availability of water provides conditions suitable for vegetation colonization, thereby promoting stabilization of interdune flats and limiting the capability of the wind to erode such substrates. Similarly, the deposition of mud drapes via settling from suspension over wide areas in the aftermath of repeated flood events will also limit the availability of underlying sediment for aeolian transport.

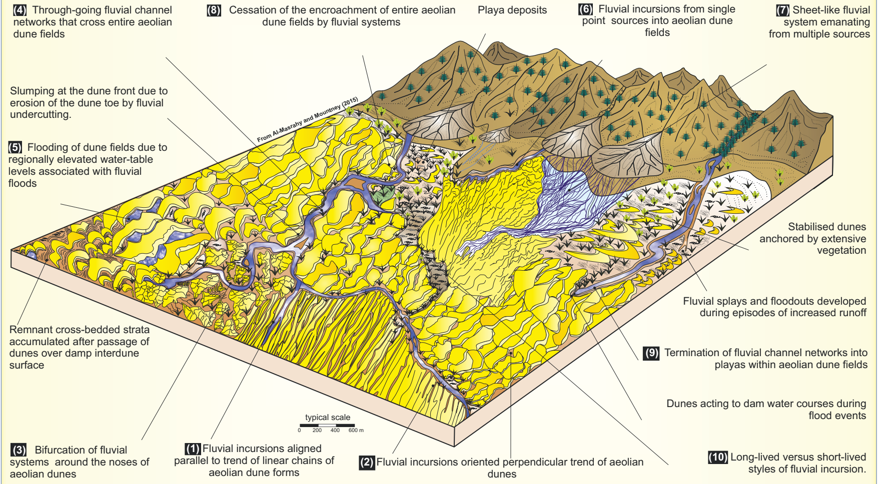


Frequency of types of fluvial-aeolian system interactions for the 130 case studies form 60 deserts around the world, (Al-Masrahy and Mountney, 2015).



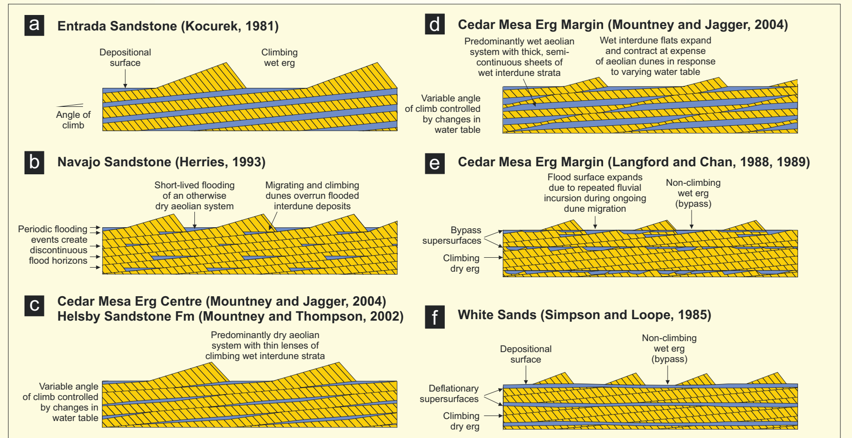
Relationship between aeolian-fluvial interaction type and mean maximum extent of fluvial channel penetration into aeolian dune fields from 120 studied dune-field systems.

Classification Scheme for Fluvial-Aeolian System Interaction



Schematic model summarizing a generic classification scheme for types of aeolian-fluvial system interaction. Numbers in black boxes relate to the 10 types of fluvial-aeolian system interaction discussed by **Al-Masrahy and Mountney (2015)**. The classification scheme is based on analysis of styles of aeolian-fluvial system interaction from 130 notable case-study examples present in a range of modern desert systems.

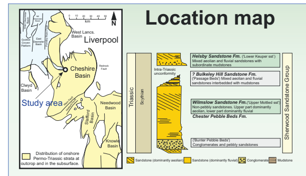
Architectural Expression of Fluvial Incursions into Aeolian Dune-Field Successions



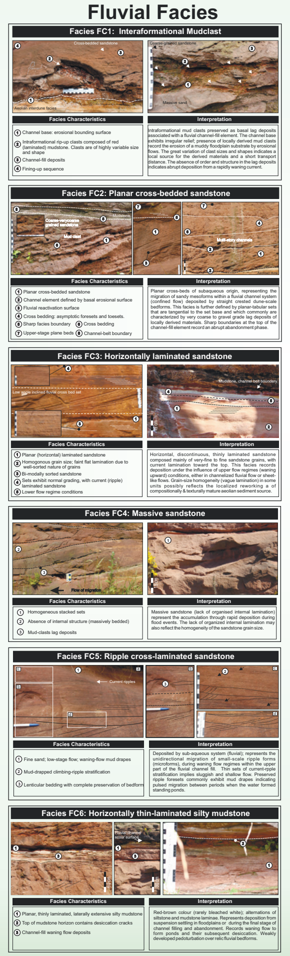
Geometries could potentially be generated at a variety of scales. After Mountney and Thompson (2002).

Ancient Examples: Triassic Wilmslow & Helsby formations, Cheshire Basin, UK

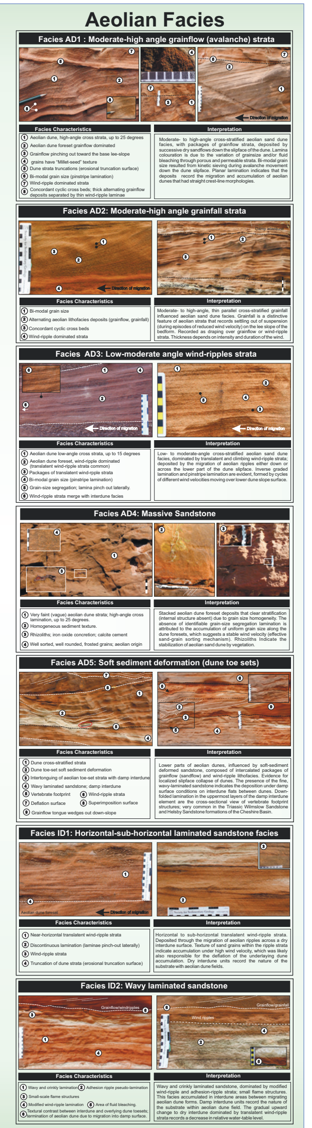
Location map



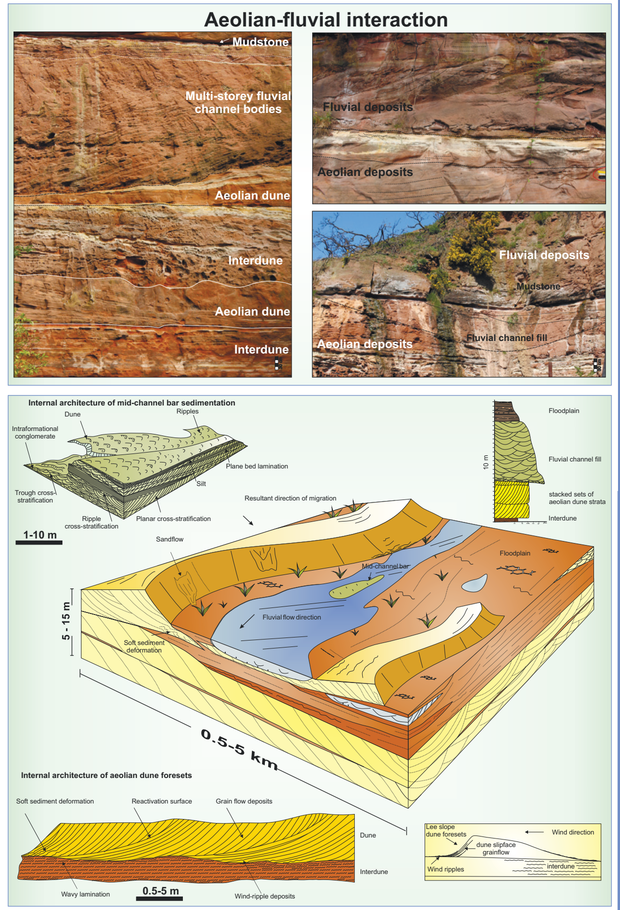
Fluvial Facies



Aeolian Facies



Aeolian-fluvial interaction



Summary

The physical boundaries between geomorphic systems are dynamic over short temporal time-scales. Across desert margins where fluvial and aeolian systems interact, the location of assemblages of surface landforms may change gradationally or abruptly. The varied range of temporal and spatial scales over which aeolian-fluvial processes interact means that simple generalized models for the classification of types of interaction must be applied with caution when interpreting ancient preserved successions, especially those known only from the subsurface. An increased understanding of interactions has been revealed by a a database of modern systems and ancient preserved successions that can be used to account for types of aeolian-fluvial interactions preserved in subsurface reservoir intervals. From an applied standpoint, quantitative depositional models arising from this database-driven approach serve to minimize uncertainties relating to stratigraphic heterogeneity in subsurface reservoir settings and aid inter-well correlation and prediction.

PetroleumLeeds

Fluvial & Eolian Research Group
School of Earth and Environment
Leeds LS2 9JT UK

Contact: Mohammed Al-Masrahy
Email: eemaa@leeds.ac.uk
URL: http://frg.leeds.ac.uk

AREVA bhpbilliton ConocoPhillips MURPHY OIL CORPORATION nexen Saudi Aramco Shell TULLOW woodside YPF

A Quantitative Approach to the Characterization of Sedimentary Architecture in Mixed Aeolian-Fluvial Reservoir Successions

Mohammed Al-Masrahy[1] and Nigel Mountney[1]

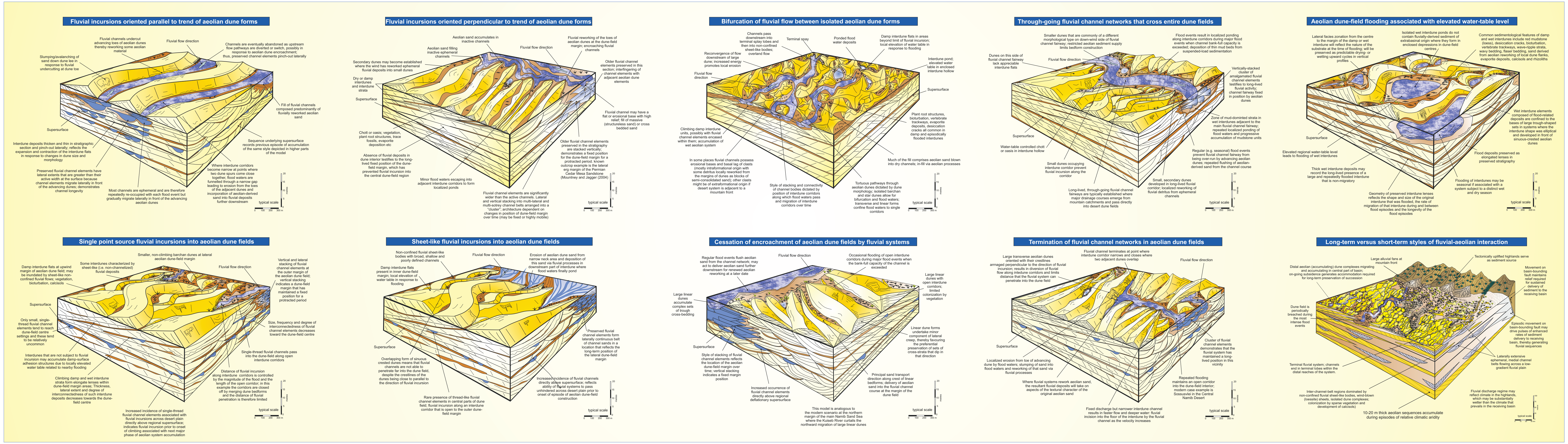
1. Fluvial Research Group, School of Earth and Environment, University of Leeds, Leeds, United Kingdom.

Mixed Aeolian-Fluvial Reservoirs

Mixed aeolian and fluvial systems exhibit a range of styles of sedimentary interaction in many modern arid climatic settings and preserved sedimentary architectures interpreted to record the stratigraphic response to such types of interaction are well documented from numerous outcropping ancient successions. From an applied perspective, mixed aeolian and fluvial successions are known to form several major reservoirs for hydrocarbons, including the Permian Unayzah Formation of Saudi Arabia, the Permian Rotliegend Group of the southern and Central North Sea, the Triassic Sherwood Sandstone Group of the East Irish Sea, and part of the Jurassic Norphlet Sandstone of the Gulf of Mexico. However, quantitative stratigraphic prediction of the three-dimensional form of heterogeneities arising from aeolian and fluvial interaction is notoriously difficult: (i) interactions observed in one-dimensional core and well-log data typically do not yield information regarding the likely lateral extent of sand-bodies; (ii) stratigraphic heterogeneities of these types typically occur on a scale below seismic resolution and cannot be imaged using such techniques.

Implications for Aeolian Reservoir Prediction and Modelling

- Reservoir anisotropy in aeolian successions profoundly affects reservoir performance throughout the producing life of a field. Although aeolian reservoirs are internally complex, they are predictable and can be managed efficiently once their three-dimensional internal architecture has been accurately characterized and modelled. Temporal and spatial variations in original dune and interdune morphology act as a primary control on resultant preserved set architecture. This study has quantified how aeolian dune, interdune and dryland fluvial morphological arrangements can be expressed in a variety of styles, in many cases predictably, across the zone transition from a dune-field centre to its margin. This represents an important step in the development of generic quantitative models with which to account for aeolian and mixed aeolian-fluvial reservoir architectural variability where changes are considered to occur spatially across a play, or within a single field. Each development project should be carefully characterized prior to initiating a more extensive drilling program. Aeolian and fluvial processes exert an important control on landform development and therefore ultimately on accumulated and preserved sedimentary architecture; such processes rarely operate independently and discretely in most arid to semi-arid environments. Interactions between aeolian and fluvial systems in dryland settings have important implications for the land geomorphology and preserved stratigraphy. Development of a series of qualitative and quantitative predictive models with which to account for the distribution of facies and architectural elements in aeolian and mixed fluvial-aeolian reservoir successions is important for the development predictive sequence stratigraphic models. This study has utilized modern outcrop analogue data for the development of a suite of models designed to develop a bridging link between data provided by sedimentological studies and its appropriate application in the construction of reservoir models. The internal reservoir sedimentary architecture, together with the smaller-scale fabric and sedimentary structure of component lithofacies, ultimately control the path of fluid migration during oil and gas emplacement and subsequent extraction. This architecture is, in turn, the product of the depositional and diagenetic processes that created the sediment body. If the an understanding of the origin of the reservoir is developed, reservoir architecture, and hence fluid flow paths, become predictable (North and Prosser, 1993). In arid regions, it is common for fluvial and aeolian processes and resultant strata to occur inter-mixed, with the result that overall preserved successions exhibit marked complexity (Glennie, 1990). Thus, to understand the fluid flow properties of mixed fluvial-aeolian reservoirs, it is important to determine the geometry and the relationship of sedimentary bodies of fluvial and aeolian origin (Newell, 2001). The presence of stratigraphic complexity and heterogeneity at a scale below seismic resolution, coupled with stratigraphic architectures characterized by notable lateral facies changes, means that prediction of 3D stratigraphic architecture in subsurface reservoirs is challenging (e.g., Sweet, 1999). Therefore, studying appropriate outcrops and modern analogues is imperative to provide insight into reservoir heterogeneity and potential variability in geological model (e.g., Herrise, 1993; Mountney et al., 1998; North and Boering, 1999; Visser and Chessa, 2000; Newell, 2001; Bongiolo and Scherer, 2010).



Conclusions

The physical boundaries between many desert geomorphic systems are dynamic. Along desert dune-field margins where aeolian and fluvial processes interact, the location of the boundary and the assemblage of surface landforms present may change either gradually or sharply over both space and time. Short-term shifts in the positions and form of such boundaries are controlled by the competition between fluvial flash-flood events and on-going aeolian dune construction. Medium- and long-term changes in boundary position and form are governed by changes to climate and tectonic basin evolution, respectively.

Aeolian and fluvial processes in desert-margin settings rarely operate independently: they are usually dynamically linked and exhibit a range of styles of sedimentary interaction documented from modern arid systems. Interactions between aeolian and fluvial systems are important and widespread in modern deserts, as revealed by global satellite imagery. A diverse range of styles of system interaction gives rise to considerable complexity in terms of geomorphology, sedimentology and preserved stratigraphy. Ten distinct styles of fluvial-aeolian interaction are recognized: fluvial incursions aligned parallel to trend of linear chains of aeolian dune forms; fluvial incursions oriented perpendicular trend of aeolian dunes; bifurcation of fluvial systems around the noses of aeolian dunes; through-going fluvial channel networks that cross entire aeolian dune fields; flooding of dune fields due to regionally elevated water-table levels associated with fluvial floods; fluvial incursions emanating from a single point source into dune fields; incursions emanating from multiple sheet sources; cessation of the encroachment of entire aeolian dune fields by fluvial systems; termination of fluvial channel networks into playas within aeolian dune fields; long-lived versus short-lived styles of fluvial incursion. Recognition of these interaction types forms the basis for a classification scheme that can be applied to desert dune-field systems generally.

Across desert margins where fluvial and aeolian systems interact, the location of assemblages of surface landforms may change gradationally or abruptly. The varied range of temporal and spatial scales over which aeolian-fluvial processes are known to interact means that simple generalized models for the classification of styles of interaction must be applied with caution when interpreting ancient preserved successions, especially those known only from the subsurface. By understanding the nature and surface expression of various types of aeolian and fluvial interaction, and by considering their resultant sedimentological expression, prediction can be made regarding how the of preserved deposits of such interactions might be predicted in the ancient stratigraphic record and assessment can be made of the spatial scale over which such interactions are likely to occur.

Given the economic importance and complex stratigraphical and sedimentological nature of aeolian and fluvial successions, it has become essential to develop both qualitative and quantitative models with which to account for dynamic spatial and temporal aspects of aeolian-fluvial system behaviour at the dune-field & basin scales. This modelling-based approach and associated classification framework is the overarching theme of this wider research project and it has potential applications in the development of predictive models with which to account for reservoir heterogeneity in aeolian reservoirs targeted for the production of hydrocarbons. Results from this project are being used to generate a range of synthetic three-dimensional stratigraphic architectural models (e.g. Mountney, 2012) with which to illustrate the range of possible sedimentological complexity likely to be present in preserved dune-field-margin successions (Al-Masrahy and Mountney, 2013 and 2015). Appreciation of this complexity has significant applied implications because interdune and dune-plinth elements typically act as principal and subordinate baffles to flow, respectively, in aeolian hydrocarbon reservoirs, whereas dune lee-slope elements typically represent effective net reservoir. Results from this study are being used as input into reservoir models that are used to account for heterogeneity in aeolian and mixed fluvial-aeolian successions, from which predictions are made regarding reservoir heterogeneity and flow behaviour.

References

Al-Masrahy, M.A., Mountney, N.P, (2013) Remote sensing of spatial variability in aeolian dune and interdune morphology in Rub'Al-Khali, Saudi Arabia. Aeolian Research 11, 155-170.
Al-Masrahy, M.A., Mountney, N.P, (2015) A classification scheme for fluvial–aeolian system interaction in desert-margin settings.Aeolian Research 17, 67-88.
Benan, C.A, Kocurek, G. (2000) Catastrophic flooding of an aeolian dune field: Jurassic Entrada and Todilto Formations, Ghost Ranch, New Mexico, USA. Sedimentology 47, 1069-1080.
Bongiolo, D.E., Scherer, C.M. (2010) Facies architecture and heterogeneity of fluvial-aeolian reservoir of Serge formation (Upper Jurassic) Recôncavo Basin, Marine and Petroleum Geology 27, 1885-1897.
Bullard, J.E., McTainsh, G.H. (2003) Aeolian-fluvial interactions in dryland environments: scales, concepts and Australia case study. Progress in Physical Geography 27, 471-501.
Cain, S.A. and Mountney, N.P. (2009) Spatial and temporal evolution of a terminal fluvial fan system: the Permian Organ Rock Formation, south east Utah, USA: Sedimentology, v. 56, p. 1774–1800.
Cain, S.A. and Mountney, N.P. (2011) Downstream changes and associated fluvial-aeolian interactions in an ancient terminal fluvial fan system: the Permian Organ Rock Fm., SE Utah. SEPM 97, 165-187.
Clarke, M.L., Rendell, H.M. (1998) Climate change impacts on sand supply and the formation of desert sand dunes in the southwest USA, Journal of Arid Environments 39, 517-531.
Glennie, K.W. (1990) Lower Permian-Rotliegend. In, Glennie, K.W. (ed.) Introduction to the petroleum geology of the North Sea. 3rd edition. Blackwell Scientific Publications, Oxford, 120-152.
Glennie, K. W. (2005) The desert of southeast Arabia: Desert Environments and Sediments. Gulf Petrolink, Bahrain. 215 p.
Graf, L.W., (1988) Fluvial processes in dryland rivers, Springer-Verlag, Berlin. p.346.
Hartley, A., Weissmann, G.S., Nichols, G.J., Warwick, G.L. (2010) Large Distributive Fluvial Systems: Characteristics, Distribution, and Controls on Development. Journal of Sedimentary Geology 80, 167- 183.
Harvey, A (2011) Dryland alluvial fans. In Arid zone Geomorphology, Process, Form and Change in Drylands, third edition (ed. Thomas, D. S.), John Wiley and Sons, Ltd., 333- 401.
Herries, R.D. (1993) Contrasting style of fluvial-aeolian interaction at a downwind erg margin: Jurasic Kayenta-Navajo transition, northeastern Arizona, USA. Geological Society special publication 73, 199-218.
Kocurek, G.A., 1981. Significance of interdune deposits and bounding surfaces in eolian dune sands. Sedimentology 28, 753-780.
Krapf, C.B.E., Stanistreet, I.G., Stollhofen, H. (2005) Morphology and fluvio-aeolian interaction of the tropical latitude, ephemeral braided river dominated Koigab Fan, north-west Namibia,. IAS S.P. 35, 99-120.
Langford, R.P., Chan, M.A. (1988) Flood surfaces and deflation surfaces within the Cutler Formation and Cedar Mesa Sandstone (Permian), southeastern Utah. GSA Bull. 100, 1541-1549.
Langford, R.P., Chan, M.A., 1989, Fluvial-aeolian interactions; Part II, Ancient systems. Sedimentology 36, 1037-1051.
Loope, D.B., Swinehart, J.B., Mason, J. P. (1995) Dunedammed paleovalleys of the Nebraska Sand Hills: intrinsic versus climatic controls on the accumulation of lake and marsh sediments. AAPG,107 396-406.
Mountney, N. P. (2012) A stratigraphic model to account for complexity in aeolian dune and interdune successions. Sedimentology 59, 964-989.
Mountney, N.P., Thompson, D. B.(2002) Stratigraphic evolution and preservation of aeolian dune and damp/wet interdune strata: an example from the Triassic Helsby Sandstone Formation, Cheshire Basin, UK. Sedimentology (2002) 49, 805-833.
Mountney, N.P., Jagger, A., 2004. Stratigraphic evolution of an aeolian erg margin system: the Permian Cedar Mesa Sandstone, SE Utah, USA. Sedimentology 51, 713-743.
Mountney, N.P., Russell. A.J. (2009) Aeolian dune-field development in a water table-controlled system: Skeidararsandur, Southern Iceland, Sedimentology 56, 2107-2131.
Mountney, N.P., Howell, J.A., Flint, S., Jerram, D.A. (1998) Aeolian and alluvial deposition within the Mesozoic Etjo Sandstone Formation, northwest Namibia, Journal of African Earth Sciences 27, 175-192.
North, C.P., Boering, M. (1999) Spectral gamma ray logging for facies discrimination in mixed fluvial-aeolian succession: a cautionary tale. American Association of Petroleum Geologist, Bulletin 83, 155-169.
North, C.P., Prosser, D. J (1993) Characterization of fluvial and aeolian reservoirs: problem and approaches. Geological Society special publication, no. 73, pp. 1-6.
Stanistreet, I.G., Stollhofen, H. (2002) Hoanib River flood deposits of Namib Desert interdunes as analogues for thin permeability barrier mudstone layers in aeolianite reservoirs. Sedimentology 49, 719-736
Simpson, E.L., Loope, D.B. (1985) Amalgamated interdune deposits, white sands, New Mexico. Journal of Sedimentary Petrology 55, 361-365.

PetroleumLeeds

Fluvial & Eolian Research Group
School of Earth and Environment
Leeds LS2 9JT UK

Contact: Mohammed Al-Masrahy
Email: eemaa@leeds.ac.uk
URL: http://frg.leeds.ac.uk