PS Approaches to Modeling Stratigraphic Heterogeneity in Mixed Fluvial and Aeolian Hydrocarbon Reservoirs*

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

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Abstract

Dynamic relationships between coevally active fluvial and aeolian systems give rise to a range of styles of sedimentary interaction that are documented from both modern arid-climate systems and analogous ancient preserved outcrop and subsurface successions. Mixed fluvial and aeolian successions are known to form several major reservoirs for hydrocarbons, including the Permian Unayzah Formation of Saudi Arabia, the Permian Rotliegend Group of the North Sea, and the Jurassic Norphlet Sandstone of the Gulf of Mexico and typically give rise to stratigraphic heterogeneity at a number of scales. Quantitative stratigraphic prediction of the three-dimensional form of heterogeneities arising from fluvial and aeolian interaction is notoriously difficult: (i) the preserved products of system 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 typically occur on a scale below seismic resolution and cannot be imaged using such techniques. A database recording the temporal and spatial scales over which aeolian and fluvial events operate and interact in a range of present-day and ancient desert-margin settings has been collated using high-resolution satellite imagery, aerial photography and field observation. Together, these data have been used to develop a series of dynamic facies models to predict the arrangement of architectural elements that define gross-scale system architecture. Case-study examples have enabled the construction of a series of depositional models to account for the diversity of styles of fluvial and aeolian system interactions. Several styles of aeolian-fluvial interaction have been documented and the preserved deposits can now be predicted through quantitative geological models that account for spatial and temporal changes in system dominance. For example, the preserved architectural elements of fluvially flooded interdunes tend to expand laterally as successive flood deposits develop in front of advancing aeolian dunes. In non-climbing aeolian systems, such behavior favors the development of sheet-like bypass surpersurfaces. In aeolian systems that climb at low angles and for which fluvial incursions are episodic, thin and laterally impersistent fluvial elements tend to accumulate. The scale and connectivity of fluvial flood deposits tends to diminish with increasing distance toward the aeolian dune-field center.

Approaches to Modelling Stratigraphic Heterogeneity in Mixed Fluvial and Aeolian Hydrocarbon Reservoirs

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Styles of Fluvial and aeolian system interaction in desert-margin settngs

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Abstract

Dynamic relationships between coevally active fluvial and aeolian systems give rise to a range of styles of sedimentary interaction that are documented from both modern arid-climate systems and analogous ancient preserved outcrop and subsurface successions. Mixed fluvial and aeolian successions are known to form several major reservoirs for hydrocarbons, including the Permian Unayzah Formation of Saudi Arabia, the Permian Rotliegend Group of the North Sea, and the Jurassic Norphlet Sandstone of the Gulf of Mexico. Such successions typically give rise to stratigraphic heterogeneity at a number of scales. Quantitative stratigraphic prediction of the three-dimensional form of heterogeneities arising from fluvial and aeolian interaction is notoriously difficult: (i) the preserved products of system 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 typically occur on a scale below seismic resolution and cannot be imaged using such techniques.

A database recording the temporal and spatial scales over which aeolian and fluvial events operate and interact in a range of present-day and ancient desert-margin settings has been collated using high-resolution satellite imagery, aerial photography and field observation. Together, these data have been used to develop a series of dynamic facies models to predict the arrangement of architectural elements that define gross-scale system architecture. Case-study examples have enabled the construction of a series of depositional models to account for the diversity of styles of fluvial-aeolian system interactions.

Several styles of aeolian-fluvial interaction have been documented and the preserved deposits can now be predicted through quantitative geological models that account for spatial and temporal changes in system dominance. For example, the preserved architectural elements of fluvially-flooded interdunes tend to expand laterally as successive flood deposits develop in front of advancing aeolian bedforms. In non-climbing aeolian systems, such behavior favours the development of sheet-like bypass supersurfaces. In aeolian systems that climb at low angles and for which fluvial incursions are episodic, thin and laterally impersistent fluvial elements tend to accumulate. The scale and connectivity of fluvial deposits tends to diminish with increasing distance toward the aeolian dune-field centre.

Aims and Objectives

The aim of this study is to propose a generalised framework with which to account for the diverse styles of interaction known to exist between coevally active eolian-fluvial depositional systems, and to discuss the significance of interaction for the geomorphological and sedimentological evolution of mixed eolian-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 bedforms 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 palaeoenvironmental reconstruction of ancient preserved counterparts. 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 models to account for geomorphic landscape evolution, and for predicting heterogeneity in preserved subsurface reservoir successions.

Data and Methods

The morphological expression and areal distribution of flood deposits present between aeolian dunes located in the outer margins of a series of desert dune fields from around the world have been mapped using high-resolution satellite imagery. Studied desert systems include sand seas of parts of the Arabian Peninsula (e.g. the Rub' Al-Khali sand sea and An Nafud sand sea in Saudi Arabia and Wahiba sand sea in Oman), the Namib Desert and Skeleton Coast of Namibia, the Taklamakan Desert of northwest China, the Rigestan Desert in southwestern Afghanistan, the Sahara Desert in North Africa, the Algodones dune field in southeastern California, United States, White Sands in southern New Mexico, United States, and deserts of Australia (Figure 1). Google Earth Pro™ software provides public-release imagery that covers remote desert regions and provides a high-resolution images that can be exported as seamless tiles that are each up to 4,800 pixels wide. Such images provide an opportunity to analyse styles of aeolian-fluvial interaction that operate at a range of spatial scales. This study has examined and documented styles of interaction from 43 deserts around the world; 66 type examples have been used to illustrate common styles of aeolian and fluvial system interactions.

Introduction & Concepts

Desert dune fields are not necessarily continuously covered with aeolian bedforms; most additionally include other morphological bodies of aeolian-derived or aeolian-related sediment deposits, including interdunes, sand sheets, soils, lacustrine systems, and perennial, intermittent or ephemeral fluvial systems. In many cases these geomorphic forms are developed between active aeolian dunes; in other cases they define the limits of dune fields, either as sharp or gradational boundaries. A great diversity in the arrangement and style of interaction of competing depositional sedimentary systems is recognized from modern desert dune fields and their marginal areas and these give rise to complex yet predictable geomorphological patterns that commonly vary over space and time (e.g. Lancaster, 1989; Cooke, et al., 1993; Al-Masrahy and Mountney, 2013). The record of these interactions is also recognized in the ancient sedimentary record (e.g. Spalletti, and Veiga, 2007) where spatial and temporal changes in the style of interaction between aeolian dune and associated desert sub-environments are known to lead to the preservation of complex arrangements of sedimentary deposits and stratigraphic architectures (e.g. Mountney, 2012).

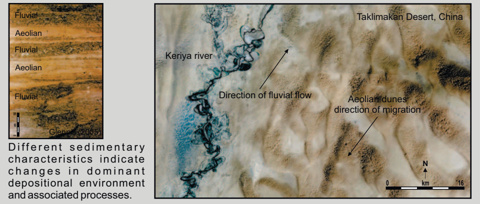
Permanent, intermittent and ephemeral fluvial systems are known from many dryland regions, including Australia, India, Saudi Arabia, and the Southwestern United States (Schick, 1988; Tooth, 2000) and many exhibit complex and long-lived interactions with aeolian dunes. Large and permanently flowing water courses, such as the Nile in Sudan and Egypt and smaller, ephemeral water courses (widyan), such as Wadi Ad Dawasir in Saudi Arabia and the Kuiseb River in Namibia give rise to a range of styles of fluvial-aeolian interaction. Some fluvial systems serve to generate a significant supply of sediment that is later made available for aeolian-dune construction, as in the Kelso Dune Field, Mojave Desert, California (Sharp, 1966; Kocurek and Lancaster, 1999). Similarly, alluvial-fan systems that form laterally extensive bajadas may contribute significant sources of sediment for aeolian landform construction, as is the case for the Mojave River, south-eastern California (Blair and McPherson, 2009; Belnap, 2011) and the alluvial fan systems that border parts of the Rub' Al-Khali Sand Sea, Saudi Arabia. Others fluvial systems act to limit the spatial extent of dune fields and serve to remove significant volumes of sediment transported into river beds via aeolian processes from desert sedimentary systems (e.g. The Kuiseb River, Namibia, Goudie, 1972; Ward, 1983).

The role of fluvial systems in aeolian-dominated deserts is significant; they are one of the most important landscape-forming and developing agents in many dryland systems (Wainwright and Bracken, 2011). Although many studies have documented styles of interactions between aeolian and fluvial systems in both modern systems (e.g. Langford, 1989; Trewin, 1993; Stanistreet and Stollhofen, 2002; Bullard and McTainsh, 2003) and their ancient preserved successions recognized in the geological record (e.g. Langford and Chan, 1988; 1989; Herries, 1993; Chakraborty and Chaudhuri, 1993; 1993; Mountney and Jagger, 2004; Jordan and Mountney, 2010; Spalletti, et al., 2010), relatively few geomorphological studies have explicitly focused on styles of interaction between contemporaneously active aeolian and fluvial systems (e.g. Frostick and Reid, 1987; Cooke, et al., 1993; Tooth, 2000; Bull and Kirkby, 2002; Parsons and Abrahams, 2009; Reid and Frostick, 2011). This is important because styles of interaction between competing aeolian and fluvial sedimentary systems are complex and diverse such that the impact of one system type on the other is pronounced and has implications for regional geomorphic patterns and for the reconstruction of the palaeoenvironments (cf. Trewin, 1993; Herries, 1993; Yang, et al., 2002; Al Farraj and Harvey, 2004; Simpson, et al., 2008; Jordan and Mountney, 2010).

The increasing availability and global coverage of high-resolution satellite and aerial-photograph imagery via resources such as Google Earth™ (Butler, 2006; Yu and Gong, 2011; Fisher. et al., 2012) has enabled the study of geomorphological relationships in detail for remote dryland settings (e.g. Tooth, 2006; Bullard et al., 2011; Al-Masrahy and Mountney, 2013). This study continues this trend by utilizing the latest generation of imagery to investigate the nature of aeolian and fluvial system interactions.

This study proposes a generalized framework with which to account for the diverse styles of interaction known to exist between coeval aeolian and fluvial depositional systems, and discusses the significance of these interactions for the

Fluvial-Aeolian Interaction



Different sedimentary characteristics indicate changes in dominant depositional environment and associated processes.

It is important to understand the temporal and spatial scales at which aeolian and fluvial systems interact. For example in drylands regions there are many places where river channels have been blocked by aeolian dune fields. This usually takes place when the rivers flow only intermittently and the intervening period is long enough for aeolian deposits to accumulate.

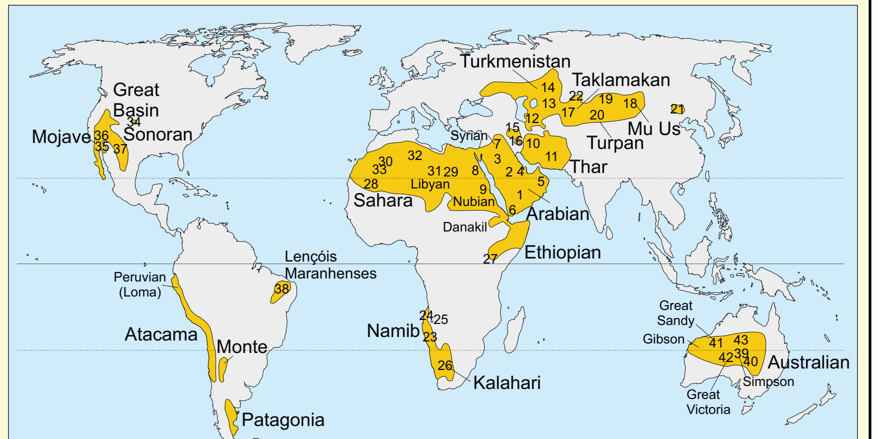
Geographic Locations of Studied Desert Systems

The geomorphological expression and areal distribution of flood deposits present between aeolian dunes located in the outer margins of a series of desert dune fields have been collated. Specific desert systems studied are listed below.

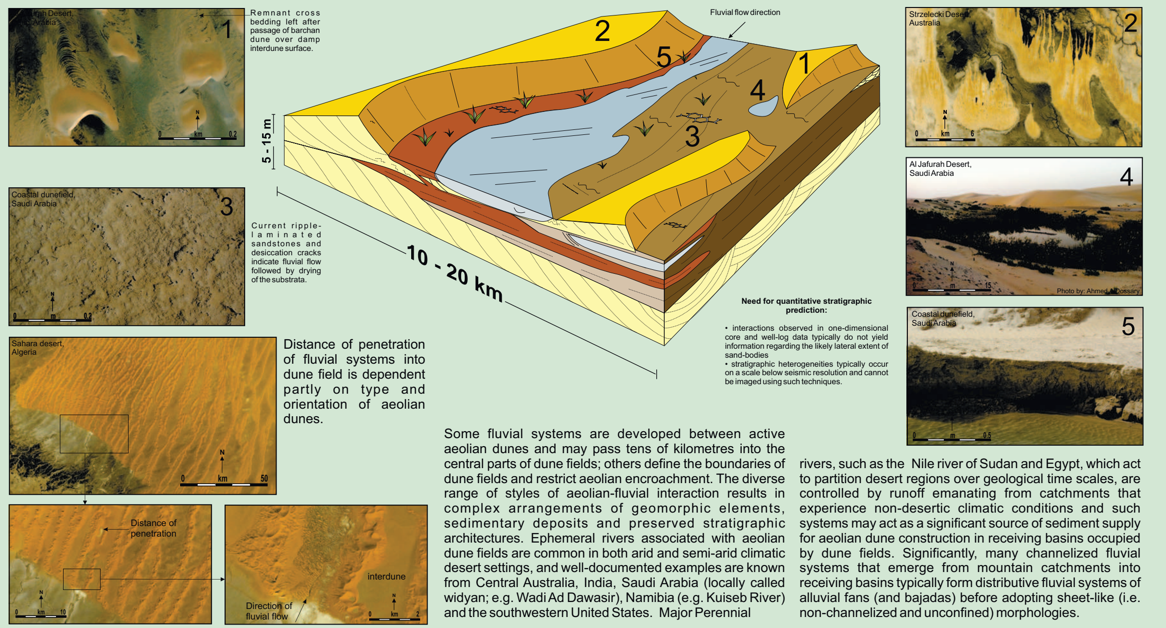
1. Rub' Al-Khali, Saudi Arabia
2. An Nafud Sand Sea, Saudi Arabia
3. Ad Dahna Desert, Saudi Arabia
4. Al Jafurah Desert, Saudi Arabia
5. Wahiba Sand Sea, Oman
6. Coastal dune field southern Yemen
7. Syrian Desert, Syria
8. Eastern Sahara, Egypt
9. Nubian Desert, northern Sudan
10. Rigestan Desert, Afghanistan
11. Thar Desert, Pakistan
12. Garagum Desert, Turkmenistan
13. Qizilqum Desert, Uzbekistan
14. Betpaqdala Desert, Kazakhstan
15. Kavir Desert, Iran
16. Lut Desert, Iran
17. Taklimakan Desert, China
18. Mu Us Desert, China
19. Gobi Desert, China
20. Turpan Desert, China
21. Horqin Desert, Inner Mongolia
22. Gurbantünggüt Desert, China
23. Namib Desert, Namibia
24. Skeleton Coast, Namibia
25. Giribes Plain, Namibia
26. Kalahari Desert, Botswana
27. Chalbi Desert, Kenya
28. El Djouf Desert, Mauritania
29. Idhan Murzuq Desert, Libya
30. Grand Erg Occidental, Algeria
31. Tassili-N-Ajjer Desert, Algeria
32. Erg Iguidi Desert, Algeria
33. Hamada Du Draa Desert, Algeria
34. White Sands, New Mexico, USA
35. Algodones, California, USA
36. Mojave Desert, California, USA
37. Sonoran Desert, NE Mexico
38. Lençóis Maranhenses, NE Brazil
39. Simpson Desert, Australia
40. Strzelecki Desert, Australia
41. Great Sandy Desert, Australia
42. Great Victoria Desert, Australia
43. Tanami Desert, Australia

Mixed fluvial and aeolian successions are known to form several major reservoirs for hydrocarbons:

- Permian Unayzah Formation, Saudi Arabia
- Permian Rotliegend Group, North Sea
- Triassic Sherwood Sandstone Group of the East Irish Sea
- Jurassic Norphlet Sandstone, Gulf of Mexico



Common Fluvial-Aeolian Depositional Processes at Aeolian Dune-Field Margins

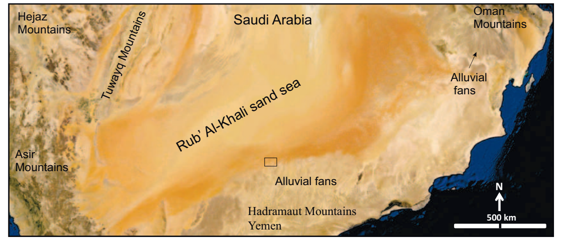


Distance of penetration of fluvial systems into dune field is dependent partly on type and orientation of aeolian dunes.

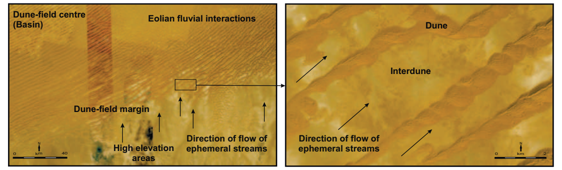
Some fluvial systems have been active aeolian dunes and may pass tens of kilometres into the central parts of dune fields; others define the boundaries of dune fields and restrict aeolian encroachment. The diverse range of styles of aeolian-fluvial interaction results in complex arrangements of geomorphic elements, sedimentary deposits and preserved stratigraphic architectures. Ephemeral rivers associated with aeolian dune fields are common in both arid and semi-arid climatic desert settings, and well-documented examples are known from Central Australia, India, Saudi Arabia (locally called widyan; e.g. Wadi Ad Dawasir), Namibia (e.g. Kuiseb River) and the southwestern United States. Major Perennial rivers, such as the Nile river of Sudan and Egypt, which act to partition desert regions over geological time scales, are controlled by runoff emanating from catchments that experience non-desertic climatic conditions and such systems may act as a significant source of sediment supply for aeolian dune construction in receiving basins occupied by dune fields. Significantly, many channelized fluvial systems that emerge from mountain catchments into receiving basins typically form distributive fluvial systems of alluvial fans (and bajadas) before adopting sheet-like (i.e. non-channelized and unconfined) morphologies.

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.



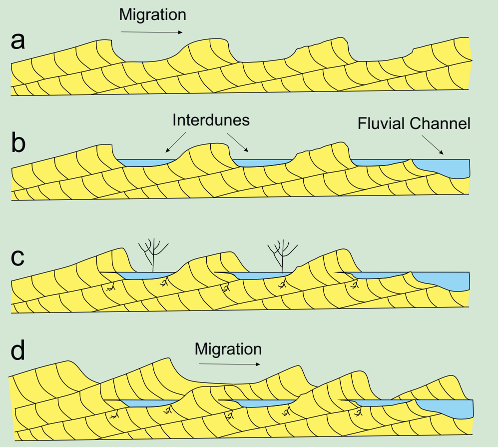
Google Earth image of the southern Arabian Peninsula showing the location of the Rub' Al-Khali Sand Sea and surrounding mountains. Note the alluvial systems surrounding the dune fields.



Aeolian and fluvial systems are important agents for landform development; they rarely operate independently and discretely in most arid to semi-arid environments. Interactions between the two system types are common and the nature of these interactions has important implications for landscape evolution, and this in turn dictates sedimentology and preserved stratigraphy. Long-term changes in climate and basin evolution (allogenic controls) dictate the types of system interaction that operate.

Fluvial-Aeolian Processes

Aeolian and fluvial systems do not operate independently in arid areas; they are linked dynamically by sediment flux. These ties can be important in shaping the geomorphology of desert-margin regions due to complex changes linked to variations in climate. Hence, climate change will influence sediment flux and may potentially initiate local geomorphic changes within an evolving system. System interactions may be either coeval (i.e. contemporary) and operate on a local spatial scale, or may be temporally discrete and operate over longer time-scales. The boundaries between fluvial-dominated and aeolian dominated areas will tend to be mobile over time.



a: Dune and interdunes climb while migrating and preserve underlying dune deposits.

b: Flooding occurs. Fluvial channels incise into underlying aeolian sand deposits. Discontinuous erosion surface buried by flood deposits.

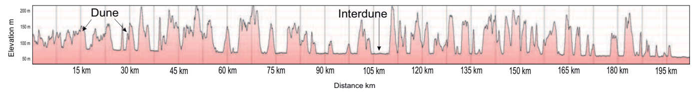
c: Continued non-climbing migration of dunes across flood surface. A localized rise in water-table level associated with flooding allows vegetation to colonize low-lying areas, producing a rooted horizon.

d: Continued dune migration and flooding produce interbedded shale and dune foresets. Dunes now migrate across the elevated accumulation surface.

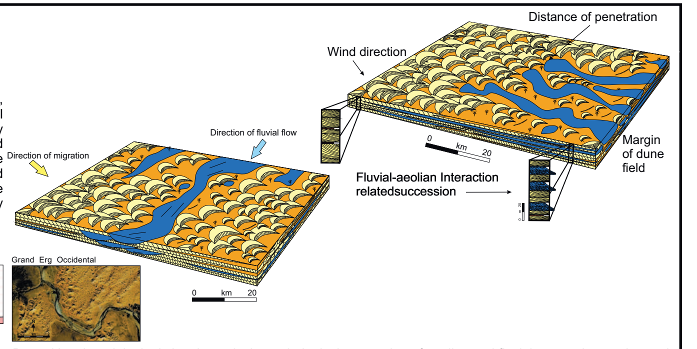
Model for the generation of bypass (flood) supersurfaces in response to fluvial incursion. Modified after Langford and Chan (1988).

Aeolian Morphology and Fluvial Incursion

Geomorphological elements in desert settings tend to change systematically from the central parts of dune fields, where aeolian processes are dominant, to dune-field margins, where non-aeolian systems including ephemeral fluvial streams dominate. Aeolian dunes tend to systematically decrease in both size (wavelength and height) and connectivity towards dune-field margins, whereas interdune flat areas developed between dunes tend to increase in width and connectivity. As a result, many desert systems are subject to fluvial incursions that pass into the marginal areas of dune fields but which tend to terminate as dune-dammed pond deposits at positions where dune topography and interconnectivity increases such that it acts to form a natural dam to further incursion. Exceptions to this are where dune fields are characterized by elongate and open interdune corridors along which fluvial systems can pass, thereby allowing fluvial flooding into the central parts of dune fields.



Cross-sections from the Rub' Al-Khali Sand Sea showing elevation data reflecting variation in dune and interdune morphology and spacing from the centr of the dune field to its margin. Modified after Almasrahy and Monuntney, 2013.



Depositional models depicting the typical morphological expression of aeolian and fluvial system interaction and related stratigraphy. Note the variation in the distance of penetration of fluvial systems into the dunefield, which is dependent partly on type and orientation of aeolian dunes and their interconnectivity.

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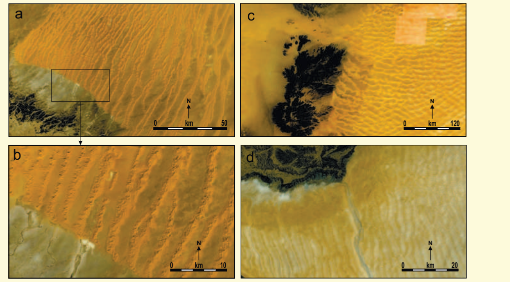
Types of fluvial activity in aeolian dune fields

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 styles of system interaction occur. Rivers in such settings undertake a range of downstream changes in channel morphology and floodouts at channel termini (cf. Cain and Mountney, 2009, 2011). 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 (Graf, 1988). 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 floods episodically extend. Ten distinct styles of interaction are recorded and illustrated by a set of case-study examples from around the world: fluvial incursions oriented parallel to trend of aeolian dune forms; fluvial incursions oriented perpendicular trend of aeolian dune forms; bifurcation of fluvial systems around the noses of aeolian dune forms; 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 into dune fields that emanate from a single point source; incursions that emanate from sheet-like sources; cessation of the encroachment of entire aeolian dune fields by fluvial systems; termination of fluvial channel networks into playas within aeolian dune fields; and long-lived versus short-lived styles of fluvial incursion.

Fluvial incursions oriented parallel to trend of aeolian dune forms

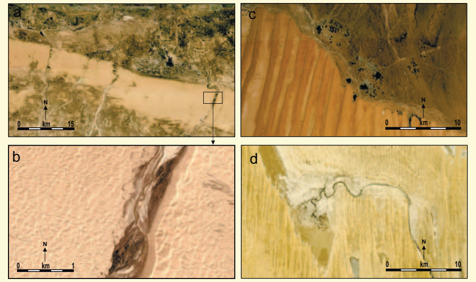


In cases where the configuration of aeolian dunes is such that they form elongate ridges with crestlines aligned close to parallel to the direction of fluvial flow and where neighbouring dune ridges are separated by interdune flats, fluvial systems are typically able to penetrate along interdune corridors into the aeolian dune field, in some cases for many tens of kilometres. Such processes supply sediment suitable for aeolian dune construction to interdune region, thereby potentially encouraging further dune construction and limiting the effects of aeolian deflation in interdune corridors.

This style of interaction may result in the deposition of ribbon-like fluvial deposits in cases where the aeolian dunes that funnel the flood waters into specific interdune corridors are fixed in position. Alternatively, in cases where the dunes ridges and their intervening interdunes gradually creep laterally between successive flood events, fluvial deposits arising from successive floods may expand laterally to form more sheet-like deposits (cf. Langford and Chan, 1988). In both cases, the opportunity for aeolian reworking of fluvial flood deposits is significant and winnowing of sand and finer fractions by the wind is likely, possibly resulting in the generation of armoured lag deposits (Krapf et al., 2005; Simpson et al., 2008).

Above: (a & b) Sahara Desert (Great Erg Oriental), Algeria. (c) Sahara Desert (Idhan Murzuq desert), Libya. (d) Sahara Desert, Mauritania.

Fluvial incursions oriented perpendicular to trend of aeolian dune forms

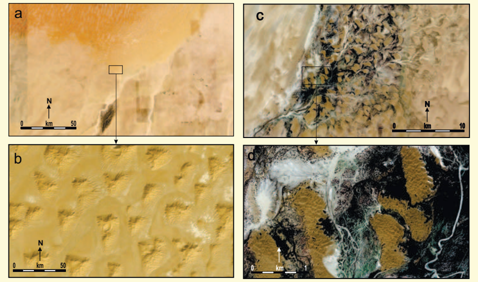


In cases where the configuration of aeolian dunes is such that they form elongate ridges with crestlines aligned close to perpendicular to the direction of fluvial flow, aeolian topography will exert a significant control on the distribution of fluvial flood pathways and will likely change the nature of the flooding event.

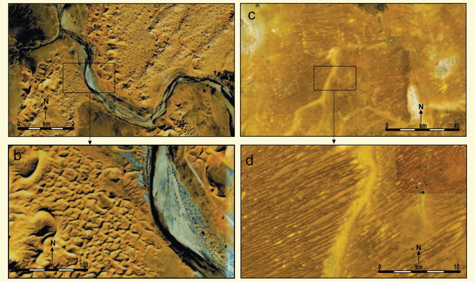
This style of interaction will typically lead to a sharp boundary between fluvial deposits and adjoining aeolian deposits. Where fluvial flood waters repeatedly pond against the leading edge of an aeolian dune field, fine-grained mudstone layers will progressively accumulate (e.g., Wadi Al Ayn and Wadi Al Batha, Oman, Glennie, 2005). In cases where flood waters are saline and where ponded water evaporates or infiltrates only slowly, salts such as calcium carbonate, gypsum, halite or potash may be precipitated (Valyashko, 1972). For example, the salt flats of Umm as Samim occur in a low-lying areas between alluvial fans to the north and aeolian dunes of the Rub' Al Khali to the west and south (Goodall, et al., 2000). If the outer edge of the aeolian dune field gradually expands over time via dune migration, aeolian deposits may become juxtaposed over flood deposits. Conversely, if the outer edge of the aeolian dune field gradually retreats (contracts), aeolian deposits may become overlain by flood deposits.

Above: (a & b) Mu Us Desert, China. (c) Wahiba Sand, Oman. (d) Simpson Desert, Australia.

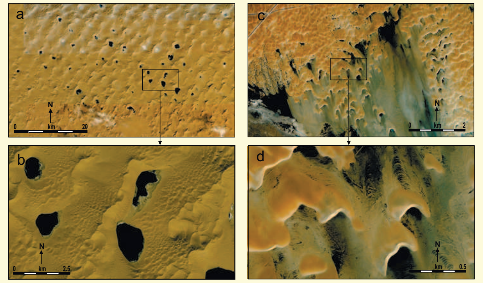
Bifurcation of fluvial flow between isolated aeolian dune forms



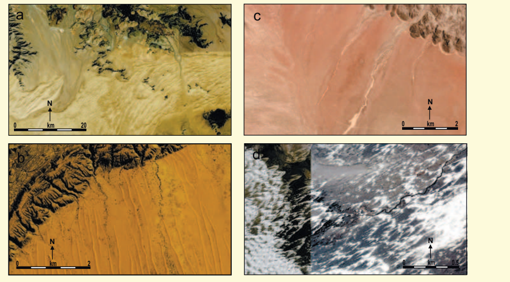
Through-going fluvial channel networks that cross entire dune fields



Aeolian dune-field flooding associated with elevated water-table level



Single point source fluvial incursions into aeolian dune fields

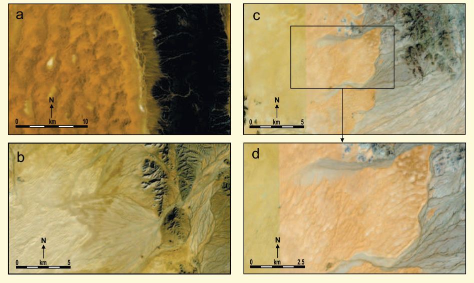


The geomorphological arrangement of landforms at the margins of desert sedimentary basins can act as a fundamental control on the nature of fluvial-aeolian interaction (Mountney, 2005). In many desert settings fluvial systems emanate from basin-bounding highland areas to pass as single-thread systems into the receiving desert basin in which aeolian dune fields are developed. An example of this is the wadis of the southern edge of the Rub' Al-Khali (Glennie, 1970). Thus, fluvial systems commonly intersect aeolian dune fields at specific points along their margins. One common scenario is where an aeolian dune field lies in front of a valley where a mountain stream emerges from its catchment. The confinement of the stream within a valley system, the short distance from the catchment to the aeolian dune field and the generally high gradient of the fluvial profile reduces the opportunity for fluvial avulsion, thereby confining the river to a single point over a protracted period.

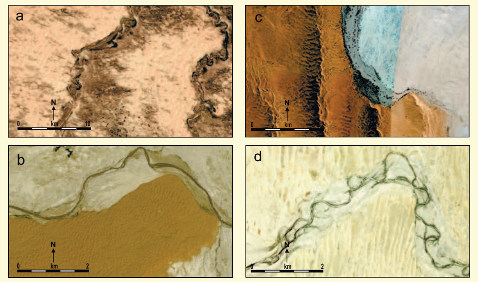
The sedimentary expression of single-thread fluvial channels will be limited to the zone of penetration of the fluvial system into an aeolian dune field and this will tend to be over a limited area in cases where the fluvial systems are fixed in position for protracted episodes.

Above: (a) Sonoran Desert, Arizona. (b) Simpson Desert, Australia. (c) Giribes Plain, Namibia. (d) White Sands, New Mexico, USA.

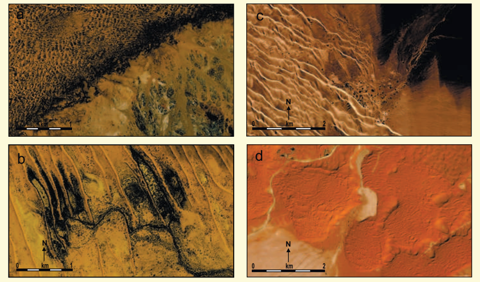
Sheet-like fluvial incursions into aeolian dune fields



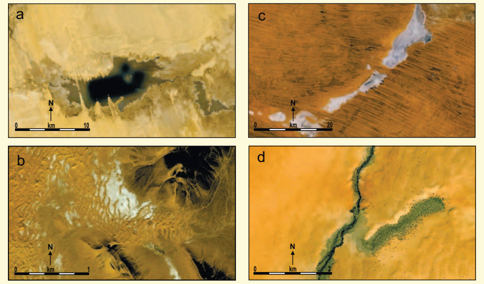
Cessation of encroachment of aeolian dune fields by fluvial systems



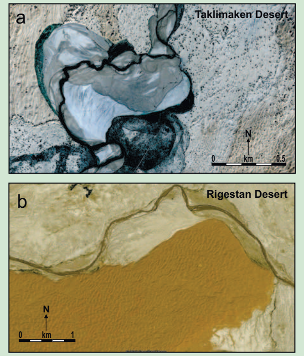
Termination of fluvial channel networks in aeolian dune fields



Long-term versus short-term styles of fluvial-aeolian interaction



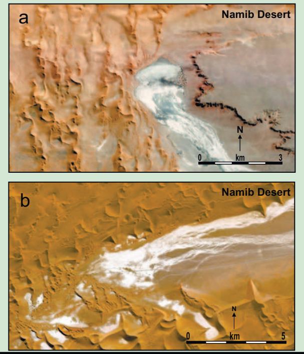
Fluvial flooding as a control on aeolian dune field expansion and contraction



Although climate is the dominant factor that controls the distribution and extent of sandy deserts, aeolian dune fields are present in a range of arid and semi-arid settings as well as in humid, non-desert settings, where sediment supply and wind regimes are sufficient to enable aeolian bedform construction. Climate can play an important role in driving the expansion and contraction of aeolian systems on seasonal and longer time scales (e.g., Herries-1993; Clarke and Rendell, 1998; Yang and Li Ding, 2013).

Channelized fluvial systems have the capability to erode and rework older aeolian deposits, thereby restricting the migration of aeolian systems (e.g., Pickup, et al., 2002; Bullard and McTainsh, 2003). The availability of water at or near the surface promotes colonization by vegetation, which may act to stabilize sandy substrates and thereby limit sediment availability for aeolian and dune construction (e.g., Levin et al., 2009). Floods events re-charge and raise the level of the groundwater table beneath aeolian dune fields, possibly resulting in the development of wet aeolian systems. This process limits the aeolian activity by restricting sediment availability; conversely, it increases preservation potential (e.g Mountney and Russell, 2009).

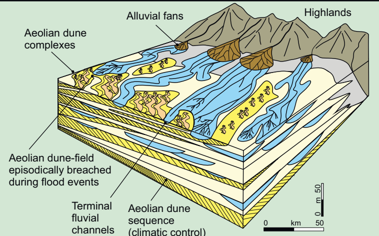
Geomorphic & sedimentary impact of fluvial-aeolian interactions



Where aeolian dune-field margins are characterized by connected trains of large aeolian dunes, fluvial systems may not be able to penetrate but instead by become ponded or be diverted in orientations parallel to the trend of the dunes at outer dune-field margin. Where flood waters pond, the water level may rise to a point where saddles (cols) between neighbouring dune crests are breached, thereby allowing fluvial incursion into inner parts of the dune field. Fluvial breaching at specific sites will rapidly lead to erosion and incision as flow if forced through a narrow gap between dunes. Examples where this process is known to occur include interactions around Sossusvlei (central Namib Desert) and along the Kuiseb River (northern margin of Namib Desert).

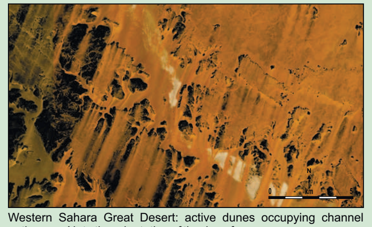
Dune-field margin

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 styles of interaction must be applied with caution when interpreting ancient preserved successions, especially those known only from the subsurface. An increased understanding of contemporary interactions serves as the basis for a database of modern analogues that can be used to account for types of aeolian-fluvial interactions preserved in the stratigraphic record.



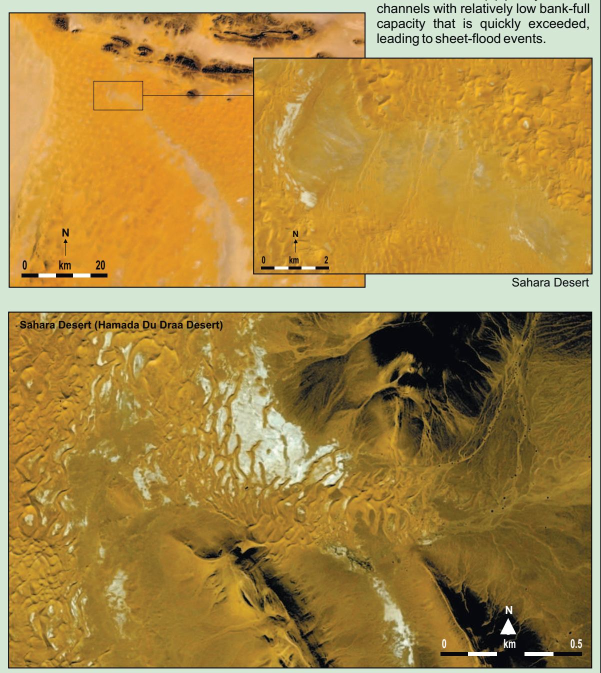
Modified After Cain (2009)

Fluvial & aeolian reworking of older desert deposits



Western Sahara Great Desert: active dunes occupying channel pathways. Note the orientation of the dune forms.

Rivers present in dryland settings are sensitive to climate and especially so where they pass through aeolian dune fields. Such systems are prone to flash floods due to several factors: (1) high-intensity rainfall events with rapid rise to peak flood discharge that exceeds bank-full channel capacity, leading to non-confined overland flow and flooding into the central parts of aeolian dune fields; (2) high-velocity of advancement of flood front; (3) presence of only modest vegetation cover, which is of minimal effect in retarding and dampening surface run-off thereby resulting in rapid rise to peak discharge as water collect into channel networks; (4) low infiltration capacity or rate where surface crusts are present, thereby leading to increased runoff; (5) poorly defined channels with relatively low bank-full capacity that is quickly exceeded, leading to sheet-flood events.



The inability of fluvial incursions to reach the interior parts of dry aeolian systems arises because of the increased density and connectivity of aeolian dunes and the closed nature of interdune depressions in central dune-field locations. This configuration limits the opportunity for aeolian sediment reworking via fluvial processes in such settings. Minor and localised fluvial streams may, however, develop in such settings in response to surface run-off associated with local rainfall events. Typically, sediment reworking associated with any such flows will be limited in extent and resultant deposits will be composed solely of fluvially reworked aeolian sand (Svendsen et al., 2003; Stromback et al., 2005).

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Approaches to Modelling Stratigraphic Heterogeneity in Mixed Fluvial and Aeolian Hydrocarbon Reservoirs

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Styles of Fluvial and aeolian system interaction in desert-margin settngs

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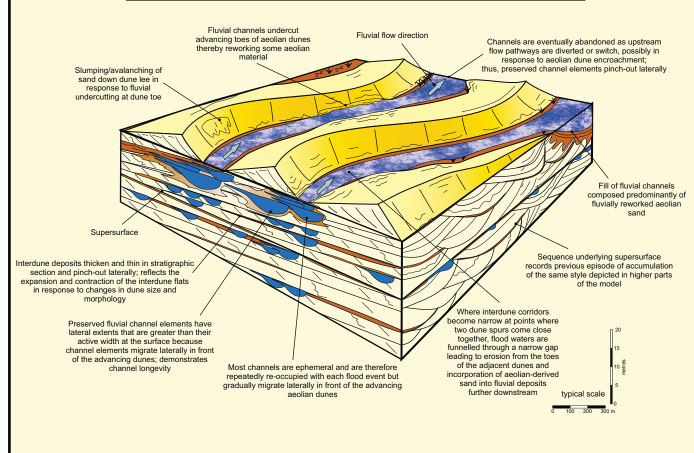
Mixed fluvial and aeolian reservoirs

Mixed fluvial and aeolian systems exhibit a range of styles of sedimentary interaction in many modern and ancient 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 fluvial and aeolian 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 fluvial and aeolian 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.

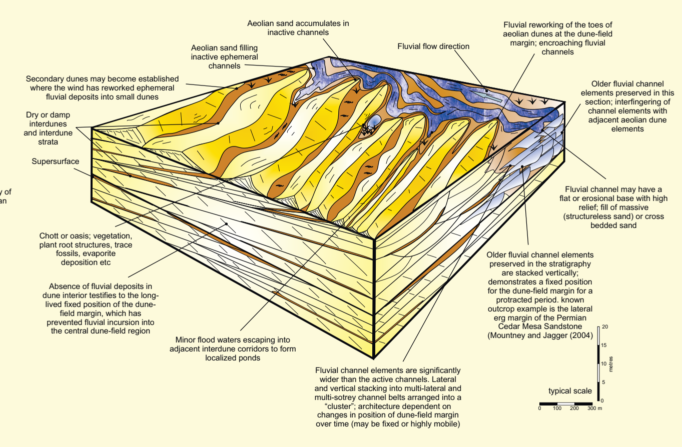
Implications for aeolian reservoir prediction and modelling

- Reservoir anisotropy in aeolianites 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 developing generic quantitative models with which to account for aeolian and mixed fluvial-aeolian 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 fluvial and aeolian 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 developed by bridging 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 which created the reservoir. 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, North and Prosser, 1993). 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., North and Prosser, 1993; 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., Herries, 1993; Mountney et al., 1998; North and Boering, 1999; Visser and Chessa, 2000; Newell, 2001; Bongiolo and Scherer, 2010).

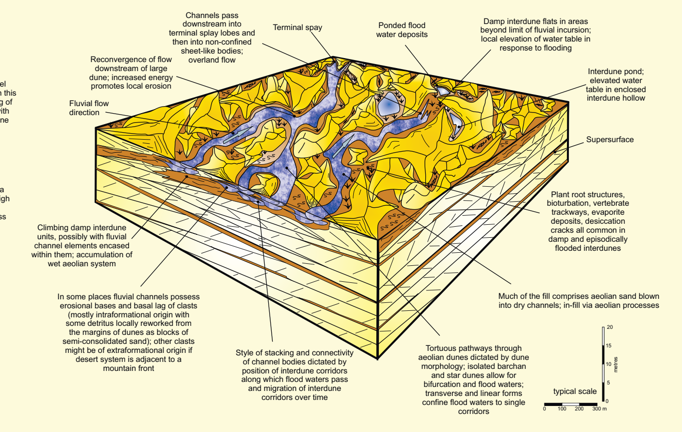
Fluvial incursions oriented parallel to trend of aeolian dune forms



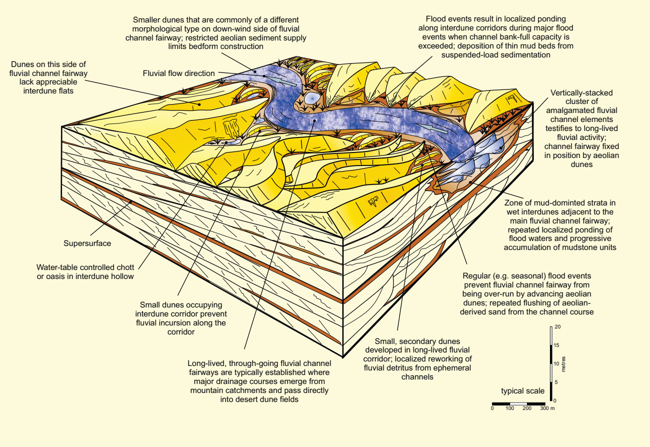
Fluvial incursions oriented perpendicular to trend of aeolian dune forms



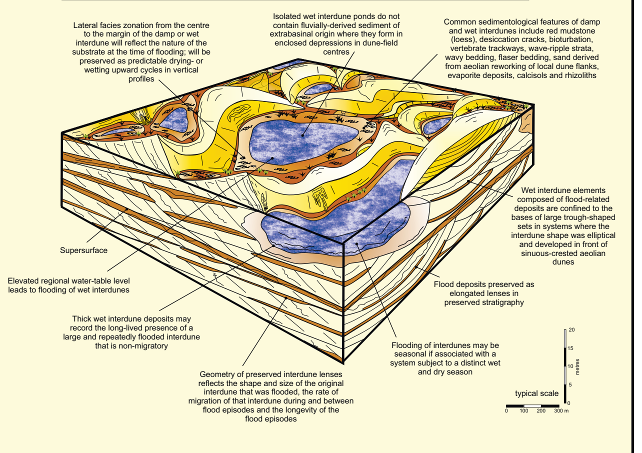
Bifurcation of fluvial flow between isolated aeolian dune forms



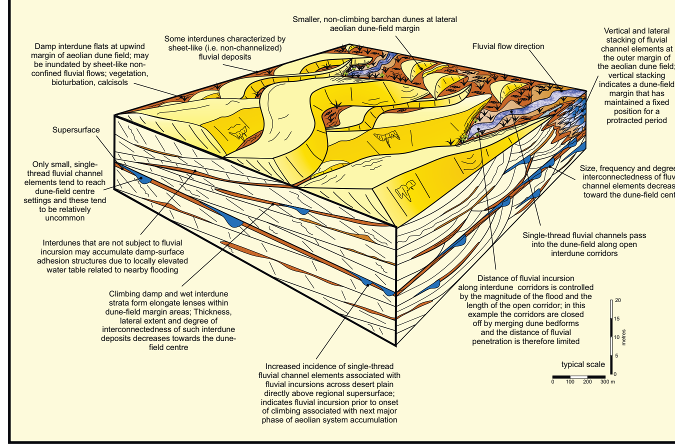
Through-going fluvial channel networks that cross entire dune fields



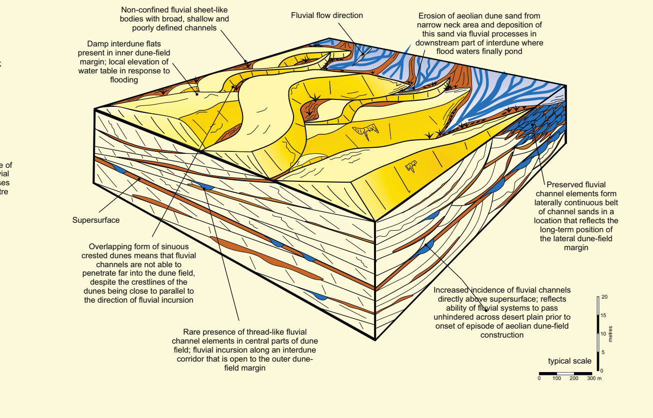
Aeolian dune-field flooding associated with elevated water-table level



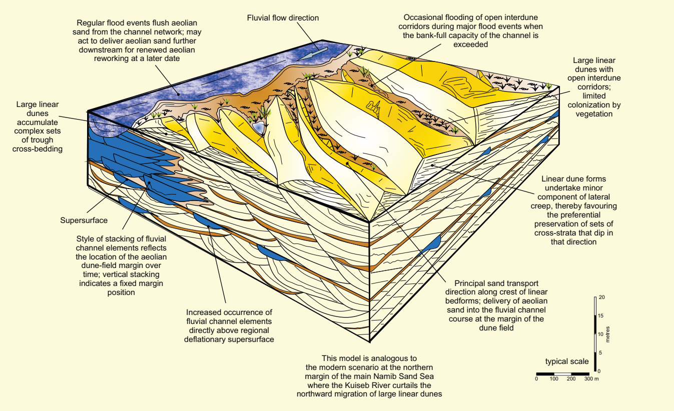
Single point source fluvial incursions into aeolian dune fields



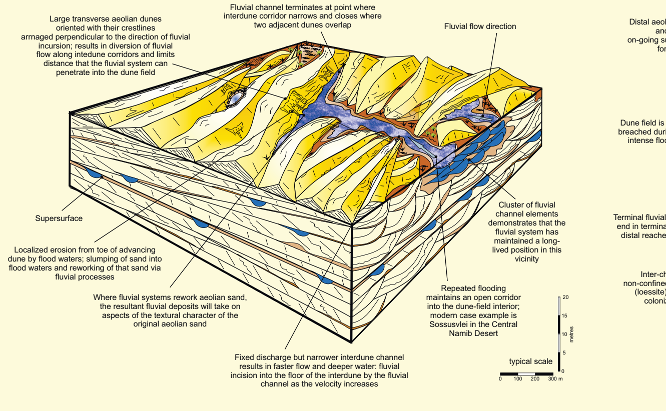
Sheet-like fluvial incursions into aeolian dune fields



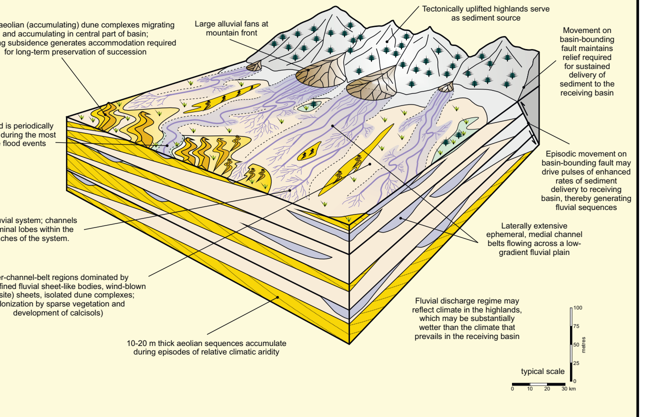
Cessation of encroachment of aeolian dune fields by fluvial systems



Termination of fluvial channel networks in aeolian dune fields



Long-term versus short-term styles of fluvial-aeolian interaction



Conclusions

The physical boundaries between many desert geomorphic systems are dynamic. Along desert dune-field margins where fluvial and aeolian 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.

Fluvial and aeolian 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 fluvial and aeolian 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 styles of aeolian and fluvial interaction and by considering their resultant sedimentological expression and mechanisms of accumulation, predictions can be made about how the preserved deposits of such interactions might be recognized in the ancient stratigraphic record.

Future work

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. 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.

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