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PS Spatial Variability in Eolian Dune and Interdune Morphology in the Rub' Al-Khali Dunefield, Saudi Arabia*

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Abstract

Significant lithological heterogeneities in eolian successions arise from the juxtaposition of dune elements with generally favorable reservoir properties against interdune elements that may act as baffles to flow. Prediction of the arrangement of such elements in subsurface successions is therefore important in developing eolian reservoir models, yet such predictions are difficult because the preserved thickness, continuity and internal facies composition of both dune and interdune elements vary spatially both locally and regionally. Important controls on spatial architectural variability include the morphology and migratory behavior of the original bedforms and their intervening interdunes at the time of accumulation.

The Rub'Al-Khali desert of Saudi Arabia is covered by the latest generation of public-release satellite imagery, which reveals a varied range of dune types, the morphology of which changes systematically from the dune-field center to its margins. Analysis of geomorphic relationships between dune and interdune sub-environments documents how the morphology, geometry, internal facies arrangement and relationship of the various depositional architectural elements produced by these geomorphic features vary over space from central to marginal settings. A series of quantitative approaches have been employed to characterize the complexity present in areas where large, morphologically complex and compound bedforms gradually give way to smaller, simpler bedform types at dune-field margins. Parameters describing bedform spacing, parent morphological type, style of subordinate bedform superimpositioning, bedform orientation, lee-slope expression, along-crest sinuosity and amplitude have each been recorded in a relational database, as have parameters describing interdune size (long and short axis dimensions), orientation, style of connectivity to neighboring interdunes, substrate condition (dry, damp, wet), and nature of any associated sedimentological processes. Results have been used to generate a series of synthetic 3-D stratigraphic architectural models with which to illustrate the range of possible sedimentological complexity expected for preserved eolian dune and interdune successions. This work has applied implications because interdune and dune-plinth elements typically act as principal and subordinate baffles to flow, respectively, in eolian hydrocarbon reservoirs, whereas dune lee-slope elements typically represent effective net reservoir.

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Spatial variability in eolian dune and interdune morphology in the Rub' Al-Khali dunefield, Saudi Arabia

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Abstract

Significant lithological heterogeneities in eolian successions arise from the juxtaposition of dune elements with generally favorable reservoir properties against interdune elements that may act as baffles to flow. Prediction of the arrangement of such elements in subsurface successions is therefore important in developing eolian reservoir models, yet such predictions are difficult because the preserved thickness, continuity and internal facies composition of both dune and interdune elements vary spatially both locally and regionally. Important controls on spatial architectural variability include the morphology and migratory behavior of the original bedforms and their intervening interdunes at the time of accumulation. The Rub'Al-Khali desert of Saudi Arabia is covered by the latest generation of public-release satellite imagery, which reveal a varied range of dune types, the morphology of which changes systematically from the dune-field center to its margins. Analysis of geomorphic relationships between dune and interdune sub-environments documents how the morphology, geometry, internal facies arrangement and relationship of the various depositional architectural elements produced by these geomorphic features vary over space from central to marginal settings. A series of quantitative approaches have been employed to characterize the complexity present in areas where large, morphologically complex and compound bedforms gradually give way to smaller, simpler bedform types at dune-field margins. Parameters describing bedform spacing, parent morphological type, style of subordinate bedform superimpositioning, bedform orientation, lee-slope expression, along-crest sinuosity and amplitude have each been recorded in a relational database, as have parameters describing interdune size (long and short axis dimensions), orientation, style of connectivity to neighboring interdunes, substrate condition (dry, damp, wet), and nature of any associated sedimentological processes. Results have been used to generate a series of synthetic 3D stratigraphic architectural models with which to illustrate the range of possible sedimentological complexity expected for preserved eolian dune and interdune successions. This work has applied implications because interdune and dune-plinth elements typically act as principal and subordinate baffles to flow, respectively, in eolian hydrocarbon reservoirs, whereas dune lee-slope elements typically represent effective net reservoir.

Geological Background

The study has involved analysis of parts of the Rub' Al-Khali desert or the Empty Quarter of south-eastern Saudi Arabia; a region that is home to one of the largest continuous sand deserts in the world, and occupies most of the southern part of the Arabian Peninsula with aeolian dunes and interdunes covering an area of 660,000 km^2.

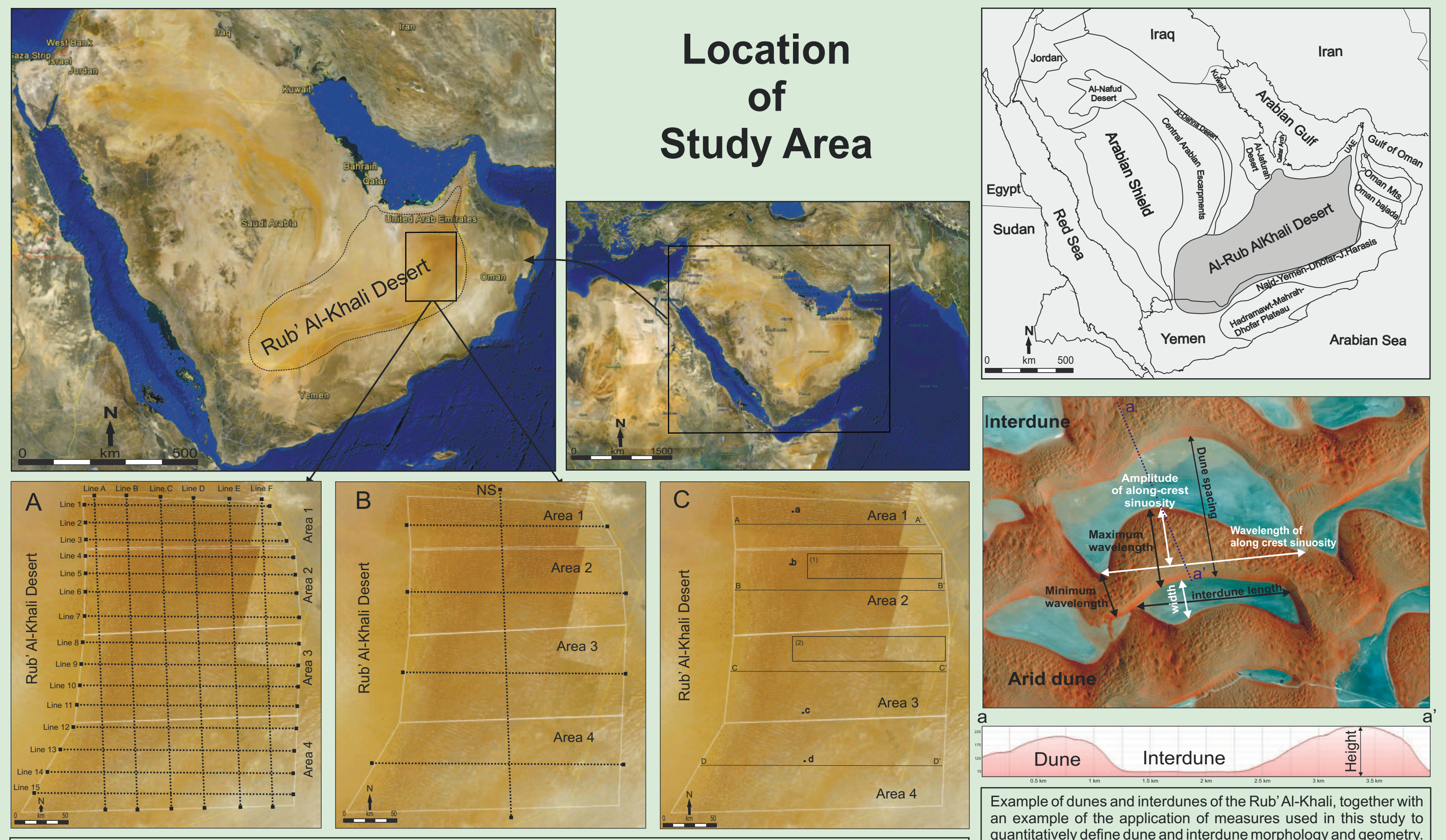
The Rub' Al-Khali desert lies in a structural depression that forms a sedimentary basin characterized as an embayment with a structural axis trending from northeast to southwest and bordered on the northwest and west by the Arabian Shield, and from the south and southeast by the Hadramawt-Dhofar Arch; the northern end of Rub' Al-Khali basin opens into the Arabian Gulf through the United Arab Emirates. The desert is also constrained by the great arc of the Oman Mountains and towards the northwest by Qatar Arch. The active sand sea extends from the United Arab Emirates and Oman in the east to south-western Saudi Arabia and the area directly north of Yemen.

Introduction & Concepts

Significant advances in our understanding of the spatial arrangement of eolian dune patterns have been made possible through the increasing availability of high-resolution satellite imagery in recent years. Eolian dune-field patterns are a product of self-organizing systems in which the development of simple or complex distributions of genetically related groups of eolian 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. This study utilizes the latest generation of public-release satellite imagery to quantify the form of geomorphic relationships between dune and interdune sub-environments in both the central and marginal parts of four modern dunes fields of the Rub' Al-Khali (Empty Quarter) of Saudi Arabia. The overall aim of this work is 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, style of bedform superimpositioning 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 styles 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. This research is important because understanding the morphology and architectural distribution of the deposits of aeolian dune and interdune sub-environments serves to constrain the development of models with which to explain the principal controls on desert dune distributions. Further, the establishment of spatial trends in dune morphology and geometry aids the reconstruction of ancient eolian palaeoenvironments and guides the prediction of sedimentary architecture in subsurface reservoir successions. Understanding the morphological complexity present in a range of modern aeolian desert systems is a primary control on preserved stratigraphic complexity and is the first step in developing a series of generic models with which improve our understanding of the mechanisms by which complex sedimentary architectures arise in ancient preserved eolian successions. Thus, there exists a need to document the morphology of modern desert systems to understand how spatial morphological changes in dune type and size might impact preserved stratigraphic architecture.

Data and Methods

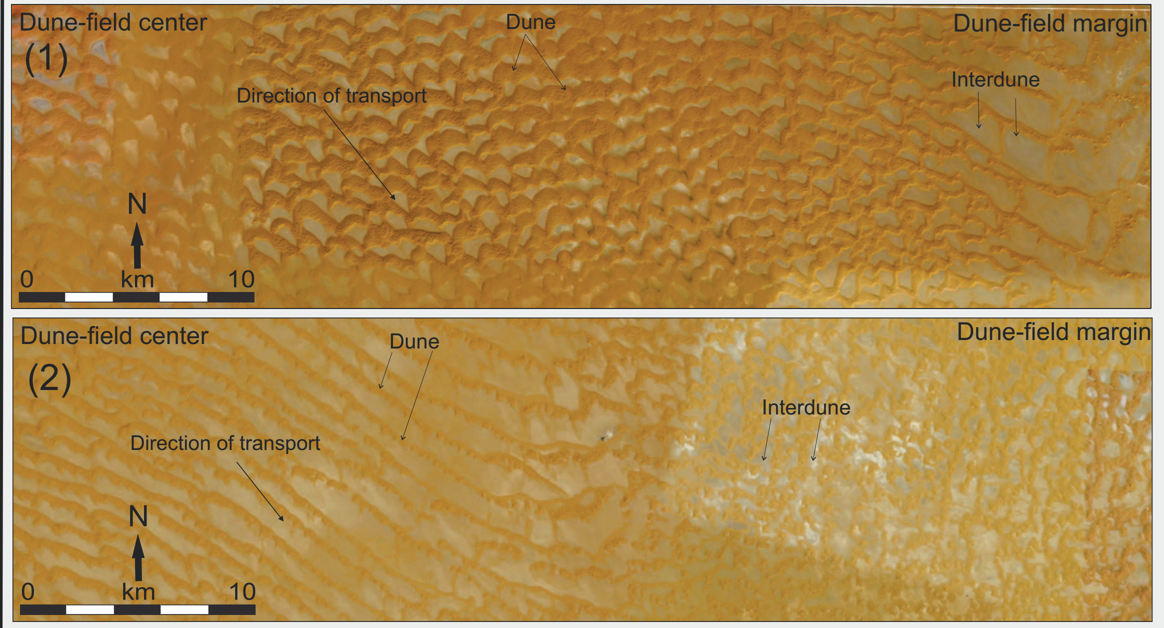
This study has entailed work in four distinct geographic areas of the Al Rub' Al-Khali, herein called Areas 1, 2, 3 and 4 (location maps), which collectively cover an area of 73,200 km^2. These areas were selected for study according to the following specific criteria: (i) chosen locations document spatial 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. Satellite imagery from the studied areas has a spatial resolution of resolution 15 m per pixel, derived from 15 to 30 m-resolution multispectral Landsat data that have been pan-sharpened with panchromatic Landsat image processing software. Individual high-resolution images are each 4800 x 2442 pixels and images recording adjacent areas have been seamlessly tiled to render larger visualizations of each study area. Collected dune and interdune data have been recorded in a relational database and this has been queried to discern trends between measured parameters. Spatial variation in both dune and interdune size and shape in directions both close to parallel and close to perpendicular to the overall direction of net sand transport has been recorded, with the resultant net direction of sediment transport having been identified from the analysis of dune bedform type and slipface orientation. Attributes recorded for dunes are bedform height, along-crest length, bedform spacing, maximum and minimum wavelength, planform wavelength and amplitude of along-crest sinuosity, bedform long-axis orientation, and distance from dune-field centre. Attributes recorded for interdunes are length, width, long-axis orientation, and distance from dune-field centre.



Maps of south-eastern Saudi Arabia showing the location of the studied areas, named 1, 2, 3, and 4. (A) and (B) Maps of the study areas depicting the location of transects from which quantitative data regarding dune (A) and interdune (B) morphology and geometry were collected. (C) Letters A-D refer to the location of the DEM images to the far-right. Lines A-A' to D-D' are transects across different locations in the study areas.

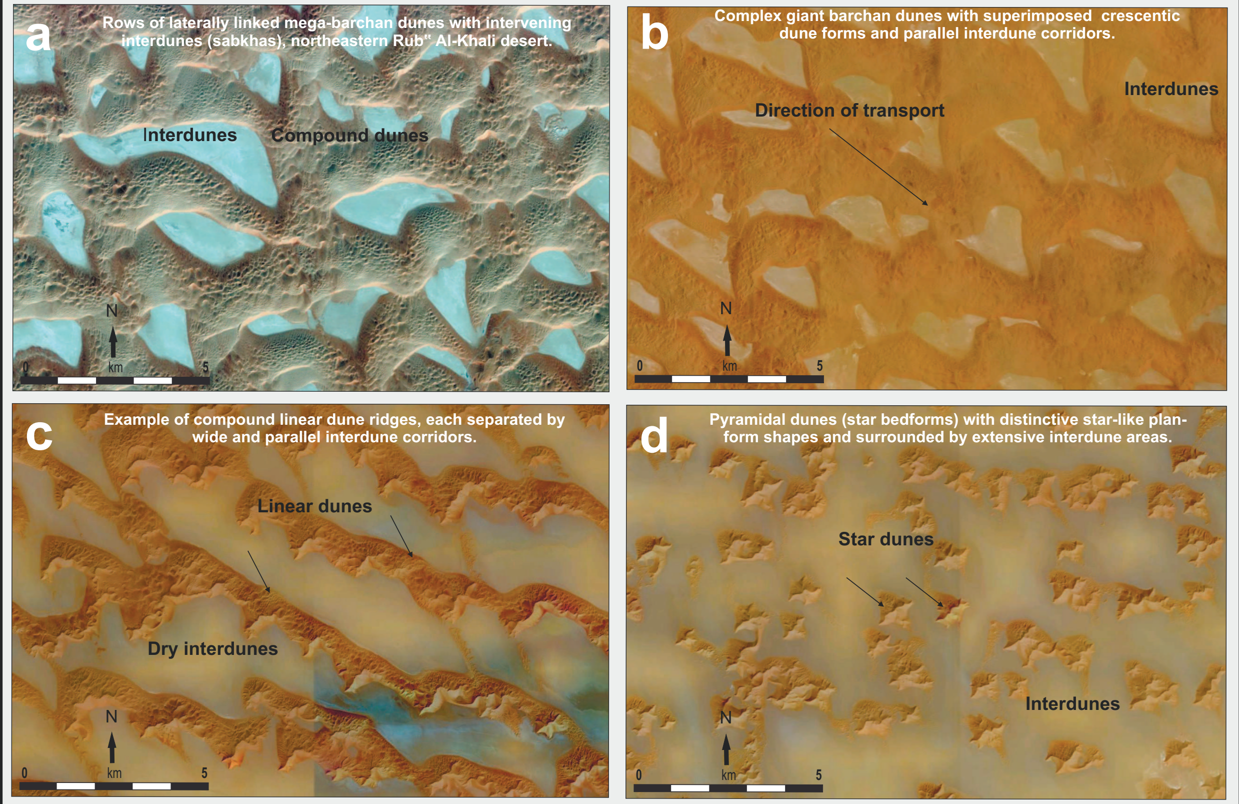
Example of dunes and interdunes of the Rub' Al-Khali, together with an example of the application of measures used in this study to quantitatively define dune and interdune morphology and geometry. Measurements (including cross-section a-a" shown in lower image) were made using Google Earth Pro software and were tabulated in a relational database to determine common trends that describe spatial change in morphology across the dune field.

Few eolian desert sand dunes exist in isolation. Most cluster, with many examples forming large dune fields in which systematic patterns of groups of genetically related dunes can be recognized, in some cases repeating with spatial regularity or with one or more defining attribute of the dune-form changing progressively in a given direction from, say, the canter of a dune field to its margin. Groups of dunes collectively form larger geomorphic elements typically referred to as sand seas, dune fields or ergs. Dune fields are not necessarily continuously covered with active eolian sand dunes and most additionally include other morphological bodies of eolian-derived or eolian-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 eolian 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.



Satellite images from the study area depicting the typical geomorphology of the dune fields and the variation in dune morphology and distribution from the central part of the dune fields toward their margins. Note the reduction in dune size in a direction toward the dune-field margins, and the increase in the extent and connectivity of interdunes and playa areas. Images from Google Earth Pro.

Modern eolian dune-field systems are composed of complex arrangements of geomorphic elements, including dunes, draa and interdunes, which occur on a range of scales and are characterized by a variety of morphologies and geometries. In many dune-field systems, the form of geomorphic elements and their relationship with adjacent elements varies systematically and predictably as a function of position within the overall eolian system.

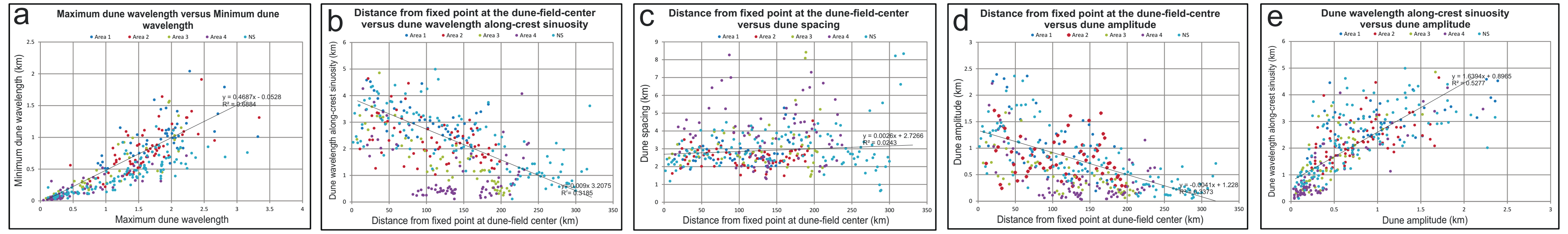


Satellite images from different locations across the Rub' Al-Khali desert depicting typical variations in dune and interdune morphology. Note the contrast in dune form and size between each image (all images have the same scale; see overview maps for locations). (a) Image from the northern part of Study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

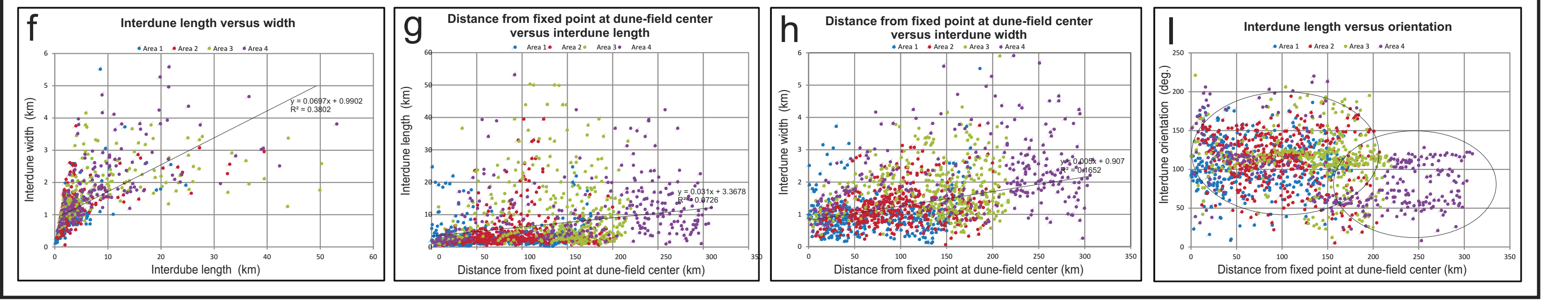
Cross sections from the study areas with elevation data reflecting variation in dune and interdune morphology and spacing from the center of dune field to the margin. The location of the cross sections is shown in Figure C on the overview maps. Digital Elevation data from Google Earth Pro are accurate to +/- 1 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 center 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 center 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 recognised 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.

Examples of data demonstrating relationships present in aspects of dune bedform morphology in the Rub Al' Khali dune field, showing the relationship between different parameters measured in the study area



Examples of data demonstrating relationships present in aspects of interdunes of the Rub Al' Khali dune field. The scatter plots demonstrate several relationships between measured interdune parameters



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Spatial variability in eolian dune and interdune morphology in the Rub' Al-Khali dunefield, Saudi Arabia, implication for reservoir prediction

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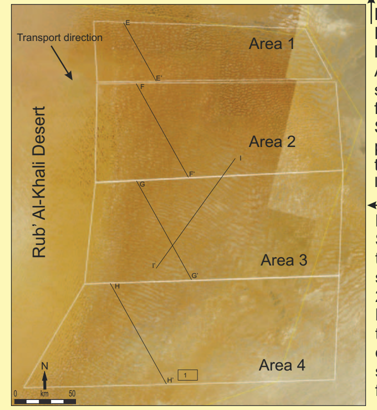
Rub' Al-Khali spatial variability

Many sand seas exhibit clear patterns of spatial transitionl of dune types, dune size and spacing, crest orientation and sediment thickness. Since the late 1970s, satellite images have been used to observe and illustrate spatially and temporally changing patterns of eolian sedimentation (dune and interdune type and style of interaction), including bedform distribution in the Rub' Al-Khali sand seas. Large compound and complex dunes of the Rub' Al-Khali are imaged in detail on the latest generation of public-release satellite imagery. Although eolian dune bedform types in the Rub' Al-Khali are many and varied, they can be categorized into three types at a fundamental level: transverse, linear and star forms, depending on whether the dune crest orientation is close to perpendicular or close to parallel to the dominant wind direction, or whether the forms exhibit a pyramidal morphology, respectively. These fundamental types of sand dunes are distributed into three regions: crescentic transverse dunes dominate in the northeast, linear dunes throughout the western half, and star dunes along the eastern and southern margins. The compound crescentic dunes in the north-eastern Rub' Al-Khali are mostly large, with a mean width of 2.8 km and mean length of 2.1 km. The compound linear dunes at the southwestern Rub' Al-Khali have mean width of 0.7 km and length of more than 100 km. Bedforms at the southeastern margin of Rub' Al-Khali are mainly complex star dunes. Dunes in sand seas are commonly separated from each other by extensive interdune-flat areas whose well defined shapes are associated with dunes of certain types, regardless of the scales of the dunes or their geographic location. Interdunes in the Rub' Al-Khali vary in shape and in size, with the size typically increasing toward the margins of the dune field, where the sand supply is less and the water table is closer to the depositional surface. Interdune lengths vary from 0.5 km at the dune field center to in excess of 21 km at the margin.

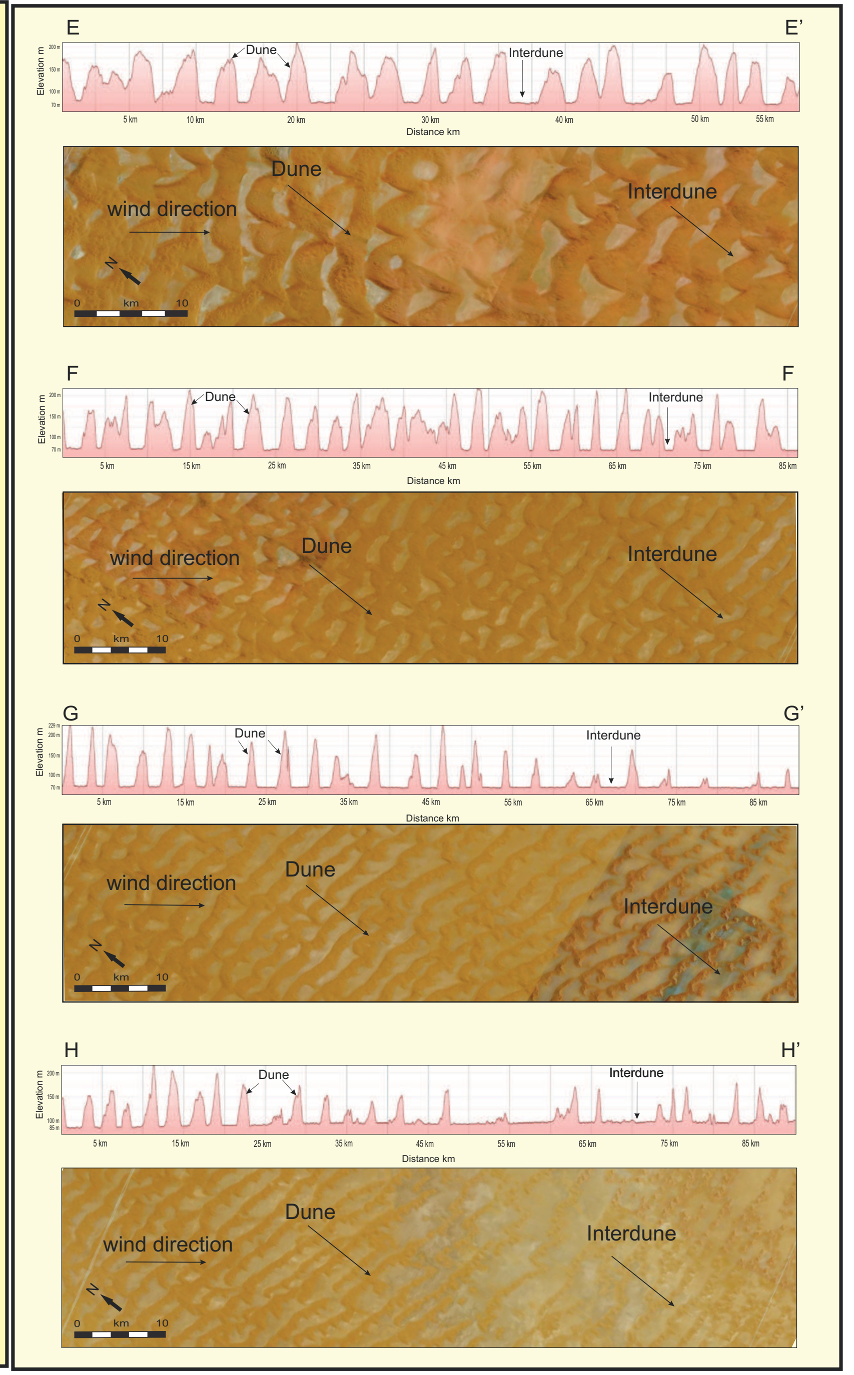
Map of the Arabian Peninsula showing the location of the Rub' Al-Khali desert, sand-seas within which are the focus of this study. Square highlights position of the figure to the right.
Image from Google Earth Pro.

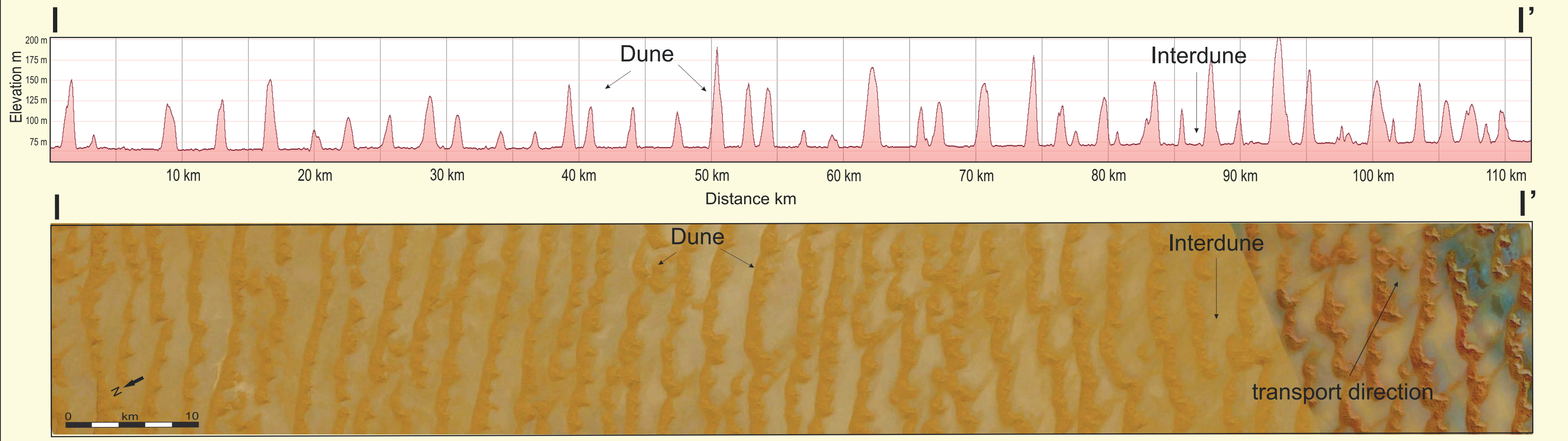


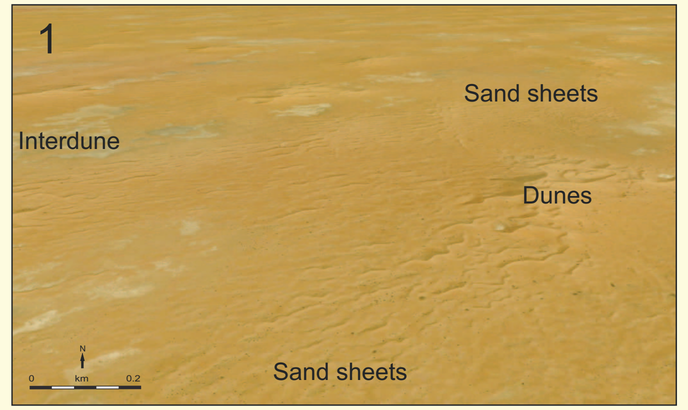
Map of south-eastern Saudi Arabia showing the location of the studied areas, named 1, 2, 3, and 4 for this study. Lines E-E' to I-I' are transects across different locations in the study areas shown in the figures to the right.

The extracted elevation data describing surface topography, which were acquired as a series of transects recording changes in dune spacing, height and morphology from different locations and in different orientations across the study areas, show clear examples of dune and interdune variability in the Rub' Al-Khali sand sea. The central part of the dune field contains the largest and most connected dune forms, many of which exceed 200 m in height (up to 230 m high), and this reflects bedform construction enabled by a large sand supply. Transects show spatially isolated interdune depressions within the central dune-field regions that 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.

In transects oriented in an upwind-to-downwind direction located in more central parts of the dune field (e.g. transects E-E' and F-F'), there exists no discernible downwind change in mean bedform height, wavelength or spacing. By contrast, in transects oriented in an upwind-to-downwind direction but located in the zone of transition between the central and marginal parts of the dune field (e.g. transects G-G' and H-H'), there exists a general reduction in dune height and wavelength, and associated increase in interdune width in a downwind direction and this is indicative of a spatial reduction in the availability of sand for bedform construction in downwind dune-field margin regions.



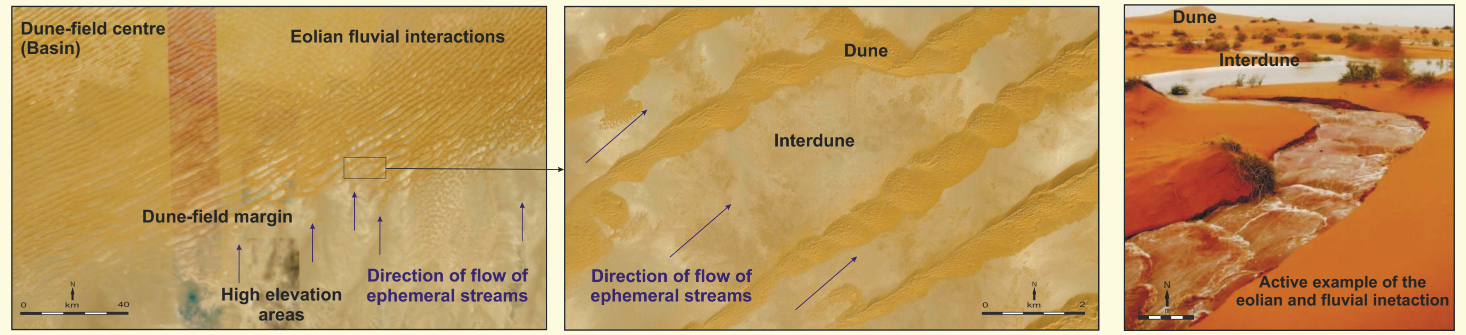




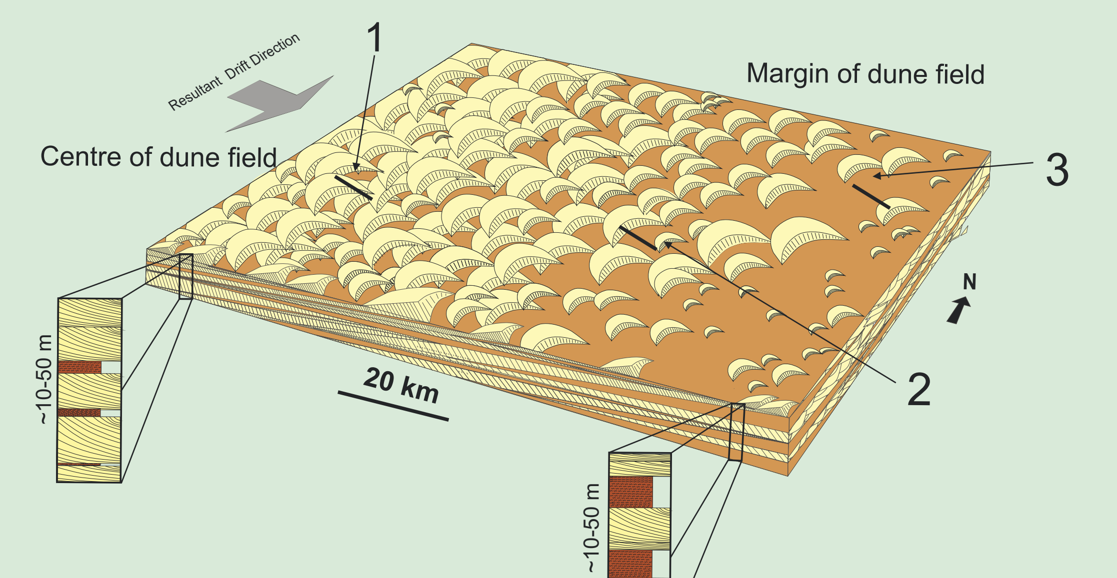
The Rub' Al-Khali comprises a series of dune fields, some spatially discrete and some merging into neighboring fields, within which self organised patterns of eolian bedforms and adjoining interdunes are developed. The largely unconsolidated sand dune deposits of the Rub' Al-Khali are characterized by large bedforms (dunes and draa), individual examples of which range from 50 to 250 m in height, and the majority of which are each separated by broad interdune flats, some up to 5 km in width in dune-field margin settings. The majority of the Quaternary sediments of the Rub' Al-Khali are composed chiefly of eolian reworked Pliocene alluvial sediments, and locally by modern alluvial (wadi) sediments.

The Rub' Al-Khali region is influenced by winds with a high drift potential (the energy of surface winds in terms of their capability to induce sand transport), chiefly because of the action of trade winds in mid-latitude depressions. Directional variability of effective winds – south-southwest in winter and northwest in spring and summer (the so-called Shamal wind) – influences both the sand transporting potential of the wind (and therefore the bedform migration rate) and the Resultant Drift Direction (itself a control on dune migration direction) in the Rub' Al-Khali. This explains the high system activity and the pronounced variety of bedform patterns, sizes and orientations. Unidirectional winds are responsible for the construction of large crescentic (barchan) dunes, which attain heights in excess 200 m in some areas in the northern part of the desert system. Seasonally varying Shamal winds form linear dune ridges; more complex multi-directional winds form the star dune complexes that dominate in the southern part of the dune field.

The majority of dunes in the studied sand seas are separated from each other by extensive interdune-flat areas whose shapes are at least partly dictated by the morphology of adjoining dunes of different types. Interdunes in the Rub' Al-Khali vary in shape and in size, with the size and continuity typically increasing toward the margins of the dune fields, where the supply of sand and its availability for eolian bedform construction is less, especially in areas where the water table lies close to the accumulation surface, such that the draw-up of moisture form the shallow subsurface via capillary action leaves the surface damp, thereby encouraging adhesion of sand. Open interdune corridors vary in length from 0.5 km in the central parts of dune fields to in excess of 50 km at dune-field margins; widths vary from 0.2 to 6 km.

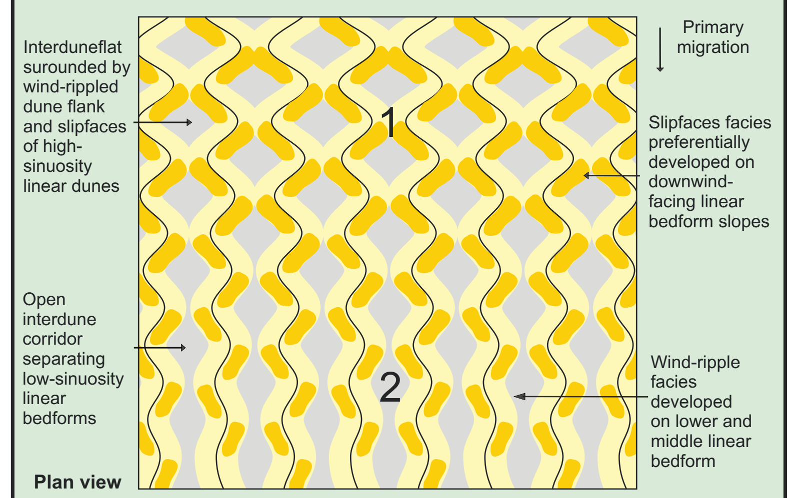


eolian and fluvial systems have important actions in landform development, they rarely operate independently and discretely in most arid to semi-arid environments. There is considerable interaction between the two systems that have important implication for the land geomorphology and preserved stratigraphy. The change in climate and structure usually dictate the interaction between depositional systems, therefore, it is difficult to construct realistic geological models based on single process domains.

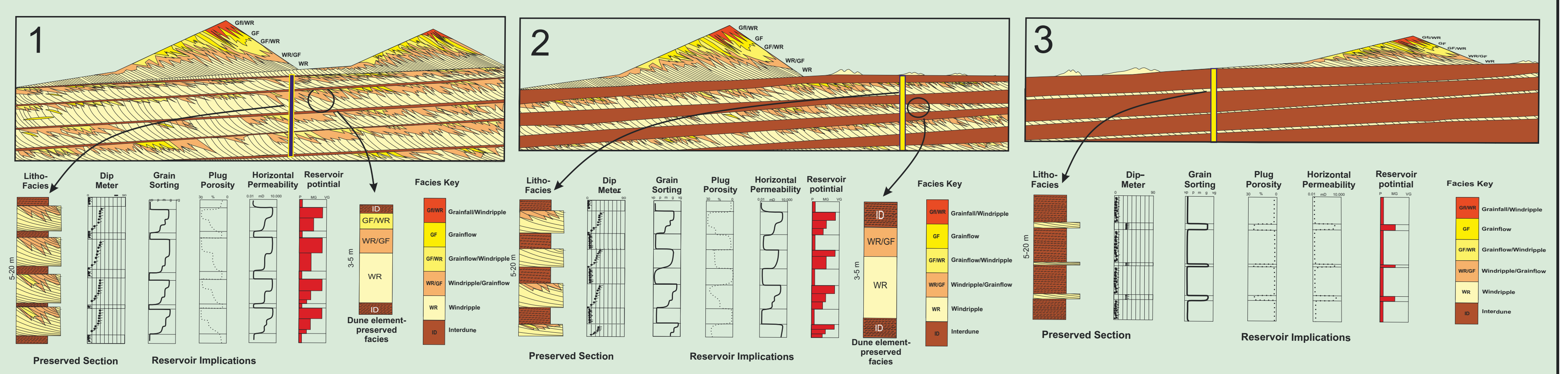


Studying modern desert dune-field analogs allows geologists to draw conclusions about the spatial pattern of desert systems and this knowledge can be applied to predict the likely arrangement of elements in preserved ancient desert paleoenvironments. This serves as the basis for the development of more sophisticated architectural-element and sequence stratigraphic models.

The analysis undertaken as part of this study regarding the geomorphic relationships between dune and interdune sub-environments within the modern active dune fields of the Rub' Al-Khali desert documents how the morphology, geometry, internal facies arrangement and relationship of the various depositional architectural elements produced by these geomorphic features vary over space from dune-field-center to dune-field-margin settings.



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 degree of interconnectivity 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 interconnectivity of dune slipface architectural elements). 2: an area of open interdune corridors separating low-sinuosity linear bedforms (reduced likelihood of interconnectivity 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. This study has quantified how eolian dune and interdune morphology can vary spatially in a variety of styles, in many cases predictably, across the zone transition from a dune-field center to its margin. This represents an important first step in developing generic quantitative models with which to account for eolian 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.

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Spatial variability in eolian dune and interdune morphology in the Rub' Al-Khali dunefield, Saudi Arabia, implication for reservoir prediction

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Implication for aeolian reservoir prediction and modeling

The data collected from the Rub' Al-Khali desert reveal changes across the sand sea, especially from the center of the dune field to its margin where the interdunes are wider and non-eolian sub-environments become increasingly dominant. The cut-off for the distance down the lee slope that the grainflow avalanches travel is a function of dune type, wind behaviour over time (direction, gustiness etc) and will vary around a dune field. At a local scale, variations in the development of dune lee slopes at the angle of repose whereby packages of grainflow strata accumulate is likely to be difficult to predict. The nature of eolian-dune reservoirs is strongly influenced by stratification types (in decreasing order of quality: grainflow, grainfall, wind-ripple deposits) and their packaging by internal bounding surfaces. The in turn, a function of dune surface processes and migration bedform, understanding of which enables the development of predictive models of reservoir behavior. Migrating, simple crescentic dunes produce tabular bodies consisting mainly of grainflow cross-strata, and tend to form the best, most predictable reservoirs. Reservoir character tends to improves, because fewer grainfall deposits and a lower percentage of dune-apron deposits occur in the cross-strata. It is probable that many linear and star dunes migrate laterally leaving a blanket of packages of wind ripple laminae reflecting deposition of broad, shifting aprons. This is distinct from models generated by "freezing" large portions of these dunes in place. Trailing margins of linear and star dunes are prone to reworking by sand-sheet processes that decrease potential reservoir quality. Compound crescentic dunes, perhaps the most preservable dune type, may yield (1) single sets of cross-strata, (2) compound sets derived from superimposed simple dunes, or (3) a complex of diverse sets derived from superimposed transverse and linear elements.

Mixed fluvial and aeolian systems

Mixed fluvial and eolian 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 fluvial and eolian successions are known to form several major reservoirs for hydrocarbons, including the Permian Unayzah Formation of Saudi Arabia, the Permian Rotiegend Group of the 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 eolian 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.

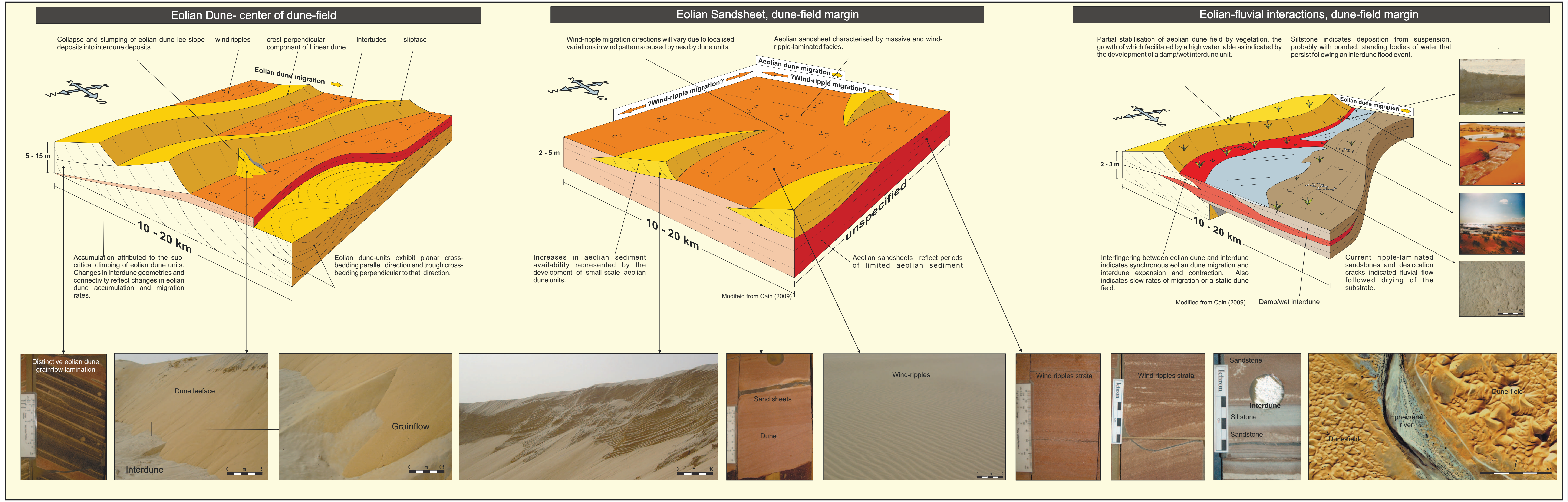
Eolian Reservoirs

Reservoir anisotropy in eolianites profoundly affects reservoir performance throughout the producing life of a field. Although eolian reservoirs are internally complex, they are predictable and can be managed effectively once their three-dimensional internal architecture has been accurately characterized and modelled. Temporal and spatial variations in original dune and interdune morphology can act as a primary control on resultant preserved set architecture. This study has quantified how eolian dune and interdune morphology can vary spatially in a variety of styles, in many cases predictably, across the zone transition from a dune-fieldcenter to its margin.This represents an important first step in developing generic quantitative models with which to account for 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.

Development of a series of qualitative and quantitative predictive models with which to account for the distribution of facies and architectural elements in eolian reservoir successions is important for the development predictive eolian sequence stratigraphic models. This ongoing study has utilized modern outcrop analog data for the development of a suite of tools and models designed to develop a bridging link between data provided by sedimentological studies and its appropriate application in the construction of reservoir models.

Eolian-Fluvial Interactions

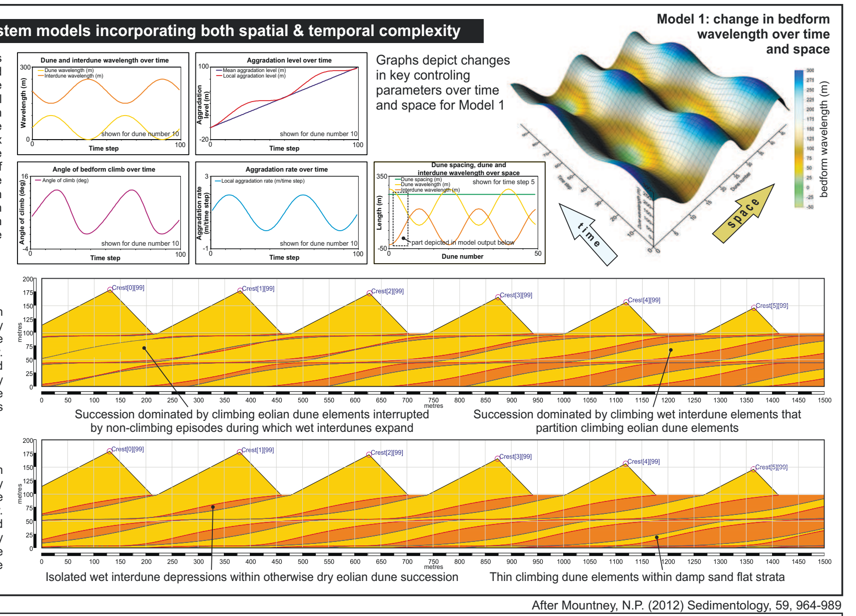
Eolian and fluvial systems exert an important control on landform development, they rarely operate independently and discretely in most arid to semi-arid environments. There is considerable interaction between the two systems that have important implications for the landform geomorphology and preserved stratigraphy. The change in climate and structure usually dictate the style of interaction between depositional systems, therefore, it is difficult to construct realistic geological models based on single- process domains.



Modelling temporal and spatial variation in eolian dune elements

Dynamic eolian system models incorporating both spatial & temporal complexity

Dynamic models incorporating both spatial and temporal complexity generate the most complex stratal architectures in which eolian dune elements vary in size and geometry in a complex manner. Such models can be used to account for many of the complex dune-interdune stratal architectures known from dune-field margin systems such as the Permian Cedar Mesa Sandstone (Mountney & Jagger, 2004).



Model 1

Dynamic model in which dunes reduce in size spatially in addition to varying in size and angle of climb temporally. Wet interdune units expand and become increasingly interconnected towards the dune-field margin. Bypass supersurface generation.

Model 2

Dynamic model in which dunes reduce in size spatially in addition to varying in size and angle of climb temporally. Wet interdune units expand and become increasingly interconnected towards the dune-field margin. Note difference to Model 1.

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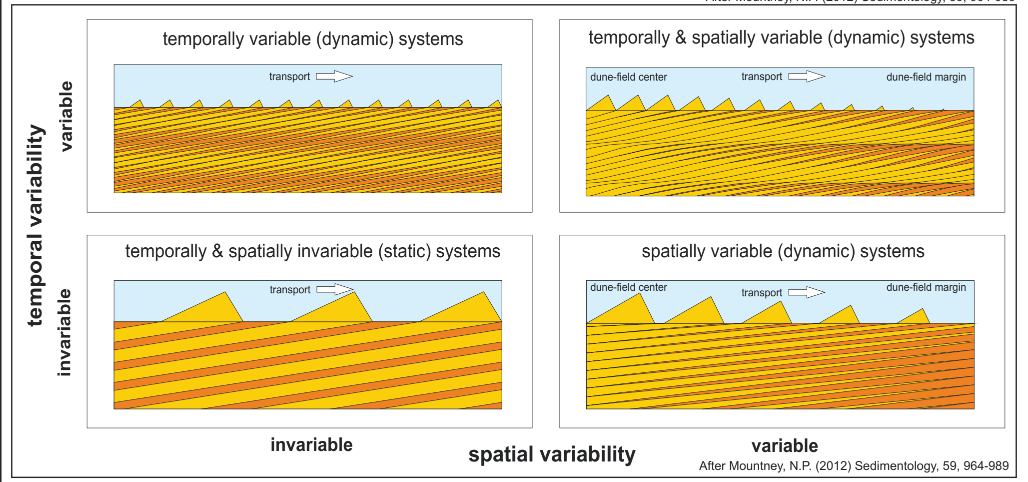
Dynamic model output from DuneModeller stratigraphic modelling software to account for the accumulation of dune and interdune elements in response to spatial variation in dune size from a relatively dry system in the erg center setting to a water-table-controlled erg margin setting and temporal variation in dune size and angle of climb. Model 1: interdunes expand to their maximum extent at times of non-climbing bypass supersurface generation. Graphs depicting the values of controling parameters are shown. The graphs depicting temporal change are for the outer margin of the dune field (not shown on the cross section of resultant architecture) where the dunes vary in wavelength from 0 to 100 m over time. Model 2: interdunes expand to their maximum extent at times of maximum angle of system climb.



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A simple scheme for the classification of dune and interdune elements according to their spatial and temporal variability. Examples of dune and interdune stratigraphic architectures resulting from various combinations of spatially and temporally invariable and variable controlling conditions. Dune wavelength, interdune wavelength (which together define dune spacing), lateral migration rate and vertical accumulation rate are four fundamental variables that can vary either spatially or temporally and which act to dictate the geometry and architecture of eolian system accumulations.

Conclusion

Satellite imagery of dunes and interdunes in desert dune fields has provided the basis of an approach for qualitative and quantitative studies of patterns of arrangement of large-scale eolian bedforms and adjoining interdunes in large and widely distributed sand seas. Collection of data relating to primary landform morphology has enabled an improved understanding of modern desert sedimentary systems and the spatial arrangement of various sub-environments within these systems. In particular, the morphological changes and distributions of eolian 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 eolian preserved successions, several of which form important reservoirs for hydrocarbons. The observations from modern dune-field margins have enabled the spatial rate of change of morphology of eolian sub-environments to be characterized and described through empirical relationships. Results are enabling the proposition and development of a range of dynamic facies models for eolian systems that can be used as predictive tools for subsurface reservoir characterization. A combination of morphological and architectural data from a range of modern dune fields and their ancient counterparts preserved as successions in the geologic record can be used to constrain forward stratigraphic models for the prediction of eolian reservoir heterogeneity. Such heterogeneity is likely to vary in three-dimensions within a reservoir volume. The Rub' Al-Khali of south-eastern Saudi Arabia is covered by the latest generation of public-release satellite imagery, which reveals a varied range of dune types, the morphology of which changes systematically from central dune-field areas to marginal areas where aeolian interdunes, sand sheets, and ephemeral fluvial systems dominate. Analysis of geomorphic relationships between dune and interdune sub-environments within a series of modern dunes fields of the Rub' Al-Khali has been undertaken to document how the morphology, geometry, internal facies arrangement and relationship of the various depositional architectural elements produced by these geomorphic features vary over space from dune-field-center to dune-field-margin settings. Analysis of this active modern dune-field system shows a characteristic reduction in eolian dune size and degree of connectivity and a corresponding increase in interdune size and degree of connectivity towards outer dune-field margins. A series of quantitative approaches have been employed to characterize the complexity present in a range of dune-field settings where large, morphologically complex and compound bedforms gradually give way to smaller and simpler bedform types at dune-field margins. Parameters describing bedform spacing, parent morphological type, style of subordinate bedform superimpositioning, bedform orientation, lee-slope expression, along-crest sinuosity and amplitude have each been recorded in a relational database. Additionally, parameters describing interdune size (long and short axis dimensions), orientation, style of connectivity to neighboring interdunes, substrate condition (dry, damp, wet), and nature of any associated sedimentological processes are also recorded.

Future work

Given the economic importance and complex stratigraphic and sedimentologic nature of eolian successions, it has become essential to develop both qualitative and quantitative models with which to account for dynamic spatial and temporal aspects of eolian system behaviour at the dune-field scale. 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 eolian 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 eolian hydrocarbon reservoirs, whereas dune lee-slope elements typically represent effective net reservoir. Results from this study are being used as input into reservoir models with which to account for heterogeneity in aeolian successions and with which to make reservoir predictions.

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