PSSedimentology of Reservoir-scale Aeolian-Fluvial Interactions, Wadi Batha, Northern Wahiba Sand Sea, Oman*

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Abstract

The Wahiba Sands are a coastal dune field of about 12,500 km^2 in northeast Oman. The evolution of the Wahibas has occurred in distinct stages defined by changes in fluvial and wind processes over the last 230,000 years (Goudie et al., 1987; Pease, 1999; Radies et al., 2004; Pease and Tchakerian, 2004; Robinson et al., 2007; Glennie et al.; 2011; Pease and Tchakerian, 2014). These multiple growth (and erosion) stages have been driven by glacially controlled fluctuations in the strength and direction of the monsoonal wind system, in the activity of major drainages, and in sea level (Glennie et al., 2011). The dune field has been characterized by barchanoid and linear dunes of various sizes that dominate at various times, but has had few if any star dunes. Our study area is in the northern Wahiba Sands along Wadi Batha, where we focus on the interaction of modern wind and water processes along the wadi, and the resulting sedimentary facies. In this area, northward- migrating linear megadunes and smaller barchan and linear dunes encounter the south and eastward directed ephemeral flows in Wadi Batha. Our study was aided by the fact that there are two basic populations of sand found along Wadi Batha. First, there are reddish, well sorted, quartzose sands blown into the wadi from the south as small dunes, or as streamers. Second, there is a population of dark sands and gravels brought down Wadi Batha by floods from the Oman Mountains. These sediments consist of dark mafic sands and gravels from ophiolites in the mountains, with some dolomites and quartz sands from Hawasinah Formation outcrops.

Using modern weather records, we describe the seasonal wind energy distribution for Oman and the Wahiba Sand Sea. Our sand trap measurements and field observations confirm that there is currently a geologically significant northward drift of sand in the northern "High Sands" of the Wahiba and onto the course of ephemeral Wadi Batha. This study has further shown that the Wahibas exist in an annual climate regime in which peak wind energy is offset from peak rainfall, creating a "flood-and-dry" environment of deposition. During winter rains (and some summer convective storms) the aeolian deposits including the High Wahiba are truncated by floods moving down Wadi Batha. The sand eroded from dunes and other aeolian deposits is recycled into fluvial deposits. In summer, the wind becomes dominant, creating small dune fields and sand sheets in the floodplain of the wadi. During this time, the wind will pick-up fluvially deposited sand and in turn, recycle it into

aeolian deposits. Our trenches revealed that these basic process regimes have created complex facies variants that are intermixed at fine (trench) scale within the floodplain of the wadi. Our further studies illustrate that, should such sand packages become petroleum reservoirs, they will have high heterogeneity and restricted sweep efficiency.

Main Climatic Results

- A wind energy gradient exists along the east coast of Oman, characterized by strong winds at the coast grading to weaker winds inland.
- Wind regimes along the coast are regionally compatible with barchanoid and linear dunes, with subtle variations due to bedrock terrain, and to antecedent aeolian bedforms.
- A wind energy gradient across the High Sands from east to west has caused differences in relative dominance of wind versus water deposition in and along Wadi Batha. In the west, where winds are weak, fluvial processes dominate. In the east, where winds are stronger, aeolian processes dominate, and ultimately overwhelm the wadi channel.
- Peak rainfall in the catchment of Wadi Batha (Oman Mountains) occurs in winter, while the strongest wind season is during the summer Indian Monsoon. This offset creates alternate dominance of wind and rainfall processes within a single year. Rainfall and resultant floods dominate in winter, aeolian processes in summer.
- One unanticipated event during our sand trap studies was the occurrence of typhoon Gonu. This storm tracked close to Muscat with strong winds, heavy rain and flooding. Our measurements confirmed that extreme tropical storms, such as typhoon Gonu, can temporarily reverse the dominant northward drift of windblown sand in the Wahibas. Rainfall from Gonu also caused the entire northern Wahibas to “green up” with fresh grassy vegetation. However, we could not document any long- term effect on the dune field as a result of Gonu.
- Floods along Wadi Batha sink into the Wahiba Sands near the extensive agricultural oases of Al Khamil and Jalan Bani Buhassan. The original watercourse beyond these towns, mostly dry these days, continues northward and reaches the coast of the Indian Ocean at a barred lagoon 19 km north of Al Ashkharah.
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Main Sedimentological Results

- Trenches in the floodplain of Wadi Batha revealed complex, small-scale interbedding of aeolian and fluvial sediments. Trenches sometimes exhibited upward-drying or upward-wetting cycles, depending upon location. In other places fluvial and aeolian sands appeared to be stacked “randomly” in the trenches.
- Eolian geobodies in Wadi Batha are elongate parallel to the dominant current direction (southeast). Dunes formed on these geobodies are oriented with respect to the wind from the south. Linear dunes extend toward the north, with alternate west- and east-facing slipfaces. Barchan dunes have slipfaces facing north most of the year. This produces surprising cross-bedding patterns in the resultant geobodies that are of interest from the standpoint of petroleum reservoir modeling.
- Both fluvial and aeolian genetic units in the outcrops and trenches, which ranged from 3.0 to .5 meters deep, thin upward on average, perhaps due to local accommodation space controls.
- Aeolian geobodies in the Wadi Batha floodplain are mainly sand sheets, with dunes and interdunes as secondary facies.

- Fluvial geobodies of small size have built-up a broad, undifferentiated floodplain. Sand bars and gravel bars are the constructive elements. Fluvial bar geobodies are small compared to aeolian geobodies; however, they build thick composite sequences to form the floodplain. Where exposed in deep cuts and excavations, these sequences commonly consist of stacked bar forms with interbedded aeolian sands.
- Fluvial processes shape the proportions of both aeolian and fluvial geobodies; however, aeolian geobodies - namely sand sheets and dune fields - tend to be much larger than fluvial gravel and sand bars.
- Fluvial floods are mostly shallow, balanced between sheetfloods and channelized flows at various places during the same event. Floods typically last a few days, followed by ponding and drying; thus "flood and dry" sequences tend to form and be preserved.
- Sand is presently sourced along the wadi from Oman Mountains to north by fluvial floods, and from the south by wind flows. The Oman Mountains (sourced) sediments consist of poorly sorted dark sands and gravels, with some light suspended fines from erosive particles and weathering products of ophiolites, volcanic rocks, and dark carbonates. Sands from the High Wahibas are reddish-whitish and moderately to well sorted. They consist of a sub-arkosic mix of quartz, commonly with red clay coatings on the grains, feldspar and carbonate. The different colors and textures associated with two different local sources for sediment have helped us interpret the process frameworks that produced the lithologies seen in our trenches.
- Interdunes of the large linear megadunes are commonly flooded a few hundred meters southward from places where they intersect Wadi Batha. These floods are commonly low-velocity "overbank" type events spilled from the main channels. They deposit a mix of suspended load muds, and some fluvial sand bars. These sediments ultimately become interbedded with aeolian sediments of the interdune.
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Applications to Oil and Gas Exploration and Development

- It is likely that the small-scale intercalation of aeolian and fluvial sands, with differences in cross-bedding and texture, would, if preserved, create distinctive small-scale flow units in petroleum reservoirs.
- Preliminary models injector-producer models based on our trenches suggest that inefficient sweep of hydrocarbons may occur in a reservoir with lithologies similar to those seen in our trenches. This is due to inherent permeability contrasts at bed and lamination scale, and the small size of geobodies that comprise the petroleum reservoir.

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Sedimentology of reservoir-scale a -fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman

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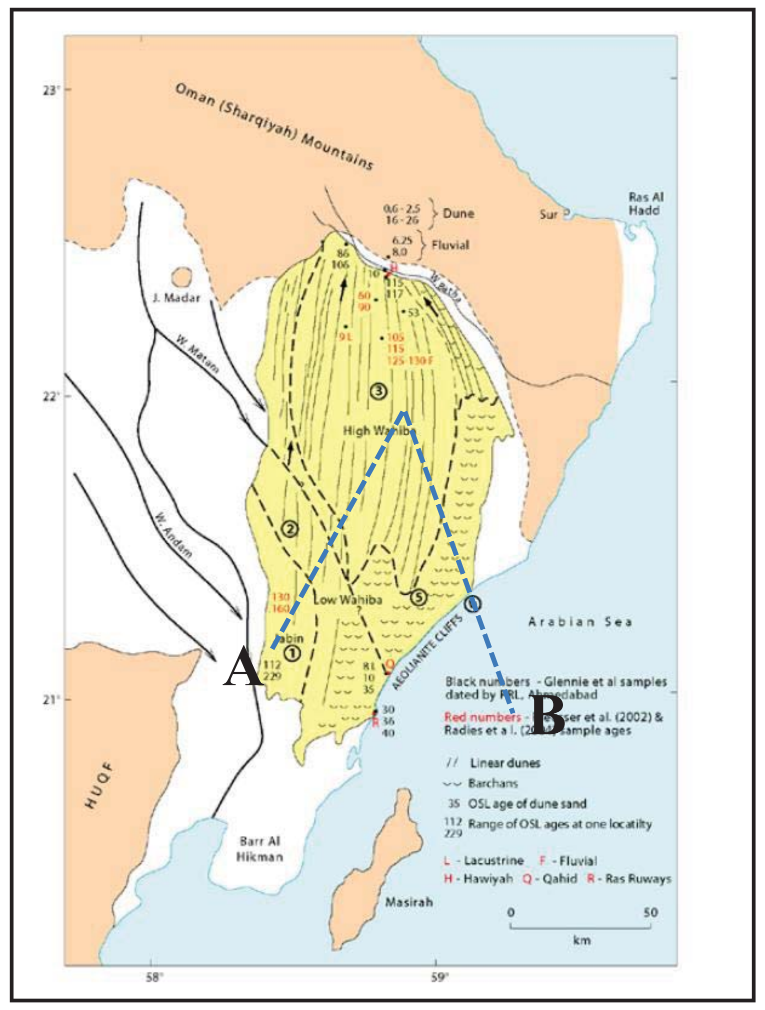
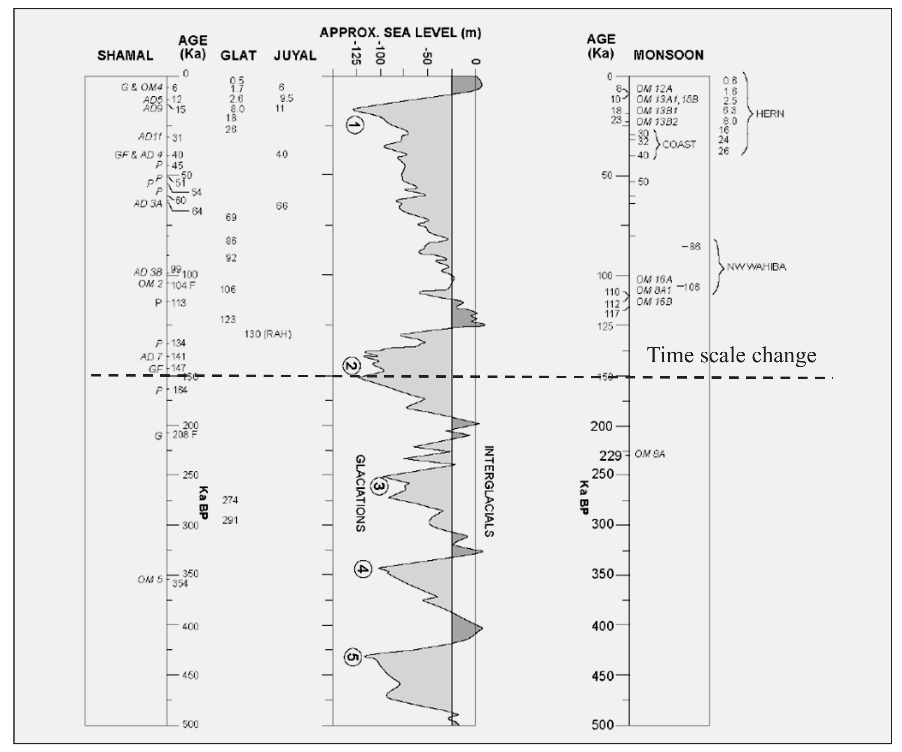
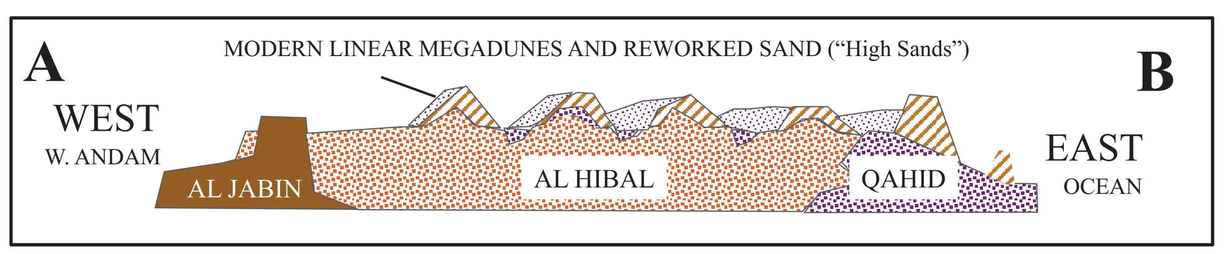
Poster 1: Abstract and Geological overview



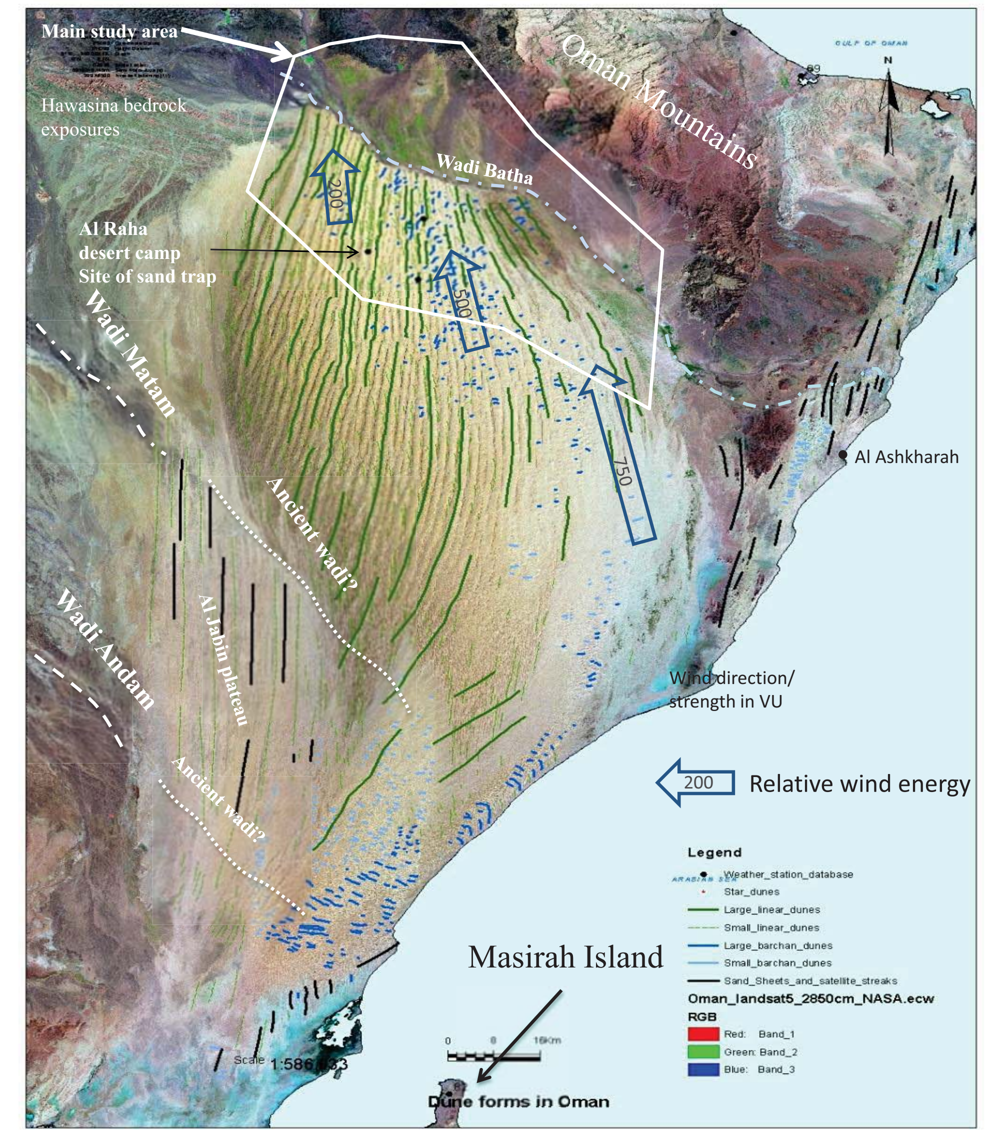
Summary dates in and around the Wahiba Sands, with an outline of the five major divisions of the Wahiba Sands. Linear and transverse dunes that comprise the main geographic and age units are shown schematically. This study is concerned with Wadi Batha along the northern margin of the High Wahiba. Black numbers indicate ages of sands (1000 ka) dated at NPL and those in red at other dating centers. Area 5 "Barchans" are mainly transverse (barchanoid) dunes. (After Glennie, et al, 2011).



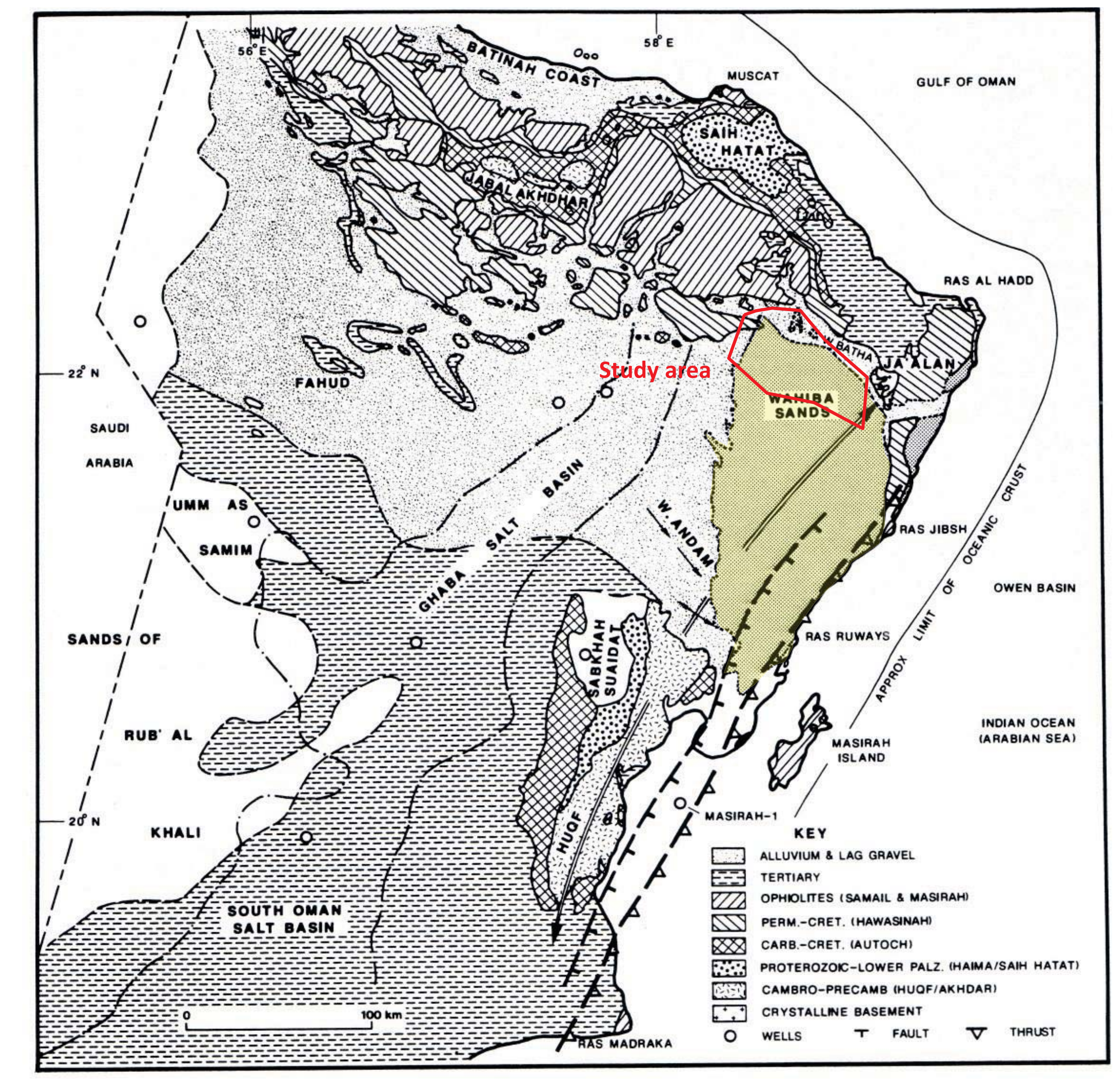
Above: A simplified diagram showing of changes in global sea level over the past 500 ka (modified from Boulton, 1993). Note the change in time scale at 150 ka. Distribution of OSL dated sands (1000 ka) of SW Monsoon origin is in right-hand column and those of Shamal origin to the left of the sea-level curve. Boundary between glacial and interglacial conditions is shown arbitrarily at 25 m below present sea level. Samples marked G and P in the Shamal column were collected separately by Goodall and Pugh and dated in UK. Although the issues and story of age dating in the Wahiba Sands is not our focus in this report, we present these summaries to provide a framework. The reader is referred to referenced publications and bibliography on the last slide of this report for further discussion and information on the stratigraphy of the Wahiba Sand Sea as a whole. (After Glennie, et al, 2011).



A rough stratigraphic cross section through the Wahiba Sands (route shown on map to left), after Radies, et al. (2014).



Landsat image of the Wahiba Sand Sea and surrounding regions. Dune types are shown by colored lines. Dark and light green lines represent large and small linear bedforms, respectively. Dark and light blue lines represent the traces of slipfaces of large and small barchanoid dunes respectively. Black lines show streaks caused by strong winds on the land surface – probably small dune fields, sand sheets and wind scour depressions. We observed no star dunes in the study area. Landsat imagery was processed by Petroleum Development Oman. Our study area along Wadi Batha is shown by the white polygon.



A geological map of regions surrounding the Wahiba Sand Sea, after Glennie (1988). This map shows structural elements and sand source areas. Dark sediments from the Samail and Masirah ophiolites as well as the dolomites and lighter sands and carbonates of the Hawisinah probably sourced much of the Northern Wahibas (Pease and Tchakerian, 2002, 2014). The present situation is good for sedimentologists, because Wadi Batha fluvial sediments are dark, and the sands of the Dunes of the northern Wahibas are mostly reddish. Thus, it is possible to infer source systems of sediments within the mix of sub-environments along Wadi Batha.

Abstract

The Wahiba Sands are a coastal dune field of about 12,500 Km2 in northeast Oman (see satellite image above, right). The evolution of the Wahibas has occurred in distinct stages defined by changes in fluvial and wind processes over the last 230,000 years (Goudie et al., 1987; Pease, 1999; Radies et al., 2004; Pease and Tchakerian, 2004; Robinson et al., 2007; Glennie et al.; 2011; Pease and Tchakerian, 2014). These multiple growth (and erosion) stages have been driven by glacially controlled fluctuations in the strength and direction of the monsoonal wind system, in the activity of major drainages, and in sea level (Glennie et al. , 2011). The dune field has been characterized by barchanoid and linear dunes of various sizes that dominate at various times, but has had few if any star dunes. Our study area is in the northern Wahiba Sands along Wadi Batha, where we focus on the interaction of modern wind and water processes along the wadi, and the resulting sedimentary facies. In this area, northward-migrating linear megadunes and smaller barchan and linear dunes encounter the south and eastward directed ephemeral flows in Wadi Batha. Our study was aided by the fact that there are two basic populations of sand found along Wadi Batha. First, there are reddish, well sorted, quartzose sands blown into the wadi from the south as small dunes, or as streamers. Second, there is a population of dark sands and gravels brought down Wadi Batha by floods from the Oman Mountains. These sediments consist of dark mafic sands and gravels from ophiolites in the mountains, with some dolomites and quartz sands from Hawasinah Formation outcrops (see geological map this slide, after Glennie, 1988).

Using modern weather records, we describe the seasonal wind energy distribution for Oman and the Wahiba Sand Sea. Our sand trap measurements and field observations confirm that there is currently a geologically significant northward drift of sand in the northern "High Sands" of the Wahiba and onto the course of ephemeral Wadi Batha. This study has further shown that the Wahibas exist in an annual climate regime in which peak wind energy is offset from peak rainfall, creating a "flood-and-dry" environment of deposition. During winter rains (and some summer convective storms) the aeolian deposits including the High Wahiba are truncated by floods moving down Wadi Batha. The sand eroded from dunes and other aeolian deposits is recycled into fluvial deposits. In summer, the wind becomes dominant, creating small dune fields and sand sheets in the floodplain of the wadi. During this time, the wind will pick-up fluvially deposited sand and in turn, recycle it into aeolian deposits. Our trenches revealed that these basic process regimes have created complex facies variants that are intermixed at fine (trench) scale within the floodplain of the wadi. Our further studies illustrate that, should such sand packages become petroleum reservoirs, they will have high heterogeneity and restricted sweep efficiency.

The main climatic results of our study are as follows:

- A wind energy gradient exists along the east coast of Oman, characterized by strong winds at the coast grading to weaker winds inland.
- Wind regimes along the coast are regionally compatible with barchanoid and linear dunes, with subtle variations due to bedrock terrain, and to antecedent aeolian bedforms.
- A wind energy gradient across the High Sands from east to west has caused differences in relative dominance of wind versus water deposition in and along Wadi Batha. In the west, where winds are weak, fluvial processes dominate. In the east, where winds are stronger, aeolian processes dominate, and ultimately overwhelm the wadi channel.
- Peak rainfall in the catchment of Wadi Batha (Oman Mountains) occurs in winter, while the strongest wind season is during the summer Indian Monsoon. This offset creates alternate dominance of wind and rainfall processes within a single year. Rainfall and resultant floods dominate in winter, aeolian processes in summer.
- One unanticipated event during our sand trap studies was the occurrence of typhoon Gonu. This storm tracked close to Muscat with strong winds, heavy rain and flooding. Our measurements confirmed that extreme tropical storms, such as typhoon Gonu, can temporarily reverse the dominant northward drift of windblown sand in the Wahibas. Rainfall from Gonu also caused the entire northern Wahibas to "green up" with fresh grassy vegetation. However, we could not document any long- term effect on the dune field as a result of Gonu.
- Floods along Wadi Batha sink into the Wahiba Sands near the extensive agricultural oases of Al Khamil and Jalan Bani Buhassan. The original watercourse beyond these towns, mostly dry these days, continues northward and reaches the coast of the Indian Ocean at a barred lagoon 19 km north of Al Ashkharah.

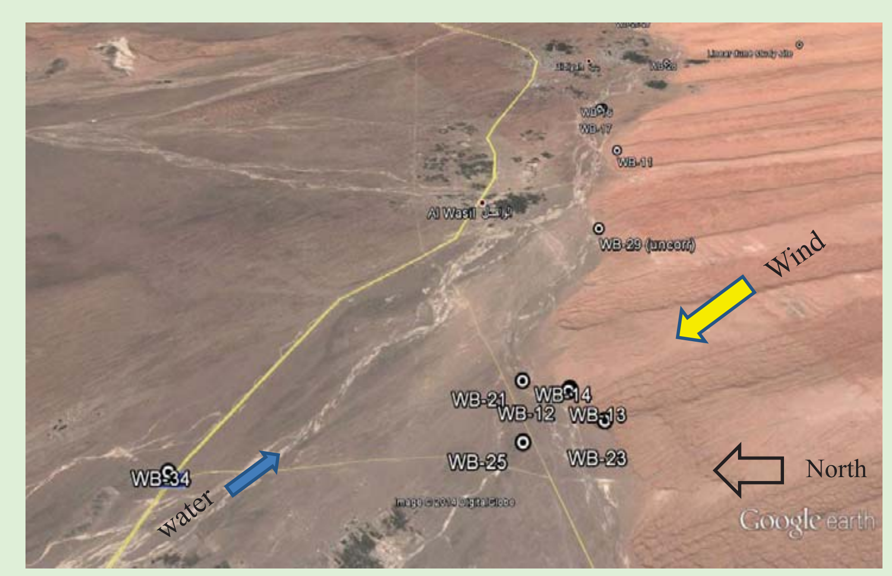
The main sedimentological results are as follows:

- Trenches in the floodplain of Wadi Batha revealed complex, small-scale interbedding of aeolian and fluvial sediments. Trenches sometimes exhibited upward-drying or upward-wetting cycles, depending upon location. In other places fluvial and aeolian sands appeared to be stacked "randomly" in the trenches.
- Eolian geobodies in Wadi Batha are elongate parallel to the dominant current direction (southeast). Dunes formed on these geobodies are oriented with respect to the wind from the south. Linear dunes extend toward the north, with alternate west- and east-facing slipfaces. Barchan dunes have slipfaces facing north most of the year. This produces surprising cross-bedding patterns in the resultant geobodies that are of interest from the standpoint of petroleum reservoir modeling.
- Both fluvial and aeolian genetic units in the outcrops and trenches, which ranged from 3.0 to .5 meters deep, thin upward on average, perhaps due to local accommodation space controls.
- Aeolian geobodies in the Wadi Batha floodplain are mainly sand sheets, with dunes and interdunes as secondary facies.
- Fluvial geobodies of small size have built-up a broad, undifferentiated floodplain. Sand bars and gravel bars are the constructive elements. Fluvial bar geobodies are small compared to aeolian geobodies; however, they build thick composite sequences to form the floodplain. Where exposed in deep cuts and excavations, these sequences commonly consist of stacked bar forms with interbedded aeolian sands.
- Fluvial processes shape the proportions of both aeolian and fluvial geobodies; however, aeolian geobodies - namely sand sheets and dune fields - tend to be much larger than fluvial gravel and sand bars.
- Fluvial floods are mostly shallow, balanced between sheetfloods and channelized flows at various places during the same event. Floods typically last a few days, followed by ponding and drying; thus "flood and dry" sequences tend to form and be preserved.
- Sand is presently sourced along the wadi from Oman Mountains to north by fluvial floods, and from the south by wind flows. The Oman Mountains (sourced) sediments consist of poorly sorted dark sands and gravels, with some light suspended fines from erosive particles and weathering products of ophiolites, volcanic rocks, and dark carbonates. Sands from the High Wahibas are reddish-whitish and moderately to well sorted. They consist of a sub-arkosic mix of quartz, commonly with red clay coatings on the grains, feldspar and carbonate. The different colors and textures associated with two different local sources for sediment have helped us interpret the process frameworks that produced the lithologies seen in our trenches.
- Interdunes of the large linear megadunes are commonly flooded a few hundred meters southward from places where they intersect Wadi Batha. These floods are commonly low-velocity "overbank" type events spilled from the main channels. They deposit a mix of suspended load muds, and some fluvial sand bars. These sediments ultimately become interbedded with aeolian sediments of the interdune.

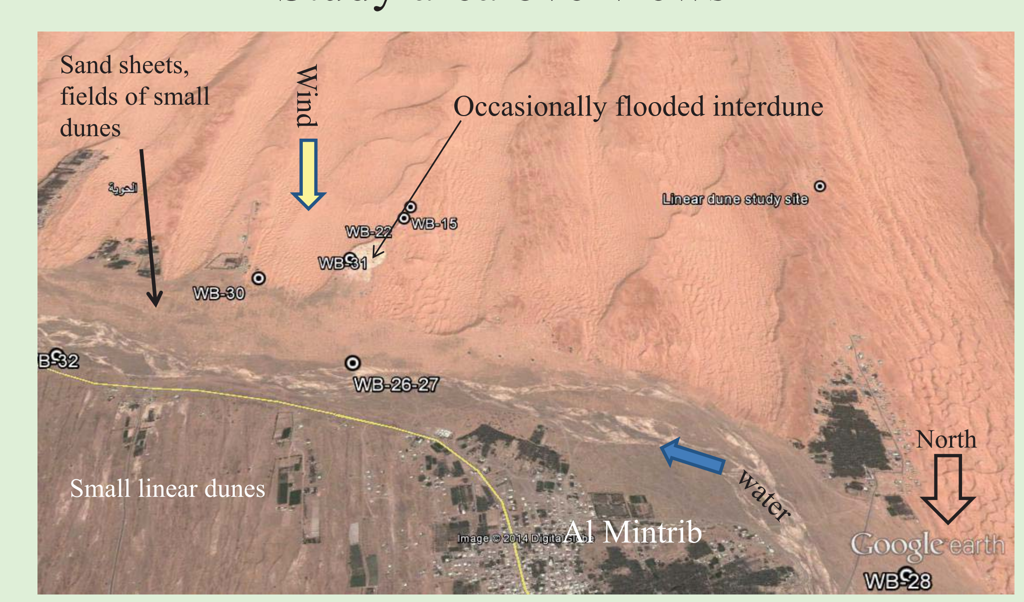
Applications of this study to oil and gas exploration and development are as follows:

- It is likely that the small-scale intercalation of aeolian and fluvial sands, with differences in cross-bedding and texture, would, if preserved, create distinctive small-scale flow units in petroleum reservoirs.
- Preliminary models injector-producer models based on our trenches suggest that inefficient sweep of hydrocarbons may occur in a reservoir with lithologies similar to those seen in our trenches. This is due to inherent permeability contrasts at bed and lamination scale, and the small size of geobodies that comprise the petroleum reservoir.

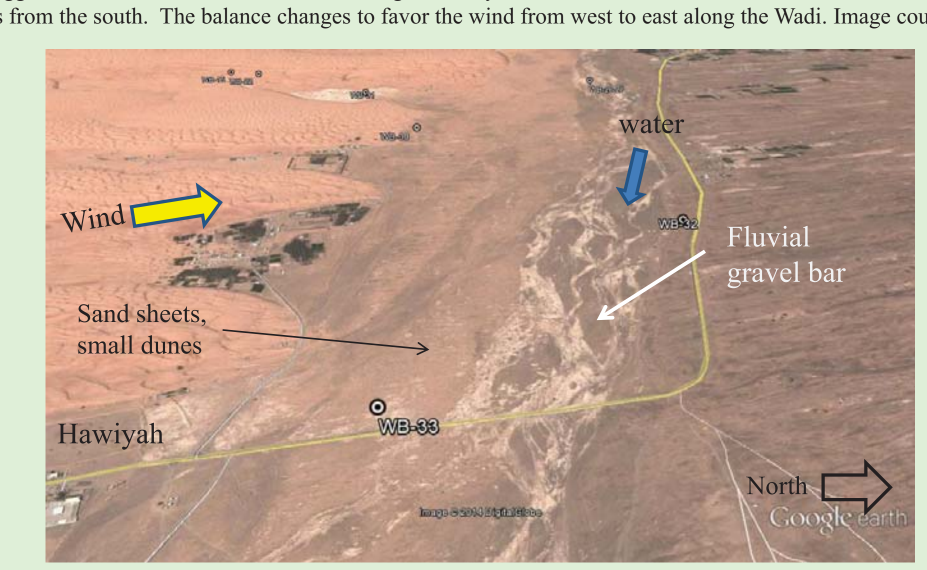
Study area overviews



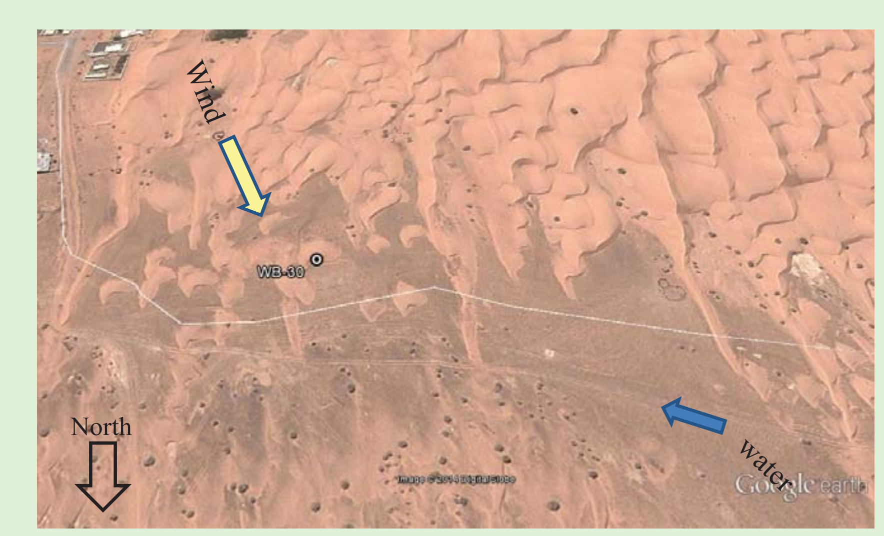
The view downstream (eastward) from WB-34 showing channel morphology on Feb 24, 2012. On right are the linear megadunes or "High Wahiba" of the northern Wahibas. In this western part of our study area, interdunes are partly bare, exposing Hawasina clastics (bedrock). Farther east, in distance, modern interdunes at the base comprise deposits of considerable antiquity , possible 110K years BP (Glennie et al., 2011). In the field, interdunes of the linear megadunes are commonly cemented by carbonate and clay. Geomorphic relationships suggest a balance between erosion of the megadunes by Wadi Batha floods versus northward extension of large and small dunes by winds from the south. The balance changes to favor the wind from west to east along the Wadi. Image courtesy of Google Earth.



View to the south showing Wadi Batha and bordering dune fields and sand sheets near the town of Mintrib. WB-30 on this image is the site of the field of small barchan and linear dunes shown below, and discussed on other pages. In this area, south winds are stronger than farther west. Thus, they have begun to maintain sand sheets and dune fields within the channel (arrow). Image courtesy of Google Earth.



A view to the west along Wadi Batha near the crossing to Hawiyah. On the left, the linear megadunes of the Northern Wahiba. These do not appear truncated like those to the west, possibly because they are protected by bordering sand dunes. On the right, linear and parabolic dune fields have been built from sand that crossed the wadi from the south and escaped recycling by the fluvial system. Note increase in intra-channel aeolian dune fields and sand sheets on this easternmost view of Wadi Batha. Fluvial-bar forms are prominent in the modern channel shown above. Image courtesy of Google Earth.



The field of small barchanoid and linear dunes at WB-30. These dunes survive due to protection from major floods by sand sheets and dune fields to the north (bottom of page in this view). Floods sometimes reach this area, but mostly these are low-velocity flows that deposit suspended load as whitish muds; or truncate dunes and recycle aeolian sand into fluvial deposits without modifying dune morphology very much. View to South. Image courtesy of Google Earth.

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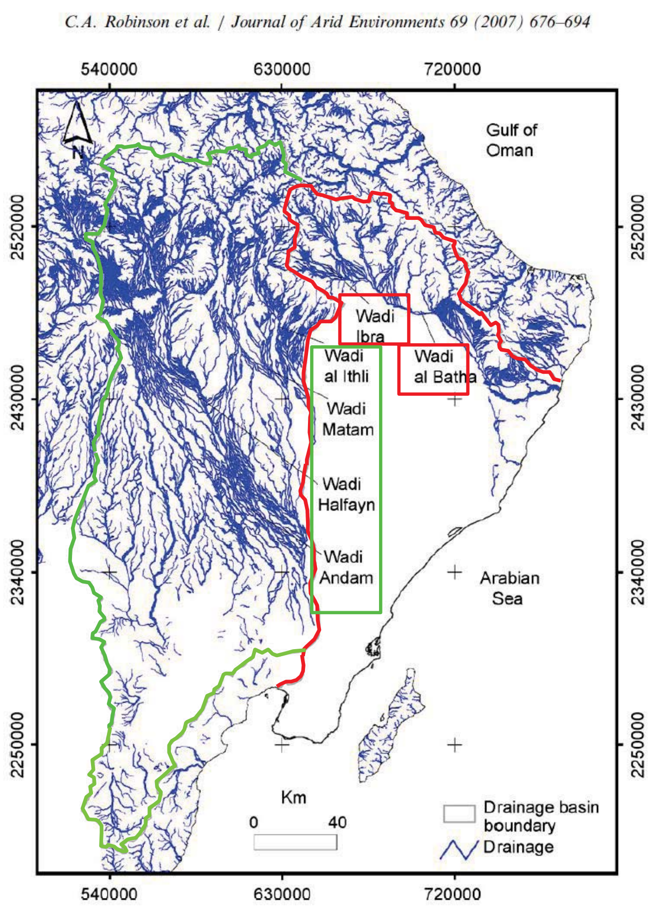
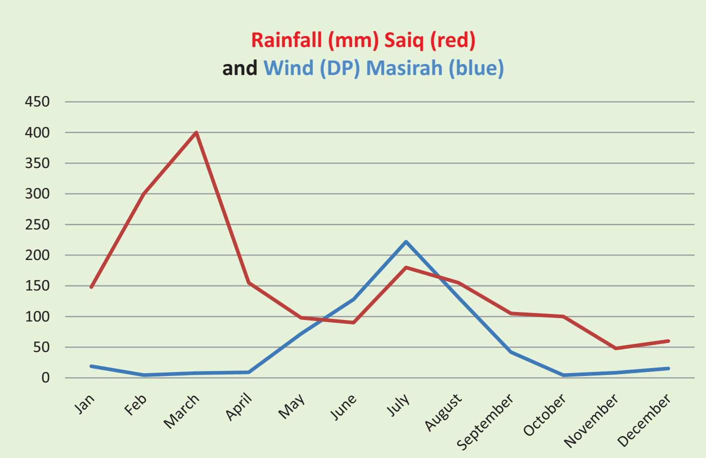
Poster 2: Climatic setting, wind regimes and fluvial systems

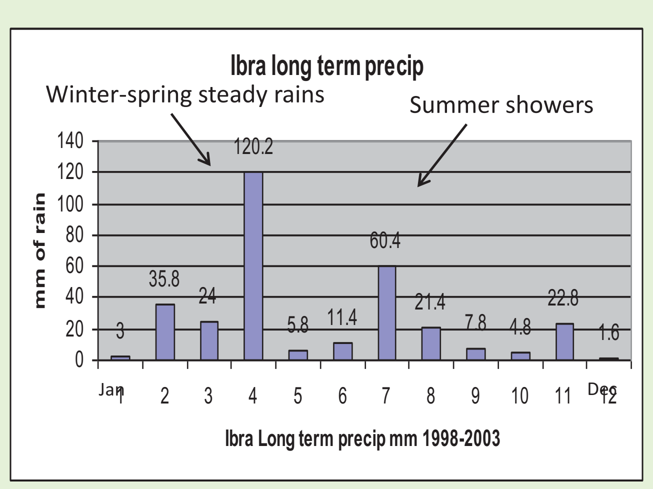


A map showing the principal drainage patterns in the Wahiba region. The Wadi al Batha-Wadi Ibra drainage basin (**red outline**) dominates the northeast. In the west, wadis Ibra, Al Ithli, Matam, Halfayn and Andam end in a direction leading to the Wahiba basin before they reach the ocean (**green outline**). Note the linearity of the main channel paths, suggesting at least some structural control. These wadis are thought to have transported much of the original material stripped from the watercourses to form the dunes of the Wahiba sands, and for the extensive volumes of groundwater now stored in the dune sands. After El Baz (2002).

Wind vs. rainfall seasons

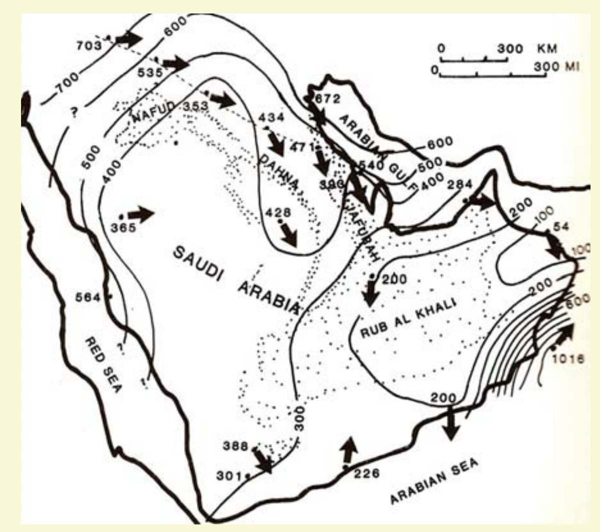


Saiq, which is in the Oman Mountains, shows the winter pattern of rainfall. Note that there is much less rain in summer, during the July maximum of wind energy, as shown by the station at Masirah, thus offsetting wind and flood seasons. Based on long term records for both stations. Much of the water in Wadi Batha flows from "out of the frame", that is, outside the limits of much of the effective wind system shaping the dunes (see drainage map above).

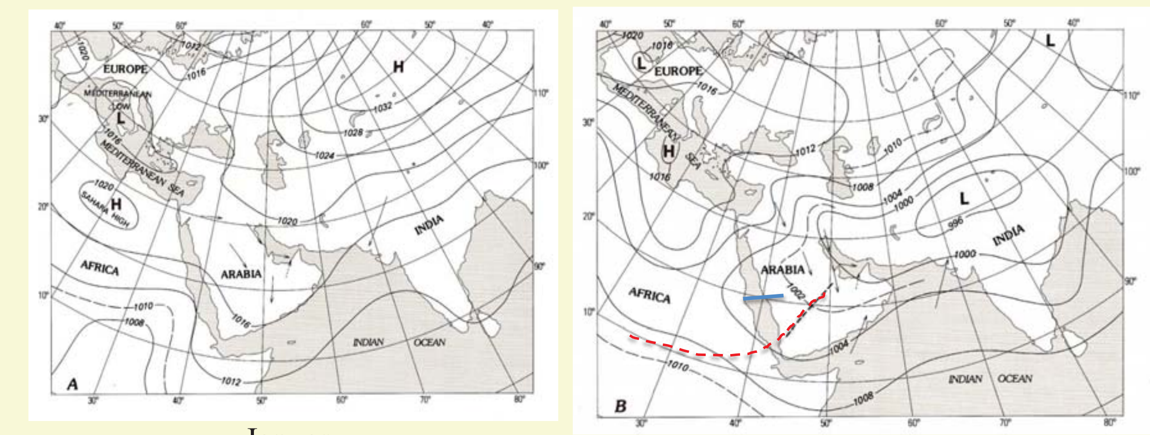


Long term precipitation record for Ibra, near the Wahiba Sand Sea (a few Km NW). There is a winter-spring maximum, and secondary peak in July. Winter peak for rainfall explains the tendency for Wadi Batha to flood mainly in winter, although summer floods also occur due to runoff from convective showers in the Oman Mountains.

Aeolian system



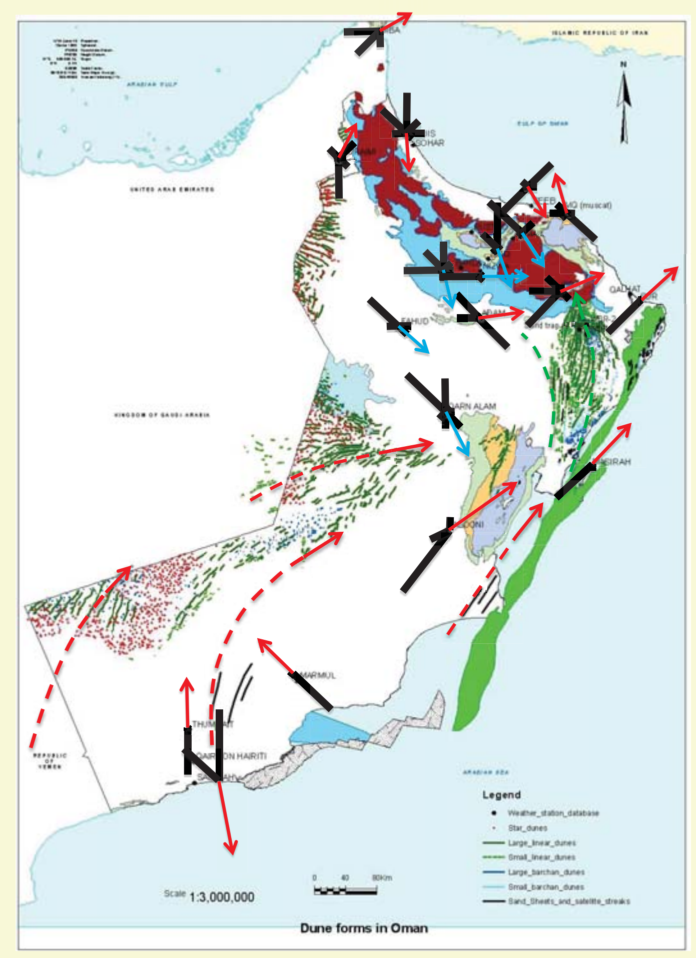
Contour map of drift potentials on the Arabian Peninsula. Drift potentials are proportional to potential sand moving power of the wind using methods of Fryberger (1979). 1 "vector unit" equals about .07 m3/m-width of sand transport. Arrows show resultant drift directions. Figure after Fryberger, et al, (1984).



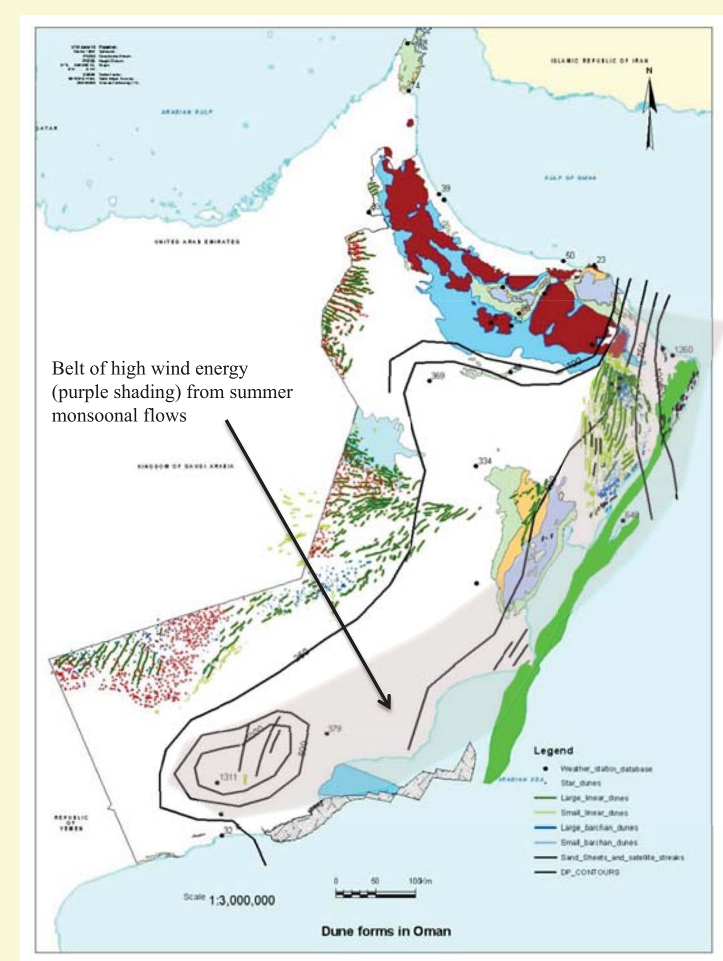
January

June

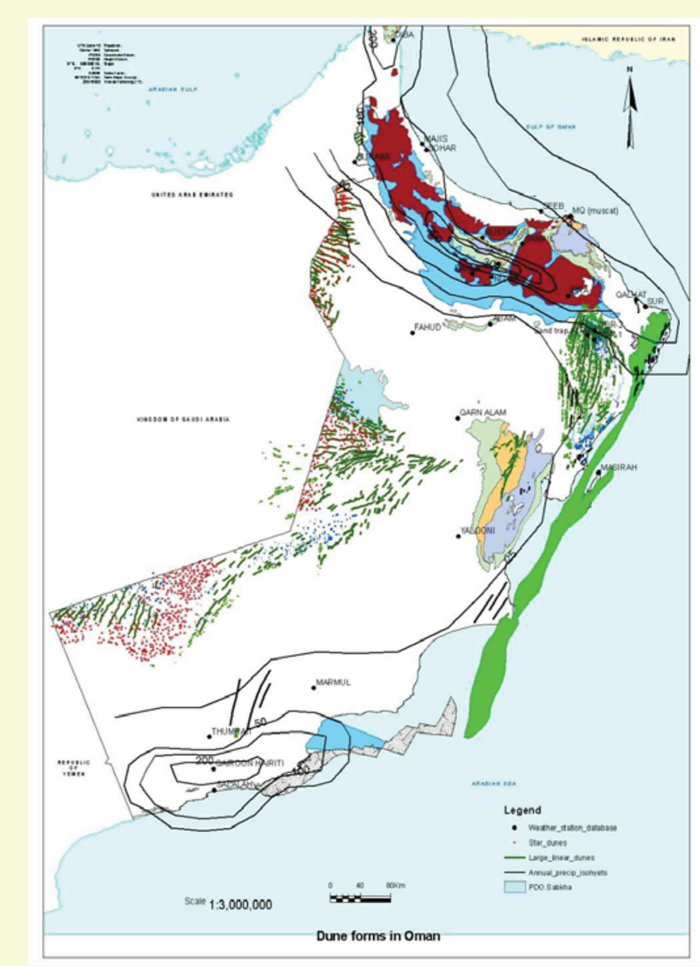
Pressure systems of the Arabian Peninsula and North Africa. A: January B: June. Red dashed line shows approximate position of ITCZ (inter-tropical convergence zone) across Oman during summer. Blue line shows region of thermal low on the Arabian Peninsula in summer. After Crutcher and Meserve (1970) in Breed et al. (1979) and Preusser et al. (2002).



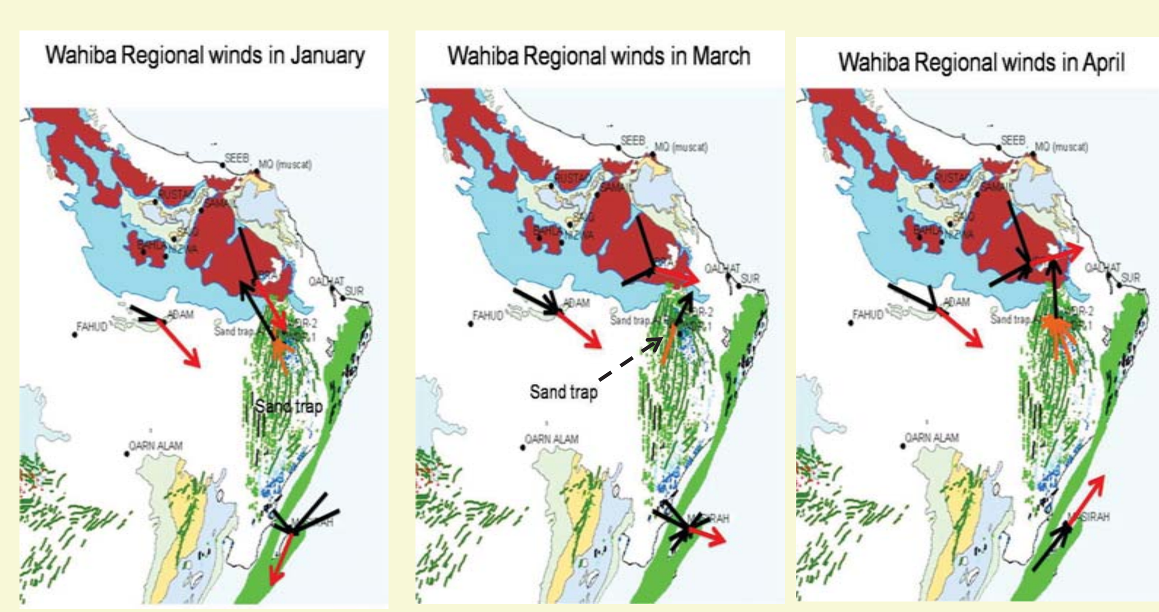
Annual sand roses based on wind stations in Oman. Map also shows interpreted (simplified net annual sand flow directions from wind stations based as well as orientation of dunes, and streaks on Landsat imagery. Arms of sand roses (black bars) face into the wind, proportional to sand transporting power. Arrows on sand roses show annual resultant drift direction. Blue lines and arrows (dashed where winds are weaker) show component of sand transport due to westerly through northerly winds from the winter Shamal associated with regions north of the ITCZ. Green lines (dashed where winds weaker) show component of transport due to the Indian Ocean Monsoon, a component of the wind regime that is south of the ITCZ. Red arrows indicate resultant winds. Most stations in Oman show a mixture of the northerly Shamal and the southerly monsoon. Background map shows interpreted major dune forms interpreted from satellite imagery. Green lines are linear dunes, red stars are star dunes, blue colours are barchanoid dunes. The north wind at Salalah may reflect katabatic winds from the mountains.



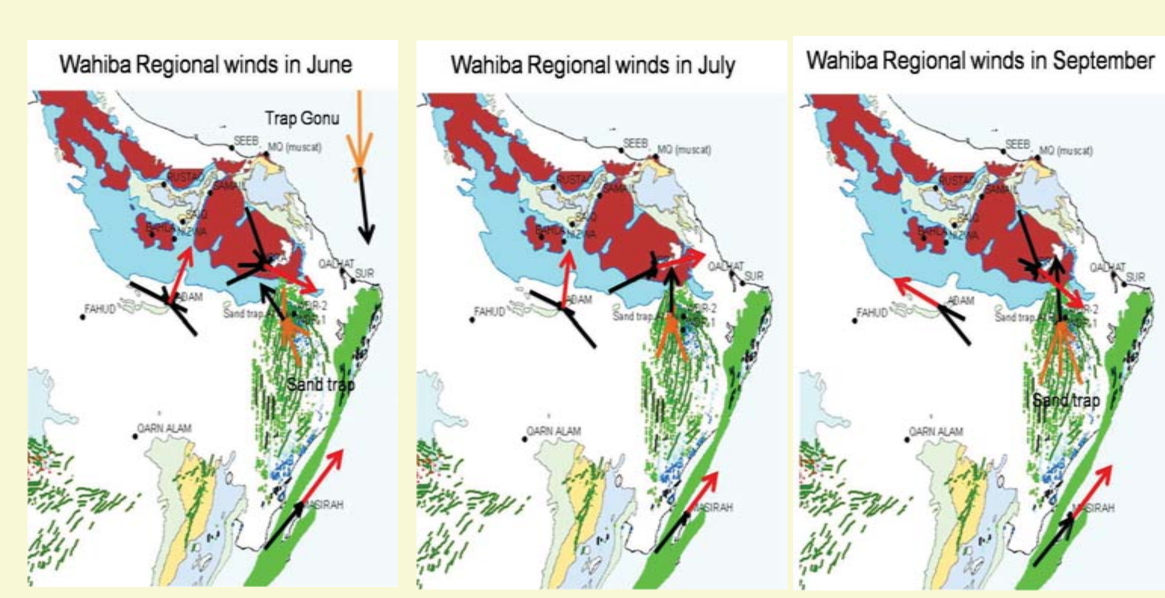
Annual drift potentials contoured (sand moving power of wind) and distribution of dune types in Oman. Green lines are linear dunes, red stars are star dunes, blue colours are barchanoid dunes. Dots with numbers show sites of meteorological data and values for annual drift potential, which is proportional to the sand moving power of wind (Fryberger ,1979). Purple shaded area shows belt of high wind energy along the coast of Oman, the mainly unimodal effective wind regimes powered by the Indian Monsoon. Background elements of the map show outcrop geology of older rocks.



Annual precipitation contours in millimetres, and distribution of dune types in Oman. Towns with names show sites of meteorological data, which was provided courtesy of the Meteorological office in Muscat. Background map shows interpreted major dune forms from satellite imagery. Green lines follow crests linear dunes; red stars are star dunes; blue colours follow crests of barchanoid dunes. The dune distribution map shown here is significantly reduced in scale from the original mapping.



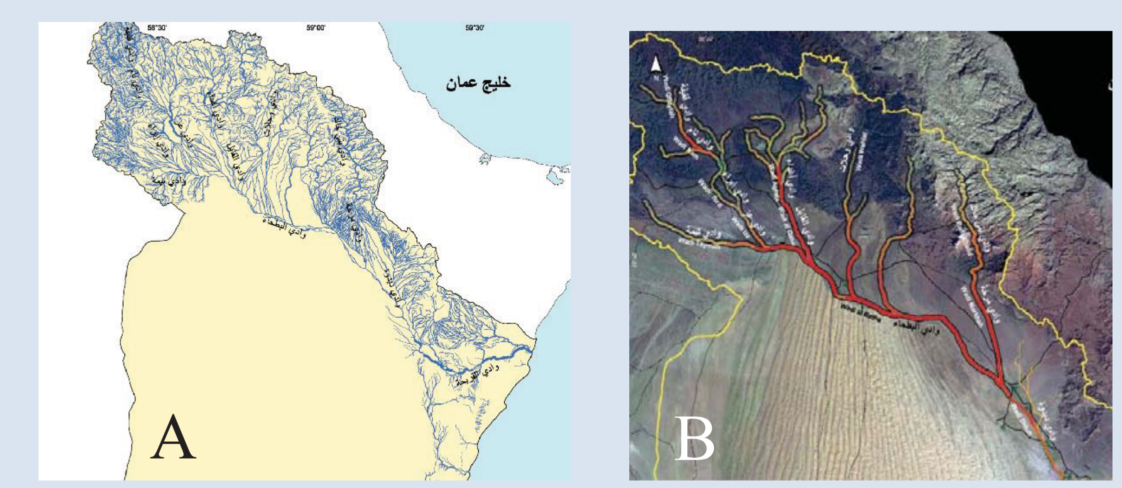
Seasonal sand transport directions, based on wind records from stations in and near the Wahiba Sands, January through March. Dashed arrow on map for March shows location of sand trap.



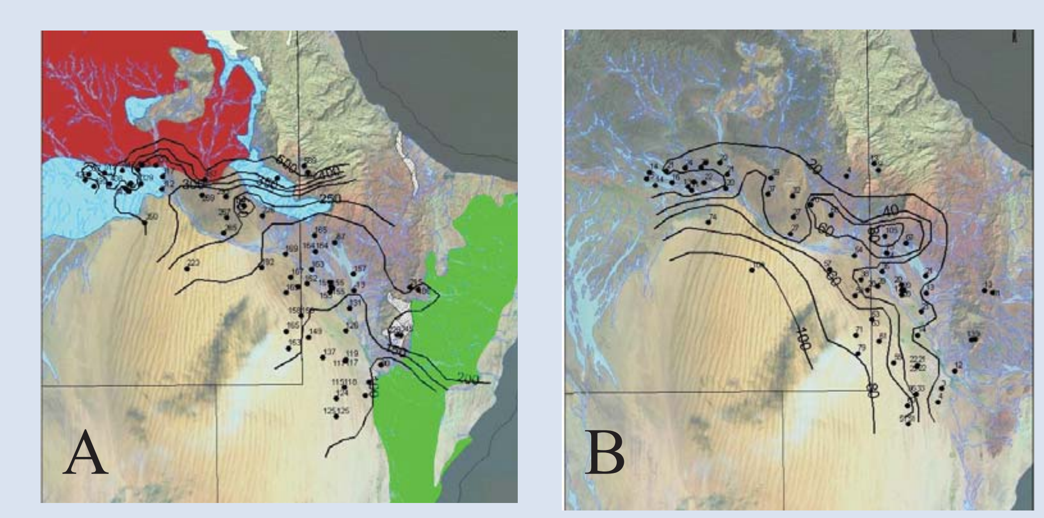
Seasonal sand transport directions, based on wind records from stations in and near the Wahiba Sands, June through September. Based on wind records of 10 years of more duration.

Fluvial system

The Wadi Batha fluvial-dune environment. This satellite view of Wadi Batha from northwest to southeast, shows the pattern of channels where flows truncate the linear megadunes. Fields of small linear dunes begin on north side of Wadi Batha and extend out of the image to the left. These dunes have formed in part from sand that crosses the Wadi through surface drift during sandstorms. Image courtesy of Google Earth. Foreground interdunes are underlain by the Hawasina Group quartz clastics and carbonates (red H).



Flow patterns of Wadi Batha. A, Drainage network in the catchment of Wadi Batha. B, Flood hazard map of Wadi Batha drainage showing increasing chance of flood (warm colours) as Wadi Batha flows along the northern end of the dunes toward the sea (southeast). Flood danger diminishes where floods sink into sands on east side of dune field. Maps after El Baz (2002). Yellow line shows catchment area.



Groundwater in the Northern Wahiba Sands. A, Average elevation of water table (true vertical depth above sea level) in 2006 in metres. Most wells are drilled in low spots, thus elevation is not controlled directly by dune morphology. Elevation of water descends toward the coast. B, Average measured depth to water in 2006, metres. Depth to water increases under the dune sands where boreholes reflect thickening of the sand sea as a whole beneath interdunes.

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Poster 3 : Fluvial Processes and geomorphology

This page shows floods along Wadi Batha, and the resulting deposits, including bars and bar margins in gravel and sand that builds-up the floodplain. These floods also rework aeolian sediments that may have blown into the wadi between floods.

Long-term preservation of the deposits shown here is based ultimately on geological subsidence. In the shorter term, interaction of both wind and water has piled-up sand in the region of Wadi Batha and "preserved" the sequences we trenched. Lower resultant wind energy along the line of sand drift has built-up the sand in the big dunes of the High Sands. Deceleration of water velocity in Wadi Batha drops fluvial sediment more or less permanently unless recycled by wind.

Flooding in Wadi Batha

Sandy deposits along the margin of a channel in Wadi Batha shortly after winter flooding. This is the typical aspect of Wadi Batha after flooding. The low gradient and irregular topography, in part created by wind-formed sand sheets and dunes, leaves abundant standing water. Drying mud has turned white.

Wadi Batha shortly after winter flooding, with water still in a channel area. Waters dry rapidly, leaving mud layers behind over gravel or sand. View to northwest.

Close up of wet mud deposited over linquoid fluvial ripples. Current from right to left.

Wet mud deposited over fluvial ripples in western part of study area. Mud turns white upon drying. Small sand bar (arrow) and scoured dune with slumps in distance. The slumps inject aeolian sand into streamflows for redeposition. View to south.

Waters from Wadi Batha have flooded an interdune on the north side of big linear dunes of the Wahiba. Repeated flooding of this area has incorporated suspended load fines (mud layers) into aeolian sands of the interdune. Site is a few km West of Hawiyah at location WB-31. View to west.

Winter flood waters flowing from right to left have created sand bars and sandy mud flats on the north side of Wadi Batha. Waters are still flowing (arrow) in main channel. View to south.

Small fluvial bar (arrow), and fluvial ripples are draped by mud from standing floodwaters near WB-33 locality. Water is still standing in foreground. In background, aeolian sand sheet with coppice dunes has been partly flooded and draped with mud from suspended load. Footprints in mud for scale.

Drying in Wadi Batha

The broad fluvial floodplain of mixed sand and gravel created by the stronger currents of Wadi Batha flows. This plain is created from the amalgamation of many smaller gravel and sand bars over time. On the left, aeolian sands have been deposited after blowing across the floodplain during summer monsoonal wind seas. They have collected near a shallow terrace on the left. In the distance, and on the right, are the linear megadunes of the Wahiba Sands.

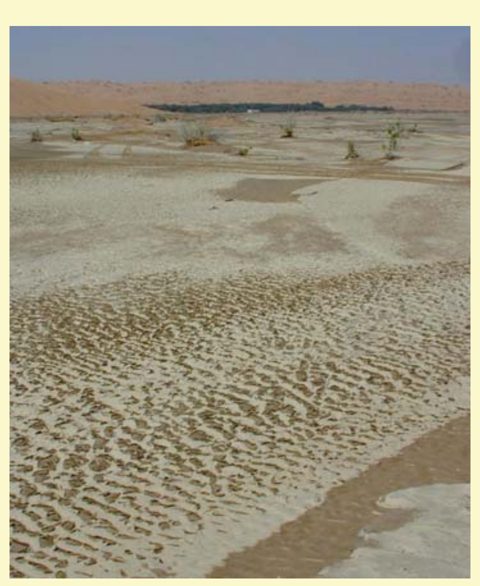
Fluvial floodplain (left) and gravel bars (right, arrow) in the western, upstream part of the study area. In this area, due to the strength of fluvial currents versus wind, fluvial processes dominate. Farther east along Wadi Batha, downstream of Hawiyah where winds are stronger, there are more aeolian sand sheets and dune fields in the floodplain. View is to the south. Recent flooding has created the fresh slumps in the big Wahiba dunes.

A fluvial Sand bar truncated by floodwaters. View to west.

Truncation and scour of large linear dune by floodwaters.

Mud cracks forming in a low, ponded part of a channel (foreground). On the left, relatively mud-free sand bars have fluvial rippleforms. Current directions within the original flow are shown by blue arrows.

A channel cut across a field of small dunes during winter floods has begun to fill with windblown sand in summer. View to the east (fluvial current direction). Prevailing wind is from the right (south).



Fluvial ripples covered by mud that has dried and cracked. This process creates small mud clasts that are blown into aeolian sands that recycle from fluvial sand bars, or are blown in as streamers or dunes by monsoon winds.

Mud deposited in the pond in the foreground is thick enough to form large polygonal mud cracks.

The thinner the mud layers, the more extreme the curling effect as the mud dries and cracks into polygonal patterns. This extensive mud layer was deposited in the interdune (WB-31) pictured in flooded state above on this page. View to south. Mud cracks are small when mud is thin.

A channel has excavated the north end of one of the linear megadunes (right). When the waters receded, mud was deposited in the channel, followed by cracking. Relatively white muds on left may be recycling Barzamanite or clays from older fluvial deposits sourced by the Oman Mountains that lie upstream.

Mud curls formed by drying of a thin layer of mud over sand. These are typically formed during the winter floods, then break-up to small clasts that are redistributed by both wind and water in later seasons.

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Sedimentology of small-scale aeolian-fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman

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Poster 4: Aeolian processes and geomorphology

Aeolian ground level
Aeolian geomorphology and process
Dune, interdune sand sheet
Summer wind season
Reworking fluvial mud and sand

A view south across Wadi Batha. In the foreground, a small barchan dune migrates northwestward under the influence of summer monsoon winds. In the background the northern end of a linear megadune is being reworked on the left by small barchanoid dunes moving under the southwest wind. In the center, it appears that several linear dunes have formed where there is more exposure to Shamal winds from the northwest during winter (arrow). Dark sediments in foreground are mainly sands and gravels brought down Wadi Batha from the Oman Mountains. Small linquoid granule ripples in foreground have formed by reworking of fluvial sands.

Trenching in Wadi Batha

The typical routine of the aeolian sedimentologist. Here, participants on a PDO field trip are trenching a sand sheet where it was cut along a channel margin by flooding during winter. Winds from the south and southwest have already begun to fill the scarp (as described by Glennie, 1987). View toward the south.

Participants in a PDO Field trip discuss a trench in a small barchan dune at locality WB-30 of this study. View to the south. Although this dune is small, sedimentary structures, especially primary strata, are representative in many ways of larger dunes.

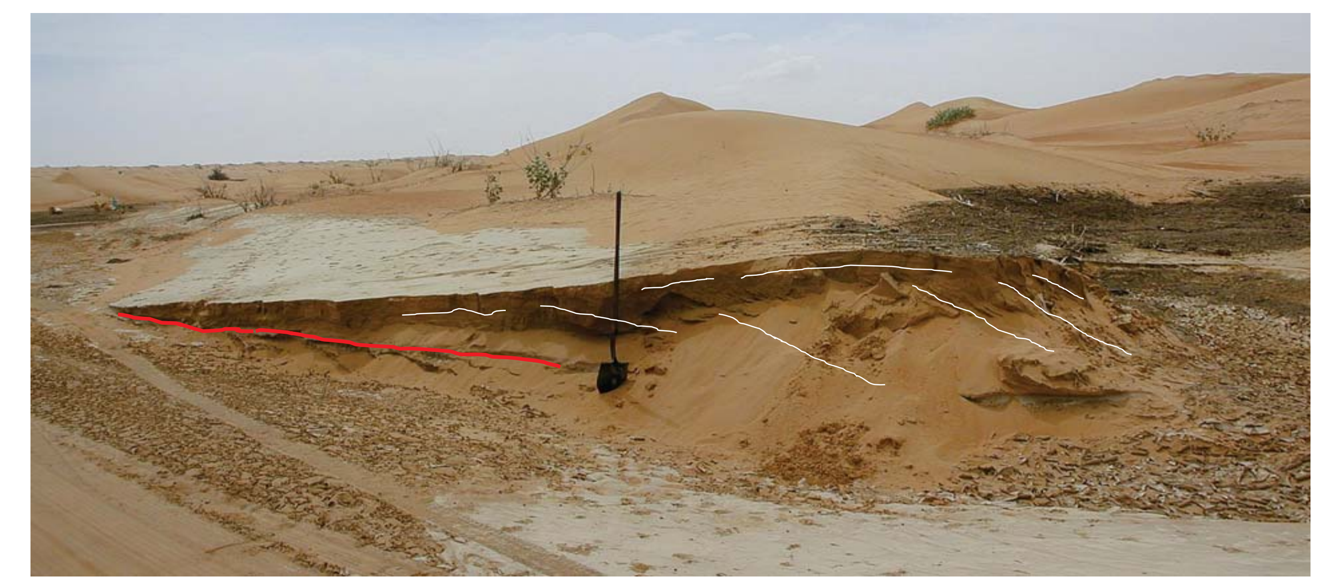
Dunes retain moisture well, thus it was possible to get a trench in the slipface of this small barchan at WB-30. View to west. The trowel is standard equipment for smoothing rough trenches created with the shovel.

Barchanoid dunes, such as these small bedforms, are very common in Wadi Batha as stand-alone bedforms. Barchanoid ridge dunes are common as secondary elements on the linear megadunes seen in the background. These forms and linear dunes of a wide range of sizes are common along Wadi Batha. Star dunes were not observed in the study area. The view here is to the southeast in the late afternoon of a dusty day. Note that these dunes at WB-30 are migrating across a substrate of dark fluvial floodplain sands sourced from the Oman Mountains and delivered by Wadi Batha. Ultimately, even the reddish dune sands in this image probably have mainly Oman-Mountain sources; however, they have been reprocessed and transported significant distances by wind from wadis to the south other than Wadi Batha (please see map on Poster 1).

Flat, light muds in this sandy interdune records a former flood in Wadi Batha. After the muds dried, the wind cut through the lightly armored surface and removed sand below, creating the gullying seen in this image. Barchan dunes in the background are burying this irregular surface. Such surfaces were seen in our trenches in the sediments of Wadi Batha. View to the south.

Mixed aeolian and fluvial sediments near Hawiyah, looking downstream. Winter floods have truncated small dunes where confined (arrow 1 in background). In foreground, plant and human debris has collected along the base of a dune with an inactive winter slipface (arrow 2). Hat in foreground provides scale.

A moderate-sized linear dune in the floodplain of Wadi Batha, view along the crest toward the southeast. Slipfaces form in response to wind events, flipping back and forth over the year to create the steep crestal profile atop and gently-sloping base or "plinth". In the Wahiba interior, linear dunes break into linked barchans and re-form as small linear dunes through one yearly climatic cycle. Linear megadunes in background. The Wahiba sands in general offer a remarkable opportunity to study linear dunes of all sizes. It would appear at this area that in the current wind regime, the smaller linear dunes, such as the one in the image, are in equilibrium, whereas the largest dunes are slowly being reworked.



An interesting cut in a small linear dune, caused by flood waters, that reveals the internal structure very well. Some strata are highlighted by white lines, base of dune with red line. Note the mud layer draped well up the plinth (sloping side) of the dune. Slipfaces in middle distance flip back and forth between storms, and between seasons.

Water and wind processes. A flood has ponded, and deposited a thin white mud layer that has dried, cracked and curled. Later, wind has recycled dark "fluvial" sand of Oman-Mountain origins and deposited it between the mud curls. This and many other interactions create suites of sedimentary structures diagnostic of deposition in a wadi where wind and water deposition are in delicate balance.

The advancing tips of several linear dunes. One of these is the dune shown in the image at the top of this poster, with the person for scale. At the time of the photograph, during summer, there was a small west-facing slipface on these leading parts of larger linear dunes. View to east.

A thin sand sheet in the flood plain of Wadi Batha. Here, the sand is mostly reddish-yellowish in color, signifying provenance from the dune field in the background. Sand was transported across the wadi by wind when the wadi was dry (which is most of the time). Sand sheets commonly incorporate sedimentary structures from burrowing by insects, and plant roots and rhizomes; described here and by Fryberger, et al. (1979).

A sand sheet in the floodplain of Wadi Batha comprised of sands blown from the dunes to the south. Bare spot (dark area in middle distance) is typical of the thin, shifting sand sheets of the wadi. Note vegetation and scattered flood debris (sticks) picked-up by wind and dropped on the sand sheet.

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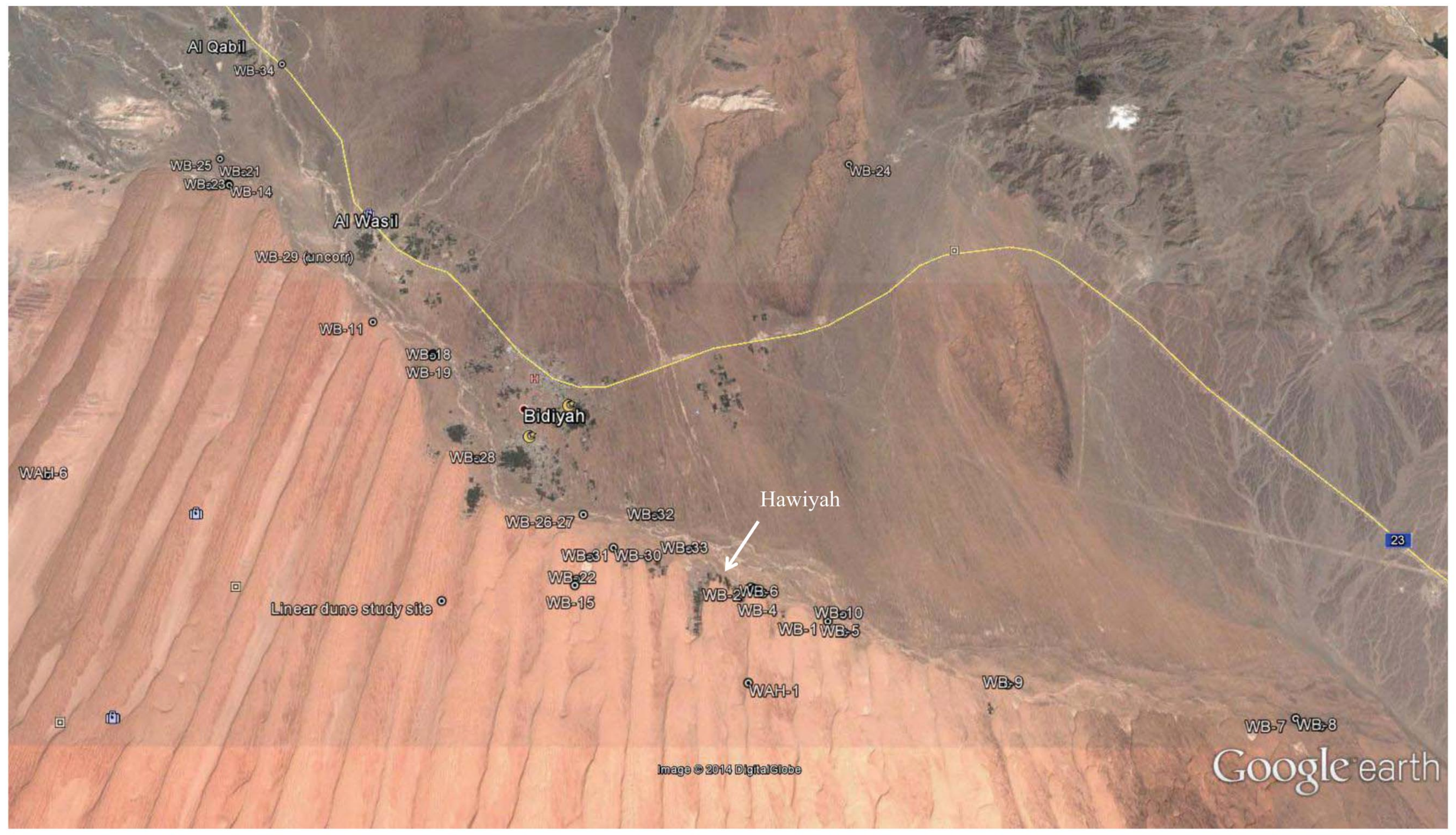
Sedimentology of small-scale aeolian-fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman

Steven G. Fryberger, Caroline Y. Hern, and Ken Glennie

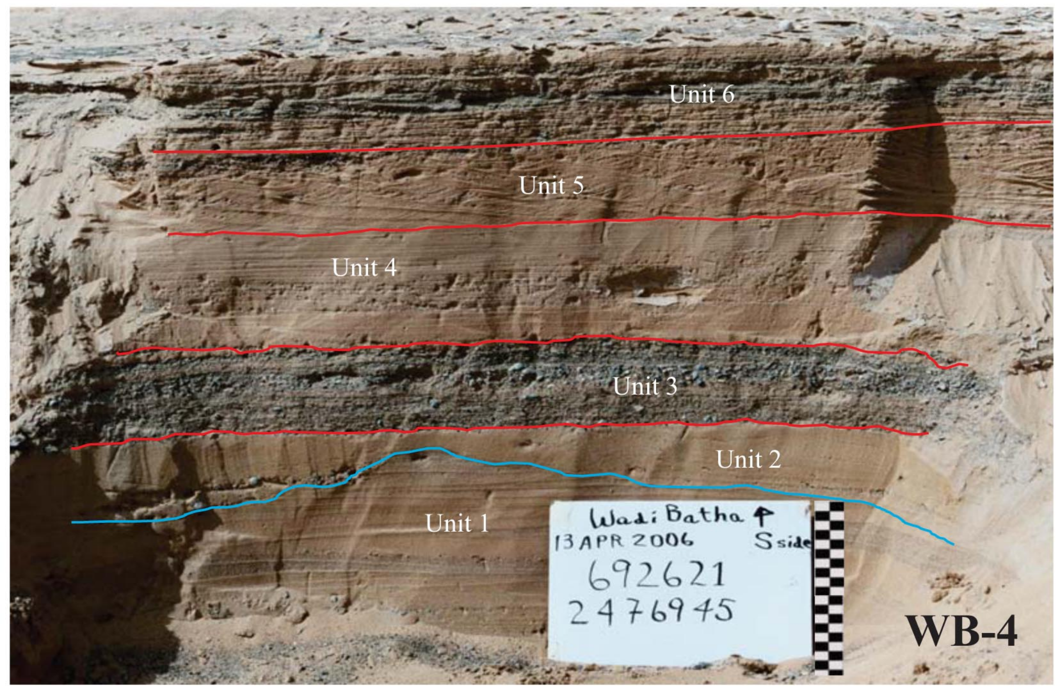
Poster 5: Overview of sedimentological trenches Part I

This panel illustrates some of the trenches dug for this study, and the analysis undertaken on them. Images of the trenches were measured by planimeter, to determine precise proportions of genetic units. We chose the genetic units based on our recognition of facies after 8 years of studying Wadi Batha. The genetic units are interpreted here to serve as analogues for small-scale flow units within a petroleum reservoir. They are commonly bounded by erosional surfaces. Internally they are built from aeolian or fluvial primary strata, or mixtures of both. In this article we present the results of our work on the genetic units and the overall sedimentology of aeolian-fluvial relationships along Wadi Batha, a system characterized by a monsoonal wind regime.

Our further work on the trench data envisions small-scale modeling of trench-sized elements as injector producer pairs. The purpose would be to examine petroleum sweep efficiencies in these small genetic units, to assist in the construction of digital petroleum reservoir models. Indeed, much of the work presented here was driven by concerns related to reservoir analysis in terms of hydrocarbon flow through geobodies at the scale of our trenches, or at the scale we observed them to exist in Wadi Batha (see following posters).

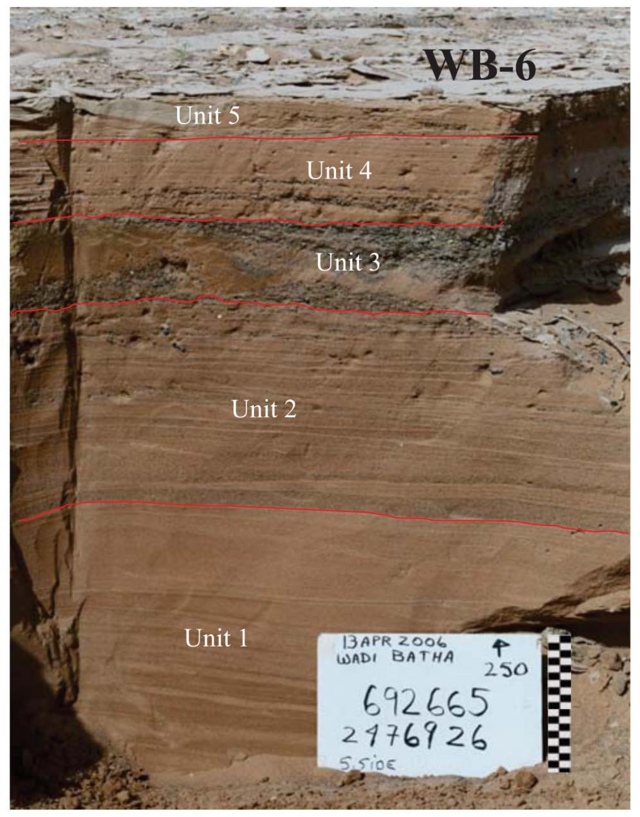


An overview of the Wadi Batha study area, with most of the locations having x-y coordinates indicated (there is some overprinting at this scale). Weaker winds in the west (left side of image) allow fluvial processes to dominate. In the east (right side of image), stronger southerly winds have caused the deposition of more intra-channel aeolian sand bodies. These are visible on this image provided courtesy of Google Earth.



Summary: Much reddish recycled aeolian sand, well sorted, reddish, laminated at site close to large linear megadunes, mostly deposited by shallow water fluvial processes. A good example of climbing fluvial ripples in recycled aeolian (Wahiba) sand.

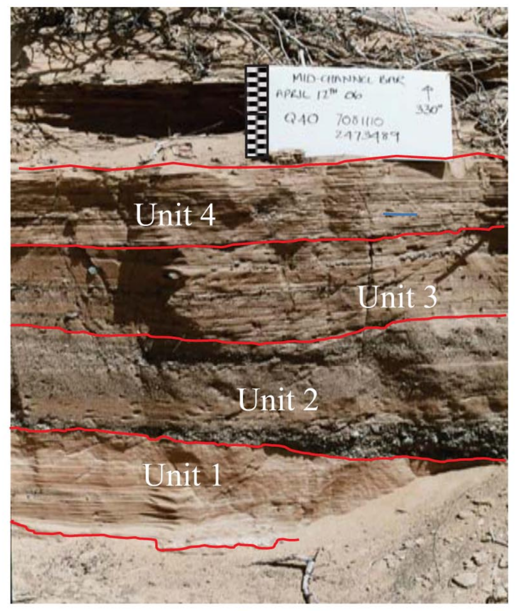
- **Unit 1**: Aeolian dune base: laminated aeolian primary strata with deep truncation by a later flood, small pebbles float, or as monolayer. Some minor fluvial flood (chaotic intervals) deposits? Mostly Oman-Mtn. grains look reworked into aeolian unit from Oman-Mtn. sources, probably nearby. Looks like base of small barchan dune.
- **Unit 2**: Fluvial, slump: faintly lam to massive flood sand, pebbles
- **Unit 3**: Fluvial: gravel-sand sheetflood deposit. Laminated, poor sorting, dark minerals from Oman-Mtn. sources, some incorporated Wahiba sand (reddish).
- **Unit 4**: Aeolian sand sheet horizontally laminated aeolian, ripples strata that incorporates some large grains, includes thin flood mud from Oman-Mtn. sources.
- **Unit 5**: Fluvial: climbing ripples with some coarse dark gravel, erosional contact with underlying aeolian unit.
- **Unit 6**: Fluvial: Laminated sand-gravel bar (sheetflood process?) with laminations.



Summary: A sedimentary cycle that moves from aeolian at base to fluvial at top. Most of this trench consists lithologically of recycled aeolian sand. There is some wadi sand (Oman-Mountain-sourced dark grains) in Units 2, 3 and 4.

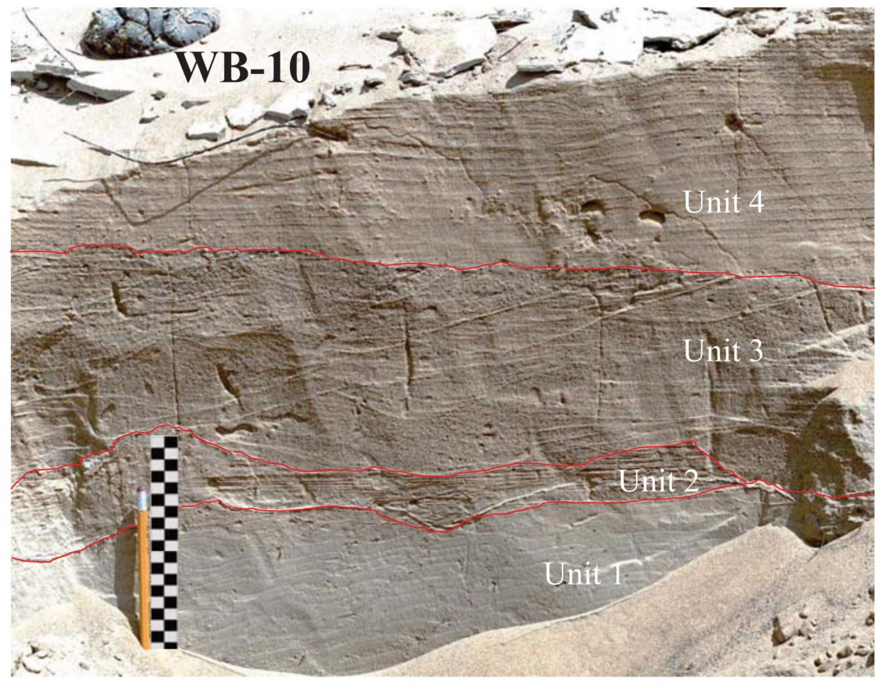
- **Unit 1**: Aeolian dune: grainfall or dome sands
- **Unit 2**: Aeolian sand sheet: dominantly aeolian dune/sand sheet strata showing admixture of grains from encroaching fluvial environment. Wind also picked up some small mud clasts.
- **Unit 3**: Fluvial gravel bar/sheetflood deposit with contained unit of churned, recycled aeolian sand
- **Unit 4**: Fluvial sand bar flat laminations with pebbles.
- **Unit 5**: Fluvial sand bar, climbing ripples recycled aeolian sand, flow tops and clay layer deposited.

WB-7



Summary: Closely-mixed aeolian and fluvial environments on a mid-channel bar subject to flooding. Topped by coppice dune that has trapped windblown sand. aeolian-to fluvial – to aeolian (coppice environment).

- **Unit 1**: Aeolian sand sheet: Finely laminated, well sorted with thin pebbles interbedded.
- **Unit 2**: Fluvial: gravel overlain by massive, poorly sorted sand and gravel.
- **Unit 3**: Aeolian sand sheet reworking man pebbles from laterally equivalent fluvial deposits to south. See large photo of site.
- **Unit 4**: Aeolian sand sheet, better sorted with laminations and bioturbation; some gravel dispersed from overlying fluvial unit not in image



Summary: A complex sequence of stacked fluvial genetic units, defined by climbing ripples and thin mud drapes, topped by inversely graded aeolian ripple strata.

- **Unit 1**: Fluvial: climbing fluvial ripples, gray with admixed wadi and dune sand
- **Unit 2**: Aeolian sand sheet: Laminated aeolian ripple strata with mud drapes from ponding of floodwaters.
- **Unit 3**: Fluvial: massive cut-and-fill and climbing ripple (or bar) lamination, thin mud horizons and drapes
- **Unit 4**: Aeolian sand sheet: aeolian ripple strata.

Aeolian and Fluvial Facies in Wadi Batha

Wadi Batha Sediments				Sedimentary features	Types present
Geomorphology	Sedimentology	Major environment	Facies Group	Description of facies	
		AEOLIAN	DUNE	Steeply dipping avalanche strata, some lower dipping ripple strata at base of dune. Pin-stripe lamination and good sorting are diagnostic, along with sandflow toes and shear features within individual sandflows.	**Small Barchan dunes**
					Linear megadunes, commonly with barchans or small linear dunes on them and in interdunes.
					Small linear dunes, in fields in the Wadi Batha floodplain, and to the north more extensively with sand sheet and parabolic dunes.
					Coppice dunes are common in the wadi channel, trapping sand blown across Wadi Batha
			Interdune	Mostly ripple strata, commonly with bioturbation due to plant growth after floods. Commonly thin clay layers deposited from suspended load by ponded flood waters, mud-cracked. Often some cementation, with occasional water ripples due to water flow from Wadi Batha. May have flood detritus from woody plants, leaves etc. Thicker interdune deposits are between the large linear Draa on the south side of the Wadi Batha floodplain. Thinner deposits are found within the floodplain proper.	**Dry interdunes** that are rarely flooded, and evolve mostly as Aeolian terrains
					Damp or occasionally flooded interdunes that commonly have fluvial clay layers, or some fluvial sands with common vegetation.
			Sand Sheet	A mixture of bimodal or sometimes well sorted flat-low dipping ripple strata. Rare avalanche strata, commonly bioturbated. May host coppice dunes with laminations built-up around vegetation. Commonly cemented more than dunes with clay or carbonate, common rhizoliths (rhizocretions) in older deposits.	**Sand sheets.** Usually dry and above flows; however, there are those that are occasionally flooded or overlapped by floods leaving deposits of fluvial sand, or mud layers (a continuum).
		FLUVIAL	Gravel Bar	A build-up in the Wadi Batha floodplain comprised of crudely bedded, or cross-bedded pebbles and gravel and with some thin irregular sand laminations or thicker massive sand beds. Usually dominated by dark sediments sourced from the Oman Mountains. Commonly very poorly sorted or bimodal with gravel and fine sand in the same deposit. Rare mud layers The gravel bars form during peak flow rates. As flow rates diminish, and water levels subside, mud is deposited on bar-margins and in hollows between bars.	
			Sand Bar	A build-up of sand in the Wadi Batha channel areas that commonly consists of flat bedded or flat-laminated sand bar formed during floods. Commonly built from recycled dune sand, or sandy component from Oman-Mountain sources.	
			Bar Margin	Cross-bedded layers that offlap sand and gravel bars, commonly with both pebbles and mud deposited by lateral migration of a bar, or by declining flows lateral to a bar.	
			Floodplain	Chaotic or very poorly bedded deposits formed in floodplain channels during peak flow periods. Comprised of a mixture of sand and gravel with "poured in" disorganized structure. May include cut-and-fill structures. Sometimes has a troughy sequence often referred to as "stacked channels" when seen in trenches, or may appear flat-bedded.	
Distinctive sedimentary structures and processes					
			Fluvial dune/ripple	Fluvial bedforms, commonly linguoid or barchanoid in shape, formed commonly in areas lateral to main channels, or during declining flows. Commonly draped by fine muds from suspended load when water flow ceases and ponds in catchments. Ripples commonly are climbing, larger bedforms less so.	
			Upper Flow Regime plane-bed lamination	Rarely, some flat-bedded sands that may or may not be part of a sand bar geomorphically, appear to be "upper flowRegime deposits" without ripples that are formed in shallow flows dominated by sand transport.	
			Slump/debris flow	Rarely,Slumps and related local debris flows form massive or poorly structured deposits locally. Each deposit is local in extent.	
			Mud drape	Commonly, ponding of water and settling of suspended load after flows produces distinctive mud drapes (light brown color) found ubiquitously intercalated with both dominantly eolian sediments, and fluvial deposits.	

Sedimentology of small-scale aeolian-fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman: Implications for petroleum reservoir performance

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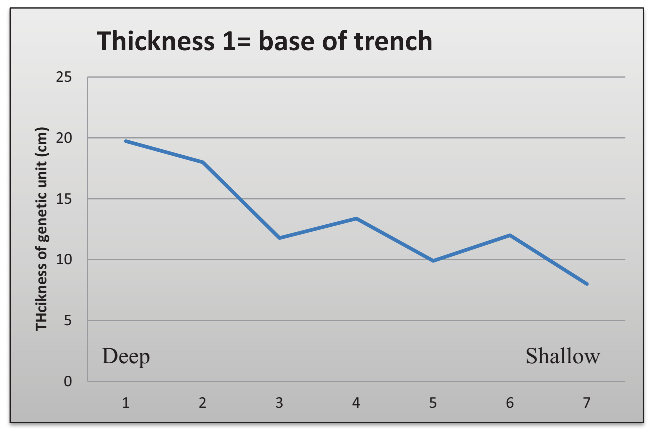
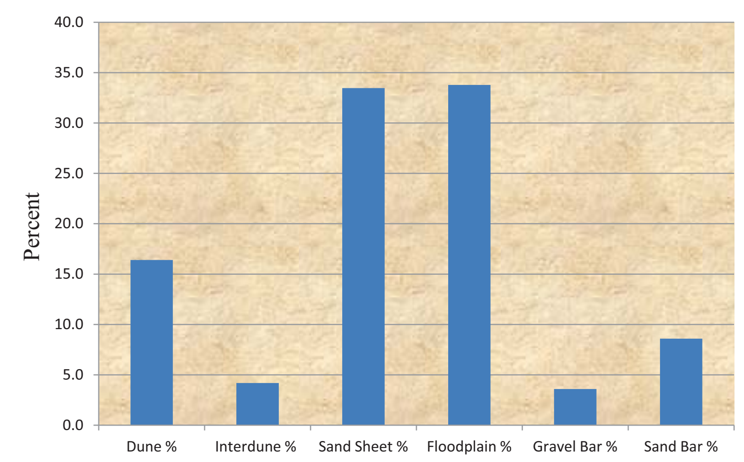
Enhanced Oil Recovery Institute

Poster 6: Overview of sedimentological trenches Part II

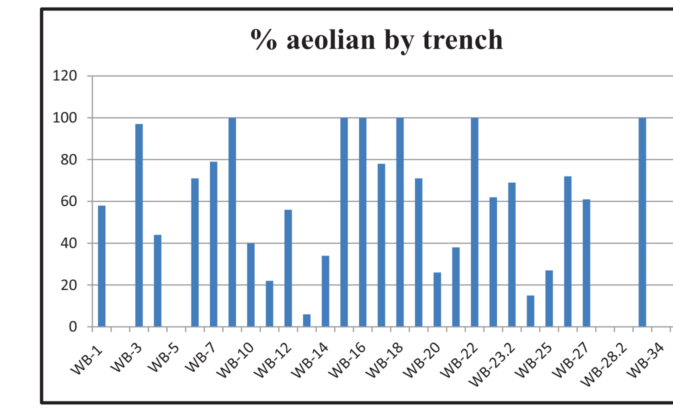
Composition and texture of sands from Wahibas and Wadi Batha
Sorting and unsorting processes fluvial and aeolian
Identification of depositional facies (criteria and examples)

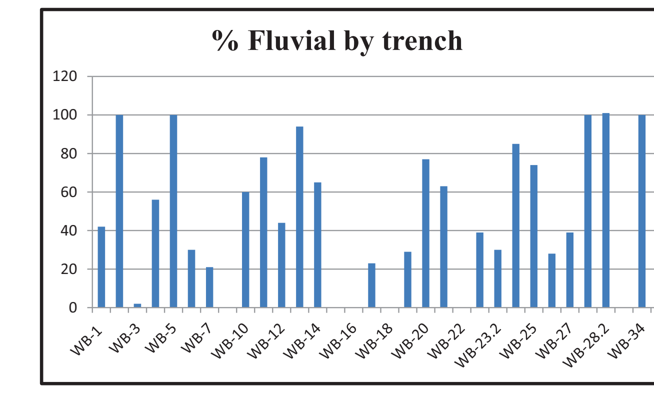


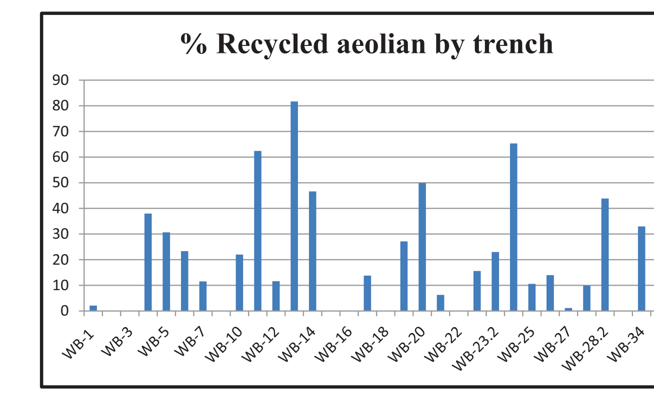
Above: Graph showing the thickness of genetic units as a function of position in trench. Genetic units were measured with 1 as the lowest. The chart, based on all data (regardless of depositional environment) shows the tendency for thinning of these units from base to top of trench. Presumably this records small-sscale accommodation space adjustments in the Wadi Batha depositional system.



The percentage of major facies groups, aeolian and fluvial, summarized for what was seen in our trenches. We did not extrapolate from the trenches into the surrounding sediment volumes; this would have involved too much speculation about the extent of geobodies that we could not trace back from the trench faces. The assumption here is that proportionate appearance in our trenches is a more or less accurate sample of proportions in nature. Dune and aeolian sand sheet facies dominate aeolian, whereas floodplain and sand-bar sediments dominate fluvial. Proportions of both fluvial and aeolian are approximately balanced when the trenches as a whole are considered.

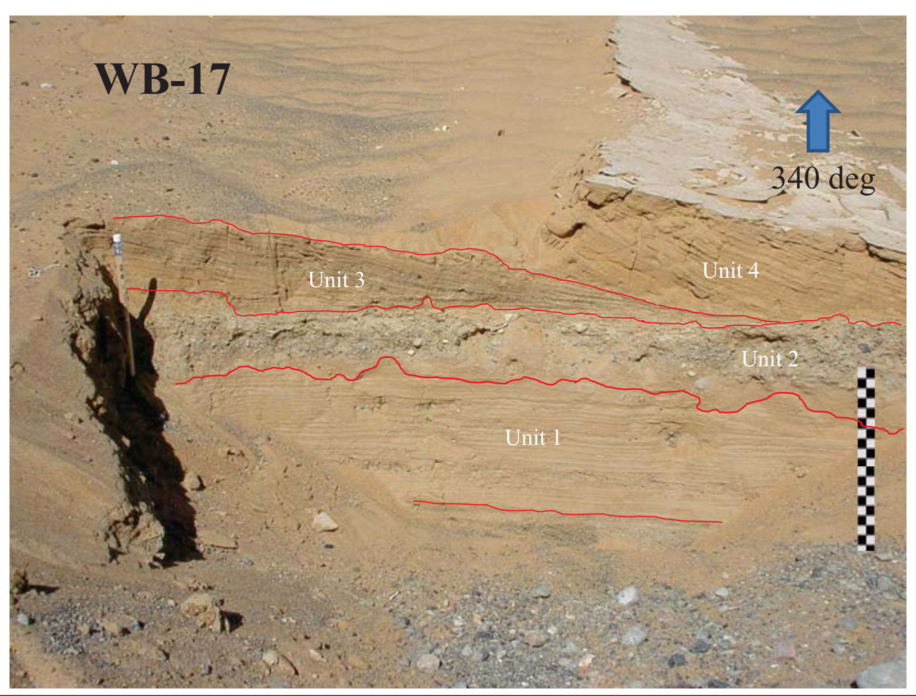






Above three charts: Percent of aeolian, fluvial and recycled aeolian sands (into fluvial) deposits varies greatly from trench to trench.

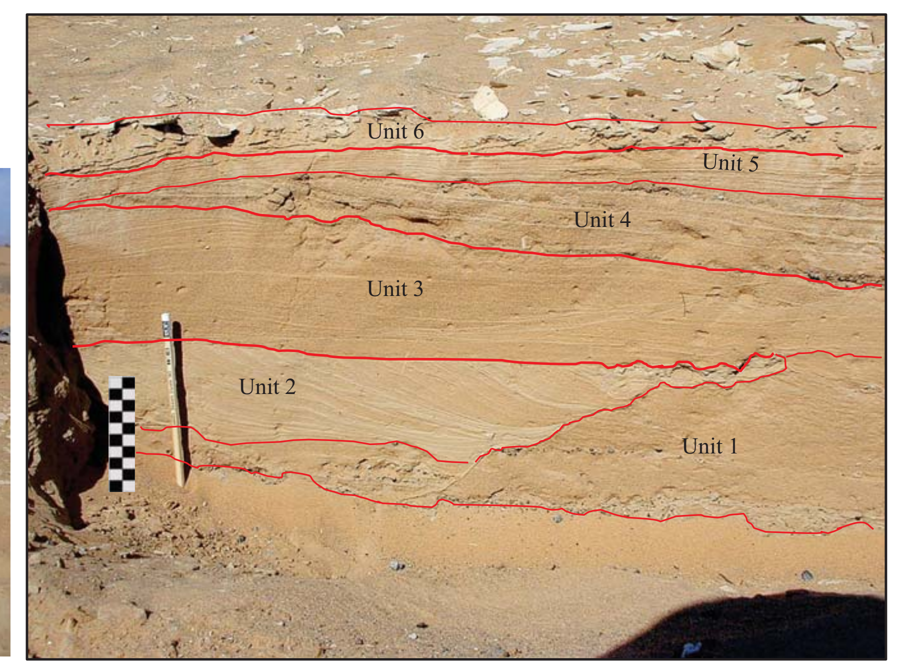
WB-17



Summary: Dark fluvial gravels (unit 2) are in the middle of the trench, with reddish aeolian sands above and below. A good example of provenance of dark (Oman Mountains) and light red (Wahiba) sand grains. This site is in small dune (remnants) in the middle of Wadi Batha .

- **Unit 1**: Aeolian sand sheet (?) with gravel scattered as monolayers and floating grains.
- **Unit 2**: Fluvial sheetflood sand-gravel unit, Oman-Mtn. sources for gravel, most sands. Erodes unit 1.
- **Unit 3**: Aeolian dune apron, inverse graded ripple strata built from dark WB sand mixed with Wahiba sand. Note dark sand of ripples at surface.
- **Unit 4**: Aeolian dune apron. This second set of aeolian strata has cleaner red Wahiba-sourced dune sand, inverse graded laminations. Capped by thin mud layer (representing ponding and drying of suspended-load fines).

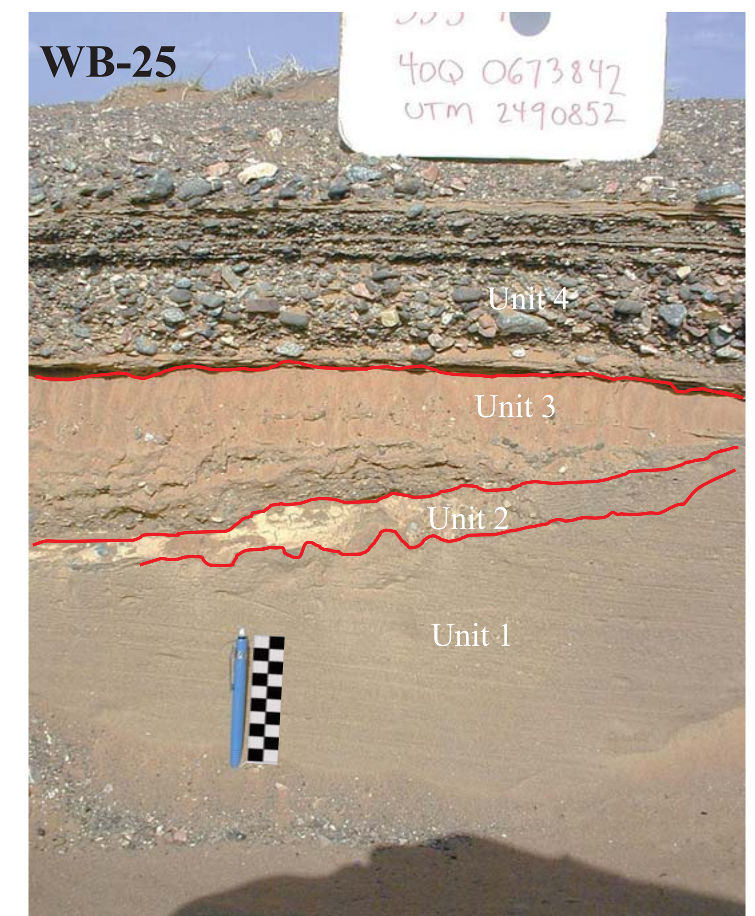
WB-19



Summary: At this locality, an aeolian sand sheet rests on channelized flood deposits. Note the site overview image that shows the build-up of the sand sheet lateral to dark gravel bars in background. Most of the sediment in the trench, whether aeolian or fluvial, appears to have origin in the Wahibas (exceptions are the dark pebbles near base of trench and muds near top).

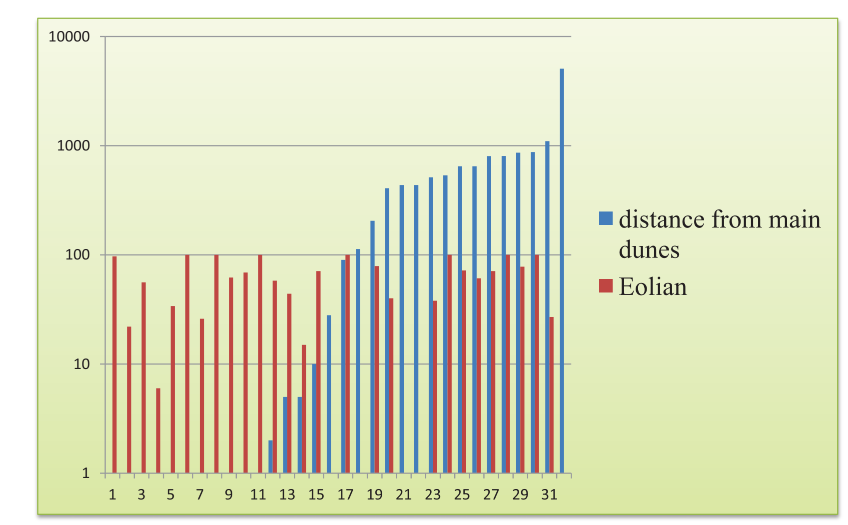
- **Unit 1**: Fluvial sand with pebble layers Massive-crudely bedded, some laminated parts.
- **Unit 2**: Aeolian dune: cross-stratified dune slipface and apron deposits, clay-rich ponding (white) layers
- **Unit 3**: Aeolian sand sheet, flat-bedded with some wind scour relief.
- **Unit 4**: Aeolian sand sheet unit rich in wadi gravel and dark sand, similar to other sand sheet layers with nearby bars of gravel that shed sediment laterally onto sand sheets.
- **Unit 5**: Aeolian sand sheet: ripple strata, clean with little, if any, gravel.
- **Unit 6**: Fluvial: decelerating flow with ponded (suspended load) clays.

WB-25



Summary: A coarsening-upward sequence with aeolian (?), well sorted, laminated sand at base overlain by a gravel bar at top.

- **Unit 1**: Aeolian dune (linear?): Well sorted, gray, aeolian? sand, may be cycled through wadi previously?
- **Unit 2**: Fluvial: thin fluvial sand with mud drape at top with erosional contact below – probably channeling.
- **Unit 3**: Fluvial: poorly sorted sand and gravel, with lots of red, aeolian, recycled sand.
- **Unit 4**: Fluvial: gravel bar with thin sand streaks.

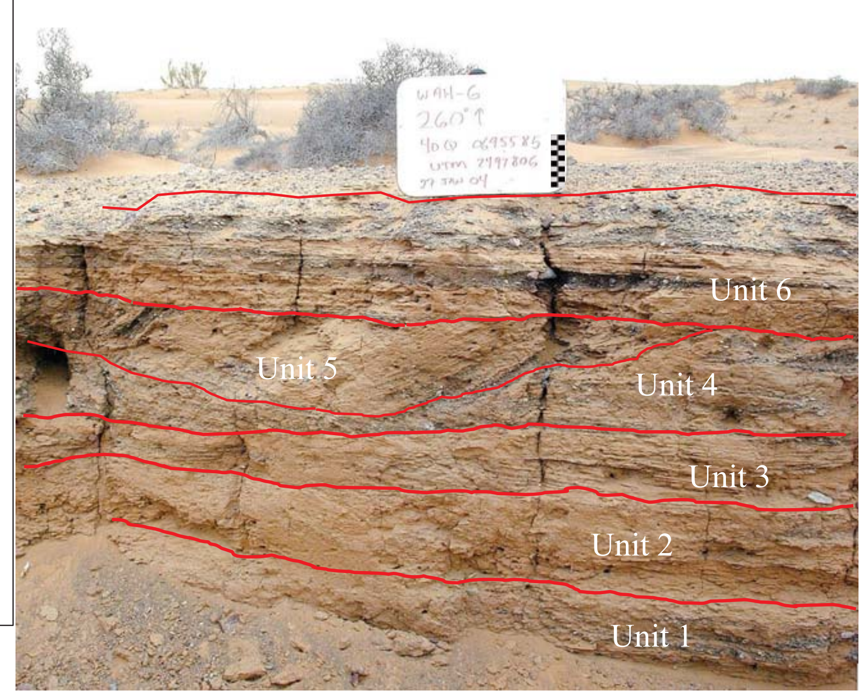


Above: The percentage of aeolian sand in any given trench was not dependent on distance from the large dunes of the Wahibas that lie to the south of Wadi Batha. A large percentage (to 100%) might be expected very near the big dunes of the Wahibas (left side of graph). What was surprising is that amount of aeolian sand did not decrease in localities farther from the dunes. This may be because of the ability of the wind to build aeolian dunes and sand sheets in the wadi course.

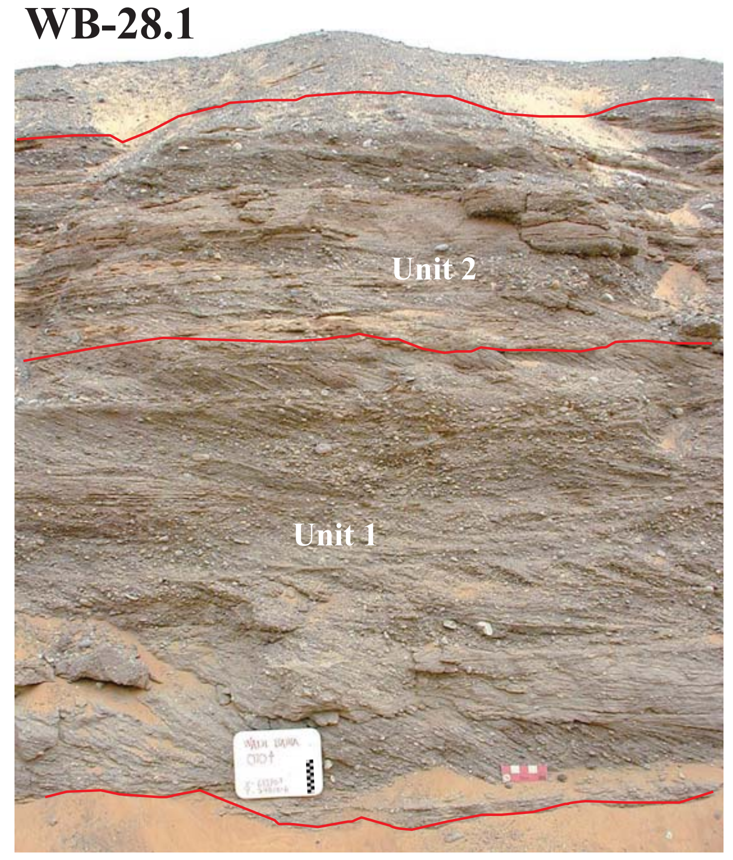
WB-24

Summary: Fluvial sediments consisting of wadi sands and recycled aeolian sands (red), lightly cemented, laminated and cross-bedded in part. This location is north of Wadi Batha along east side of Hern's (2000) study area.

- **Unit 1**: Fluvial: Poorly sorted fluvial sand and gravel
- **Unit 2**: Aeolian sand sheet: Moderately to well sorted dune sand, bioturbated, massive.
- **Unit 3**: Aeolian -laminated at low angle, with reworked pebbles from channel.
- **Unit 4**: Fluvial: laminated channel-fill deposit cutting into bar deposits. A mix of stream and dune sand, with gravel lenses.
- **Unit 5**: Fluvial: channel cutting into
- **Unit 6**: Fluvial bar or mid-wadi deposit with lenses of recycled dune sand and fluvial sand and gravel, very poorly sorted.



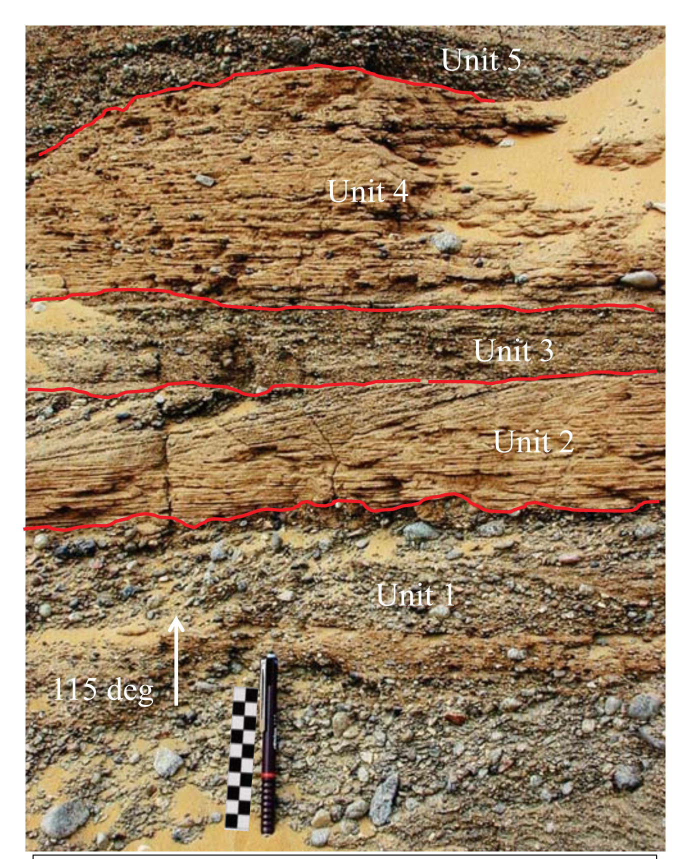
WB-28.1



Summary: A natural outcrop of fluvial sands of the floodplain in Wadi Batha consisting of coarse sand and gravel , stacked bedforms migrating downstream, cross-bedded. Units of recycled dune in unit 2.

- **Unit 1**: Floodplain: Essentially this outcrop is a stack of gravelly fluvial cross-bedded sets, unidirectional in flow. Little, if any, aeolian recycled.
- **Unit 2**: Gravel Bar: A mixed unit of gravelly fluvial (Oman Mtns.). Sources sets, cross-bedded, and flatter sets of fluvial recycled aeolian sand mixed with fluvial sand.

WB-28.2



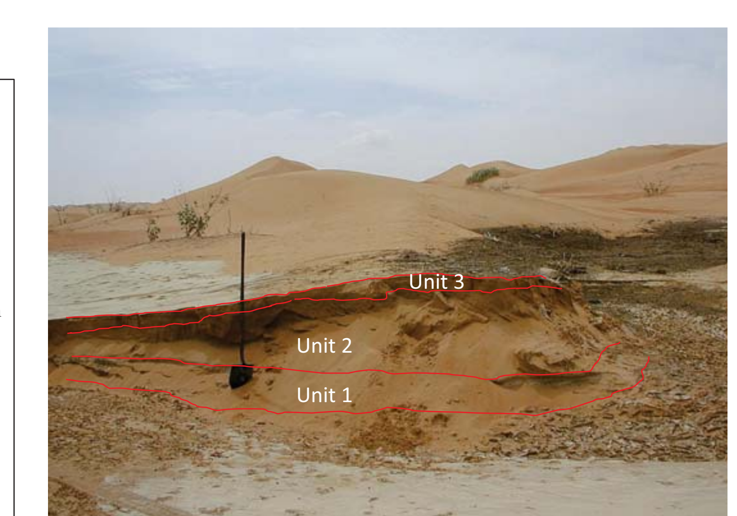
Summary: A natural outcrop of fluvial sands consisting of alternate sand and gravel, cross-bedded.

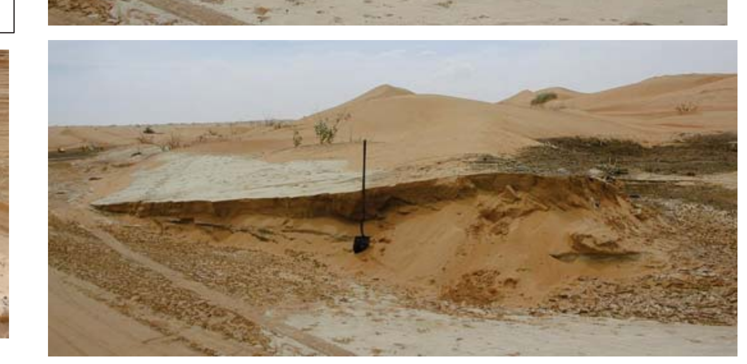
- **Unit 1**: Fluvial cross-bedded, bedded gravels and pebbles, probably a bar.
- **Unit 2**: Fluvial sand Bar: fluvial unit with red recycled aeolian sand. Migrated laterally toward left, possibly a sandy bar.
- **Unit 3**: Fluvial: pebbly unit, flat-bedded.
- **Unit 4**: Fluvial sand Bar: Flat-bedded sandy unit with pebbles, channeled by coarse gravel unit above.
- **Unit 5**: Fluvial: gravels in channel.

WB-35

Summary: A linear dune has been truncated by Wadi Batha Flooding. This image shows both mud drapes and ponding debris, as well as cross - bedding in the linear dune. (Near locality WB 30 small dunes).

- **Unit 1**: Aeolian interdune of linear dune field. Mix of Wahiba sand and some mud layers from earlier floods. Mostly aeolian sands?
- **Unit 2**: Aeolian dune: Avalanche strata of the "body" of the linear dune. This small dune is a variant of the McKee (1964) model for linear dunes of the same size that he trenched near Sebha, Libya.
- **Unit 3**: Aeolian dune: Top-set ripple strata, mainly windward slope (in current morphological state) of the linear dune.





Sedimentology of small-scale aeolian-fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman

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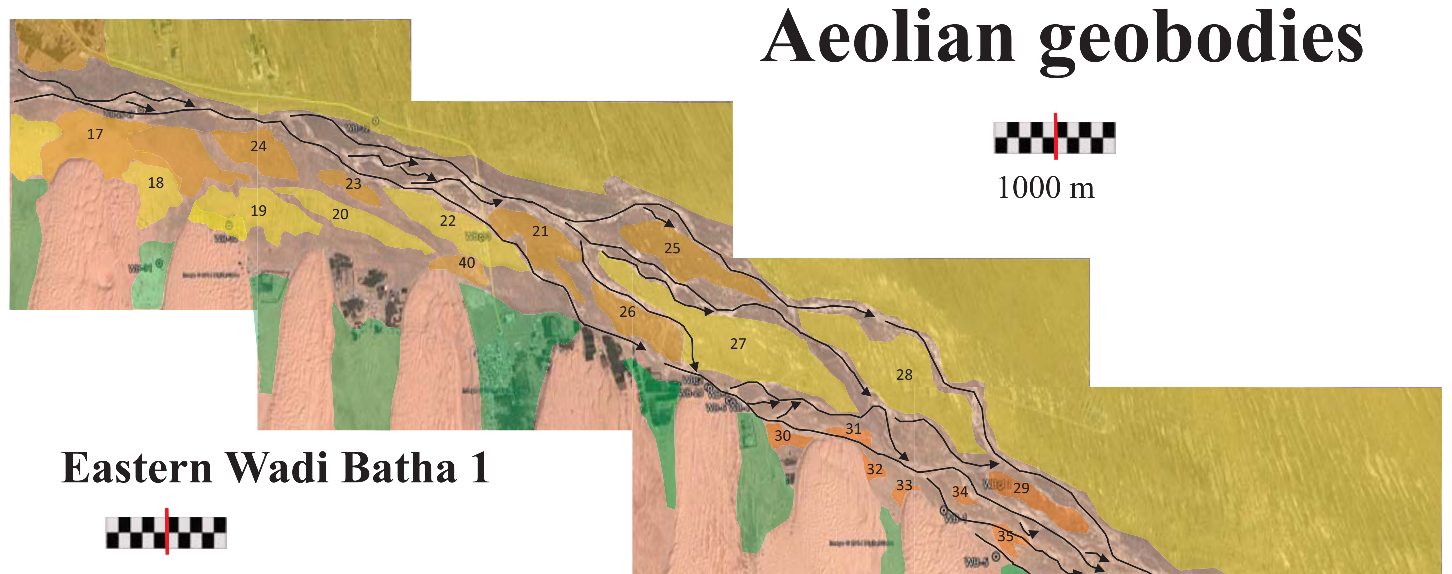
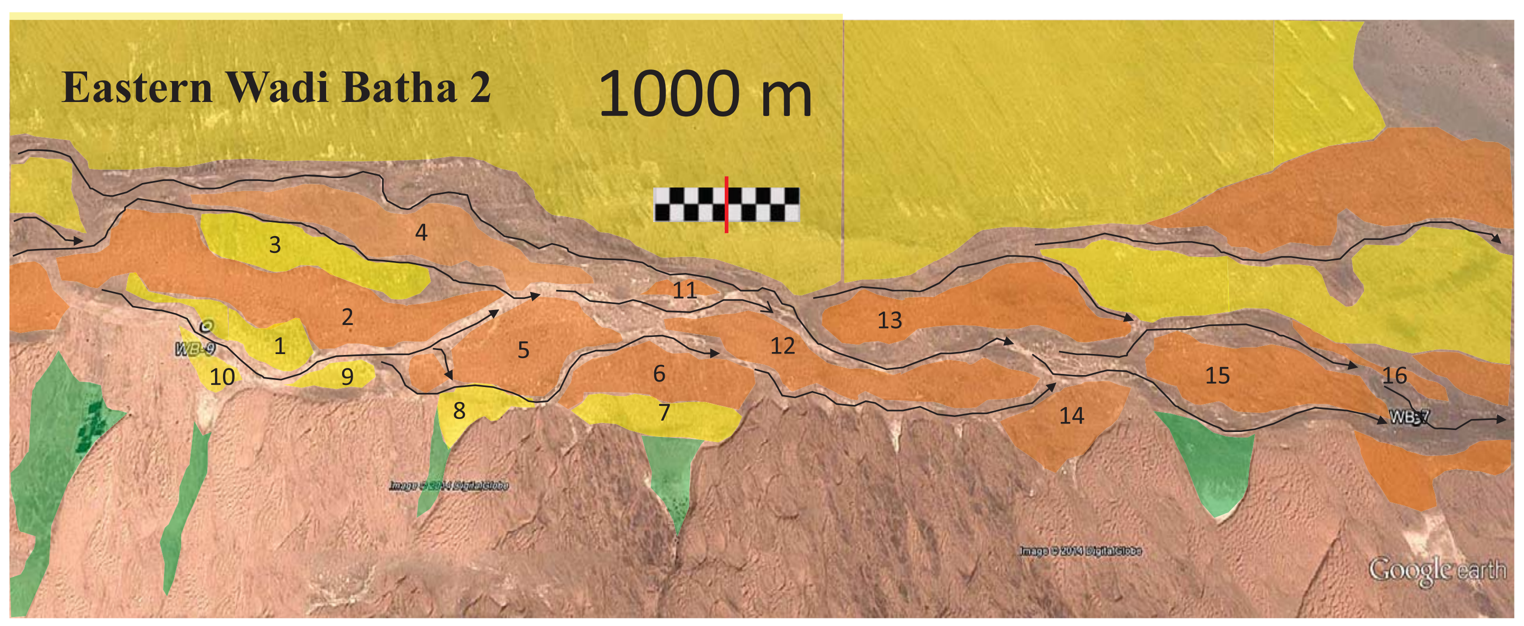
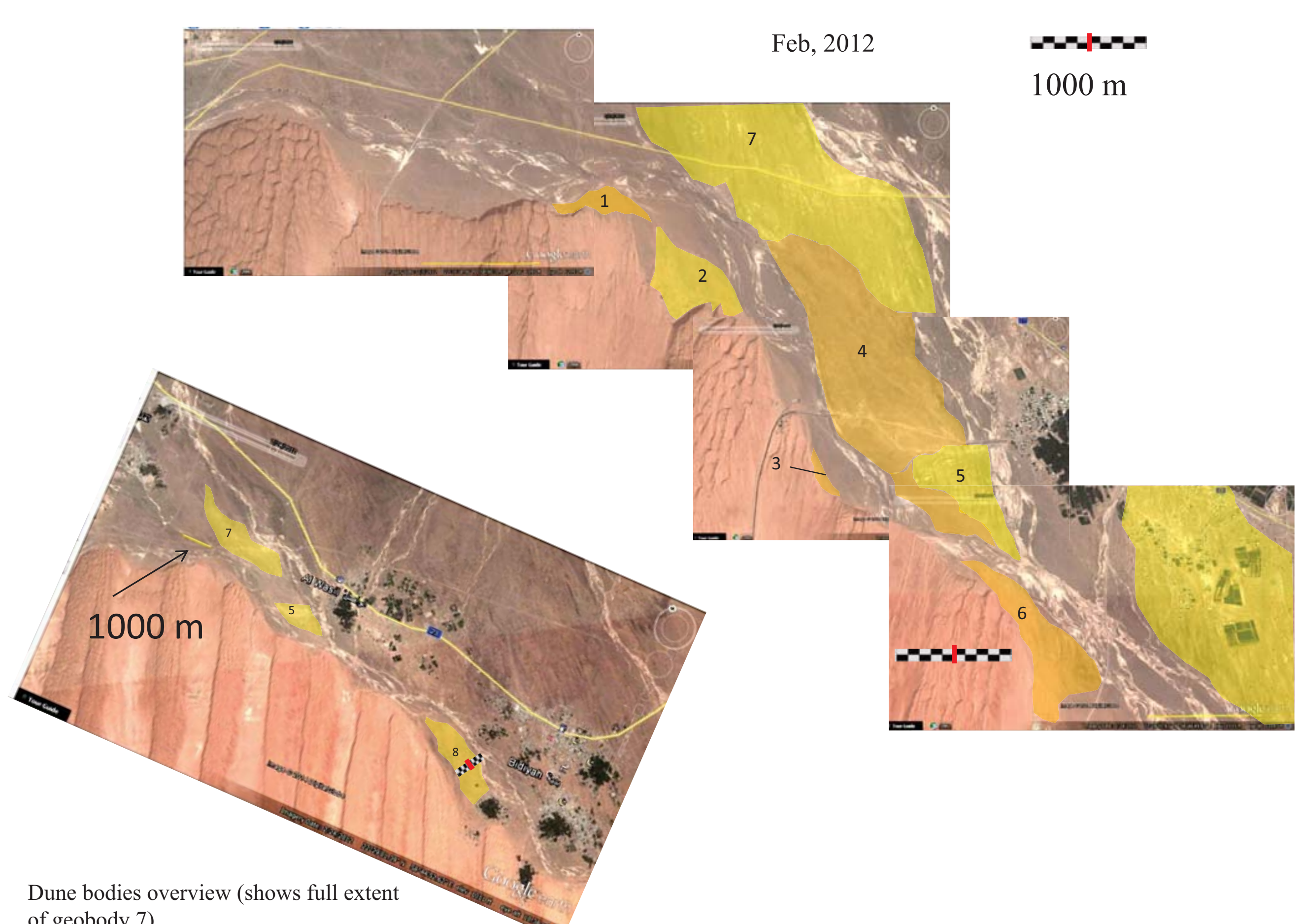
Poster 7: Geobody analysis along Wadi Batha: Feb 2012
All images courtesy of Google Earth

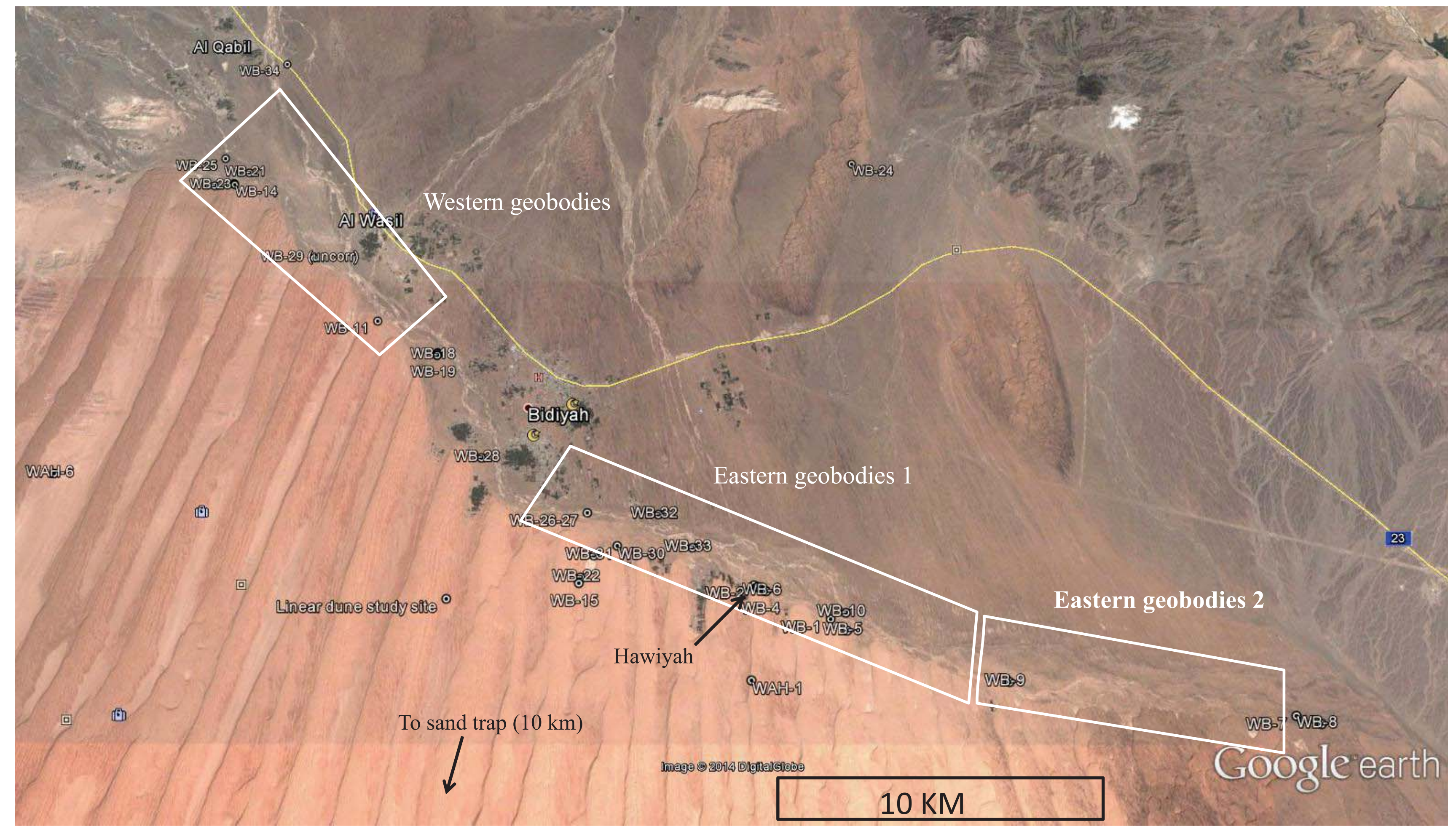
Aeolian geobodies



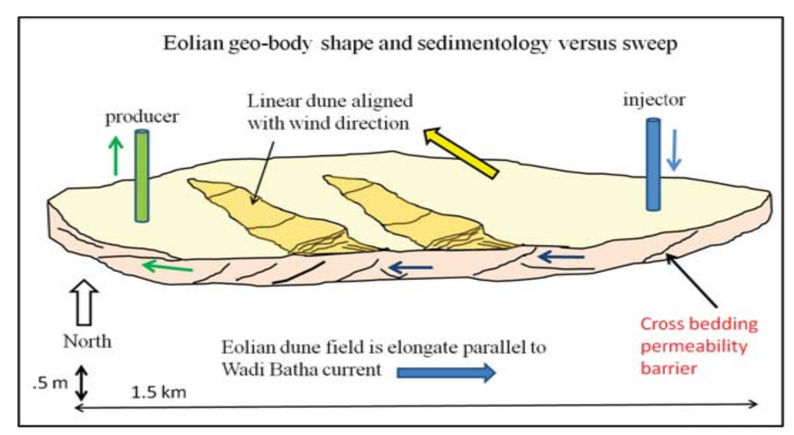
The maps on this page provide an audit trail for our measurements of geobody dimensions. The authors visited most of the sites repeatedly over the years we worked along Wadi Batha. Our measurements were restricted to the floodplain of the wadi, and thus did not include the dune fields and alluvial fans to the north and south. This is because we wished focus on the zone of interaction of the wadi and aeolian processes of dune migration and sand drift. Yellow color overlays show aeolian dune sand bodies; orange overlays show aeolian sand sheets. Green shows interdunes.

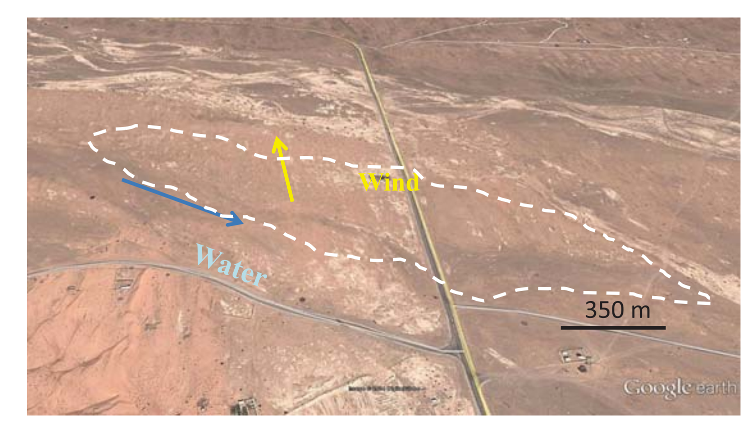




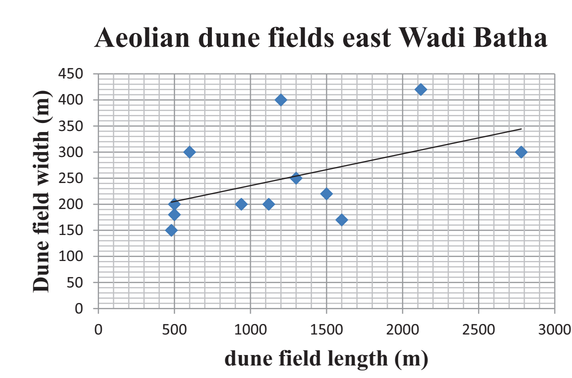


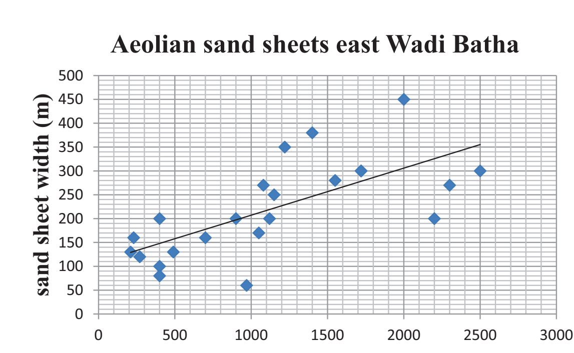
Index map of Wadi Batha showing areas where aeolian and fluvial geobodies were measured from PDO and Google Earth Imagery. We did measure the "floodplain" geobody because it is a composite of many stacked sand and gravel bars and forms a substrate upon which the mixed aeolian and fluvial system has been built..





The cartoon above shows an interesting model for combined wind and water deposition along Wadi Batha. In this example and the Google Earth image above, the shape of the geobody has been sculpted by fluvial processes and is elongate parallel to the wadi current direction. On the other hand, the dunes on this aeolian geobody are aligned with the prevailing southwest wind. Internal stratification follows the dune type and orientation. This has implications for similar geobodies in petroleum reservoirs that were formed in mixed aeolian-fluvial regimes.



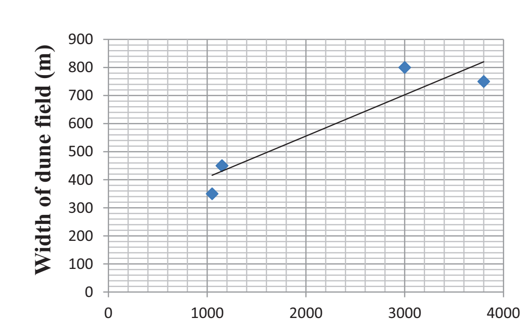


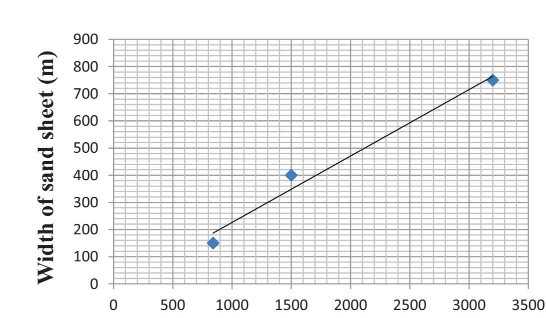
The charts above show the proportions in meters of dune and sand sheets in the eastern Wadi Batha study areas. The proportions are similar to those of fluvial bars; however, the overall size is greater (see other charts please, on this page).

Sept 26, 2011

Sept 12, 2013

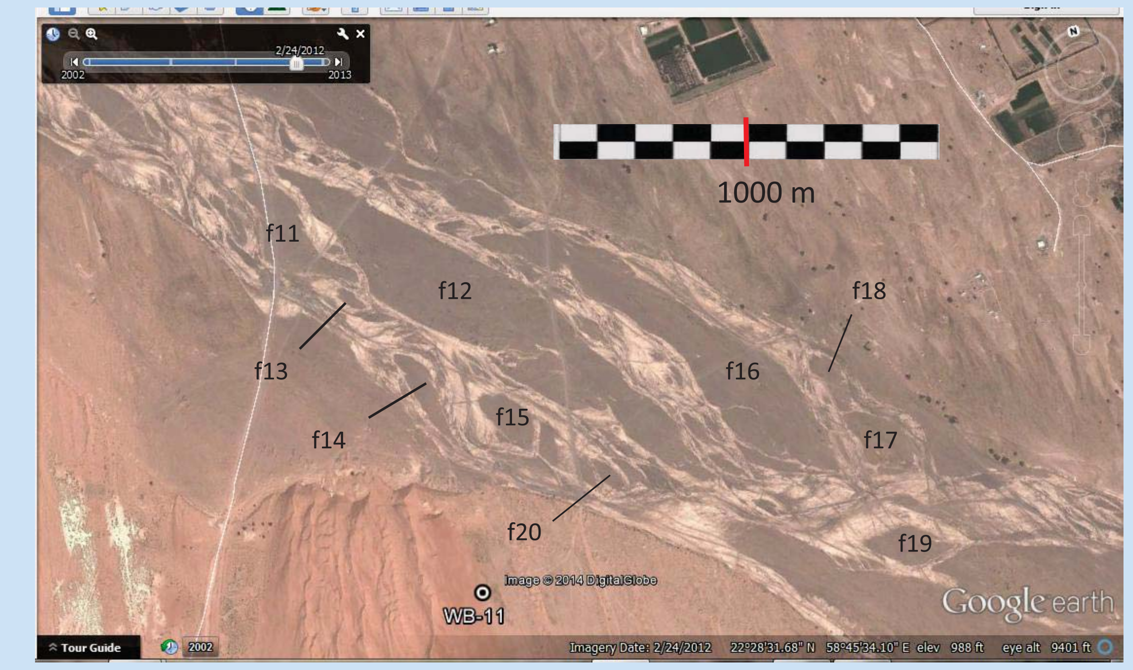
The aeolian and fluvial bedforms and geobodies are constantly shifting in Wadi Batha. As shown above, the floodplain is relatively clear of dunes on Sept 26, 2011. About two years later (bottom image) fields of small dunes have grown-up in the floodplain. Images courtesy of Google Earth.



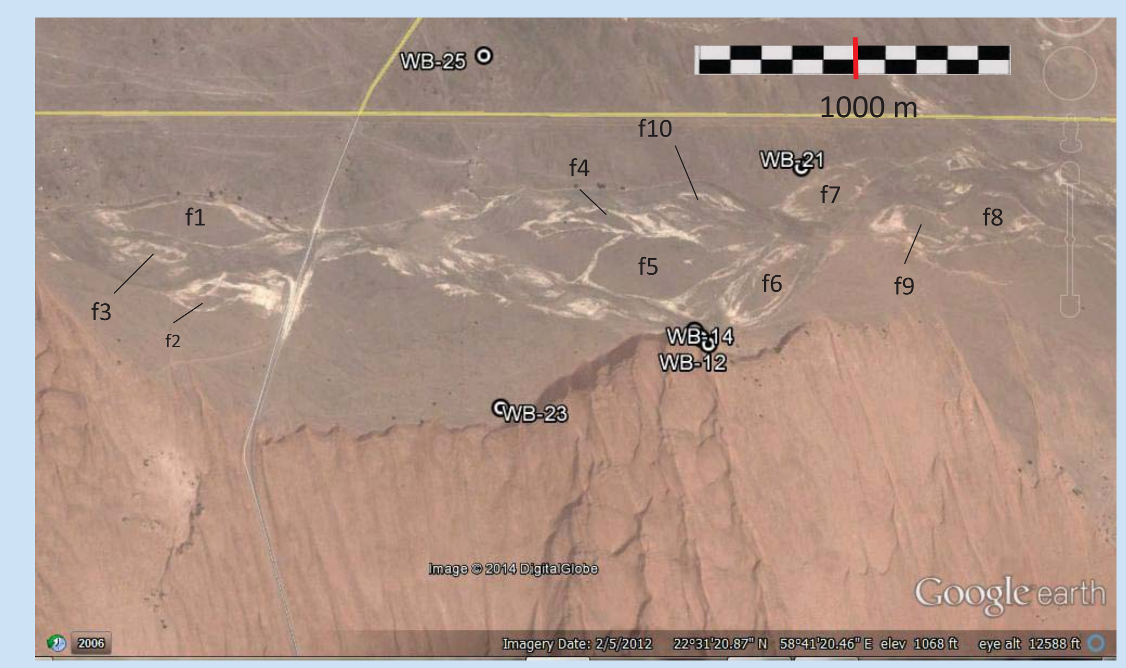


The charts above show the proportions in meters of dune and sand sheets in the Western Wadi Batha study areas. These geobodies are fewer, and much larger, than those farther east. This may be due to the dominance of fluvial processes in the western part of our study area, that tend to destroy smaller aeolian geobodies, such as dune fields and sand sheets that form in the floodplain.

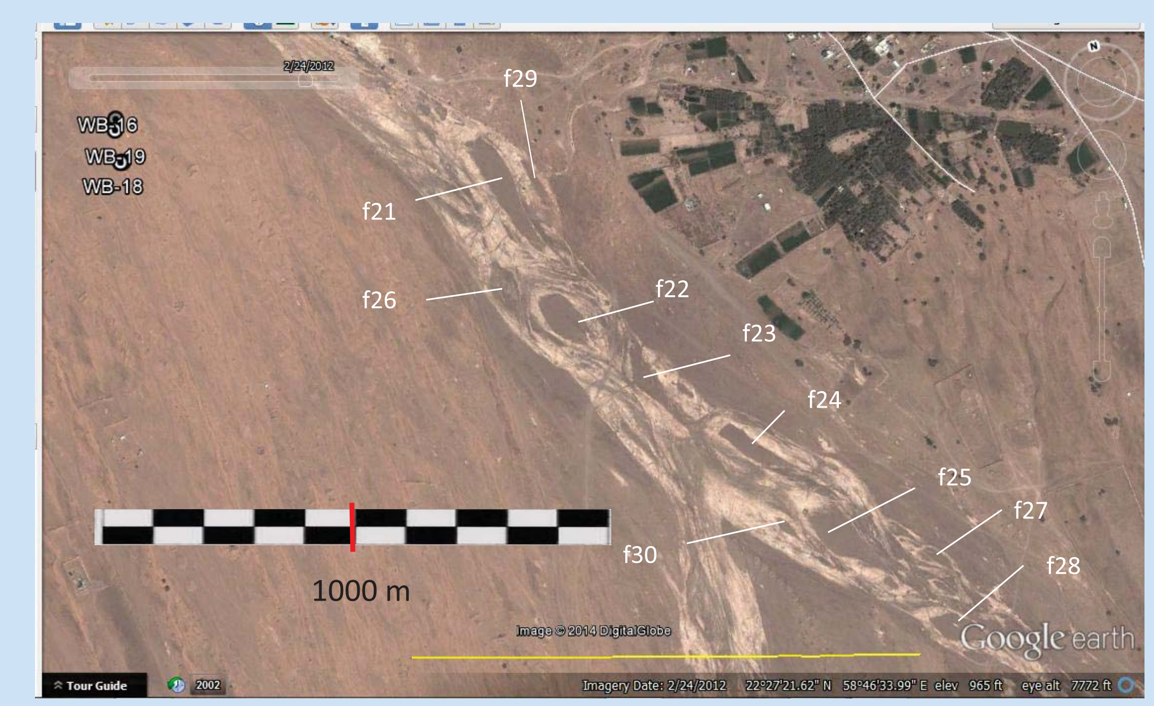
Fluvial geobodies



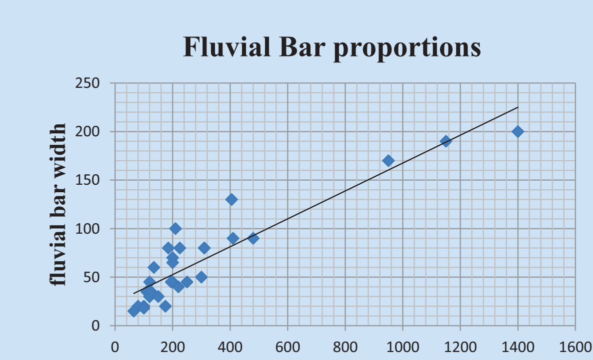
Fluvial bar forms near WB-11



Fluvial bar forms near WB-21



Fluvial bar forms near WB-16-19



Dimensions of fluvial bars measured for this study. Note the small sizes relative to aeolian dune fields and sand sheets. All dimensions in meters. Thickness of geobodies ranges from less than a meter to several meters, based on field observations and trenches.

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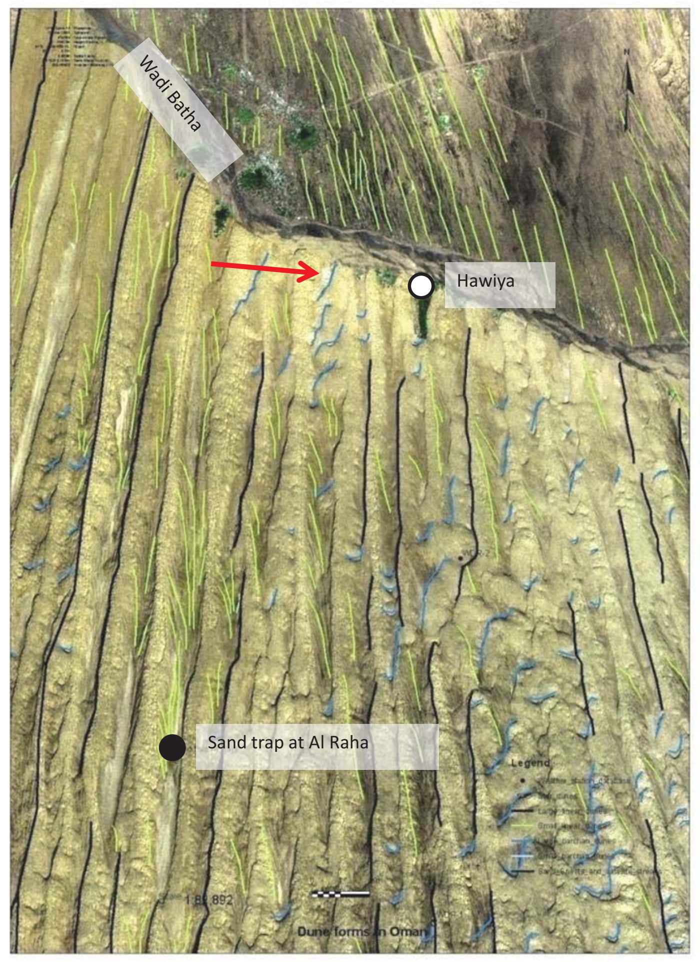
Sedimentology of small-scale aeolian-fluvial interactions, Wadi Batha Northern Wahiba Sand Sea, Oman

Steven G. Fryberger, Caroline Y. Hern, and Ken Glennie

Poster 8: Sand trap measurements

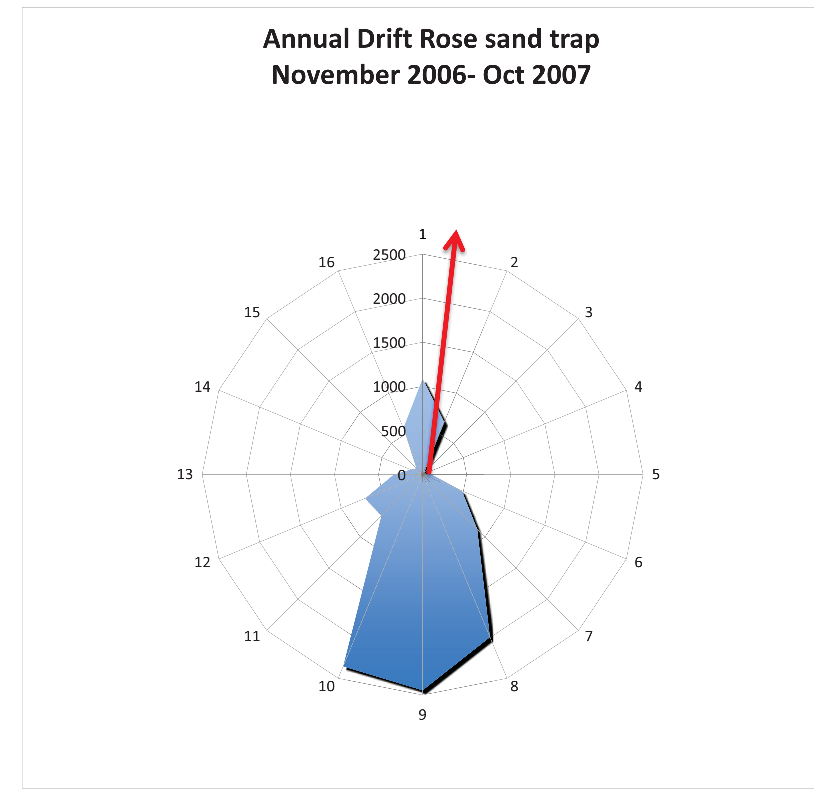


A satellite image courtesy of PDO showing the location of the sand trap at Al Raha Desert Camp. Green lines follow crests of small linear dunes. Black lines show alignment of linear megadunes. The blue lines show trends of slipfaces of barchanoid dunes, many of which are reworking sand from the linear megadunes. The interdune that flooded frequently, and that we studied in detail (WB-31), is indicated by the red arrow. Glennie (2005) reported dates in dune sand above gravel in a well at Hawiyah of 110 and 127K YBP, which may fix a maximum age for the linear dunes in that area. At the north end of the village wadi gravels interbedded with thin aeolian sand were dated at 10 K YBP in foundation excavations for a new school. Our sand trap was in a broad interdune between two linear megadunes. To the east, the linear megadunes are being reworked into barchanoid dunes by the winds of the SE Monsoon.

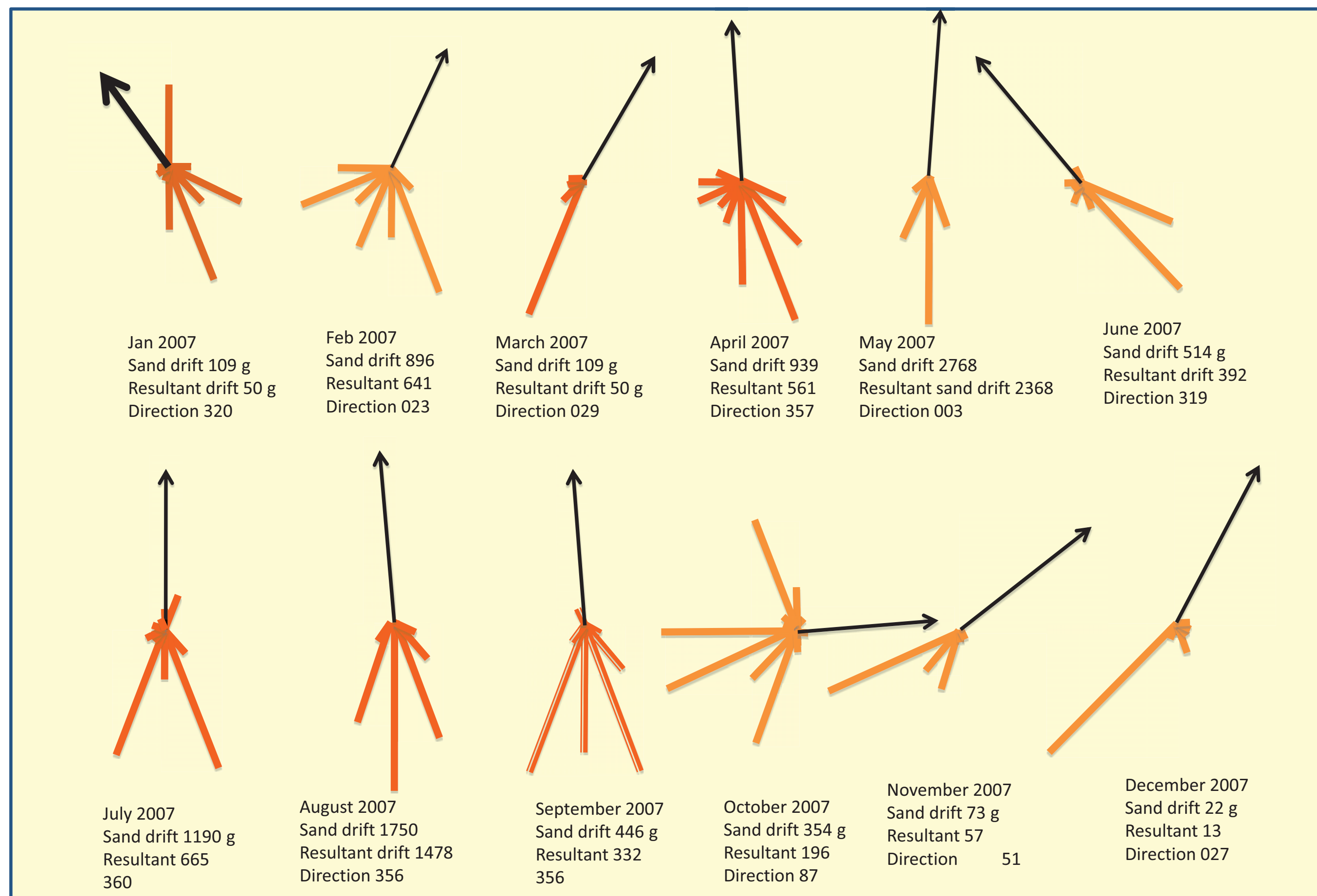
Discussion:

Our sand trap studies were undertaken to provide a quantitative confirmation of our estimates of sand drift based on wind records from around Oman. We include here the basic data from our sand trap observations, which extended for over a year in the interdune of a linear megadune near Al Raha Desert Camp. Our studies confirm that sand drift in the Wahibas is geologically significant under the present wind regime. We also recorded a rare reversal of predominant southerly winds by Typhoon Gonu, which passed along the coast of Oman near Muscat, creating strong northerly winds and dropping much rain on the desert. The rains caused much growth of grass on the dunes.

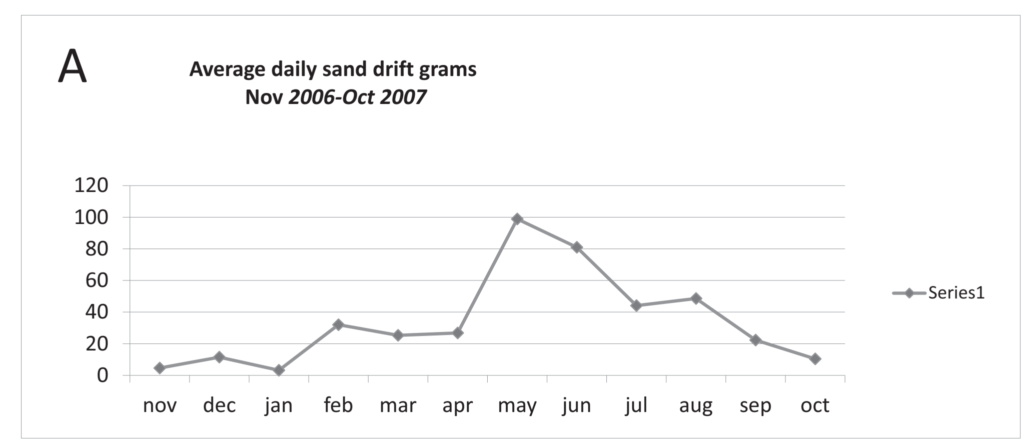
An oblique view of the interdune near Al Raha Desert Camp where the sand trap was placed for about 1.5 years. The trap was checked monthly by the authors (and spouses!). The staff at Al Raha kept an eye on the trap and provided the wire fence that deterred curious camels from disturbing the trap and test site. View is to the north, toward Wadi Batha. Localities shown at the north end of the interdune are from a study we conducted on smaller linear dunes that develop on the larger dunes, and in the interdunes (not included in this report). Image courtesy of Google Earth.

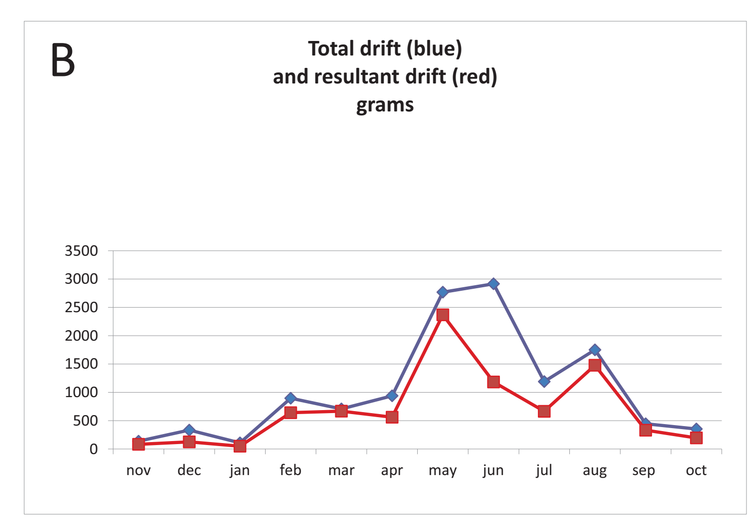


Annual drift rose based on all sand retained by the sand trap, in grams. Blue areas face "into the wind". Red arrow is the computed resultant of all measurements for the 12 months of the study. Trap was actually in the ground about 1.5 years. The wind regime on the top of the big dunes was more energetic, and probably shifted much more sand than we measured in the interdune. However, we had only this one trap, which we knew to be reliable, the design having been tested at White Sands National Monument, New Mexico. Future studies would benefit from more traps.



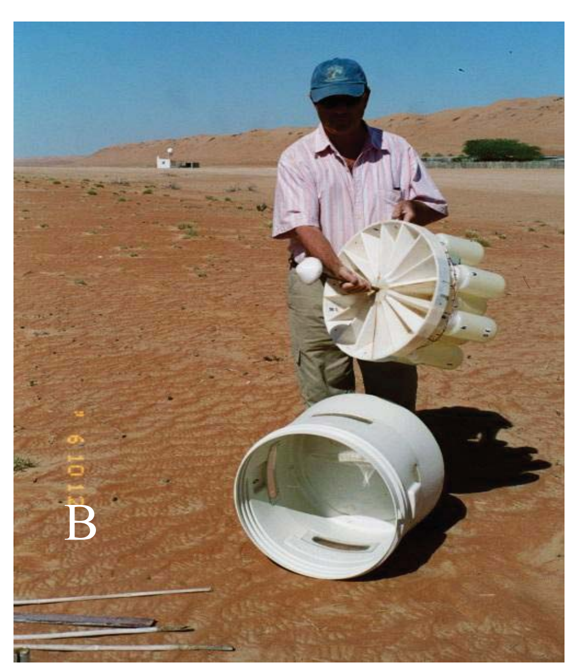
Monthly drift roses measured at the sand trap. Values for actual drift (measured in grams) and resultant drift (computed) are noted below drift roses



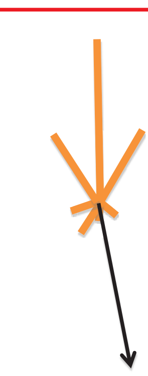


Sand Trap Results: A, average daily sand drift rate (grams) over one year. This value is computed by dividing the total sand in the trap by the number of days between visits. Due to our schedule, traps were checked at slightly different days of the month; thus this graph smoothes results; B, comparison of total and resultant drift – a measure of wind variability.

View of the sand trap during a typical sandstorm from the southwest. Saltating sand enters a thin slot in the front of the fin and falls into one of the 16 pie-shaped compartments beneath the trap. When the trap is checked, the top of the trap is removed (sand catching assembly) and the sand in each compartment (of the "sand retention assembly") is weighed. Our experience with this and other traps suggests that they are not perfectly efficient – usually failing to catch all of the surface creep (larger grains that do not saltate). Thus, our measurements are minimum values for sand transport. Light plume of drifting sand from a wind gust is marked by arrow.

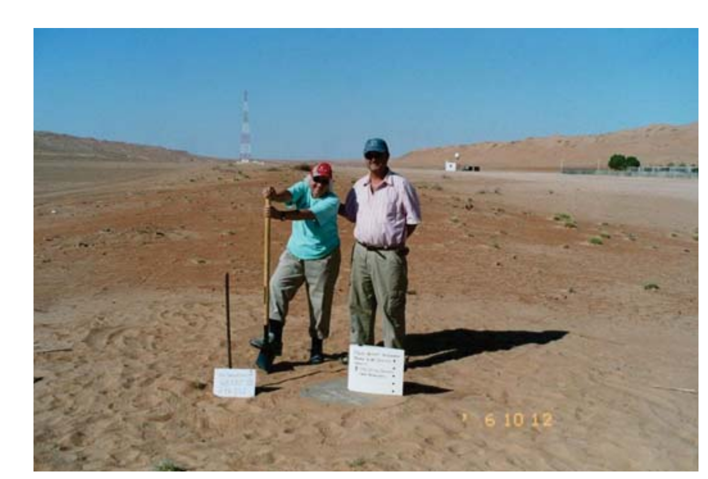


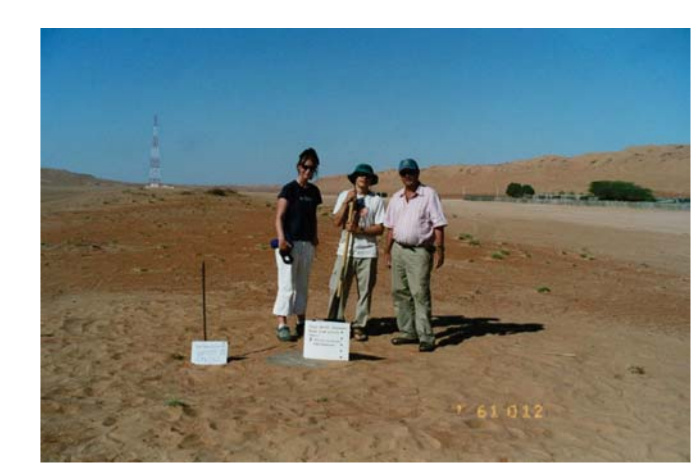
Placement and design elements of our aeolian sand trap. A, The trap was placed approximately in the center of an interdune between linear megadunes, on a slightly domed sand sheet that provided stable ground. This photo was taken during a sandstorm, thus the haze in the image. Vehicle belongs to Shuram, who provided great driving and other support for some of our trips. View to north; B, the inside of the sand retention assembly, essentially a plastic bucket modified for the trap, displayed by Fryberger. In background are small trees at Al Raha Desert Camp. View toward the north-northeast along the interdune of a large linear megadune. The pie-shaped dividers of sandflow trap sand by direction. The sand strap is oriented in the ground to match directions indicated by the labels.; D, Close-up view of the internal design of the trap, including the plastic bottles that fit within the retention assembly and retain the sand – along with occasional insects, seeds and other detritus that are blown into the trap.



Sand drift 2402 g
Resultant 1466
Resultant direction 176
degrees south

Sand trap rose for the period (about a month) from May 31-June 21 2007. This rose reflects mainly the effects of cyclone Gonu that struck Muscat in June of 2007. Although the center of the storm at its height was north of Muscat, northerly winds were felt with great force in the desert, along with much rain – sufficient to green-up the desert for months afterwards. Slipfaces on smaller dunes flipped in response to this "catastrophic" storm; however, the big dunes were little affected.





Images of the sand trap site and the crew that worked on the project. A, The author and wife Franci just after device was installed, view toward the south along the interdune. B, left to right, Caroline Hern (co-author), husband Carlos Fonseca, with Fryberger on right. Carlos and Franci were a huge help on the sand trap project, and during the study as a whole.

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Poster 9: References , Trench location data

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Thanks also to Juma Al Maskari for the release of his PhD thesis, a report that was very helpful in understanding details of the working of the southeast monsoon, particularly the 3-dimensional structure of the wind regimes that has controlled so much of the history of the Wahibas.

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We also thank Shuram drivers and staff for great and safe travel on our expeditions and for all the ways they made it easier to study the desert without having to worry about setting-up camp and preparing meals.

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Location and study site data

(original gps locations based on older technology, were corrected slightly for this poster)

Oman Field Work locations (UTM)

Site Data

Locality	date	Distance downstream (m)	Distance Main Dunes (m)	Description	Easting	E. Corrected	Northing	N. Corrected	comment
WB-1	13-Apr-06	29.54	Lo	Mud flakes on floor of wadi from mud layer after flood over dune avalance sand	694592	694831	2476111	2476374	process analogue
WB-2	13-Apr-06	27.18	27.8	Erosional ridges on floor of wadi	692288	692527	2477106	2477369	process analogue, also for current direction reading
WB-3	13-Apr-06	27.31	0	Trench in sand sheet along S. margin of Wadi Batha	692405	692644	2477056	2477319	
WB-4	13-Apr-06	27.53	5	Trench shows mixture of fluv gravel, fluv recycled sand, aeolian	692621	692860	2476945	2477208	
WB-5	13-Apr-06	30.12	113	Trench in fluvial and recycled aeolian, maybe some aeolian x-lams eroded as hill at base of trench	695077	695316	2476038	2476301	climbing fluvial ripples, some red aeolian laminae?
WB-6	13-Apr-06	27.59	10	Trench in mixed succession mud, gravel, fluv + aeol. See UAS-15 for strata similar to those at base of trench. May be grainfall deposits on dome-like dunes.	692665	692904	2476926	2477189	graded beds, clay clasts in sand build and fill of fluv ripples, pebble lags
WB-7	12-Apr-06	41.81	205	Trench in mid-channel bar, east end of W Batha, dark seds, clean aeol at base?, other sand with small pebbles, build and fill	708110	708349	2473489	2473752	pebble lags, cut-and-fill, pebble agglomeration. Side trench shows true dip of various units
WB-8	2-Apr-06	42.54	0	Surface sample and photo of many dark grains on surface of a dune (at edge of main dunes)	708807	709046	2473268	2473531	
WB-9	12-Apr-06	34.6	535	trench, flat gently dipping cross-strata, clay layers, curls on top	699811	700050	2474340	2474603	Cut-and-fill by fluvial on an aeolian?, stack of hard-to-interpret well sorted sands
WB-10	13-Apr-06	29.73	408	trench with aeolian strata unconformably abv 2 fluvial units	695050	695289	2476311	2476574	well sorted ,inverse graded aeolian ripple strata above fluv poor sorted, very good fluv climbing ripples at base, good color coding 3 units
WB-11	no date	12.64	0	Original WAH-52 location. Steep fluvial cross-beds, sand and gravel	679884	680123	2485945	2486208	
WB-12	no date	5.66	0	interdune/fluvial sediments (per note on board) along south margin of Wadi Batha. Big dune immediately to West.	674326	674565	2490781	2491044	nice older trench same green pen area- as WB-11
WB-13	no date	5.66	0	Trench in older sand sheet deposits next to W Batha	674312	674551	2490807	2491070	flat beds, gravels and aeolian mixed
WB-14	no date	5.71	0	trench in older fluvial deposits along W Batha	674345	674584	2490757	2491020	climbing fluvial ripples, bioturbation 3 units
WB-15	3-Nov-05	23.2	0	trench in dune apron at edge of W Batha, old WAH-51, considered zero distance to main dunes		687428		2477805	bioturbation, clays
WB-16	no date	14.71	873	trench in relict relief on floor of W Batha, old WAH-53	681954	682193	2484570	2484833	trench cut 2 directions for true dip, steep dip northward and setting (see GE) suggest northward migrating barchan dune fragment
WB-17	no date	14.69	863	trench in floor of w batha, good genetic units, old WAH-54	681959	682198	2484593	2484856	good mix of aeolian x-beds at surface over fluv gravel. RARE example of Oman Mts. Dark sand recycled into aeolian ripple laminations!
WB-18	no date	14.89	804	trench possible scour in sand sheet aeolian, old WAH-55	681954	682193	2484570	2484833	
WB-19	no date	14.8	802	trench with cut-and-fill, old WAH-56	681959	682198	2484501	2484764	complex cut-and-fill, several genetic units poss including aeolian
WB-20	12-Oct-06	27.34	0	Trench with fluvial gravel in x-beds, mixed with red aeolian sand from dunes	692428	692667	2477049	2477312	
WB-21	27-Jan-04	5.34	514	Trench in Wadi Batha (original WAH-1) near west side of dune field	674762	675001	2491242	2491505	ripple strata (unknown type) beneath mud layer w/cracks
WB-22	no date	23.65	0	Trench in same flooded interdune as WB-15, bioturbated, this is also interdune that is being filled by laterally migrating barchan. Old Wahiba 50. Considered zero distance to main dunes		687448		247026	bioturbated, no x-beds visible? XY coordinates may be off for some reason, but close
WB-23.1	no date	5.69	0	The first of two trenches, very closely spaced. Trench along Wadi Batha, Old Wahiba 3 locality	673655	673894	2490700	2490963	At margin of dune, stacked dune units atop fluvial
WB-23.2	no date	5.69	0	Second of two closely spaced trenches along the margin of Waid Batha near big dunes. Old WAH 3 locatlity	673658	673897	2490705	2490968	
WB-24	27-Jan-04	22.95	5	Original Wahiba-6 Locality. Field notes indicate site may be NE of Mintrib, 2497806 changed to 2491806 figuring misread of GPS, Caroline's thesis area, considered zero from main dunes	695585	695824	2491806	2492069	poorly sorted fluvial pebbles, gravels, cross-bedded with large percentage of recycled aeolian sand
WB-25	Jan 2004	4.58	1100	In Wadi Batha	673842	674081	2490852	2491115	big scour and fill beneath thin gravel bar, recycled aeolian sand not as red as other locs
WB-26	27 Jan 2004	22.07	648	Original Wadi Batha-1 locality, located in middle of wadi near Bidiyah	687131	687370	2479292	2479555	mostly red, recycled aeolian sand
WB-27	27 Jan 2004	22.07	648	Original Wadi Batha-2 locality, middle of wadi near Bidiyah	687131	687370	2479292	2479555	Mostly red, recycled aeolian sand, with some possible aeolian ripple strata at base below erosional surface
WB-28	2004?	18.64	436	Trench in cross-bedded fluvial sands and gravels, dark	683707	683946	2481016	2481279	
WB-29	no date	9.44	0	massive and cross-bedded sands in (smoothed) outcrop carved by Wadi Batha along low place on dune front. Uncorrected UTMs work best	677724	677963	2488208	2488471	
WB-30		23.46	100	Small barchan and linear dune study site		688348		2478519	
WB-31		23.31	0	Flooded interdune study area (process) along S. side Wadi Batha, considered zero distance to main dunes		687651		2478204	group of images of flood in progress, and afterward. Trenches, Includes trenches WB-15 and WB22
WB-32		23.55	1117	Overview of Wadi Batha Floodplain from road to Hawiyah, also a field trip stop for PDO trips "overview"		689567		2479526	
WB-33		25.06	386	Wadi Batha main channel after flood a few days before, distance to Qabil varies, as does to main dunes, walk-around "surface processes" area		690644		2478495	
WB-34	no date	2.36	5070	deep trenches cut by machinery to install water pipes near Al Qabil		67564		2496019	Near turnoff to road leading to dunes at Nasirah's place
WB-35	no date	23.19	90	Linear dunes truncated by Wadi Batha flows. Good examples of linear dune x-bedding, as well as flood deposits of mud and debris.		688040		2478668	Near the "baby barchan" study locality, on road to flooded interdune site.