Chapter 2

Geomorphology, Geoarchaeology and Paleoenvironments

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1 Introduction

Environmental change during the Holocene in eastern Saudi Arabia is poorly understood. Few detailed records have been examined to date, with limited evidence available from dunes, lakes and sea-level records. While the geomorphological setting of the Jubail region has been described in detail by Barth,[1] the chronology for the development of this landscape is largely unknown. Lacustrine deposits from the Al Sulb Plateau,[2] Al-Hasa,[3] Nafud As Sirr[4] and the southern playa of Bahrain[5] record wetter conditions during the Early to mid-Holocene. These sites have yielded radiocarbon dates between 7900 and 4700 cal. BC (8300–5800 ^{14}C BP) but no detailed physical, chemical or biological analyses have been conducted. Therefore, the environmental backdrop against which the occupation at Dosariyah can be set is limited.

An area approximately 3 x 2 km was mapped in detail (**Figure 2.1**) to record the geomorphology of the site and its surroundings through field observations, logging of natural and artificial quarry sections, and test pit evaluation to record sub-surface stratigraphy and collect samples for paleoenvironmental analyses. Geomorphological and paleoenvironmental research in the Dosariyah area was conducted over 10 days of field investigation, during which parts of the wider region were also visited. The topography in and around the site is generally low lying, comprising small bedrock outcrops up to 20 m high, eolianites, dune sands, sand sheets, sabkhas and coastal spits, bars and barrier complexes.

2 Geomorphology

Along much of the southern coast of the Arabian Gulf extensive outcrops of cemented eolian sands occur. These are the remnants of deflated longitudinal dunes with their axis tending in

[1] Barth 1998; 2002.
[2] Jado and Zötl 1984.
[3] Larsen 1983.
[4] Schulz and Whitney 1986.
[5] Doornkamp et al. 1980.

a north-northwest–south-southeast direction. At Dosariyah two remnant ridges of these deflated eolian sands were mapped, both of which are orientated parallel to the modern coast and are up to 15 m asl (above mean sea level). The coastal facing side of the ridges is exposed to intensive eolian erosion with exposed eolianite at the surface, while on the landward side younger, secondary dunes have formed on the leeward side of these ridges from the reworking of the primary eolian bedforms (**Figure 2.1**).

Figure 2.1. Geomorphological map of the Dosariyah area (geomorphological mapping: A. Parker and M. Morley).

To the south of Dosariyah, Hussain refers to deposits of Dammam Eolianite.[6] This eolianite is dominated by carbonate material, comprising mostly ooliths, rounded skeletal fragments (coral, shell debris) and peloids, cemented by calcite, aragonite and gypsum. The cemented dunes comprise pale brown-buff calcareous grainstone with over 85% carbonate grains. The Dammam Eolianite is characterized by well-sorted, fine to medium sand-size particles. Glennie noted that carbonate sand grains are eroded by wind action 2–4 times as fast as quartz grains and thus carbonate allochems in eolianite are usually fairly well rounded.[7] Outcrops of Dammam Eolianite are exposed at Dosariyah at the surface along the coastal strip (**Figure 2.1**). They form a resistant cap (**Figure 2.2**), which in places has been faceted by wind action to form yardangs (**Figure 2.3**) or is covered by younger dunes. Goudie notes that yardangs are developed by unidirectional or narrow bimodal wind directions and are often found in areas associated with barchans.[8] In exposed sections, foreset strata dip at varying angles between 9° and 21° while individual laminae are typically 1–3 mm thick, giving rise to well-developed pin-stripe lamination. These laminae are commonly formed by coarser grain flows of larger, well-rounded carbonate grains (ooliths, skeletal material and peloids) interbedded with finer-grained carbonate material. Further inland from the coast, the material contains an increasing amount of quartz and other siliciclastic material.

Figure 2.2. Carbonate-rich Dammam Eolianite capping quartz-rich uncemented sand in coastal cliff exposure, Dosariyah. The lower weakly cemented sand unit underlying the carbonate-rich cemented cap unit was OSL dated to 6.8 ± 0.5 ka (4.8 ± 0.5 ka BC) (photograph: A. Parker).

[6] Hussain 2006.
[7] Glennie 1970.
[8] Goudie 2007.

Sections through these cemented dune ridges show they are formed from more than one generation of eolian deposits. Underlying the cemented Damman Eolianite cap rock several exposures revealed soft, uncemented, well-sorted medium sands comprising ~95% quartz, and less than 1% ooids. Key exposures were noted in a disused quarry section, where up to 8 m of the deposits were exposed beneath a 1 m thick Damman Eolianite cap (N26°54’52.1” E049°44’21.5”), and also in a coastal cliff section (**Figure 2.2**) under a 0.5 m cap (N26°55’34.3” E049°44’30.8”).

In the United Arab Emirates carbonate cemented sands, mapped as ‘miliolite’ by Huntings[9] as they contained many miliolid foraminifera, equate to the Damman Eolianite observed in the eastern coastal region of Saudi Arabia. More recently, however, they have been termed the Ghayathi Formation[10] after a type section at Jabal Marban in Abu Dhabi. The Ghayathi Formation consists of carbonate-dominated paleo-dune sandstones, which form a series of semi-continuous outcrops across the region. These generally occur as extensive deflated sheets occupying low-lying areas. Small isolated outcrops of miliolite draping the older orange quartz-rich sands, which are synonymous with the Madinat Zayed Formation of the UAE,[11] occur locally.

Low dunes, reworked and emplaced during the Holocene, are found superimposed on the main eolianite dunes. They are most conspicuous on the north-northwest–south-southeast trended deflated linear dune closest to the coast. Here they top the summits of the high ground and are draped over the eolianite surface on the landward side. In places these dunes are up to 3 m above the eolianite surface and are whitish in color, having largely been reworked from the Dammam Formation. They trend north-northeast–south-southwest, with several wind gaps between the white dune areas. These dunes are covered in scrubby vegetation. Areas of cross-bedded and planar-bedded grainstone occur locally between areas of low dune or sand veneer. These are exposed as corrugated pavements, which are flat in nature due to deflation by wind, which has exposed the bedding planes. Good examples occur at N26°55’11.0” E049°44’42.0” and N26°55’13.6” E049°44’35.5”. Within the wind gaps and on the dune flanks of the sabkha areas at Dosariyah extensive areas of low, small scrubby nebkha dunes up to 1 m high occur.

9 Huntings 1979.
10 Hadley et al. 1998.
11 Farrant et al. 2012.

Across much of the desert interior to the northwest and west of the site active transverse barchanoid dunes occur. Driven by the shamal winds, these move at rates of up to 3 m/yr.[12] Barth suggests that overgrazing has reduced the vegetation cover to such an extent that previously stable fossil dunes have once again become active.[13]

Within the southeastern coastal area yardangs are common features of the landscape, often found on low-lying hills and ridges of the Upper Tertiary Rus, Dammam and Hofuf formations, and Quaternary carbonate eolianite formations. At Dosariyah meso-scale yardangs were mapped adjacent to the coast, developed in carbonate-rich eolianites. The yardangs here are up to 1.5 m high, 3 m wide and up to 15 m in length (**Figure 2.3**).

The dominant orientation of the yardangs is to the south-southeast and roughly parallel to the present-day prevailing wind patterns along the Arabian Gulf coastline. Yardangs faceted into Hadrukh bedrock were also noted in the vicinity of Jebel Bari (N26°54'26.4" E049°29'59.2"). To the west and northwest of the study site, barchanoid ridges and barchan dunes overlying sabkha deposits are also found. These dunes have migrated across the sabkhas in the same prevailing wind direction.[14] Elsewhere in the Arabian Gulf region meso-scale yardangs up to 10 m high have developed on resistant dolomitic Eocene limestones (Rus Formation) in the southwest corner of the main island of Bahrain's central depression, while yardangs up to 4–6 m high are also found on eroded eolianites on Jiddah Island, off the west coast of Bahrain.[15]

Figure 2.3. Yardang faceted into coastal eolianite, Dosariyah (photograph: A. Parker)

3 Coastal Processes

The coastline running south of Jubail to the desalination plant, south of Dosariyah, is dominated by a series of complex coastal barriers, spits, lagoons and sabkhas. The coastal configuration comprises several headlands and embayments, which are heavily influenced by coastal processes, especially tidal patterns, wave refraction and longshore drift. Tidal patterns within the Arabian Gulf are complex with regional variations in tidal range,[16] including two amphidromic points that have been noted where there is no tidal range. The

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[12] Barth 2002.
[13] Barth 1999; for further details see Barth 1998.
[14] Anton and Vincent 1986; Barth 2002.
[15] Doornkamp et al. 1980.
[16] Barth 2002.

first is located off the northern Saudi Arabian coast to the north of Dosariyah, and the second is located off the western Abu Dhabi coast (UAE). Tidal ranges increase away from these nodes. Over most of the Gulf the tidal range offshore is < 0.6 m but increases to 1–2 m near land.[17] At Jubail the tides mainly follow a semi-diurnal regime with a mean spring tide range of *c.*1.5 m and a neap tidal range of 0.8 m.[18]

At Ras al Qulay'ah, 15 km southeast of Dosariyah, calculated tidal data for 2016 show a Mean High Water (MHW) of 1.61 m, Mean Low Water (MLW) of 0.55 m and mean tidal range of 1.09 m. Mean Highest High Water (MHHW) was calculated to be 1.70 m and Mean Lowest Low Water (MLLW) to be 0.44 m with a tidal range of 1.26 m. The Highest Astronomical Tide (HAT) was 2.05 m and Lowest Astronomical Tide (LAT) 0.09 m. Al-Subhi reported semidiurnal dominance in the region with astronomical tide variation accounting for 90% of the total water variation.[19] The rest of the variation was attributed to atmospheric pressure and water density variations, especially during the winter months. The Gulf coastline in the proximity of Dosariyah thus shows a low tidal range. In addition to the normal tidal range, shamal wind generated high amplitude storm surges, coupled with changes in atmospheric pressure, topography and tidal effects that can lead to significant changes in sea level of several meters.[20] From historical data it has also been suggested that earthquake activity in Iran has led to probable tsunami events in the Arabian Gulf leading to coastal inundation.[21] To date, no (paleo-)tsunami deposits have been reported from the Gulf coast region.

Present-day coastal processes have been severely impacted by development and infrastructure along the coast, in the form of artificial islands, marinas and groynes, leading to sediment supply and delivery issues. In places this has led to the starvation of sediment resupply leading to erosion of the coastal barrier island and spits. At Dosariyah a coastal barrier-spit complex has developed, behind which a series of lagoons and channels has formed. These coastal features formed across coastal embayments at the mouth of the now dry sabkha inlets. At least two barriers were mapped: the present barrier lies approximately 250 m from the coastal cliff line, while an older, former barrier abuts the land and is clearly visible in the CORONA satellite images (**Figure 2.4**). This feature lies across the entrance to the northern sabkha where it now forms a low dune. The coastal barrier deposits comprise a complex mix of beach, eolian and washover sands. These form complex elongate hooked spits curving inland. Current coastal processes are eroding this feature because of the

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17 Sheppard et al. 1992.
18 Barth 2002.
19 Al-Subhi 2010.
20 El-Sabh and Murty 1989; Thoppil and Hogan 2010.
21 Bou-Rabee and VanMarcke 2001; Jordan 2008.

starvation of new sediment supply due to coastal development and the construction of breakwaters to the north. The spits and barrier islands are aligned parallel to the coast and the coastal barriers are interspersed by intertidal and lagoonal sediments.

Figure 2.4. CORONA satellite image for the Dosariyah region.

Inland, these features have largely infilled to form extensive sabkha deposits. Compared to the classic barrier-lagoon systems found in the UAE around Abu Dhabi, the Dosariyah system tends to lack carbonate mud and algal mats. This observation was previously noted by James and Little.[22] They suggest that this may be the result of groundwater influences from aquifers within the Pleistocene dune and Miocene Hadrukh bedrock formations. The sabkhas comprise flat areas, partially cemented by salt (sodium chloride) and calcium sulphate (gypsum) often forming pustulose surfaces (**Figure 2.5**).

Figure 2.5. Pustulose sabkha surface with salt, southern sabkha, Dosariyah (photograph: A. Parker).

Two areas of sabkha are found close to the site at Dosariyah (**Figure 2.1**), one to the north and the other to the south. The southern sabkha is of particular importance because of its location adjacent to the Neolithic archeological site. In this area three different sabkha levels, representing former sea-level shoreline limits, were mapped at 1.2, 1.5 and 2.0 m asl. A series of test pits (TP 1–5) were dug into the sabkhas. TP1, 2 and 3 were located in the southern sabkha and TP4 and 5 in the northern sabkha. These sections record phases of development from open water to intertidal flats and finally sabkha development. The sections were sampled for sedimentological and paleoenvironmental analyses and are described below.

4 Methods and Sampling

The Neolithic site of Dosariyah is situated on an area of higher ground, ~5 m asl, surrounded on three sides by low-lying sabkha and to the east by coastal dunes and the Arabian Gulf coastline. The sabkha surface in this area comprises flat, low-lying gypsiferous surfaces with coarse gypsum crystals, medium to coarse sand and abundant relict marine gastropod shells of the genus Cerithidea, a mollusk favoring an intertidal environment. The sabkha in this area

[22] James and Little 1994.

of Jubail is unusual as it is nourished by artesian groundwater that appears to be important in the maintenance of this area as a salt flat.[23] To the south of the site the sabkha can be broadly divided into an upper, middle and lower elevation surface, with the elevation dropping towards the south away from the site. To the north of the site the higher ground is formed by Pleistocene and Holocene dune systems, and the sabkha appears to comprise one main surface that extends out to the north and west.

Profiles across the site were surveyed using a total station in relation to sea level and these are shown in **Figure 2.6**. Five test pits were excavated into the sabkha deposits located to the north and south of the Dosariyah archeological site. The depths excavated were limited by the modern water table. The sediment sections were logged and described and are shown in m asl (**Figure 2.7**).

Figure 2.6. Cross sections across Dosariyah showing the topographic profiles and locations of the sampling sites.

Figure 2.7. Test pit profiles from the southern sabkha (TP1, PT2, TP3) and northern sabkha (TP4, TP5); all sections are presented in m asl.

4.1 Sedimentology

Profiles within these test pits were recorded and sampled for paleoenvironmental analyses. Mass-specific, low-frequency magnetic susceptibility measurements were made on each sample using a Bartington MS2 meter with an MS2B sensor at 0.1 SI unit sensitivity.[24] Loss-on-ignition analyses followed the method described by Heiri et al.[25] Samples of < 2 mm were oven dried at 105°C, followed by a first combustion at 550°C to remove organic carbon then a second burn at 950°C to drive off carbonates. Results are reported as percentages of the dry weight. To determine grain size, samples of air-dried sediment < 2 mm were gently disaggregated in de-ionized water with 5% Calgon (hexametaphosphate) and analyzed using a Malvern Mastersizer 2000. Grain size statistics are based on the logarithmic graphical measures of the (original) Folk and Ward method for sorting, skewness and kurtosis.[26] The mean particle size calculations are based on the modified Udden-Wentworth scale and are reported in microns (µm).

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[23] James and Little 1994.
[24] Dearing 1999.
[25] Heiri et al. 2001.
[26] Folk and Ward 1957.

4.2 Dating

Samples were collected from cleaned sections using black, opaque, light-proof tubes (50 mm diameter x 200 mm length). Sample locations are listed in **Table 2.1**. Using the procedure outlined in Armitage et al.[27] 212–180 µm diameter quartz grains were extracted from the sample tubes. Stimulation (60 s at 125°C) was provided by blue LEDS (wavelength 470 nm) and OSL signals, derived from the first 0.5 seconds of stimulation (with a background signal obtained from the last 6 seconds), were detected with an EMI 9235QA photomultiplier tube via 7 mm of Hoya U-340 optical filter. All equivalent doses (De) were determined using the SAR protocol[28] using small (2 mm) aliquots comprising approximately 150 individual grains. Aliquots showing poor OSL characteristics (recycling ratios outside 10% of unity, recuperation > 5% of the natural OSL signal or evidence of feldspar contamination[29]) were rejected from the analysis. At least 22 aliquots passing these rejection criteria were used to determine the sample equivalent dose. Beta and gamma dose rates were calculated for each sample using radioisotope concentrations measured by ICP-MS (U and Th) and ICP-AES (K). Dose rates were corrected using an assumed water content of 5 ± 2.5%.

Table 2.1. Summary dosimetry and OSL dating results. [1]Uncertainties are based on the propagation, in quadrature, of errors associated with individual errors for all measured quantities. In addition to uncertainties calculated from counting statistics, errors due to 1) beta source calibration (%) (Armitage and Bailey 2005); 2) ICP-MS calibration (10%); 3) dose rate conversion factors (3%); and 4) attenuation factors (2%) have been included (Murray and Olley 2002).

Sample	Sample details	Radionuclide concentrations			Sample depth	Water content	OSL sample grain size	Cosmic dose rate	Dose rate	Equivalent dose	n	Age
		K (%)	U (ppm)	Th (ppm)	(m)	(%)	(µm)	(Gy/ka)	(Gy/ka)	(Gy)	(accept)	(ka)[1]
OSL1	Dosariyah (TP3)	0.90 ± 0.09	0.89 ± 0.09	1.67 ± 0.17	1.3 ± 0.2	5 ± 2.5	212–180	0.169 ± 0.004	1.23 ± 0.07	7.14 ± 0.34	27	5.8 ± 0.4
OSL2	Dosariyah (TP3)	0.41 ± 0.04	2.00 ± 0.20	0.67 ± 0.07	0.35 ± 0.2	5 ± 2.5	212–180	0.212 ± 0.027	1.03 ± 0.05	1.23 ± 0.12	22	1.2 ± 0.1
OSL3	Dosariyah (QP1)	0.34 ± 0.03	1.81 ± 0.18	4.80 ± 0.48	1.1 ± 0.2	5 ± 2.5	212–180	0.173 ± 0.005	1.15 ± 0.05	8.33 ± 0.41	21	7.2 ± 0.5
OSL4	Dosariyah (QP1)	0.47 ± 0.05	1.67 ± 0.17	0.62 ± 0.06	0.5 ± 0.2	5 ± 2.5	212–180	0.199 ± 0.018	0.99 ± 0.05	2.95 ± 0.16	22	3.0 ± 0.2
OSL5	Dosariyah (coastal section)	0.90 ± 0.09	0.74 ± 0.07	1.80 ± 0.18	0.5 ± 0.2	5 ± 2.5	212–180	0.199 ± 0.018	1.23 ± 0.07	8.36 ± 0.33	27	6.8 ± 0.5

AMS radiocarbon dating was carried out at Scottish Universities Environmental Research Centre (SUERC) and dates were determined on marine shells. Dates were calibrated using

27 Armitage et al. 2011.
28 Murray and Wintle 2000; Murray and Wintle 2003.
29 Duller 2003.

the 95% confidence limits in Calib 7.1 using the Marine 13 curve[30] and corrected for the Arabian Gulf Marine reservoir effect using the delta R value of 180 ± 53.[31] All ages are reported in BC. **Table 2.2** shows the radiocarbon ages for nine samples taken from the test pits.

Table 2.2. Radiocarbon dates from the paleoenvironmental test pits.

Samples			Reconstruction of paleo-sea level band									Calibrated ages	
Sample name	Depth (m b.s.)	Ele-vation (m a. MSL)	Upper Limit (m a. MSL)	Lower Limit (m a. MSL)	Upper limit paleo-MHHW (m a. MSL)	Upper limit paleo-MSL (m a. MSL)	Lower limit paleo-MSL (m a. MSL)	Lab ID (SUERC)	Material	^{14}C BP	δ^{13}C (‰)	Age cal. BC (2σ)	Age cal. BP (2σ)
DOS 14/8TP5	0.32	1.39	1.53	-0.44	3.45	2.92	0.95	54501	*Pillucina cf. angela/ Dosinia alta*	4266 ± 30	1.2	2386–2000	3949–4335
DOS 14/9TP5	0.48	1.23	1.53	-0.44	3.29	2.76	0.79	54502	*Dosinia cf.alta*	4482 ± 30	1.8	2651–2286	4235–4600
DOS 14/2TP1	0.48	0.84	1.53	-0.44	2.90	2.37	0.40	54492	*Tellinia incarnate/ wallaceae*	4690 ± 30	2.9	2885–2576	4525–4834
DOS 14/1TP1	0.42	0.90	1.53	-0.44	2.96	2.43	0.46	54491	*Tellinia incarnate/ wallacea*	4706 ± 30	2.9	2899–-2586	4535–4848
DOS 14/4TP4	0.22	1.69	1.53	-0.44	3.75	3.22	1.25	54497	*Dosinia cf. alta*	5273 ± 30	2.3	3624–3360	5309–5573
DOS 14/5TP4	0.64	1.27	1.53	-0.44	3.33	2.80	0.83	54498	*Dosinia cf. alta*	5642 ± 30	2.4	4026–3734	5683–5975
DOS 14/3TP2	0.45	1.09	1.53	-0.44	3.13	2.60	0.63	54496	*Pillucina cf. angela/ Dosinia alta*	5976 ± 30	2.6	4399–4085	6034–6046
DOS 14/6TP4	0.86	1.05	1.53	-0.44	3.11	2.58	0.61	54499	*Dosinia cf. alta*	6139 ± 30	2.1	4540–4318	6267–-6489
DOS 14/7TP4	1.17	0.74	1.53	-0.44	2.80	2.27	0.30	54500	*Dosinia cf. alta*	6444 ± 31	2.6	4929–4610	6559–6878

4.3 Mollusk identification and quantification

Bulk samples (1 kg) were collected and processed for molluscan analysis. Remains were identified using published identification guides and keys.[32] The assemblages from the five test pits were quantified in terms of number of identified specimens (NISP), minimum number of valves (MNV) and minimum number of individuals (MNI) based on apex and aperture presence for gastropods, and on umbo presence for bivalves. Bivalves were attributed to right or left sides where possible. For bivalves the recorded dimensions (shell size, below) were taken into consideration when calculating MNV and MNI.

Mollusks were measured to the nearest 0.1 mm using Mitutoyo Absolute Digimatic calipers. For bivalves, measurements for valve length (VL) and valve height (VH) were taken, as described by Claassen.[33] Valve depth was also measured in bivalves. For gastropods, shell

30 Reimer et al. 2013.
31 Southon et al. 2002.
32 Bosch and Bosch 1989; Oliver 1992; Willan 1993; Hasan 1994; Bosch et al. 1995; Glover and Taylor 2001; DuPont and Al Tamimi 2008; Jahangir et al. 2012.
33 Claassen 1998: 109.

height (SH) and width was measured, also as described by Claassen.[34] Specimens were not measured if they were not complete (e.g. with missing apex or missing or damaged apertures in the case of gastropods, and absent umbo or margin damage for bivalves).

In addition to recording fragmentation each specimen was subjected to observation for taphonomic impacts. This includes recording any evidence of predation by other animal taxa, hosting for tubeworms (e.g. Vermetidae) or any other surface modification of known or unknown origin.

Molluscan taxa are often highly sensitive to variation in environmental conditions; as such, their presence, absence and relative abundance in stratified sediments can be used to aid reconstruction of past environmental conditions, and changes in these over time and space. Habitats for taxa identified at Dosariyah can be found in **Appendix Table 2.1** and **Figure 2.8** and the species found in **Appendix Table 2.2**.

Figure 2.8. Tidal and shore zones.

It is essential in the study of both recent and ancient mollusks that the use of current, accepted taxonomy is ensured. In Arabia, many molluscan taxa remain understudied, and as such, taxonomy is not always agreed upon between specialists. Ensuring a correct taxonomic identification impacts upon the environmental conditions that can be reconstructed using molluscan data. The taxonomy for molluscan species is continuously being updated, and therefore any taxonomic name listed here could be revised in the future. To avoid confusion each identified taxa will include a referral to the published source of its taxonomic description.

4.4 Calculation of relative sea levels (RSL)

Sea-level index points (SLIPS) were used to fix the position of past RSL in time and space[35] and tend to form at or around mean highest high-water tide (MHHWT), rather than at the paleo-mean sea level.[36]

All the ^{14}C samples dated in this study are considered as primary SLIPS, as their elevations, ages and vertical relationships to contemporaneous tide levels (indicative meaning) can be

34 Claassen 1998: 110.
35 *Sensu* Tooley 1998.
36 Shennan et al. 2002; 2006.

deduced. The OSL ages are regarded only as secondary SLIPS as they lack indicative meaning values. Horizontal error bars indicate the maximum and minimum ages as determined by the ^{14}C calibration. The vertical error calculation includes the sum of all the quantified or estimated height errors, including field levelling, present tide heights and interpretation of indicative meaning (total error = $\sqrt{(e^2_1 + e^2_2 + \cdots e^2_n)}$).[37] Due to the nature of the sediments and the shallow depths sampled, the effects of compaction and sediment consolidation were regarded as negligible.[38] All ages were made on *Dosinia* sp., *Pillicina* cf. *angela* and *Tellineae incarnate/wallacea*. Estimation of habitat range for these species was based on El-Sorogy et al. and Feulner and Hornby when considering the intertidal plus the uppermost meter of the shallow subtidal range.[39] The upper and lower limits calculated for the paleo-MSL and upper limit for the MHHW are shown alongside the radiocarbon ages in **Table 2.2**.

5 Results

5.1 Dune sections

The quarry section yielded an age of 7.2 ± 0.5 ka (5200 ± 500 BC, QP1 OSL3) for the quartz-rich weakly cemented sand unit 1.05 m below the surface. The upper carbonate-rich cemented unit with up to 50% ooids was dated to 3.0 ± 0.2 ka (3000 ± 200 BC, QP1 OSL4) at 55 cm depth. The quartz-rich sand unit below the carbonate-rich eolianite cap unit from the coastal section (**Figure 2.3**, **Table 2.1**) was dated to 6.8 ± 0.5 ka (4800 ± 500 BC, Coastal Section OSL5). The ages and differences in the composition of the two sediment units imply that they were formed in two phases of deposition with a break in sedimentation sometime in between. The lower unit is eolian in origin and derived from quartz and other siliciclastic terrestrial sources with minor carbonate elements. The sediments in the upper unit, rich in ooids, were originally derived from a shallow marine origin and transported by eolian processes.

5.2 Southern sabkha, test pit 1 (TP1), N26°54’50.5” E049°44’41.5”

TP1 is situated at a point where a tongue of higher ground forms a low promontory extending out into the northwestern area of the southern sabkha (**Figure 2.6a**). The surface height was

37 Horton et al. 2000.
38 *Sensu* Lokier et al. 2015.
39 El-Sorogy et al. 2016; Feulner and Hornby 2006.

measured at 132 cm asl and the water table was reached at 70 cm below surface (b.s.). TP1 exhibited a very well-defined stratigraphic sequence, with medium to coarse eolian sands (in a lagoonal context) overlying a highly distinctive white fine silt unit with a sticky consistency and a very pure composition. The sedimentology of TP1 is described in **Appendix Table 2.3** and shown in **Figure 2.9a**. The molluscan assemblage is shown in **Figure 2.9b**. A total of 119 mollusk shells were recovered from the three samples taken from TP1. These represented six individual gastropods and 113 bivalve valves (**Appendix Table 2.4**). Gastropods are represented by one taxa of the family Potamididae. Bivalves are represented by at least three taxa, from two families, Ungulinidae and Tellinidae. Bivalves are more frequent than gastropods in the TP1 sequence, within which *Tellina* cf. *arsinoensis* and *Tellina incarnata*/*wallaceae* are most abundant in the assemblage. Unlike the molluscan remains from the other test pits at Dosariyah, those from TP1 included substantial amounts of fragmentary material, especially at 46–50 cm, which contained 127 fragments of unidentified Tellinid remains. Two radiocarbon samples were measured at 90 cm asl (42 cm b.s.) and 84 cm asl (48 cm b.s.) which yielded ages of 4706 ± 30 ^{14}C BP (SUERC-54491, 2899–2586 cal. BC 2σ) and 4690 ± 30 ^{14}C BP (SUERC-54492, 2885–2576 cal. BC 2σ) (**Table 2.2**).

Figure 2.9a. Sedimentology diagram for TP1.

Figure 2.9b. Molluscan diagram from TP1.

The sequence in TP1 shows a very marked change in depositional environment from fine-grained silts (less than 50 µm) in the lowermost Unit 10 (68–60 cm b.s., 66–72 cm asl) to medium- to coarse-grained sands (up to 250 µm) in Unit 9 (60–52 cm b.s., 72–80 cm asl), returning to fine-grained clays (up to 30%) and silts (up to 50%) in Unit 8 (50–38 cm b.s., 82–94 cm asl) with medium- to coarse-grained sands in the overlying Units 7 to 2. Unit 8, which comprised homogeneous carbonate-rich fine-grained clays and silts, contained mollusks in life position. There is a decline in the proportion of sand (< 10–25%) and increases in silt (~50–60%) and clay (25–35%) in this unit. The silty sediments in Unit 8 and Unit 7 are very poorly sorted, platykurtic and near symmetrical. This unit is indicative of a very low-energy environment where silts and clays have settled out of suspension in a marine-proximal environment with marine shells deposited in life position.

Occasional thin (< 4 cm) lenses and stringers of coarser sands in the lower part of this sequence (e.g. Unit 9) may represent horizons when water depths were shallower. In Unit 8 the layers of abundant marine bivalves in life position mark the stabilization of water levels at a depth conducive to supporting bivalve communities in higher numbers. A deeper water marine environment is suggested by the presence of *Tellina incarnate/wallaceae*, which is the most abundant species in Unit 8. The mollusks present in the upper part of Unit 8 and Unit 7 suggest a shallowing up sequence with an increase in the presence of intertidal species including *Potamides conicus*, *Diplodonta* cf. *globosa* and *Tellina* cf. *arsinoenis*. Both radiocarbon dates are statistically identical and place Unit 8 at *c.*2900–2585 cal. BC. The bulk of the lower Units 10 to 8 were laid down during a marine transgression event when a sufficient water column existed for the deposition of clays and silts.

The sands of Units 6 to 2 indicate a reduction of water depth and the contraction of the lagoonal shoreline allowing sand to be introduced to the lagoonal environment by eolian processes. The sediments coarsen upwards from silts in Unit 6 to fine sand in Unit 2 and change from near symmetrical to strongly fine-skewed, meso/platykurtic to very leptokurtic and very poorly sorted to poorly sorted. Clay content decreases sharply at 34 cm b.s. (98 cm asl) to ~5%. Organic content increases in Unit 5 and the lower part of Unit 4 to ~8%, declines slightly in the upper part of Unit 4 and increases again in Unit 3 to ~4%. MS values follow the organic curve. There is a steep decline in carbonate content to ~5% in the upper four units. These units represent the development of sabkha deposits. Shell fragments of marine bivalves are found in very low frequencies, usually comprising only small fragments of larger shells, indicating a possible wind-blown origin of these lighter inclusions.

The upper 10 cm of the sabkha profile (Unit 1) and the present-day surface comprises well-cemented gypsiferous sands, gypsum crystals, salt heave features and abundant cerithid shells. The latter are consistent with intertidal sand flats, signifying a coastal marginal environment during the sea-level regressive event.

5.3 Southern sabkha**, test pit 2 (TP2), N26°54'48.76" E049°44’44.8”**

TP2 was located at the northwest margin of the middle sabkha, at the point where this level interdigitates with higher sabkha deposits. The surface was 152 cm asl and a single radiocarbon age determination was made from a sample at 109 cm asl (45 cm b.s.) (5976 ± 30 ^{14}C BP, SUERC-54496, 4399–4085 cal. BC 2σ) (**Table 2.2**). The results from the sedimentological analyses are shown in **Figure 2.10a** and molluscan analysis in **Figure 2.10b**. The 80 cm deep sequence recorded in TP2 was divided into five units (**Appendix Table 2.5**). Only 36 mollusk shells were recovered from the eleven samples taken from TP2 (**Appendix Table 2.6**). These are represented by four individual gastropods and 32 bivalve valves. Gastropods are represented by at least two taxa of two families — Potamididae and

Columbellida. Bivalves are represented by at least five taxa, from four families — Lucinidae, Tellinidae, Psammobiidae and Veneridae. Bivalves are more frequent than gastropods in the TP2 sequence, within which *Dosinia* sp. and *Tellina* cf. *arsinoensis* are most abundant in the assemblage, though both are still only present in relatively low numbers.

Figure 2.10a. Sedimentology diagram for TP2.

Figure 2.10b. Molluscan diagram from TP2.

The oldest, basal context (Unit 5) comprises medium–fine near symmetrical, mesokurtic, moderately sorted eolian sands that have been reworked and deposited into a marine marginal environment, most likely at the fringes of an intertidal flat during a transgressive phase. Fine silts and the presence of a few shells including *Dosinia* cf. *alba* indicate a shallow to moderate water depth, suggesting a tidal influence close to the site at Dosariyah to the north. Shells are absent between 72 and 50 cm b.s. (80–102 cm asl) suggesting a contraction in marine/lagoonal waters is evident up-profile (Unit 5). The molluscan assemblage records lower shore and intertidal taxa during the main transgression phase in the upper part of Unit 5 between 50 and 39 cm b.s. (102–113 cm asl) dated to 4399–4085 cal. BC 2σ (SUERC-54496, **Table 2.2**) with a change to intertidal taxa in Unit 4 (39–15 cm b.s., 113–137 cm asl). The sediments in Unit 4 change to near fine-skewed, leptokurtic and poorly sorted fine sands and most likely represent sediment infilling and a lateral shift in environment. Unit 3 indicates an intertidal sand flat and the development of a sabkha from ~15 cm b.s. (137 cm asl, Units 3 and 2) with an increase in magnetic susceptibility and organic carbon values.

The depth for the development of sabkha occurred at 135 cm asl in TP2 and ~138 cm asl in TP4. A switch to eolian dominated sands is seen in Unit 2, with a disturbed upper layer representing recent to sub-recent turbation of the sabkha surface. The presence of artesian water in the area has resulted in a persistent gypsiferous/halite surface as hydraulic pressure forces (brackish) groundwater up through gypsiferous sediments.

5.4 Southern sabkha**, test pit 3 (TP3), N26°54’56.9” E049°44’33.1”**

TP3 was located at the northern fringes of the upper sabkha surface, closest to the site of Dosariyah. The surface level was at 202 cm asl and a 144 cm deep profile was sampled. No samples were radiocarbon dated from this pit, but two OSL ages were measured (**Table 2.1**). TP3 OSL1 was sampled at 67 cm asl (135 cm b.s) and yielded an age of 5.8 ± 0.4 ka (4200–

3400 BC). TP3 OSL2 at 167 cm asl (35 cm b.s.) provided an age of 1.2 ± 0.1 ka (AD 900–700). The sequence recorded in TP3 shows seven lithological units (**Appendix Table 2.7**) with the area close to the site changing markedly in terms of the environments present and the influence of marine inundation. The sedimentological results are shown in **Figure 2.11a** and the molluscan diagram in **Figure 2.11b**. In total, 387 mollusk and mollusk fragments were recovered from 14 samples taken from TP3. These represented 369 individual gastropods and 18 bivalve valves (**Appendix Table 2.8**). Gastropods are represented by at least five taxa of four families — Litterinidae, Cerithiidae, Potamididae, and Vermetidae. Bivalves are also represented by at least five taxa, but from five families — Lucinidae, Ungulinidae, Tellinidae, Psammobiidae and Veneridae.

Figure 2.11a. Sedimentology diagram for TP3.

Figure 2.11b. Molluscan diagram from TP3.

The lower part of Unit 7 (150–110 cm b.s., 52–92 cm asl) indicates eolian sedimentation with the deposition of fine, coarse-skewed, mesokurtic, moderately to poorly sorted, sands. These fine up the sequence with a small rise in silt and clay content but these remain low. Organic content is characteristically low at ~1.5%. Mollusks are absent in Unit 7.

At ~110 cm b.s. (92 cm asl) the presence of mollusks occurs from Unit 6 with a continued fining up of sediments and an increase in clays and silts. The sediments are fine-skewed, leptokurtic and poorly sorted fine sands. The gastropod *Potamides conicus* (Potamididae) is by far the most abundant taxa throughout the TP 3 sequence. The molluscan assemblage mainly represents an intertidal environment dominated by *Potamididae conicus* with some subtidal and lower shore elements but these occur in low frequencies. This marks a phase of marine transgression and a switch to an intertidal environment. This continues into Unit 5 until around 60 cm b.s. (142 cm asl). The sediments are fine-skewed to strongly fine-skewed, very leptokurtic and poorly sorted fine to very fine sands. This indicates slow or standing water, probably at the fringes of a lagoon. The subsequent lowering of sea level and the development of a sabkha, as indicated by the increased values for magnetic susceptibility and organic content and the peaks in clay and silt, are shown in Unit 4. The sediments in Unit 4 comprise near symmetrical, platykurtic, very poorly sorted silts. Unit 3 is characterized by a sharp increase in medium-coarse sands, reduction in magnetic susceptibility, organic content and increase in carbonates. The sediments are strongly fine-skewed, very leptokurtic, poorly sorted fine to medium sands. This unit represents the possible interdigitation between wind-blown sands and marginal marine sediments. An OSL date of

AD 900–700 was determined from this unit. Unit 2 denotes the development of sabkha while Units 3 and 1 represent wind-blown sands.

5.5 Northern sabkha**, test pit 4 (TP4), N26°55'20.6" E49°43'59.6"**

TP4 was situated at the southern margin of the northern sabkha 1.91 m asl, where it is overlain by dune sands. Seven lithological units were identified from a 140 cm deep section (**Appendix Table 2.9**). Four radiocarbon dates were measured from marine shell samples of *Dosinia* cf.*alta* (**Table 2.2**). The sedimentology is shown in **Figure 2.12a** and the molluscan diagram in **Figure 2.12b**. In total, 749 mollusks and mollusk fragments were recovered from 16 samples taken from TP4. These represented 615 individual gastropods and 134 bivalve valves (**Appendix Table 2.10**). Gastropods are represented by at least nine taxa of six families — Trochidae, Littorinidae, Cerithiidae, Potamididae, Columbellidae and Olividae. Bivalves are also represented by at least five taxa, but from four families — Lucinidae, Tellinidae, Psammobiidae and Veneridae. The gastropod *Potamides conicus* (Potamididae) is by far the most abundant taxa throughout the TP 4 sequence.

Figure 2.12a. Sedimentology diagram for TP4.

Figure 2.12b. Molluscan diagram from TP4.

The northern sabkha joins a much larger area of low, flat ground that extends over a very wide area of sabkha to the north and west of Dosariyah. At the base of Unit 7 the sediments comprise homogeneous, fine-skewed, mesokurtic, moderately sorted fine to medium sands. These then become fine to strongly fine-skewed, leptokurtic to very leptokurtic, fine to medium sands with localized iron staining. Organic content is low (~1%) and carbonate content is also low and gently increases up-unit from ~5 to 10%. This unit represents interdigitation between wind-blown sands and marginal marine facies representing the onset of marine transgression. Silt and clay contents are low but increase up-unit. The lowest age from Unit 7 at 74 cm asl (116–118 cm b.s.) gave a date of 6444 ± 31 ^{14}C BP (SUERC-54500, 4929–4610 cal. BC 2σ) and denotes the onset of transgression. At 105 cm asl (84–88 cm b.s.) the ^{14}C age of 6139 ± 30 ^{14}C BP (SUERC-54499, 4540–4318 cal. BC 2σ) occurs during the transgression in Unit 7. The molluscan assemblage records intertidal species dominated by *Potamides conicus*, which accounts for ~20–30% below 95 cm b.s. (96 cm asl) and increases to 60–80% in the upper part of Unit 7. Lower shore and below taxa comprise *Dosinia* sp. and *Dosinia* cf. *alta*. These account for ~25% of the assemblage in the lower parts of the unit and steadily decrease up-unit to ~5% at the top of Unit 7.

Unit 6 represents a transitional zone represented by finer-grained coarse silts with a mean particle size of ~50 μm. Sand decreases to ~71–55% with silts ~23–35% and clays ~6–8%. The facies exhibits strongly fine-skewed, platykurtic, very poorly sorted silts with an increase in carbonate from 18 to 27% and a slight increase in organics to ~3%. There is a slight rise in MS to 0.04 x $10^{-6}m^3kg^{-1}$. Mollusk values decrease in this unit with the disappearance of lower shore and below species and also a decline in intertidal taxa. *Potamides conicus* values decline to less than 20%. Unit 6 represents the development of lower-energy, tidal flats. A ^{14}C age of 5642 ± 30 ^{14}C BP (SUERC-54498, 4026–3734 cal. BC 2σ) dates this phase at 127 cm asl (62–66 cm b.s.).

Units 5 and 4 in the profile show an increase in energy and in marine elements representing a second phase of transgression. Mean particle size values increase to ~130 μm representing fine sands (~80%) with decreases in silt (~15%) and clays (~3%). These sediments are strongly fine-skewed, leptokurtic to mesokurtic, very poorly sorted fine to very fine sands. Carbonate content increases to 34% in Unit 5 and MS values increase slightly when compared to Unit 6 below. The mollusk assemblage shows very low numbers present in the lower part of Unit 5 but increases towards the top of Unit 5 and into Unit 4. Intertidal taxa dominate in both units with *Potamides conicus* and *Clypepmorus bifasciatus persicus*, the main species represented in Unit 5. In Unit 4 both species increase sharply to 80% and 15% respectively. Other intertidal species that increase in Unit 4 include *Mitrella blanda*, *Pillucina vietnamica*, *Tellia* cf. *arsinoensis* and *Echinolittorina* cf. *millegrana.* The subtidal species *Cerithium scabridum* appears throughout both units with values increasing to ~10% in Unit 4.

Lower shore and below species reappear from 42 cm b.s. (142 cm asl) with *Dosinia* sp. and *Dosinia* cf. *alta* present. These taxa are also present in Unit 4 but in lower numbers. The lower part of Unit 5 represents the development of lagoonal marginal facies. The upper part of Unit 5 and Unit 4 represents the interdigitation of wind-blown sands with marginal marine facies. Unit 4 was ^{14}C dated to 5273 ± 30 ^{14}C BP (SUERC-54497, 3624–3360 cal. BC 2σ) at 169 cm asl (20–24 cm b.s.). The presence of Cerithid gastropods in Unit 4 suggests intertidal conditions and that this area was never completely inundated, but high-stand sea levels may have resulted in a shallow marginal water depth into which wind-blown sands were laid down. Following a gradual lowering of sea level in the upper part of Unit 4 a salt flat developed in this location (Units 3 to 1), increasingly dominated by groundwater rather than direct marine influence with fine–medium eolian-derived sands.

5.6 Northern sabkha**, test pit 5 (TP5), N26°55'27.6" E49°43'53.3"**

TP5 was located approximately 1200 m from the Dosariyah archeological site on the northern sabkha. The test pit was at an altitude of 1.71 m asl and a 126 cm deep section was excavated. The sedimentological results are shown in **Figure 2.13a** and the molluscan assemblage in **Figure 2.13b**. Two radiocarbon samples were dated at 123 cm asl (48 cm b.s.) and 139 cm asl (32 cm b.s.). These yielded ages of 4482 ± 30 ^{14}C BP (SUERC-54502, 2651–2286 cal. BC 2σ) and 4266 ± 30 ^{14}C BP (SUERC-54501, 2386–2000 cal. BC 2σ) (**Table 2.2**). In total, 292 mollusk and mollusk fragments were recovered from 16 samples taken from TP5. These represented 203 individual gastropods and 68 bivalve valves (**Appendix Table 2.12**). Gastropods are represented by at least six taxa of four families — Trochidae, Cerithiidae, Potamididae, and Columbellidae. Bivalves are also represented by at least six taxa of four families — Lucinidae, Tellinidae, Psammobiidae and Veneridae. The gastropod *Potamides conicus* (Potamididae) is by far the most abundant taxa throughout the TP 5 sequence.

Figure 2.13a. Sedimentology diagram for TP5.

Figure 2.13b. Molluscan diagram from TP5.

Seven sediment units were identified from TP5 (**Appendix Table 2.11**). Unit 7 represents the deposition of eolian sands. These are fine-skewed, leptokurtic, poorly sorted medium–fine sands, which are coarser towards the base of the unit (385–200 μm). The sediments fine upwards from 100 cm b.s. (71 cm asl) to ~180 μm (fine sands), which are near symmetrical, mesokurtic and poorly to moderately sorted. Sands account for ~94%+ of the sediment in Unit 7 with low silt (~5%) and clay (~1%) present. The organic content is low, ~1.5%, and carbonates are ~5–10% in the lower part of the unit but increase to ~12% from 96 cm b.s. (75 cm asl) to the top of the unit. No mollusks were present in Unit 7.

Unit 6 marks the onset of marine transgression with an increase in sea level. In Units 6 and 5 the proportion of sand decreases to ~90% with a slight increase in silts (~13%) and clays (~2%) suggesting a lower energy environment. The sediments are fine to strongly fine skewed, very leptokurtic and poorly sorted. Carbonate values rise to ~16% in Unit 6 and increase further into Unit 5 where values reach 27% at the top of the unit. The organic content in both units remains ~1.5%. In Unit 4 there is an increase in mean particle size to ~275 μm and a decrease in silts (~10%) and clays (~1%). The sediments are strongly to fine-skewed, remain very leptokurtic to poorly sorted. In Unit 6, mollusca first appear but in very low numbers with intertidal Cerithids and the lower tidal species *Dosinia* cf. *alta* present. Units 5 and 4 show increasingly large proportions of intact marine bivalves, often recovered in life position, indicating a strong marine influence at this time with sea levels rising high enough to inundate this area. The assemblage is dominated by intertidal species with *Priotrochus kotschyi/obscurus*, *Pillucina vietnamica*, *Clypeomorus bifasciatus persicus*, *Potamides conicus* present. *Hiatula mirabahensis* peaks in Unit 4 to ~6%. Subtidal taxa include *Cerithium scabridum* in the lower part of Unit 5 and the upper part of Unit 4 only. Lower shore taxa include *Dosinia* sp. and *Calista umbonella*. Unit 5 was dated to 4482 ± 30 ^{14}C BP (SUERC-54502, 2651–2286 cal. BC 2σ).

Unit 3 comprises poorly sorted, strongly fine-skewed, leptokurtic fine sands, with occasional gypsum crystals, and a decrease in mean particle size from ~230 to 150 μm at the top of the unit. This is associated with a rise in silt content from 10 to 20% representing a lower energy environment. Carbonate content increases to 33% at ~24 cm b.s. (147 cm asl) and falls to 23% at the top of Unit 3. Organic content also increases from this point to 10%. Mollusks in Unit 3 are almost entirely dominated by intertidal taxa with *Potamides conicus* accounting for ~25%.

Unit 3 appears to show the development of large intertidal salt and sand flats dominated by the presence of intertidal taxa, which favors these periodically inundated habitats. The base of Unit 3 was dated to 4266 ± 30 ^{14}C BP (SUERC-54501, 2386–2000 cal. BC 2σ). As sea level drops to roughly the modern-day level the saltpans (Unit 2) are conducive to the growth of thick gypsum deposits at or near the surface. Unit 1 reveals the input of wind-blown sand onto the groundwater-fed sabkha surface with MS values rising to ~1.0 x $10^{-6}m^3kg^{-1}$.

6 Discussion — Paleoenvironments and Relative Sea Level Changes

The Arabian Gulf is a shallow epicontinental sea formed in the late Miocene. During the Quaternary, relative sea-level fluctuations would have ranged from high stands up to 10 m+ above present levels to low stands of –120 m.[40] Glennie suggested that at times of glacially lowered sea level the continental shelves of the Arabian Peninsula were exposed to deflation of marine carbonates, with sediment blown inland, which led to the formation of Dammam Eolianite in Saudi Arabia and Ghayathi Formation in the UAE.[41] These formations comprise moderately to well-cemented carbonate-rich dunes that crop out extensively along and for a

40 Felber et al. 1978; Lambeck 1996; Uchupi et al. 1996; Williams and Walkden 2002b.
41 Glennie 1998.

short distance inland from the coast, often forming wind-eroded and deflated outcrops.[42] These calcarenites contain abundant bioclasts including corals, ooids, and shell fragments, which indicate a marine origin for the sediment, suggesting that these dunes were formed from carbonate sediment blowing in from the Arabian Gulf.[43] Within the UAE the heavy mineral signature of the minor siliciclastic component has been suggested as supporting this view.[44]

At Dosariyah, OSL ages of 7.2 ka (5200 BC) and 6.8 ka (4800 BC), coastal section QS1) were derived from red quartz-rich eolian sands that underlie the calcareous eolianites indicating an early Holocene age for this unit (**Table 2.1**). It is likely that the cores of the dunes (which are up to 14 m thick at the highest point in the mapped area) pre-date these ages and are of Late Pleistocene/Early Holocene age. A date of 10 ± 2 ka (*c.*8000±2000 BC) was reported from a weakly developed soil from a dune 37 km northwest of Tanaqib in eastern Saudi Arabia.[45] Munro et al. reported a similar paleosol from a coastal section at Tanaqib to the north of Dosariyah and inferred that the 11 m eolian sequence below the paleosol was late Pleistocene in age.[46]

The ages suggest that the siliclastic sands were deposited in the Early mid-Holocene and are overlain by carbonates rich in ooids derived from a coastal source. The upper carbonate-rich, cemented eolianite from the quarry section was dated to 3.0 ka (1000 BC). Glumac et al. have shown that ooids form in shallow (less than 2 m deep) near-shore environments extending approximately 200 m offshore.[47] Typically these environments are characterized by a barren sea bottom with sand sculpted into sand ripples and sand waves. The ooid-rich material is transported onshore and lithified into eolianite. The carbonate-rich eolianite at Dosariyah was formed by rapid cementation due to meteoric leaching either during a period of increased wetness or at the saltwater/freshwater interface. These eolianites have formed largely on the seaward side of the paleo-dune ridges in the Jubail area, but gradually merge into unconsolidated redder-colored, less carbonate-rich dune ridges further inland. Farrant et al. suggest that dunes cement rapidly during humid periods due to the meteoric leaching of unstable aragonitic material, which is reprecipitated as inter-granular, meniscus vadose cement, along with gypsum.[48] This rapid cementation is confirmed by OSL dating, which indicates the most recent phase of carbonate dune deposition occurring during the Late

42 Farrant et al. 2012.
43 Teller et al. 2000.
44 Farrant et al. 2012; Garzanti et al. 2003; 2013.
45 Munro et al. 2013.
46 Munro et al. 2013.
47 Glumac et al. 2012.
48 Farrant et al. 2015.

Holocene, followed by cementation and stabilization.[49] While the formation of the Dammam Eolianite has previously been suggested to be the result of carbonate-rich materials deflated from the exposed Gulf basin during low sea-level stands,[50] it is suggested that this is not the case for the cemented carbonates dunes at Dosariyah due to the 3.0 ka Late Holocene age for this unit and the Early Holocene ages for the underlying quartz-rich sand unit, which is 7 ka and older based on OSL. As the eolianite is characterized by a rapid landward increase in quartz the carbonate dunes represent a coastal dune field at and relatively close to the present coastline.

Engel et al. demonstrated that carbonate-rich coastal dunes do not require vast exposed shelves to form as suggested by Glennie.[51] They suggest that a broad beach and offshore barriers exposed at low tide, where carbonate sands are constantly compensated, are sufficient to lead to the development of bioclast-rich coastal dunes. As these conditions are very common in the southern Gulf and occur in the Dosariyah coastal location, this mechanism is proposed for the carbonate-rich dunes found at Dosariyah. The high abundance of bioclasts in the carbonate eolianite is a good indicator for a very proximal position to beach and barrier sources as found at Dosariyah. The formation of coastal dunes under such a regime also supports the notion that the underlying quartz-rich sands accumulated from pre-transgressive sediment sources, that is, latest Pleistocene–Early Holocene, which has a terrestrial signature with a low carbonate content.

6.1 Holocene relative sea level (RSL) evidence from Dosariyah

RSL variations from the Gulf region have been postulated by a number of authors and several sea-level curves produced.[52] It should be noted that, with the exception of Engel and Brückner and Lokier et al.,[53] all of the records are based on uncalibrated ^{14}C ages and without correction for marine reservoir effects on dated shell materials. Most sea-level reconstructions were carried out in the 1970s and 1980s and lack precision with regard to dating control, effects of neotectonic changes, indicators of sea level used, errors in elevation of sedimentary units used and the relationship of actual tides. Differences in the use and assessment of these factors have led to several interpretations of sea-level variability during the Holocene from the Gulf region.

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49 Farrant et al. 2012; 2015.
50 Glennie 1998; Teller et al. 2000.
51 Engel et al. 2015; cf. Glennie 1998.
52 Felber et al. 1978; Ridley and Seeley 1979; Al-Asfour 1982; McClure and Vita Finzi 1982; Bernier et al. 1995; Lambeck 1996; Engel and Brückner 2014.
53 Engel and Brückner 2014; Lokier et al. 2015.

The RSL curve for Dosariyah is shown in **Figure 2.14** and is based on primary sea-level index points (SLIPS) for the calibrated ^{14}C ages showing the 2σ age ranges as horizontal error bars. The vertical errors are based on the sample elevation relative to present MSL and using an indicative meaning based on the habitat range for the species dated. The relative sea-level curve envelope shows the range for the lowest paleo-MSL and highest paleo-MSL levels. In addition, the upper paleo-MHHW level is shown as a broken line above the upper paleo-MSL level and denotes the highest paleo-tide levels excluding HATs. The two OSL samples from TP3 (Units 3 and 7) are shown; they are not used to infer a vertical relationship for RSL, but as secondary SLIPS to denote age, error range and elevation of these samples.

In addition, a number of radiocarbon dates have previously been made on shell material collected from assumed high-stand beach deposits between Lawdhan (to the north of Jubail) and (southward) the Gulf of Salwah.[54] The deposits ranged between +1 m and +3 m asl. These ages were calibrated and corrected using the ΔR 180±53 value for the Arabian Gulf,[55] plotted at the 2σ level and are shown in **Figure 2.14**. The use of these ages as RSL indicators are more ambiguous as the shell material from beaches may incorporate allochthonous rather than just *in situ* components and therefore the host deposit may be younger than the material it contains. These ages should, therefore, be treated as maximum ages only, and they would have formed above the MHHW level most likely as the result of storm events. **Figure 2.14** also shows the height (m asl) and calibrated age range for the archeological occupation levels at Dosariyah. This shows the relationship and the phase of occupation at the site and RSL at this time. In addition, the eustatic sea-level function and predicted RSL for Fao at the head of the Gulf[56] are also shown. During the Holocene the predicted sea levels at Fao, located in the north of the Gulf some 350 km from Dosariyah, lie above the eustatic change and a small amplitude high stand ~2.5 m higher than today developed in *c.*5000 BC.[57]

Figure 2.14. Relative sea level curve for the Dosariyah area since the mid-Holocene. The sea level band is based on sea-level index points (crosses) of relative sea level (RSL). The vertical extent of the crosses specifies the range of the assumed sea-level position associated with the sedimentary environment of the sample. The lateral extent of the crosses indicates the 2σ range of calibrated radiocarbon ages BC. The phase of occupation (dated to

54 Felber et al. 1978; Ridley and Seeley 1979; McClure and Vita Finzi 1982.
55 Southon et al. 2002.
56 Lambeck 1996.
57 Lambeck 1996.

2σ range) and depth of the archeological layers is shown above sea level (grey box). The ages for dated shell beach deposits (2σ range) from previously published sites along the eastern Saudi Arabian Gulf coast are plotted as asl for regional comparison.

From the Dosariyah record, the earliest age for the onset of marine transgression was recorded in TP4 located *c.*1 km away in the northern sabkha area. The sediments from Unit 7 comprise sands representing interdigitation between wind-blown sands and marginal marine facies during the onset of marine transgression, which fine upwards. The onset of the transgression 66 cm asl (125 cm b.s.) is marked by the presence of lower shore species, such as *Dosinia alta*, and intertidal taxa including *Tellenia* cf*. arsinoensis* and *Potamides conicus* (**Figure 2.12b**). These species live on sandy substrates. While a small number of shells were found lower down the sequence, the taxa found are known to burrow up to 10–15 cm into sediment.[58] A radiocarbon age at 117 cm b.s. (74 cm asl) was dated to 6444 ± 31 ^{14}C BP (4929–4610 cal. BC 2σ; 6878–6559 cal. BP 2σ) and immediately post-dates the onset of transgression. This age corresponds to the period of occupation at Dosariyah showing a marine influence close to the site at this time. This period of marine influence continued until shortly after 6139 ± 31 ^{14}C BP (4540–4318 cal BC 2σ; 6489–6267 cal. BP 2σ) (105 cm asl; 86 cm b.s.) during which there is a change from medium to fine sands, suggesting slack-water lagoonal sedimentation followed by the deposition of finer-grained clayey silts (**Figure 2.12a**). The molluscan assemblage shows a change from lower shore and intertidal taxa, to littoral fringe intertidal conditions. This occurred between 105 cm asl and 127 cm asl and was dated from 6139 ± 31 ^{14}C BP (4540–4318 cal. BC 2σ; 6489–6267 cal. BP 2σ) to 5642 ± 30 ^{14}C BP (4026–3734 cal BC; 5975–5683 cal. BP 2σ) (**Figure 2.14**).

In the southern sabkha region TP2 (~300 m from the archeological site at Dosariyah) shows a similar sequence of events with a transgressive phase dated at 1.09 m asl at 5976 ± 30 ^{14}C BP (4339–4045 cal. BC; 6406–6034 cal. BP 2σ) (**Figure 2.14**). Higher relative sea level (~1.04–1.12 m asl) was marked by a dominance of *Dosinia* sp. and *Dosinia* cf. *alta* indicating lower shore to intertidal conditions. These give way to intertidal species (~112–127 cm asl) indicating shallower water conditions with periodic inundation (**Figure 2.10b**). In TP2 marine regression also led to the development of clayey silt sabkha (1.37–1.52 m asl) (**Figure 2.10a**). An OSL age towards the base of TP3 at 71 cm asl (**Table 2.1**), which is closest to the site at Dosariyah (less than 200 m), shows evidence of this transgression sometime around 4200–3400 BC (5.8 ± 0.4 ka) (**Figures 2.11a–b**), which within the error range corresponds with the transgressive phase shown in TP4 and TP2 (**Figure 2.14**). The evidence from TP4

58 Feulner and Hornby 2006.

and TP2 shows that the elevations for the onset of deposition for marine sediments during the transgression occurred at 0.74 and 1.05 m asl respectively. The upper paleo-MSL and upper limit for the paleo-MHHW were ~2.3 m asl and 2.80 m asl for TP4 and 2.60 and 3.10 m asl for TP2.

In the northern sabkha, TP4 shows the development of intertidal conditions at 127 cm asl shortly after 5642 ± 30 ^{14}C BP (4026–3734 cal. BC 2σ; 5975–5683 cal. BP 2σ) (**Figure 2.12a**) is followed by the appearance of intertidal and subtidal mollusks including *Clypeomorus bifasciatus persicus*, *Ptamides conicus*, *Mitrella blanda*, *Pillicina vietnamica*, *Tellinia* cf. *arsinoensis* and *Cerithium scabridum* (**Figure 2.12b**). This transgression ended at 5273 ± 30 ^{14}C BP (3624–3360 cal. BC 2σ; 5573–5309 cal. BP 2σ) (**Figure 2.12a**; **Figure 2.7**). The paleo-MSL range at this time was 1.25 to 3.22 m asl with the upper limit to the paleo-MHHW at 3.75 m asl. After this, there is no evidence for higher relative sea levels during the Holocene in the TP4, TP3 and TP2 sections, noting that these three sections are altitudinally closest to the site. Supratidal sabkha development was characterized by the increase in organic matter, decrease in carbonates, enhanced magnetic susceptibility values and the presence of gypsum in the uppermost sediments in these sections.

Evidence of later Holocene transgression is recorded in both the southern and northern sabkhas, from TP1 and TP5, which are furthest away from the site. In TP1 an incursion of marine waters, 0.90 m asl, occurred 4706 ± 30 ^{14}C BP (2899–2586 cal. BC 2σ; 4848–4535 cal. BP 2σ) (**Figures 2.9a**–**b**; **Figure 2.7**). The sediments comprised very fine-grained, white, clayey silt with a high carbonate component and shells in life position suggesting deposition in a low-energy environment. In TP5 the onset of transgression at ~1.00 m asl occurred before 4482 ± 30 ^{14}C BP (2651–2286 cal. BC 2σ; 4600–4235 cal. BP 2σ, dated at 1.23 m asl) and ended after 4266 ± 30 ^{14}C BP (2368–2000 cal. BC 2σ; 4335–3949 cal. BP 2σ) at 1.39 m asl (**Figures 2.13 a**–**b**; **Figure 2.7**). The paleo-MSl range was 0.95 to 2.92 m asl and the upper limit for the paleo-MHHW was 3.45 m asl. Given that there is statistical overlap at the 2σ level for the TP1 regression and also the lower age from TP5, and that the marine transgression in TP5 started before the lower age, the two sections appear to record the same rise in sea level.

After 2200 BC the northern and southern sabkhas became cut off from marine incursion due to sediment infilling and also to the associated fall in RSL with no further evidence of marine deposition. The supratidal sabkhas became subjected to eolian as well as evaporative processes. An OSL age at 1.67 m asl from sabkha sediments in TP3 (Unit 3) gave an age of

700-900 ACE. These led to diagenetic overprinting of gypsum crusting and deflated supratidal surfaces as seen in the uppermost layers of all the test pit sites.

At the archeological site the deepest levels where artifacts were recovered differ from trench to trench, although the occupation phases all overlap chronologically, indicating a short period of occupation (**Figure 2.14**). In the southern part of the site, the anthropogenic sequence starts at +4.7 m asl (*c.*1.5 m below the present site surface), while in trench E1 artifacts were found down to +3 m asl (*c.*2.7 m below the surface of the site). This would indicate that without water there is a 2.08 m difference in height between the lowest occupation levels and the lowermost intertidal sediments in TP3 and a 1.55 m difference to the uppermost marine sediments (Unit 5) in TP3. The uppermost sabkha unit is at 2.01 m asl which is 0.99 m below the lowest occupation levels. In TP 2 the differences between the lowest levels of occupation and marine sediment deposition are 2.33 m (onset of marine sediments at 0.77 m asl) and 1.73 m (1.27 m asl) for the end of the transgression. The sabkha surface for TP2 is 1.52 m asl which is 1.48 m below the lowest occupation levels at the site. In TP4, on the northern sabkha, the onset of the transgression is recorded at 0.60 m asl and 1.11 m asl for the end (2.40 m and 1.89 m respectively below the lowest occupation levels).

The stratigraphic elevation data for the lowest occupation layers and sea-level ranges from TP 2, 3 and 4 suggest that based on the upper limits of the paleo-MSL and paleo-MHHW curves, the site was at or close to sea level during the mid-Holocene transgression. During periods of higher tidal influence, including highest astronomical tides (HATs), strong winter shamal conditions[59] and periodic storms surge conditions,[60] it is plausible that the lower parts of the site may have become periodically inundated.

Figure 2.15. Sea level reconstruction using a +2 m increase during the Neolithic transgression. Red dot: location of Dosariyah.

Bibby recorded barnacle-encrusted remnants of plaster-covered reed walls 4 m above high-tide level at Dosariyah and suggested that the site was exposed to higher sea levels.[61] This led Ridley and Seeley to propose that remnants of those walls were submerged by a RSL rise, which was then exposed by uplift or lowering of sea level,[62] but this was contested by

59 Thoppil and Hogan 2010.
60 El-Sabh and Murty 1989.
61 Bibby 1973.
62 Ridley and Seeley 1979.

McClure and Vita Finzi.[63] The stratigraphic layers at the site do not provide much further evidence for this but in the lower stratigraphic sequence in trench S2 a distinct layer with high amounts of small snails could be traced across most of the southern part of the trench. The same mollusks were also found in great quantities along the edge of the sabkha south of the site.[64] It cannot be excluded that this distinct layer represents a tidal inundation event with the deposition of intertidal Cerithid mollusks, suggesting that the site was at least once affected by inundation.

Figure 2.15 shows a +2 m higher than present sea level reconstruction for Dosariyah on different scales, which demonstrates that the site became an island during the transgression phase. During this period, it is likely that higher sea level would have inundated the present-day sabkha areas and that the archeological site at Dosariyah would in effect have been an island at high tide or perhaps even during low tides, as was previously suggested by Bibby.[65]

The shells dated from beach ridge deposits in the eastern Saudi Arabian Gulf region (**Figure 2.14**), which were proposed as representing high-level sea level stands, mostly represent supratidal deposits formed above the MHHW, perhaps under storm surge conditions. Ten km south of Dammam, McClure and Vita Finzi dated *Circe arabica* shells 1.2 m above sea level, which yielded an age of 6020 ± 80 ^{14}C BP (4504–4057 cal. BC 2σ; 6006–6453 cal. BP 2σ)[66] (**Figure 2.14**) and falls within the paleo-MSL envelope for Dosariyah. McClure and Al-Shaikh reported additional ages from the same Ain as-Sayh complex of sites which yielded overlapping ages in the range 4942–4351 cal. BC (6891–6407 cal. BP 2σ).[67] The altitudes for these samples were not reported, however, and are therefore not shown on **Figure 2.14**. The 2σ age ranges from these dates correspond with the final occupation phase at Dosariyah.

The following ages all post-date the occupation at Dosariyah (**Figure 2.14**) but overlap with ages reported at Dosariyah from TP1 and TP5 between 2889 and 2000 cal. BC 2σ (4535–4335 cal. BP 2σ). The beach deposits dated by McClure and Vita Finzi at Salwah (1 m asl, 4585 ± 60 ^{14}C BP [2584–2506 cal. BC 2σ]) and Qurayyah 2 (2 m asl, 4460 ± 60 ^{14}C BP [2672–2435 cal. BC 2σ]) fall within the paleo-MSL envelope for Dosariyah.[68] The dates from

63 McClure and Vita Finzi 1982.
64 Drechsler 2012.
65 Bibby 1973.
66 McClure and Vita Finzi 1982.
67 McClure and Al-Shaikh 1993.
68 McClure and Vita Finzi 1982.

Ras Tannurah (2.5 m asl, 4670 ± 70 ^{14}C BP [3281–2741 cal. BC 2σ])[69] and Lawdhan (3 m asl, 4205 ± 70 ^{14}C BP [2367–2115 cal. BC 2σ])[70] lie between the upper limit paleo-MSL and upper limit paleo-MHHW curves as dated at Dosariyah, suggesting that they were most likely formed during the highest tides or during storm surges. The remaining shell ages from beach deposits[71] were deposited after the mid-Holocene transgression shown at Dosariyah and lie in the paleo-MSL or paleo-MHHW envelope during the projected Holocene regression.

6.2 The question of tectonics?

Neotectonic uplift and subsidence are often overlooked and have not been calculated from most sites in the Arabian Gulf, although some attempts have been made.[72] Given the structural geological anticlinal and synclinal complexities across the region, however, as well as the impacts of salt doming, it is difficult to calculate uplift rates for sites without direct measurements because of localized effects. Evidence of uplift in the Jubail region has been suggested by Wood et al. from OSL dating of Pleistocene age eolian sands capped by marine carbonates.[73] The lower eolian dune sand facies yielded an age of 43.5 ± 6.2 ka, while the upper marine facies was dated to 30.3 ± 3.5 ka. Wood et al. suggest that the sediments were uplifted post-deposition where they were faceted into a coastal zeugen. Based on the elevation of the zeugen, at 3.9 m asl, they calculated an average annual uplift rate of 3.4 mm/yr. The ages calculated by Wood et al. from Jubail and other coastal zeugen sites in the UAE have been challenged by Stevens et al. on the basis of their dating of similar features in the UAE, which they suggest are related to high sea-level stands during the last interglacial, and that measured accumulated dose rate differences by Wood et al. therefore yielded ages which were too young.[74] In contrast to Wood et al.,[75] Stevens et al. conclude that the Fuwayrit Formation zeugen dates all conform to the last interglacial (127–87.3 ka). They postulated that RSL change was primarily controlled by global eustatic effects and shoreline progradation. Based on these ages they suggest that there is no need to invoke tectonically or halokinetic-driven uplift as proposed by Wood et al.[76]

69 Felber et al. 1978.
70 McClure and Vita Finzi 1982.
71 Felber et al. 1978; Ridley and Seeley 1979; McClure and Vita Finzi 1982.
72 Ridley and Seeley 1979; McClure and Vita Finzi 1982.
73 Wood et al. 2012.
74 Stevens et al. 2014; cf. Wood et al. 2012.
75 Wood et al. 2012.
76 Wood et al. 2012.

Pedoja et al. suggested a mean eustasy-corrected vertical uplift rate for the Arabian Gulf of 0.16 mm/yr during the late Quaternary (since MIS 5e).[77] This does not, however, account for localized variations. At Jubail, Alothman et al. presented vertical land-motion measurements, recorded from geodetic measurements from 2011–2014, as 0.12 ± 0.75 mm/yr.[78] This has important potential implications for RSL calculations at Dosariyah if a constant rate of uplift is determined for the site since it was occupied.

If neotectonic uplift rates are considered, based on the 0.12 mm/yr geodetic observations from Jubail,[79] the site would have been 0.85–0.77 m lower during the phase of occupation than today and thus the anthropogenic layers at the site would have been only 2.15 to 3.93 m asl when the site was inhabited. If the estimate of 0.16 mm/yr uplift is applied[80] then the site would have been 1.14–1.02 m lower during the phase of occupation. The upper paleo-MSL estimates during occupation are ~2.3–2.6 m asl and the upper limit for the paleo-MHHW are 2.8–3.1 m asl. At maximum transgression the upper paleo-MSL estimate during occupation is ~3.2 m asl and the upper limit for the paleo-MHHW is 3.75 m asl. If an uplift rate of ~0.8 m has occurred then the RSL would be 0.8 m lower, thereby suggesting that the upper paleo-MSL and upper limit for the paleo-MHHW estimates during occupation would have been ~1.8 m asl and ~2.2 m asl. The sea level reconstructions using a +2 m increase during the Neolithic transgression (**Figures 2.15a–b)** therefore provide the best estimate for the site during the phase of occupation. During the Holocene transgression maximum, the upper paleo-MSL estimate would have been ~2.4 m asl and the upper limit for the paleo-MHHW 2.95 m asl. These adjusted estimates fit well with the predicted 2.5 m mean RSL calculated by Lambeck for this region of the Gulf.[81]

6.3 Holocene relative sea levels in the Gulf

Within the Arabian Gulf Lambeck suggested that the rise in sea level began around 14 ka BP (12,000 BC) and proceeded rapidly to near present levels shortly before 6 ka BP (4000 BC).[82] Teller et al. postulated that if sea level flooded across the 1000 km length of the Arabian Gulf, from the Straits of Hormuz to the Tigris-Euphrates delta, between 13 and 6 ka (11 ka BC and 4 ka BC), the average lateral rate of change would have been 140 m per

[77] Pedoja et al. 2011.
[78] Alothman et al. 2014.
[79] Alothman et al. 2014.
[80] Pedoja et al. 2011.
[81] Lambeck 1996.
[82] Lambeck 1996.

year.[83] They suggested that the transgression reached its maximum at about 6 ka BP (4000 BC). It has been suggested that sea level was between 2.5 m higher than at present in the central Gulf during the mid-Holocene[84] and 3.5 m in the northern part of the Gulf[85] above present levels.

In Abu Dhabi, Lokier et al. suggested that during the mid-Holocene transgression, RSL was at least 20 cm higher than today ~7100–6900 cal BP.[86] Transgression, with rapid flooding and shallow subtidal deposition, took place between 6890–6570 cal BP and continued until 5290–4750 cal BP when a still stand phase occurred. It was suggested that this was in excess of +1 m asl, with the accommodation space infilled by shallow subtidal carbonates.[87] Following this a regressive phase, characterized by a rapid fall in RSL, took place leading to the exposure, deflation and precipitation of evaporate minerals in the shallow sub-surface sediments. A low stand phase led to the progradation of the Late Holocene sabkha system and it was inferred that RSL had fallen to near present-day levels by 1440–1170 cal BP.[88]

Engel and Brückner dated a series of mid-Holocene beach ridges in Qatar that were formed at 6656–6473 cal BP and 6431–6282 cal BP, and suggested that the transgression was ~+2 m higher than today.[89] The end of the mid-Holocene rise in sea level was dated *c.*5894–5725 cal BP. At the head of the Arabian Gulf, beach ridges in Kuwait were dated between *c.*6990 cal BP and *c.*3370 cal BP.[90] Unlike Dosariyah, these ridges were deposited in an open-water, high-energy marine environment. Reinink-Smith suggested that during the mid-Holocene mean sea level was ~+3.5 m during which the beach berms were formed with storm beaches deposited up to +5 m above msl.[91]

The timing for mid-Holocene rise in RSL at Dosariyah broadly agrees with those suggested from Kuwait, Qatar and Abu Dhabi (UAE). This occurred prior to 4929–4610 cal. BC (6878–6559 cal. BP) when the lower limit for paleo-MSL was at least 0.30 m higher than today (with an upper paleo-MSL limit of 2.27 m). The sediments indicate local erosion of eolian dune material and reworking into the overlying transgressive quartz-rich carbonate units. The molluscan assemblages indicate subtidal to intertidal conditions at Dosariyah. Transgression continued until shortly after 3624–3360 cal. BC (5573–5309 cal. BP) with estimated lower

83 Teller et al. 2000.
84 Felber et al. 1978.
85 Lambeck 1996.
86 Lokier et al. 2015.
87 Lokier et al. 2015.
88 Lokier and Steuber 2008.
89 Engel and Brückner 2014.
90 Reinink-Smith 2015.
91 Reinink-Smith 2015.

paleo-MSL ranges up to 1.25 m asl and upper paleo-MSL ranges up to 3.22 m asl, after which regression occurred with a rapid fall in sea level leading to the development of supratidal flats with sabkha development with exposure and deflation. This is in accord with the record presented by Lokier et al. from Abu Dhabi where the same pattern and similar timings are observed.[92]

6.4 Conclusions

Radiometric dating results from archeological excavations at Dosariyah suggest that the site was occupied between 5200 and 4500 cal. BC (7200–6500 cal. BP; see **Chapter 6**). This period corresponds to the mid-Holocene marine transgression during which rapid RSL rise occurred. The sedimentary evidence shows that sea levels were +1 m asl and the calculated upper paleo-MSL levels would have been +2 m higher than today during the phase of occupation. The rise in sea level during the Neolithic occupation of the site, coupled with the proposed effects of neotectonic uplift, would certainly have transformed the area around Dosariyah into an island or certainly cut it off tidally from the mainland during this time. In addition, Engel and Brückner suggested from coastal survey of southern Qatar that there is multiple evidence of a RSL high stand of up to ~+2 m around 4000 BC (6000 cal. BP).[93]

It is suggested that the proximity of the site to the sea was very close, permitting maritime exchange activities to occur. The occupation of the site was short lived and the phase of abandonment occurred during the transgression after which sea level continued to rise reaching its peak at ~3600–3350 cal. BC (5600–5300 cal. BP). At Ain as Sayh, located 10 km south of Damman, McClure and al-Shaikh suggested that a rise in sea level during the second half of the fifth millennium BC led to several phases of displacement of the population further inland.[94] This site is located at ~1.2 m asl and the rise in sea level led to the inundation of habitation and occupation sites by ~4500 cal. BC. While there is limited evidence for the inundation of the occupation layers at Dosariyah, the rise in sea level is suggested as a potential driver for the abandonment of the site. It is suggested that the site became separated from the mainland, at least at high tide. Another factor that might have contributed to the site being left is that during the latter half of the fifth millennium BC the climate of the region was becoming increasingly arid with a decrease in regional rainfall and reduced availability of fresh water affecting the availability of terrestrial resources.[95] More

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92 Lokier et al. 2015.
93 Engel and Brückner 2014.
94 McClure and al-Shaikh 1993.
95 Preston et al. 2015; Parker et al. 2016.

work on Holocene environmental change from terrestrial records is required to test this further.

Post-abandonment and after the peak in mid-Holocene transgression, sea level fell after ~−2200 cal. BC leading to the development of the modern sabkhas to the north and south of the site. Later phases of human occupation at Dosariyah are recorded in the later Holocene with some evidence of Iron Age pottery as well as Islamic-period occupation and evidence of shell middens close to the site.

Appendix

Appendix Table 2.1. Habitat preferences for molluscan taxa at Dosariyah.

	Tidal/shore zone	Substrate preference	Habitat
Gastropods			
Trochidae			
Priotrochus kotschyi/obscurus	Intertidal[1]		
Umbonium vestiarium	Intertidal[1]	Sand[1]	
Littorinidae			
Echinolittorina cf. *millegrana*	Intertidal[1]	Rock[1]	
Cerithiidae			
Cerithium scabridum	Subtidal[1]	Sand[1]	
Clypeomorus bifasciatus persicus	Intertidal[1]	Rock[1]	
Potamididae			
Cerithidea cingulata	Intertidal[1]	Sand[1]	Mangroves[1]
Potamides conicus	Intertidal[1]	Muddy sand[1]	
Vermetidae			
Serpulorbis variabilis		Rock/flat surfaces[1]	
Columbellidae			
Mitrella blanda	Intertidal[2]	Sand[1]	
Olividae			
Ancilla cf. *boschi*	Intertidal[1]	Sand[1]	
Bivalves			
Lucinidae			
Pillucina cf. *angela*	Offshore[1]		
Pillucina vietnamica	Intertidal[1]	Muddy sand[1]	Lagoons and mudflats[1]
Ungulinidae			
Diplodonta cf. *globosa*	Intertidal[1]	Muddy sand[1]	Eelgrass beds and khors[1]
Tellinidae			
Tellina cf. *arsinoensis*	Intertidal[1]	Mud[1]	Mudflats[1]
Tellina incarnata/wallaceae	Offshore[1]		
Psammobiidae			
Hiatula mirabahensis	Intertidal[1]	Sand[1]	Sandflats[1]
Veneridae			
Callista umbonella	Lower shore and below[1]	Sand[1]	Sandflats[1]
Dosinia alta	Lower shore and below[1]	Sand[1]	

[1]Bosch et al. 1995. [2]Kohan et al. 2012.

Appendix Table 2.2. Summary of molluscan taxa represented in the five test pits (TP1-TP5) at Dosariyah. NISP values.

Gastropods	**TP1**	**TP2**	**TP3**	**TP4**	**TP5**
Trochidae					
Priotrochus kotschyi/obscurus	0	0	0	3	4
Umbonium vestiarium	0	0	0	2	0
Littorinidae					
Echinolittorina cf. *millegrana*	0	0	8	6	0
Cerithioidea					
Unidentified Cerithoid	0	0	0	7	1
Cerithiidae					
Cerithium scabridum	0	0	5	31	14
Cerithium cf. *scabridum*	0	0	0	0	1
cf. *Cerithium scabridum*	0	0	1	0	0
Clypeomorus bifasciatus persicus	0	0	10	35	20
Unidentified Cerithid	0	0	3	8	1
Potamididae					
Cerithidea cingulata	0	0	0	0	7
cf. *Cerithidea cingulata*	0	0	0	1	2
Potamides conicus	6	1	341	506	146
Unidentified Potamid	0	0	0	1	0
Vermetidae					
Serpulorbis variabilis	0	0	1	0	0
Columbellidae					
Mitrella blanda	0	2	0	9	5
cf. *Mitrella blanda*	0	0	0	0	1
Mitrella cf. *blanda*	0	0	0	3	0
Mitrella sp.	0	1	0	1	1
Olividae					
Ancilla cf. *boschi*	0	0	0	1	0
Unidentified Gastropod	0	0	0	1	1
Bivalves					
Lucinidae					
Pillucina cf. *angela*	0	1	0	1	3
Pillucina vietnamica	0	2	3	12	14
Pillucina sp.	0	1	0	6	0
Ungulinidae					
Diplodonta cf. *globosa*	4	0	2	0	0
Tellinidae					
Tellina cf. *arsinoensis*	34	9	5	56	11
cf. *Tellina arsinoensis*	0	0	2	3	0
Tellina incarnata/wallaceae	64	0	0	0	0
Unidentified Tellinid	144	2	0	2	0
Psammobiidae					
Hiatula mirabahensis	0	6	1	4	38
Veneridae					
Callista umbonella	0	0	0	0	1
Dosinia alta	0	0	0	0	3
Dosinia cf. *alta*	0	1	0	21	8
Dosinia sp.	0	14	5	34	0
Unidentified Venerid	0	1	0	0	1
Unidentified Bivalve	1	9	6	20	9

Appendix Table 2.3. Summary of main lithological units for test pit 1 (TP1).

Depth below surface (cm)	Context	Description	Field interpretation
0–5	1	Pustulose gypsum crust with abundant Cerithids, weakly cemented, 7.5YR 4/3 brown, diffuse lower contact	Modern sabkha surface
5–17	2	Silty fine to medium sand. Homogeneous. No obvious inclusions. 7.5YR 6/6 reddish yellow. Weak discontinuous greyish banding, sub-horizontal, sharp lower contact	Eolian sedimentation on groundwater-nourished sabkha surface. Sporadic periods of sustained surface water
17–25	3	Same as above but higher silt content. 7.5YR 5/4 brown. Moderately sharp contact	Eolian sedimentation on groundwater-nourished sabkha surface
25–30	4	Granular, moderately cemented sand with silt intraclasts, pelloidal. 7.5YR 5/4 brown. Moderately sharp contact	Eolian sedimentation on relict intertidal zone following regression
30–33	5	Silty fine to medium sand, no obvious inclusions, 10YR 6/2 light brownish grey	Eolian sedimentation on tidal flat
33–36	6	Transition between sand and salt pan, finer-grained sandy silt, granular inclusions, gypsum cemented intraclasts, 10YR 6/3 pale brown, hard pan at base	Intertidal salt flat, tidal inundation
36–38	7	Mottled coarse sand, sharp lower contact. 2.5YR 5/6 red	Regressive sequence, reduction in water depth, erosive surface
38–52	8	Fine carbonate-rich silt with abundant bivalves and small gastropods and shell fragments, 5YR 8/1 white, homogeneous. Horizon at 46 cm with more shells. Moderately sharp lower contact.	Low energy, lagoonal environment, sea level high stand
52–60	9	Mottled medium to coarse sand, coarsening up slightly. 7.5YR 7/2 pinkish grey. Moderately diffuse lower contact	Contraction of lagoon/backwater environment, higher energy marginal environment
60–68	10	Fine to medium silty sand, few shell fragments, 5YR 8/1 white	Low energy, lagoonal environment, sea level transgression

Appendix Table 2.4. Molluscan taxa recorded in samples from TP1. Values are MNI for gastropods and MNV for bivalves.

		Bivalves					
	Potamididae	**Ungulinidae**	**Tellinidae**			**Bivalvia**	
Depth (cm)	*Potamides conicus*	*Diplodonta* cf. *globosa*	*Tellina* cf. *arsinoensis*	*Tellina incarnata/wallaceae*	Unidentified Tellinid	Unidentified bivalve	Total
36–38		4	14		4		22
38–46	6		14	16	1	1	38
46–50			6	48	4		58
Total	6	4	34	64	10	1	119

Appendix Table 2.5. Summary of main lithological units in test pit 2 (TP2).

Depth (cm)	Context	Description	Field interpretation
0–10	1	10 YR 6/3 pale brown, homogeneous silty fine sand. Loose, friable and moist. No inclusions. Medium to poorly sorted	Reworked, mixed and bioturbated eolian sand
10–11	2	10YR 5/3 brown, fine silty sand with small Cerithid shells (< 5%). Sharp interface with (1). Calcareous.	Eolian sands intermixed with marine facies
11–15	3	Well-cemented (salt/gypsum) coarse sandstone with < 10% Cerithid shells	Marginal intertidal salt flat
15–39	4	10YR 7/2 light grey, calcareous silty fine sand. Weakly to moderately cemented. Changes to 10YR 6/2 light brownish grey at 23 cm bgl.	Lagoon marginal sediments, eolian input into shallow marine sediments
39–80	5	10 YR 6/3 fine silty sand with very occ. (< 2%) marine bivalves and occ. (< 5%). Shells present.	Lagoon marginal sediment, eolian input into shallow marine sediments

Appendix Table 2.6. Molluscan taxa recorded in samples from TP2. Values are MNI for gastropods and MNV for bivalves.

	Gastropods			**Bivalves**										
	Potamididae	**Collumbellidae**		**Lucinidae**			**Tellinidae**		**Psammobiidae**	**Veneridae**			**Bivalvia**	
Depth (cm)	*Potamides conicus*	*Mitrella blanda*	*Mitrella* sp.	*Pillucina* cf. *angela*	*Pillucina vietnamica*	*Pillucina* sp.	*Tellina* cf. *arsinoensis*	Unidentified Tellinid	*Hiatula mirabahensis*	*Dosinia* cf. *alta*	*Dosinia* sp.	Unidentified Venerid	Unidentified bivalve	Total
4–10			1											1
15–19				1	2		5			1				9
23–27	1										1			2
27–31		1						2	1		1			5
31–35		1							1			1		3
35–39							1							1
39–43											2			2
43–47						1	1				4			6
47–51											1			1
71–75							1				2		1	4
75–79											2			2
Total	1	2	1	1	2	1	8	2	2	1	13	1	1	36

Appendix Table 2.7. Summary of main lithological units in TP3.

Depth (cm)	Context	Description	Field interpretation
0–5	1	Loose medium to coarse sand, 2.5Y 7/3 pale yellow. Homogeneous with rootlets	Eolian sands
5–20	2	Medium to coarse sand, rounded to sub-rounded, minor shell fragments, 2.5Y 7/4 pale yellow	Sabkha development
20–40	3	Compacted and cemented, medium to coarse sand, granular with gypsum crystals, rounded to sub-rounded, 2.5Y 8/2 pale yellow	Eolian medium sands
40–55	4	Dense clayey silt with large gypsum crystals, rounded to sub-angular, 10YR 5/3 brown	Sabkha development
55–100	5	Homogeneous fine to medium sand with gypsum crystals, sub-angular with minor shell fragments, 2.5Y 6/2 light brownish grey	Intertidal sediments with fining up sequence becoming lagoonal
100–110	6	As above with higher frequency of shell fragments and Cerithids, 2.5Y 6/3 light yellowish brown	Rising sea levels, margins of lagoonal area. Onset of transgression
110–150	7	Homogeneous fine sand, sub-rounded, 2.5Y 5/3 light olive brown, OSL samples at 1.3 and 0.35 m	Eolian sand, low sea level

Appendix Table 2.8. Molluscan taxa recorded in samples from TP3. Values are MNI for gastropods and MNV for bivalves.

	Gastropods							**Bivalves**						
	Littorinidae	**Cerithiidae**				**Potamididae**	**Vermetidae**	**Lucinidae**	**Ungulinidae**	**Tellinidae**		**Psammobiidae**	**Veneridae**	
Depth (cm)	*Echinolittorina* cf. *millegrana*	*Cerithium scabridum*	cf. *Cerithium scabridum*	*Clypeomorus bifasciatus persicus*	Unidentified Cerithid	*Potamides conicus*	*Serpulorbis variabilis*	*Pillucina vietnamica*	*Diplodonta* cf. *globosa*	*Tellina* cf. *arsinoensis*	cf. *Tellina arsinoensis*	*Hiatula mirabahensis*	*Dosinia* sp.	Total
52–54						3								3
58–60	3	1		2	2	36								44
64–66		1		2		15		3	1	2			1	25
70–72	1	1		2		52			1	2			2	61
74–76	3			2	1	44					1			51
78–80	1	1				44								46
78–82						12								12
82–86						23					1			24
86–90						33	1			1		1	1	37
90–94						9								9
94–98		1		2		21								24
98–102			1			40								41
102–106						4								4
106–110						5							1	6
Total	8	5	1	10	3	341	1	3	2	5	2	1	5	387

Appendix Table 2.9. Summary of lithological units in TP4.

Depth (cm)	Context	Description	Field interpretation
0–4	1	Loose sand, poorly sorted, 7.5YR 7/6 light brown	Eolian sand deposition
5–6	2	Gypsum salt pan, well cemented, medium to coarse sand, 7.5YR 8/1 white	Salt flat
6–10	3	Silty coarse sand, poorly sorted, occasional gypsum crystals, 7.5YR 6/2 pinkish grey	Sabkha with diagenetic overprint. Regression
10–30	4	Coarse sandy silt, very poorly sorted, mottled lenses, fine grained inclusions, 7.5YR 7/2 pinkish grey	Possible interdigitation between wind-blown sands and marginal marine facies. Transgression
30–60	5	Gritty silt bed, occasional coarse inclusions, slight clay component, 7.5YR 7/1 pinkish white	Intertidal salt flat/sabkha, lagoon marginal facies
60–74	6	Transitional zone, silty fine to medium sand, occasional Fe staining, occasional Cerithid shells	Moderate energy, intertidal tidal flats, periodic inundation
74–140	7	Homogeneous, well-sorted medium sand, very occasional coarse grains, localized Fe staining, 2.5Y 7/2 light grey	Eolian sand deposition, sub-aerial weathering at base of unit. Interdigitation between wind-blown sands and marginal marine facies. Transgression stage

Appendix Table 2.10. Molluscan taxa recorded in samples from TP4. Values are MNI for gastropods and MNV for bivalves.

	Gastropods															**Bivalves**										
				Cerithioidea																						
	Trochidae		**Littorinidae**	**Cerithioidea**	**Cerithiidae**			**Potamididae**				**Columbellidae**		**Olividae**	**Gastropoda**	**Lucinidae**			**Tellinidae**			**Psammobiidae**	**Veneridae**		**Bivalvia**	
Depth (cm)	*Priotrochus kotschyi/obscurus*	*Umbonium vestiarium*	*Echinolittorina* cf. *millegrana*	Unidentified Cerithioid	*Cerithium scabridum*	*Clypeomorus bifasciatus persicus*	Unidentified Cerithid	cf. *Cerithidea cingulata*	*Potamides conicus*	Unidentified Potamid	*Mitrella blanda*	*Mitrella* cf. *blanda*	*Mitrella* sp.	*Ancilla* cf. *boschi*	Unidentified gastropod	*Pillucina* cf. *angela*	*Pillucina vietnamica*	*Pillucina* sp.	*Tellina* cf. *arsinoensis*	cf. *Tellina arsinoensis*	Unidentified Tellinid	*Hiatula mirabahensis*	*Dosinia* cf. *alta*	*Dosinia* sp.	Unidentified bivalve	Total
20–24	1		1		6	6			61		2						1	3					4	1		86
24–28			1		9	4	3		29		3		1	1			1		3					1		56
28–32				5	10	15	2		76		1	2					6	1	4			1	1	2	1	127
36–40	1				3	2	1		30		1							1	1					2		42
44–48						2			8							1	1							1		13
52–56			1		1				11		1															14
60–64					1				14						1				1							17
68–72									33															1	1	35
76–80		1	2	2		2			64			1					1	1	3		1		1	3		82
84–88		1	1						87								1		15				3	7		115
92–96					1	1			23										5			1	1	4		36
100–104	1								16								1		11			2	2	2		35
108–112									19										3				2	1	1	26
116–120						3		1	32											1			6	8		51
124–128							2		3	1									5				1	1		13
132–136											1															1
Total	3	2	6	7	31	35	8	1	506	1	9	3	1	1	1	1	12	6	51	1	1	4	21	34	3	749

Appendix Table 2.11. Summary of lithological units in TP5.

Depth (cm)	Context	Description	Field interpretation
0–8	1	Brown sand grading into gypsum, medium to coarse sand, loose and poorly sorted, 7.5YR 7/6	Eolian
8–12	2	Gypsum crust/salt pan, well cemented, 7.5YR 8/2 pinkish white	Sabkha development and development of salt crust
12–35	3	Silty fine to medium sand, poorly sorted, occasional gypsum crystals, occasional Cerithid shells, 2.5Y 8/1 white	Marine regression phase and development of tidal flats
35–46	4	Medium to fine silty sand, occasional gypsum crystals, Cerithids, bivalves and shell fragments, 10YR 7/2 light grey	Intertidal and subtidal
46–66	5	Coarse silt fine sand, small and large bivalves, occasional Cerithids, slightly more cohesive, 5Y 7/1 light grey	Transgression with intertidal and subtidal conditions
66–76	6	Mottled orange grey sandy unit. Medium to fine sand, small shell fragments, 2.5Y 7/3 pale yellow	Onset of transgression
76–120	7	2.5Y 6/2 light brownish grey. Coarse to medium sand, sub-angular to sub-rounded. No shells	Eolian

Appendix Table 2.12. Molluscan taxa recorded in samples from TP5. Values are MNI for gastropods and MNV for bivalves.

	Gastropods												**Bivalves**										
	Trochidae	**Cerithiidae**				**Potamididae**			**Columbellidae**			**Gastropoda**	**Lucinidae**		**Tellinidae**	**Psammobiidae**	**Veneridae**				**Bivalvia**	
Depth (cm)	*Priotrochus kotschyi/obscurus*	*Cerithium scabridum*	*Cerithium* cf. *scabridum*	*Clypeomorus bifasciatus persicus*	Unidentified Cerithid	*Cerithidea cingulata*	cf. *Cerithidea cingulata*	*Potamides conicus*	*Mitrella blanda*	cf. *Mitrella blanda*	*Mitrella* sp.	Unidentified gastropod	*Pillucina* cf. *angela*	*Pillucina vietnamica*	*Tellina* cf. *arsinoensis*	*Hiatula mirabahensis*	*Calista umbonella*	*Dosinia alta*	*Dosinia* cf. *alta*	Unidentified Venerid	Unidentified bivalve	**Total**
14–18		1						23	1													25
18–22								12							1	1						14
22–26				1				7								1						9
26–30				1				9							1	4						15
30–34				1				11					3		3	2		2				22
34–38		3		1			1	3						1		4						13
38–42		1						9							1	6						17
42–46	1			6	1	1		17	1	1				2	2	4			1			37
46–50				1				10				1				1		1	1			15
50–54	2		1	1				10						4		2						20
54–58				2			1	7			1				1	1						13
58–62	1	4		1		5		8	1					6	1	1	1					29
62–66		5		4		1		15	2					1					5	1	1	35
66–70				1				3														4
70–74								2											1			3
86–90																						0
Total	4	14	1	20	1	7	2	146	5	1	1	1	3	14	10	27	1	3	8	1	1	**271**