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AMS-dated mollusks in beach ridges and berms document Holocene sea-level and coastal changes in northeastern Kuwait Bay

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ABSTRACT

In northeastern Kuwait, ancient beach ridges and associated berms are separated from the present shoreline by a 4–6 km-wide sabkha. A diverse mollusk fauna in the beach ridges attests to a former open marine environment. A total of 21 AMS dates were obtained in this study. Thirteen mollusk samples from beach ridges yielded AMS dates ranging from ~6990 cal yr BP in the southeast to ~3370 cal yr BP in the northwest, suggesting a southeast to northwest age progression during the Holocene transgression. In contrast, four samples from berms throughout the study area yielded AMS dates of 5195–3350 cal yr BP showing no age progression; these berms consist largely of *Conomurex persicus* gastropods that aggregated by storms during a highstand at ~5000–3500 cal yr BP. The berms are presently at ~+6 m above sea level, 2–3 m above the beach ridges. Human settlements were common on the ridge crests before and after the highstand. Regression to present-day sea level commenced after the highstand, which is when the sabkha began forming. A landward, marine-built terrace, which yielded AMS dates >43,500 ^{14}C yr BP, probably formed during Marine Oxygen Isotope Stage 5e and hence is not genetically related to the beach ridges.

Introduction

The coastal area of northeastern Kuwait Bay, in the Al-Bahra and As-Subiyah area (hereafter referred to by their commonplace names Bahra and Subiya), will soon be transformed into a new, sprawling metropolis, Madinat Al Hareer (Silk City). A proposed bridge, Sheik Jaber Al-Ahmad Al-Sabah Bridge, will extend across northern Kuwait Bay from present-day Subiya to Kuwait City. Road-building, infilling, and bulldozing are proceeding at a fast rate. Understanding the coastal geology of the region is therefore urgent, since anthropogenic activities will extensively modify or obliterate the present shoreline, making it increasingly difficult to interpret geological processes and past sea-level changes for this part of the coast. Along this threatened coastline are poorly mapped, yet well-exposed, relict Holocene beach ridges, which are the focus of this study.

The goals of this investigation are to map and correlate the beach ridges, age-date them, relate them to Holocene sea-level changes, and interpret the paleoenvironment in which they formed. Beach ridges are here defined as relict wave/swash-built strand-plain ridges (Otvos, 2000) that soon after deposition were cemented by calcite to form beachrock. Mollusks incorporated in some of the beachrock were liberated when the calcite cement subsequently dissolved. This has left lag deposits resembling modern beaches as uninterrupted continuations of the beach ridges. Hereafter these disaggregated beach ridges are referred to as "beaches." Reworked mollusks form berms above the beach ridges; Otvos (2000) describes such berms as "shell-enriched backshore berm ridges." Berms serve as useful indicators of sea level and paleoenvironment. AMS (accelerator mass spectrometry) radiocarbon dates in this study are derived mainly from mollusks cemented in the beach ridges; a few dates are from unconsolidated mollusk-rich berms; and two dates are from a landward, marine-built depositional terrace (also referred to as a "raised beach") (as defined by Pirazzoli, 2005). AMS dates presented in this study provide insight into the history of Holocene coastal changes in northeastern Kuwait Bay and build on previous geologic work on marine terraces by Al-Asfour (1978, 1982) and on archeological and geological work by Carter et al. (1999) and Carter and Crawford (2002, 2003).

Quaternary sea-level changes as inferred from the Arabian Gulf basin

The broad outline of the Quaternary history of sea-level fluctuations in the Arabian Gulf is fairly well known (Fig. 1). The Gulf area was entirely flooded during the last interglacial period, with peak flooding at ~122 ka (Pedoja et al., 2011) during Marine Oxygen Isotope Stage (MIS) 5e (Martinson et al., 1987). Sea level fell to a low of ~120 m below present during the last glacial maximum, at ~21–20 ka, leaving the Gulf basin entirely exposed. A broad river valley formed with lakes and marshes (Lambeck, 1996), and older Quaternary marine deposits were eroded (Lambeck, 1996; Uchupi et al., 1996; Alsharhan et al., 1998; Alsharhan and Kendall, 2003). The Strait of Hormuz (Fig. 2)

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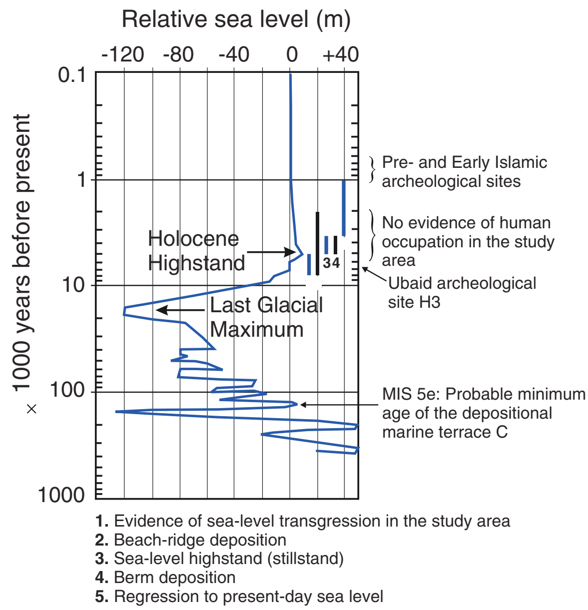

Figure 1. Pleistocene and Holocene sea-level curve for the Arabian Gulf, modified from Jameson and Strohmenger (2012).

opened ~14,000 yr, and between 12,000 and 6000 yr the sea transgressed more than 1000 km into the Arabian Gulf area at a rate that may at times have exceeded 1 km/yr (Kassler, 1973; Weijermars, 1999; Teller et al., 2000; Al-Farraj, 2005; Bruthans et al., 2006; Parker and Goudie, 2008). As the sea level rose, it reached its present level ~8400–4000 yr at different times and locations, depending on elevation. According to Kassler (1973), Weijermars (1999), and Al-Farraj (2005), the sea continued to rise more slowly between 1 and 2 m above present sea level with peak flooding at ~5000 yr, before it receded again to its present level (Bernier et al., 1995; Lambeck, 1996; Kirkham, 1997, 1998; Williams and Walkden, 2002; Kennett and Kennett, 2007). The timing of the Holocene peak flooding varies according to author and location along the margin of the Gulf basin.

Local tectonic activity may have partly controlled sea level in the Gulf area (Vincent, 2008). Similarly, Jameson and Strohmenger (2012) and Wood et al. (2012) invoked regional tectonics in explaining paleomarine shorelines between Al Jubail (in Saudi Arabia) and Dubai (in the United Arab Emirates) (Fig. 2). Wood et al. (2012) stated that the mechanisms for tectonic subsidence and uplift involved a combination of plate tectonics and salt dynamics. In contrast, Lambeck (1996), Aqrawi (2001), Sanlaville and Dalongeville (2005), and Kennett and Kennett (2007) considered tectonic influence to have been relatively minor in the Gulf compared to glacioeustatic effects since 15 ka.

Using the well-dated MIS 5e as a marker horizon, Kopp et al. (2009) and Pedoja et al. (2011, 2014) presented evidence that, worldwide, most paleoshorelines have been uplifted relative to sea level. Pedoja et al. (2011) suggested that the notion of stable platforms is unrealistic and that the concept of long-term continental accretion causing compression of continental plates could explain uplift at the continental margins. This hypothesis could possibly explain "all observations" of Quaternary coastal uplift (Pedoja et al., 2011). According to Pedoja et al. (2011), the mean eustasy-corrected vertical uplift rate in the Arabian Gulf area has been 0.16 mm/yr since MIS 5e (past 125 ka).

Beach ridges related to archeological sites

Evidence of ancient human settlements is present on beach ridges and associated beaches in the study area (Figs. 3 and 4a–e). The locations of these settlements are important in determining the timing of the Holocene sea-level highstand in northeastern Kuwait Bay. At least 14 significant archeological sites, a few of which are from the Ubaid period (~6500–3800 BC = 8450–5750 cal yr BP) (Carter and Philip, 2010), are located on a gravel promontory called Jazirat Dubaij (Fig. 4c). Several of these sites, as well as archeological sites from other areas of the study area, are fenced or outlined with rebar. Most sites are partially obscured by wind-blown sand. The Ubaid sites were first reported by Reda (1986) and later excavated by British archeological teams (Carter et al., 1999; Carter and Crawford, 2001, 2002, 2003; Carter, 2002, 2003). Other ancient settlements, although unmarked, can be recognized by concentrations of potsherds littering the surface. Stone structures that look like dwellings, but not marked as archeological sites, are also located on or near the beach ridges.

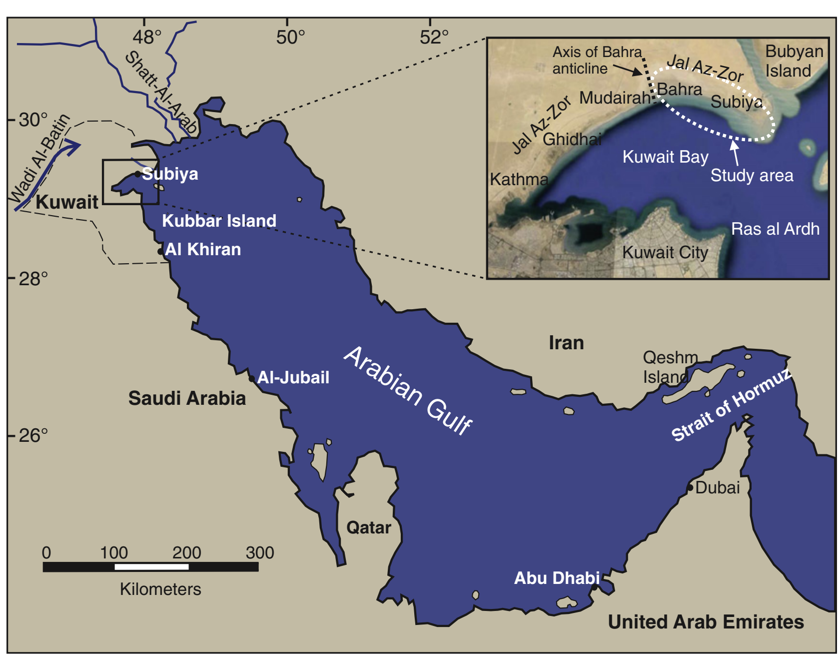

Figure 2. Map of the Arabian Gulf showing Kuwait Bay and the study area; only geographical names used in the text are depicted.

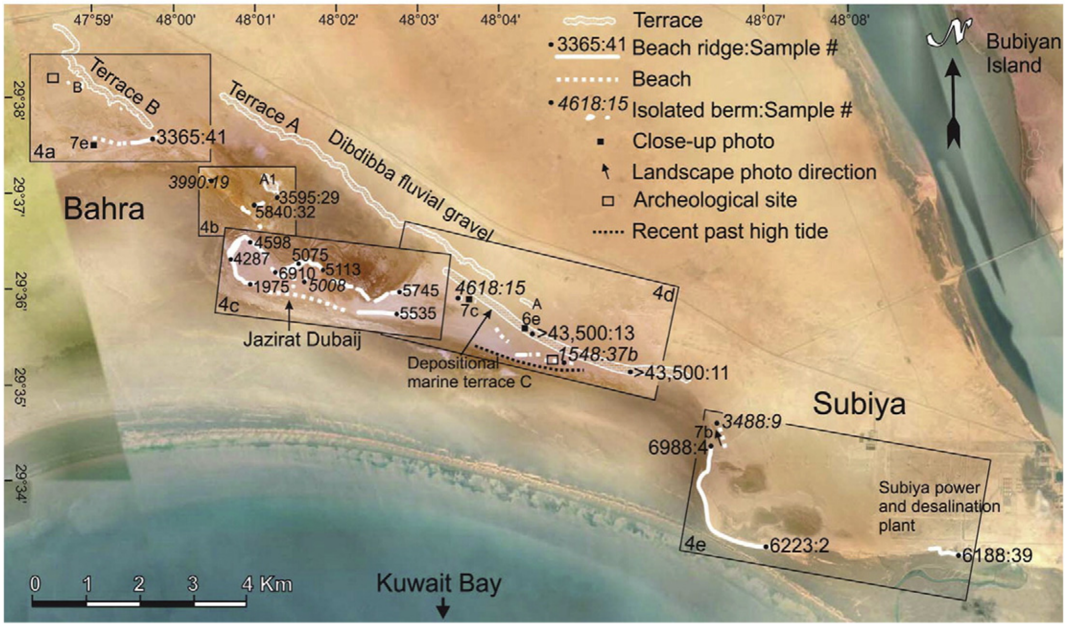

Figure 3. Composite base map with black rectangles outlining areas shown in greater detail in Figs. 4a–e. For example, sample numbers shown in Fig. 4c are not included in the composite base map. AMS dates shown in the composite base map and Figs. 4a–e are midpoints of the 2σ calibration range (Table 1). The outlines of terraces A and B and the dated depositional marine terrace C are generalized and do not accurately show the terrace widths, although the southwest-facing scarps of terraces A and B are accurately located on the map.

Methodologies

The entire study area (Figs. 2 and 3) was investigated in detail to discern subtle geomorphological features in the nearly flat landscape. Even the most obvious features are no more than ~6 m above mean sea level (MSL) and only 1–2 m above the present sabkha, which is a muddy/sandy, supratidal, salt-flat environment. An automatic level was used in a few instances for comparison of elevations from one feature to the next. Beach ridges, commonly disaggregated into rubble, were correlated by walking their entire lengths. Unconsolidated beaches, which are continuations of weathered beach ridges, were also physically traced. Such beaches are mostly sand, shell debris, and occasionally loose beachrock.

The beach ridges and other sites sampled for AMS-dating and thin sections were mapped and located using a Garmin Oregon 650 GPS device with horizontal spatial accuracy of ~5 m. Because of a lack of adequate aerial photos or maps, the data were transferred to Google-Earth-based maps which were then hand-stitched into composites (Fig. 4a–e). Maps with photo acquisition dates of 01/03/2005 were used, because more contrasting and detailed features of the study area are shown on the 2005 map than on more recent Google Earth maps.

The most accurate elevations in the study area are from the Jazirat Dubaij promontory (Fig. 4c), where Carter and Crawford (1999) conducted archeological work. Leveling in this study closely matched their elevations. Vertical elevations in other parts of the study area are less accurate, because they are based on Google Earth elevations and because the only available map (1:50,000) has a contour interval of 5 m.

A total of 21 AMS dates were obtained in this study. Of these, 14 are from single mollusk shells extracted from 14 beachrock samples collected from beach ridges throughout the study area. Of the other seven samples, four are from gastropod-rich berms; one is from a weathered, unconsolidated extension of a beach ridge; and two are from a landward depositional marine terrace (Fig. 4d). In selecting shells for AMS dating, emphasis was given to extracting shells of well-preserved, thick-shelled gastropods such as *Conomurex persicus* (Table 2, Fig. 5), which are less likely to have been contaminated by near-surface weathering. Care was taken to select sample sites in the middle of beaches and berms away from the periphery where mixing with more recent material could have occurred. Most samples were obtained by digging ~10 cm below the present-day land surface.

The mollusk shells were dated by accelerator mass spectrometry (AMS ^{14}C) at Beta Analytic, Inc., in Miami, Florida, USA. Beta Analytic applied its standard protocol for AMS dating of shells as follows: The measured dates (Table 1) were corrected for isotopic fractionation and reported as conventional ages, i.e. radiocarbon years before present (^{14}C yr BP). Calendar-calibrated dates (i.e., cal yr BP and yr BC) were calculated in accordance with the Marine13 database (marine radiocarbon calibration curve) as described by Talma and Vogel (1993), Heaton et al. (2009), and Reimer et al. (2013). A local Delta $\pm$ R correction of 180 $\pm$ 53 yr, from Qatar (Southon et al., 2002) was applied to each sample.

Results

Beach ridges, berms, and associated AMS dates

Beach ridges in the study area, including those surrounding Jazirat Dubaij (Figs. 4c and 6a, b), commonly occur as disjointed but linear patches and protuberances. All of the beach ridges are differentially eroded, in some places to such an extent that they have been buried by the more recent sabkha. The 14 samples from the beach ridges yield AMS ages between 7145 and 1830 cal yr BP (Table 1). Berms, with a maximum aerial distribution of ~200 m^2, occur in irregular patches at the highest points above the beach ridges (Figs. 4b, c, 6c, d, and 7a–d), which typically are ~6 m above MSL. The age ranges for the four samples from berms are 5195–3350 cal yr BP. The only sample (37b, Fig. 4d) from a beach exhibits the youngest age of 1695–1400 cal yr BP (2170 $\pm$ 30 ^{14}C yr BP; Beta 363541).

Relationship of beach ridges to present sea level

In the supratidal zone of the study area, present-day tides rarely reach near the base of the beach ridges but appear to have done so more often in the recent past. A debris zone including such objects as glass bottles, wooden planks, and boat lines and rigging, undoubtedly transported by storm tides, extends to within 50 m of

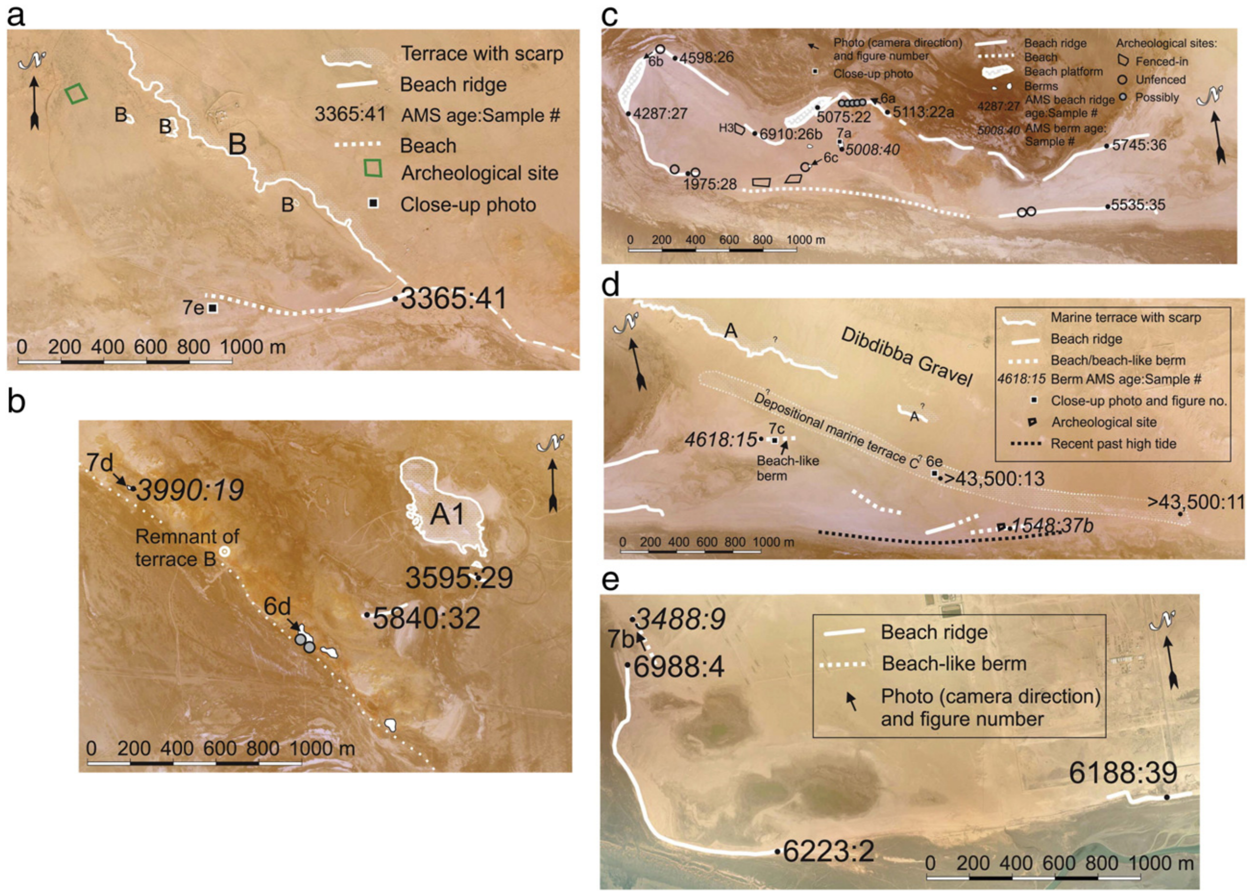

Figure 4. a. Map of the northwestern-most beach ridge and terrace B. The rocks making up the scarp of terrace B are not well-exposed along its southwestern-facing cliff because of erosion. Parts of terrace B are present only as small erosional remnants (labeled with small "B") on the sabkha. The scarp continues to the southeast where it is cut directly into the Ghar Formation basement rocks (see b and Figs. 8 and 10). b. Scarp of the Ghar Formation (white dotted line) trending northwest–southeast underlies terrace B. Berms (photos 6d, 7d) have accumulated at the high points along the scarp. A1 is an erosional remnant of terrace A. For explanation of symbols, see c. c. Map of Jazirat Dubaij promontory. Beach ridges, beaches, and berms are most abundant in this area. Beach ridges wider than ~20 m are referred to as beach platforms and may include the foreshore of a former lagoon. Filled small gray circles mark possible archeological sites of man-made structures devoid of potsherds. d. Map showing nearly the entire length of depositional marine terrace C and part of terrace A. The dated terrace C is currently mostly obliterated by construction in this area. Recent past tides reached close to the archeological site near sample 37b; tides are currently blocked from reaching close to this site owing to construction. e. Map of the southeastern-most part of the study area. The oldest beach ridges line the former coastline here. Most surface features have been demolished by construction associated with the Subiya power and desalination plant.

the base of the south-facing beach ridges on Jazirat Dubaij in Fig. 4c and right up to the NW/SE-trending outcrop in Fig. 4b. Such high tides, however, are neither common nor contribute to erosion of the beach ridges or to new beach sedimentation. For example, based on bottle characteristics, glass bottles within the debris zone were manufactured mostly between 1940 and 1960 (some as early as the 1920s), indicating high tides were more common in the recent past; the glass has been frosted by exposure to numerous sandstorms. Flooding of the supratidal zone depends on the concurrence of high spring tides and winds from the southeast, a rare situation, presumably occurring once or twice a year (although evidence of such high tides was not observed even once by the author between the years 2011 and 2015). The normal tidal cycle affects only a narrow 0.6–0.7 km-wide band parallel to the coast when the prevailing wind (the Shamal) is from the northwest (Gunatilaka, 1986). Within this narrow zone, washed-up glass bottles were manufactured more recently than ~1960 and are not frosted. None of these new bottles were found near the beach ridges.

Beach-ridge composition from thin sections

Samples from beach ridges on south-facing shores are similar in composition and characteristics to one another; they contain 40–70% well-rounded quartz grains occasionally with quartz overgrowths and embayments. Most quartz grains are enveloped by concentric layers of algae or micrite. Large, rounded, micrite clasts contain fine angular to subangular, probably wind-blown quartz grains. Skeletal grains (5–50%) are derived mostly from gastropods and are commonly fringed by acicular aragonite cement. Aragonite also grows toward the interiors of gastropod chambers and occasionally on the micritic rims of quartz grains. Minor plagioclase grains and ooids are also present.

Beach ridges on north-facing shores, towards former lagoons and land, are characterized by less quartz (1–30%), are poorly sorted, and contain rounded to subangular quartz grains with rare quartz overgrowths. Skeletal material, commonly from cerithids (10–80%), may form the framework in a matrix of micrite. Gastropods and quartz grains may be fringed by thick, acicular, aragonite cement, which is also found lining gastropod chambers. Ooids are common (20–30%); grapestones and peloids are present but uncommon.

Khalaf (1988) described thin sections of "intertidal Quaternary beachrocks" in Kuwait and subdivided them into quartzitic and calcarenitic types; he classified beachrocks in the Subiya area as quartzitic. In general, Khalaf's (1988) descriptions are similar to beachrock in beach ridges from this study, although Khalaf did not differentiate between beachrock from north-facing beach ridges (facing north toward lagoons) versus beachrock from south-facing beach ridges (facing south toward the sea).

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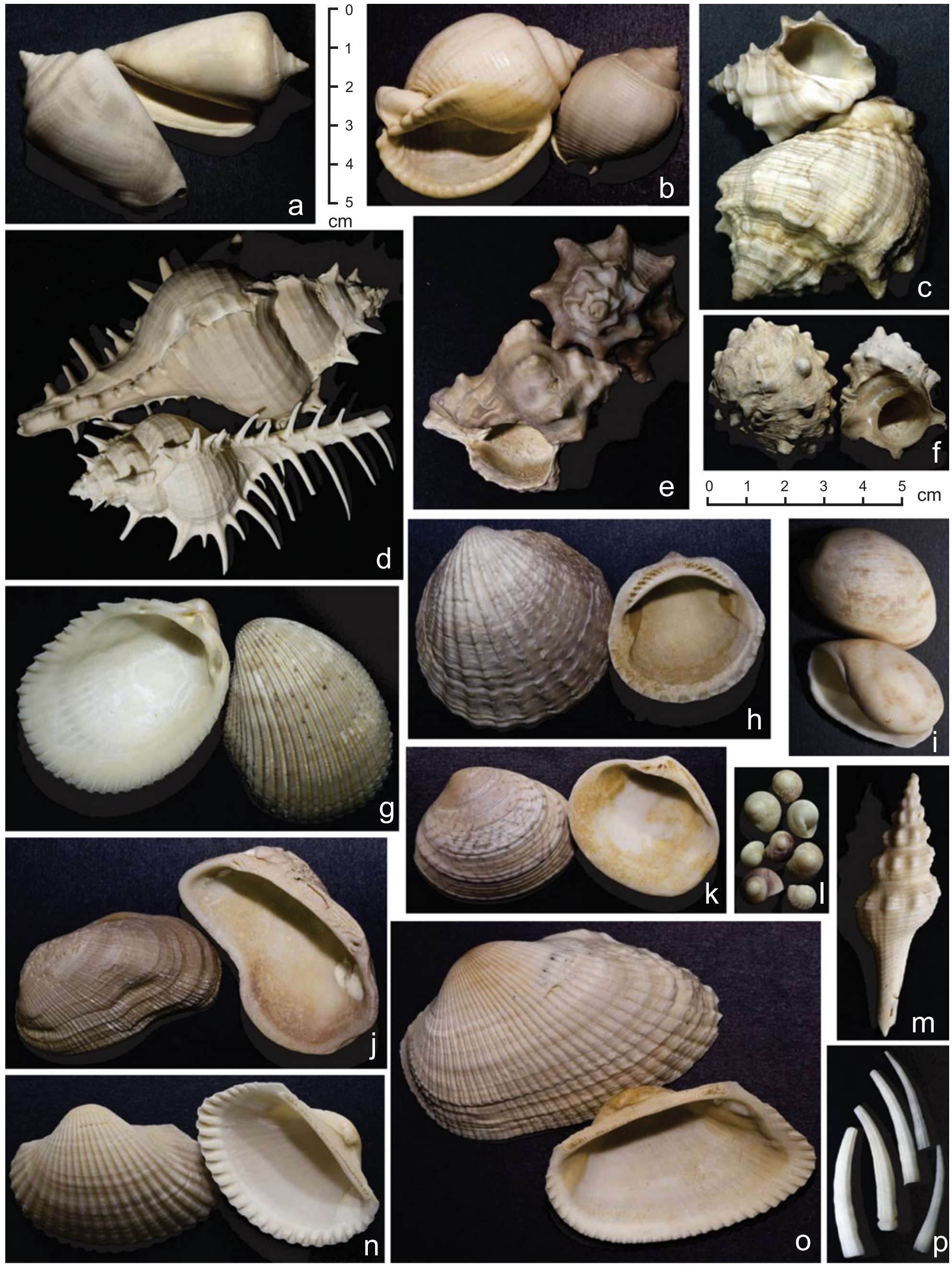

Figure 5. A representative selection of mollusks from beach ridges and beaches in Fig. 4a and from around Jazirat Dubaij (Fig. 4c): a: *Conomurex persicus*; b: *Semicassis faurotis*; c: *Indothais lacera* (thick-shelled like *C. persicus*, but not common); d: *Murex scolopax*; e: *Hexaplex kuesterianus* (may have originally been concentrated in a shell midden in the northwestern corner of Jazirat Dubaij); f: *Lunella coronata*; g: *Vasticardium assimile lacunosum* (this is the most common bivalve on the beach ridges); h: *Glycymeris glycymeris*; i: *Bulla ampulla*; j: *Barbatia setigera*; k: *Circenita callipyga*; l: *Umbonium vestiarium*; m: *Fusinus arabicus*; n: *Anadara ehrenbergi*; o: cf. *Mosambicarca erythraeonensis* (found mostly on former intertidal sand flats together with *U. vestiarium*); p: *Dentalium octangulatum*.

Mollusk diversity

Mollusk species in the beach ridges, beaches, and berms are listed in Table 2, and a selection of mollusks is shown in Fig. 5. *C. persicus* (Figs. 5a and 7a) is the most common species in both beach ridges and correlative beaches, and it dominates in berms. *Lunella coronata* (Figs. 5f and 7c) is present in small, well-defined patches on and near two of the berms (samples 9 and 15). Both *C. persicus* and *L. coronata* appear to be concentrated *in situ* by deflation and commonly are present to a depth of at least 20 cm within the shelly/sandy debris. Only those species that are most common, conspicuous, and useful for environmental interpretations are mentioned in Table 2. Many minute-sized and juvenile species were not identified or included unless abundant.

A depositional marine terrace

A depositional marine terrace (Figs. 4d, 6e and 8) at an elevation of ~3–7 m (Google Map elevations) exhibits no scarp, only a gentle rise. This terrace is the lowest terrace in the Bahra/Subiya area and is herein referred to as terrace C. Two higher step-like terraces (designated A and B) occur in the study area, but they are not discussed further since no dateable material was found on their surfaces. A new pipeline and road were built on terrace C, which was nicely exposed in cross section

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Table 1
Mollusk AMS dates from Holocene beach ridges, berms, and a depositional marine terrace. The conventional radiocarbon ages represent the measured radiocarbon ages corrected for isotopic fractionation, calculated using the delta ^{13}C.

Sample number Subiya:	BETA laboratory number	Sample types (BR: beach rock; B: berm; B1: beach; T: terrace)	Measured age (^{14}C yr BP)	δ ^{13}C‰	Conventional age (^{14}C yr BP)	2σ calibration (95% probability) cal yr BP	2σ calibration (95% probability) yr BC (except as noted)
2	361100	BR: Bivalve	5540 ± 30	+2.2	5990 ± 30	6335–6110	4385–4160
4	361101	BR: Gastropod	6190 ± 30	+3.7	6660 ± 30	7145–6830	5195–4880
9	361102	B: *C. persicus*	3360 ± 30	-0.1	3770 ± 30	3625–3350	1675–1400
11	361103	T: Oyster	NA	+0.6	>43,500		
13	361104	T: Oyster	NA	0.0	>43,500		
15	361105	B: *C. persicus*	4190 ± 30	+1.5	4620 ± 30	4805–4430	2855–2480
19	361107	B/B1: *C. persicus*	3720 ± 30	+2.5	4170 ± 30	4150–3830	2200–1880
22	361108	BR: Gastropod	4540 ± 40	+2.4	4990 ± 40	5285–4865	3335–2915
22a	361109	BR: Shell frags.	4540 ± 30	+3.6	5010 ± 30	5290–4935	3340–2985
26	361110	BR: *C. persicus*	4170 ± 30	+0.9	4590 ± 30	4785–4410	2833–2460
26b	363540	BR: Bivalve	6160 ± 40	+2.0	6600 ± 40	7085–6735	5135–4785
27	362478	BR: *C. persicus*	3900 ± 30	+4.6	4390 ± 30	4440–4133	2490–2185
28	361111	BR: Shell frags.	2090 ± 30	+1.7	2530 ± 30	2120–1830	170 BC–AD 120
29	361112	BR: Gastropod	3450 ± 30	-0.2	3860 ± 30	3750–3440	1800–1490
32	361114	BR: *Cerithidea*	5240 ± 30	-0.2	5650 ± 30	5975–5705	4025–3755
35	361115	BR: Shell frgs.	4960 ± 30	-1.0	5350 ± 30	5640–5430	3690–3480
36	361116	BR: *Cerithidea*	5140 ± 40	+0.5	5560 ± 40	5895–5595	3945–3645
37b	363541	B1: *C. persicus*	1770 ± 30	-0.8	2170 ± 30	1695–1400	AD 255–550
39	361117	BR: Bivalve	5540 ± 40	+1.0	5970 ± 40	6315–6060	4365–4110
40	361118	B: *C. persicus*	4450 ± 30	+2.5	4900 ± 30	5195–4820	3245–2870
41	361119	BR: *C. persicus*	3210 ± 30	+3.0	3670 ± 30	3505–3225	1555–1275

as a result of construction. Beneath 30–50 cm accumulations of sand and gravel on the surface of terrace C is a 10–25 cm layer of oyster- and barnacle-encrusted pebbles and cobbles and localized pieces of indurated, calcareous beachrock and coquina (Fig. 6e). Bioturbation is intense under this pebbly layer. The oyster shells were dated and are surprisingly well preserved considering the >43,500 ^{14}C yr BP ages from samples 11 and 13 (Table 1).

Discussion

Beach ridges as related to paleoenvironment, AMS ages, and sea-level changes

The beach ridges of the southern and southwestern parts of the Jazirat Dubaij promontory (Fig. 4c) were clearly deposited along the shore, with an open-water, high-energy marine environment to the south. Well-rounded quartz grains and a high diversity of mollusk species (Table 2, Fig. 5) in the beach ridges are in marked contrast to the low diversity of mollusks on the present-day muddy sabkha, represented by stranded, thin cheniers of mostly cerithid gastropods and the bivalves *Solen dactylus* (Cosel, 1989), *Amiantis umbonella* (Lamarck, 1818), *Protapes sinuosa* (Lamarck, 1818), and *Protapes cor* (Sowerby II, 1853).

The wide range in AMS dates in this study can perhaps best be interpreted as reflecting formation of beach ridges during the middle Holocene transgression (~8000–5000 cal yr BP) as shown in Fig. 9. The range in AMS dates from the mollusks probably represents nearly the entire age span of beach-ridge formation, from 7145–6830 cal yr BP (6660 ± 30 ^{14}C yr BP; Beta 361101) to 2120–1830 cal yr BP (2530 ± 30 ^{14}C yr BP; Beta 361111). Only the bases of the southeasternmost beach ridges (Fig. 4e) may be older (~8000 cal yr BP). Plotting the ages on a map (Fig. 3) reveals an overall age progression: beach ridges in the southeastern corner of the study area (Fig. 4e) yielded the oldest dates, whereas beach ridges in the northwestern corner (Fig. 4a) yielded the youngest dates.

AMS dates from a few beach-ridge samples (26b, 28, and 32) diverge from the overall decrease in AMS dates from southeast to northwest across the study area. Sample 26b (Fig. 4c), with a date of 7085–6735 cal yr BP (6600 ± 40 ^{14}C yr BP; Beta 363540), is from the central area but has one of the oldest ages; it was sampled close to the elevation of the sabkha and likely represents a thin, basal layer of the initial Holocene transgression (Fig. 9). Sample 32 (Fig. 4b), with a date of 5975–5705 cal yr BP (5650 ± 30 ^{14}C yr BP; Beta 361114), is also from close to the sabkha and probably represents a time before any significant beach build-up. The beach ridges in the southeastern part of the study area (Fig. 4e) yield ages similar to sample 26b, which implies sampling closer to the tops of those ridges, the bases of which may have been deposited when the Holocene transgression initially reached the present sea level ~8000 cal yr BP (Bernier et al., 1995; Lambeck, 1996; Kirkham, 1997, 1998; Kennett and Kennett, 2007). These prominent, southeastern beach ridges are located closer to the open sea and thus started forming before beaches farther inland (northwest) (Fig. 9). This is consistent with ^{14}C ages reported by Al-Zamel (1985) for freshwater peats on Bubiyan Island (Fig. 2) from a subsurface core at a depth of −20 to −24 m below MSL; these peats, which have reported ages of 8490 ± 100 ^{14}C yr BP to 7870 ± 90 ^{14}C yr BP (recalibrated to ~9430–8730 cal yr BP in Table 3), were probably deposited just prior to the deposition of the bases of the beach ridges in Fig. 4e. Pournelle (2003) shows that farther north, the present Euphrates valley was inundated by seawater by ~7500 yr.

Sample 28 is also from the central part of the study area (Fig. 4c), ~250 m southwest of sample 26b, yet it yielded the youngest beach-ridge age of 2120–1830 cal yr BP (2530 ± 30 ^{14}C yr BP; Beta 361111). It was collected within a few meters of a pre- or early Islamic (7th century AD) archeological site studied by Carter et al. (1999). Although the sampled beachrock rubble exposed on the surface could possibly have been used for building material, it was unlikely to have been transported to the site by the ancient inhabitants from elsewhere, because beachrock and bedrock were readily available on-site, just as they are today. Therefore, whether used for building material or not, the rock from which sample 28 was derived is most likely from the underlying beach ridge.

The sample 28 beachrock may be from a "regressive beach ridge" reflecting the final stage of progradation of the beach at a rate of ~1.5–2 m/yr, concurrent with withdrawal of the sea ~3000–2000 cal yr BP to present sea level (Al-Asfour, 1978; Al-Zamel, 1983; Gunatilaka, 1986; Saleh et al., 1999; Jameson and Strohmenger, 2012). The beach probably prograded southward until muddy sabkha replaced the shallow marine environment when all wave activity ceased. Similarly, beach sample 37B (Fig. 4d), with an AMS date of

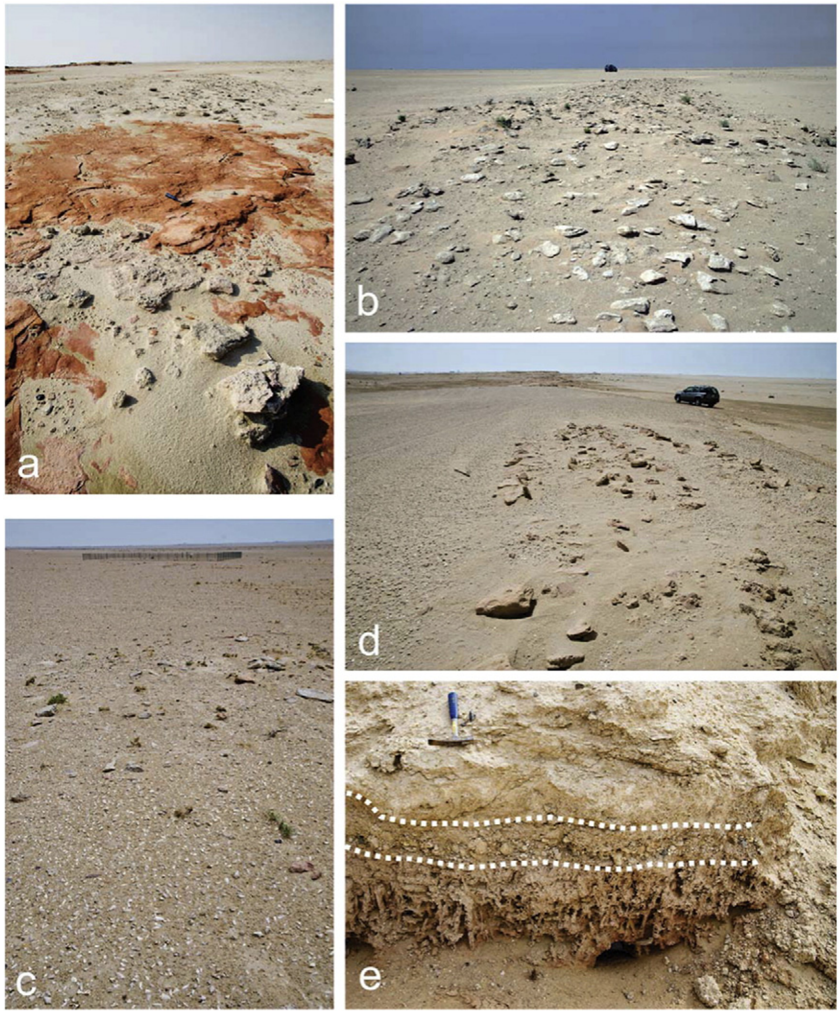

Figure 6. Photos of beach ridges, berms, and depositional terrace C. a. This beach ridge, directly deposited on the Ghar Formation (red in color), was severely weathered and denuded during a recent rain storm (see text). The calcite cementing the framework grains entirely dissolved in some areas as seen here, and the beach ridge was weathered down to the Ghar bedrock (location in Fig. 4c). b. A beach ridge (~10–20 m wide) in the form of continuous rubble, northwestern part of Jazirat Dubaij (location in Fig. 4c). c. *Conomurex persicus* forms a berm, which covers a possible ancient dwelling site with potsherds (location in Fig. 4c). d. An old man-made structure is obscured by a *S. persicus* berm (location in Fig. 4b). e. The pebble/cobble layer of the dated depositional marine terrace C is marked between stippled lines (location in Fig. 4d).

1695–1400 cal yr BP (2170 $\pm$ 30 ^{14}C yr BP; Beta 363541), exhibits the youngest AMS age of the 21 samples and probably represents either a regressive beach or a disaggregated beach ridge. An archeological site 20 m west of sample 37B (Fig. 4d) suggests settlements on the beach ridge prior to the final regression.

Lawler (2002) estimated that sediments of the Tigris–Euphrates flood plain prograded 130–150 km seaward during the last 5000 yr. The Shatt-Al-Arab estuary (Fig. 2) formed at ~2500 cal yr BP, and deltaic sediments including carbonate mud, clay minerals, and eolian sediments were deposited (Saleh et al., 1999; Aqrawi, 2001; Heyvaert and Baeteman, 2007). This would have contributed to sabkha formation in the nearby Bahra and Subiya coastal areas. Several authors state that the primary influence on the Holocene deltaic evolution in southern Iraq was eustatic sea-level fall in the Gulf (rather than local tectonic activity) (Gunatilaka, 1986; Aqrawi, 2001; Pournelle, 2003; Sanlaville, 2003). A similar paleoenvironmental succession was described by Kendall et al. (2003) where the southwestern part of the United Arab Emirates (U.A.E.), which is now covered by sabkha deposits, was covered by open lagoons during the early Holocene; the open-water environment increasingly filled with sediment, shallowed, and became more restricted after ~2000 yr. Seaward-stepping strandlines in Qatar and Abu Dhabi also suggest a falling sea level from ~2000 yr to the present (Jameson and Strohmenger, 2012).

Beach ridges, mollusks, and corals

The deposition of mollusks and sand likely occurred contemporaneously, after which cementation turned the debris into beachrock. Beachrock formation can be observed today in the littoral zone of sandy beaches along the coast of mainland Kuwait, such as in Salmiya (Ras al Ardh) and on the southern shore of Bubiyan Island (Fig. 2). The mollusks (Table 2, Fig. 5) in the beach ridges and on the disaggregated extension of the beach ridges appear to be nearly identical to mollusks found on present-day sandy beaches of mainland Kuwait. Fragile species, however, may not have been preserved in the ancient beach ridges, and future detailed investigations will likely reveal more differences between modern versus fossil fauna than reported here.

In general, water depth, temperature, salinity, and the local substrate determine the benthic community structure (Al-Yamani et al., 2012). The relatively high diversity of mollusks in the beach ridges and associated beaches indicates that water and substrate conditions along the Bahra/Subiya coast were favorable for mollusk adaptation in the early to middle Holocene. Moreover, heads of coral incorporated in the beach ridges imply contemporaneous reefs nearby, although the fossil reefs are probably buried under the present-day sabkha. The growth of coral near the beach ridges indicates a coastal

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Figure 7. Close-up photos of berms and the foreshore. a. A berm with sand and *C. persicus* gastropods. A ~20-cm-long lizard sits on a Dibdibba conglomerate cobble in the center for scale (location in Fig. 4c). b. A beach-like berm (boundaries approximated by white dotted lines) with *C. persicus* is partly covered by wind-blown sand. c. *Lunella coronata* concentrated in a shell midden (location in Fig. 4d). d. This beach with beachrock fragments and mollusks formed as a spit caused by waves from opposing directions (location in Fig. 4b). e. Tiny *Umbonium vestiarium* (Fig. 5l) shells are left on a sandbar once deposited by waves (from the beach in Fig. 4a).

environment adjoined by clear, clean water in the early to middle Holocene. The water along the coast of Kuwait is not as clean today. Sedimentation, tidal action, and sunlight are the main limiting factors for coral growth in the Gulf region (Basson et al., 1977; UNEP/IUCN, 1988; KFUPM/RI, 1990a), and present-day hermatypic corals along the coast of Kuwait can only grow to a depth of ~10 m because of their sensitivity to turbid water (Basson et al., 1977). Thus, coral reefs are presently common only around offshore islands where the water is cleaner.

The distribution of mollusk species on the beach ridges in the study area is also helpful in determining the landward versus seaward directions on Jazirat Dubaij. For example, *Cerithidea* gastropods, which prefer mudflats, are most abundant in beach ridges on north-facing shores, toward former lagoons; they are least abundant in beach ridges on south-facing shores, toward the open sea. Near Abu Dhabi, U.A.E. (Fig. 2), chenier-like stranded beach ridges of cerithid gastropods were reported adjacent to lagoons (Kirkham, 1997; Kendall et al., 2003), similar to beach ridges on north-facing shores in this study. The beach ridges near Abu Dhabi formed 4000–3000 yr and now stand 1 m above the surrounding sabkha (Patterson and Kinsman, 1981; Kirkham, 1997).

Isolated C. persicus berms and implications for a sea-level highstand

C. persicus shells are not only common in the beach ridges but also strongly dominate the sandy/shelly debris (samples 9, 15, 19, and 40) from the isolated, swash/storm-built high berms (Figs. 4b–e, 5a, 6c and 7a). The AMS ages derived from *C. persicus* shells in these four samples fall between 5195 and 3350 cal yr BP (Table 1), implying that the high berms and beach ridges in the northwestern part of the study area (Fig. 3) formed during the Holocene sea-level highstand (Fig. 1). Although the berms from which samples 9 (Fig. 4e) and 15 (Fig. 4d) were obtained are dominated by *C. persicus* (Figs. 5a and 7a), *L. coronata* (Figs. 5f and 7c) also occurs in small, well-defined, patchy clusters both within and outside the *C. persicus* shell hash. Carter and Crawford (2003) mention that *L. coronata* was collected as food by the Ubaid inhabitants of an archeological site named “H3 As-Sabiyah” (Fig. 4c). Considering that the opercula of *L. coronata* are found accumulated together with the shells, the patchy clusters probably represent shell middens. Apparently, the shells and inedible opercula were discarded simultaneously when the mollusks were eaten on the beach *after* the sea level had begun to recede from the stillstand that prevailed between ~5000 and 3500 cal yr BP (Fig. 1).

Table 2
List of the most common mollusks in the beach ridges, berms, and former foreshores of the study area. The mollusks were identified using information from Al-Asfour (1982), Glayzer et al. (1984), Sharabati (1984), Jones (1986), Bosch and Bosch (1989), Bosch et al. (1995), Al-Yamani (2012), and World Register of Marine Species (2014). This table is not intended as a complete list of the fossil mollusk fauna.

Family	Subfamily	Genus species	Common name
Class Bivalvia			
Arcidae	Arcinae	*Barbatia foliata* Forsskål, 1775	Decussate ark
		B. setigera Reeve, 1844	
	Anadarinae	*Anadara. ehrenbergi* Dunker, 1868 cf. *Mosambicarca erythraeonensis* Philippi, 1851	Ark clam
Cardiidae	Laevicardiinae	*Fulvia fragile* Forsskål, 1775	Fragile cockle
	Trachycardiinae	*Vasticardium assimile lacunosum* Reeve, 1845	
Glycymerididae		*Glycymeris glycymeris* Linnaeus, 1758	Comd dog cockle
		Circenita callipyga Born, 1778	Arabian circe
Ostreidae		*Ostrea* sp.	Oyster
Psammobildae		*Asaphis violascens* Forsskål, 1775	Violet asaphis
Pectinidae	Chlamydinae	*Mimachlamys sanguinea* Linnaeus, 1758	Noble scallop
Pteriidae		*Pinctada radiata* Leach, 1814	Gulf pearl oyster
		*P.*cf. *margaritifera* Linnaeus, 1758	Black lipped pearl oyster
Spondylidae		*Spondylus spinosus* Schreibers, 1793	Red thorny oyster
Veneridae	Pitarinae	*Callista umbonella* Lamarck 1818	Venerid clam
	Tapetinae	*Marcia cordata* Forsskål, 1775	Venus clam
Class Gastropoda			
Bullidae		*Bulla ampulla* Linnaeus, 1758	Pacific/large true bubble
Cassidae	Phaliinae	*Semicassis faurotis* Jousseaume 1888	Faurot's bonnet
Cerithiidae	Cerithiinae	*Cerithium* spp.	Cerithid
Cypraeidae		*Cypraea* (*Erosaria*) *turdus* Lamarck, 1810	Thrush cowrie
Fasciolariidae	Fusininae	*Fusinus arabicus* Melvill, 1898	Spindle/tulip snail
Muricidae	Muricinae	*Hexaplex kuesterianus* Tapparone-Canefri 1875	Küster's murex
		Murex scolopax Dillwyn, 1817	False venus comb
Naticidae	Polinicinae	*Neverita didyma* Röding, 1798	Moon snail
Olividae	Ancillinae	*Ancilla farsiana* Kilburn, 1981	Ancilla snail
		Ancilla castanea G.B. Sowerby I, 1830	Olive shell
Siphonariidae		*Siphonaria savignyi* Krauss, 1848	False limpet
Strombidae		**Conomurex persicus* Swainson, 1821	Persian conch
Turbinidae	Turbininae	*Lunella coronata* Gmelin, 1798	Crowned turban shell
Turritellidae		*Turritella* cf. *fultoni* Melvill, 1898	Turret shell
	Thaidinae	*Indothais lacera* Born, 1778	Carinate rock snail
Umboniinae		*Umbonium vestiarium* Linnaeus, 1758	Button top snail
Vermetidae		*Vermetus* sp.	Worm snail
Class Scaphopoda			
Dentaliidae		*Dentalium octangulatum* Donovan, 1803	Tusk shell

* There are several synonyms for the most abundant mollusk, *C. persicus,* of which the two most common are *Strombus persicus* Swainson, 1821 and *Strombus decorus raybaudii* Nicolay and Manoja, 1983 (Gofas et al., 2001; Streftaris et al., 2005; Rosenberg, 2014). *C. persicus* has also been misidentified as *Strombus decorus* Röding, 1798, but unlike *C. persicus*, which was originally restricted mostly to the Arabian Gulf, *S. decorus* has a broader distribution in the Indian Ocean.

Sample 19 was collected from a berm on a beach ridge located on an isolated outcrop of Ghar Sandstone (Figs. 8 and 10). Apparently the beach ridge and berm were shaped by waves converging from two opposing directions (Figs. 4b and 7d). The berm is dominated by robust *C. persicus* shells and chunks of beachrock. This berm may have been deposited on a beach ridge that extended parallel to the shoreline but only this remnant remains. The rest of this beach ridge was disaggregated as a result of dissolution of its cement.

The isolated *C. persicus* berm from which sample 40 was collected on Jazirat Dubaij (Figs. 4c and 7a) is ≥10 cm higher than Ubaid archeological site H3, which is ~600 m to the west. Two smaller *C. persicus* berm remnants (not sampled), parallel to the paleocoastline

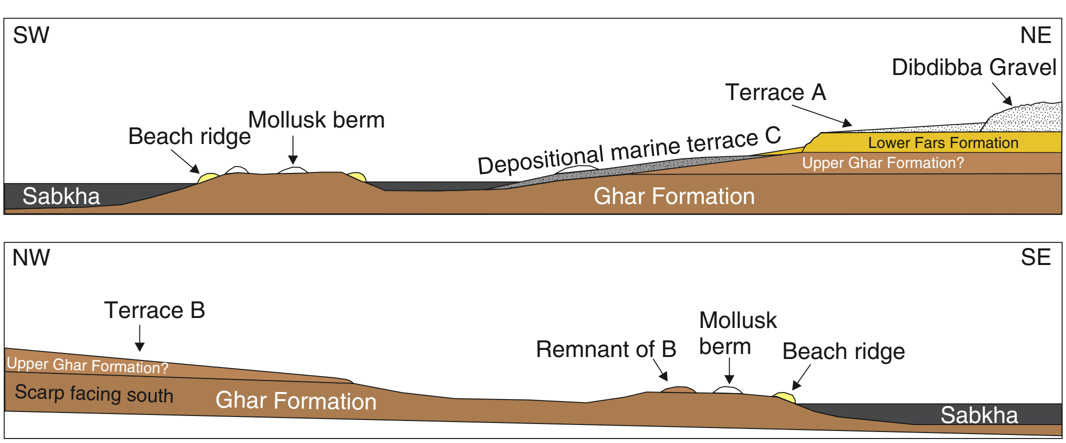

Figure 8. Cross-sections (not drawn to scale in either vertical or horizontal dimensions) illustrating a conceptual model explaining the possible relationships among beach ridges, berms, and terraces, and their geographic orientations. Note that the Ghar Formation underlying terrace B is shown as having a dip (not to scale) to the northeast (as described by Saleh et al., 1999).

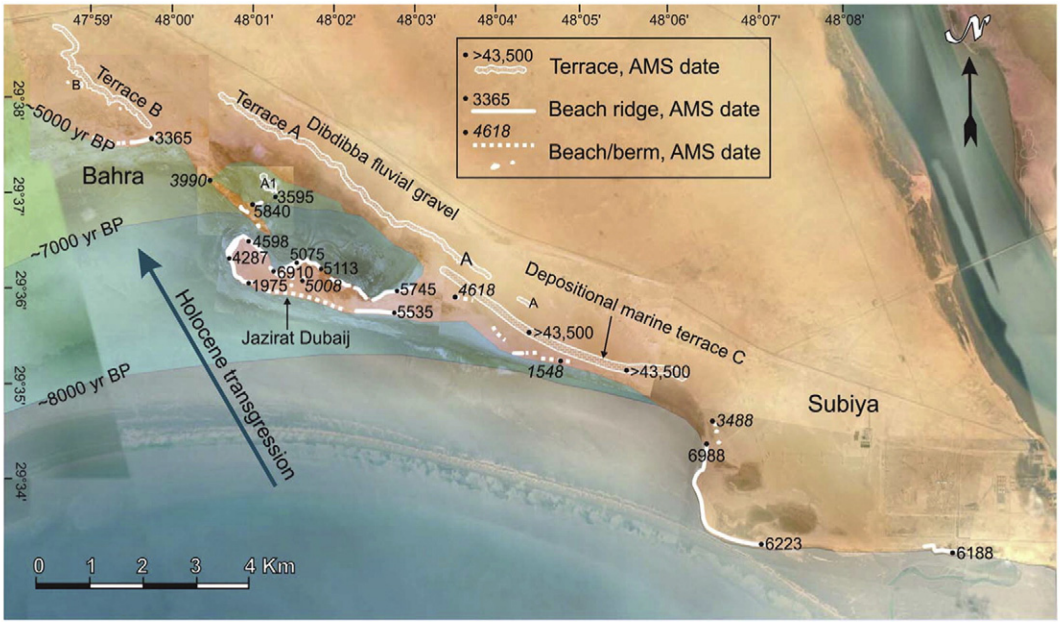

Figure 9. Conceptual visualization of the progress of the middle Holocene transgression and how it affected the Bahra/Subiya coastal area; approximate timelines of the approaching sea are marked at 8000, 7000, and 5000 cal yr BP. All AMS-dates are midpoints of the 2σ calibration range (Table 1).

and at a distance of ~400 m from site H3, are 25 and 40 cm higher than H3 (Fig. 4c). H3 was reported by Carter et al. (1999) to be at an elevation of 6.4–6.6 m above present MSL. Shells, which are nearly entirely *C. persicus*, were apparently washed up by innumerable storm tides that flooded even the highest points on Jazirat Dubaij, including all the beach ridges and archeological sites in the study area (Figs. 4b, 6c and 7a). Otvos (2000) stated that high beach berms like these exceed even the highest tides and commonly form during episodes of "wind-induced record water levels" (i.e., storm berms). There is no evidence, such as the growth of barnacles on the abundant pebbles, rocks, or potsherds scattered on Jazirat Dubaij and other parts of the field area, that would indicate this area was continually under water.

The four sampled berms yielded AMS ages consistent with all but the oldest and youngest beach ridges. The date of 5195–4820 cal yr BP (4900 ± 30 ^{14}C yr BP; Beta 361118) for sample 40 is from one *C. persicus* shell; all the shells making up the berm probably washed up over a period of time concurrent with their living presence in the marine environment. As mentioned above, berm samples 9, 15, and 19 (Fig. 4b, e) are also dominated by *C. persicus* and yielded AMS ages of 4805–3350 cal yr BP. Thus, for ~2000 yr between 5195 and 3350 cal yr BP, the spring/storm tides were so high that no permanent settlements could have existed on Jazirat Dubaij or elsewhere along the beach ridges of the study area—perhaps not until the pre- or early Islamic periods when the sea had receded enough to again allow human habitation. This is consistent with Carter et al.'s (1999) mentioning the apparent absence of human occupation on Jazirat Dubaij from the end of the Ubaid occupation until the "early centuries of the current era." Evidently, the sea withdrew quite rapidly after the Holocene highstand. For example, *Umbonium vestiarium* ("button tops") (Table 2, Figs. 5l and 7e), which thrives in coarse, clean, intertidal sands devoid of mud and which prefers wave action (Kalyanasundaram et al., 1974; Berry, 1990), were left *in situ* in large numbers, undisturbed by recent tides, and concentrated just south of the beach ridges in Fig. 4a where they once burrowed into sand bars.

Preservation of ~5195–3350 cal yr BP *C. persicus* shells in the highest berms on Jazirat Dubaij implies that the spring/storm tide swash zone reached ~5 m above present MSL during the middle Holocene transgression by the following reasoning: At present, the highest points on the Kuwait series 1:50,000 map of Jazirat Dubaij is 7 m above PWD, which is a vertical datum provided by Kuwait Oil Company for all of onshore Kuwait. PWD, which is an acronym for mean lower low water at Kuwait City, is 1.03 m below MSL. The highest elevations on Jazirat Dubaij, therefore, are ~6 m above MSL. Applying Pedoja et al.'s (2011) uplift rate of 0.16 mm/yr for 5000 yr implies that these highest berms were at 6 m − 0.8 m = +5.2 m above present MSL at 5000 cal yr BP.

If spring/storm tides were responsible for the swash zone's reaching ~5 m above the present MSL, how high was the actual Holocene highstand? Its height can only be approximated because variables such as wind-induced waves, water density variations, atmospheric effects, water circulation, fresh-water input from estuaries (for example, Shatt al-Arab), and paleo-bathymetry can affect MSL calculations (Pugh, 1987). Moreover, tidal-range changes can occur over distances as short as a few km (Shennan and Horton, 2002). Wind-induced waves can probably be excluded because, according to Khalaf and Ala (1980), Lo et al. (2003), and Nolte et al. (2004), the effects of wind-generated waves and associated currents are of secondary importance to

Table 3
Recalibrated dates of Al-Zamel (1985) and Carter et al. (2001, 2003, 2010).

Authors	Value (^{14}C yr BP)	Calibrated at 95.4% probability yr BC (cal yr BP)	Recalibrated at 95.4% probability yr BC (cal yr BP)	Dated material
Carter and Crawford (2002, 2003, 2010)	6480 ± 45	5530–5340 (7480–7290)[1]	5529–5356 (7479–7306)[2]	Ash from a firepit
	6160 ± 40	5220–4990 (7170–6940)[1]	5217–5000 (7167–6950)[2]	Ash from a firepit
	6135 ± 50	5220–4940 (7170–6890)[1]	5216–4945 (7166–6895)[2]	Ashy material
Al-Zamel (1985)	8490 ± 100	No calibrated dates available	7751–7205 (9701–9155)[2]	Freshwater peat
	7870 ± 90	Not available	7046–6515 (8996–8465)[2]	Freshwater peat

[1] Original, published dates calibrated with OxCal 3.1 (Ramsey, 1995, 2001) using the IntCal04 atmospheric curve (Reimer et al., 2004).
[2] Recalibrated at Arizona AMS lab with OxCal 4.2 (Ramsey et al., 2013) using the IntCal13 atmospheric curve (Reimer et al., 2013).

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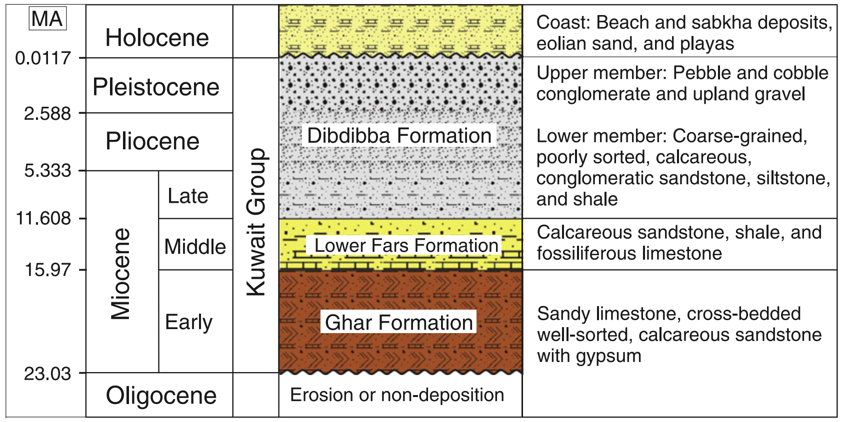

Figure 10. Simplified stratigraphic column for northeastern Kuwait modified from Duane et al. (2015) as compiled from Alsharhan and Nairn (1995), Mukhopadhyay et al. (1996), Al-Ruwaih et al. (2007), and Al-Hurban and Al-Sulaimi (2009). All important contributors (in addition to those reported here) to this stratigraphic column are documented by Mukhopadhyay et al. (1996). This stratigraphic column is not applicable in southern Kuwait. The Neogene and Quaternary geology of Kuwait is known mostly from oil-exploration wells, from water wells, and from extrapolating the stratigraphy in southern Iraq. No absolute ages have been reported for this stratigraphic column in northeastern Kuwait. Absolute ages on the geologic time scale are from the International Chronostratigraphic Chart, version 2015/01, International Commission on Stratigraphy (www.stratigraphy.org).

astronomical tides in Kuwait. None of the above variables are known for the middle Holocene. Thus, the paleo MSL is best estimated using the present tidal range in Kuwait Bay compared to the elevation of the *C. persicus* berms in the middle Holocene.

Local tides today in Kuwait Bay are semidiurnal with reported tidal ranges (mean lower low water to mean higher high water) of ~2.5–3.5 m during neap tides and ~3.3–4.3 m during spring tides (Khalaf and Ala, 1980; Al-Khalidi et al., 2011) (the numbers vary somewhat between different authors). Dividing the midpoints of the neap (3.0 m) and spring (3.8 m) tidal ranges by 2 yields 1.5 m and 1.9 m, the average of which is 1.7 m. Thus, assuming the tidal ranges were similar in the middle Holocene, a rough estimate of the MSL during the middle Holocene highstand is 5.2 m − 1.7 m = +3.5 m above the present MSL. Similar calculations of mean tidal ranges have been used for historical estimates of average sea level (Pugh, 1987) even though mean tidal level is not exactly the same as MSL, because of the influence of shallow-water tidal harmonics (Pugh, 1987).

The +3.5 m estimated height estimate for the Holocene highstand in northeastern Kuwait is higher than the maximum height (+2.0 ± 0.5 m) mentioned by Gunatilaka (1986) to be responsible for sea level reaching as far as 5 km inland from the present shoreline in northeastern Kuwait Bay. The +3.5 m highstand estimate in northeastern Kuwait derived in this study is also higher than the previously reported maximum estimates of +2 to +2.5 m responsible for other Holocene beach ridges in the Arabian Gulf (Gunatilaka, 1986; Lambeck, 1996; Kennett and Kennett, 2007; Jameson and Strohmenger, 2012). Some beach ridges in Qatar and Abu Dhabi are at elevations of 2–4 m above MSL as far as 5–15 km inland (Alsharhan and Kendall, 2003).

Although most authors agree on the concept of a Holocene sea-level highstand in the Arabian Gulf, they differ on the exact timing. For example, the beach ridges in Qatar and Abu Dhabi are reported to have formed during a highstand at ~7000–3000 yr (Jameson and Strohmenger, 2012). Uchupi et al. (1996)) and Pournelle (2003) reported that the maximum transgression in the Arabian Gulf occurred at 6000 yr. Gunatilaka (1986) stated that the highstand in northeastern Kuwait occurred between "4730–4530 ± 60 yr BP" (referred to as "available, though as yet unpublished dates" by Gunatilaka); this is a much shorter age-range and is much more consistent with the ~5000–3500 cal yr BP age-range for the highstand in this study.

The highstand inferred from the AMS dates (~5000–3500 cal yr BP) of this study does not take into account possible influences from regional or local tectonics. For example, although the Zagros orogeny could have caused local uplift (Tanoli et al., 2012), Zagros tectonism in Kuwait is thought to have ceased by the late Pleistocene (Pícha and Saleh, 1977). Even so, the Bahra anticline (Fig. 2) may have continued to develop, possibly resulting in subsidence on its flanks (Milton, 1967); this anticline may be largely responsible for the regional dip of ~1.5 m/km toward the east-northeast (Saleh et al., 1999) in the study area. Terraces on Jal Az-Zor may have been subjected to this local subsidence as evidenced by correlative terraces having increasingly lower elevations toward the east (Al-Asfour, 1982). Thus, possible continental uplift (Pedoja et al., 2011) combined with possible subsidence along the flank of the Bahra anticline may have self-cancelled to minimize any local vertical tectonic movements. If so, the middle Holocene storm surges/spring tides may have reached +6 m above the paleo MSL, which is *presently* the highest elevation at which *C. persicus* berms have been found in the study area.

Berms and the persistence of C. persicus

Why are there only a few remaining *C. persicus*-rich berms at high points (~6 m) in the study area when they almost certainly were more extensive in the past? The answer probably lies in the erosional power of rainstorms throughout the millennia. The denudation of a *Conomurex*-rich berm was noticed at the location of sample 19 (Fig. 4b); the beach ridge on which this berm is located was severely reduced in size during a cloudburst on November 20, 2013. During that storm, 50 mm of precipitation was reported on nearby Bubiyan Island (Fig. 2), and 36–94 mm was reported at other locations in Kuwait. In addition to erosion of this *Conomurex* berm, new wadis and ephemeral lakes formed, Miocene bedrock was washed clean of sand and debris, sediments shifted from one place to another, and the power of erosional processes was evident everywhere. Since 1934, four similar cloudbursts have occurred (in addition to the 2013 deluge), during which 48–300 mm of precipitation fell within 1.5 h (Zaghloul and Al-Mutairi, 2010). For comparison, the average annual rainfall in the study area is 122.4 mm (Saleh et al., 1999). In addition, severe dust storms may have contributed to deflation ever since the climate turned more arid at ~5500 yr (Kennett and Kennett, 2007; Wood et al., 2012). Cloudbursts after duststorms could easily have removed *Conomurex* shells exposed by deflation, and this cycle would have repeated episodically. Thus, only patches of formerly extensive berms cap the highest points, but the edges of these berms are intermittently being eroded.

Why is *C. persicus* so ubiquitous compared to all other mollusks on the berms? There could be at least three explanations: its ability to withstand the abrasive forces of surf, its seasonal manifestation, and its invasive capacity. Shell thickness is a predictor of shell strength, which is an adaptation to environmental stresses (Chave, 1964; Driscoll and Weltin, 1973; Kotler et al., 1991; Zuschin and Stanton, 2001). Reduction in shell size, in particular, is a function of surface area per unit weight (Driscoll and Weltin, 1973). The most important factors in shell destruction are the degree to which boring organisms, solution, and abrasion have affected the shell (Driscoll and Weltin, 1973). Borings in shells of *C. persicus*, however, were seldom observed in this study, and solution appears to have had only a minor to moderate effect. Abrasion is the most significant factor in a high-energy littoral environment (Driscoll and Weltin, 1973), such as along the middle Holocene Bahra/Subiya coast. Chave (1964) showed in experiments that gastropods are more resistant to abrasion than most bivalves, corals, bryozoans, echinoids, and coralline algae.

C. persicus may also have been concentrated in the littoral environment prior to being washed up on the beaches. For example, Glayzer et al. (1984) reported that, during the 1972/73 winter season in Kuwait, juvenile "*strombus decorus persicus* [synonymous for *Conomurex persicus*] were seen in large colonies which covered several square meter areas"; large concentrations were not seen again until the winter of 1974/1975. On the Israeli coast, invasive *Conomurex* has been observed in high concentrations of tens of specimens per m^2 (Fishelson, 2000). Along the Syrian coast, *Conomurex* species have been reported to account for 75–93% of the biomass (Kucheruk and Basin, 1999). Such concentrations in the past would have resulted in *C. persicus* shells accumulating on the emerging beach ridges with a higher likelihood of withstanding abrasion by storm tides because the gastropods would likely be washed up on the nearby berms and buried by successive layers of gastropods and wind-blown sand.

Beach ridges and implications for ancient settlements

Carter (2002) suggested that the Jazirat Dubaij promontory "directly bordered the sea in antiquity" and that its northern margin, where archeological Ubaid site H3 is located (Fig.4c), formed the foreshore of a shallow lagoon. Based on dated pottery (Stein, 1994; Carter and Philip, 2010), the Ubaid period, which lasted from ~6500–3800 BC (~8450–5750 yr), refers to a culture with an origin in southern Mesopotamia. The Ubaid period has been subdivided into six phases designated Ubaid 0 to 5. Site H3, now mostly covered by sand, was described as Ubaid 2/3 5200–4900 BC (7150–6850 yr) (Pournelle, 2003), a time period as well as a cultural assemblage (Carter and Crawford, 2002). Slightly older ^{14}C dates from Carter and Crawford (2002, 2003, 2010) of ~5530–4950 BC (~7480–6900 cal yr BP) (Table 3) are from the lowest, pre-building level at site H3. A ^{14}C date of 5216–4945 BC (7166–6895 cal yr BP) was obtained from an early building level and conforms almost exactly to the Ubaid 2/3 phase. Evidently, sea level was rising slowly and the beach depositional environment was relatively stable during the Ubaid occupation, at which time communities thrived off near-shore marine life.

H3 is only ~120 m northwest of where the AMS date of 5135–4785 BC (7085–6735 cal yr BP; Beta 363540) was obtained from sample 26b (Fig. 4c). This sample was collected from the base of a beach ridge that is now approximately level with the floor of the former lagoon, which formed at ~7000 cal yr BP when the sea first encroached in the vicinity of site H3; the lagoonal sediments have since mixed with eroded bedrock from Jazirat Dubaij proper as well as with eroded beach rock and wind-blown sand. The stratigraphic position of the early building level at site H3 appears to be nearly identical to sample 26b, and their dates are in good agreement.

Jazirat Dubaij promontory may have been a narrower strip of land during the Ubaid occupation than during the later pre- and early- Islamic occupation. The sea was rising slowly during the Ubaid occupation, and people may have lived on the more protected northern margin facing the lagoon. Carter (2002) referred to a sea-level highstand ~2000 BC (~3950 yr), which could have destroyed middle Holocene geomorphic features on Jazirat Dubaij. The archeological sites from the Ubaid period would have been flooded and uninhabitable during this sea-level highstand, which is within the range of the ~5000–3500 cal yr BP highstand inferred in this study. Yet, few locations including the archeological sites on Jazirat Dubaij are currently covered with *C. persicus* gastropod shells. Carter et al. (1999) did mention, however, that site H3 was originally covered in "large quantities of unstratified, deflated marine gastropods." A beach berm with 100% *C. persicus* (plus sand) overlies a presumed archeological site inferred from potsherds near sample 40 (Figs. 4c and 6c). Furthermore, one apparently ancient, man-made structure, not on Jazirat Dubaij and apparently not reported as an archeological site, is still overlain by mostly *C. persicus* shells, although this particular mollusk deposit was not dated (Figs. 4b and 6d). The structure was constructed from the local red bedrock of the Miocene Ghar Formation (Figs. 8 and 10) and sits directly on Ghar bedrock. Given the absence of associated potsherds or other artifacts, it seems that the bedrock on which the structure sits was washed clean by waves prior to deposition of *C. persicus* shells.

A cluster of younger, late pre-Islamic or early Islamic sites located at the southern margin of the Jazirat Dubaij promontory indicates that the southern margin was inhabited in the 1st millennium AD (Carter et al., 1999) during the late Holocene regression that followed the middle Holocene highstand (Fig. 1). During the Islamic occupation, it would have been beneficial to live on the seaward, southern side of the promontory, especially if the lagoon behind the northern margin was drying up and the beach on the southern margin was prograding toward the sea.

Several of the same mollusk taxa described in this study were also reported by Carter and Crawford (2003) from site H3. They recognized 25 mollusk taxa, the majority of which they described as having lived in sandy, rocky intertidal zones, not in a muddy sabkha like the present environment. A Polish–Kuwaiti archeological team, excavating dwellings and burial mounds 3–4 km inland from the stranded beach ridges, also suggested that the seashore had been much closer to those archeological sites than today (PCMA Newsletter, 2010).

Origin of marine depositional terrace C

The staircase topography along northeastern Kuwait Bay (Fig. 8) is mainly of wave-cut and marine-built origin (Al-Asfour, 1978, 1982). Terrace C in Figs. 4d and 8 however, does not exhibit a scarp, but was formed by a rising sea, which flooded and apparently reworked a pre-existing blanket of Dibdibba gravel, probably during MIS 5e, which was the last time prior to the middle Holocene highstand, when MSL was higher (probably by 4–5 m) than the present sea level (Pascucci et al., 2014). Barnacles and oysters attached to the pebbles and cobbles (Fig. 6e) indicate a shallow intertidal zone subjected to regular tides. Storm tides may have dislodged pieces of coeval beachrock and coquina, which then mixed with the gravel.

The two old (>43,500 ^{14}C yr BP) AMS dates from terrace C are from elevations of 3–7 m, which is in stark contrast to the much higher elevations (40–63 m) from which Al-Asfour's (1978, 1982) old (~42,950–23,350^{14}C yr BP) dates were derived from marine-cut terraces in Kathma, Ghidhai, and Mudairah (Fig. 2). In particular, Al-Asfour's sample from the highest elevation (63 m) yielded a date of ~28,350 ^{14}C yr BP. Al-Asfour's (1982) dated mollusks were found "scattered" and "strewn" and "spread throughout the area without any regularity in age." Such shells could have been moved by any agent including human beings or eroded from higher levels; thus reliable dates would be difficult to obtain from these terraces, even if the shelly debris originally was deposited during marine incursions. Al-Asfour (1978) admitted that those ages were probably unreliable, because of mixing and contamination of sediments and even the possibility that the shells are of Tertiary age. Rare, single gastropod shells found on terraces A and B (Figs. 3 and 8) by the author appear no different from those found in the middle to late Holocene beach ridges, suggesting that they may well be contaminants. Thus, no attempt was made to determine AMS dates from mollusks on terraces A and B in this study.

Thus, the ages of terraces A and B (as well as other high-elevation terraces mentioned by Al-Asfour, 1982) are still a question for future research. It may not be possible to determine their ages unless remnants of beach rock can be found cemented *onto* the terrace surfaces. Moreover, any dateable material on the surface of those terraces will probably be older than the limits (<43,500 ^{14}C yr BP) for AMS ^{14}C-dating. Employing the U–Th or U–He series, for example, may resolve the problem concerning accurate ages but not the issue of finding reliable material for dating. Alternatively, perhaps a new method using ^{10}Be and ^{26}Al from cosmic rays could be used, since that technique would indicate how long a marine terrace *surface* has been exposed since the sea withdrew (Perg et al., 2001).

Summary and conclusions

Beach ridges formed along ancient shorelines, ~8000–2000 cal yr BP in the Subiya and Bahra areas of northeastern Kuwait Bay. Today, those beach ridges are 4–7 km inland and intermittently border the present-day sabkha. The ridges, which were originally lithified into calcareous, fossiliferous sandstones or coquinas, are now mostly broken-up rubble. AMS ages of 7145–1830 cal yr BP from mollusks incorporated in the beachrock likely represent nearly the entire time-span of beach-ridge deposition; they reveal a time-transgressive age progression, probably reflecting the middle Holocene marine transgression proceeding from the southeast to the northwest across the study area. A sea-level highstand apparently occurred between ~5000 and 3500 cal yr BP. Initial beach-ridge formation may have begun as early as 8000 cal yr BP, at the base of beach ridges in the easternmost part of Subiya. The youngest "regressive" beach ridges apparently formed at ~1830 cal yr BP, recording the final withdrawal of the sea to its present-day level.

Shelly/sandy beach berms with high concentrations of *C. persicus* are presently found in areas of relatively high elevation (~6 m above MSL), 2–3 m above the beach ridges. These mollusk berms became well-sorted by repeated wave action, and *C. persicus* withstood abrasion because of its thick shell. During the middle Holocene, MSL in Kuwait Bay probably approached ~+3.5 m, and the sea regularly flooded during storms to ~+5 m and inundated the developing beach ridges, as well as ancient settlements, to form high storm berms. AMS dates ranging from 5195 to 3350 cal yr BP derived from the berms indicate that the area was uninhabitable to permanent settlement for the ~2000 yr time-span between those ages. There is, however, evidence of human settlements in the study area prior to and after that 5195–3350 cal yr BP sea-level highstand.

A marine depositional terrace yielded ages >43,500 ^{14}C yr BP and probably represents a tide- and storm-generated pebble-cobble strandplain terrace that may have formed during MIS 5e. Dating methods other than radiocarbon would be necessary to determine the ages and associations of terraces at higher elevations (i.e., ~6–100 m) than the beach ridges. In future work, accurate and precise measurements of elevations in the study area would further elucidate morphological and timing relationships.

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