Geological Quarterly, 2014, **58** (2): 207–216
DOI: http://dx.doi.org/10.7306/gq.1144

Unraveling cementation environment and patterns of Holocene beachrocks in the Arabian Gulf and the Gulf of Aqaba: stable isotope approach

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Koeshidayatullah, A., Al-Ramadan, A., 2014. Unraveling cementation environment and patterns of Holocene beachrocks in the Arabian Gulf and the Gulf of Aqaba: stable isotope approach. Geological Quarterly, **58** (2): 207–216, doi: 10.7306/gq.1144

This paper analyses Holocene beachrocks from the Arabian Gulf and the Gulf of Aqaba to explain the mechanisms that influence the cementation process in these areas. Holocene beachrocks in the Gulf of Aqaba are composed of predominantly terrigenous material derived from erosion of adjacent uplifted Precambrian basement, while the beachrocks in the Arabian Gulf are composed mainly of marine bioclasts and wind-blown siliciclastic sands. The cements of beachrocks in both areas show three textural varieties: (1) isopachous phreatic acicular aragonite; (2) a micritic envelope of high-Mg calcite (HMC); (3) meniscus and gravitational vadose HMC. Radiocarbon dating of beachrock samples from the Arabian Gulf yielded ages from ca. 2300 to 660 yr cal BP whereas samples from the Gulf of Aqaba range in age between 5500 and 2800 yr cal BP. Oxygen isotope values range from 2.6 to 4.4‰ respectively for the Arabian Gulf whereas the Gulf of Aqaba values range from 1.2 to 1.5‰. Carbon isotope values range from 3.2 to 5.9‰ for the Arabian Gulf whereas those from the Gulf of Aqaba range from 3.8 to 4.6‰. The values of $^{18}O_{VPDB}$ and $^{13}C_{VPDB}$ in the beachrocks of both areas suggest a marine origin. The beachrocks of the Arabian Gulf were precipitated under high evaporation conditions, while beachrocks from the Gulf of Aqaba were precipitated in normal shallow-marine conditions. The mineralogy and textural habits suggest that cementation of these beachrocks started within the shallow-marine phreatic zone.

Key words: cementation, beachrocks, stable isotope, Arabian Gulf, Gulf of Aqaba.

INTRODUCTION

Beaches fringe about 40% of the world's coastlines, and generally consist of unconsolidated deposits of carbonate sand and gravel (Bird, 2011). Precipitation of carbonates in the fluctuating water table zone within a beach, related to the tides, can cement beach sands into hard layers known as beachrocks (Bird, 2011); this commonly occurs within the intertidal zone (Bricker, 1971). Dissolution and precipitation of high-Mg calcite (HMC) and aragonite are the dominant processes in the intertidal zone, followed by minor formation of dolomite and low-Mg calcite (LMC). Carbonate minerals are precipitated from groundwater in the zone between high and low tide level, and also may be aided by the activity of microorganisms, such as bacteria, that inhabit the beach close to the water table and may increase the pH of the pore waters and thus facilitate carbonate precipitation (Bird, 2011). Beachrocks, in many instances, experience rapid cementation processes (Holail and Rashed, 1992; Kneale and Viles, 2000). Formation of beachrocks is also assisted by high evaporation, which causes upward movement of water and dissolved carbonate minerals in the beach sand (Stoddart and Cann,1965). A range of different general explanations have been suggested to explain the initiation of beachrock; this list is probably still not complete, because the processes and materials, particularly the cementation processes, vary from area to area depending on the type of beach sand and hydrological conditions (Kneale and Viles, 2000). Several mechanisms have been proposed to explain the cementation of beachrocks (Scholten, 1972), including: (1) precipitation of $CaCO_3$ from heavily charged groundwater at the water table level (Russell, 1962; Russell and McIntire, 1965); (2) mixing of marine and meteoric water vs. $_PCO_2$ degassing in the intertidal zone (Hanor, 1978); (3) precipitation associated with the evaporation of seawater (Stoddart and Cann, 1965; Milliman, 1974); (4) precipitation in the marine-freshwater mixing zone (Schmalz, 1971; Moore,1973).

Generally the cements of beachrocks are mainly composed of HMC or aragonite, which are known to form in a marine environment. The precipitation of these marine cements has been attributed to evaporation of seawater which increases the saturation of $CaCO_3$ and enhances cementation in the intertidal zone (Stoddart and Cann, 1965; Longman, 1980). Additionally, LMC and dolomite cement may occur in landward settings of beachrock deposits as a product of pCO_2-degassing or lake processes (Hanor, 1978). Despite the different cementation

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Received: August 3, 2013; accepted: November 13, 2013; first published online: January 20, 2014

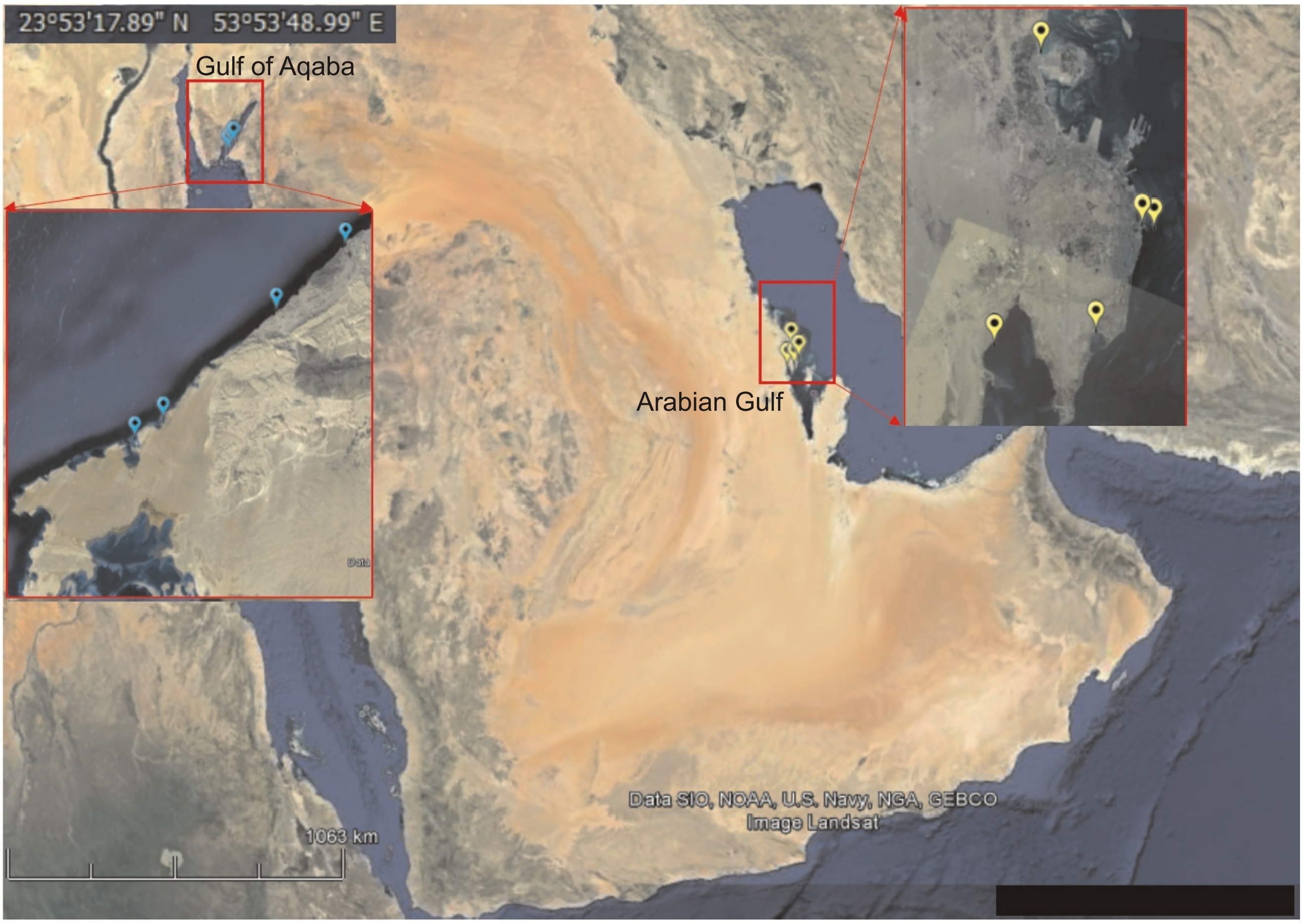

Fig. 1. Map of Arabian plate showing the study locations

processes and products, there is one common important factor in beachrock formation; cementation commonly occurs within the intertidal zone (Bricker, 1971; Spurgeon et al., 2003). Beachrocks have been extensively studied in many regions in the world, such as on the coast of the Red Sea (e.g., Holail and Rashed, 1992; Ghandour et al., 2014), the Black Sea (Erginal et al., 2012, 2013), Florida (e.g., Spurgeon et al., 2003), the Mediterranean (e.g., Alexandersson, 1972; El-Sayed, 1988), Central America and the Caribbean (e.g., Beier, 1985), India (Kumar et al., 2000, 2012), the Arabian Gulf (e.g.,Taylor and Illing, 1971), Hawaii (Meyers, 1987), Australia (e.g., Chivas et al., 1986) and Scotland (e.g., Kneale and Viles, 2000). Beachrocks, a common feature of the eastern and northwestern coastlines of Saudi Arabia, have been subject of a large number of modern coastal studies because of their function in the interpretation of coastal dynamics (Chaves and Sial, 1998) and their importance as an indicator of past sea level (Spurgeon et al., 2003). So far, just a few studies have been performed in this study area. Therefore, this study compares cementation habits and environments between Holocene beachrocks of the Arabian Gulf and the Gulf of Aqaba. Carbon and oxygen isotopic analysis are the primary tools used in this study to characterize the pore fluids from which the cements precipitated. Combinations of powder X-ray diffraction (XRD) and petrographic analyses also added the data and revealed the mineralogical composition and the texture of the cements.

SAMPLING AND METHODS

The beachrocks of both the Gulf of Aqaba and the Arabian Gulf occur as linear deposits, patchy in their outcrop with planar-bedded layers that dip gently (<10°) towards the sea. For this study, a total of nine Holocene beachrocks were sampled along the Arabian Gulf and the Gulf of Aqaba from the exposed part of the succession (Fig. 1) representing the main characteristics of each gulf and of well-preserved material within the beachrocks (Fig. 2). Thin sections were studied using conventional petrographic techniques. Cement morphology and its composition were analysed using a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectroscopy (EDS) and a backscattered electron detector (BSE). Modal analyses of the constituents of the samples were examined by counting 300 points in each thin section. Ca, Mg and Fe contents in the carbonate cements were determined by electron probe micro-analysis (EPMA). Powder XRD analyses were performed on eight samples for semi-quantitative estimation of the relative abundances of various carbonate minerals. Stable oxygen and carbon isotope analyses were performed on nine whole-rock samples. Radiocarbon dating analyses were determined for four whole-rock samples, two each from the Arabian Gulf and the Gulf of Aqaba. Stable isotope analysis was carried out at Leeds University, UK.

Fig. 2. Examples of beachrock exposures in the Arabian Gulf

A – the beachrock strata dip towards the sea (10°); **B** – patchy beachrocks distribution in more seawards; **C** – exposed beachrocks extend more than 12 metres perpendicular to the shoreline; **D** – algal mat occurrence on top of beachrocks in both gulfs

RESULTS

DETRITAL COMPONENTS AND POROSITY

Four samples collected from the Gulf of Aqaba are made up mainly of moderately to poorly sorted coarse-grained terrigenous fragments (Table 1), such as quartz, feldspar, some plutonic (volcanic and igneous) and metamorphic rock fragments,and small amounts of bioclasts (Fig. 3A, B). Five samples of the Arabian Gulf beachrocks are composed mainly of skeletal and non-skeletal grains reworked from the adjacent carbonate platforms by wave, storm or tidal processes. The grains consist predominantly of skeletal particles and intraclasts (Table 1), and also a small amount of rounded quartz that probably derived from wind-blown sand. Skeletal particles are predominantly fragments of bivalves, benthic foraminifers, green algae and gastropods. Most of the skeletal grains are dissolved and the internal structure is not shown due to calcite cement infilling cavities and the micritisation of the skeleton by boring algae. Micritisation of bioclasts (gastropods and foraminifers) is extensive at grain boundaries; micritic envelopes may be developed locally within meniscus fabrics. Beachrocks from both areas generally have similar mineralogical compositions to the associated loose beach sediments.

Thin sections showed inter- and intra-granular pores as a major, and vuggy pores as a minor porosity types. Porosity is larger in beachrocks of the Arabian Gulf than in the Gulf of Aqaba. The presence of intragranular pores are mainly due to the dissolution of bioclastic internal structure, with some from partial dissolution of non-skeletal grains. In the Arabian Gulf, the framework grains are dominated by point and elongate contacts with good interconnectivity between primary and secondary pores. The inter- and intra-granular pores of the Gulf of Aqaba beachrocks are extensively lined by radial acicular aragonite that forms isopachous rim cements and creates barriers between grains that lead to occluded pore throats.

CEMENTATION TYPES

Beachrocks from both gulfs are mainly cemented by micritic envelopes and isopachous acicular aragonite cements. Locally, meniscus and gravitational HMC cements also occur in interparticle pores and around sand grains (Table 1). Micritic envelopes, which are commonly brown in colour, are defined in this study as cryptocrystalline carbonate cements (crystal size <5 μm) that cover grains. The micritic cement is mainly composed of HMC (11–14.5 mol% $MgCO_3$). These envelopes are predominantly covered by acicular aragonite cements. All of the allochem materials show well-developed micritic envelopes, which are largely non-luminescent. Micritic HMC cement in the Gulf of Aqaba beachrocks occurs as envelopes around the terrigenous grains and carbonate bioclasts. Micritic envelopes and pore-filling calcite cement are non-luminescent. Many interparticle pores are filled with lime mud matrix. In a few sam-

Table 1

Petrographic description of beachrock samples from the Arabian Gulf and the Gulf of Aqaba

Sample	Description
AG-1	Large gastropod and bivalve fragments. Common benthic and agglutinated foraminifers. Grains extensively micritised. Fibrous aragonitic cements restricted mainly to gastropod chambers. Inter- and intraparticle porosity. Local meniscus cement.
AG-2	Mixed carbonate grain content, skletal and non-skeletal (ooids), abundant terrigenous grains. Grains commonly micritised or with micritic envelopes.Common, fine (<20 μm long), radial acicular calcite/aragonite lining pores.
AG-4	Varied bioclasts content, such as miliolids, agglutinated foraminifers and non-skeletal grains (oncoids), abundant terrigenous grains. Common micritised grains and micrite envelopes. Well-developed acicular pore lining and infilling calcite/aragonite, crystals <200 μm in length. Local meniscus cement.
AG-5	Mainly large, thick-walled bivalve shells, hollow, with extensive intragranular porosity. Minor thin shelled bivalves. Minor benthic foraminifers and glaucony. Abundant terrigenous grains entrapped within the bioclastic shell. Locally well-developed radial acicular pore linings and calcite/aragonite fills, crystals <200 μm long.
Hardground	Fine-grained sandstone. Well-developed micritic grain coatings. Locally with well-preserved intergranular porosity; elsewhere, porosity is reduced by micritic cements, which are commonly overlain by later radial, acicular calcite/aragonite cements (crystals <150 μm in length), which line, or commonly fill pores.
GA-1	Very coarse-grained, calcite cemented sandstone. Grains are coated with thin tangential to radial micritic carbonate coatings – oolitic? Intergranular areas are near-pervasively cemented by early radial acicular calcite/aragonite, crystals <100 μm in length. Centers of large pores are locally cemented by more equant, blocky carbonate cement.
GA-2	Laminated, calcareous sandstone. Lime mud matrix has “clotted” and irregularly laminated texture possible in-situ algal structures? Radial, acicular calcite/aragonite cement, crystals <200 μm in length in coarse areas.
GA-3	Lithic sandstone. Abundant reworked nummulitic foraminifera, algal fragments, micritic limestone clasts and organized limestone clasts. All grains have micrite envelopes/coatings. Very well-developed early, radial, acicular calcite/aragonite cements, crystals <200 μm long, commonly pore-filling, locally overlies thin isopachous cement.
GA-4	Feldspathic sandstone. Occasional reworked nummulites and other benthic foraminifera.Thin, micritic grain coatings and intergranular lime mud matrix. Common radial pore linings and in filling acicular calcite/aragonite cements, crystals <100 μm long.

ples, there are non-skeletal grains including peloids and oncoids as well as some grains that are coated by red algae and densely cemented with micritic HMC. Acicular aragonite (Fig. 3A–C), which is the most common cement in the beachrocks studied, forms isopachous rims exhibiting pointed terminations arranged perpendicular to grain surfaces. In the Arabian Gulf beachrocks, the acicular aragonite cement lines the internal chamber and external parts of gastropods, but foraminifer shells are only coated externally (Fig. 3G). The acicular crystals are generally <5 μm in length and bladed/fibrous in shape. The acicular aragonite crystals, which line the intergranular pores, have a length of <40 μm while those occur in gastropod chambers are generally 20 μm in length.

POWDER X-RAY DIFFRACTION (XRD)

Powder XRD studies were used to show the presence of aragonite, HMC, LMC (<4 mol% $MgCO_3$) and minor dolomite content within the studied beachrocks samples (Fig. 4). Generally, beachrocks from the Arabian Gulf have a higher aragonite content than those from the Gulf of Aqaba. However, HMC content in the Gulf of Aqaba is relatively higher than the Arabian Gulf. Also, trace amounts of iron minerals, such as siderite and hematite and also clay minerals have been observed in almost all of the samples.

AGE AND ISOTOPIC COMPOSITION

Determining the age of the studied beachrocks is important for explaining the preservation conditions on the beach at the time of beachrock formation and the palaeogeographic location (Spurgeon et al., 2003). However, using whole-rock samples will give only an approximation because we measured a mixture of carbonate particles and cement. Therefore, the data must be interpreted carefully.

RADIOCARBON DATING

Radiocarbon (^{14}C) dating was used on four whole-rock samples, two from the Arabian Gulf and two from the Gulf of Aqaba. This analysis was carried out in the Scottish Universities Environmental Research Centre (SUERC), University of Glasgow. The beachrocks from the Arabian Gulf yielded ages of 2300 and 660 yr cal BP, while the Gulf of Aqaba beachrock ages are 5500 and 2800 yr cal BP (Table 2).

CARBON AND OXYGEN ISOTOPES

The $\delta^{18}O_{VPDB}$ values of beachrocks in the Arabian Gulf range from 2.6 to 4.4‰, whereas beachrocks from the Gulf of Aqaba range from 1.2 to 1.5‰ (Table 3). $\delta^{13}C_{VPDB}$ values of the Arabian Gulf range from 3.2 to 5.9‰ and from 3.8 to 4.6‰ in the Gulf of Aqaba beachrocks (Table 3). This paper gives $\delta^{18}O_{SMOW}$ values in both areas, where in both the Arabian Gulf and the Gulf of Aqaba the isotopic value of seawater is 1.7 ± 0.2‰ (Table 3; Cooke and Rohling, 2003).

DISCUSSION

The high amounts of terrigenous fragments, including plutonic, metamorphic and volcanic rock fragments, in the Gulf of Aqaba beachrocks most probably were derived from the adjacent Precambrian basement which is nearby the study area and became a primary source for the beachrock components (Holail et al., 2004). Siliciclastic grain supply might also have re-

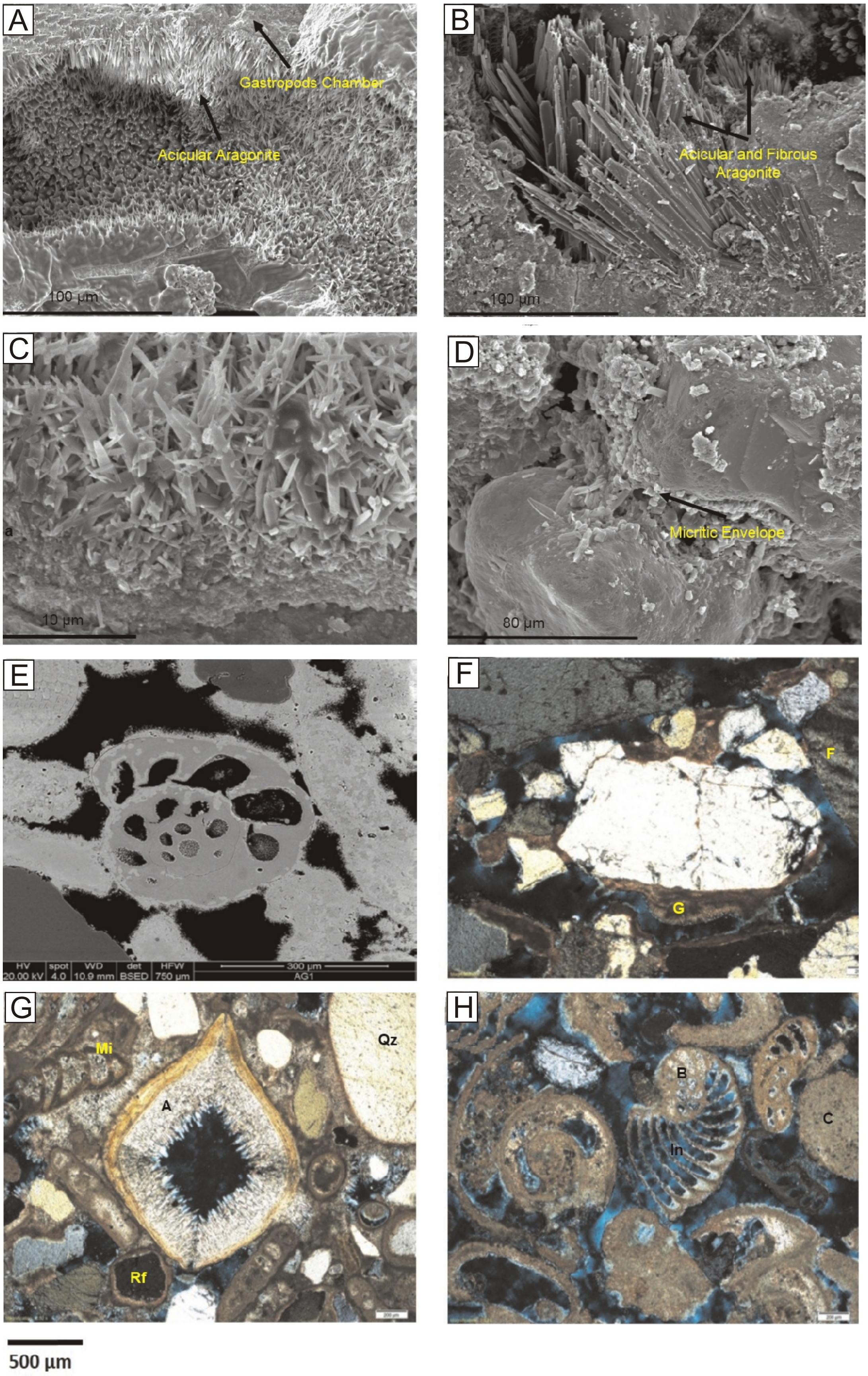

Fig. 3A–C – SEM micrograph showing acicular aragonite cements coating a skeletal grain (gastropod chamber) and non-skeletal grain; D – micritic envelope coating the grain; E – BSEM image showing pore bridge cements by HMC and also intragranular porosity within the mollusc chamber; F – thin section micrograph showing micritic gravitational cement in a Gulf of Aqaba beachrock; G – thin section micrograph showing acicular aragonite cement inside bioclast chamber in an Arabian Gulf beachrock; H – thin section micrograph showing various foraminifers in an Arabian Gulf beachrock

A – acicular aragonite cement, B – bioclast), C – calcite, F – feldspar, G – gravitational micritic cement, In – intragranular porosity, Mi – micrite envelope, Qz – quartz, Rf – rock fragment

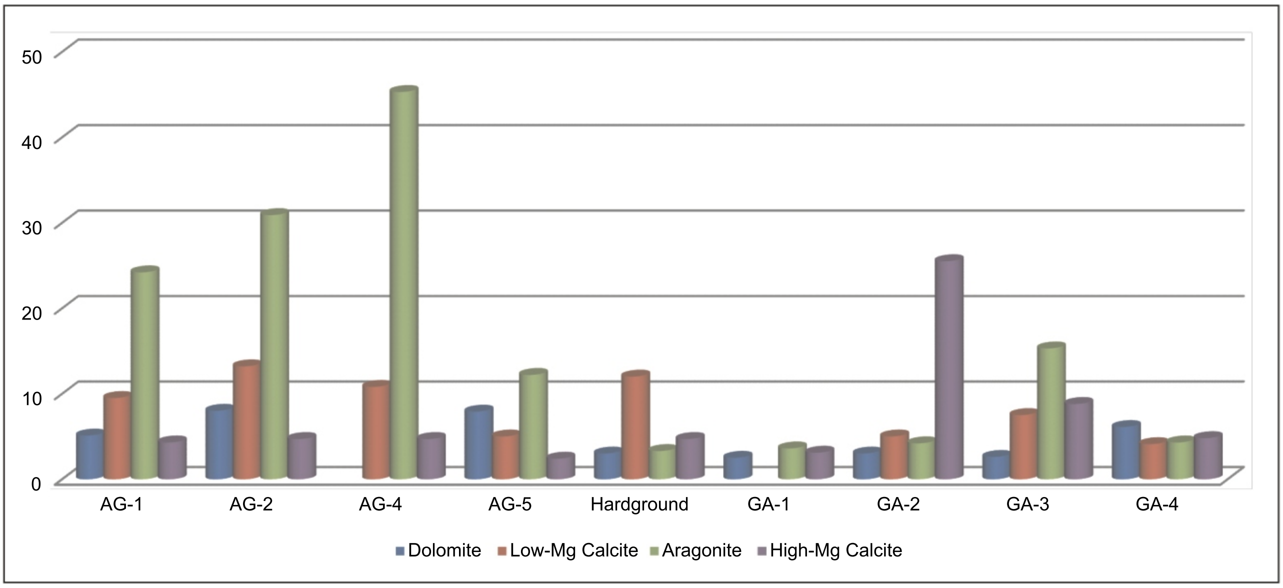

Fig. 4. Amounts of various types of cement including aragonite, HMC, LMC and dolomite in both gulfs, seen as XRD-analyses

Table 2

Beachrock radiocarbon age dating analyses from both areas using bulk carbon

Sample code	Lab code	Material dated	^{14}C year BP (Measured age)	^{14}C year BP (Conventional age)	Calibrated age year BP (2 sigma)
AG-2	SUERC-37789	bulk carbonate	655 ± 30	960 ± 30	660–575
GA-1	SUERC-37790	bulk carbonate	5075 ± 30	5320 ± 30	5500–5350
GA-3	SUERC-37791	bulk carbonate	2745 ± 30	3040 ± 30	2920–2800
Hardground	SUERC-37792	bulk carbonate	2185 ± 30	2430 ± 30	2300–2150

Calibration of samples based on calibration database information (MARINE09 from INTCAL09; Reimer et al., 2009; Erginal et al., 2013)

Table 3

Beachrock isotopic and radiocarbon age dating analysis from both areas; also, shown are stable oxygen values of the seawater from both gulfs (Cooke and Rohling, 2003)

Beach rock of the	Sample ID	$^{13}C_{VPDB}$ [‰]	$^{18}O_{VPDB}$ [‰]	$^{18}O_{SMOW}$ [‰]
Arabian Gulf	AG-1	5.83	3.92	1.7 ± 0.2
	AG-2	5.74	3.97	
	AG-4	5.90	4.40	
	AG-5	3.22	2.65	
	HG (Hardground)	3.72	3.61	
Gulf of Aqaba	GA-1	4.64	1.50	1.5 ± 0.2
	GA-2	3.93	1.31	
	GA-3	3.96	1.49	
	GA-4	3.83	1.16	

sulted from sea cliff erosion and redistribution of grains of sand size along the beach by strong long-shore currents. Marine skeletal and non-skeletal grains reworked from the adjacent carbonate platform by wave, storm or tidal processes in the Arabian Gulf are also major grain components of the beachrocks.

Beachrock cementation patterns. Cementation is the most important diagenetic feature in the studied beachrocks of the Arabian Gulf and the Gulf of Aqaba. Other diagenetic features that include micritisation, mechanical compaction, grain fracturing and dissolution are less significant. The beachrocks of both gulfs have three main cement fabrics including a micritic HMC envelope, isopachous acicular aragonite, and meniscus and gravitational HMC. In spite of the variations in calcium carbonate crystal size and shape, the cementation sequences in the beachrocks of both gulfs are almost identical. The non-development of LMC as a cement mineralogy suggests that the beachrocks were deposited under fully marine influence.

The brown micritic envelopes around skeletal and non-skeletal grains represent early-stage of diagenesis and probably the micritisation of calcareous grains was mediated by microbial activity (Neumeier, 1999). The micritic envelope provided a substrate for the growth of acicular aragonite cement and facilitated nucleation of the cement mosaics on the grain surface (Holail et al., 2004; Vieira and Ros, 2006).

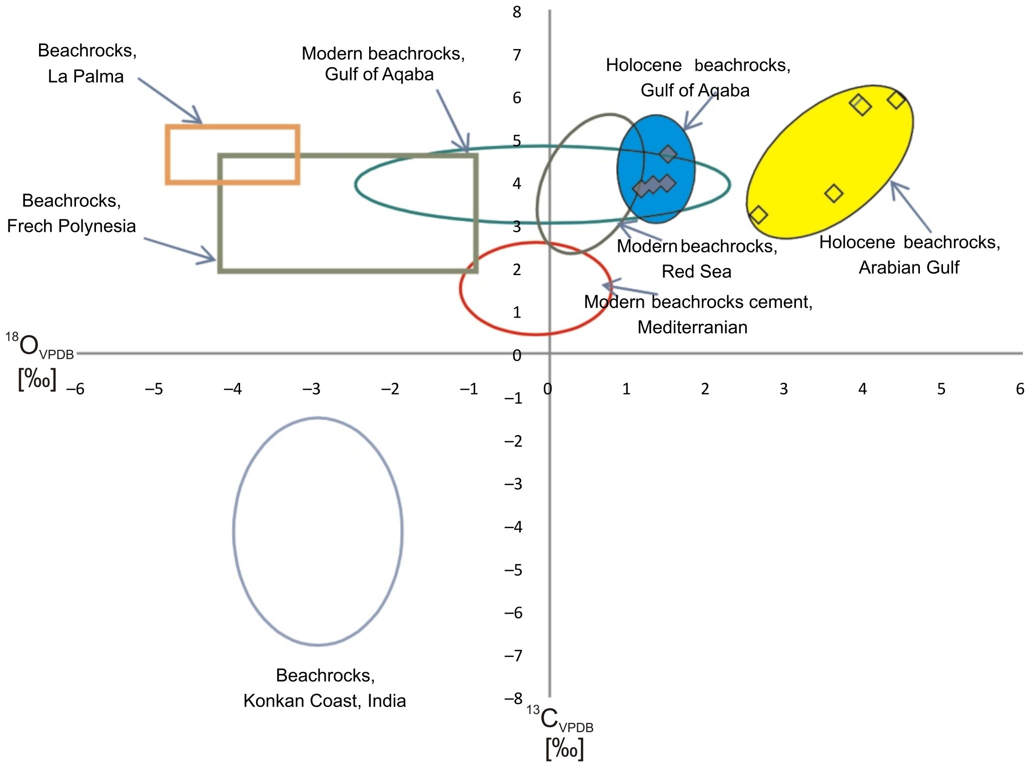

Fig. 5. Plotted groups of carbon and oxygen isotope compositions from other beachrocks for comparison with the beachrocks of the Arabian Gulf and the Gulf of Aqaba

Field of India beachrocks is from Kumar et al. (2000); fields of beachrocks of the Gulf of Aqaba, Red Sea and the Mediterranean are from Holail and Rashed (1992); field of beachrock of the Mediterranean coast is from Alexandersson (1972); field of beachrocks from French Polynesia is from Neumeier (1999) and beachrock from La Palma, Canary Islands is from Calvet et al. (2003)

Almost all the beachrocks from both gulfs are mainly composed of an isopachous radial acicular aragonite cement that covers, and thus postdates, the HMC micritic cement. Cementation by isopachous acicular aragonite requires large volumes of supersaturated marine pore-water to be pumped into the intertidal beach sediments (Longman, 1980; Vieira and Ros, 2006). This may have been enhanced by tidal pumping that causes rapid degassing of CO_2 and provides continual supply of marine pore water which subsequently evaporates during low tides and hence results in rapid cementation. Isopachous acicular aragonite and micritic envelope HMC, which occur in most of the studied samples in both gulfs, indicate precipitation in a marine phreatic environment where pores were constantly water-filled. The local presence of meniscus and gravitational cements in both gulfs is suggestive of minor influence of vadose cementation (Thorstenson et al., 1972; Meyers, 1987).

^{18}O and ^{13}C stable isotopes. The isotopic values of the studied beachrock samples in both gulfs are compared with isotopic values from beachrocks in other areas (Fig. 5). $^{18}O_{VPDB}$ and $^{13}C_{VPDB}$ values of beachrocks from the Gulf of Aqaba fall within the range of modern beachrock in the Red Sea (Holail and Rashed, 1992). The Arabian Gulf beachrocks show high $^{18}O_{VPDB}$ and $^{13}C_{VPDB}$ values compared to other beachrocks (e.g., Red Sea and Mediterranean; Fig. 6). Indeed, $^{18}O_{VPDB}$ values are unexpectedly high when compared to beachrocks from other areas. In this study, the differences between coexisting aragonite and HMC contents in the beachrocks from both gulfs are responsible for the contrast in values of oxygen and carbon isotopes. The various type of cement that occur in the beachrocks may be attributed to the differences in precipitation temperatures and water composition during cementation (González and Lohmann, 1985).

High ^{18}O isotopic values (mean 3.7‰) in the Arabian Gulf beachrocks suggest that the cement was mainly precipitated in evaporative settings (Fig. 6) which increases the concentation of calcium carbonate. Two mechanisms of enrichment of calcium carbonate are possible: (1) movement of the water through semipermeable beds of clay that may allow cations of calcium carbonate to be concentrated; (2) the original seawater may have evaporated intensely if it was trapped within a closed basin or partly isolated basin (Tiab and Donaldson, 2004). Based on these mechanisms, a possible explanation is that the Arabian Gulf was a partly isolated basin system during the Holocene via the presence of the Strait of Hormuz (Musandam Peninsula) that separated the Indian Ocean and the Arabian Gulf (Al-Sharhan and Kendall, 2003). The resultant trapping of seawater led to very rapid evaporation related to a counterclockwise density current, resulting in enrichment and hence precipitation of calcium carbonate. Intense evaporation in the Arabian Gulf was also triggered by contrast salinity difference between the Indian Ocean and the Arabian Gulf (Al-Sharhan and Kendall, 2003; Fig. 7). Especially in arid regions, evaporative areas demonstrate surface water ^{18}O enrichment (Cooke and Rohling, 2003). Other supporting evidence is the absence of skeletal structures within the cements, suggesting that the Arabian Gulf beachrock cementation was most probably caused by

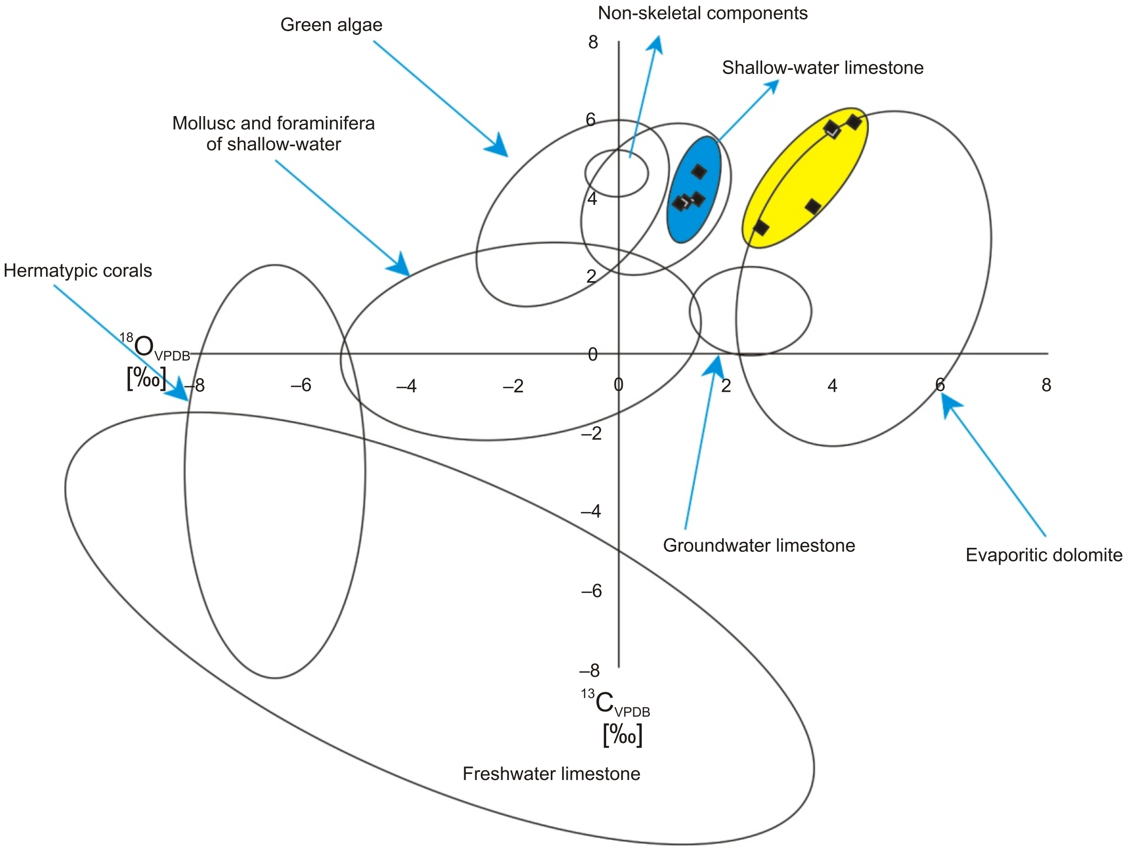

Fig. 6. Carbon and oxygen isotope plot for beachrock samples from this study (yellow circle is for the Arabian Gulf and blue circle is for the Gulf of Aqaba)

See Table 2 for analyses; stable isotope characteristics of Quaternary carbonate sediments are from Milliman (1974)

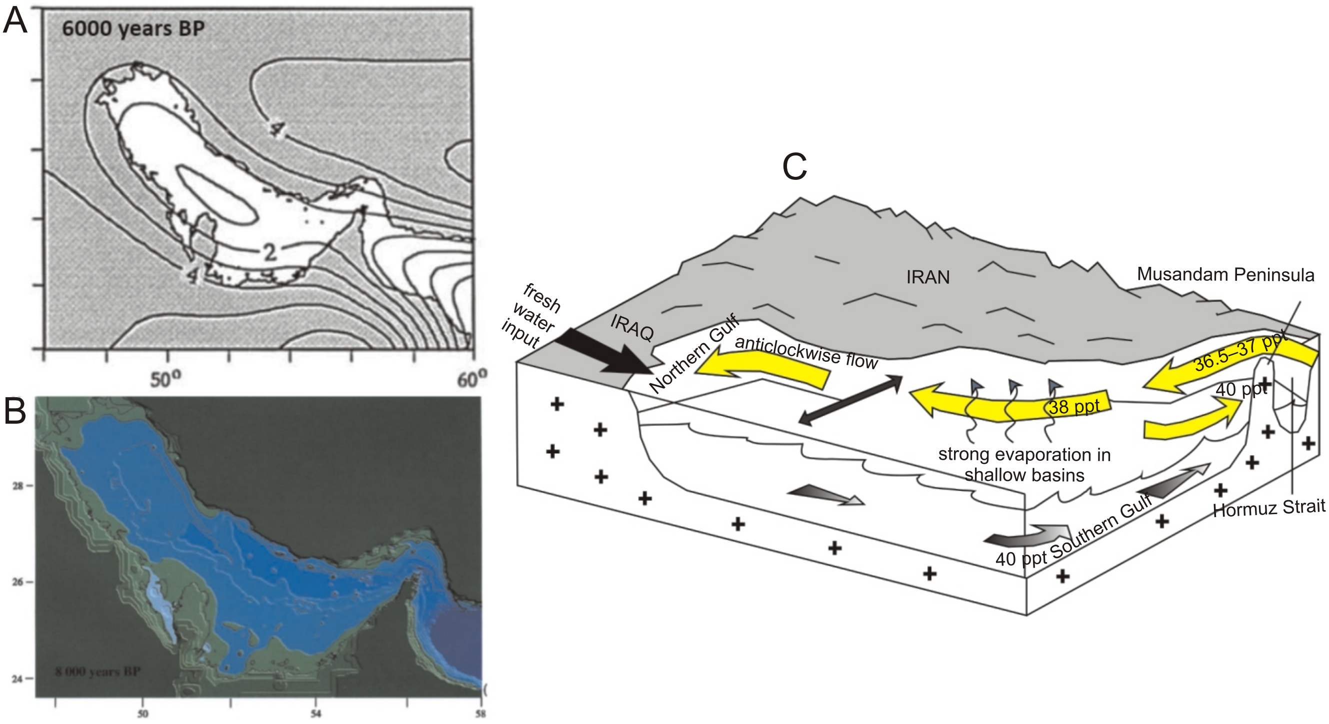

Fig. 7A – total sea level change in the Arabian Gulf at 6000 year BP; B – palaeoshoreline reconstructions of the Arabian Gulf at 8000 year BP (Lambeck, 1996); C – Arabian Gulf counter-clockwise circulation patterns driven by density currents because of the salinity difference with the Indian Ocean and strong evaporation in the shallow basin (near the shoreline; after Al-Sharhan and Kendall, 2003)

the evaporation of entrapped seawater in this hot arid climatic area (Vieira and Ros, 2006).

CONCLUSIONS

Beachrocks developed in the Arabian Gulf and the Gulf of Aqaba reflect a variety of cementation mechanisms. The present work shows that:

1. The beachrocks of the Arabian Gulf consist dominantly of carbonate grains (skeletal and non-skeletal grains), whereas the beachrocks of the Gulf of Aqaba are dominated by terrigenous siliciclastic grains.

2. Radiocarbon dating of beachrock samples from the Arabian Gulf yielded ages of 2300 and 660 yr cal BP whereas the Gulf of Aqaba samples gave ages of 5500 and 2800 yr cal BP.

3. Stable isotope studies from both gulfs gave oxygen isotope values that range from 2.6 to 4.4‰, for the Arabian Gulf whereas the Gulf of Aqaba values range from 1.2 to 1.5‰, while carbon isotopic values range from 3.2 to 5.9‰ for the Arabian Gulf, whereas the Gulf of Aqaba values range from 3.8 to 4.6‰.

4. The Arabian Gulf was located in a closed basin system that trapped seawater and which underwent rapid evaporation, resulting in enhanced precipitation of calcium carbonate that in turn resulted in high $^{18}O_{VPDB}$ values.

5. The values of $^{18}O_{VPDB}$ and $^{13}C_{VPDB}$ signatures of both beachrock types indicate marine origin and show isopachous textural habits, suggesting cementation in the shallow-marine phreatic zone.

6. Possible factors explaining the diversity of oxygen isotope and carbon isotope values measured in the studied beachrocks could be: (1) the palaeosalinity of the seawater in the Gulf of Aqaba and the Arabian Gulf; (2) the palaeotemperature of the seawater in the intertidal zone in the Gulf of Aqaba and the Arabian Gulf; (3) the influence of meteoric water.

Acknowledgments. The British Council provided funding for Dr. K. Al-Ramadan to pursue a postdoctoral summer program at Leeds University. King Fahd University of Petroleum and Minerals provided their additional funding and support. We acknowledge also constructive reviews from A.E. Erginal, M. Vieira, S.K Donovan, A. Strasser and T.M Peryt that improved this paper.

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