High-resolution facies analysis of a coastal sabkha in the eastern Gulf of Salwa (Qatar): A spatio-temporal reconstruction

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ABSTRACT

Sabkhas are key landforms along the southern coast of the Arabian Gulf and represent modern analogues for depositional and diagenetic processes controlling properties and quality of ancient hydrocarbon-bearing carbonates. While previous investigations of coastal sabkhas in Qatar have mainly focused on dolomitization processes, presented here is one of the first studies reconstructing facies changes and coastal formation in great detail. In the sabkha of Al-Kharayej (Gulf of Salwa), fifteen different facies types were distinguished based on twelve sediment cores, two trenches, as well as grain-size distribution, X-ray powder diffraction, thin section and microfossil analyses. Age estimates were based on seventy-eight 14C-AMS and optically stimulated luminescence data. The sabkha parasequence comprises pre-transgressive dune sands, a thin, transgressive layer of reworked dune material, a mid-energy open-coast to open-lagoon facies, a low-energy lagoon facies, saline lake facies (salina: swallow-tail gypsum and gypsum mush) and the supratidal sabkha characterized by diagenetic overprinting (buckled gypsum crusts and halite crust). Transgressive marine flooding created open-coast to open-lagoon sedimentation after ca 7000 cal yr BP, followed by initial spit formation at the northern sabkha end at the beginning of the relative sea-level highstand (6000 cal yr BP). This main outer spit prograded southward and a more narrow, low-energy spit, diverted landward, closing a small lagoon in the northern sabkha 4500 to 4000 cal yr BP. The falling relative sea-level and longshore drift intensified the southward extension and widening of the main spit, and the main lagoon became more shallow. At 2000 to 1500 cal yr BP, the outer spit had almost closed the main lagoon, leading to salina and, finally, sabkha conditions. It is shown how specific local conditions (coastline orientation; wind, wave, tidal energy, longshore drift; depositional relief; sediment sources) created a spit-controlled sabkha that is genetically distinct from the classical model of shore-perpendicular accumulation of coarser sediment during high tides or storms.

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INTRODUCTION

The term ‘sabkha’ is the Arabic expression for salt flat and includes all types of coastal and inland salt flats in arid environments prone to varying frequency and duration of inundation. Evaporite deposition prevails, either within the sediment or at the surface, in combination with clays, silts and sands. The salinity of groundwater in sabkhas may reach up to 600 g L\(^{-1}\), where mostly Na\(^+\) and Mg\(^{2+}\) as ions, and Cl\(^-\) and [SO\(_4\)]\(^2-\) result in the precipitation of gypsum and anhydrites (e.g. Alsharhan & Kendall, 2003; Al-Farraj, 2005; Al-Jaloud & Hussain, 2006). Sabkhas have extremely flat, salt-encrusted or gypsum-encrusted surfaces with elevation controlled by the top of the groundwater capillary fringe (Warren et al., 1985). They are very common landforms along the protected southern shores of the Arabian Gulf (Evans et al., 1969; Taylor & Illing, 1969; Barth, 1998; Al-Farraj, 2005; Alsharhan & Kendall, 2011; Evans, 2011; Strohmenger et al., 2011; Billeaud et al., 2014; Whitaker et al., 2014; Strohmenger & Jameson, 2015, 2018; Brauchli et al., 2016).

The common model for coastal sabkhas of the southern Arabian Gulf implies that they are continuously fed by highly saline seawater replacing evaporative losses in the supratidal through a hydraulic gradient, i.e. ‘evaporite pumping’ (Hsu & Siegenthaler, 1969) and, in many cases, gravitational replacement of groundwater by seawater during highest tides (Butler, 1969; McKenzie et al., 1980; Barth, 1998). In the Abu Dhabi sabkhas, it has also been shown that the main source of water and solutes may derive from continental groundwater (Wood et al., 2002). Sabkhas may prograde into lagoons forming behind barrier islands, as along the Abu Dhabi coast (Alsharhan & Kendall, 2011; Strohmenger et al., 2011). However, the initial formation of sabkhas can also be related to longshore dynamics in prograding coastal settings, where spit formation and high sediment input lead to the formation of a gradually closing lagoon, which at some point is cut off from the sea, becoming a hypersaline salina (saline lake), later overprinted by sabkha-type interstitial evaporite deposition and surface crust formation (Purser, 1985; Homewood et al., 2007; Mettraux et al., 2011).

While previous investigations of coastal sabkhas of Qatar have mainly focused on dolomitization processes (e.g. Illing & Taylor, 1993; Whitaker et al., 2014; Shalev et al., 2021), this paper presents one of the first studies along the Qatari coast aiming at deciphering facies changes and coastal formation processes through time in detail. The studied record reflects environmental changes from a pre-Holocene to early Holocene terrestrial environment to shallow marine flooding during the mid-Holocene relative sea-level (RSL) highstand. This was followed by the closure of the lagoon triggering the formation of a salina and, finally, a coastal sabkha. The coastal sabkha of Al-Kharayej was chosen, as it represents the widest and best developed example along the eastern part of the shallow Gulf of Salwa.

Present day arid-climate coastal systems, like those of Qatar, provide analogues for depositional and diagenetic processes that control the quality of ancient reservoirs. Many major reservoirs in Qatar and the Middle East (for example, Permian-Triassic Khuff and Jurassic Arab formations) formed under conditions that are remarkably similar to those shaping the Qatari coastline today (e.g. Jameson et al., 2009; Strohmenger & Jameson, 2015).

STUDY AREA

The Qatar peninsula represents an anticlinal structure of uplifted Tertiary limestones, dolomites, marls, chalks and shales protruding into the southern Arabian Gulf (Fig. 1). Sedimentation started in a shallow-marine shelf environment during the Palaeocene. These thick sequences are overlain by Lower and Middle Eocene carbonates (Dammam Formation), today covering 80% of Qatar’s surface. They are intercalated by evaporites and were also deposited in shallow water, although clays within the Upper Dammam Formation indicate gradual subsidence and greater depths. Tectonic uplift and folding since the end of the Middle Eocene caused the emergence of Qatar, resulting in continental conditions and a lack of preserved sediments from the Upper Eocene and Oligocene (e.g. Al-Yousef,
Recently, Rivers & Larson (2018) and Rivers et al. (2019a) provided evidence for high-angle faulting underlying the roughly north–south-trending dominant structural landform of the Dukhan ‘anticline’, which, therefore, has been reinterpreted to be a reactivated graben system.

Miocene sedimentary rocks are mainly found in southern Qatar, represented by the shallow marine Dam and continental Hofuf formations. Quaternary deposits and landforms mainly comprise aeolian sand as sheets or barchan dunes (Embabi & Ashour, 1993; Engel et al., 2018), silt to coarser-grained alluvium covering inland karst depressions (riyad) (Engel et al., 2020), mixed siliciclastic–carbonate inland and coastal sabkhas (e.g. Al-Yousef, 2003; Billeaud et al., 2014; Whitaker et al., 2014; Strohmenger & Jameson, 2015, 2018), as well as skeletal beach sands (Shinn, 1973a; Strohmenger & Jameson, 2015; Parker 2003). The Arabian Gulf is a semi-enclosed, shallow sea with an average depth of 35 m (Fig. 1A). During the Last Glacial Maximum (LGM), global sea-level was about 120 to 130 m lower than today (Sarnthein, 1972; Kassler, 1973; Lambeck, 1996; Lambeck et al., 2014) and the Arabian Gulf was dry until 14 000 years BP, with an ancient Shatt Al-Arab river feeding two separate freshwater lakes (Lambeck, 1996). After flooding, current sea-level was reached ca 7000 to 6500 years ago (Lambeck, 1996; Engel & Brückner, 2014; Strohmenger & Jameson, 2015; Parker 2003).
et al., 2020). A RSL highstand of at least 2 m at around 6000 to 4500 years ago is indicated by stranded beach ridges, tidal channels and elevated sabkha deposits, for example, along the coastlines of Qatar, the United Arab Emirates (UAE) and Saudi Arabia (Strohmenger et al., 2011; Engel & Brückner, 2014; Strohmenger & Jameson, 2018; Parker et al., 2020). Regression since then induced shoreline migration of up to several kilometres in Qatar, for which, however, detailed, field-based spatio-temporal data are scarce (Cuttler & Al-Naimi, 2013; Billeaud et al., 2014; Engel & Brückner, 2014; Strohmenger & Jameson, 2018).

The study site at Al-Kharayej protrudes into the Gulf of Salwa (Fig. 2), which is a very shallow extension of the Arabian Gulf, 110 km long and only 11 km wide at its southern end (Fig. 1A). It results from Quaternary tectonic subsidence (Kassler, 1973). The water depth is mostly <20 m (Fig. 1A). The tidal range is 30 cm for Dukhan, north-east Gulf of Salwa (State of Qatar, 2009), and water temperatures range between 20 to 35°C. The salinity increases

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**Fig. 2.** Overview of the sabkha of Al-Kharayej, south-west Qatar, with location of sediment cores, deep wells, trenches and surface age dating sites with calibrated ¹⁴C data (cal yr BP). The black frame around T2 indicates the map location of Fig. 12. White lines indicate the north–south (Fig. 3) and west–east (Fig. 4) transects. L-M Mio, Lower to Middle Miocene; Mio/Plio, Miocene/Pliocene. Satellite image: WorldView 2 from 2011; geological map based on Seltrust Engineering Ltd (1980).
Fig. 3. North–south transect through the sabkha of Al-Kharayej (location in Fig. 2) showing facies distribution and calibrated age data (Tables S1 and S3). Sedimentary and microfossil data that led to the differentiation of facies are presented in Figs 5 to 7, 9 and 11).
towards the southern end (Sugden, 1963), ranging between 50 to 60 psu (Rivers et al., 2019b), and partially up to 70 psu (Purser & Seibold, 1973; Sheppard et al., 2010). The dominant regional Shamal wind system operating in a NNW–SSE direction (Rao et al., 2001; Engel et al., 2018) drives a moderate southward longshore drift at both sides of the Gulf of Salwa (Chao et al., 1992).

**METHODS**

Ten vibracores up to a length of 8 m (AZ-W1 to AZ-W5; AZ-W8 to AZ-W12) were taken across the entire sabkha; they were documented and sampled in the field. Two wells with a diameter of 10 cm, up to 20.5 m deep, were drilled (AZ-W6 and AZ-W7) by Gulf Laboratories Co., Doha, Qatar, using a truck-mounted drill rig. Furthermore, two trench profiles were analyzed. All sampling sites were located using a digital global navigation satellite system (DGNSS).

The reconstruction of sedimentary environments and processes is mainly based on grain size (laser diffraction; high-speed camera), X-ray powder diffraction (XRD), thin section and microfossil analyses (foraminifera, ostracods). Grain-size data were analyzed with univariate statistical measures using GRADISTAT (Blott & Pye, 2001), and for data from cores AZ-W1 to AZ-W5 by end-member modelling using the R package EMMA-geo (Dietze & Dietze, 2019). The XRD and microfossil data were analyzed qualitatively and by principal component analysis (PCA) (Past 3.11 software; Hammer et al., 2001). Age data were derived from 78 14C-AMS and optically

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**Fig. 4.** West–east transect through the central part of the sabkha of Al-Kharayej (location in Fig. 2) showing facies distribution and calibrated age data (Tables S1 and S3). A legend to the core logs can be found in Figs 3 and 5. Sedimentary and microfossil data that led to the differentiation of facies are presented in Figs 5 to 7, 9 and 11.
## Table 1: Summary of the facies model

| Facies | Lithology | Grain size | Sedimentary environment | Microfossils | Bedding | Hardground | Photographic documentation |
|--------|-----------|------------|--------------------------|--------------|---------|------------|---------------------------|
| A Mudstone/wackestone: | Partly cemented crust at the surface (backed by lenticular gypsum on top, salt polygons in the centre) | Fine to medium, medium to poorly sorted | Recent coastal sabkha, supratidal, diagenetic | Few poorly preserved cerithid shells and indeterminable mollusc fragments | – | – | See also the stratigraphic profiles and proxy data (Figs 5, 7, 9, 11 and 13), thin section photographs (Fig. 6) and the photographic documentation from the field (Figs 8, 10, S2, S5 and S6) for details on facies characteristics. |
| B Prismatic, twinned gypsum, minor occurrence of halite, aragonite, quartz | Poorly sorted | Saline lake, shallow subtidal to intertidal | Abundance of foraminifera (P. planatus, P. pertusus) and ostracods (Xestoleberis spp.) | – | Non-bedded to bioturbated | – |
| Cl Mudstone/sandstone: | Poorly sorted | Low-energy, protected lagoon, carbonate-dominated | Many well-preserved mollusc shells, bivalves in living position (e.g. \textit{P. planatus}) | Rich in foraminifera (\textit{P. planatus}, \textit{P. pertusus}, \textit{Ammonia tepida}, \textit{Elphidium spp.}) and ostracods (\textit{Xestoleberis spp.}, \textit{Cyprideis torosa}, \textit{Loxoconcha spp.}, \textit{Keijella spp.}, \textit{Hemicytheridea spp.}) | Non-bedded to bioturbated | – |
| D1 Medium to coarse-grained skeletal-peloidal packstone: | Poorly sorted | Intercalated hardgrounds or hardground clasts | Many mollusc shells, some even articulated, large shell fragments | Rich in foraminifera (\textit{Q. poeyana}, \textit{P. planatus}, \textit{P. pertusus}, \textit{Ammonia tepida}, \textit{Elphidium spp.}, \textit{Cyprideis torosa}, \textit{Loxoconcha spp.}, \textit{Keijella spp.}, \textit{Hemicytheridea spp.}) | Non-bedded to bioturbated | – |

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| Facies | Lithology | Grain size | Macrofossils | Microfossils | Bedding | Hardground | Sedimentary environment |
|--------|-----------|------------|--------------|--------------|---------|------------|------------------------|
| D2     | Coarse-grained grainstone with varying amount of very coarse skeletal debris: quartz grains, often carbonate-coated | Poorly to very poorly sorted | Larger mollusc shells and fragments | Minor amounts of foraminifera (P. planatus, P. pertusus) and ostracods | Non-bedded | Intercalated hardgrounds or hardground clasts | Open lagoon/open coast, high-energy shallow subtidal |
| D3     | Fine-grained peloid–skeletal packstone: high amount of quartz grains, minor amount of clay minerals | Moderately to well sorted | Finer mollusc shells and fragments | Rich in foraminifera (Q. poeyana) and ostracods | Horizontally bedded (millimetre-scale) | Intercalated hardgrounds or hardground clasts | Low-energy, deeper subtidal |
| E1     | Sandstone: quartz grains with minor carbonate coating, minor amounts of carbonate material (fine-crystalline dolomite, peloids, coated grains, skeletal grains) | Medium, moderately to well sorted | Very few shell fragments | – | Wavy bedded to non-bedded | Intercalated hardgrounds | Early Holocene transgression facies, reworked dune |
| E2     | Sandstone: quartz grains, moderately to well-rounded, occasionally coated | Medium, well sorted | – | – | Low-angle cross-bedded to parallel bedded | – | Pre-Holocene aeolian dunes (sea-level lowstand facies) |
| F1     | Skeletal–peloid grainstone: varying amounts of quartz, partly cemented (beachrock) with fenestral structures, pelagosite-type aragonite coatings | Medium to coarse, poorly to moderately sorted | Mollusc shells and large fragments (Pinctada radiata) concentrated in particular horizons | Not studied | Low-angle, cross-bedded, inclined seaward | Cemented as beachrock in some parts | Outer beach barrier: Mid-energy to high-energy foreshore environment, intertidal |
| Facies | Lithology | Grain size | Macrofossils | Microfossils | Bedding | Hardground | Sedimentary environment |
|--------|-----------|------------|--------------|--------------|---------|------------|------------------------|
| F2     | Sandstone: dominated by quartz grains, minor occurrence of skeletal carbonate, partly cemented (beachrock) with fenestral structures | Medium to coarse, moderately to well-sorted | Some cerithid and very few large bivalve shells | Some *Peneroplis* sp. | Low-angle cross-bedded to parallel bedded | Cemented as beachrock in some parts | Protected beach and beach spit: mid-energy foreshore, intertidal |
| G      | Skeletal–peloid grainstone | Medium to coarse | Rich in mollusc shell fragments, few entire shells | Not studied | Cross-bedded, inclined landward | – | Backshore |
| H      | Very coarse skeletal–peloid grainstone: dominated by massive shells | Very coarse, very poorly sorted | Rich in large mollusc shells (e.g. *P. radiata*) and shell fragments | Not studied | Low-angle seaward inclined onlap structures | – | High-energy foreshore |
| I      | Grainstone with high amount of rounded to subrounded quartz grains | Medium to coarse, moderately to well-sorted | Few mollusc shells | Not studied | Cross-bedded to parallel bedded | – | Aeolian deposition in swales of the backshore |
| J1     | Skeletal–peloid grainstone: varying amounts of quartz grains and coarse skeletal particles (occurring in pockets) | Medium to coarse, poorly sorted | Varying amount of mollusc shells and shell fragments, mostly concentrated in pockets | Not studied | Wavy bedding | – | Mid-energy upper shoreface |
stimulated luminescence (OSL) datings. All methodological details can be found in Appendix S1.

RESULTS

In total, 15 different facies types were identified in the study area, covering a wide range of texture and porosity. These facies types can be separated into those representing the sedimentary wedge underlying the modern sabkha (A, B, C1, C2, D1, D2, D3, E1, E2) and those forming the morphological barriers (F1, F2, G, H, I, J1). Their spatial distribution is indicated based on a north–south transect (Fig. 3) and an east–west transect (Fig. 4).

Facies types of the sedimentary wedge underlying the modern sabkha

The characteristics of all facies types are summarized in Table 1. Facies A occurs on top of all cores inside the sabkha (Figs 5, 6A and 7). It is usually cemented by a buckled gypsum crust, bassanite, anhydrite and, in the centre, halite. At the landward margins, this crust only very thinly covers the sand-dominated Facies C2 with articulated bivalves in living position indicating ongoing deflation. In the centre, where Facies A reaches a thickness of up to a few decimetres, surface structures comprise polygons (Fig. 8A), sometimes associated with characteristic tepee structures, and circular mounds created by

Fig. 5. Sediment core AZ-W5 (location in Fig. 2) with core log and data of particle-size distribution, end-member scores and mineralogy. Colours of end-member scores refer to the distribution of the four end members deciphered from the entire dataset AZ-W1 to AZ-W5 as shown in Fig. S3. The upper 40 cm of the stratigraphy are shown in detail on Fig. 8D.
insular growth of large gypsum crystals (Fig. 8B and C). In the deep well AZ-W6, Facies A was also found at the base (Figs 9 and S2).

Facies B only occurs in the innermost part of the sabkha around core AZ-W5, where it underlies Facies A. It consists of a basal layer of almost pure millimetre-scale to centimetre-scale gypsum mush, partly cemented, confined by a massive layer of prismatic, twinned gypsum (swallow-tail gypsum), *ca* 10 cm in thickness (Figs 5 to 8D). The XRD reflects minor occurrences of halite, aragonite and quartz (Fig. 5).

Facies C1 (Figs 6D and 7) has a patchy occurrence, always underlying Facies A or B (or F2 in case of the inner barrier), with some bivalves of *Hiatula mirbahensis* in living position and exposed at the surface by deflation in the north near AZ-W1 (Fig. 10). C1 appears non-bedded and bioturbated, indicated by vertical burrows well-preserved in the weakly consolidated carbonate near AZ-W4 (Fig. 10A and B). Facies C2 (Figs 6E and 7) occurs throughout most of the sabkha, in a thickness of up to 2 m close to the surface. The particle-size distribution is fully represented by end member 1, the distribution of which is very broad, peaking at 100 µm (Fig. S3). Associations of foraminifera and ostracods are both more abundant and diverse compared to C1 (Fig. 11).

Facies D1 is the most common facies inside the sabkha, found at a depth of *ca* 1 to 4 m below the present sea-level (Figs 6F, 6G and 7). D1 is poorly sorted, best represented by the coarsest end member 4 with a main peak near 900 µm, a broad distribution and two smaller peaks close to 100 µm and <1 µm (Figs 5 and S3). Facies D2 (Figs 6L, 6H and 7) is only found in the deep core AZ-W6 from the outer barrier at a depth of 1010 to 700 cm b.s. (below surface) (Fig. 9). Facies D3 (Figs 6J and 7) is also only found in AZ-W6, where it occurs below D2 and alternates with D1 (Fig. 9).

Facies E1 (Fig 6K and 7) is typically thin and found in between D1 and E2. It is not identified in all cores. Minor amounts of carbonate comprise fine-crystalline rhombs of dolomite (Fig. S4). The particle-size distribution is best represented by unimodal end member 3 peaking in medium to coarse sand (Figs 5 and S3). Facies E2 (Figs 6L and 7) either underlies D1 or E1. It resembles E1, but lacks carbonate, apart from very few large but poorly preserved foraminiferal tests of *P. planatus* documented in the field, and occasional grain coatings. The particle-size distribution is almost equally represented by end members 2 and 3, the former showing two minor peaks in the clay category and at the silt/sand boundary in addition to the main one, which is shifted towards the fine/medium sand boundary (Figs 5 and S3). E2 represents the bottom facies in every core (Figs 3 and 4).

**Facies types of the barriers**

The sabkha comprises two different types of barriers with six different documented facies types (Table 1). The main barrier is up to 1 km wide, up to 2.5 m higher than the sabkha floor, and separates the sabkha from the Gulf of Salwa (Figs 2, 12 and 13). Another narrow barrier, only 250 m wide, up to 2 m higher than the sabkha floor, and with a snaky outline runs across the northern part of the sabkha from the outer barrier inland in a south-eastern direction, thereby constantly losing width (Figs 2 and 14).

Facies F1 mostly comprises the top part of the outer beach ridge (Figs 4 and 13) and shows onlapping structures and low-angle cross-bedding with seaward inclination. Facies F2 makes up most of the narrow, snaky barrier (Figs 2 and 14). The particle-size distribution peaks in the coarse-sand category; minor peaks at the upper end are caused by single large shells (Fig. 15). Some isolated patches, where the sandstone is cemented (for example, AZ-W2 in Fig. 3) and preserves fenestral structures (Fig. 15), stand out for up to 1 m above the non-cemented barrier (for example, AZ-W3 in Fig. 3 or Fig. 15), indicating post-depositional deflation.

Facies G is only observed in AZ-T2, where it occurs in two patches on top of the sequence (Fig. 13). Facies H occurs as lenses or thin onlapping strata mostly intercalating with Facies F1 in AZ-T2, where it may fill small channel-like structures (Fig. 13). Facies I only occurs inside small channel structures where it overlies Facies H. Facies J1 generally underlies F1. Both facies are similar, whereas J1 shows distinct wavy bedding (Fig. 13).

**Age data**

*Radiocarbon data from sediment cores and surface samples*

Radiocarbon dating of bulk carbonate sediment from basal Facies E2, overlying the Dammam limestone, reveals the oldest, Pleistocene ages in cores AZ-W1 (27 475 to 27 180 cal yr BP), AZ-W3 (22 490 to 22 275 cal yr BP), AZ-W4 (39 719 to 38 511 cal yr BP) and AZ-W5 (38 529 to 36 979 cal yr BP). A cerithid shell found in Facies E2 in core AZ-W7 (9.25 m b.s.), however, was dated to 5381 to 4963 cal yr BP, while the
uppermost dating of Facies E1/E2 right below the contact with Facies D1 is 8332 to 8134 cal yr BP (microbial mat in AZ-W4; Figs 3 and S6). Right above the contact, $^{14}$C data of Facies E1 and the lowermost part of Facies D1 range between 7917 to 7658 cal yr BP (cerithid shell; AZ-W12) and 6009 to 5702 cal yr BP (bivalve shell fragment; AZ-W5) with an apparent trend towards younger ages inland, where the contact between Facies E1/E2 and Facies D1 rises (Fig. 4).

Facies D1, present in all cores, accumulated over several millennia. Its upper part shows constantly younger ages towards the south reaching from 5551 to 5276 cal yr BP in the north (bivalve shell fragment in AZ-W1; cerithid shells: 5540 to 5235 cal yr BP and 6612 to 6312 cal yr BP), to 3728 to 3397 cal yr BP in the central part of the sabkha (bivalve shell fragment; AZ-W5) and 1869 to 1565 cal yr BP in the southernmost core AZ-W12 (cerithid shell; parallel dating of plant remains: 2355 to 2184 cal yr BP). Facies D1 is overlain by Facies C1 (central part of the sabkha) and C2 (northern and southern ends of the sabkha), respectively, which are dated to 5585 to 5310 cal yr BP in the north (AZ-W3; cerithid shell), 2511 to 2139 cal yr BP in the centre (AZ-W5;
articulated bivalve shell), and 1794 to 1479 cal yr BP in the south (AZ-W12; cerithid shell). A comparison between AZ-W5 and AZ-W9, where the upper part of Facies C1 is dated to 3711 to 3390 cal yr BP (cerithid shell), shows that its accumulation stopped significantly earlier at the landward margin of the sabkha. Facies C is in most of the cores overlain by Facies B and A, for which no ages could be obtained, apart from surface dates shown in Fig. 2.

The snaky barrier (Facies F2) shows a radiocarbon date of 5886 to 5611 cal yr BP (AZ-W3; gastropod shell). The seaward barrier (mainly Facies F1) shows a broad distribution of $^{14}$C data: In the wide, central section, ages of 6443 to 6191 cal yr BP, 5826 to 5516 cal yr BP (AZ-W6; cerithid shells) and 5238 to 4856 cal yr BP (AZ-W7; cerithid shell) were obtained from the central and landward part of the barrier; some of them are not in stratigraphic order. The ages from the seaward part of the barrier obtained in the north are younger, ranging from 3609 to 3316 cal yr BP at the landward edge of AZ-T2 to 1217 to 938 cal yr BP at its seaward end. A cerithid surface from cemented surface beachrock at the narrow palaeo-spit inland of the main barrier in the central part of the sabkha provides an age of 3755 to 3417 cal yr BP (AZ-Spit 1; Fig. 2), whereas a cerithid shell from the active beach in the south gives a modern age. In general, there is a stark contrast between surface data from the very northern, sandy landward margin of the sabkha (5534 to 5209 cal yr BP and 5440 to 5061 cal yr BP at AZ-OSL-7; articulated Hiatula mirbahensis and cerithid shells) and those from the southern counterpart ranging from 3387 to 3065 cal yr BP (AZ-6-12; cerithid shell) to 1036 to 752 cal yr BP (AZ-3-12; cerithid shell).

The age distributions from the vibracores, including adjacent surface data (Fig. 2), show no inconsistencies. Where different material is dated from the same stratigraphic depth, the $2\sigma$ age spans either overlap (AZ-W1), show moderate or, as in one case only, extreme discrepancy (AZ-W12). Radiocarbon data from the deeper wells AZ-W6 and AZ-W7, however, almost entirely fall into the range of 6000 to 5000 years ago and show numerous inconsistencies (Fig. 4).

Optically stimulated luminescence (OSL) ages A comparably large scatter of equivalent-dose ($D_e$) distributions is observed in all OSL samples. However, while AZ-T1 and AZ-W7 show normally
distributed $D_2$ with moderate over-dispersion values of 17 to 63%, the AZ-T2 samples are characterized by over-dispersion values of 84 to 100% and right-skewed dose distributions (Fig. S1).

The OSL age estimate from Facies E2 at the base of AZ-W7 (Figs 4 and S5) gives a latest Pleistocene, pre-transgressive age of 12060 ± 910 years. Samples of the narrow, snaky barrier, for which the

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**Fig. 7.** Thin sections, core sections and grain-size distribution of the sabkha facies types. Details on thin sections can be found in Fig. 6. The red frame on the core sections indicates where samples for thin sections and grain-size analysis were taken. Grain-size diagrams: x axis = grain size (µm), y axis = amount of grains in specific class (vol. %). Red scale bar = 1 mm, yellow scale bar = 0.5 mm.
central age model (CAM; Galbraith et al., 1999) was chosen, are dated to 7682 ± 884 years and 5414 ± 467 years (AZ-T1). At AZ-T2, ages of 1244 ± 118 years and 918 ± 229 years were obtained using the minimum age model (MAM; Galbraith et al., 1999) for the landward and seaward ends of the trench, respectively.

**DISCUSSION**

Resolving the facies architecture of the Al-Kharyej sabkha

*Facies E2: Pre-transgressive dunes*

The moderately to well-rounded quartz grains of Facies E2 underlie the transgressive wedge of the sabkha and represent the aeolian dunes of the dry, late Pleistocene Gulf of Salwa. Its characteristic unimodal grain-size distribution corresponds to modern aeolian sands of barchan dunes and surface depressions found in Qatar today (Embabi & Ashour, 1993; Engel et al., 2018, 2020) and is directly related to the drowned barchan dunes, which have been identified inside the Gulf of Salwa (Kassler, 1973; Al-Hinai et al., 1987).

*Facies E1: Reworked dune (transgression facies)*

The rounded quartz grains with minor carbonate coating and minor amounts of carbonate of Facies E1 (Fig. S6A) represent dune sand
overprinted by marine reworking during the rapid early to mid-Holocene transgression. E1 occurs in the form of a thin transition layer between the predominantly late Pleistocene dunes (E2) and the coarse-grained, mid-energy open lagoon (D1) throughout the sabkha.

Facies D1: Mid-energy open lagoon to open coast
The medium to coarse-grained skeletal–peloidal packstone, poorly sorted and with minor occurrences of coated quartz grains, indicates a higher-energy environment, i.e. a subtidal, open-lagoon environment. Its thickness of up to several metres in the entire sabkha corresponds to rapid accumulation during the RSL highstand in the southern Arabian Gulf around 6000 to 4500 years ago (Lokier et al., 2015; Strohmenger & Jameson, 2018; Parker et al., 2020; Rivers et al., 2020). In contrast to C2, Facies D1 lacks shallow, protected-lagoon ostracods of *Cyprideis torosa* and *Hemi-cytheridea*, but shows a higher diversity, which

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![Image](https://example.com/image.png)  
**Fig. 9.** Deep well AZ-W6 (location in Fig. 2) on top of the outer barrier, with core log as well as data on grain-size distribution, mineralogy and microfossil content. A legend for the core log is shown in Figs 3 and 5.
may be attributed to a decrease in terrigenous input in the deepening lagoon (Mostafawi, 2003). It is also rich in serpulids, often showing straight attachment surfaces, indicating growth on seagrass leaves (Fig. 6F). The abundant ostracod taxa of *Loxoconcha* spp. and *Xestoleberis* spp. have also been found to be dominant elsewhere in moderately restricted parts of the Gulf of Salwa (Hughes Clarke & Keij, 1973).

**Facies D2: High-energy open lagoon to open coast**

The coarse-grained sand with varying amounts of skeletal debris representing D2 is only found in deep well AZ-W7 on the outer barrier. It represents the highest-energy facies of the study area. It is very similar to Facies D1, but slightly coarser and contains a higher number of coated quartz grains, which are typical for higher-energy, outer lagoon environments of the Gulf of Salwa (Rivers et al., 2019b).

**Facies D3: Deeper subtidal**

The laminated fine-grained peloid–skeletal packstone is also only found relatively deep in AZ-W7, where it alternates with Facies D1. It likely corresponds with the rapid transgression until 7000 to 6000 years ago leading to quick flooding and water depths of several metres. Whether the alternation of D1 (coarse-grained) and D3 (fine-grained) in AZ-W7 is the result of rapid vertical fluctuations in relative sea-level, event-type, storm-wave deposition, or lateral coastal changes remains open.

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**Facies C2: Low-energy, carbonate-dominated lagoon**

Facies C2 represents a low-energy, carbonate-dominated lagoon. It is characterized by a high amount of autochthonous aragonite mud and low input of aeolian sand. In AZ-W10, the foraminiferal assemblage of the upper part of C2 is dominated by *Ammonia tepida* and *Elphidium* spp. *Ammonia* and *Elphidium* represent the only foraminiferal taxa in the very shallow (<1 m) parts of a protected, siliciclastic embayment along the Saudi Gulf coast, explained by the resistance of their tests against mechanical abrasion (cf. Arslan et al., 2016). *Ammonia tepida* is also the most common species in the mud-dominated tidal flats of Kuwait, northern Gulf (Al-Abdul-Razzaq et al., 1983). In the lower part of C2 in AZ-W10, *Quinqueloculina* spp. becomes abundant – besides *Peneroplis planatus* and *P. pertusus* – which is very common in the intertidal to deeper subtidal environments of the southern Gulf (Ahmed, 1991).

The ostracod *Hemicytheridea*, also associated with very shallow, restricted conditions of inner embayments (Al-Abdul-Razzaq et al., 1983), occurs only in C2 in significant numbers. *C. torosa* is only found in the upper part of C2, where it supports the interpretation of a shallow, sheltered and hypersaline lagoon environment according to its high abundance in similar challenging environments of Abu Dhabi (Bate, 1971; Stewart et al., 2011).

The high amount of aragonite in C2 (Fig. 11) derives from evaporation-driven salinity increase,
which in marginal-lagoon settings of Qatar may add up to 90 psu, and diagenetic aragonite precipitation in the water column. Further salinity increases following marine regression, and gradual shallowing and silting up of the lagoon under evaporation pressure then leads to gypsum and halite precipitation towards the top of the sediment column (Facies B and A) (Rivers et al., 2019b). With its hardground at around the groundwater level in AZ-W10 (Fig. 11), Facies C2 corresponds to the bioclastic or peloid/C0 skeletal packstone of the lowermost intertidal to shallow subtidal lagoon environment identified by Strohmenger et al. (2011) near Al-Qanatir (Al-Rufayq) Island and by Strohmenger et al. (2010) inside the Mussafah Channel (both Abu Dhabi). It also corresponds to the soft-pelleted, skeletal lime muds of the restricted, shallow lagoons of Sabkha Faishakh and Sabkha Hussain, north-western Qatar (Taylor & Illing, 1969; Illing & Taylor, 1993).

The separation between open-lagoon (D1) and protected low-energy lagoon (C2) facies is clearly demonstrated by the PCA of proxy data of AZ-W10 (Fig. S7). Principal component (PC) 1 explains >40% of the distribution. Based on the negative values of aragonite, which is mostly present in the low-energy lime muds (e.g. Illing & Taylor, 1993), and positive values of quartz, derived from the reworking of dunes in higher-
energy environments, PC 1 is interpreted to positively correlate with hydraulic energy, i.e. low values representing protected-lagoon conditions (C2) and high values representing higher-energy open-lagoon conditions (D1). PC 2 may positively correlate with water depth.

Facies C1: Low-energy, sand-dominated lagoon

Facies C1 represents a low-energy, sand-dominated lagoon, similar to C2, but with a significantly higher input of quartz sand. Macro- and microbenthic remains indicate a shallow and protected lagoon, still permanently connected to the Gulf of Salwa. Parts of this lagoon may have been intertidal, as *Hiatula mirbahensis* bivalves, found in living position, endure temporary exposure and usually populate such soft, fine-sandy to muddy, protected habitats along the Emirates coast (Morris & Morris, 1993; Feulner & Hornby, 2006). Likewise, *Peneroplis planatus* is abundant in the intertidal zone of the low-inclination coastlines along the southern Arabian Gulf (Al-Abdul-Razzaq et al., 1983; Ahmed, 1991; Al-Kathany et al., 2015). In Qatari waters, the genus *Peneroplis* was found in the shallowest environments (Al-Hitmi, 2000). Ostracods of the genus *Xestoleberis*, i.e. *X. rhomboidea* and *X. rotunda*, which dominate Facies C1, are also associated with soft-bottom intertidal zones of protected bays along the southern and western Gulf. They are competitive in high salinities (42 to 72.45‰) and a wide range of water temperatures (21 to 35°C) (Al-Abdul-Razzaq et al., 1982; Mostafawi, 2003). The second prominent genus, *Loxoconcha* spp., could not be determined to species level. Four species of *Loxoconcha* have been identified along the coast of the southern Arabian Gulf. They are predominantly distributed on the nearshore shelf, but also in tidal channels and protected lagoons (Bate & Gurney, 1981).

In the north, C1 formed during the mid-Holocene (AZ-W1; Fig. 3). Quartz sand dominates and indicates long-distance aeolian input by the Shamal at a time when upwind dune fields in the north-western peninsula still existed (cf. Engel et al., 2018). The occurrence of similar Facies C2 grainstone in the south (AZ-W12; Fig. 3) at a later stage during the late Holocene, when upwind sand sources had ceased (cf. Engel et al., 2018), is dominated by aragonite, testifying to only local aeolian input from the seaward barrier which, to a large part, consists of skeletal grains.

The protrusion of articulated *H. mirbahensis* and exposure of vertical burrows (Fig. 10A and B) in the northern part around AZ-W4 (Figs 2 and 3) indicate deflation driven by a gradual lowering of the capillary fringe to produce a Stokes surface (Fryberger et al., 1988), which in
Qatari sabkhas lies mostly around 0.5 m above the groundwater table (Whitaker et al., 2014). In the Asaila Basin, central-eastern Qatar, deflation is also dominant and controlled in a similar way by a lowering groundwater level and Stokes surface after the mid-Holocene RSL highstand. Ground

![Figure 13](image-url)

**Fig. 13.** Trench AZ-T2 (for location see Figs 2 and 12) showing the facies architecture of the northernmost seaward barrier. It is separated into four sections and has a gap between ca 13.5 m and 16 m from its western end (numbers in bold on top of the profile sections refer to distance in metres from the western end of the trench; those in regular font indicate the thickness of the profile in metres).
Surface lowering has been estimated to a minimum of 1.5 m, inferred from the elevation of remnant yardang-type mounds (Engel et al., 2020).

**Facies B: Saline lake/lagoon (salina)**
Facies B only occurs in the very central part of the sabkha (AZ-W5), where, in combination with the overlying supratidal sabkha deposits, it forms a regressive evaporite sequence. The prismatic gypsum mush (selenite) embedded in a soft, grey mud followed by a layer of large displacive and replacive twinned gypsum minerals of >10 cm length, indicate subaqueous formation from a highly concentrated brine in the final, shallow stages of the salina body (Warren, 1996; Strohmenger & Jameson, 2018). Extremely high surface temperatures during summer dehydrate and transform exposed parts of prismatic gypsum crystals (swallow tails) to bassanite/anhydrite (exposed, whitish parts in Fig. 8C).

**Facies A: Recent supratidal sabkha**
Gypsum-encrusted and halite-encrusted quartz grains, as well as lenticular and prismatic gypsum crystals in Facies A, combined with a buckled crust, are typical for active supratidal...
sabkha environments (e.g. Al-Yousef, 2003; Strohmenger et al., 2011; Strohmenger & Jameson, 2015). In some places, clear polygonal structures are indicative of supratidal conditions (Billeaud et al., 2014). In Facies A, a small percentage of gypsum is replaced by bassanite and anhydrite through dissolution and reprecipitation (Gunatilaka et al., 1985; Warren et al., 1985; Alsharhan & Kendall, 2003; Strohmenger et al., 2011), mostly in the capillary zone above the palaeo-groundwater table as thermalites (Wood et al., 2005; Strohmenger et al., 2010). Occasional cerithid shells and small, indeterminable bivalve shell fragments are likely introduced by strong Shamal winds from the seaward barrier, because muddy intertidal feeding grounds with microbial mats and algae cover required by the surface-grazing Cerithium sp. (cf. Stewart et al., 2011) are currently absent. Similar modern sabkha environments have been described elsewhere in Qatar, such as in Al Dakhirah (Billeaud et al., 2014) or Sawda Nathil (Strohmenger & Jameson, 2018).

Thus, the parasequence described here, starting with pre-transgressive dunes (E2), overlain by reworked dunes (E1), open lagoon (D1), protected lagoon (C1/C2), salina and sabkha deposits (Fig. 3), is quite similar to the classical sabkha sequence often found along the southern coast of the Arabian Gulf (e.g. Alsharhan & Kendall, 2003; Evans, 2011; Strohmenger et al., 2011).

**Resolving the barrier architecture**

**Facies J1: Mid-energy upper shoreface**

The skeletal–peloid grainstone of Facies J1 underlies the foreshore and represents the shallow subtidal upper shoreface (Fig. 13). The coexistence of planar and wavy or trough cross-
beds is characteristic for depositional environments right below mean low water (e.g. Reinson, 1979; Dashtgard et al., 2012).

Facies F1: Outer beach barrier, mid to high-energy foreshore environment
The peloid–skeletal grainstone of Facies F1 with very low-angle seaward inclination makes up the upper, subaerial part of the barrier separating the sabkha from the Gulf of Salwa. The cemented sections with fenestral structures (keystone vugs) indicate formation in the swash zone of the foreshore and later preservation as beachrock. It largely corresponds with the linear ridge of ‘type 1 deposit’ identified as the mid-Holocene beach associated with landward shallow-lagoon deposits at Al-Ruwais, northern Qatar (Rivers et al., 2020). Mauz et al. (2015, p. 7) link “low angle seaward-dipping tabular cross bedding and

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Fig. 16. (A) to (G) Scenarios of beach, lagoon and sabkha formation at Al-Kharayej during the Holocene based on the age data and facies model established in this study. For further information, refer to text. Numbers in (G) indicate the location of the ten vibracores. The green dots indicate the location of the trenches.
keystone vugs” in beachrock with formation from the mean tidal level to mean high-water level.

**Facies H: High-energy foreshore**
The foreshore of the outer barrier shows several onlap structures of very coarse skeletal–peloid grainstone with massive shells (Fig. 13), indicating higher-energy deposition. Interbedded with F1, they form a progradational, seaward dipping foreshore architecture with several bounding surfaces (e.g. Neal et al., 2002). The distribution of larger mollusc shells in pockets can also be observed in the modern upper foreshore environment.
**Facies G: Backshore**

In contrast to the dominant occurrence of Facies F1, small sections of the uppermost part of AZ-T2 show landward inclination. These are interpreted as supratidal backshore deposits, mostly resulting from small-scale storm overwash (cf. Davis, 1978; Schwartz, 1982). Thus, the barrier architecture as exposed in AZ-T2 corresponds to the regressive (prograding) barrier parasequence as, for instance, summarized in Reinson (1979).

**Facies I: Aeolian deposition in swales**

The quartz-dominated Facies I is only found in small backshore depressions. The moderately to well-sorted medium to coarse sand with only few shell components indicates aeolian deposition in the backshore, whereas the absence of vegetation on the barrier prevents proper foredune formation.

**Facies F2: Protected beach/spit (snaky barrier)**

Sand grains of F2 along the snaky barrier are moderately to well-rounded and show a unimodal distribution, similar to E2. However, the deposit is significantly coarser (peaking in the coarse-sand category) than the aeolian facies. Beachrock cementation, again showing fenestral structures (Fig. 15), support the interpretation of a foreshore environment, but exposed to lower energy compared to F1.

**Chronostratigraphy**

All calibrated $^{14}$C ages represent maximum ages, because *post-mortem* relocation of the dated objects can never be entirely excluded, apart from articulated shells in living position (i.e. *H. mirbahanensis*) and the thin microbial mat in AZ-W4. However, the majority of $^{14}$C data from the vibracores (AZ-W1 to AZ-W5; AZ-W8 to AZ-W12) in combination with surface samples show no inconsistencies. They are in accordance with the regional RSL history, and can be used with confidence for reconstructing sabkha formation in space and time. Nevertheless, multiple datings from the same depth in the upper part of Facies D1 in AZ-W12 (Fig. 3) show that individual $^{14}$C data could be overestimating the age of sedimentation by up to several hundreds of years.

The $^{14}$C data from Facies E2 ranging from 22,000 to 40,000 yr cal BP may overestimate the age of deposition by thousands of years, if compared to the more reliable basal OSL age of AZ-W7 of ca 12,000 years. This OSL age, however, confirms the latest Pleistocene, pre-transgressive age of the dunes underlying the sabkha sequence, when sand dunes covered large parts of the entire dry Gulf (Sarnthein, 1972; Strohmenger & Jameson, 2015). The $^{14}$C data derived from the deep wells of AZ-W6 and AZ-W7 show multiple inconsistencies and generally cover the age range of the earlier part of the mid-Holocene RSL highstand only. They are not in accordance with the consistent chronostratigraphy of the vibracores. Reasons may include longshore reworking of dated *Cerithium* shells along the outer barrier and possible incorporation into deeper parts of the well through the coring process. Thus, age data of AZ-W6 and AZ-W7 were not considered for the model of sabkha formation.

The OSL ages show relatively low precision due to low dose rates (0.6 to 1.1 Gy ka$^{-1}$) and spatially heterogeneous beta radiation in the heterogeneous coastal sediments dominated by quartz and different carbonate, similar to that experienced by Brill *et al.* (2017). Thus, for the aeolian (Facies E2) and low-energy foreshore (Facies F2) sediments from AZ-T1 and AZ-W7, which show no indication of incomplete OSL signal resetting in their $D_e$ distributions, large aliquots of 8 mm diameter in combination with the CAM reduce the influence of spatial dose-rate variability and increase OSL signal intensities. The higher-energetic foreshore deposits (Facies F1) of AZ-T2, in contrast, show clear indication of incomplete OSL signal resetting in their $D_e$ distributions. Smaller 2 mm aliquots combined with the MAM for burial-dose determination were applied to account for these effects. The resulting OSL ages are in stratigraphic order and either agree with (seaward part of AZ-T2) or are significantly younger than $^{14}$C-AMS ages from similar strata, which are prone to reworking. Thus, the OSL data are considered to provide robust chronologies for sediment deposition of all dated facies.

**Sabkha formation in space and time**

During MIS stages 4 to 2, the Arabian Gulf was a large river valley draining the Euphrates and Tigris basin and receiving numerous tributaries from the Iranian landmass (short, steep gradient) and the Arabian Shield (longer, low gradient). The pre-transgressive (before 14,000 to 12,000 years ago) sedimentation inside the Gulf was dominated by fluvial and aeolian quartz sand and silt (Sarnthein, 1972; Stoffers & Ross, 1979; Ross *et al*., 1986; Strohmenger & Jameson,
In the marginal Gulf of Salwa, barchanoid dunes dominated under a presumably hyperarid climate regime before the onset of the Holocene (Al-Hinai et al., 1987; Goudie et al., 2000; Leighton et al., 2014) and the transgression, respectively (Fig. 16A). Massive gypsum (Facies A) at the base of AZ-W6 (Figs 9 and S2) indicates the localized formation of a pre-transgressive sabkha or saline lake inside an interdunal depression.

Based on the few systematically dated and published RSL index points of the mid-Holocene RSL highstand in Qatar (Vita-Finzi, 1978; Engel & Brückner, 2014; Rivers et al., 2020), rising RSL reached present-day levels around 6500 years ago – 1000 years later than estimated in Puls et al. (2009) and Billeaud et al. (2014). At that time, the area of the sabkha of Al-Kharayej became flooded and a narrow beach started to form (Figs 16B and 17). At the time of the highstand, ca 6000 years ago (Strohmenger & Jameson, 2015; Rivers et al., 2020), a flying spit started to grow from the beach to form the nucleus of the later broad outer barrier.

At 5500 to 5000 cal yr BP, the main spit diverted landward, developed a snaky outline and started to enclose the northern section of today’s sabkha (Figs 16C and 17). Thus, the northern section quickly evolved from open-coast to open-lagoon and protected-lagoon conditions within ca 1000 years. Deviations of spits have been observed in various coastal settings elsewhere, but whether they are triggered by major storms or thresholds in the feedback between the production and distribution of sediment and substrate morphology (Kwarteng et al., 2005) is difficult to decipher, even though it was previously found that spit curvature is linked to wave-energy reduction (Allard et al., 2008). Small-scale cuspatte spits along both sides of the snaky spit (Fig. 14) indicate a longshore drift towards the south-east on the southern side and – less distinct – towards the north-west on the northern, inner side, where it was possibly driven by tidal currents. These diverging mechanisms forming the spit on both sides might have led to its snaky outline. The entire spit until this time had grown by a rate of ca 2.5 to 3.0 m yr⁻¹.

At 4500 to 4000 cal yr BP, the snaky barrier had nearly constrained the northern sabkha section. The closed lagoon gradually filled with clastic deposits, skeletal grains and evaporites from south to north, driven by the tidal current entering from the south and indicated by accretionary, curved shorelines visible in Fig. 14 (‘linear accretion features’). Meanwhile, the spit of the outer barrier had grown further south increasing the area of protected-lagoon conditions in today’s main sabkha section (Fig. 16D). An increase of evaporation rates supporting the further transformation into a salina and sabkha later on can be inferred from significant aridization trends after the early to mid-Holocene humid phase across the Arabian Peninsula (Fleitmann et al., 2003; Parker et al., 2016; Engel et al., 2017, 2020). Shallowing of the entire coastal geomorphic system was driven by both gradual coastal and aeolian sedimentation and the initiation of the RSL fall at that time (cf. Parker et al., 2020). The RSL-related lowering of the capillary fringe in the supratidal sabkha of the northern section resulted in deflation (cf. Fryberger et al., 1988), which has also been observed in the landward part of sabkhas elsewhere in Qatar (Strohmenger & Jameson, 2015) and the karst basin of Asaila close to the Gulf of Salwa coast (Engel et al., 2020). A gradual reduction of aeolian sand supply and sand movement in the form of barchanoid dunes within the Shamal corridor, which is roughly shore-parallel at the study site, has to be expected as the transgression had cut off the upwind sand source inside the Bahrain Ridge and the Gulf of Salwa, leading to long-term deprivation of sand on the entire peninsula (Embabi & Ashour, 1993; Engel et al., 2018).

At 3500 to 3000 cal yr BP, the tidal connection had closed and a salina had formed, gradually transitioning into a supratidal sabkha. Rapid progradation of the outer spit (ca 6 m yr⁻¹ since 5500 to 5000 cal yr BP) was fuelled by RSL fall (cf. Nielsen & Johannessen, 2008) and led to the extension of the open lagoon south of the snaky barrier. At the same time, the main spit accreted westward and widened. Several potential small-scale tidal inlets and tidal deltas cutting the older part of the spit can be identified in the satellite image (Fig. 14). In the northern part of this lagoon, conditions became increasingly protected, while at the northernmost margin the sabkha started to form (Fig. 16E). Beach ridge-type features identifiable on satellite imagery and between the inner boundary of the main spit and the deviating snaky spit, labelled as ‘linear accretion features’ in Fig. 14, reflect contraction of the protected lagoon. Whether these features correspond to beach ridges or cheniers (Shinn, 1973a, 2011), as they are underlain and flanked by muddy lagoonal facies (cf. Otvos, 2000), is difficult to infer, because they were not morphologically visible in the field.
At 2000 to 1500 cal yr BP, the main spit had almost reached the modern shape of the outer barrier constraining the sabkha. A tidal connection in the south was still open permitting limited exchange of water (Fig. 16F). The inner part of this closed lagoon, as reflected by AZ-W5, subsequently developed into a salina, before the closure of the barrier in the south led to present-day supratidal sabkha conditions (Figs 16G and 17). Further lowering of the Stokes surface resulted in deflation over the last two millennia, even though these effects are not as severe as in the northern section (Fig. 10).

Based on this spatio-temporal reconstruction, the sabkha of Al-Kharayej is a suitable example for a longshore transport-driven, spit-controlled formation, as systematically outlined by Purser (1985). Along the north-eastern coast of Qatar, however, similar lagoons are not yet entirely closed off (Shinn, 1973a; Billeaud et al., 2014). The sabkha of Al-Kharayej stands in genetic contrast to the Mesaieed sabkha in the south-east of Qatar (Strohmenger & Jameson, 2015), which formed mainly due to coastal progradation fed by high detrital input of ‘calving’ barchan dunes in combination with evaporite pumping and the infiltration of seawater (Shinn, 1973b). Furthermore, it does not entirely comply with the classical model of sabkha formation as developed along the UAE coast, where the shore-perpendicular accumulation of coastal deposits during high tides or storms in combination with the mid-Holocene to late Holocene RSL fall results in the progradation of wide, low-inclination tidal flats into the lagoons and the precipitation of interstitial evaporites in the supratidal zone (Evans, 2011).

The regressive sabkha sequence of AZ-W5 in the centre of the main sabkha, showing by far the highest concentration of halite, supports the bull’s eye model, describing the concentric sequence of different evaporitic minerals depending on their solubility. According to the contraction of the lagoon and salina from the margins to the centre, the mineral of highest solubility, i.e. halite, is dominant in the centre, followed by gypsum and carbonates towards the margins (Warren et al., 1985; Sonnenfeld & Perthuisot, 1989; Ginau et al., 2012).

**Diagenetic modification of the sabkha: implications for reservoir characteristics**

Many of the oil and gas reservoirs in the Middle East formed under conditions similar to the mid-Holocene to late Holocene coastal progradation along the coastline of Qatar. Sabkha sequences, such as the one described here, represent baffles or seals in the sedimentary record, due to the abundance of porosity-destroying evaporites (Strohmenger & Jameson, 2015). After burial, the primary precipitated gypsum will be transformed to anhydrite-after-gypsum, forming efficient barriers or seals, depending on the lateral and vertical continuity and thickness. Thus, the sabkha of Al-Kharayej represents a modern analogue for depositional and diagenetic processes controlling reservoir property and quality of the arid-climate carbonates, represented by the Permo-Triassic Khuff and the Jurassic Arab formations, even though its siliciclastic content is higher than in the fossil examples. Based on the main controlling factors driving coastal sedimentation – some of which equally affect the entire peninsula (RSL; climate), whereas others are site-specific (coastline orientation; wind, wave and tidal energy; depositional relief; sediment sources) – coastal sedimentation patterns in Qatar can be separated into windward, oblique and protected sections (Strohmenger & Jameson, 2015).

For instance, the oblique coastal system of the Mesaieed sabkha (south-east Qatar), characterized by an upper, middle and lower sabkha, as well as the coastal area, all evolving since ca 8000 years ago, differs from Al-Kharayej. While the upper and middle sabkha lithosomes show signs of significant deflation and diagenetic over-printing through gypsum precipitation (especially laminated and buckled gypsum crust in the upper part), the lower sabkha and coastal area consist of a series of prograding spits of coarse skeletal material with surprisingly grainy facies in the associated back-beach-lagoon and tidal-flat environments (Strohmenger & Jameson, 2015).

The sabkha of Al-Kharayej also experiences longshore sediment transport, but under lower wave and tidal-energy conditions and a shore-parallel main wind direction. In contrast to the sabkha of Mesaieed, where the Shamal wind drives the longshore current away from the coast in an oblique angle, forcing a sequence of spits to prograde into the Gulf, at Al-Kharayej only one major spit made up of coarse skeletal and quartz sand formed. Furthermore, there is a relatively porous section of dune sands of unknown thickness between the transgressive marine to coastal wedge of the sabkha and the Eocene bedrock, which has not been described at Mesaieed (Strohmenger & Jameson, 2015). At Al-Kharayej, the majority of the sabkha lithosome consists of mid-energy open to protected lagoon facies.
Coastal sabkha formation in Qatar is driven by regional [relative sea-level (RSL) changes; climate] and local (coastline orientation; wind, wave and tidal energy, longshore drift; depositional relief; sediment sources) factors. Among these, RSL changes are the main driver of the general pattern of early to mid-Holocene transgression and subsequent regression, leading to coastal progradation and the formation of narrow beach-ridge sequences (for example, Al-Sirriyah; Engel & Brückner, 2014), wider spit sequences with tidal flats in between (for example, Mesaieed; Strohmenger & Jameson, 2015) or various forms of coastal sabkhas, such as at the protected coast of Al-Kharayej.

At Al-Kharayej, the coastline runs roughly parallel to the Shamal winds causing a mainly oblique angle of approaching waves. This in combination with a low to mid-energy wave regime, a low tidal range, as well as abundant sediment available in the Gulf of Salwa through reworking of drowned dunes and the authigenic production of skeletal carbonates led to the formation of a large coastal sabkha above the pre-transgressive, Pleistocene dune surface. Fifteen different facies types were identified from 12 sediment cores and two trenches. The sabkha’s parasequence comprises pre-transgressive dune sands (Facies E2), a thin, transgressive layer of reworked dune material (Facies E1), a mid-energy open-coast to open-lagoon facies (Facies D1), overlain by a low-energy lagoonal facies (Facies C1, C2), closed lagoon to salina (Facies B) and, finally, the supratidal sabkha diagenetic overprint (Facies A).

In combination with the $^{14}$C and optically stimulated luminescence (OSL) dataset, marine flooding of the area resulted in open-coast to open-lagoonal sedimentation and the formation of a beach at its landward margin. Initial spit formation at the very northern end can be reconstructed for the transition from the mid-Holocene transgression to RSL highstand, around 6000 cal yr BP. During the following millennium, this main outer spit prograded southward and a snaky, low-energy spit diverted landward, gradually closing off a lagoon in the northern part of the sabkha around 4500 to 4000 cal yr BP. The falling RSL and longshore
drift resulted in further southward extension and widening of the outer spit as well as shallowing of the open lagoon south of the snaky barrier. Around 2000 to 1500 cal yr BP, the outer spit had almost reached its current shape, gradually closing the landward lagoon, leading to salina and, finally, sabkha conditions. This almost complete separation of the lagoon from the Gulf of Salwa caused the formation of a back-barrier salina (saline lake), where subaqueous prismatic gypsum precipitated in the form of gypsum swallow-tail crystals (Figs 5, 8C and 8D). After drying out, the salina deposits were thinly covered by aeolian sand and overprinted under sabkha conditions. In some parts, deflation led to the erosion of the uppermost layer.

In contrast to most other sabkhas described in literature, such as the famous examples along the United Arab Emirates coast (e.g. Alsharhan & Kendall, 2003; Evans, 2011), sabkha genesis at Al-Khareyeyj mainly results from the longshore drift and sediment availability nurturing a spit system that creates a protected, shallowing lagoon. In combination with RSL fall after the mid-Holocene highstand, this low-energy environment dominated by carbonate muds silted up and transformed into a supratidal coastal sabkha. This is also in contrast to the east coast of Qatar, for example, the coarser-grained MesaeideeE sabkha, as grainstone facies at Al-Khareyeyj is mostly restricted to the main outer barrier and the thinner and narrower snaky barrier. Diagenetic overprinting is mostly present in the form of a buckled gypsum crust (sabkha-type gypsum and minor salt precipitation within the upper centimetres of the sediment). Unlike at Messeidee, where extensive early diagenetic gypsum precipitation significantly reduced the pore space, plugging of the pore space by gypsum cementation has a less intense impact on reservoir properties at Al-Kharayej.

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DATA AVAILABILITY STATEMENT

Data from this paper can be made available by the authors upon reasonable request.

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**Supporting Information**

Additional information may be found in the online version of this article:

Appendix S1. Detailed methods and supplementary data.