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Holocene marine hardground formation in the Arabian Gulf: Shoreline stabilisation, sea level and early diagenesis in the coastal sabkha of Abu Dhabi

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ABSTRACT

This study provides the first comparison between a seaward and a landward section of the same diachronous hardground surface observed in the coastal sabkha of Abu Dhabi. This hardground is described here in terms of its mode of formation, its diagenetic environment and its impact on shoreline stabilisation during transgression. The hardground is exposed in the intertidal zone and buried by a late Holocene prograding succession of carbonates, evaporites and microbial sediments in the supratidal zone. The hardground itself is composed of bioclastic grains, primarily of aragonitic composition, that originate from intertidal depositional environments. Aeolian silt to sand-sized quartz grains are also observed. Lithification occurred through the precipitation of pore-filling aragonite, high-Mg calcite and dolomite cements from sea and interstitial water that was marked by high salinities and temperatures, as confirmed by stable isotope analyses. High-Mg calcite and non-stoichiometric dolomite are also observed as secondary recrystallisation products. The formation of these two mineral phases as recrystallisation products was possibly microbially-mediated. Lithification progressed in two phases, the older phase of which is marked by higher amounts of non-stoichiometric dolomite and high-magnesium calcite as compared to the younger phase. Transgressive reworking of precursor siliciclastic sands was inhibited by the development of transgressive pore-filling gypsum cements in the supratidal zone.

1. Introduction

The Arabian (Persian) Gulf, hereafter referred to as the Gulf, is well-known for hosting extensive intertidal carbonate and supratidal evaporite deposits (Evans et al., 1964; Evans, 1966; Taylor and Illing, 1969; Kirkham, 1998). Recent research activity has focused on the microbial communities of the intertidal zone of the southern and southeastern Gulf, with particular focus being those of the coastal sabkhas of Abu Dhabi (Kendall and Skipwith, 1968; Butler, 1969; Kenig and Huc, 1990; Kenig et al., 1990; Baltzer et al., 1994) and Qatar (Brauchli et al., 2016; Słowakiewicz et al., 2016). These microbial communities occur as surficial sheets or mats, and are recognised to mediate and/or to control the formation of dolomites (Vasconcelos et al., 1995; Warthmann et al., 2000; Bontognali et al., 2010).

The base of the modern sabkha succession is formed by a marine hardground (Kirkham, 1998; Lokier and Steuber, 2008). This hardground crops out in the lower intertidal zone of the sabkha where it is marked by active lithification (Shinn, 1969; Taylor and Illing, 1969; Kirkham, 1998; Lokier and Steuber, 2009). This lithification occurs through the primary precipitation of acicular aragonite and dog-tooth high-Mg calcite cements (Shinn, 1969; Khalaf et al., 1987). Part of the high-Mg calcite cements are secondary products of dissolution and re-precipitation of previously aragonitic components (Taylor and Illing, 1969). Landwards, in the subsurface of the middle and upper intertidal zone and in the supratidal zone, this hardground is covered by a succession of carbonate, evaporite and microbial deposits with increasing thickness (see Lokier and Steuber, 2008).

Shallow-marine hardgrounds like this one have long been studied, but the processes that lead to their formation remain elusive (Christ et al., 2015). Present day shallow marine hardgrounds are found in a variety of near-shore and deep-marine settings (Purser, 1969; Wilson and Palmer, 1992; Christ et al., 2015). These hardgrounds are known to form in depositional settings with extremely low sediment accumulation rates (Wilson and Palmer, 1992). As marine hardgrounds are commonly associated with transgressions (Catuneanu, 2006), regressions and maximum flooding surfaces they represent important correlative markers in the stratigraphic record. The association of marine hardgrounds with these specific phases of sea level cycles is of particular importance in the Arabian Gulf, were Holocene sea level rise lead to rapid re-flooding of the sedimentary basin (Siddall et al., 2003; Clark et al., 2009; Lokier et al., 2015).

The history of late Pleistocene to Holocene sea level variations in the Gulf, after the last glacial maximum at 19,000 yrs BP (Clark et al., 2009),

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is marked by a transgression reaching the Gulf after 12,000 yrs BP and flooding the siliciclastic aeolian sand dunes (Sarnthein, 1972). The majority of the Gulf's sedimentary basin was submerged by about 8000 yrs BP (Lambeck, 1996). Subsequently, at 7100–6890 cal yrs BP, a stillstand in relative sea level was followed by renewed transgression with a subsequent stillstand phase at 5290–4570 cal yrs BP, a regression until about 1440–1170 cal yrs BP and the modern transgression (Lokier et al., 2015).

In addition to the implications for sea level that can be deduced from studying hardgrounds, these surfaces also control fluid flow within aquifers and hydrocarbon reservoirs, acting as aquitards and/or baffles which lead to the compartmentalisation of carbonate successions (Mancini et al., 2004). The accurate identification of shallow marine hardgrounds in both wells and field-sections is thus important for hydrocarbon and groundwater exploration, and also for the development of accurate reservoir models.

The primary focus of this study is to describe and compare a seaward and a landward site of the same diachronous hardground surface in order to constrain and explain early diagenetic processes within a sabkha setting. In addition, linking both sites through time and space will enable us to explain the formation of the hardground within the framework of Holocene sea level changes in the Gulf and the progradation of the modern sabkha depositional system. Ultimately, the comparison will allow to better constrain the timing of reflooding of the southeastern Gulf region during the Holocene.

2. Study area

The study area is located approximately 50 km to the southwest of Abu Dhabi City (Fig. 1 A). This region is marked by a northeast to southwest trending coastline that is restricted from open-marine conditions by several barrier islands. Large-scale tidal channels dissect the shallow lagoon that separates the mainland from these barrier islands. Small tributary tidal channels occur in the lower intertidal zone. The mainland behind the lagoon is marked by a laterally extensive transition from intertidal towards supratidal conditions, related to the very shallow angle of slope. The micro-tidal regime in this coastal area is of mixed semi-diurnal character, resulting in two high and two low tides per day, with the amplitude of one tide larger than the other. The sea water chemical composition is marked by high amounts of Ca^{2+} and Mg^{2+} ions and high Mg/Ca ratios (Wood et al., 2002).

The coastline experiences summer temperatures reaching 50 °C and winter temperatures as low as 7 °C, with diurnal ranges between 26 °C and 2 °C (Lokier, 2012). Average annual rainfall amounts to no >72 mm per year, predominantly occurring between February and March as torrential downpours (Raafat, 2007). The prevalent wind pattern is the northwestern Shamal. Wind directions switch twice a day between onshore and offshore due to adiabatic processes related to differential heating and cooling of seawater and land.

3. Materials and methodology

For this study, samples from a seaward and a landward site of the same diachronous marine hardground surface were selected for analyses (Fig. 1 B,C). The lateral relationship between the two sites was established based on a previously published cross-section of the same area (Lokier and Steuber, 2008). The specimen of the seaward site was removed from an area that is characterised by large-scale intertidal hardground polygons (N 24° 7.79016′, E 54° 1.30422′). The specimen of the landward site was taken from an excavated trench, located 3708 m to the southeast of the seaward site (N 24 7.09692′, E 54 3.35370′). This location forms part of the supratidal zone of the coastal sabkha.

Samples of the landward site were dated using accelerated mass spectroscopy (AMS) ^{14}C radiocarbon dating (*Beta Analytic Inc., Miami, Florida, USA*). Two gastropods were extracted at 0.4 cm and 4.1 cm from the top, respectively. Care was taken to remove secondary cements as much as possible during the extraction process. An acid etch pre-treatment procedure was conducted. Subsequent calibration was performed in CALIB 7.1 (Stuiver and Reimer, 1986, 1993) with the Marine13 calibration curve (Reimer et al., 2013). A regional reservoir age correction (ΔR) of 180 ± 53 years was applied, as derived from a sample collected off the coast of the Qatar peninsula (Hughen et al., 2004). Radiocarbon ages are reported in calibrated years before present (cal yrs BP). A radiocarbon age for the top of the seaward site has been reported previously (Lokier and Steuber, 2009, p. 615).

Petrographic thin sections were prepared for samples from both sites. Specimens were impregnated with blue resin in order to enhance the visibility of pores. An Alizarin red stain was applied to one half of each thin section in order to distinguish between calcite and dolomite phases (see Friedman, 1959).

A Quanta 200 (*FEI*) scanning electron microscope (SEM) at the Petroleum Institute was used to investigate the microstructure of samples from the two sites. Pieces of each specimen were carefully broken off, cleaned with compressed air, mounted on metal stubs, and coated with a palladium-gold mixture. Thin sections were analysed using the backscatter electron diffraction (BSED) mode of the SEM. Additionally, electron-dispersive spectroscopy (EDS) was employed to semi-quantitatively characterise elemental compositions.

Powdered samples for X-ray diffractometry (XRD) were prepared using a handheld drill. Drilling focussed on areas that appeared visually different in terms of colour and carbonate texture, but no distinction was made between cements and other sediment while sampling. As a result the reported mineralogy reflects all confounded mineral phases of both cements and skeletal grains. The drilled sediment was subsequently powdered in an agate mortar. The powder of each sample was analysed in a Hydro 2000MU laser granulometre (*Malvern*) in order to ensure an average grain size was below 60 µm. A total of 15 samples were analysed, 9 from the seaward and 6 from the landward site. XRD measurements were performed at the Petroleum Institute, on a Panalytical X'pert Pro with an X'celerator detector installed. Step size was set to 0.033° 2θ, with a 20 s count time per step; measuring range was between 10 and 70° 2θ.

Qualitative and semi-quantitative phase identifications and analyses of the XRD spectra were performed using Rietveld refinement (Rietveld, 1969; Bish and Post, 1993) in the open-source software package Profex (Doebelin and Kleeberg, 2015), in conjunction with the open-source Rietveld refinement software package BGMN (Bergmann et al., 1998). This method takes into account all peaks of an individual mineral phase, in contrast to other methods that use only the most significant peak of an individual mineral phase (compare to Petschick, 2002). The method then calculates a least-squares crystal structure model (Gregg et al., 2015), and ultimately computes the percentage of each mineral relative to the fully integrated area of an XRD spectrum. Chi squared (χ^2) errors were generally above 1.00 and below 3.80, with a maximum at 3.76. The following structures were included in each analysis (in alphabetical order): albite, anhydrite, aragonite, calcite, high-Mg calcite, celestine, dolomite, gypsum, halite, magnesite and quartz. Additionally, corundum was used as a structural standard only in the Rietveld analyses under the presumption that it would not occur in the sabkha area

Fig. 1. A – Bathymetric map of the Arabian (Persian) Gulf. Study area is located to the southwest of Abu Dhabi in the United Arab Emirates (red rectangle). B – Close-up view of the study area, showing the location of the seaward and landward sites of the hardground, the positions relative each other, and the positions relative to the modern coastal sabkha depositional environment. The location of the cross-section shown in C is indicated. C – Cross-section through the subsurface between the seawards and landward sites of the hardground. The lateral relationship between the seaward plug and the landward outcrop are shown.