

Facies patterns of a tropical heterozoan carbonate platform under eutrophic conditions: the Banc d'Arguin, Mauritania

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Abstract High-nutrient tropical carbonate systems are known to produce sediments that, in terms of skeletal composition, are reminiscent of their extra-tropical counterparts. Such carbonate systems and associated carbonate grain assemblages in the tropics are rare in the present-day world. Nonetheless, it is crucial to gain a better understanding of those ecosystems, including their drivers and players because such settings potentially represent models for ancient depositional systems as well as for predicted future environmental conditions. One of the modern occurrences of eutrophic tropical carbonate systems is the northern Mauritanian Shelf. The marine environment is characterized by an eastern boundary upwelling system that pushes cool and nutrient-rich intermediate waters onto a wide epicontinental platform (Golfe d'Arguin) where the waters warm up to tropical temperatures. The resulting facies is mixed carbonate–siliciclastic with a dominant foramol association grading into bimol and barnamol grain assemblages in

the shallowest areas forming the Banc d'Arguin. Besides this cool water-related heterozoan association, the carbonate sediment is characterized by tropical molluscan species, while chlorozoan biota (e.g., corals and algal symbiont-bearing foraminifers) are entirely absent. We here present a first comprehensive facies analysis of this model example of eutrophic tropical carbonates. Furthermore, we reconstruct the loci of carbonate production and provide a conclusive depositional model of the Banc d'Arguin that received little attention to date due to its poorly accessible nature.

Keywords Tropical carbonate platform · Heterozoan carbonates · Barnamol · Foramol · Eutrophication · Upwelling

Introduction

The impact of climate change, rising sea level, and the fingerprint of human-induced eutrophication make comprehensive studies on tropical marine ecosystems more important than ever for predicting future developments (Hallock 2005; Solomon 2007; Taylor et al. 2012). Marine ecosystems in low latitudes such as mangroves, seagrass meadows, and coral reefs provide a wide range of socio-economic services, besides their important role as biodiversity hotspots that need efficient protection against the disturbances by human activity (Myers et al. 2000; Hoegh-Guldberg et al. 2007; Gilman et al. 2008; Gattuso and Hansson 2011; Fourqurean et al. 2012). Therefore, research integrating environmental steering factors, processes, and threats on carbonate sedimentation is essential for acquiring reliable insights into future developments of coastal marine ecosystems.

Biogenic sediments provide a range of proxies that can be used to reconstruct environmental conditions and settings

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through time (Scholle et al. 1983; Mutti and Hallock 2003; Halfar et al. 2004; Pomar et al. 2004; Wright and Burgess 2005). Particularly, the analysis of carbonate-grain assemblages has become a key tool for paleoenvironmental reconstructions from the tropics up to the polar realm (Chave 1967; Lees and Buller 1972; Hayton et al. 1995; James and Clarke 1997). Such biofacies patterns shed light on the spatial and temporal distribution of marine ecosystems in relation to past and present climatic conditions.

In the last decades, two major classification concepts of carbonate sediments have been developed. The first one is based on a combination of composite terms, such as foramol (foraminifers and mollusks) and chlorozoan (chlorophyta, hermatypic corals, and mollusks) (Lees and Buller 1972), while the more recent concept uses a bimodal approach (photozoan vs. heterozoan carbonate association), accentuating the presence or absence of photosymbiotic carbonate-producing benthic organisms (James and Clarke 1997). Both schemes provide a framework for the interpretation of modern and ancient carbonate deposits in various environmental contexts (see case studies in Flügel 2010). However, the terms heterozoan and photozoan have become, in some cases, simplified synonyms for the descriptive approach to classify non-tropical, cold-water versus tropical, warm-water regimes (cf. Nelson 1988; Nelson et al. 1988). The ongoing discussion demonstrates that both concepts have strengths and shortcomings, but that the influence of a wider range of environmental controls needs to be considered (Hallock 1988; Betzler et al. 1997a, b; Brandano and Corda 2002; Samankassou 2002; Pomar et al. 2004; Brandano et al. 2009; Kindler and Wilson 2010; Westphal et al. 2010; Betzler et al. 2011; Schäfer et al. 2011; Reijmer et al. 2012). Knowledge of the ecological context and environmental steering parameters is thus crucial for an interpretation of sub-recent and fossil facies (Martín et al. 1996, 2001; Samankassou 2002; Perry and Taylor 2009; Barange et al. 2010; Doney et al. 2012). These factors include biological evolution, temperature, salinity, trophic conditions, water depth, oxygen and CO₂ concentrations, Mg/Ca ratio in the seawater, alkalinity, bathymetry, type of substrate, illumination, internal waves, and water stratification (see Westphal et al. 2010 and references therein). Neglecting one or a combination of these controls might result in paleoenvironmental misinterpretations (cf. Edinger et al. 2002; Samankassou 2002; Pomar et al. 2004). The restricted occurrences of modern heterozoan carbonate depositional systems in tropical latitudes provide a key to better constrain the multi-dimensional ecological control on carbonate sedimentation (Halfar et al. 2004; Kindler and Wilson 2010; Westphal et al. 2010; Schäfer et al. 2011; Reijmer et al. 2012).

Here we discuss the Golfe d'Arguin offshore northern Mauritania as one of the present-day tropical heterozoan

carbonate factories. Previous sedimentological studies took place in different parts of the shelf such as the Baie de Lévrier (Koopmann et al. 1978, 1979), the outer shelf (Hanebuth and Lantzsich 2008; Michel et al. 2011a, b; Hanebuth et al. 2013; Klicpera et al. 2013, 2014), the innermost shelf (Barusseau et al. 2007, 2010; Aleman et al. 2014), and in the vicinity of Tidra Island (Proske et al. 2008). However, none of these studies provides a comprehensive picture of the sedimentary facies distribution. One reason for the rather low research intensity is the restricted access to the shallow waters of the Banc d'Arguin. It cannot be accessed by larger research vessels and is by far too extensive for coverage by small boats (Wolff et al. 1993c).

In this study, we combine samples from the outer Banc d'Arguin (Westphal et al. 2007; 2014) with earlier investigations from the inner Banc d'Arguin (Piessens 1979) to a comprehensive facies pattern model. The aim is to identify areas of tropical heterozoan carbonate production and facies distribution by reconstructing the sedimentation dynamics in the Golfe d'Arguin and to infer from this example general patterns of eutrophic tropical carbonate deposition.

Study area

Off northern Mauritania, the narrow West African shelf (~50 km in width) opens up into a wide gulf of more than 150 km in east–west extension (Einsele et al. 1972; Piessens 1979). The so-called Golfe d'Arguin (GdA; Fig. 1) stretches between the Baie du Lévrier (BdL; 21°10'N) and the Cap Timiris Shelf (CTS; 19°20'N) over a distance of about 200 km (Piessens and Chabot 1977).

The depositional profile of the northern GdA describes a flat-topped platform (gradient 0.3 m km⁻¹; Fig. 1, transect A), on which extensive carbonate deposits (Banc d'Arguin; BdA) developed largely in water depths <10 m (mbsl). Vast areas of the BdA are covered by mixed carbonate–siliciclastic sediments dominated by barnamol assemblages (balanids and mollusks) sensu Hayton et al. (1995) plus admixed eolian siliciclastics (Sarnthein and Walger 1974; Westphal et al. 2007, 2014). These sediments accumulate into extensive shoals, occasionally causing water depths below 5 mbsl (Prévost 1746; Piessens 1979; Sevrin-Reyssac 1993). The bank edge forms a sharp morphological step, suddenly deepening from 10–20 mbsl down to 30–50 mbsl, and separates the inner shelf environments (<5–10 mbsl; carbonate bank) from those of the outer shelf (>30 mbsl; open platform, see Hanebuth et al. 2013).

Foramol assemblages (foraminifers and mollusks) sensu Lees and Buller (1972) and bimol assemblages (bivalve mollusks) sensu Hayton et al. (1995) with admixed eolian silt characterize the platform cover in the outer shelf (Sarnthein and Walger 1974, Piessens 1979; Michel et al. 2009).

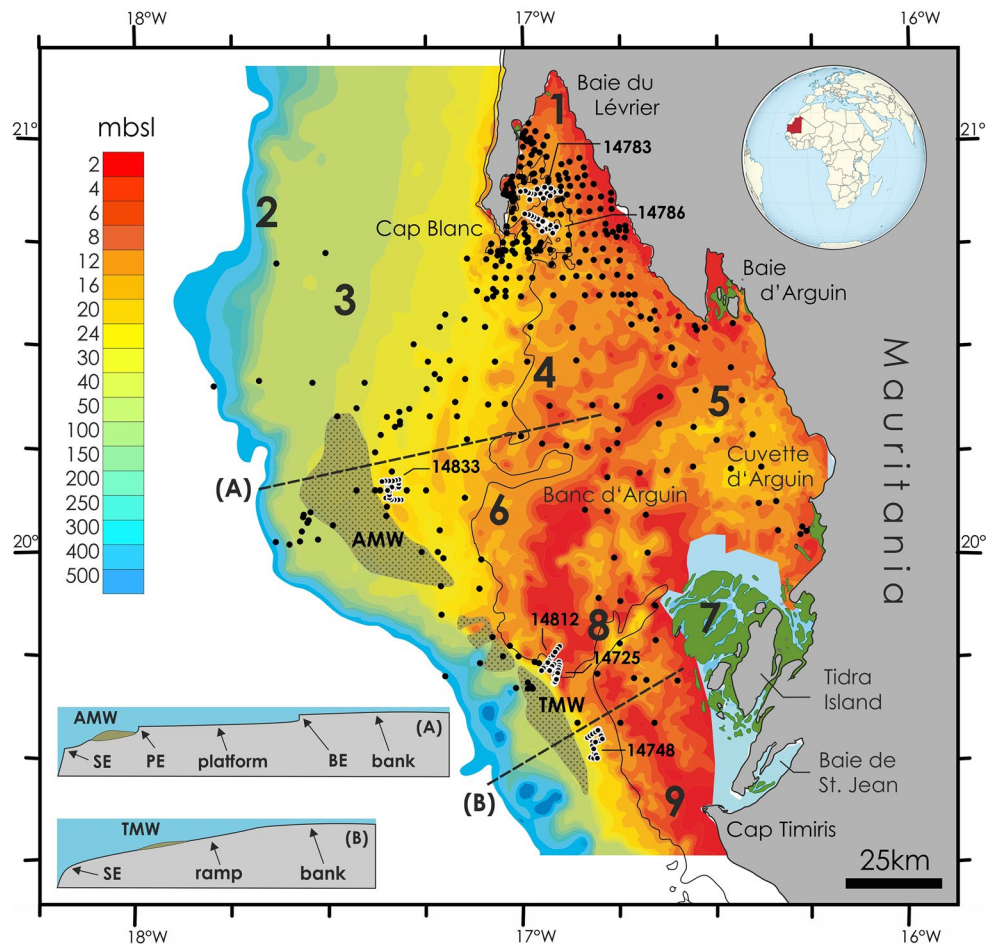


Fig. 1 The Golfe d'Arguin off northern Mauritania and the shallow Banc d'Arguin with vast areas <10 m below sea level (mbsl). *White circles* indicate MSM16-3 sampling sites; *black dots* refer to sampling sites compiled from other studies (Piessens 1979; Michel et al. 2011a). The shallow bank edge follows roughly the 10–20-m isobaths, while the shelf margin of the outer platform is located in 80–100 mbsl. Fine-grained sedimentary bodies characterize the Arguin (AMW) and Timiris (TMW) mud wedges situated in a platform-like depositional setting in the northern gulf (transect A) and a ramp-like setting in the south (transect B). Bathymetry according to Ale-

man et al. (2010, 2014); regional map modified after Hanebuth and Lantzsch (2008). Fine-grained deposits are the Arguin (AMW) and Timiris (TMW) mud wedges situated in a platform-like depositional setting (transect A) and a ramp-like setting in the south (transect B), respectively. Profile nomenclature: *SE* shelf edge, *PE* platform edge, *BE* bank edge (sensu Hanebuth et al. 2013); topographic features in the entire Golfe d'Arguin: 1 Baie du Lévrier, 2 shelf break (in 80–110 mbsl), 3 outer shelf, 4 Bank d'Arguin margin, 5 inner Banc d'Arguin (Cuvette d'Arguin), 6 central outer Banc d'Arguin, 7 Tidra Island intertidal zone, 8 southern Banc d'Arguin, 9 Cap Timiris shelf

In the central and southern outermost shelf, silt-sized quartzose materials (mode at 35 μm) form confined bodies referred to as the Arguin mud wedge (AMW) and Timiris mud wedge (TMW) (cf. Hanebuth and Lantzsch 2008). These deposits started to form with transgression early in the Holocene and have grown continuously and rapidly over the past 9 kyrs (Sarnthein and Diester-Haass, 1977; Hanebuth and Lantzsch 2008). Locally, the AMW and TMW deposits are incised by gullies and canyons towards the shelf break lying at around 80–110 mbsl (Hanebuth et al. 2013). The southernmost GdA describes a homoclinal ramp profile (gradient 3–4 m km^{-1}) with vast intertidal plains around Tidra Island (Wolff et al. 1993a, b; Proske et al. 2008; Fig. 1, transect B).

Oceanographic setting

The oceanography of NW Africa is characterized by tropical waters (>24 °C; <35 ‰) of the northward-directed Guinea Current and cool waters of the southward flowing Canary Current (<24 °C; >35 ‰). Additionally, nutrient-enriched upwelling waters (<18 °C; <36 ‰) are pumped onto the shelf and into the photic zone by Ekman transport, induced by equatorward Trade Winds that control the eastern boundary Canary Current (Maigret 1972). During winter, a branch of the Canary Current is displaced as far south as 20°N, while during summer, the Guinea Current and thus tropical waters dominate the hydrology of the GdA (Mittelstaedt 1991; Van Camp et al. 1991). As a

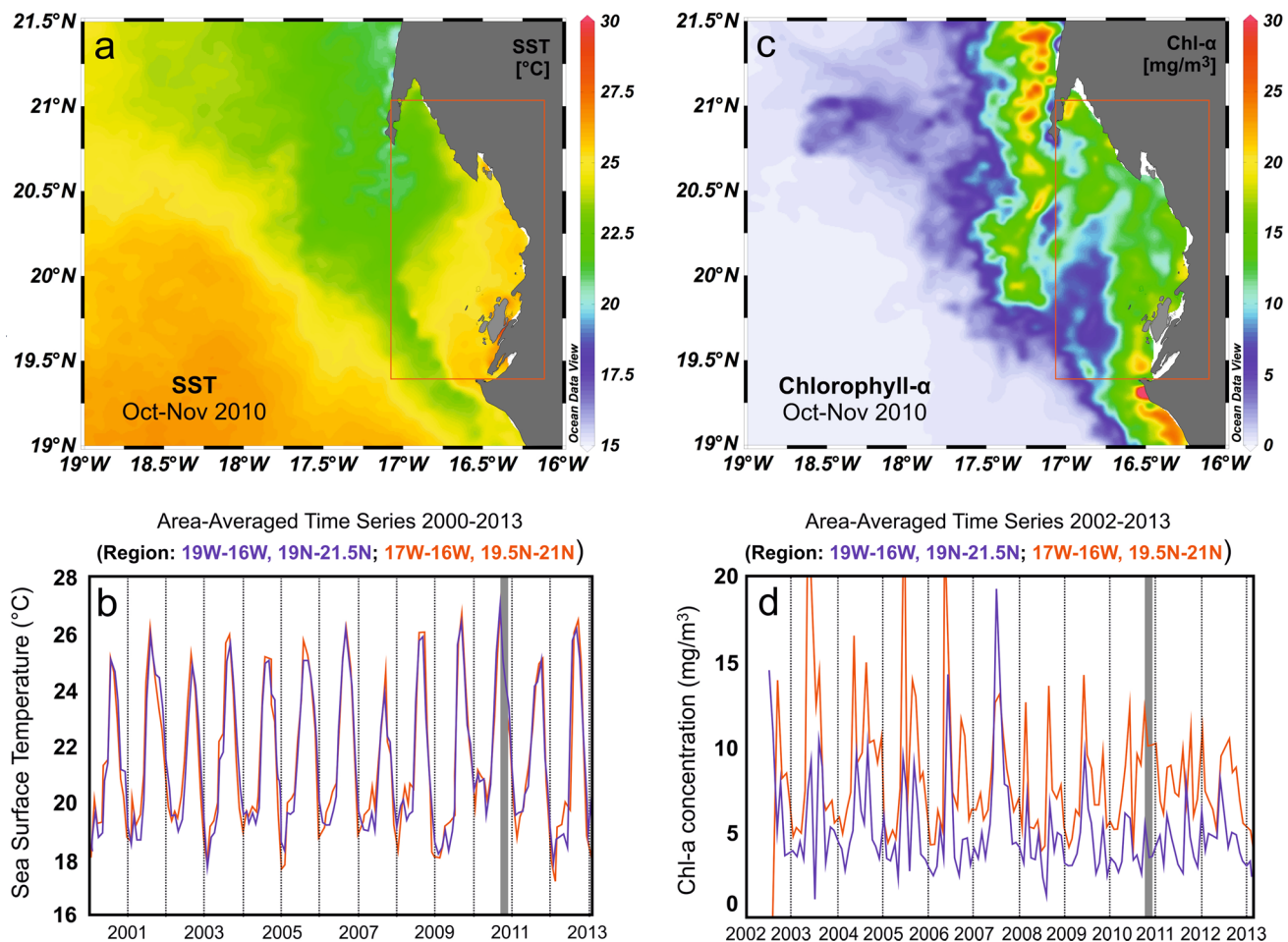


Fig. 2 Sea surface temperature (**a**) and chlorophyll *a* concentration (**c**) based on remote-sensing data (Acker and Leptoukh 2007) for the time of sampling (October–November 2, 2010). Area-averaged SST time series from 2000 to 2013 (*MODIS terra*) are given in **b** and area-

averaged Chl-*a* time series from 2002 to 2013 (*MODIS aqua*) in **d**. Grey bars in **b** and **d** indicate the time of sampling, the blue curve presents regional data, and the red curve shows data limited to the Banc d'Arguin

result, a perennial upwelling cell occurs year-round north of 21°N (Cap Blanc), whereas the upwelling activity is seasonal-controlled south of this latitude and in the study area (maximum upwelling intensities February–June and October–December, cf. Sevrin-Reyssac 1993; Fig. 2). These oscillating upwelling conditions allow for water stratification to develop during non-upwelling periods and nutrients to concentrate in calm photic water layers where they push the primary production (Huntsman and Barber 1977). As a consequence, the primary productivity off Cap Blanc is one of the highest worldwide with values exceeding $325 \text{ g C m}^{-2} \text{ year}^{-1}$ (annual mean of $200 \text{ g C m}^{-2} \text{ year}^{-1}$) and chlorophyll *a* (Chl-*a*) values of 3 to $>10 \text{ mg m}^{-3}$ (Marañón and Holligan 1999; Fig. 2).

Mean annual water temperatures ($>23 \text{ }^\circ\text{C}$) in the GdA show a pronounced seasonality with lowest sea surface temperatures (SST) of 16–17 °C recorded near Cap Blanc (April–May) corresponding to spring upwelling. Maximum

water temperatures of $>26 \text{ }^\circ\text{C}$ occur during September–October (Fig. 2) in the nearshore and intertidal areas around Tidra Island (Sevrin-Reyssac 1993). Strong insolation in spring and summer leads to a pronounced temperature gradient across the area and a high seasonal variability (Peters 1976; Koopmann et al. 1978, 1979; Ould Dedah 1993; Hagen 2001). Strong surface currents ($2\text{--}3 \text{ m s}^{-1}$) characterize the GdA, particularly the shallow BdA, and are related to tidal currents, the wind regime and upwelling swell. In restricted areas, such as the Baie de Saint Jean (BdSJ) the conditions become extreme with highest water temperatures and salinities reaching hypersaline concentrations (Sevrin-Reyssac 1993).

Materials and methods

Surface sediments were collected during the research cruise “PHAETON” aboard the R/V *Maria S. Merian* (MSM16/3,

Table 1 Sampling stations and gears of the R/V *MS Merian* cruise 16–3 in the Golfe d'Arguin, Mauritania

Station (ID)	14783	14786	14833	14812	14725	14748
Latitude	20°87'N	20°81'N	20°16'N	19°73'N	19°71'N	19°53'N
Longitude	–16°94'W	–16°94'W	–17°35'W	–16°92'W	–16°91'W	–16°82'W
Location	BdL	BdL	Central BdA	Southern BdA	Southern BdA	CTS
WD (range in mbsl)	6–13	4.5–16	20–30	4.5–38	6–26	8–31
Sediment grabs (<i>N</i> =)	23	22	22	20	15	23
CTD casts (<i>N</i> =)	9	9	5	7	9	10
SD casts (<i>N</i> =)	7	9	5	7	6	10
COMP-DATA (sites =)	–1, –7, –12	–2, –9, –14	–6, –17, –20	–6, –10	–3, –6, –2	–6, –9, –13
COMP-MOL (sites =)	–7	–9	–7, –21	–10	–2	–10, –11

Locations: *BdL* Baie du Lévrier, *BdA* Banc d'Arguin, *CTS* Cap Timiris Shelf, mbsl meters below sea level, *CTD* conductivity, temperature, depth probe, *SD* Secchi disk, *COMP-DARA* station sub-samples (=site ID) analyzed for component data, *COMP-MOL* station sub-samples (=site ID) analyzed for mollusk assemblages

October–November 2010; Westphal et al. 2014). To access the shallow, westernmost parts of the BdA from the seaside, an auxiliary zodiac was deployed from the research vessel. Six remote sites within the BdL (station IDs 14783, 14786), along the central BdA (station ID 14833), the southern BdA (station IDs 14812, 14725), and in the CTS area (station ID 14748) were sampled (Table 1). For each of these stations, 15–24 sub-samples (Sed_{Bulk}) were taken using a Van Veen grab (surface sediments; $N = 125$). Additionally, oceanographic profiles of the water column were measured with a miniCTD probe (temperature and salinity; $N = 49$) and a Secchi disk (light penetration depth; $N = 44$).

Carbonate content

Carbonate contents were determined as the mean weight percentage (wt % $CaCO_3$) of four replicates per bulk sample ($N = 468$) following the carbometer method of Müller and Gastner (1971). The internal error of this procedure is less than ± 1 % $CaCO_3$. To improve precision, the carbometer device was calibrated at least twice daily with a calcium carbonate standard (99.5 % $CaCO_3$).

Grain size determination

Sediment samples were classified on board the vessel into two textural groups that defined their further treatment: (1) coarse-grained bulk sediments ($N = 75$) that were washed and dried at $+60$ °C; (2) fine-grained materials ($N = 45$), directly wet-stored as bulk material in a cooling facility at $+4$ °C to reduce biodegradation of organic material. Back to the laboratory, the coarse-grained samples were dry-sieved by means of a sieve shaker, while the fine-grained sediments were first split at 500 μm and then either wet-sieved (>500 μm) or analyzed by means of a laser granulometer (<500 μm ; cf. Blott et al. 2004).

Laser granulometer raw data were re-calculated in Gradistat (Blott and Pye 2001) to make the applied techniques and datasets comparable. Additional grain-size data were extracted from Piessens (1979), Koopmann et al. (1979), and Michel et al. (2011a). All data were subsequently split in eight grain-size classes (<62 , 62–125, 125–250, 250–500, 500–1,000, 1,000–2,000, and $>2,000$ μm) following Wentworth (1922). Measurements are given as the weight percentage (wt %) of the bulk sediment (Sed_{Bulk}).

Component analysis

The component analysis was undertaken on surface sediments by determining a minimum of 300 skeletal grains per fraction ($N = 18,823$ counts). Analyzed component groups are given as mean percentages of the three coarsest fractions (>500 –1,000, 1,000–2,000 and $>2,000$ μm) of sediments sampled at three sites per station ($N = 18$; Table 1). The high identification potential (>94 %) of the fraction >500 μm allowed to differentiate bivalves, gastropods, foraminifers, bryozoans, echinoderms, serpulids, coralline red algae, balanids, and undeterminable bioclasts. Bivalve and gastropod grains were determined, where possible, down to species level ($N = 3,287$; Suppls. 1, 2). Non-skeletal grains are classified as siliciclastics, aggregates, pellets, and undeterminable material.

Additional sediment samples were provided by an environmental monitoring program carried out by the Mauritanian government (BdSJ sediments; IMROP, 2013). Other component data were taken from Piessens (1979), Koopmann et al. (1979), and Michel et al. (2011a). All data were recalculated on a percentage basis excluding unidentified components and standardized with respect to component groups used to allow direct comparability. The abundance scale used follows the recommended classification scheme, cf. Flügel (2010, p 262).

Table 2 Oceanographic data extracted from CTD measurements (cruise MSM16-3) undertaken in the Golfe d'Arguin, Mauritania

	October–November 2010 (MSM16-3)	Baie du Lévrier (14786; 14783) (<i>N</i> = 584)			Central Banc d'Arguin (14833) (<i>N</i> = 366)			Southern Banc d'Arguin (14725; 14748; 14812) (<i>N</i> = 943)		
		Mean	Max	Min	Mean	Max	Min	Mean	Max	Min
Salinity (‰)		36.04	36.79	35.33	35.95	36.44	35.66	36.04	38.03	35.12
SSS		36.06	36.57	35.54	35.99	36.40	35.73	36.14	38.03	35.12
SBS		36.12	36.46	36.02	35.93	35.94	35.93	36.03	36.34	35.88
Temperature (°C)		21.54	24.08	19.58	19.97	21.23	19.36	20.30	24.34	18.17
SST		22.41	24.08	21.10	20.85	21.23	20.30	21.11	24.33	18.66
SBT		20.84	21.78	19.58	19.67	19.99	19.36	19.76	24.32	18.17

Bold and italic values indicate maximum and minimum values, respectively

SSS sea-surface salinity, *SBS* sea-bottom salinity, *SST* sea-surface temperature, *SBT* sea-bottom temperature

Statistical analysis and mapping program

Sedimentary facies types were determined on the basis of grain size and composition of the sediment. A hierarchical cluster analysis (dendrogram using Ward's method; Ward 1963) was performed using JMP data analysis software for MacOS version 9.0.2 (Fig. 5) to statistically distinguish groups and clusters of samples. Non-determinable grains were not included in the statistical analysis.

Mapping of facies data was achieved using Ocean Data View (ODV) version 4.6.2. Areas of poor sample resolution were interpolated by the Diva gridding method provided in ODV (Schlitzer 2012). The resulting facies map was later processed in a vector graphics software and manually translated into a hexagonal grid (Fig. 7) to allow a better overview of facies zones identified.

Results

Oceanographic data

CTD casts from the outer BdA give a total temperature range (water column) between 18.2 and 24.3 °C (mean = 20.6 °C; October–November 2,010). SSTs range between 18.7 and 24.3 °C (mean = 21.1 °C); sea bottom temperatures (SBT) show values between 18.2 and 24.3 °C (mean = 19.8 °C). The highest temperature contrast (entire water column) is observed in the southern BdA, where SBTs and SSTs range between 18.2 and 24.3 °C respectively (mean = 20.3 °C). The lowest temperature contrast occurs in the central BdA where SBTs and SSTs range between 19.4 and 21.2 °C respectively (mean = 19.9 °C; Table 2).

CTD-based salinity measurements show a total range between 35.1 and 38.0 ‰ (mean = 36.0 ‰) that correspond to the range of sea surface salinities (SSS; mean = 36.1 ‰). Sea bottom salinities (SBS) range from 35.9 to 36.5 ‰ (mean = 36.0 ‰). The greatest contrasts occur in the

southern BdA, where the mixed surface water layer ranges between 35.8 and 38.0 ‰ (mean = 36.0 ‰). The lowest SSS range was measured in the central BdA with values between 35.7 and 36.4 ‰ (mean = 36.0 ‰; Table 2).

Secchi disk measurements (Table 3) show a light penetration averaging at 3 mbsl (*N* = 43). The lowest water transparencies of <2 mbsl (*N* = 10) are observed in the BdL and in the southern BdA (station 14748). Intermediate water transparencies of 2–4 mbsl (*N* = 22) are ubiquitous with the exception of the central BdA where transparencies of >4 mbsl (*N* = 11) are observed. Greater light penetration depths occur in the southern BdA (stations 14725, 14812) and near the CTS (Tables 2, 3).

Multi-annual remote sensing data show well-defined seasonal cycles. Area-averaged SSTs range from 18 to 26 °C for the entire area (19.0°N–21.5°N; 19.0°W–16.0°W) and are slightly higher for the GdA (19.0–27.0 °C; 19.5°N–21.0°N; 17.0°W–16.0°W) (Fig. 2a, b). The Chl-*a* concentrations show a seasonal pattern oscillating around 5 mg m⁻³ for the entire area with prominent peaks in the order of 10 to >20 mg m⁻³ for the GdA (Fig. 2c, d).

Sedimentary facies

Surface sediment texture

The outer BdA is covered by two sediment types: (1) Coarse-grained bioclastic sands with minor portions of rounded quartz (*N* = 75) and (2) quartzose sands with a low amount of coarse skeletal grains (*N* = 45). Rocky hardgrounds occur along the bank margin resulting in empty grabs (station 14748; *N* = 5) or in the recovery of cemented aggregates.

Towards the outer shelf (>30 mbsl; Fig. 1, transect A), the bioclastic sands grade into quartzose sands and silts with increasing water depth (Fig. 3b, c, d). Silt-sized muddy bodies (AMW, TMW) separate the outermost shelf with locally exposed erosion surfaces from the shelf break (Fig. 1, see Hanebuth et al. 2013 for nomenclature used).

Table 3 Measurements conducted during cruise MSM16-3 in the outer Banc d'Arguin, Mauritania

Station (ID)	14783	14786	14833	14812	14725	14748
Location	BdL	BdL	Central BdA	Southern BdA	Southern BdA	CTS
Depth range (mbsl)	6–13	4.5–16	20–30	4.5–38	6–26	8–31
Secchi disk (mbsl)	1.5	1.9	6.4	3.3	3.8	3.3
Chl- <i>a</i> (mg m ⁻³)	8.3	8.3	4.5	3.9	3.9	8.3
% CaCO ₃ /mean	34–85/56	40–83/57	39–45/42	21–85/42	15–84/56	31–52/37
Dominant biota	Balanids, mollusks	Balanids, mollusks	Bivalves	Balanids	Balanids	Bivalves

BdL, Baie du Lévrier; *BdA*, Banc d'Arguin; *CTS*, Cap Timiris Shelf

Carbonate content

Dry bulk sediments from the outer BdA and BdL range from 16 to 85 % in calcium carbonate content ($N = 468$; Table 3). The highest values are recorded in the BdL (34–85 %; mean = 56 %) and in the southern BdA (21–85 %; mean = 55 %). Sediments from the central BdA range from 39 to 45 % (mean = 42 %), while the southernmost CTS shows lowest measured contents ranging from 16 to 52 % (mean = 37 %).

Over the entire GdA, carbonate contents exceed >80 % in the northern GdA and in the vicinity of Cap Blanc with slightly decreasing contents from north to south and from shallow to deeper water. The lowest carbonates contents occur in nearshore settings and around Tidra Island (Fig. 3a).

Grain-size distribution

Sand-sized fractions dominate (82 %) the bulk sediments from the BdA and BdL throughout ($N = 113$; Fig. 3) with fine-grained (125–250 μm) and coarse-grained (500–1,000 μm) sands averaging at 25 and 21 %, respectively. Silt and clay-sized materials (<63 μm) average at 14 %; gravel-sized sediments (>2,000 μm) at 3 %. Restricted areas such as the BdL show a shift towards finer grain-size classes, dominated by sand-sized fractions (70 %) with fine-grained sand accounting for 21 % and medium-grained sand (250–500 μm) for 15 % of the bulk sediment. Silt and clay-sized materials average at 29 %; gravel-sized at material not more than 1 %. Particle size curves (Fig. 3) show monomodal distributions in the southern BdA (mode 500–1,000 μm at station 14725) and the CTS (mode 125–250 μm at station 14748) or polymodal distributions of particles in the BdL (stations 14783, 14786), the central BdA (station 14833) and the southern BdA (station 14812).

GdA-wide grain-size distributions show a dominance of sand-sized classes with larger areas covered by 80–100 % sand (Fig. 3c) south of Cap Blanc and towards the outer shelf, in the central to southern BdA and around Tidra Island. Gravel-rich deposits occur in the area between the

central BdA and Cap Blanc as well as in the CTS (Fig. 3b). Periplatform muds (<63 μm) are restricted to the BdL (<40 %), the Cuvette d'Arguin (<60 %) and to off-bank settings below the storm wave-base (>20 mbsl). On the outer shelf (>50–100 mbsl), the AMW and TMW show accumulations in the silt to fine-sand range (35–125 μm) of <40 and <80 %, respectively (Fig. 3d).

Non-skeletal components

Abiogenic grains are rare to sparse constituents throughout the outer BdA sediments averaging at 3 % of the component-analyzed samples (fractions >500 μm). Siliciclastics average at 2 % with a maximum of 9 % in the southern BdA (station 14725). Aggregated grains average at 1 % but can show elevated contents of up to 5 % (BdL, station 14783).

Over the entire GdA, abiogenic grains occur in quantities exceeding >25 % of the component-analyzed samples (fractions >500 μm) along nearshore areas (e.g., Cap Blanc, Cuvette d'Arguin, Timiris Island) but also offshore in the AMW area. Siliciclastics (quartz grains; Fig. 4a) average at 19 % with local enrichments (<89 %) south of Cap Blanc and in the southern BdA. Fecal pellets average at 8 % with maximum contents of up to 35 % restricted to low-energy settings such as the BdL and the Cuvette d'Arguin (Fig. 4b). Aggregates average at 6 % but can reach contents of 63 % along nearshore environments (e.g., south of Cap Blanc; BdL) and close to submarine outcrops. Accumulations in aggregates (>50 %) can also occur as allochthonous deposits within low-energy regimes (e.g., Cuvette d'Arguin; Fig. 4b).

Skeletal components

Mollusks The variety of mollusk grains present in the BdA and BdL sediments is characteristic of an environment influenced by mixed coastal and open marine conditions (Michel et al. 2011a, b). Whole and reworked shells occur as common to abundant constituents in most sediment types and water depths averaging at 50 % of

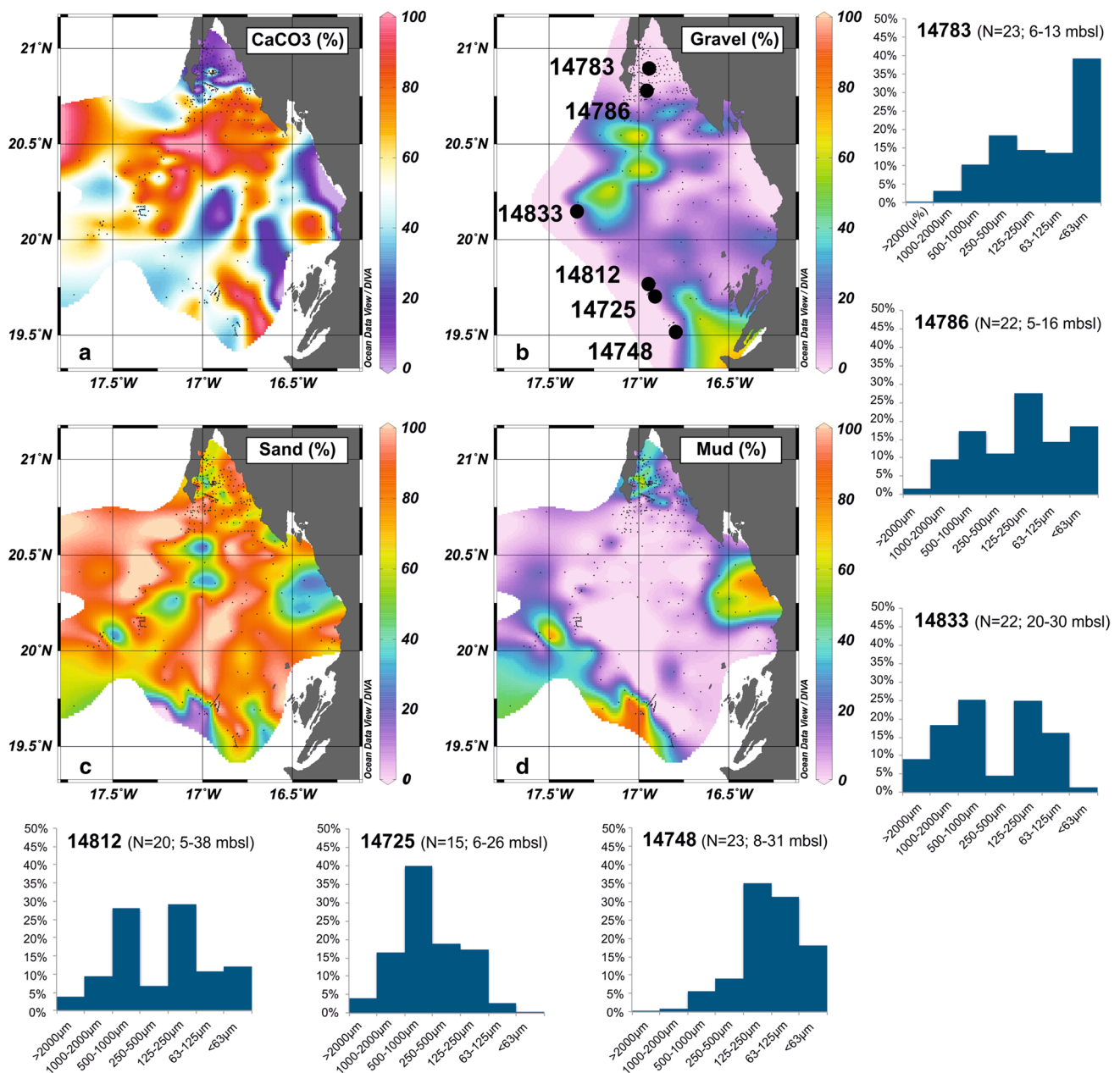


Fig. 3 Carbonate content (a) and large-scale grain-size distribution of gravel (b), sand (c), and mud (d) of surface sediments sampled in the Golfe d'Arguin (Mauritania). Data are compiled from the present study and additional data taken from Koopmann et al. (1979), Pies-

sens (1979), and Michel et al. (2011a) using Ocean Data View (ODV) version 4.6.1 (<http://odv.awi.de>; Schlitzer 2012). The bar diagrams in the right and lower panel show the grain-size distribution in localized sampling sites, cf. (b) sampled during MSM16-3

the component-analyzed materials (fractions $>500 \mu\text{m}$). The highest contents (82 %) were found in the central BdA.

The GdA-wide distribution of mollusk shells shows abundant contents averaging at 56 % (fractions $>500 \mu\text{m}$) and a maximum of up to 93 % in the central BdA and around Cap Blanc. Lower contents of 83 % occur in the northern Cuvette d'Arguin and in nearshore areas close to the Baie d'Arguin.

Balanids Hard-substrate-related balanid grains (*Balanus* cf. *trigonus*; Darwin, 1854) are ubiquitous in the outer BdA (Gravel 1912). Such balanid accumulations average at 35 % (fractions $>0.5 \text{ mm}$) with highest concentrations of 67 % in the northern BdL (station 14783). Percentages around 55 % occur in the southern BdL (station 14786) and in the southern BdA (stations 14725 and 14812).

Over the entire GdA, balanid grains average at 17 % (fractions $>500 \mu\text{m}$; Fig. 4d) with dominant occurrences ($>50 \%$)

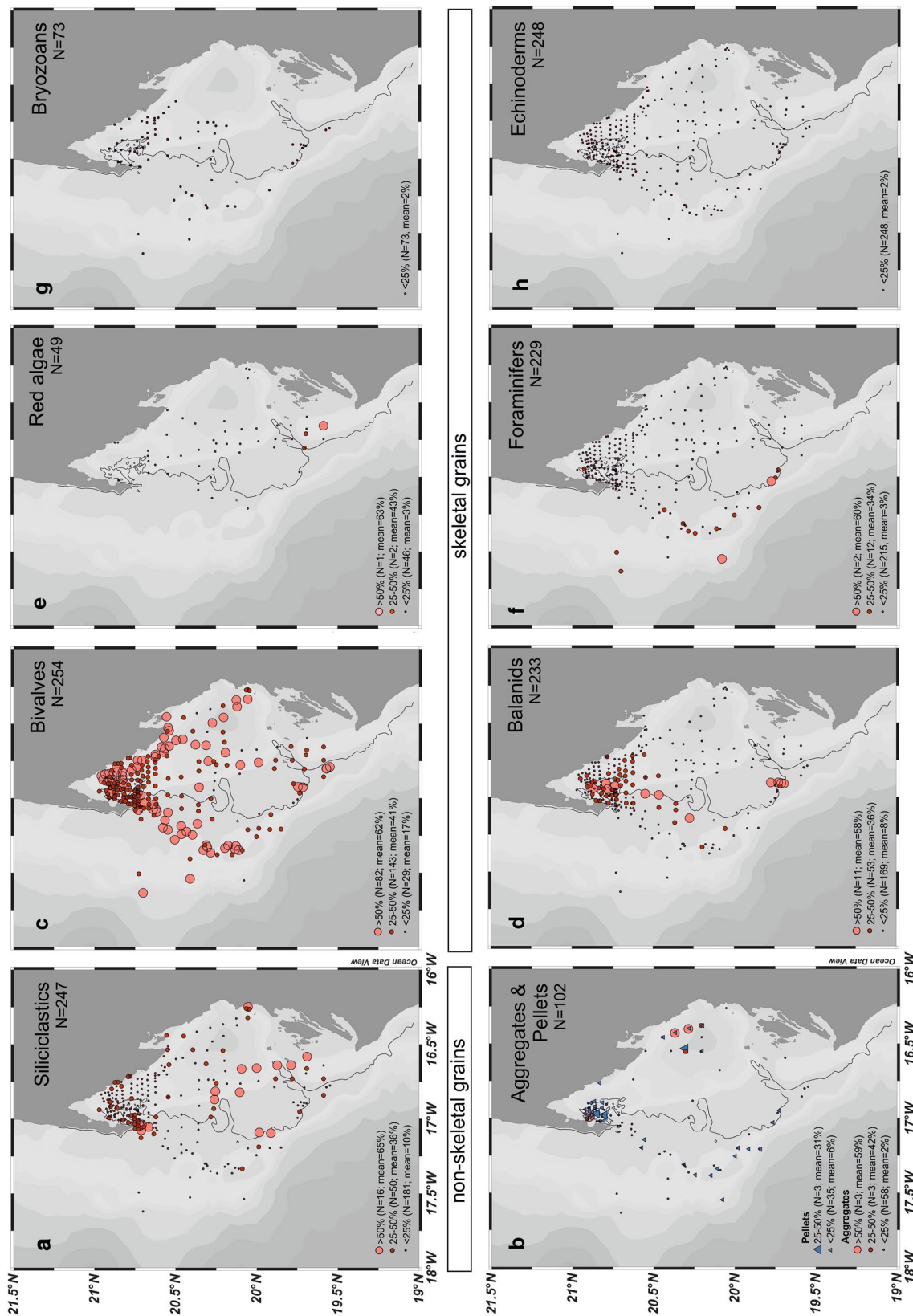


Fig. 4 Relative abundance of non-skeletal grains (a, b and skeletal grains (c–h) in the Golfe d'Arguin offshore Mauritania. The *thin black line* indicates the bank edge in 10–20 mbsl. Data are compiled from

the present study and additional data extracted from Koopmann et al. (1979), Piessens (1979), and Michel et al. (2011a)

restricted to shallow subtidal waters (<10 mbsl) in the BdL (60 %), the northern BdA (56 %), and in the southern BdA (58 %). Balanid sands can accumulate to extensive shoals forming shallows of <5 mbsl more than 100 km offshore. The majority of balanid grains recovered from the BdA are disarticulated plates, however, some entire shells are found as clusters attached to rocks (southern BdA) or to larger mollusk shells such as *Venus crebrisulca* in the central BdA.

Coralline red algae Sediment samples from the outer BdA and BdL provide no significant records of coralline red algae, however, their abundance over the entire GdA averages at 6 % (fractions >500 μm ; Fig. 4e) with enrichments of up to 63 % restricted to the southern BdA.

Foraminifers Foraminifers are very rare (<2 %) in the outer BdA. The GdA-wide distribution of foraminifers averages at 5 % (Fig. 4f) with higher concentrations in fine-grained sediments alongside the outer shelf and in the CTS area. The highest occurrences (>30 %; Fig. 6g, h) of the bulk sediment were identified as *Tetragonostomina rhombiformis* (Mikhalevich 1975). Other sparse to common distributed taxa are the benthic taxa *Siphonaperta* sp., *Quinqueloculina* sp., *Eponides* sp., *Homotrema* sp., and the planktonic *Globigerinoides ruber* (Cushman 1927) see details in Reymond et al. (2014).

Bryozoans Samples from the BdA margin and BdL show rare to sparse bryozoan records averaging at 2 % (fractions >500 μm). The highest contents are restricted to the southern BdA (station 14812) where bryozoans may reach up to 10 % of the sediment constituents.

The same quantity in distribution and local appearance applies for the entire GdA. In the central BdA, abundant in situ bryoliths were identified formed by symbiotic associations between the bryozoan *Acanthodesia commensale* (Kirkpatrick and Metzelaar 1922) and hermit crabs (Klicpera et al. 2013). Other common (<10 %) bryozoans in the CTS area are free-living cupuladriid colonies (e.g., *Discoporella* spp., *Reussirella* spp., and *Cupuladria* spp.; Klicpera et al. 2014).

Echinoderms Remains of echinoderms average at 1 % (fractions >500 μm) in the samples from the BdA. However, their abundance in the fraction >2 mm can be as high as 7 %, especially in the southern BdA where the infaunal species *Heliophora orbicularis* (Linnaeus, 1758) is a common constituent in surface sediments (Fig. 6e).

The GdA-wide distribution of echinoderm grains averages at 2 % (Fig. 4h) with local accumulations of up to 18 % of the sediment constituents in the southern BdA and up to 17 % in the outer shelf area south of Cap Blanc (northern BdA).

Mollusk taphonomy

Mollusk assemblages from the BdA were further investigated taxonomically for their ecological significance in the

study area. In total, 109 taxa were identified from 3,657 mollusk shells that were picked from eight sampling sites in BdL and BdA and one additional sample from the BdSJ (fractions >500 μm). Among these, 3,287 identified bivalve grains account for 90 % of the mollusk grains (Table 4; Fig. 4c) and clearly highlight the dominance of bivalve mollusks in the GdA.

Sediment samples from the outer BdA and BdL show high abundances of the bivalves *Donax burnupi* (Sowerby III, 1894) with >50 % (occasionally >90 %) in BdL and CTS; *Timoclea ovata* (Pennant, 1777) with >50 % in CTS area, and *Papillicardium papillosum* (Poli, 1791) with 30–50 % in BdL area of the component analyzed fractions (Table 4). The complete list of bivalve and gastropod taxa identified is given as supplements to this study.

Over the entire GdA, extensive deposits of *Venus crebrisulca* (Lamarck, 1818) shells indicate economically significant stocks that were investigated in Goudswaard et al. (2007). In nearshore areas, the species *Senilia senilis* (= *Anadara senilis*; Linnaeus, 1758) yields abundant archaeological material and represents the main mollusk exploited by ancient human populations living in the GdA hinterland (Barusseau et al. 2007). The deeper outer shelf (>30 mbsl) shows remains and in situ records of *Pinna rudis* (Linnaeus, 1758) and scattered shells identified as the chemosymbiotic bivalve *Solemya togata* (Poli, 1791) prospering in muddy to fine-grained sediments (Westphal et al. 2014).

Integrated facies analysis

The facies-type definition of surface sediments is based on a cluster analysis ($N = 251$; Fig. 5) gathering data from the present study and from the literature (re-analyzed datasets; cf. section **Materials and methods**). In total, six grain assemblages (F1 to F4 including subgroups F3A, F3B, F4A and F4B) are distinguished (Fig. 7), whose characteristics and interpretations are listed in Table 5.

Discussion

Cool-water-related grain assemblages in the GdA highlight a strong environmental control under which marine carbonate-secreting biota have developed. A complex oceanographic regime and the co-occurrence of tropical key species together with a dominant cool-water-related community suggest that temperature–depth relationships alone may not account for the presence of heterozoan carbonates at low latitudes. The following environmental parameters were identified to have a significant effect on the formation of tropical heterozoan carbonates in the GdA: (1) upwelling-induced high nutrient water conditions, (2) low water transparencies due to high Chl-*a* levels and

Table 4 Identified mollusk taxa in more than rare abundance (> 5 % of mollusk grains) from the inner shelf of the Golfe d'Arguin, Mauritania

	Depth range (mbsl)	Substrate	Ecology	Environment	14783-7	14786-9	14833-7	14833-21	14812-10	14725-2	14748-10	14748-11	Baie de Saint Jean
Bivalvia					BdL	Central BdA	southern BdA	CTS					BdSJ
<i>Carditamera contigua</i>	1-5	rock	SF	TR, UP	VR		S						
<i>Cerastoderma cf. edule</i>	1-100	Sa	SF	COS			S						C
<i>Chama crenulata</i>	0-60	Rock	SF	TR	VR	VR	C	R			VR		
<i>Corbula gibba</i>	3-100	sM, fS	OM, B	TE	C	VR	VR						
<i>Cuna gambiensis</i>	1-20	sM, fS	PP	TR-ST, UP	S		VR	VR			VR		
<i>Donax burnupi</i>	1-40	Sa	PP	TR-ST, UP	VR	A	S	R			VC		
<i>Dosinia sp.</i>	3-20	Sa	PP	COS	R	VR	VR	VR			VR		C
<i>Fraginae sp.1</i>	-	-	-	-									C
<i>Gregariella petagnae</i>	>3	fS, Sa	OM	COS			R	C			VR		
<i>Nuculana bicuspidata</i>	1-60	sM, fS	OM	TR, UP	C								
<i>Papillicardium papillosum</i>	20-60	Sa	SF	COS	VC	VR	VR					VR	
<i>Tellina densistriata</i>	15-35	fS	OM	TR	S								
<i>Tellina rubicincta</i>	10-100	sM, fS	OM	TR-ST	S								
<i>Timoclea ovata</i>	30-200	fS, Sa	PP	COS	VR	R	VC	A			VC		
<i>Venus crebriculca</i>	4-25	Sa	PP	TR-ST, UP		VR	C				C		
<i>Carditamera contigua</i>	1-5	rock	SF	TR, UP	VR		S						
Gastropoda													
<i>Bititium reitculatum</i>	0-5	S	HV	COS									S
<i>Pusillina sp.</i>	18-50	m/fS	-	-									C
Rissooidea	>2	-	-	-									C
<i>Tricolia pullus</i>	0-10	rock	HV	COS				S					

Abundance scale cf. Flügel (2010) p 262

A abundant (>50 %), VC very common (30-50 %), C common (10-30 %), S sparse (5-10 %), R rare (2-5 %), VR very rare (<2 %)

Locations: BdL Baie de Lévrier, BdA Banc d'Arguin, CTS Cap Timiris Shelf, BdSJ Baie de Saint Jean

Mollusk substrate: M mud, sM sandy mud, fS fine Sand, Sa sand

Mollusk environment: Tr tropical, ST subtropical, COS cosmopolitan, UP upwelling-related

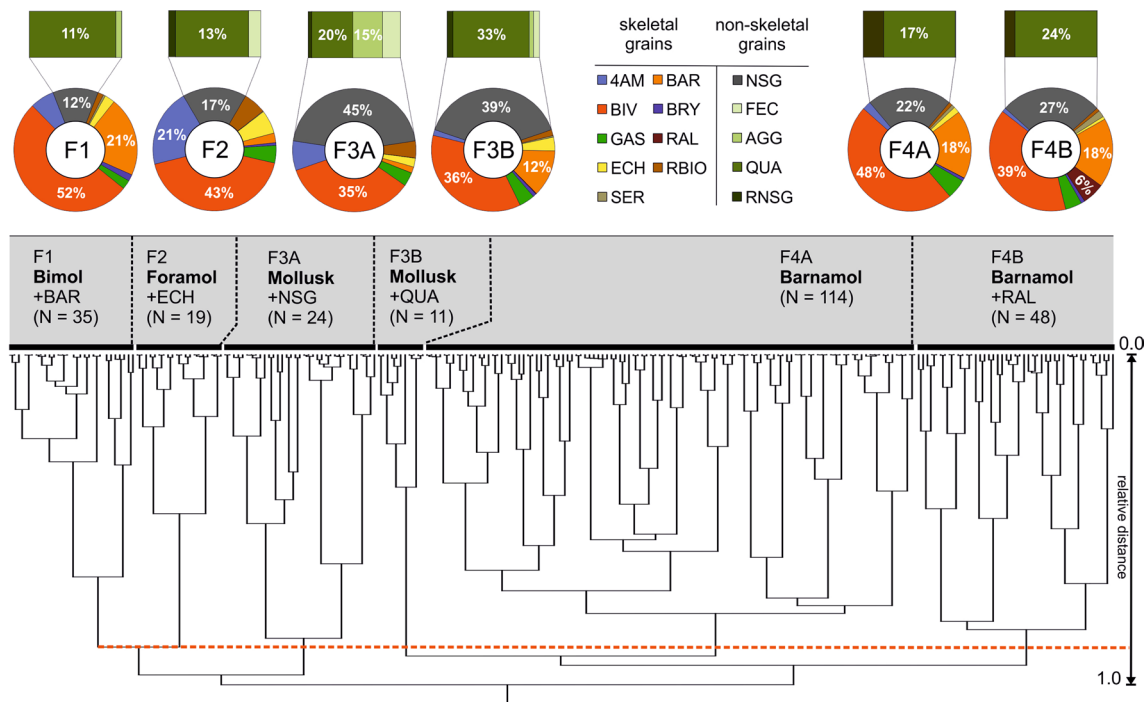


Fig. 5 Dendrogram and sediment composition of grain assemblages (F1 to F4B) from the Golfe d'Arguin. The hierarchical clustering follows the Ward's method and is based on 251 sediment samples compiled from Koopmann et al. (1979); Piessens (1979); Michel et al. (2011a, b), and the present study. 4AM foraminifers, BIV bivalves,

GAS gastropods, BAR barnacles, BRY bryozoans, RAL red algae, ECH echinoderms, SER, serpulids, RBIO remaining bioclasts, NSG non-skeletal grains, FEC fecal pellets, AGG aggregates, QUA siliciclastics, RNSG remaining non-skeletal grains

re-suspended sediments, (3) a strong hydrological regime, and (4) annual high water temperatures. Additionally, the availability of hard bottoms and other topographic shelf features in the shallow BdA act as steering factors affecting carbonate production. The impact of these controls on benthos ecology, sediment formation, reworking, and distribution results in a characteristic facies zonation (Fig. 7) discussed in the following sections.

Oceanographic parameters

Temperature

The remote sensing SST dataset (Fig. 2) and the studies of Cuq (1993), Ould Dedah (1993), and Ould Mahfoudh et al. (1991) showed that water temperatures in the GdA undergo significant seasonal variations. This pattern is attributed to the changing influence of (1) the tropical Guinea Current (<35 ‰, >24 °C); (2) the temperate Canary Current (>35 ‰, <24 °C) coupled with upwelling-induced cool intermediate waters, and (3) shallow subtidal to intertidal coastal waters (BdA and BdL; >39 ‰, >28 °C) heated by solar-driven evaporation. Seasonal displacements of either cold (Canary Current) or warm (Guinean Current) water masses in the GdA thus cause a pronounced hydrographic

heterogeneity in both, a spatial and temporal dimension (Sevrin-Reyssac 1993).

The CTD dataset taken in October–November 2010 (MSM16-3) indicates a temperature contrast of up to 5.6 °C (18.7–24.3 °C; Table 2) in the southern BdA. This significant variation in temperature is related to cold upwelled waters (<20 °C) and warm coastal waters (>22 °C) from the intertidal settings close by. The temperature variation, however, is in agreement with Ould Dedah (1993) reporting a maximum temperature variability of up to 9 °C in the southern BdA. Such upwelling-induced cool water intrusions in epicontinental seas cause distinct thermal fronts, to which the benthos adapts by forming 'atypical' eurythermal communities in the shallow bank (cf. Westphal et al. 2010; Michel et al. 2011a, Schäfer et al. 2011; Reijmer et al. 2012; Table 6.). Nonetheless, such conditions put intensive stress on most carbonate secreting biota and explains the absence of temperature-sensitive groups (e.g., chlorozoan biota; Halfar et al. 2006).

Salinity

Similar to water temperature, the salinity pattern displays distinct variations over the year with values between 35.5 and 37.0 ‰ for the seaward part of the BdA and values

Table 5 Facies characteristics of analyzed samples collected in the Golfe d'Arguin

Facies	F1	F2	F3A	F3B	F4A	F4B
Number of samples referring to facies	N = 25	N = 19	N = 24	N = 11	N = 114	N = 48
Skeletal grain assemblage	Bivalve dominated; Bimol grain assemblage	Mollusks and benthic foraminifers; Foramol grain assemblage	Mollusks and non-skeletal grains; Mixed mollusk-non-skeletal grain assemblage type A	Mollusks and non-skeletal grains; Mixed mollusk-non-skeletal grain assemblage type B	Mollusks and balanids; Barnamol grain assemblage type A	Mollusks and balanids; Barnamol grain assemblage type B
Depth range (meters below sea level)	Subtidal to slope 6–161 mbsl	Subtidal 15–42 mbsl	Subtidal to outer shelf 5–89 mbsl	Subtidal 8–38 mbsl	Subtidal to outer shelf 13–72 mbsl	Subtidal 4–10 mbsl
Carbonate content (wt % CaCO ₃)	Carbonate content 16–91 % (mean = 57 %)	Carbonate content 11–85 % (mean = 51 %)	Carbonate content 1–87 % (mean = 25 %)	Carbonate content 11–93 % (mean = 42 %)	Carbonate content 1 and 89 % (mean = 18 %)	Carbonate content 1 and 88 % (mean = 45 %)
Skeletal grains (with abundant and minor components)	Skeletal grains (88 %); Incl. bivalves (52 %); Balanids (21 %)	Skeletal grains (83 %); Incl. bivalves (43 %); Benthic foraminifers (21 %); Echinoderms (6 %)	Skeletal grains (55 %); Incl. bivalves (35 %); Benthic foraminifers (8 %); Gastropods (4 %)	Skeletal grains (61 %); Incl. bivalves (36 %); Balanids (12 %); Gastropods (4 %); Echinoderms (4 %)	Skeletal grains (78 %); Incl. bivalves (48 %); Balanids (18 %)	Skeletal grains (73 %); Incl. bivalves (39 %); Balanids (18 %); Calcareous red algae (6 %)
Non-skeletal grains (with abundant and minor components)	Non-skeletal grains (12 %); Incl. siliciclastics (11 %)	Non-skeletal grains (17 %); Incl. siliciclastics (13 %)	Non-skeletal grains (45 %); Incl. siliciclastics (20 %); Aggregates (16 %); Pellets (9 %)	Non-skeletal grains (39 %); Incl. siliciclastics (33 %)	Non-skeletal grains (22 %); Incl. siliciclastics (17 %)	Non-skeletal grains (27 %); Incl. siliciclastics (24 %)
Grain size range	Medium-grained sand to gravel	Silt to medium-grained sand	Silt to coarse-grained sand	Medium-grained sand to gravel	Medium-grained sand to gravel	Coarse-grained sand to gravel
Grain sorting	Moderate to good	Moderate to good	Poor to moderate	Moderate to good	Good	Moderate to good
Substrate for carbonate producers	Sand to gravel	Muddy silt to sand	Silt to sand	Sand	Rocky bank margin	Sand with hardgrounds
Occurrences in the Golfe d'Arguin	F1 concentrated in the northern GdA along both, the coast and the outer margin of the BdA. Restricted occurrences in the intertidal areas of the southern BdA (Figs. 4c, 6c, 6d, 7)	F2 is common in restricted areas in the outer shelf where it covers a corridor off the bank margin that extends from the BdL to the southern BdA following roughly the 30-m isobaths (Figs. 4f, 6g, 6h, 7)	F3A shows a patchy distribution that is limited to restricted areas within the BdL and the inner BdA (Cuvette d'Arguin) (Figs. 4b, 6, 7)	The distribution of F3B shows no clear pattern, with accumulations in the inner southern BdA and intertidal areas (Figs. 4a, 7)	F4A shows a clear pattern extending from Cap Blanc in southward direction along the outer BdA margin to the southern BdA (Figs. 4d, 7)	F4B occurs in the central BdA and a North–South extending corridor in the southern BdA (Figs. 4d, 6e, 6f, 7)

Table 5 continued

Facies	F1	F2	F3A	F3B	F4A	F4B
Facies interpretation	High-energy subtidal environment under the influence of upwelling swell (<i>Donax</i> -rich deposits along the bank edge). The limited occurrence of living species is interpreted as sporadic productions related to upwelling-controlled food availability	Low energetic subtidal environment below the wave base (outer shelf), often preserved in a patchy distribution related to the complex hydraulic regime. Chemosynthetic bivalve taxa indicate constraining conditions (limited light, oxygen, food settings)	Low energy subtidal environment in the inner shelf setting and BdL where calmer water conditions occur. The high amount of non-skeletal grains (e.g., aggregates and peloids) is interpreted as a shallow basinal setting in proximity of a rocky shore	Medium energy wide-spread over the entire GdA. Often characterized as transition-facies between productive zones and siliclastic sources (e.g., hinterland, intertidal areas around Tidra Island)	High-energy shallow subtidal environment along the bank margin that provide extensive rocky outcrops. The accumulation of balanid remains under such strong hydrological conditions indicates a production in situ or close-by	Medium energy shallow subtidal environment with parautochthonous deposits of balanids, mollusks and in situ records of red algae that argue for eutrophic mesophotic conditions. Possibly, offshore extensions of the intertidal flats around Tidra Island

Sample dataset is based on surficial sediment samples collected in the late 1970 (Koopmann et al. 1979; Piessens 1979) and from two former cruises in 2007 (POS346; Westphal et al. 2007; Michel et al. 2011a, b) and MSM16-3 in 2010 (Westphal et al. 2014; this study)

GdA Golfe d'Arguin, BdA Banc d'Arguin, BdL Baie du Lévrier, mbsl meters below sea level

exceeding 38 ‰ for inshore environments (Ould Dedah 1993). CTD measurements taken in October–November 2010 (MSM16-3) agree with those of previously reported ranges showing a range between 35.1 and 38.0 ‰ (mean = 36.1 ‰) for the outer BdA and BdL. Again, the highest contrasts are identified in the southern BdA, where salinity-depleted waters of the Guinean Current collide with salinity-enriched coastal waters. The highest salinity records are reported from isolated and restricted bays in the innermost BdA such as the semi-enclosed BdSJ, where salinities can exceed 52.0 ‰ and peak up to 80.0 ‰ (Sevrin-Reyssac 1993). Apart from these extremes, the salinity contrast in the southern BdA and other nearshore areas under upwelling control (BdL; Table 2) restricts stenohaline biota, while euryhaline species (e.g., osmoregulating balanids, cf. Anderson (1994); mollusks, cf. Michel et al. (2011a); and *Zostera noltii* seagrass meadows, cf. Vermaat et al. (1993)) prosper under such conditions.

Nutrients and photic zone

Trophic-controlled settings with eutrophic conditions are known to influence the formation of chlorozoan versus heterozoan communities in tropical marine environments (Hallock and Schlager 1986; Birkeland 1987; Halfar and Ingle 2003; Halfar et al. 2004, 2006; Pomar et al. 2004; Reijmer et al. 2012). The nutrient availability in the GdA is thus the most important steering factor coupled with the following environmental controls: (1) seasonal trade winds that push the Canary Current south of 21°N, inducing upwelling of nutrients (Mittelstaedt 1991; Sevrin-Reyssac 1993; Barton 1998; Martinez et al. 1999; Pastor et al. 2008); (2) calm water conditions during non-upwelling periods that allow waters to stratify and phytoplankton to grow in the photic layer (Huntsman and Barber 1977) and (3) seasonal offshore-directed winds from the Saharan hinterland providing iron-rich dust as additional fertilizer (Sarnthein and Walger 1974; Sarnthein and Diester-Haass 1977; Brust et al. 2011).

Hence, eutrophic waters play a key role in the ecology of the GdA (see also Fig. 2c, d), particularly in those areas where the plankton-enriched water layers can interact with macrobenthic communities in the shallow BdA (cf. Wolff et al. 1993c). These contact zones were identified at the bank margin along a corridor stretching from north to south between Cap Blanc and Cap Timiris (Fig. 7). Here, the highest Chl-*a* values occur with peaks of >20 mg/m³ (Chl-*a*; Fig. 2d). Secchi-disk measurements support the eutrophic to mesotrophic nature of the outer BdA with oligotrophic waters restricted to the innermost shelf where extensive seagrass meadows prosper. This eutrophic environment makes the NW African waters one of the most productive areas of our oceans (Marañón and Holligan

1999). A high biological productivity (cf. Berghuis et al. 1993) is furthermore indicated by the sedimentological record indicating largely dysoxic and aphotic conditions in the outer shelf of the GdA. Such limiting settings hamper the development of photoautotrophic carbonate biota (e.g., zooxanthellate corals, calcareous green algae, photosymbiont-bearing foraminifera), while filter-feeding, light-independent marine organisms prosper. Profiteers are fast growing high nutrient-related mollusks (e.g., chemoautotrophs; cf. Michel et al. 2011a), filter-feeding balanids and bryozoans; cf. Klicpera et al. 2013, 2014).

Thermocline and hydrodynamic regime

CTD casts taken in the proximal outer shelf and bank environment (topographic nomenclature cf. Hanebuth et al. 2013) show a poor water stratification throughout due to water depths of largely <30 mbsl (Table 1). In addition, offshore-directed winds and a M2-type tidal regime (principal lunar semi-diurnal with amplitudes averaging at 1.61 m; Wolff and Smit 1990) result in strong bank-top currents (velocities of $>3 \text{ m s}^{-1}$), often appearing as a series of stationary waves of up to 1 m in height along the BdA margin (Westphal et al. 2014). These observations agree with local topographic features such as hardgrounds along bank and platform margin, occasionally incised by valleys and large-scale gullies at the BdA margin and in the outer shelf (Fig. 1). Moreover, these features are indicative of a complex oceanography with density currents following topographic contours (Peters 1976). The high-energy setting has also been reported by Sevrin-Reyssac (1993) who related the high diversity of marine environments in the BdA to the complex and strong hydrology. Such hydrological conditions, in particular, make it challenging for marine biota prospering under low-energy regimes, while infaunal or sessile epifaunal filter-feeding taxa benefit from it.

Shelf morphology and substrate

Shelf morphology and substrate relationships were shown in Betzler et al. (1997a, b), Pomar (2001); Pomar and Ward (1995), (1999), and Pomar et al. (2004) to be important drivers of carbonate production. While vast areas of the platform-like northern BdA (Fig. 1, transect A) are covered by mixed carbonate-siliciclastic sands, some exposed Mid-Pleistocene erosion surfaces along the bank margin provide escarpment structures and hardgrounds (details in Hanebuth et al. 2013). Such rare hard substrates meet the ecological requirements of most hardground-related biota (e.g., certain bivalves, balanids, bryozoans) in the GdA and might explain the high amount of balanid grains several tens to up to 100 km away from rocky shoreline (see also

Domain 1985; Duineveld et al. 1993; Michel et al. 2011b; Klicpera et al. 2013, 2014).

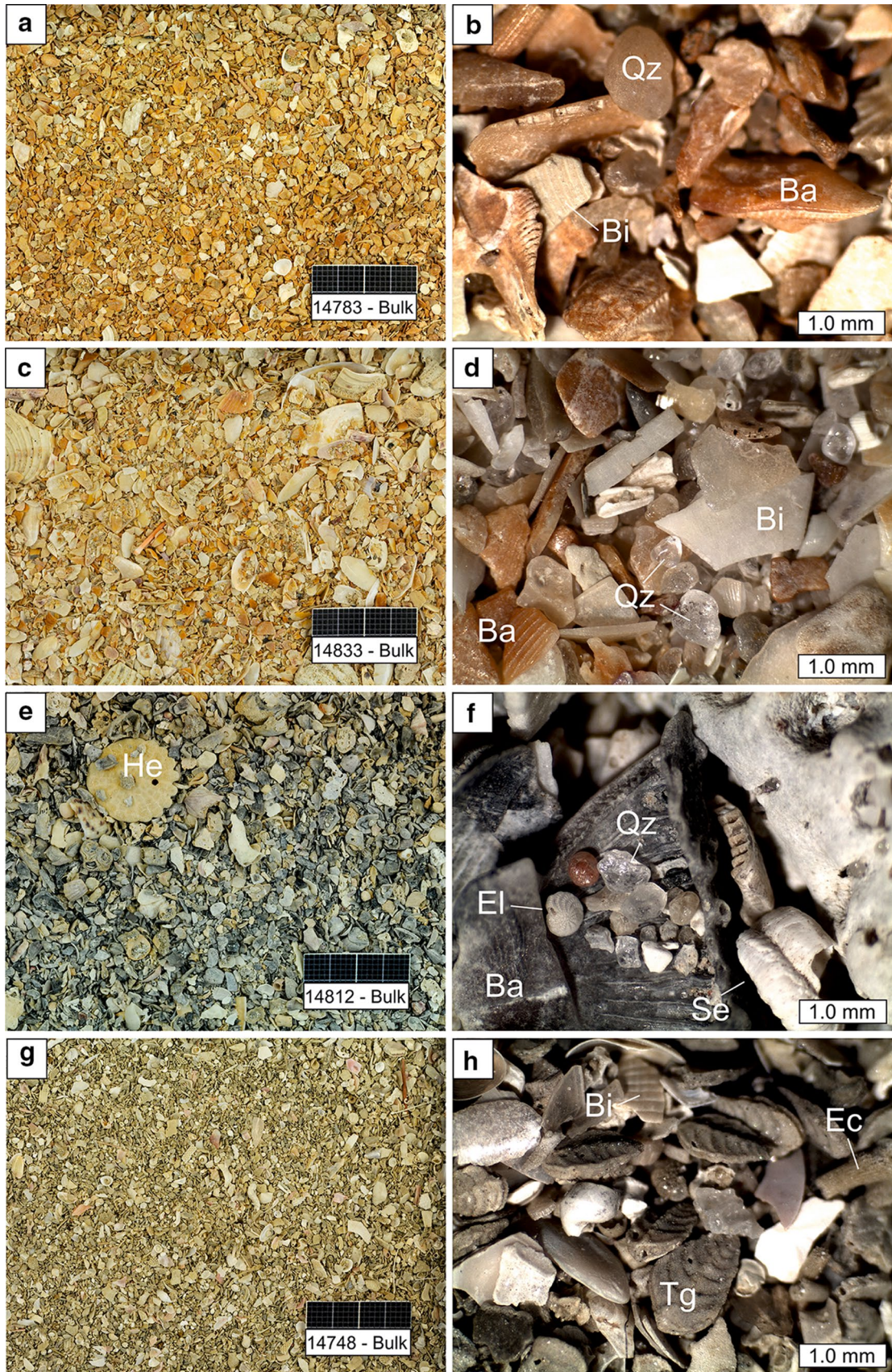
Towards the southern GdA, the shelf profile turns into a ramp profile (Fig. 1, transect B) with a significant siliciclastic input derived from intertidal settings close-by. The development of a platform in the northern GdA and a ramp in the southern half might be related to different relationships between shelf morphology and biotic settings (see Betzler et al. 1997a, b) or unknown regional differential tectonics (cf. Hanebuth et al. 2013).

Terrigenous influence

Input of terrigenous material into the GdA occurs throughout the year but increases during winter storms attributed to Harmattan trade winds (Holz et al. 2004; Michel et al. 2009; Mulitza et al. 2010). Lying adjacent to and downwind of the Saharan Desert and Sahel zone, the GdA is connected to a large source of silt-sized eolian dust (Sarnthein and Walger 1974; Sarnthein and Diester-Haass 1977; Glacum and Prospero 1980), and lies beneath the prevailing dust-loaded wind trajectories. D'Almeida (1989) estimated the amount of Saharan dust at 0.6–0.7 Pg (1 Pg = 10^9 metric tons) year⁻¹, of which about one-third is blown into the North Atlantic Ocean (Duce et al. 1991). The absence of fluvial runoff turns eolian dust into the only terrigenous source of bio-available nutrients (e.g., iron and phosphorus-rich dust; Brust et al. 2011). Winnowing and partitioning lead to redistribution across the shelf and to selective downslope transport along topographically and hydrodynamically defined pathways (Michel et al. 2009; Hanebuth and Henrich 2009). More sand-sized terrestrial input comes from migrating siliciclastic dunes that occupy the coastline bordering the innermost BdA (cf. Mount 1984). Minor amounts of siliciclastics are hydrodynamically reworked submarine paleodunes of which some onshore records are exposed in the Cap Blanc area (Westphal et al. 2014). As a result, resuspended eolian sediments affect most marine habitats in the BdA thus causing reduced water transparencies and aphotic conditions below 2 mbsl. Such settings are restrictive to light-dependent, sessile and slow-growing organisms, not capable to adapt to high sedimentation rates and low light conditions. In contrast, fast-growing soft-bottom dwellers (e.g., certain infaunal mollusks) non-sensitive to high terrestrial loads and aphotic conditions prosper under such setting.

Facies distribution across the entire Golfe d'Arguin

Present biogenic sediments represent a mixture of fresh (Fig. 6c, h; herein called modern) and relict material (Fig. 6a, e; herein called sub-recent) that have been generated in the last several 1,000 years (detailed radiocarbon



◀ **Fig. 6** Bulk sediments collected during MSM16-3 cruise along the platform margin (Banc d’Arguin, Mauritania). **a, b** Baie du Lévrier sample (barnamol assemblage, 14783). **c, d** Central Banc d’Arguin sample (bimol assemblage, 147,833). **e, f** Southern Banc d’Arguin sample (barnamol assemblage with siliciclastics, 14,812). **g, h** Cap Timiris Shelf sample (foramol assemblage with *Tetragonostomina rhombiformis* (Tr), 14,748. *Qz* quartz, *Ba* balanids, *Bi* bivalve mollusks, *Se* serpulids, *Ec* echinoderm fragments, *He* *Heliophora* sp., *El* *Elphidium* sp

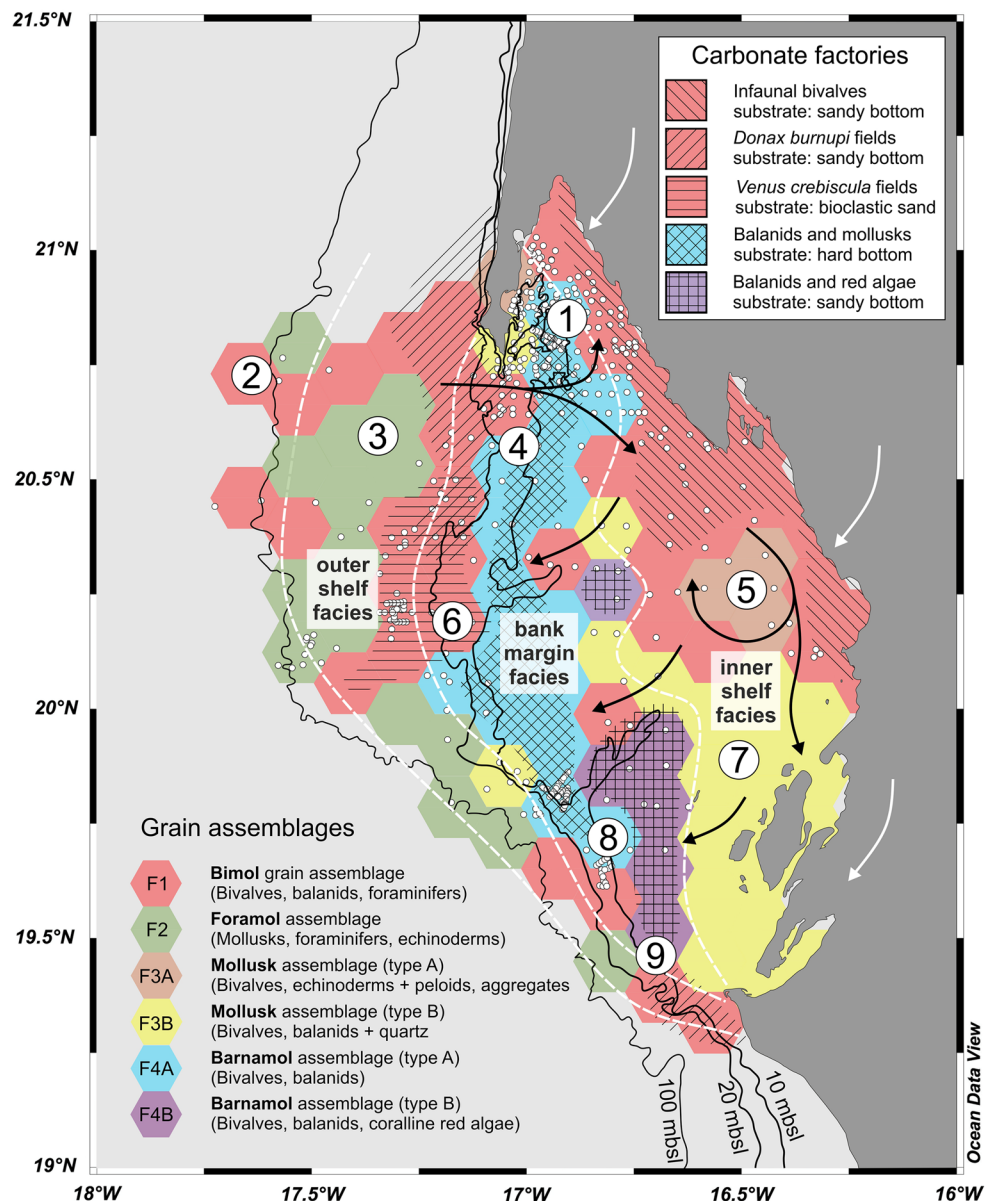
ages in Michel et al. 2011a). Three large facies belts are distinguished in the GdA: (1) a mollusk-dominated inner shelf facies, locally enriched in (a) bivalves (F1; northern GdA), (b) mud with peloids and aggregates (F3A, intrabank depression) or (c) siliciclastics (F3B, southern GdA and intertidal plains); (2) a bank margin facies characterized by

(a) high amounts of balanids and mollusks (F4A) and (b) enrichments in coralline red algae (F4B, southern BdA); and (3) an outer shelf facies showing scattered parautochthonous and allochthonous skeletal material (benthic foraminifers, mollusks, echinoderms) in silty to fine-sandy siliciclastic material (Figs. 7, 8).

Inner shelf facies

The inner shelf shows contrasting marine environments. Bimol grain assemblages (F1) dominate and cover more than 50 % of the inner shelf facies (Fig. 7, Table 5). North of 20°N, the GdA (including bank margin and outer shelf areas) is covered by up to 75 % of sediments referring to the assemblage F1. This pattern coincides with the

Fig. 7 Local distribution of sedimentary facies, grain assemblages and carbonate factories in the Golfe d’Arguin (Mauritania). *Black arrows* indicate swell and wind-controlled surface currents, *white arrows* the prevailing wind trajectories; *numbers* are topographic shelf features: 1 Baie du Lévrier, 2 shelf break (in 80–110 mbsl), 3 outer shelf, 4 Bank d’Arguin margin, 5 inner Banc d’Arguin (Cuvette d’Arguin), 6 central outer Banc d’Arguin, 7 Tidra Island intertidal zone, 8 southern Banc d’Arguin, 9 Cap Timiris shelf. The bank margin follows roughly the 10–20-m isobaths and the shelf edge along the 100-m isobaths



maximum southward displacement of the Canary Current during winter (Mittelstaedt 1991; Hagen 2001; Pastor et al. 2008), which is known to induce upwelling offshore and thus pushes the primary production. Trajectories of oceanic swell and surface currents suggest that the inner shelf bivalve community is linked to food-enriched waters provided by upwelling (Fig. 7). Such bimol assemblages are also known from other modern upwelling regions such as the Western Sahara shelf (Summerhayes et al. 1976), the southern Australian shelf (James et al. 1992, 2001), the Gulf of California (Halfar et al. 2004, 2006) or the Gulf of Panama (Reijmer et al. 2012) and clearly demonstrate that a high-productive but low-diverse bimol assemblage can exist in low latitudes.

Parts of the innermost shelf (Cuvette d'Arguin, Fig. 1) show increasing water depths (>20 mbsl) with a low-energy mollusk grain assemblage (F3A) dominated by benthic foraminifers, aggregates, and peloid grains in a very

fine-grained matrix (Fig. 7, Table 5). These elements indicate calm hydrological conditions below storm wave-base, a setting limited to restricted marine environments in the Cuvette d'Arguin and in the BdL that are protected from oceanic swell (Aleman et al. 2014).

The southern inner shelf facies around Tidra Island is characterized by intertidal conditions with extensive sea-grass plains and a dominant siliciclastic input. The sedimentary cover shows an undifferentiated infaunal mollusk grain assemblage (F3B) with high contents of terrestrial quartz grains due to the proximity to the desertic hinterland (Fig. 7, Table 5). Seagrass plains (*Zostera noltii*) represent the largest primary producer of organic carbon (Wolff and Smit 1990) and provide similarly a rich food resource and habitat for intertidal mollusk and decapod species. The abundant bivalve *Anadara senilis*, for example, provides a biomass contribution of (8.1 g m⁻² ash free dry weight = 48 % of the total tidal flat biomass; Wolff et al.

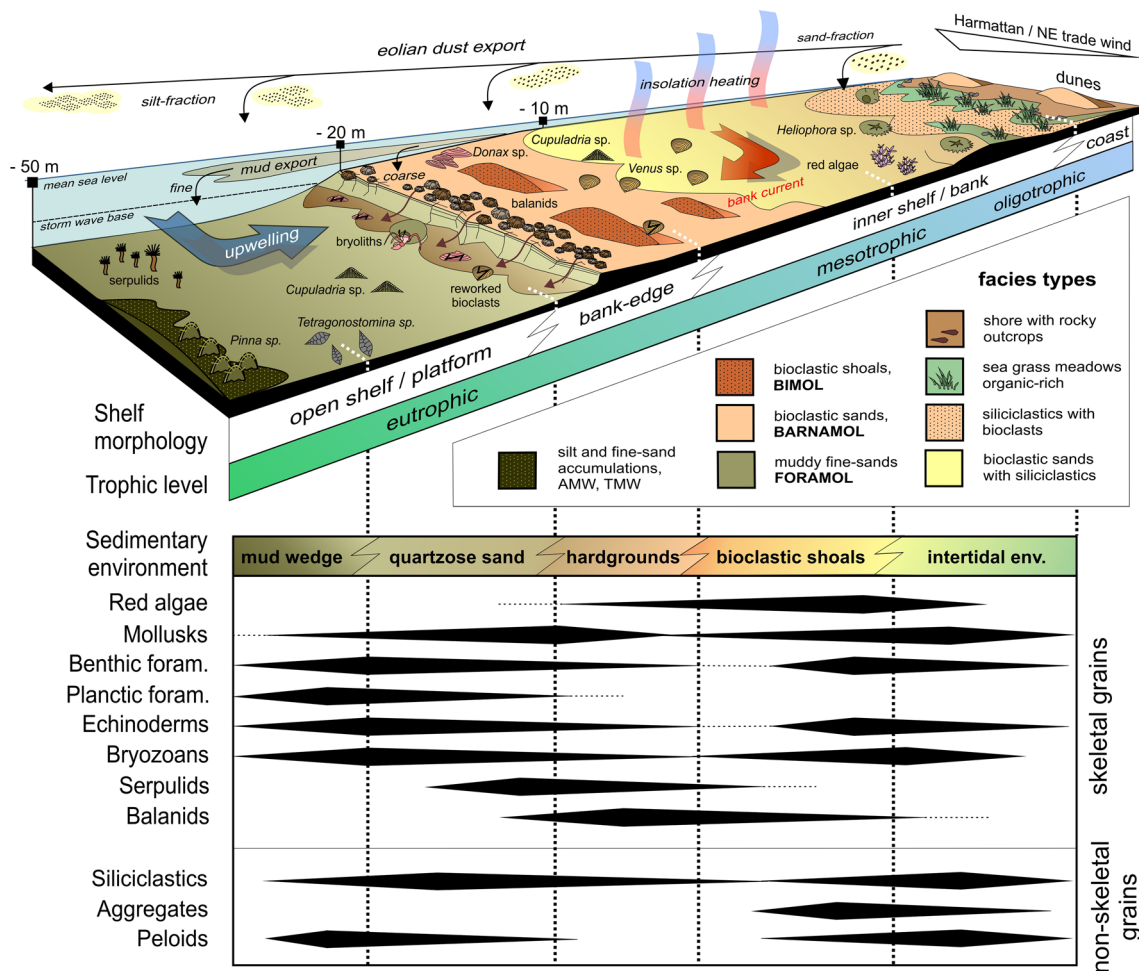


Fig. 8 Facies model of an idealized transect from the outer shelf (platform environment; 20–50 mbsl) over the bank margin in 10–20 mbsl to the inner shelf (Banc d'Arguin; <10 mbsl) and intertidal plains of the nearshore environments (<5 mbsl). Skeletal and non-

skeletal grains characterize the depositional environments and define grain assemblages that are organized in related facies zones (cf. Fig. 7)

1993b) thus representing the most important macrobenthic mollusk taxon in the intertidal inner shelf and a main contributor to nearshore bimol assemblages.

Bank margin facies

The facies distribution in the outer BdA shows a dominant barnamol assemblage (F4A; Fig. 7; Table 5) that covers the entire bank margin (10–20 mbsl) along a narrow corridor from the BdL over the central BdA down to the CTS (19.5°N). Exposed Mid-Pleistocene erosion surfaces provide submarine hardgrounds along the bank margin that favor the development of a light-independent and suspension-feeding balanid community, able to cope with strong hydrodynamics and eutrophic conditions. Modern and sub-recent balanid remains (mostly preserved as disarticulated plates) are ubiquitous in all samples from the bank margin and BdL and indicate an important, yet relatively poorly investigated contributor of carbonate. Although barnamol assemblages are usually associated with cool-temperate water regimes (cf. Hayton et al. 1995), balanids are today cosmopolitan players due to human-mediated translocations (Carlton et al. 2011).

Larger bimol grain assemblages (F1, Fig. 7) appear close to upwelling hotspots (south of Cap Blanc and in the CTS area) and indicate high-nutrient settings by an often-dominant appearance of *Donax burnupi* (1–40 mbsl) and *Venus crebriculca* (4–25 mbsl). The ecological requirements of these two species agree with upwelling conditions; they are well known for their high productivity in nutrient-rich waters (cf. Ansell 1983).

Towards the southern BdA, barnamol assemblages are enriched in remains of calcareous red algae (F4B; Fig. 7; Table 5). Although the presence of red algae could not be confirmed by the MSM16-3 cruise, a number of studies provide data on restricted red algae occurrences (Piessens 1979; Koopmann et al. 1979; John et al. 2004). Some even confirm the presence of Maërl-forming taxa (e.g., *Lithothamnion* sp.; *Lithophyllum* sp.) in the outer BdA (Birkett et al. 1998; Jackson 2003; Goudswaard et al. 2007). Based on the component analysis of GdA-wide data, red-algal contents remain low (<3 % in the inner BdA) with restricted enrichments of up to >50 % (fractions >500 µm; Fig. 4e) in the southern BdA (Piessens 1979).

Outer shelf facies

The outer shelf (>30 mbsl) shows sediments with a fine-grained quartzose texture and scattered reworked bioclasts of the foramol assemblage (F2; Figs. 4g, h; 7; Table 5). Skeletal grains are largely reworked by biological (e.g., boring sponge *Cliona* sp.) and physical abrasive processes, implying that the material originates from remote

production areas (e.g., bank-, nearshore environments). Such processes were shown in Hallock (1988) to significantly influence carbonate production and accumulation, especially under eutrophic tropical conditions. The outer shelf thus acts as a large-scale depositional plane for parautochthonous and allochthonous skeletal and fine-clastic material (e.g., AMW, TMW; Fig. 8) deposited under comparatively little hydrodynamic activity and below the storm wave-base (Michel et al. 2009). The presence of endobenthic chemosymbiotic bivalves (e.g., *Anodontia* sp., *Solemya togata*) in the outer shelf underlines the constraining nature of this environment characterized by an upwelling-induced high productivity with resulting dysoxic and aphotic sea bottom conditions (Figs. 7, 8).

Past and present tropical heterozoan carbonate systems

The sedimentary composition in the GdA largely corresponds to the temperate-water foramol association sensu Lees and Buller (1972). Within this association, distinct heterozoan grain assemblages exist, whose constituents show both, elements typical of extra-tropical carbonates (e.g., mollusks, balanids, bryozoans, foraminifers, red algae), and tropical indicators (e.g., tropical bivalves and gastropods), see Kindler and Wilson (2010) for details. This dichotomy suggests that modern heterozoan carbonate formation in low latitudes (Table 6) is not straightforward, and that classical depositional models sensu Lees and Buller (1972) or James and Clarke (1997) should be used carefully and with critical reflection. As shown in this study, the oceanographic setting largely overprints carbonate formation by seasonally shifting thermal fronts, intermittent mixing processes and an upwelling-induced high-nutrient regime causing low light conditions. Coastal environments, in contrast, are less influenced by upwelling phenomena but show more terrestrial influences.

This ‘atypical’ modern carbonate production is reflected best in the diversity pattern of bivalves representing ubiquitous components in all samples from the GdA. Their biodiversity is remarkably low (approx. 200 species; Michel et al. 2011a, b) compared to other tropical and sub-tropical locations (650–1200 species; Crame 2000), while their composition shows cosmopolitan and endemic NW African and tropical taxa (Table 4, Suppl. 1).

Such a pattern is characteristic of eutrophic marine environments favoring the development of a high productive filter-feeding communities (e.g., bivalves, balanids, bryozoans) that are well adapted to only sporadic food availability and changing hard substrate availability.

Similar heterozoan carbonate environments are known from other modern and ancient settings worldwide (see also Table 6). The careful analysis of carbonate sediments including associated drivers, but also players, ideally on species level, is the key to identify the environmental context

Table 6 Selected modern and ancient heterozoan carbonates in subtropical to tropical warm-water settings

Location	Latitude/Longitude	Temp (°C)	Chl- <i>a</i> (mg/m ³)	Trophic regime	Carbonate grain assemblage	Environmental steering factors	Period (age)	Reference
Golfe d'Arguin (NW-African Shelf)	20°7'N/16°59'W	<18–>26	3–>10	Mesotrophic—eutrophic	Foramol, bimol, barnamol	Upwelling, dust-input	Modern	This study; Michel et al. 2011a
Gulf of Panama	8°7'N/79°34'W	20–28	0.2–>10	Mesotrophic—eutrophic	Foramol, barnamol	Upwelling	Modern	Reijmer et al. 2012
Gulf of California	27°50'N/111°58'W	10–<19	<1–1.5	Oligotrophic—eutrophic	Chlorozoan	Upwelling	Modern	Halfar et al. 2006
Gulf of Mexico (Yucatan Shelf)	22°22'N/88°31'W	17–30	1	Mesotrophic—eutrophic	Foramol	Upwelling	Modern	Logan et al. 1969
Gulf of Mexico (West Florida Shelf)	27°44'N/84°3'W	18–30	0.5	Mesotrophic	Chloralgal	Nutrients fluvial input	Modern	Goud and Steward 1956
Gulf of Mexico (Nicaragua rise)	14°8'N/82°16'W	25–30	0.2–0.3	Oligotrophic—mesotrophic	Chloralgal	Upwelling	Modern	Halloek et al. 1988
Balearic Islands (W-Mediterranean)	39°21'N/2°4'E	Tropical	Changing trophic conditions	Changing trophic conditions	Foramol, rhodalgal, chlorozoan	Changing climate, terrigenous input	Miocene	Pomar et al. 2004
Latium-Abuzzi platform (Apennines)	41°51'N/13°53'E	Subtropical – tropical	Change from oligotrophic to eutrophic settings	Change from oligotrophic to eutrophic settings	Foramol, rhodalgal, chlorozoan	Orogenic activity	Miocene	Brandano and Corda 2002

Data extracted from Westphal et al. (2010) and Reijmer et al. (2012)

and to achieve a robust reconstruction or paleoenvironmental settings. The GdA provides such a valuable example for a world without coral reefs and thus serves as a modern analogue for conditions preserved in the fossil record.

Conclusions

- (1) Modern heterozoan carbonates in the tropical Golfe d'Arguin off northern Mauritania are characterized by a strong multi-dimensional control that is attributed to upwelling-induced eutrophic settings, low illuminations, and tropical water temperatures governing a shallow-marine carbonate factory (Banc d'Arguin).
- (2) A characteristic foramol association with distinct bimol and barnamol grain assemblages exists in the shallowest areas. Dominant components are bivalves, balanids, benthic foraminifers and other filter feeders—subordinate components are serpulids, echinoderms, and red algae. Photosymbiotic organisms such as zooxanthellate corals are entirely absent, although the setting is tropical.
- (3) By combining new and existent surface sediment data, we could reconstruct the full sediment pattern in the Golfe d'Arguin. Sedimentary components are mixed carbonate–siliciclastic showing a well-adapted, light-independent marine biota whose skeletal remains are organized in six mollusk-dominated assemblages and along three larger facies belts.
- (4) This modern analogue of a tropical heterozoan carbonate system demonstrates the response of a shallow-marine ecosystem to eutrophication and desertification. Moreover, it clearly demonstrates that a “cool water-related” heterozoan carbonate fauna can exist in low-latitude high-nutrient settings. It thus provides invaluable insights for the classification and interpretation of tropical eutrophic settings in the fossil record and provides an important model for future perspectives in the context of climate change.

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