Heterozoan carbonate sedimentation on a eutrophic, tropical shelf of Northwest Africa (Golfe d'Arguin, Mauritania)

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Hiermit erkläre ich, dass ich die vorliegende Doktorarbeit selbständig und ohne Zuhilfenahme unerlaubter Hilfsmittel erstellt habe. Weder diese noch eine ähnliche Arbeit wurde an einer anderen Abteilung oder Hochschule im Rahmen eines Prüfungsverfahrens vorgelegt, veröffentlicht oder zur Veröffentlichung vorgelegt. Ferner versichere ich, dass die Arbeit unter Einhaltung der Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft entstanden ist.

Julien Michel

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ABSTRACT

Modern carbonate sedimentation takes place on the northern Mauritanian shelf (20°N), where typical tropical components (e.g. hermatypic reefs, calcareous green algae) are absent. Such deposits are reminiscent of extratropical sediment in the geological record. The tropical open shelf of Mauritania is influenced by large siliciclastic dust input and upwelling, highly fertilizing the ocean, as well as strongly limiting the light penetration. In this context, temperature does not appear to be the steering factor of carbonate production. This thesis describes the depositional system of the Golfe d'Arguin off Mauritania and focuses on environmental conditions that control the depositional pattern, in particular carbonate production. The description of this modern analogue provides a tool for paleoenvironmental interpretation of ancient counterparts.

The Golfe d'Arguin is a broad shallow shelf comprising extensive shoals (<10 m water depth; i.e. the Banc d'Arguin) on the inner shelf where waters warm up. The sediments collected in water depths between 4 and 600 m are characterized by mixed carbonate and siliciclastic (dust) deposits. They vary from clean coarse-grained, almost pure carbonate loose sediments to siliciclastic-dominated fine-grained sediments. The carbonate content and sediment grain size show a north-south decreasing pattern through the Golfe d'Arguin and are controlled by the hydraulic regime influenced by wind-driven surface currents, swell, and tidal currents.

The carbonate grain association is heterozoan. Components include abundant molluscs, foraminifers, and worm tubes, as well as barnacles and echinoderms, elements that are also abundant in extratropical sediments. The spatial distribution of the sedimentary facies of the Golfe d'Arguin does not display a depth zonation but rather a mosaic (i.e. patchy distribution). The depth and climatic signatures of the different sedimentary facies are determined by taxonomic and ecological investigations of the carbonate-secreting biota (molluscs and foraminifers). While certain planktonic foraminifers and molluscs represent upwelling elements, other components (e.g. mollusc and benthic foraminifer taxa) demonstrate the tropical origin of the sediment. The nutrient-rich (and thus also low light-penetration) conditions are reflected in the fact that symbiotic and photosynthetic carbonate-producing organisms (e.g. hermatypic corals) are absent.

The Mauritanian deposits represent an environment that is rare in the modern world but might have been more common in the geological past when global temperatures were higher. Taxonomic and ecological studies allow for distinguishing carbonate sediments formed under either tropical high-nutrient or extratropical conditions, thus improving paleoclimate reconstruction.

ZUSAMMENFASSUNG

Auf dem nördlichen Schelf vor Mauretanien (20°N) findet rezente Karbonatsedimentation statt, wobei tropische Karbonat-Komponenten (z.B. hermatype Riffe, kalkige Grünalgen) nicht ausgebildet sind. In fossilen Gesteinsabfolgen werden solche Karbonatsedimente oft als nicht-tropische Karbonat-Ablagerungen interpretiert. Der tropische Schelf vor Mauretanien ist durch erhöhten Staub-Eintag von Siliziklastika und Auftrieb von kaltem, nährstoffreichem Wasser („upwelling") charakterisiert. Diese Faktoren führen zu einem erhöhtem Nährstoffangebot im Oberflächenwasser und vermindern dadurch die Eindringtiefe des Sonnenlichtes. Die vorliegende Arbeit beschreibt den Sedimentationsraum im Golf d'Arguin auf dem mauretanischen Schelf, unter besonderer Berücksichtigung der Umweltfaktoren welche die Karbonatproduktion steuern. Anhand der Beschreibung dieses Rezent-Beispiels lassen sich Rückschlüsse auf Paläo-Umweltbedingungen in ähnlichen Ablagerungsräumen der geologischen Vergangenheit ziehen.

Der Golfe d'Arguin auf dem inneren Schelfbereich ist überwiegend Flachwasser dominiert (Wassertiefe < 10 m, Banc d'Arguin) und das kalte Tiefenwasser erwärmt sich dort. Sedimentproben aus Wassertiefen zwischen 4 und 600 m bestehen aus kalkigen Komponenten, sowie siliziklastischem Material (Staubeintrag). Die Korngrößen variieren zwischen grobkörnigen, kalkigen Lockersedimenten und feinkörnigen Siliziklastika. Die Korngröße und der Karbonatgehalt der Sedimente im Golfe d'Arguin zeigen einen Nord–Süd Trend, wobei die Korngröße und der Karbonatgehalt nach Süden hin abnehmen. Diese beiden Parameter sind durch das hydraulische Regime gesteuert, welches durch die Gezeiten, Dünung und wind-gerichtete Oberflächenströmungen beeinflusst wird.

Die Assoziation der Karbonatkomponenten ist „Heterozoan" mit zahlreichen Arten von Mollusken, Foraminiferen, Röhrenwürmer, Balaniden und Echinodermaten. Diese Faunengemeinschaft ist vergleichbar mit nicht-tropischen Faunen. Eine Tiefenzonierung der Karbonatsedimentfazies ist nicht erkennbar. Die räumliche Verbreitung der Sedimente ist ungleichmäßig. Die Wassertiefe und die klimatischen Bedingungen während der Ablagerung der Sedimente wurde anhand der Taxonomie und Ökologie der häufigsten karbonatproduzierenden Organismen (Mollusken und Foraminiferen) ermittelt. Bestimmte Arten von planktonischen Formainiferen und Mollusken zeigen den Einfluss von kaltem Wasser durch upwelling, wohingegen einig Arten benthonischer Foraminiferen und Mollusken tropische Bedingungen anzeigen. Symbiontische oder Photosynthese-Betreibende Karbonatproduzenten (z.B. zooxanthellate Korallen) sind nicht vorhanden, was auf den erhöhten Nährstoffgehalt und die dadurch reduziert Eindringtiefe des Sonnelichtes zurückzuführen ist.

Die Ablagerungsbedingungen für Karbonatsedimente wie sie heute auf dem mauretanischen Schelf vorkommen sind weltweit nur selten ausgebildet. In der geologischen Vergangenheit waren ähnliche Sedimentationsräume in warmen Perioden vermutlich häufiger vorhanden. Hochauflösende, taxonomische und ökologischen Studien der Faunengemeinschaften liefern wichtige Hinweise für die Diskriminierung zwischen nicht-tropischen Karbonaten und Karbonatsedimenten aus nährstoffreichen tropischen Ablagerungsräumen und verbessern Paläoklima-Rekonstruktionen.

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I. INTRODUCTION

The occurrence of *cold-water carbonates* in warm waters and the occurence of *non-tropical carbonates* in the tropics are obvious paradoxes of shallow-water carbonate sedimentation. These paradoxes do not only represent a misleading nomenclature but point out the limitation of carbonate sedimentation models based solely on water temperature and latitudinal distribution (cf. Rao, 1996; Flügel, 2004). Carbonate associations that are typical for non-tropical and cool-water settings do occur in the tropics where other environmental factors than temperature (e.g. light penetration, nutrient level, salinity, substrate, water energy, and water chemistry) constrain the development of the carbonate-producing biota (cf. Henrich et al., 1995; Pomar et al., 2004; Wilson & Vecsei, 2005; Westphal et al., subm.). The common picture of tropical carbonates corresponding to coral reef, green algae, or lime mud environments hides away the broader diversity of tropical carbonate shelves. This should be kept in mind when interpreting paleoenvironments and paleoclimates of "non-tropical" carbonates. Furthermore, systematic recognition and distinction of "non-tropical" carbonate grain associations from tropical and temperate realms should be investigated.

In the context of modern climate change, there is an increasing demand for future climatic projections. These climatic projections are primarily constrained by current knowledge of past climate. Therefore, the accuracy of sedimentary models is a crucial prerequisite of past climate reconstructions. Shallow-marine carbonate deposits constitute an excellent tool for revealing earth history. Carbonate sediments which are produced by organisms reflect the environmental conditions at their contemporaneous time of formation. Therefore, carbonate sediments and rocks are multiproxy archives (e.g. temperature, salinity, trophic resources, water depth, light intensity, oxygen, and water energy) for paleoenvironmental reconstructions (Tucker & Wright, 1990; Flügel, 2004).

Three different carbonate factories are currently recognized: (1) the tropical shoal-water factory, (2) the cool-water factory, and (3) the mud-mound factory (Schlager 2000, 2003). Characteristic components of the tropical factory are photo-autotrophic organisms (e.g. calcareous green algae, hermatypic corals, certain foraminifers, and certain molluscs) and abiotic-precipitated products such as marine cements and ooids. In the modern ocean, the tropical factory is found between the latitudes 30°N and 30°S. The cool-water factory is dominated by heterotrophic organisms that include non-symbiotic molluscs and foraminifers, bryozoans, barnacles, and red algae. The oceanic environment of the cool-water factory is described as photic or aphotic waters that are cool enough to exclude competition by the tropical factory and sufficiently winnowed to prevent burial by terrigenous fines. The characteristic component of the mud-mound factory is fine-grained carbonate the precipitation of which is caused by a complex interplay of biotic and abiotic reactions with microbes (Pratt, 2000). The typical environment of the mud-mound factory is dysphotic or aphotic, nutrient-rich waters which are low in oxygen but not anoxic.

Such carbonate model which opposes the tropical and the cool-water factories finds its origin in the history of carbonate sedimentation research. Until the end of the 1960s, carbonate environments were exclusively considered in tropical warm waters (cf. James, 1997; Pomar et al., 2004). Hermatypic coral reefs, ooids, and lime mud represented the typical carbonate elements used as analogue for paleoclimate studies. The publications of Chave (1967), Lees and Buller (1972), and Lees (1975) were the founding works for the recognition of extra-tropical carbonates, the so-called foramol association in which typical tropical elements (e.g. hermatypic coral reefs, calcareous green algae, and ooids) are absent. In the foramol association, foraminifers and molluscs are almost always present and may be dominant (cf. Tab. I.1). Other constituents of this association are echinoderms, bryozoans, barnacles, ostracods, sponges (calcareous spicules), worms (tubes), ahermatypic corals, and calcareous red algae. Synonyms of the foramol association that are based on latitude, water temperature, and light dependence are non-tropical (Nelson, 1988a), cool-water (Rao, 1996; Schlager, 2000), and heterozoan (James, 1997) carbonates, respectively. In addition to the elements of the foramol association, the tropical associations chlorozoan and chloralgal always contain hermatypic corals and calcareous green algae, respectively (cf. Tab. I.1). These two associations constitute the tropical (Nelson, 1988a; Rao, 1996; Schlager, 2000) or photozoan (James, 1997) carbonates. Lees and Buller (1972) and Lees (1975) showed that while chlorozoan and chloralgal associations were prominent and exclusively found in tropical latitudes, foramol associations were present in higher latitudes as well as inside the tropical belt (i.e. between 30°N and 30°S).

From the 1980s onward, carbonate sedimentology focused on foramol associations which are found in temperate and polar waters (i.e. outside the tropical belt; e.g. Nelson, 1988b; James et al., 1992; Freiwald & Henrich, 1994; James & Clarke, 1997). Carbonate sediments were classified in terms of latitude, mostly based on the water-temperature factor controlling the carbonate production (cf. Tab. I.2). Tropical and non-tropical carbonates, the latter being further split into temperate and polar, were recognized (Nelson, 1988a; Rao, 1996; Schlager, 2003). In addition, warm-temperate and cold-temperate associations were defined (Brookfield, 1988; Betzler et al., 1997; cf. Tab. I.3). Inside the cool-water carbonate group and based on high taxonomic levels, several subassociations were described such as rhodalgal, molechfor, bryomol, and bimol (Carannante et al., 1988; Nelson et al., 1988; Hayton et al., 1995; cf. Tab. I.1). In such a context, shallow-water heterozoan carbonates found in tropical areas were considered as exceptions due to upwelling occurrence (e.g. Carannante et al., 1988) or cold-water current influence (Nelson, 1988a; Rao, 1996; Fig. I.1) and no further attention was given to them. However, heterozoan associations are encountered under different climatic regimes. Foramol carbonates are produced off the Sahara desert as well as off the Norwegian fjords, and therefore, paleoclimatic interpretation of such deposits should be constrained by accurate environmental proxies.

Tab. I.1 Terminology of shallow-water carbonate grain associations (see Flügel, 2004 for a more extensive list, Box 12.9, p.627).

Carbonate associations *sensu* Lees & Buller (1972)	**Descriptive-term association**	**Dominant or characteristic biota**	**Additional biota**	**Light-related term (James, 1997)**	**Latitude-related term (Nelson, 1988; Schlager, 2000)**
Chlorozoan	Chlorozoan (Lees & Buller, 1972)	Zooxanthellate corals and calcareous green algae	Benthic foraminifers, branching coralline algae, molluscs, non-skeletal grains	Photozoan	Tropical
	Chloralgal (Lees, 1975)	Calcareous green algae	Benthic foraminifers, branching coralline algae, molluscs		
Foramol (s.l.)	Foramol (s.l.) (Lees & Buller, 1972)	Benthic foraminifers and molluscs	Echinoderms, bryozoans, barnacles, ostracods, sponge spicules, worm tubes, ahermatypic corals and calcareous red algae	Heterozoan	Non-tropical or cool-water
	Bryomol (Nelson, 1988)	Bryozoans (>50%) and bivalve molluscs (infaunal and epifaunal)	Benthic foraminifers, echinoderms, calcareous red algae, barnacles		
	Rhodalgal (Carannante et al., 1988)	Encrusting coralline algae (>80%)	Bryozoans, benthic foraminifers, barnacles, bivalves, echinoderms		
	Molechfor (Carannante et al., 1988)	Molluscs and benthic foraminifers	Echinoderms, barnacles, serpulids and bryozoans		
	Bimol (Hayton et al., 1995)	Bivalves (infaunal and/or epifaunal; >60%, up to 80%)	Bryozoans, benthic foraminifers, echinoderms, calcareous red algae, barnacles		

Tab. I.2 Latitudinal distribution and critical sea-water temperatures of modern tropical, temperate, and polar carbonate settings (after Flügel, 2004, Fig. 2.9, p.34).

	Latitudinal range	Sea-water temperature	Sub-division	Latitudinal range	Sea-water temperature
Polar carbonates	>50° N and S	Cold water <5-10°C (mean) -1.5 to 16°C (range)	Polar	>60°N and S (to >70°N)	<5°C
			Subpolar	>50° to <60°N and S	5-10°C
Temperate carbonates	30°-50° (60°) N and S	Cool water ~10-18°C (mean) >10 to 25°C (range)	Cool-temperate	30° to 50°N and S	5-10°C
			Warm-temperate	25° to >30°N 25° to 30°S	10-18°C
Tropical carbonates	30°N to 30°S	Warm water 18 to 22°C (mean) 18 to 30°C (range)	Subtropical	30°N to 30°S	18-22°C
			Tropical		>22°C

Tab. I.3 Main characteristics of „non-tropical“ or „cool-water“ carbonate associations: warm-temperate, cold-temperate, and polar carbonates (cf. Brookfield, 1988; Betzler, 1997).

Carbonate association	Environment	Non-carbonate flora	Dominant/characteristic biota	Additional biota
Warm-temperate	Protected from open ocean swell (mobile or phytal substrate)	Seagrass	Large benthic foraminifera, red algae, bryozoans	Molluscs, foraminifera, echinoderms, sponge, solitary corals
	Open shelf (hard-and rockgrounds and phytal substrate)	Kelp		
Cold-temperate		Seagrass/kelp	Bivalves, bryozoans, serpulids, barnacles, red algae, echinoderms	Molluscs
Polar		Kelp	Red algae, sponges	Brachiopods, bryozoans, echinoderms, molluscs

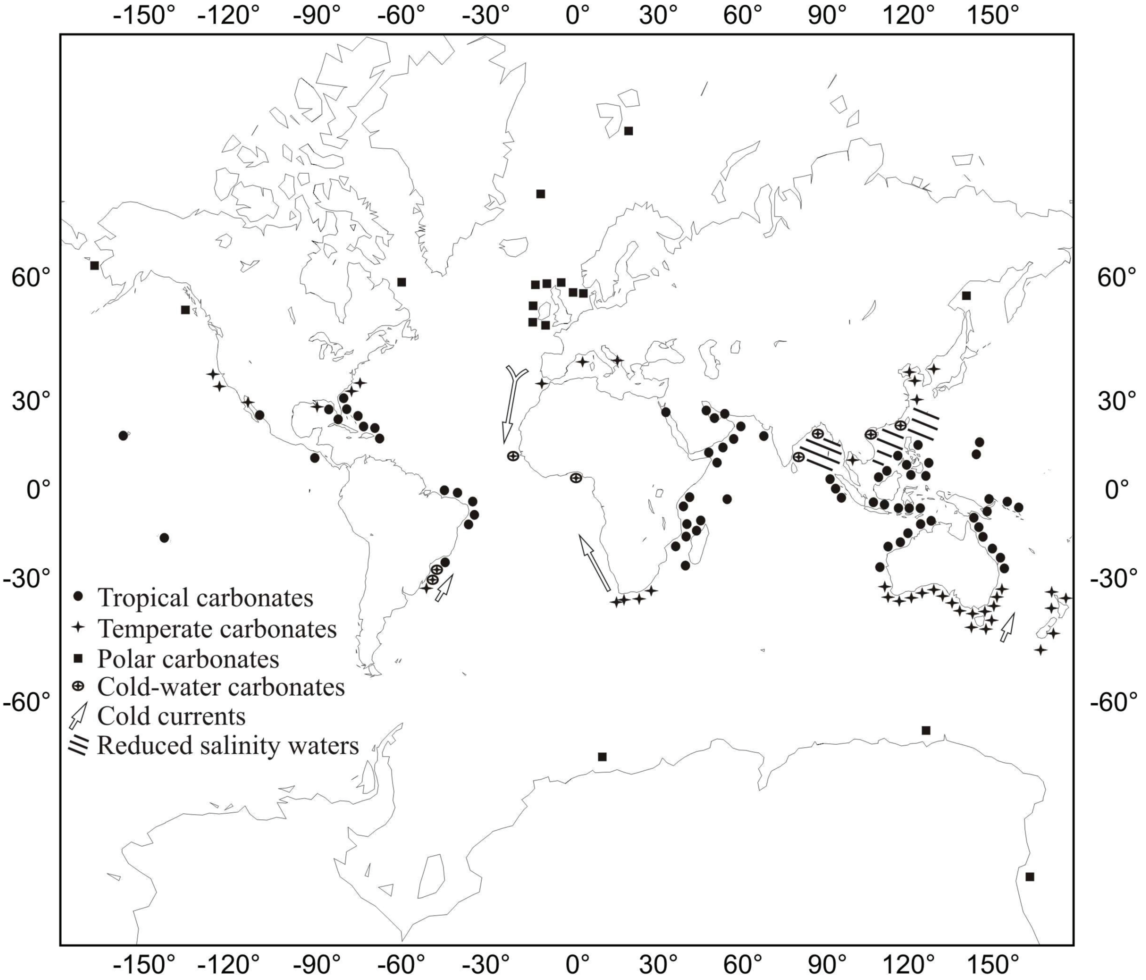

Fig. I.1 Localities of documented occurrences of tropical, temperate and polar shoal-water carbonates. The presence of cold-water carbonates in tropical regions is explained by cold current incursions or reduced salinity waters (redrawn from Nelson, 1998; Rao, 1996).

Carbonate grain association models based solely on temperature and/or latitude clearly underestimate the complex interplay of the wide spectrum of environmental factors (e.g. temperature, salinity, trophic resources, light penetration, and substrate) affecting carbonate production. During the last decades, an increasing number of works dealing with enhanced nutrient levels and their effects on carbonate production allow for a more complex understanding of carbonate-producing biota ecosystems (Margaleff, 1968; Hallock & Schlager, 1986; Birkeland, 1987; Wood, 1993; Brasier, 1995; Mutti & Hallock, 2003; Hallock, 2005). These works represent a base to study modern heterozoan carbonate occurrences at low latitudes (Whalen, 1995; Wilson & Vecsei, 2005; Halfar et al., 2006; Westphal et al., subm. and reference therein) and ancient nutrient-rich, tropical and subtropical carbonate settings (Upper Cretaceous-Gischler et al., 1994; Miocene-Brandano & Corda, 2002; Carboniferous-Samankassou, 2002; Miocene-Pomar et al., 2004; Palaeogene-Coffey & Read, 2007; Miocene-Cornée et al., 2009; cf. Tab. I.4).

Tab. I.4 List of sedimentary records of warm-water heterozoan carbonate grain assciation and their environmental interpretation.

Sites	Period	Carbonate grains	Paleoenvironment/Interpretation	Reference
Zsámbék Basin, Hungary	Miocene (Sarmatian)	Lagoon and carbonate ramp (up to 50 m water depth): Dominance of non-skeletal grains (peloids, ooids, oncoids, aggregates and lithoclasts), poorly diversified biota; benthic foraminifers, bryozoans, molluscs, ostracods, serpulid worms, nubeculariids, microbialites, red algae	Tropical Fluctuating salinities, meso- to eutrophic conditions	Cornée et al., 2009
Balearic Islands, Spain	Miocene (Tortonian)	Carbonate ramp: -Inner: molluscs-foraminifers (interpreted as seagrass meadows) -Middle: red algae, echinoids, bryozoans, molluscs; benthic and large foraminifers -Upper: red algae; benthic foraminifers, echinoids, bryozoans, molluscs	Tropical Fluvial runoff, nutrient delivery (mesotrophic), low light penetration	Pomar et al., 2004
Apennines, Italy	Miocene (Aquitanian-Tortonian)	Carbonate ramp: -Inner: barnacles, molluscs-benthic foraminifers (mud-rich) and red algae (interpreted as seagrass meadows), *Porites sp* -Middle: red algae, molluscs, large foraminifers -Outer: echinoids, benthic and planktonic foraminifers, pectinids, bryozoans, sponge spicules	Tropical Elevated nutrient levels	Brandano & Corda, 2002; Pomar et al., 2004
North Carolina, USA	Paleogene	Warm water-related large foraminifers and molluscs within bryozoan-mollusc-rich carbonate assemblage; echinoderms, diatoms, barnacles, brachiopods, sponge spicules, benthic and planktonic foraminifers	Subtropical Warm, nutrient-rich waters	Coffey & Read, 2007
Northern Spain	Upper Cretaceous	Carbonate ramp: Large benthic foraminifers, bryozoans, echinoderms, bivalves, peloids; coralline algae, solitary corals	Tropical-Subtropical? Warm waters, nutrient surplus (runoff from land or upwelling?)	Gischler et al., 1994
Carnic Alps, Austria-Italy	Carboniferous (Pennsylvanian)	Brachiopods-bryozoans; foraminifers, ostracods, red algae, crinoids, sponge spicules	Equatorial Upwelling	Samankassou, 2002

The lack of both systematic description and sedimentary model leads to the problematic recognition of tropical carbonate deposits produced under cooler water-influenced, nutrient-rich, and/or light-depleted conditions. Therefore, as achieved in the present thesis, a taxonomic, sedimentological, and oceanographic description of modern analogues and the determination of suitable proxies will allow for a better recognition of such sedimentary environments and their interpretation.

II. OBJECTIVES

Studies on deposits of both tropical photozoan and extra-tropical heterozoan carbonates have defined a useful framework to interpret the sedimentary record on the basis of grain associations (Lees & Buller, 1972; Lees 1975; Nelson, 1988a; James, 1997). However, heterozoan carbonates in the tropics have received less attention and this leads to the problematic recognition of ancient deposits (Wilson & Vecsei, 2003; Pomar et al., 2004; Westphal et al., subm.). The objective of the present thesis is to fill this gap in our knowledge. For this purpose, we study a modern analogue of a warm-water heterozoan carbonate sedimentation that will allow for the comparison with sedimentary records produced under eutrophic tropical conditions. Off Northwest (NW) Africa, the broad and shallow open shelf of the Golfe d'Arguin represents a rare example of the modern world where nutrient-rich waters are upwelled in a warm-water setting and, therefore, constitutes a unique place to undertake this modern analogue study. We investigate the spatial distribution and the grain composition of the sediments, as well as the environmental conditions (e.g. water energy, water temperature, and trophic conditions) that control the carbonate production. In addition, investigation focuses on the ecological requirements of the dominant carbonate-secreting biota (i.e. molluscs and foraminifers) that relate the carbonate production to its environment.

To be more specific, this study aims at:

- defining the sedimentation pattern; i.e. spatial distribution and transport of carbonate and siliciclastic materials of the northern Mauritanian shelf.
- describing the sedimentary facies for determining the texture and grain composition of these deposits.

- investigating taxonomic and ecological data in order to understand the sedimentary environment and to define suitable proxies for the interpretation of such deposits in the sedimentary record.

III. STUDY AREA

Large carbonate shelfal deposits in nutrient-rich tropical settings are rare in recent times. The broad and shallow shelf of the Golfe d'Arguin (Mauritania; 20°N) located in one of the most productive area in the modern world off NW Africa, however, displays extensive heterozoan carbonate deposits. Therefore, this sedimentary environment constitutes an ideal area to study eutrophic tropical shallow-water carbonates.

III.1 Geological setting

The NW African continental margin (Fig. III.1) is one of the oldest passive margins of the modern oceans (Seibold, 1982). Rifting of the Central Atlantic margin and seafloor spreading began in Late Triassic times (Davison, 2005). The NW African continental margin was formed during the Mesozoic and during most part of the Cenozoic by prograding sedimentation on a subsiding basement (Summerhayes et al., 1971). The thickness of sediment accumulation on top of the Paleozoic basement is estimated from 2 to 3 km along the northern Mauritanian coastline to more than 10 km offshore Mauritania (Wissmann, 1982). Major Cenozoic regressions during the Pleistocene ended to shape the shelf surface as a marine erosion plane, whose formation apparently began during the Oligocene. Recent sedimentation did not significantly affect the shelf morphology (Summerhayes et al., 1971). Along the modern NW African continental margin, sediments are provided by marine biological production of skeletal material, fluvial inputs of fine-grained mud (i.e. rivers from the Atlas region and Senegal river), and eolian inputs from the desert (Summerhayes et al., 1976; Fütterer, 1983).

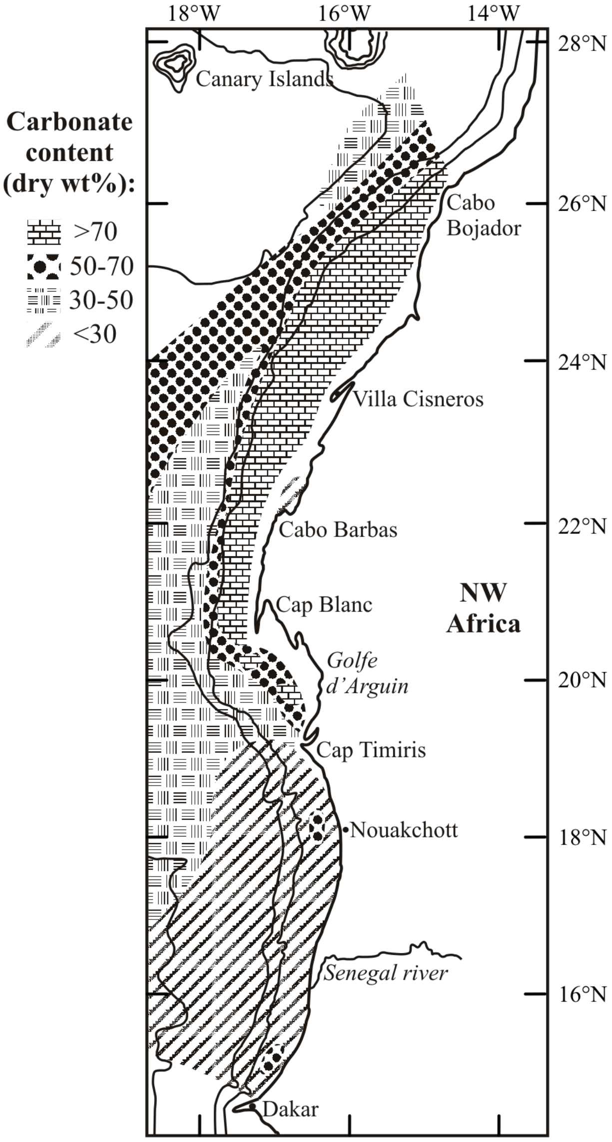

Fig. III.1 Distribution of carbonate contents (dry wt%) of bulk surface sediment along the NW African continental margin (redrawn from Fütterer, 1980, Fig. 14).

III.2 Oceanographical setting

The NW African upwelling is one of the four upwelling systems in the world induced by Eastern Boundary Currents (the three other are found off SW Africa, NW and SW America; Smith, 1992; Hagen, 2001; Köbrich, 2008). The maritime Trade winds, blowing equatorwards, drive the surface waters toward the south over the shelf and slope and are responsible for the offshore Ekman transport of surficial layers of the ocean (Fig. III.2). This latter offshore flow is compensated by the upwelling of deep waters close to the continent. The intrusion of the cool, nutrient-rich water masses in the photic zone results in planktonic blooms and high productivity (cf. Gillbricht, 1977; Gabric et al., 1993). Furthermore, the vertical oceanographic motion induces a recirculation cell on the shelf. Off Mauritania, this recirculation cell on the broad and shallow shelf is separated from another one situated offshore by an oceanographic front, parallel to the coastline (Giraud, 2001; Hagen, 2001; Fig. III.2). This pattern allows for effective recycling of detritus, organic matter, and nutrients and thus favours a high biological productivity.

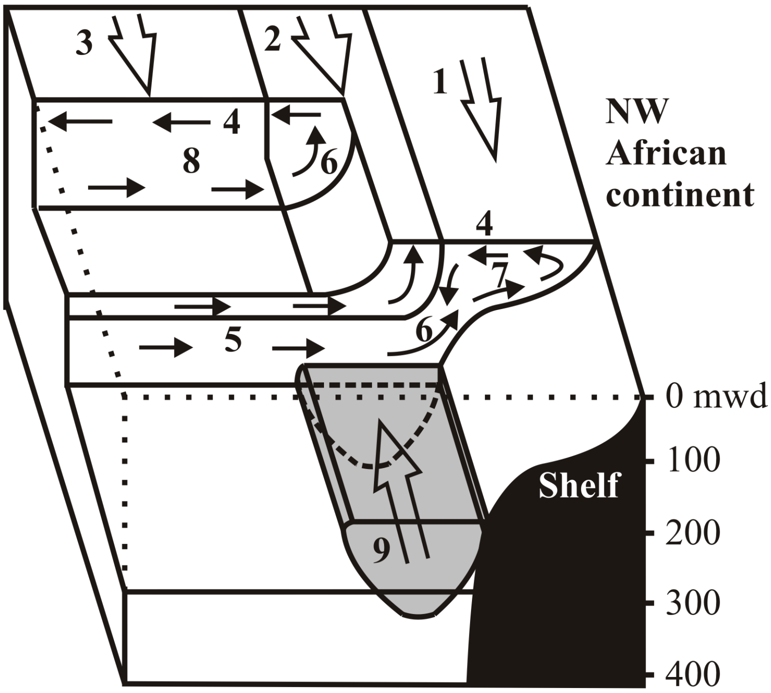

Fig. III.2 Sketch of the oceanographic patterns off Mauritania (modified from Hagen, 2001). 1) Primary upwelling zone over the shelf with southward wind-driven surface waters; 2) Main frontal zone along the shelf edge; 2) Canary Current as eastern branch of the anticyclonic gyre circulation; 4) Wind-generated offshore current; 5) Onshore compensation current, main source of upwelling water; 6) Upward motion of (5) feeding upwelling water; 7) Recirculation cell over the shelf; 8) Recirculation cell seaward of (2); 9) Poleward flowing undercurrent characteristic of eastern boundary upwelling systems.

The upwelling system varies seasonally and interannually (Hagen, 2001). It moves from the north in summer (occurrence between 20°N and 33°N) to the south in winter (occurrence between 10°N and 25°N), following the meridional extension of the Trade winds that is defined by the Inter-Tropical Convergence Zone (ITCZ) position. The upwelling duration increases from one month at the latitudinal periphery of the upwelling zone (i.e. 10°N and 33°N) to permanent between 20°N and 25°N (Fütterer, 1983; Van Camp et al., 1991; Hagen, 2001; Fig. III.3). In this permanent upwelling region off northern Mauritania, the waters are among the most productive marine areas in the world (3 $\mu g.L^{-1}$ Chl-a [chlorophyll-a]; Marañón & Holligan, 1999) and are important fishing grounds (Binet et al., 1998). In particular, the phytoplankton distribution shows a pronounced maximum in the Cap Blanc region (21°N; Gillbricht, 1977).

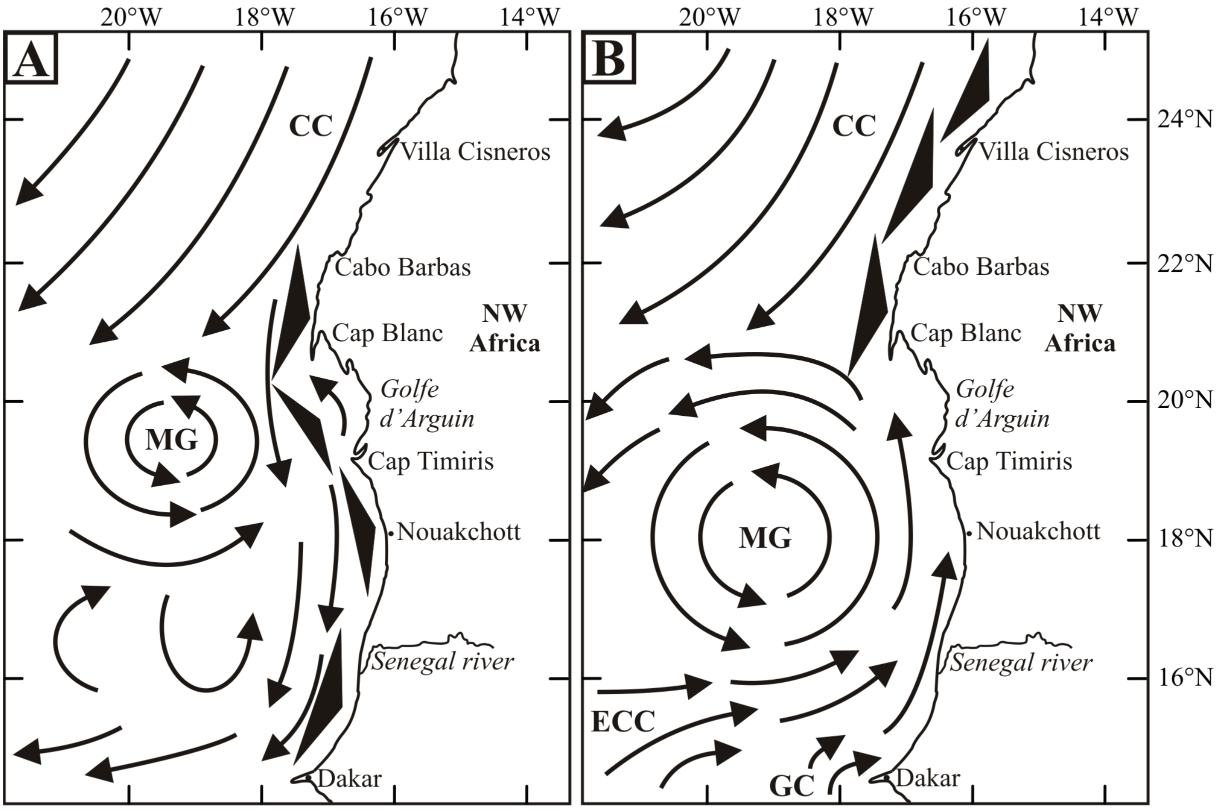

Fig. III.3 Idealized surface circulation off NW Africa: A. Circulation in winter. B. Circulation in summer. CC: Canary Current; ECC: Equatorial Counter Current; GC: Guinean Current; MG: Mauritanian Gyre; black triangles indicate upwelling occurrence (modified from Rébert, 1979; Mittelstaedt, 1991).

In the Golfe d'Arguin, nutrient levels are very high which allows for the biological production to reach chlorophyll-a concentration of 11 µg.L^{-1} (Quack et al., 2007). Sea surface temperatures oscillate throughout the year between 17.5 and 29°C on the Banc d'Arguin (Brahim et al., 2003), and between 15.4 and 25.8°C seaward of the Banc d'Arguin (Quack et al., 2007; Zonneveld et al., in press). The coldest sea surface temperatures are observed in spring when the upwelling is the strongest, whereas the warmest sea surface temperatures occur in summer. Salinity varies seasonally from 35.79 to 36.13 psu (Quack et al., 2007).

At the latitude of the Golfe d'Arguin around 20°N, an oceanographic frontal zone is present in surface waters (Pastor et al., 2008; Fig. III.3). To the north, the Golfe d'Arguin is located at the southern limit of the subtropical North Atlantic gyre, where the Canary Current detaches from the African coast to flow in a southwest direction. To the south, the study area consists of the northernmost corner of a recirculation gyre, that comprises the Canary Current, the North Equatorial Current, the North Equatorial Counter-Current and a northward-flowing current along the African coast (Rébert, 1979; Mittelstaedt, 1991). This latter poleward-flowing current is referred to as a branch of the Guinean Current (Shaffer, 1974; Rébert, 1979). The complex oceanographic pattern taking place in the frontal zone of these two mesoscale oceanographic entities, where upwelling occurs, still remains unclear (Pastor et al., 2008).

III.3 The Golfe d'Arguin

The Golfe d'Arguin stretches from Cap Blanc (21°10′N) to Cap Timiris (19°20′N; Fig. III.4). Whilst about 200 km separate the northernmost and southernmost points of the gulf, a maximum of 150 km lies between the coast and the shelf break. The latter is located at 80–110 m water depth (mwd). North of 20°N the shelf is wider and narrows to the south where the shelf edge is incised by a series of small canyons (Shaffer, 1974; Krastel et al., 2004). From west to east, the shelf can be subdivided into a deeper outer shelf (50–110 mwd), a middle shelf (20–50 mwd), and a broad shallow inner shelf (<20 mwd; i.e. the Banc d'Arguin and the littoral zone). The Banc d'Arguin displays water depths shallower than 10 m over large parts and isolates the littoral zone of the gulf (e.g. Baie de Saint-Jean, Baie d'Arguin, and Cuvette d'Arguin) from the open ocean (Piessens, 1979; Sevrin-Reyssac, 1993; Wolff et al., 1993). The inner shelf is separated from the middle and outer shelves by a steep, ~20-m-high escarpment, the origin of which is unknown. The Banc d'Arguin National Park is listed in the UNESCO World Heritage List and hosts many wading birds (Fig. III.4). These shorebirds feed in particular on the abundant mollusc fauna present in the area (Wolff & Smit, 1990).

The shelf is characterized by high-water energy (Summerhayes et al., 1976; Piessens, 1979). This water energy is particularly strong in the northern-half of the Golfe d'Arguin where the shelf faces the swell coming from NW direction. In addition to this, on the Banc d'Arguin and in the Baie du Lévrier, tidal (1–1.5 m amplitude; Hanebuth & Lantzsch, 2008) and wind-driven (Peters, 1976; Mittelstaedt, 1991) currents play an important role.

The Golfe d'Arguin adjoins the Sahara Desert and is under a hyper-arid climatic regime (present-day average precipitation of 28 mm/year at Nouhadibou; Khallahi, 2004). Consequently, no fluvial material has been supplied to the shelfal waters for the past 2,000 years (Hanebuth, unpublished data). The two major features influencing the modern marine sedimentation of northern Mauritania are the coastal upwelling system and the dust input (cf. Nowald et al., 2006).

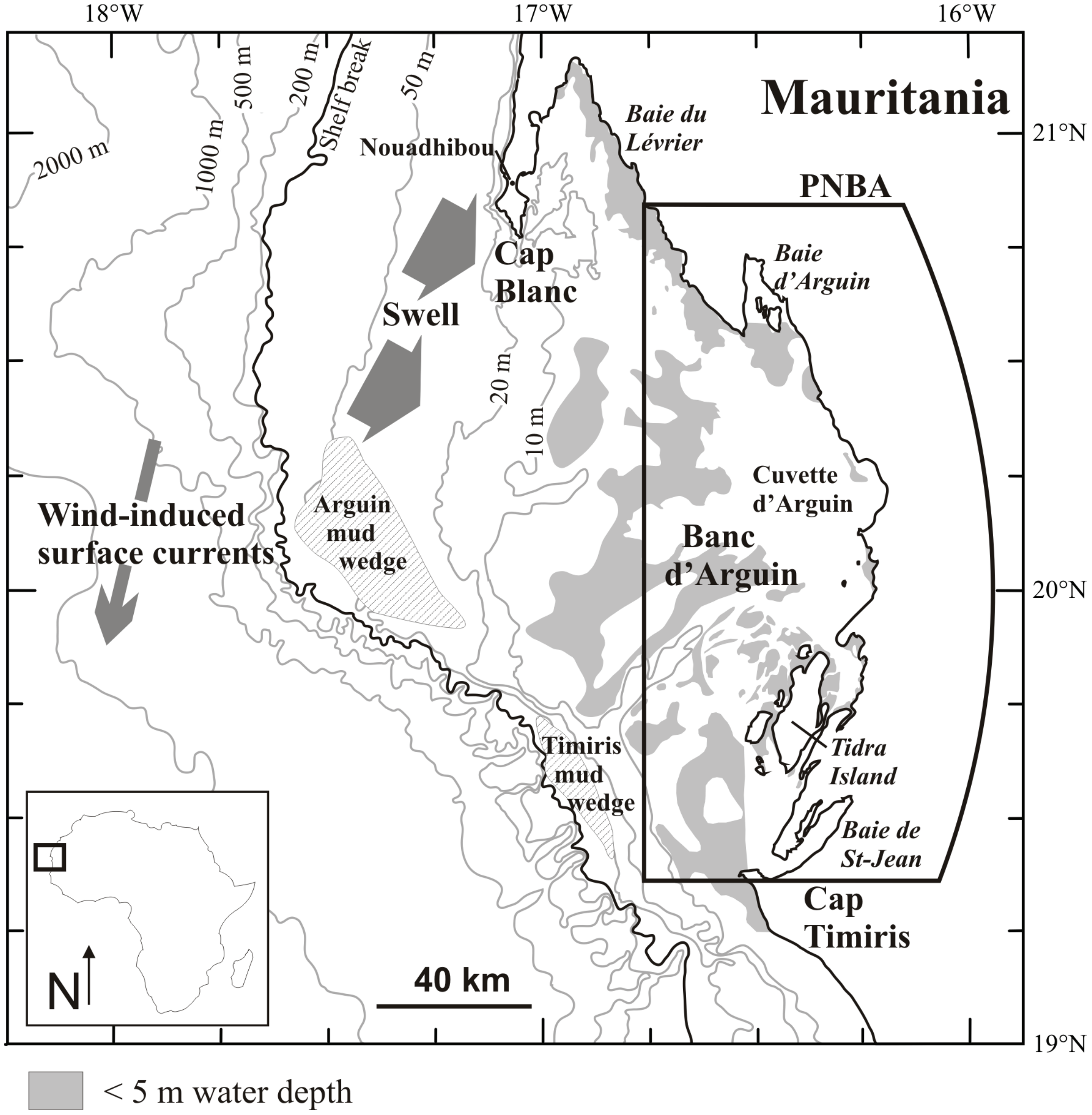

Fig. III.4 Map of the Golfe d'Arguin showing the National Park area (PNBA, National Parc du Banc d'Arguin), the fine-grained bodies on the shelf (Arguin and Timiris mud wedges), and important hydrological features (swell and wind-induced surface currents; modified from Piessens, 1979; Domain, 1984; Hanebuth & Lantzsch, 2008).

III.4 Modern sedimentation

III.4.1 *Carbonate sediments*

Off NW Africa, carbonate-rich sediments (>90 % of calcium carbonates) are found on the middle and outer shelves between 20° and 30°N (Summerhayes et al., 1976; Fütterer, 1980; Fig. III.1) The carbonate material which is rich in relict grains consists mainly of bivalve shell fragments (Summerhayes et al., 1976; Zonneveld et al., 2010; Westphal et al., subm). The presence of such coarse-sand, carbonate-rich deposits are explained by the interplay of climatic factors (i.e. the inland aridity that prevents any river discharge), the wind system (i.e. the Trade winds blowing parallel to the coastline and thus limiting the dust input), oceanographic factors (i.e. strong current and wave regimes), and “historical factors” (i.e. Pleistocene sea-level lowstand and the following transgression; cf. Summerhayes et al., 1976; Barusseau et al., 1988).

In the southernmost part of this carbonate-rich sediment region (i.e. Mauritania, 20°N; Fig. III.1), bioclastic deposits are present in the inner, middle, and outer shelves of the Golfe d’Arguin (Domain, 1985). However, sedimentological studies were only carried out on top of the Banc d’Arguin and in the Baie du Lévrier (Piessens & Chabot, 1977; Koopmann et al., 1979; Piessens, 1979; Fig. III.4).

III.4.2 *Dust*

Apart from the upwelling, the other major environmental phenomenon taking place in NW Africa is the eolian transport of dust that can be observed on satellite images (cf. Koopmann, 1981; Sarnthein et al., 1981; Holz, 2004; Fig. III.5). Dust is lifted up from deserts (i.e. Sahara and Sahel deserts) and transported toward the west to the Atlantic Ocean and, depending on the atmospheric circulation, finer eolian material can reach the European or American continent (Glaccum & Prospero, 1980; Goudie & Middleton 2001; Engelstaedter et al., 2006; Stuut, et al., 2009). The major winds of NW Africa are the maritime Trade winds, the Harmattan or continental Trade winds, and the Saharan Air Layer. The term “maritime Trade winds” is here used to describe the winds linked to the Azores High zone and to distinguish them from the Harmattan or continental Trade winds linked to the high-pressure zone located above the Maghreb in winter (cf. Khallahi, 2004). The maritime Trade winds are constantly blowing from north to northeast (Mittelstaedt, 1991) and thus transport material in the Cape Verde Island direction. Harmattan winds are blowing westward and sporadically (but especially during the winter season) transport large amounts of coarse material to the Eastern Atlantic Ocean (Stuut et al., 2005). The Saharan Air Layer is blowing westward and transports fine material at mid-tropospheric altitudes from northern Africa across the entire tropical Atlantic (Glaccum & Prospero, 1980; Prospero & Lamb, 2003).

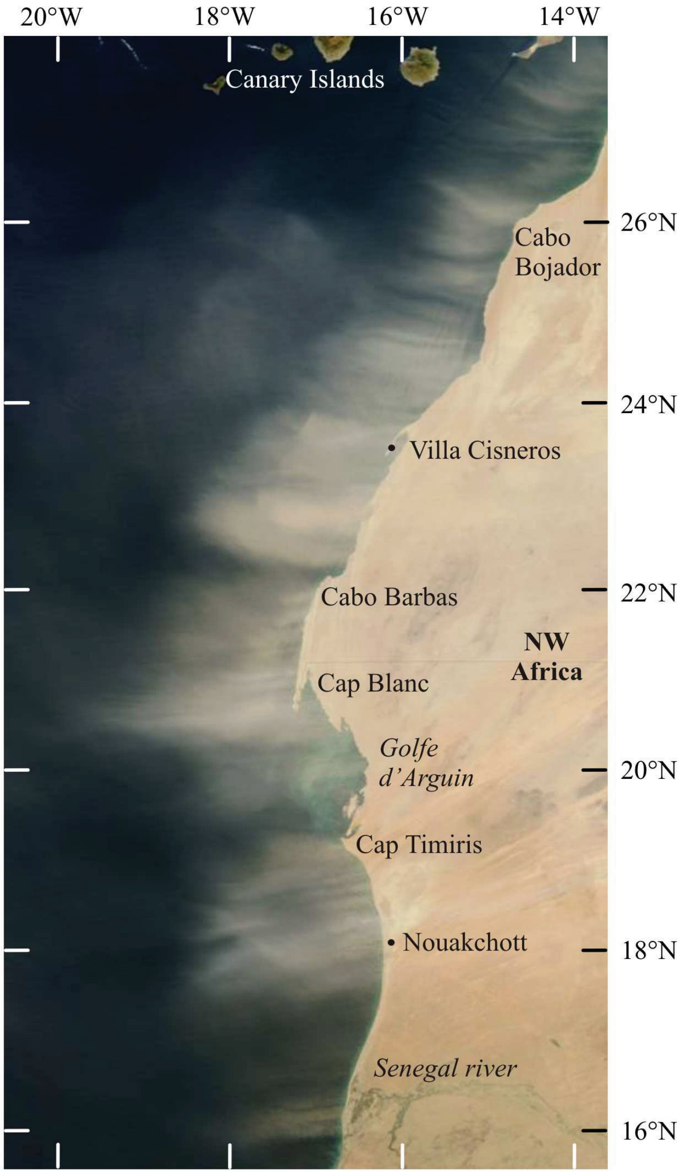

Fig. III.5 Satellite picture during dust transport by Harmattan winds from NW Africa to the eastern Atlantic (January 2007).

IV. MATERIAL STUDIED

The loose surface sediments studied in the present thesis were collected during two cruises of the german R/V Poseidon, namely Pos-346 (December 2006-January 2007; 62 samples; Westphal et al., 2007) and Pos-366 (May 2008; 13 samples; Zonneveld et al., 2010; cf. Appendix). Grab samples and box cores (n=75; Fig. IV.1) were retrieved mainly along the drop-off from the Banc d'Arguin to the open shelf in water depths of 10 to 45 m (n=40), whereas the rest of the samples are from the open shelf and slope (maximum water depth of 604 m; n=34). The extensive waters on the Banc d'Arguin were too shallow (<10 m) to be sampled from the research vessel, with the exception of one sample retrieved in the southern part of the bank at 4 mwd with a hand-held dredge employed from a zodiac (GeoB11591).

The later obtained samples of Poseidon-366 cruise were only analysed in term of carbonate content and mineralogy. Grain-size measurements are ongoing. Picking was not undertaken.

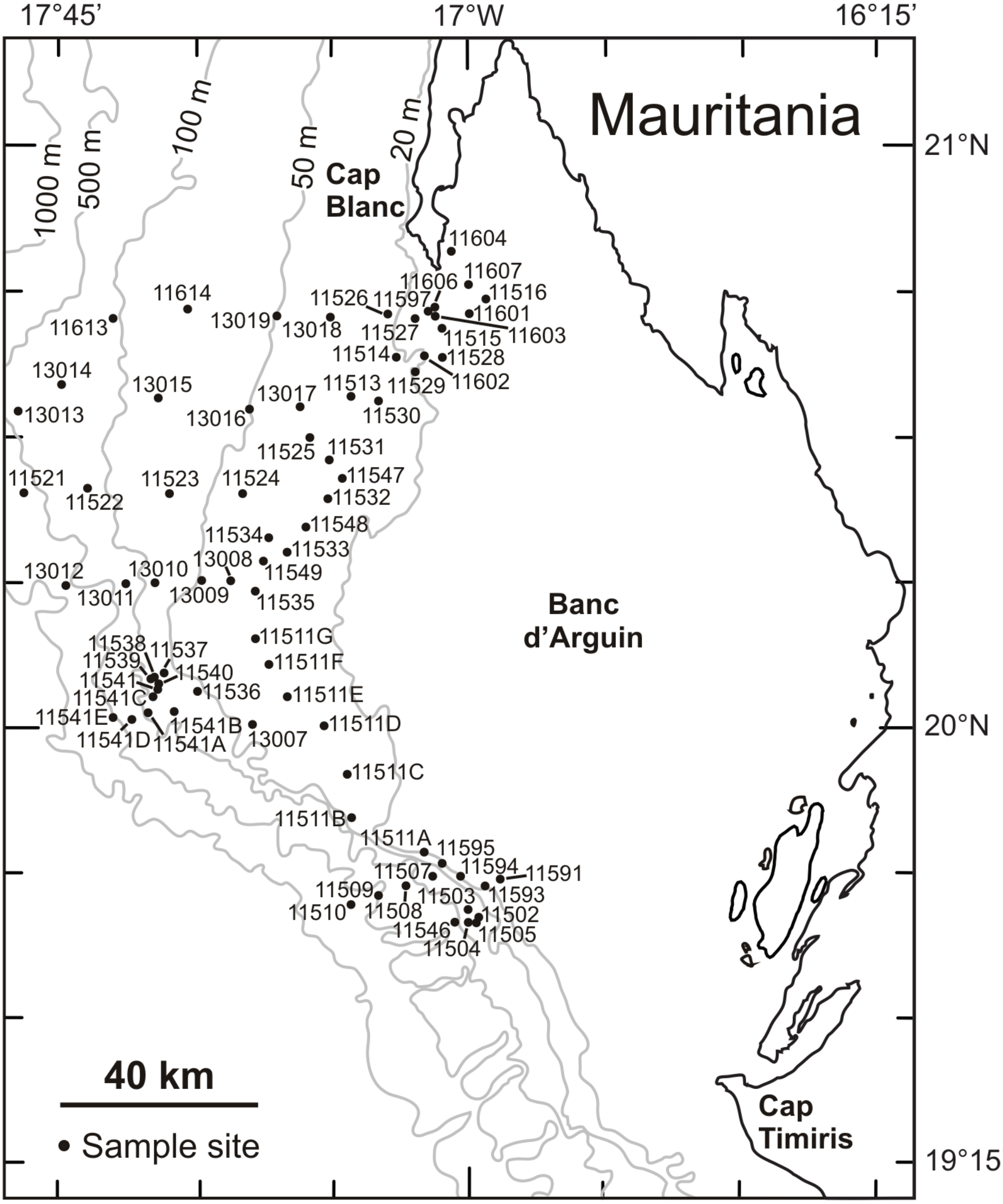

Fig. IV.1 Surface sample (grab and box core) locations taken in the Golfe d’Arguin during the cruises R/V Poseidon 346 and 366. Sample numbers are GeoB numbers.

V. METHODS

V.1 Carbonate content and grain-size analyses

On board, bulk sediments were subsampled from the box cores and grab samples and the rest of the material was sieved in order to keep two fractions of the coarse material (1–2 mm and >2 mm). After the cruise, all analyses were carried out at the MARUM, University of Bremen (Germany). Carbonate content (dry wt%) was measured on bulk sediment using a carbonate bomb (Müller & Gastner, 1971). For grain-size analysis, bulk sediments were wet sieved in order to split the mud (<63 µm) and sand/gravel (>63 µm) fractions.

V.1.1 *Grain-size analysis of the mud fraction (<63 µm)*

The clay content was assumed to be very low (<2%; Hanebuth and Lantzsch, 2008). Nevertheless, prior to drying and in order to determine the maximum clay content in the studied area, Atterberg settling separation (Müller, 1967; cf. Nizou, 2010) was undertaken for two samples from the muddiest part of the studied area (i.e. Timiris mud wedge; cf. Hanebuth and Lantzsch, 2008; GeoB11502: 89%; and GeoB11546: 84% of mud in the bulk sediment). The clay content of these two samples was found to be less than 0.3% of the mud. In consequence, the mud fraction was considered to consist of silts and the clay fraction was not further considered in this study.

After wet sieving, the mud fraction was dried and weighted. A portion of mud of ~2.5 g was weighted for SediGraph analysis. This portion was treated with 12.5% HCl (~15 min.) in order to dissolve calcareous components. After diluting the acid until the solution was neutral and drying, each sample was weighed in order to determine the carbonate content of the mud fraction. Subfractions were treated with diluted calgon (sodium hexa-meta phosphate 0.05%) in small bottles (~50 ml volume) and shaken for at least 48 h in order to disintegrate artificial particle aggregates resulting from drying; this was followed by few seconds (~2 s) of ultrasonic treatment immediately prior to analysis. The grain-size distribution of the carbonate-free fine fractions (<63 µm) of 46 samples was then measured using a SediGraph 5100 in the particle size range of 0.63–100 µm. For 15 samples from the northern part of the Golfe d'Arguin comprising more than 99% coarse fraction, insufficient fine material was available for SediGraph analysis.

Five samples of airborne dust were collected on 1–5 January 2007, when a massive dust outburst occurred draping the deck of the vessel with a several millimeter-thick layer every day. This dust was carefully sampled daily and checked under the binocular for cleanness. Grain-size measurements were performed on these samples as described above for the marine samples.

V.1.2 *Grain-size analysis of the coarse fraction (>63 µm)*

After wet sieving, the coarse fraction was dried and weighted. Dry sieving was then undertaken for splitting grain-size fractions based on the Wentworth classification (63–125, 125–250, 250–500, 500–1000, 1000–2000 and >2000 µm, corresponding to very fine, fine, medium, coarse, and very coarse sand and gravel). Sonic siefter was used but did not permit to separate gravel from very coarse sand. This relative grain-size abundances were determined while hand sieving the coarsest fractions (>1 mm) for picking analyses.

V.2 Mineralogical analysis

V.2.1 *Carbonate mineralogy*

The carbonate mineralogical composition of 74 samples was determined on the bulk sediment using an X-ray diffractometer (XRD) with the following scan parameters: measuring range 2θ from 3 to 85°, measuring time 100 s/step, wave length λ=1.5418 Å (Cu Kα), geometry of the Bragg-Brentano diffractometer. The percentage of the carbonate minerals (aragonite, high-Mg calcite = HMC, and low-Mg calcite = LMC) relative to total carbonate content was calculated from peak area ratios using calibration curves. These calculations are based on the observation that the relative amount of a mineral is related to the reflection intensity, which is proportional to the peak area in the diffractogram (Neumann, 1965). The non-linear relationship between calcite and aragonite (Milliman, 1974) was calculated from ratios calibrated from standard minerals measured on the same diffractometer at MARUM in Bremen, Germany. For the relative amounts of HMC and LMC, a linear relationship was

V.2.2 *Carbonate-free mud mineralogy*

Mineralogical analyses of quartz and mica were carried out on the carbonate-free fine fraction (<63 µm) of 15 sediment samples using an X-ray diffractometer (XRD) with the following scan parameters: measuring range 2θ from 3 to 85°, measuring time 100 s/step, wave length λ=1.5418 Å (Cu Kα), geometry of the Bragg-Brentano diffractometer.

V.3 Component analysis

The sedimentary components of 39 samples were analysed quantitatively in order to determine sorting and composition. For compositional analysis, a minimum of 300 components per grain-size fraction >125 µm (cf. paragraph V.1.2, p. 29) was picked. The following groups were considered: red algae, planktonic foraminifers, benthic foraminifers, bivalves, gastropods, pteropods, scaphopods, bryozoans, decapods, barnacles, ostracods, ahermatypic corals, echinoderms, alcyonarian spicules, sponge spicules, serpulids, aggregated worm tubes, fish remains, fecal pellets, aggregated grains, and quartz grains. Non-determinable grains were not considered for facies definition.

In order to obtain information on the grains indeterminate by loose-sediment analysis, 18 artificial thin sections were prepared by embedding bulk sediment in epoxy-resin. Subsequently, the quantities of the same component groups as for the loose-sediment analysis were determined by point-counting (for the point-counting method see chapter 6 in Flügel, 2004).

V.4 Taxonomic analysis

Quantification and determination of molluscs was performed on the fraction >1 mm using a minimum of 300 grains, except for the sample retrieved from the slope (GeoB11509) where the low material quantity required analysis of a lower number of grains. The fractions <1 mm were not studied here.

Taxonomic determination of the mollusc fauna was based on Nicklès (1950), Gofas et al. (1985), and Ardovini & Cossignani (2004). Taxonomic determination of the bivalve fauna was further based on Cosel (1995) and on extensive knowledge which are currently combined by Cosel (in prep.). The fact that West African marine gastropod taxonomy is in need of thorough revision has limited further accuracy on the taxonomic determination of this mollusc class. For the determination of the foraminifers, the nomenclature of Loeblich & Tappan (1987) was employed.

V.5 Statistical analysis

Statistical analyses on the quantified grains were performed using Primer for Windows (version 6.1.5). Cluster analyses ("Group Average" cluster mode using the "S17 Bray Curtis similarity" resemblance measure) were used to group the samples with similar compositions. The sedimentary facies groups were determined on the basis of carbonate content, grain size (mud, sand, and gravel contents), and composition of the loose-sediment analysis (excluding the unidentified grains). The mollusc assemblage groups were determined on the basis of the taxonomic composition.

V.6 Radiocarbon dating

Radiocarbon ages were determined for mollusc shells from surface samples. The measurements were undertaken by AMS ^{14}C at the University of Poznan, Poland. The raw ^{14}C date was calibrated using CALIB version 5.0.1 (Stuiver & Reimer, 1993) and the Marine radiocarbon age calibration "Marine04" (Huguen et al., 2004).

VI. THESIS OUTLINE

The outcomes of this thesis are presented in three manuscripts that are introduced below. At the end, a summary and further implications of the study are given before presenting future research perspectives.

- Sediment partitioning and winnowing in a mixed eolian-marine system (Mauritanian shelf):

The first study is dedicated to the sedimentary environment of the Golfe d'Arguin that is largely influenced by eolian input from the Sahara and Sahel deserts. The scientific target of the manuscript is to highlight the influence of shelfal sedimentation and material transport for the slope and deep-sea deposits. First, the knowledge of the complex oceanographic pattern taking place in the Golfe d'Arguin and offshore northern Mauritania were reviewed. Then, grain-size analyses were carried out on the bulk fraction and on the siliciclastic silt fraction specifically. The grain-size and thus the soft-bottom substrate distribution is defined. The sediment winnowing and transport throughout the Golfe d'Arguin are highlighted.

Coarser sediments (i.e. medium and coarse sand and gravel) occur in the northern part of the gulf, while finer grains (i.e. silts and fine sand) are transported and deposited in the southern part. This sediment transport implies the export of important quantities of fine material (silts) off the shelf. Such sediment transport could disturb the records of dust downslope and in the deep sea.

- Modern heterozoan carbonate facies from a eutrophic tropical shelf (Mauritania):

The second study describes the depositional system of the Golfe d'Arguin. The sediment consists of a mixture of siliciclastic (dust) and carbonate grains. On the basis of carbonate content, grain size, and grain composition, five different facies were determined in the studied area. The carbonate grain association is dominated by mollusc shells and foraminifer tests. Such a foramol carbonate association is reminiscent of cool-water settings but is described here from a eutrophic shelf which displays warm-water conditions in the inner part and mixed temperature conditions on the outer shelf. The tropical realm of these open-shelf deposits is only revealed by taxonomic data (i.e. warm-water-related mollusc and foraminifer taxa). Thus, this manuscript provides a facies description which can be used as a modern analogue of warm-water heterozoan deposits.

- The mollusk fauna of soft sediments from the tropical, upwelling-influenced shelf of Mauritania (NW Africa):

The third study focuses on the dominant carbonate-secreting biota of the Golfe d'Arguin, the mollusc fauna. The scientific target of the manuscript is to use ecological requirements of the biota to find suitable proxies that clearly define the sedimentary environment. The picking and determination of mollusc shells permit the definition of six taphocoenoses that are overwhelmingly dominated by bivalves and are depth- and substrate-related. These mollusc assemblages present on a tropical soft-sediment open shelf display a low diversity. The poorly diverse mollusc fauna and its ecology are constrained by eutrophic and highly variable environmental conditions. This bivalve-rich fauna is well adapted to eutrophic environment and is found in the warm-water setting of the Golfe d'Arguin. Thus, the modern sediment of northern Mauritania cautions against using the common extra-tropical interpretation of "cool-water" carbonates in the geological record.

First Manuscript

Sediment partitioning and winnowing in a mixed eolian-marine system
(Mauritanian shelf)

VII. SEDIMENT PARTITIONING AND WINNOWING IN A MIXED EOLIAN-MARINE SYSTEM

(MAURITANIAN SHELF)

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Abstract Continental shelf systems are highly dynamic sedimentary environments, where sediments from biogenic production as well as from terrigenous sources are redistributed in the shelf depositional system, and partly exported off the shelf to the slope and the deep sea. The Golfe d'Arguin (Mauritania, NW Africa) is dominated by such redistribution processes, involving clastic silt imported as dust from the Sahara desert and biogenic carbonates of marine origin. Indeed, surface-sediment grain size and mineralogy show a clear north–south partitioning of sediment type. Fine material is winnowed from the northern part of the gulf, and transported toward the southern part off the Banc d'Arguin, where coarse silt settles on the outer shelf and upper slope, at least down to 600 m water depth. Particles of the fine silt fraction, estimated in terms of eolian material collected aboard the research vessel, are thought to be exported further offshore as they correspond to grain sizes previously reported from adjacent deep-sea sediments. These findings suggest that the interpretation of dust records from the continental slope and rise off NW Africa must consider reworking and partitioning processes active on the Mauritanian shelf.

VII.1 Introduction

Ideally, paleoclimatic investigations should be based on undisturbed sediment records. Hemipelagic settings potentially provide such continuous records reflecting the supply of terrestrial sediment by eolian and/or fluvial processes through time. Rate of deposition and grain-size distributions represent two common proxies for assessing terrigenous inputs (Chamley et al. 1977; Weltje and Prins 2003; Holz et al. 2004; Stuut et al. 2005; McCave and Hall 2006). In order to retrieve undiluted records, sites as proximal as possible to terrigenous sources are chosen for analysis. One problem with this approach is that continental shelf systems have been affected by glacio-eustatic sea-level changes that may have redistributed sediment winnowed from previous highstand deposits. Shelves therefore are complex and dynamic sedimentary environments. The common sampling approach is to retrieve sediment cores on the continental slope or rise, well below the influence of shallow water processes where sedimentation is considered to mirror an undisturbed process (besides possible bioturbation). However, lateral transport processes are not fully understood in such settings, and their effects may thus be overlooked or underestimated (Nowald et al. 2006).

In this paper, the hydrodynamic redistribution of sediment on the shelf off northern Mauritania, NW Africa, is investigated. In this region, large amounts of dust from the Sahara and Sahel deserts are deposited on the continental shelf and slope. This dust represents a sensitive proxy for aridity and wind intensity in northern Africa, and has been extensively studied in cores from the continental slope and the adjacent deep sea off Mauritania (Koopmann 1979, 1981; Glaccum and Prospero 1980; Sarnthein et al. 1981, 1982; Martinez et al. 1999; deMenocal et al. 2000; Zhao et al. 2000; Goudie and Middelton 2001; Holz et al. 2004, 2007; Stuut et al. 2005; Engelstaedter et al. 2006; Wien et al. 2006; Zühlsdorff et al. 2007; Hanebuth and Henrich 2009). By comparison, the wide continental shelf adjoining the desert off northern Mauritania, where the greatest volumes and the coarsest fractions of eolian material settle, has received much less attention (Lancaster et al. 2002).

Sedimentation in the Golfe d'Arguin is governed by complex hydrographic processes (Peters 1976). Sediments are reworked on the inner shelf, in particular on the Banc d'Arguin (Piessens and Chabot 1977; Piessens 1979). Surprisingly, the combined effects of shelf and slope sedimentation processes have to date not been assessed in this region. Yet, the circulation in the Golfe d'Arguin potentially controls downslope sediment transport, e.g., by means of water masses entering and exiting the gulf due to tides and ocean currents.

The present study investigates the distribution of bottom sediments in the Golfe d'Arguin, and aims at highlighting the partitioning of sediments supplied to this shelf system.

In addition, the consequences of selective transport toward the slope are examined, including its potential influence on regional slope and deep-sea sedimentary records.

VII.2 Study area

VII.2.1 *Geographic and physiographic setting*

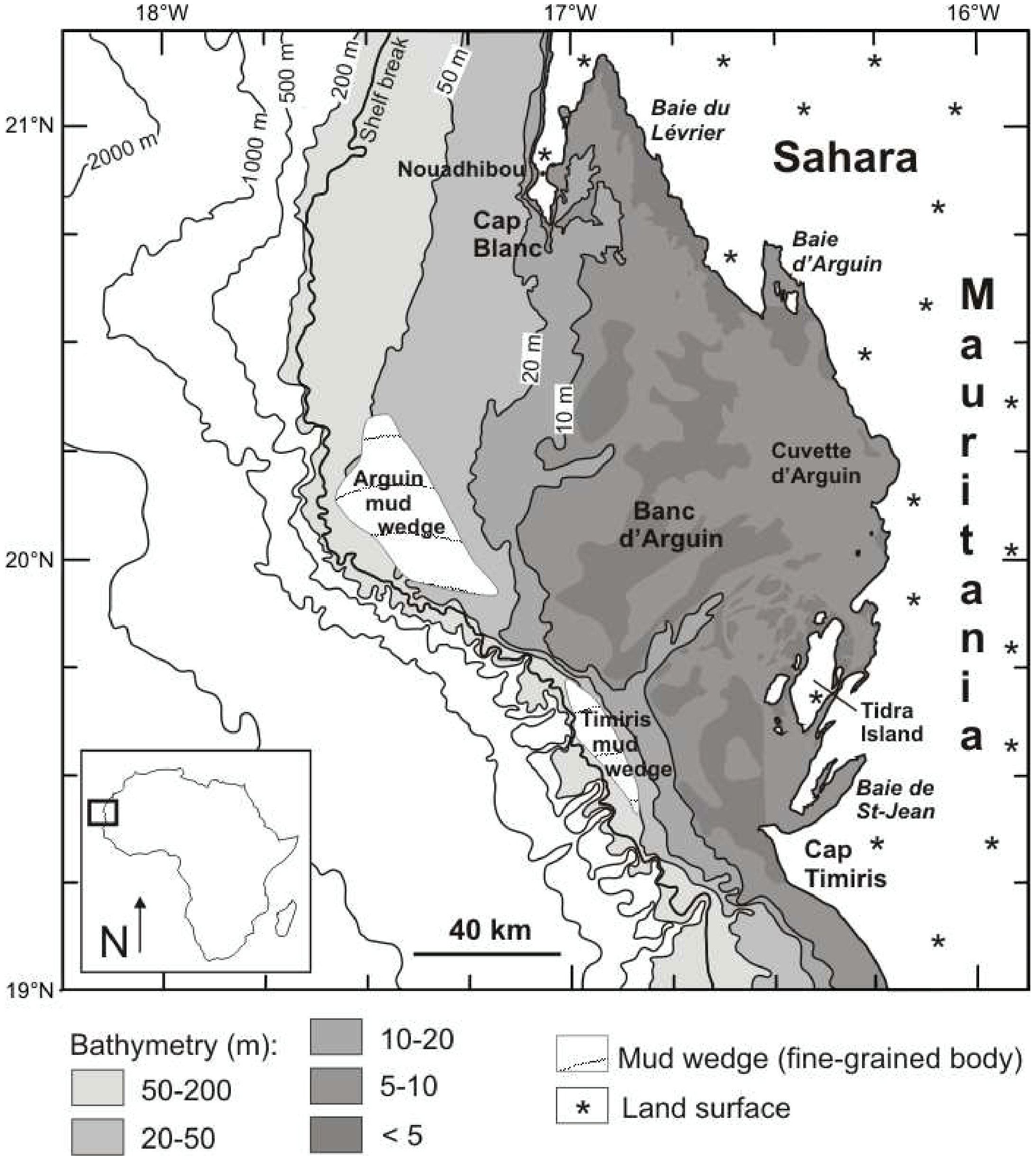

Fig. VII.1 Location and bathymetry of the Golfe d'Arguin study area between Cap Blanc and Cap Timiris. Note the large expanse of shallower water (less than 10 mwd) in the center of the gulf, known as the Banc d'Arguin, and comprising some distinct areas with water depths of less than 5 m. Two well-delimited fine sediment bodies are also shown: the Arguin and the Timiris mud wedges (modified from Domain 1985; Hanebuth and Lantzsch 2007)

The NW African shelf is generally narrow (less than 60 km wide), but widens off northern Mauritania to 150 km between the coast and the shelf break. This so-called Golfe d'Arguin has a water depth of generally less than 30 m (Fig. 1). It adjoins the Sahara Desert, and the present-time hyper-arid climatic regime (average precipitation at Nouhadibou: 28 mm/year; Khallahi 2004) prohibits fluvial discharge, whereas potential evaporation is very high in the entire area (Peters 1976; Koopmann et al. 1979).

The Golfe d'Arguin covers some 15,000 km^2, and stretches from Cap Blanc in the north (21°10′N) to Cap Timiris in the south (19°20′N). The shelf is wider north of 20°N, and narrows to the south where the shelf edge is incised by a series of small canyons (Shaffer 1974; Krastel et al. 2004). From west to east, the shelf can be subdivided into a deeper outer shelf (20–150 m water depth, mwd), and a broad shallow inner shelf (the Banc d'Arguin and the littoral zone). The Banc d'Arguin has water depths shallower than 10 m over large areas, and isolates the littoral zone of the gulf (e.g., Baie de Saint-Jean, Baie d'Arguin, Cuvette d'Arguin) from the open ocean (Piessens 1979; Sevrin-Reyssac 1993; Wolff et al. 1993). The inner and outer shelves are separated by a steep, about 20-m-high escarpment, the origin of which is unknown.

VII.2.2 *Oceanography*

The Atlantic Ocean off NW Africa features one of the major modern zones of coastal upwelling, which has attracted the interest of oceanographers for many decades (e.g., Shaffer 1974, 1976; Mittelstaedt 1991; Van Camp et al. 1991; Smith 1992; Hagen 2000; Giraud 2001, 2006). The regional hydrography off northern Mauritania (Fig. 2) is, however, complex and is far from being fully understood (Pastor et al. 2008). Upwelling waters interact here with the southward-flowing Canary Current, which detaches from the continental slope between 25 and 21°N and continues southwestward (Mittelstaedt 1991; Van Camp et al. 1991; Cuq 1993; Pastor et al. 2008). In addition, a northward-directed current seasonally and episodically pushes water into the Golfe d'Arguin. Consequently, several water masses are involved in the oceanographic circulation off northern Mauritania.

The Canary Current is driven southward by the maritime Trade Winds along the NW African coast up to 21°N (the term "maritime Trade Winds" is here used to describe the winds linked to the Azores High zone, and to distinguish these from the Harmattan or continental Trade Winds linked to the high-pressure zone located above the Maghreb in winter; see Khallahi

2004). During winter, the influence of the Canary Current thus extends farther south, when waters from this current can enter the Banc d'Arguin area along a northern route (Cuq 1993).

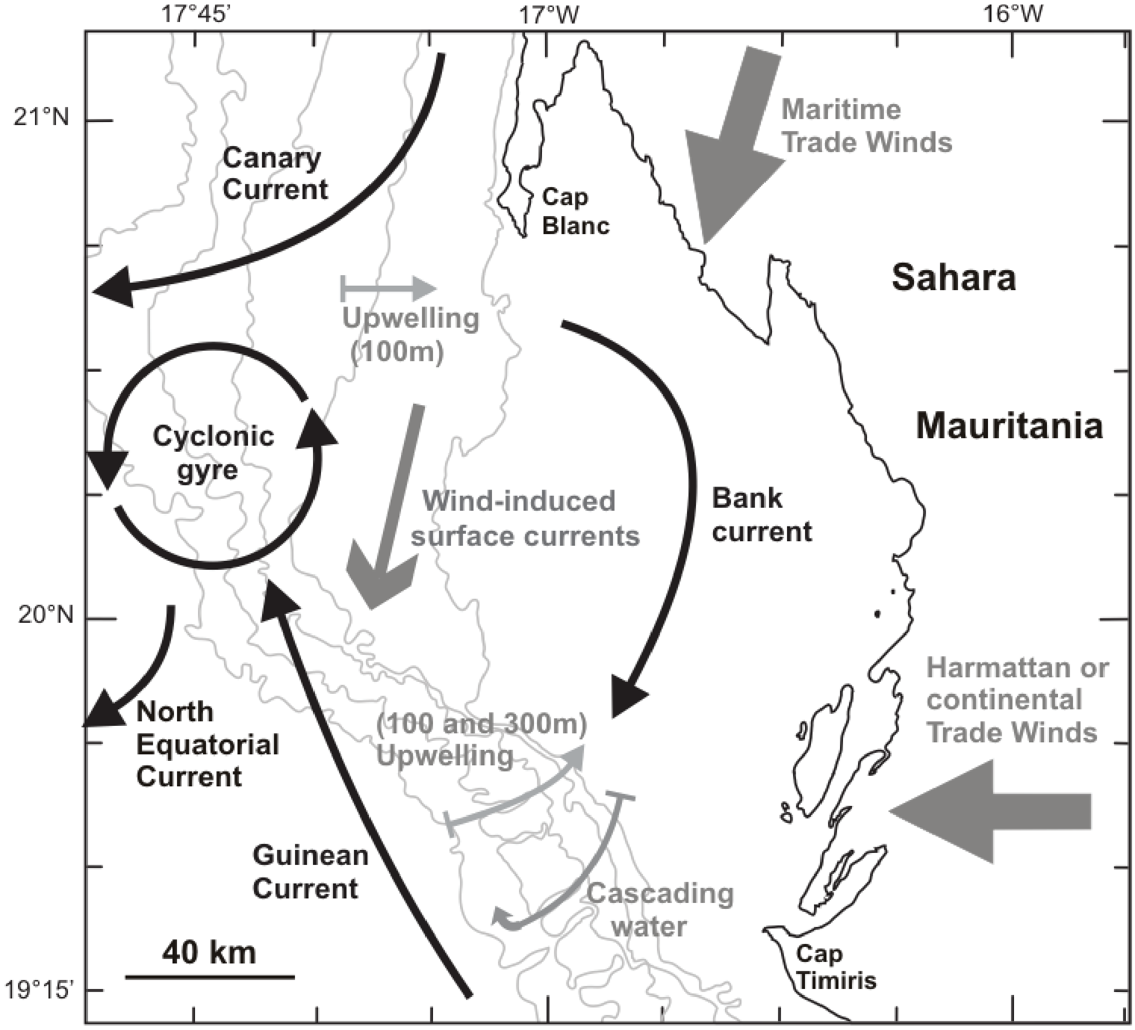

Fig. VII.2 Winds and currents occurring in the Golfe d'Arguin area. Dominant wind direction (*thick grey arrows* on land), surface current direction (*black arrows*), vertical currents (*thin grey arrows*), dominant wind-induced surface current direction (*thick grey arrow* on sea) are noted

South of the Canary Current, a cyclonic gyre (Fig. 2) comprising a branch of the Canary Current, the North Equatorial Current, the North Equatorial Countercurrent, and a poleward-flowing current component offshore the African continent is found (Mittelstaedt 1991). This latter poleward-flowing current is referred to as a branch of the Guinean Current in the literature (Shaffer 1974; Rebert 1979). The Mauritanian gyre delimits the influence of the Canary Current, in particular when it reaches its northernmost position during summer (Mittelstaedt 1991; Pastor et al. 2008). Thus, the Golfe d'Arguin is located at the northernmost edge of this large-scale cyclonic recirculation.

The Mauritanian gyre implies a northward flow of onshore waters in the Golfe d'Arguin. However, the quasi-uninterrupted southward-blowing maritime Trade Wind induces a southward surface-layer flow in the gulf (Van Camp et al. 1991; Binet et al. 1998). Over the shelf, local winds, together with the tides, are considered as the main driving forces for the water masses in the area (Mittelstaedt 1991), increasing the temporal dynamic variability of the system. The upwelling events, associated with eddy and meander activities, lead to strong mixing of the various water masses.

Because Cap Blanc is located immediately north of the northernmost position of the Intertropical Convergence Zone, upwelling here occurs all year round (Van Camp et al. 1991). Nevertheless, seasonal cycles still induce variations in upwelling intensity (Mittelstaedt 1991).

VII.2.3 *Sediment sources and sedimentation*

For the past 2,000 years, no fluvial material has been supplied to the Mauritanian shelf waters (Hanebuth et al., unpublished data). Instead, terrigenous material has been derived exclusively from the Sahara and Sahel deserts by eolian transport. In the Cap Blanc region, the direction of the maritime Trade Winds is constantly from north to northeast (Mittelstaedt 1991). The strongest winds occur in spring (Ould-Debah 1993; Khallahi 2004). Harmattan winds, or continental Trade Winds blowing westward, sporadically (but especially during the winter season) transport large amounts of coarser material to the Atlantic Ocean (Stuut et al. 2005). The Saharan Air Layer transports fine material at mid-tropospheric altitudes from northern Africa across the tropical Atlantic (Glaccum and Prospero 1980; Prospero and Lamb 2003). Nevertheless, compared to the coarser input by low-level winds, only small quantities of this fine-grained sediment are deposited in African shelf waters by the maritime Trade Winds and the Harmattan winds (Chiapello et al. 1995). Although several source areas (e.g., Mauritania, the Atlas region, and to a lesser extent, the Chad depression) are known to provide eolian sediments to the Golfe d'Arguin region, there are no quantitative data available (Goudie and Middleton 2001; Stuut et al. 2005, 2008; Engelstaedter et al. 2006). Considering that the wind climate is identical at Nouadhibou (20°50′N) and at 19°50′N (Ould-Debah 1993), and based on the general dust transport pattern (cf. North Atlantic sediments and models; Koopmann 1979; Chiapello et al. 1997; Goudie and Middleton 2001; Holz et al. 2004; Stuut et al. 2005, 2008; Engelstaedter et al. 2006), we assume that terrigenous inputs are uniform over the Golfe d'Arguin.

The dust accumulates below the local wave base in depocenters along the shoreline (Piessens 1979), and in the form of mud-rich wedges (Arguin mud wedge and Timiris mud wedge; Hanebuth and Lantzsch 2008; note: the terms "mud belt" and "mud wedge" are used here as defined by Hanebuth and Lantzsch 2008 to include also the silt-dominated and sand-bearing parts of these wedge-shaped accumulations). Abrupt steps in seafloor topography cause sudden flow expansion that results in a lee-side accumulation of fine-grained sediment in the form of a clinoform wedge. Local sediment sources include coastal lowlands and dune fields that migrate directly into the ocean (Lancaster et al. 2002; Barusseau et al. 2007).

High carbonate contents are caused by in situ production on the inner shelf of the gulf, especially in its northwestern part, in the Baie du Lévrier, and west of Tidra Island (Piessens and Chabot 1977; Piessens 1979; Koopmann et al. 1979). The bioclastic carbonate association is dominated by heterotrophic organisms (foramol-type sediments sensu Lees and Buller 1972; Lees 1975; Pomar et al. 2004).

In the Golfe d'Arguin, high hydrodynamic energy (swell, wave-base action, tidal currents) leads to good sorting of the sediment, and to the winnowing of finer fractions. Grain-size spectra are modified by in situ production of coarse-grained carbonate particles, such as bivalve or gastropod shells. Part of the winnowed sediment is transported downslope (Diester-Hass 1981).

VII.3 Materials and methods

The German R/V *Poseidon* cruise Pos-346 visited Mauritanian waters between Cap Blanc (20°50′N) and Nouakchott (18°05′N) during December 2006 and January 2007. In the Golfe d'Arguin, 61 surface sediment samples (grab samples and box cores, 50×50×50 cm) were collected between 13 and 600 mwd, 36 of these in water depths of less than 45 m (Fig. 3). Of those shallow samples, 33 were taken along a transect immediately off the seaward boundary of the Banc d'Arguin (13–42 mwd). Of the shallow samples not considered part of the transect, two samples are located in the Baie du Lévrier and one seaward of the transect at 43 mwd (20°24′N). The wide bank area as such (less than 13 mwd) was too shallow for the research vessel. Another 13 samples collected during R/V *Poseidon* cruise Pos-366 in May 2008 were also analyzed.

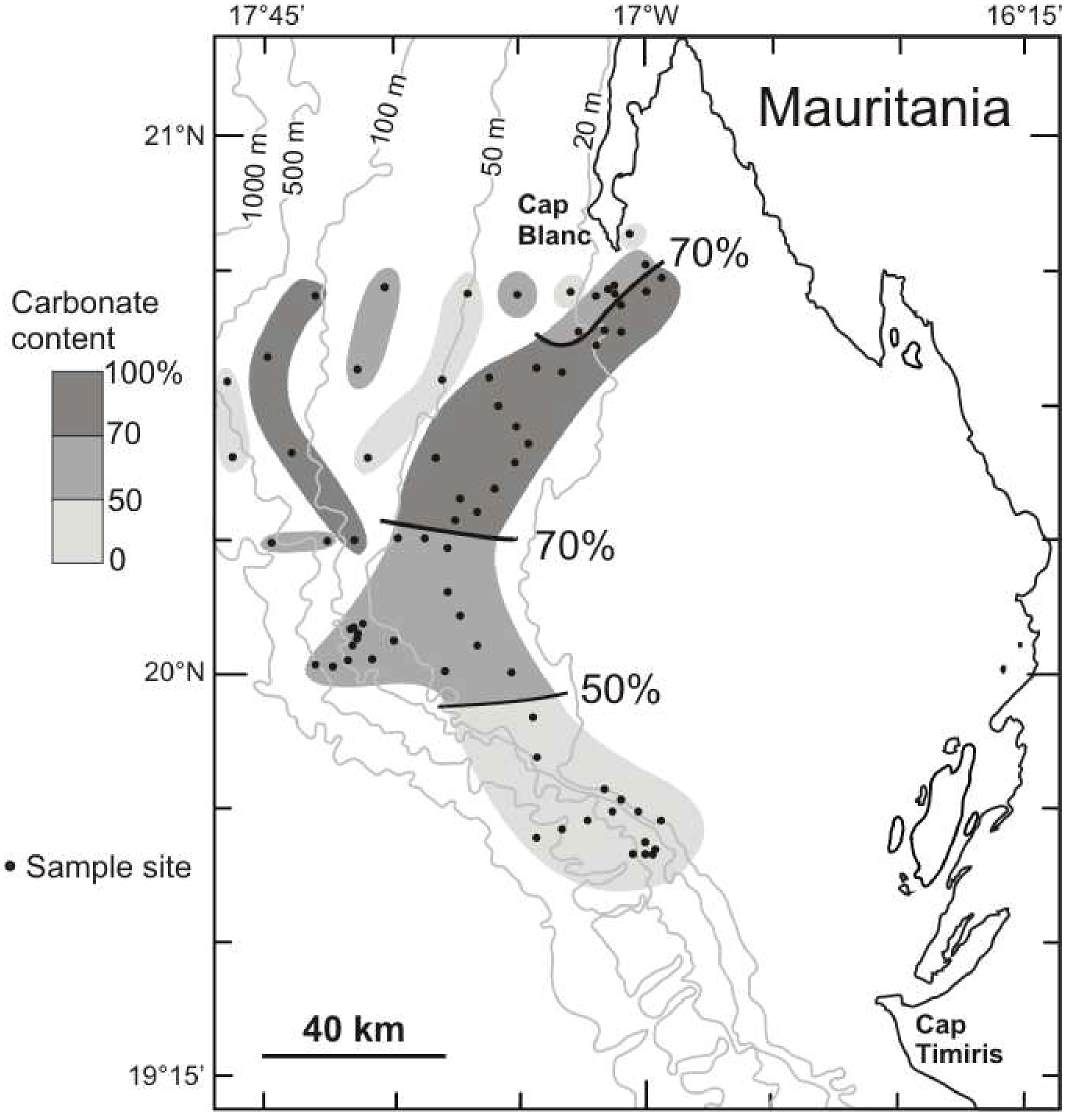

Fig. VII.3 Distribution of carbonate contents (dry wt%) of bulk sediment surface samples in the Golfe d'Arguin, showing a distinct north–south pattern (except for the northernmost samples close to Cap Blanc). *Dots* Sample locations

Carbonate contents (dry wt%) of bulk sediments were determined using the Carbometer method (Müller and Gastner 1971). Every sample was analyzed at least three times in order to obtain accurate results. The internal error is less than 1%.

For grain-size analyses, all Pos-346 bulk samples were wet sieved at 63 µm. After drying and weighing both fractions, the coarse fraction was split into different sub-fractions by means of a sonic sifter (cf. 63–125, 125–250, 250–500, 500–1,000, and >1,000 µm, corresponding to very fine, fine, medium, coarse and very coarse sand together with gravel in the internationally used Wentworth 1922 classification).

The fine fraction (<63 µm, mud) was treated with 12.5% HCl in order to dissolve calcareous components. After drying, each sample was weighed in order to determine the carbonate content of the mud fraction. Subfractions were treated with diluted calgon (sodium hexa-meta phosphate 0.05%), and shaken for at least 48 h in order to disintegrate artificial particle aggregates resulting from drying; this was followed by ultrasonic treatment immediately prior to analysis. The grain-size distributions of the carbonate-free fine fractions (<63 µm) of 46 samples were then measured using a SediGraph 5100 in the particle size range of 0.63–100 µm. For 15 samples from the northern part of the gulf comprising more than 99% coarse fraction, insufficient fine material was available for SediGraph analysis. Modal grain size is used to describe the central tendency of unimodal frequency curves.

Five samples of airborne dust were collected on 1–5 January 2007, when a massive dust outburst took place, draping the deck of the vessel with a several millimeter-thick layer every day. This dust was carefully sampled daily, and checked under the binocular for cleanness. Grain-size measurements were performed on these samples as described above for the marine samples.

In order to obtain a quantitative idea of the fine fraction possibly affected by winnowing and exporting processes, the raw data from the SediGraph 5100 analyses were used. For this, the percentage values of the <35 µm fractions in the mud fractions of both seafloor and vessel outburst samples were compared. The 35 µm grain-size limit was arbitrarily chosen to represent the grain size differentiating these two groups of samples.

Mineralogical analyses of quartz and mica were carried out on the carbonate-free fine fraction (<63 µm) of 15 sediment samples using an X-ray diffractometer (XRD) with the following scan parameters: measuring range 2θ from 3 to 85°, measuring time 100 s/step, wave length λ=1.5418 Å (Cu Kα), geometry of the Bragg-Brentano diffractometer. Of these, four samples (three shallow, 30–35 mwd, and one deep, 70 mwd) were from the northern part of the gulf, three from the shallow central part (27–32 mwd), five from the mud belts (two from the Arguin mud wedge, 90 mwd, and three from the Timiris mud wedge, 27–100 mwd), and three from the vicinity of the mud belts (one seaward of the Arguin mud wedge at 330 mwd, and two seaward of the Timiris mud wedge at 130 and 370 mwd). As the dust inputs are considered uniform for the area, these XRD measurements served to determine the effect of hydraulic sorting on the terrigenous silt fraction. The grain shape of platy minerals, such as micas, lets these to be more easily transported and remobilized than grains approaching a spherical shape, such as quartz grains. Quantification is in terms of peak areas.

VII.4 Results

VII.4.1 *Carbonate content*

In most samples, the carbonate fraction is dominated by coarse bivalve shells, with lower amounts of gastropods, bryozoans, and other carbonate skeletons (Michel et al., personal observation). The carbonate contents of the bulk sediment range from 35 to 93%, with a mean of 60% for the 74 samples (Fig. 3). Values exceeding 70% calcium carbonate are restricted to north of 20°15′N (*n*=22). Samples with lower carbonate contents in this northern region are found in the direct vicinity of Cap Blanc (44–62%, *n*=9), and below the 40 m isobath (39–68%, *n*=7). Twenty of the 21 samples between 20 and 20°15′N have intermediate carbonate contents of 50–69% (except one value of 45% found at 80 mwd). The samples located south of 20°N display the lowest carbonate contents (35–50%, *n*=15).

In contrast to the bulk sediment, the mud fractions do not show a similar north–south trend in carbonate contents. They vary between 40 and 60%, with no recognizable spatial trend.

VII.4.2 *Grain size*

Sand fractions

For the coarse fraction (>63 µm) of the bulk sediment, two distribution patterns are recognized: (1) a distinct general decrease in grain size from north to south, and (2) a less distinct decrease in grain size from shallower to deeper waters (Fig. 4).

From 20°45′ to 20°15′N, and above 50 mwd, medium sand together with coarser material dominate the sediment (*n*=23). Directly south and southwest of Cap Blanc, the sediment is finer grained and enriched in fine to medium quartz sands (average content 81% of bulk sediments, *n*=6). Slightly farther south of Cap Blanc and further southeast, the sediment is composed of coarse to very coarse sand- to gravel-sized carbonate components (average of 68%, *n*=6). North of 20°45′N, the two samples from the Baie du Lévrier consist of unsorted sediment with grain sizes varying from very coarse sand to mud.

Below 50 mwd and south of 20°15′N, very fine sand and fine sand, together with mud dominate the sediment (average of 75%, *n*=36). Below 550 mwd, and in two well-delimited shallow areas (centered around 60 and 80 mwd) forming part of the mud belt, mud contents are higher than sand contents.

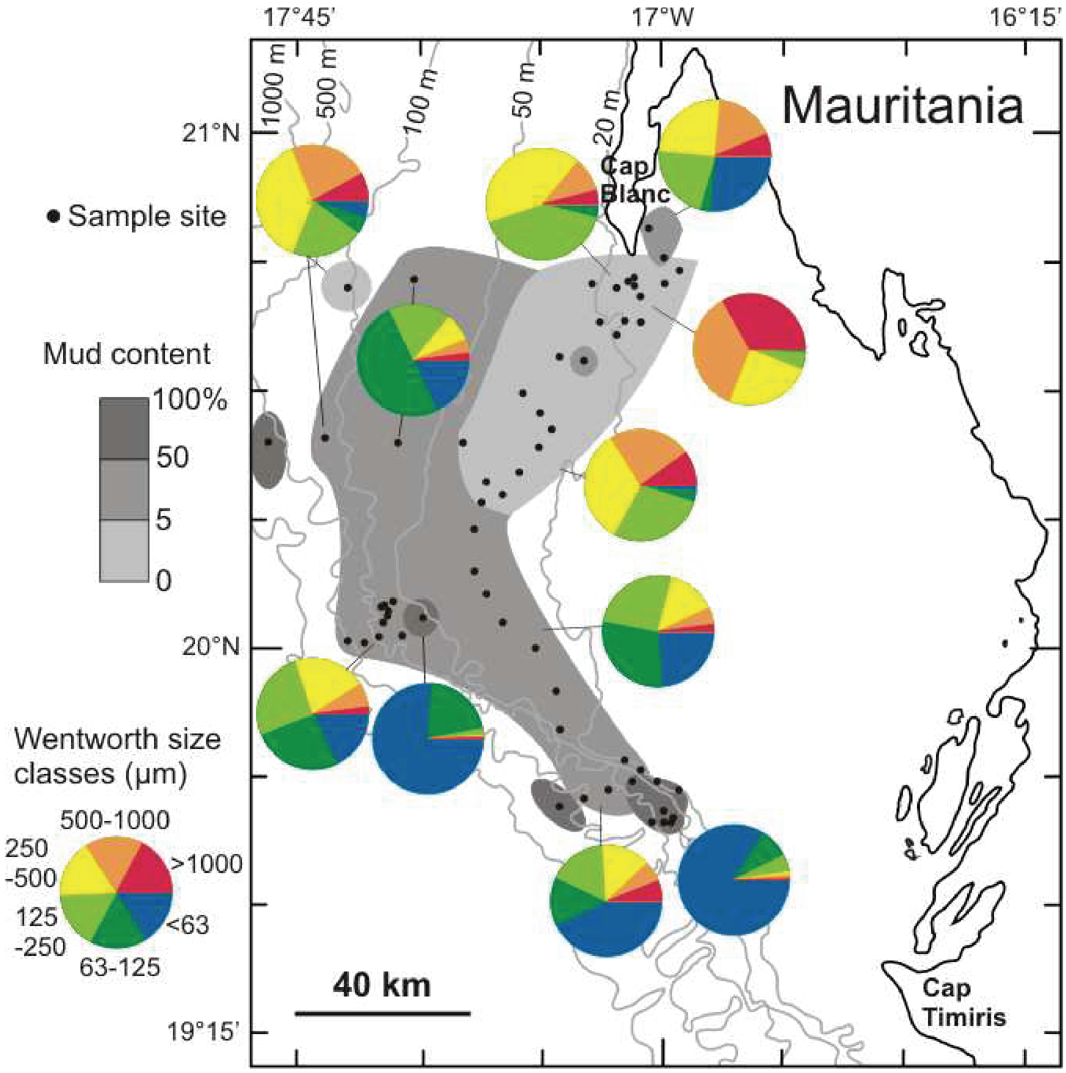

Fig. VII.4 Grain-size distribution in the Golfe d'Arguin, based on the mud contents (dry wt%) of bulk sediment surface samples (*grey shading*), and the contents of specific grain-size classes in various areas (pie diagrams). Note the north–south fining pattern

Mud fractions

The mud contents of bulk sediments range from 0 to 94%, with a mean of 24% for the 61 samples (Fig. 4). Most of the samples (*n*=22) with mud contents of 5% or less are from an area between 20°45′ and 20°15′N above the 50 m isobath. Between 19°50′ and 20°15′N, 17 of 18 samples have mud contents between 5 and 50%. South of 19°50′N, for 12 of 13 samples mud contents exceed 40%. At water depths below 550 m, mud contents are above 50%. Samples from the two mud wedges (one sample from the Arguin mud wedge, and eight samples from the Timiris mud wedge) show mud contents exceeding 69% (Fig. 4).

The clay (<2 µm) contents are extremely low for all samples. In the sand-dominated samples, no measurable clay fraction is present; in the mud-dominated samples, the clay fraction reaches a maximum of 2%. The fraction finer than 63 µm therefore essentially consists of silt-sized material. The low clay content is reflected in the non-cohesive nature of the sediments. Only few pellets and aggregates were found in the fresh sediments.

Modal silt grain size

Variations in modal silt grain sizes reveal a striking heterogeneity in proximal settings at shallow water depths (16–43 m) immediately seaward of the Banc d'Arguin (Fig. 5), along a north-south transect (27–42 mwd), offshore of this transect (43 mwd), and in the Baie du Lévrier (16–18 mwd). Note that for ten coarse-grained samples, most from north of 20°15′N, the modal silt grain sizes are based on only 1–4.5% of the bulk sediment mass (cf. low silt contents). Nevertheless, the results are consistent with those of the other samples along the transect, indicating that they are of acceptable quality (Table 1). The coarsest modal silt grain sizes, 45–50 µm, are from the northern part of the Golfe d'Arguin between 19°50′ and 20°45′N (average of 48.1 µm, *n*=15). In this area, the lower values are found between 20°05′ and 20°15′N (modal silt grain size of 45 µm, *n*=3). North of 20°45′N, the two samples located in the Baie du Lévrier display smaller modal silt grain sizes (39 and 42 µm). The smallest modal silt grain sizes are observed south of 19°45′N (33 µm; average of 38.9 µm, *n*=4).

Samples from deeper areas (50–500 mwd) define three main regions that display a clear north–south fining pattern: (1) north of 20°15′N, silt mode values range between 40 and 50 µm (average of 46.4 µm, *n*=5); (2) the Arguin mud-wedge area has silt mode values between 35 and 47 µm (average of 40.4 µm, *n*=11); (3) the Timiris mud-wedge area shows lowest values between 33 and 38 µm (average of 34.6 µm, *n*=9).

The dust outburst samples taken aboard the ship show modal silt grain sizes between 28 and 35 µm (average of 32.5 µm, *n*=5).

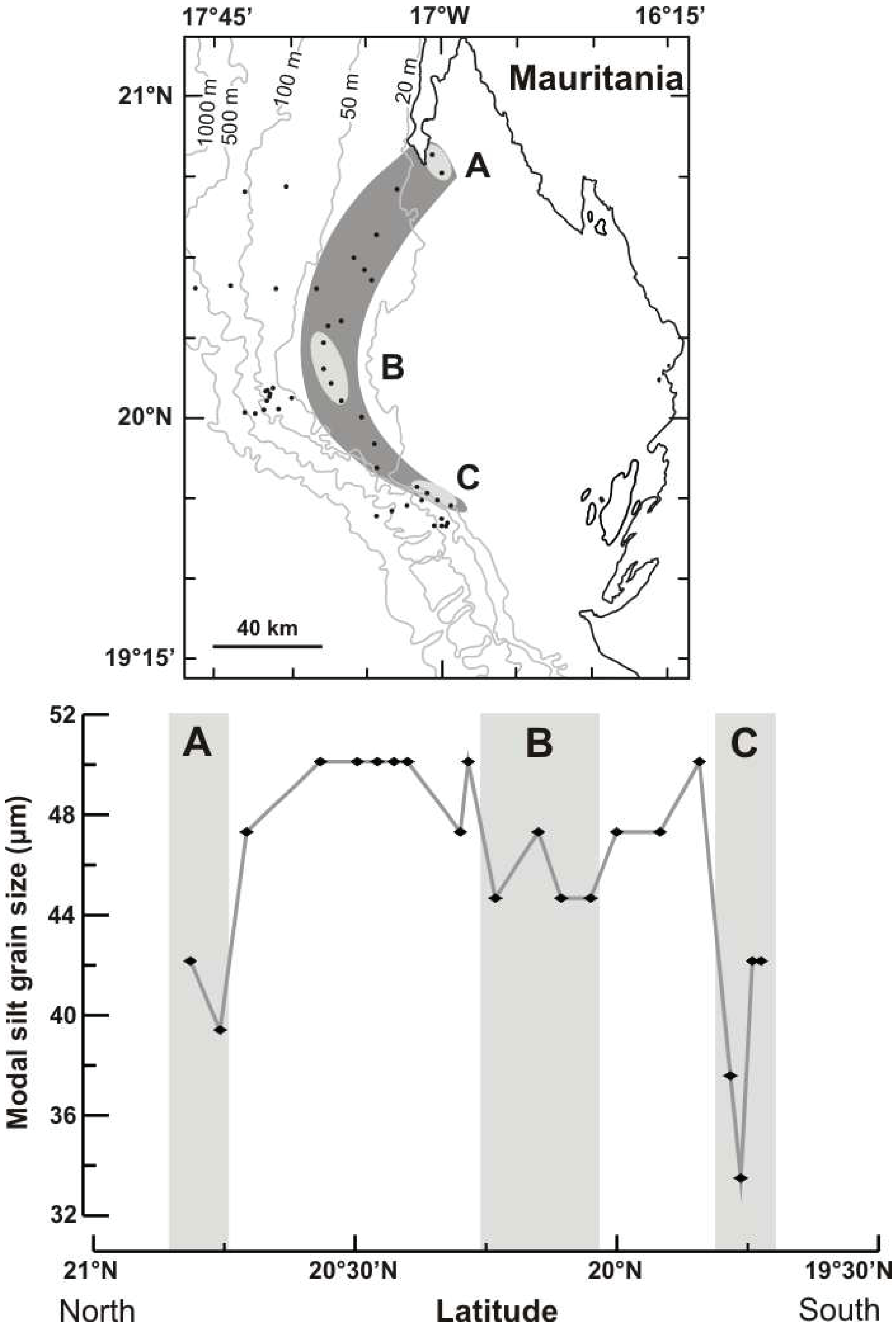

Fig. VII.5 Silt modal grain size along a north–south transect, plotted against latitude (*n*=21). In the upper diagram, the *grey shading* denotes the transect of samples (less than 50 mwd) evaluated in the bottom diagram. *A–C* (*light shading*) highlight groups of samples showing lower values

Table VII.1 Silt grain-size results (mode, mean, and percentage of the finer population, less than 35 µm grain size) from SediGraph 5100 measurements. The surface sediment samples (*n*=46) are given from north to south. The *asterisk* (*) identifies those samples selected for assessment of modal silt grain size along the transect of shallow samples (<50 mwd, *n*=21; cf. main text and Fig. 5). Outburst samples are named after the day they were taken

Sample GeoB	Latitude (N)	Longitude (W)	Depth (m)	Mode (µm)	Mean (µm)	<35 µm content (%)
116-04-1*	20.81507	17.01660	16.1	42.17	19.81	74
116-07-1*	20.75810	16.98500	17.9	39.41	17.07	82
116-14-1	20.71592	17.49993	72.3	44.67	37.21	42
115-26-1*	20.70770	17.13306	29.5	47.32	35.93	42
116-13-2	20.70005	17.63655	103.3	50.12	28.46	55
115-13-2*	20.56642	17.20050	35.5	50.12	37.83	43
115-25-1*	20.49588	17.27573	38.4	50.12	40.74	37
115-31-1*	20.45750	17.24048	35.1	50.12	42.49	37
115-47-1*	20.42600	17.21634	29.9	50.12	36.85	38
115-22-1	20.40877	17.68343	155.3	39.81	21.74	67
115-21-2	20.40102	17.80018	564.3	47.32	30.99	56
115-24-1*	20.39970	17.39913	42.8	50.12	38.60	41
115-23-1	20.39952	17.53325	63.3	50.12	40.46	31
115-33-1*	20.29908	17.31742	38.3	47.32	27.98	58
115-49-1*	20.28373	17.36118	33.2	50.12	33.40	41
115-35-1*	20.23217	17.37597	36.3	44.67	36.92	44
115-11-G*	20.15027	17.37570	31.4	47.32	41.92	34
115-11-F*	20.10620	17.35103	31.7	44.67	34.85	46
115-37-1	20.09142	17.54302	82.3	35.48	36.82	44
115-38-1	20.08438	17.56102	90.3	39.81	20.95	66
115-39-1	20.08138	17.56722	92.3	37.58	27.72	62
115-40-1	20.07287	17.55275	89.3	39.81	37.08	46
115-41-1	20.06313	17.55458	89.3	39.81	31.61	57
115-36-1	20.05968	17.48170	58.3	37.58	28.63	58
115-11-E*	20.05050	17.31717	32.6	44.67	35.74	45
115-41-C	20.05050	17.56353	93.3	47.32	31.54	56
115-41-B	20.02500	17.52453	79.3	39.81	36.75	60
115-41A2	20.02288	17.57257	182.0	44.67	28.98	60
115-41-E	20.01473	17.63665	506.0	44.67	28.07	61
115-41-D	20.01148	17.60222	333.0	39.81	18.73	76
115-11-D*	20.00037	17.24992	30.4	47.32	43.20	35
115-11-C*	19.91715	17.20740	31.4	47.32	41.45	28
115-11-B*	19.84233	17.19930	28.5	50.12	42.86	37
115-11-A*	19.78318	17.06648	27.0	37.58	23.29	69
115-95-1*	19.76350	17.03340	41.5	33.50	27.10	68
115-07-2	19.74153	17.05038	77.3	37.58	25.30	67
115-94-1*	19.74148	16.99958	37.3	42.17	29.90	59
115-08-2	19.72517	17.09950	132.3	35.48	25.11	74
115-93-1*	19.72478	16.95458	27.6	42.17	35.74	47
115-09-1	19.70823	17.15000	374.0	34.90	18.47	82
115-10-1	19.69262	17.20037	604.3	35.48	20.89	74
115-03-1	19.68408	16.98573	71.3	33.50	22.61	74
115-02-1	19.67078	16.96613	62.3	33.50	27.99	66
115-46-2	19.66237	17.01005	107.0	33.50	24.15	74
115-04-1	19.66175	16.98558	79.3	33.50	22.78	70
115-05-1	19.66108	16.97060	68.3	33.50	28.66	65
1 Jan. 2007	19.67000	17.00000	Eolian	35.48	30.58	55
2 Jan. 2007	20.30000	17.30000	Eolian	33.50	30.04	60
3 Jan. 2007	20.40000	17.75000	Eolian	31.62	24.39	75
4 Jan. 2007	20.30000	17.30000	Eolian	33.50	26.20	71
5 Jan. 2007	20.00000	17.50000	Eolian	28.18	23.86	78

Compared to the dust outburst samples, the percentages of the <35 µm fraction in the mud fraction of the seafloor samples give information on the quantity of fine material that may have been winnowed and exported. The dust samples from the different days of the outburst show two distinct patterns: in the samples from 1st and 2nd January 2007, 55 to 60% of the mud fractions are finer than 35 µm, whereas for the samples from 3rd to 5th January 2007, 71–78% are finer than 35 µm.

Clearly, this dust outburst was a very forceful one, with a wind speed reaching 8 Beaufort. It carried rather coarse grain sizes, and might not be representative. Compared to the sediment samples, this appears probable because in most samples (*n*=16 of 18) from the northern and shallow (<50 mwd) part of the Golfe d'Arguin only 28–46% fall into the <35 µm fraction (average 39%; cf. except for two samples of 58 and 69%, in which important worm tube populations are thought to have accumulated fine particles). In deeper areas and in the mud belt, 44 to 82% represent the <35 µm fraction (average of 64%, *n*=28). Highest values (>70%) are found in the Timiris mud wedge, the Baie du Lévrier, and at 333 mwd in the middle part of the gulf (~20°N).

VII.4.3 *XRD measurements*

The peak areas of micas and quartz in the X-ray diffractograms of the silt separate the samples into two populations (Fig. 6). One population (*n*=8) displays lower mica:quartz (M:Q) ratios. All but one sample of this population are from the north of 20°15′N, and between 19°50′ and 20°15′N in shallow waters (ca. 30 mwd). The other population with higher M:Q ratios represents samples from the vicinity of the two mud wedges.

A plot of M:Q ratios versus silt modal grain sizes (Fig. 7) reveals an inverse relationship between these two parameters. The modal grain sizes are larger (>40 µm) for samples with lower M:Q ratios, and vice versa.

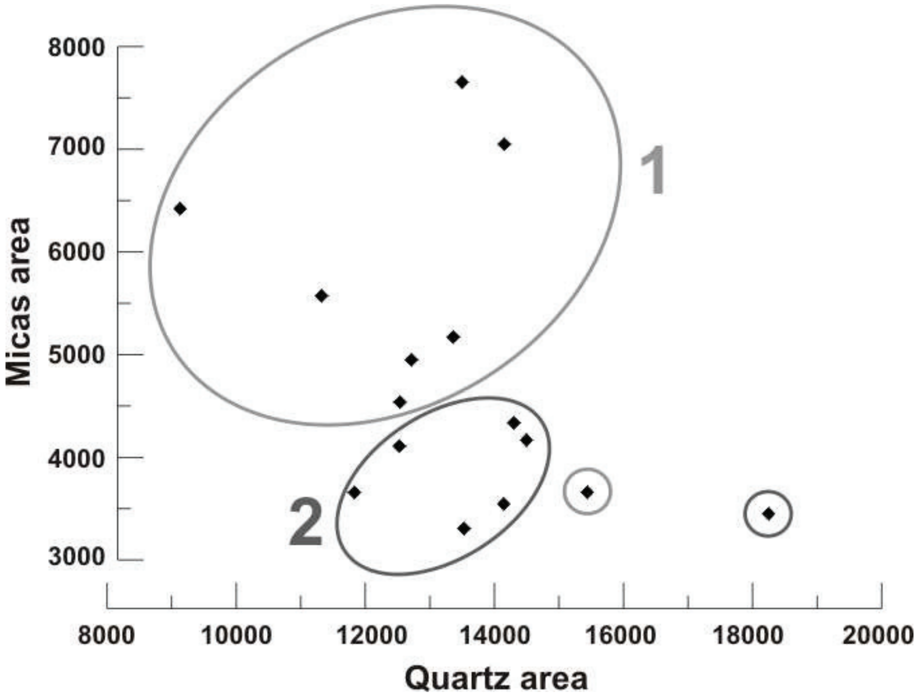

Fig. VII.6 Relationship between micas and quartz XRD areas, showing two groups of samples belonging to contrasting depositional areas: (1) the mud belt and vicinity in the middle and southern part of the Golfe d'Arguin, and (2) the northern part of the Golfe d'Arguin, and the shallow area (<50 mwd) immediately offshore the Banc d'Arguin

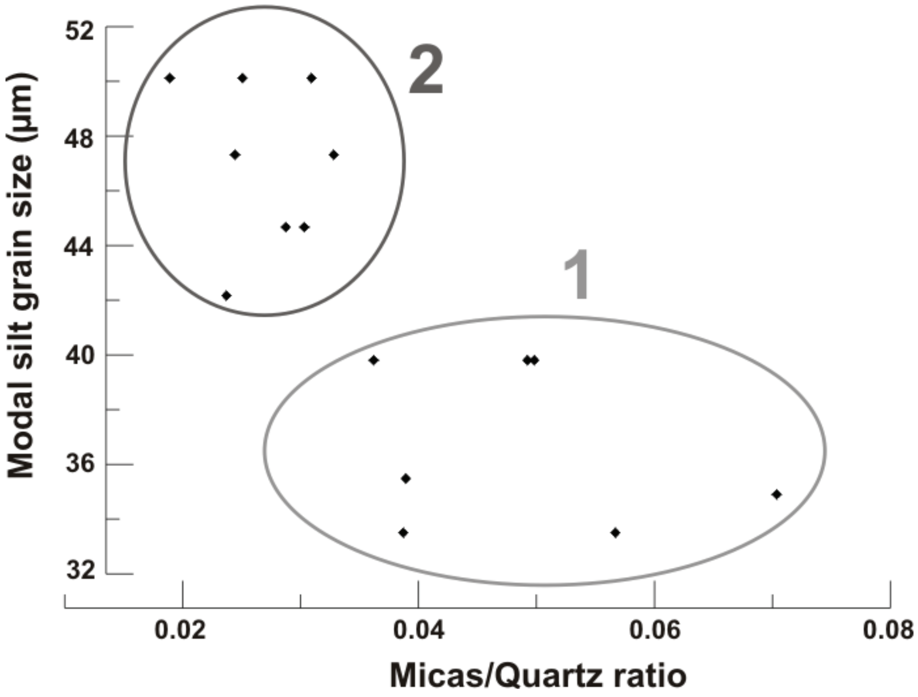

Fig. VII.7 Relationship between modal silt grain sizes and micas/quartz XRD ratios, showing two groups of samples belonging to contrasting depositional areas: (1) the mud belt and vicinity in the middle and southern part of the Golfe d'Arguin, and (2) the northern part of the Golfe d'Arguin, and the shallow area (<50 mwd) immediately offshore the Banc d'Arguin

VII.5 Discussion

The findings presented above show that in situ-produced bioclastic carbonate grains and eolian sediments that originate from the Sahel and Sahara Desert are not uniformly distributed on the Mauritanian shelf. Differences are clearly visible along the transect immediately seaward of the Banc d'Arguin, which reveals fining from north to south. Assuming that the dust supply is uniform over the whole shelf area, this observation implies that hydrodynamic processes redistribute the primary input material over the shelf, resulting in a latitudinal gradient in sediment grain size.

Carbonate contents roughly co-vary with sand/gravel contents in the sediment. This reflects that the material with grain sizes larger than 250 µm is of biogenic origin. A similar co-variation has been described earlier for the adjacent Banc d'Arguin (Piessens and Chabot 1977; Piessens 1979), and for the Baie du Lévrier (Koopmann et al. 1979), where pure bioclastic carbonate sands occur on the banks and flanks, and carbonate-poor muds and muddy sands in deeper shelf settings. A noteworthy exception to this trend is seen south and southwest of Cap Blanc, where fine- and medium-grained quartz sands dominate the bulk sediment. These quartz sediments are imported by winds from the adjacent Cap Blanc, where they are mobilized from coastal dune fields.

The grain-size distribution reflects the local hydrodynamic energy regime. The northwest side of the Golfe d'Arguin, characterized by a gentle slope, faces strong swells (Piessens 1979). In addition, tidal currents enter the gulf on this side (Peters 1976; Sevrin-Reyssac 1993). These strong hydrodynamic forces lead to winnowing of the fine sediment fractions, and silts and very fine sands are absent in most samples from this area. In situ production of coarse bioclastic carbonate components such as cm-sized bivalve shells is higher in the northern part of the gulf (as a result of ecological factors; Michel et al., unpublished data), resulting in a pronounced difference in the grain-size spectra. The area is thus characterized by lag deposits of reworked shelly material, finer sediments being winnowed and carried away. The coarse shell material creates a very porous substrate that promotes efficient winnowing. The winnowed silts and other fine sediment are initially transported in suspension toward the coast (Piessens 1979). However, a large part of this suspended material is thought to be then redirected seaward, in a southward and westward direction following the bank currents (Fig. 8). This transport is reflected in the large volumes of silt particles that are deposited on the shelf and the slope on the way south.

The modal silt grain-size distribution in water depths shallower than 50 m immediately seaward of the Banc d'Arguin reveals a significant heterogeneity, finer silt particles being absent in the swell-exposed area, a feature interpreted to reflect winnowing. The winnowed silts are preferentially deposited in the Baie du Lévrier, and immediately east of the two mud wedges. On the other hand, the southwestern side of the Golfe d'Arguin is protected from the ocean swell. The southern part, and the deeper-water areas west of the steep margin of the Banc d'Arguin thus receive less hydrodynamic energy, facilitating the deposition of fine-grained sediments. This is reflected in the fact that south of 20°15′N, silts and very fine to fine sands dominate the sediment. Modal silt grain sizes of the deeper samples also demonstrate a distinct southward-fining pattern.

In the southern part of the Golfe d'Arguin, the water from the bank leaves the shelf and enters the open ocean (Shaffer 1974; Peters 1976), transporting large volumes of material of eolian origin (Hanebuth and Lantzsch 2008). The Arguin mud wedge and the Timiris mud wedge represent depocenters of fine-grained sediments located behind morphological steps along the pathways of the seaward-flowing currents. Sedimentation rates of the Timiris mud wedge reach 110–200 cm/1,000 years for the last 1,000 years (Diester-Haass 1981; Hanebuth and Lantzsch 2008). Samples from the two mud wedges are characterized by high M:Q ratios in the mud fraction (<63 µm) that are interpreted to represent higher deposition and little winnowing. Similarly, the M:Q ratios are higher in deeper areas seaward of the mud wedges, supporting the notion that the silt fraction has been winnowed from the northern part and the shallow bank to be transported and deposited in settings with reduced hydrodynamic energy.

The dust outburst samples collected aboard the vessel show finer silt grain sizes (28–35 µm) than do most of the sediment samples from the shelf and slope (up to 600 mwd; 35–50 µm). Only some grain-size modes recorded in Timiris mud-wedge samples (33 µm) match the larger modal silt grain sizes of the dust outburst samples. The shelf and slope, at least down to 600 mwd, therefore appear to selectively accumulate coarser eolian sediment, whereas finer material would be exported further downslope. This concept is supported by the amount of fine grains (<35 µm) in the mud fraction of both seafloor and atmospheric samples. Only few areas (e.g., Timiris mud wedge, Baie du Lévrier, and around 300 mwd at 20°N) match the fine-grained (<35 µm) portion of the dust outburst samples, whereas most of the mud belt and deeper (>50 mwd) samples are in concert with the ones from the extraordinary dust outburst. This implies that part of the fine-grained silts (<35 µm) is missing on the shelf, and is thought to be exported downslope. This in turn means that the terrigenous material deposited on the shelf represents only part of the primary dust input, and that a systematic elimination of certain fractions of the eolian sediment takes place on the shelf.

Assuming a uniform eolian input for the study area, hydrodynamic processes are responsible for the repartitioning of the shelf sediments, leading to a silt deficit in the north and in the shallow parts of the south, and excess accumulations as mud wedges in hydrodynamic shadows, besides a potential voluminous export (Fig. 8). This sedimentary pattern raises the question as to how large this export may be, and how strongly it influences the grain-size spectra recorded at greater water depths on the continental slope and rise. When interpreting deeper-water sediment cores, this issue certainly needs to be addressed.

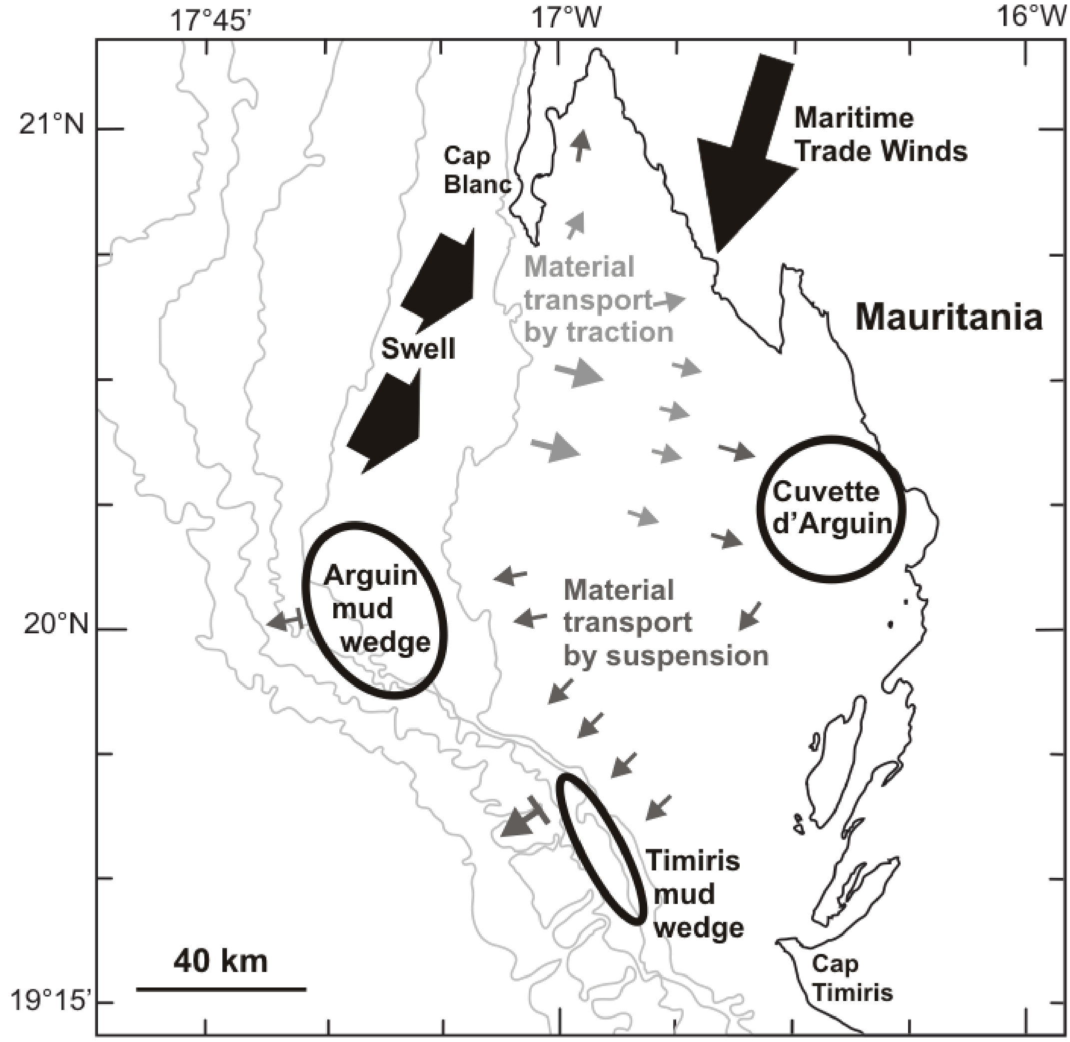

Fig. VII.8 Present-day sedimentation patterns in the Golfe d'Arguin, showing the swell effect (*large black arrows*), major material transport by traction (*light grey arrows*) and by suspension (*dark grey arrows*), as well as the maritime Trade Winds (*large black arrow*), the main surface-water driving force on the Banc d'Arguin. The *circles* indicate specific fine-grained depositional areas for suspended material on the shelf

Atmospheric dust samples collected from a spring dust plume over the slope and the deep sea off Mauritania have been shown to have modal silt grain sizes varying from 7 µm, characterized as long-distance transport, to 30 µm, corresponding to proximal transport (Holz et al. 2004). This grain-size range matches the silt grain-size spectra that the present study has identified to potentially have been winnowed off the shelf. Therefore, deposition of suspended material originating from the shelf might be missed in grain-size analyses.

Recently, vertical water-column camera profiles have shown increased particle loads above the seafloor off the Golfe d'Arguin, down to more than 2,000 mwd (Nowald et al. 2006). The source of this particle load was suggested to be the shelf, but the mechanisms of downslope transport were unclear. Cascading of dense waters from the Banc d'Arguin has been observed in the past (Shaffer 1976), but storm activity would also be a potential driver of suspended material transport toward the slope and the open ocean (Wright et al. 1991). Such transport mechanisms have to be taken into account when interpreting core records. Furthermore, estimates of direct eolian input based on core data could be too high when considering the reworking and lateral supply models.

The concept of selective export of material from the shelf has a number of paleoclimatological implications. For instance, a change in sea level would modify the coastline, and therefore the shelf morphology and associated sedimentation pattern. Aerial exposure of the Banc d'Arguin prior to 7,000 years B.P. (Hébrard 1973) would have restricted the north–south decoupling of sedimentary provinces. Furthermore, a lower sea level would lead to the emergence of land surfaces that might act as additional sources of terrigenous material, and to a seaward shift of the corresponding sedimentation pattern relative to the present-day situation. This, in addition, alters the processes involved in creating sedimentary archives on the continental slope and rise.

VII.6 Conclusions

Grain-size and mineralogical analyses of the Golfe d'Arguin display selective sediment redistribution throughout the shelf system, despite the rather uniform dust input over the region. Two fining trends occur: one from east to west, related to water depth, and another from north to south seaward of the bank. While in situ biological carbonate production has a strong influence on the composition of sand to gravel grain sizes, the fining trend in the silt spectrum is the result of hydrodynamically controlled reworking and deposition.

The present sedimentological approach has demonstrated that winnowing and partitioning of the shelf sediments of the Golfe d'Arguin lead to redistribution, and potentially to voluminous selective downslope transport of dust material toward the open ocean along topographically and hydrodynamically defined pathways. Lateral transport is thought to involve large quantities of dust sediment, thereby influencing sedimentation on the continental slope and rise. This lateral transport of terrigenous material potentially disturbs the primary dust signal of hemipelagic records and could thus have important implications in paleowind and paleoclimatic interpretations. The transport mechanisms from the inner shelf to the deep sea outlined in this study need to be considered as a process that couples coastal to deep-sea sedimentation in this region.

VII.7 Acknowledgements This paper is dedicated to Karl Gürs, friend and mollusk taxonomist aboard Poseidon-346, but who sadly passed away before this work was completed. Thanks are due to P. De Boer, an anonymous reviewer, and the journal editors for their helpful comments. We would like to thank the crews and participants of the R/V Poseidon-346 and R/V Poseidon-366 cruises, and the authorities of Mauritania for permission to work in their exclusive economic zone. Saskia Schwarze, Nadine Peichert, Brit Kockisch, Bastian Rogers, and Michael Wendschuh of the University of Bremen are acknowledged for technical support. Hermann Bange (IFM-GEOMAR, Kiel) is thanked for discussions. The MARUM (DFG-Research Center / Excellence Cluster "The Ocean in the Earth System") is acknowledged for providing infrastructure and support for this research. This study was supported by the German Science Foundation (We-2492/5).

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Second Manuscript

Modern heterozoan carbonate facies from a eutrophic tropical shelf (Mauritania)

VIII. MODERN HETEROZOAN CARBONATE FACIES FROM A EUTROPHIC TROPICAL SHELF

(MAURITANIA)

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ABSTRACT

Heterozoan carbonates are typical for extratropical sedimentary systems. However, under mesotrophic to eutrophic conditions, heterozoan carbonates also form in tropical settings. Nevertheless, such heterozoan tropical sedimentary systems are rare in the modern world and therefore are only poorly understood to date. Here a carbonate depositional system is presented where nutrient-rich upwelling waters push onto a wide shelf. These waters warm up in the shelf, giving rise to the production and deposition of tropical heterozoan facies. The carbonate facies on this shelf are characterized by a mixture of tropical and cosmopolitan biogenic sedimentary grains. Study of facies and taxonomy are the key for identifying and characterizing tropical heterozoan carbonates and for distinguishing them from their cool-water counterparts, in particular in the past where the oceanography cannot be determined directly.

VIII.1 INTRODUCTION

Carbonate sediment formation is related to the biological activity within the ecosystem of a given depositional system. Thus, beside temperature, multiple factors such as salinity, type and availability of substrate, nutrient concentration, water depth, light penetration, water energy, and sea-water chemistry control the production of carbonate sediment (Hallock and Schlager, 1986; Carannante et al., 1988; Pomar, 2001a; Mutti and Hallock, 2003; Pomar et al., 2004; Pomar and Hallock, 2008; Wright and Burgess, 2005; Westphal et al., subm.). In consequence, carbonate sediments are multiparameter archives of environmental conditions and are useful for reconstructing palecology and paleoclimate.

In the modern world, most tropical settings are characterized by oligotrophic warm waters. In such settings, carbonates are predominantly produced by autotrophic and mixotrophic biota such as corals and calcareous green algae (chlorozoan association *sensu* Lees and Buller, 1972; photozoan association *sensu* James, 1997). In contrast, associations dominated by heterotrophic biota (i.e., foramol *sensu* Lees and Buller, 1972; heterozoan associations *sensu* James, 1997) dominate modern carbonate sediments from temperate to polar regions (e.g., Nelson and Bornhold, 1983; Freiwald, 1993; Freiwald and Henrich, 1994; Henrich et al., 1995; Rao, 1996). However, these heterozoan associations not only form in cool to cold-water settings but stretch through all climate belts from the poles to the tropics (Lees and Buller, 1972; Lees, 1975; Mutti and Hallock, 2003; Wilson and Vecsei, 2005). In consequence, interpreting heterozoan versus photozoan occurrences as cold/temperate versus warm climatic conditions is an oversimplification that can result in misleading paleoclimatic and paleoenvironmental interpretations (cf. Pomar et al., 2004).

An increasing number of ancient examples of heterozoan tropical carbonates have recently been described (Neogene: Brandano and Corda, 2002; Pomar et al., 2004; Triassic: Hornung et al., 2007; Permian: Samankassou, 2002). However, the number of ancient examples is comparably low, possibly indicating that other occurrences still have to be recognized as such.

For a better understanding of nutrient-rich warm-water settings, and in order to recognize and improve the interpretation of such occurrences in the fossil record, detailed facies description, including taxonomic determination of the skeletal components, and correlation to environmental parameters are important. In addition to detailed study of the rock record, modern analog studies are required to gain a better understanding of high-nutrient tropical settings. Only a limited number of examples of modern heterozoan associations are known to form in tropical to subtropical settings. They in most cases reflect the oceanographic conditions leading to increased nutrient levels such as upwelling phenomena (Hallock and Schlager, 1986; James, 1997; cf. Westphal et al., subm.). High-nutrient waters suppress oligotrophic and euphotic biocoenoses and lead to the development of ecosystems dominated by heterotrophic organisms independent of latitude. Upwelling waters, however, in most cases at the same time lower the temperature of settings in tropical latitudes. Here we present a rare example of a warm-water eutrophic carbonate depositional system, namely the shelf offshore northern Mauritania. In this example, upwelled nutrient-rich waters warm up on a wide shelf and give way to the establishment of warm-water eutrophic ecosystems that may serve as analog for such occurrences in the past.

VIII.2 STUDY AREA AND MATERIAL

The narrow continental shelf of NW-Africa (<65 km) widens off northern Mauritania to the Golfe d'Arguin that is some 150 km wide (Fig. 1). This extensive gulf hosts the shallow Banc d'Arguin with water depths of less than 10 m, and in many areas less than 5 m (Piessens, 1979; Sevrin-Reyssac, 1993; Wolff et al., 1993). Here, the Banc d'Arguin and the coastal parts are referred to as the inner shelf, the mid shelf being defined between the drop-off of the bank (~20 meter water depth; mwd) and the 50 m-isobath which corresponds to a sedimentological boundary (Domain, 1985), and the outer shelf extending from 50 m to the shelf break (100 to 150 mwd). The waters off northern Mauritania are among the most productive marine areas in the world (3 mg*m^{-3} Chl-a [chlorophyll-a]; Marañón and Holligan, 1999) and are important fishing grounds (Binet et al., 1998). The origin of the high productivity lies in the elevated nutrient levels caused by oceanic upwelling plus additional fertilization by high desert dust input.

Oceanic upwelling along the NW-African coastline stretches from 12° N to 33° N (Mittelstaedt, 1991; Van Camp et al., 1991) as is reflected in the cool-water carbonates of most parts of this region (Summerhayes et al., 1976). Where the upwelling waters enter the Banc d'Arguin, minimum temperatures are 16 °C. In the shallow Golfe d'Arguin, however, the upwelling waters warm up to subtropical-tropical temperatures. On the bank water-temperature exceeds 25 °C in summer and does not drop below 18 °C in winter (Sevrin-Reyssac, 1993; Quack et al., 2007). At the same time the trophic level remains high, resulting in mesotrophic to eutrophic warm-water conditions. The Golfe d'Arguin is characterized by high water energy caused by swell from the northwest, waves, tides, and wind-driven currents (Peters, 1976; Mittelstaedt, 1991).

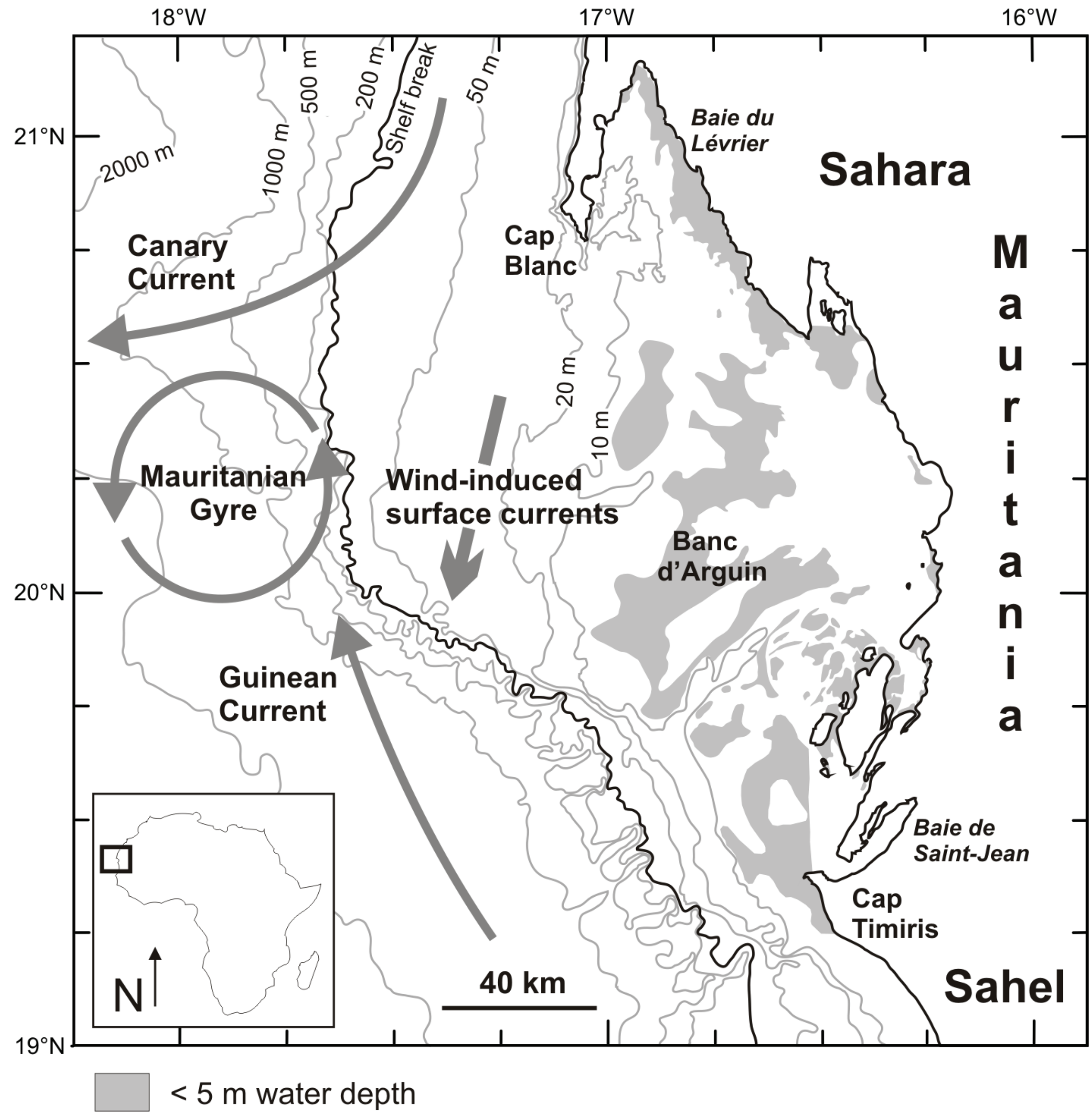

Fig. VIII.1 Location and bathymetry of the Golfe d'Arguin study area between Cap Blanc and Cap Timiris. Note the large expanse of shallower water (<10 mwd) in the center of the gulf, known as the Banc d'Arguin, and comprising some distinct areas with water depths of less than 5 m. Large-scale surface currents (grey arrows) and dominant wind-induced surface current direction (large grey arrow) are shown (modified from Domain, 1985; Hanebuth and Lantzsch, 2008; Michel et al., 2009).

The sedimentary system of the Golfe d'Arguin is characterized by mobile sand waves in the northern part including the Baie du Lévrier. This coarse sediment is largely biodetrital, and carbonate contents reach up to 90%. Along the pronounced drop-off of the shallow Banc d'Arguin, to the outer, deeper part of the Golfe d'Arguin, bioclastic sandy material accumulates. Towards the south, finer-grained sediment dominates that is largely composed of eolian dust, and carbonate contents are below 50% (Michel et al., 2009). In the southernmost part of the Golfe d'Arguin, the shelf is incised by a series of small canyons which on the slope merge to the Timiris canyon (Shaffer, 1974; Krastel et al., 2004). Seafloor material retrieved from this latter area at 370 mwd reveals the presence of deep-water corals (i.e., *Lophelia* and *Madrepora*; Michel et al., subm.).

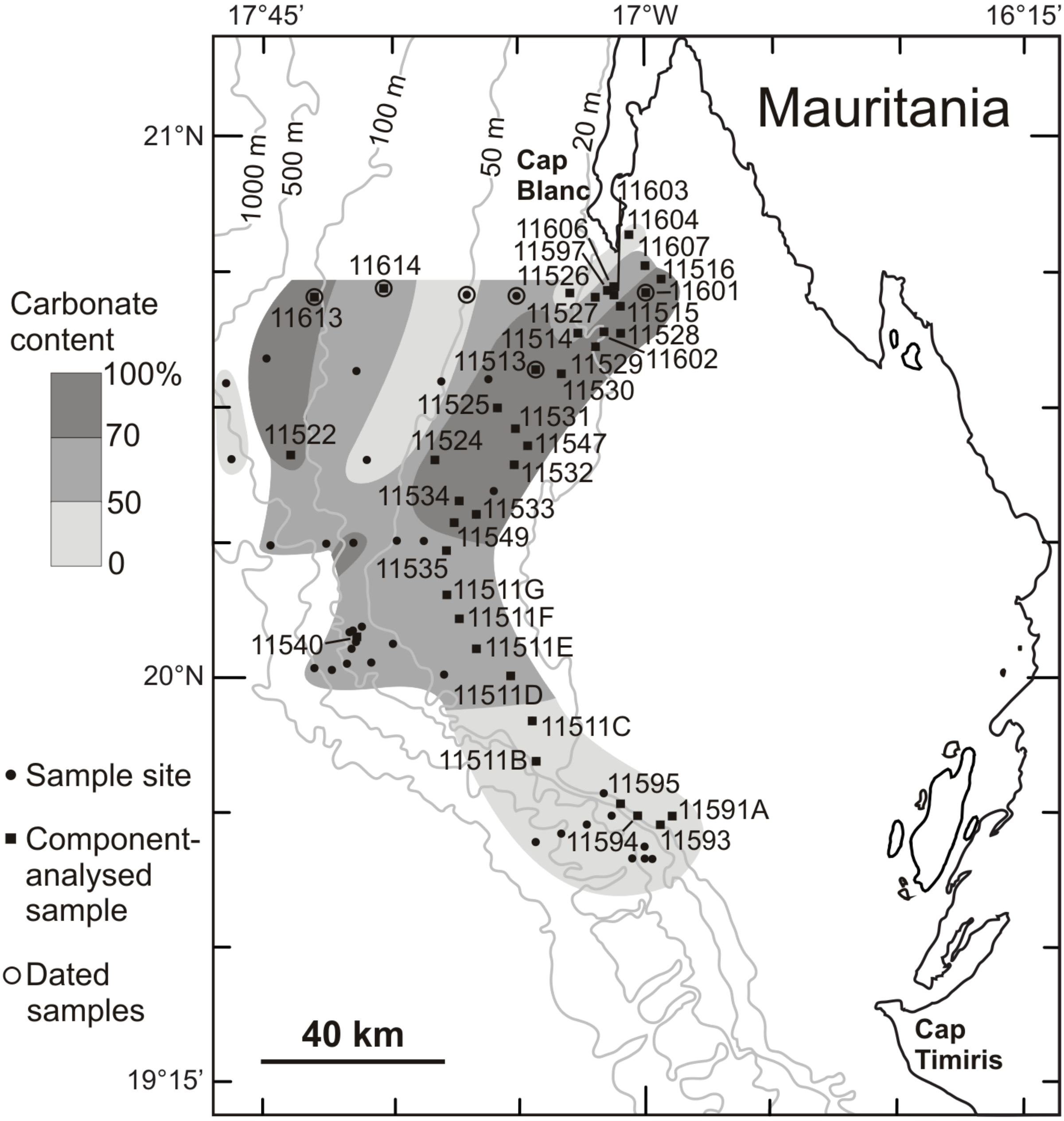

Fig. VIII.2 Distribution of carbonate contents (dry wt%) of bulk sediment surface samples in the Golfe d'Arguin, showing a distinct north–south pattern at shallow water depths (<40 mwd; except for the northernmost samples close to Cap Blanc). *Dots*: Sample sites; *Squares*: Component-analysed samples; *Circles*: Dated samples. Sample numbers of the component-analysed samples (squares) are shown and are GeoB numbers.

The 74 grab samples and box cores studied here were collected during two cruises of R/V Poseidon, namely Pos-346 (December 2006-January 2007; 61 samples; Westphal et al., 2007) and Pos-366 (May 2008; 13 samples; Zonneveld et al., in press). Two samples are from the Baie du Lévrier in the northern part of the Golfe d'Arguin, one sample is from the shallow Banc d'Arguin (4 m water depth; mwd), 36 samples have been collected along the drop-off from the Banc d'Arguin to the open shelf in water depth of 10 to 40 m, whereas 35 samples are from the open shelf (maximum of 604 mwd; Fig. 2).

VIII.3 METHODS

Carbonate contents as a percentage of the bulk sediment were determined using the Carbometer method (Müller and Gastner, 1971). Each sample has been measured three to four times. The internal error is less than 1 %.

The carbonate mineralogical composition of 74 samples was determined using an X-ray diffractometer (XRD) with the following scan parameters: measuring range 2θ from 3 to 85°, measuring time 100 s/step, wave length λ=1.5418 Å (Cu Kα), geometry of the Bragg-Brentano diffractometer. The percentage of the carbonate minerals (aragonite, high-Mg calcite = HMC, and low-Mg calcite = LMC) relative to total carbonate content was calculated from peak area ratios using calibration curves. These calculations are based on the observation that the relative amount of a mineral is related to the reflection intensity, which is proportional to the peak area in the diffractogram (Neumann, 1965). The non-linear relationship between calcite and aragonite (Milliman, 1974) was calculated from ratios calibrated from standard minerals measured on the same diffractometer at MARUM in Bremen/Germany. For the relative amounts of HMC and LMC, a linear relationship was used. Non-carbonate mineralogies were not quantified.

For grain-size analyses, bulk samples (n=61) were wet sieved at 63µm. After drying and weighing both fractions, the coarse fraction was split into different sub-fractions with a sonic sifter (63–125 µm, 125–250 µm, 250–500 µm, 500–1,000 µm, >1,000 µm, corresponding to very fine, fine, medium, coarse and very coarse sand and gravel), except for sample GeoB11510 (604 mwd) where not enough sandy material was present. Further dry sieving were performed on the bulk material of selected samples in order to determine the respective amounts of the very coarse sand (1,000–2,000 µm) and gravel (>2,000 µm) fractions.

The sedimentary components of 39 samples were analysed quantitatively in order to determine sorting and composition. In order to obtain a detailed description of the shallow-water carbonate deposits, the component-analysed samples are mostly from the shallow subtidal zone (10–50 mwd) along the Banc d'Arguin (n=34) and the top of the bank (n=1).

Other component-analysed samples comes from deeper waters (70–155 mwd, n=4), three of them being from the northern carbonate-rich part of the Golfe d'Arguin, and allow for a broader understanding of the open-shelf sedimentation. For compositional analysis, a minimum of 300 components per grain-size fraction >125 µm was determined. The following groups were considered: red algae, planktonic foraminifers, benthic foraminifers, bivalves, gastropods, pteropods, scaphopods, bryozoans, decapods, barnacles, ostracods, ahermatypic corals, echinoderms, alcyonarian spicules, sponge spicules, serpulids, aggregated worm tubes, fish remains, fecal pellets, aggregate grains (include organically-aggregated grains and, for the sample GeoB11591 from the Banc d'Arguin, intraclasts), and quartz grains. Non-determinable grains were not considered for facies definition. Molluscs and foraminifers were classified to species level where possible. For the determination of the molluscs, the nomenclature of Niklès (1950), Gofas et al. (1985), Cosel (1995, in prep.), and Ardovini and Cossignani (2004) was used; for that of the foraminifers, the nomenclature of Loeblich and Tappan (1987) was employed.

In order to obtain information on the grains indeterminate by loose-sediment analysis, 18 artificial thin sections were prepared by embedding bulk sediment in epoxy-resin. Thin-section analysis allows for identification of internal structures of bioclasts that in many cases are indicative for the carbonate-secreting organism. Subsequently, the quantities of the same component groups as for the loose-sediment analysis were determined by point-counting (for the point-counting method see chapter 6 in Flügel, 2004).

Different sedimentary facies from the shelf of the Golfe d'Arguin were determined on the basis of grain size and composition of the loose-sediment analysis. Hierarchical cluster analysis ("Group Average" cluster mode using the "Bray Curtis" similarity based on grain size, carbonate content, and composition excluding the unidentified grains) was performed to statistically confirm the facies groups.

Radiocarbon ages were determined for eroded mollusc shells from surface samples from the northern Golfe d'Arguin in order to assess the intensity of reworking. The measurements were undertaken by AMS ^{14}C at the University of Poznan, Poland. The raw ^{14}C date was calibrated using CALIB version 5.0.1 (Stuiver and Reimer, 1993) and the Marine radiocarbon age calibration "Marine04" (Huguen et al., 2004).

VIII.4 RESULTS

VIII.4.1 *Carbonate contents and grain sizes*

The carbonate contents in the sediments of the Golfe d'Arguin range from 35 to 93% (mean: 60%, n=74; Tab. 1 and Fig. 2). A north-south trend is obvious: Highest carbonate contents are present north of 20°15′N (>70%, n=22), intermediate values between 20°N and 20°15′N (45–70%, n=21), and lowest values south of 20°N (35–50%, n=15). In the vicinity of Cap Blanc in the north, the carbonate contents locally are lowered as a result of quartz sand input from migrating dunes (44–62%, n=8). In the northern part of the study area, a strike-parallel pattern is observed in downslope direction where carbonate contents decrease (from >70% to <50%) before increasing again between 100 and 200 mwd (81–85%, n=3).

Tab. VIII.1 Data from the 74 samples from the Golfe d'Arguin showing location (longitude and latitude), depth (mbsl: meter below sea level), carbonate content Carb (dry wt%), carbonate mineralogy Carb min (% t.c.: percentage of total carbonate; Aragonite Arag, Low Magnesium Calcium LMC, and High Magnesium Calcium HMC) and grain-size contents (dry wt%).

Sample	Longitute (°W)	Latitude (°N)	Depth (mbsl)	Carb (%)	Carb min (% t.c.)			Grain size (%)					
					Arag	HMC	LMC	>1000 µm	500-1000 µm	250-500 µm	125-250 µm	63-125 µm	<63 µm
GeoB11503	16°59.14'	19°41.04'	71.3	40	69	9	22	0	0	0	2	4	94
GeoB11504	16°59.13'	19°39.71'	79.3	39	70	7	23	0	1	2	6	6	86
GeoB11505	16°58.24'	19°39.66'	68.3	42	68	7	25	0	0	0	2	6	92
GeoB11507	17°03.04'	19°44.49'	77.3	41	67	12	21	0	0	0	3	5	92
GeoB11508	17°06.00'	19°43.50'	132.3	49	55	19	26	2	8	17	25	20	28
GeoB11509	17°09.00'	19°42.49'	374.3	40	73	5	22	16	9	10	11	7	47
GeoB11510	17°12.02'	19°41.56'	604.3	35	61	6	33	No available data					71
GeoB11511A	17°03.99'	19°46.99'	27.0	42	68	7	25	6	4	11	25	4	50
GeoB11511B	17°11.96'	19°50.54'	28.5	37	60	10	30	0	1	1	28	62	8
GeoB11511C	17°12.44'	19°55.03'	31.4	44	66	10	24	1	5	12	19	51	11
GeoB11511D	17°15.00'	20°00.02'	30.4	56	71	7	22	0	1	4	25	30	39
GeoB11511E	17°19.03'	20°03.03'	32.6	56	69	8	23	2	2	7	25	33	32
GeoB11511F	17°21.06'	20°06.37'	31.7	56	67	11	22	1	4	10	66	9	11
GeoB11511G	17°22.54'	20°09.02'	31.4	63	70	6	24	2	5	17	50	20	5
GeoB11513	17°12.03'	20°33.99'	35.5	84	68	10	22	10	11	34	34	5	5
GeoB11514	17°07.04'	20°38.01'	23.3	56	78	3	18	19	24	46	10	0	0
GeoB11515	17°02.03'	20°41.00'	21.1	83	91	2	7	54	25	14	6	0	1
GeoB11516	16°57.20'	20°44.00'	13.4	74	78	4	18	32	45	22	1	0	0
GeoB11521	17°48.01'	20°24.06'	564.3	41	66	6	28	0	0	1	5	40	53
GeoB11522	17°41.01'	20°24.53'	155.3	81	87	3	10	5	22	45	15	4	9
GeoB11523	17°32.00'	20°23.97'	63.3	46	57	15	28	0	1	5	13	54	27
GeoB11524	17°23.95'	20°23.98'	42.8	77	52	9	39	20	12	37	27	4	1
GeoB11525	17°16.54'	20°29.75'	38.4	82	60	9	31	4	8	36	46	5	2
GeoB11526	17°07.98'	20°42.46'	29.5	44	55	9	36	4	3	8	71	11	3
GeoB11527	17°04.97'	20°41.99'	20.1	56	45	6	49	3	3	32	61	0	0

Tab. VIII.1 continued

Sample	Longitute (°W)	Latitude (°N)	Depth (mbsl)	Carb (%)	Carb min (% t.c.)			Grain size (%)					
					Arag	HMC	LMC	>1000 µm	500-1000 µm	250-500 µm	125-250 µm	63-125 µm	<63 µm
GeoB11528	17°01.98'	20°38.01'	22.3	78	88	2	10	51	27	15	5	0	1
GeoB11529	17°04.96'	20°36.52'	23.3	71	90	2	9	49	30	18	2	0	0
GeoB11530	17°09.01'	20°33.52'	33.2	71	71	6	23	7	15	27	21	9	20
GeoB11531	17°14.43'	20°27.45'	35.1	85	73	7	20	8	12	33	37	5	4
GeoB11532	17°14.57'	20°23.45'	35.3	87	90	2	8	35	38	24	4	0	1
GeoB11533	17°19.05'	20°17.94'	38.3	82	74	6	20	18	35	26	16	3	2
GeoB11534	17°21.08'	20°19.42'	33.3	93	87	3	10	27	46	24	3	0	0
GeoB11535	17°22.56'	20°13.93'	36.3	69	66	9	25	1	2	7	47	30	13
GeoB11536	17°28.90'	20°03.58'	58.3	59	56	13	31	0	0	0	2	21	76
GeoB11537	17°32.58'	20°05.49'	82.3	45	58	13	30	0	1	3	11	35	50
GeoB11538	17°33.66'	20°05.06'	90.3	59	72	10	18	2	9	25	23	21	19
GeoB11539	17°34.03'	20°04.88'	92.3	59	68	9	22	1	6	25	30	22	15
GeoB11540	17°33.17'	20°04.37'	89.3	53	50	41	9	1	5	15	24	34	21
GeoB11541	17°33.27'	20°03.79'	89.3	59	71	8	21	1	6	26	28	26	13
GeoB11541A	17°34.35'	20°01.37'	182.3	59	67	9	24	3	6	11	34	35	12
GeoB11541B	17°31.47'	20°01.50'	79.3	50	74	12	15	1	7	33	49	7	5
GeoB11541C	17°33.81'	20°03.03'	93.3	62	78	8	15	2	13	41	32	8	4
GeoB11541D	17°36.13'	20°00.69'	333.3	64	84	4	11	13	19	32	9	5	22
GeoB11541E	17°38.20'	20°00.88'	506.3	53	69	8	23	0	1	4	20	54	22
GeoB11546	17°00.60'	19°39.74'	107.3	43	69	7	24	0	1	3	4	8	84
GeoB11547	17°12.98'	20°25.56'	29.9	91	75	5	20	6	30	29	28	5	2
GeoB11548	17°16.99'	20°20.53'	32.3	89	76	5	19	2	17	47	32	1	0
GeoB11549	17°21.67'	20°17.02'	33.2	81	67	10	23	3	10	32	52	2	1
GeoB11591	16°54.79'	19°44.19'	4.0	50	68	8	24	40	50	9	1	0	0
GeoB11593	16°57.27'	19°43.49'	27.6	39	64	10	25	0	0	1	9	21	69
GeoB11594	16°59.97'	19°44.49'	37.3	39	62	13	25	0	0	1	14	13	71
GeoB11595	17°02.00'	19°45.81'	41.5	50	64	10	26	12	10	16	23	14	26
GeoB11597	17°03.54'	20°42.74'	15.4	55	49	0	51	3	11	84	2	0	0
GeoB11601	16°59.01'	20°42.50'	16.5	75	47	6	47	54	44	0	1	0	0
GeoB11602	17°03.96'	20°38.16'	21.9	85	86	2	12	53	26	16	4	0	0
GeoB11603	17°02.77'	20°42.22'	24.5	62	94	1	5	13	15	15	55	1	1
GeoB11604	17°01.00'	20°48.90'	16.1	45	59	5	36	7	11	16	21	1	43
GeoB11606	17°02.79'	20°43.17'	24.4	51	66	8	25	2	8	42	47	1	0
GeoB11607	16°59.10'	20°45.49'	17.9	51	57	7	37	11	18	28	31	1	10
GeoB11613	17°38.19'	20°42.00'	103.3	85	87	4	9	9	23	30	28	8	1
GeoB11614	17°30.00'	20°42.96'	72.3	63	77	8	16	7	9	16	33	26	9
GeoB13007	17°21.98'	20°00.01'	40.0	57	61	12	27	No available data					
GeoB13008	17°25.00'	20°15.00'	40.0	60	56	16	29						
GeoB13009	17°29.99'	20°14.98'	47.0	51	60	10	30						
GeoB13010	17°35.01'	20°14.99'	80.0	84	70	8	22						
GeoB13011	17°36.99'	20°14.99'	287.0	63	75	5	19						
GeoB13012	17°43.00'	20°15.00'	545.0	59	70	7	24						
GeoB13013	17°47.99'	20°33.00'	348.0	48	64	8	28						
GeoB13014	17°42.98'	20°34.96'	178.0	85	86	3	11						
GeoB13015	17°31.98'	20°33.99'	125.0	68	66	14	20						
GeoB13016	17°24.00'	20°33.00'	49.0	39	65	13	22						
GeoB13017	17°16.99'	20°33.00'	36.0	77	47	15	38						
GeoB13018	17°14.98'	20°42.00'	37.0	62	55	24	21						
GeoB13019	17°21.49'	20°42.00'	53.0	44	70	8	22						

As for the carbonate contents, the grain-size distribution in the Golfe d’Arguin displays a striking north-south trend (Tab. 1). In the north, medium to coarse sand dominates, where between 20°15′N and 20°45′N in less than 45 mwd, medium sand to gravel are dominant. In the south, mud and very fine to fine sand are most abundant (for silt grain-size distribution see Michel et al., 2009).

VIII.4.2 *Component analysis of the loose sediment*

Quartz grains and unidentified bioclasts are not considered in the carbonate grain associations as given below. The abundance of quartz grains is highly variable and ranges from 0 to 70% of the bulk identified grains (average of 16%). Unidentified bioclasts range between 1 and 42% of the sediment (average of 19%; Tab. 2).

Bivalves, small benthic and planktonic foraminifers, barnacles, and echinoderms are the most commonly identified bioclasts in the sediments. Bivalve shells dominate (30–90%) the grain associations of 33 out of 39 samples and in none of the samples constitute less than 19% of the determined bioclastic grains (Tab. 2). Of the six remaining samples with less than 30% bivalve shells, one is dominated by barnacle fragments (41%) and is found in the Baie du Lévrier, and five are dominated by benthic foraminifer tests (32–48%) and are from the southern part of the Golfe d’Arguin (south of 20°05′N). Small benthic foraminifers are present (~0–48%) in most parts of the gulf and are most abundant south of 20°15′N seaward of the Banc d’Arguin (12–48%; n=11). Planktonic foraminifers display abundances >5% of the identified grains in nine samples, four of which are from the outer shelf (11–30%; 70–150 mwd) and five from the mid shelf (5–33%). Barnacle fragments is predominantly present on the Banc d’Arguin (20%; n=1) and in the shallow northern part of the Golfe d’Arguin (8–42%; n=13; 13–23 mwd). Echinoderm fragments are frequent but abundances >5% of the identified grains are restricted to the Baie du Lévrier (9%; n=1) and the mid shelf (5–22%; n=15). The clear dominance of molluscs and foraminifers in most of the samples places the sediment of the Golfe d’Arguin in the foramol grain association of Lees and Buller (1972) and the heterozoan association of James (1997).

Less frequent bioclasts include molluscs other than bivalves such as gastropods which are ubiquitous but exceed 5% of the identified grains only in six samples, four of them from the southernmost part of the area (south of 20°N). Scaphopods are rare. Aggregated worm-tube fragments show abundances >5% in the Baie du Lévrier (7%; n=1) and on the mid shelf south of 20°25′N (5–13%; n=6). Crustaceans other than barnacles are rare in the sediment and include decapods and ostracods. Bryozoan fragments occur in all samples but do not exceed 5% of the identified bioclasts. Fish remains, fecal pellets, organically-aggregated grains that might correspond to fragments of aggregated worm tubes, and sponge spicules are rare, while alcyonarian spicules, serpulids, pteropods, and ahermatypic coral pieces are very rare. Red algae fragments (6%) and intraclasts (counted as aggregates in Table 2: 8%) were observed exclusively in the sample from the shallow Banc d'Arguin.

VIII.4.3 *Grain determination in artificial thin sections*

Loose-sediment analyses left up to 42% of the grains unidentified (Tab. 2). To improve the determination of those grains, artificial thin sections of 18 samples have been analysed in order to study the internal structure of the grains.

Quantitative analysis by point-counting of the thin sections (Tab. 3) has confirmed that among the bioclasts, bivalves, small benthic and planktonic foraminifers, barnacles, and echinoderms are the most abundant components. A total of 13 out of the 18 analysed samples are dominated by bivalves (40–91% of the identified bioclasts; n=10) and benthic foraminifers (30–59%; n=3). In addition to confirming these findings, thin-section analyses showed that echinoderms and barnacles fragments are significantly more abundant than indicated by loose-sediment analysis (Tabs. 2, 3). These grains are more easily identified in thin-section analysis where internal structures allow for identification than from the outside, in particular when reworking obscures the shapes.

While loose-sediment analysis was performed on the granulometric fraction larger than 125 µm, thin sections were prepared from the bulk sediment. This explains the higher counts of quartz grains that are mainly in the silt-size range in the thin sections (3–85%; average of 42%) where they dominate the grain association of 11 out of the 18 analysed samples. Additionally, in loose-sediment analysis, each grain is counted once, which gives an estimate of the absolute frequency of the components. In the point-counting, grains are determined along a grid of points, and large components can be covered by more than one point; this method gives the volume of the types of components in the sediment. This effect explains in particular the higher abundances of barnacles and ahermatypic corals in thin sections.

Tab. VIII.2 Loose-sediment quantification of the 39 component-analysed samples as percentages (white background) and normalized percentages of the identified bioclasts (i.e., excluding quartz grains and unidentified bioclasts; italic, grey background). RAL: red algae; PFOR: planktonic foraminifers; BFOR: benthic foraminifers; BIV: bivalves; GAST: gastropods, PTER: pteropods; SCAP: scaphopods; BRY: bryozoans; DEC: decapods; BAR: barnacles; OST: ostracods; COR: ahermatypic corals; ECH: echinoderms; ALC: alcyonarian spicules; SPO: sponge spicules; SER: serpulids; WRM: aggregated worm tubes; FSH: fish remains; FEC: fecal pellets; AGG: aggregates; BIO: unidentified bioclasts; QUA: quartz grains.

GeoB	RAL	PFOR	BFOR	BIV	GAST	PTER	SCAP	BRY	DEC	BAR	OST	COR	ECH	ALC	SPO	SER	WRM	FSH	FEC	AGG	BIO	QUA
11511B	0	3.13	25.56	31.64	1.19	1.88	0.04	0.01	0.01	0.08	2.82	0	3.84	3.76	0.95	0.05	0.03	0.11	0.34	0.28	21.43	2.86
11511B	*0*	*4.13*	*33.76*	*41.79*	*1.57*	*2.48*	*0.05*	*0.01*	*0.01*	*0.11*	*3.72*	*0*	*5.07*	*4.97*	*1.25*	*0.07*	*0.04*	*0.15*	*0.45*	*0.37*	-	-
11511C	0	1.93	8.65	40.07	5.08	0	0.04	0.93	0.08	4.56	0.86	0	5.69	0.17	0.34	0	4.95	0.01	0.69	0.02	13.41	12.52
11511C	*0*	*2.61*	*11.68*	*54.1*	*6.86*	*0*	*0.05*	*1.26*	*0.11*	*6.16*	*1.16*	*0*	*7.68*	*0.23*	*0.46*	*0*	*6.68*	*0.01*	*0.93*	*0.03*	-	-
11511D	0	2.29	21.84	27.81	3	0	0.01	0.05	0.02	0.34	3.14	0	5.16	0.27	4.15	0	10.63	0.01	1.99	0.01	14.85	4.42
11511D	*0*	*2.84*	*27.06*	*34.45*	*3.72*	*0*	*0.01*	*0.06*	*0.02*	*0.42*	*3.89*	*0*	*6.39*	*0.33*	*5.14*	*0*	*13.17*	*0.01*	*2.47*	*0.01*	-	-
11511E	0	3.74	35	22.79	0.11	0.19	3.81	0.06	0.01	0.05	1.61	0	0.23	0	0.01	0	1.46	0.06	3.82	0.01	21.65	5.41
11511E	*0*	*5.13*	*47.97*	*31.24*	*0.15*	*0.26*	*5.22*	*0.08*	*0.01*	*0.07*	*2.21*	*0*	*0.32*	*0*	*0.01*	*0*	*2*	*0.08*	*5.24*	*0.01*	-	-
11511F	0	2.96	19.7	40.21	1.81	2.45	0	0.31	0.01	0.03	3.27	0	0.24	0	0	0.82	0	0.93	1.22	0	21.77	4.26
11511F	*0*	*4*	*26.64*	*54.37*	*2.45*	*3.31*	*0*	*0.42*	*0.01*	*0.04*	*4.42*	*0*	*0.32*	*0*	*0*	*1.11*	*0*	*1.26*	*1.65*	*0*	-	-
11511G	0	3.22	10.8	33.88	2.44	0	0	0.41	0.01	2.05	0.3	0	3.89	0	0.9	0	4.11	0	0.76	0	28.89	8.32
11511G	*0*	*5.13*	*17.21*	*53.97*	*3.89*	*0*	*0*	*0.65*	*0.02*	*3.27*	*0.48*	*0*	*6.2*	*0*	*1.43*	*0*	*6.55*	*0*	*1.21*	*0*	-	-
11513	0	0.88	9.65	54.42	2.18	0	0.08	0.66	0.03	0.84	0.25	0	11.62	0	0	0	3.1	0.13	0.13	0.13	13.73	2.16
11513	*0*	*1.05*	*11.47*	*64.71*	*2.59*	*0*	*0.1*	*0.78*	*0.04*	*1*	*0.3*	*0*	*13.82*	*0*	*0*	*0*	*3.69*	*0.15*	*0.15*	*0.15*	-	-
11514	0	0.16	1.71	41.52	1.32	0	0	0.27	0.17	4.08	0.08	0	0.29	0	0	0	0.19	0	0	0.28	10.42	39.51
11514	*0*	*0.32*	*3.42*	*82.92*	*2.64*	*0*	*0*	*0.54*	*0.34*	*8.15*	*0.16*	*0*	*0.58*	*0*	*0*	*0*	*0.38*	*0*	*0*	*0.56*	-	-
11515	0	0.04	0.82	65.81	2.49	0	0.09	0.62	0.09	13.89	0	0	0.95	0	0	0	0.16	0	0	0.06	8.24	6.76
11515	*0*	*0.05*	*0.96*	*77.41*	*2.93*	*0*	*0.11*	*0.73*	*0.11*	*16.3*	*0*	*0*	*1.12*	*0*	*0*	*0*	*0.19*	*0*	*0*	*0.07*	-	-
11516	0	0	0.22	36.58	2.75	0	0	0.27	0	29.58	0	0	0.15	0	0	0	0.83	0	0	0.02	10.37	19.23
11516	*0*	*0*	*0.31*	*51.96*	*3.91*	*0*	*0*	*0.38*	*0*	*42*	*0*	*0*	*0.21*	*0*	*0*	*0*	*1.18*	*0*	*0*	*0.03*	-	-
11522	0	10.6	3.92	59.35	2.09	0.52	0	1.74	0	0.54	0.17	0	0.53	0	0.51	0	0.02	0.01	0	2.17	9.99	7.85
11522	*0*	*12.9*	*4.77*	*72.23*	*2.54*	*0.63*	*0*	*2.12*	*0*	*0.66*	*0.21*	*0*	*0.65*	*0*	*0.62*	*0*	*0.02*	*0.01*	*0*	*2.64*	-	-
11524	0	0.83	5.3	32.08	3.69	0	0.13	2.39	0.3	1.77	0.09	0.17	9.03	0	0	0	5.61	0.06	0	0.72	32.14	5.68
11524	*0*	*1.34*	*8.53*	*51.6*	*5.94*	*0*	*0.21*	*3.84*	*0.48*	*2.85*	*0.14*	*0.27*	*14.52*	*0*	*0*	*0*	*9.02*	*0.1*	*0*	*1.16*	-	-
11525	0	1.75	11.48	45.62	1.05	0	0	1.47	0	0.1	0	0	3.3	0	0	0.88	0.02	0.26	0	0.02	32.55	1.49
11525	*0*	*2.65*	*17.41*	*69.17*	*1.59*	*0*	*0*	*2.23*	*0*	*0.15*	*0*	*0*	*5*	*0*	*0*	*1.33*	*0.03*	*0.39*	*0*	*0.03*	-	-
11526	0	0	7.7	32.63	1.09	0	0.01	0.1	0.1	0.74	0.34	0	12.49	0	0.37	0	1.83	0	0.01	0	17.63	24.95
11526	*0*	*0*	*13.41*	*56.84*	*1.9*	*0*	*0.02*	*0.17*	*0.17*	*1.29*	*0.59*	*0*	*21.76*	*0*	*0.64*	*0*	*3.19*	*0*	*0.02*	*0*	-	-
11527	0	0	9.74	14.15	0.44	0	0	0.11	0	2.37	0	0	1.82	0	0	0	0	0	0	0.55	26.83	44
11527	*0*	*0*	*33.38*	*48.49*	*1.51*	*0*	*0*	*0.38*	*0*	*8.12*	*0*	*0*	*6.24*	*0*	*0*	*0*	*0*	*0*	*0*	*1.88*	-	-
11528	0	0	0.7	52.83	2.72	0	0	0.61	0	19.23	0.17	0	0.87	0	0	0	0.05	0	0	0.41	9.29	13.12
11528	*0*	*0*	*0.9*	*68.09*	*3.51*	*0*	*0*	*0.79*	*0*	*24.8*	*0.22*	*0*	*1.12*	*0*	*0*	*0*	*0.06*	*0*	*0*	*0.53*	-	-
11529	0	0	0.25	57.16	1.85	0	0	0.26	0	12.52	0.06	0	0.23	0	0	0	0.37	0	0	0.33	7.48	19.48
11529	*0*	*0*	*0.34*	*78.27*	*2.53*	*0*	*0*	*0.36*	*0*	*17.1*	*0.08*	*0*	*0.31*	*0*	*0*	*0*	*0.51*	*0*	*0*	*0.45*	-	-
11530	0	0.6	5	59.71	2.5	0	0.13	0.32	0.06	1.24	0.23	0	9.94	0	0.3	0	3.62	0	0.43	0	14.37	1.55
11530	*0*	*0.71*	*5.95*	*71.02*	*2.97*	*0*	*0.15*	*0.38*	*0.07*	*1.47*	*0.27*	*0*	*11.82*	*0*	*0.36*	*0*	*4.31*	*0*	*0.51*	*0*	-	-
11531	0	0.52	7.32	54.78	0.98	0	0	0.34	0.24	0.44	0.5	0	14.14	0	0.12	0	2.56	0.43	0	0.19	15.21	2.23
11531	*0*	*0.63*	*8.87*	*66.35*	*1.19*	*0*	*0*	*0.41*	*0.29*	*0.53*	*0.61*	*0*	*17.13*	*0*	*0.15*	*0*	*3.1*	*0.52*	*0*	*0.23*	-	-
11532	0	0.01	1.16	62.33	3.57	0	0.08	2.15	0.32	4.45	0.01	0	2.23	0	0	0	0.57	0.13	0	0.43	17.25	5.3
11532	*0*	*0.01*	*1.5*	*80.49*	*4.61*	*0*	*0.1*	*2.78*	*0.41*	*5.75*	*0.01*	*0*	*2.88*	*0*	*0*	*0*	*0.74*	*0.17*	*0*	*0.56*	-	-

Tab. VIII.2 continued

GeoB	RAL	PFOR	BFOR	BIV	GAST	PTER	SCAP	BRY	DEC	BAR	OST	COR	ECH	ALC	SPO	SER	WRM	FSH	FEC	AGG	BIO	QUA
11533	0	0.18	2.81	42.21	2.82	0	0.1	1.05	0	5.46	0	0	5.71	0	0.1	0	0.91	1.25	0	1.19	28.92	7.3
11533	*0*	*0.28*	*4.41*	*66.17*	*4.42*	*0*	*0.16*	*1.65*	*0*	*8.56*	*0*	*0*	*8.95*	*0*	*0.16*	*0*	*1.43*	*1.96*	*0*	*1.87*	-	-
11534	0	0.09	3.68	76.55	2.36	0.03	0	0.76	0.2	0.33	0	0	0.66	0	0	0.1	0	0.24	0	0	14.65	0.35
11534	*0*	*0.11*	*4.33*	*90.06*	*2.78*	*0.04*	*0*	*0.89*	*0.24*	*0.39*	*0*	*0*	*0.78*	*0*	*0*	*0.12*	*0*	*0.28*	*0*	*0*	-	-
11535	0	24.17	9.13	34.09	1.28	0.13	0.03	0.51	0.13	0	0.96	0	1.69	0	0.25	0	0.42	0.06	0.57	0.12	24.4	2.05
11535	*0*	*32.87*	*12.42*	*46.36*	*1.74*	*0.18*	*0.04*	*0.69*	*0.18*	*0*	*1.31*	*0*	*2.3*	*0*	*0.34*	*0*	*0.57*	*0.08*	*0.78*	*0.16*	-	-
11540	0	25.1	29.48	16.16	1.87	0	0	0.02	0.01	0.03	0.87	0	0.04	0	0.01	0.87	0.09	7.45	0.54	0.45	15.7	1.3
11540	*0*	*30.24*	*35.52*	*19.47*	*2.25*	*0*	*0*	*0.02*	*0.01*	*0.04*	*1.05*	*0*	*0.05*	*0*	*0.01*	*1.05*	*0.11*	*8.98*	*0.65*	*0.54*	-	-
11547	0	10.84	12.18	55.56	0.72	0.91	0	1.26	0.04	0.04	0	0	2.85	0	0.3	0	0.05	0.92	0	0.07	13.32	0.93
11547	*0*	*12.64*	*14.21*	*64.8*	*0.84*	*1.06*	*0*	*1.47*	*0.05*	*0.05*	*0*	*0*	*3.32*	*0*	*0.35*	*0*	*0.06*	*1.07*	*0*	*0.08*	-	-
11549	0	1.52	19.95	52.61	1.36	0	0.1	0.03	0	0.03	0	0	0.91	0	0	0	0.21	0.1	0	0.52	22.12	0.54
11549	*0*	*1.97*	*25.8*	*68.02*	*1.76*	*0*	*0.13*	*0.04*	*0*	*0.04*	*0*	*0*	*1.18*	*0*	*0*	*0*	*0.27*	*0.13*	*0*	*0.67*	-	-
11591	6.06	0	0.95	30.26	2.87	0	0	0.45	0	12.46	0	0	0.85	0	0	0.33	0	0	0	7.63	11.93	26.21
11591	*9.8*	*0*	*1.54*	*48.92*	*4.64*	*0*	*0*	*0.73*	*0*	*20.1*	*0*	*0*	*1.37*	*0*	*0*	*0.53*	*0*	*0*	*0*	*12.33*	-	-
11593	0	1.53	27.32	14.23	4.49	0	0.02	0.06	0.04	0.83	2.65	0	6.68	0	2.12	0	3.78	0.14	0.18	0	27.13	8.79
11593	*0*	*2.39*	*42.64*	*22.21*	*7.01*	*0*	*0.03*	*0.09*	*0.06*	*1.3*	*4.14*	*0*	*10.43*	*0*	*3.31*	*0*	*5.9*	*0.22*	*0.28*	*0*	-	-
11594	0	0.69	24.12	16.35	4.67	0	0.04	2.48	0.09	3.49	2.1	0	15.64	0	0.59	0	4.85	0.07	0.04	0	14.99	9.8
11594	*0*	*0.92*	*32.07*	*21.74*	*6.21*	*0*	*0.05*	*3.3*	*0.12*	*4.64*	*2.79*	*0*	*20.79*	*0*	*0.78*	*0*	*6.45*	*0.09*	*0.05*	*0*	-	-
11595	0	19.34	30.19	17.02	8.79	0.54	0.38	3.18	0.04	0.1	0.27	0.77	2.58	0	0	0	2.46	0.38	2.72	0.32	10.93	0
11595	*0*	*21.71*	*33.89*	*19.11*	*9.87*	*0.61*	*0.43*	*3.57*	*0.04*	*0.11*	*0.3*	*0.86*	*2.9*	*0*	*0*	*0*	*2.76*	*0.43*	*3.05*	*0.36*	-	-
11597	0	0	2.46	8.19	1.09	0	0	0.05	0	6.73	0	0	0.66	0	0	0	0.04	0	0	0	35.66	45.12
11597	*0*	*0*	*12.8*	*42.61*	*5.67*	*0*	*0*	*0.26*	*0*	*35*	*0*	*0*	*3.43*	*0*	*0*	*0*	*0.21*	*0*	*0*	*0*	-	-
11601	0	0	0.02	82.05	1.41	0	0	0.25	0	10.89	0.01	0	0.89	0	0	0.44	0	0	0	0.07	1.39	2.58
11601	*0*	*0*	*0.02*	*85.44*	*1.47*	*0*	*0*	*0.26*	*0*	*11.3*	*0.01*	*0*	*0.93*	*0*	*0*	*0.46*	*0*	*0*	*0*	*0.07*	-	-
11602	0	0	0.16	67.66	1.55	0	0.16	0.46	0.38	9.42	0	0	0.74	0	0	0	0.09	0	0	0.12	13.43	5.82
11602	*0*	*0*	*0.2*	*83.8*	*1.92*	*0*	*0.2*	*0.57*	*0.47*	*11.7*	*0*	*0*	*0.92*	*0*	*0*	*0*	*0.11*	*0*	*0*	*0.15*	-	-
11603	0	0.24	5.16	17.25	1.3	0	0.05	0.37	0.03	9.61	0.05	0	1.25	0	0	0	0.91	0	0	0.25	22.59	40.94
11603	*0*	*1*	*14.15*	*47.3*	*3.56*	*0*	*0.14*	*1.01*	*0.08*	*26.4*	*0.14*	*0*	*3.43*	*0*	*0*	*0*	*2.5*	*0*	*0*	*0.69*	-	-
11604	0	0	1.17	14.16	0.82	0	0	0.2	0.05	15.85	0	0	3.3	0	0	0	2.72	0	0	0.16	42.47	19.12
11604	*0*	*0*	*3.04*	*36.85*	*2.13*	*0*	*0*	*0.52*	*0.13*	*41.2*	*0*	*0*	*8.59*	*0*	*0*	*0*	*7.08*	*0*	*0*	*0.42*	-	-
11606	0	0	6.9	7.71	0.78	0	0	0.92	0	5.46	0	0	3.83	0	0	0	0.06	0	0	0.17	32.93	41.24
11606	*0*	*0*	*26.71*	*29.85*	*3.02*	*0*	*0*	*3.56*	*0*	*21.1*	*0*	*0*	*14.83*	*0*	*0*	*0*	*0.23*	*0*	*0*	*0.66*	-	-
11607	0	0	9.89	33.43	0.19	0.21	0	0.66	0.01	7.51	1.06	0	1.54	0	0	1.29	0	0.01	0	0.62	29.98	13.61
11607	*0*	*0*	*17.53*	*59.25*	*0.34*	*0.37*	*0*	*1.17*	*0.02*	*13.3*	*1.88*	*0*	*2.73*	*0*	*0*	*2.29*	*0*	*0.02*	*0*	*1.1*	-	-
11613	0	16.44	9.59	39.65	1.83	0.31	0	2.7	0.02	0.04	0.34	0	2.22	0	0	0	0.1	2.93	0	0.05	21.31	2.47
11613	*0*	*21.57*	*12.58*	*52.02*	*2.4*	*0.41*	*0*	*3.54*	*0.03*	*0.05*	*0.45*	*0*	*2.91*	*0*	*0*	*0*	*0.13*	*3.84*	*0*	*0.07*	-	-
11614	0	8.12	16.57	37.33	2.6	0.49	0	2.2	0.36	0.58	1.52	0	1.2	0.51	0.01	0.49	1.45	0.6	0	1.75	17.95	6.28
11614	*0*	*10.72*	*21.87*	*49.26*	*3.43*	*0.65*	*0*	*2.9*	*0.48*	*0.77*	*2.01*	*0*	*1.58*	*0.67*	*0.01*	*0.65*	*1.91*	*0.79*	*0*	*2.31*	-	-

Tab. VIII.3 Point-counter quantification of 18 artificial thin sections as percentages (white background) and normalized percentages of the identified bioclasts (i.e., excluding quartz grains; italic, grey background). RAL: red algae; PFOR: planktonic foraminifers; BFOR: benthic foraminifers; BIV: bivalves; GAST: gastropods, PTER: pteropods; SCAP: scaphopods; BRY: bryozoans; DEC: decapods; BAR: barnacles; OST: ostracods; COR: ahermatypic corals; ECH: echinoderms; ALC: alcyonarian spicules; SPO: sponge spicules; SER: serpulids; WRM: aggregated worm tubes; FSH: fish remains; FEC: fecal pellets; AGG: aggregates; QUA: quartz grains.

GeoB	RAL	PFOR	BFOR	BIV	GAST	PTER	SCAP	BRY	DEC	BAR	OST	COR	ECH	ALC	SPO	SER	WRM	FSH	FEC	AGG	BIO	QUA
11511B	0	0	6.52	1.09	0	0	0	0	0	0	0	0	4.35	0	2.17	0	0	0	0	1.09	0	84.78
11511B	*0*	*0*	*42.84*	*7.16*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*28.58*	*0*	*14.26*	*0*	*0*	*0*	*0*	*7.16*	-	-
11511E	0	0.53	7.45	1.60	0.53	0	0	0	0	0	0	0	3.72	0	5.32	0	0	0	0	11.70	0	69.15
11511E	*0*	*1.72*	*24.15*	*5.19*	*1.72*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*12.06*	*0*	*17.24*	*0*	*0*	*0*	*0*	*37.93*	-	-
11511F	0	0	9.62	54.62	1.15	0	0	0	0	0.38	0	0	6.54	0	0	0	0	0	0	0	0	27.31
11511F	*0*	*0*	*13.23*	*75.14*	*1.58*	*0*	*0*	*0*	*0*	*0.52*	*0*	*0*	*9.00*	*0*	*0*	*1*	*0*	*0*	*0*	*0*	-	-
11514	0	0	2.12	56.36	1.27	0	0	0	0	5.08	0	0	2.12	0	0	0	0	0	0	0	0	33.05
11514	*0*	*0*	*3.16*	*84.18*	*1.90*	*0*	*0*	*0*	*0*	*7.59*	*0*	*0*	*3.16*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11516	0	0	0.83	27.39	2.90	0	0	0	0	21.58	0	0	0	0	0	0	0	0	0	0	0	47.30
11516	*0*	*0*	*1.57*	*51.97*	*5.51*	*0*	*0*	*0*	*0*	*40.94*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11525	0	0.64	18.59	32.05	0.64	0	0	0	0	0	0	0	28.21	0	0	0	0	0	0	0	0	19.87
11525	*0*	*0.80*	*23.20*	*40.00*	*0.80*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*35.21*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11527	0	0	15.70	8.72	0	0	0	0	0	0	0	0	2.33	0	0	0	0	0	0	0	0	73.25
11527	*0*	*0*	*58.69*	*32.60*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*8.71*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11534	0	0	0	88.21	0.47	0	0	0	0	0	0	0	3.30	0	0	0	0	0	0	5.19	0	2.83
11534	*0*	*0*	*0*	*90.78*	*0.48*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*3.40*	*0*	*0*	*0*	*0*	*0*	*0*	*5.34*	-	-
11535	0	1.63	13.07	42.04	0	0	0	0	0	0	0.41	0	21.63	1.22	0	0	0	0	0	0	0	20.00
11535	*0*	*2.04*	*16.34*	*52.55*	*0*	*0*	*0*	*0*	*0*	*0*	*0.51*	*0*	*27.04*	*1.53*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11540	0	9.35	11.21	6.54	0	0	0	0	0	0	0	0	16.36	0	0.93	0	0	0	0	2.34	0	53.27
11540	*0*	*20.01*	*23.99*	*14.00*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*35.01*	*0*	*1.99*	*0*	*0*	*0*	*0*	*5.01*	-	-
11547	0	0	11.52	59.69	1.57	0	0	0	0	1.05	0	0	17.27	0	0	0	0	0	0	0	0	8.90
11547	*0*	*0*	*12.65*	*65.52*	*1.72*	*0*	*0*	*0*	*0*	*1.15*	*0*	*0*	*18.96*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11549	0	0	10.91	26.67	0.61	0	0	0.61	0	0	0	0	19.39	0	0	0	0	0	0	0	0	41.81
11549	*0*	*0*	*18.75*	*45.83*	*1.05*	*0*	*0*	*1.05*	*0*	*0*	*0*	*0*	*33.32*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11591	2.06	0	0.34	8.26	0.34	0	0	0	0	24.40	0	0	0	0	0	0	0	0	0	6.87	0	57.73
11591	*4.87*	*0*	*0.80*	*19.54*	*0.80*	*0*	*0*	*0*	*0*	*57.72*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*16.25*	-	-
11595	0	10.75	17.56	2.88	1.43	0	0	1.79	0	0	0	6.45	2.87	0	0	0	0	0	0	13.98	0	42.29
11595	*0*	*18.63*	*30.43*	*4.99*	*2.48*	*0*	*0*	*3.10*	*0*	*0*	*0*	*11.18*	*4.97*	*0*	*0*	*0*	*0*	*0*	*0*	*24.22*	-	-
11601	0	0	0.71	38.43	0	0	0	0	0	15.66	0	0	0	0	0	0	0	0	0	0	0	45.20
11601	*0*	*0*	*1.30*	*70.13*	*0*	*0*	*0*	*0*	*0*	*28.58*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11607	0	0.41	0.82	10.25	0.41	0	0	0	0	45.08	0	0	0.82	0	0	0	0	0	0	0.41	0	41.80
11607	*0*	*0.70*	*1.41*	*17.61*	*0.70*	*0*	*0*	*0*	*0*	*77.46*	*0*	*0*	*1.41*	*0*	*0*	*0*	*0*	*0*	*0*	*0.70*	-	-
11613	0	14.15	8.49	27.36	0	0	0	0	0	0	0	0	10.38	0	0	0	0	0	0	0	0	39.62
11613	*0*	*23.43*	*14.06*	*45.31*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*17.19*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	-	-
11614	0	9.88	8.72	11.64	0	0	0	0	0	0.58	0	0	13.37	0	1.74	0	0	0	0	0	0	54.07
11614	*0*	*21.51*	*18.99*	*25.34*	*0*	*0*	*0*	*0*	*0*	*1.26*	*0*	*0*	*29.11*	*0*	*3.79*	*0*	*0*	*0*	*0*	*0*	-	-

VIII.4.4 *Mineralogical analysis of the carbonate fraction*

Aragonite constitutes 45–94% of the total carbonate portion and thus is the dominant carbonate mineral (mean of 68%; Tab. 1 and Fig. 3). Only four samples contain less than 50% aragonite. The highest aragonite contents (75–94%, n=18) are mostly found north of 20°15′N (16 of 18 samples): in shallow water depths along the Banc d'Arguin (13–33 mwd, n=11), and at greater water depths (70–290 mwd, n=5; Fig. 3). Two isolated samples with high aragonite contents are encountered around 20° N. Lowest aragonite contents (45–60%, n=17)

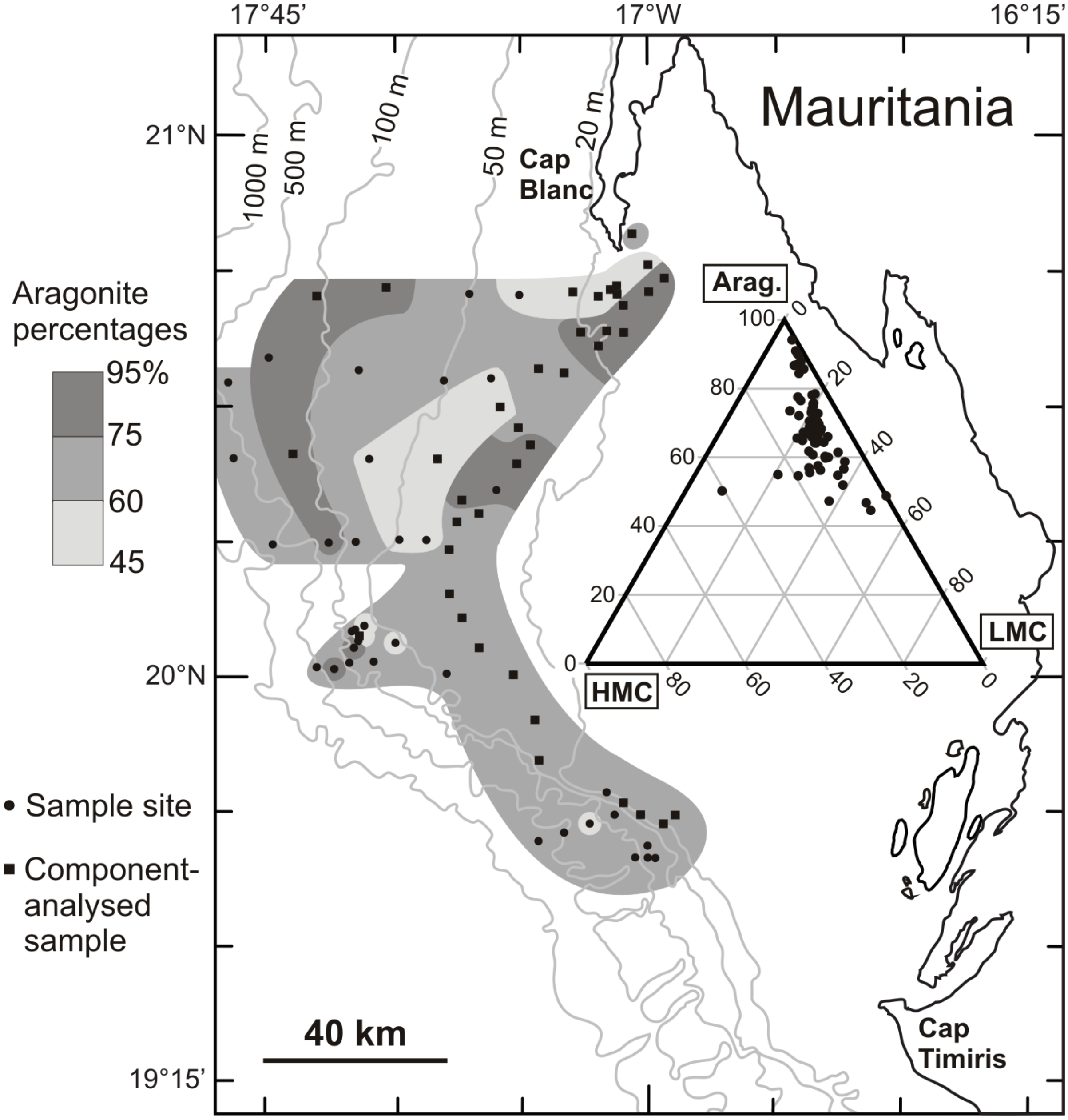

Fig. VIII.3 Distribution of aragonite contents in the Golfe d'Arguin as percentages of total carbonate, determined by X-ray diffraction. Aragonite, LMC and HMC percentages of the 74 samples are displayed in the triangle plot showing the overwhelming dominance of aragonite.

are found in the vicinity of Cap Blanc between 15 and 40 mwd (47–59%, n=7), in an area located between 35 and 65 mwd and between 20°15′N and 20°33′N (47–60%, n=6), and in four isolated samples around 20°05′N and around 19°45′N. Samples outside these areas display aragonite contents between 60 and 75% (mean of 68%, n=39, 4–604 mwd).

LMC averages at 23% (5–51%) of the total carbonate, whereas HMC constitutes an average of 8% (0–41%). Only three samples located directly south of Cap Blanc contain more LMC than aragonite ones. HMC content generally is low and reaches 41% only in one sample from the central open shelf.

VIII.4.5 *^{14}C ages*

The reworked mollusc shells, considered to represent the oldest grains of the samples, show increasing ages with water depth (Tab. 4): Above 40 mwd, ages reach a maximum of 300 cal yr BP, whereas in 50–100 mwd ages between 9,500 and 15,500 cal yr BP were determined.

Tab. VIII.4 Radiocarbon measurements and age calibration of eroded mollusc shells from surface samples. Depths are given in meter below sea level (mbsl).

Lab No.	**Sample**	**Sample depth (mbsl)**	**Material**	**^{14}C ages [^{14}C yrs BP]**	**1σ calibrated [cal yrs BP]**	**Intercept [cal yrs BP]**
Poz-31069	GeoB11501	16.5	*Donax burnupi* valve	Modern	Modern	Modern
Poz-31070	GeoB11501	16.5	Bivalve piece	525±30	118-238	180±60
Poz-31073	GeoB11513	35.5	Gastropod piece	600±30	149-290	220±70
Poz-26879	GeoB11613	103.3	Bivalve piece	13350±70	15127-15426	15275±150
Poz-26880	GeoB11614	72.3	Bivalve piece	8870±50	9466-9565	9515±50
Poz-26881	GeoB13018	37.0	Bivalve piece	640±30	255-310	285±30
Poz-26882	GeoB13019	53.0	Bivalve piece	10250±50	11179-11262	11220±40

VIII.5 SEDIMENTARY FACIES AND THEIR DISTRIBUTION

VIII.5.1 *Sedimentary facies*

On the basis of grain size and composition, five sedimentary facies were recognized on the seafloor of the Golfe d'Arguin (Tab. 5 and Fig. 4). These groups of samples and facies determination are supported by statistical analysis (Fig. 5). Three facies (F3, F4, and F5) comprise deposits from a range of water depths (i.e., mid and outer shelf). The facies distribution thus is not predominantly depth-related but rather represents a facies mosaic (cf. Wright and Burgess, 2005).

Facies F1 --- This facies is present in the shallow northern part of the Golfe d'Arguin (17–23 mwd, between 20°35′N and 20°45′N, n=5) and in one sample located further south at 35 mwd (Tab. 5). F1 sediments are moderately to well sorted and are coarse-grained (i.e., medium sand to gravel sizes; Tab. 1). Carbonate content ranges from 71 to 87% (mean of 80%). Bivalves overwhelmingly dominate the grain composition (68–85% of the identified bioclasts) and barnacle fragments (6–26% of the identified bioclasts) and quartz grains (5–19% of the grains >125 µm) are abundant (Tab. 2). The bivalve species composition is almost monospecific and is dominated by *Donax burnupi* (Fig. 6a). *Donax burnupi* shells are preserved as clean, variably fragmented and abraded shells with numerous cm-sized, entire valves (Fig. 4a).

Interpretation: The environment of this *D. burnupi*-dominated facies closely follows the ecological requirements of this *Donax* species: highly energetic subtidal environment caused by the swell from northwest in the Golfe d'Arguin, high trophic resources (i.e., phytoplankton) related to upwelling, and tropical to subtropical climate (cf. Ansell, 1983; Michel et al., subm.). The low number of living organisms is interpreted to indicate that carbonate production occurs shoreward of the sample location; i.e., on the outer part of the Banc d'Arguin where there is no accommodation space available. Material would be then shed off the Bank and reworked by high hydrodynamics. Quartz material is thought to come from migrating sand dunes onshore Cap Blanc.

Additionally to predominant *D. burnupi* shells, the mollusc assemblage is composed of the bivalve species *Crassatina marchadi* (Fig. 6b) and *Gari jousseaumeana* that show a clear tropical affinity (cf. Cosel, 1995). Subtidal (few meters to 25 mwd), bioclastic sandy-

Tab.VIII.5 Sedimentary facies (F) of the Golfe d'Arguin (Mauritania) based on the grain size (dry wt%), sorting, carbonate content ($CaCO_3$; dry wt%), and sediment composition of the samples.

FACIES	SAMPLE	TEXTURE (%) AND SORTING	SEDIMENT COMPOSITION	$CaCO_3$ (%)
F1 *Donax burnupi*	GeoB11515, GeoB11528, GeoB11529, GeoB11532, GeoB11601, GeoB11602	gravel: 10-23; sand: 76-90; mud: 0-1 moderately to well sorted	Quartz grain- and barnacle-rich, bivalve-dominated Variably fragmented and abraded shells, clean rubble	71-87
F2 Mixed bivalve-quartz	GeoB11514, GeoB11516, GeoB11526, GeoB11527, GeoB11591, GeoB11597, GeoB11603, GeoB11606	gravel: 0-6; sand: 94-99; mud: 0-3 moderately to well sorted	Barnacle-rich, quartz grain- and bivalve-dominated, with variable amount of benthic foraminifers and echinoderms Variably fragmented and abraded shells, clean sand	44-74
F3 Bivalve	GeoB11513, GeoB11522, GeoB11524, GeoB11525, GeoB11530, GeoB11531, GeoB11533, GeoB11534, GeoB11547, GeoB11549, GeoB11613	gravel: 0-14; sand: 78-99; mud: 0-20 poorly to moderately sorted	Foraminifer-rich, bivalve-dominated, with variable amount of echinoderms Highly fragmented and abraded shells	71-93
F4 Foramol	GeoB11511B, GeoB11511C, GeoB11511F, GeoB11511G, GeoB11535, GeoB11607, GeoB11614	gravel: 0-2; sand: 87-94; mud: 5-13 very poorly to well sorted	Quartz grain-rich, benthic foraminifer- and bivalve-dominated, with variable amount of planktonic foraminifers Mixed eroded-unabraded skeletal grains	37-69
F5 Muddy foramol	GeoB11511D, GeoB11511E, GeoB11540, GeoB11593, GeoB11594, GeoB11595, GeoB11604	gravel: 0-5; sand: 29-79; mud: 21-71 poorly to moderately sorted	Bivalve- and foraminifer-dominated, with variable amount of echinoderms and quartz grains Mixed eroded-unabraded skeletal grains	39-56

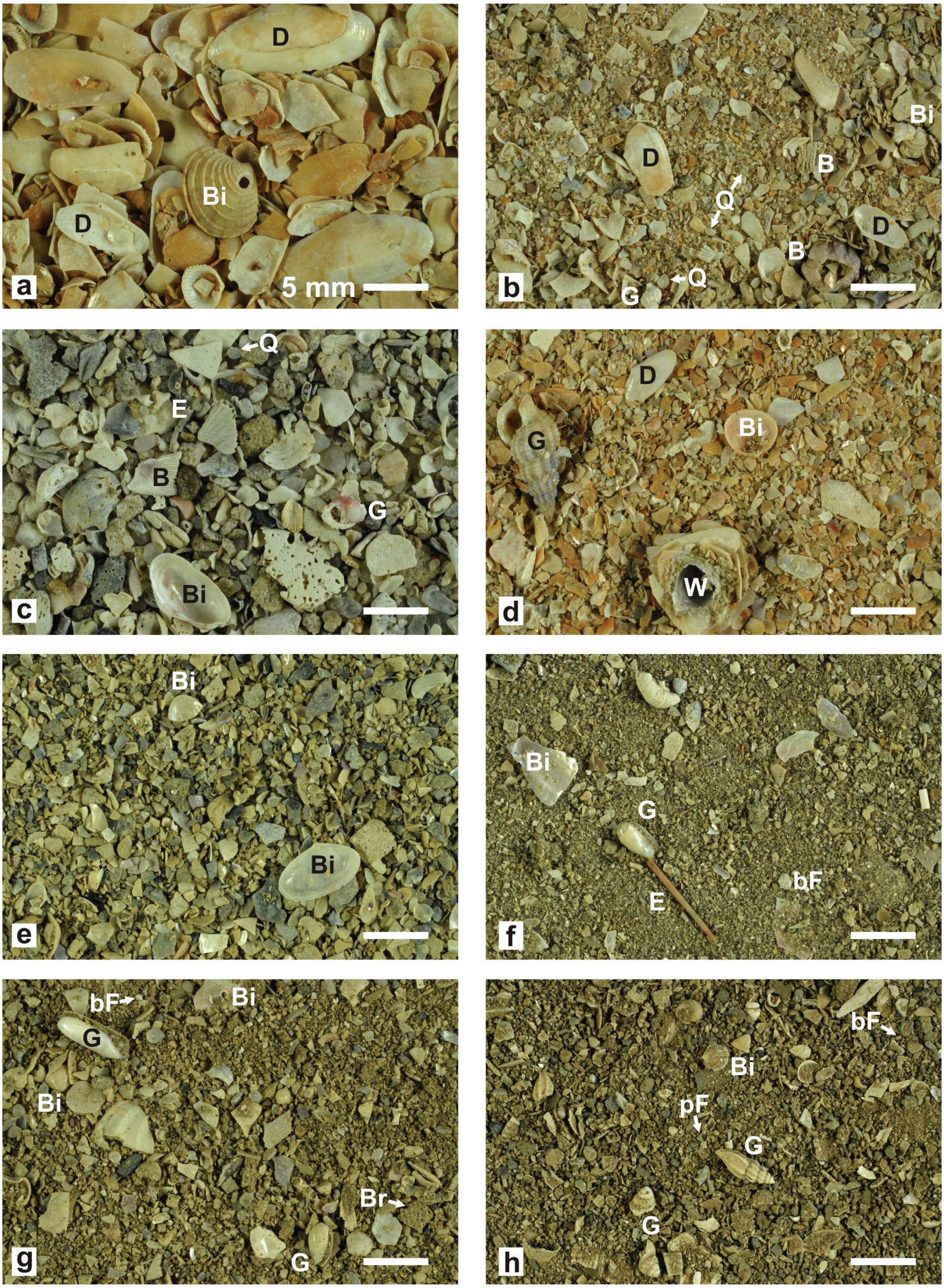

Fig. VIII.4 Sedimentary facies: a. F1, *Donax burnupi* facies, skeletal sand, GeoB11515, 21 mwd; b. F2, mixed facies, siliciclastic and skeletal sand, GeoB11603, 25 mwd; c. F2, mixed facies, siliciclastic and skeletal sand, GeoB11591, 4 mwd; d. F3, bivalve facies, skeletal sand, GeoB11547, 30 mwd; e. F3, bivalve facies, relict skeletal sand, GeoB11613, 103 mwd; f. F4, foramol facies, siliciclastic and skeletal sand, GeoB11511C, 31 mwd; g. F4, foramol facies, siliciclastic and relict skeletal sand, GeoB11614, 72 mwd; h. F5, muddy foramol facies, silty-siliciclastic and skeletal sand, GeoB11595, 41 mwd (cf. Tab. 5). B: barnacle, Bi: bivalve, Br: bryozoan, D: *Donax burnupi*, E: echinoderm, bF: benthic foraminifer, pF: planktonic foraminifer, G: gastropod, Q: quartz grain, W: aggregated worm tube. Scale is 5 mm for each picture.

bottom related molluc taxa include bivalves such as *Dosinia exoleta* and *Venus crebrisulca* and gastropods such as *Mesalia opalina* (Fig. 6h; cf. Nicklès, 1950).

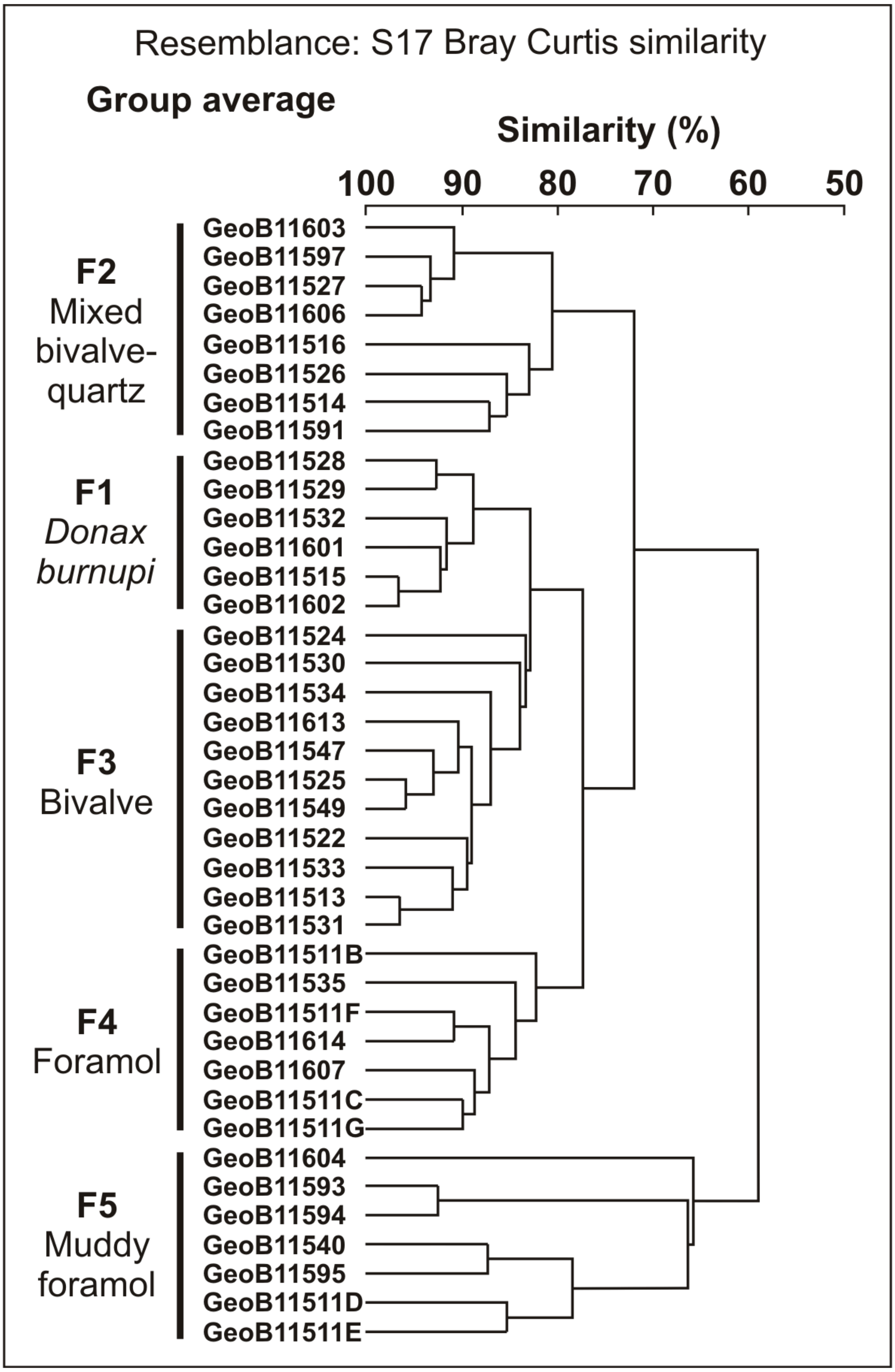

Fig. VIII.5 Hierarchical cluster analysis based on carbonate content, grain size (see Tab.1), and composition (excluding unidentified bioclasts) from the loose-sediment analysis (see Tab. 2). The five determined facies (F1, F2, F3, F4, and F5) correspond to five different groups of samples.

Facies F2 --- This facies is present in shallow waters in the vicinity of Cap Blanc (13–30 mwd, n=7) and on top of the Banc d'Arguin (4 mwd; n=1; Tab. 5). Sediments are moderately to well sorted and fine to coarse sand-dominated. Quartz material is abundant (19–45% of the grains >125 µm) and dilutes the carbonate content which ranges from 44 to 74% (mean of 56%). Bioclasts are dominated by bivalves (30–83% of the identified bioclasts), while whole barnacle shells, some still attached to their substrate, and barnacle fragments are abundant (1–42%; Tab. 2). Small benthic foraminifers show higher abundances (13–33% of the identified bioclasts) in the fine to medium sand-dominated samples located in the close vicinity of Cap Blanc (n=5). Echinoderm fragments range from ~0 to 22% of the identified bioclasts. This clean, mixed carbonate-terrigenous material is variably fragmented and abraded and is dominated by *D. burnupi* shells close to Cap Blanc (Fig. 4b) and by several other bivalve species on top of the Banc d'Arguin (e.g., *Venus spp.*; Fig. 4c). Red algae fragments (10% of the identified bioclasts) and intraclasts (12%) are present on top of the Banc d'Arguin.

Interpretation: The environment of this mixed bivalve-quartz grain facies is similar to that of F1 (i.e., shallow subtidal and swell-exposed), but F2 is additionally influenced by terrigenous quartz material of Cap Blanc. F2 is dominated by finer grain sizes (i.e., fine to medium sand). The accumulation of terrigenous quartz is a submerged extension of Cap Blanc as observed on the seafloor morphology (Fig. 1). On top of the Banc d'Arguin in the southern part of the Golfe d'Arguin, terrigenous quartz grains are also abundant but are coarser (i.e., medium to very coarse sand). The very shallow water of the Banc d'Arguin (4 mwd) is the only location of the Golfe d'Arguin where photic-related carbonate grains (i.e., red algae fragments) were found (also cf. Piessens, 1979).

Phytoplankton-feeding organisms (e.g., barnacles and the bivalve species *D. burnupi*) overwhelmingly dominate the bioclast composition. Warm water-related taxa include the tropical bivalve *Pitar belcheri* and the tropical-subtropical gastropods *Marginella senegalensis* (Fig. 6e) and *Persicula blanda* in the vicinity of Cap Blanc and the bivalves *Carditamera contigua* and *Diplodonta dautzenbergii* on the Banc d'Arguin. The shallow-subtidal bivalves *D. exoleta* and *C. contigua* are present. Benthic foraminifers include sediment dwellers (e.g., non-keeled *Elphidium* spp. and Miliolids) and other species, many of them associated to phytal substrates (e.g., *Cibicides refulgens* and *Elphidium crispum*).

Facies F3 --- This facies is present on the mid shelf (30–43 mwd, between 20°15′N and 20°35′N, n=9) and on the outer shelf (103–155 mwd) in the northern part of the Golfe d'Arguin (Tab. 5). F3 sediments consist of poorly to moderately sorted carbonate sand (carbonate content is 71 to 93%, mean 83%) and are medium and coarse sand-dominated. Bivalves dominate the carbonate grain association (52–90%) and benthic foraminifers are abundant (4–26% of the identified bioclasts; Tab. 2). Planktonic foraminifers are abundant in three samples (13–22% of the identified bioclasts), two of these samples being located on the outer-shelf. Echinoderm fragments range from 1 to 17% of the identified bioclasts. The grains of this bivalve-dominated facies are highly fragmented, abraded, and bioeroded (Fig. 4d, e).

Interpretation: This bivalve-dominated facies is present in two different settings (i.e., the mid and outer shelves) that display similar grain sizes, sorting, carbonate contents, and dominant biota. While planktonic foraminifers are always abundant in the outer-shelf samples, similar abundance is also found in a mid-shelf sample. Differences between the mid- (Fig. 4d) and outer-shelf (Fig. 4e) deposits relate to the erosion of grains and the taxa present. Sediments from the outer shelf display more intense erosion and dissolution. Whereas *D. burnupi* shells dominate the swell-exposed, mid-shelf assemblages, deep-water bivalves (e.g., *Anodontia senegalensis*) and gastropods (e.g., *Mesalia flammifera*; Fig. 6g) are found on the outer shelf but only represent minor modern carbonate production elements. Eroded and superficially dissolved, shallow water-related *Ervilia castanea* shells prevail in the outer-shelf associations (cf. Morton, 1990; Michel et al., subm.). Therefore the outer-shelf deposits are interpreted as relict sediments which remained exposed on the seafloor for thousands of years. Such relict deposit is typical for many heterozoan carbonates that have slow sedimentation rates (cf. Smith and Nelson, 2003). This interpretation is supported by ^{14}C dates of highly eroded bivalve material at 103 mwd of 15.5 kyrs cal BP (Tab. 4).

The mollusc assemblage of F3 displays a mixture of cosmopolitan and typical NW-African taxa. The endemic malacofauna includes both bivalves and gastropods (e.g., the NW-African species *Mesalia mesal* and *Turritella bicingulata*; Fig. 6i, j; cf. Ardovini and Cossignani, 2004); some of them clearly point to a tropical environment (e.g., *Modiolus nicklesi*, *Venus erronea*, *Persicula cingulata*, and *Persicula cornea*; Fig. 6f; cf. Nicklès, 1950). On the mid-shelf, shallow-water, sandy-bottom species occur including bivalves such as *D. exoleta* and *Laevicardium crassum* and gastropods such as *M. opalina* and *P. cingulata* (Fig. 6f, h).

The foraminiferal assemblage is composed of a mixture of small benthic and planktonic taxa. The benthic association is dominated by sediment dwellers such as *Pararotalia* sp., non-keeled *Elphidium* spp., miliolids, and textulariids. In addition,

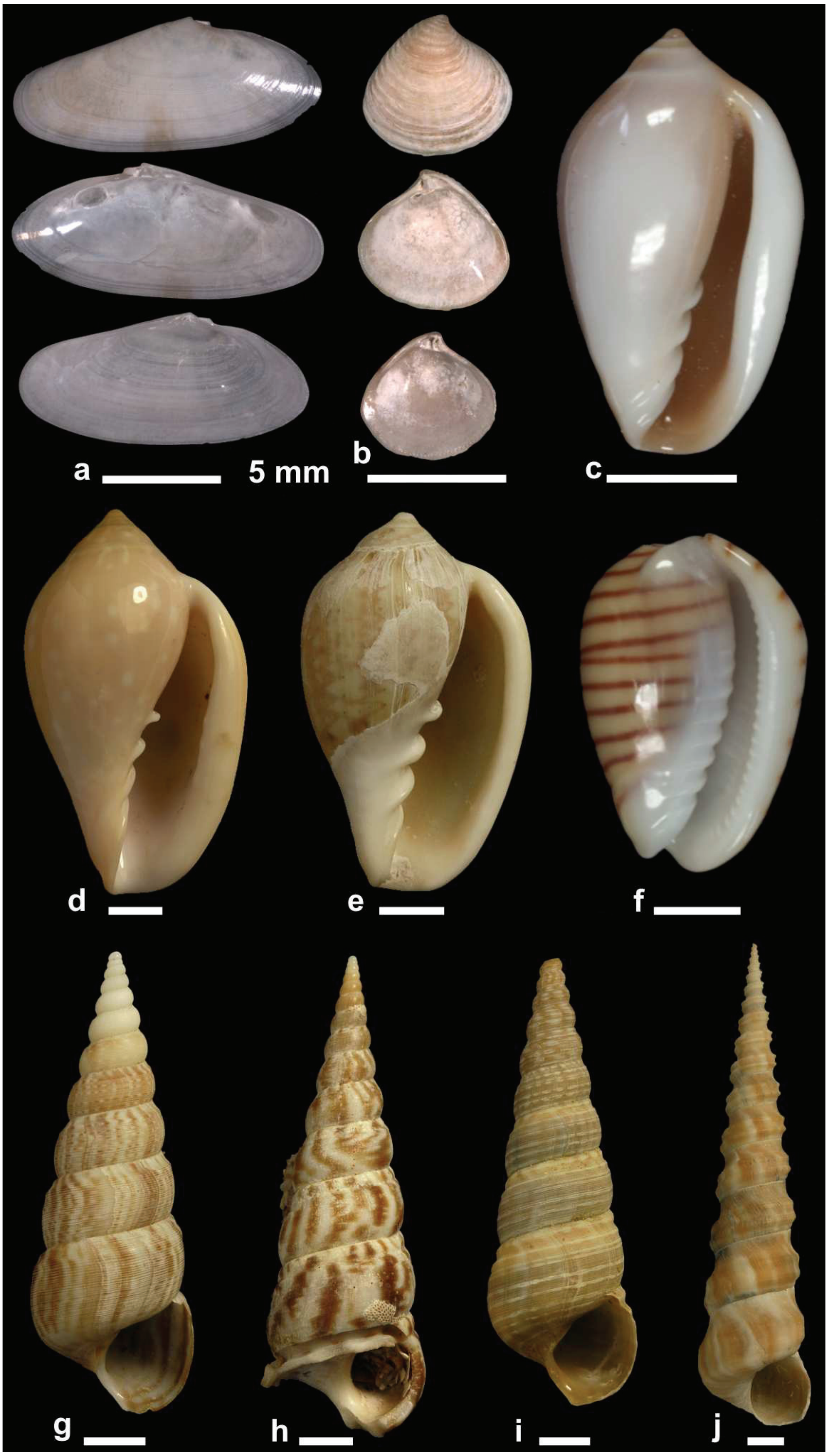

Fig. VIII.6 Pictures of mollusc shells: a. *Donax burnupi*, 20 mwd; b. *Crassatina marchadi* 22 mwd; c. *Prunum annulatum*, 32 mwd; d. *Marginella glabella*, 77 mwd; e. *Marginella senegalensis*, 21 mwd; f. *Persicula cingulata*, 33 mwd; g. *Mesalia flammifera*, 155 nwd; h. *Mesalia opalina*, 21 mwd; i. *Mesalia mesal*, 36 mwd; j. *Turritella bicingulata*, 77 mwd. Scale is 5 mm for each picture.

permanently or temporally encrusting species, in many cases associated with phytal substrates (cf. Langer, 1993) are also abundant: *C. refulgens, Elphidium macellum, Lobatula lobatula,* and *Miniacina miniacea*. Rare taxa (i.e., *Cassidulina laevigata,* bolivinids, buliminds, and uvigerinids) are related to low-oxygen conditions (cf. Bernhard and Sen Gupta, 1999). Benthic foraminifers that tend to be abundant in deep-water settings (i.e., genera *Euuvigerina, Lenticulina*, and *Planulina*; cf. Colom, 1974; Murray, 2006) are rare. Most of the benthic taxa present are ubiquitous and thus are not indicative of particular environmental conditions; the genus *Pararotalia*, in contrast, indicates warm climatic conditions (cf. Murray, 2006).

The planktonic taxa mostly are deep-water species (i.e., *Globorotalia inflata* and *Neogloboquadrina pachyderma*), typical of depths greater than 100 m (*sensu* Bé, 1977). However, the epipelagic (< 50 mwd, *sensu* Bé, 1977) *Globigerinoides trilobus* is also abundant. Regarding their climatic significance, the planktonic foraminiferal association consists of a combination of cold (e.g., *Globigerina bulloides* and *N. pachyderma*), but mostly transitional (e.g., *Gr. inflata*) and subtropical to tropical (i.e., *Globigerina calida*, *Globorotalia crassula*, *Globorotalia menardii*, and *Pulleniatina obliquiloculata*) taxa. This is interpreted to reflect the different water-masses of this upwelling region. This is in agreement with previous observations of the living planktonic foraminiferal assemblage (Miró, 1973; Thiede, 1975a, b; Mateu, 1979).

Facies F4 --- This facies is found on the mid shelf in the southern part of the Golfe d'Arguin (29–36 mwd, between 19°50′N and 20°15′N, n=5), in the Baie du Lévrier (18 mwd, n=1), and on the northern outer shelf at 72 mwd (n=1; Tab. 5). The dominant grain size is sand with minor amounts of mud and extremely rare gravel. Sediments are poorly to well sorted; the sample from the Baie du Lévrier is very poorly sorted. Generally the sediment is very fine and fine sand-dominated (Tab. 1). Carbonate content ranges from 37 to 69% (mean of 55%). The carbonate grain association corresponds to foramol *sensu stricto*: bioclasts mostly consist of bivalves and foraminifers (42–59% and 14–45% of the identified bioclasts, respectively; Tab. 2). Quartz grains range from 2 to 14% of the grains >125 µm.

Interpretation: As for F3, the foramol-facies F4 is found in various settings of the shelf (i.e., in the Baie du Lévrier, the mid and outer shelf). This mosaic-type distribution is related to the fact that different hydraulic regimes lead to similar grain-size deposition; i.e., fine-grained sediments deposited in mud patches on the mid shelf (Fig. 4f; Hanebuth and Lantzsch, 2008), in protected settings of the Baie du Lévrier (Koopmann et al., 1979), and below 50 mwd where wave action is reduced (Fig. 4g). In addition, the carbonate production in the Golfe d'Arguin that is dominated throughout by bivalves and foraminifers is quite homogenous throughout the outer, mid, and parts of the inner shelf. Consequently, different areas on the shelf display similar deposits.

The mollusc assemblage consists of a mixture of endemic NW-African taxa and cosmopolitan species. Some species of bivalves (e.g., *Cardiocardita ajar* and *Tellina densestriata*) and gastropods (e.g., *P. cingulata* and *Prunum annulatum*; Fig. 6f, c) show a clear tropical affinity (cf. Nicklès, 1950; Cosel, 1995). Other taxa, especially bivalves such as *Cuna gambiensis* and *D. burnupi* (Fig. 6a) are well-adapted to high-nutrient environments such as upwelling areas (cf. LeLoeuff and Cosel, 1998; Branch et al., 2002).

The foraminiferal assemblage mostly consists of benthic species with minor planktonic taxa. The benthic foraminiferal taphocoenosis is mostly composed of sediment-dwellers (e.g., *Cancris auriculus,* non-keeled *Elphidium* spp., miliolids, and textulariids) and species associated to phytal substrates (e.g., *C. refulgens*, *L. lobatula*, *M. miniacea*, *Planorbulina mediterranensis*, and *Rosalina macropora*; cf. Langer, 1993; Murray, 2006). Some other benthic taxa are related to low-oxygen conditions (e.g., *Bolivina* sp. and *Textularia* spp.; cf. Bernhard and Sen Gupta, 1999) or deep-water environments (i.e., *Planulina ornata*; cf. Colom, 1974).

The scarceness of the planktonic foraminifers is in agreement with the relatively shallow water depths of the loci of deposition. The dominant taxa are epi- and mesopelagic species (e.g., *Globigerina spp*. and *Globigerinoides spp*.), whereas deep-water taxa (e.g., *Globorotalia* and *Neogloboquadrina*) are rare. As for the other facies, the planktonic fauna comprises species with variable climatic significance. In F4, cold-water species (e.g., *G. bulloides*) coexist with transitional (e.g., *Gr. inflata*) and tropical to subtropical (i.e., *Gr. crassula* and *Gr. menardii*) taxa. This reflects the upwelling of deep, cool water masses, mixing at the surface with warmer water masses.

Facies F5 --- This facies is represented by mud-rich and mud-dominated sediments in the southernmost part of the study area (~19°45′N, 27–42 mwd, n=3), in the mid to outer shelf between 20°N and 20°10′N (30–90 mwd, n=3), and in the Baie du Lévrier (16 mwd, n=1; Tab. 5). . Carbonate contents range from 39 to 56%. F5 is characterized by high mud contents (21–71%), very poor to moderate sorting, and a bivalve- and foraminifer-dominated biota (19–37% and 3–66% of the identified bioclasts, respectively; Tab. 2; Fig. 4h). The sample from the Baie du Lévrier is dominated by barnacle fragments (41% of the identified bioclasts). Subordinate components include echinoderms (~0–21% of the identified bioclasts), aggregated worm tubes (~0–13% of the identified bioclasts), and quartz grains (0–19% of the picked grains >125 µm). F5 shows a comparably high variability between the samples as is illustrated by the lower similarity (<70%) in statistical analysis (Fig. 5)

Interpretation: The mollusc assemblage consists of a mixture of cosmopolitan, endemic, and tropical taxa. The bivalves *C. gambiensis* and *T. densestriata* and the gastropods of the family Marginellidae such as *Marginella glabella* (Fig. 6d) reflect tropical water temperatures (cf. Niklès, 1950; Cosel, 1995). Bivalves (*Nuculana commutata* and *Tellina compressa*) and gastropods (e.g., *Alvania fariai*, *Benthonellania gofasi*, and *Lepetella laterocompressa*) are present that are commonly found in deep-water environments (cf. Cosel, 1995; Ardovini and Cossignani, 2004). Additionally, molluscs are present that indicate a muddy substrate (e.g., *Nuculana bicuspidata*, *N. commutata*, and *T. compressa*). The occurrence of the bivalves *Anodontia sp.*, *Myrtea spinifera*, and *T. flexuosa* is related to low-oxygen conditions.

The foraminiferal assemblage comprises small benthic and planktonic taxa. Among the small benthic species, several low-oxygen-tolerant taxa are present, many of them associated to muddy bottoms (e.g., *Ca. laevigata,* bolivinids, buliminds, and uvigerinids). Other soft-bottom dwellers found in this facies are miliolids, textulariids, non-keeled elphidiids, and nonionids. The presence of Cibicididae (e.g., *C. refulgens* and *L. lobatula*) and encrusting forms (i.e., *M. miniacea* and *P. mediterranensis*) often reported as epiphytic forms (cf. Langer, 1993) may be related to the occurrence of phytal substrates (i.e., seagrass) that have been described from inner parts of the Banc d'Arguin (Wolff and Smit, 1990; Hemminga and Nieuwenhuize, 1991).

The planktonic taxa are dominated by meso-epipelagic species. As in other facies, the planktonic foraminiferal assemblage consists of a mixture reflecting different climatic requirements. Thus, subartic to transitional species (e.g., *G. bulloides*, *Gr. inflata*, and *N. pachyderma*) co-occur with species adapted to subtropical to tropical conditions (e.g., *G. calida*, *Gr. crassula*, *Gr. menardii*, *Globorotalia tumida*, and *P. obliquiloculata*).

VIII.5.2 *Facies distribution*

The distribution of the sedimentary facies in the Golfe d'Arguin (Fig. 7a) forms a mosaic rather than belts parallel to strike direction. The distribution of the facies is not directly related to water depth and thereby to the gradients of temperature and light penetration associated to depth. Siliciclastic input by eolian transport from the Sahara and Sahel desert is spread uniformly over the entire Golfe d'Arguin (cf. Stuut et al., 2005). The deposition, however, is controlled by reworking steered by hydrodynamics (Michel et al., 2009). The orientation of the Banc d'Arguin relative to the swell from northwest coupled to the prevailing winds leads to a north-south-directed hydraulic regime (Fig. 1). This leads to winnowing, transport and sedimentation of the eolian silt in the southern part of the Golfe d'Arguin. The result is an overall north-south trend from coarse, carbonate-dominated sediments to fine, siliciclastic-dominated deposits (Michel et al., 2009).

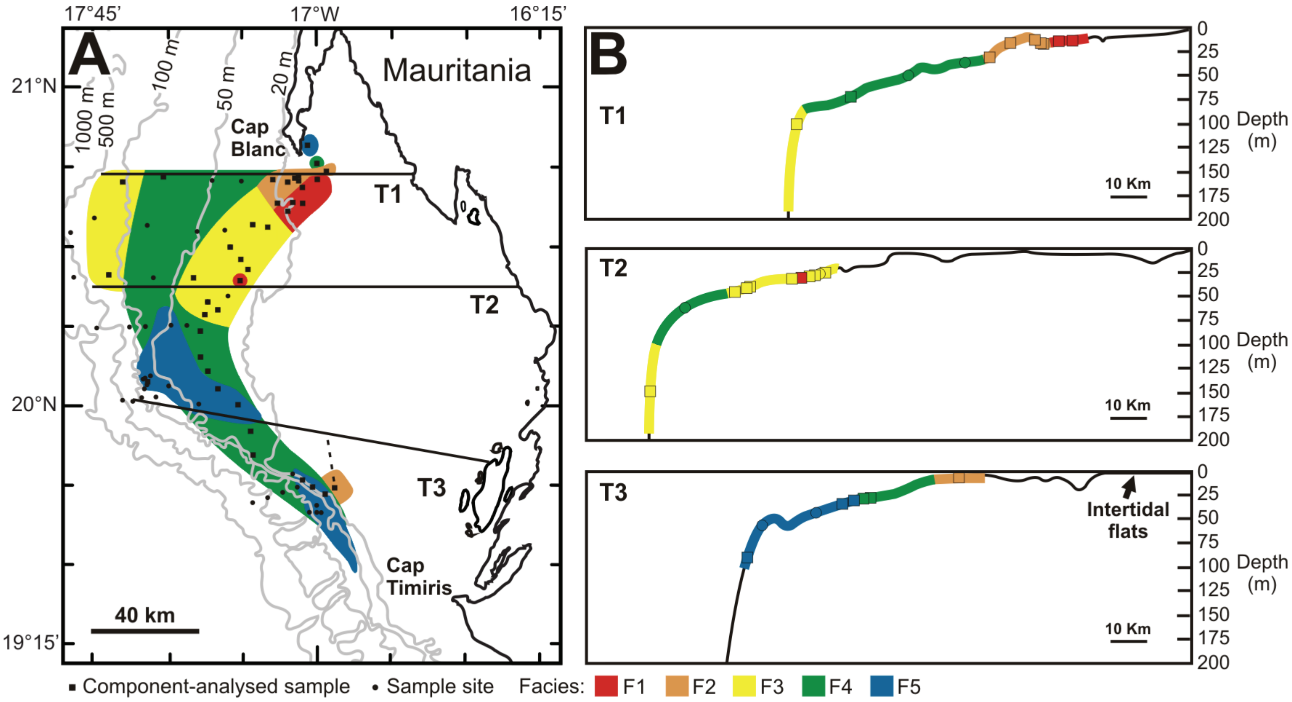

Fig. VIII.7 Facies distribution in the Golfe d'Arguin. A. Facies distribution in the area. B. Facies distribution along onshore-offshore transects (shown on map A). The samples (*Squares*: Component-analysed samples; *Circles*: Sample sites), which give the facies distribution along the transects, are projected on the transect lines according to bathymetry. Interpolation between component-analysed samples is performed using other sample material and previous sedimentological data from Domain (1985).

The carbonate deposits largely lack a photic-related zonation, because all carbonate-secreting organisms are aphotic, except scarce red algae on top of the Banc d'Arguin. The bioclastic composition of the five facies therefore is similar throughout, being dominated by shells and fragments of bivalve and foraminiferal tests. As for purely siliciclastic sediments, sorting and deposition are controlled by the hydraulic regime partly overruling the influence of biogenic production on grain-size spectra. Thus, the facies arrangement reflects the complex interaction between: (1) the factors controlling the carbonate production (biology and ecology of the carbonate-secreting biota; e.g., the large portion of cm-sized *D. burnupi* shells present in the northern shallow part of the Golfe d'Arguin; F1, F2, and F3), and (2) the factors controlling the dispersion and distribution of the carbonate and non-carbonate sediments (hydrodynamics and topography; e.g., greater mud contents in the southern part of the Golfe d'Arguin; F4 and F5).

The coarse skeletal grains are relict material on the outer shelf that may represent shallow-water (<50 mwd), bivalve-rich sediment deposited during the last transgression. The very low sedimentation rate of open-shelf heterozoan carbonates (cf. Nelson, 1988a; James, 1997) and the strong current regime (cf. Bein and Fütterer, 1977) might have been responsible for the exposure of these sediments on the seafloor for thousands of years. Consequently, these outer-shelf deposits show similar grain sizes and a similar carbonate grain association to the modern swell-exposed mid-shelf sediments.

VIII.6 ARCHITECTURE OF THE CARBONATE DEPOSITIONAL SYSTEM

The sedimentary architecture of the depositional system in the Golfe d'Arguin is a carbonate ramp composed of clastic carbonate-siliciclastic sediments (Fig. 7b). The morphology of a mature carbonate ramp is determined by the grain size of the biogenic production of skeletal material, and by the loci of maximum production (Pomar, 2001a, b). The Banc d'Arguin has been submerged during the postglacial sea-level rise around 7 kyrs BP (Hanebuth and Lantzsch, 2008). This postglacial sea-level rise is reflected by ^{14}C dates of eroded relict grains that decrease from 15.5 cal kyrs BP at 103 mwd to modern at 16.5 mwd (Tab. 4). Seismic data reveal that sediments form a thin veneer on the substrate, and maximum thickness of some 10 m is observed in depocenters in erosional features associated to Pleistocene eustacy (Hanebuth and Lantzsch, 2008). The present carbonate depositional system established in the Golfe d'Arguin thus is relatively young, and is still strongly influenced by the preexisting morphology.

Sediments tend to disperse until they reach the sediment-equilibrium profile which corresponds to the balance between sediment input and hydrodynamics (Swift and Thorne, 1991). When sediment accumulates it fills up the available space between the seafloor and the wave-base level (accommodation space). In contrast to purely siliciclastic systems, in carbonates, production and accommodation are interdependent factors and beside the physical processes and the inherited topography, ecological accommodation (Pomar, 2001a; Pomar et al., 2004, 2005) controls the depositional profile. The ecological accommodation is the ability of the various carbonate-producing biota to resist a different hydrodynamic energy level by building a framework or by producing large grain sizes. Thus, accommodation depends not only on the amount, but also on the type of the sediment produced, on biological processes (binding, trapping, baffling), on the hydraulic energy at the locus of production, and on early diagenetic processes (Pomar, 2001a, b).

In the study area, heterozoan carbonates are produced in different parts of the shelf and subsequently redistributed by strong and highly variable currents (Michel et al., 2009). Neither a framework nor large heavy shells are produced here. The sediment thus is expected to produce a low-angle, homoclinal profile after compensating the morphology of the inherited morphology. In such a young system, the depositional profile therefore is firstly controlled by the original topography of the substrate, and secondly by reworking and redistribution of the carbonate and eolian sediment by highly variable and strong hydrodynamics.

VIII.7 MINERALOGY OF THE CARBONATE FRACTION

Aragonite is the dominant carbonate species in all samples and varies between 45% and 80% of the carbonate fraction (Fig. 3). These high aragonite contents reflect that in shallow-water settings, infaunal bivalves with aragonite shells (e.g., *D. burnupi* and *Tellina spp.*) contribute more than 80% of the sediment grains. In particular, the bivalve *D. burnupi* dominates many shallow-water (<40 mwd) mollusc assemblages. Other aragonite contributors include gastropods, serpulids, and scaphopods.

Larger calcite portions are associated to the occurrence of benthic and planktonic foraminifers, barnacles, epifaunal bivalves (i.e., Anomiidae and Pectinidae), and echinoderms. Barnacles and benthic foraminifers of the order Rotaliida are the most common LMC contributors in samples from shallow water depth (<40 mwd). Samples from deeper water settings contain more LMC tests of planktonic foraminifers. HMC is abundant exclusively in samples where echinoderm fragments dominate. The anticipation of calcite being dominant in heterozoan carbonates while aragonite dominates photozoan associations (cf. Nelson, 1988a; James, 1997; Chapter 7 of Flügel, 2004) thus is not confirmed for infaunal bivalve-dominated grain associations. Other aragonite-dominated heterozoan associations are known from cool-water deposits from New Zealand (Hood and Nelson, 1996; Nelson et al., 2003) and the South Australian Shelf (James et al., 2005). The dominance of aragonite together with the high organic contents of the sediment reduces the preservation potential of the biotic association considerably (cf. Smith and Nelson, 2003; Wright and Cherns, 2007). Therefore, from the perspective of the geological timescale, valuable information for interpreting paleoenvironmental conditions from carbonate associations might be lost in comparable systems as a result of diagenesis. Similar early dissolution processes have been shown to have introduced a severe bias in the fossil record (e.g., Silurian, Jurassic, and Plio-Pleistocene mollusc-rich benthos; Cherns and Wright, 2000; Wright et al., 2003; Caron and Nelson, 2009). Under certain conditions (e.g., high sedimentation rate), aragonitic mollusc fauna may be preserved (e.g., Pliocene deposits; Nelson et al., 2003), however this is rather the exception than the rule.

VIII.8 IMPLICATIONS: HETEROZOAN WARM-WATER CARBONATES

The carbonate facies in the study area are dominated by bivalve fragments and foraminifers and thus are heterozoan carbonates *sensu* James (1997). The only photodependent carbonate components present are scarce fragments of red algae found on top of the Banc d'Arguin. The depositional environment is a eutrophic tropical shelf. The nutrient-rich waters lead to increased plankton productivity and subsequently to high turbidity. In addition, the seasonal variability following the ITCZ movements (i.e., summer Guinean Current influence versus winter Canary Current influence; Fig. 1) associated to the year-round upwelling occurrence results in strong oceanographic instability and in annual sea-surface temperature variations of about 10°C in the Golfe d'Arguin. Direct interpretations of carbonate associations (photozoan versus heterozoan) as tropical versus extratropical environments fail to integrate these conditions. Temperatures on the Banc d'Arguin (18–29°C) are tropical and the ones of the mid and outer shelf (16–25°C) correspond to the boundary of tropical and warm-temperate conditions (cf. Flügel, 2004). Independent from water temperatures, variable and eutrophic conditions lead to a simple food web based upon phytoplankton as opposed to an oligotrophic food web based upon benthic algae and detritus (cf. Wood, 1993; Taylor, 1997; Mutti and Hallock, 2003; Pomar and Hallock, 2008). Such eutrophic conditions suppress phototrophic and mixotrophic organisms and limit the presence of photo-dependent organisms. Characteristic components of both photozoan (i.e., hermatypic corals, calcareous green algae; James, 1997) and warm-temperate (i.e., large foraminifers, red algae; Betzler et al., 1997) carbonate associations thus are inhibited. The only elements of these associations found in the Golfe d'Arguin is the local occurrence of ooids that are restricted to the hypersaline (up to 80 psu) Baie de Saint-Jean (Stein, 1980), and seagrass patches found in the inner parts of the Banc d'Arguin (Wolff and Smit, 1990; Hemminga and Nieuwenhuize, 1991). However, the tropical realm of the Golfe d'Arguin is indicated throughout the entire shelf by warm water-related mollusc and foraminifer taxa that allow for distinguishing the biota from a temperate ones. The example studied here thus points out that the interpretation of shallow-water heterozoan carbonates has to be undertaken carefully. The occurrence of heterozoan carbonates can indicate a wide range of environmental conditions from polar waters (e.g., Henrich et al., 1995), to cool/cold waters (e.g., Nelson, 1988b; Betzler et al., 1997; James and Clarke, 1997), and to warm waters as demonstrated here.

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Third Manuscript

The mollusk fauna of soft sediments from the tropical, upwelling-influenced shelf of Mauritania (NW Africa)

IX. THE MOLLUSK FAUNA OF SOFT SEDIMENTS FROM THE TROPICAL, UPWELLING-INFLUENCED SHELF OF MAURITANIA (NW AFRICA)

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ABSTRACT

Ecological and taxonomical study of the rich mollusk fauna of the Golfe d'Arguin (N-Mauritania) reflects the various environmental influences affecting this tropical shelf. The upwelling of nutrient-rich waters leads to a highly productive environment under tropical conditions. The resulting mixed carbonate-siliciclastic sediment contains a large portion of calcareous components produced by heterotrophic organisms (e.g., mollusks, foraminifers, worm tubes, barnacles) that are reworked on the open shelf. On the basis of mollusk assemblages, six taphocoenoses are defined, all being characterized by a mixed fauna of tropical (e.g., *Tellina densestriata*), subtropical (e.g., *Macoma cumana*) and temperate (e.g., *Spisula subtruncata*) species. Differences between the assemblages point toward the substrates (grain size range from mud to gravel) related to local hydrodynamic conditions and water depth. For example, the *Donax burnupi* shells that are very abundant in the swell-exposed, northern part of the Golfe d'Arguin are related to tropical-subtropical, high-energy and high-nutrient waters. Mollusk assemblages are demonstrated to be a sensitive tool for deciphering complex environmental conditions in sedimentary archives.

IX.1 INTRODUCTION

In the modern tropical marine realm, soft-sediment ecosystems so far have received markedly less attention than coral reef biotopes (Alongi, 1990; Mackie et al., 2005). Soft-sediment ecosystems usually are dominated by heterotrophic organisms such as mollusks, foraminifers, echinoderms, and barnacles. The incomplete knowledge of such modern systems leads to the problematic recognition of comparable deposits in the sedimentary record. In consequence, they may appear as rare exceptional variations of carbonate sedimentation models (cf. fig.1.1 of Rao, 1996; fig.2.9 of Flügel, 2004), and ancient occurrences might be misinterpreted. When recognized in the rock record, low-latitude heterozoan carbonates are described as anomalous or problematic for the perceived view of classical warm-water tropical carbonates (cf. Samankassou, 2002; Pomar et al., 2004; Wilson and Vecsei, 2005; Cornée et al., 2009). Studies of modern analogs therefore are needed in order to better understand and define the full spectrum of tropical carbonate depositional systems.

For calibration of carbonate grain associations, the study of modern analogs is a useful exercise as the environmental influence on the biological assemblages can be directly determined, whereas in the fossil record it can only be inferred. The possibility of direct measurement of physical parameters in the modern world is well suited for constraining the relationship between organisms and their environment and the resulting sedimentation patterns. Particularly, the definition of proxies which are useful analogs in the sedimentary record are crucial for paleoclimatic interpretations. Moreover, modern realms display the entire range of biota that define an ecosystem. This is not the case with ancient deposits where only parts of the biota are preserved as fossils.

In the present study, a modern analog for a eutrophic tropical carbonate depositional system is studied. Such eutrophic tropical environments are rare in the modern world but might have been more abundant in the past (Westphal et al., subm.). On the wide shelf of northern Mauritania, the Golfe d'Arguin, a year-round upwelling pushes deep, cool and nutrient-rich waters to the ocean surface, leading to planktonic blooms (van Camp et al., 1991). Such oceanographic patterns in a tropical setting contrast with the oligotrophic and euphotic tropical waters typical for regions in which extensive carbonate reefs are found (e.g., Bahamas, Caribbean, Pacific Islands; e.g., Tucker and Wright, 1990). The faunal assemblage of the Golfe d'Arguin is dominated by mollusks and foraminifers (Michel et al., in prep.), and therefore represents a foramol association *sensu* Lees and Buller (1972) and a heterozoan association *sensu* James (1997). Such a carbonate grain association is atypical for modern tropical settings, and could mislead interpretation (i.e., extratropical) of such deposits in the sedimentary record (see Westphal et al., subm., for a review). Here we present a taxonomical and ecological study on the modern mollusk assemblage deposited in the Golfe d'Arguin in order to improve interpretation of mollusk-rich carbonate grain associations in the geological record.

IX.2 STUDY AREA

The Golfe d'Arguin is located off northern Mauritania (NW Africa) between Cap Blanc (21°05'N) and Cap Timiris (19°20'N). The up to 150 km wide shelf features an extensive shallow-water area, the Banc d'Arguin, with water depths less than 5 m for large parts (Fig. 1). This inner shelf is separated from the outer shelf by a steep escarpment of some 20 m, the origin of which is unknown. The Golfe d'Arguin is situated between the Sahara Desert and the open Atlantic Ocean and receives no freshwater input apart from rare rainfall (average precipitation at Nouhadibou: 28 mm/year; Khallahi, 2004).

The Golfe d'Arguin (Fig. 1) is influenced by the cool Canary Current, nutrient-rich upwelling waters, and warm tropical waters entering the shelf from the south as a branch of the Guinean Current (Mittelstaedt, 1991; Binet, 1998). The position of the Golfe d'Arguin at the border between the northern subtropical and southern tropical waters leads to a seasonal cycle. The intrusion of the warm Guinean Current waters during summer and the advance of the Canary Current during winter follow the seasonal shifts of the intertropical convergence zone (ITCZ; Van Camp et al., 1991; Cuq, 1993). Despite the seasonality of the sea-surface temperatures, the upwelling occurs all-year round off Cap Blanc and induces a quasi-continuous influence of nutrient-rich waters in the Golfe d'Arguin. The high biological production with a maximum chlorophyll *a* concentration of 11 $\mu g\ L^{-1}$ reflects the eutrophic conditions (Quack et al., 2007). In addition, the shelf is characterized by high water energy caused by tide currents, wind-driven currents, swell, and waves (Peters, 1976; Mittelstaedt, 1991).

The modern sediment cover consists of a mixture of carbonate and siliciclastic grains. The carbonate material which is dominated by mollusks and foraminifers (Michel et al., in prep.) is produced *in situ*, whilst the siliciclastic material is imported by winds from the Sahara desert (NE Trade Winds, Harmattan and Saharan Air Layer; Stuut et al., 2005). Seafloor sediments range from nearly pure coarse-grained carbonate sand and gravel to muddy siliciclastic sediments (Piessens, 1979; Koopmann et al., 1979; Michel et al., 2009). Patches of uncovered rocky outcrop also occur on the shelf (Domain, 1985).

Previous studies dealing with the benthic fauna of the Golfe d'Arguin include non-exhaustive mollusk lists (Elouard and Rosso, 1982; Wolff et al., 1987, 1993a, 1993b; Berghuis et al., 1993; Duineveld et al., 1993a, 1993b; Kuipers et al., 1993; Wijnsma et al., 1999; Wolff and Montserrat, 2005; Honkoop et al., 2008; Wolff and Michaelis, 2008). Among these, most studies are restricted to the coastal area in the vicinity of Tidra Island where seagrass beds occur (cf. Wolff and Smit, 1990; Fig. 1).

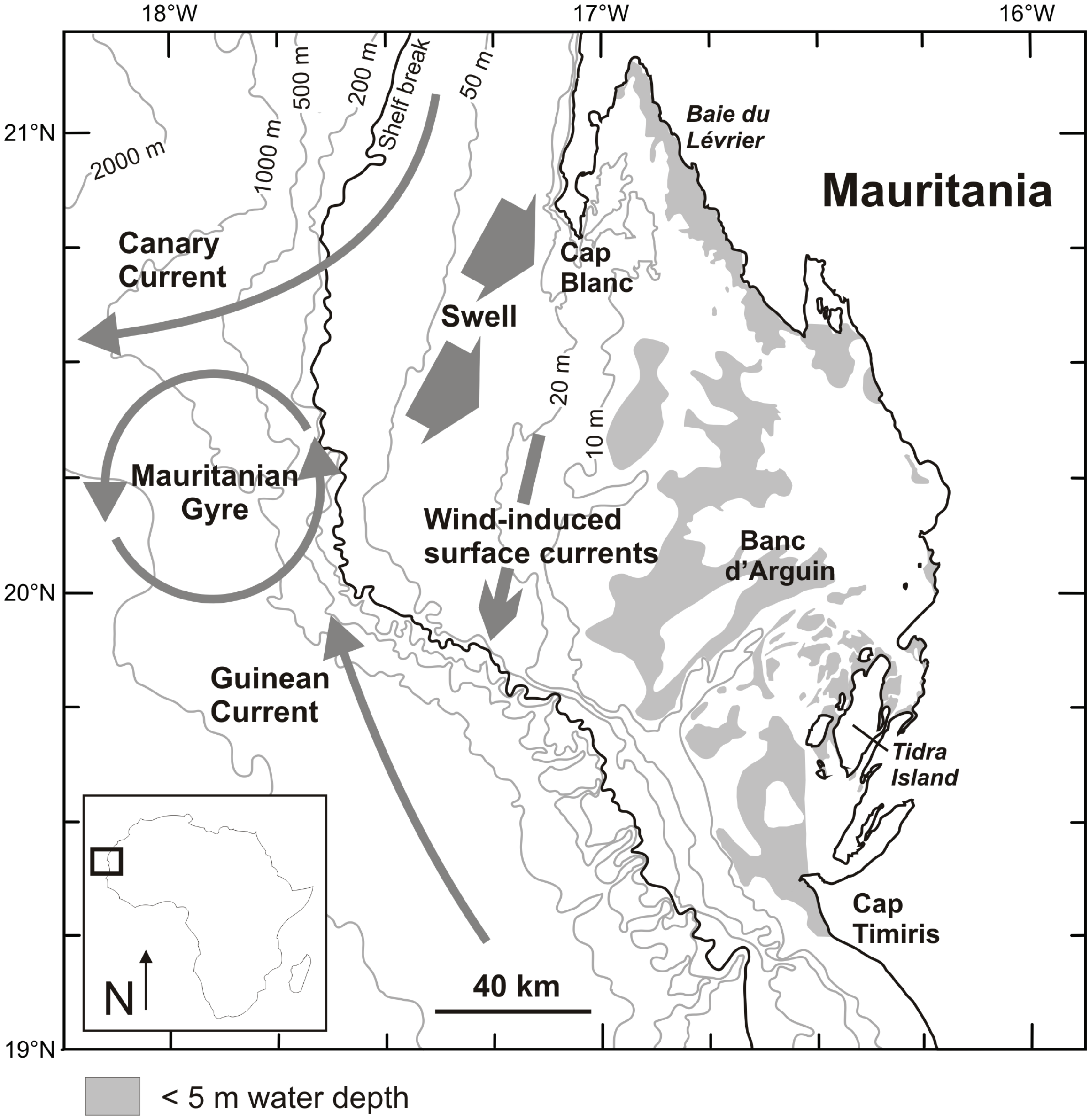

Figure IX.1–Map of the Golfe d'Arguin with the main oceanographic patterns influencing the shelfal environment (Modified from Hanebuth and Lantzsch, 2008; Michel et al., 2009).

IX.3 MATERIALS AND METHODS

A total of 74 giant box cores and Van Veen grab samples were taken during R/V Poseidon-346 (December 2006-January 2007) and R/V Poseidon-366 (May 2008) cruises in the study area and were studied earlier in terms of sedimentology (Michel et al., 2009, in prep.). Here, the mollusk assemblages of 18 of these samples are examined in detail (Fig. 2): 12 samples from water depths between 15 and 50 m around the Banc d'Arguin, four samples from the outer shelf and shelf break areas (70–155 m water depths, mwd), and one sample from the slope at 370 mwd (GeoB11509). The extensive waters on the Banc d'Arguin were too shallow (<10 m) to be sampled from the research vessel. One sample was retrieved from the southern part of the bank at 4 mwd with a hand-held dredge employed from a zodiac deployed from the research vessel (GeoB11591).

Quantification and determination of molluscs was performed on the fraction >1 mm using a minimum of 300 grains, except for the sample retrieved from the slope (GeoB11509) where the low material quantity required analysis of a lower number of grains. The fractions <1 mm were not studied here.

Taxonomical determination of the bivalve fauna was based on Nicklès (1950) and von Cosel (1995; in prep.). Taxonomical determination of gastropods and scaphopods was based on Gofas et al. (1985) and Ardovini and Cossignani (2004). Statistical analysis on the quantified mollusk association was performed using Primer for Windows (version 6.1.5). Cluster analysis ("Group Average" cluster mode using the "Bray Curtis" similarity) was employed to group the samples with similar assemblages.

Table IX.1–Quantitative analysis of mollusk taxa. Given is the total abundance per species (N) and per sample (including totals of bivalves, gastropods and scaphopods).

	11509	**11511B**	**11511E**	**11511F**	**11522**	**11525**	**11527**	**11534**	**11535**	**11540**	**11547**	**11549**	**11591**	**11595**	**11601**	**11607**	**11613**	**11614**	N
BIVALVES																			
Nucula crassicostata					2				1			1						17	**21**
Nucula nicklesi	1							1											**2**
Nucula nitidosa																3			**3**
Nuculana bicuspidata			1											95		2		3	**101**
Nuculana commutata										1				12					**13**
Nuculana gruveli		3							3			1							**7**
Nuculana sp																1			**1**
Yoldiella philippiana					2					1									**3**
Anadara polii										3									**3**
Anadara sp							1												**1**
Arcidae		8												5			1		**14**
Limopsis sp	1																		**1**
Glycymeris sp								6					1						**7**
Modiolus nicklesi				4	7				1			4					36	1	**53**

Table IX.1–continued

	11509	**11511B**	**11511E**	**11511F**	**11522**	**11525**	**11527**	**11534**	**11535**	**11540**	**11547**	**11549**	**11591**	**11595**	**11601**	**11607**	**11613**	**11614**	**N**
Modiolus sp			1	2		8	1	4		8	1	7		2		1			**35**
Mytilidae					1								18					18	**37**
Atrina sp		2	2																**4**
Limaria cf. gwyni												1							**1**
Ostreola stentina												1				1			**2**
Ostreidae			1																**1**
Similipecten similis					3					3				3				49	**58**
Aequipecten flabellum								2											**2**
Aequipecten opercularis						2			3		1				2				**8**
Aequipecten sp		2		4															**6**
Manupecten pesfelis	5																		**5**
Pectinidae	2	1	1						5	2		2	1			1	1	1	**17**
Anomia ephippium		1										1			3	1			**6**
Anomia sp									1					1					**2**
Heteranomia squamula										1									**1**
Anomiidae	4																		**4**
Lamellolucina reyrei																		1	**1**
Linga adansoni									3										**3**
Myrtea spinifera	2					1				8				1				4	**16**
Myrtea sp					1					2									**3**
Anodontia senegalensis										7							4	1	**12**
Anodontia sp									2										**2**
Lucinidae	4									1								3	**8**
Thyasira flexuosa										1								3	**4**
Thyasira sp														1					**1**
Chama crenulata		1											6						**7**
Chama sp															2				**2**
Chamidae													3						**3**
Diplodonta dautzenbergii													1						**1**
Diplodonta rotundata															1				**1**
Diplodonta sp	4		3		1			1	1					1		2			**13**
Bornia sp			1	1			1			1		1		1		1		1	**8**
Coracuta sp		1																	**1**
Kurtiella bidentata						1													**1**
Montacutidae				1						2			1	1					**5**
Scacchia sp		9	8	7			1		1	2				8		1			**37**
Cardiocardita ajar		3	13	5												1			**22**
Cardiocardita cf. lacunosa																1			**1**
Cardita sp											1								**1**
Glans aculeata	1																		**1**
Carditamera contigua				3								1	13	7					**24**
Carditidae														2			1		**3**
Crassatina marchadi								1			1				3			2	**7**
Crassatina sp					1								1	1			1	1	**5**
Digitaria digitaria					6	1		3			12			2	7		3	1	**35**
Plagiocardium papillosum		3	7			6	1		2	1	6	6		3	1	1		5	**42**
Plagiocardium sp	2	15	5	10	4	4		1	3	30				13	1	17		5	**110**
Laevicardium crassum				1		4		6	6		1	5				3		2	**28**
Cardiidae																23	1		**24**
Cuna gambiensis		21	18	9	2	3	1			78		9			1	27	1	53	**223**
Mactra glabrata												1							**1**
Mactra inconstans		2																	**2**
Mactra sp		26							11	2						1			**40**
Spisula subtruncata		9	5	1	5	6		11		1	3	2			1		2		**46**
Spisula sp															1	1			**2**
Mactridae			2		1													3	**6**
Phaxas tenellus		3							1							1			**5**
Ensis goreensis		2	1			6			17		2	3		1		1			**33**
Tellina boucheti						1		2	2			4				11			**20**
Tellina compressa										33				1			1	2	**37**
Tellina densestriata		81	73	18		1			95									6	**274**
Tellina donacina					1													4	**5**
Tellina hanleyi							3				3								**6**
Tellina posteli												3							**3**
Tellina pseudopusilla				3							3				1	11			**18**
Tellina rubicincta														21		9		1	**31**
Tellina sp									2					2			3	19	**26**
Macoma cumana		1		1										102		7			**111**
Macoma melo														1					**1**
Donax burnupi		38	100	125		267	288	232	81		473	259	3	15	407	98			**2386**

Table IX.1–continued

	11509	**11511B**	**11511E**	**11511F**	**11522**	**11525**	**11527**	**11534**	**11535**	**11540**	**11547**	**11549**	**11591**	**11595**	**11601**	**11607**	**11613**	**11614**	**N**
Donax oweni		1																	**1**
Donacidae			1																**1**
Gari depressa															1				**1**
Gari fervensis																11			**11**
Gari jousseaumeana											6					4			**10**
Gari pseudoweinkauffi						4									1				**5**
Gari sp								1				1							**2**
Abra alba																2			**2**
Abra lecointrei										3				7					**10**
Abra sp										1						3			**4**
Ervilia castanea		3	31	79	306			29	83	26	1	71					232	14	**875**
Venus crebrisulca								5			3				16				**24**
Venus erronea								1											**1**
Venus punctigera						1													**1**
Venus sp		4													5	4	1		**14**
Circomphalus foliaceolamellosa									3										**3**
Timoclea ovata		10	16	6		12	2	79	6	8	77	19	16	2	21	16	2	24	**316**
Gouldia minima					1					12								5	**18**
Gouldia sp	1																		**1**
Dosinia adami																		1	**1**
Dosinia exoleta															4	12			**16**
Dosinia lupinus afra				2												1			**3**
Dosinia sp																17			**17**
Pitar belcheri							1			5				10		3		12	**31**
Pitar sp		3		1		1			3										**8**
Callista floridella																5			**5**
Venerupis dura															1	6			**7**
Veneridae					11					8			114				6	10	**149**
Corbula gibba		6	2			5				4				1		27		6	**51**
Corbula laticostata																6			**6**
Corbula sp			3						1				1						**5**
Hiatella arctica	7																		**7**
Thracia phaseolina								1											**1**
Pandora cf. oblonga																2			**2**
GASTROPODS																			
Fissurellidae	3												1						**4**
Gibbula joubini		1								2	1	2	18	1	1	4			**30**
Gibbula sp																		4	**4**
Trochidae			1		3											6			**10**
Skeneidae																1			**1**
Tricolia pullus													45	2					**47**
Alvania fariai														1					**1**
Alvania cf. internodula					2									2			1	2	**7**
Alvania marioi		2			1												1		**4**
Alvania parvula				1														1	**2**
Alvania sp										1			2	2			1		**6**
Benthonella sp					1														**1**
Zebina sp	1																		**1**
Rissoidae		17			1														**18**
Barleeia sp		1	1							2			46					2	**52**
Calyptrea africana										1	3				1	4	5	8	**22**
Crepidula porcellana					3	3				1	2		3		2	3	5	3	**25**
Euspira grossularia										1									**1**
Natica adansoni														2					**2**
Natica fulminea															2	2			**4**
Natica turtoni		5												2					**7**
Natica sp														1					**1**
Naticidae		3	1	1					1	2		1	2	3		2		3	**19**
Bufonaria marginata										1									**1**
Mesalia flammifera					3												1		**4**
Mesalia freytagi			1	1						2									**4**
Mesalia opalina															1				**1**
Mesalia sp												2							**2**
Turritella bicingulata											1								**1**
Turritella sp									1								2		**3**
Turritellidae		24	4	4	5					2	2		3		1	2	3	3	**53**
Triphoridae	1				1								1						**3**
Cirsotrema cochlea											1								**1**
Epitonium sp				1															**1**
Epitoniidae	1	1														1		1	**4**

Table IX.1– continued

	11509	**11511B**	**11511E**	**11511F**	**11522**	**11525**	**11527**	**11534**	**11535**	**11540**	**11547**	**11549**	**11591**	**11595**	**11601**	**11607**	**11613**	**11614**	**N**
Eulimidae		2			1					3									**6**
Pagodula fraseri											1								**1**
Trophon gruveli											1								**1**
Chauvetia joani											1								**1**
Chauvetia sp		2	2								1					3			**8**
Buccinidae																		10	**10**
Nassarius argenteus											1								**1**
Nassarius atlantideus										2									**2**
Nassarius elatus										50				3				5	**58**
Nassarius denticulatus														12			2		**14**
Nassarius desmouloides																	2		**2**
Nassarius goreensis										1	1			1					**3**
Nassarius miga														2		6			**8**
Nassarius sp		17	6	4		2			4			2		19		4			**58**
Nassariidae									2	6									**8**
Fusinus sp	3				1														**4**
Dentimargo bojadorensis																	1		**1**
Marginella cleryi										1									**1**
Marginella poppei					1												1		**2**
Marginella sp										1									**1**
Volvarina ambigua															5				**5**
Volvarina sp				2		1		1		4				2					**10**
Marginellidae		3			2												2	2	**9**
Persicula cingulata		1										1				1			**3**
Persicual cornea						1													**1**
Persicula sp															1				**1**
Gibberula chudeaui			2								1								**3**
Gibberula sp	6				8							1		3					**18**
Granulina sp				2	9			1								2	3	2	**19**
Cystiscidae		4														1	2		**7**
Marginellidae or Cystiscidae		10	7		1			2		8			1	5		2	11	4	**51**
Bela sp											1								**1**
Clavatula mystica										1	1					2			**4**
Asthenotoma lamothei																	1	1	**2**
Brachycythara atlantidea											1								**1**
Raphitoma sp																		6	**6**
Sinistrella sinistralis											1								**1**
Turridae					3					1							1		**5**
Terebridae			1																**1**
Basisulcata lepida										2									**2**
Odostomia sp	1	6	1							1		2	9				2	2	**24**
Chrysallida sigmoidea				1															**1**
Chrysallida sp			1																**1**
Turbonilla lactea				1															**1**
Turbonilla cf. lactea						1													**1**
Turbonilla sp		6	1																**7**
Pyramidellidae	13	2											6					1	**22**
Pyrunculus hoernesii						1										2	2	3	**8**
Volvulella acuminata		2																	**2**
Ringicula conformis		1		2								2		2				1	**8**
Ringicula sp			1							3								3	**7**
Acteocina knockeri		2						1					1					3	**7**
Cylichna cylindracea		1																2	**3**
SCAPHOPODS																			
Fustiaria maltzani		1	2																**3**
Fustiariidae				1															**1**
Scaphopoda		2								4						1		2	**9**
Total bivalves	34	259	295	283	355	334	300	386	337	255	594	403	179	322	480	346	296	278	**5736**
Total gastropods	29	113	30	20	46	9	0	5	8	99	21	13	138	65	14	48	49	72	**779**
Total scaphopods	0	3	2	1	0	0	0	0	0	4	0	0	0	0	0	1	0	2	**13**
Total abundance	**63**	**375**	**327**	**304**	**401**	**343**	**300**	**391**	**345**	**358**	**615**	**416**	**317**	**387**	**494**	**395**	**345**	**352**	**6528**

IX.4 RESULTS AND INTERPRETATION

IX.4.1 *Composition of the mollusk assemblage*

A total of 6528 individuals that belong to 209 taxa were determined (Tab. 1). The bivalves overwhelmingly dominate the assemblage in abundance (5736 individuals of 35 families). The 118 bivalve taxa were determined at species level wherever possible (n=76), and otherwise at genus level (n=29) and at family level (n=13). The taxonomic poverty of the bivalves is comparable to the low bivalve diversity observed elsewhere on West African shelves (Crame, 2000). Gastropods are present in markedly lower abundance (779 individuals of 26 families). The 88 gastropod taxa were determined at species level (n=49), at genus level (n=23), and at family level (n=17). The scarce scaphopods (n=13 individuals) belong to three taxa (one determined to species level, one to family level, one to order level). Many of the mollusk specimens determined at family level are juveniles.

The bivalve *Donax (Capsella) burnupi* Sowerby, 1894 is the most abundant mollusk species in the shallow-water sediment samples (<50 mwd; n=2386) and dominates half of the studied samples (n=9; Tab. 1; Fig. 2). The bivalve *Ervilia castanea* (Montagu, 1803) is the second most abundant species (n=875; Tab. 1; Fig. 2). Further abundant bivalves are *Cuna gambiensis* Nicklès, 1955 and *Timoclea ovata* (Pennant, 1777) that are widespread in the Golfe d’Arguin (total abundance of 223 and 316 individuals, respectively; Tab. 1; Fig. 2). Mollusk species such as the gastropod *Crepidula porcellana* (Linné, 1758) and the bivalves *Plagiocardium (Papillicardium) papillosum* (Poli,1795), *Plagiocardium sp*, and *Spisula subtruncata* (da Costa,1778) show high frequencies in the samples, but usually low abundance (Tab. 1). In contrast, other species show restricted spatial distributions, but high abundance (e.g., the gastropod *Nassarius elatus* (Gould, 1845) and the bivalves *Macoma cumana* (O.G.Costa,1829), *Tellina (Oudardia) compressa* Brocchi, 1814, *Tellina (oudardia) densestriata* Cosel, 1995; Tab. 1; Fig. 2).

IX.4.2 *Taphocoenoses and ecological interpretation*

Six taphocoenoses were defined based on the mollusk assemblages (Tab. 2). A cluster analysis based on the mollusk taxa supports the definition of the taphocoenoses (Fig. 3). The low similarity level of 30% between the groups reflects that several species are restricted to single samples with low numbers of individuals. The distribution of the taphocoenoses is depth-related as a result of the dominance of species with preferred water-depth ranges (e.g., *D. burnupi*, relict *E. castanea* shells). The taphocoenoses and their ecological interpretation therefore are given in order of increasing depth. The taphocoenoses in addition are determined by different substrates at given depth ranges.

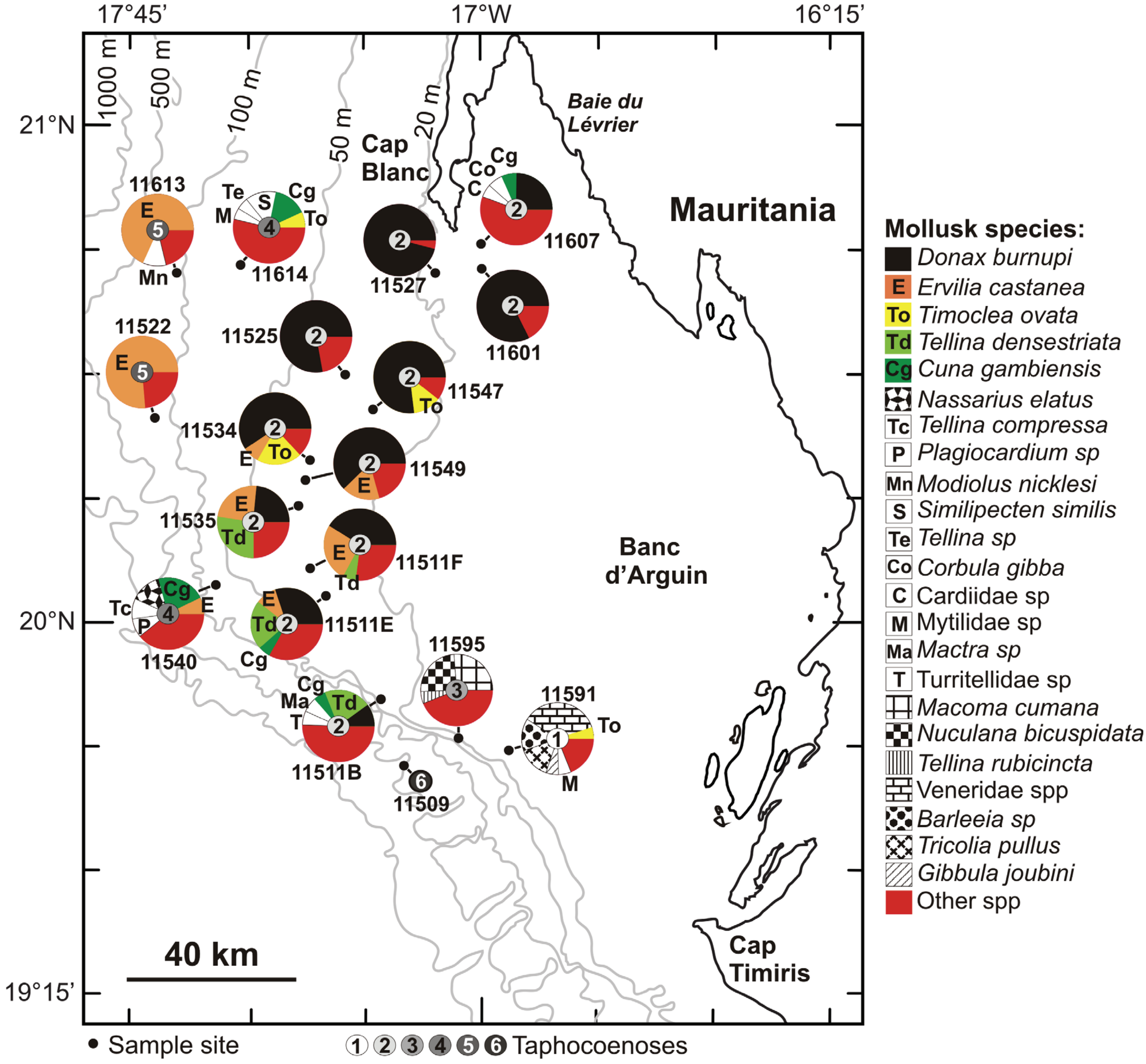

Figure IX.2–Sample locations and the proportions of the dominant mollusk species per sample (>5 % of the total abundance of the sample; pie diagrams). The taphocoenosis number of each mollusk assemblage is given in the center of the pie diagrams. Proportions of sample GeoB11509 is not shown because of the low numbers of mollusks present in the sample.

Table IX.2–Summary of the main characteristics of the six taphocoenoses.

Taphocoenosis	Sample (GeoB)	Water depth	Substrate	Characteristic species	Dominant relict species
T1	11591	Banc d'Arguin (4 m)	Rocky	Veneridae, *Tricolia pullus*, *Gibbula joubini*	
T2	11525, 11527, 11534, 11547, 11549, 11601	Subtidal (15–40 m)	Fine sand to gravel	*Donax burnupi*	
	11511B, 11511E, 11511F, 11535	Subtidal (25–40 m)	Muddy, fine to medium sand	*Cardiocardita ajar*, *Cuna gambiensis*, *Nassarius sp*, *Tellina densestriata*, Turritellidae	*Donax burnupi* (reworked), *Ervilia castanea*
	11607	Baie du Lévrier, subtidal (18 m)	Muddy, fine to coarse sand	*Cuna gambiensis*, *Corbula gibba*	*Donax burnupi* (reworked)
T3	11595	Subtidal (40 m)	Muddy fine sand	*Macoma cumana*, *Nuculana bicuspidata*, *Tellina rubicincta*	
T4	11540, 11614	Outer shelf (70-90 m)	Muddy fine sand	*Nassarius elatus*, *Plagiocardium sp*, *Similipecten similis*, *Tellina compressa*	*Cuna gambiensis*, *Ervilia castanea*
T5	11522, 11613	Shelf break (100-150 m)	Fine to coarse sand	*Mesalia flammifera*, *Plagiocardium sp*, *Similipecten similis*	*Ervilia castanea*, *Modiolus nicklesi*
T6	11509	Slope (370 m)	Sandy mud	Lucinidae, Pyramidellidae	*Hiatella arctica* (reworked), *Manupecten pesfelis* (reworked)

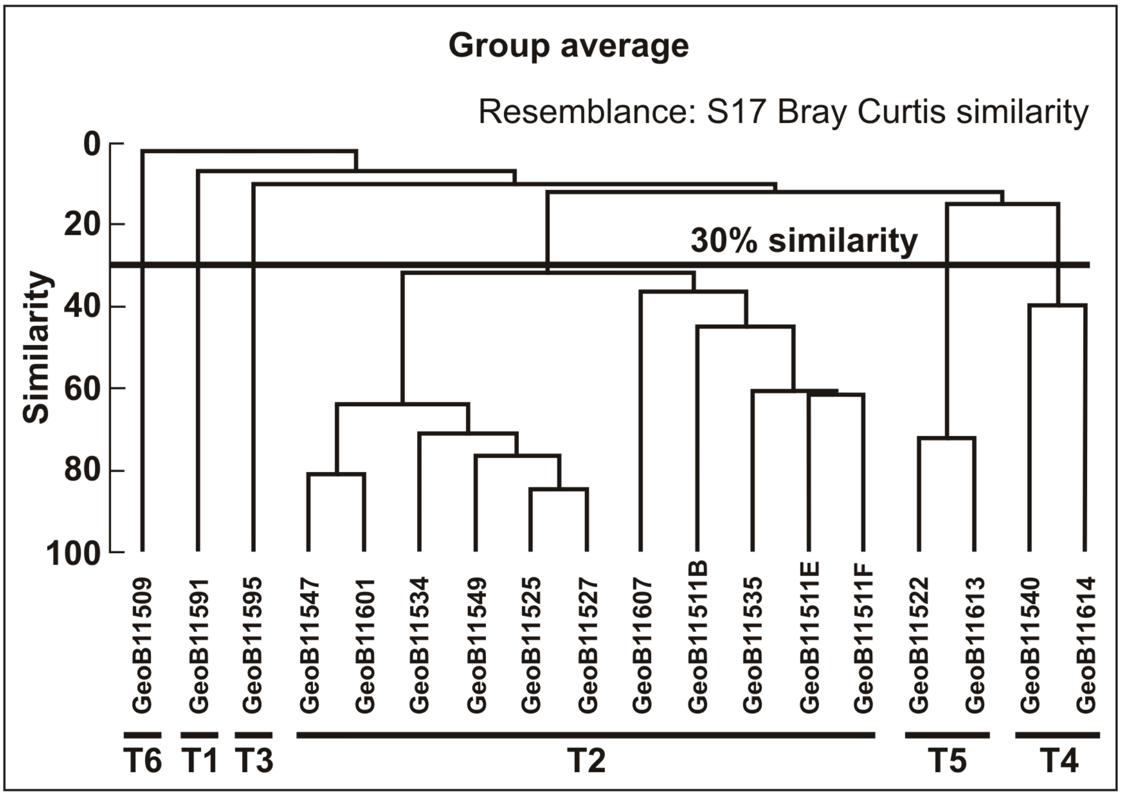

Figure IX.3–Hierarchical cluster analysis based on the mollusk taxa (Tab. 1) that groups samples together refered to as taphocoenosis (T1–T6; Tab. 2).

Taphocoenosis 1: T1 is represented by a sample (GeoB11591) located in the subtidal zone on top of the Banc d'Arguin (4 mwd; Fig. 2). Bivalve specimens from the Veneridae family are the most abundant mollusks of the assemblage (36% of the total abundance). Most abundant gastropods are *Barleeia sp.* (15%) and *Tricolia pullus* (Linné, 1758) (14%). Further taxa present are the bivalves *T. ovata* (5%) and Mytilidae (6%) and the gastropod *Gibbula joubini* Dautzenberg, 1910 (6%).

Species of the family Veneridae that characterize this sample from the top of the Banc d'Arguin could not be determined to genus or species level. The large portion of highly eroded bioclasts and shell fragments reflect the strong hydrodynamic conditions on the top of the Banc d'Arguin and hamper the taxonomical identification. The mollusk assemblage contains distinct shallow-water species (e.g., *Carditamera contigua* Dautzenberg, 1910, Fissurellidae, *Gibbula joubini*, *Tricolia pullus*; cf. Ardovini and Cossignani, 2004; Tab. 3). Rocky substrate-related mollusks (e.g., *C. contigua*, Fissurellidae, *Gibbula sp*, *T. pullus*, Triphoridae; K. Gürs, personal communication, 2007; cf. Ardovini and Cossignani, 2004) indicate the presence of rocky outcrops on the seafloor of the bank (cf. Domain, 1985; Westphal et al., 2007).

Several of the species present have a clear tropical affinity. The distribution of *Carditamera contigua* is restricted to two upwelling-influenced regions in tropical West

Africa, the Northwest African upwelling from Cap Blanc (Mauritania) to Guinea and the Benguela upwelling from Gabon to southern Angola (von Cosel, unpublished data). The species *Diplodonta dautzenbergi* Thiele, 1931 also reflects tropical conditions. The species *Timoclea ovata*, in contrast, is ubiquitous and thus not indicative of specific conditions.

Taphocoenosis 2: T2 is widespread in the subtidal zone between 15 and 40 mwd in the vicinity of Cap Blanc and directly seaward of the Banc d'Arguin (n=11; Fig. 2). The mollusk fauna is overwhelmingly dominated by the bivalve species *Donax burnupi* (10–96% of the total abundance). The bivalves *Ervilia castanea* (0–26%), *Tellina densestriata* (0–28%), and *Timoclea ovata* (1–20%) are abundant in some of the samples, while the bivalves *Cuna gambiensis* (0–7%), Cardiidae (6%), *Corbula (Varicorbula) gibba* (Olivi, 1792) (0–7%), and *Mactra sp.* (0–7%) as well as the gastropods Turritellidae spp. (0–6%) occur in lower abundances.

Donax burnupi (Fig. 4A) is known from upwelling areas of Africa (e.g., South Africa: Branch et al., 2002; Mauritania, northern Senegal: LeLoeuff and von Cosel, 1998). Living specimens of *D. burnupi* were not found in the samples, but extensive deposits of fresh, uneroded material have accumulated as largely monospecific assemblage in the northern part of the Golfe d'Arguin, where the broad shelf faces the swell coming from northwest direction (Figs. 1, 2). In this swell-exposed area, the sediments that constitute submarine dunes are referred to here as *Donax burnupi*-rubble. This mobile substrate is reworked and moved by strong hydrodynamics (e.g., swell, storm). Species of the genus *Donax* are known to be the dominant bivalves in high-energy, sandy beaches and shallow subtidal sandflats under highly productive, tropical to subtropical conditions (cf. Ansell, 1983). As is the case in the vicinity of Cap Blanc, *Donax burnupi*-rubble occurs where coarse quartz grains (i.e., fine to coarse sand) are present in large quantities (cf. Alongi, 1990). Further south and in the Baie du Lévrier, the abundance of *D. burnupi* shells and fragments decreases. Furthermore, the *D. burnupi* shells from these locations show more intense erosion than the fresh-looking shells in the swell-exposed area. The shells from the swell-exposed area are thought to be transported across the entire gulf and are deposited seaward of the Banc d'Arguin down to some 50 mwd. In the northern Golfe d'Arguin, numerous other mollusk species occur with a clear preference for clean medium to coarse sand and gravel substrate (*Dosinia exoleta* (Linné, 1758), *Gari (Psammobia) fervensis* (Gmelin, 1791), *Gari (Psammobia) jousseaumeana* Bertin, 1880, *Laevicardium crassum* (Gmelin, 1791), *Linga adansoni* (d'Orbigny, 1839), *Tellina (Moerella) boucheti* Cosel, 1995, *Tellina (Moerella) pseudopusilla* Cosel, *Paphia*

Table IX.3–Summary of the ecological requirements of the mollusk species discussed in the text, including depth range, substrate, trophic resource when available or trophic group and geographical distribution (compiled from Nicklès, 1950; Cosel, 1995, in prep.; Nielsen et al., 2006).

	Depth range	**Substrate**	**Trophic resources or trophic group**	**Distribution**
BIVALVES				
Nucula crassicostata	6-200 m	muddy sand, fine sand	organic matter	tropical-subtropical
Nucula nicklesi	1-80 m	muddy sand, fine sand	organic matter	tropical
Nuculana bicuspidata	1-60 m	sandy mud, fine sand	organic matter	tropical-subtropical
Nuculana commutata	10-200 m	sandy mud, muddy sand	organic matter	cosmopolitan
Yoldiella philippiana	80-300 m	muddy bottoms	organic matter	cosmopolitan
Modiolus nicklesi	15-70 m	muddy sand, sand	suspension-feeder	tropical
Similipecten similis	10-250 m	muddy sand	suspension-feeder	temperate
Manupecten pesfelis	50-200 m	sand	suspension-feeder	tropical-subtropical
Heteramonia squamula	50-110 m	soft bottoms	suspension-feeder	cosmopolitan
Lamellolucina reyrei	40-200 m	muddy fine sand	chemosymbiont	tropical
Linga adansoni	low tide-35 m	sand	chemosymbiont	tropical
Myrtea spinifera	90-250 m	sandy mud, fine sand	chemosymbiont	cosmopolitan
Anodontia senegalensis	60-230 m	muddy bottoms	chemosymbiont	tropical
Thyasira flexuosa	circalittoral to bathyal	muddy sand	chemosymbiont	subtropical-temperate
Diplodonta dautzenbergii	2-150 m	sand	?	tropical
Cardiocardita ajar	low tide-30 m	sand	suspension-feeder	tropical, upwelling
Glans aculeata	50-200 m	sand	suspension-feeder	tropical-subtropical
Carditamera contigua	low tide-5 m	rocky coasts	suspension-feeder	tropical, upwelling
Crassatina marchadi	7-50 m	fine sand	suspension-feeder	tropical
Digitaria digitaria	15-250 m	sand	suspension-feeder	temperate
Plagiocardium papillosum	20-60 m	sand	suspension-feeder	cosmopolitan
Laevicardium crassum	10-80 m	sand	suspension-feeder	cosmopolitan
Cuna gambiensis	1-20 m	sandy mud, fine sand	phytoplankton	tropical-subtropical, upwelling
Mactra inconstans	1-50 m	muddy fine sand	phytoplankton	tropical, upwelling
Spisula subtruncata	intertidal-200 m	muddy sand	phytoplankton	temperate
Tellina boucheti	low tide-35 m	sand	organic matter	tropical, upwelling
Tellina compressa	50-200 m	sandy mud, muddy sand	organic matter	warm-temperate
Tellina densestriata	15-35 m	fine sand	organic matter	tropical
Tellina pseudopusilla	15-60 m	sand	organic matter	tropical, upwelling
Tellina rubicincta	10-100 m	sandy mud, muddy sand	organic matter	tropical-subtropical
Macoma cumana	1-20 m, also deeper	muddy fine sand	organic matter	tropical-subtropical
Macoma melo	10-70 m	sand	organic matter	tropical-subtropical
Donax burnupi	low tide-40 m	sand	phytoplankton	tropical-subtropical, upwelling
Gari fervensis	10-30 m	sand	suspension-feeder	cosmopolitan
Gari jousseaumeana	10-50 m	sand	suspension-feeder	tropical, upwelling
Abra lecointrei	30-200 m	muddy bottoms	organic matter	tropical, upwelling
Ervilia castanea	subtidal-40 m (to 1800 m relict)	coarse sand	suspension-feeder	cosmopolitan
Venus crebrisulca	4-25 m	sand	phytoplankton	tropical-subtropical, upwelling
Venus erronea	5-20 m	sand	phytoplankton	tropical
Circomphalus foliaceolamellosa	10-30 m	sand	phytoplankton	tropical
Timoclea ovata	30-200 m	muddy sand, sand	phytoplankton	cosmopolitan
Dosinia exoleta	3-20 m	sand	phytoplankton	cosmopolitan
Pitar belcheri	15-100 m	muddy sand, fine sand	phytoplankton	tropical
Venerupis dura	low tide-40 m	sand	phytoplankton	tropical-subtropical
Corbula gibba	3-100 m	sandy mud, muddy sand	organic matter, bacteria, diatoms	temperate
Hiatella arctica	1-60 m	hard substrate	suspension-feeder	cosmopolitan
GASTROPODS				
Gibbula joubini	coastal	rock	herbivore	tropical-subtropical
Tricolia pullus	0-10 m	rock	herbivore	cosmopolitan
Alvania fariai	offshore	muddy sand	herbivore	tropical-subtropical
Crepidula africana	offshore	soft bottoms	suspension-feeder	tropical-subtropical
Natica adansoni	offshore	muddy sand	carnivore	tropical-subtropical
Mesalia flammifera	outer shelf	muddy sand, sand	filter-feeder	tropical-subtropical
Nassarius elatus	offshore	muddy sand	carnivore	tropical-subtropical
Nassarius denticulatus	offshore	muddy sand	carnivore	tropical-subtropical
Marginella cleryi	offshore	muddy sand	carnivore	tropical
Persicula cingulata	offshore	sand	carnivore	tropical
Persicual cornea	offshore	sand, gravel	carnivore	tropical
Ringicula conformis	offshore	sand	carnivore?	subtropical-temperate

(Callistotapes) dura Gmelin, 1791), *Venus erronea* Fischer-Piette, 1975, and *Venus crebrisulca* Lamarck, 1818; Tab. 3). The mollusk assemblage clearly points towards a subtidal position (10–50 mwd; e.g., *Cardiocardita ajar* (Bruguière, 1792), *Crassatina marchadi* Cosel, 1995, *D. burnupi*, *D. exoleta*, *G. fervensis*, *G. jousseaumeana*, *L. adansoni*, *Mactra inconstans* Cosel, 1995, *T. boucheti*, *T. densestriata*, *T. pseudopusilla*, *V. erronea*, and *V. crebrisulca*; Tab. 3).

The most abundant cosmopolitan species in T2 are *Ervilia castanea*, *Plagiocardium papillosum*, *Spisula subtruncata*, and *Timoclea ovata*. These species occur on a wide range of substrates from muddy fine sand to coarse sand. *Ervilia castanea* shells are strongly eroded, and therefore are considered subrecent and not produced in the current setting (cf. Morton, 1990). *Tellina densestriata* (Fig. 4E) that preferentially lives in fine sand sediments is therefore found in larger abundance (from 6 to 28 % of the mollusk fauna) exclusively in the southern part of the Golfe d'Arguin where fine-grained siliciclastic sediment of eolian origin accumulates (Michel et al., 2009; Fig. 2). *Tellina densestriata* is a tropical species with a distribution stretching from Mauritania (20°N) to Guinea (9°N) in water depths <50 m (von Cosel, 1995). Other tropical mollusks include *Circomphalus foliaceolamellosus* (Dillwyn, 1817), *Crassatina marchadi*, *Persicula cingulata* Dillwyn, 1917, *Persicula cornea* (Lamarck, 1822) and *Venus erronea* (Tab. 3). Upwelling-related taxa include besides *Donax burnupi* also *Cardiocardita ajar*, *Cuna gambiensis*, *Gari jousseaumeana*, *Mactra inconstans*, *Tellina boucheti*, and *Tellina pseudopusilla*.

In the Baie du Lévrier (15 mwd; Fig. 2), the eroded *Donax burnupi* shells are thought to have been transported by strong, northward directed currents from the swell-exposed area south of Cap Blanc into the bay (cf. Koopmann et al., 1979). The presence of the shallow-water species *Cuna gambiensis* (<20 mwd) together with *Corbula gibba*. reflects the presence of fine-grained sediments (mud to fine sand; Tab. 3). *Corbula gibba* additionally indicates high levels of organic matter content in the sediment and a highly instable environment that can be related to hydrodynamics, temperature, and oxic conditions (cf. Gonzales Delgado et al., 1995).

Taphocoenosis 3: T3 corresponds to a sample (GeoB11595) seaward of the Banc d'Arguin in the muddy, southernmost part of the studied area (41 mwd; Fig. 2). This muddy sediment body, the so-called Timiris-mud wedge, is characterized by fine siliciclastic sediment (muddy fine sand) deposited immediately seaward of a morphological step on the steep shelf (Hanebuth and Lantzsch, 2008). The dominant mollusk species are the bivalves

Macoma cumana (26% of the total abundance), *Nuculana (Lembulus) bicuspidata* (Gould, 1845) (25%) and *Tellina (Moerella) rubicincta* Römer, 1870 (5%; Fig. 4F).

These three bivalve species that are known from tropical and subtropical West Africa require a fine-grained clastic substrate (mud to fine sand; Tab. 3). *Nuculana bicuspidata*, as species of the genus *Nuculana*, is an infaunal bivalve with a low mobility that lives close to the sediment-water interface in organic-rich, fine-grained material (cf. Rhoads et al., 1972). This species is thus well adapted to the highly productive study area where large quantities of organic matter are produced and deposited on the seafloor. Other species characteristic of West African waters are present here in lower abundances, including *Alvania fariai* Rolán and Fernandez, 1990, *Macoma melo* (Sowerby, 1866), *Nassarius denticulatus* (Adams, 1851), *Natica adansoni* Blainville, 1825 and *Pitar belcheri* (Sowerby, 1851) (cf. Ardovini and Cossignani, 2004). Only very few cosmopolitan individuals are found (i.e., *Corbula gibba*, *Ringicula conformis* Monterosato, 1877, *Similipecten similis* Laskey, 1811, and *Timoclea ovata*). Most of the mollusk species of this assemblage are found in the permanent upwelling zones and in subtropical settings as well as in warm and rainy regions (e.g., Gulf of Guinea; Tab. 3). T3 thus reflects the fine-grained substratum on West African shelves but does not allow for distinguishing between different climatic regimes. Merely the distribution of *Abra lecointri* Nicklès, 1955, *Macoma melo*, and *Donax burnupi*, the latter present as reworked debris, is restricted to upwelling regions.

The ecological requirements of the dominant species in T3 (i.e., *Macoma cumana*, *Nuculana bicuspidata*, and *Tellina rubicincta*) clearly indicate water depths of <60 m for the locus of production (Tab. 3). Shallow-water species are restricted to the allochtonous, rocky-substrate related species *Carditamera contigua*, *Gibbula joubini* and *Tricolia pullus* (cf. Ardovini and Cossignani, 2004). In contrast, species that are commonly found in deep waters (e.g., *Myrtea spinifera* (Montagu, 1803), *Similipecten similis*, *Tellina compressa*; Tab. 3) are present. The aspect of this assemblage thus is reminiscent of deeper-water production than the true water-depth. One explanation relates to the effect of the upwelling in the southern part of the Golfe d'Arguin (cf. Shaffer, 1974). The upwelling leads to hydrologic conditions more typical of deeper-water settings (e.g., lower water temperature, lower oxygen concentration, higher nutrient content). Another factor contributing to the deeper-water aspect is that the setting is characterized by fine-grained sediment bodies usually more typical of deeper water depths.

Taphocoenosis 4: T4 is present in water depths around 70 m offshore Cap Blanc and in water depths of some 90 m in the middle part of the Golfe d'Arguin (n=2; Fig. 2). The most abundant mollusk taxa in T4 include the gastropod *Nassarius elatus* (1-14%; Fig. 4G) and the bivalves *Cuna gambiensis* (15-22%), *Similipecten similis* (1-14%), *Ervilia castanea* (4-7%), *Timoclea ovata* (2-7%), *Tellina compressa* (1-9%; Fig. 4D), *Plagiocardium sp.* (1-8%), *Tellina sp.* (0-5%), and Mytilidae (0-5%).

The shallow-water (<20 mwd) bivalve *Cuna gambiensis* (Fig. 4B) with its strong preference to muddy fine sand substrates (von Cosel, unpublished data) occurs in high abundance exclusively on the outer-shelf area off the Banc d'Arguin. This discrepancy of locus of deposition and water-depth of production together with the poor preservation of the shells implies that the *C. gambiensis* shells represent a relict material from the last transgression when the outer shelf was being successively flooded.

The association of *Similipecten similis* with *Plagiocardium sp.* in northern Mauritania corresponds to the same biocenosis as the cosmopolitan association *S. similis-Parvicardium minimum* (Philippi, 1836). These associations indicate outer-shelf settings (around 80 mwd; S. Gofas, personal communication, 2009). *Heteranomia squamula* (Linné, 1758) and *Yoldiella philippiana* (Nyst, 1845) also point to a deep-shelf setting. Other species that reflect the outer shelf environment but specifically point to in a muddy fine sand substrate include *Anodontia (Loripinus) senegalensis* Cosel, 2005, *Myrtea spinifera*, *Nassarius. elatus*, and *Tellina compressa* (cf. Cosel, 1995; Rueda and Salas, 2003). *Abra lecointrei*, *Nucula crassicostata* E.A. Smith, 1871, *Nuculana bicuspidata*, and *Nuculana (Sacella) commutata* (Philippi, 1844) indicate a fine-grained substrate (Tab. 3).

Bivalve species of the families Lucinidae and Thyasiridae, which host chemosymbiontes and are tolerant of suboxic and anoxic sediments, are commonly found in T4 (e.g., *Anodontia senegalensis*, *Lamellolucina reyrei* Nicklès, 1955, *Myrtea spinifera*, and *Thyasira flexuosa* (Montagu, 1803)). Their presence indicates a high organic-matter concentration in these muddy sand sediments that are interpreted as a consequence of the upwelling and its associated high productivity in the water column. A mixed fauna of temperate water species (e.g., *Corbula gibba*, *Similipecten similis*, and *Spisula subtruncata*) and tropical species (e.g., the bivalves *Abra lecointrei*, *Modiolus nicklesi* Ockelmann, 1983 and *Pitar belcheri* and the gastropods *Marginella cleryi* Petit de la Saussaye, 1836, *Persicula cingulata*, and *Persicula cornea*) reflect the influence of different water masses (Tab. 3).

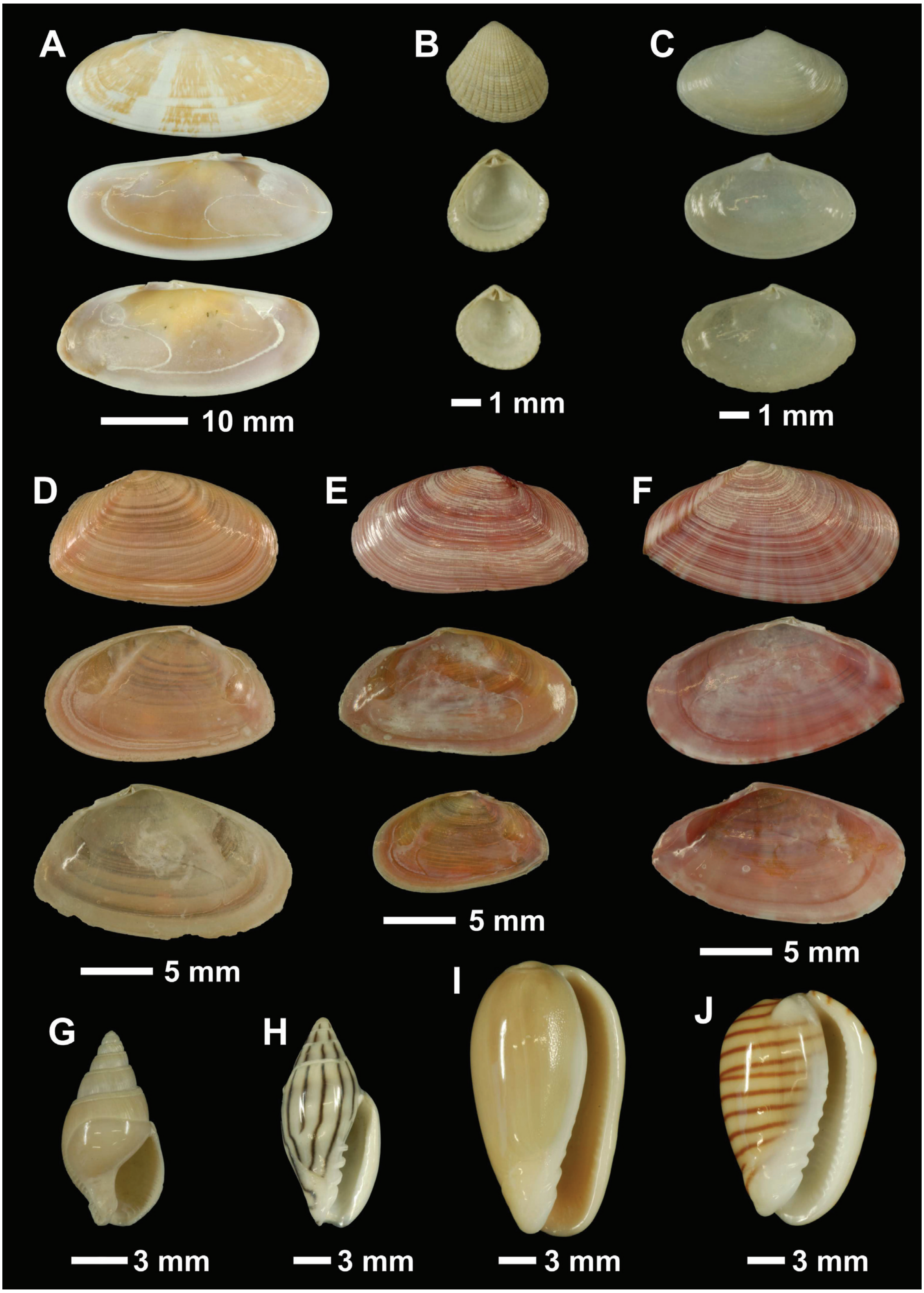

Figure IX.4–Photographs of mollusk species from the Golfe d'Arguin (Mauritania): A. *Donax burnupi*, 15 mwd; B. *Cuna gambiensis*, 89 mwd, 18 mwd; C. *Ervilia castanea*, 103 mwd; D. *Tellina compressa*, 92 mwd; E. *Tellina densestriata*, 53 mwd; F. *Tellina rubicincta*, 53 mwd; G. *Nassarius elatus*, 92 mwd; H. *Marginella cleryi*, 71 mwd; I. *Percicula cornea*, 38 mwd; J. *Persicula cingulata*, 33 mwd. For bivalves, external and internal views of the same valve are shown (upper pictures), while internal view of the other valve shows a different specimen (lower picture). Scale for each species is shown on the figure.

Taphocoenosis 5: T5 is present above the shelf break in the northern part of the Golfe d'Arguin in water depths of around 100-155 mwd (Fig. 2). It is dominated by eroded and in many cases superficially dissolved bivalve shells of the cosmopolitan species *E. castanea* (67-76% of the total abundance; Fig. 4C). The bivalve *M. nicklesi* is abundant in the northernmost sample (GeoB11613; 10%).

The mollusk assemblage of T5 consists mainly of physically eroded shells. Bioclastic sand consisting of highly eroded shells are common in similar depths off tropical Northwest Africa and are referred to as "outer shelf carbonate sand belt" (Barusseau et al., 1988). These deposits plus further *Ervilia castanea* deposits from the eastern Atlantic and the Mediterranean Sea have been interpreted as relict sediments (see Morton, 1990 for a review). Living specimens of *E. castanea*, in contrast, are exclusively found in shallow, high-energy waters (0–40 mwd; Morton, 1990). The *E. castanea* deposits described from the study area are interpreted as part of the "outer shelf carbonate sand belt" formed during the last Pleistocene while sea level was around 100 m below its present position. This is supported by a calibrated ^{14}C age of a strongly eroded bivalve shell from 103 mwd pointing to a post-LGM age (15 275±150 cal yrs BP; Michel et al., in prep). The low sedimentation rate coupled with strong current regimes (Bein and Fütterer, 1977) could have been responsible for continued exposition of the shells at the sediment surface.

While T5 is strongly dominated by relict sediment, the association of *Digitaria digitaria* (Linné, 1758), *Mesalia flammifera* Locard, 1896, *Plagiocardium sp.*, and *Similipecten similis*, together with *Anodontia senegalensis*, *Nucula crassicostata*, and *Yoldiella philippiana* represents the present-day deposition on the outer shelf off northern Mauritania. T5 contains tropical species such as *A. senegalensis*, *Crassatina sp*, and *Modiolus nicklesi*, together with the temperate species *D. digitaria*, *S. similis*, and *Spisula subtruncata* (Tab. 3), reflecting the complex hydrological and sedimentary situation.

Taphocoenosis 6: T6 represents a sample from 370 mwd in the southern area of the deeper shelf of the Golfe d'Arguin that is cut by numerous canyons (Fig. 2). Only few mollusks were present in the sample (n=63). The taphocoenosis is a deep-water coral (*Lophelia* and *Madrepora*) environment in muddy sediments. Most mollusks present have been transported downslope from shallower water depths (e.g., *Glans aculeata* (Poli, 1795), *Hiatella arctica* (Linné, 1767), *Manupecten pesfelis* (Linné, 1758), *Myrtea spinifera*, *Nucula nicklesi* Cosel, 1995, and *Plagiocardium* sp.) as reflected by the strong mechanical erosion of the shells. A mixed mollusk fauna with both tropical (e.g., *N. niclesi*) and cosmopolitan species (e.g., *H. arctica* and *M. spinifera*; Tab. 3) is present.

IX.5 DISCUSSION

IX.5.1 *Diversity and environmental significance of the mollusk assemblage*

The bivalve fauna of the Golfe d'Arguin displays low diversity (little more than 200 species) in comparison with other tropical faunas (typically some 650–1200 species; e.g., east and west of the central American isthmus, southern China-Indonesia-northeastern Australia region; cf. Crame, 2000). The low mollusk diversity is interpreted as the result of the constraining environmental conditions in the studied environment. The oceanographic system on the northern Mauritanian shelf is highly variable. The characteristics of the shelfal waters depend on the seasonal cycle (influenced by the Canary Current in winter; influenced by the Guinean Current in summer), and on intermittent mixing processes and oceanographic fronts related to the upwelling phenomena (Hagen, 2001; Pastor et al., 2008). This oceanographic pattern contrasts with the continuous warm-water conditions in areas with high bivalve diversity, in both, oligotrophic (e.g., Carribean, Seychelles) and eutrophic waters (e.g., Southeast Asian continental margins; cf. Taylor, 1997; Crame, 2000; Mackie et al., 2005).

In the shallow subtidal zone (<50 mwd) on the outer part of the Banc d'Arguin and seaward of the bank, the high water energy (swell, tidal currents, wind-induced currents) lead to soft-sediment remobilisation that does not allow for a diverse fauna to establish (cf. Wilson, 1988). In the Golfe d'Arguin, diversity is lowest in the northern swell-exposed area (15–40 mwd) where the sediments are almost entirely composed of fresh, empty shells of *D. burnupi* (>75%) forming extensive mobile sediment bodies. The high water energy results also in the remobilization and transport of eolian dust throughout the entire northern Mauritanian shelf (Michel et al., 2009). This high load of suspended silt in the water column results in strongly reduced light penetration as reflected in the absence of photosymbiotic organisms and the extreme scarcity of photosynthetic organisms (Michel et al., in prep.).

The paleobiogeographical evolution additionally influences the modern mollusk assemblages of tropical West Africa. *Circomphalus foliaceolamellosus* and *Yoldiella philippiana*, which are present in the study area, have been described from Pliocene deposits of northern Italy and Portugal (cf. da Silva et al., 2010), and Pleistocene deposits of Sicily (cf.

Salas, 1996). After the Miocene and during the Pliocene, the tropical faunal association of the Euro-West African province (i.e., large Tethys, low latitude eastern Atlantic), lost its tropical elements and shifted toward a temperate association (Le Loeuff and von Cosel, 1988). Subsequently, repeated cooling during the Pliocene and Pleistocene did not allow the reestablishment of a fully tropical fauna even in tropical Northwest Africa. The abundance of cosmopolitan species in Northwest African mollusk faunas and the faunal similarity with the temperate eastern Atlantic and western Mediterranean (von Cosel, 1993) is a result of this evolutionary pattern.

In summary, the low mollusk diversity in the study area appears to be governed by local (e.g., hydrodynamic conditions) and mesoscale (e.g., oceanographic circulation) environmental characteristics (cf. Gray and Elliott, 2009), and by the faunal evolutionary pattern (Le Loeuff and von Cosel, 1988; Crame, 2000). These characteristics are not linearly distributed over the latitudes. The absence of latitudinal gradients in the macrobenthic diversity was previously observed (e.g., Kendall and Aschan,1993). While the regions with the highest diversity of bivalves are found within the tropical belt, they correspond to specific environmental settings (e.g., coral reef regions; cf. Crame, 2000; soft sediments of both eutrophic and oligotrophic Indo-Pacific waters; Taylor, 1997; Mackie et al., 2005). In general, in contrast to oligotrophic biotopes, eutrophic environments display simpler food webs and a lower diversity (cf. Kohn, 1997; Taylor, 1997). However, this is contradicted in the Indo-Pacific region by the highly diverse bivalve fauna of eutrophic waters that exceeds the diversity of bivalves in coral reef settings in the same area (Taylor, 1997). The low diversity in the study area therefore is interpreted to reflect above all the instability of the environmental conditions.

Each of the mollusk assemblages of the Golfe d'Arguin displays a mixed tropical and cosmopolitan fauna. The tropical elements in the fauna allow for clearly distinguishing these sediments from temperate carbonates. The gastropods of the family Marginellidae (e.g., *Marginella cleryi*, *Persicula cingulata*, *Persicula cornea*; Figs. 4H, I, J) and the bivalve species such as *Modiolus nicklesi* and *Tellina densestriata* unequically reflect the tropical setting. This taxonomic pattern that reflects the influence of the different water masses (i.e., tropical, subtropical, upwelled waters) corresponds to the mixed planktonic foraminifer assemblages (Thiede, 1975; Mateu, 1979).

IX.5.2 Depositional patterns

On the northern Mauritanian shelf, hydrodynamics and the morphology of the seafloor govern the sedimentation patterns (Michel et al., 2009), and thus define the type of substrate that then influences the development of the biota. In turn, the carbonate-secreting organisms themselves influence the grain size distribution and thereby the substrate by *in situ* sediment production. Hydrodynamics are responsible for the post-mortem reworking and destruction of the shells and their transport to the locus of deposition. Large portions of the sample material consist of eroded shell fragments (depending in the setting 1–55 % of the grains; Michel et al., in prep.). This is common for open-shelf sedimentation under high water energy conditions (Wilson, 1988; Coffey and Read, 2007).

The highly productive eutrophic conditions and the high suspended sediment load lead to an aphotic environment with oligophotic conditions being restricted to the shallowest parts of the Banc d'Arguin. Under such environmental conditions, the distribution of organisms lacks a light-related depth zonation. The grain-size distribution also lacks a clear depth-related gradient, but shows a north-south gradient (Michel et al., 2009). A depth zonation, however, is introduced by the ecological requirements of the mollusk assemblages including substrate and dependence on the tides as well as by reworking. The shallow-water setting on top of the Banc d'Arguin is clearly characterized by intertidal and rocky substrate-related mollusk species (e.g., *Carditamera contigua*, *Gibbula joubini*, and *Tricolia pullus*; T1). The presence of reworked material on the shallow bank reflects the high water energies induced by tidal and wind-driven currents (Ould-Debah, 1993). Offshore the Banc d'Arguin, accumulations of *Donax burnupi* indicate swell-exposed, subtidal water depths. *Donax burnupi*-rubble is found where winnowing and sediment remobilisation occur in the northern-half of the Golfe d'Arguin (T2). In the southern part of the Golfe d'Arguin, silty fine sands are being deposited seaward of a morphological step on the shelf by the seaward-directed current system of the Banc d'Arguin (T2 and T3; Fig. 1; Hanebuth and Lantsch, 2008; Michel et al., 2009). Downshelf (T3) and downslope (T6) transport occurs on the steep shelf (also see Diester-Haas, 1981). These differences in substrate are clearly reflected in the differences between the taphocoenoses. Because of the great importance of substrate requirements, different taphocoenoses are present in the same water-depth ranges (Tab. 3).

On the outer shelf of the northern part of the Golfe d'Arguin, the eroded relict shells of shallow-water species (e.g., *Cuna gambiensis*, *Ervilia castanea*, and *Modiolus nicklesi*; T4 and T5) are abundant and are interpreted to represent a shallow-water depositional setting during early deglacial times (around 15ky BP; T5). The modern deeper-water setting (70 to 155 mwd) is reflected by well-preserved taxa characteristic of deep-shelf settings, including *Plagicardium sp.* and *Similipecten similis*. The abundance of relict grains indicates a low sedimentation rate resulting in a condensed sedimentary succession for the past several thousand years (cf. Wilson, 1988; Michel et al., in prep).

IX.5.3 Mollusk-rich carbonate sediments

The sediment in the Golfe d'Arguin is dominated by carbonate shells plus quartz grains originating from desert dust and coastal sand dunes (cf. Lancaster et al., 2002; Michel et al., 2009). The carbonate sediment is dominated by bivalves, most of which are infaunal suspension and filter feeders and thus are well adapted to the soft-sediment, mostly coarse-grained substrate. Bivalve-dominated associations of carbonate sediments and ancient rocks are well-known from temperate to cool-water settings, and have been referred to as "bimol" associations (Hayton et al., 1995). Mollusk-dominated, and in particular bivalve-dominated assemblages are also known from modern upwelling regions such as the Western Sahara shelf (Summerhayes et al., 1976), the southern Australian shelf (James et al., 1992, 2001), and the Gulf of Mexico (Halfar et al., 2006).

Bivalve organisms as deposit-, filter-, and suspension-feeders are well adapted to eutrophic conditions (Rhoads et al., 1972; Taylor, 1997). In particular, suspension-feeding bivalves in eutrophic regimes can develop high fecundity, early maturity, and fast growth rates, that enable them to respond to pulses of nutrient and phytoplankton growth (Taylor, 1997). These adaptive characteristics appear to be independent of latitude or water temperature (cf. Alongi, 1990). While the above mentioned mollusk-dominated assemblages are found in cool-water settings, the bivalve-dominated association described in the present study has developed under tropical conditions on the inner part of the shelf and mixed, instable temperature conditions on the outer shelf. The trophic regime plays an important role in controlling the carbonate-producing biota in particular under tropical conditions by pushing the system towards heterotrophic strategies (cf. Wood, 1993; Mutti and Hallock, 2003; Pomar et al., 2004; Westphal et al., subm).

Taxonomical data are crucial for the distinction between heterozoan associations developed under different temperature and trophic regimes. Therefore high taxonomical accuracy is required for paleoenvironmental interpretation. The ecological study of modern mollusk-rich deposits could permit to define proxies for the identification of eutrophic shelves in the sedimentary record. The low preservation potential of aragonitic shells, in particular in coarse-grained sediment (Melim et al., 1995), however, limits the suitability of such deposits as environmental archives. Aragonite grains can be dissolved from unlithified sediment without leaving molds, as observed in Neogene sediments of the Southern Australian shelf (James et al., 2005) and the Bahamas (Westphal et al., 2000). The eutrophic and highly productive conditions of the Golfe d'Arguin shelf would likely lead to such early dissolution of the aragonitic grains, being driven by organic matter oxidation (cf. Melim et al., 2002; Sanders, 2003). This could result in "black holes" in the rock record (e.g., Wright and Cherns, 2004, 2007). In order to assess the potential of mollusk faunas as that of the Golfe d'Arguin as paleoenvironmental analog, study of core material is required to assess the preservation of aragonitic shell material during earliest diagenesis.

IX.6 CONCLUSIONS

The soft sediments of the tropical, eutrophic Golfe d'Arguin are dominated by light-independent, heterotrophic organisms, specifically by bivalves. Such carbonate associations, although reminiscent of extratropical carbonates, carry a clear tropical signature in their taxonomical spectrum. The taxonomical assemblage reflects the influence of the various water masses, namely oceanic upwelling and equatorward as well as poleward-directed currents, the high oceanographic seasonal variability (water temperature, nutrient load), hydrodynamics (e.g., swell and tidal currents), and eolian dust input. The sediment reworking and deposition are controlled by the coupled effects of hydrodynamics and the topography of the shelf. The volumetrically important *Donax burnupi* material found in the north of the Golfe d'Arguin is the characteristic sediment of the swell-exposed mid shelf (<40 mwd). On the outer shelf, abundant relict shells (e.g., *Ervilia castanea*) from the last deglacial transgression are present.

Study of the mollusk fauna in the modern sediments of the Golfe d'Arguin allows to link the assemblage to the complex environmental conditions. Steering parameters are the water energy at the locus of production, the substrates, water temperature, and trophic conditions. The ecological requirements and the zoogeographical characteristics of the taxa allow for using them as an accurate tool for interpretation of carbonate deposits of the recent past.

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X. SUMMARY AND CONCLUSIONS

The present thesis identifies a modern analogue for carbonate sediments that are produced under eutrophic tropical conditions. We have described the heterozoan carbonate grain association of the Golfe d'Arguin (Mauritania) and its associated environment. In the sedimentary record, this heterozoan grain association is reminiscent of extra-tropical or cool-water setting. Ecological data of molluscs and foraminifers of the bivalve-rich carbonate deposits, however, reflect the eutrophic (i.e. upwelling-influenced) conditions under the tropical climate of the Golfe d'Arguin.

X.1 Summary of the main outcomes

- The sedimentary facies description of the Golfe d'Arguin provides a modern analogue and allows for the comparison with heterozoan grain associations in the sedimentary record.

The carbonate sediment that is produced on the open shelf of the Golfe d'Arguin is a foramol association *sensu stricto* (i.e. dominated by foraminifers and molluscs). Barnacle, echinoderm, and worm tube fragments are abundant. Other minor bioclastic grains include bryozoans, ostracods, sponge spicules, fish remains, and fecal pellets. Scarce photic-related carbonate-secreting biota are only found on top of the Banc d'Arguin in few meters water depth (i.e. uncommon red algae fragments).

Bivalve-dominated carbonate deposits are found in the northern-half of the study area. These coquinas and clean carbonate sand are present on highly energetic inner and middle shelf environments (e.g. swell-exposed) and on the outer shelf as palimpsest (i.e. a mixture of modern and relict grains). In the southern part where downshelf and downslope transports occur, siliciclatic-rich sediments dominated by foraminifers and bivalves as well as siliciclastic-dominated muddy sediment bodies are described.

- The taxonomic study provides a catalogue of mollusc and foraminifer taxa that can be used as paleoenvironmental proxies at least throughout the Cenozoic.

Foraminifers and molluscs display mixed-taxonomic populations of both cool and warm water-related species. The eutrophic environment is indicated by the presence of upwelling-related bivalve species and organisms that are well adapted to nutrient-rich and highly-productive environments (e.g. phytoplankton-feeding bivalves and barnacles, high organic- and low oxygen-related species). The presence of cool water-related species is explained by the open oceanic system, the influence of deep, cool upwelled waters, and by the recent (Plio-Pleistocene) climatic history of the tropical East Atlantic that controlled the zoogeographic distribution of the molluscs. Warm water-related species clearly indicate the low-latitude setting of the carbonate-producing environment. These taxonomic data provide the only proxies of the tropical realm of the heterozoan carbonate grain association.

- The environmental and ecological study enhances our understanding of the factors controlling the carbonate production.

The modern example of carbonate deposits of the Golfe d'Arguin shows that a heterozoan association dominated by bivalves and foraminifers is well adapted to a warm-water environment influenced by upwelling. The eutrophic conditions promote short-lived, generalist, *r*-selected species against long-lived, specialist, *K*-strategy organisms. In the meantime, increasing trophic resources decrease the light penetration and results in oligophotic to aphotic conditions. Eutrophic conditions, therefore, supress light-related symbiotic strategies (e.g. hermatypic corals, large foraminifers) and lead to a simple food web. Enormous planktonic blooms provide food for suspension- and filter-feeder bivalves which, in turn, are eaten by generalist benthic predators, fish, and birds. In such a context, trophic conditions are a prominent factor controlling the carbonate production. Water temperature controls the species selection within this food-web type and thus appears as a secondary factor of carbonate production.

- The bivalve-rich deposits of the Golfe d'Arguin result in an aragonite-dominated mineralogy of the heterozoan carbonate association.

The carbonate mineralogy of heterozoan associations is mostly calcite-dominated (Nelson, 1988a; James, 1997). However, carbonate sediments dominated by infaunal bivalves such as the assemblage of the Golfe d'Arguin are aragonitic. Such an open-shelf deposit has a high diagenetic potential (e.g. dissolution) and thus, aragonitic grains may be lost before entering the sedimentary record (cf. Hood & Nelson, 1996; Smith & Nelson, 2003; James et al., 2005; Wright & Cherns, 2007). The aragonite-dominated carbonate material of northern Mauritania represents a precious modern example of taphonomic processes occurring on a tropical soft-sediment, open-shelf setting.

- The oceanographic circulation and the topography of the shelf explain the complex depositional pattern and the different facies occurring throughout the Golfe d'Arguin.

The mixed heterozoan carbonate-siliciclastic deposits result in a soft-sediment bottom. The mollusc- and foraminifer-rich carbonate production is unable to build wave-resistant structures (e.g. reefs). Consequently, the deposition of clastic sediments in the Golfe d'Arguin is controlled by the hydrodynamic conditions coupled with the inherited topography of the shelf. In turn, the sediment distribution, which defines the substrate type (i.e. from coarse to fine-grained), is influenced by the carbonate production *in situ*. Such a depositional system leads to a sedimentary facies mosaic (cf. Wright & Burgess, 2005) that biases simple depth-related sediment distribution. Here, the combination of the topographic high of the Banc d'Arguin (i.e. shoals), the swell direction, and the prevailing winds which drive the surface flow causes an overall N-S trend of deposits: both carbonate content and grain size decrease from coquinas and clean carbonate sand in the north to siliciclastic-rich and muddy siliciclastic-dominated sediments in the south. Such a physically-driven sedimentation is characteristic of clastic heterozoan association. The depositional system is controlled by the physical accomodation (cf. Pomar, 2001) and results in an open-shelf system.

X.2 Implications for paleoenvironmental reconstructions

- Carbonate grain association models

The current carbonate sedimentation models (i.e. tropical and non-tropical, tropical and cool-water, photozoan and heterozoan carbonates) are useful guides for interpreting ancient grain associations (e.g. reefs and loose grains, skeletal and non-skeletal grains; Lees & Buller, 1972; Lees, 1975), erosion and diagenesis (e.g. abrasion, dissolution, cementation, and lithification; Nelson, 1988a; James, 1997), and platform architectures (e.g. ramp and rimmed platforms; e.g. Betzler et al., 2005). However, such grain association models are problematic for paleolatitude and paleotemperature reconstructions. Since the early 1970s (Lees & Buller, 1972; Lees, 1975), it has been clearly stated that whilst tropical grain associations are restricted to low latitudes, cool-water carbonate associations are found throughout all climate belts (e.g. James, 1997; Wilson & Vecsei, 2003; Westphal et al., subm.). Therefore, despite the misleading nomenclature, tropical and cool-water associations are not strictly antagonistic for paleotemperature interpretations. For accurate paleoenvironmental interpretation, other parameters such as for instance food web should be considered.

- Food web and ecology

As part of the food web, carbonate-producing biota are controlled by primary producers. However, the latter organisms (e.g. phytoplankton, kelp-forest, and seagrass) are often not preserved in the geological record from open-shelf settings because they are either washed out (e.g. calcified and silicified microscopic grains) or not fossilized (e.g. phaeophytes). This is the case for many shallow-water heterozoan associations. Therefore, only heterotrophic carbonate-secreting biota are recorded (except calcareous red algae and ahermatypic corals) and primary production can only be inferred by the trophic requirements of these heterotrophic organisms. In photozoan associations in contrast, the primary production is part of the characteristic carbonate-secreting biota as photosymbiotic organisms (i.e. zooxanthellate coral reefs), as calcareous green and red algae, or as picophytoplankton. Therefore, such deposits record in their carbonate assemblages both phototrophic primary production and heterotrophic organisms (e.g. molluscs, benthic foraminifers). Consequently, heterozoan and photozoan carbonates display different food webs that reflect different trophic levels.

- Failure of carbonate grain association models based solely on water temperature

Water temperature-based carbonate models have shown their efficiency for paleoenvironmental interpretation of photozoan associations, especially coral reef environments. Most hermatypic corals have a sharp biological threshold of water temperature that unable the biota development with temperatures cooler than 18°C (Newell, 1971; Belasky, 1996). Therefore, in the limit of actualism, zooxanthellate coral reef deposits indicate warm-water temperatures. However, such definite threshold is not observed for other carbonate grain associations. For instance, molluscs and red algae can be found through all climate belts and under very diverse conditions of temperature, trophic level, salinity, and hydrodynamic (e.g. Clarke & Crame, 1997 for mollucs; Freiwald, 1998 for red algae). Moreover, settings with high seasonal variability (e.g. range of ~10°C in the Golfe d'Arguin) do not fit easily in such water-temperature threshold models.

The water temperatures of the Banc d'Arguin (17.5–29°C) places the studied carbonate association within the tropical carbonate model (18–30°C; cf. Tab. I.2, p.15), while the open-shelf (i.e. middle and outer shelf) water temperatures (15.4–25.8°C) of the Golfe d'Arguin tend to classify the association within the warm-temperate model (10–25°C; cf. Tab. I.2, p. 15). However, the carbonate grain association of the Golfe d'Arguin that lacks phototrophic and mixotrophic biota differs from both tropical photozoan and warm-temperate associations. If seagrasses are present in inner parts of the inner shelf of the Golfe d'Arguin, characteristic carbonate grains of the warm-temperate association (cf. Tab. I.3, p.15) are absent apart from scarce red algae and uncommon bryozoan fragments. Nevertheless, the presence of ooids, although restricted to the Baie de Saint-Jean (cf. Fig. III.4, p. 24), and warm-water-related mollusc and foraminifer taxa indicates the "true" tropical realm of the deposits. Therefore, the carbonate grain association of the Golfe d'Arguin is referred to as a warm-water heterozoan association. This nomenclature emphasizes on the one hand the diversity of tropical carbonate grain associations that can be photozoan or heterozoan, and on the other hand the diversity of heterozoan associations that can reflect warm, cool, cold, and polar waters.

XI. RESEARCH PERSPECTIVES

The deposits of the Golfe d'Arguin represent a rare example of aragonite-rich, loose sediments in a tropical open-shelf setting. This case study of modern, warm-water heterozoan carbonate sedimentation increases our knowledge about carbonate production. Furthermore, the results presented here help to define accurate models which allow for better paleoclimatic interpretations, and hence, better reconstructions of the conditions under which ancient heterozoan carbonates formed.

However, in order to compare this modern analogue with ancient counterparts, further investigations are needed, for instance with regard to preservation potential and lithification processes of such a carbonate deposit. Modern production loci should be identified and the effects of reworking (e.g. abrasion and fragmentation) and bioerosion need to be quantified. By using core material (Westphal et al., 2007), early diagenetic processes (e.g. dissolution) can be studied as well as the depth of remobilized material. Thus, a preservation/loss budget can be estimated. Paleoclimate studies can make use of the taxonomic and ecological data of the modern carbonate-secreting biota presented here. The mollusc and foraminifer assemblages of the core material from the Golfe d'Arguin (Westphal et al., 2007; Zonneveld et al., in press) could be analysed in order to look for changes in upwelling intensity off Mauritania through the late Pleistocene and Holocene. Taxa indicative of cold and/or nutrient-rich waters are expected to prevail during periods of stronger upwelling, while abundances of warm-water-related taxa would be increased during times of weaker upwelling.

Moreover, a comparison of the carbonate sediments from the Golfe d'Arguin with those from other upwelling-influenced shelves (e.g. Gulf of California, Yucatan Peninsula, Galapagos Islands, Morocco and Western Sahara, Australia and New Zealand) would permit investigation of reliable global proxies of eutrophic-related carbonate production (e.g. ecological requirements of biota and food web). Such a study would improve paleoenvironmental and paleoceanographic interpretation of ancient heterozoan carbonates.

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XIII. APPENDIX

Tab. XIII.1 Data from the 75 samples from the Golfe d'Arguin and the 5 samples from Western Sahara analysed during this thesis (GeoB and Poseidon sample numbers) showing location (longitude and latitude), depth (mbsl: meter below sea level), TOC content, carbonate content (Carb), carbonate mineralogy (Carb min; % t.c.: percentage of total carbonate; Aragonite Arag, Low Magnesium Calcium LMC, and High Magnesium Calcium HMC), and grain-size contents.

Sample GeoB	Sample Poseidon	Longitute (°W)	Latitude (°N)	Depth (mbsl)	TOC (%)	Carb (%)	Carb min (% t.c.)			Grain size (%)					
							Arag	HMC	LMC	>1000 µm	500-1000 µm	250-500 µm	125-250 µm	63-125 µm	<63 µm
GeoB11502	Pos346-02-1	16°57.97'	19°40.25'	62.3	0.669	43	No available data			1	0	1	2	6	89
GeoB11503	Pos346-03-1	16°59.14'	19°41.04'	71.3	0.859	40	69	9	22	0	0	0	2	4	94
GeoB11504	Pos346-04-1	16°59.13'	19°39.71'	79.3	0.782	39	70	7	23	0	1	2	6	6	86
GeoB11505	Pos346-05-1	16°58.24'	19°39.66'	68.3	0.750	42	68	7	25	0	0	0	2	6	92
GeoB11507	Pos346-07-1	17°03.04'	19°44.49'	77.3	0.942	41	67	12	21	0	0	0	3	5	92
GeoB11508	Pos346-08-2	17°06.00'	19°43.50'	132.3	0.856	49	55	19	26	2	8	17	25	20	28
GeoB11509	Pos346-09-1	17°09.00'	19°42.49'	374.3	0.711	40	73	5	22	16	9	10	11	7	47
GeoB11510	Pos346-10-1	17°12.02'	19°41.56'	604.3	1.537	35	61	6	33	No available data					71
GeoB11511A	Pos346-11A	17°03.99'	19°46.99'	27.0	1.698	42	68	7	25	6	4	11	25	4	50
GeoB11511B	Pos346-11B	17°11.96'	19°50.54'	28.5	1.104	37	60	10	30	0	1	1	28	62	8
GeoB11511C	Pos346-11C	17°12.44'	19°55.03'	31.4	0.247	44	66	10	24	1	5	12	19	51	11
GeoB11511D	Pos346-11D	17°15.00'	20°00.02'	30.4	0.288	56	71	7	22	0	1	4	25	30	39
GeoB11511E	Pos346-11E	17°19.03'	20°03.03'	32.6	0.465	56	69	8	23	2	2	7	25	33	32
GeoB11511F	Pos346-11F	17°21.06'	20°06.37'	31.7	0.421	56	67	11	22	1	4	10	66	9	11
GeoB11511G	Pos346-11G	17°22.54'	20°09.02'	31.4	0.343	63	70	6	24	2	5	17	50	20	5
GeoB11513	Pos346-13-2	17°12.03'	20°33.99'	35.5	0.297	84	68	10	22	10	11	34	34	5	5
GeoB11514	Pos346-14-1	17°07.04'	20°38.01'	23.3	0.290	56	78	3	18	19	24	46	10	0	0
GeoB11515	Pos346-15-1	17°02.03'	20°41.00'	21.1	0.062	83	91	2	7	54	25	14	6	0	1
GeoB11516	Pos346-16-1	16°57.20'	20°44.00'	13.4	0.120	74	78	4	18	32	45	22	1	0	0
GeoB11521	Pos346-21-2	17°48.01'	20°24.06'	564.3	0.070	41	66	6	28	0	0	1	5	40	53
GeoB11522	Pos346-22-1	17°41.01'	20°24.53'	155.3	1.680	81	87	3	10	5	22	45	15	4	9
GeoB11523	Pos346-23-1	17°32.00'	20°23.97'	63.3	0.290	46	57	15	28	0	1	5	13	54	27
GeoB11524	Pos346-24-1	17°23.95'	20°23.98'	42.8	0.776	77	52	9	39	20	12	37	27	4	1
GeoB11525	Pos346-25-1	17°16.54'	20°29.75'	38.4	0.309	82	60	9	31	4	8	36	46	5	2
GeoB11526	Pos346-26-1	17°07.98'	20°42.46'	29.5	0.267	44	55	9	36	4	3	8	71	11	3
GeoB11527	Pos346-27-1	17°04.97'	20°41.99'	20.1	0.201	56	45	6	49	3	3	32	61	0	0
GeoB11528	Pos346-28-1	17°01.98'	20°38.01'	22.3	0.022	78	88	2	10	51	27	15	5	0	1
GeoB11529	Pos346-29-1	17°04.96'	20°36.52'	23.3	0.110	71	90	2	9	49	30	18	2	0	0
GeoB11530	Pos346-30-1	17°09.01'	20°33.52'	33.2	0.071	71	71	6	23	7	15	27	21	9	20
GeoB11531	Pos346-31-1	17°14.43'	20°27.45'	35.1	0.343	85	73	7	20	8	12	33	37	5	4
GeoB11532	Pos346-32-1	17°14.57'	20°23.45'	35.3	0.349	87	90	2	8	35	38	24	4	0	1
GeoB11533	Pos346-33-1	17°19.05'	20°17.94'	38.3	0.162	82	74	6	20	18	35	26	16	3	2
GeoB11534	Pos346-34-1	17°21.08'	20°19.42'	33.3	0.335	93	87	3	10	27	46	24	3	0	0
GeoB11535	Pos346-35-1	17°22.56'	20°13.93'	36.3	0.091	69	66	9	25	1	2	7	47	30	13
GeoB11536	Pos346-36-1	17°28.90'	20°03.58'	58.3	0.486	59	56	13	31	0	0	0	2	21	76
GeoB11537	Pos346-37-1	17°32.58'	20°05.49'	82.3	0.850	45	58	13	30	0	1	3	11	35	50
GeoB11538	Pos346-38-1	17°33.66'	20°05.06'	90.3	0.885	59	72	10	18	2	9	25	23	21	19
GeoB11539	Pos346-39-1	17°34.03'	20°04.88'	92.3	0.596	59	68	9	22	1	6	25	30	22	15
GeoB11540	Pos346-40-1	17°33.17'	20°04.37'	89.3	0.624	53	50	41	9	1	5	15	24	34	21
GeoB11541	Pos346-41-1	17°33.27'	20°03.79'	89.3	0.793	59	71	8	21	1	6	26	28	26	13
GeoB11541A	Pos346-41A2	17°34.35'	20°01.37'	182.3	0.605	59	67	9	24	3	6	11	34	35	12

Sample GeoB	Sample Poseidon	Longitute (°W)	Latitude (°N)	Depth (mbsl)	TOC (%)	Carb (%)	Carb min (% t.c.)			Grain size (%)					
							Arag	HMC	LMC	>1000 µm	500-1000 µm	250-500 µm	125-250 µm	63-125 µm	<63 µm
GeoB11541B	Pos346-41B	17°31.47'	20°01.50'	79.3	0.786	50	74	12	15	1	7	33	49	7	5
GeoB11541C	Pos346-41C	17°33.81'	20°03.03'	93.3	0.261	62	78	8	15	2	13	41	32	8	4
GeoB11541D	Pos346-41D	17°36.13'	20°00.69'	333.3	0.296	64	84	4	11	13	19	32	9	5	22
GeoB11541E	Pos346-41E	17°38.20'	20°00.88'	506.3	0.724	53	69	8	23	0	1	4	20	54	22
GeoB11546	Pos346-46-2	17°00.60'	19°39.74'	107.3	0.940	43	69	7	24	0	1	3	4	8	84
GeoB11547	Pos346-47-1	17°12.98'	20°25.56'	29.9	0.142	91	75	5	20	6	30	29	28	5	2
GeoB11548	Pos346-48-1	17°16.99'	20°20.53'	32.3	0.259	89	76	5	19	2	17	47	32	1	0
GeoB11549	Pos346-49-1	17°21.67'	20°17.02'	33.2	0.157	81	67	10	23	3	10	32	52	2	1
GeoB11591	Pos346-91A	16°54.79'	19°44.19'	4.0	0.072	50	68	8	24	40	50	9	1	0	0
GeoB11593	Pos346-93-1	16°57.27'	19°43.49'	27.6	0.582	39	64	10	25	0	0	1	9	21	69
GeoB11594	Pos346-94-1	16°59.97'	19°44.49'	37.3	0.793	39	62	13	25	0	0	1	14	13	71
GeoB11595	Pos346-95-1	17°02.00'	19°45.81'	41.5	0.857	50	64	10	26	12	10	16	23	14	26
GeoB11597	Pos346-97-1	17°03.54'	20°42.74'	15.4	0.011	55	49	0	51	3	11	84	2	0	0
GeoB11601	Pos346-100-1	16°59.01'	20°42.50'	16.5	0.044	75	47	6	47	54	44	0	1	0	0
GeoB11602	Pos346-101-1	17°03.96'	20°38.16'	21.9	0.087	85	86	2	12	53	26	16	4	0	0
GeoB11603	Pos346-102-1	17°02.77'	20°42.22'	24.5	0.089	62	94	1	5	13	15	15	55	1	1
GeoB11604	Pos346-103-1	17°01.00'	20°48.90'	16.1	0.094	45	59	5	36	7	11	16	21	1	43
GeoB11606	Pos346-98-1	17°02.79'	20°43.17'	24.4	0.814	51	66	8	25	2	8	42	47	1	0
GeoB11607	Pos346-105-1	16°59.10'	20°45.49'	17.9	0.252	51	57	7	37	11	18	28	31	1	10
GeoB11613	Pos346-111-2	17°38.19'	20°42.00'	103.3	0.230	85	87	4	9	9	23	30	28	8	1
GeoB11614	Pos346-112-1	17°30.00'	20°42.96'	72.3	0.530	63	77	8	16	7	9	16	33	26	9
GeoB13007	Pos366-07-1	17°21.98'	20°00.01'	40.0	0.669	57	61	12	27	No available data					
GeoB13008	Pos366-08-1	17°25.00'	20°15.00'	40.0	0.738	60	56	16	29						
GeoB13009	Pos366-09-3	17°29.99'	20°14.98'	47.0	0.916	51	60	10	30						
GeoB13010	Pos366-10-1	17°35.01'	20°14.99'	80.0	0.273	84	70	8	22						
GeoB13011	Pos366-11-1	17°36.99'	20°14.99'	287.0	0.832	63	75	5	19						
GeoB13012	Pos366-12-2	17°43.00'	20°15.00'	545.0	0.810	59	70	7	24						
GeoB13013	Pos366-13-1	17°47.99'	20°33.00'	348.0	0.758	48	64	8	28						
GeoB13014	Pos366-14-1	17°42.98'	20°34.96'	178.0	0.282	85	86	3	11						
GeoB13015	Pos366-15-1	17°31.98'	20°33.99'	125.0	0.525	68	66	14	20						
GeoB13016	Pos366-16-1	17°24.00'	20°33.00'	49.0	0.406	39	65	13	22						
GeoB13017	Pos366-17-1	17°16.99'	20°33.00'	36.0	0.499	77	47	15	38						
GeoB13018	Pos366-18-1	17°14.98'	20°42.00'	37.0	0.523	62	55	24	21						
GeoB13019	Pos366-19-1	17°21.49'	20°42.00'	53.0	0.508	44	70	8	22						
GeoB13021	Pos366-21-2	17°03.75’	22°59.99’	105.0	0.452	86	76	11	14						
GeoB13022	Pos366-22-1	16°50.25’	23°00.01’	47.0	0.127	92	96	1	3						
GeoB13023	Pos366-23-1	16°31.33’	22°59.97’	27.0	0.118	90	83	3	13						
GeoB13028	Pos366-28-1	15°56.78’	25°12.40’	100.0	0.325	82	69	11	20						
GeoB13029	Pos366-29-1	15°33.33’	24°57.78’	49.0	0.106	92	92	3	5						

XIV. EPILOGUE

Je n'ai pas toujours été l'homme que je suis. J'ai toute ma vie appris pour devenir l'homme que je suis, mais je n'ai pour autant pas oublié l'homme que j'ai été, ou à plus exactement parler les hommes que j'ai été. Et si entre ces hommes-là et moi il y a contradiction, si je crois avoir appris, progressé, changeant, ces hommes-là quand, me retournant, je les regarde, je n'ai point honte d'eux, ils sont les étapes de ce que je suis, ils menaient à moi, je ne peux pas dire moi sans eux.

Je connais des gens qui sont nés avec la vérité dans leur berceau, qui ne se sont jamais trompés, qui n'ont pas eu à avancer d'un pas de toute leur vie, puisqu'ils étaient arrivés quand ils avaient encore la morve au nez. Ils savent ce qui est bien, ils l'ont toujours su. Ils ont pour les autres la sévérité et le mépris que leur confère l'assurance triomphale d'avoir raison. Je ne leur ressemble pas. La vérité ne m'a pas été révélée à mon baptême, je ne la tiens ni de mon père ni de la classe de ma famille. Ce que j'ai appris m'a coûté cher, ce que je sais je l'ai appris à mes dépens. Je n'ai pas une seule certitude qui ne me soit venue autrement que par le doute, l'angoisse, la sueur, la douleur de l'expérience. Aussi ai-je le respect de ceux qui ne savent pas, de ceux qui cherchent, qui tâtonnent, qui se heurtent. Ceux à qui la vérité est facile, spontanée, bien entendu j'ai pour eux une certaine admiration mais, je l'avoue, peu d'intérêt. Quand ils mourront, qu'on écrive donc sur leur tombe : il a toujours eu raison…, c'est ce qu'ils méritent et rien de plus. Il faut appeler les choses par leur nom."

Louis Aragon

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