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Paleoenvironmental Changes in the Lagoon of Mayotte Associated with the Holocene Transgression

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ABSTRACT. The volcanic island of Mayotte (12°50'S, 45°10'E) belongs to the Comoro archipelago located in the SW Indian Ocean (Northern Mocambique Channel). It is surrounded by an almost continuous ribbon barrier reef system which encircles a large lagoon of 1500 km² with a maximum water depth of 80 m. The objective of this study is to determine paleoenvironmental changes associated with the Holocene transgression. The physical (grain size), mineralogical (aragonite, calcite) and geochemical (carbonate, organic carbon and terrigenous content) sedimentary parameters show significant changes during the Holocene transgression. Rising sea level interacted with the complex morphology of the lagoon floor and produced different sedimentary environments at different times with varying water depths. The transgressive and highstand systems tract are characterised by their specific mineralogy, geochemistry, grain size distribution and magnetic susceptibility. Local processes like climatic variations (monsoonal precipitation, solar insolation, shift of the Intertropical Convergence Zone) or volcanism influenced the sedimentary processes during specific time intervals. Higher precipitation during the early Holocene (11–9 ka BP) caused by an intensified NE-monsoon enhanced runoff of terrigenous sediments into the lagoon. A mid-Holocene period (6–4 ka BP) of major volcanic activity on the eastern Petite Terre volcano disturbed the carbonate production in the neighbouring lagoons for a few hundred years. Maximum carbonate concentrations are found between 4–1 ka BP and coincide with a time of maximum solar insolation. A dramatic change in carbonate production occurred after 1 ka BP. This is probably linked to the ultimate stillstand in sea level rise at this time and anthropogenic input, which caused progradation of terrigenous sediments. Anthropogenic changes overprint the natural changes in the geochemistry and mineralogy of the lagoonal sediments after the first human settlement on the island around 1.2–0.8 ka BP.

KEY WORDS: Holocene, lagoonal sedimentation, geochemistry, mineralogy, grain size, SW Indian Ocean.

Introduction

The present study documents the evolution of the sedimentary sequences in the lagoon of Mayotte during the Holocene transgression. We will focus on the role of sea level, lagoonal topography and climate dynamics for the facies development. Finally, we will answer the questions when and how anthropogenic input occurred.

Methods and results

10 gravity cores were examined derived from various settings within the lagoon of Mayotte. Bulk sediment samples were taken every 10 cm. All samples were oven-dried at 50 °C and subsamples (~ 0.5 g) ground by hand for four minutes in an agate mortar.

Calcium carbonate, organic carbon and terrigenous contents were determined by LECO-analysis. X-ray diffraction was performed to quantify the abundance of carbonate minerals in the samples. The program Mac Diff 3.1.5 was used to determine the amount of calcite and aragonite within the sediment, by measurement of peak area. The relative weight percentages of calcite and aragonite where than calibrated with an in-house calibration curve (Andresen, 2000). X-ray fluorescence (XRF) were performed to determine the amount of major and minor elements within specific facies realms in the individual cores.

For grain size analysis the bulk sediment samples were at first wet-sieved for a devision into coarse (> 63 µm) and fine fraction (< 63 µm). The weighed coarse fraction was further divided into subfractions by dry-sieving.

A chronological framework for the postglacial sedimentation within the lagoon was established by conventional and AMS-^{14}C dating at specific levels within the individual cores (measured at Leibniz-Laboratory Kiel). All radiocarbon ages are converted to calendar years before present (Stuiver and Braziunas, 1993). The results of our analyses are summarized in Table 1.

^{14}C-age (cal kyr BP)	systems tracts & lagoonal setting	Lithology	Carbonate Mineralogy	Geochemistry
11–9	early transgressive proximal lagoon	terrigenous mud- to wackestones	Aragonite (1–18%), HMC + LMC (1–14%)	$CaCO_3$ (1–10%) C_{org} (0.3–0.8%) IR (> 90%) enriched in Si, Al, Fe, Ti, K, Rb, Zr, Ga
	early transgressive distal lagoon	mangrove muds and mixed carbonate-terrigenous wackestones	not determined	$CaCO_3$ (20–40%) C_{org} (5–15%) IR (> 50%) enriched in Al, Ni, Fe, Mn, Cu, Cr
9–6	late transgressive proximal lagoon	terrigenous mud- to wackestones	Aragonite (15–30%) HMC + LMC (10–14%)	$CaCO_3$ (20–40%) C_{org} (0.3–0.8%) IR (> 60%) enriched in Si, Al, Ti, Fe, Ga, Zr increase in Ca, Sr, Mg
	late transgressive distal lagoon	mixed carbonate-terrigenous or carbonate wackestones	not determined	$CaCO_3$ (40–60%) C_{org} (0.8–1%) IR (< 40%) increase in Ca, Sr, Mg
6–4	early highstand proximal lagoon	mixed carbonate-terrigenous mud- to wackestones	Aragonite (15–55%) HMC + LMC (8–20%)	$CaCO_3$ (10–55%) C_{org} (0.2–0.5%) IR (> 60%) enriched in Ca, Sr
	early highstand distal lagoon	carbonate wackestones	Aragonite (~ 40%) HMC + LMC (~ 15%)	$CaCO_3$ (~ 60%) C_{org} (~ 1%) IR (< 40%) enriched in Al, Mn, Cr
4–1	early highstand proximal lagoon	mixed carbonate-terrigenous wacke- to packstones	Aragonite (30–65%) HMC + LMC (10–18%)	$CaCO_3$ (40–80%) C_{org} (0.2–0.5%) IR (20–60%) enriched in Ca, Sr, Mg
	early highstand distal lagoon	carbonate wackestones	Aragonite (40–50%) HMC + LMC (15–20%)	$CaCO_3$ (60–80%) C_{org} (0.25–1.1%) IR (20–40%) enriched in Ca, Sr, Mg
1–present	late highstand proximal lagoon	terrigenous wackestones	Aragonite (3–40%) HMC + LMC (1–14%)	$CaCO_3$ (5–45%) C_{org} (0.3–1%) IR (> 50%) enriched in Al, Si, Fe, Ti, Ga, Pb, Zr, Zn, P depleted in Ca, Sr, Mg
	late highstand distal lagoon	mixed carbonate-terrigenous wackestones	Aragonite (25–55%) HMC + LMC (10–17%)	$CaCO_3$ (40–60%) C_{org} (0.5–1.2%) IR (40–60%) enriched in Al, Zn, Cu, Cr, Ni, Fe

Tab. 1. Lithology, mineralogy and geochemistry of the sediments from various settings in the lagoon of Mayotte during specific time intervals. HMC = high magnesium calcite, LMC = low magnesium calcite, IR = insoluble residue (terrigenous). Percentages are given as weight percentages of the bulk sediment.

Discussion

Sea level

The Holocene transgression interacted with the morphology of the lagoon floor and produced different sedimentary environments at different times with varying water depths. The first flooding occurred around 12 ka BP and sea level reached a position of 60–70 metres below present sea-level (Dullo et al., 1998). Terrigenous input was high during the early stages of the Holocene transgression (11–9 ka BP). The carbonate input in the distal environments increased after 9 ka BP, while the proximal lagoons remained under terrigenous influence throughout the entire Holocene. With ongoing sea-level rise between 9–6 ka BP, the shoreline further retreated and most of the topographic irregularities were drowned. With reduced rates in sea level rise after 6 ka BP the carbonate content of the sediments in the entire lagoon reached maximum concentrations. The enhanced carbonate input between 4–1 ka BP is related to the reef growth pattern and the overall shallow-water carbonate production. During times of rising sea level initial reef growth was vertical (keep-up phase). During the stabilisation of sea level, the reefs started to prograde horizontally in a leeward direction. During this progradation phase large amounts of reef detritus were shed into the lagoon resulting in enhanced carbonate percentages of the lagoonal sediments. Volcanic events between 6–4 ka BP perturbed the carbonate production in the lagoon. Present sea level position was reached around 2.5 ka BP. By this time, the erosion of the shoreline with their smooth morphology increased. The terrigenous shoreline deposits started to prograde over most of the proximal lagoonal deposits. The carbonate content decreased due to the transport of turbid water plumes caused by the dispersal of resedimented coastal muds during the wet-season and/or storm events. The middle and distal lagoon were not affected by terrigenous input.

Climatic forcing

Rainfall, temperature and salinity are important climate-induced controlling mechanisms on the type of carbonate sedimentation and/or terrigenous runoff (Sarg, 1988). Wave energy is another parameter controlled by climate.

The sea-surface temperatures (SST) have changed significantly from glacial (18.2 ka BP) to Holocene interglacial times. A rise in SST by about 5 °C for the period between 18 ka BP and 7.2–7.5 ka BP is inferred from oxygen isotope values in corals from Mayotte (Colonna et al., 1996). This SST increase probably enhanced carbonate precipitation in the surface ocean and the shallow lagoonal waters (Riding, 1996). Small changes in tropical SST (0.5–1 °C) can have large effects on climate dynamics like evaporation-precipitation ratio, cloudiness, rainfall and monsoonal strength (Beck et al., 1997). Especially the monsoonal circulation depends on the temperature and atmospheric pressure difference over the Southern Indian Ocean. The NE-monsoon causes the heaviest rains on Mayotte, while the SW-monsoon is rather dry and cold. Variations in the strength of these two climatic regimes will have a certain impact on hinterland weathering rates, erosion and terrigenous runoff into the lagoon.

Studies of various pollen assemblages in core 89026 from the SW-Mayotte lagoon has shown, that humid climatic conditions prevailed during the early Holocene period (11–7 ka BP) caused by an intensified NE-monsoon (Elmoutaki et al., 1992). Oxygen isotope data from the reef core and foreslope corals show a significant shift towards more negative values during this time interval (Colonna et al., 1996). A humid climate with higher precipitation during this period is also inferred from other studies over E-Africa, Madagaskar, the Arabian Sea and the Red Sea (Almogi-Labin et al., 1991; Sirocko, 1993; Gasse and Van Campo, 1998; Wang et al., 1999). It probably also caused a higher runoff of terrigenous material.

The maximum carbonate concentration in all cores coincides with a maximum in mean annual solar insolation in the southern hemisphere between 4–1 ka BP (Berger and Loutre, 1991). Thus, insolation may have had an effect on carbonate productivity through enhanced light penetration in the watercolumn causing an increase in photosynthetic activity. This resulted in optimized conditions for carbonate production.

The change to lowered carbonate concentrations after 1 ka BP coincides with a pronounced shift to more negative values in the oxygen isotope curve for Mayotte during this time (Colonna et al., 1996; Camoin et al., 1997). Terrigenous runoff increased during this late Holocene period. Increased humidity and temperatures are suggested as the main driving mechanisms for this process (Colonna et al., 1996). Insolation reached an absolute maximum at about 1 ka BP (Berger and Loutre, 1991), which caused probably higher SST over the S-Indian Ocean and a stronger NE-monsoon with higher rainfall.

Anthropogenic changes overprint the natural changes in the geochemistry and mineralogy of the lagoonal sediments after the first human settlement on the island around 1.2–0.8 ka BP. This was caused by deforestation and intensive landuse, which increased the rates of hinterland erosion, especially during the wet season.

Conclusions

Our studies focussed on the determination of physical, chemical and mineralogical parameters of the sediments from specific systems tracts. Aforementioned parameters steer the thickness and facies of each systems tract and are controlled by the rate and amplitude of sea level rise, lagoonal topography, environmental changes and climate dynamics. Sedimentation in the lagoon of Mayotte, as seen today, is spacially separated into proximal terrigenous and distally carbonate dominated provinces for the last 9 ka. Maximum carbonate concentrations are preserved between 4–1 ka BP and coincide with a time of maximum solar insolation. A general decrease in carbonate concentrations are observed after 1 ka BP, which coincides with a normal regression of the proximal lagoon and an increased anthropogenic input.

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Geomorphic Response to Quaternary Environmental Changes in the Wadi Mujib Canyon (Jordan)

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ABSTRACT. The preliminary results of an ongoing research project on the geomorphology and the Quaternary geology of the Wadi Mujib Canyon in Jordan are presented. Deep incision of the canyon in the Cretaceous marine sediments of the Jordanian plateau took place in the last 5 to 6 million years as part of the tectonical development of the Dead Sea Rift. Tectonics play a major role in the geomorphological development (through huge mass movements, a.o.) of the canyon but several geomorphological indicators (travertines, river terraces, periglacial-type slope deposits, etc.) testify of important climatic shifts (alternation of warm arid phases with cooler Pluvials) which took place during the Quaternary.

KEY WORDS: Dead Sea Rift, tectonics, Quaternary, mass movements, travertine, river terrace, periglacial-type slope deposits, absolute datings.

Introduction

This paper presents preliminary results of a research project titled "Geomorphology and Quaternary Geology of the Wadi Mujib Canyon (Jordan)" (Homes-Frédéricq et al., 1997; De Jaeger et al., 1999; De Jaeger and Risack, 1999; De Jaeger et al., 2000).

The Wadi Mujib, flowing in Jordan from east to west into the Dead Sea (-410 m b.s.l.), has eroded one of the most impressive canyon systems over the world with a mean valley depth of 600 m. The Dead Sea Rift is a part of the 6000 km long East African Rift, that runs from Mozambique up to southern Turkey. Most authors agree that intensive tectonic movements started about 30 million years ago, during the Late Tertiary (Late Oligocene/Early Miocene) (Freund et al., 1970; Garfunkel, 1970; Ben-Avraham and Ten Brink, 1989; Ginat et al., 1998). Following these first movements, the Cretaceous marine sediments (limestone, chert, marl, chalk intercalated with gypsum evaporitic layers) of west central Jordan were uplifted. According to Abed (1985a) the Mujib area in particular must have been subjected to uplifting phases yet from the Lower Cenomanian on, becoming an island in the region, followed by phases of sub-