Influence of sediment permeability and mineral composition on organic matter degradation in three sediments from the Gulf of Aqaba, Red Sea

Mohammed Rasheed\textsuperscript{a,b,*}, Mohammad I. Badran\textsuperscript{b}, Markus Huettel\textsuperscript{a}

\textsuperscript{a}Max Planck Institute for Marine Microbiology, Celsiusstrasse 1, D-28359 Bremen, Germany  
\textsuperscript{b}Marine Science Station, University of Jordan and Yarmouk University, P.O. Box 195, Aqaba, Jordan

Received 10 May 2002; received in revised form 10 September 2002; accepted 17 September 2002

Abstract

In order to investigate the influence of sediment physical and chemical characteristics on the degradation of deposited organic matter, decomposition in three sediments from the Gulf of Aqaba (Red Sea) that differ in permeability and mineral composition were compared. Freeze-dried \textit{Spirulina} was added to coarse carbonate and silicate sands from a shallow nearshore region and silt-clay sediment from the deeper center region of the Gulf incubated in laboratory chambers. The stirring in the chambers caused higher solute exchange in the coarse permeable sands relative to the fine less permeable silt due to the generation of advective fluid exchange between the sediment and overlying water. This enhanced exchange increased the decomposition rates of organic matter in the incubated sands. The decomposition rates of total organic carbon in the permeable carbonate (3.0 mg C m\textsuperscript{-2} d\textsuperscript{-1}) and silicate sands (2.0 mg C m\textsuperscript{-2} d\textsuperscript{-1}) exceeded that in the fine-grained sediment (1.4 mg C m\textsuperscript{-2} d\textsuperscript{-1}). Oxygen consumption in the coarse sands was 3-fold higher than in the silt-clay sediment, with highest rates in the carbonate sand. In carbonate and silicate sands of the same grain size, the carbonate sediment was more permeable than the silicate, resulting in 1.4-fold higher fluid exchange rates and 1.4-fold larger sedimentary organic matter mineralization rates. An in situ experiment comparing trapping efficiencies in carbonate and silicate sands showed that the higher fluid exchange rate in the carbonate sand results in larger filtration rates and a faster accumulation of particulate organic matter from the boundary layer. These experiments demonstrate that with respect to sedimentary mineralization rates, higher transport rates in permeable coarse sediments can outweigh the effect of a higher specific surface area in fine-grained silt sediments. In permeable sands, however, the higher specific surface area and fluid exchange in biogenic carbonate sands result in higher mineralization rates than in silicate sands of the same grain size.

© 2003 Elsevier Science B.V. All rights reserved.

Keywords: carbonate; silicate; silt-clay; sediment; permeability; organic matter decomposition

1. Introduction

The decomposition of organic matter in marine sediments is controlled by a number of physical, chemical and biological parameters of which mixing intensity, temperature, availability of electron acceptors and activity of benthic organisms are some of the most important ones (Aller, 1980; Canfield, 1993; Holmer, 1996). In this contribution, the importance of sediment permeability and the sediment mineral matrix characteristics on the decomposition process were investigated by contrasting mineralization in coarse and fine sediments from the Gulf of Aqaba including carbonate and silicate sands.

Permeability controls whether diffusive or advective transport dominates in the upper sediment layer and, thus, is a key parameter affecting the exchange of metabolites between the seabed and the overlying water (Rusch & Huettel, 2000). The permeability of marine sediments depends on their grain size distribution and sorting and normally increases with decreasing water depths (Huettel & Rusch, 2000). In the deep ocean,
water currents above the sediment are usually weak permitting the deposition of fine material (Boudreau & Guinasso, 1982). The ensuing bottom sediments are relatively impermeable, and diffusion is the most important mechanism for transport of solutes in the seabed (Revsbech & Jorgensen, 1986). In the shallow coastal environment, stronger bottom currents and wave orbital motion reaching the seabed winnow from the sediment fine materials resulting in coarser sediments with relatively high permeabilities (Jahnke, Nelson, Marinelli, & Eckman, 2000; Marinelli, Jahnke, Craven, Nelson, & Eckman, 1998). Huettel and Gust (1992) and Huettel, Ziebis, and Forster (1996) have shown that in sediments with permeabilities exceeding $10^{-12}$ m$^2$ advective pore water flows enhance the transport of dissolved and particulate matter into and out of the seabed. In permeable sediments organic matter can penetrate deeper and the degradation rates in the flushed layers are accelerated (Huettel & Rusch, 2000; Shum & Sundby, 1996). In laboratory flume experiments, Forster, Huettel, and Ziebis (1996) compared oxygen consumption in sediments with different permeabilities and found that oxygen consumption in the coarse sediment was up to $91\pm 23\%$ higher than in the fine-grained sediment.

Since most of the sedimentary organic matter and bacteria are attached to the sediment grains (Rusch, Forster, & Huettel, 2001), the size, morphology and physical and chemical characteristics of these grains should be important factors determining the mineralization potential of the respective sediment. Biogenic carbonate sands that are composed of fragments of corals, shells, foraminifera and coralline algae, etc. differ fundamentally in their sedimentological characteristics from terrigenic quartz sands that are frequently found in temperate and boreal coastal environments. Oxygen consumption rates in coarse reef sediments (e.g. $50.7 \text{ mmol m}^{-2} \text{d}^{-1}$, Knoppers et al., 1996), that are mainly composed of carbonate sands indicate high mineralization potential in these sediments, although they have a relatively low organic content (0.15–1%, Sorkin, 1995).

The aim of this study was to investigate the effect of the mineral composition of the sediment grains on the decomposition process and to contrast this effect to the effect of grain size. To this end, decomposition in permeable carbonate and silicate sands from the Gulf of Aqaba (Red Sea) was evaluated and mineralization was compared in Gulf sediments with different permeabilities.

### 2. Materials and methods

The study combines three laboratory chamber incubation experiments and one in situ incubation experiment addressing filtration and degradation in sediments of different permeabilities and mineral compositions. The results are used to interpret measurements obtained from natural sediments immediately after retrieval (Table 1).

**2.1. Sampling sites**

Sediment samples were collected from two shallow nearshore sites (Fig. 1A, B, ca. 5 m water depth) and one deeper site (Fig. 1C, ca. 825 m water depth), all situated in the Northern Gulf of Aqaba (Fig. 1). The shallow sites A and B were located in the marine preserve close to the Marine Science Station on the Jordanian coast (29°27′N, 34°58′E, Fig. 1). The sediment at site A was mainly biogenic carbonate sand composed of coral and shell fragments, remains of foraminifera, calcareous red algae and sea urchins. The sediment at site B was terrigenous, composed primarily of quartz sand. The

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sediment used for incubation</th>
<th>Added material</th>
<th>Number of incubated cores</th>
<th>Measured parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laboratory incubation #1</td>
<td>Natural shallow-water silicate and carbonate sands and slit-clay sediments</td>
<td>0.1 g of <em>Spirulina</em> was added to the overlying water. Controls without addition</td>
<td>Two with <em>Spirulina</em> and two controls for each sediment type</td>
<td>Nutrients, oxygen and sediment parameters</td>
</tr>
<tr>
<td>Laboratory incubation #2</td>
<td>Sieved silicate and carbonate sands (250–500 μm)</td>
<td>3 g of <em>Spirulina</em> was mixed with the sediment. Controls without <em>Spirulina</em></td>
<td>Four with <em>Spirulina</em> and two controls for each sediment type</td>
<td>Nutrients, oxygen and sediment parameters</td>
</tr>
<tr>
<td>Laboratory incubation #3</td>
<td>Sieved silicate and carbonate sands (250–500 μm)</td>
<td>Fluoresceine added to the overlying water</td>
<td>Two for each sediment type</td>
<td>Fluoresceine and sediment parameters</td>
</tr>
<tr>
<td>In situ incubation</td>
<td>Sieved silicate and carbonate sands (250–500 μm)</td>
<td>Natural sedimentation and filtration added organic matter to cores</td>
<td>Six for each sediment type</td>
<td>Pigments, oxygen consumption in retrieved subcores of sediment</td>
</tr>
</tbody>
</table>

Table 1

Summary of the incubation experiments carried out in this study with the added material, number of incubated cores and the parameters that were measured during and after the incubations.
The distance between sites A and B was 200 m. The sediment cores at site A and B were collected by divers using acrylic cylinders with 9.5 cm inner diameter and 40 cm length. Site C was located at 29° 25' N, 34° 55' E (Fig. 1), halfway across the Gulf of Aqaba. The sediment at this site was silt-clay. Cores were collected using a multicorer system during the Meteor Cruise (GeoB 5801-2) that took place during January–May 1999. The core samples were frozen until experimental incubation.

Physical and chemical properties of the sediments are summarized in Table 2. The permeabilities of the silicate and carbonate sediments were measured using a constant head permeameter as described by Klute and Dirksen (1986). With permeabilities \( k < 10^{-12} \text{ m}^2 \), the fine-grained deep sediment was relatively impermeable, while both nearshore carbonate and silicate sands were highly permeable \( (k > 10^{-11} \text{ m}^2) \). Sediment porosities were calculated from weight loss of wet sediment after drying at 60°C for 24 h. Specific surface areas for the sieved sediment were assessed after drying at 80°C for 30 min by measuring the nitrogen absorbed to the grain surfaces using a Quantachrome Quantasorb instrument. In order to demonstrate the grain surface characteristics of carbonate and silicate sands, pictures of selected grains were taken using Electronic Scanning Microscopy (Fig. 2).

### 2.2. Measurements in natural sediments

In the sediment cores collected from deep site C in March, concentration profiles of oxygen were measured immediately after retrieval using a micromanipulator operated microelectrode (Revsbech, 1989). In addition, two cores (9.5 cm diameter, 15 cm length) were cut into 1 cm (first 6 cm) and 2 cm slices (6–12 cm) for pore water extraction and subsequent nutrient analyses. Sediment

---

**Table 2**

<table>
<thead>
<tr>
<th></th>
<th>Shallow sediment</th>
<th>Deep sediment</th>
<th>Sieved sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carbonate</td>
<td>Silicate</td>
<td>Carbonate</td>
</tr>
<tr>
<td>CaCO\textsubscript{3} content (%)</td>
<td>75–85</td>
<td>4–6</td>
<td>30</td>
</tr>
<tr>
<td>Mean grain size (μm)</td>
<td>559</td>
<td>229</td>
<td>45</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>47</td>
<td>33</td>
<td>58</td>
</tr>
<tr>
<td>Permeability (m\textsuperscript{2})</td>
<td>$143 \times 10^{-12}$</td>
<td>$19 \times 10^{-12}$</td>
<td>$&lt;1 \times 10^{-12}$</td>
</tr>
<tr>
<td>Organic carbon (%)</td>
<td>0.36</td>
<td>0.24</td>
<td>0.4</td>
</tr>
<tr>
<td>Surface area (m\textsuperscript{2} g\textsuperscript{-1})</td>
<td>6.95</td>
<td>0.41</td>
<td>0.27</td>
</tr>
</tbody>
</table>
cores from the nearshore sites A and B, collected also in March, were approximately 15 cm long. For pore water extraction and nutrient analysis 50 cm$^3$ of each sediment slice was used. Then 2 cm$^3$ sediment was kept at −80 °C for pigment analysis.

2.3. Analytical procedures

Pore water was extracted by centrifugation (12,500 g, 4°C, 15 min) and filtered through 0.45 μm syringe filters. Nutrient analyses were made spectrophotometrically in duplicates following the methods of Strickland and Parsons (1972). Pigments were analyzed by HPLC using the method described by Rusch, Forster, and Huettel (2001). According to this method, chlorophyll (chl) a, chlorophyll b and fucoxanthine were analyzed using 90% acetone as extraction agent. Calcium carbonate content of the sediment was measured by complexometric titration of calcium carbonate with 0.1 N of hydrochloric acid according to Muller (1967). The Spirulina powder used for the laboratory experiments and the investigated sediments were analyzed for particulate carbon (PC) and particulate nitrogen (PN) contents using a Fisons NA1500N elemental analyzer with sulfanilamide as a calibration standard. The phosphorus content of the Spirulina powder was determined using the ignition method for particulate phosphate (PP) analysis (Andersen, 1976). Following this method, 0.2 g of Spirulina was combusted in a furnace (450°C) and the ash was boiled in 1 N HCL for 15 min. The sample was diluted to 100 ml with distilled water. Phosphate was then measured spectrophotometrically following the method of Strickland and Parsons (1972).

2.4. Incubation experiments

2.4.1. Laboratory incubation #1 with natural sediments

This experiment investigated the degradation of deposited organic matter in natural sediments from the Gulf of Aqaba with different mineral composition and permeabilities. Sediment cores retrieved from the shallow-water sites (four carbonate and four silicate sand) as well as the four sediment cores collected at the deep site were incubated in acrylic flux chambers with 9.5 cm inner diameter and 40 cm height. The lengths of sediment cores were about 23 cm and the depth of the water column above the sediments was approximately 15 cm. The chambers were covered with gas-tight plastic lids with two sampling ports such that no air was enclosed in the chambers. To avoid stratification, the water above all sediments was stirred (18 rpm) using a rotating disk of 7 cm diameter placed 5 cm above the sediment surface.

At the beginning of the experiment, 0.1 g of freeze-dried Spirulina (containing 10% N and 0.78% P) was added to the water of two chambers of each sediment type. The other four chambers were used as controls and remained without Spirulina. After initiating stirring, dissolved oxygen was measured in the water above each core at different time intervals (shown in Fig. 6) using a Clarke type microelectrode (Revsbech, 1989). For nutrient analyses, 50 ml of the overlying water was withdrawn at different time intervals (shown in Fig. 6) using a 50 ml syringe, and replaced by 50 ml of sea water originating from the location where the sediment cores were collected. The duration of the experiment was 390 h.

Fluxes of solutes were calculated from linear regressions of solute concentrations over time for the initial
ments, respectively. (0–76 h for nutrients and 0–44 h for oxygen) and final period of the incubation (76–336 h for nutrients and 44–390 h for oxygen). Diffusive flux of nutrients was calculated from concentration gradients at the sediment water interface from the nutrient profiles in March using Fick’s first law of diffusion according to Rasheed, Badran, Richter, and Huettel (2002).

2.4.2. Laboratory incubation #2 with sieved sediments

This experiment investigated the degradation of organic matter in silicate and carbonate sands of the same grain size. Carbonate and silicate sediments were collected at the shallow sites in the Gulf of Aqaba by divers. The collected sediments were washed, dried, and the fraction of 250–500 μm grains was extracted by sieving. The sieved carbonate sand had a permeability of \(43.8 \times 10^{-12} \text{m}^2\) and the sieved silicate of \(22.6 \times 10^{-12} \text{m}^2\). The experiment and measurements were performed as described for laboratory incubation #1, except that here six chambers were used for each sediment type. In four of these six chambers, 3 g of Spirulina powder was mixed thoroughly with the sediment before incubation, corresponding to an addition of 21.6 mmol N and 0.7 mmol P. The remaining two chambers were used as controls. This experiment was designed to compare the decomposition of organic matter within the two sediment types, no Spirulina was mixed to the water column of the chambers. The duration of the experiment was 390 h.

2.4.3. Laboratory incubation #3 with sieved sediments and tracer

In this experiment the fluid exchange rates between overlying water and sieved silicate and carbonate sediments (250–500 μm) were compared, using an inert solute tracer. The experimental set-up was identical to that described for laboratory incubation #1 except that only four chambers were used, two for each sediment type. Instead of organic matter, fluoresceine was added to the water of each chamber to a final concentration of 43.8 \(\mu\text{mol L}^{-1}\). During the experiment, 5 ml of water was withdrawn at different time intervals (shown in Fig. 8) and replaced by the same volume of unstained water. The fluoresceine concentration in the samples was measured spectrofluorometrically. The duration of the experiment was 48 h.

2.4.4. In situ incubation with sieved sediments

This experiment compared filtration and mineralization rates in sieved carbonate and silicate sands under field conditions. The carbonate and silicate sands for this experiment were collected and treated in the same manner as in laboratory incubation #2. The organic carbon contents prior to the experiment were 0.11 ± 0.03 and 0.06 ± 0.02% for the carbonate and silicate sediments, respectively.

Six cylinders (24 cm inner diameter, 20 cm length) were filled with the sieved carbonate sand, another six with the sieved silicate and sealed at the top and bottom with tough plastic foils secured by rubber bands. The sands were saturated with 0.2 μm filtered see water. At the selected sublittoral site (at about 5 m water depth, Fig. 1), 12 acrylic pipes (28 cm inner diameter, 40 cm length) were inserted 35 cm into the seabed and the sediment inside the pipes was removed to approximately 19 cm depth. The cylinders containing the sieved sediments were then inserted into these pipes. Afterwards, the lower foil covers were removed from the sediment cylinders by pulling strings attached to the rubber bands and plastic foils. The gaps between pipes and cylinders were filled with sediment. The upper surfaces of the embedded sediments extended slightly above the seabed. Then the pipes were removed. After 20 h for temperature equilibration, first the upper foils and then the cylinders were removed, leaving the sieved sands embedded in the seabed. Finally, the surfaces of the embedded sand cores were adjusted to the elevation of the surrounding sediment.

After 10 days, six of the embedded sediment cores (three carbonate and three silicate) were sampled. One large subcore (9.5 cm inner diameter, 20 cm long) and four small subcores (3.6 cm inner diameter, 20 cm long) were taken from the central part of each of the six embedded sediments. The large subcores were sliced (upper 6 cm: 1 cm slices, and below that 2 cm slices). For pore water extraction, 50 cm\(^3\) of each sediment slice was used, another 2 cm\(^3\) for the assessment of organic carbon content. Three carbonate and three silicate subcores (from the retrieved small cores) were immediately tested for oxygen consumption. The cores were cut into three layers (0–5, 5–10, and 10–15 cm). The sediment layers were homogenized and 25 cm\(^3\) of each layer was incubated individually in gas-tight bottles (250 ml) with seawater (ca. 225 ml, filtered through 0.2 μm filter). For the controls, the cleaned sieved silicate and carbonate sediments were incubated. Before the bottles were tightly closed, the oxygen concentration in the water of each bottle was measured using a microelectrode. The oxygen measurements were repeated after 12 and 24 h of incubation. For the pigment analysis, two of the small subcores (one of each sediment type) were sliced (1 cm in the upper 6 cm and 2 cm down to 10 cm). Then 2 cm\(^3\) of sediment from each layer was removed using cut-off syringes and frozen at \(-80\degree\text{C}\) until analysis. After 22 days, a second set of subcores was collected in the same manner from the sieved sediments incubated in the seabed, and the same measurements were performed.

2.5. Statistical analysis

To evaluate the significance of the difference in some measurements in shallow and deep sediments, ANOVA analysis (5% significance level) was performed.
3. Results

3.1. Concentration profiles in natural silicate and carbonate sediments

The pore water profiles in the permeable sands from the shallow sites showed higher concentrations of all measured nutrients in the upper sediment layer (0–2 cm) relative to the profiles measured in the sediment from the deep site (Fig. 3, Table 3). This difference was most pronounced in the ammonium and phosphate profiles. Below 5 cm depth, nutrient concentrations in all tested sediments were similar except for nitrate and nitrite, for which relatively high concentrations were recorded in the carbonate sand down to 8 cm depth. In the fine-grained sediment from the deep site, nitrate and nitrite were limited to the upper 2 cm and free oxygen could not penetrate deeper than 1.5 mm (Fig. 4). Pigment profiles in carbonate and silicate sands from the shallow sites showed higher concentrations in the carbonate sediment (factors 2.0, 2.7, and 2.6 for chl \textit{a}, chl \textit{b}, and fucoxanthine, respectively, for the whole sediment depth Fig. 5, Table 3). These differences were most pronounced in chl \textit{b} and fucoxanthine in the upper 2 cm of the sediments.

3.2. Laboratory incubation \#1 with natural sediments, effect of permeability

After closing the lids, the oxygen concentrations in the water of all chambers immediately started to

---

**Table 3**

\( P\)-values for some measurements obtained from ANOVA test at a significance level of 5% calculated based on differences between measurements in the three investigated sediments

<table>
<thead>
<tr>
<th>Measurement or experiment</th>
<th>Variable</th>
<th>C, Si</th>
<th>C, D</th>
<th>Si, D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural measurement</td>
<td>Ammonium</td>
<td>0.0556</td>
<td>0.0020</td>
<td>0.0251</td>
</tr>
<tr>
<td></td>
<td>Nitrate and nitrite</td>
<td>&lt;0.0001</td>
<td>&lt;0.0001</td>
<td>0.3533</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>0.2479</td>
<td>0.0037</td>
<td>0.0499</td>
</tr>
<tr>
<td></td>
<td>Silicate</td>
<td>0.8742</td>
<td>0.960</td>
<td>0.1285</td>
</tr>
<tr>
<td></td>
<td>Chl \textit{a}</td>
<td>0.0765</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chl \textit{b}</td>
<td>0.0198</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fucoxanthine</td>
<td>0.0822</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laboratory incubation #1</td>
<td>Ammonium</td>
<td>0.0778</td>
<td>0.0090</td>
<td>0.3469</td>
</tr>
<tr>
<td></td>
<td>Nitrate and nitrite</td>
<td>0.8489</td>
<td>0.0491</td>
<td>0.6091</td>
</tr>
<tr>
<td></td>
<td>Phosphate</td>
<td>0.0072</td>
<td>0.9376</td>
<td>0.1312</td>
</tr>
<tr>
<td></td>
<td>Silicate</td>
<td>0.5078</td>
<td>0.0016</td>
<td>0.2428</td>
</tr>
<tr>
<td></td>
<td>Oxygen</td>
<td>0.1632</td>
<td>0.006</td>
<td>0.1186</td>
</tr>
<tr>
<td>Laboratory incubation #3</td>
<td>Fluoresceine</td>
<td>0.4626</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In situ incubation</td>
<td>Chl \textit{a}</td>
<td>0.0105</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Chl \textit{b}</td>
<td>0.2906</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fucoxanthine</td>
<td>0.0060</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

C, Si: carbonate and silicate sediments; C, D: carbonate and deep site sediments; Si, D: silicate and deep site sediments.

---

Fig. 3. Nutrient concentration (\( \mu \text{M} \)) profiles in carbonate (triangles), silicate (diamonds) and silt-clay (solid squares) sediments in March. Error bars represent the differences between two measured profiles.

Fig. 4. Oxygen profile (\( \mu \text{M} \)) in the silt-clay sediment. Error bars represent the difference between two measured profiles.
decrease, with highest consumption rates in the chambers with permeable sands (Figs. 6 and 7, Table 3). Maximum consumption rates were recorded in the chambers with *Spirulina*, reaching a peak value of 15.5 mmol m\(^{-2}\) d\(^{-1}\) in the carbonate sand chamber, 12.1 mmol m\(^{-2}\) d\(^{-1}\) in the silicate sand chamber, and 11.3 mmol m\(^{-2}\) d\(^{-1}\) in the silt chamber. Forty-four hours into the experiment, the oxygen in the chambers with *Spirulina* had dropped below 35% of the start concentration, while in the control chambers more than 60% was still available.

In all chambers, concentrations of ammonium, phosphate and silicate concentrations grew throughout the incubation period, with strongest increases within the first 76 h (Fig. 7). The only exception was ammonium in the control chamber with silt that showed a concentration decrease during the last 72 h of the incubation. Nitrate and nitrite initially increased for a period of about 18 h, and then dropped until the end of the incubation. Ammonium fluxes from the permeable control sands were 1.4 (silicate) to 2.0 (carbonate) times higher than from the silt, while silicate and phosphate fluxes were higher in the chamber with the silt. In all chambers with *Spirulina*, ammonium and phosphate concentrations increased faster than from the silt, while silicate and phosphate fluxes were higher in the chamber with the silt. In all chambers with *Spirulina*, ammonium and phosphate concentrations increased faster than in the control chambers throughout the incubation (Figs. 6 and 7). Highest fluxes in ammonium (10.4 mmol m\(^{-2}\) d\(^{-1}\)) and phosphate (0.54 mmol m\(^{-2}\) d\(^{-1}\)) were recorded in the chambers with carbonate sand exceeding the fluxes in the chamber with silt (4.7 mmol NH\(_4\)\(^+\) m\(^{-2}\) d\(^{-1}\), 0.23 mmol PO\(_4\)^{3-} m\(^{-2}\) d\(^{-1}\)) by factor 2.2 and 2.3, respectively.

### 3.3. Laboratory incubation #2 with sieved sands, effect of mineral composition

Due to the cleaning and sieving of the sediments, the control chambers nutrient concentrations in this incubation were in general lower than in the previous experiment. Analogous to the incubations with natural sediments, oxygen concentrations decreased and nutrient concentrations increased (except for nitrate and nitrite) during the incubation of the sieved sands. In the control chambers, oxygen consumption rates and ammonium and silicate fluxes in the two sediment types were not significantly different, while the phosphate flux in the chamber with carbonate was higher than in the chamber with silicate sand (0.02 vs. 0.01 mmol m\(^{-2}\) d\(^{-1}\), Fig. 7). However, the carbonate sand showed a stronger reaction to the addition of organic matter (*Spirulina*) relative to the silicate sand. Oxygen fluxes into the carbonate sediments were higher than into the silicate (33.4 vs. 24.3 mmol m\(^{-2}\) d\(^{-1}\)) and fluxes of ammonium and phosphate were 1.4, and 1.9 times higher than in the chambers with silicate sands.

### 3.4. Laboratory incubation #3 with sieved sands, effect of mineral composition

With values exceeding 10\(^{-12}\) m\(^2\), the permeabilities of silicate and carbonate sands permitted advective pore water exchange. The radial pressure gradient generated by the rotating water column forced chamber water with solute tracer into, and pore water without tracer out of the sands. The curves depicted in Fig. 8A reflect the gradual dilution of the fluoresceine-stained chamber water with clear pore water. Fluoresceine influx was higher in the carbonate sediment than in the silicate (initial flux: factor 1.4 Fig. 8B, Table 3). For the chamber geometry and water volume used in the experiments, 8.3 and 11.1 ml h\(^{-1}\) water were flushed through the silicate and carbonate sand, respectively.

### 3.5. In situ experiment

#### 3.5.1. In situ sediment incubation

The pigment analyses in the dissected subcores after 10 and 22 days of incubation revealed that the carbonate sands accumulated higher amounts of particulate organic matter during the in situ incubation than the silicate sands (profiles not shown, Table 3). The calculated fluxes indicate a 2 to 3-fold higher accumulation rate in the carbonate sand (4.7 vs. 2.3, 0.3 vs. 0.1, and 2.1 vs. 0.8 mg m\(^{-2}\) d\(^{-1}\) for chl *a*, chl *b*, and fucoxanthine, respectively). The differences in the concentration profiles between the two samplings (Fig. 9) show that the accumulation of chl *a*, chl *b* and fucoxanthine occurred deeper in the carbonate sand relative to the silicate. Oxygen consumption rates in the incubated carbonate and silicate sands decreased with sediment depth (Fig. 10). At the end of the incubation, the consumption rates of the two upper layers (0–5 cm: 2.3 µmol cm\(^{-3}\) d\(^{-1}\), 5–10 cm: 2.0 µmol cm\(^{-3}\) d\(^{-1}\)) of the carbonate sand were 1.5 and 1.7 times higher than those
Fig. 6. Time course of nutrient and oxygen concentrations (µM) during the incubation of natural carbonate (triangles), silicate (diamonds) and silt-clay deep site (squares) sediments. Number of incubation chambers two for control and four with *Spirulina*. Error bars represent the standard deviations of the concentrations from different chambers.
of the respective layers in the silicate sand (0–5 cm: 1.6 mmol cm\(^{-2}\) d\(^{-1}\), 5–10 cm: 1.4 mmol cm\(^{-2}\) d\(^{-1}\)). Below 10 cm depth, the rates were lower and similar in both sediments.

4. Discussion

The present findings highlight the differences in degradation rates of organic material in shallow coarse sand sediments and deep site silt sediments with different permeabilities and mineral compositions. In situ measurements of nutrient profiles showed higher concentrations in coarse permeable sediment compared to the silt, which indicates different degradation rates of organic matter. Nutrient and pigment profiles in shallow site carbonate and silicate sands also reveal higher decomposition activity in the biogenic sediments. The main differences between the three sediments are highlighted below and the processes that cause these differences are discussed.

4.1. In situ measurements

The concentrations of DIN and DIP of shallow coarse sand were higher than in the silt-clay (2.3 and 1.8-fold for the whole sediment column, respectively; Fig. 3, Table 3) and the concentration in carbonate sand was
higher than those in the silicate sand (1.8, 1.2-fold, Table 3). Pigment concentrations were also higher in carbonate sediments compared to silicate (Fig. 5, Table 3). These differences can be an indication of different organic matter mineralization rates and decomposition pathways that can be linked to the different properties of these sediments, i.e. the permeability, specific surface area and mineral composition. The effect of high sediment permeability on biogeochemical processes was demonstrated by Falter and Sansone (2000) who studied DIN and oxygen distribution in permeable sediments. Through the measurement of nutrients and oxygen profiles, they found different metabolic rates and decomposition pathways depending on sediment permeability. However, from in situ results alone solid conclusions about the important factors which cause these differences could not be made because numerous factors may play a role in these differences including all ecological parameters, such as temperature, current velocity and anthropogenic input. To exclude these factors from the possible reasons, lab incubations under controlled conditions were carried out to study the effect of permeability, mineralogical characteristics, and grain surface area.

4.2. Benthic nutrient fluxes

Fluxes of nutrients in the laboratory control cores (Fig. 7) were comparable to fluxes reported in the literature for carbonate, silicate and silt-clay sediments (Table 4). Oxygen consumption rates in the present sediments were relatively low compared to rates reported for coastal sediments in the literature. For example Reay et al. (1995) found higher oxygen consumption rates and higher ammonium and phosphate fluxes in Chesapeake Bay sediments, however, these sediments also had higher organic matter content (0.7 and 4.7%, respectively) than our sediments (0.1 and 0.4%, respectively, Table 2). Clavero et al. (2000) also reported high nutrient fluxes and high oxygen consumption rates from Palmes Estuary and attributed the high values to high organic content in the silt-clay
sediment that they investigated (8%). It is clear that besides organic content, many other factors affect the solute fluxes in marine sediments. Clavero et al. (2000) and Friedl, Dinkel, and Wehrli (1998) demonstrated the dependence of fluxes on temperature and reported higher flux values with higher temperature, which caused high diffusion rates and biological activity. Abundance of benthic microalgae has been found to affect fluxes of nutrients (Bertuzzi, Faganeli, & Brambati, 1996). Shum and Sundby (1996) emphasized the importance of different physical properties of the sediments for the oxygen uptake. Diffusive fluxes are usually inferred from pore water profiles and Fick’s first law of diffusion (Berelson et al., 1998) after subtraction of the degradation rates under oxic conditions (oxygen less than 5% of saturation), the mineralized carbon was calculated using the fluxes of DIP, DIN and oxygen in the spiked chambers assuming a Redfield ratio of C : N : P (106 : 16 : 1) and a ratio of 1 for CO₂ : O₂ (e.g. Berelson et al., 1998) after subtraction of the fluxes recorded in the control chambers. The mineralization rates under oxic condition were estimated from the initial fluxes because these fluxes were recorded when oxygen concentrations in all chambers were still higher than 5% oxygen air saturation. The initial mineralization activity in the chambers and the resulting DIP and DIN fluxes (Fig. 6) were considered to correspond to the mineralization activity taking place under oxic conditions with more than 5% oxygen air saturation. Analogously, the late fluxes (Fig. 7) were used to estimate the rates under suboxic/anoxic conditions. The mineralization rates of *Spirulina* in coarse sediments estimated from DIP and DIN were approximately two times higher than those estimated for the fine silt sediments, and the coarse carbonate sand showed a higher degradation rate than the coarse silicate sediment (~1.5-fold, Tables 6 and 7). In the natural sediments, the mineralization rates estimated from DIP and DIN were always higher than the rates estimated from oxygen consumption, which indicated the importance of anaerobic mineralization of organic matter in these sediments. The degradation rates under oxic conditions were higher than the rates under suboxic/anoxic conditions.

### Table 4

<table>
<thead>
<tr>
<th>Location</th>
<th>Sediment types</th>
<th>Ammonium</th>
<th>Phosphate</th>
<th>Oxygen</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Araruama Lagoon, Brazil</td>
<td>Sandy carbonate</td>
<td>0.62 ± 0.32</td>
<td>0.01 ± 0.01</td>
<td>–50.7 ± 12.05</td>
<td>Knoppers et al. (1996)</td>
</tr>
<tr>
<td>Kanoeohe Bay, Hawaii</td>
<td>Sandy carbonate</td>
<td>0.47</td>
<td>0.03</td>
<td>–20.93</td>
<td>Reay, Gallagher, and Simmons (1995)</td>
</tr>
<tr>
<td>Chesapeake Bay, USA</td>
<td>Sandy silicate</td>
<td>–(1.06)–8.59</td>
<td>–0.13–1.008</td>
<td>–53.28</td>
<td>Clavero, Izquierdo, Fernandez, and Niell (2000)</td>
</tr>
<tr>
<td>Palmones Estuary, Spain</td>
<td>Silt-clay</td>
<td>–(0.72)–14.76</td>
<td>–0.08–0.86</td>
<td>–62.5–87.4</td>
<td>Clavero, Izquierdo, Fernandez, and Niell (2000)</td>
</tr>
<tr>
<td>This study (Gulf of Aqaba)</td>
<td>Sandy carbonate</td>
<td>3.41 ± 0.32</td>
<td>0.03 ± 0.002</td>
<td>–5.92 ± 0.5</td>
<td>Clavero, Izquierdo, Fernandez, and Niell (2000)</td>
</tr>
<tr>
<td></td>
<td>Sandy silicate</td>
<td>2.15 ± 0.26</td>
<td>0.02 ± 0.001</td>
<td>–5.07 ± 0.5</td>
<td>Clavero, Izquierdo, Fernandez, and Niell (2000)</td>
</tr>
<tr>
<td></td>
<td>Silt-clay</td>
<td>1.57 ± 0.25</td>
<td>0.04 ± 0.002</td>
<td>–1.89 ± 0.5</td>
<td>Clavero, Izquierdo, Fernandez, and Niell (2000)</td>
</tr>
</tbody>
</table>

Positive values are efflux out of the sediment and negative values are influx into the sediment.

### Table 5

<table>
<thead>
<tr>
<th>Variable</th>
<th>Silicate</th>
<th>Carbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonium</td>
<td>88.5</td>
<td>114.2</td>
</tr>
<tr>
<td>Phosphate</td>
<td>3.5</td>
<td>7.8</td>
</tr>
<tr>
<td>Silicate</td>
<td>14.4</td>
<td>11.6</td>
</tr>
</tbody>
</table>

4.3. Mineralization rates of *Spirulina* in different sediments under oxic and anoxic conditions

The laboratory experiments with addition of *Spirulina* showed the same general trends. The mineralization rates of *Spirulina* depended on the type of the incubated sediment and its permeability (Fig. 7). In order to get an estimate of the mineralization rates of *Spirulina* in different sediments under oxic and suboxic/anoxic conditions (oxygen less than 5% of saturation), the mineralized carbon was calculated using the fluxes of DIP, DIN and oxygen in the spiked chambers assuming a Redfield ratio of C : N : P (106 : 16 : 1) and a ratio of 1 for CO₂ : O₂ (e.g. Berelson et al., 1998) after subtraction of the fluxes recorded in the control chambers. The mineralization rates under oxic condition were estimated from the initial fluxes because these fluxes were recorded when oxygen concentrations in all chambers were still higher than 5% oxygen air saturation. The initial mineralization activity in the chambers and the resulting DIP and DIN fluxes (Fig. 6) were considered to correspond to the mineralization activity taking place under oxic conditions with more than 5% oxygen air saturation. Analogously, the late fluxes (Fig. 7) were used to estimate the rates under suboxic/anoxic conditions. The mineralization rates of *Spirulina* in coarse sediments estimated from DIP and DIN were approximately two times higher than those estimated for the fine silt sediments, and the coarse carbonate sand showed a higher degradation rate than the coarse silicate sediment (~1.5-fold, Tables 6 and 7). In the natural sediments, the mineralization rates estimated from DIP and DIN were always higher than the rates estimated from oxygen consumption, which indicated the importance of anaerobic mineralization of organic matter in these sediments. The degradation rates under oxic conditions were higher than the rates under suboxic/anoxic conditions.
for all sediment types (>2.5-fold) except the mineralization estimated from DIP and DIN in sieved sediment (Tables 6 and 7). Several studies compared organic matter decomposition rates in oxic and suboxic/anoxic conditions. Some authors demonstrated that the rates were not significantly different (e.g. Lee, 1992; Westrich & Berner, 1984). Others found that anoxic mineralization was greater than under oxic conditions (Sun, Lee, & Aller, 1993), unless macrofauna were present (Kristensen & Blackburn, 1987). The present study, however, showed that the oxic degradation rates of organic matter were higher than the suboxic/anoxic degradation rates, which agrees with some other studies (e.g. Benner, Maccubbin, & Hodson, 1984; Henrichs & Reeburgh, 1987; Sun, Wakeham, & Lee, 1997). Several theories have been suggested to explain the lower decomposition rates under anoxic conditions. Some of the decomposition pathways could not be catalyzed under anoxic conditions or inhibitory metabolites may build up and reduce degradation rates in anoxic sediment (Schink, 1988).

In laboratory incubation #1, specific amounts of *Spirulina* were added to the water column above the sediment, and most of the added *Spirulina* were deposited on the sediment surface shortly after start of the experiment. In the case of the silt sediment, most of the organic matter degraded on the surface of the sediment. Due to the high permeabilities of the coarse sands, which allowed some organic matter to penetrate into the sediment (Huettel & Rusch, 2000), degradation in these coarse sands occurred on the surface and within the upper sediment layer. The degradation rate then depends also on how deep the organic matter penetrated into the sediment. Under same stirring conditions, the permeability of the sediment was the controlling factor that determined the penetration depth as has been shown in similar experiments by Huettel and Rusch (2000).

In laboratory incubation #2, *Spirulina* was mixed with the sieved sediment in order to minimize the effect of permeability and to study the effect of mineral composition and grain surface area on the mineralization of organic materials. In this experiment, carbonate and silicate sediments of same grain sizes were used to compare mineralization of organic matter in the two sand types. Despite the similarity of the size distribution, permeability of the carbonate sediment was twice as high as that of the silicate sediment (Table 2). The grain surface area of the carbonate sediment was also higher than that of the silicate sediment (factor 1.5, Table 2) and the grains of the carbonate were more porous and rough compared to the less porous and smooth silicate grains (Fig. 2). Also in this experiment, the degradation rate of *Spirulina* in the carbonate sediments was always higher than in the silicate sediments under both oxic and suboxic/anoxic conditions (factor at least >1.2, Table 7). In a study by Marinelli et al., 2000 that used sediments with similar median grain size (250–500), the authors emphasized the importance of the permeability as a key factor for enhancing nutrient fluxes as a result of pore water advection in such sediments. Laboratory experiment #3 with fluoresceine showed that in the carbonate sediment, which was more permeable than the silicate (2-fold, Table 1), the fluoresceine flux into the sediment was higher (factor 1.4, Fig. 8). This implied a stronger advective transport in the carbonate sediment compared to the less permeable silicate sediment. This finding is in agreement with results of Forster et al. (1996) who found in a flume experiment with rhodamine as a tracer, stronger and deeper flux in permeable sediments. Our experiment with an inert tracer demonstrates that in sand with the same grain size, interfacial water flows are higher in the biogenic carbonate sands than in the terrigenous silicate sands (factor 1.3). Pores within the individual grains and a less rounded shape with very rough grain surfaces are the main factors for the higher permeability in the carbonate (Fig. 2). These interfacial water flows carry dissolved and particulate organic matter into the sediment (Huettel & Rusch, 2000; Jahnke et al., 2000; Pilditch, Emerson, & Grant, 1998; Rusch & Huettel, 2000) and, thus, could be responsible for the higher fluxes and mineralization rates observed in the carbonate sand.

The in situ incubation experiment tested the trapping efficiency of organic particles in the sieved carbonate and silicate sediments. During the incubation, more pigments (chl *a*, chl *b* and fucoxanthine) were trapped in the carbonate sediment than in the silicate (average factor of 2 for all measured pigments). Moreover, the pigments penetrated deeper into the carbonate sediment (average of 6 and 4 cm, respectively). This increase in

**Table 6**

*Spirulina* mineralization rate (mg C m\(^{-2}\) d\(^{-1}\)) calculated from DIN and DIP fluxes and oxygen consumptions in natural carbonate, silicate and silt-clay sediments under oxic and suboxic/anoxic conditions (calculations can be found in the text)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Oxic</th>
<th>Anoxic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>DIN</td>
<td>DIP</td>
</tr>
<tr>
<td>Carbonate</td>
<td>3.7</td>
<td>4.5</td>
</tr>
<tr>
<td>Silicate</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Silt</td>
<td>1.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

The negative values indicate higher fluxes or consumptions in control chamber than the chambers with *Spirulina*.

**Table 7**

*Spirulina* mineralization rate (mg C m\(^{-2}\) d\(^{-1}\)) calculated from DIN and DIP fluxes and oxygen consumptions in sieved carbonate, and silicate sediments under oxic and suboxic/anoxic conditions (calculations can be found in the text)

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Oxic</th>
<th>Anoxic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable</td>
<td>DIN</td>
<td>DIP</td>
</tr>
<tr>
<td>Carbonate</td>
<td>1.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Silicate</td>
<td>1.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>
pigment content in the sediments during the incubation can be attributed mainly to the filtration of water through the permeable sediments. To calculate trapping rates of PON, chl \(a\) was converted to POC assuming a conversion factor of 60 for chl \(a\); POC ratio as reported in Yahel et al. (1998). A factor of 0.15 was used to convert POC to PON according to Redfield ratio. With these conservative calculations, trapping rates of 21 and 42 mg m\(^{-2}\) d\(^{-1}\) PON were obtained in silicate and carbonate sediments, respectively. These values are comparable to other values reported in tropical regions (e.g. Charpy & Charpy-Roubaud, 1991 (36 mg m\(^{-2}\) d\(^{-1}\)); Clavier, Chardy, & Chevillon, 1995 (23–35 mg m\(^{-2}\) d\(^{-1}\)).

In order to estimate the difference in filtration rates between silicate and carbonate sands, the seawater volume that needed to be filtered (100% filtration efficiency) through the upper sediment layer was calculated to account for the increase of organic matter in both sediments during the incubation period. In these calculations, the trapping rates of chl \(a\) in 9 cm (Fig. 9) of the carbonate and silicate sediments after 22 days (2.3 and 4.7 mg m\(^{-2}\) d\(^{-1}\), respectively) and the chl \(a\) value in seawater (0.22 \(\mu g\) l\(^{-1}\), Rasheed et al., 2002) were used. According to these calculations, minimum flushing rates of 348 and 712 l m\(^{-2}\) month\(^{-1}\) were estimated for silicate and carbonate sediment, respectively. The higher carbonate filtration capacity (2-fold) can be expected due to the 2-fold higher permeability of the carbonate sediment (Table 2). The oxygen consumption measurements of the sieved sediment cores emphasized these findings. The rates of oxygen consumption were higher in the carbonate sediment than in the silicate (factor 1.5 in all layers, Fig. 10) indicating higher organic matter trapping rate in the carbonate. A decrease of consumption with increasing depth in both sediments indicated that more organic material was trapped in the surface sediment layers.

4.4. What controls organic matter decomposition in sediments?

Significant differences in organic matter mineralization and consequently release of inorganic nutrients to the water column were found in the three different sediment types used in the study. The different experiments carried out have pinpointed some possible reasons for these differences. Among these are permeability, grain surface area and mineralogical characteristics.

4.4.1. Permeability

Different permeabilities of the three sediment types (Table 2) cause different oxygen transport rates and penetration depths that lead to different degradation rates under oxic conditions. Oxygen penetration depth of the silt-clay was 1.5 mm (Fig. 3), compared with a penetration depth of more than 5 mm for permeable sands (Huettel & Rusch, 2000). Ziebis, Huettel, and Forster (1996) have reported even higher oxygen penetration in more permeable sediments. Increased oxygen consumption related to increased organic matter degradation with increasing sediment permeability (Table 2 and Fig. 10) was reported by several authors (Dauwe, Middelburg, & Herman, 2001; Forster et al., 1996; Marinelli et al., 1998). In silt-clay, the transport of electron acceptors for the degradation of organic matter is limited by diffusion (Froelich et al., 1979), while in permeable sands, advection co-acts on transport of electron acceptors in addition to diffusion (Forster & Graf, 1995; Huettel & Gust, 1992) promoting higher organic matter degradation rates.

The present experiments with sieved carbonate and silicate sediments of the same grain size demonstrated how differently the two sediments controlled organic material trapping and degradation, fluoresceine penetration, oxygen consumption and nutrient fluxes. The findings of these experiments are in good agreement with Huettel and Rusch (2000), who reported an increase in organic matter penetration depth and degradation rates with increasing sediment permeability. These authors suggest that the enhanced supply of electron acceptors and increased removal of decomposition products by pore water advection cause the higher mineralization activity in permeable sediment. Huettel and Gust (1992) determined the critical permeability required for advective interfacial fluxes of water and microalgae to be \(1 \times 10^{-12}\) m\(^2\). The permeability of the silicate sediments of the present study is \(22.6 \times 10^{-12}\) m\(^2\), well above the critical value. Therefore, advective flux of material cannot be ruled out.

4.4.2. Grain surface area of the sediment

The grain size of the deep sediment was much smaller than that of the shallow sediment (8-fold, Table 2). Consequently, the specific surface area of the silt-clay was much higher than that of the sieved carbonate and silicate sediments of the shallow site (17 and 26-fold, Table 2). Inverse correlation between grain size and organic carbon content was reported by Anderson, 1988 and Oades, 1988, and direct correlation between grain surface area and organic matter content was reported by several authors (Adams & Bustin, 2001; Mayer, 1994; Ransom, Kim, Kastner, & Wainwright, 1998). Mayer, Jumars, Taghon, Macko, and Trumbore (1993) pointed out that most organic matter in sediments is adsorbed to the mineral surfaces. Small pores and large surface area in fine sediments protect organic matter against digestive attack (Hedges & Keil, 1995; Marshman & Marshall, 1981; Mayer et al., 1993). The fine sediments from the deep site had higher organic contents than the carbonate and silicate sediments from the shallow site (9-fold, Table 2) and lower nutrient concentrations in the sediment surface layer (Fig. 3), which is in agreement...
with the mentioned findings. The incubation experiment of the sieved carbonate and silicate sediments with fluoresceine and the in situ sediment incubation demonstrated that more water was flushed (factor 1.3 Fig. 8) and more organic matter accumulated in the carbonate sediments (factor 1.5, Fig. 9), which had a higher grain surface area than the silicate sediments (1.5-fold, Table 2). In the incubation experiments with sieved sands, the carbonate sediments were more reactive than the silicate sediments. These results reveal that organic matter mineralization was faster and went further in the carbonate sediment than the silicate sediment. This implies that protection of the organic matter was not efficient in this case. A likely explanation for this observation is the higher transport velocity in the carbonate sediment that results in strong advective processes which accelerate mineralization of the organic material (Rusch & Huettel, 2000).

4.4.3. Mineralogical characteristics

Carbonate sediments contain mainly CaCO₃ (ca. 80%, Table 2), while silicate and silicous silt-clay sediments usually contain a low percentage of CaCO₃ (ca. 5 and 20%, Table 2). In carbonate sediment, pore water is automatically buffered upon release of CO₂ during the oxidation of organic matter (Buddemeier & Oberdorfer, 1986), which has a direct impact on the degradation process. Ransom et al. (1998) confirmed that sediment mineralogical was the primary factor for organic carbon accumulation. Carbonate sediments contain many small pores resulting from the skeletal remains of corals and sea urchins, etc. which produce these sediments (Fig. 2). These pores increase the surface area of the carbonate grains and surface roughness which in turn increase the ability of the sediment to accumulate more organic matter (Mayer, 1994).

4.5. Consequences for natural environments

The present investigation shows that organic matter mineralized at a higher rate in the coarse shallow sediments, including carbonate and silicate, in comparison with silt-clay bottom sediments due to different chemical and physical properties. The present study shows the importance of the shelf sediments, which comprise 8% of the total ocean seaﬂoor area (Ott, 1988) in the mineralization of organic matter and sustaining the primary productivity of the ocean. The results suggest that relatively large volumes of water are flushed through the silicate and carbonate sediments (348 and 7121 m²•month⁻¹) which implies an important role of shallow sediments in filtration of organic matter and subsequent mineralization and nutrient release. Coarse permeable shelf sands, thus, can be important nutrient regenerators for primary production. This emphasizes the findings of several authors that the importance of the bottom sediment to organic matter mineralization is inversely related to the water column depth (e.g. Jorgensen, 1983) and that continental shelves may be as important as the deep sea in carbon and nitrogen biogeochemical cycles (Jorgensen, 1996; Walsh, 1991).

Acknowledgements

This work was a part of the Red Sea Program and has been funded by the German Federal Ministry of Education and Research (BMBF grants no. 03F0245A) and Max Planck Institute for Marine Microbiology in Bremen, Germany. Thanks are due to Dr Martin Kölling from the Geology Department, Bremen University for his assistance in the determination of sediment surface area. Thanks also to the staff members of the Marine Science Station in Aqaba, Jordan for their full support and help during the study, especially to Al-salamm, Al-trabean, Al-sokhni, Mansreh, and Hammad.

References


