Temporal and Spatial Variations in Concentrations of Sediment Nutrients and Carbon in the Keta Lagoon, Ghana

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Abstract

Sediment characteristics and dating show that the Keta Lagoon about 976 ^{14}C year BP (calibrated age AD 1333-1399) changed from accumulating dark, fine-grained sediments with a high content of remains of wood and plant debris and no molluscs (1.2% C, 0.7% N and 0.18‰ P) to accumulating lighter, coarse sediments with many mollusc (2% C, 0.8% N and 0.2‰ P) indicating a shift from anaerobic to aerobic conditions in the accumulated sediments. Near fully marine conditions and temperatures similar to present day temperatures are indicated by δ^{13}C and δ^{18}O values, respectively, obtained from shell material in the transition layer. The average sedimentation rate in the period ~1365 - 1902 was 0.2 mm/year. Since 1902, the sedimentation rate has gone up from 0.2 to 1.3 mm/year. A comparison of maps from 1975 and satellite images from 1999, showing a smaller present area of the lagoon, suggests that the sedimentation rate is high at the NE fringe of the lagoon. Due to a long flushing time (no flushing in the dry season), the present nutrient contents of the sandy surface sediments (0-0.08% N and 0.04-0.36‰ P) are relatively high when compared to other shallow estuaries with higher terrestrial supply of nutrients. Low nutrient contents in the inlet from the open sea indicate that nutrients in the lagoon are of local origin. The content of carbon and phosphorus in the surface sediment depends on resuspension potential and is high in the deepest parts of the study area. Very high values are, however, found close to Keta, apparently from sources associated with farming activities. The spatial distribution of nitrogen appears to be more random.

Introduction

Coastal lagoons are environments suitable for human activities such as habitation, tourism, fishing, aquaculture and transportation (Isla, 1995). A detailed knowledge of these coastal features, therefore, becomes crucial because changes could impact greatly on many people. Numerous studies have been carried out in order to assess the effects of nutrient input to oceans and estuaries (Christiansen *et al.*, 1997; Emeis *et al.*, 2000). These studies have shown that anthropogenic influence in the form of high population densities, industrial activity and use of fertilizers may disturb the natural balance of nutrient fluxes.

Few studies, however, have been carried out in shallow tropical lagoons characterized by weak hydrodynamics and low but regular wind stress (Arfi *et al.*, 1993; Andrews *et al.*, 1998). Tropical lagoons may behave differently from lagoons in high and mid latitudes. From time to time, some of the tropical lagoons become hypersaline with a higher salinity in the lagoon than the coastal water (Isla, 1995). Once a lagoon is hypersaline it is under the influence of an inverse estuarine circulation. This process may cause inflow of water at the surface and outflow of the denser saline water near the bottom in the inlets (Babu *et al.*, 2000). Tropical lagoons often have oxidized sediments because of oxygen supply to the bottom by vertical circulation in the water column induced by surface water evaporation, (Brunskill *et al.*, 2001).

Sediments in tropical lagoons are often reported to have low nutrient contents (Brunskill *et al.*, 2001; Babu *et al.*, 2000). However, this may change with time. Nutrient dynamics influence productivity of lagoon ecosystems and their sedimentary deposits are a function of the environmental conditions under which they were deposited. They preserve within them a record of the physical and biological processes, which caused their formation. Unravelling this record has potential benefits both for hind casting ancient depositional conditions and for the prediction of future effects of present-day environmental alterations (Kranck *et al.*, 1996).

The aim of the present study is, therefore, to assess the temporal and spatial variation in sedimentation and nutrient content of the sediment (C, N and P) in the shallow and well oxidized tropical Keta Lagoon. Knowledge on these issues will help to understand the fate of nutrients in tropical lagoons.

Materials and methods

The study area

The study was carried out in the Keta Lagoon in January 2001. The location is about 140 km east-northeast of the city of Accra, on the south coast of the Volta Region, southeast Ghana (Fig. 1). Generally, fishing and extensive farming are the main occupations of the population in the area. However, an intensive onion production takes place on the barrier seperating the lagoon from the sea.

The Keta Lagoon is part of the Volta system; 27 km long with a variable width of the up to 16 km and a surface area of 28.400 ha. It has an average depth of 0.8 m (maximum 2 m) and an average salinity of 18.7 PSU (Anonymous, 1993). The coastline

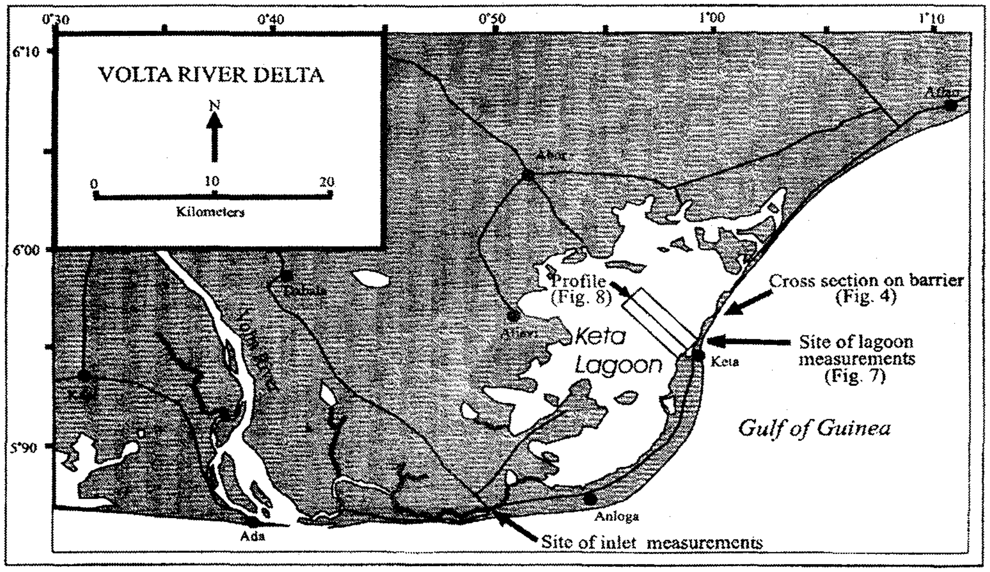

Fig. 1. Location of the Keta Lagoon and sites of measurements

estuary of the River Volta is 750 m wide, but immediately upstream the channel widens to 5 km and contains several small islands (Anonymous, 1998). The Kata Lagoon has no direct outlet through the bar at present, but outlets in the barrier have existed in the 1960s (Tamakloe, 1966). The lagoon is connected to the open sea through a tributary of the Volta. The tidal range in the open sea is around 1.0 m (Hydrographer of the Navy, 2000), whereas the tidal range in the lagoon is less than 10 cm due to tidal chocking (Tide Board Readings at Marine Office, Havedzi, Ghana). The delay of the tidal progression causes high water to occur 5 h later in the lagoon than on the open coast. Furthermore, the lagoon is fed from several rivers in the north with an unknown discharge.

From a geological point of view there are two main formations in the region around the Keta Lagoon. The northern half of the region is dominated by a tertiary formation of limonitic residuals, both consolidated and unconsolidated. The general appearance of the formation is reddish with widely spread ferrunginised sheets (Tamakloe, 1966). The rest of the region consists mainly of Pleistocene to recent formations of mud, clays and gravels. Towards the sea, beach sand and raised beach sand become more abundant, and areas with clays containing crystals of gypsum and soluble salts are found in the lagoon area. The site is a lowland area with sandy loam, clay and laterite constituting the main soil types (Tamakloe, 1966).

The climate in the region is semi-arid tropical with average daily temperatures of 27-28 °C and no pronounced variation during the year. The winds of this part of coastal West Africa are generally weak and regular with predominant southeasterly winds between March and November (Arfi *et al.*, 1993). During the Harmattan season (December-February), winds occasionally blow from the northwest. These winds follow the intertropical convergence zone (ITCZ) and create a seasonal pattern of rainfall with the main rainy season from April to July. The monthly average wind speed in Ada (Fig. 1) ranges between 1.7 and 2.6 m/s (Canadian International Development Agency, year unknown). This part of Ghana is one of the driest parts of the country with a mean annual rainfall of 783 mm at Keta compared to a mean annual evaporation of 1964 mm. The relative humidity in the area is generally more than 90% during the night and early morning. During the day the humidity decreases to as low as 65% with a seasonal variation of 15%. Periods of very low humidity occur during the Harmattan. The usual tropical rains of squally nature accompanied by thunder are almost absent in the Keta region (Tamakloe, 1966), making it different from many tropical regions.

The site falls within the coastal savanna region of Ghana. These climatic conditions only support the growth of tropical grassland. But around the lagoon area, small and scattered clumps of short trees are present (Anonymous, 1998). Along the river sides small scrubs are present in a more evenly spread manner due to the extra input of freshwater. At the fringes of the lagoon itself the vegetation consists of small and scattered clumps of the mangrove *Rhizophora racemosa* and isolated patches of the grass *Paspalum* sp. and the herb *Sesurium portulacastrum*. In the less brackish areas of the lagoon, the sedge *Cyperus articulatus* and the cat-tail *Typha* *domingensis* are common.

Field investigations

A line was established across the main tributary at the location shown on Fig. 1. Flow to and from the lagoon was measured at three verticals with a horizontal spacing of 3.5 m at half-hour intervals during daylight for 2 days with an OTCR-80491 current-meter. Discharge was determined using the mid-section method as described by Shaw (1994). Salinity (Digimeter L21 conductivity meter), temperature and water level were measured continuously. Four water samples were collected with a Nansen Sampler and analysed for sediment concentration by filtration under suction using 0.45 µm Millipore filter paper. Just downstream of the line, a 50-cm core (inlet core) was taken with a KC-Denmark kajak-corer (www.kc-denmark.dk).

On the narrowest point of the barrier (Fig.1), a profile was measured with a levelling instrument. On the shoreline on both the sea and lagoon side a hole was dug, and the vertical difference in the groundwater level was determined. Using the groundwater level eliminates the uncertainty in water level caused by up-swelling waves. Error as determined by repeated measurement was less than 1 mm.

In the lagoon, surface sediment sampling, salinity and temperature measurements were undertaken in a grid previously established by Dr A. K. Armah, University of Ghana. The grid consists of poles spaced 1 km apart in a rectangular net and the location is indicated in Fig. 1. Depths, salinity and temperature were also measured at numerous other locations, which were positioned by using a Germin GPS. Furthermore, two 50-cm cores (core F3A and F3B) were taken with the KC-Denmark kajak-corer.

Laboratory methods

The sediment in the core F and F3A was cut in 1-cm sections and subjected to a number of analyses. Bulk density was estimated from dry weight of the sections divided by wet volume of the sections. Grain-size distributions were obtained using laser diffraction (Malvern-E) technique (Agrawal *et al.*, 1991), and grain-size parameters determined as described by Folk & Ward (1957). The organic matter content was determined by weight-loss on ignition at 550 °C for 2 h. The temperature used for combustion is sufficient to oxidize all organic matter, as well as drive off hygroscopic water and convert pyrite to ferric oxide. According to Ball (1964) these two latter losses can be assumed to be minimal. Total nitrogen (TN) was determined using a LECO FP-428 2.03. Total phosphorus (TP) was determined after ignition (Andersen, 1976) by the ascorbic reduction method on a Milton Roy Spectronic 1201 spectrophotomete-r. Total carbon (TC) was determined on a Dohrmann DC-190 analyser. Uncertainty on duplicates of chemical analyses were 17% for nitrogen and 10% for phosphorus.

Sediment accumulation rates were determined in core F3B from ^{210}Pb dating of the core using low-level gamma spectrometry with the method described by Kunzendorf *et al.* (1998). The historical profile was constructed using physical core data (density) and the constant rate of supply (CRS) model for unsupported ^{210}Pb (Robbins, 1978). ^{14}C dating was carried out at the AMS dating facilities, University of

Aarhus, as described by Andersen *et al.* (1989). The oxygen and carbon isotopes were also determined at the AMS dating facilities and standardized to PDB following the methods described in Beets & Beets (2003). In short, the samples were reacted at 80 °C with phosphoric acid in a carbonate preparation line and the resulting CO_2 measured for isotopic composition. The reference gas was pure CO_2 calibrated against carbonate standard (NBS19).

Four maps from December 1975, covering the lagoon, were digitised on a Calcomp 9100 digitising table. The area of the lagoon was then determined by the use of ESRI Geographical Information System (ArcView 3.2). With the WinChips software (www.geogr.ku.dk/chips), a Landsat image dating from April 1999 was rectified with the help of GPS point-data, measured on location with a Germin GPS. The resolution of the satellite photo is 30 m by 30 m.

Wave induced resuspension was calculated in three steps outlined in Christiansen *et al.* (1997) and Pedersen *et al.* (1995).

1. Using the formulas in Beach Erosion Board (1975) the wave height and period was estimated.
2. Maximum orbital velocity (U_m) at the bottom was found using Airy wave theory:

$$U_m = \frac{\pi H}{T \sinh(2\pi h/L)} \qquad (1)$$

where H is wave height, T is wave period, sinh is the hyperbolic sine, L is wavelength, and h is water depth.

3. Threshold grain size (D) for the calculated velocities was found by

$$\frac{(\rho_w U_m^2)}{(\rho_s-\rho_w)\, gD} = 0.30\sqrt{(H/\sinh(2\pi h/L)D} \qquad (2)$$

where ρ_w is density of seawater, ρ_s density of sediment and g is acceleration due to gravity (Komar & Miller, 1973). Wind data was obtained from a meteorological station in Ada. The fetch was obtained using ArcView 3.2 by measuring the distance from the position of each station to the line

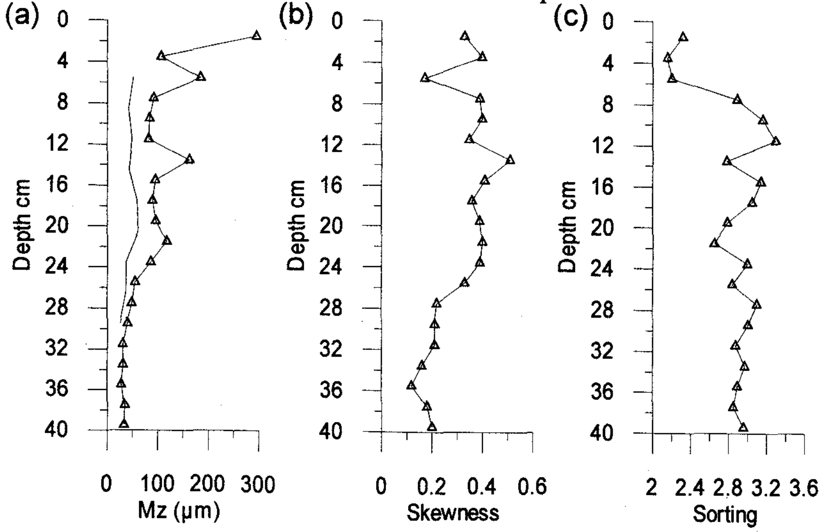

Fig. 2. Down core variations in grain-size parameters of the lagoon core (triangles). For comparison is also shown down core distribution of the mean grain-size of the inlet core (line). Skewness and sorting are in Phi units.

separating land from the lagoon in the direction from which the wind blows.

Results

Temporal variations

Grain-size distributions. Fig. 2 shows the sediment properties of core F3A. The down core distribution of the mean grain-size of the inlet core is also shown for comparison. The core is characterized by a general down core fining of the sediment from a mean grain-size (Mz) of 300 µm in the top layer to a Mz of 26 µm in the bottom layer.

According to the Folk & Ward (1957) classification, all sediments in the core are very poorly sorted, with the top 6 cm better sorted than the rest. All layers in the core have a positive skewness but the bottom 15 cm of the core has a less pronounced skewness than the rest of the core. The positive skewness indicates a sedimentary environment (Kranck *et al.*, 1996) and correlates well with the study area being as a lagoon.

At closer inspection of the grain size distribution, the core can be divided into three sections. Section one consists of the top 6 cm and is characterized by a coarse Mz, relative good sorting and a positive skewness. The second section runs from 7 -24 cm. Here the Mz is finer, the skewness is at its highest levels and the sorting is poorer. The third and last section from 25 - 42 cm is dominated by much finer sediment than the rest of the core. The skewness is still positive but at its lowest levels while the sorting is as in section two.

The core contained mollusc fragments and poorly decomposed wood, and it is striking that the distribution of both seems to agree well with the core sectioning based on grain-size distributions. Section one is characterized by large amounts of mollusc fragments down to 7 cm, where the second section begins. In the second section, the contents of mollusc fragments are varying but decreasing. No molluscs were found in section three, but large chips of poorly decomposed wood. The colour and odour of this section indicated anaerobic conditions.

Nutrients content. Qualitatively three

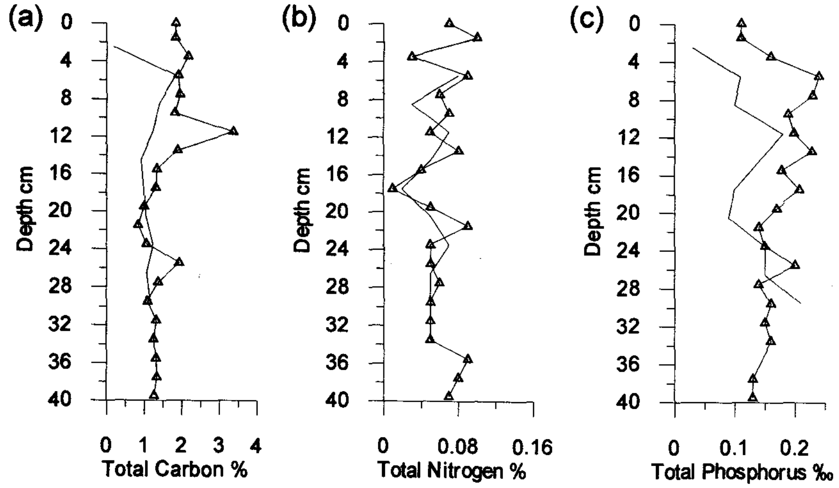

Fig. 3. Down core variations in carbon and nutrient content of the lagoon core (triangles) For comparison is also shown down core variations in carbon and nutrient content of the inlet core (line).

groups are recognized in the down-core content of TC, which ranges from 0.83% to 3.37% in the lagoon (Fig. 3): i) in the top 10 cm a high and steady level of TC content in the relatively coarse sediment, ii) from 10-28 cm the TC content varies, and iii) in the deepest part of core (28-40 cm) TC is relatively steady, but on a lower level than in the top. The content of TN ranges between 0.01% and 0.10% with variation through the depth of the core. As seen in Fig. 3, the TN content varies strongly down core with a tendency of a more constant level from 24-40 cm. In the lagoon the minimum content of TP is 0.13‰ increasing to 0.24‰ in the top layer sediments. It is noteworthy that the contents of TP and TN tend to vary more in the top 0-25 cm and, conversely, show relatively constant values in the bottom-end of the core, the latter also being the case for the TC-content (Fig. 3).

Sedimentation. An estimate of the sedimentation rate in the lagoon may be obtained from the discharge measurements in the inlet. Only a short period of observations is available. However, assuming these values to be representative, the average cross section velocities in and out of the lagoon reached a maximum of 0.51 m/s with a corresponding maximum discharge of 5.3 m^3/s. During one flood period the volume of water transferred to the lagoon was 84446 m^3. The average velocity during the flood period of 0.38 m/s resulted in a tidal excursion of 5.4 km. This tidal excursion was just about long enough to allow suspended sediment to reach the lagoon.

Given an average depth of 0.8 m in the lagoon, the flushing time (F) of the lagoon can be calculated according to Ketchum (1951):

$$F = Vol_{lagoon} / Q_{in} \qquad (3)$$

where Vol$_{lagoon}$ is volume in the lagoon and Qin is water supply. The estimate of 3.8 years ignores the input of water from the Tordzie River and other streams. In addition, some seepage through the very narrow barrier may be expected as the barrier consists of coarse material (Mz 1000 µm at the sea side and 680 µm at the lagoon side (Fig. 4)). At the time of levelling across the barrier, a 40 cm higher water level in the sea than in the lagoon existed over a distance of 100 m and the salinity in the lagoon was highest (37 PSU) close to the barrier.

The water samples, which were collected approximately 50 cm under the surface at the inlet yielded suspended matter at concentrations of 36 mg/l during flood and 17 mg/l during ebb tide. Assuming that

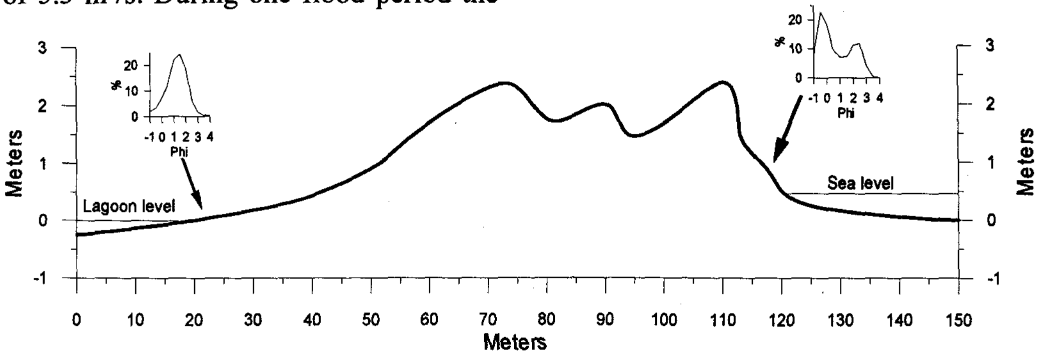

Fig. 4. Cross-section of the barrier. Also shown are grain-size distributions of the sediments on the two sides of the barrier. The location of the cross-section is shown in Fig. 1.

these samples were representative of average sediment concentration in the entire water column, the total sediment flux into the lagoon during flood was 3041 kg whereas the flux out during ebb was 1426 kg. This resulted in a net flux into the lagoon of 1615 kg in one tidal period and equals 1156000 kg of sediment per year.

Assuming that the sediment is equally spread over the lagoon area this gives an accumulation rate of 4.06 g/m^2/year. With a dry bulk density of 1.057 g/cm^3, the sedimentation rate is 0.0038 mm/year. This is a very low accumulation rate and does not include contributions from the two inlets with unidirectional flow running into the lagoon from the north and surface run-off during the rainy season as well as atmospheric deposition and input from biogenic *in situ* production. The atmospheric deposition in Anloga is 6 g/m^2/year (personal communication from Dr Breuning-Madsen), corresponding to 0.5% of the total accumulation rate in the lagoon in 1977 (Fig. 5). The biogenic *in situ* production can be evaluated from the TC content (up to 1.84%. Thus fluvial derived sediment appears to be the most important contribution. A much better estimate of the sedimentation rate, including contributions from these ignored sources, may be derived from radioisotope (^{14}C and ^{210}Pb) dating made on core F3B from the lagoon. The results from this dating are shown in Table 1 and Fig. 5. The obtained age of ~1365 AD for the -21.5 cm layer in the core indicates that the sedimentation rate up to ~1900 AD (-5.5 cm layer) was 0.2 mm/year. Since then, the sedimentation rate has gone up to recent rates of 1.3 mm/year. Concurrent with the increasing bulk sedimentation rate the accumulation rate of TP has gone up to 0.15 P/m^2/year. Also the accumulation rate of TC and TN shows increasing trends up to 1997.

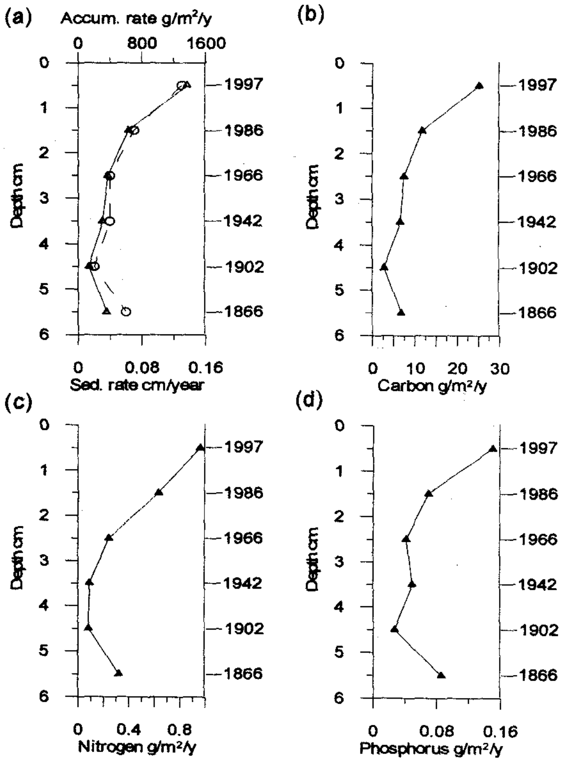

Fig. 5. Changes with time in sediment, carbon and nutrient accumulation rates in the Keta Lagoon. Circles: Sedimentation rate. Triangles: Accumulation rate. (a) Accumulation and sedimentation rate, (b) Accumulation rate of total carbon, (c) Accumulation rate of total nitrogen, (d) Accumulation rate of total phosphorus.

Spatial variations

Morphology. Fig. 6 shows the area of the lagoon in 1975 and in 1999. The most striking feature is the conversion of the north-eastern part of the lagoon into land. In 1975 this area was covered with islands separated by narrow channels. In 1975 the lagoon covered an area of 304 km^2 whereas in 1999 the lagoon area was 274 km^2. The map from

TABLE 1

Results from ^{14}C dating of shell material from the -21.5 cm layer in the lagoon core. Also shown are $\delta^{13}C$ and $\delta^{18}O$ values of the same shell material

AAR#	*Sample type*	*^{14}C age (BP)*	*Reservoir corrected ^{14}C age (BP*)*	*Calibrated age ±1 stdv.*	*$\delta^{13}C$ (‰) VPDB*	*$\delta^{18}O$ (‰) VPDB*
AAR-7302	Shell	976±38	576±38 (Res. age: 400)	AD 1333-1399 AD 1318-1411	-0.50	-1.52

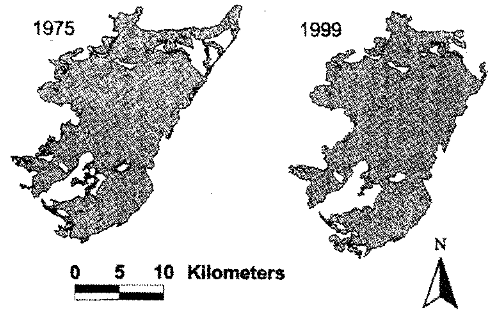

Fig. 6. The spatial extent of the lagoon in December 1975 and April 1999.

1975 was based on aerial photo's from December, and the satellite image in 1999 was taken in April. The two representations of the lagoon area thus indicate the end and beginning of the rainy season, respectively. Therefore, part of the difference between the areas may be due to a higher water level in December because of the ending rainy season.

Grain-size, nutrient and carbon distributions. The top sediments of the Keta Lagoon are generally sandy with a

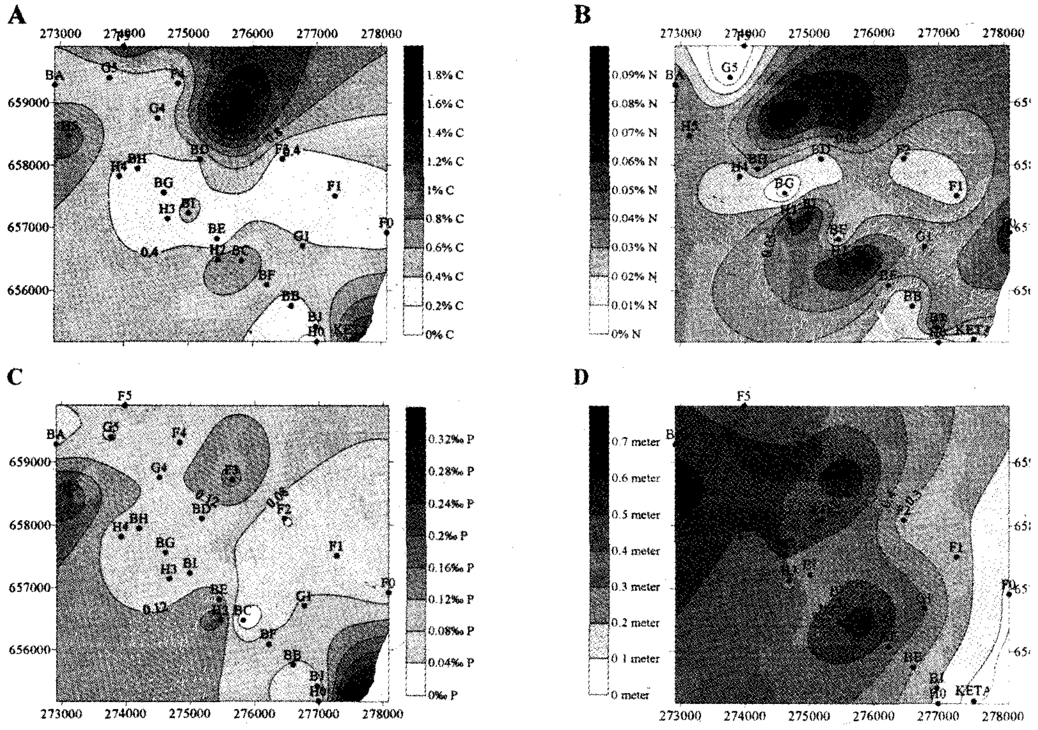

Fig. 7. Spatial distribution of carbon (A), nitrogen (B), phosphorous (C) and bathymetry (D) of the study area.

clay content between 0 and 6.5%. The spatial grain size distribution shows a relatively low content of clay near the shore, higher values in the grid section located around F3, H2 and H3, and lower values in the outer part of the grid. The carbon content varies spatially from 0.14% to 1.84% and, as shown in Fig. 7, there is no apparent spatial pattern in the distribution. However, comparing the bathymetry with the TC distribution there is some coincidence between greater depths and greater TC contents. The distribution of the nitrogen content shows no obvious spatial pattern as shown in Fig. 7. The values of TN vary between 0 and 0.08%. The phosphorus content varies between 0.04‰ and 0.36‰, with the highest value found near Keta. Normalizing the TC, TN and TP-content with the fine-grained material (< 63 µm) in a profile starting near Keta (Fig. 1) shows a strong tendency of decreasing carbon and nutrient content with increasing distance from the shore (Fig. 8).

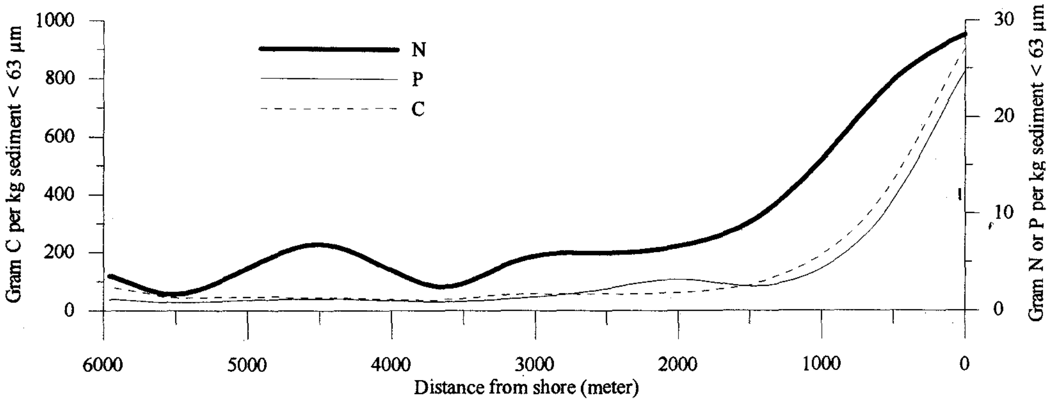

Fig. 8. Carbon and nutrient concentrations normalized with fine-grained material (<63 µm) as a function of the distance from Keta in the NW direction. The location of the profile is shown in Fig. 1.

Resuspension. The grain sizes available for resuspension were calculated on the basis of the average wind speed in January of 2.2 m/s in 2 m height from SE, which is the predominant wind direction. This wind speed creates resuspension of up to 15% of the sediment in 2/3 of the samples. During the calm conditions of the study period, the suspended particles had a mean grain size < 10 µm indicating that these particles constantly are in suspension and form the background level of suspended matter in the lagoon. The wind velocity threshold for resuspension thus seems to be less than 2.2 m/s and resuspension thus occurs frequently in the lagoon. By including all wind speeds up to the maximum monthly average wind speed of 2.6 m/s more than 50% of the grains are brought into resuspension in 2/3 of the samples. For wind speeds exceeding 4 m/s the threshold value for resuspension was exceeded for all particles.

Discussion

Temporal changes

The up-core changes in the sediments grain-size distributions and their content of TC strongly point at a change in the depositional environment taking place about 600-650 years ago. The fine sediments of the oldest section three point to accumulation in a low-energy environment. The presence of pieces of wood combined with lack of molluscs indicates a calm and anaerobic environment. The coarser sediment of section two points towards deposition in a somewhat higher-energy environment. The occurrence of molluscs implies aerobic conditions, possibly due to an opening of the connection to the sea and/or increased wave activity. This is indicated by the near fully marine $\delta^{13}C$ values of -0.50‰ of the ^{14}C dated shell material compared to the general terrestrial value of –29.0‰. The $\delta^{18}O$ value of -1.5‰ (Table 1) shows that temperatures at that time were similar to present temperatures (Jansen, 1989).

Opening of an inlet to the open sea may also help to explain the disappearance of the fine part of the grain size distributions, which may be flushed out of the estuary during the rainy season. The youngest, uppermost section deposited during the 20th century has the coarsest sediments and highest amount of molluscs fragments reflecting high levels of oxygen at the bottom. This could be caused partly by the low water depth combined with resuspension and partly by vertical circulation in the water column induced by increased surface salinity because of strong evaporation in the dry season (Brunskill *et al.*, 2001). The higher level of TC in the top section of the lagoon core may originate from the $CaCO_3$ content of mollusc fragments.

It appears that the temporal accumulation of nitrogen in the lagoon is very limited, and the relatively constant level of TN may reflect the fact that the anthropogenic nutrient input to the system is more or less non-existing. Emeis *et al.* (2000) report diffusion of phosphate from the sediment during anoxic conditions in the bottom water. With low water depths in recent times in the Keta Lagoon, oxic conditions could imply no diffusion of phosphate in the sediment and, thereby, possibly explaining the increasing trend from a depth of 25 cm to the top. Though the sectioning recognized on the basis of grain-size distribution and nutrient contents are not completely identical, it is very likely that the different sectioning in the two cores represent the same events of change in the sedimentation environment. The discrepancy in the sectioning could be due to the overall low content of nutrients, making it difficult to recognize changes in this system.

Spatial variations

With a tidal range of 0.10 m, tides play a limited role in turbulence generation. In shallow, micro tidal environments like the Keta Lagoon wave action is one of the primary factors controlling the spatial distribution of sediments (Christiansen *et al.*, 1997). Successive resuspension episodes create unconsolidated bottom sediment, which makes the bottom sediment easily resuspendable since the threshold velocity for resuspension is a function of resuspension history (Valeur *et al.*, 1995). Furthermore, frequent resuspension events keep the bottom sediment well oxygenated. Wave-induced turbulence also influences the productivity of such ecosystems through enrichment of the water column by nutrients originating from the bottom sediment. The nutrient input is related to processes as desorption of nitrogen and phosphorus and mixing of the pore water nutrients into the water column (Pedersen *et al.*, 1995). Consequently, frequent resuspension results in a decrease of phosphorus content in the sediments of the shallowest parts of the study area. This may be explained by rapid uptake of phosphate on fine-grained particles (Lopez *et al.*, 1996; Jürgensen *et al.*, 1997) resuspended near the coast and deposited in deeper water.

Another sink for fine-grained sediments may be the natural sediment traps in the form of mangrove vegetation. In spite of cutting of mangrove for firewood purposes, it appears that because of sediment accumulation along the NE fringe of the lagoon, the area of the lagoon has diminished during the last 25 years. The cutting of mangrove could not be recognized from the map analysis, suggesting that this activity is of minor importance in the lagoonal spatial development through time.

When the phosphorus content is normalized with the fine-grained material (<63 µm), the TP-content clearly decreases away from Keta (Fig. 7) indicating that the phosphorus source is located near Keta. Such findings reflect the importance of physical processes governing sediment entrainment, transport and accumulation in relation to the distribution of phosphorus-containing particles (McComb *et al.*, 1998).

Sediments in tropical lagoons are reported to have low nutrient contents due to

TABLE 2

Camparison of nutrient levels in shallow water coastal lagoons and estuaries

Location	*Environment*	*Sedimentological characteristica*	*Carbon Wt %*	*Nitrogen Wt %*	*Phosphorus Wt%*	*Author*
Keta Lagoon Ghana	Shallow coastal lagoon Depth: 0.8 m (av.)	Generally sandy clay< 6.5%	C_{tot} 0.14-1.84	N_{tot} <0.08	P_{tot} 0.004-0.036	This study
Hunts Bay Jamaica	Surface sediment Depth: 1.5 m (av.)	Predominantly muddy with occasional silt-liminae	C_{org} 0.09-5.22	N_{tot} 0.02-0.40	-	Andrews *et al.* (1998)
Balearic Islands Spain	Coastal lagoon Depth: 1.37 m (av.) Urbanized	-	C_{tot} 3.49-9.34	N_{tot} 0.17-0.44	P 0.051-0.107	Lopez *et al.* (1996)
Ashtamudi Estuary, India	Surface sediment Urbanized Depth: 1-6 m	Clay: 7.21%-65.10%	C_{org} 0.74-3.86	N_{tot} 0.08-0.27	P_{tot} 0.009-0.028	Babu *et al.* (2000)
Peel-Harvey Estuarine System, Australia	Peel depth < 2 m Harvey depth < 3.5 m	Peel: Coarse sand Harvey: Fine silty mud with organic matter content	-	-	P Peel: 0.017-0.027 Harvey: 0.023-0.071	McComb *et al.* (1998)
Ringkjøbing Fjord, Denmark	Shallow coastal lagoon Depth: 2 m (av.)	Generally sandy	Organic material % wt: 0.5-2.0	N_{tot} 0.02-0.08	P_{tot} 0.06-0.22	Pedersen *et al.* (1995)

extensive farming systems in the surroundings, lack of industrial activity and generally low population densities (Brunskill *et al.*, 2001; Babu *et al.*, 2000). However, as shown in Table 2, nutrient concentrations in the sandy sediments of the Keta Lagoon are in the same order of magnitude as in sandy sediments in lagoons with much higher terrestrial supply of nutrients. This points to the importance of the long flushing time in the lagoon and, thereby, corroborates the findings by Josefson & Rasmussen (2000) who showed that, in general, nutrient concentrations in estuaries depend on both terrestrial supply and residence time of the water.

The TN-content is of the same level in the inlet and the lagoon sediment. In spite of the smaller mean grain-size of the inlet-sediment (Fig. 2 and 3) the TP-content is at a higher level in the inlet sediment. This leads to a greater N/P-ratio in the inlet and a lack of nitrogen relative to phosphorus in the lagoon sediment. Lack of nitrogen in marine sediments can be caused by a relatively high rate of denitrification leading to a N/P ration smaller than the Redfield ratio (Bordovskiy, 1965). The long flushing time thus makes the lagoon vulnerable to possible future higher supply of nutrients from the land.

Presently, anthropogenic influence on nutrient concentrations in the sediments seems to be reflected in very high carbon and nutrient concentrations near Keta. Regarding the sources of nutrients, analysis of the nutrient content of the soils surrounding the Keta Lagoon shows higher levels (TN=0.07% and TP=0.41‰ from 0 to 5 cm) than found in the sediments of the lagoon, whereas the nutrient content in lower soil depths (TN=0.01% and TP=0.07‰ from 50 to70 cm) is smaller than in the lagoon sediments (personal communication from Lars Krogh). This may indicate that contribution of nutrients through ground water percolation is of minor importance, whereas overland flow during the rainy season and the associated leaching of nutrients play a dominant role in the nutrient supply to the lagoon. Again the long flushing time of 3.8 years, a salinity difference of 34 PSU between the inlet and the lagoon, and similar TP levels in the inlet and the lagoon sediments, despite the more fine-grained (Mz = 63 µm) sediment of the inlet, suggest that the inlet is not the source of phosphorus. When normalizing with the fine-grained material (<63 µm) the spatial distribution of nutrients supports this by a decreasing carbon and nutrient level with distance from the barrier as seen in Fig. 8, and this indicates that the dense population of Keta and the intensive farming of shallots (in the sense of several harvests in a season) on the barrier separating the lagoon from the ocean may make up local nutrient sources for the lagoon.

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References

Agrawal Y. C., McCave I. N. and **Riley J. B.** (1991). Laser diffraction size analysis. In *Principles, methods, and application of* *particle size analysis*. Ed. J. P. M. Syvitski. Pp. 119-128. Cambridge University Press, Cambridge.

Andersen J. M. (1976). An ignition method for determination of total phosphorous in lake sediments. *Water Res.* **10**: 329-331.

Andersen G. J., Heinemeier J., Nielsen H. L., Rud N., Thomsen M.S., Johnsen S., Sveinbjörnsdóttir A. and **Hjartason A.** (1989). AMS ^{14}C dating on the Fossvogur sediments, Iceland. *Radiocarbon*. **31**: 592-600.

Andrews J. E., Greenaway A. M. and **Dennis P. F.** (1998). Combined carbon isotope and C/N ratios as indicators of source and faith of organic matter in a poorly flushed tropical estuary: Hunts Bay, Kingston Harbour Jamaica. *Estuar. Coast. Shelf Sci.* **46**: 743-756.

Anonymous (1993). *Ramsar Library: The Directory of Wetlands of International Importance,* 4th ed. *www.ghanaweb.com*

Anonymous (1998). *Ramsar Library: The Directory of Wetlands of International Importance. www.ghanaweb.com*

Arfi R., Gurial D. and **Bouvy M.** (1993). Wind-induced resuspension in a shallow tropical lagoon. *Estuar. Coast. Shelf Sci.* **36**: 587-604.

Ball D. F. (1964). Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *J. Soil Sci.* **15**: 84-89.

Babu K. N., Ouseph P. P. and **Padmalal D.** (2000). Interstitial water sediment geochemistry of N, P and Fe and its response to overlying waters of tropical estuaries: a case from the southwest coast of India. *Environm. Geol.* **39**: 633-640.

Beets C. T. and **Beets D. J.** (2003). A high resolution stable isotope record of the penultimate deglaciation in lake sediments below the city of Amsterdam, the Netherlands. *Quart. Sci. Rev.* **22**: 195-207.

Bordowskiy O. K. (1965). Accumulation of organic matter in bottom sediments. *Mar. Geol.* **3**: 33-82.

Beach Erosion Board (1975). *Shore Protection Manual*. Vol. 1, Washington. 440 pp.

Brady N. C. and **Weil R. R.** (1999). *The nature and properties of soils*. Pp. 552-566. Prentice-Hall Inc. US.

Bremner J. M. (1965). Total nitrogen. In *Methods of soil analysis*. Ed. C. A. Black. Pp. 1149-1178. Madison, American Society of Agronomy.

Brunskill G. J., Orpin A. R., Zagorskis I., Woolfe, K. J. and **Ellison J.** (2001). Geochemistry and particle size of surface sediments of Exmouth Gulf, Northwest Shelf, Australia. *Continent. Shelf Sci.* **21**: 157-201.

Canadian International Development Agency (year unknown). *South East Ghana Development (SEGAD) Project.* Ministry of Agriculture. Ottawa, Canada.

Christiansen C., Gertz F., Laima M. J. C., Lund-Hansen L. C., Vang T. and **Jürgensen C.** (1997). Nutrient (P, N) dynamics in the southwestern Kattegat, Scandinavia: sedimentation and resuspension effects. *Environm. Geol.* **29**: 66-77.

Emeis K.-C., Struck U., Leipe T., Pollehne F., Kunzendorf H. and **Christiansen C.** (2000). Changes in the burial rates in some Baltic Sea sediments over the last 150 years - relevance to P regeneration rates and the phosphorus cycle. *Mar. Geol.* **167**: 43-59.

Folk R. L. and **Ward C. W.** (1957). Brazos river bar: A study in the significance of grain-size parameters. *J. Sed. Petrol.* **27**: 3-26.

Hydrographer of the Navy (2000). *Admiralty tide table*, Vol. 2. Taunton, Somerset.

Isla F. I. (1995). Coastal lagoons. In *Geomorphology and sedimentology of estuaries*. Ed. G. M. I. Perillo. Pp. 241-267. Elsevier, Amsterdam.

Jansen E. (1989). The use of stable isotope stratigraphy as a dating tool. *Quart. Inter.* **1**: 151-166.

Josefson A. B. and **Rasmussen B.** (2000). Nutrient retention by benthic macrofaunal biomass of Danish estuaries: Importance of nutrient load and residence time. *Estuar.*

Coast. Shelf Sci. **50**: 205-216.

Jürgensen C., Christiansen C., Lund-Hansen L. C., Laima M. J. C. and **Vang T.** (1997). Nutrient dynamics in southwestern Kattegat, Scandinavia: Modelling transport, budget and consequences of reduced terrestrial loads. *Dan. J. Geogr.* **97**: 1-10.

Ketchum H. B. (1951). The flushing of tidal estuaries. *Sewage and Industrial Waste.* **23**: 198-209.

Komar P. D. and **Miller M. C.** (1973). The threshold of sediment movement under oscillatory water waves. *J. Sed. Petrol.* **43**: 1101-1110.

Kranck K., Smith P. C. and **Milligan T. G.** (1996a). Grain-size characteristics of fine-grained unflocculated sediments I: one-round distributions. *Sedimentology.* **43**: 589-596.

Kunzendorf H., Emeis K.–C. and **Christiansen C.** (1998). Sedimentation in the central Baltic Sea as viewed by non-destructive Pb-210 dating. *Dan. J. Geogr.* **98**: 1-9.

Lopez P., Lluch X., Vidal M. and **Morguí J. A.** (1966). Adsorption of phosphorous on sediments of the Balearic Islands (Spain) related to their composition. *Estuar. Coast. Shelf Sci.* **42**: 185-196.

McComb A. J., Qiu S., Lukatelich R. J. and **McAuliffe T. E.** (1998). Spatial and temporal heterogeneity of sediment phosphorus in the Peel-Harvey estuarine system. *Estuar. Coast. Shelf Sci.* **47**: 561-577.

Pedersen O. B., Christiansen C. and **Laursen M. B.** (1995). Wind induced long term increase and short term fluctuations of shallow water suspended matter and nutrient concentrations, Ringkøbing Fjord, Denmark. *Ophelia.* **41**: 273-287.

Robbins J. A. (1978). Geochemical and geophysical applications of radioactive lead. In *The biogeochemistry of lead in the environment.* Ed. J.O. Nriagu. Pp. 285 - 393. Elsevier, Amsterdam.

Rysgaards S., Fossing H. and **Jensen M. M.** (2001). Organic matter degradation through oxygen respiration, denitrification, and manganese, iron, and sulphate reduction in marine sediments (The Kattegat and The Skagerrak). *Ophelia* **55**: 77-91.

Shaw E. M. (1994). *Hydrology in Practice*, 3rd ed. Chapman and Hall, London.

Tamakloe E. K. (1966). Geomorphology of Keta Lagoon and its Environs. BA (Hons) *Dissertation.* University of Ghana.

Valeur R. J., Jensen A. and **Pejrup M.** (1995). Turbidity, particle fluxes and mineralisation of C and N in a shallow coastal area. *Mar. Freshw. Res.* **46**: 409-418.