Sediment and carbon accumulation in a small tidal basin: Yuehu, Shandong Peninsula, China

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Abstract A small sedimentary basin (the Yuehu lagoon), located at the eastern tip of Shandong Peninsula, China, was selected to study its filling by sediment and the vertical flux of particulate organic carbon in response to natural/anthropogenic processes. Surficial and short core sediment samples were collected and analyzed to obtain data sets of grain size, organic carbon content, deposition rates and vertical fluxes of sediment and organic carbon. The analytical results show that the lagoon is covered mainly with fine-grained sediments with high deposition rate and particulate organic carbon content being found from the central part of the mud deposit. The sediment balance of the lagoon indicates high denudation rates of the catchment basin, which may be related to soil erosion in response to farming and land use pattern changes. Furthermore, preliminary analysis of the organic carbon fluxes of the Yuehu lagoon and other embayments of the region shows that these coastal systems make an important contribution to the regional shallow sea carbon burial.

Keywords Coastal sedimentation · Coastal organic carbon burial · Tidal inlet · Eastern China coast · Land based drivers

by terrestrial input, high rate of biological production, intense air-sea exchange, deposition of organic matter and sediment, exchange at the margin/ocean boundary, and perturbations of the marine ecosystem. Large rivers with large drainage basins make a major contribution. For example, sediment and nutrients from the Yellow and Changjiang Rivers play an important role in the material budget and the formation of mud deposits over the Yellow and East China Seas (Alexander et al. 1991; Dronkers and Miltenburg 1996). On the other hand, small sedimentary catchment basins are comparably important in a regional and global context. These systems respond quickly to external drivers making them highly sensitive to natural processes and human activities, and they collectively may significantly affect material flux to and cycling in the coastal zone. Studies on sediment delivery by the rivers have already provided an example: globally, small rivers discharge a higher amount of sediment than large rivers (Milliman and Syvitski 1992; Milliman et al. 1999).

This paper describes a study of the Yuehu tidal inlet system, a small sedimentary basin with a total drainage area of around 15.2 km^2. Sediment infilling and the vertical flux and accumulation of particulate organic carbon (as an example of nutrient fluxes), in response to natural evolution of the system and human activities, will be investigated. On the basis of the data obtained from this particular basin, the implications of the fine-grained sediment flux and the organic carbon burial on a regional scale will be examined.

Introduction

Coastal seas are important areas for sediment and nutrient fluxes and cycling. The coastal environment is characterized

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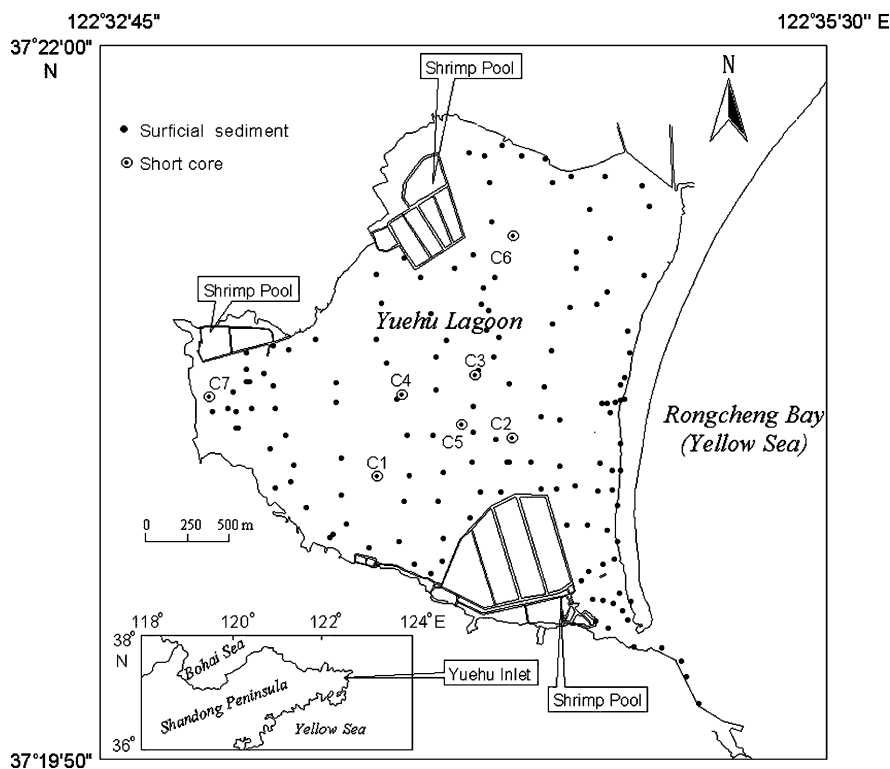Tel.: +86-25-3597082
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The study area

The Yuehu (meaning "moon-shaped lake") basin is located in the eastern part of Shandong Peninsula, China (Fig. 1). It is a tidal basin (i.e. lagoon) of an inlet system with an area of 4.94 km^2 (Wei and Zhuang 1997) and an inter-tidal area of 1.57 km^2. The lagoon is shallow; the water depth is mostly less than 1.5 m measured at mean sea level with a maximum water depth of around 3.5 m at high water on springs (Xue 2000). The mean water level is 0.34 m higher in the summer than in the winter. Five small rivers discharge seasonally into the lagoon; the catchment basin is characterized by low hills consisting of Cretaceous igneous rocks and sand stones. The lagoon is separated from the open sea by a sand spit, which is about 2.5 km in length. Longshore drift along the beach on the open-sea

Fig. 1
Map showing the location of Yuehu and sites for surficial sediment and short core sampling

side is directed towards the south (Wang et al. 2000). An entrance channel of 132 m in width connects the lagoon with the open sea. The tidal range is 1.15 m on springs and 0.64 m on neaps, measured at the entrance to the lagoon (State Oceanic Administration 1991). In the inner part of the lagoon, the bed is covered with fine-grained sediments (Cai and Cai 1984; Li et al. 1987).

Yuehu is a well-known habitat for white swans. Historically, about 10,000 swans winter there. They feed on *Zostera marina* (known as "broad-leaf algae" by the local people), which grows well in the tidal basin. Hence, the area became a National Natural Reserve in 1988 and measures were taken to protect the birds (Chen et al. 1991). However, because of the environmental changes in the area and the reduction of the production of *Zostera marina* in particular, fewer swans come for the winter. For instance, during the winter (December) of 1998, there were only about 4,000 swans and 1,500 wild ducks.

Human activities in the area have been intensive. Aerial photographs show that since the mid-1960s majority of the catchment basin has been cultivated for crops (mainly wheat, maize, peanuts and sweet potatoes). The tidal basin and adjoining areas have been used for sea farming since the 1970s. Since 1986, 0.59 km^2 of the inter-tidal land have been reclaimed for shrimp farming (Fig. 1). Outside the tidal basin, edible sea kelps and scallops are the major products of sea farming: the lower layer of the water column is occupied by the kelps, and the upper part is used for scallop farming. The beaches of the sand spit, which semi-encloses the tidal basin, have been developed for tourism and the local people have been dredging the beach sand near the inlet entrance for construction since the early 1990s.

Material and methods

Surficial sediment samples and short cores were collected in 1998 and 1999. During the sampling, the position was fixed using a (Magellan 2000XL) portable GPS. Approximately 130 surficial sediment samples and 7 short cores were obtained (Fig. 1). Most of the short cores were 0.22–0.8 m in length, except for C5, which was 1.46 m in length, and taken from the central mud deposit area (Fig. 1).

In the laboratory, grain size analysis was carried out using a Cilas 940L laser particle sizer, for the sediment samples. For the short cores, sub-samples were taken every 2 cm to analyze grain size parameters and water content values (water content is defined as the ratio of water to dry sediment mass). The contents of sand, silt and clay fractions were determined, and grain size parameters (i.e. mean, sorting coefficient, skewness and kurtosis) were calculated using a moment method (McManus 1988).

For the short cores taken from muddy sediment areas (i.e. cores C1, C2, C3, C4 and C5), ^{210}Pb activity was measured. The sub-samples were taken in 3∼20-cm intervals; 36 sub-samples were analyzed. The deposition rate was calculated using the following equation:

$$D_R = \frac{\lambda D_S}{\ln \frac{I_0}{I_S}} = \frac{\lambda}{k}$$

where D_R is deposition rate, D_s is the depth below the surface, T is time, I_0 is the initial intensity of ^{210}Pb activity, I_s is the intensity of ^{210}Pb activity after T, and λ is the disintegration constant of ^{210}Pb. The procedure of calculating the k value can be found in Alexander et al. (1991) and Li (1993).
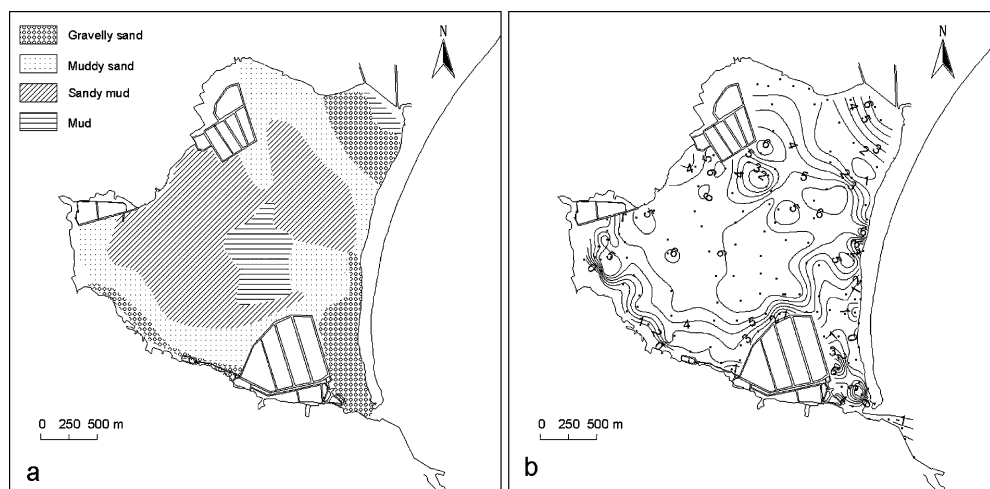
Fig. 2
Sediment types with the nomenclature following Blair and McPherson (1999) (**a**), and mean grain size distributions in ϕ values (**b**), in the tidal basin

Using the water content (W, the ratio of water mass to dry sediment mass) and deposition rate data, dry bulk density of sediment, ρ_{dry}, and the vertical flux of sediment, F_s, were derived:

$$\rho_{dry} = \frac{\rho_S \rho_W}{W \rho_S + \rho_W}$$

$$F_s = D_R \rho_{dry}$$

where ρ_S and ρ_W are densities of sediment particles and water, respectively.

For analysis of organic carbon, 20 sub-samples throughout core C5 were used. The content of particulate organic carbon (for dried sediment, in terms of mass) was measured using a Perkin-Elmer 240C Elemental Analyzer. Thus, the vertical flux of particulate organic carbon were calculated by:

$$F_c = C_c D_R \rho_{dry}$$

where F_c is the vertical flux of organic carbon, and C_c is the organic carbon content.

Results

Sediment characteristics

The central part of the tidal basin is covered with fine-grained sediments (Fig 2). Mud and sandy mud account for about half of the lagoon area. Sand and gravelly sand are found near the entrance channel, along the southern shoreline of the lagoon, and on the eastern side of the lagoon, accounting for about 20% of the area. The remaining area is covered by muddy sand with a mud content of 20 to 50%. Thus, the lagoon is generally dominated by fine-grained material.

The vertical profile of C5 can be divided into three sections according to grain size parameters (Fig. 3). The upper (0~0.6 m) and lower (below 1.1 m) sections are characterized by relatively finer mean grain sizes (with ϕ values of around 7.5), and the materials of the middle section

(0.6–1.1 m) are coarser (ϕ values of around 7.0). Further, the middle section is more poorly sorted and more negatively skewed than the upper and lower sections. From the point of view of vertical grain size changes, coarsening-upward sequences are present for the sections of 0~0.3 m and 0.8~1.3 m, and fining-upward sequences can be seen in the sections of 0.3~0.8 m and below 1.3 m. The minimum clay contents occur at 0.8 m and the bed surface, whereas the maximum clay contents are found at 0.3 m and 1.25 m below the bed surface.

Away from the central mud area, the depositional conditions are somewhat different, as indicated by the vertical distributions of mean grain size for cores C1, C2, C3, C4, C6 and C7 (Fig. 4). In core C1, mud dominates below 0.08 m, which is overlain by sandy materials. In core C2, a fining-upward trend is observed with the transition from fine-grained to coarse-grained sediments occurring at 0.1 m. The vertical distribution of grain-size in core C3 is
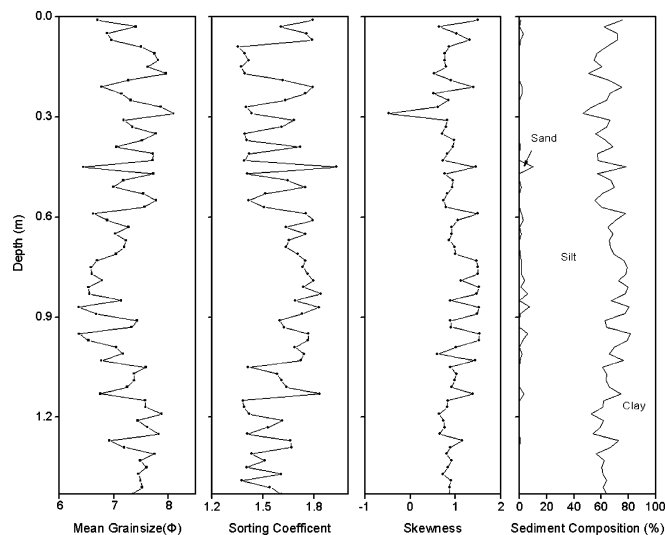

Fig. 3
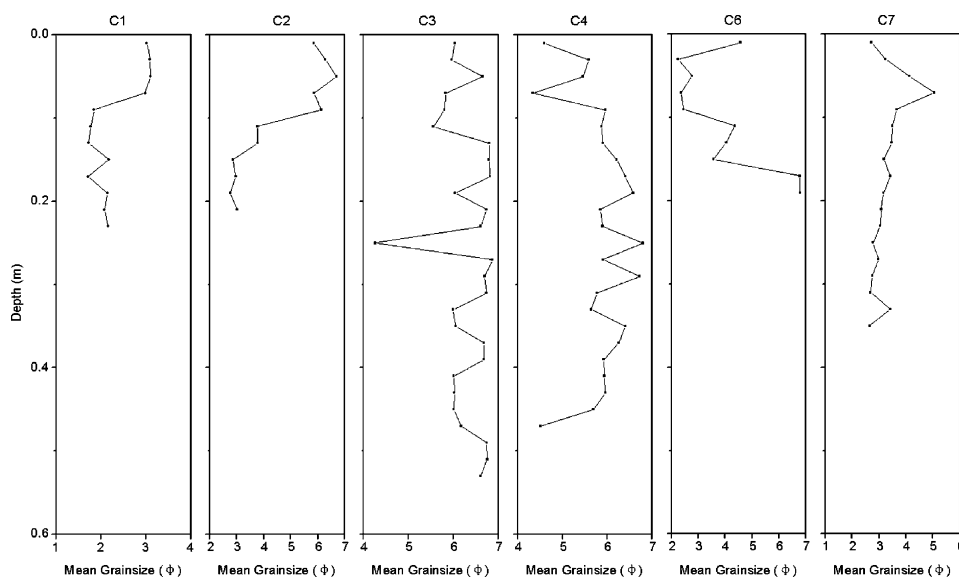Sediment grain size characteristics of core C5

Fig. 4
Vertical distributions of mean grain size of the short cores

relatively stable, dominated by fine-grained materials. In core C4, the surficial layers and lower section (i.e. 0~0.07 m and below 0.48 m) consist of sandy materials, whilst the middle part is dominated by muddy sediment. Core C6 has an overall coarsening-upward trend with a boundary dividing coarse- and fine-grained sediments being located at around 0.17 m. Finally, C7 is characterized by sandy sediments with fining-upward sequence being located below 0.08 m and coarsening-upward sequence in the surficial layer. Cores C1, C4, C6 and C7 all show the newest sediment is coarse-grained material, indicating an increase in sandy sediment input from land. The fining-upward trend at C2 may be interpreted as a shift of mud deposition center towards the east.

Organic carbon contents

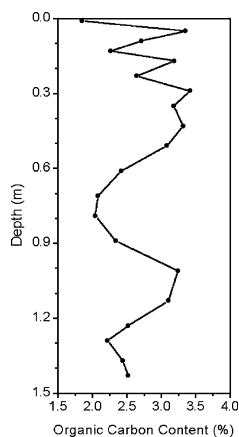Within core C5, the content of organic carbon varies from the bed surface towards the lower part (Fig. 5). Maximum values are at 0.3 and 1.0 m, whilst minimum values are found at the bed surface, 0.8 and 1.3 m below the bed surface. The patterns of vertical changes of carbon content and mean grain size are to some extent correlated. For instance, in the 0~0.3 m section, mean grain size increases (Fig. 3) and carbon content decreases (Fig. 5). Such correlations can be seen also in the 0.3~0.8 section and below 1.3 m. However, there appears to be an exception in the 0.8~1.3 section, which may be caused by the factor that the samples for carbon content analysis were fewer than for grain size analysis (when only the samples with both grain size and carbon content data are considered, a good correlation can be obtained).

On the basis of the samples analyzed, the content of particulate organic carbon is 2.7% on average with the highest and lowest values of 3.35% and 1.85%, respectively. The lowest value is for the sub-sample of the bed surface, probably due to an oxidizing environment near the bed.
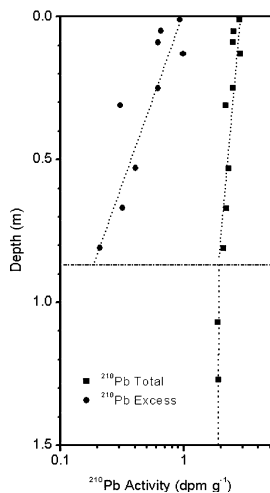

Fig. 5
Content of particulate organic carbon in core C5

Fig. 6
Total and excess ^{210}Pb activities throughout core C5

Table 1
Deposition rates and mean vertical sediment fluxes calculated for the short cores

Core	Length (m)	Number of sub-samples for ^{210}Pb analysis	Deposition rate (mm yr^{-1})	Dry density (kg m^{-3})	Vertical flux of sediment (kg m^{-2} yr^{-1})
C1	0.24	6	2.0	802	1.69
C2	0.22	5	5.8	974	5.67
C3	0.54	7	2.3	776	1.78
C4	0.48	7	1.4	856	1.18
C5	1.46	11	18.2	644	11.7

Deposition rates and vertical sediment/carbon fluxes

The results of ^{210}Pb analysis for core C5 are shown in Fig. 6. The radioisotope activity of total ^{210}Pb decreases from 2.81 dpm g^{-1} at the bed surface to 1.87 dpm g^{-1} at 1.07 m and 1.90 dpm g^{-1} at 1.27 m. Hence, the value of 1.89 dpm g^{-1} has been used as a background value in the calculation of excess [210]Pb. As shown in Table 1, the calculated deposition rate for the 0–0.8 m vertical profile is 18.2 mm yr^{-1}, representing a temporal scale of 40 years. The significant linear relationship between the sample depth and the ^{210}Pb activity (Fig. 6) indicates that the sediment sequence is continuous. Within the tidal basin, the tidal currents are weak (below the threshold for initial sediment motion) and the waves are small (Jia 2001). Under such conditions, the seabed cannot be very mobile and resuspension does not occur frequently.

Deposition rates are smaller at the remainder sites (Table 1). Therefore, the area around C5 should represent a deposition center of the mud areas. The average deposition rate for the five cores is 5.9 mm yr^{-1}.

Using the water content and deposition rate data, values for the dry bulk density and vertical fluxes of sediment are derived (Table 1). In the calculation, it is assumed that ρ_S and ρ_W are 2,650 kg m^{-3} and 1,025 kg m^{-3}, respectively. For core C5, the vertical flux of organic carbon is also calculated. The mean water content of the sediment samples from C5 is around 1.2, and the dry bulk density is 644 kg m^{-3} on average, which is equivalent to a wet bulk density of 1,420 kg m^{-3} (for a formula to calculate the wet bulk density, see Gouleau et al. 2000). The bulk density is similar throughout the core with some fluctuations; such a pattern is different from deep ocean cores. For example, at a site in the deep ocean, the wet bulk density at the seabed was around 1,220 kg m^{-3}, but this increased to 1,370 kg m^{-3} at 1.5 m below the bed surface (Preiss 1968). This is because in the deep ocean the sediment is extremely fine, which means a smaller bulk density, and the deposition rate is small, which means that the sediment is subjected to long-term compaction processes (Rieke and Chilingarian 1974). Apparently, these conditions do not exist for a shallow coastal lagoon like the Yuehu. According to the data obtained, average vertical fluxes of sediment and organic carbon at C5 are 11.73 kg m^{-2} yr^{-1} and 0.34 kg m^{-2} yr^{-1}, respectively. These values probably represent the highest of the study area, because at other sampling sites the deposition rate is lower.

Discussion

Influences of anthropogenic processes

The fine-grained material balance for the lagoon consists of the amount of net deposition, the sediment transported into the basin through the entrance channel, and the supply from the land and the atmosphere. Jia et al. (2003) have attempted to carry out sediment budgeting analysis. Here we adopt a simpler approach to deriving estimates by the order of magnitude. Assuming that the mean deposition rate obtained from the short cores is applicable to an area of 2.5 km^2, and using a dry density of 800 kg m^{-3} (cf. Table 1), the net accumulation of fine-grained sediment will be of the order of 1.2×10^4 t yr^{-1}.

Based upon the measurements of tidal currents and suspended sediment concentrations within the entrance channel during four tidal cycles, Xue (2000) has analyzed net transport patterns of suspended sediment in the entrance channel. The results showed that the suspended sediment concentration was generally low, ranging between 0.001 and 0.016 kg m^{-3}. The channel was ebb-dominated with peak depth-averaged current velocities being 1.73 m s^{-1} on springs and 1.32 m s^{-1} on neaps, during the ebb phase of the tide, and 1.34 m s^{-1} on springs and 1.05 m s^{-1} on neaps, during the flood. The calculation indicated that during three of the four tidal cycles net transport of suspended sediment was directed towards the open sea; when averaged over the four tidal cycles, the net transport was also directed to seaward.

In this region, the supply from the atmosphere (dust or aerosol) can result in a deposition rate of up to 0.05 mm yr^{-1} on average (Li 1997), although intense aerosol settling occurs during dust storms (Li et al. 1998). If this value is applicable to the Yuehu lagoon, then the resultant aerosol input will be of the order of 2×10^3 t yr^{-1}. Thus, a major part of the fine-grained material that is accumulated in the Yuehu lagoon, i.e. around 1.0×10^4 t yr^{-1}, should be derived from land. This value is equivalent to a denudation rate of 660 t km^{-2} yr^{-1} (the catchment basin has an area of 15.2 km^2) without taking into account the coarse-grained material in the total sediment supply. It should be noted that the catchment basin is a hilly area with a maximum height of less than 300 m, mostly composed of Cenozoic igneous and sedimentary rocks, and rain fall here is around 770 mm yr^{-1} (State Oceanic Administration 1991). Hence, the catchment represents a typical area of temperate maritime climate with a gentle

relief. Under such conditions, natural denudation rates of the land should be 5–100 t km^{-2} yr^{-1} according to statistical data from Selby (1993). Since the estimated denudation rate, as outlined above, is much higher, the destruction of vegetation cover and intensified soil erosion in response to human activities may be considered as major factors. Until 1960, most of the catchment region was covered by dense, natural vegetation. However, by 1984 almost the entire catchment had been cultivated for farming (Jia et al. 2003). Because the farmland is mostly located in hilly, slopping areas, soil erosion must have been intensified after protection of the natural vegetation was removed. Although more quantitative studies are required to confirm this hypothesis, it is likely that changes in land use patterns have resulted in the high denudation rates and caused changes in sediment budget of the Yuehu lagoon.

Implication on regional carbon burial

The high organic carbon contents observed in the Yuehu lagoon may imply that the coastal embayments make an important contribution to the regional, shallow sea carbon burial rate. Along the coastlines of the Bohai and Yellow Seas, there are numerous coastal bays, estuaries and tidal inlets. However, because the existing carbon content data are not adequate for any accurate calculations, the contribution of these embayments cannot be evaluated precisely. Nevertheless, it is possible to obtain some useful information, by analyzing the organic matter data of some 30 coastal embayments that are distributed along the shoreline of the northeastern Bohai Sea and Shandong Peninsula (these sections of coastlines account for about half of the total length of the Bohai-Yellow Sea coastlines); these data sets are available from State Oceanic Administration (1991, 1993, 1997).

These embayments are mainly formed on rocky coasts, and can be divided into three groups: (1) coastal bays along the northeastern Bohai Sea shorelines; (2) coastal bays on the Shandong Peninsula coast; and (3) tidal inlet systems on the Shandong Peninsula coast (the Yuehu is one of these systems). The number of embayments, the basin area and the average and maximum organic matter contents for each of the categories are listed in Table 2. Assuming that 58% of organic matter consists of particulate organic carbon (State Oceanic Administration 1975), the carbon content can be derived. The weighted average

organic carbon contents for these three types are 0.74, 0.40 and 1.40%, respectively, in terms of dry mass.

Direct measurements of deposition rates for these embayments are rare. Recently, four short cores were collected from Jiaozhou Bay (Wang 2000), which is a large embayment (397 km^2 in area) located to the southwest of the Yuehu lagoon. Analysis of ^{210}Pb activity shows that the deposition rate is on average 6.0 mm yr^{-1} with a maximum of 8.9 mm yr^{-1} and a minimum of 3.3 mm yr^{-1}. This average value is close to that of the Yuehu lagoon (i.e. 5.9 mm yr^{-1}). Thus, it may be realistic to use a deposition rate of 5 mm yr^{-1} for the region.

The organic carbon burial rate (F_T) of the embayments involved can be written as:

$$F_T = AC_{av}D_R\rho_{dry}$$

where A is the total area of the embayments, C_{av} is the average organic carbon content, D_R is the deposition rate, and ρ_{dry} is the dry bulk density of sediment.

Using the carbon content and basin area data derived, in conjunction with the assumption that D_R=5 mm yr^{-1} and ρ_{dry}=800 kg m^{-3}, the burial rate of particulate organic carbon of the 30 embayments is 0.9×10^5 t yr^{-1}. Since this quantity does not include the organic carbon buried in other minor embayments of the coastal region that were not described in the reports of the State Oceanic Administration (1991, 1993, 1997), and in those embayments along the Korean coastlines, it underestimates the total carbon burial rate for all the embayments on the Bohai-Yellow Sea coast. It may be expected that the total carbon burial rate has an order of magnitude of between $10^5\sim10^6$ t yr^{-1}.

Such a quantity is not small compared with the value for the adjacent continental shelves. Over the Yellow and Bohai Seas, mud deposits cover an area of some 1.0×10^5 km^2 (on the basis the information given by Lee and Chough (1989), Dronkers and Miltenburg (1996), Lee et al. (1998) and Cheng (2000)). With an average deposition rate of around 1.5 mm yr^{-1} (Zhao et al. 1990) and a content of particulate organic carbon of 0.8% (Luan 1985; Zhao and Yan 1994), the total particulate organic carbon burial will be 8×10^5 t yr^{-1} (information on water content and bulk density of Yellow Sea muddy sediments can be found in Lee et al. (1987)). Hence, the coastal embayments should be taken into account in the analysis of continental margin carbon budget.

Table 2
Organic matter contents of the major coastal embayments along the northeastern Bohai Sea and Shangdong Peninsula coastlines

Region (basin type)	Number of embayments	Total area (km^2)	Organic matter content (%)	
			Average	Maximum
Northern Bohai Gulf (coastal bays)	7	1,430	0.56~1.62	1.49~3.32
Shandong Peninsula (coastal bays)	19	1,160	0.36~1.62	0.78~4.14
Shandong Peninsula (tidal inlet basins)	4	431	1.63~2.67	3.74~12.5

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