Sedimentary phosphorus species and sedimentation flux in the East China Sea

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Abstract

Core sediment samples were collected from the middle shelf of the East China Sea (ECS) to study the phosphorus forms, \( \text{P accumulation rate (PAR), P burial efficiency and the burial flux in the ECS.} \) The sediment samples were sequentially extracted and directly extracted to analyze different forms of sedimentary \( \text{P}: \) loosely sorbed \( \text{P} \) and iron-bound \( \text{P} \) (\( \text{PCDB} \)); inorganic \( \text{P} \) associated with francolite (carbonate fluorapatite, CFA), biogenic hydroxyapatite, smectite, and \( \text{CaCO}_3 \) (\( \text{PCFA} \)); detrital \( \text{P} \) (\( \text{PDetrital} \)); organic \( \text{P} \) (\( \text{POrganic} \)); and total \( \text{P} \). In addition, the \( \text{Fe} \) contents in the citrate-dithionite-bicarbonate (CDB) extracted solution were also measured.

The total concentrations of \( \text{P} \) in the surface sediments in the study area ranged from 13.5 to 22.3 \( \mu \text{mol g}^{-1} \). Inorganic \( \text{P} \) was the major form and accounted for 72–93\% of the total \( \text{P} \) pool. The average percentage of each fraction of \( \text{P} \) followed the sequence: \( \text{P}_{\text{Detrital}} \) (70\%) > \( \text{POrganic} \) (15.5\%) > \( \text{PCDB} \) (8.4\%) > \( \text{PCFA} \) (5.8\%). The distribution pattern of total \( \text{P} \) in the surface sediment was similar to that of \( \text{P}_{\text{Detrital}} \) and \( \text{POrganic} \), but different from that of \( \text{PCDB} \) and \( \text{PCFA} \). The profile variation of \( \text{POrganic} \) was the most significant among the phosphorus forms at the study stations. The concentrations of \( \text{PCDB} \) and \( \text{PCFA} \) showed minor variation with depth. These results may suggest that transformations of \( \text{POrganic}, \text{PCFA} \) and \( \text{PCDB} \) occurred at the study stations during sedimentary \( \text{P} \) burial.

Based on the concentrations of total \( \text{P}, \text{PCDB} \) and \( \text{Fe}_{\text{CDB}} \) obtained in the present study and the mass accumulation rate (MAR) reported in the literature, the values of the PAR, the \( \text{P} \) diffusion flux (\( \text{J}_{\text{DFe}} \)) supplied by reducible iron hydroxides and the \( \text{P} \) burial efficiency were calculated. The calculated results for PAR and \( \text{J}_{\text{DFe}} \) in the study area ranged from 1.02 to 24.23 \( \mu \text{mol cm}^{-2} \text{yr}^{-1} \) and from 0.1 to 2.11 \( \mu \text{mol cm}^{-2} \text{yr}^{-1} \), respectively. The phosphorus burial efficiency (PBE) was approximately 90\%. The ECS is a phosphorus sink, and the average annual \( \text{P} \) burial flux has been reasonably estimated to be in the range of \( 20–25 \times 10^9 \) \( \text{mol yr}^{-1} \).

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1. Introduction

Phosphorus is one of the major elements controlling marine productivity, which influences the global biogeochemical cycles (Broecker and Peng, 1982). The major source of phosphorus entering marine
environments is riverine transportation. Meybeck (1982) estimated that the annual riverine input is $21 \times 10^{12}$ g P yr$^{-1}$ and found that phosphorus is mainly present in the solid phase, accounting for 90–95% of the total P pool. Meybeck (1982) also indicated that, upon transfer from a continental environment to the marine realm, approximately 90% of the total phosphate becomes buried without any interaction with the marine part of the biosphere. However, numerous studies have indicated that significant diagenetic reorganization of P occurs during burial, especially in the continental margin sediments (Sundby et al., 1992; Ruttenberg and Berner, 1993; Berner and Rao, 1994; Slomp et al., 1996; Anschutz et al., 1998; Schenau et al., 2000; Filippelli, 2001; Schenau and De Lange, 2001).

The classical diagram of P recycling after burial in marine sediment is that the non-refractory fraction of sedimentary phosphorus is released to interstitial waters due to the degradation of organic materials or due to desorption of redox-sensitive phosphorus associated with iron oxyhydroxides. This released P may be adsorbed to grain surface or captured by iron oxyhydroxides, but P is ultimately taken up in situ in a mineralized form, within the sediments, most likely the authigenic mineral carbonate fluorapatite (CFA) (Ruttenberg and Berner, 1993; Filippelli and Delaney, 1996). The CFA and detrital forms of P are considered as the refractory fraction of sedimentary phosphorus and are not regenerated during the diagenetic processes.

The East China Sea (ECS), located around latitude 26–31°N and longitude 121–126°E, is surrounded by China to the west, the Kuroshio Current to the east, Taiwan and the Taiwan Strait to the south, and the Yellow Sea to the north. The ECS is one of the larger marginal seas in the western Pacific of the northern hemisphere and it is also the main discharge area of the Changjiang River which is the world’s fourth largest river when reviewed in terms of suspended load and its annual transportation of suspended load is approximately $478 \times 10^6$ t yr$^{-1}$ (Milliman, 1991). It is estimated that the annual total riverine P of the Changjiang River is about $11.8 \pm 2.3 \times 10^9$ mol P yr$^{-1}$, accounting for approximately 1.7% of the global riverine P flux, and over than 95% of the riverine P is present in the solid phase (Qu et al., 1993; Fang, 2004). In addition, the ECS also receives a rich supply of phosphorus, $14.3 \times 10^9$ mol P yr$^{-1}$, from the upwelling of the Kuroshio Intermediate Water (Chen, 1996). Based on the box model to calculate P budget on the ECS, Fang (2004) indicated that approximately $34.3 \pm 21.5 \times 10^9$ mol P yr$^{-1}$ deposits in the ECS sediment, and Chen and Wang (1999) showed that the total organic P burial rate on the ECS is $5.7 \pm 2 \times 10^9$ mol P yr$^{-1}$.

As mentioned above, however, sedimentary P may be regenerated during the diagenetic processes. For better quantifying the burial flux of P in marine sediments, it is necessary to distinguish the contents of reactive- (potentially bio-available) P and refractory-P in sediments (Ruttenberg, 1992). Comparing with the other marginal seas in the world, the information of phosphorus forms in sediments of the western Pacific in the northern hemisphere is very limited, especially in the ECS. In order to fill this gap and to more fully understand the P geochemistry in the ECS, the present study employed a selective sequential extraction method (SEDEX) (Berner and Rao, 1994) to quantify the different forms of sedimentary phosphorus in the middle shelf of the ECS and to estimate the burial flux of phosphorus in the whole ECS. The advantage of the selective SEDEX (Berner and Rao, 1994) over the SEDEX (Ruttenberg, 1992) is that the different forms of sedimentary phosphorus and are not regenerated during the diagenetic processes.

2. Sampling and methods

2.1. Study area

The sediment cores were collected using the box core method onboard the R/V Ocean Research-I. The sampling stations (Fig. 1) were located outside of the mouth of the Changjiang River in the middle shelf area at water depths <100 m. Upon collection of core samples, sediments were extruded vertically with a hydraulic jack and sampled at 1–2 cm intervals. The outer rim (~0.5 cm) of each sediment slab was timed off to avoid contamination between layers. The sectioned samples were sealed and kept frozen for further processing in the home laboratory. More detailed descriptions of the sampling and treatment of the samples can be found elsewhere (Huh and Su, 1999; Su and Huh, 2002).

The major source of the fine-grained sediment in this continental shelf of the ECS is the Changjiang River, which accounts for $478 \times 10^6$ t yr$^{-1}$ (Milliman, 1991).
1991) compared to no more than $0.06 \times 10^8$ yr$^{-1}$ from other small rivers (Li et al., 1991). Most of the suspended sediments consist of silt and clay. A large portion of this sediment supply is moved southward by the Jian-Su coastal current (Cao et al., 1989). A portion of the suspended sediments is transported east and northeast into the ECS (Sternberg et al., 1985). From the $^{210}$Pb profile, DeMaster et al. (1985) obtained an accumulation rate of up to $4.5$ cm yr$^{-1}$ near the mouth of the Changjiang River. In a recent study based on measurements of $^{137}$Cs throughout the ECS, Huh and Su (1999) found that the sedimentation rates in the ECS varied by two orders of magnitude, from 2 to $0.02$ cm yr$^{-1}$, and generally decreased southward along the inner shelf and eastward offshore. Based on the spatial distributions of the grain size, carbonate, organic carbon contents, metals/aluminum ratios and $\delta^{13}$C of the organic carbon, the ECS continental shelf was divided into five major regions of sediments: the Delta, inner shelf, middle shelf, outer shelf and northeast outer shelf (Lin et al., 2002). The major types of sediments occurring there include terrigenous sediments from the Changjiang River, relict sediment from the middle shelf, biogenic carbonate from the outer shelf and sediments from the Yellow Sea (Lin et al., 2002).

2.2. Analytical methods

A selective solvent extraction method established by Berner and Rao (1994) was employed to determine the different fractions of sedimentary P in samples. The detailed analytical scheme and procedures can be seen in literature (Berner and Rao, 1994). A briefly analytical procedure is described here. The bulk sediment samples were divided into three sub-samples. One sub-sample was extracted by a 30 ml of citrate-dithionite-bicarbonate (CDB) mixture solution ($0.3$ M $C_6H_5Na_3O_7+1$ M $NaHCO_3+0.06$ M $Na_2S_2O_4$) at pH $7.6$ in a water bath at $85$ °C for $0.5$ h, afterwards, in a shaker at room temperature for $24$ h; this fraction represents as easily exchangeable P plus P strongly adsorbed to ferric oxides/hydroxides and hereafter refers to as $P_{CDB}$. After CDB extraction, the residue was washed with $30$ ml of Milli-Q water twice to
remove any residual CDB solution. Then, the residue was extracted with a 30 ml of acetate buffer solution (acetic acid/Na acetate; 1 M CH₃COONa buffered to pH 4 with acetic acid). This fraction represents the sum of the authigenic calcium phosphate, bone apatite and P associated with CaCO₃ and hereafter refers to as PCFA. The other two sub-samples were separately analyzed for total P and total inorganic P. Total P was determined by ashing samples at 550°C for 12 h, followed by extraction with 1 N HCl acid for 24 h. Total inorganic P was measured in the same way as total P but without the ashing step. Sedimentary P extracted by 1 N HCl acid was analytically defined as the total inorganic phosphorus, and the fraction of organic phosphorus (POrganic) was indirectly obtained from the difference between the total P and total inorganic P (Aspila et al., 1976). The difference between the total inorganic P and the sum of PCDB plus PCFA was assumed to represent the detrital apatite (PDetrital), which is soluble in 1 N HCl acid but not in CDB solution or acetate buffer. The PDetrital represented coarser-grained inert material derived from the erosion of igneous and metamorphic rocks and separation of it from authigenic apatite (Berner and Rao, 1994).

All of the extractants were centrifuged at 4000 rpm for 5 min. Due to the phosphorus content differing from each extractant, thus, a different proportion of the supernatant in each extractant was transferred into 30 ml polypropylene vials and was diluted to 25 ml with Milli-Q water. The diluted solution was analyzed using the molybdenum blue spectrophotometric method (Hansen and Koroleff, 1999). The dilution of each extractant can also eliminate the interference from the extracting chemicals and the matrix leached from the samples. It should be noted that the determination of P in the CDB extractant, where there are interferences from both dithionate and citrate (Logan et al., 1979). Excess sodium dithionate was allowed to oxidize several days before analysis, and additional ammonium molybdate solution was added to compensate for the interference from citrate (Logan et al., 1979). The chemical treatment, reaction mechanisms and relative standard deviation of each analytical procedure are shown in detail in Table 1. The iron content in each CDB extraction sample (FeCDB) was also analyzed using flame atomic absorption spectrophotometry with a Perkin Elmer Analyst 800A. The CDB-extractable Fe was assumed to consist of Fe from Fe oxides, although it can also extract some Fe from clay minerals and Fe sulfides (Slomp et al., 1996).

3. Results

3.1. Spatial distribution of phosphorus

The concentration and percentage ranges of different forms of sedimentary P in the surface sediments found in the present study are summarized in Table 2. The total concentration of P in the surface sediments in the study area ranged from 13.5 to 22.3 μmol g⁻¹. Among the four forms of sedimentary phosphorus, the P concentration ranges were 0.89–1.87 μmol g⁻¹ (average 1.45 μmol g⁻¹) for PCDB, 0.53–1.77 μmol g⁻¹ (average 1.0 μmol g⁻¹) for PCFA, 9.34–17.21 μmol g⁻¹ (average 12.28 μmol g⁻¹) for PDetrital and 1.09–5.88 μmol g⁻¹ (average...
2.75 μmol g⁻¹) for P_{Organic}. The average percentage of each fraction of P followed the sequence: P_{Detrital} (70%) > P_{Organic} (15.5%) > P_{CDB} (8.4%) > P_{CFA} (5.8%). Basically, the inorganic P was the major form, accounting for 72–93% of the total P pool, and the contribution of P_{Organic} was relatively small at the study stations, as shown in Fig. 2.

The surface concentration contours of different fractions of P are shown in Fig. 3. The contours were generated using the Generic Mapping Tools and interpolation within 10 km × 10 km grids. The concentration of P_{CDB} in the surface sediments seemed to increase eastward. The minimum contour of P_{CDB} appeared near 123.5°E and 30°N, which is outside off Hangzhou Bay. In contrast, the maximum contour of P_{CFA} was located outside of Hangzhou Bay, and the concentration of P_{CFA} decreased eastward. The distribution of P_{Detrital} differed from those of P_{CDB} and P_{CFA} and there were two higher values of P_{Detrital} in the study area. One was close to 123.5°E and 32°N, approximately 200 km east of the mouth of the Changjiang estuary, and the other was located 125°E and 29°N, in the south-western part of Hangzhou Bay. The distribution pattern of total P was similar to that of P_{Detrital}. The maximum contour of P_{Organic} also appeared about 200 km east of the mouth of the Changjiang estuary. Using statistics to calculate the correlation...
between pairs of data, we found that there was good correlation among the total P, \( P_{\text{Detrital}} \), and \( P_{\text{Organic}} \). However, we found poor correlation between \( P_{\text{CDB}} \) and \( P_{\text{CFA}} \), and between the other fractions of P obtained.

### 3.2. Vertical profile of phosphorus

The vertical profiles of different forms of P at each station are shown in Fig. 4. The profile variation of \( P_{\text{Organic}} \) was the most significant among the phosphorus species studied and showed concentrations decreasing with depth at many stations, such as stations 3, 6, 10, 20 and 29. Since the concentrations of \( P_{\text{CDB}} \) and \( P_{\text{CFA}} \) at the studied stations were generally low (<3 \( \mu \text{mol g}^{-1} \)), it was not easy to evaluate the profile variation of both forms of P at each station. To more accurately evaluate the profile variation of each fraction of phosphorus at each station, we employed a statistical method, coefficient of variation, in which one standard deviation of each fraction of P at each station is divided by its average concentration. The statistical results showed that the concentration variation of \( P_{\text{CDB}} \) and \( P_{\text{CFA}} \) at most of the stations was generally in the range of 10–20%. The variation in the \( P_{\text{Detrital}} \) value at most of the stations was generally less than 5%. These results may suggest that the transformation of \( P_{\text{Organic}} \), \( P_{\text{CFA}} \) and \( P_{\text{CDB}} \) occurred at most of the stations during sedimentary P burial. In contrast, the transformation of \( P_{\text{Detrital}} \) was relatively minor during sedimentary P burial.

### 4. Discussion

#### 4.1. Phosphorus form

The total concentration of phosphorus in the suspended material in the world’s rivers varies from 18.1 to 64.6 \( \mu \text{mol g}^{-1} \), with a mean value of 37.0 \( \mu \text{mol g}^{-1} \) (Martin and Meybeck, 1979). The phosphorus content in igneous and sedimentary rocks is in the range of 5.5–36.4 \( \mu \text{mol g}^{-1} \), and sandstone and basalt have the minimum and maximum values, respectively (Faure, 1991). Marine sediments are composed of terrestrial and marine materials. Due to the dilution effect, it has been found that the total concentration of sedimentary P generally ranges from 15 to 25 \( \mu \text{mol g}^{-1} \) in marginal seas, such as the Bohai and Yellow Seas (Liu et al.,...
2004), the Iberian margin (van der Zee et al., 2002), the Gulf of Mexico (Filipek and Owen, 1981), the Amazon Shelf (Berner and Rao, 1994; Ruttenberg and Goni, 1997), the California Shelf (Kim et al., 1999) and the North Sea (Slomp et al., 1998). The total concentrations of sedimentary P reported for the Amazon Shelf were in the range of $15–23 \text{ mol g}^{-1}$ (Berner and Rao, 1994; Ruttenberg and Goni, 1997). These values consistently agree with those obtained in the present study. The total concentration of riverine particulate P was $23 \text{ mol g}^{-1}$ in the Changjiang River (Qu et al., 1993) and $21 \text{ mol g}^{-1}$ in the Amazon River (Berner and Rao, 1994).

In the present study, we found that $P_{\text{Detrital}}$ was the most important sedimentary P form in the study area. This result is in agreement well with those of studies on sediment in the Changjiang River mouth (Rao and Berner, 1997) and the Bohai and Yellow Seas (Liu et al., 2004). However, $P_{\text{Detrital}}$ was found to be a minor form (<30% total P pool) in sediments in the Amazon shelf (Rao and Berner, 1997; Ruttenberg and Goni, 1997), the Arabian Sea (Schenau and De Lange, 2001), the Iberian shelf (van der Zee et al., 2002) and the Mediterranea Sea (Eijsink et al., 1997; Slomp et al., 2004), and a very minor form (<1% total P) in deep-sea sediments in the equatorial Pacific (Filippelli and Delaney, 1996).

The sediment samples collected in the present study were taken from the middle shelf region. This area is characterized by relict coarse-grained quartz sand with low concentrations of metals and organic carbon, and is also a transition zone from an inner shelf dominated by detrital sediments to an outer shelf dominated by biogenic sediments (Niino and Emery, 1961; Lin et al., 2002). As a result, $P_{\text{Detrital}}$ was the dominant form of sedimentary P in the study area. Combining these results with the results reported for Bohai and Yellow Sea sediments (Liu et al., 2004), we conclude that $P_{\text{Detrital}}$ is the major fraction of sedimentary P throughout the continental shelf of the ECS.

4.2. Phosphorus regeneration and accumulation rate

Following its burial in the suboxic zone of the sediment, organic matter degradation causes iron
oxides to dissolve, and adsorbed phosphate is then released into the interstitial waters. The supply of P associated with reducible iron hydroxides (\(J_{\text{Fe}}\), \(\mu\)mol P cm\(^{-2}\) yr\(^{-1}\)) can be estimated with the following equation (Ingall and Jahnke, 1997; Schenau and De Lange, 2001):

\[
J_{\text{Fe}} = \frac{\text{Fe}_{\text{CDB}} \times \text{MAR}}{(\text{Fe/P})_{\text{red}} \times 55,800},
\]

(1)

where \(\text{Fe}_{\text{CDB}}\) (ppm) and \((\text{Fe/P})_{\text{red}}\) are the concentration of iron oxides and the molar ratio of iron and phosphorus, respectively, in the surface sediment. In this study, fractions of both iron and phosphorus were extracted using CDB mixed reagent. The concentrations of \(\text{Fe}_{\text{CDB}}\) and \(\text{P}_{\text{CDB}}\) at each station are listed in Table 3. Mass accumulation rate (MAR, g cm\(^{-2}\) ka\(^{-1}\)) data for each station were taken from literature (Huh and Su, 1999; Su, 2000; Su and Huh, 2002). Based on the concentrations of total \(P\), \(P_{\text{CDB}}\) and \(\text{Fe}_{\text{CDB}}\) obtained in the present study and the MAR data obtained from literature, we calculated the phosphorus accumulation rate (PAR) and the \(J_{\text{Fe}}\) value at each station. In addition, phosphorus burial efficiency (PBE) in sediments can also be calculated using the equation (Ingall and Jahnke, 1994; Schenau and De Lange, 2001):

\[
PBE(\%) = 100 \times \frac{\text{PAR}}{(\text{PAR} + J_{\text{Fe}})}.\]

(2)

The calculated results for PAR, \(J_{\text{Fe}}\) and PBE at each station are listed in Table 4.

The values of PAR and \(J_{\text{Fe}}\) in the study area range from 1.02 to 24.23 \(\mu\)mol cm\(^{-2}\) yr\(^{-1}\) and from 0.1 to 2.11 \(\mu\)mol cm\(^{-2}\) yr\(^{-1}\), respectively. The percentage ranges of PBE at all stations are in the range of 90–95%. The values of PAR and \(J_{\text{Fe}}\) obtained in the present study are slightly higher than those found in the Yellow Sea, where the corresponding values were found to be 2.60 ± 1.79 and 0.086 ± 0.031 \(\mu\)mol cm\(^{-2}\) yr\(^{-1}\), respectively (Liu et al., 1999).
et al., 2004). The PBE in the Yellow Sea was found to be almost 100% (Liu et al., 2004). The high values of PBE found in the ECS were attributed to the high percentage of detrital P, which is not regenerated during diagenetic processes, and to the high sediment accumulation rate, as in the Yellow Sea (Liu et al., 2004). Filippelli (1997) compiled data from several margins and estimated that the PAR for continental margins ranged between $0.09$ and $8.0 \text{mol cm}^{-2} \text{yr}^{-1}$. High values of PAR were recorded for several margins of the Mississippi Delta and the St. Lawrence Seaway. The PAR value found in the ECS was relatively higher than those found in other continental margins by Filippelli (1997). This difference is attributable to the contribution of the Changjiang River discharge to the ECS.

### 4.3. Phosphorus burial flux

Recently, Huh and his colleague employed the radionuclide method ($^{210}$Pb, $^{137}$Cs and $^{239,240}$Pu) to comprehensively study the sedimentation rate, MAR and budget of sediments in the ECS (Huh and Su, 1999; Su, 2000; Su and Huh, 2002). Their results showed that the MAR in the ECS varied from $>2$ to $0.05 \text{g cm}^{-2} \text{yr}^{-1}$. The maximum MAR appeared in the mouth of the Changjiang River, and the value generally decreased southward along the inner shelf and eastward offshore. Based on this valuable published data, an attempt is made to calculate the phosphorus burial flux in the ECS. To facilitate the calculation, the calculated area is divided into five boxes: estuary (box I), inner shelf (box II), middle shelf (boxes III and IV), and outer

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**Table 4**

<table>
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<th>Station</th>
<th>Sedim. rate $^a$ (cm yr$^{-1}$)</th>
<th>Mass accum. rate$^a$ (g cm$^{-2}$ yr$^{-1}$)</th>
<th>P accum. rate (μmol cm$^{-2}$ yr$^{-1}$)</th>
<th>$\text{J}_{\text{Fe-P}}$ (μmol cm$^{-2}$ yr$^{-1}$)</th>
<th>P burial efficiency (%)</th>
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<tr>
<td>26</td>
<td>0.12</td>
<td>0.13</td>
<td>2.555</td>
<td>0.168</td>
<td>93.8</td>
</tr>
<tr>
<td>27</td>
<td>0.30</td>
<td>0.40</td>
<td>6.774</td>
<td>0.556</td>
<td>92.4</td>
</tr>
<tr>
<td>28</td>
<td>0.51</td>
<td>0.61</td>
<td>10.876</td>
<td>0.919</td>
<td>92.2</td>
</tr>
<tr>
<td>29</td>
<td>0.06</td>
<td>0.07</td>
<td>1.557</td>
<td>0.107</td>
<td>93.6</td>
</tr>
<tr>
<td>30</td>
<td>0.06</td>
<td>0.08</td>
<td>1.705</td>
<td>0.115</td>
<td>93.7</td>
</tr>
</tbody>
</table>

ND: not determined.

$^a$Data taken from Su (2000) and Su and Huh (2002).
shelf (box V) (Fig. 5), according to the value of MAR in each box observed by Huh and his colleague (Huh and Su, 1999; Su, 2000; Su and Huh, 2002) and to the phosphorus content in surface sediments found in the present study and by Fang (2000, unpublished data). The middle shelf area is divided into two boxes because the MAR in the northern middle shelf slightly differs from the southern middle shelf.

Due to the ECS close connection with the Yellow Sea to the north and with the North Pacific Ocean to the east, neither of which have specific boundaries, the total area of the ECS is not easy to determine. Two widely accepted values are approximately $0.74 \times 10^6 \text{km}^2$ for the total area and $0.51 \times 10^6 \text{km}^2$ for the area with water depths $<200 \text{m}$ (Wong et al., 2000, and references cited therein). The calculated area of the present study is approximately $0.405 \times 10^6 \text{km}^2$, which accounts for about 60% of the whole ECS area and about 80% of the continental shelf area.

The present study investigated a portion area of the ECS. Based on total concentration of P in the inner shelf sediments in the ECS (Fang, unpublished data) and the adjacent Yellow Sea sediments (Liu et al., 2004), it was found that the total P concentration in the sediments in the ECS area remained within a narrow range, 14–23 $\mu \text{mol g}^{-1}$. Thus, the error in calculation caused by the variation of the total P concentration in sediments in different boxes was probably less than 20%. Table 5 shows the values of the parameters used in the calculations and the calculated results. The P burial flux was found to be in the range of $9.03–26.68$ (average $16.5) \times 10^9 \text{mol yr}^{-1}$ for the calculated area. Since the MAR value of the outer shelf is much less than those of the inner and middle shelves of the ECS, we believe that the average annual P burial flux in the whole ECS should fall in the range of $20–25 \times 10^9 \text{mol yr}^{-1}$. Using the box model calculation, the P burial flux in the ECS was previously estimated to be about $5.7 \times 10^9 \text{mol yr}^{-1}$.
Table 5
The area, mass accumulation rate, P total concentration, P accumulation rate and P burial flux for each box of the East China Sea

<table>
<thead>
<tr>
<th>Box</th>
<th>Area (km²)</th>
<th>Mass accum. rate (g cm⁻² yr⁻¹)</th>
<th>P total conc. (µmol g⁻¹)</th>
<th>P accum. rate (µmol cm⁻² yr⁻¹)</th>
<th>P burial flux (10⁹ mol yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>42400</td>
<td>0.6–1.0 (0.8)</td>
<td>15.8–17.2 (16.1)</td>
<td>9.48–17.2 (12.88)</td>
<td>4.02–7.29 (5.46)</td>
</tr>
<tr>
<td>II</td>
<td>38200</td>
<td>0.2–0.4 (0.3)</td>
<td>14.5–19.8 (16.5)</td>
<td>2.90–7.92 (4.95)</td>
<td>1.11–3.03 (1.89)</td>
</tr>
<tr>
<td>III</td>
<td>57400</td>
<td>0.2–0.5 (0.35)</td>
<td>13.5–22.2 (17.5)</td>
<td>2.72–11.13 (6.13)</td>
<td>1.55–6.37 (3.52)</td>
</tr>
<tr>
<td>IV</td>
<td>69700</td>
<td>0.1–0.4 (0.25)</td>
<td>17.5±3.6 (5)</td>
<td>1.42–8.41 (4.38)</td>
<td>0.98–5.85 (3.05)</td>
</tr>
<tr>
<td>V</td>
<td>197000</td>
<td>0.05–0.1 (0.075)</td>
<td>17.5±3.6 (5)</td>
<td>0.71–2.12 (1.31)</td>
<td>1.37–4.13 (2.59)</td>
</tr>
<tr>
<td>Total</td>
<td>404700</td>
<td></td>
<td></td>
<td></td>
<td>9.03–26.68 (16.50)</td>
</tr>
</tbody>
</table>

Value in parentheses is an average.

*Data taken from Huh and Su (1999), Su (2000) and Su and Huh (2002).


Assumed value based on the average value of box III with 20% deviation.

(Chen and Wang, 1999) and about 34.3 ± 21.5 × 10⁹ mol yr⁻¹ (Fang, 2004). Because the data for some parameters used in the box model calculation in these previous studies were assumed or indirectly obtained, the P burial flux was either underestimated or overestimated in both studies.

5. Conclusions

This paper has presented data for different forms of sedimentary P in the middle shelf of the ECS. The total concentrations of P in the surface sediments in the ECS ranged from 13.5 to 22.3 µmol g⁻¹, and this result agrees with those reported for the Amazon shelf and other shelves around the world. Detrital P was found to be the major form of sedimentary P and generally accounted for more than 70% of the total P pool. Organic P was found to be a minor form and the contribution was generally less than 15% of the total P pool. The calculated results for the PAR and the supply of P associated with reducible iron hydroxides in the study area range from 1.02 to 24.23 µmol cm⁻² yr⁻¹ and from 0.1 to 2.11 µmol cm⁻² yr⁻¹, respectively. Due to the high percentage of detrital P in the sediments and the high sediment accumulation rate, the P burial efficiency was higher than 90% in the ECS. Based on the PAR and the total area of the ECS, we estimate that the average annual P burial flux in the ECS is in the range of 20–25 × 10⁹ P mol yr⁻¹.

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