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# Influences of phosphorus concentration and porewater advection on phosphorus dynamics in carbonate sands around the Weizhou Island, northern South China Sea

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ABSTRACT

A series of flow-through reactor experiments were undertaken to assess the potential effect of porewater advection and dissolved inorganic phosphorus (DIP) concentration on benthic DIP dynamics in permeable sediments collected from the Weizhou Island, northern South China Sea. The flux of DIP ranged from −0.13 to 0.05 mmol $m^{-2}$ $h^{-1}$, and the reversal from DIP efflux to influx occurred when the DIP concentration reached a threshold. DIP release from the sediment into the seawater peaked at intermediate advection rate, which perhaps provide optimum conditions for DIP release related to $CaCO_3$ dissolution. Phosphorus limitation in seawater could be relieved by DIP release from the sediment, and $CaCO_3$-bound P in carbonate sands may play a major role in benthic DIP release and decrease in the molar nitrogen/phosphorus ratio in seawater around the Weizhou Island.

## 1. Introduction

Phosphorus (P) is an important biogenic element that limits algal growth, influences primary productivity, and biogeochemical cycling of other biogenic elements such as carbon (C) and nitrogen (N), and has been identified as the biolimiting nutrient in numerous coastal marine ecosystems around the world (Tyrrell, 1999; Xu et al., 2008; Jiang et al., 2014). Rivers are the major pathway through which land-derived organic matter with associated nutrients including P are transported to the ocean (Benitez-Nelson, 2000) although recent studies have shown that submarine ground water discharge could also play a significant role in supplying terrestrial nutrients to aquatic environments (Jeong et al., 2012; Zhang et al., 2017; Wang et al., 2020). In overall, surface sediment serves as a natural repository for organic matter and nutrients, and plays important roles in the biogeochemical cycling of P in marine environments (Paytan and McLaughlin, 2007).

Shallow water coral reefs extend over ~0.1% of the marine environment, and are mostly found in warm and/or oligotrophic waters, which span across ~30° N to 30° S, where the reefs are influenced by a lot of environmental stressors, including over-fishing, climate change, and eutrophication due to anthropogenic nutrient input (Hoegh-Guldberg et al., 2017). However, the complexity of coral reefs makes them hotspots for marine biodiversity as diverse aquatic species obtain their food and habitation from coral reef ecosystem (Reaka-Kudla, 1997). Despite the fact that coral reefs thrive in oligotrophic waters, their productivity is nevertheless high (Crossland et al., 1991), and may be linked to efficient nutrient recycling processes, in addition to the presence of organisms with characteristics photosynthetic endosymbionts (Ferrier-Pagès et al., 2016). On the other hand, diffusive fluxes of nutrients in organic-poor and coarse-grained carbonate sediments seem to have little contribution to primary productivity of coral reefs. Nevertheless, studies have shown that porewater advection can enhance the rate at which organic matter is mineralized, which makes permeable sandy sediments being active biogeochemical reactors (Rocha, 2008; Bourke et al., 2017), and thus, play important roles in the cycling of C, N, and P in coral reef ecosystems (Rasheed et al., 2002, 2004; Monbet et al., 2007).

Human activities affect not only nutrient concentration, but also nutrient ratio and structure. The classic Redfield stoichiometric ratio of N and P (N/P = 16) is generally and often used to judge whether N or P

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were milled around the inflow and outflow ports. Briefly, homogenized sediment was packed into each Plexiglas column. Seawater was pumped from the bottom up through the sediments at variable flow rates (see below) from a large carboy, with continuous air flushing. The sides of the sediment columns were covered with aluminium foil to allow light penetration only to the top of the columns. During incubations, the sediment columns were immersed in an outdoor tank filled with seawater (28–30 °C). Flux measurements began 6 h after the start of the core percolation to acclimatize under the laboratory condition. The measurements of both inflow and outflow characteristics were conducted twice, with the intervals of 1 h, and the duration of flux measurement was within 2 h. At each sampling time, seawater samples for nutrient analysis, including $Ca^{2+}$ and $Fe^{2+}$ were collected directly from the outflow, and the inflow seawater samples were collected from the source using 60 ml syringes. 40 ml of each seawater sample was filtered through 0.45 μm pore-size syringe filters and frozen at −20 °C. Additionally, the dissolved oxygen (DO), and the pH of inflow and outflow seawater were measured using a multiparameter probe (YSI ProDSS), and the precision was < 5% coefficient of variation (CV). The FTR experiments were carried out in duplicate.

Three FTR experiments were performed in this study. In the first experiment, sediments and seawater collected from each station were incubated to investigate the benthic DIP dynamics. In the second experiment, all the sediments collected from different stations were mixed and repacked in FTRs, and different DIP doses were added into the inflow seawater with the final DIP concentrations of 0.15, 0.23, 0.35, 2.50 and 3.15 μmol $l^{-1}$, respectively. The influent DIP concentrations were within the concentration range previously reported in the Weizhou Island seawater and sediment porewater (Ning et al., 2019). The porewater flow rate in the former two experiments was maintained at 1 ml $min^{-1}$ (equivalent to 48 l $m^{-2}$ $h^{-1}$), with a residence time of 1 h, but the rate in the natural environment are highly variable both spatially and temporally. Thus, it is important to assess how porewater advection could control benthic fluxes. In the third experiment, mixed sediments were used as in the second experiment, and the seawater without P amendment was pumped through the FTRs at variable flow rates (1, 2 and 3 ml $min^{-1}$, respectively). These rates (equivalent to 48, 96 and 144 l $m^{-2}$ $h^{-1}$, respectively) are typical in coral reefs (Santos et al., 2012).

### 2.3. Analytical methods and calculations

Nutrient concentrations were measured using an autoanalyzer (QuAAtro, SEAL Analytical). The precisions for $NH_4^+$, $NO_2^-$, $NO_3^-$, and dissolved inorganic phosphorus (DIP) analyses were < 6% CV (Ning et al., 2019). Concentrations of the dissolved inorganic nitrogen (DIN) were obtained as the sum of $NO_3^-$, $NO_2^-$ and $NH_4^+$. Alkalinity was determined by Gran titration (precision < 0.2%). The pH and alkalinity in the inflow and outflow seawater of each FTR were used to calculate the dissolved inorganic carbon (DIC) and aragonite saturation state ($\Omega_{Ar}$) using the Excel macro CO2SYS (Lewis et al., 1998). Dissolved Fe (assumed to be present as $Fe^{2+}$) was measured by inductively coupled plasma optimal emission spectroscopy, while $Ca^{2+}$ was measured by ethylene glycol tetraacetic acid titrations (Tsunogai et al., 1968). The precisions were < 5% CV.

Each frozen sediment sample was freeze-dried, and then the $CaCO_3$ content was measured through acid-base titration according to Müller, 1966. The total organic carbon (TOC) content was determined using a CHNOS Elemental Analyser (Vario EL III, Elemental Analyser). Prior to the determination, inorganic carbon was removed via acidification with 4 mol $l^{-1}$ HCl (Ning et al., 2016). The inorganic P (IP) content in sediments was determined using a procedure involving extraction with 1 mol $l^{-1}$ HCl, and analyzed for DIP. To determine total P (TP), the sediment samples were combusted at 550 °C for 2 h, extracted with HCl, and analyzed as IP. The concentration of organic P (OP) content was estimated by subtracting IP from TP contents (Aspila et al., 1976; Yang et al., 2018). All samples were analyzed in triplicates, with measurement precision less than 5% CV.

Fluxes (mmol $m^{-2}$ $h^{-1}$) were calculated from the differences in the concentrations of DIP, DIN, DO, DIC, $Ca^{2+}$ and $Fe^{2+}$ between the influent and effluent seawater, flow rate, and cross-sectional area of the sediment column according to Eq. (1) (Santos et al., 2012; Ning et al., 2019). In parallel, the yield/uptake of DIP from/by sediment (μmol $g^{-1}$ wet sediment) was calculated from the difference in DIP concentration between the influent and effluent seawater, volume of seawater in FTR, and the weight of wet sediments according to Eq. (2), since DIP yield/uptake should also be related to the amounts of sediment in addition to flow rate. Positive values represent efflux out of the sediment, while negative values represent influx into the sediment.

$$F = (C_{out} - C_{in}) \times R/S \quad (1)$$

$$F = (C_{out} - C_{in}) \times V/m \quad (2)$$

where $C_{in}$ and $C_{out}$ are the concentrations of DIP, DIN, DO, DIC, $Ca^{2+}$ and $Fe^{2+}$ in the influent and effluent seawater, respectively. $R$ is the flow rate, $S$ is the cross-sectional area of the sediment column (12.56 $cm^2$), $V$ is the volume of seawater in FTR (48–58 ml), and $m$ is the weight of wet sediments (220–230 g wet weight).

The data was subjected to a one-way analysis of variance (ANOVA) to know whether the variations and distributions of the measured parameters were statistically significant at the 95% confidence level. Pearson's correlation analysis with a two-tailed test of significance was carried out to evaluate the relationship between the measured parameters. All statistical analyses were performed using a Statistical Package for the Social Sciences (SPSS) software (version 22.0), and the statistical significance was judged at the criterion of $p < 0.05$.

## 3. Results

### 3.1. Chemical characteristics of the surface seawater and sediment around the Weizhou Island

There was no significant difference in the physical and chemical characteristics of the surface seawater at different stations around the Weizhou Island (ANOVA; $p > 0.05$; $n = 10$) (Table 1). However, seawater temperature and salinity in September 2019 were slightly lower than those in May 2018. The concentration of DIN in September was approximately twice the level measured in May, while the concentration of DIP was lower in September than in May. Thus, the DIN/DIP ratio in September 2019 ranged from 26.6 to 350, while the DIN/DIP ratio in May 2018 was 11.5–21.7, closer to the Redfield N/P ratio of 16:1.

The concentrations of DIN and DIP in sediment porewater samples were higher than those in the overlying seawater (Table 1). Porewater DIN concentration in September 2019 was higher than that in May 2018, but the opposite abundance was found for DIP, such that the DIN/DIP ratio became significantly higher in September 2019 than in May 2018. Concentration of $Fe^{2+}$ in porewater was as low as 1.05 μmol $l^{-1}$, and the highest concentration was found at station I5 in September 2019. $CaCO_3$ contents in the sediments at stations I3, I4 and I5 (representing carbonate sediment) were approximately twice the level at stations I1 and I2 (representing silicate sediment). Low levels of organic content were observed in the Weizhou Island sands, and the highest concentrations of TOC and OP were recorded at station I2. The molar TOC/OP ratio in all the investigated stations was higher than the Redfield C/P ratio of 106:1. IP was the dominant sedimentary P form in the Weizhou Island sediments, and OP constituted only a smaller part (6.1–28%) of the sedimentary TP pool (Table 1). Concentrations of sedimentary IP correlated significantly with the $CaCO_3$ content in carbonate sediments (Fig. 2).

**Table 1**
Physical and chemical characteristics of the surface seawater and sediment around the Weizhou island during May 2018 and Sep. 2019. The data of May are from Ning et al. (2019). The acronyms T, S, DIN, DIP, and TOC represents temperature, salinity, dissolved inorganic nitrogen, dissolved inorganic phosphorus, and total organic carbon, respectively.

| Time | Station | Seawater | | | | | Sediment | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | T (°C) | S (psu) | DIN (μmol $l^{-1}$) | DIP (μmol $l^{-1}$) | DIN/DIP | DIN (μmol $l^{-1}$) | DIP (μmol $l^{-1}$) | DIN/DIP | $Fe^{2+}$ (μmol $l^{-1}$) | $CaCO_3$ (%) | TOC (%) | IP (μmol $g^{-1}$) | OP (μmol $g^{-1}$) | TOC/OP |
| May | I1 | 32.5 | 32.40 | 3.26 | 0.27 | 11.9 | 6.52 | 0.68 | 9 | 1.28 | 40 | 0.04 | 0.20 | 0.05 | 667 |
| | I2 | 28.7 | 32.35 | 4.74 | 0.24 | 19.9 | 349 | 1.78 | 196 | 4.12 | 34 | 0.12 | 0.34 | 0.11 | 909 |
| | I3 | 33.3 | 32.10 | 2.31 | 0.16 | 14.9 | 11.9 | 1.12 | 11 | 1.35 | 67 | 0.07 | 0.26 | 0.08 | 748 |
| | I4 | 30.5 | 32.30 | 3.16 | 0.28 | 11.5 | 9.81 | 2.79 | 4 | 1.05 | 72 | 0.06 | 0.45 | 0.09 | 556 |
| | I5 | 31.7 | 32.38 | 5.69 | 0.26 | 21.7 | 7.14 | 2.04 | 4 | 1.31 | 61 | 0.04 | 0.23 | 0.09 | 379 |
| | **Means** | **31.3** | **32.31** | **3.84** | **0.24** | **16.0** | **76.9** | **1.68** | **45** | **1.57** | **55** | **0.07** | **0.30** | **0.08** | **652** |
| Sep. | I1 | 30.5 | 30.59 | 5.39 | 0.02 | 350 | 16.6 | 0.46 | 36 | 1.48 | 42 | 0.04 | 0.32 | 0.04 | 891 |
| | I2 | 29.4 | 30.26 | 11.09 | 0.08 | 144 | 225 | 0.54 | 418 | 1.15 | 26 | 0.04 | 0.36 | 0.09 | 380 |
| | I3 | 29.7 | 31.51 | 2.88 | 0.08 | 37.5 | 114 | 0.54 | 213 | 1.43 | 70 | 0.04 | 0.52 | 0.03 | 995 |
| | I4 | 29.4 | 30.04 | 6.63 | 0.15 | 43.1 | 67.5 | 0.50 | 135 | 1.36 | 69 | 0.02 | 0.30 | 0.08 | 172 |
| | I5 | 30.0 | 30.24 | 11.47 | 0.43 | 26.6 | 158 | 0.69 | 229 | 7.74 | 64 | 0.03 | 0.31 | 0.07 | 361 |
| | **Means** | **29.8** | **30.53** | **7.49** | **0.15** | **120** | **104** | **0.57** | **206** | **2.80** | **54** | **0.03** | **0.36** | **0.06** | **560** |




**Fig. 2.** Linear relationship between IP and $CaCO_3$ contents in carbonate sediments around the Weizhou Island. Dashed lines represent 95% confidence intervals.

**Fig. 3.** Benthic fluxes (or expressed as the yield/uptake) of (a) DIP and (b) DIN at the investigated sites in the Weizhou Island during May 2018 and Sep. 2019. The May data are from Ning et al. (2019). The error bars show SD.

### *3.2. The first FTR experiment: benthic P flux at different stations*

In the first experiment, the DIP flux varied at different stations and differed in the two periods (Fig. 3a). At most of the stations, DIP was transferred from the seawater to the sediment in May with the exception of station I2, and released from the sediment into the seawater in September with the exception of station 15 (Fig. 3a). DIP flux correlated with OP content in sediments, but had no correlations with the fluxes of DO, DIC, $Ca^{2+}$ and $Fe^{2+}$, but the relationship between the fluxes of DO, DIC, and $Ca^{2+}$ was significant (Table 2). The fluxes of DO, DIC, $Ca^{2+}$ and $Fe^{2+}$ at different stations during the two investigated period are shown in Table S1. DIN was transferred from seawater to the sediment at most of the investigated stations (Fig. 3b). In September, considerable DIN influx was only observed at stations I1 and I2 with the highest DIN/DIP ratio in seawater. Flowing through the sediments, the DIN/DIP ratio in the effluent seawater decreased in comparison with those in the

the changing DIP concentrations as discussed in Section 4.2 below.

### 4.2. Impacts of DIP concentration in seawater on P dynamics in permeable sediments

The concentration of DIP in seawater varied by a factor of 10 around the Weizhou Island, and the benthic DIP flux was tightly related to the concentration of DIP in seawater after ruling out the dissimilarity in sediments at different stations in the second FTR experiment. The transfer of DIP to the sediments may be favourable for $CaCO_3$ calcification and Ca-P formation, as $CaCO_3$ calcification occurred under condition of the high DIP concentration (Fig. 5b). This observation is consistent with the previous finding that carbonate sediments efficiently trap P through strong adsorption of DIP onto $CaCO_3$ particles (Monbet et al., 2007). The mechanism involves initial adsorption of DIP at the surface kink sites of $CaCO_3$ particles, followed by incorporation of some surface-associated DIP into the crystal structure as growth occurs (Walter and Burton, 1986; House and Donaldson, 1986).

The dissolution of $CaCO_3$ occurred when DIP concentration was lower than $1.11 \pm 0.35$ μmol $l^{-1}$, as the inhibition of $CaCO_3$ dissolution by adsorption of DIP at surface kink sites was weakened (Walter and Burton, 1986). However, there was no DIP release from the sediment to the seawater when DIP concentration was in the range of 0.40–1.11 μmol $l^{-1}$, indicating that the released DIP from $CaCO_3$ dissolution was still adsorbed by the $CaCO_3$ particles under the intermediate concentration of DIP in seawater. Only when the DIP concentration was lower than $0.40 \pm 0.06$ μmol $l^{-1}$, both adsorbed and co-precipitated P were released with the dissolution of $CaCO_3$, which happened to relieve P limitation in seawater. The tightly coupled relationship between DIP in seawater and $CaCO_3$ precipitation/dissolution in sediments also explains why the concentrations of sedimentary IP exhibited a linear relationship with $CaCO_3$ content in carbonate sediments (Fig. 2). In fact, the data obtained from the first FTR experiment deviated from the regression line of DIP concentration and DIP flux (Fig. 5). The first reason is that the dominant DIP release pathway from the sediment may be remineralization of OP rather than $CaCO_3$ dissolution at sites with higher OP content (such as station I2). The second reason may be due to the dissimilarity in seawater characteristics such as pH and $\Omega_{Ar}$. Great $Ca^{2+}$ influx was observed at stations I4 and I5 with the high $\Omega_{Ar}$ in seawater (Table S1), due to negative correlation between $Ca^{2+}$ flux of carbonate sediments and the $\Omega_{Ar}$ of the overlying seawater (Eyre et al., 2018; Ning et al., 2019), even with the fact that DIP concentration was lower than $1.11 \pm 0.35$ μmol $l^{-1}$ (Fig. 5b). The $\Omega_{Ar}$ was > 1 at the outlet of all the FTRs (data are not shown), but $CaCO_3$ dissolution still occurred at $\Omega_{Ar} > 1$, which suggests that the bulk porewater $\Omega_{Ar}$ may not be the actual condition at the site of dissolution. This could be due to the presence of microzones of high $pCO_2$ caused by aerobic respiration in intragranular pores of $CaCO_3$ grain, and the diagenesis-dependent low pH in microzones may have facilitated dissolution (Kessler et al., 2020). Porewater advection also transports DO into the permeable sediment, which stimulates aerobic respiration and enhances dissolution (Cyronak et al., 2014).

### 4.3. Impacts of porewater advection rates on P dynamics in permeable sediments

Previous studies have assessed the limitations in the use of FTR, which represents a 1-dimensional, steady state, and unidirectional system, and the fluxes obtained from the FTR should be seen as potential in situ rates (Santos et al., 2012; Ning et al., 2019). Comparisons between fluxes obtained from the FTR experiments with other approaches need to be undertaken with care, because the direction of flow, advective rates, and the length of sediment column are different. In fact, porewater advection rates in the natural environment are highly variable spatially and temporally (Santos et al., 2012). In this study, the variation of DO consumption rate was consistent with the findings reported for other study areas (Rasheed et al., 2004; Cook et al., 2007; Glud et al., 2008; Santos et al., 2012). The DIP release rates from organic matter remineralization calculated from DO fluxes increased with advection rates (Fig. 6b). However, a major discrepancy between the total and remineralization-dependent fluxes of DIP suggests that a large portion of DIP release was derived from sedimentary IP pool. This is consistent with previous study of Suzumura et al. (2002) who reported that desorption of P from $CaCO_3$ particles represents an important pathway, which supplies DIP from carbonate sediment to the overlying seawater. The highest DIP flux was observed at the intermediate advection rate, but little is known about the mechanism. This could be explained based on a tentative conceptual model from Santos et al. (2012), and according to the four premises in this study. First, the pool of Ca-P in sediments significantly affects DIP flux. Second, the $CaCO_3$ precipitation/dissolution is controlled by $\Omega_{Ar}$ in seawater. Third, diagenesis-dependent $\Omega_{Ar} < 1$ in microzones of the $CaCO_3$ grain pores are sites for dissolution, although bulk porewater $\Omega_{Ar}$ was > 1. Fourth, higher DIP concentration inhibits $CaCO_3$ dissolution.

At low advection rate (48 l $m^{-2}$ $h^{-1}$), porewater probably follows a tortuous path around the grains (Santos et al., 2012). There is longer time for DO consumption and DIP release from OP remineralization in sediment column. However, DIP adsorption on the surface of sediment grains due to low advection rate may inhibit the dissolution of $CaCO_3$. At high advection rate (144 l $m^{-2}$ $h^{-1}$), DO concentration around and within the sand grains is expected to increase (Santos et al., 2012), preventing the development of $\Omega_{Ar} < 1$ microenvironments within the grains. Meanwhile, higher DO concentrations within the grains allow for the formation of Fe oxides that bind P (van Helmond et al., 2020). At intermediate advection rate (96 l $m^{-2}$ $h^{-1}$), seawater within grains would be partially flushed creating a steep oxygen gradient in porous sands (Santos et al., 2012). Since the $\Omega_{Ar}$ in the inner parts of the grains may be < 1, the DO transferred from the outer parts into the inner parts would facilitate organic matter mineralization, and the diagenesis-dependent low pH would also facilitate dissolution, which is accompanied by DIP release. The release of DIP could be brought from the inner parts to the outer parts by intermediate advection, rather than being adsorbed by the $CaCO_3$ particles under low advection rates. Thus, intermediate advection would be suitable for $CaCO_3$ dissolution and substantial release of DIP. This rate is typically found on continental shelves, implying that the $CaCO_3$ precipitation/dissolution in carbonate sands may play a major role in P cycling in coral reefs.

### 4.4. Comparison of P content in sediments of the Weizhou Island and worldwide coastal areas

Bulk sedimentary P pool contributes to the DIP levels in the overlying seawater and plays important roles in P cycling in coral reefs (Suzumura et al., 2002; Ferrier-Pagès et al., 2016). The concentrations of P in surface sediments around the Weizhou Island were lower than the levels reported for other study areas as shown in Table 3. The differences are related in part to the texture of sediment, as fine-grained sediments dominated by clay and/or silt have stronger affinity with organic matter and P than coarse sandy sediments (Dan et al., 2020a). Thus, the content of P is expected to be lower in coral reefs permeable sediments as observed in this study. On the other hand, terrestrial and anthropogenic influence may account for higher P content in reef sediments as reported for the Kavaratti island, Indian Ocean (Joy et al., 2019) and Great Barrier Reef (Alongi et al., 2006; Monbet et al., 2007). However, the input of terrigenous organic matter with elevated TOC/OP ratio may also contribute to low OP content (especially if the OP is relatively labile) in sediments. According to the official data published by local government (http://xxgk.beihai.gov.cn/bhshjbhj/tszl_84510/hbxxgk/swrfz/index.html), the TOC/OP ratio of suspended particulate matter in sewage outlet water of a wastewater treatment plant on the Weizhou Island is ~167, and the ratio in untreated wastewater could be twice that of treated wastewater. In addition, the OP produced by

**Table 3**
Comparison of the IP and OP contents in the surface sediments of the Weizhou Island with other worldwide coastal areas, including reef areas. Values in parentheses indicate the percentage of the OP form with regard of total phosphorus.

| Locations | IP content (μmol $g^{-1}$) | OP content (μmol $g^{-1}$) | References |
|---|---|---|---|
| Maowei Sea, northern Beibu Gulf | 2.9–16 | 1.1–12 (25–56%) | Yang et al., 2019 |
| northern South China Sea | 4.6–15 | 0.47–5.8 (7.2–32%) | Yang et al., 2018 |
| Cross River estuary, West Africa | 7.1–16 | 0.32–2.9 (13%) | Dan et al., 2020b |
| Mid and outer shelf of Great Barrier Reef | 6.0–11 | 2.4–3.7 (16–28%) | Monbet et al., 2007 |
| Arlington and Sudbury Reefs, Great Barrier Reef | 11–14[a] | | Alongi et al., 2006 |
| reefs of Ishigaki Island, Japan | 6.1–7.2 | 0.92–1.1 (13%) | Suzumura et al., 2002 |
| reefs of the Florida Keys, USA | < 0.19[a] | | Szmant and Forrester, 1996 |
| reefs of Kavaratti island, Indian Ocean | 0.61 ± 0.16 | 4.2 ± 1.5 (87%) | Joy et al., 2019 |
| Weizhou Island, northern South China Sea | 0.20–0.52 | 0.03–0.11 (6.1–28%) | This study |

[a] The value represented total phosphorus content in sediments.

organisms in the water column could be readily remineralized before reaching the sediment or at the early stage of diagenesis in the uppermost sediments, resulting in low OP concentration and large fraction of refractory OP component in reef sediments (Suzumura et al., 2002). All these may help explain why OP constituted only a smaller fraction of the sedimentary TP pool in different study areas (Table 3). At least, most of the anthropogenic and natural P input in the coastal waters from land appears to be taken up by the nearshore algae before reaching patch reef areas (Szmant and Forrester, 1996), and this accounted for the lower content of P in reef sediments of the Florida Keys as shown in Table 3. In summary, the relatively low P content in sediments around the Weizhou Island is somewhat related to sediment textures, terrestrial supply of organic matter with higher TOC/OP ratios and biogeochemical processes.

## 5. Conclusions

This study evaluated the benthic phosphorus (P) dynamics in permeable sediments under the changing environments around the Weizhou Island, surrounded by coral reefs. The higher DIN/DIP in seawater and the high TOC/OP ratio in sediments pointed to P limitation in the aquatic environment around the Weizhou Island. The release of DIP from sediments and uptake of DIN in sediments could help address the lingering higher DIN/DIP ratio in seawater around the Weizhou Island. The potential fluxes of DIP at different stations were positively related to OP content in sediments, but the relatively low OP content in sediments around the Weizhou Island makes it difficult for benthic DIP efflux to make up for the deficiency of P in the water column. However, intermediate advection rate enhanced sedimentary $CaCO_3$ dissolution and accompanied DIP release, implying that $CaCO_3$-bound P in carbonate sands may play a major role in P cycling in coral reefs. Furthermore, the reversal from DIP efflux to influx occurred when the concentration of DIP in seawater reaches a threshold of 0.40 ± 0.06 μmol $l^{-1}$, which could be coupled to adsorption and co-precipitation of P on $CaCO_3$ particles in sediments.

## CRediT authorship contribution statement

**Zhiming Ning:** Conceptualization, Methodology, Investigation, Writing. **Cao Fang:** Methodology, Investigation, Data curation. **Kefu Yu:** Resources, Supervision, Project administration. **Bin Yang:** Conceptualization, Formal analysis, Supervision. **Solomon Felix Dan:** Writing - Review & Editing. **Ronglin Xia:** Investigation, Resources. **Yukun Jiang:** Investigation, Validation. **Ruihuan Li:** Validation, Visualization. **Yinghui Wang:** Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2020.111668.

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