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Research Article

Characteristics of Phosphorus Compounds and Their Effects in Sediments of an Eutrophic Chaohu Lake, China

Surface sediments and sediment cores in a shallow eutrophic lake, Chaohu Lake, were analyzed by ³¹P-NMR to reveal the phosphorus (P) species and their effects on upper water quality. Total P (TP) in the NaOH-EDTA extracts was dominated by inorganic phosphate (P_i), with higher levels being observed in the heavily eutrophic western lake (79.1 ± 1.7%) than in the eastern lake (68.1 ± 2.4%). These findings were opposite to those for organic phosphorus (P_o). P_i (*ortho*-phosphate and pyrophosphate) and P_o (phosphonates, *ortho*-phosphate monoesters and phospholipids, DNA) were detected in the NaOH-EDTA extracts of the sediments by ³¹P-NMR. The majority of P_o consisted of *ortho*-phosphate monoesters (80.2 ± 2.7%). For sediment cores, the contents of phospholipids and DNA declined more rapidly than that of *ortho*-phosphate monoesters and pyrophosphate as sediment depth increased, with these compounds primarily occurring in the top 10 cm of sediment. The positive relationship between P_o in sediment and TP in the water showed that P_o compounds in the sediment would be released to the water. These compounds of P_o will be mineralized to P_i and potentially bioavailable for recycling to surface water, supporting further growth of aquatic organisms and leading to algal blooms.

Keywords: Eutrophication; Nutrient sources; Organic phosphorus; ³¹P-NMR; Water quality

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1 Introduction

The release of phosphorus (P) from sediment is a vital nutrient source that will induce continuous eutrophication in lakes even if external inputs are reduced [1]. Sediment-basic P recycling depends to a large extent on the forms of P in sediments [2]. Sediment P includes inorganic phosphorus (P_i) and organic phosphorus (P_o), and P_o constitutes a major P fraction in some sediments. Indeed, P_o accounts for about 87% [3], 40–90% [4], and 10–70% [5] of total phosphorus (TP) in swamp sediments, Everglades, and lake sediments, respectively. The components of P_o have been shown to be much more bioavailable to aquatic organisms than previously assumed [6]. Specifically, P_o constituents can be hydrolyzed to phosphate and provide bioavailable P under some conditions [7, 8]. Stable P_o (e.g., phosphonate) can also be utilized by plankton and lead to algal blooms [9, 10]. P_o is a key part of P recycling that provides a nutrient source for aquatic organisms. Transformation and releasing of P_o in the sediment can accelerate eutrophication, especially in eutrophic lakes. Studies have focused on P_i and its

bioavailability [11], however, investigations of the species, concentrations, dynamics and effects of P_o in sediment have been limited because of its complexity and limitations of analytical methods [12, 13].

Several analytical methods have been developed to elucidate P_o compounds, and these were usually estimated from the difference between TP and P_i or fractionation with different acids and alkalis [14–16]. Although these methods have provided usefully information pertaining to P biogeochemical cycling in aquatic environments, they have not yielded sufficient insight into identification of specific P compounds [17]. Phosphorus-31 NMR spectroscopy (³¹P-NMR) is a non-destructive, non-invasive technique for identifying chemical forms that has the advantage of enabling multiple P compounds to be characterized simultaneously with distinct binding properties [12]. Therefore, it is an ideal technique for use in analysis of P_o species in marine or freshwater sediment [18]. Several P compounds have been detected by ³¹P-NMR, including phosphonates, *ortho*-phosphate, *ortho*-phosphate monoesters, *ortho*-phosphate diesters, pyrophosphate, and polyphosphate [19]. ³¹P-NMR spectroscopy can provide detailed information pertaining to P_o species and concentrations, which will contribute to P_o transformation and recycling. Application of ³¹P-NMR for detection of P_o has also been shown to be more accurate than molybdate colorimetry because labile P_o compounds may be hydrolyzed with the addition of acid [20, 21].

Lake eutrophication is a serious environmental problem in China [22], especially in areas that are densely populated or in which

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Abbreviations: NMR, nuclear magnetic resonance; OM, organic matter; P_i, inorganic phosphorus; P_o, organic phosphorus

industry-agriculture has developed, such as Taihu Lake, Chaohu Lake and Dianchi Lake [22–25]. Accordingly, lake eutrophication has increasingly become a threat to water quality, human health and social development in the last 30 years in China [26]. Since the 1990s, studies have mainly focused on concentration of TP and P_i and their transformation by P fractionation. However, little is known about the species and dynamics of P_o in the sediments of eutrophic lakes. In this study, the Chaohu Lake was selected as a typical lake for investigation of sediment P compounds. The specific objectives of this study were to detect the P compounds in surface sediment and sediment cores by ^{31}P -NMR and study the relationship between P in sediment and water quality. This study provides useful information pertaining to the compounds and dynamics of P in eutrophic lakes and management of lake eutrophication.

2 Materials and methods

2.1 Study area and sediment sampling

The Chaohu Lake, which is located in Anhui Province, eastern China, is one of the five largest freshwater lakes in China. The lake sits along the left bank of the Yangtze River between $31^\circ 25' - 31^\circ 43' \text{N}$ and $117^\circ 17' - 117^\circ 52' \text{E}$. The Chaohu Lake is a shallow lake, with a surface area of 750 km^2 and a mean depth of 3 m. As the largest freshwater lake in Anhui province, the Chaohu Lake plays a vital role in shipping, fisheries, agricultural irrigation and a drinking-water source. The lake has undergone serious eutrophication because of the excessive input of nutrients [27]. The Chaohu Lake is divided into eastern and western parts by Laoshan (an island in the Chaohu Lake) and Zhongmiao (a town). Owing to differences in socioeconomic development and pollutant input, algal blooms have occurred with

increasing frequency and intensity in the western lake, and eastern lake regions have much better water quality.

To select representative sites in the Chaohu Lake, ten sampling grids were set up in July 2011 according to previously reported lake survey guidelines [28]. Each sampling grid had one sampling point that was selected based on water quality. Sites 1–4 and 5–10 were located in the western and eastern lake, respectively. Sediment cores were collected using a gravity corer (Uwitec, Austria) with PVC sampling tubes (diameter 6.3 cm and length 60 cm). Three surface (2 cm) sediment samples of each site were collected (Fig. 1). Samples at the same site were pooled and homogenized to obtain a representative sample. Two sediment cores were sampled for sites 1 and 8 using a gravity core sampler, and sediment cores were then transected into 2 cm segments in sequence. All of the samples were collected in July of 2011. The samples were freeze-dried under -50°C by FD-1 freeze-dryers upon arrival in the laboratory. Dried samples were ground and sieved to pass through a 100-mesh sieve. Quartering of the samples was taken as the representative samples, and then the samples stored in sealing plastic bag and stored at room temperature until analysis.

2.2 Analysis of sample properties

TP in sediment was measured by treating the samples at 500°C (2 h), followed by extraction with 1 M HCl (16 h). P_i was extracted without combustion with 1 M HCl (16 h). The P_o concentrations in the sediments were calculated as the difference between TP and P_i [14]. Organic matter (OM) in sediments was determined based on the loss on ignition after heating at 550°C for 4 h [29]. TP in the water was measured using the molybdenum blue method after the digestion by persulfate, and the quality control of the analysis were carried

Figure 1. Location of sampling sites in the Chaohu Lake (R1, Pai River; R2, Fengle-hangbu River; R3, Baishishan River; R4, Mawei River; R5, Shuangqiao River; R6, Zhegao River; R7, Qiyang River; R8, Tongyang River; R9, Nanfei-dianbu River).

out by deionized water [30]. The annual average TP in the water column was calculated for each site using monitoring data collected from 2009 to 2011. Three replicates were performed for each index, and the mean value was calculated.

2.3 NaOH-EDTA extraction and ^{31}P -NMR analysis

Sediment samples (3 g) were extracted with 30 mL of a solution composed of 0.05 mol/L EDTA and 0.25 mol/L NaOH for 16 h at room temperature [31, 32]. Aliquots of the EDTA/NaOH extracts were then used to analyze P_i and TP using the molybdenum blue method before and after digestion with $\text{K}_2\text{S}_2\text{O}_8$, after which the P_o was determined based on their difference. The remaining solution was frozen and lyophilized and then used for ^{31}P -NMR analysis. The freeze-drying method has the risk to cause the loss of some organic P compounds because a considerable amount of freeze-dried powders could not be re-dissolved [32].

The lyophilized NaOH/EDTA extracts (0.3 g) were re-dissolved in 0.6 mL D_2O and 0.1 mL 10 M NaOH and then subjected to ultrasonication for 30 min, after which they were allowed to equilibrate for 5 min. The supernatants were subsequently centrifuged for 15 min at 14 000 rpm and then transferred to 5-mm NMR tubes. Solution ^{31}P -NMR spectra were obtained using a Bruker 400 MHz spectrometer (Bruker, Billerica, MA, USA) at 129.53 MHz with a 90°C observation pulse, relaxation delay of 2 s and acquisition time of 0.6 s. Spectra were collected based on around 20 000 scans (Beijing NMR Center) and chemical shifts were recorded relative to 85% H_3PO_4 standard ($\delta = 0$ ppm). Signals were assigned to P species based on data in previous reports [12, 33, 34]. The peak area was calculated by visual inspection and an automated peak analysis tool. The form of different P species areas and contribution of the each P compound group *ortho*-phosphate (*ortho*-P: 6 to 7 ppm), phosphonates (*phon*-P: 18 to 20 ppm), pyrophosphate (*pyro*-P: -3.5 to -4.5 ppm), *ortho*-phosphate monoesters (*mono*-P: 4 to 6 ppm), DNA (*DNA*-P: 0 ppm), and phospholipids (*lipids*-P: 1–3 ppm) was calculated relative to the P_o in the NaOH/EDTA extract.

3 Results

3.1 Phosphorus variation in sediment and water

The TP in surface sediments of the Chaohu Lake displayed a marked variability between the western and eastern lake, with higher concentrations being observed in the western lake. However, the percentage of P_o showed opposite trends in the sediments ($p < 0.01$) (Tab. 1). Among the ten sediment samples, TP varied greatly from 420.36 to 1089.82 mg/kg, with an average of 686.93 mg/kg. Additionally, the highest TP values were observed in the sediment of the western lake, which was algal-dominated region. The concentration of P_o in the sediment ranged from 149.60 to 226.68 mg/kg, accounting for 20.56 to 36.69% of the TP. Moreover, TP in the water column ranged from 0.031 to 0.145 mg/L, with the highest value being observed in the algal-dominated western lake. TP in the NaOH/EDTA extract ranged from 173.13 to 844.20 mg/kg, accounting for 31 to 77% of TP in the sediment. P_i in extracts ranged from 117.86 to 679.41 mg/kg, while P_o in extracts ranged from 55.27 to 164.79 mg/kg and P_o recovery by the NaOH/EDTA extractions ranged from 30 to 73%.

Table 1. Physicochemical properties and concentrations of extracted P compounds in NaOH/EDTA extracts of surface sediments as determined by solution ^{31}P -NMR

Site	Sediment				NaOH/EDTA extract (mg/kg)							Water (mg/L)
	OM (g/kg)	TP (mg/kg)	P_i (mg/kg)	P_o (mg/kg)	TP	<i>ortho</i> -P	Mono-P	Lipids-P	DNA-P	Pyro-P	Phon-P	
1	22.63	1089.82	863.14	226.68	844.20	668.6 (79.2) ^{a)}	133.8 (15.8)	1.4 (0.2)	25.8 (3.1)	10.8 (1.3)	3.9 (0.5)	0.145
2	25.64	1012.35	804.22	208.12	694.85	552.0 (79.4)	105.0 (15.1)	1.9 (0.3)	28.5 (4.1)	4.9 (0.7)	2.5 (0.4)	0.121
3	21.13	945.78	743.46	202.32	470.25	369.7 (78.6)	79.6 (16.9)	1.4 (0.3)	14.3 (3.0)	2.4 (0.5)	2.9 (0.6)	0.076
4	15.71	834.55	636.00	198.55	262.03	199.7 (76.2)	45.6 (17.4)	1.6 (0.6)	13.5 (5.2)	1.6 (0.6)	nd	0.055
5	13.56	554.29	370.86	183.42	173.13	115.8 (66.9)	45.6 (26.3)	0.3 (0.2)	9.4 (5.4)	2.0 (1.2)	nd	0.076
6	12.37	498.24	332.90	165.33	233.96	156.3 (66.8)	62.4 (26.7)	0.7 (0.3)	13.2 (5.6)	1.3 (0.6)	nd	0.076
7	16.00	525.78	370.41	155.37	320.52	225.8 (70.5)	72.6 (22.6)	1.1 (0.4)	18.8 (5.8)	1.8 (0.6)	0.4 (0.1)	0.072
8	19.24	453.38	303.78	149.60	224.80	150.6 (67.0)	58.6 (26.1)	0.7 (0.3)	12.7 (5.6)	2.2 (1.0)	nd	0.031
9	19.77	420.36	266.12	154.24	315.84	199.9 (63.3)	93.4 (29.6)	1.0 (0.3)	18.5 (5.9)	2.6 (0.8)	0.4 (0.1)	0.043
10	9.64	534.74	369.27	165.47	187.17	129.3 (69.1)	46.1 (24.6)	nd	9.8 (5.2)	2.0 (1.1)	nd	0.039

nd, not detected.

^{a)}Numbers in parentheses are percentages.

The average concentration of P_o in the western lake (208.92 mg/kg) was higher than that in the eastern lake (162.24 mg/kg), but the ratio of P_o and TP in the western lake (21.64%) was lower than that in the eastern lake (32.74%). The concentrations of OM varied with those of TP. The contents of OM in the western lake were higher than those in the eastern lake, as indicated by averages of 21.28 and 15.10 g/kg, respectively.

3.2 ^{31}P -NMR spectra of NaOH/EDTA extracts of surface sediments

The NMR spectra of the surface lake sediments are shown in Fig. 2 and Tab. 1. Six and five ^{31}P -NMR compounds were observed in the NaOH/EDTA extracts of the western and eastern lake surface sediments, respectively. The concentrations of P_o differed between the western and eastern lake sediments, and mono-P was the main component of P_o . All NMR spectra showed compounds in the area of phon-P, *ortho*-P, mono-P, lipids-P, DNA-P, and pyro-P. The concentrations of various P compound groups in surface sediment are presented in Tab. 1. The concentration of *ortho*-P ranged from 115.8 to 668.6 mg/kg, accounting for 63.3 to 79.4% of TP. Mono-P ranged from 45.6 to 133.8 mg/kg, accounting for 15.1 to 29.6% of TP. Lipids-P ranged from 0 to 1.9 mg/kg, accounting for 0 to 0.6% of the TP. DNA-P ranged from 9.4 to 28.5 mg/kg, accounting for 3.1 to 5.9% of the TP. Pyro-P ranged from 1.3 to 10.8 mg/kg, accounting for 0.5 to 1.3% of the TP. The levels of phon-P ranged from 2.5 to 3.9 mg/kg, accounting for 0.4 to 0.6% of TP. In surface sediments, mono-P was the main component of P_o of the TP. Phon-P was primarily found in sediments of the western lake, which were highly polluted. P_o species and concentrations in the sediments of the western and eastern lake were also affected by the different statuses of lake eutrophication.

3.3 ^{31}P -NMR spectra of NaOH/EDTA extracts of the sediments cores

To identify and quantify P species and elucidate their transformation process, we analyzed sediment cores by ^{31}P -NMR. A total of six

and five P components in the sediment cores were detected by ^{31}P -NMR in the western and eastern lake, respectively (Fig. 3 and Tab. 2), including phon-P, *ortho*-P, mono-P, lipids-P, DNA-P, and pyro-P. As the sediment depth increased (0–30 cm), the concentrations of TP decreased from 1089.8 to 265.0 mg/kg and 453.4 to 267.6 mg/kg in the western and eastern lake, respectively. The ratio of P_o to TP also decreased from 20.8 to 11.5% and 33.0 to 8.0% with increasing depth in the western and eastern lake, respectively. Phon-P was only found in western lake sediment cores, with low levels being observed in the surface sediment and increasing to 10.4 mg/kg at 10 cm.

As sediment core depth increased, the species and concentration of P decreased, with a greater decrease being observed in western lake sediment than eastern lake sediment. In western sediment cores, the *ortho*-P concentration declined from 668.6 to 106.4 mg/kg, while the mono-P concentration decreased from 133.8 to 13.5 mg/kg. Moreover, the diesters P concentration declined from 29.1 to 0 mg/kg. The pyro-P concentration declined from 10.8 to 0.4 mg/kg. Lipids-P and DNA-P were not detected below 8 and 10 cm, respectively. In sediment cores from the east lake, the *ortho*-P concentration declined from 150.6 to 147.2 mg/kg, while the mono-P concentration decreased from 58.6 to 12.6 mg/kg. Additionally, diesters P decreased (from 13.4 to 2.0 mg/kg) with increasing sediment depth and was not detected below 14 cm. Pyro-P concentration declined from 2.2 to 0.2 mg/kg.

4 Discussion

4.1 P forms identified by ^{31}P -NMR

Mono-P is an important P_o compound in sediments that includes inositol P, sugar phosphates, and mononucleotides. Inositol phosphates are considered to be the most abundant P_o in aquatic sediment, which could be mineralized under anaerobic or aerobic conditions [35]. In this study, mono-P comprised 73.2–80.6% of P_o in the sediment, being the majority of P_o in the sediment. Diesters P is a mixture of numerous compounds with varying lability [36]. In this study, DNA-P and lipids-P were detected in the surface sediment.

Table 2. Concentrations of P compounds in NaOH/EDTA extracts of the sediment cores determined by solution ^{31}P -NMR (mg/kg)

Sampling site	Depth (cm)	TP in sediments	TP in extractions	<i>ortho</i> -P	Pyro-P	Mono-P	Lipids-P	DNA-P	Phon-P
Core 1	0–2	1089.8	844.2	668.6 (79.2) ^{a)}	10.8 (1.3)	133.8 (15.8)	1.4 (0.2)	25.8 (3.1)	3.9 (0.5)
	2–4	1201.3	757.4	613.3 (81.0)	5.4 (0.7)	106.2 (14.0)	1.3 (0.2)	26.6 (3.5)	4.7 (0.6)
	4–6	1169.7	876.6	731.3 (83.4)	5.0 (0.6)	111.8 (12.8)	0.9 (0.1)	21.2 (2.4)	6.4 (0.7)
	6–8	1056.8	911.2	795.3 (87.3)	3.3 (0.4)	84.4 (9.3)	1.5 (0.2)	14.7 (1.6)	12.1 (1.3)
	8–10	1004.2	762.8	659.9 (86.5)	2.4 (0.3)	79.2 (10.4)	nd	10.8 (1.4)	10.4 (1.4)
	16–18	745.5	212.4	196.2 (92.4)	0.1 (0.1)	15.5 (7.3)	nd	0.6 (0.3)	nd
	20–22	554.7	176.2	161.7 (91.8)	0.3 (0.2)	14.2 (8.0)	nd	nd	nd
	28–30	265.0	120.2	106.4 (88.5)	0.4 (0.3)	13.5 (11.2)	nd	nd	nd
	0–2	453.4	224.80	150.6 (67.0)	2.2 (1.0)	58.6 (26.1)	0.7 (0.3)	12.7 (5.6)	nd
	2–4	469.3	269.00	184.1 (68.4)	2.1 (0.8)	69.3 (25.8)	0.8 (0.3)	12.7 (4.7)	nd
Core 8	4–6	459.1	291.60	200.3 (68.7)	2.0 (0.7)	75.2 (25.8)	0.8 (0.3)	13.2 (4.5)	nd
	6–8	463.8	289.03	211.1 (73.0)	1.6 (0.5)	63.3 (21.9)	0.7 (0.2)	12.3 (4.3)	nd
	8–10	432.1	280.40	216.6 (77.3)	1.3 (0.5)	53.9 (19.2)	0.8 (0.3)	7.8 (2.8)	nd
	12–14	431.7	163.44	131.9 (80.6)	0.5 (0.3)	29.2 (17.8)	0.4 (0.3)	1.6 (1.0)	nd
	16–18	321.6	155.22	130.1 (83.8)	0.3 (0.2)	24.8 (16.0)	nd	nd	nd
	20–22	295.0	138.60	121.2 (87.4)	0.4 (0.3)	17.1 (12.3)	nd	nd	nd
	28–30	267.6	159.91	147.2 (92.0)	0.2 (0.1)	12.6 (7.8)	nd	nd	nd

nd, not detected.

^{a)} Numbers in parentheses are percentages.

Figure 2. ^{31}P -NMR spectra of NaOH/EDTA extracts of surface sediments in the Chaohu Lake (a: phosphonates; b: *ortho*-phosphate; c: *ortho*-phosphate monoesters; d: phospholipids; e: DNA; f: pyrophosphate).

DNA-P primarily originates from bacteria and hydrophytes [37]. The Chaohu Lake is a shallow and eutrophic lake, where the algae-derived organic matter source and high productivity may be the main sources of DNA-P [38, 39]. The amount of pyro-P was less than that of DNA-P. Some studies have suggested that pyro-P may originate from poly-P and esters, which could be hydrolyzed during alkaline extraction [40]. Pyro-P can be directly utilized by aquatic organisms [41]. This study found phon-P in the western lake surface sediment, which is similar to the results of studies of the eutrophic Taihu Lake and Hongfeng Lake [24, 42].

Biogenic P (phon-P, mono-P, diesters P, and pyro-P) generally decreased as sediment depth increased. When combined with the loss of TP to the water and sediment (Tab. 2) [43], these findings might reflect degradation processes over time as well as loss of sediment P to the overlying water column, and also the biogenic P species would increase immobilization phosphorus by the sediment solids [44, 45]. Reitzel et al. [46] reported that half-lives of the P species in Lake Erken were as follows: mono-P (29 years) > DNA-P (22 years) > TP (six years) > poly-P (two years) > *ortho*-P (one year). Ahlgren et al. [47] reported half-lives of mono-P, diesters P, and pyro-P of 23 years, 21 years, and 13 years, respectively, in the same lake. In the present study, the most labile P species was lipids-P, which was found in the top 5 cm of sediment, and mono-P, DNA-P, and pyro-P, which were mostly common in the top 10 cm of sediment. The result in this research was similar with the Taihu Lake, which was also a shallow lake. Ding et al. [44, 45] reported that half-life of the P_o compound varied from 3 to 27 years in Taihu Lakes, and the following order was mono-P > lipids-P > DNA > pyro-P. The Chaohu Lake is a shallow lake with an average depth of only 3 m. The lake was heavily used by the shipping and fishery industries; therefore, the surface is subject to disturbance that will affect the

water-sediment interface and change the redox conditions or microbial populations. These disturbances will influence the transformation rate of mono-P, DNA-P, and pyro-P. Labile forms of P_o such as DNA-P and lipids-P mineralize to *ortho*-P or are utilized by aquatic organisms directly. Accordingly, P_o in the sediments may be available for recycling to the surface water and supporting the growth of phytoplankton.

4.2 P species and lake eutrophication

The concentrations of TP and P_o in the sediment of the western lake were higher than those in the eastern lake. Specifically, the levels of *ortho*-P were 78.4 and 67.3% in the western and eastern lake, respectively. The main reason for this distribution was differences in drainage and pollution sources [27, 48]. The industrial and municipal wastewater, and urban non-point source was discharged into the western region of the lake and the non-point source pollution of agriculture was primary in eastern lake region [22]. It is important to note that algal blooms produce organic materials, including abundant P_o , but that the level of *ortho*-P in eutrophic lake sediments is higher than in mesotrophic sediments, indicating that the rate of organic matter mineralization in eutrophic lakes is faster than in mesotrophic lakes. The positive relationship between total P_o in sediment and TP in the water column ($R_{[\text{Po}(\text{sediment}) - \text{TP}(\text{water})]} = 0.81$, $p < 0.01$) indicates that P_o in the sediment may be released into the water, and may be the P_o was origin from the increased input and accumulation of organic matter in surface sediments through the surface water [38, 44]. Mono-P ($R_{[\text{mono-P}(\text{sediment}) - \text{TP}(\text{water})]} = 0.77$, $p < 0.01$) and pyro-P ($R_{[\text{pyro-P}(\text{sediment}) - \text{TP}(\text{water})]} = 0.76$, $p < 0.01$) were positively related with TP in the water column. Mono-P is more stable than diesters P, and that is a wide range important P_o in the sediment, such as inositol hexaphosphoric acid, which can be combined with multivalent ions to form precipitate, but studies have reported that it can be mineralized into P_i under anaerobic conditions [49]. Pyro-P was the labile P_o in the sediment, with a short half-life time (three years in Taihu Lake) [45]. As a P_i , the pyro-P will be utilized by the aquatic organism. No correlations were found with TP in the water for the DNA and lipids-P in the sediment. The half-life time of DNA-P was twelve years in Taihu Lake [45], which may be similar with the Chaohu Lake because of the same condition in the two lakes. So we deduced that the DNA-P in the surface sediment may be buried before mineralization [24]. Although lipids-P has long half-life (14 years in Taihu Lake) [45], lipids-P will loss in the alkaline extraction because of hydrolysis or precipitation under strongly alkaline condition [24].

5 Conclusions

In this study, the concentration and compounds of P_o and P recycling in shallow and eutrophic lakes were determined by ^{31}P -NMR. Six P compounds were detected in the sediments, with *ortho*-P and mono-P being the dominant forms in the surface sediments. As sediment core depths increased, the compounds and concentration of P decreased. Phon-P, lipids-P, DNA-P, and pyro-P were primarily found in the top 10 cm of sediments. Analysis of the relationships between P compounds and water quality indicated that the P recycling rate and mineralization rate of P_o were faster in eutrophic lakes than that in mesotrophic lakes. Overall, the results demonstrate that compounds, distribution and transformation process are complex in the sediment of eutrophic lakes.

Figure 3. ^{31}P -NMR spectra of NaOH/EDTA extracts of the sediments cores in the Chaohu Lake (a: phosphonates; b: *ortho*-phosphate; c: *ortho*-phosphate monoesters; d: phospholipids; e: DNA; f: pyrophosphate; right: 1, left: 8).

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