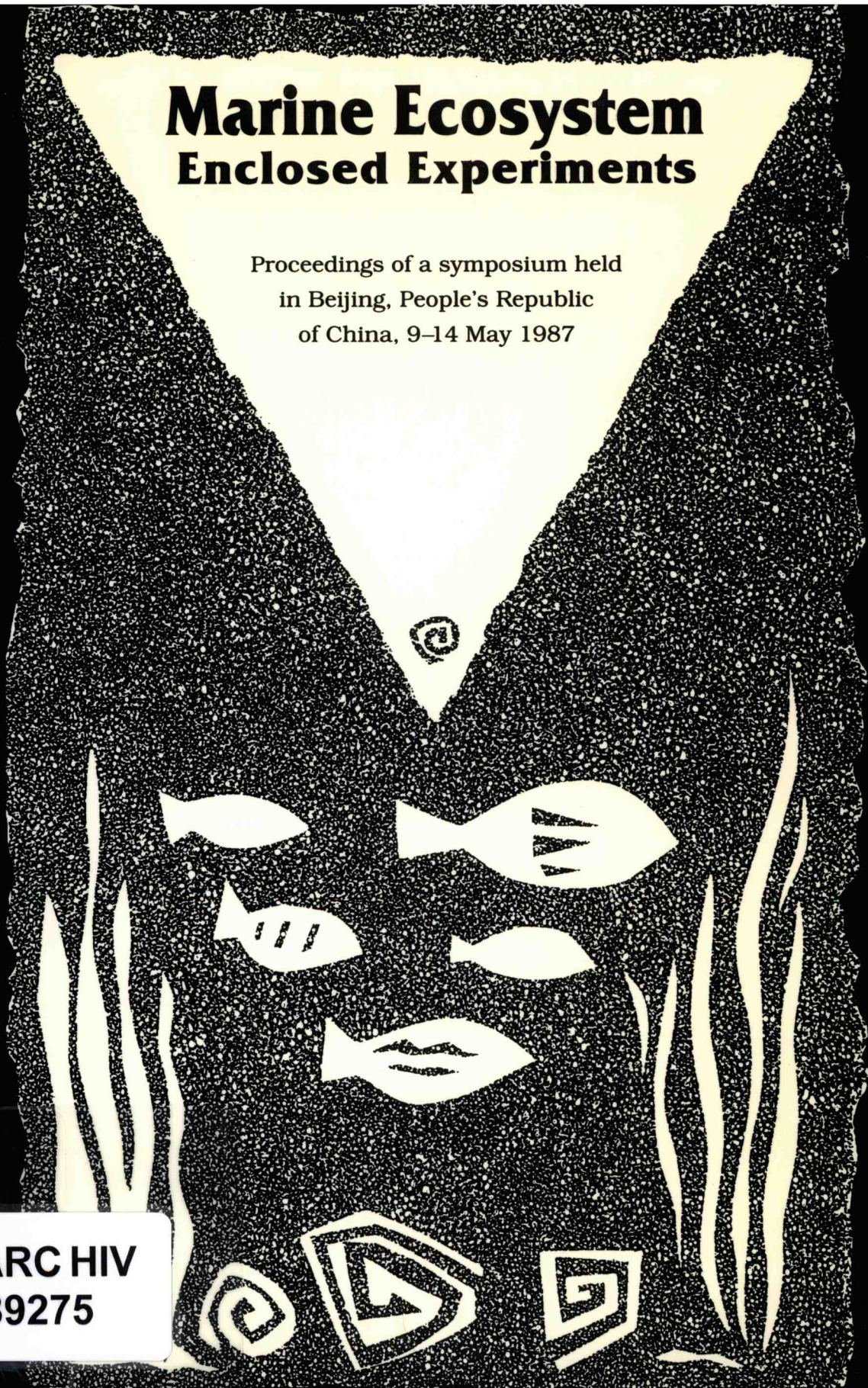
Marine Ecosystem
Enclosed Experiments

Proceedings of a symposium held
in Beijing, People's Republic
of China, 9–14 May 1987



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Marine Ecosystem Enclosed Experiments

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Editor: C.S. Wong and P.J. Harrison

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Abstract

This symposium on marine ecosystem enclosed experiments (MEEE) consists of nine review papers that describe various types of ecosystem enclosures and a series of papers resulting from enclosure experiments in Xiamen, People's Republic of China, and Saanich Inlet, BC, Canada. The reviews on types of enclosures include benthic enclosures for rocky and sandy shores and the effects of pollutants (primarily hydrocarbons) on bacteria, macroalgae, and invertebrates. The pelagic enclosures were used to study the control of phytoplankton blooms, the uptake and release of dissolved organic substances, and the effects of pesticides on freshwater ecosystems.

Six enclosure experiments were conducted in China and Canada from 1986–87. Some of these experiments examined the effects of contaminated sediments, primarily heavy metals, on bacteria, phytoplankton, and zooplankton and the pathways and fates of these heavy metals in the seawater. Other experiments studied the chemistry and biological effects of chemically dispersed oil.

Résumé

Ce compte rendu du symposium sur les expériences faites en écosystèmes marins comprend neuf communications qui décrivent les écosystèmes retenus et les expériences faites à Xiamen en République populaire de Chine et à Saanich Inlet, C.-B., au Canada. Les communications portent, notamment, sur les écosystèmes benthiques des littoraux rocheux et sablonneux et sur les effets des polluants (surtout les hydrocarbures) sur les bactéries, les grandes algues et les invertébrés. Les expériences sur le contrôle des brutales pullulations ("blooms") du phytoplancton furent menées dans les écosystèmes pélagiques, ainsi que l'absorption et le dégagement des substances organiques dissoutes et les effets des pesticides sur les écosystèmes d'eau douce.

Six expériences ont été faites en Chine et au Canada entre 1983 et 1987. Certaines ont porté sur les effets des sédiments contaminés, principalement par des métaux lourds, sur les bactéries, le phytoplancton et le zooplancton et sur le cheminement et le sort de ces métaux lourds dans l'eau salée. D'autres expériences portaient sur la chimie et les effets biologiques du pétrole dispersé chimiquement.

Resumen

Este simposio sobre Experimentos Marinos en Ecosistemas Cerrados (MEEE) consistió en nueve trabajos de análisis que describen varios tipos de enclaustramientos ecosistémicos y una serie de trabajos derivados de experimentos con estos enclaustramientos en Xiamen, República Popular de China, y en Sannich Inlet, Canadá. Los estudios incluyen enclaustramientos bentónicos para costas rocosas y arenosas, y los efectos de los contaminantes (fundamentalmente hidrocarburos) sobre bacterias, macroalgas e invertebrados. Los enclaustramientos pelágicos se utilizaron para estudiar el control de la reproducción del fitoplancton, la ingestión y expulsión de substancias orgánicas disueltas y los efectos de pesticidas en los ecosistemas de agua dulce.

Se realizaron seis experimentos en ecosistemas cerrados en China y Canadá, de 1983 a 1987. Algunos de estos experimentos examinaron los efectos que ejercen los sedimentos contaminados, fundamentalmente los metales pesados, sobre bacterias, fitoplancton y zooplancton, y el ciclo y destino final de estos metales pesados en el agua de mar. Otros experimentos estudiaron los efectos químicos y biológicos de los aceites crudos dispersados por medios químicos.

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B. Hydrocarbons

Releasing Experiment of Mine Tailings from Alice Arm, BC, Canada

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This 1984 study was conducted in Alice Arm, BC, Canada, using a portable marine enclosure platform (PMEP). After the addition of mine tailings to the enclosed water column, changes in the concentrations of dissolved and particulate Cu, Pb, Zn, Cd, Fe, and Ni were determined. The effects of mine tailings on primary productivity, chlorophyll a, particulate organic carbon, and the biological removal of trace metals in the water column are discussed. Primary productivity and chlorophyll concentrations were not affected by the addition of mine tailings in low concentrations (tank PCEE-10), but were inhibited by the addition of mine tailings in high concentrations (tank PCEE-100). The phytoplankton bloom was also delayed in PCEE-100. About 96 h after the addition of mine tailings, primary productivity and chlorophyll concentrations in PCEE-100 were only 14 and 15% of the respective peak values observed during a phytoplankton bloom in PCEE-10. Concentrations of dissolved Fe and Zn declined significantly from initial values before the addition of mine tailings. A small increase in the concentration of dissolved Cu was observed in both tanks. Concentration of dissolved Cd and Pb also increased with time as Cd and Pb were released from the mine tailings. In PCEE-10, dissolved Ni stayed at the same level before and after the experiment, whereas in PCEE-100, it showed a significant increase. The different behaviours of trace metals were explained in terms of flocculation and sedimentation of Fe colloids, organic complexing, scavenging and settling of biogenic detritus, and adsorption of trace metals on hydrous oxides.

The behaviour of mine tailings disposed of in the ocean is gradually being understood. In seawater, the chemical properties of mine tailings are rather unstable. Observations in the laboratory reveal that the addition of mine tailings to seawater alters the concentrations of trace metals due to interaction of the mine tailings and the seawater (Hoff et al. 1982). Many scientists also recognize the environmental impacts associated with disposing of mine tailings in the ocean (Waldichuk 1978; Waldichuk and Buchanan 1980). Marine enclosed ecosystems have been used to study the effect of mine tailings on concentrations of trace metals in seawater (Wong et al. 1983). The controlled enclosures facilitate studying interactions among disposed mine tailings, seawater, and the marine environment.

Mine tailings are complex materials and, as they come into contact with seawater, many chemical reactions — such as ion exchange, dissolution, sorption,

desorption, hydrolysis, and sedimentation — occur. This report focuses on three topics: first, variations in concentrations of Cu, Pb, Zn, Cd, Fe, and Ni after the addition of mine tailings; second, effects of mine tailings on primary productivity, and concentrations of chlorophyll and particulate organic carbon (POC); and third, the role of organisms on the removal of trace metals in the water column.

Methods

The experiment was conducted between 28 June and 5 July 1984, in Alice Arm, BC, Canada. A portable marine enclosure platform (PMEP) (Wong et al., this volume) was designed for easy transportation to and assembly at the experimental site. The platform consisted of two cylindrical fibreglass tanks (0.9 m in diameter × 1.8 m deep), an aluminum frame, and two fibreglass floats. A peristaltic pump was used to fill the tanks with 1 100 L of seawater drawn from the 50-m layer of station AA5. The tanks were designated as PCEE-10 and PCEE-100, which were treated with 10 and 100 ppm of the mine tailings respectively. A cubical polyethylene tank with a volume of 26 L was used as the control (PCEE-C).

Time-sequence samples were taken at 0, 1.5, 4, 10.5, 25, 45, 70.5, and 93 h. A polyethylene tube pretreated with acid was used to obtain water samples integrally from the whole water column. Filtration of the water samples was carried out in the ventilation cabinet on board the ship. The samples were filtered through an acid-treated membrane filter (0.45-μm Nuclepore). Both the filtrates and the filters were stored at 4°C for chemical analyses later in the ultraclean laboratory at the Institute of Ocean Sciences (Wong et al. 1983).

Basically, the method used to determine dissolved trace metals in the seawater followed that of Danielsson et al. (1978). In brief, trace metals in the seawater were extracted with a mixture of 1% APDC/DDDC and Freon, then back-extracted in a 5% solution of Milli-Q distilled water and HNO_3. Each filter and its retained particles were dried at 60°C for 24 h. The filter and associated particles were placed in a Teflon bomb using the method of Eggiman and Betzer (1976) together with 0.75 mL of redistilled HCl and left for 30 min at room temperature. Another 0.25 mL of redistilled HNO_3 and 0.05 mL of HF were added in the digestion bomb, which was then closed and placed in a water bath at 90–100°C for 3 h. The digested solution was diluted with 25–30 mL of metal-free water for subsequent analyses. An atomic absorption spectrophotometer (Perkin-Elmer 503 model equipped with an HGA-400 graphite furnace) was used to determine the concentrations of several trace metals in the extracts and the digested solutions. Table 1 gives the blank determinations and repeatability of the analyses.

A modified method of Strickland and Parsons (1972) was used to analyze the POC and particulate organic nitrogen (PON) (Wong et al. 1983). The seawater

Table 1. Blank determinations and deviation of analyses of dissolved and particulate trace metals.

	Cu	Pb	Zn	Cd	Fe	Ni
Dissolved metals blanks	3.5	0.9	33	0.4	35	27
Percentage deviation	6	13	10	10	20	7
Particulate metals blanks	0.6	0.2	5.4	0.1	43	3.7

sample was filtered through a precombusted (500°C for 4 h) fibreglass filter (Whatman GF/C). The materials retained on the filter were washed with 3% NaCl, dried at 60°C, and analyzed with a CHN elemental analyzer (Perkin-Elmer 240) at 750°C.

Results

Table 2 lists the concentrations of nutrients (nitrate, phosphate, and silicate), chlorophyll, POC and PON, and the primary productivity. Figures 1-3 illustrate the variations of these parameters with time.

Table 2. Variations of nutrients (nitrate, phosphate, and silicate), particulate organic carbon (POC), and particulate organic nitrogen (PON), chlorophyll (CHL), and primary productivity (PP) in seawater.

Time (h)	NO_3 (μM)	PO_4 (μM)	SiO_3 (μM)	POC ($\mu g \cdot L^{-1}$)	PON ($\mu g \cdot L^{-1}$)	CHL ($mg \cdot m^{-3}$)	PP (mg C·$m^{-3} \cdot h^{-1}$)
			PCEE-10				
0	13.8	1.56	31.3	81.5	13.6	0.21	0.90
2	13.8	2.66	30.3	—	—	—	0.84
6.5	—	—	—	—	—	0.25	0.83
23.5	13.8	1.64	29.8	149	19.8	0.41	2.53
47.5	13.2	1.46	26.5	218	44.5	3.75	22.7
73	4.2	0.86	18.8	725	142	18.9	80.2
95	2.4	0.61	15.5	693	126	16.7	48.4
99	—	—	—	—	—	14.4	—
			PCEE-100				
0	13.8	1.55	22.1	89.8	10.4	0.18	1.18
2	13.8	2.66	30.3	—	—	—	0.84
6.5	—	—	—	—	—	0.08	0.36
23.5	13.8	1.86	35.0	175	17.3	0.11	0.32
47.5	14.1	1.65	28.6	94.5	16.3	0.25	0.76
73	13.8	1.50	29.0	171	19.3	0.96	3.64
95.5	12.8	1.28	27.9	153	33.5	2.87	11.3
99	—	—	—	—	—	3.68	--
			PCEE-C				
0	14.1	1.58	30.3	60.9	11.6	0.20	0.24
6.5	—	—	—	—	—	0.14	0.37
10.5	—	—	—	—	—	—	0.48
23.5	14.2	1.63	30.1	93.5	16.5	0.45	0.25
27.5	—	—	—	—	—	—	2.95
47.5	14.0	1.51	17.8	133	26.7	1.38	2.28
73	9.5	1.07	28.1	358	81.5	5.54	12.8
77	—	—	—	—	—	7.14	33.0
83	—	—	—	—	—	13.6	11.3
95.5	0.1	0.47	12.9	845	142	21.7	17.8
99	—	—	—	—	—	12.5	20.0

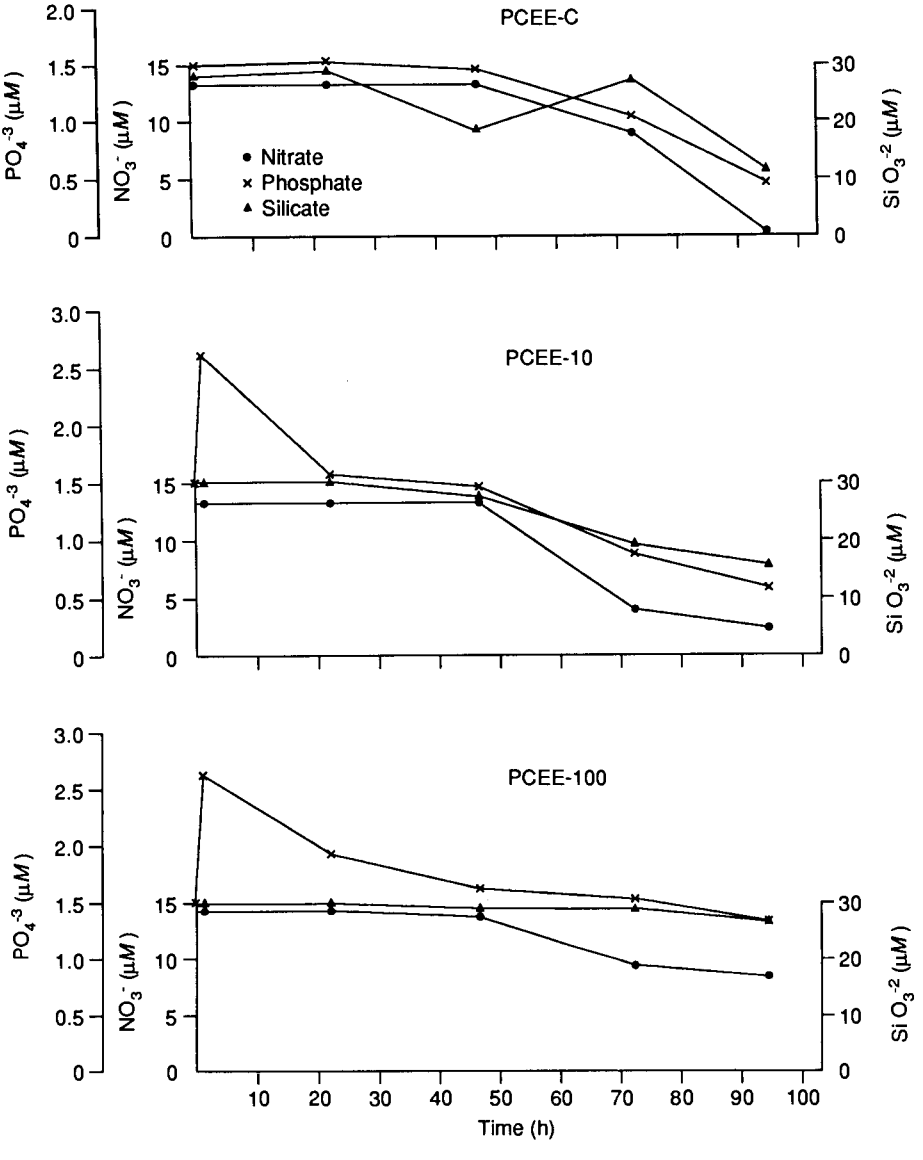

Fig. 1. Variations of nitrate, phosphate, and silicate in PCEE-C, PCEE-10, and PCEE-100.

Before the addition of mine tailings, primary productivities in all of the tanks were fairly low, about 2.6 mg $C \cdot m^{-3} \cdot h^{-1}$, and chlorophyll concentrations were less than 0.45 $mg \cdot m^{-3}$. Concentrations of nitrate, phosphate, and silicate remained relatively stable during the first 23 h of the experiment. Thereafter, primary productivities and chlorophyll concentrations in PCEE-C and PCEE-10 increased significantly, whereas those in PCEE-100 showed only a small change. At the same time, nitrate concentrations in PCEE-C and PCEE-10 began to decrease, but the nitrate concentration in PCEE-100 remained about the same.

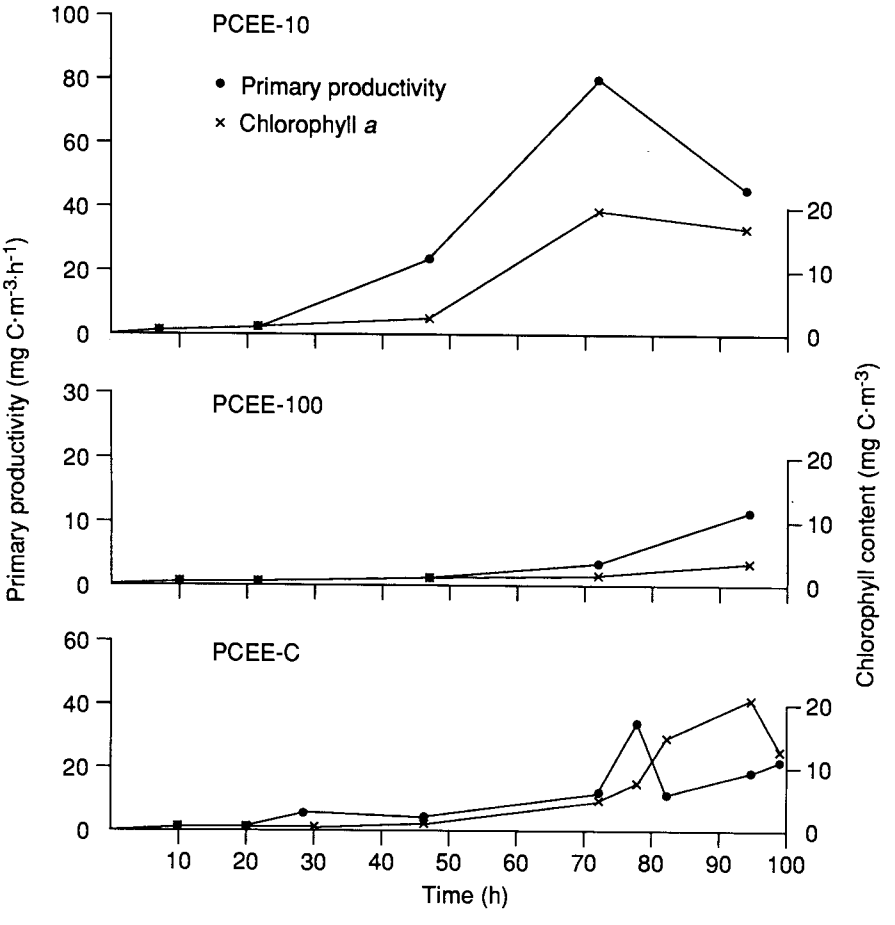

Fig. 2. Variations of primary productivity and chlorophyll content in PCEE-C, PCEE-10, and PCEE-100.

By the end of the experiment, nitrate concentrations in PCEE-C and PCEE-10 had decreased to 0.1 and 2.4 μM, respectively, whereas that in PCEE-100 still remained at a relatively high level of 12.8 μM. About 73 h after treatment, primary productivity and chlorophyll concentrations in PCEE-10 reached their peak values of 80.2 mg $C \cdot m^{-3} \cdot h^{-1}$ and 18.9 mg $\cdot m^{-3}$ respectively. In PCEE-C, primary productivity increased to a maximum of 33 mg $C \cdot m^{-3} \cdot h^{-1}$ 77 h after treatment, whereas the maximum chlorophyll concentration of 21.7 mg $\cdot m^{-3}$ was obtained 95.5 h after the addition of mine tailings. After the planktonic blooms, both primary productivities and chlorophyll concentrations decreased from their peak values. In PCEE-100, the primary productivity and chlorophyll concentration increased gradually at very low levels until 47 h, after which time the rates of increase became much higher. At the end of the experiment (95.5 h), the primary productivity was 11.3 mg $C \cdot m^{-3} \cdot h^{-1}$ and the chlorophyll concentration was 2.87 mg $\cdot m^{-3}$.

Concentrations of dissolved and particulate trace metals (Cd, Cu, Fe, Ni, Pb, and Zn) and suspended matter are given in Table 3. Figures 4–6 depict the variations of these concentrations with time. In PCEE-10, 69% of the suspended matter was lost

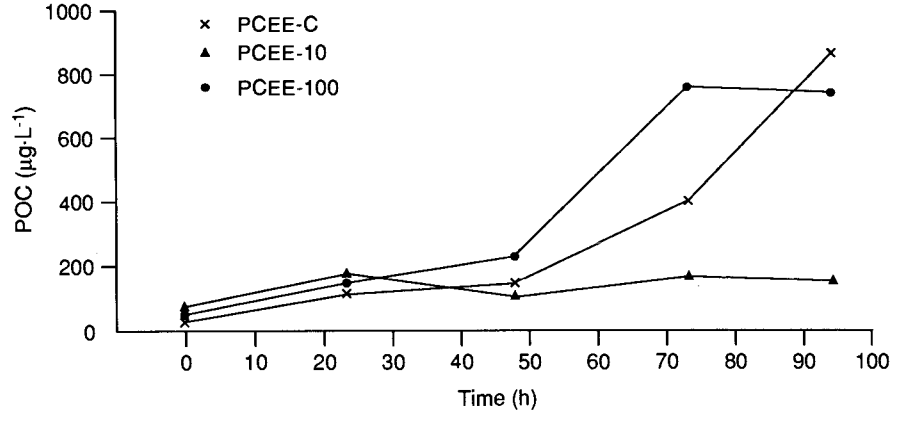

Fig. 3. Variations in the concentration of particulate organic carbon (POC) in PCEE-C, PCEE-10, and PCEE-100.

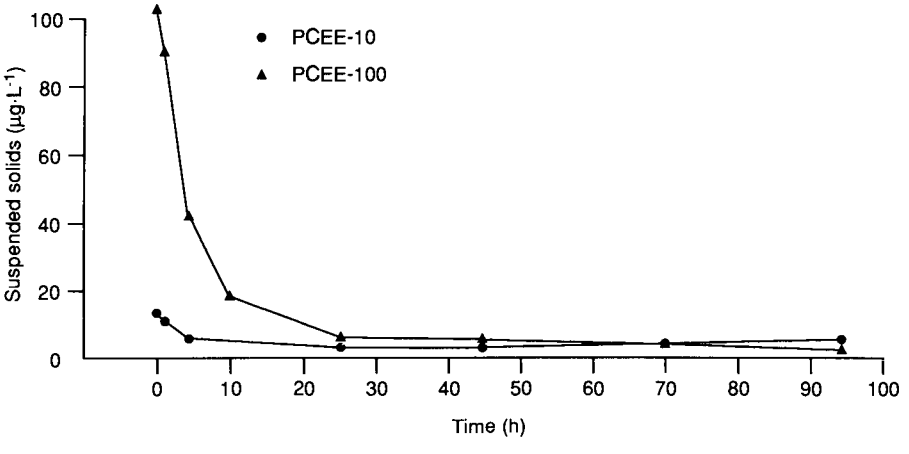

Fig. 4. Variations in the concentration of suspended particles in PCEE-10 and PCEE-100.

during the first 25 h, and 27.8% was lost between 25 h and 93 h; whereas in PCEE-100, 93% was lost during the first 25 h, but only 4% during the next 70 h.

In PCEE-10, the concentration of dissolved Cu increased from the background level of 187 $ng \cdot kg^{-1}$ to 210 $ng \cdot kg^{-1}$ (an increase of 15%) and then stayed at a steady level, averaging 237 $ng \cdot kg^{-1}$ (sd = 9%; $n = 7$). After the addition of mine tailings, concentrations of particulate Cu increased during the first 10.5 h; double in PCEE-10 and 1.5 times in PCEE-100. Thereafter, concentrations of particulate Cu in these two tanks decreased gradually.

The level of dissolved Ni in PCEE-10 did not change substantially after treatment. The average concentration was 799 $ng \cdot kg^{-1}$ (sd = 5%; $n = 8$). In PCEE-100, the concentration of dissolved Ni was nearly twice the background level of 717 $ng \cdot kg^{-1}$, with a final value of 1 369 $ng \cdot kg^{-1}$. Concentrations of particulate Ni in the two tanks increased initially and then decreased with time.

Table 3. Variations in the concentrations of dissolved (DTM, $ng \cdot kg^{-1}$) and particulate (PTM, $\mu g \cdot g^{-1}$) trace metals in seawater.

Time (h)	Cu		Pb		Zn		Cd		Fe		Ni		Suspended particles ($mg \cdot kg^{-1}$)
	DTM	PTM	DTM	PTM	DTM	PTM	DTM	PTM	DTM	PTM	DTM	PTM	
PCEE-10													
—[a]	187	53	24.6	293	1.26	—	46.7	0	201	47	—	812	0.72
0	210	66	57.4	238	0.93	476	66.1	8.2	156	56	778	—	13.0
1.5	245	84	74.4	308	1.03	530	51.6	10.5	243	29	823	73	11.5
4	222	91	60.2	296	1.12	497	62.4	8.5	226	36	828	86	6.7
10.5	222	101	28.3	266	1.10	360	76.5	9.0	256	35	853	51	5.2
25	241	91	46.4	210	1.13	286	79.1	6.5	110	36	750	42	4.0
45	270	63	59.6	212	1.45	81.7	93.1	4.5	60	26	739	27	4.5
71	—	56	—	169	—	144	—	3	—	23	—	32	3.9
93	247	38	41.9	149	0.49	133	97.4	1.4	54	9.7	810	18	5.4
PCEE-100													
—[a]	333	26	182	364	1.63	621	56.3	0	176	27	717	49	1.26
0	321	68	451	200	2.22	272	77.3	9.9	295	8.7	1 106	47	103
1.5	297	90	447	226	1.75	297	65.0	11.9	216	9.4	1 051	44	89.9
4	395	101	184	158	1.37	306	62.5	13.1	193	18	1 027	48	41.3
10.5	369	173	437	312	1.53	258	75.0	10.6	111	23	1 174	55	17.1
25	363	104	441	440	1.39	299	70.5	10.0	79	32	1 483	95	7.1
45	375	68	152	342	1.15	273	78.5	10.2	53	28	1 332	46	6.5
71	—	63	—	284	—	234	—	4.5	—	30	—	50	3.3
93	377	105	180	340	1.20	250	81.6	4.3	61	21	1 369	38	2.6

[a] Before additions.

Initially, the concentration of dissolved Pb in PCEE-10 increased from about 24.6 $ng \cdot kg^{-1}$ to 57.4 $ng \cdot kg^{-1}$; and, in PCEE-100, from 182 $ng \cdot kg^{-1}$ to 451 $ng \cdot kg^{-1}$.

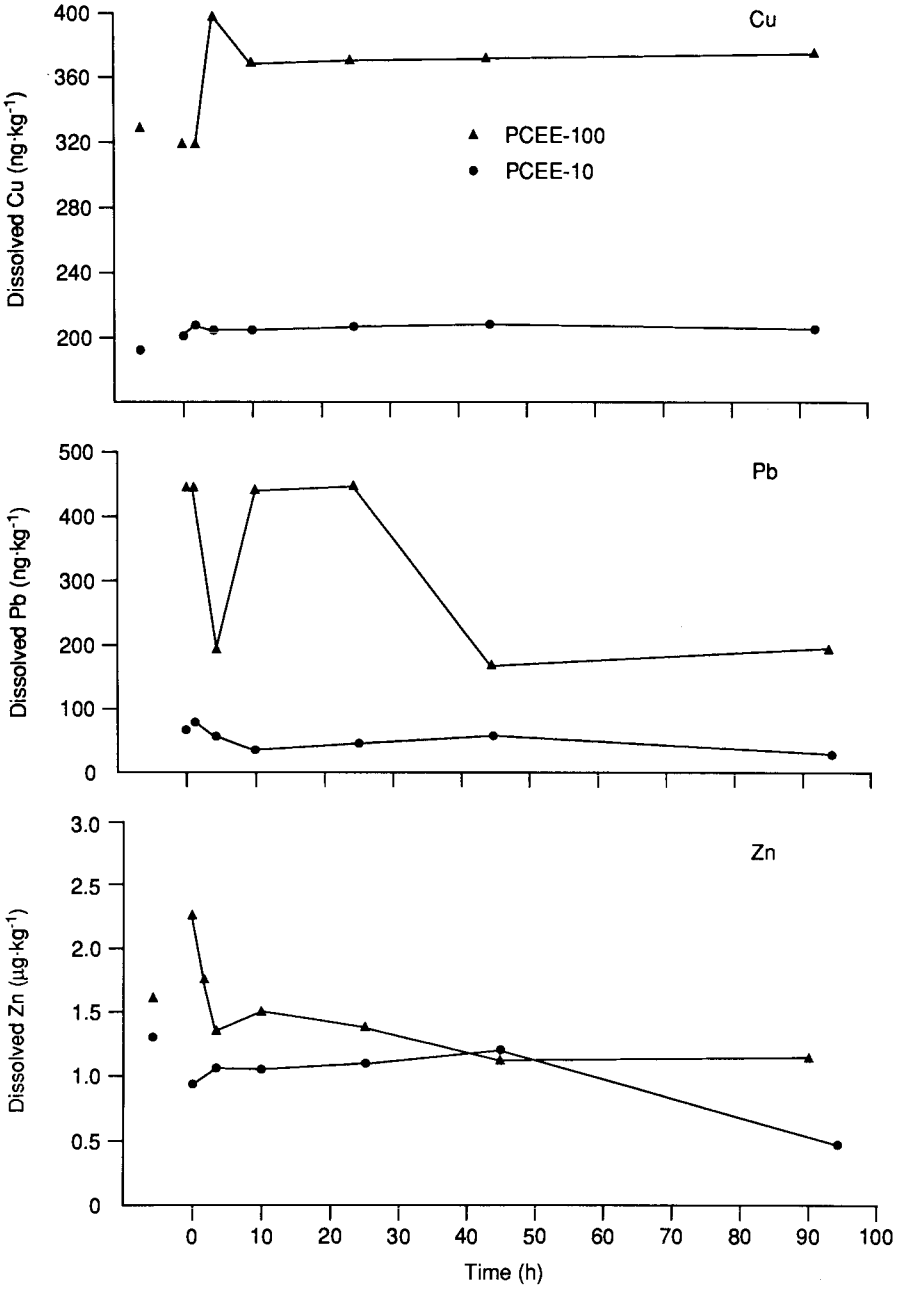

Fig. 5(a). Variations in the concentrations of dissolved trace metals in PCEE-10 and PCEE-100.

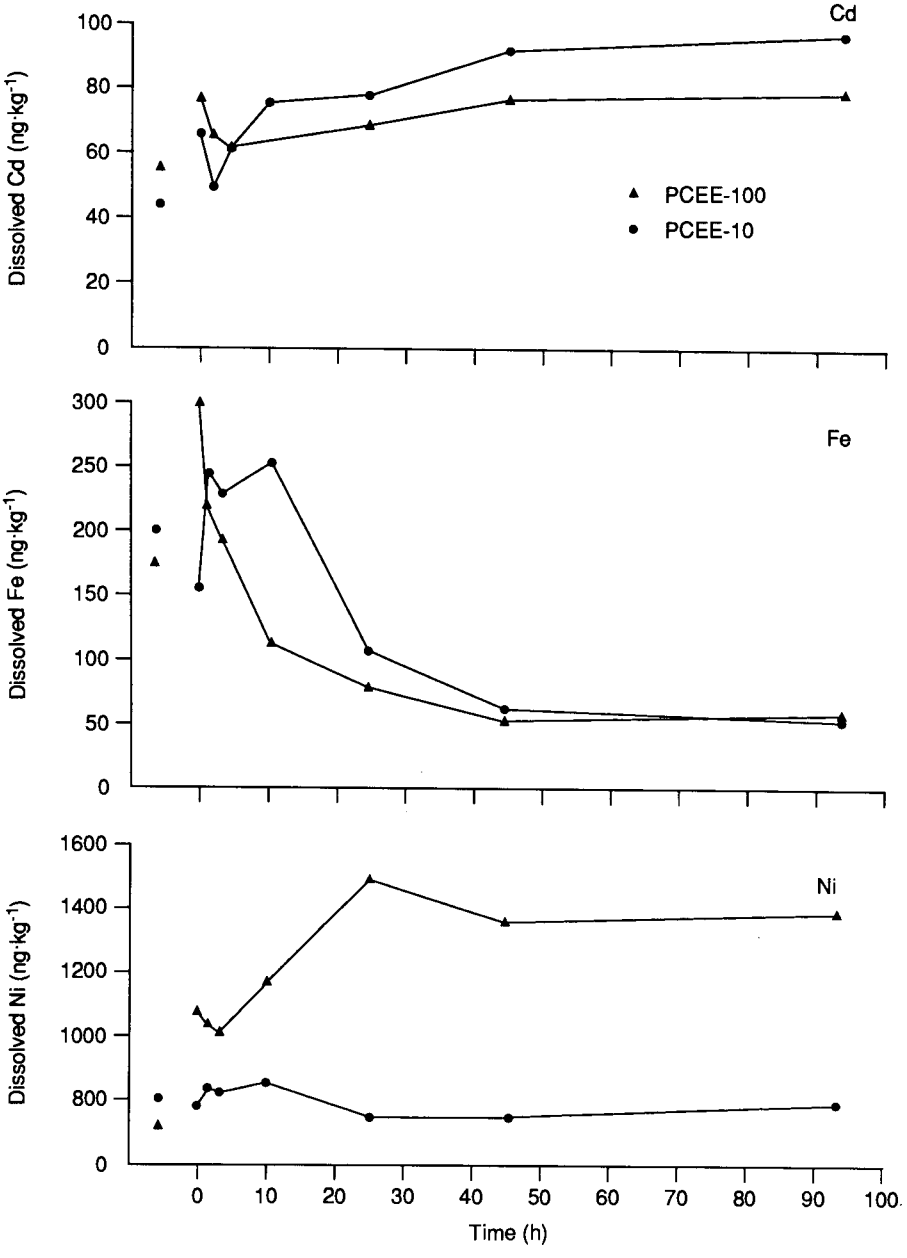

Fig. 5(b). Variations in the concentrations of dissolved trace metals in PCEE-10 and PCEE-100.

The concentrations then showed decreasing trends in general. At the end of the experiment, the concentration of dissolved Pb in PCEE-10 was even lower than the background level, whereas the concentration in PCEE-100 had returned to the background level. In both tanks, the concentrations of particulate Pb also showed an initial increase and then decreased gradually. At the end of the experiment, the

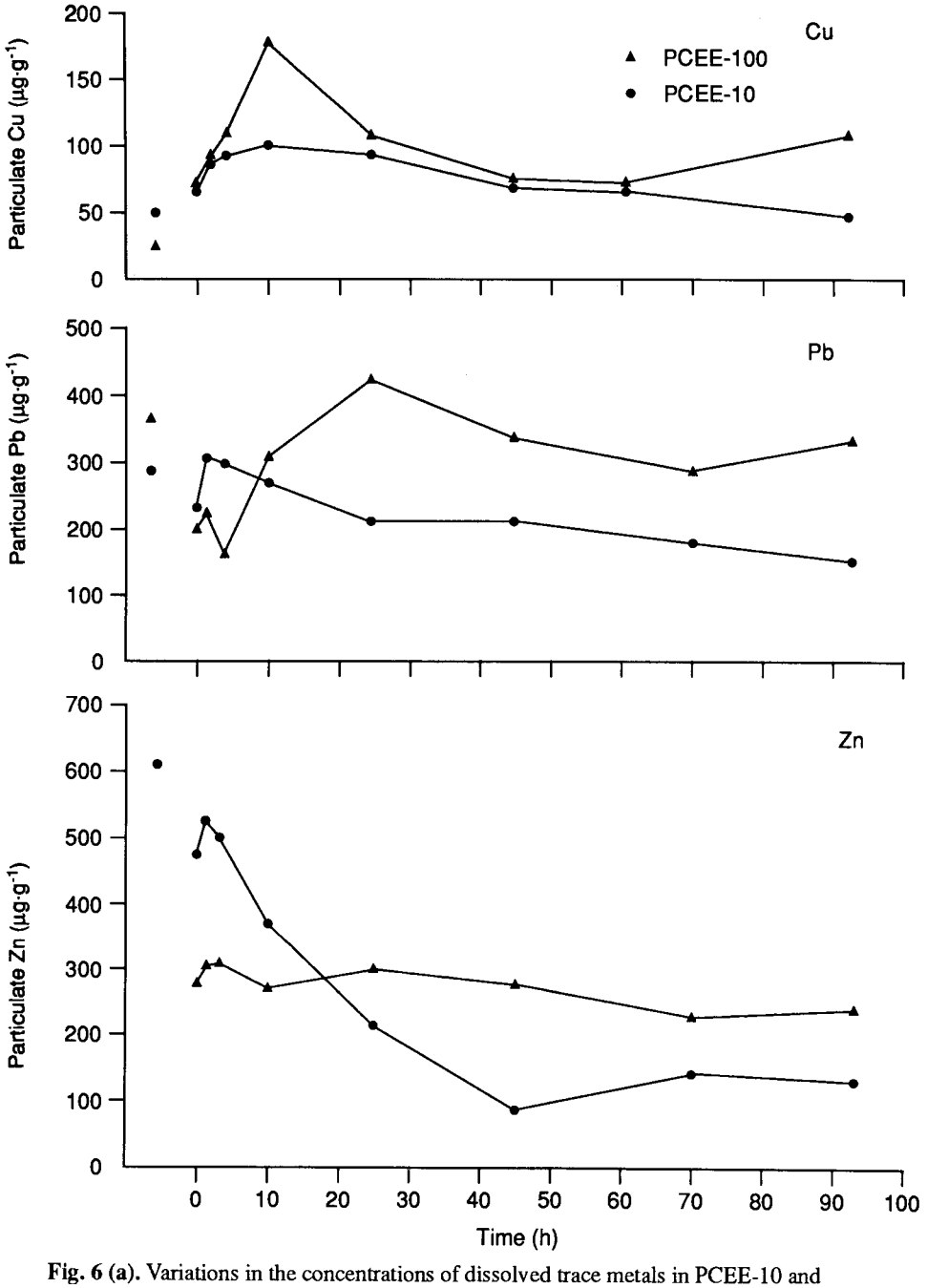

Fig. 6 (a). Variations in the concentrations of dissolved trace metals in PCEE-10 and PCEE-100.

concentration of particulate Pb in PCEE-10 was lower than the background level, whereas that in PCEE-100 was higher.

The behaviour of Zn in PCEE-10 differed from that in PCEE-100. As mine tail-

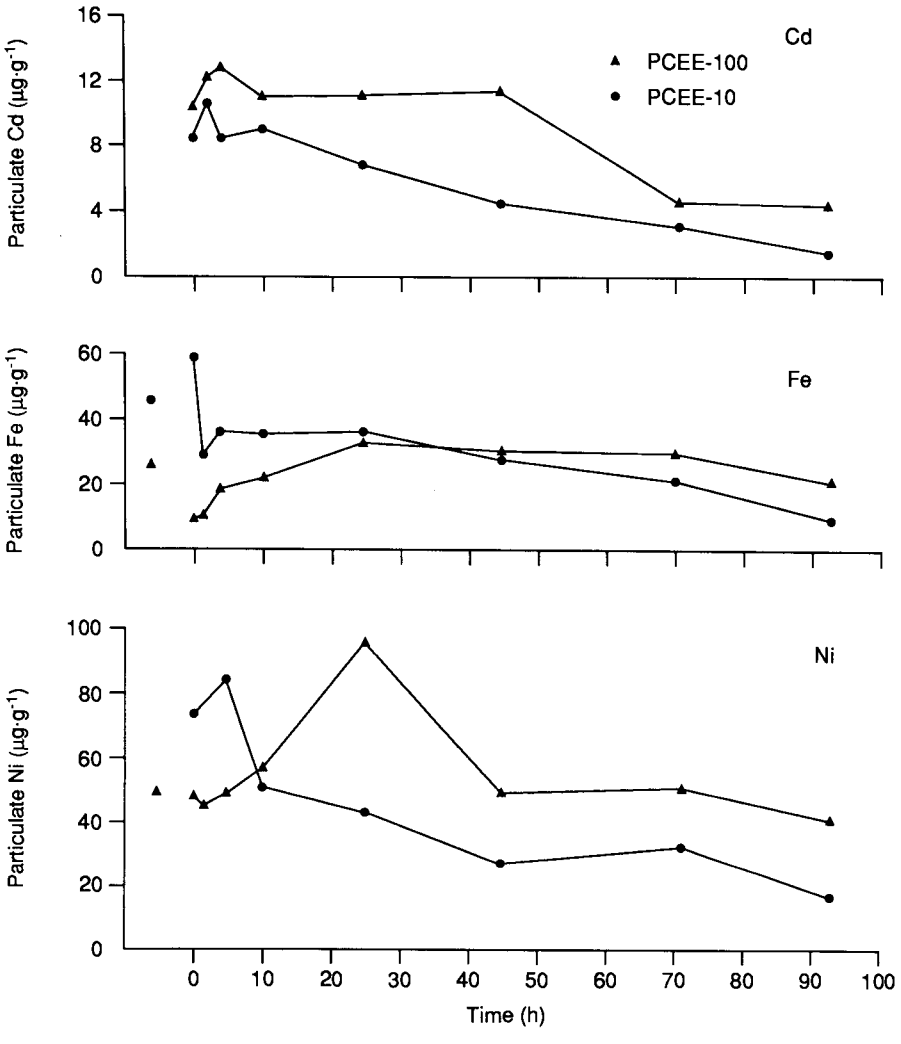

Fig. 6 (b). Variations in the concentrations of dissolved trace metals in PCEE-10 and PCEE-100.

ings were added to PCEE-10, the concentration of dissolved Zn decreased immediately to 26% below the background level and then remained at about the same level for the next 25 h, averaging 1.06 $\mu g \cdot kg^{-1}$ (sd = 8%). There was another significant decrease, 20 h later. Ninety-three hours after treatment, the concentration of dissolved Zn was only 0.49 $\mu g \cdot kg^{-1}$, which was lower than the value before the addition of mine tailings. In PCEE-100, there was a 36% increase in the concentration of dissolved Zn right after treatment. During the experiment, the amount of particulate Zn in PCEE-10 remained fairly stable, whereas the amount in PCEE-100 increased with time.

After the addition of mine tailings, the concentration of dissolved Cd in PCEE-10 increased by 42%, from 46.7 $ng \cdot kg^{-1}$ to 66.1 $ng \cdot kg^{-1}$, and then increased grad-

ually to two times the background level by the end of the experiment. For PCEE-100, the concentration of dissolved Cd initially increased from 56.3 $ng \cdot kg^{-1}$ to 77.3 $ng \cdot kg^{-1}$, and then remained at a stable level of 72.9 $ng \cdot kg^{-1}$ (sd = 10%; $n = 7$). Concentrations of particulate Cd in both PCEE-10 and PCEE-100 were quite similar; there were no large changes before the plankton blooms, but decreases occurred after the blooms.

The concentration of dissolved Fe in PCEE-10 increased 1.5 h after the addition of mine tailings, but then began decreasing after 10.5 h. At the end of the experiment, the concentration was only 54 $ng \cdot kg^{-1}$, much less than the background level of 201 $ng \cdot kg^{-1}$. A similar trend was observed in PCEE-100. The initial increase of 68% in the concentration of dissolved Fe was followed by a gradual decrease to a value of 61 $ng \cdot kg^{-1}$ by the end of the experiment. This value was also lower than the background level. For particulate Fe, concentrations decreased with time and final concentrations were lower than background levels.

Discussion

The concentration of nitrate is known to correlate closely with primary productivity and chlorophyll concentration (Takahashi et al. 1982). As primary productivity increases, a rapid loss of nitrate from the water body occurs (Parsons et al. 1984). This observation allows us to project the biological activities in an enclosed ecosystem from relationships between nitrate concentration and primary productivity, chlorophyll content, or the concentration of POC. Results from the present experiment demonstrated that variations in nutrient concentrations (nitrate, phosphate, and silicate), primary productivity, and chlorophyll content were very similar. In PCEE-10, during the first 25 h, nutrient concentrations showed no significant changes, and primary productivity was less than 2.6 mg $C \cdot m^{-3} \cdot h^{-1}$. Between 45 and 95 h, the concentration of nitrate decreased substantially, but primary productivity and amounts of chlorophyll and POC increased rapidly to their respective peak values. These phenomena were also observed in PCEE-100 but the transition point of the trends occurred 73 h after the addition of mine tailings.

At the beginning of the experiment, the concentration of phosphate increased from 1.56 μM to 2.66 μM. This increase probably resulted from dissolution of phosphate in the mine tailings.

The two treatment concentrations used in the present experiment, i.e., 10 and 100 ppm, simulated disposal concentrations of tailings from the Alice Arm mine into the ocean. Compared with the control (PCEE-C), the amount of mine tailings in PCEE-10 did not alter its primary productivity and chlorophyll content. However, the tailings seemed to affect biological activity in PCEE-100 by lowering primary productivity and the chlorophyll concentration and delaying the occurrence of the bloom. In PCEE-100 after 96 h, primary productivity (11.3 mg $C \cdot m^{-3} \cdot h^{-1}$) and chlorophyll concentration (2.87 $mg \cdot m^{-3}$) were only 14 and 15%, respectively, of the peak values observed in PCEE-10.

The experimental observations can be divided into two stages according to the concentration of suspended particles and the activity of organisms. The first stage was a physicochemical process including the settling of large particles. During this stage, biological activity was low; thus the behaviour of trace metals depended

mostly on interactions between the mine tailings and the seawater. Wong et al. (1986) indicated that 24 h after the addition of mine tailings, there were only 2–10 μM of particulates in the water body. In the present study, variations in the concentrations of suspended particles were also very small (Fig. 4). The second stage included both physicochemical and biological processes. During this stage, most of the settling materials were organic detritus or resulted from the coagulation of fine particles.

In PCEE-10, the time separating these two stages was about 25 h after the addition of mine tailings; in PCEE-100, separation between the two phases occurred at about 73 h. Changes in species composition of the ecosystems, which are probably essential to understand the effects of mine tailings on the environment, were not observed. For example, the change in silicate concentration in PCEE-100 was more conspicuous than changes in the concentrations of nitrate and phosphate. This might reflect changing responses of different plankton species to mine tailings. Although the volume of seawater in PCEE-C was much less than in PCEE-10 and PCEE-100, many characteristics of the biological activities in PCEE-C and PCEE-100 were similar. However, the degree of similarity with respect to species composition in these two tanks was not known.

After the addition of mine tailings, the rapid increase in dissolved and particulate Fe (Figs 5e and 6e) was probably caused by the release of soluble Fe compounds in the mine tailings or by the transformation of insoluble Fe compounds into soluble Fe compounds. These releases were also noticed by Rohatzi and Chen (1975) in their study involving mixing polluted water with seawater. After these initial processes, concentrations of dissolved and particulate Fe decreased with time, probably due to hydrolysis of dissolved Fe or coagulation of colloidal Fe. Aston and Chester (1973) indicated that suspended particles could enhance precipitation of Fe. The effect of fine particulate matter was to increase both the settling rate and the settling mass of Fe in seawater. During the second stage, concentrations of dissolved and particulate Fe continued to decrease but exhibited no direct cause-and-effect relationship. Similarly, there were no close relationships between biological activity and the change in concentration of either dissolved Fe or particulate Fe. Other studies have also shown that scavenging by particulates is important in the transfer of Fe and Mn in the ocean (e.g., Singh and Subramanian 1984).

The concentration of total Cu (including dissolved and particulate Cu) increased significantly after the addition of mine tailings. In PCEE-10, the increase was 3.6 times; whereas in PCEE-100, it was 19 times. Thereafter, because of the settling of suspended particles, the amount of total Cu decreased, but the amount of dissolved Cu remained almost the same. Topping and Windom (1977) noticed that Cu is removed from seawater by adsorbing onto bodies of plankton and organic detritus. With respect to the present study, we speculate that, during the second stage of the experiment, two processes were in operation: continuous release of Cu from the mine tailings as well as complexing of dissolved Cu with inorganic or organic compounds and their subsequent adsorption onto suspended particles (Bourg 1982; Singh and Subramanian 1984). Copper was then removed from the water with the settling particles. Because the rates of these two processes were basically the same, the concentration of dissolved Cu also remained relatively unchanged.

Rohatzi and Chen (1975) suggested that Ni can be released from polluted water to seawater. In the present experiment, dissolved Ni increased initially, then decreased. During the first stage of the experiment, Ni was released from the tail-

ings to the seawater. Thereafter, through various chemical reactions, such as adsorption of hydrous oxides, complexing and coprecipitation, metal was removed from the water body together with the settling particles. During the second stage, the concentration of dissolved Ni remained relatively stable, probably because of the equilibrium established between the rate of Ni release from the tailings and the transfer rate of Ni from other hydrous oxides and organic detritus. In PCEE-10, the concentration of particulate Ni decreased with the increase in biomass; whereas in PCEE-100, the concentration remained relatively stable because of the suppression of biotic activities.

As mine tailings were dispersed in seawater, the rate of Cd released from the tailings was higher than the transfer rate of Cd into the water. Early controlled ecosystem pollution experiment (CEPEX) studies supported the observation that the biological transfer of Cd was a slow process. Results from the present study also indicated that the concentration of dissolved Cd was still increasing at a much slower rate during the second stage of the experiment. Because the activity of organisms had little effect on the transfer of Cd, variations in the concentrations of dissolved Cd in PCEE-10 and PCEE-100 were basically the same.

The variations in dissolved Pb revealed in this experiment were also observed in a laboratory study (Hoff et al. 1982) and in an enclosure experiment (Wong et al. 1983). The decrease in dissolved Pb occurred mainly during the first stage suggesting that the transfer of Pb is a chemical process. Wong et al. (1983) also observed that Pb is not transferred by binding with settling organic matter. Although the concentration of dissolved Pb increased right after the addition of tailings, it returned to the background level by the end of the experiment, suggesting that the settling of suspended tailings particles was an important factor in the transfer of dissolved and particulate Pb.

Many studies have confirmed that Zn can be adsorbed onto hydrous ferric oxide or organic detritus. Zinc is also a micronutrient that can exist in a complex with other organic compounds. Thus, in the present study, Zn was probably transferred by physicochemical processes during the first stage of the experiment. During the second stage, Zn settled and was removed from the water body by complexing with organic compounds or by becoming adsorbed onto organic detritus. However, in PCEE-10, concentrations of Zn were reduced by 71 and 12% during the first and second stages respectively; whereas in PCEE-100, the reductions were 90 and 3% respectively. These results strongly suggest that Zn was transferred by some physicochemical processes.

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