

**ASSESSMENT OF THE ENRICHMENT OF CADMIUM AND OTHER  
METALS IN THE SEDIMENTS OF PORT MOODY AND INDIAN  
ARMS, BRITISH COLUMBIA**

by

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## Abstract

Major and minor element data along with organic carbon, nitrogen and  $^{210}\text{Pb}$  measurements from four cores are used to derive an explanation for the widespread enrichments of Cd seen in both surface and buried sediments in Port Moody Arm, an industrially-developed extension of Vancouver Harbour. Cd and Mo are enriched at depth in the sediments of adjacent Indian Arm, probably as a result of a natural diagenetic process which has been previously seen elsewhere in British Columbian coastal sediments. Past dredging and dumping activities in Port Moody Arm have produced a complicated and locally variable sedimentary history. In addition to Cd, enrichments of Zn, Pb and Cu are widespread and persist to depths of several decimetres in cores from the area. At one site in the western portion of the Arm, a highly contaminated but buried horizon contains Zn and Cu concentrations up to 3000 and 1500  $\mu\text{g g}^{-1}$ , respectively, and 29 wt. % Fe. Cd is enriched at depth at one location in the Arm in sediments which clearly were deposited before anthropogenic activities could have influenced the composition of the deposits. This implies that natural diagenetic processes are adding Cd to the sediments in the embayment, as is happening in Indian Arm. Thus, the widespread occurrence of Cd in Port Moody Arm sediments at concentrations higher than the ocean dumping criterion for the element ( $0.6 \mu\text{g g}^{-1}$ ) appears to reflect a natural uptake by the deposits in addition to anthropogenesis.

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## 1.0 Introduction

Recent studies have been carried out on the distribution of cadmium in sediments in Port Moody Arm, an extension of Burrard Inlet (Vancouver Harbour), for the purpose of evaluating sediment quality for ocean disposal and to assess the environmental state of the harbour. It is clear that the sediments are Cd-enriched at almost all sites in the Arm. While the concentrations of trace metals in coastal marine sediments are known to vary widely in response to a variety of factors, harbour sediments are invariably enriched in such elements because of the ubiquitous metal contents in urban and industrial inputs to such areas. There are, however, examples where sedimentary or diagenetic conditions have naturally increased the concentrations of some metals, such as Cd and Mo, in sediments (e.g. Pedersen et al., 1989).

Most trace metals, including cadmium, are toxic in certain forms and as a result are restricted for ocean disposal. Under the Canadian Environmental Protection Act (CEPA) regulations, marine disposal is prohibited for materials containing more than  $0.6 \mu\text{g g}^{-1}$  Cd in the solid phase. Concentrations in marine sediments generally fall below this level, but in some areas, such as Port Moody Arm, relatively high concentrations have been observed in both surface deposits and sediments at depth in cores (Goyette and Boyd, 1989). The Port Moody Arm area shares some similarities with Ucluelet Inlet on the west coast where natural Cd enrichments occur in the sediments (Pedersen et al., 1989), in that rainfall is high in both regions ( $\sim 3300$  and  $\sim 1800 \text{ mm yr}^{-1}$ , respectively in the Ucluelet and Port Moody areas) and both are shallow and protected embayments which have no major freshwater inputs or associated direct injections of fluvial sediments. The most significant difference between Ucluelet Inlet and Port Moody Arm is that the both the shore area and the watershed of the latter are relatively heavily developed. Industrial and urban development have been proceeding for more than 100 years in the area, and particularly since 1886 when Port Moody became the Canadian transcontinental railway terminus.

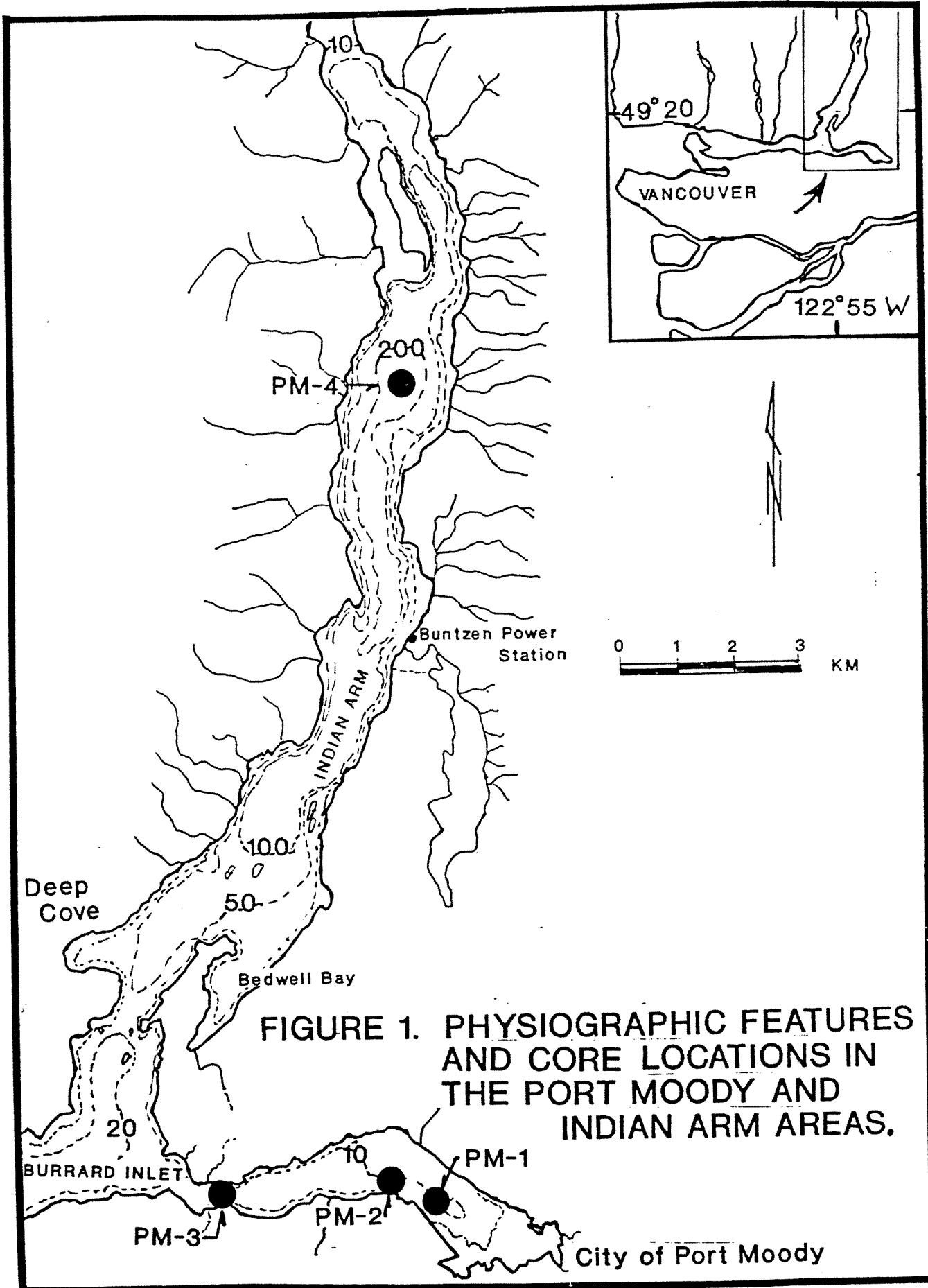
In this report we focus on the composition of a trio of cores collected from Port Moody Arm and a single core raised from the adjacent Indian Arm (Fig.1) in an effort to assess the mechanism of the cadmium enrichment in the sediments of the former basin. The assessment will be based on a wide range of chemical analyses, including major and minor element data, organic carbon and nitrogen measurements, and  $^{210}\text{Pb}$  measurements.

## 2.0 Environmental Setting and Historical Overview

Port Moody and Indian Arms are extensions of Burrard Inlet and are connected through Vancouver Harbour to Georgia Strait (Fig. 1). The Burrard Inlet system is collectively 120 km<sup>2</sup> in area and drains a basin totalling some 1000 km<sup>2</sup>. Port Moody Arm is ~8 km long and relatively shallow - the average depth is about 12 m. Freshwater input to the arm is minor; circulation is thus tidally dominated. In contrast, Indian Arm is a typically long and narrow fjord (21 km by 1 km) fronted by a 30 to 40 m deep sill; the maximum depth in the inner basin is 218 m. The Indian River at the north end of Indian Arm and the Buntzen Power Station on the eastern shore halfway up the inlet, provide a significant flow of freshwater into the Arm. Circulation in both arms is influenced by semidiurnal tides which have a maximum amplitude of about 5 m (S. Pond, pers. comm.).

Port Moody Arm historically has been developed to a much higher degree than Indian Arm, which probably reflects the physical constraints imposed by the steep terrain in the latter. Prior to colonization by Europeans in the 18th and 19th centuries, the area was utilized by bands of the Musqueam and Squamish Tribes. During the 1800's in particular the area became more industrialized as the lowlands surrounding Port Moody Arm became a processing and transportation centre for resources derived from the coast regions and the interior, including furs, salmon, timber and gold. Since this time the Arm has been transformed into an urban bay which receives industrial, shipping, and domestic wastes as well as urban runoff. Only recently, i.e. since the 1970's, have there been any attempts to improve the quality of the discharges. Industries in the area over the years have included steel and lumber mills, oil refineries, a ship and railway transportation centre, and more recently, metal plating, barrel washing and bulk materials handling (mainly sulphur and methanol).

As part of the ongoing development of the area, the physical form of the inlet has been altered to enable better ship access and to improve adjacent uplands for industrial use. The alterations have included dredging portions of the basin to deepen ship-berthing areas and filling in parts of the foreshore. While much of the dredged material apparently went to form the new foreshore land, such as at the Bulk Terminal, dredge spoil was also dumped in deeper areas of the inlet, such as the basin opposite the Allied Chemical Company





plant (Fig. 2). Until the introduction of the Ocean Dumping Control Act (the predecessor to CEPA), the process of ocean disposal was uncontrolled - regulations did not exist and there were no designated dump sites. Known dump sites are shown in Figure 2, which also includes notations describing some historic land uses in the Port Moody Arm area.

The geology of the immediate area around Port Moody Arm is dominated by Quaternary glaciomarine, glaciofluvial and alluvial deposits, particularly Vashon Drift tills and glaciofluvial gravels and Capilano Sediments, which consist of raised marine, deltaic and fluvial deposits, predominantly poorly-sorted sand and gravel (Geol. Surv. Can. Map 1484A, New Westminster). The bedrock consists of diorite in the area between Bedwell Bay and Port Moody Arm, while middle Eocene and younger sandstone, shale and conglomerate bound the southern shore of the Arm below Burnaby Mountain. There is no permanent fluvial input to the Arm in this area, however; surface runoff from Burnaby Mountain is ephemeral.

In contrast to the Port Moody Arm area, the Indian River watershed, which supplies the bulk of the terrigenous detritus input to Indian Arm, is characterized by coast plutonic rocks, mainly quartz diorite, granodiorite, diorite and migmatite (Geol. Surv. Can. Map 1151A, Pitt Lake). Jurassic to Lower Cretaceous volcanoclastics of the Gambier Group, and pre-Jurassic metasediments of the Twin Island Group crop out locally near the southern end of the Arm, but probably make a negligible contribution to the sedimentary input to the basin. Mineralization is known in the region but not in the immediate vicinity of Indian Arm. Pockets within the Gambier Group in the Indian River Valley are known to be mineralized, and pyritization has been noted in the lower valley.

### **3.0 Summary of Field Operations and Core Descriptions**

A suite of sediment cores was collected from Port Moody and Indian Arms during inclement weather in the late spring of 1989, using the lightweight 8 cm I.D. catcher- and cutter-free gravity corer described by Pedersen et al. (1985) and a 6 m aluminum workboat equipped with a davit and gas-powered winch. Core locations are shown in Figure 1. Cores PM-1 and PM-2 were raised from relatively shallow depths (Table 1) in the centre of the trough which occupies the southern half of the eastern end of the inlet (Fig. 1). Both locations

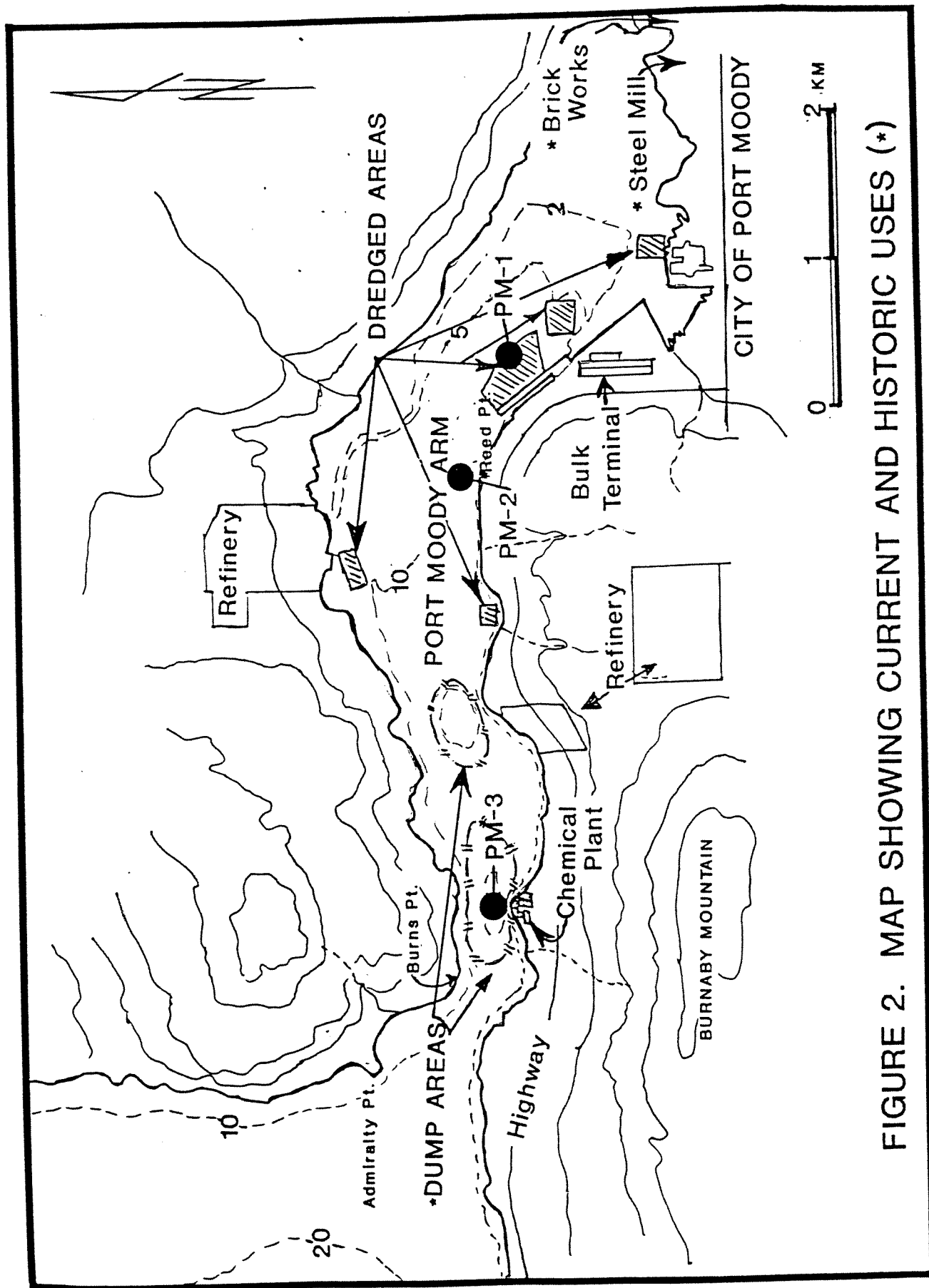


FIGURE 2. MAP SHOWING CURRENT AND HISTORIC USES (\*)

are proximal to the industrialized southern shore of the Arm. Core PM-3 was collected from the deepest point in the basin southeast of Burns Point, at a location immediately opposite the Allied Chemical Company plant. Core PM-4 was raised from the deep basin in north-central Indian Arm, 2 km south of Croker Island (Fig. 1). The locations of the three cores collected from Port Moody Arm were selected to yield representative vertical profiles for Cd and other metals in areas adjacent to industrial sites, while the Indian Arm core was collected as a "geochemical control", in order to obtain comparative data from a proximal area which was free of direct industrial inputs. The cores are described in detail in Table 1. Note that active bioturbation was observed at all coring sites, despite the occurrence of H<sub>2</sub>S at shallow depths at some locations.

**Table 1.** Core location data and log descriptions.

CORE	LOCATION AND WATER DEPTH	DESCRIPTION
PM-1	49° 17' 22" N, 122° 51' 48" W. Eastern end of Port Moody Arm, 200 m northeast of Pacific Coast Bulk Terminals; 11 m depth.	26 cm total length. Homogeneous olive-gray (5Y3/2) silty clay; live burrowing worms on surface; 0-6 cm clearly bioturbated. 0-0.5 cm: watery, trace H <sub>2</sub> S odour, silty clay. 1-1.5: trace H <sub>2</sub> S odour. 1.5-2.0: stronger H <sub>2</sub> S odour (increases with continuing depth). 5-6: sandy silty-clay. 6-7: some wood fibres. 7-8: rare sand-size shell fragments. 8-9: same texture, but becoming more compact. 14-16: cohesive, wood chips present. 16-18: wood chips present. 18-20: thin quartz-rich sand layer at 20 cm.

continued...

CORE	LOCATION AND WATER DEPTH	DESCRIPTION
PM-2	49° 17' 37" N, 122° 52' 22" W. Eastern-central Port Moody Arm, 150 m north of Reed Point; 11 m depth.	<p>36 cm total length. Light olive-gray (5Y5/2) silty clay to clay throughout. No obvious lithological changes. Gradually darkens to 5Y3/2 in lower half. Worm tubes protruding from surface. White worm observed against wall of core actively burrowing at 16 cm depth. Open burrow visible against wall from 11-16 cm depth.</p> <p>0-0.3 cm: interface slightly disturbed (tilted). Well-bioturbated. Black streaks evident at surface, extending down inner barrel wall to ~10 cm. No H<sub>2</sub>S evident in top 20 cm!</p> <p>7-8 : Nereid worm.</p> <p>8-9: remarkably cohesive, compact clay encountered.</p> <p>9-10: abundant worm burrows.</p> <p>10-12: no H<sub>2</sub>S. Nereid burrow has light-brown oxidized halo.</p> <p>14-16: live Nereid, no H<sub>2</sub>S.</p> <p>16-18: wood fragment removed and discarded.</p> <p>20-22: hint of H<sub>2</sub>S.</p> <p>26-28: definite strong H<sub>2</sub>S odour.</p> <p>30-32: whole butter clam shell removed, very rotten.</p> <p>32-34: twig removed.</p>
PM-3	49° 17' 30" N, 122° 54' 41" W. Western Port Moody Arm, 100 m north of shore adjacent to Allied Chemical; 31 m depth.	<p>39.5 cm total length. Undisturbed interface. One opaque worm tube protruding from surface (4 mm diam.). Two clear tubes protruding from surface with "waving" feathered appendages, actively pumping in water. One crab (1 cm diam.) crawling on surface. Well-bioturbated - burrows extend to ~10 cm depth. One burrow extending against barrel wall to 9 cm has light rusty brown filling and halo. Reddish worm seen against wall at 19 cm depth.</p> <p>0-0.5 cm: dark yellowish-brown (10YR4/2) silty clay, no H<sub>2</sub>S.</p> <p>1.5-2: leaf present; no H<sub>2</sub>S, but abundant black streaks. Grading to olive-gray (5Y3/2).</p>

continued...

CORE	LOCATION AND WATER DEPTH	DESCRIPTION
PM-3 (cont'd)		<p>3-4: wood chips and fibre present; black but no H<sub>2</sub>S.</p> <p>5-6: big burrow with oxic halo. live crab in burrow at 6 cm.</p> <p>7-8: wood fibre.</p> <p>8-9: crab, 1 cm diam.</p> <p>9-10: oxidized halo around a burrow, more wood chips.</p> <p>16-18: polychaete present.</p> <p>18-20: big piece of bark removed.</p> <p>24-26: abundant shell fragments, no H<sub>2</sub>S. Live worm at 26 cm.</p> <p>26-28: sand and gravel lens at 28 cm.</p> <p>28-30: big wood chip removed; gravelly sand mixed with clay.</p> <p>30-32: big shell fragment removed; still gravelly.</p> <p>32-34: few pieces of gravel.</p> <p>38-39: sand-bearing silty clay.</p>
PM-4	<p>49° 24' 49" N, 122° 52' 07" W. North-central Indian Arm, axial trough, 2 km south of Croker Island; 210 m depth.</p>	<p>60.5 cm total length. Good interface. Fine-grained (fine silty clay) throughout. Dark yellowish-brown surface fluff - 10YR4/2. Core somewhat disturbed over top 6 cm : extraction gaps formed during processing.</p> <p>0-1.5 cm: yellowish brown (10YR4/2) oxic top, very fine-grained.</p> <p>1.5-2: no H<sub>2</sub>S</p> <p>5-6: black streaks and patches abundant. Polychaete tube at 6 cm.</p> <p>7-8: Faecal pellets highly abundant. Some wood chips, lots of worm tubes at 8 cm.</p> <p>8-9: abundant faecal pellets. Long worm tube pulled gently out, 30 cm long!</p> <p>9-10: no H<sub>2</sub>S.</p> <p>10-12: worm tubes present.</p> <p>12-14: abundant faecal pellets at 12 cm, hint of H<sub>2</sub>S.</p> <p>16-18: abundant worm tubes.</p> <p>22-24: slight H<sub>2</sub>S odour.</p> <p>34-38: strong H<sub>2</sub>S, no more worm tubes, faecal pellets still present.</p> <p>42-46: abundant faecal pellets.</p>

## 4.0 Sampling and Methods

The four cores were sequentially subsampled on a purpose-built extrusion table by driving a piston up each vertical core barrel with a scissors jack and slicing off the extruded material with a very thin polycarbonate sheet and a plastic spatula. A high-resolution sampling interval was employed during the extrusion: 5 mm increments were taken over the top 2 cm, followed by 1 cm thick slices to 10 cm, and 2 cm thick slices for the remainder of each core. The bulk sediment samples were frozen, freeze-dried, ground to fine powders in a Tema tungsten carbide disc mill, and used for radioisotope analysis and subsequent determinations of elemental composition.

Several analytical methods were used:

(a) Inductively-coupled argon plasma spectrometry was used to measure the concentration of Mo following digestion of 300 mg porcelain-ground samples in an HCl-HNO<sub>3</sub> mixture which was heated in sealed teflon bombs using microwave radiation. Cd was analysed in the leachate by graphite furnace AAS. Blanks were carried through the entire procedure and the accuracy and precision of both sets of measurements were assessed respectively by including a pair of certified NRC reference sediments (MCSS and BCSS) and a number of replicate subsamples. The procedure is described in detail elsewhere (EPS, 1986, unpublished). Estimated precision for Mo at the 5 µg g<sup>-1</sup> level (1  $\sigma$ , Relative Standard Deviation, n=4) is about 10%, while that for Cd at the 2 µg g<sup>-1</sup> level is <4 % RSD (1  $\sigma$ , n = 5). The measurements were made at the Environmental Protection Service laboratories in West Vancouver.

(b) X-ray fluorescence spectrometry was used to determine major and minor element concentrations on fused glass discs and pressed powder pellets, respectively, using the Philips PW1400 spectrometer and Rh tube at the UBC Department of Oceanography. Corrections for mass absorption effects were obviated for major elements by using a lanthanum-bearing flux for fusion, following a slight modification of the method of Norrish and Hutton (1970), which eliminates the need to apply specific corrections for matrix effects. For minor elements, a method similar to that described by Harvey and Atkin (1982) was used. The samples were prepared by forming a mixture of 4 g sample and 0.5 g finely-divided wax (Hoechst Wax C) into 32-mm diameter discs in a hydraulic press. Calibration for both sets of measurements was provided by a wide range of international geochemical reference standards, with discs

prepared in the appropriate way, and using the element concentrations recommended by Abbey (1983). Accuracy was assessed by randomly including several geochemical reference samples as unknowns in the analytical run. The results of these measurements are listed in Table 2. As can be seen the accuracy of the major element measurements is excellent.

**Table 2.** XRF major element quality control data, comparing concentrations determined for geochemical reference standards in this study (m), with concentrations recommended (r) by Abbey (1983).

		Fe	Ti	Ca	K	Si	Al	Mg	P	Na
STANDARD NIMG	(m)	1.38	0.06	0.56	3.12	35.37	6.51	0.01	0.00	1.25
	(r)	1.41	0.05	0.56	3.19	35.35	6.39	0.04	0.01	1.25
AGV1	(m)	4.78	0.63	3.53	1.83	27.94	8.74	0.92	0.22	1.59
	(r)	4.76	0.64	3.53	1.87	27.83	9.09	0.92	0.22	1.60
W2	(m)	7.52	0.64	7.71	0.42	24.15	7.70	3.80	0.06	0.83
	(r)	7.60	0.64	7.79	0.40	24.66	8.19	3.85	0.06	0.82
NIMS	(m)	1.04	0.01	0.49	10.01	31.82	9.56	0.26	0.06	0.14
	(r)	0.98	0.02	0.49	9.81	29.71	9.17	0.28	0.05	0.16
G2 G2 (Repeat)	(m)	1.83	0.31	1.37	2.77	32.16	8.22	0.55	0.06	1.65
	(m)	1.83	0.30	1.37	2.79	32.32	8.09	0.49	0.06	1.51
	(r)	1.88	0.29	1.40	2.85	32.32	8.15	0.45	0.06	1.51
BEN	(m)	8.89	1.52	9.97	0.91	17.87	5.04	7.78	0.46	1.12
	(r)	9.03	1.57	9.97	0.90	17.93	5.35	7.97	0.46	1.19
BHVO1	(m)	8.73	1.62	8.31	0.35	23.67	7.24	4.34	0.12	0.85
	(r)	8.56	1.61	8.10	0.35	23.30	7.33	4.41	0.12	0.85
MRG1	(m)	12.38	2.18	10.57	0.13	18.37	4.44	7.94	0.03	0.27
	(r)	12.48	2.21	10.56	0.12	18.36	4.50	8.13	0.02	0.26

For the minor elements, precision varies depending on the concentration and becomes poor as the detection limit is approached. Detection limits for the elements measured are on the order of 10 µg g<sup>-1</sup>; measured concentrations near this level are precise only to within 50 %RSD. For the concentrations typically encountered in sediments discussed in this report, precision is typically better than + 5% (1σ, RSD). In this study, only the Ni and rarely the Pb contents approach the XRF detection limit; all other elements are well above the limit of detection. Accuracy of the measurements was assessed as for major elements. The results are listed in Table 3 and are acceptable, given that the

accuracy of the recommended reference standard values is often not that well constrained.

**Table 3.** XRF minor element quality control data, comparing concentrations determined for geochemical reference standards in this study (m), with concentrations recommended (r) by Abbey (1983).

		Zr	Sr	Rb	Pb	Zn	Cu	Ni	Co	Mn	V	Cr	Ba
AGV1	(m)	231	610	64	32	72	68	4	17	778	88	29	1123
	(r)	230	660	67	33	86	59	15	16	728	125	10	1200
BHVO1	(m)	171	369	14	3	88	142	97	40	1224	190	279	104
	(r)	180	420	10	n.a.	105	140	120	45	1316	300	320	135
W2	(m)	92	180	21	9	63	91	44	38	1218	202	93	162
	(r)	100	190	21	n.a.	80	105	70	43	1300	260	92	175
NIMS	(m)	35	60	483	3	12	16	25	4	69	23	12	2269
	(r)	33	62	530	5	10	19	7	4	80	10	12	2400
MRG1 MRG1(r)	(m)	105	254	9	6	164	133	154	86	1128	360	522	10
	(m)	92	178	17	n.a.	139	140	120	69	1031	326	408	10
	(r)	105	260	8	10	190	135	195	86	1320	520	450	50
G2	(m)	291	437	152	29	76	11	n.d.	5	260	32	16	1863
	(r)	300	480	170	30	84	10	3	5	265	36	8	1900
GSP1	(m)	459	220	231	53	94	35	12	7	300	38	20	1234
	(r)	500	240	250	54	105	33	9	7	326	54	12	1300
SY2	(m)	260	237	171	72	225	6	48	12	2406	35	11	462
	(r)	280	275	220	80	250	5	10	11	2480	52	12	460

(c) CNS and CaCO<sub>3</sub> analysis: Total carbon, nitrogen and sulphur were determined using elemental analysis. Total C, N and S were measured using a Carlo-Erba NA-1500 Elemental Analyser which combusts the sample in a stream of O<sub>2</sub>, separates the combustion gases (CO<sub>2</sub>, N<sub>2</sub> reduced from NO<sub>x</sub>, and SO<sub>2</sub>) chromatographically, and measures the gas concentrations (thus C, N and S contents) by thermal conductivity. The analyser was calibrated using acetanilide and the NRC marine sediment standards MESS-1 and BCSS-1. Accuracy is excellent; agreement with the recommended values for total C and N is always within analytical precision, and for sulphur is within twice the 1σ



(R.S.D.) precision estimate. The precision of the measurements ( $1\sigma$ , RSD) was about 1.5%, 3% and 3% for C, N and S respectively.

Carbonate carbon was determined on all samples by coulometry using a Coulometrics analyser, which electrochemically measures the  $\text{CO}_2$  evolved following addition of HCl to a sample. Concentrations were very low in almost all samples (typically  $\ll 0.1$  wt. %): such values are difficult to measure precisely, and as a result precision was about 10 % ( $1\sigma$ , RSD).

Organic carbon was determined by subtracting carbonate carbon from the total C measurements. Precision of the resulting organic C value was about  $\pm 5\%$  ( $1\sigma$ , RSD).

(d)  $^{210}\text{Pb}$  analysis:  $^{210}\text{Pb}$  was measured by alpha-counting of the  $^{210}\text{Po}$  granddaughter, following digestion of a measured amount of sample in hot  $\text{HF-HNO}_3$  in a teflon beaker and plating of the dissolved Po onto a nickel disc. A spike of known activity of  $^{208}\text{Po}$  was added to determine plating efficiency, and a correction was applied in each case. The discs were counted on EG&G Ortec Si barrier detectors for a minimum of 24 hours. Precision of the method ( $2\sigma$ ) determined by replicate measurements ( $n = 4$ ) at the 7 dpm  $\text{g}^{-1}$  level is 0.1 dpm  $\text{g}^{-1}$ . At least six months elapsed between isolation of the core subsamples and the commencement of the measurements. This is sufficient to allow ingrowth of the  $^{210}\text{Po}$  over about 1.5 half-lives ( $^{210}\text{Po}$   $t_{1/2} = 138$  d). We have thus assumed that  $^{210}\text{Pb}$  and  $^{210}\text{Po}$  are at least approximately, if not fully, in secular equilibrium, and that the  $^{210}\text{Po}$  data can be used as a proxy for  $^{210}\text{Pb}$ . Thus, the  $^{210}\text{Po}$  measurements are reported as  $^{210}\text{Pb}$  in this study.

(e) Porosity and bulk density measurements: Samples were taken at selected intervals during the extrusion procedure for water content and wet bulk density measurements. For the water content determinations, samples of a few  $\text{cm}^3$  were placed in preweighed plastic vials, weighed, dried to constant weight, and weighed again. Samples for wet bulk density determinations were collected by gently inserting preweighed plastic cubes of known volume into the exposed surface of the core. The cubes were filled and excess sediment carefully removed from the edges and outer surfaces before weighing. Following drying to constant weight, the cubes were reweighed, so that both wet and dry bulk density could be calculated. Porosity ( $\phi$ ) was determined from the water content data using the equation:

$$\phi = [(\text{weight H}_2\text{O})/\rho_s] / [(\text{sediment dry weight}/\rho_g) + ((\text{weight H}_2\text{O})/\rho_s)]$$

where  $\rho_s$  is the density of bottom seawater in Port Moody and Indian Arms (assumed to be 1.03) and  $\rho_g$  is the sediment grain density, taken to be 2.5 g cm<sup>-3</sup>. Porosity profiles are shown for the four cores in Figure 3. In order to calculate a sedimentation rate at each site, the uncompacted depth ( $f(z)$ ) was determined by "decompacting" the sediments to a constant porosity equivalent to that at the interface, using the equation (Robbins and Edgington, 1975):

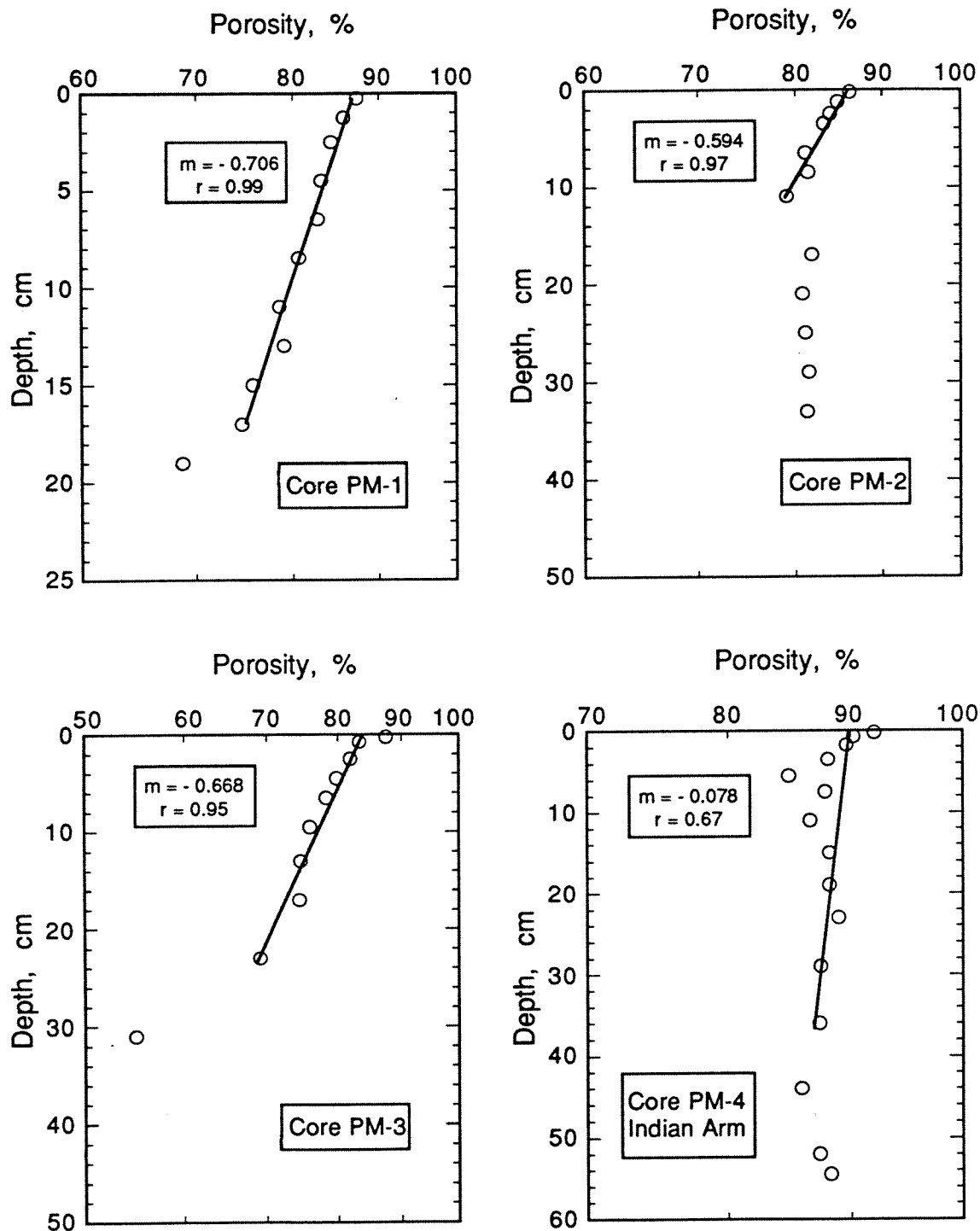
$$f(z) = \frac{1}{(1-\phi_0)} [z(1-\phi') + \frac{[\phi(z) - \phi_0]}{\beta_i}]$$

where  $\phi_0$  is the porosity at the interface,  $\phi'$  is the porosity at infinite depth, and  $\beta_i$  is the slope of the log  $\phi$  *versus* depth curves in Fig. 3. Corrected and uncorrected sample depths are given in Appendix A.4.

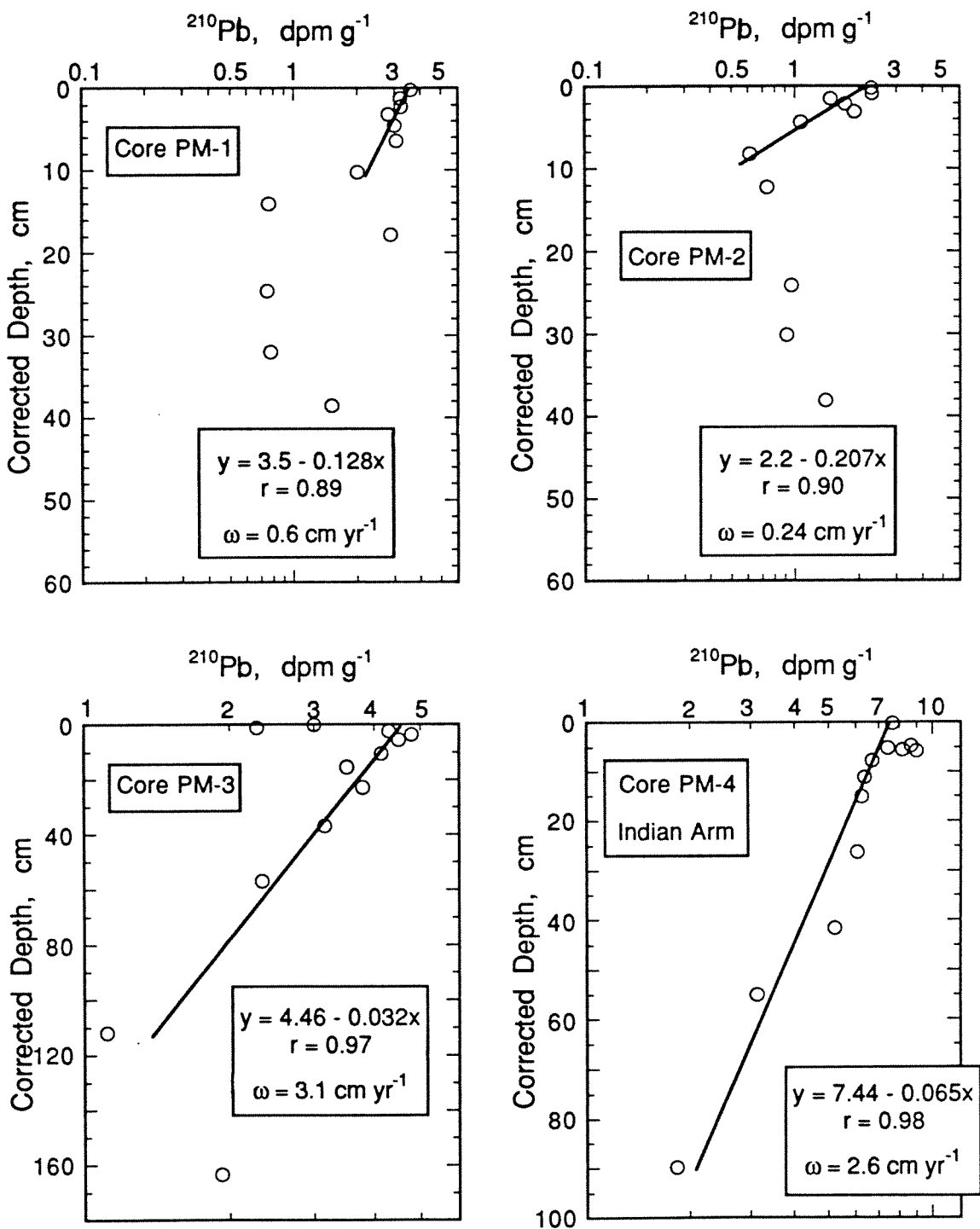
## 5.0 Results

Major and minor element data, elemental ratios, organic carbon and nitrogen data, and <sup>210</sup>Pb specific activities are listed in Appendices A.1 to A.4. It is clear from examination of the data that considerable compositional and stratigraphic variability exists among the three Port Moody Arm sites, both areally and temporally (i.e. vertically). Porosity is typically slightly less than 90% in the surface sediments at the three locations, and decreases in an approximately first-order fashion at sites PM-1 and PM-3 (Fig. 3). In Core PM-2, a cohesive, stiff, homogeneous clay layer more than two decimetres thick underlies a less compact 10-cm thick silty clay surface horizon, as noted in Table 1. This lithological contrast is reflected in the porosity profile for the core. At the Indian Arm site (PM-4), porosity is slightly higher in the surface sediments and decreases in an irregular fashion with depth (Fig. 3).

<sup>210</sup>Pb profiles are shown in Figure 4. Calculated uncompacted sedimentation rates (as described in Section 4.0) range from 0.24 to 3.1 cm yr<sup>-1</sup> at the four locations (Fig. 4). It must be emphasized that these are estimates only, and are subject to the qualifications described in Section 6.0.1.



**Figure 3.** Porosity profiles, Port Moody and Indian Arm cores. Porosity was calculated from water content data, as described on page 11. Note the differing log scales on the abscissae. The calculated slope shown in each panel corresponds only to those points in the depth range embraced by the straight lines.



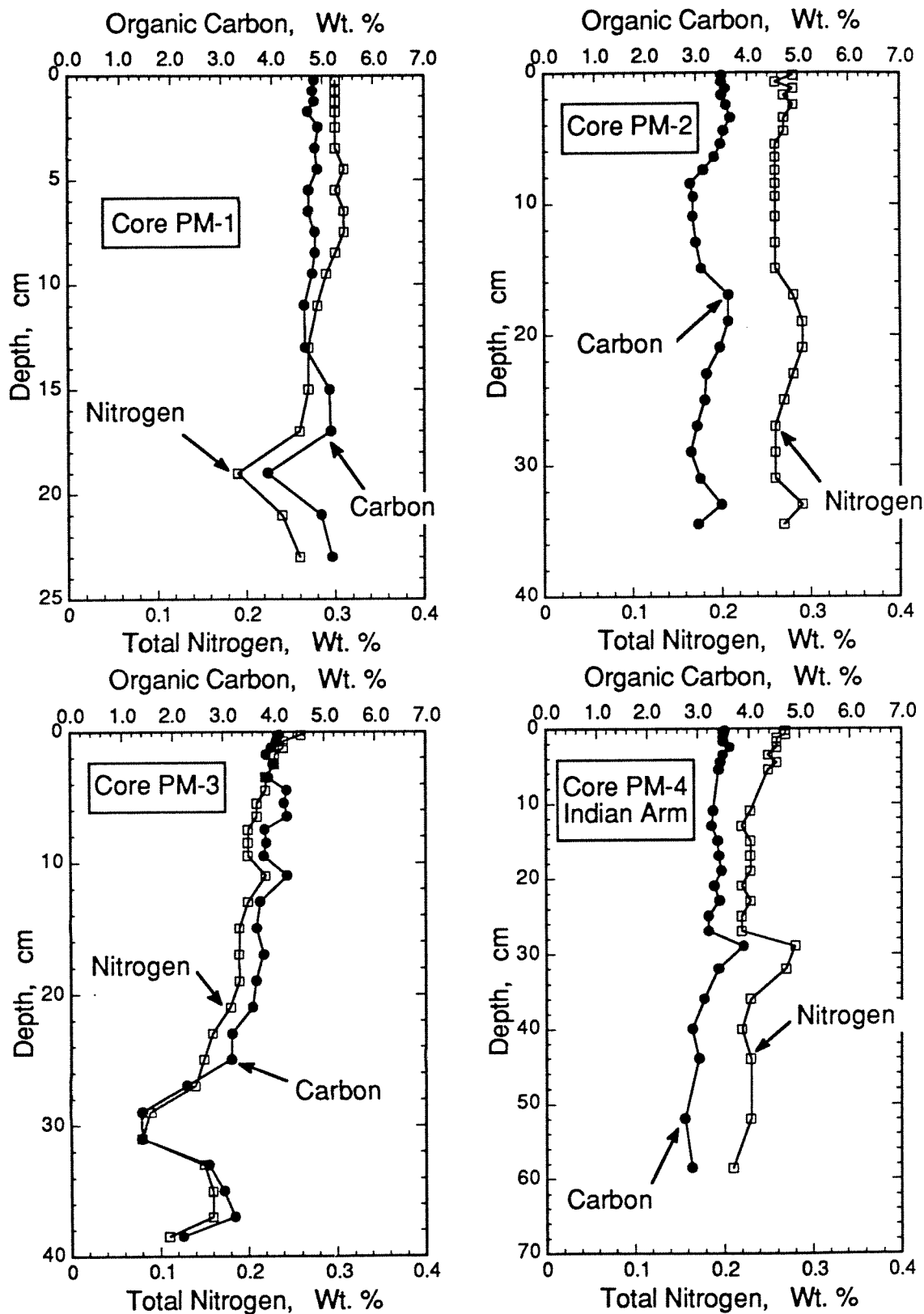
**Figure 4.**  $^{210}\text{Pb}$  activity in Port Moody and Indian Arm cores plotted against corrected (uncompacted) depth, calculated as described on page 11. Note the differing log scales on the abscissae. At each site, only the points within the depth range embraced by the straight line were used in the calculation of the slope and intercept.  $\omega$  is the uncompacted sedimentation rate.

Organic carbon concentrations exceed 3 wt. % in the upper decimetre at all sites; highest values occur in Core PM-1, near the eastern end of Port Moody Arm (Fig. 5). Carbonate carbon is scarce at all locations (Appendix A.3). The organic carbon profiles are closely paralleled by nitrogen (Fig. 5), but there are nevertheless considerable variations with depth in the  $C_{org}:N$  wt. ratio (Fig. 6). As discussed below, such variability is related to changes in organic matter sources over time.

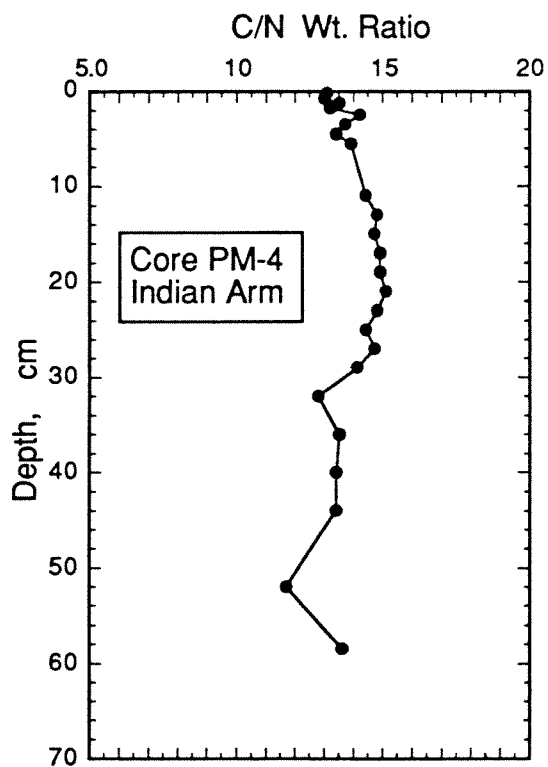
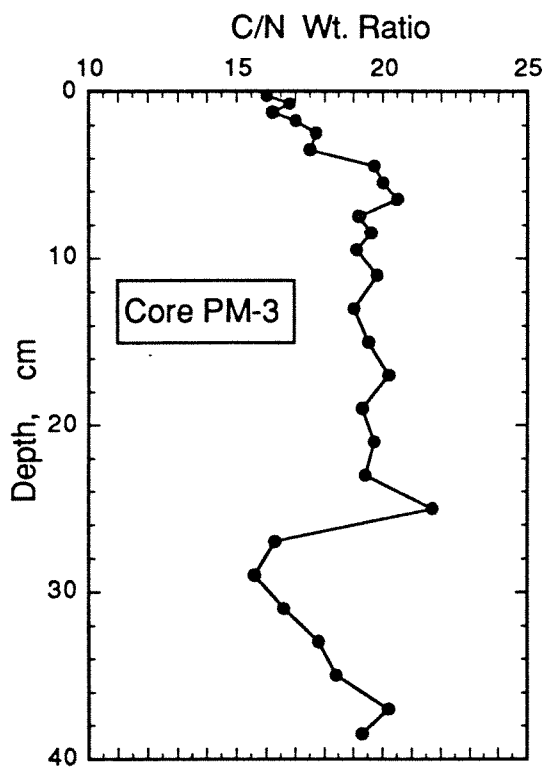
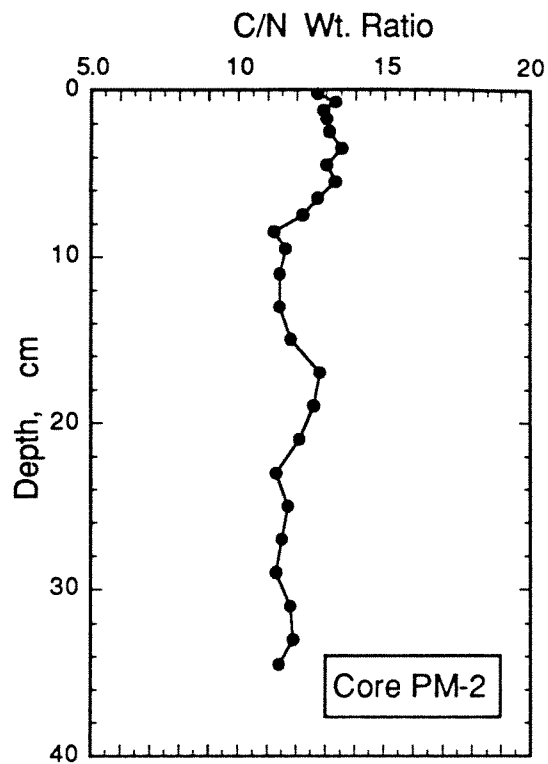
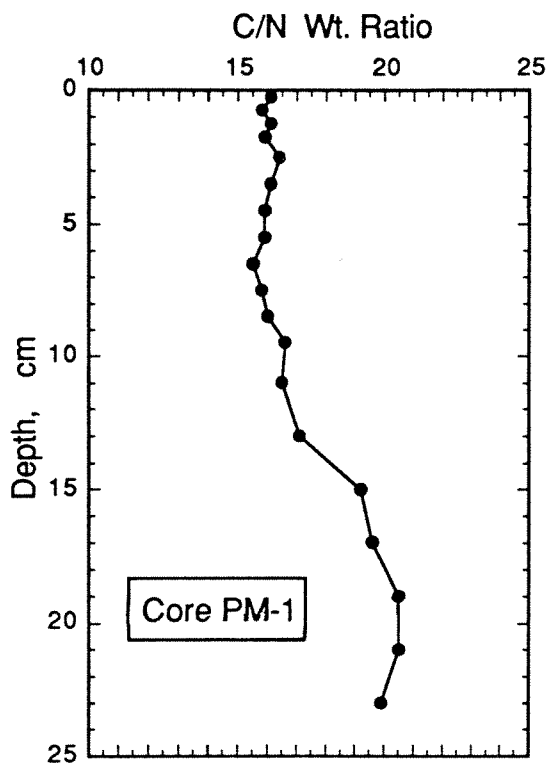
Ti and Si concentrations are listed in Appendix A.1 and are presented in Figure 7 as ratios to Al. Ratios are used because they are independent of correlations induced by dilution by non-silicate phases such as organic matter. In addition, sands are frequently quartz- and heavy-mineral rich (e.g.  $TiO_2$ ,  $FeTiO_3$ ) and clays Al-rich so that, in the absence of significant concentrations of Al-bearing feldspars, Si/Al and Ti/Al ratios can serve as indicators of relative sediment texture or mean grain size. The application is only partly useful in Port Moody Arm sediments, however: feldspars are relatively abundant in rock fragments in the gravelly clay noted at 25-35 cm depth in PM-3, so that the coarse layer is not defined by increases in the Si/Al and Ti/Al ratios. In contrast, a slight increase in Si/Al profile (from 3.8 to ~4) does define the quartz-rich sand layer at 18-20 cm depth in PM-1 (Table 1 and Fig. 7). Overall, with the exception of these two textural variations and the rather odd composition of the deposits at the base of Core PM-3, the Ti/Al and Si/Al data suggest that the sediments are in general texturally homogeneous at each location.

Fe/Al wt. ratio profiles are shown in Figure 8. Little variation with depth is seen in the Port Moody Arm cores with the exception of the quartz-rich band at 18-20 cm depth in PM-1, which appears to be relatively Fe-poor, and the extremely high Fe/Al ratios (up to ~6.4) measured near the base of Core PM-3, which correspond to Fe concentrations up to ~29 wt. % (Appendix A.1)! A more subtle enrichment of iron is evinced by the relatively high Fe/Al ratios measured in near-surface Indian Arm sediments (Fig. 8).

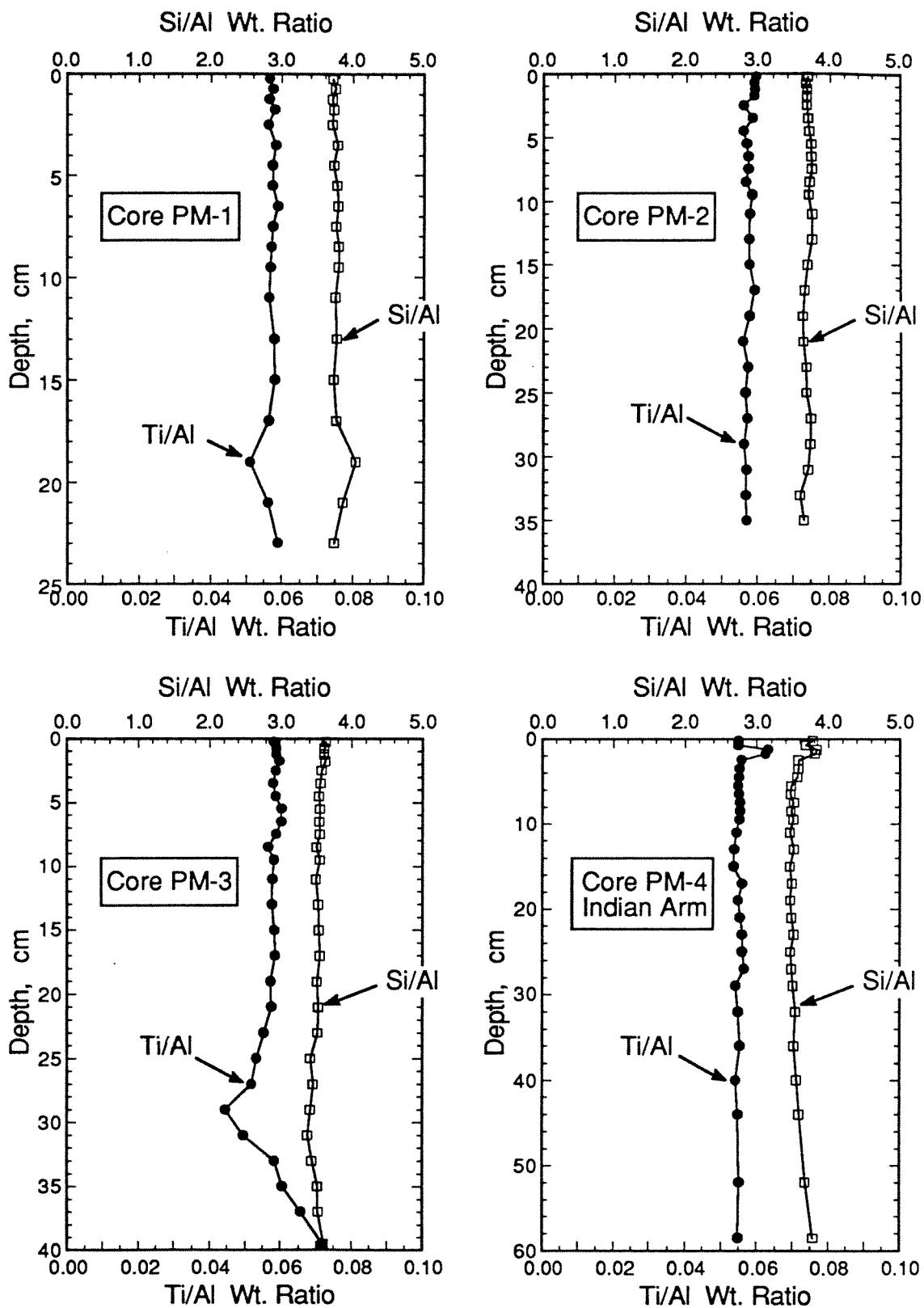
Mn levels in Port Moody Arm sediments (typically 600-700  $\mu g\ g^{-1}$ ) show little variation and are low in comparison to concentrations seen in the Indian Arm core (Fig. 8), where the Mn content exceeds 3400  $\mu g\ g^{-1}$  at the surface. The concentration decreases irregularly to about 1000  $\mu g\ g^{-1}$  at 60 cm depth in PM-4. Unusually low Mn values (~300  $\mu g\ g^{-1}$ ) characterize the compositionally and texturally anomalous layer at the base of Core PM-3.



**Figure 5.** Organic carbon and nitrogen concentration profiles in Port Moody and Indian Arm cores, plotted against true depth.

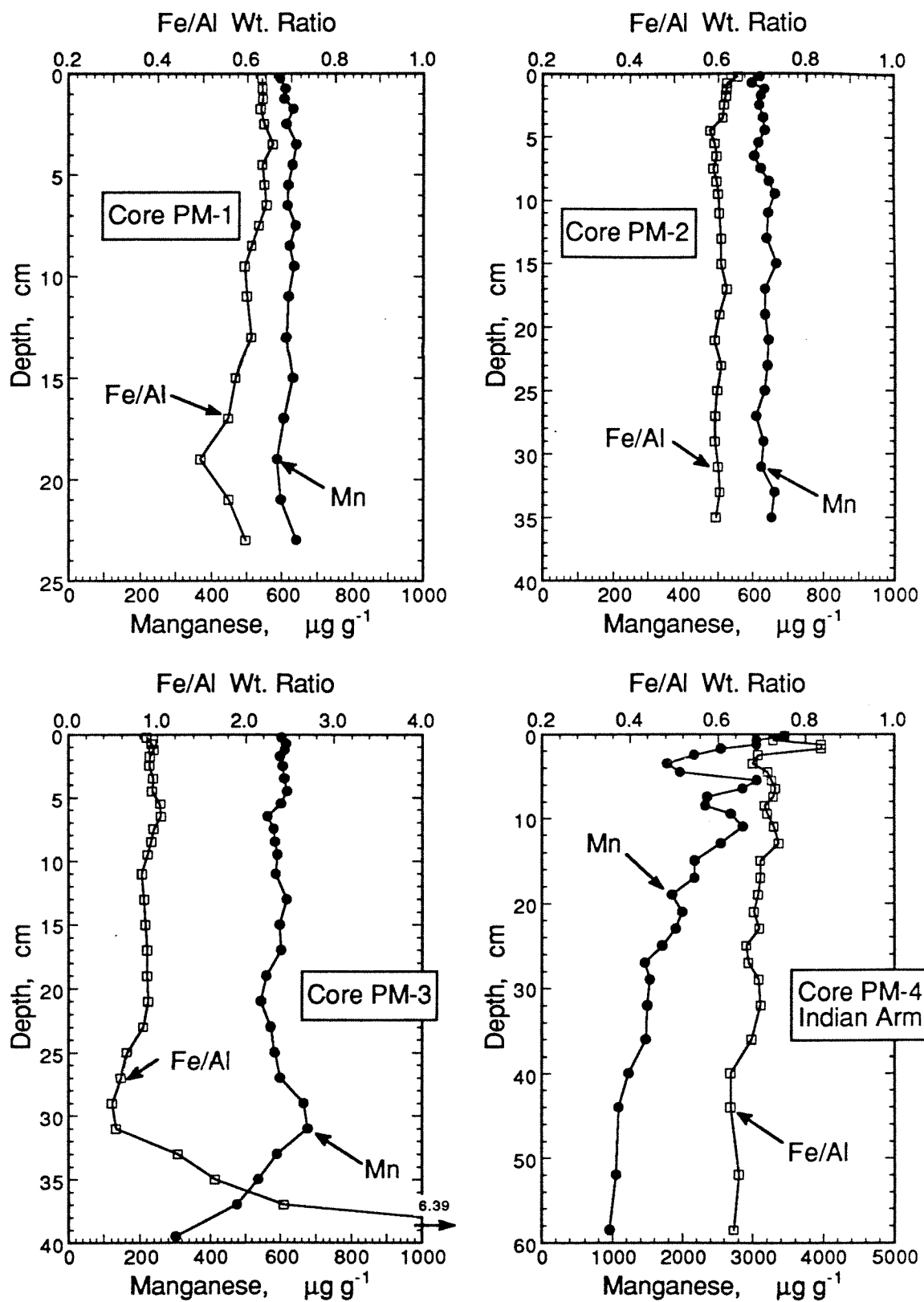


**Figure 6.** Organic carbon:N weight ratio profiles in Port Moody and Indian Arm cores, plotted against true depth.



**Figure 7.** Si/Al and Ti/Al weight ratio profiles in Port Moody and Indian Arm cores, plotted against true depth.





**Figure 8.** Fe/Al weight ratio and wt. % Mn profiles in Port Moody and Indian Arm cores, plotted against true depth. Note the varying scales on the abscissae.

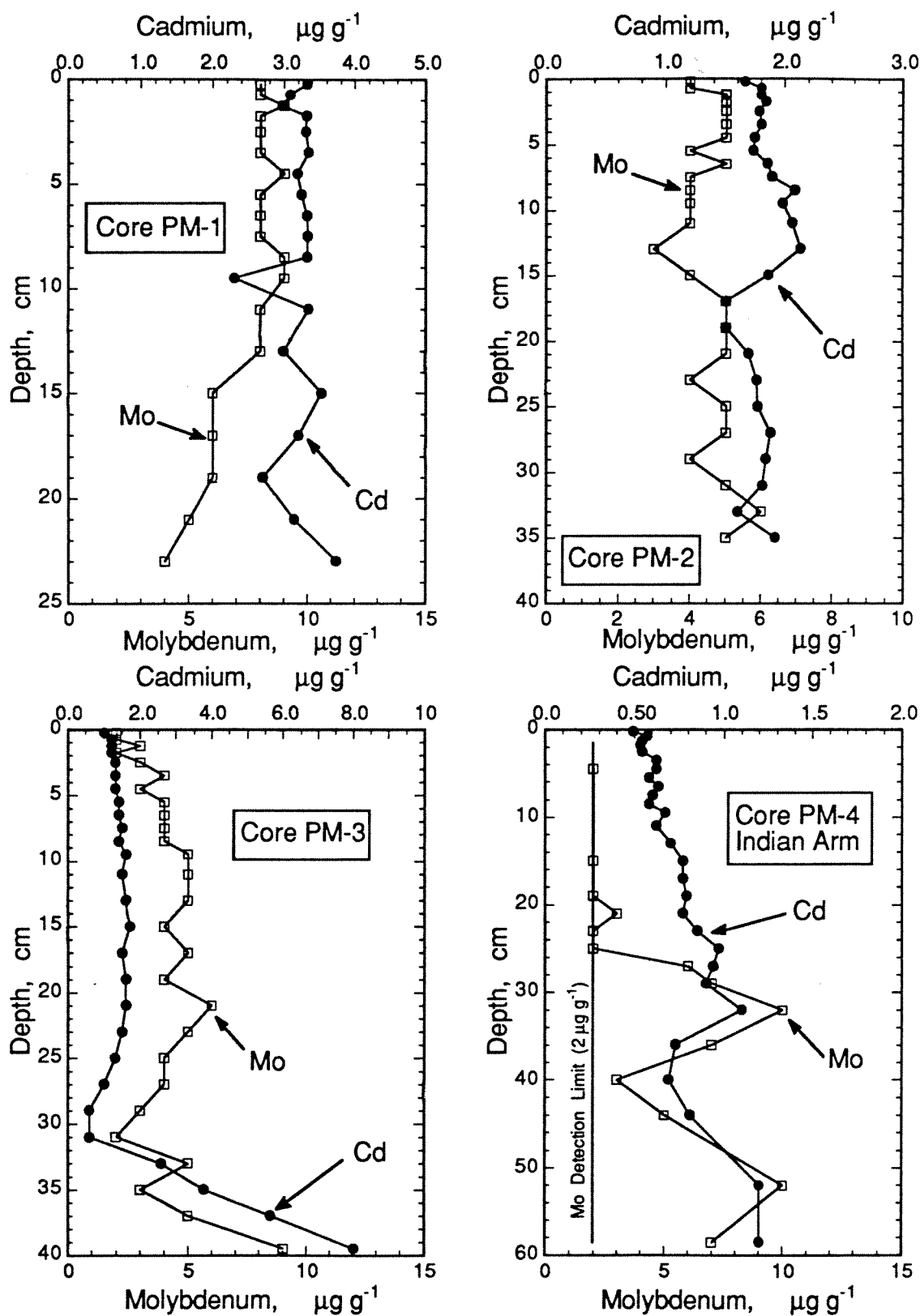
Cadmium concentrations in surface sediments (top 5 mm) range from  $>3 \mu\text{g g}^{-1}$  at site PM-1 to  $<<1 \mu\text{g g}^{-1}$  at PM-4 in Indian Arm (Fig. 9). Considerably higher concentrations (up to  $8 \mu\text{g g}^{-1}$ ) were measured in the lower two decimetres of Core PM-3. The Cd content varies irregularly with depth in cores PM-1 and PM-2, while a generally progressive increase with depth is observed in the Indian Arm core; concentrations at the base of the core exceed  $1 \mu\text{g g}^{-1}$  (Fig. 9).

Molybdenum profiles both contrast with and mimic the Cd distributions, depending on location. Concentrations in surface sediments range from being undetectable ( $<2 \mu\text{g g}^{-1}$ ) in Indian Arm to  $\sim 8 \mu\text{g g}^{-1}$  at PM-1 (Fig. 9). Mo levels increase with depth in the Indian Arm core to values exceeding  $9 \mu\text{g g}^{-1}$  in some horizons, and to similar levels at the base of Core PM-3 (Fig. 9). In contrast, concentrations decrease with depth in Core PM-1 and remain approximately constant at  $4\text{--}6 \mu\text{g g}^{-1}$  throughout Core PM-2.

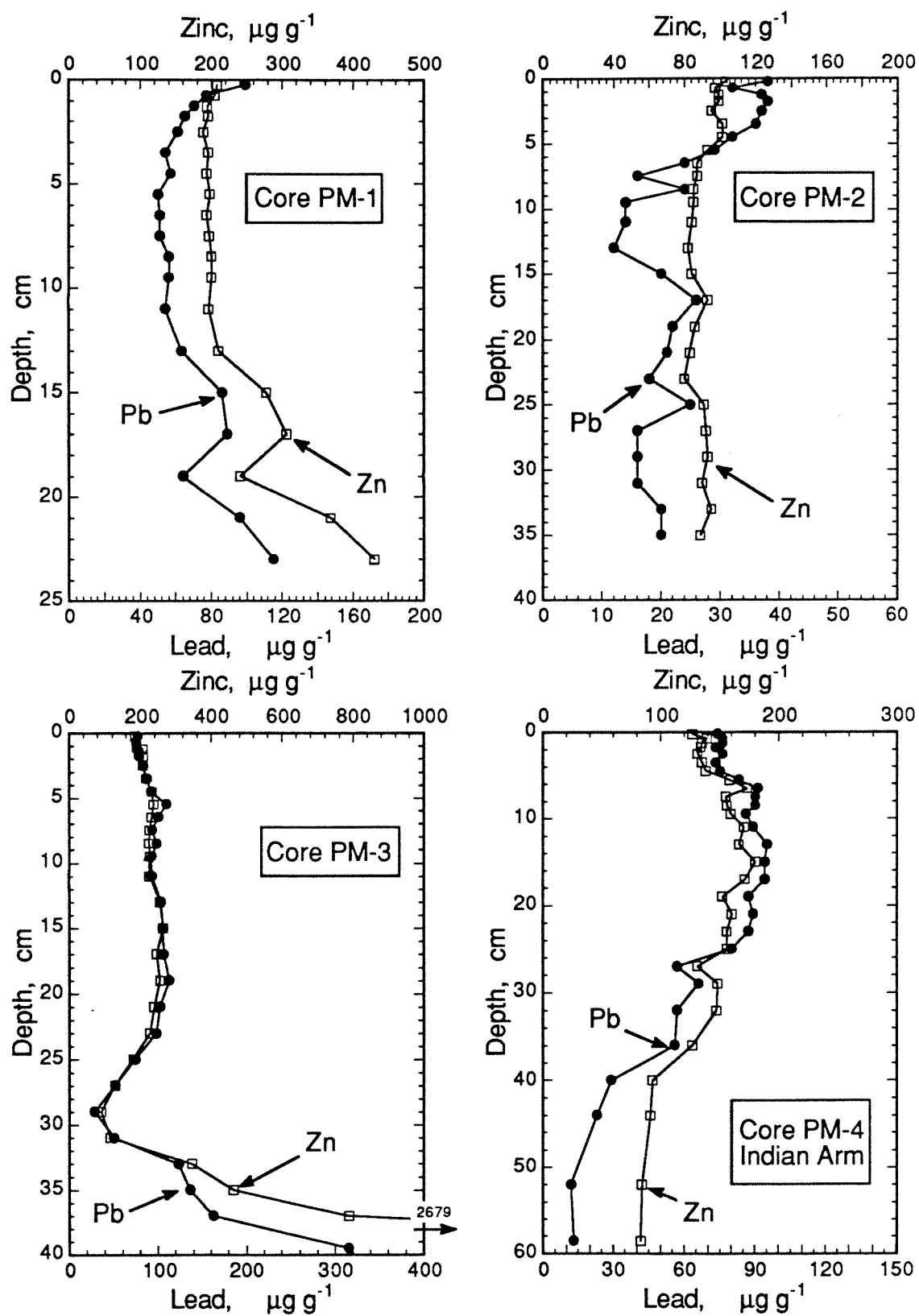
Pb and Zn distributions are shown in Figure 10. Zinc contents in surface sediments are on the order of  $200 \mu\text{g g}^{-1}$  at sites PM-1 and PM-3 and  $100\text{--}130 \mu\text{g g}^{-1}$  at PM-2 and PM-4. Concentrations increase with depth to  $\sim 180 \mu\text{g g}^{-1}$  over the upper two decimetres in the Indian Arm deposits, before decreasing to levels  $<20 \mu\text{g g}^{-1}$  at greater depths. In contrast, Zn contents increase significantly toward the base of cores PM-1 and PM-3. The highest Zn concentration measured in this study ( $>2600 \mu\text{g g}^{-1}$ ) occurs at the base of PM-3, where Cd, Mo and Fe levels are also significantly enriched. Note that the average Zn content in Core PM-2 ( $\sim 90 \mu\text{g g}^{-1}$ ) is substantially less than the levels observed in PM-1 and PM-3 (typically  $\sim 200\text{--}250 \mu\text{g g}^{-1}$ ).

Lead distributions essentially parallel the Zn profiles in cores PM-1, 3 and 4; the correlation is less well defined in PM-2. Lowest mean concentrations ( $\sim 25 \mu\text{g g}^{-1}$ ) occur in Core PM-2 and similarly low values ( $\sim 12 \mu\text{g g}^{-1}$ ) occur in the lower portions of PM-4. As is the case for most of the other metals measured in this work, the highest Pb concentration is observed at the base of Core PM-3 (Fig. 10).

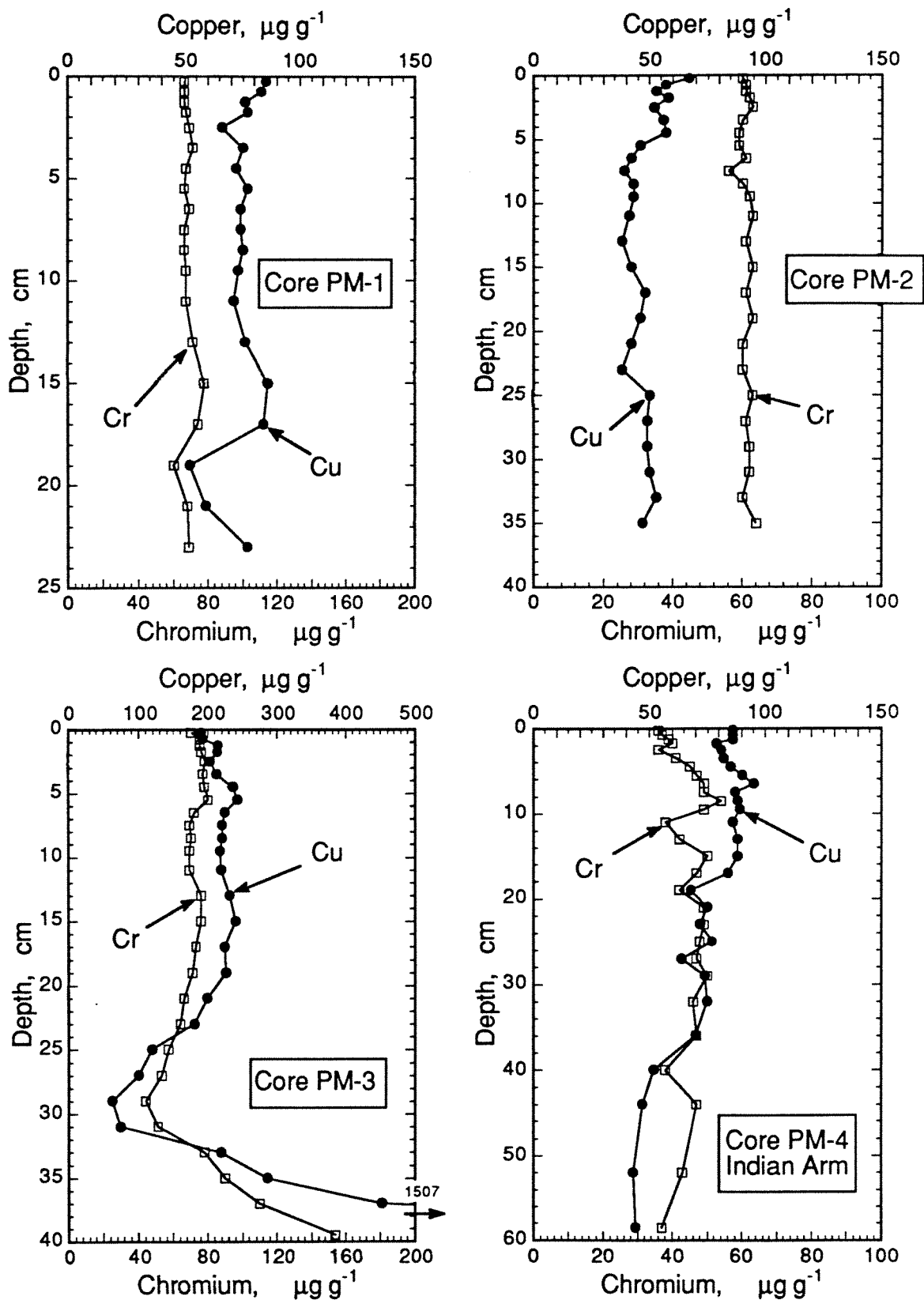
Copper levels range from  $30\text{--}90 \mu\text{g g}^{-1}$  in cores PM-1, 2 and 4 to upwards of  $200 \mu\text{g g}^{-1}$  in the upper 20 cm of PM-3 (Fig. 11). The metal-rich horizon at the base of PM-3 is marked by a Cu concentration exceeding  $1500 \mu\text{g g}^{-1}$ . The profiles in general parallel the Zn and Pb distributions. Similar considerations apply to the Cr distributions (Fig. 11) although the dynamic range of the concentrations is considerably attenuated. In the Port Moody Arm



**Figure 9.** Cadmium and molybdenum concentration profiles in Port Moody and Indian Arm cores, plotted against true depth. Note the varying scales on the abscissae.



**Figure 10.** Lead and zinc concentration profiles in Port Moody and Indian Arm cores, plotted against true depth. Note the varying scales on the abscissae.



**Figure 11.** Copper and chromium concentration profiles in Port Moody and Indian Arm cores, plotted against true depth. Note the varying scales on the abscissae.

cores, Cr levels range from ~60 to ~80  $\mu\text{g g}^{-1}$  with the exception of the enriched zone in PM-3 where the concentration reaches 154  $\mu\text{g g}^{-1}$  in the lowermost sample. Cr contents are in general lower (35-50  $\mu\text{g g}^{-1}$ ) in the Indian Arm sediments (Fig. 11).

## 6.0 Discussion

### 6.1. Rates and History of Sedimentation

It is clear from the  $^{210}\text{Pb}$  measurements that sedimentation has been disrupted, both in the past and possibly more recently (at least at PM-3) at the Port Moody Arm sites. This is not surprising given the history of dredging and spoil dumping in the area. In contrast, the reasonably constant slope of the log [ $^{210}\text{Pb}$ ] *versus* depth curve indicates that sedimentation in the deep inner basin of Indian Arm has been quasi-steady (Fig. 4). Very low specific activities of  $^{210}\text{Pb}$  occur in most of the sampled intervals below 7 cm true depth in Core PM-1 and below 4 cm depth in Core PM-2; these activities probably represent the background  $^{210}\text{Pb}$  content supported by uranium decay within the sediments. Activities are somewhat higher at depth in Core PM-3, and significantly higher in the upper 35 cm in Indian Arm deposits. The dearth of polonium in the intermediate and deep horizons in the Port Moody Arm cores suggests that these strata are anomalously old relative to the surface, given the sedimentation rates determined from the measurements made in the upper parts of the cores. At the PM-1 and PM-2 sites, this may reflect past dredging and removal of "young",  $^{210}\text{Pb}$ -bearing sediments. Indeed, historical data show that the local region around the PM-1 site was used as a "borrow area" in the mid-1960's. The occurrence of the stiff, cohesive clay at a depth of only 8 cm (Table 1) in PM-2 is also consistent with the idea that there has been past removal from the site of the less-compacted sediments that one would normally expect to encounter at such a location.

The  $^{210}\text{Pb}$  profile at Site PM-3 is anomalous in two respects. Low activities occur in the top centimetre (Appendix A.4), and the activity at a true depth of 31 cm is about half that at 38.5 cm. The latter distribution may reflect the natural U content in the deposits, with the higher measured  $^{210}\text{Pb}$  at 38.5 cm depth indicating a higher U concentration, or it may reflect the deposition of

old sediments on top of younger deposits. These possibilities cannot be distinguished given the very odd composition of the materials penetrated near the base of the core, which are described in more detail below. The low  $^{210}\text{Pb}$  activities at the top of the core, which are not seen at other sites, can be ascribed to the recent deposition of "old" sediments at that location.

The sedimentation rates shown in Figure 4, calculated after correcting for compaction at each site, range from 0.24 to 3.1  $\text{cm yr}^{-1}$ , the highest value occurring at Site PM-3. These rates must be considered relatively rough estimates, given that the fundamental assumption used in the calculations is that sedimentation has been constant with time. This assumption, which is weak at best for the Port Moody cores but is probably applicable to Indian Arm, is represented by the straight lines drawn through the data in Figure 4. The high apparent sedimentation rate at PM-3 may be an artifact; calculation of the corrected depth is based on deconvolution of the porosity profile, and the assumption inherent in this procedure is that texture is constant with depth, i.e. the decrease in porosity with depth (which is substantial at this site) is controlled only by compaction. This cannot be true for PM-3 given the occurrence of the gravely clay in the lower portion of the core. Such material has a naturally lower porosity, and because the factor  $\beta_i$  used in the decompaction algorithm (Section 4) does not take this into account, the corrected depth is greater than it would be if steady-state, constant-texture sedimentation had occurred at the site. Thus the sedimentation rate calculated for PM-3 (Fig. 4) is probably anomalously high. Using the real depth in place of the uncompacted ("corrected") depth yields a sedimentation rate of  $\sim 1 \text{ cm yr}^{-1}$ .

The rate of sedimentation estimated for the Indian Arm core ( $2.6 \text{ cm yr}^{-1}$ ) is also subject to some qualification, in that there is a relatively sharp break in the log porosity profile at about 5 cm true depth (Fig. 3). This was neglected in the calculation of the slope of the profile, in favour of determining a longer-term mean uncompacted sedimentation rate for the core. The essentially constant  $^{210}\text{Pb}$  activity in the upper 3 cm (true depth) at this site can be ascribed to bioturbation; thus the impact of the purposeful neglect of the upper 5 cm in the  $\partial\phi/\partial z$  calculation in Figure 3 on the computed sedimentation rate in Figure 4 is minor.

## 6.2. Redox State of the Sediments

The essentially constant  $^{210}\text{Pb}$  activity in the top few centimetres of Core PM-1 confirms visual observations (Table 1) that the top 6 cm are well bioturbated at the site, despite the fact that  $\text{H}_2\text{S}$  is clearly present at depths  $>1.5$  cm (Table 1). Presumably, the survival of the burrowing fauna under such hostile conditions reflects continuous ventilation of their burrows with oxygenated bottom water. Surprisingly, there is no indication in the Mn or Fe/Al profiles (Fig. 8) that manganese or iron oxyhydroxides are accumulating at or near the interface, even in the upper 5 mm. Such phases are commonly enriched in oxic coastal surface sediments because upward-diffusing dissolved  $\text{Fe}^{2+}$  and  $\text{Mn}^{2+}$ , derived from the reductive dissolution of oxyhydroxides at depth where anoxia prevails, are readily oxidized in the presence of free  $\text{O}_2$ . Oxygen is typically present in the upper horizons of sediments deposited under an oxygenated water column such as that in Port Moody Arm. Apparently, despite the presence of an active burrowing infauna, the organic-rich surface sediments at Site PM-1 are suboxic, and the diagenetic accumulation of Fe and Mn oxyhydroxide phases is inhibited. A similar situation exists in the sediments of Ucluelet Inlet on Vancouver Island (Pedersen et al., 1989), but it should be noted that this phenomenon is atypical for coastal sediments.

Near-surface oxide enrichments are also absent at the other core sites in Port Moody Arm (Fig. 8), suggesting at first glance that similarly suboxic conditions occur near or at the sediment-water interface. However, burrowing organisms are abundant at both locations to depths of 2 to 3 decimetres, and  $\text{H}_2\text{S}$  was noted only below 20 cm in Core PM-2 and not at all in PM-3. However, although sulphate reduction appears to be minor, there can be little doubt that the sediments are suboxic at relatively shallow depths, because the larger worm burrows are visually defined by oxidized haloes, indicating that oxic conditions only occur in immediate proximity to oxygenated bottom water. Note that the absence of  $\text{H}_2\text{S}$  odour in the upper portions of PM-2 and PM-3 should not be taken as firm evidence for the absence of sulphate reduction in these cores, because if sufficient available iron is present, for example from clay minerals, precipitation of highly insoluble  $\text{FeS}$  or  $\text{FeS}_2$  can effectively hold the  $\text{H}_2\text{S}$  content at near zero. This situation has been observed recently in upper Howe Sound (Drysdale, 1990), where pore water data show that sulphate is being actively reduced at shallow depths in the sediment column but the



dissolved sulphide concentration is undetectable (i.e.  $<1 \mu\text{M}$ ). On the basis of these observations, we conclude that the sampled Port Moody Arm sediments are oxygen-deplete (suboxic) at shallow depths. We suggest that the redox potential near the sediment-water interface is low enough to preclude accumulation of Mn and Fe oxyhydroxides in the upper 5 mm of the deposits.

A different geochemical regime characterizes the Indian Arm core. Manganese and iron are clearly enriched in the upper horizons of the core, which can be attributed to diagenetic recycling under approximately steady-state depositional conditions (see Pedersen et al., 1986, for a discussion). The profiles are entirely consistent with the core logs, in which an oxic yellow-brown top was noted, bioturbators were recorded as being abundant in the upper two decimetres, and  $\text{H}_2\text{S}$  was noted as being present below about 12 cm depth.

### **6.3. Organic Carbon and Nitrogen Distributions**

The sediments at all four sites are organic-rich, but the composition of the organic matter is not uniform, either areally or vertically. The C:N wt. ratio varies between values of ~6-9 in organic detritus of marine origin, which is amino-acid-rich, to ~20-200 in terrestrial organic material, which is nitrogen depleted (Emerson and Hedges, 1988). Thus, the variations in the C:N ratio seen both with depth and among the Port Moody and Indian Arm cores can be ascribed to the presence of variable proportions of marine and terrestrial organic material. In the Indian Arm core, for example, the C:N ratio averages about 14 (Fig. 6), and since it does not vary widely, the sediments contain an approximately constant mixture of organic matter derived from both sources. In contrast, the deposits at PM-1, particularly at depth in the core (Fig. 6), contain a higher proportion of terrestrial organic detritus, which is not surprising given the proximity of log booming areas at the eastern end of Port Moody Arm. Sediments between depths of ~6 and 26 cm at Site PM-3 contain proportionately the highest terrestrial organic matter content.

The composition of the organic material in sediments is one of many factors which each contribute to the bacterial oxidant demand in the deposits. Terrestrial organic matter is associated with a relatively low demand which reflects the high proportion of cross-linked structural units and carbon-carbon bonds, both of which are refractory, in such material. Marine organic matter, in contrast, contains a higher proportion of oxygen- or nitrogen-bearing lipids

which are considerably easier to degrade bacterially (Emerson and Hedges, 1988). Thus, sediments relatively rich in terrestrial organic compounds can have a lower integrated oxidant demand than sediments containing less organic matter which is of marine origin. This contrast may explain why the organic-rich deposits at PM-1 are anoxic (i.e. contain free  $H_2S$ ) at shallow depths (noted in Table 1) where the C:N ratio is ~16, while the sediments in PM-3, which contain only slightly less organic material but proportionately more terrestrial material (C:N ratio of ~20 between 6 and 26 cm depth), appear to be suboxic, as described above. Core PM-2 appears to be an intermediate case - the organic matter content is significantly lower than in PM-1, although somewhat more marine in origin (C:N ~ 13), and suboxia prevails in the upper two decimetres. Because sedimentation at this site has been disrupted (described in Section 6.1), further discussion is unwarranted.

#### **6.4. Pb, Zn and Cu Distributions**

Lead and zinc enrichments, and to a lesser extent copper, are common worldwide in lacustrine (e.g. Farmer et al., 1980) and coastal marine (e.g. Bruland et al., 1974) sediments deposited essentially since the industrial revolution, as a result of direct aqueous or particulate Pb-, Zn- and Cu- bearing discharges, or deposition of aerosols of anthropogenic origin. The profiles of Pb, Zn and Cu in the Indian Arm core (Fig. 10) give clear evidence that such inputs have influenced sediment chemistry in the area for some time. Indeed, similar profiles, albeit showing lower enrichment factors, are common in most British Columbian coastal sediments (C.J. Jones, unpublished data). The very low Pb values seen at the base of Core PM-4 are similar to expected background levels in uncontaminated sediments, as are the Zn and Cu concentrations. Hence, it is clear that the core spans a period extending back to before the time when anthropogenic sources first began to influence metal content of sediments in the fjord. The  $^{210}Pb$ -derived sedimentation rate, which is rather poorly constrained by the available data, would suggest that the core embraces about 40 years of deposition. This is almost certainly an underestimate, in that inspection of the data (Appendix A.4) suggests that the sedimentation rate was lower in the past.

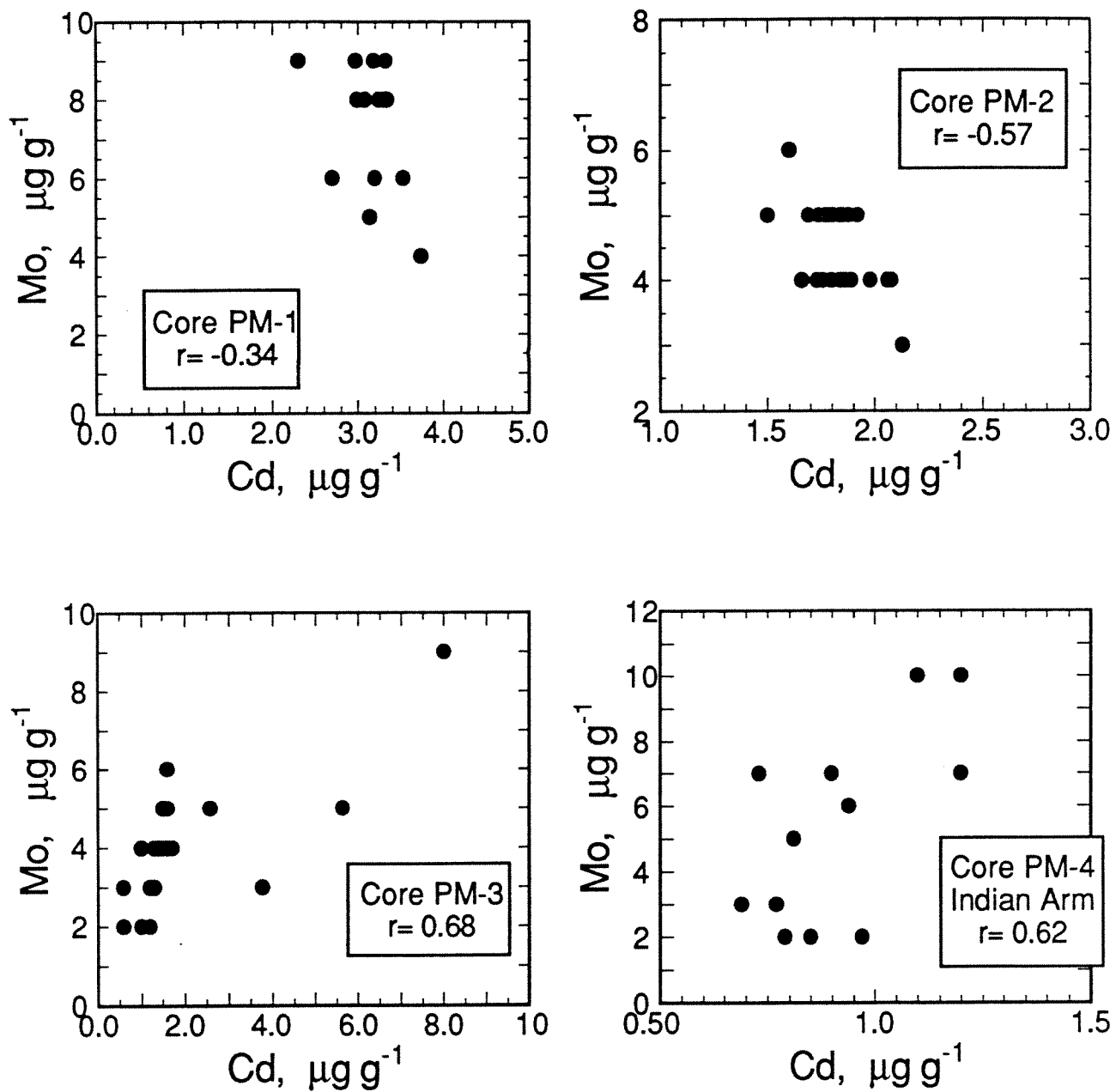
The Pb, Zn and Cu profiles have a different character at the Port Moody Arm sites. All three metals are distributed in parallel at the three locations, and

the concentrations are generally higher than in Indian Arm, particularly at PM-1 and PM-3. The high concentrations coupled with the significant coherence suggests that the distributions are controlled by a common general mechanism, in this case, input from anthropogenic sources. This suggestion does not apply to the lower three-quarters of PM-2 however, where low values of the three elements occur. The significance of these diminished concentrations is discussed below. The extreme Zn and Cu concentrations measured at the base of core PM-3 can be attributed to the deposition of an odd metal-rich contaminant, which is also discussed in more detail in the following section.

### **6.5. Cadmium and Molybdenum: Distribution and Behaviour**

As noted in Section 5.0, both Cd and Mo are enriched in Port Moody Arm sediments, both at the surface and at depth, relative to values typical for "average shale" ( $\sim 0.3 \mu\text{g g}^{-1}$  Cd and  $<3 \mu\text{g g}^{-1}$  Mo; Turekian and Wedepohl, 1961). In contrast, both elements are present in very low concentrations in Indian Arm surface sediments, but are clearly enriched at depth at the location sampled (Fig. 9). With the exception of the Indian arm surface sediments and at 30 cm depth in Core PM-3, all Cd values measured in this study exceed the ocean dumping criterion of  $0.6 \mu\text{g g}^{-1}$ .

Based on the Zn and Pb profiles (discussed above), it is clear that the sediments in the lower portion of Core PM-4 were deposited before significant anthropogenic influences could have perturbed the chemistry at that location. Where detectable Mo contents were measured (below 26 cm), the concentrations are correlated ( $r = 0.62$ ; Fig. 12). Similar correlations have been seen previously in Ucluelet Inlet, where the concentrations of both Cd and Mo are much higher. The correlative relationship was explained by Pedersen et al. (1989) as being due to precipitation of both Cd and Mo as sulphide minerals in anoxic sediments, the source of the metals in both cases being diffusion from the overlying seawater. Mo is scavenged by  $\text{MnO}_2$  in oxide-rich surface marine sediments (Shimmield and Price, 1986), and subsequent dissolution of Mo-bearing oxides at depth could promote enhanced diffusion of Mo downward to precipitation sites at depth. Such a mechanism cannot be supporting Mo accumulation in the lower half of PM-4, however, because there is no Mn-Mo association in the surface sediments at the site (at least, Mo is below detection limit in the Mn-rich intervals in the top decimetre). The same reasoning applies



**Figure 12.** Mo versus Cd plots for Port Moody and Indian Arm cores. Note the varying scales on both axes.

to Cd. Thus, we suggest that the accumulation of Cd and Mo at depth in Indian Arm sediments reflects natural diagenetic enrichment which is independent of anthropogenic influences. The low Cd and Mo contents compared to levels measured in Ucluelet Inlet can be attributed to the much higher rate of sedimentation in Indian Arm, which physically constrains the amount of the elements which can diffuse to a given precipitation site during its progressive burial.

In contrast to the Indian Arm deposits, Cd and Mo are negatively correlated in inner Port Moody Arm sediments (Fig. 12, Sites PM-1 and PM-2). Concentrations, particularly of Cd, are relatively high in surface sediments, and do not increase distinctly with depth, unlike in Ucluelet Inlet or Indian Arm. The small Cd increase near the base of PM-1, which is not seen in the Mo distribution, is mirrored by similar enrichments of Zn, Pb and Cu (Figs. 10 and 11). As noted earlier, given the magnitudes of the concentrations, which are significantly higher than seen in the pre-anthropogenic deposits at the base of Core PM-4, we suggest that the relatively high Zn, Pb and Cu levels at Site PM-1 largely represent anthropogenic inputs. The lack of association of Cd with Mo at this site, plus the general similarity of the Cd, Pb, Zn and Cu profiles in the lower decimetre of PM-1, indicates that the majority of the Cd in the sediments is also derived from unnatural, i.e. pollutant, sources. Apparently, diagenetic enrichment of the metal is minor, at best. This conclusion is not surprising, given the proximity of the PM-1 site to shore-based heavy industrial activity and urban development.

A different conclusion must be drawn for Site PM-2, however. The Pb profile clearly shows that the sediments below about 9 cm depth contain only about  $20 \mu\text{g g}^{-1}$  lead, similar to the background level measured at depth in the Indian Arm deposits. The  $^{210}\text{Pb}$  activity also shows an abrupt decline at about the same depth in PM-2 (Appendix A.4), as do the Cu and Zn contents (Figs. 10 and 11), the C:N ratio (Fig. 6), and the porosity (Fig. 3). These data collectively suggest that the deposits below the upper decimetre in Core PM-2 represent "old" sediments deposited before anthropogenesis influenced the composition. The implications of this observation are important. If the stiff, cohesive silty clays below ~10 cm depth at PM-2 represent uncontaminated deposits (and the low Pb levels are strong evidence of this, given the ubiquity of Pb as an anthropogenic contaminant in sediments), then the relatively high Cd levels measured below 10 cm ( $1.5 - 2 \mu\text{g g}^{-1}$ ) must be due to enrichment which has

occurred naturally, like the deposits at depth in Indian Arm, or the sediments in Ucluelet Inlet described by Pedersen et al. (1989). Higher Pb, Zn, Cu and Cd contents in the upper decimetre almost certainly reflect deposition of somewhat contaminated, relatively modern sediments. The inevitable conclusion of this analysis of the data is that the sediments at least at some locations in Port Moody Arm were enriched in Cd naturally, and prior to industrialization, to levels which considerably exceed the ocean dumping criterion ( $0.6 \mu\text{g g}^{-1}$ ). Thus, the vertical Cd distribution seen today, depending on location, may reflect both natural enrichments and anthropogenic additions.

The highest Cd concentrations measured in this study occur at the base of Core PM-3, where most other metals are similarly enriched, in some cases to extraordinary values. This location has been used in the past as a dumping site, and it appears that the lower decimetre in the core, which contains up to nearly 30 % Fe,  $3000 \mu\text{g g}^{-1}$  Zn, and  $1500 \mu\text{g g}^{-1}$  Cu, is composed partly of some type of slag. Given the very odd metal-rich composition at depth, the abundant burrowing fauna noted in the core (Table 1), and the apparently recent use of the site as a disposal area, it is difficult to assess how much of the Cd in the upper few decimetres reflects anthropogenesis, and how much could reflect natural enrichment. Mo and Cd are correlated in the upper 30 cm, but we are unable to determine the significance of this, given that the profiles may not represent *in situ* sedimentation, and certainly do not represent steady-state sedimentation, as confirmed by the irregular  $^{210}\text{Pb}$  (Fig. 4) and C:N ratio profiles (Fig. 6) in the upper 30 cm.

## 7.0 Summary and Conclusions

Several conclusions can be drawn from this study:

1. Sediments in inner Port Moody Arm are accumulating relatively slowly, which reflects the low input of fluvial sediments to the area. The sedimentary record at the sampled locations has been variously punctuated by past dredging and dumping activities.
2. Metals, including Cd, Mo, Zn, Pb and Cu are significantly enriched in Port Moody Arm sediments, the enrichments extending to the maximum depth of the cores, with the exception of Core PM-2 where low Pb, Zn and Cu contents (but not Cd and Mo) characterize the deposits below about 8 cm depth. In contrast

to the Port Moody Arm profiles, Cd and Mo are relatively depleted in the upper portion of the sediment column in Indian Arm, where Pb, Zn and Cu are enriched.

3. The basin adjacent to the Allied Chemical Company plant toward the western end of Port Moody Arm hosts sediments below about 30 cm depth which are seriously contaminated with metals. Zn and Cu concentrations respectively reach about 3000 and 1500  $\mu\text{g g}^{-1}$  at 39 cm depth where the Fe content is an extraordinary 29 %. This highly anomalous composition must represent past dumping of some type of metal-rich material.
4. Cd and Mo are naturally (diagenetically) enriched at depth in Indian Arm sediments, where Pb, Zn and Cu contents fall to values typical of pristine deposits. The relatively high Cd and Mo concentrations, which for Cd exceed the present ocean dumping criterion of 0.6  $\mu\text{g g}^{-1}$ , probably result from downward diffusion of Cd and Mo from the overlying seawater and their precipitation as sulphide minerals. Such a mechanism was previously invoked by Pedersen et al. (1989) to account for similar enrichments in Ucluelet Inlet on Vancouver Island.
5. High Cd concentrations ( $\sim 1.5 \mu\text{g g}^{-1}$ ) below 8 cm depth in south-central Port Moody Arm at Site PM-2 cannot be ascribed to anthropogenic input, but instead probably represent natural enrichment. It follows that at least some of the widespread Cd enrichment seen in Port Moody Arm sediments is of natural diagenetic origin.

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## APPENDICES

**Appendix A.1.** Major element composition and element ratios, Port Moody Arm and Indian Arm (Core PM-4) sediments. Analytical methods are described in Section 4.0 of the text.

INTERVAL	DEPTH cm	Fe wt. %	Ti wt. %	Ca wt. %	K wt. %	Si wt. %	Al wt. %	Mg wt. %	P wt. %
<b>CORE PM-1</b>									
0-0.5	0.25	4.04	0.36	1.79	0.92	23.71	6.39	1.50	0.16
0.5-1	0.75	4.05	0.37	1.81	0.93	23.93	6.38	1.49	0.15
1-1.5	1.25	4.13	0.37	1.83	0.95	24.09	6.50	1.46	0.16
1.5-2	1.75	4.12	0.38	1.82	0.95	24.32	6.53	1.48	0.15
2-3	2.5	4.37	0.38	1.87	0.97	25.38	6.85	1.50	0.17
3-4	3.5	4.27	0.38	1.84	0.96	24.56	6.50	1.43	0.15
4-5	4.5	4.19	0.38	1.84	0.95	24.59	6.60	1.47	0.15
5-6	5.5	4.21	0.38	1.87	0.96	24.86	6.59	1.48	0.15
6-7	6.5	4.20	0.38	1.79	0.95	24.75	6.53	1.49	0.14
7-8	7.5	4.13	0.38	1.82	0.96	24.77	6.59	1.47	0.15
8-9	8.5	3.99	0.37	1.88	0.95	24.79	6.53	1.40	0.16
9-10	9.5	3.96	0.38	1.94	0.95	25.26	6.65	1.41	0.17
10-12	11	4.03	0.38	1.98	0.95	25.16	6.70	1.45	0.16
12-14	13	4.05	0.38	1.97	0.93	24.99	6.63	1.38	0.14
14-16	15	3.93	0.40	1.92	0.95	25.46	6.83	1.43	0.14
16-18	17	3.80	0.38	1.92	0.95	25.69	6.82	1.39	0.15
18-20	19	3.37	0.35	2.20	0.92	27.55	6.82	1.18	0.16
20-22	21	3.77	0.38	1.94	0.95	26.02	6.74	1.37	0.14
22-24	23	4.08	0.40	1.82	0.94	25.50	6.82	1.37	0.12
<b>CORE PM-2</b>									
0-0.5	0.25	4.24	0.39	1.76	1.04	24.32	6.59	1.68	0.15
0.5-1	0.75	4.12	0.39	1.68	1.04	24.31	6.64	1.65	0.13
1-1.5	1.25	4.10	0.39	1.77	1.08	24.33	6.62	1.60	0.12
1.5-2	1.75	4.10	0.39	1.72	1.06	24.41	6.64	1.62	0.13
2-3	2.5	4.21	0.38	1.72	1.06	25.24	6.88	1.68	0.12
3-4	3.5	4.15	0.40	1.69	1.07	25.05	6.79	1.59	0.12
4-5	4.5	4.07	0.39	1.72	1.08	25.90	6.99	1.66	0.13
5-6	5.5	4.08	0.39	1.64	1.11	25.74	6.89	1.70	0.12
6-7	6.5	4.02	0.38	1.67	1.09	25.15	6.73	1.63	0.12
7-8	7.5	4.03	0.39	1.69	1.10	25.59	6.83	1.61	0.12
8-9	8.5	4.13	0.39	1.74	1.11	25.66	6.91	1.69	0.12
9-10	9.5	4.14	0.40	1.69	1.09	25.54	6.90	1.63	0.12
10-12	11	4.09	0.39	1.70	1.09	25.40	6.78	1.60	0.11
12-14	13	4.13	0.39	1.92	1.12	25.49	6.80	1.63	0.11
14-16	15	4.19	0.40	1.73	1.12	25.43	6.89	1.63	0.11
16-18	17	4.23	0.40	1.68	1.11	24.87	6.81	1.63	0.12
18-20	19	4.15	0.40	1.65	1.10	24.94	6.88	1.62	0.12
20-22	21	4.08	0.38	1.72	1.09	25.03	6.89	1.58	0.11
22-24	23	4.15	0.39	1.75	1.12	25.09	6.82	1.61	0.12
24-26	25	4.14	0.39	1.71	1.12	25.43	6.91	1.56	0.12
26-28	27	4.07	0.39	1.78	1.14	25.60	6.85	1.60	0.12
28-30	29	4.06	0.38	2.04	1.16	25.54	6.84	1.55	0.12
30-32	31	4.12	0.39	2.20	1.18	25.40	6.86	1.57	0.12
32-34	33	4.29	0.40	1.67	1.15	25.53	7.10	1.59	0.12
34-36	35	4.21	0.40	1.81	1.14	25.79	7.06	1.59	0.12

INTERVAL	DEPTH cm	Fe wt. %	Ti wt. %	Ca wt. %	K wt. %	Si wt. %	Al wt. %	Mg wt. %	P wt. %
CORE PM-3									
0-0.5	0.25	5.62	0.37	1.99	0.96	23.35	6.42	1.49	0.17
0.5-1	0.75	6.20	0.39	2.05	0.97	24.00	6.64	1.51	0.17
1-1.5	1.25	6.36	0.39	2.22	0.98	23.98	6.65	1.47	0.16
1.5-2	1.75	6.16	0.40	2.08	0.98	24.48	6.75	1.47	0.14
2-3	2.5	6.12	0.40	2.04	0.98	24.13	6.76	1.48	0.14
3-4	3.5	6.39	0.39	2.40	0.98	23.98	6.74	1.48	0.13
4-5	4.5	6.34	0.40	2.07	0.99	23.90	6.76	1.48	0.13
5-6	5.5	6.85	0.40	1.97	0.96	23.69	6.68	1.40	0.13
6-7	6.5	7.04	0.41	1.98	0.95	24.03	6.78	1.40	0.12
7-8	7.5	6.53	0.40	2.04	0.97	24.32	6.85	1.44	0.13
8-9	8.5	6.50	0.40	2.04	0.98	24.58	7.01	1.40	0.13
9-10	9.5	6.15	0.40	2.00	1.00	24.59	6.92	1.46	0.11
10-12	11	5.73	0.40	1.96	1.04	24.38	6.97	1.40	0.10
12-14	13	5.92	0.40	1.94	1.01	24.63	6.98	1.40	0.10
14-16	15	6.04	0.41	1.91	1.02	24.77	7.00	1.42	0.09
16-18	17	6.17	0.41	1.94	0.99	24.81	6.99	1.47	0.09
18-20	19	6.19	0.40	1.97	1.01	24.65	7.03	1.46	0.09
20-22	21	6.18	0.40	2.39	0.98	24.34	6.90	1.45	0.09
22-24	23	5.90	0.39	2.65	0.93	24.80	7.05	1.48	0.08
24-26	25	4.96	0.40	2.62	0.91	25.81	7.55	1.51	0.08
26-28	27	4.56	0.40	2.53	0.96	26.45	7.65	1.53	0.08
28-30	29	3.98	0.36	2.80	0.96	27.72	8.10	1.50	0.08
30-32	31	4.33	0.40	2.90	0.84	27.43	8.12	1.65	0.09
32-34	33	8.61	0.41	2.50	0.90	24.07	7.00	1.51	0.08
34-36	35	10.82	0.40	1.86	0.97	23.05	6.55	1.41	0.08
36-38	37	14.73	0.40	1.67	0.91	21.28	6.04	1.35	0.08
38-39	39.5	28.93	0.32	1.20	0.66	16.34	4.53	0.98	0.07
CORE PM-4									
0-0.5	0.25	4.12	0.30	1.71	0.89	20.72	5.48	1.75	0.29
0.5-1	0.75	4.21	0.32	1.72	0.93	21.35	5.80	1.73	0.25
1-1.5	1.25	4.21	0.32	1.64	0.95	19.35	5.05	1.40	0.22
1.5-2	1.75	4.26	0.32	1.68	0.91	19.48	5.10	1.36	0.21
2-3	2.5	4.25	0.34	1.78	0.97	22.01	6.15	1.74	0.19
3-4	3.5	4.28	0.35	1.81	0.98	22.60	6.31	1.72	0.16
4-5	4.5	4.44	0.34	1.79	0.97	22.22	6.23	1.74	0.16
5-6	5.5	4.59	0.35	1.84	1.01	22.15	6.36	1.82	0.17
6-7	6.5	4.72	0.35	1.74	1.04	22.39	6.45	1.88	0.17
7-8	7.5	4.66	0.35	1.67	1.04	22.54	6.41	1.79	0.15
8-9	8.5	4.59	0.36	1.77	1.05	22.62	6.51	1.74	0.14
9-10	9.5	4.58	0.35	1.79	1.02	22.57	6.43	1.80	0.14
10-12	11	4.66	0.35	1.85	1.00	22.24	6.41	1.84	0.14
12-14	13	4.70	0.34	1.99	1.00	22.39	6.36	1.82	0.14
14-16	15	4.53	0.35	1.85	1.03	22.56	6.51	1.81	0.13
16-18	17	4.48	0.36	1.92	1.03	22.48	6.44	1.82	0.13
18-20	19	4.47	0.35	1.82	0.99	22.45	6.47	1.86	0.14
20-22	21	4.43	0.36	1.87	1.01	22.71	6.51	1.86	0.12
22-24	23	4.54	0.37	1.92	1.06	23.01	6.54	1.89	0.12
24-26	25	4.42	0.37	2.20	1.07	23.11	6.65	1.85	0.12
26-28	27	4.49	0.38	1.89	1.09	23.38	6.71	1.90	0.12
28-30	29	4.45	0.35	1.78	1.05	22.54	6.43	1.78	0.11
30-34	32	4.50	0.35	1.72	1.05	22.89	6.46	1.80	0.12
34-38	36	4.48	0.37	1.74	1.08	23.30	6.62	1.83	0.11
38-42	40	4.19	0.36	1.90	1.07	23.67	6.65	1.88	0.11
42-46	44	4.20	0.37	1.78	1.13	24.00	6.68	1.80	0.11
50-54	52	4.17	0.35	1.67	1.16	23.65	6.43	1.80	0.11
58-59	58.5	4.05	0.35	1.87	1.11	24.06	6.35	1.64	0.11

INTERVAL	DEPTH cm	Fe/Al	Ti/Al	Ca/Al	K/Al	Si/Al	Mg/Al
CORE PM-1							
0-0.5	0.25	0.633	0.056	0.280	0.144	3.713	0.235
0.5-1	0.75	0.634	0.057	0.284	0.145	3.752	0.234
1-1.5	1.25	0.635	0.056	0.282	0.146	3.706	0.225
1.5-2	1.75	0.631	0.058	0.279	0.146	3.726	0.227
2-3	2.5	0.638	0.056	0.274	0.142	3.705	0.219
3-4	3.5	0.657	0.058	0.284	0.148	3.781	0.220
4-5	4.5	0.634	0.057	0.279	0.143	3.724	0.222
5-6	5.5	0.639	0.057	0.283	0.146	3.771	0.225
6-7	6.5	0.643	0.059	0.275	0.145	3.792	0.228
7-8	7.5	0.627	0.057	0.276	0.147	3.761	0.223
8-9	8.5	0.611	0.057	0.288	0.145	3.798	0.214
9-10	9.5	0.595	0.057	0.291	0.143	3.795	0.212
10-12	11	0.601	0.056	0.296	0.141	3.754	0.217
12-14	13	0.610	0.058	0.298	0.141	3.771	0.208
14-16	15	0.575	0.058	0.281	0.139	3.727	0.209
16-18	17	0.557	0.056	0.282	0.140	3.768	0.204
18-20	19	0.493	0.051	0.323	0.135	4.038	0.173
20-22	21	0.559	0.056	0.289	0.141	3.861	0.203
22-24	23	0.598	0.059	0.267	0.138	3.737	0.202
CORE PM-2							
0-0.5	0.25	0.644	0.059	0.267	0.157	3.693	0.255
0.5-1	0.75	0.621	0.059	0.253	0.157	3.661	0.249
1-1.5	1.25	0.619	0.059	0.267	0.163	3.677	0.242
1.5-2	1.75	0.617	0.059	0.259	0.160	3.673	0.243
2-3	2.5	0.613	0.056	0.250	0.154	3.670	0.245
3-4	3.5	0.611	0.058	0.248	0.157	3.689	0.234
4-5	4.5	0.582	0.056	0.245	0.154	3.703	0.237
5-6	5.5	0.592	0.057	0.239	0.161	3.734	0.247
6-7	6.5	0.597	0.057	0.248	0.161	3.737	0.242
7-8	7.5	0.590	0.057	0.248	0.161	3.744	0.236
8-9	8.5	0.597	0.056	0.251	0.161	3.712	0.244
9-10	9.5	0.600	0.058	0.246	0.158	3.700	0.236
10-12	11	0.603	0.058	0.251	0.161	3.748	0.236
12-14	13	0.608	0.057	0.283	0.165	3.750	0.240
14-16	15	0.607	0.058	0.251	0.163	3.690	0.237
16-18	17	0.621	0.059	0.247	0.163	3.653	0.239
18-20	19	0.604	0.058	0.240	0.160	3.627	0.235
20-22	21	0.593	0.056	0.249	0.158	3.634	0.229
22-24	23	0.608	0.057	0.257	0.164	3.677	0.236
24-26	25	0.599	0.057	0.247	0.163	3.681	0.225
26-28	27	0.594	0.057	0.260	0.166	3.740	0.233
28-30	29	0.594	0.056	0.299	0.170	3.734	0.227
30-32	31	0.601	0.057	0.320	0.171	3.702	0.229
32-34	33	0.604	0.057	0.236	0.162	3.596	0.224
34-36	35	0.596	0.057	0.256	0.162	3.652	0.225

INTERVAL	DEPTH cm	Fe/Al	Ti/Al	Ca/Al	K/Al	Si/Al	Mg/Al
CORE PM-3							
0-0.5	0.25	0.876	0.058	0.311	0.150	3.640	0.232
0.5-1	0.75	0.932	0.059	0.309	0.146	3.612	0.227
1-1.5	1.25	0.957	0.059	0.333	0.148	3.606	0.220
1.5-2	1.75	0.913	0.060	0.308	0.145	3.627	0.218
2-3	2.5	0.906	0.059	0.303	0.146	3.571	0.220
3-4	3.5	0.948	0.058	0.355	0.145	3.555	0.219
4-5	4.5	0.938	0.059	0.307	0.147	3.535	0.219
5-6	5.5	1.027	0.060	0.296	0.144	3.549	0.211
6-7	6.5	1.037	0.060	0.292	0.140	3.544	0.207
7-8	7.5	0.953	0.059	0.299	0.142	3.550	0.210
8-9	8.5	0.927	0.057	0.291	0.140	3.505	0.199
9-10	9.5	0.889	0.058	0.289	0.144	3.551	0.211
10-12	11	0.823	0.058	0.281	0.150	3.500	0.202
12-14	13	0.847	0.058	0.278	0.145	3.528	0.200
14-16	15	0.863	0.058	0.273	0.145	3.537	0.202
16-18	17	0.883	0.058	0.277	0.142	3.550	0.210
18-20	19	0.881	0.057	0.280	0.144	3.509	0.208
20-22	21	0.895	0.057	0.346	0.143	3.525	0.210
22-24	23	0.837	0.055	0.376	0.132	3.517	0.210
24-26	25	0.656	0.053	0.347	0.120	3.416	0.200
26-28	27	0.596	0.052	0.331	0.126	3.457	0.200
28-30	29	0.491	0.044	0.345	0.119	3.421	0.185
30-32	31	0.533	0.050	0.358	0.103	3.378	0.204
32-34	33	1.230	0.058	0.357	0.129	3.439	0.216
34-36	35	1.651	0.061	0.284	0.148	3.520	0.216
36-38	37	2.438	0.066	0.277	0.150	3.523	0.224
38-39	39.5	6.389	0.072	0.265	0.145	3.608	0.216
CORE PM-4							
0-0.5	0.25	0.753	0.055	0.312	0.162	3.784	0.321
0.5-1	0.75	0.726	0.055	0.297	0.161	3.682	0.299
1-1.5	1.25	0.835	0.063	0.326	0.189	3.834	0.278
1.5-2	1.75	0.835	0.062	0.329	0.179	3.817	0.266
2-3	2.5	0.691	0.056	0.290	0.158	3.581	0.283
3-4	3.5	0.679	0.055	0.287	0.156	3.581	0.273
4-5	4.5	0.713	0.055	0.287	0.156	3.569	0.280
5-6	5.5	0.722	0.055	0.289	0.159	3.481	0.286
6-7	6.5	0.731	0.055	0.270	0.160	3.470	0.292
7-8	7.5	0.726	0.055	0.261	0.163	3.516	0.279
8-9	8.5	0.706	0.055	0.271	0.161	3.477	0.267
9-10	9.5	0.712	0.055	0.279	0.158	3.512	0.281
10-12	11	0.727	0.054	0.289	0.157	3.469	0.287
12-14	13	0.738	0.054	0.312	0.157	3.518	0.286
14-16	15	0.696	0.054	0.285	0.158	3.467	0.278
16-18	17	0.696	0.056	0.298	0.160	3.491	0.282
18-20	19	0.691	0.055	0.281	0.153	3.471	0.287
20-22	21	0.681	0.055	0.288	0.155	3.490	0.285
22-24	23	0.693	0.056	0.293	0.162	3.517	0.289
24-26	25	0.664	0.056	0.331	0.161	3.473	0.278
26-28	27	0.669	0.056	0.281	0.162	3.485	0.283
28-30	29	0.693	0.054	0.277	0.163	3.507	0.278
30-34	32	0.697	0.055	0.267	0.162	3.544	0.278
34-38	36	0.676	0.055	0.262	0.163	3.519	0.277
38-42	40	0.630	0.054	0.286	0.161	3.559	0.283
42-46	44	0.629	0.055	0.267	0.169	3.595	0.269
50-54	52	0.648	0.055	0.259	0.180	3.680	0.280
58-59	58.5	0.637	0.055	0.295	0.175	3.786	0.258

**Appendix A.2.** Minor element analyses, Port Moody Arm and Indian Arm sediments, reported in  $\mu\text{g g}^{-1}$ . Analytical methods are described in Section 4.0 of the text.

INTERVAL	Depth cm	Zr ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm	Cd ppm	Mo ppm
CORE PM-1															
0-0.5	0.25	102	250	43	99	208	85	22	27	592	104	66	473	3.32	8
0.5-1	0.75	102	245	42	77	205	83	16	29	607	102	66	495	3.08	8
1-1.5	1.25	100	246	41	70	194	76	18	29	603	99	66	469	2.97	9
1.5-2	1.75	105	248	42	65	195	77	21	26	629	112	67	494	3.31	8
2.0-3	2.5	107	241	44	61	188	66	12	26	610	101	69	474	3.3	8
3.0-4	3.5	106	245	43	54	195	75	16	16	638	107	71	497	3.34	8
4.0-5	4.5	102	243	43	57	193	72	18	18	628	103	67	486	3.18	9
5.0-6	5.5	100	252	43	50	198	77	18	22	616	110	66	483	3.24	8
6.0-7	6.5	102	238	46	51	193	74	19	20	614	105	69	504	3.32	8
7.0-8	7.5	103	238	42	51	197	74	18	20	637	117	66	505	3.33	8
8.0-9	8.5	103	249	43	56	200	75	17	18	620	113	66	493	3.32	9
9.0-10	9.5	104	258	44	56	200	73	17	21	633	107	67	513	2.3	9
10.0-12	11	104	255	44	54	196	71	21	22	617	107	67	505	3.34	8
12.0-14	13	107	257	45	63	210	76	17	23	612	103	71	480	2.99	8
14-16	15	107	253	43	86	277	86	18	19	630	114	78	513	3.53	6
16-18	17	105	259	43	89	306	84	19	23	604	112	74	502	3.2	6
18-20	19	104	288	37	64	241	52	6	22	585	95	60	524	2.7	6
20-22	21	101	257	41	96	368	59	13	19	596	106	68	491	3.14	5
22-24	23	105	251	43	115	430	77	19	21	640	119	69	520	3.74	4
CORE PM-2															
0-0.5	0.25	104	238	51	38	103	67	20	40	618	108	60	466	1.66	4
0.5-1	0.75	99	229	51	32	97	57	20	35	594	103	61	476	1.8	4
1-1.5	1.25	105	232	52	37	99	53	20	22	630	110	61	492	1.8	5
1.5-2	1.75	101	232	52	38	99	58	19	22	620	104	62	465	1.84	5
2.0-3	2.5	102	228	51	37	95	52	17	21	615	107	63	511	1.78	5
3.0-4	3.5	103	229	52	36	101	56	23	21	627	106	60	494	1.8	5
4.0-5	4.5	105	234	52	32	101	57	26	22	631	106	59	521	1.74	5
5.0-6	5.5	104	227	54	29	93	46	22	24	614	108	59	485	1.73	4
6.0-7	6.5	101	225	55	24	87	42	20	24	602	104	61	498	1.85	5
7.0-8	7.5	101	236	57	16	87	39	21	20	621	115	56	512	1.89	4
8.0-9	8.5	102	230	56	24	85	43	24	23	644	118	60	533	2.08	4
9.0-10	9.5	102	232	55	14	85	43	27	25	661	109	62	532	1.98	4
10.0-12	11	105	228	57	14	84	41	24	23	642	118	63	534	2.06	4
12.0-14	13	101	231	55	12	82	38	24	22	638	117	61	545	2.13	3
14-16	15	102	228	56	20	84	42	24	22	666	114	63	568	1.86	4
16-18	17	99	231	55	26	93	48	24	21	634	110	61	557	1.5	5
18-20	19	103	230	55	22	86	46	24	20	634	107	63	524	1.5	5
20-22	21	100	229	53	21	83	42	22	19	644	113	60	545	1.69	5
22-24	23	96	222	55	18	80	38	20	18	641	109	60	551	1.76	4
24-26	25	103	225	56	25	91	50	22	22	633	109	63	548	1.77	5
26-28	27	105	235	58	16	92	49	27	32	608	105	61	525	1.88	5
28-30	29	103	253	56	16	93	49	24	29	629	109	62	560	1.84	4
30-32	31	104	271	57	16	90	50	26	25	623	110	62	595	1.81	5
32-34	33	105	233	58	20	95	53	30	21	661	111	60	578	1.6	6
34-36	35	105	236	53	20	89	47	25	27	652	113	64	552	1.92	5

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SUBJECT \_\_\_\_\_ CHECKED \_\_\_\_\_ DATE \_\_\_\_\_ FILE \_\_\_\_\_

Background - based on Indian Arm Cove (Pederson & Watson 1989).

Cu 30-90 ug/g. 83.6-72

Pb 12-25 ug/g. 75-43.

Zn 20-120 ug/g. 133-150

Cd. ~~1 ug/g. 1.11 ug/g.~~  
.53 - .89 ug/g.

Hg. < 1

Mo. 4-6 ug/g.

Cr. 66-80 ug/g.

4.4

INTERVAL	Depth cm	Zr ppm	Sr ppm	Rb ppm	Pb ppm	Zn ppm	Cu ppm	Ni ppm	Co ppm	Mn ppm	V ppm	Cr ppm	Ba ppm	Cd ppm	Mo ppm
CORE PM-3															
0-0.5	0.25	127	258	45	77	184	190	22	27	600	104	70	529	1	2
0.5-1	0.75	143	261	44	75	189	192	18	25	613	110	75	529	1.2	<2
1-1.5	1.25	140	272	45	76	206	214	21	29	609	107	75	548	1.2	3
1.5-2	1.75	142	272	47	78	208	213	21	23	596	102	76	519	1.2	<2
2.0-3	2.5	142	263	47	83	207	203	21	26	603	102	78	529	1.3	3
3.0-4	3.5	155	267	43	87	215	212	20	26	608	106	77	540	1.3	4
4.0-5	4.5	157	264	46	92	232	236	27	29	616	112	78	533	1.3	3
5.0-6	5.5	167	261	43	109	237	242	23	24	599	102	80	516	1.4	4
6.0-7	6.5	164	259	42	100	231	224	18	27	561	95	72	465	1.4	4
7.0-8	7.5	157	264	44	93	225	220	24	28	578	101	69	464	1.5	4
8.0-9	8.5	149	266	44	98	223	220	20	22	582	100	70	477	1.4	4
9.0-10	9.5	143	266	46	93	226	217	27	23	589	101	69	476	1.6	5
10.0-12	11	140	266	48	93	226	219	23	23	584	100	69	456	1.5	5
12.0-14	13	145	273	47	103	254	231	27	26	615	105	76	507	1.6	5
14-16	15	147	273	48	105	264	240	32	26	596	112	76	505	1.71	4
16-18	17	141	269	46	106	246	224	27	24	600	105	73	509	1.5	5
18-20	19	139	271	47	112	255	226	33	26	558	98	71	436	1.6	4
20-22	21	132	289	43	102	239	199	24	27	543	94	66	425	1.6	6
22-24	23	130	333	43	98	226	180	26	25	570	98	64	452	1.5	5
24-26	25	119	383	41	74	179	119	19	20	583	94	57	440	1.3	4
26-28	27	116	392	40	51	128	100	22	22	598	91	53	448	1	4
28-30	29	119	486	38	28	89	62	13	20	665	94	44	549	0.59	3
30-32	31	113	520	33	50	115	74	16	21	676	92	51	448	0.6	2
32-34	33	121	317	42	123	345	219	23	27	589	102	78	503	2.58	5
34-36	35	122	253	45	136	464	286	27	28	536	101	90	512	3.77	3
36-38	37	125	231	43	163	788	452	23	39	476	91	110	496	5.64	5
38-39	39.5	107	186	32	315	2679	1507	28	87	301	61	154	529	8	9
CORE PM-4															
0-0.5	0.25	75	267	41	74	127	86	10	35	3457	94	36	302	0.49	<2
0.5-1		78	260	42	76	139	86	9	36	3047	102	37	326	0.57	<2
1-1.5	1.25	79	256	41	76	135	86	9	28	3046	106	39	346	0.54	<2
1.5-2	1.75	78	247	43	73	134	79	9	27	2540	103	40	315	0.53	<2
2.0-3	2.5	78	239	42	76	131	81	11	23	2155	108	36	327	0.54	<2
3.0-4	3.5	83	233	42	73	135	82	13	26	1772	116	41	361	0.62	<2
4.0-5	4.5	79	233	41	75	138	85	9	28	1953	122	45	420	0.62	2
5.0-6	5.5	84	235	41	83	158	90	11	25	3052	128	47	423	0.58	<2
6.0-7	6.5	81	225	43	91	173	95	17	25	2846	143	49	435	0.63	<2
7.0-8	7.5	81	216	43	90	155	87	11	22	2343	128	49	389	0.6	<2
8.0-9	8.5	83	216	45	90	156	88	17	25	2318	134	54	450	0.58	<2
9.0-10	9.5	82	219	43	86	159	89	12	25	2675	135	49	419	0.67	<2
10.0-12	11	79	225	40	89	170	86	13	22	2848	117	38	352	0.62	<2
12.0-14	13	80	229	41	95	166	88	13	25	2536	127	42	360	0.7	<2
14-16	15	83	225	44	94	180	88	15	27	2168	149	50	480	0.77	2
16-18	17	83	228	44	94	171	84	13	26	2162	146	47	462	0.77	<2
18-20	19	83	220	43	87	152	68	13	27	1841	109	42	347	0.79	2
20-22	21	83	227	42	89	160	75	14	24	1987	141	49	469	0.77	3
22-24	23	85	228	43	87	156	72	12	25	1896	134	49	422	0.85	2
24-26	25	91	246	43	80	156	77	14	26	1703	136	48	431	0.97	2
26-28	27	91	230	45	57	131	64	9	29	1458	135	47	456	0.94	6
28-30	29	84	222	45	66	148	74	13	29	1528	127	50	459	0.9	7
30-34	32	83	216	46	57	147	75	14	23	1493	148	46	504	1.1	10
34-38	36	83	221	47	56	127	70	17	27	1470	140	47	471	0.73	7
38-42	40	81	218	45	29	93	52	10	22	1231	113	38	382	0.69	3
42-46	44	86	221	51	23	91	47	15	23	1085	121	47	491	0.81	5
50-54	52	86	212	50	12	84	43	18	25	1051	117	43	419	1.2	10
58-59	58.5	90	219	49	13	83	44	11	30	955	110	37	391	1.2	7



**Appendix A.3.** Carbon, nitrogen and sulphur data, Port Moody and Indian Arm sediments. Analytical methods are described in Section 4.0 of the text.

Depth	%Carb. C	% Total C	% Organic C	%N	%S	C/N Wt. Ratio
CORE PM-1						
0.25	0.010	4.84	4.83	0.30	2.65	16.1
0.75	0.014	4.81	4.80	0.30	2.64	15.8
1.25	0.013	4.84	4.83	0.30	2.72	16.1
1.75	0.014	4.72	4.71	0.30	2.60	15.9
2.5	0.013	4.92	4.91	0.30	2.58	16.4
3.5	0.015	4.86	4.85	0.30	2.56	16.1
4.5	0.014	4.91	4.90	0.31	2.55	15.9
5.5	0.015	4.73	4.72	0.30	2.53	15.9
6.5	0.014	4.74	4.73	0.31	2.60	15.5
7.5	0.013	4.87	4.85	0.31	2.57	15.8
8.5	0.014	4.86	4.85	0.30	2.65	16.0
9.5	0.012	4.81	4.80	0.29	2.03	16.6
11	0.027	4.66	4.64	0.28	2.38	16.5
13	0.030	4.68	4.65	0.27	2.32	17.1
15	0.022	5.15	5.13	0.27	2.08	19.2
17	0.016	5.17	5.16	0.26	1.98	19.6
19	0.014	3.93	3.92	0.19	1.57	20.5
21	0.007	4.97	4.97	0.24	1.92	20.5
23	0.013	5.19	5.18	0.26	2.10	19.9
CORE PM-2						
0.25	0.044	3.55	3.51	0.28	1.25	12.7
0.75	0.030	3.53	3.50	0.26	1.34	13.3
1.25	0.058	3.63	3.57	0.28	1.45	12.9
1.75	0.040	3.54	3.50	0.27	1.64	13.0
2.5	0.034	3.63	3.59	0.28	1.63	13.1
3.5	0.041	3.72	3.67	0.27	1.67	13.5
4.5	0.049	3.58	3.54	0.27	1.62	13.0
5.5	0.044	3.53	3.48	0.26	1.63	13.3
6.5	0.045	3.41	3.36	0.26	1.61	12.7
7.5	0.059	3.21	3.15	0.26	1.55	12.2
8.5	0.062	2.95	2.89	0.26	1.66	11.2
9.5	0.051	3.01	2.95	0.26	1.68	11.6
11	0.057	3.00	2.94	0.26	1.70	11.4
13	0.121	3.12	3.00	0.26	1.72	11.4
15	0.066	3.17	3.10	0.26	1.75	11.8
17	0.051	3.68	3.63	0.28	1.79	12.8
19	0.044	3.67	3.62	0.29	1.77	12.6
21	0.053	3.51	3.46	0.29	1.80	12.1
23	0.080	3.28	3.20	0.28	1.73	11.3
25	0.069	3.24	3.17	0.27	1.81	11.7
27	0.073	3.09	3.02	0.26	1.73	11.5
29	0.168	3.07	2.90	0.26	1.72	11.3
31	0.207	3.28	3.08	0.26	1.68	11.8
33	0.049	3.53	3.49	0.29	1.76	11.9
34.5	0.076	3.12	3.04	0.27	1.77	11.4

Depth	%Carb. C	% Total C	% Organic C	%N	%S	C/N Wt. Ratio
CORE PM-3						
0.25	0.052	4.17	4.12	0.26	0.81	16.0
0.75	0.067	4.13	4.06	0.24	0.80	16.8
1.25	0.107	4.06	3.96	0.24	0.77	16.2
1.75	0.066	3.93	3.86	0.23	0.80	17.0
2.5	0.076	4.07	3.99	0.23	0.99	17.7
3.5	0.188	4.08	3.90	0.22	1.02	17.5
4.5	0.092	4.36	4.26	0.22	1.08	19.7
5.5	0.063	4.27	4.21	0.21	1.13	20.0
6.5	0.043	4.31	4.27	0.21	1.16	20.5
7.5	0.050	3.88	3.83	0.20	1.15	19.2
8.5	0.044	3.90	3.86	0.20	1.13	19.6
9.5	0.044	3.85	3.81	0.20	1.10	19.1
11	0.040	4.31	4.27	0.22	1.16	19.8
13	0.028	3.77	3.74	0.20	1.24	19.0
15	0.026	3.70	3.67	0.19	1.32	19.5
17	0.032	3.84	3.81	0.19	1.44	20.2
19	0.045	3.70	3.66	0.19	1.47	19.3
21	0.152	3.74	3.59	0.18	1.44	19.7
23	0.176	3.36	3.18	0.16	1.27	19.4
25	0.082	3.25	3.17	0.15	1.12	21.7
27	0.040	2.32	2.28	0.14	1.14	16.3
29	0.019	1.42	1.40	0.09	0.71	15.6
31	0.020	1.41	1.39	0.08	0.63	16.6
33	0.094	2.82	2.72	0.15	1.19	17.8
35	0.057	3.07	3.02	0.16	1.03	18.4
37	0.031	3.26	3.23	0.16	0.99	20.2
38.5	0.011	2.21	2.20	0.11	0.96	19.3

CORE PM-4

0.25	0.070	3.60	3.53	0.27	0.52	13.1
0.75	0.073	3.58	3.51	0.27	0.54	13.0
1.25	0.080	3.57	3.49	0.26	0.54	13.5
1.75	0.076	3.57	3.50	0.26	0.54	13.2
2.5	0.087	3.71	3.62	0.26	0.60	14.2
3.5	0.079	3.57	3.49	0.25	0.74	13.7
4.5	0.059	3.50	3.44	0.26	1.06	13.4
5.5	0.101	3.51	3.41	0.25	0.74	13.9
6.5	0.075					
7.5	0.070					
8.5	0.096					
9.5	0.092					
11	0.090	3.39	3.30	0.23	0.71	14.4
13	0.138	3.40	3.27	0.22	0.81	14.8
15	0.101	3.49	3.39	0.23	0.84	14.7
17	0.119	3.53	3.41	0.23	0.87	14.9
19	0.080	3.54	3.46	0.23	0.99	14.9
21	0.082	3.40	3.32	0.22	1.01	15.1
23	0.066	3.49	3.42	0.23	1.03	14.8
25	0.165	3.37	3.21	0.22	1.10	14.4
27	0.059	3.27	3.21	0.22	1.36	14.7
29	0.084	3.97	3.88	0.28	1.44	14.1

Depth	%Carb. C	% Total C	% Organic C	%N	%S	C/N Wt. Ratio
32	0.095	3.50	3.40	0.27	1.66	12.8
36	0.075	3.19	3.12	0.23	1.52	13.5
40	0.110	3.00	2.89	0.22	1.23	13.4
44	0.075	3.10	3.02	0.23	1.29	13.4
52	0.078	2.82	2.74	0.23	1.44	11.7
58.5	0.074	2.96	2.88	0.21	1.34	13.6

**Appendix A.4.** Porosity, bulk density and  $^{210}\text{Po}$  data for Port Moody and Indian Arm sediments. Analytical methods are described in Section 4.0 of the text.

Interval	Depth in Core (cm)	Corrected Depth (cm)	Porosity %	Wet Bulk Density (g/cm <sup>3</sup> )	$^{210}\text{Po}$ dpm g <sup>-1</sup>
CORE PM-1					
0-0.5	0.25	0.25	87.3		3.59
0.5-1	0.75	1.26			3.2
1-1.5	1.25	2.28	85.7		3.23
1.5-2	1.75	3.20			2.81
2.0-3	2.5	4.57	84.2		3
3.0-4	3.5	6.48			3.06
4.0-5	4.5	8.39	83.1		
5.0-6	5.5	10.33			2
6.0-7	6.5	12.27	82.7		
7.0-8	7.5	14.12			0.76
8.0-9	8.5	15.97	80.6		
9.0-10	9.5	17.85			2.88
10.0-12	11	20.66	78.5		
12.0-14	13	24.66	79.0		0.75
14-16	15	28.20	75.6		
16-18	17	32.02	74.5		0.78
18-20	19	35.31	68.7	1.76	
20-22	21	38.60			1.52
CORE PM-2					
0-0.5	0.25	0.25	86.1		2.284
0.5-1	0.75	0.89			2.304
1-1.5	1.25	1.53	84.7		1.473
1.5-2	1.75	2.18			1.724
2.0-3	2.5	3.14	83.8		1.903
3.0-4	3.5	4.42	83.1		1.066
6.0-7	6.5	8.26	81.0		0.61
8.0-9	8.5	11.03	81.3		
9.0-10	9.5	12.28			0.736
10.0-12	11	14.16	79.0	1.60	
14-16	15	18.16			
16-18	17	20.16	81.7		
20-22	21	24.16	80.7		0.96
24-26	25	28.16	81.0	1.54	
26-28	27	30.16			0.912
28-30	29	32.16	81.4		
32-34	33	36.16	81.2		
34-36	35	38.16			1.384

Interval	Depth in Core (cm)	Corrected Depth (cm)	Porosity %	Wet Bulk Density (g/cm <sup>3</sup> )	<sup>210</sup> Po dpm g <sup>-1</sup>
CORE PM-3					
0-0.5	0.25	0.25	87.5		3.009
0.5-1	0.75	1.34	83.2		2.286
1-1.5	1.25	2.58			4.289
1.5-2	1.75	3.82			4.786
2.0-3	2.5	5.68	81.8		4.499
4.0-5	4.5	10.58	79.7		4.137
6.0-7	6.5	15.56	78.2		3.511
9.0-10	9.5	23.02	75.9		3.784
12.0-14	13	31.91	74.6		
14-16	15	37.06			3.161
16-18	17	42.21	74.4	1.73	
22-24	23	57.04	69.1		2.34
30-32	31	112.08	54.9		1.114
38-39	38.5	163.56			1.926
CORE PM-4					
0-0.5	0.25	0.25	92.0		7.637
0.5-1	0.75	4.81	90.2		8.653
1-1.5	1.25	5.20			7.43
1.5-2	1.75	5.60	89.6		8.189
2.0-3	2.5	5.83			8.977
3.0-4	3.5	6.13	88.0		
4.0-5	4.5	7.80			6.678
5.0-6	5.5	9.46	84.8		
6.0-7	6.5	11.15			6.351
7.0-8	7.5	12.83	87.8	1.51	
9.0-10	9.5	15.13			6.237
10.0-12	11	16.86	86.5		
14-16	15	26.37	88.1		6.052
18-20	19	33.40	88.1		
22-24	23	41.64	88.9	1.46	5.199
28-30	29	49.78	87.4		
30-34	32	54.95			3.111
34-38	36	61.83	87.3	1.46	
42-46	44	73.40	85.8	1.50	
50-54	52	89.84	87.3		1.829
54-55	54.5	95.62	88.2		