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Coring artifacts and contaminant inventories in lake sediment

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Abstract

Sediments of Lake 382, Experimental Lakes Area, Canada, were sampled at six sites using a 5-cm Wildco KB core sampler (KB), a similar device incorporating a ball check valve (BC), and a 0.2 m by 1.2 m flat-faced aluminum freeze core sampler (FC). Cores were sectioned at 1-cm intervals to a depth of 15 cm. Contaminant (^{210}Pb and ^{137}Cs) concentrations (Bq g^{-1}) were measured by gamma spectroscopy, and inventories (Bq cm^{-2}) were calculated following standard methods. Sediments collected using FC, BC and KB had similar contaminant concentrations, however, cores collected by FC and BC had lower estimated inventories than KB cores. Differences between estimates appear to be caused by differences in the water content (WC) of core material. Laboratory studies confirm that FC sediments have higher WC than tube-cored sediment. We hypothesize that ice crystal formation increases the WC of freeze cores, resulting in lower contaminant inventories. Loss of surficial sediment caused by a 'bow wave' may have a similar effect on BC samples. We conclude that KB core gear is appropriate for sampling sediments to measure contaminant concentrations and inventories in recently deposited sediments.

Introduction

Sediment cores are routinely used to estimate contaminant concentrations and inventories in lake sediments. Several types of coring gear are in common use, including various gravity corers and freeze corers. Artifacts caused by coring gear or technique could bias estimated contaminant inventories. Crusius & Anderson (1991) and Chant & Cornett (1991) claimed that gravity cores suffer from artifacts (smearing, core compression and surficial sediment loss), and that freeze cores are superior. Cumming *et al.* (1993) and Wright (1993) criticized Crusius & Anderson, pointing out that their gravity-core gear was poorly designed and operated.

This study was designed to compare conventional (KB) core gear with gravity and freeze-core gear similar to that used by Crusius & Anderson. The performance criteria used to assess the core types were the contaminant (^{210}Pb and ^{137}Cs) concentration and areal contaminant inventory in fine-grained sediment from Lake 382 at the Experimental Lakes Area in northwestern Ontario.

Methods

We took replicate core samples on 12 March 1991 from Lake 382 (49 ° 42′ N, 93 ° 41′ W; Fig. 1) at the Experimental Lakes Area in northwestern Ontario, Canada. Lake 382 (L382) is a softwater oligotrophic lake, typical of many on the Canadian Shield in Ontario (Malley *et al.*, 1989). Three types of gear were used to obtain sediment cores: a carefully operated Wildco® KB corer penetrating the sediment as gently as possible; a similar gravity corer using a ball check valve, penetrating the sediment after a free-fall of approximately 2 m as described by Crusius & Anderson (1991); and a

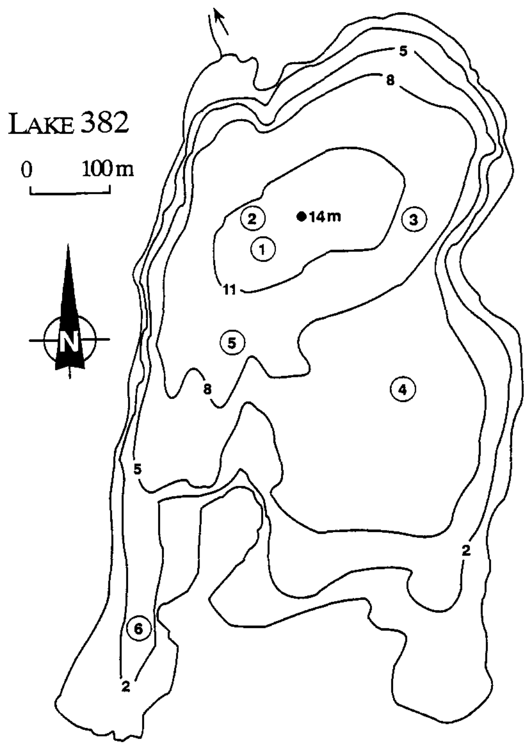

Fig. 1. Bathymetric map of Lake 382, with sampling sites marked.

freeze corer similar in design and operation to the one used by Crusius & Anderson (1991). We determined the concentrations (Bq g^{-1}) and inventories (Bq cm^{-2}) of the ubiquitous radiotracer 'contaminants', ^{210}Pb and ^{137}Cs, in L382 sediment.

The KB corer (Wildco® head, model 2402) had a custom-made acrylic core barrel (5.08-cm inside diameter, 6.03-cm outside diameter), threaded to screw into the core head at one end, and bevelled on the outside edge to penetrate sediment at the other end. No core liner or catcher was used. Sonar was used to provide accurate depth estimates prior to sampling, to help ensure gentle penetration into sediments. The corer was lowered into the sediment as gently as possible, and triggered using a 324 g messenger.

The ballcheck corer (BC) used a commercially available plumbing part (a two-inch Hayward® ballcheck valve) as the core head, with the same type of core barrel as used with the KB corer attached to it by a True Union® flange and locking ring. The acrylic core barrel was weighted on the outside with a taped-on wrap of lead sheet. To take a core, the BC was allowed to free-fall from 2 m above the sediment surface.

The freeze corer (FC) was an aluminum box, 1.2 m long, with a face-width of 0.2 m and a thickness of 0.1 m, as described by Crusius & Anderson (1991). The sides and back were insulated with polyethylene foam, and the tip was bevelled like a chisel for penetration. Lead weights inside the box helped to make it sink and a dry-ice/methanol (1:1) mixture was used as the refrigerant.

The FC was gently lowered into the sediment and allowed to freeze *in situ* for about 20 min. When the corer was retrieved the refrigerant was removed and warm water was added to release the frozen slab of sediment. With the KB, BC and FC corers we collected replicate cores at six sites (Fig. 1) between 13 and 2.5 m in depth from L382 on 12 March, 1991. Only cores with apparently undisturbed sediment-water interfaces were accepted. Cores were sectioned at approximately 1-cm intervals to a depth of at least 15 cm. The KB and BC cores were immediately sectioned in the field. A rubber puck on the end of a steel rod was used to extrude the sediment up to the top of the core tube, where it was sectioned using an acrylic ring and stainless steel spatula. The FC sediments were kept frozen and sectioned using a bandsaw in a walk-in freezer maintained at −40 °C. During sectioning, the inner and outer surfaces of the frozen slab (formerly in contact with the aluminum face of the freeze corer and unfrozen mud, respectively) were trimmed off to ensure that only 'undisturbed' sediment remained in the individual sections. Sections from KB and BC were weighed wet, oven dried at 60 °C, and re-weighed dry. Sections from FC were freeze dried.

The activities of ^{210}Pb and ^{137}Cs in the dry sediments were determined by gamma spectroscopy using a high-purity germanium intrinsic *p*-type well detector (Princeton Gamma-Tech) linked to a Nuclear Data 6700 multichannel analyzer. For ^{210}Pb and ^{137}Cs the 46.5 and 662 keV photon peaks, respectively, were examined. Contaminant concentrations were determined as Bq g^{-1} dry mass sediment. We calculated inventories (Bq cm^{-2}) by two methods. KB and BC cores had a known cross-sectional area, so we used the water content (density = 1.0) and sediment dry mass (assumed density = 2.45) to calculate section volume, thickness and contaminant inventory to a depth of 15 cm. For FC we knew the section thickness (0.9 cm), so water content and sediment dry mass were used to reconstruct the individual section surface areas and inventories to a depth of 15 cm. We corrected the estimated sediment contaminant inventory of each section for a saw kerf thickness of 0.1 cm. For the FC samples,

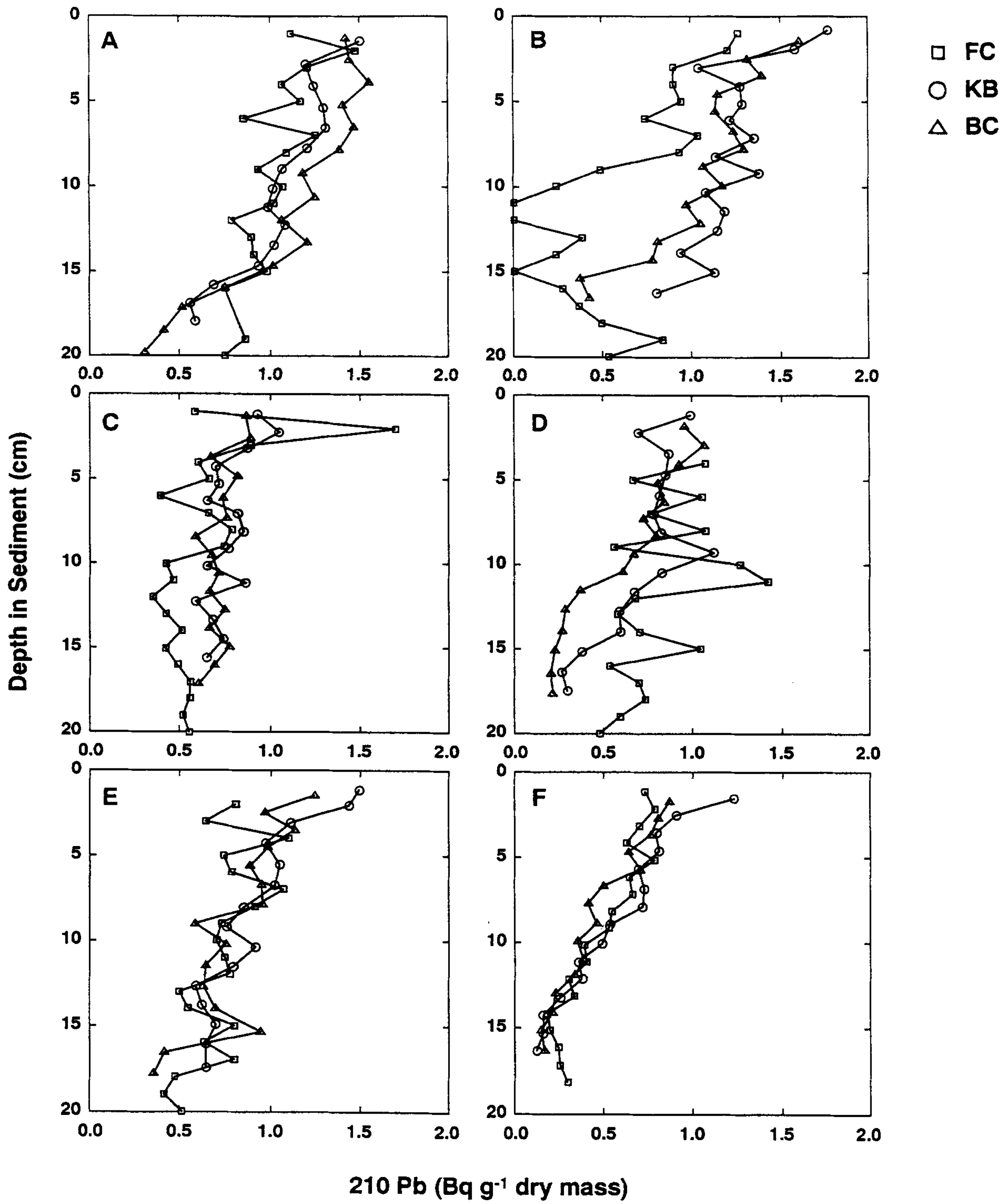

Fig. 2. ^{210}Pb concentrations (Bq g^{-1} dry mass) in sediments from 6 sites in Lake 382. Symbols indicate: ○, KB; △, BC; □, FC coring devices. Panels A to F correspond to sampling sites 1 to 6 respectively.

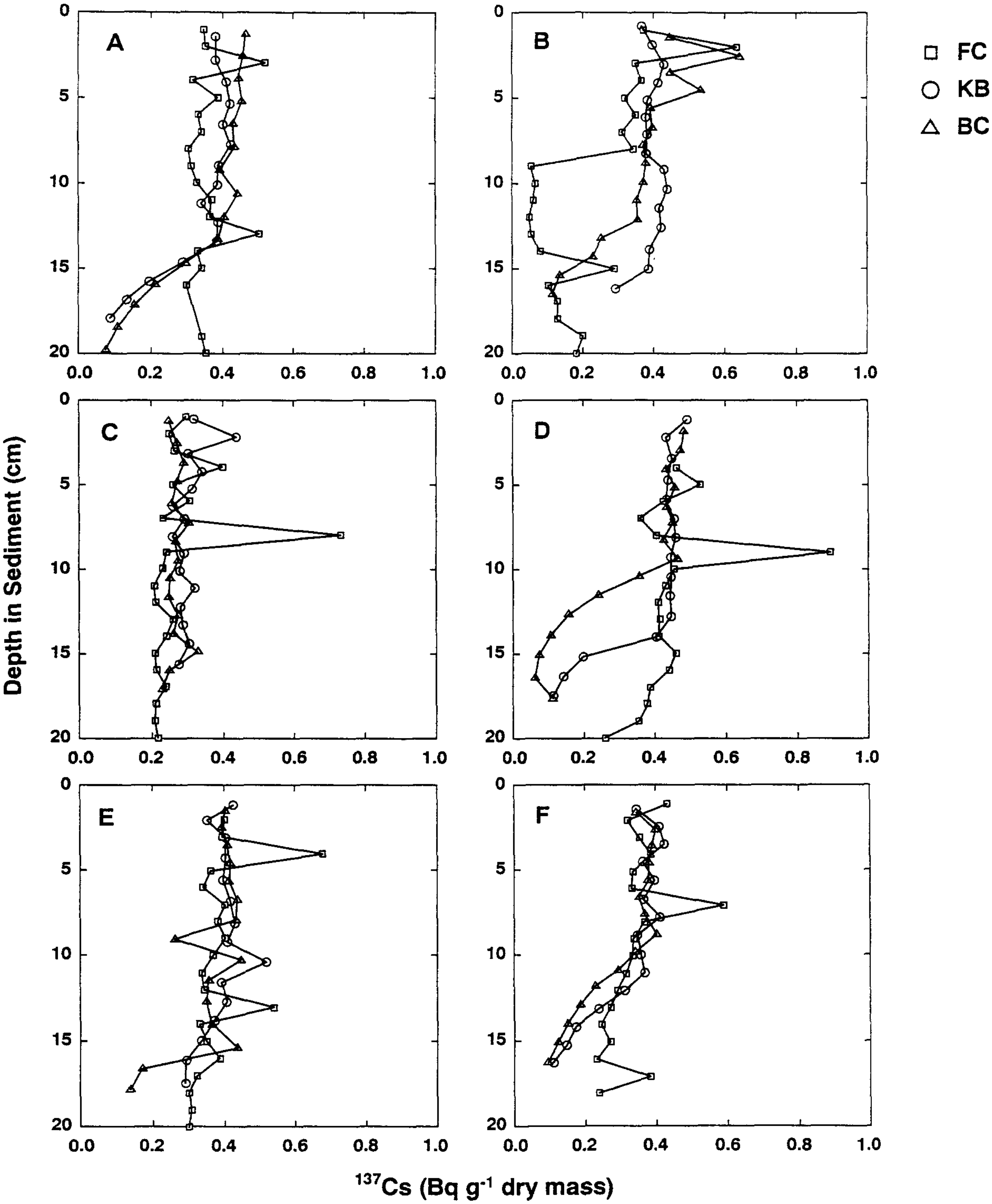

Fig. 3. ^{137}Cs concentrations (Bq g^{-1} dry mass) in sediments from 6 sites in Lake 382. Symbols indicate: ○, KB; △, BC; □, FC coring devices. Panels A to F correspond to sampling sites 1 to 6 respectively.

water content was not recorded for all core slices. We estimated the water content for those samples using a linear interpolation method starting from known water content data within each core. This method worked well when tested on cores with complete water-content data. For two FC cores, near-surface sediment samples were of insufficient mass to reliably measure ^{137}Cs and ^{210}Pb activity (Bq g^{-1}). For these cores (a total of four samples) we estimated the activity of ^{137}Cs and ^{210}Pb as the mean activity measured at the other sites in FC samples at that depth in sediment.

Results and discussion

Concentration profiles of ^{210}Pb and ^{137}Cs in sediments recovered by KB, BC and FC were generally very similar (Figs. 2, 3). The congruence of FC, KB and BC results indicates that common artifacts such as surface sediment loss (Crusius & Anderson, 1991; Cumming *et al.*, 1993), core compression or shortening (Wright, 1993), and smearing inside core tubes (Chant & Cornett, 1993), had little impact on the contaminant concentration profiles. None of the cores, however, show strong peaks of ^{137}Cs activity corresponding to the date of maximum input from atmospheric fallout, nor do they show strong gradients of ^{210}Pb activity. These observations are consistent with the existence in L382 of a thick layer of sediment that is mixed by physical or biological processes. In support of this interpretation, we observed the mixing of ^{109}Cd to a depth of 10 cm in sediments, following experimental additions to the lake water that began in 1987 (Fig. 4).

The similarity in sediment ^{210}Pb and ^{137}Cs concentrations we observe between core types contrasts with the results of Crusius & Anderson (1991), who found strong differences in sediment ^{210}Pb and ^{137}Cs concentrations from nearby ELA lakes 226 and 224 as a function of core type. They hypothesized that these differences resulted from the combined effects of surface sediment loss caused by the bow wave from their gravity core device and core compression, the exclusion of sediments from the core profile during core tube penetration.

Despite the similarity in sediment ^{210}Pb and ^{137}Cs concentrations, we observed large differences in sediment water content as a function of core type, with FC samples consistently having higher water content than KB or BC samples (Fig. 5). Although the water content observed with all three core types converged near the sediment-water interface (i.e. close to 100% water), divergence typically occurred within 2 or 3 cm of the sediment surface and was maintained throughout the deeper sediment profile. Differences in sediment water content between KB and BC core types were smaller, and were not present at all sites. Crusius & Anderson (1991) also observed higher water content in sediment recovered by FC than in sediment recovered by gravity core. Although they considered the hypothesis that the difference was due to expulsion of water during gravity coring or exclusion of solid material during freezing, they favoured the hypothesis that 5 to 15 cm of surface sediments (of high water content) were lost during gravity coring, resulting in a core with systematically lower water content from the apparent sediment-water interface, down. Our ^{210}Pb and ^{137}Cs results (Figs. 2, 3) do not support this interpretation in L382. From inspection of the contaminant concentration and water-content profiles, we conclude that BC suffers from minor surface-sediment loss (1 or 2 cm), reducing the ^{210}Pb and ^{137}Cs inventories to about 83% of those estimated using the KB corer. Results from the FC indicate that freezing increases the sediment water content. We hypothesize that ice crystal formation causes an influx of sediment pore water into the core, excluding some solids.

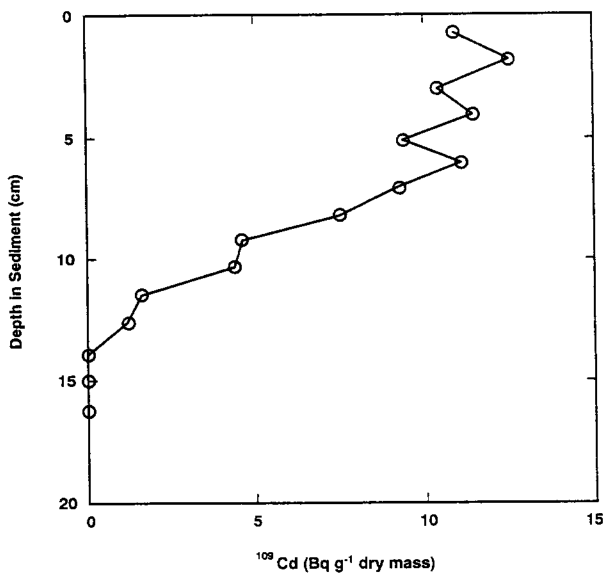

Fig. 4. ^{109}Cd concentration (Bq g^{-1} dry mass) in sediment from the KB core collected at site 2.

The higher water content in FC sediment implies a lower solids content per unit volume. Consequently, despite similar concentrations in sediment, ^{210}Pb and ^{137}Cs inventories (Bq cm^{-2}) in FC cores are con-

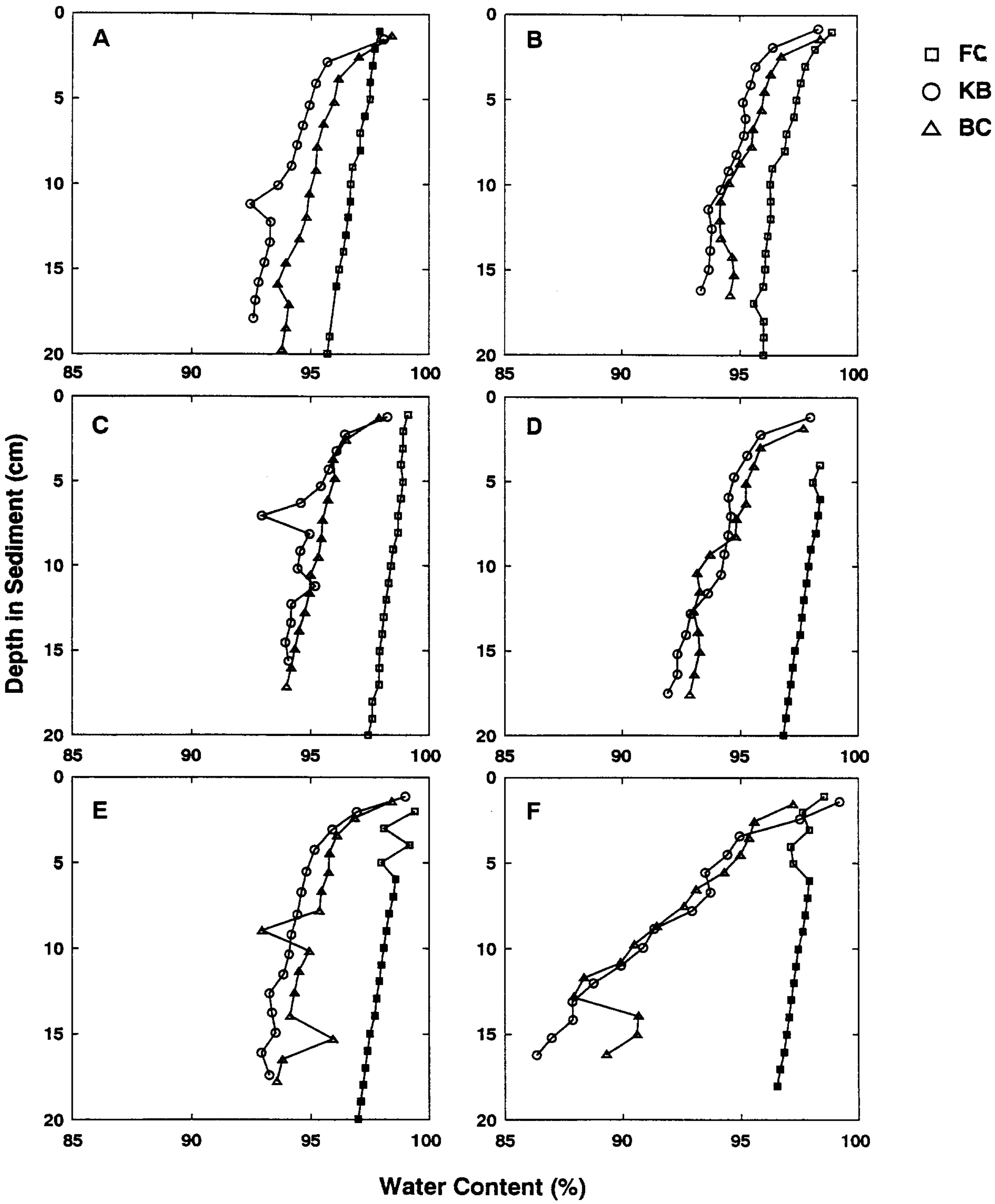

Fig. 5. Water content (% of wet weight) of sediments from 6 sites in Lake 382. Symbols indicate: ○, KB; △, BC; □, FC coring devices. Panels A to F correspond to sampling sites 1 to 6 respectively. For FC, core sections with estimated water content are indicated by filled symbols.

Table 1. ^{210}Pb and ^{137}Cs inventories (Bq cm^{-2}) of sediments to a depth of 15 cm, from six sites in Lake 382

Site	^{210}Pb inventory			^{137}Cs inventory		
	KB	BC	FC	KB	BC	FC
1	0.950	0.859	0.491	0.320	0.275	0.164
2	0.940	0.735	0.236	0.319	0.255	0.097
3	0.570	0.494	0.130	0.226	0.184	0.060
4	0.635	0.487	0.275	0.361	0.266	0.138
5	0.710	0.589	0.211	0.333	0.278	0.108
6	0.573	0.505	0.196	0.374	0.340	0.129

Table 2. ANOVA results for ^{210}Pb and ^{137}Cs. Core sites were treated as blocks. Differences between corers were highly significant

Source	DF	Sum of squares	Mean square	F-ratio	P
^{210}Pb					
site (block)	5	0.302	0.060	13.45	<0.001
core type	2	0.728	0.364	80.97	<0.001
error	10	0.045	0.004		
^{137}Cs					
site (block)	5	0.027	0.005	10.26	0.001
core type	2	0.136	0.068	128.02	<0.001
error	10	0.005	0.001		

sistently lower than those in the BC and KB cores. (Tables 1, 2). These differences occur at all sites and are highly (P<0.001) significant. At every site the highest sediment radionuclide inventories were observed with KB cores, and the lowest with FC cores. These results, likewise, contrast with those of Crusius & Anderson (1991) who observed higher ^{210}Pb and ^{137}Cs inventories in FC cores than in (disturbed) gravity cores. The major coring artifacts associated with tube core devices (surface sediment loss and core compression) should both lead to reduced sediment contaminant inventories, and it is difficult to imagine plausible coring artifacts associated with tube core devices that could inflate contaminant (^{210}Pb and ^{137}Cs) inventories. Thus, in a comparison of core gear, recovery of maximum contaminant inventories is a legitimate criterion.

Table 3. Water content (% + SE) of freeze-cored and tube-cored sediment in the laboratory. Corer effects are highly significant (p < 0.001)

Sediment type	Tube corer	Freeze corer
low water content	89.4 + 0.21	90.1 + 0.26
high water content	93.3 + 0.14	95.1 + 0.35

We tested the hypothesis that freeze coring gives a higher estimate of the water content of sediments in the laboratory, using miniature freeze core (a flat-bottomed steel centrifuge tube holder filled with dry-ice/acetone mixture) and tube core (a 10 ml disposable syringe with the end cut off, operated as a piston corer) gear. Sediment core samples were taken simultaneously in a single 500 ml beaker of lake sediment. Five replicate beakers were sampled at low (~ 90% water) and high (~ 95%) sediment water content. Wet and dry masses of sediment were determined as described above. The results of the replicated (n = 5) tests are summarized in Table 3. We found that freeze-cored sediment had significantly higher water content than tube-cored sediment, and that the difference was greater in the sediment with higher water content. Because the freezing times used in the laboratory were short (<5 min), and ice crystals tend to be larger when freezing proceeds slowly, differences between freeze-cored and tube-cored sediments are likely to be more pronounced under field conditions where freezing times are typically 20 to 30 min.

At least two major coring artifacts have been associated with the KB-core gear: loss of surficial material caused by the hydraulic 'bow wave' associated with lowering the sampler, and progressive thinning of sediment layers entering the device as frictional resistance to coring builds up inside the core tube. Although it seems inevitable that as longer cores are collected using gravity-core gear, internal frictional forces between the sediment core and the inside wall of the core barrel will create a resistance to penetration (back pressure) that will cause progressive exclusion of the sediment layers being collected, we believe that this artifact is not a problem with relatively short (<30 cm) gravity core samples. Certainly, we see no significant difference between contaminant concentrations in replicate sediment samples collected using KB and samples collected using the FC core gear which should be free from this artifact.

Loss of surface sediments is a concern with any kind of core gear, however, we believe that when used with care, the KB-core gear can reliably sample the surface sediment layers. From 1987 to 1993, the water of L382 received known additions of Cd totalling 1.62 kg, with radiotracer ^{109}Cd. Based on analyses of 23 KB cores taken in 1989, and measurements of the radiotracer ^{109}Cd, Stephenson *et al.* (in prep.) estimated the sediment inventory of experimentally added Cd to be 1.52 kg (nominal 95% confidence limits 1.06 to $>$1.62 kg), indicating that as a best estimate, 94% of the ^{109}Cd added to the lake in 1987 and 1988 was present in the lake sediment by March 1989. This estimate is consistent with the predictions of a simple mass-balance model of the fate of ^{109}Cd in L382. Thus, the KB core gear gives contaminant (^{210}Pb and ^{137}Cs) inventory estimates that are significantly higher than BC or FC core gear, and an independent test of ^{109}Cd recovery indicates that the inventory estimate made using KB gear is accurate.

Our results show that coring artifacts of various sorts may be associated with both tube and freeze-core gear. All three types of core gear we tested recovered sediments with similar ^{210}Pb and ^{137}Cs concentration profiles (indicating that surface sediment loss and core compression are not major artifacts in these cores), but differing water content and contaminant inventories (indicating another artifact, which we hypothesize is caused by the migration of sediment pore water towards the freezing front as ice crystals form in the sediment). The KB-core gear recovered the highest areal ^{210}Pb and ^{137}Cs inventories. Thus we conclude that the KB-core sampler is superior to BC or FC, and when used with care can capture the most recently deposited surface sediments to provide unbiased estimates of contaminant inventory in lake sediments.

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