

Benthic Phosphorus Cycling in Lake Champlain: Results of an Integrated Field Sampling/Water Quality Modeling Study

Part B: Field Studies

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for
Lake Champlain Basin Program

June 1999



This technical report is the thirty-fourth in a series of reports prepared under the Lake Champlain Basin Program. Those in print are listed below.

Lake Champlain Basin Program Technical Reports

1. *A Research and Monitoring Agenda for Lake Champlain.* Proceedings of a Workshop, December 17-19, 1991, Burlington, VT. Lake Champlain Research Consortium. May, 1992.
2. *Design and Initial Implementation of a Comprehensive Agricultural Monitoring and Evaluation Network for the Lake Champlain Basin.* NY-VT Strategic Core Group. February, 1993.
3. (A) *GIS Management Plan for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc., and Associates in Rural Development. March, 1993.

(B) *Handbook of GIS Standards and Procedures for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.

(C) *GIS Data Inventory for the Lake Champlain Basin Program.* Vermont Center for Geographic Information, Inc. March, 1993.
4. (A) *Lake Champlain Economic Database Project. Executive Summary.* Holmes & Associates. March 1993.

(B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin.* Holmes & Associates. March 1993

B) *Socio-Economic Profile, Database, and Description of the Tourism Economy for the Lake Champlain Basin. Appendices.* Holmes & Associates. March 1993

(C) *Potential Applications of Economic Instruments for Environmental Protection in the Lake Champlain Basin.* Anthony Artuso. March 1993.

(D) *Conceptual Framework for Evaluation of Pollution Control Strategies and Water Quality Standards for Lake Champlain.* Anthony Artuso. March 1993.
5. *Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 1.* Alan McIntosh, Editor, UVM School of Natural Resources. February 1994.

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6. (A) *Lake Champlain Nonpoint Source Pollution Assessment.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

(B) *Lake Champlain Nonpoint Source Pollution Assessment. Appendices A-J.* Lenore Budd, Associates in Rural Development Inc. and Donald Meals, UVM School of Natural Resources. February 1994.

7. *Internal Phosphorus Loading Studies of St. Albans Bay. Executive Summary.* VT Dept of Environmental Conservation. March 1994.

(A) *Dynamic Mass Balance Model of Internal Phosphorus Loading in St. Albans Bay, Lake Champlain.* Eric Smeltzer, Neil Kamman, Karen Hyde and John C. Drake. March 1994.

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(C) *Assessment of Sediment Phosphorus Distribution and Long-Term Recycling in St. Albans Bay, Lake Champlain.* Scott Martin, Youngstown State University. March 1994.
8. *Lake Champlain Wetlands Acquisition Study.* Jon Binhammer, VT Nature Conservancy. June 1994.
9. *A Study of the Feasibility of Restoring Lake Sturgeon to Lake Champlain.* Deborah A. Moreau and Donna L. Parrish, VT Cooperative Fish & Wildlife Research Unit, University of Vermont. June 1994.
10. *Population Biology and Management of Lake Champlain Walleye.* Kathleen L. Newbrough, Donna L. Parrish, and Matthew G. Mitro, Fish & Wildlife Research Unit, University of Vermont. June 1994.
11. (A) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin. Executive Summary.* Yellow Wood Associates, Inc. January 1995.

(B) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin.* Yellow Wood Associates, Inc. January 1995.

(C) *Report on Institutional Arrangements for Watershed Management of the Lake Champlain Basin. Appendices.* Yellow Wood Associates, Inc. January 1995.
12. (A) *Preliminary Economic Analysis of the Draft Plan for the Lake Champlain Basin Program. Executive Summary.* Holmes & Associates and Anthony Artuso. March 1995

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(B) *Lake Champlain Sediment Toxics Assessment Program. An Assessment of Sediment - Associated Contaminants in Lake Champlain - Phase 11.* Alan McIntosh, Mary Watzin and Erik Brown, UVM School of Natural Resources. October 1997
24. *Development of Land Cover/Land Use Geographic Information System Data Layer for the Lake Champlain Basin and Vermont Northern Forest Lands Project Areas.* Dr. Thomas Millette. October 1997
25. *Urban Nonpoint Pollution Source Assessment of the Greater Burlington Area.* Urban Stormwater Characterization Project. James Pease, VT Dept. of Environmental Conservation. December 1997
26. *Long-Term Water Quality and Biological Monitoring project for Lake Champlain.* Cumulative Report for Project Years 1992- 1996. VT Dept of Environmental Conservation and NYS Dept of Environmental Conservation. March 1998.
27. *Cumberland Bay PCB Study.* Clifford W Callinan, NY State Dept. of Environmental Conservation; Lyn McIlroy, Ph.D., SUNY Plattsburgh; and Robert D. Fuller, Ph.D., SUNY Plattsburgh. October 1998.

28. *Lake Champlain Underwater Cultural Resources Survey. Volume 1: Lake Survey Background and 1996 Results.* Scott A. McLaughlin and Anne W. Lessman, under the direction of Arthur B. Cohn, Lake Champlain Maritime Museum. December 1998.
29. *Evaluation of Soil Factors Controlling Phosphorus Concentration in Runoff from Agricultural Soils in the Lake Champlain Basin.* Frederick R. Magdoff, William E. Jokela, and Robert P. Durieux, UVM Department of Plant and Soil Sciences. June 1997.
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31. *Estimation of Lake Champlain Basinwide Nonpoint Source Phosphorus Export,* William Hegman, Associates in Rural Development, Inc., Deane Wang and Catherine Borer, UVM Water Resources & Lake Study Center, September 1999.
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33. *Ecological Effects of Sediment-Associated Contaminants in Inner Burlington Harbor, Lake Champlain.* Tetra Tech, Inc. September 1999.
34. (A) *Benthic Phosphorus Cycling in Lake Champlain: Results of an Integrated Field Sampling/Water Quality Modeling Study. Part A: Water Quality Modeling.* Jeffrey C. Cornwell and Michael Owens, University of Maryland Center for Environmental Sciences Horn Point Laboratory for HydroQual, Inc. June 1999.

(B) *Benthic Phosphorus Cycling in Lake Champlain: Results of an Integrated Field Sampling/Water Quality Modeling Study. Part B: Field Studie.* Jeffrey C. Cornwell and Michael Owens, University of Maryland Center for Environmental Sciences, Horn Point Laboratory for HydroQual, Inc. June 1999.

This report was funded and prepared under the authority of the Lake Champlain Special Designation Act of 1990, P.L. 101-596, through the U.S. Environmental Protection Agency (EPA grant #EPA X 001840-01). Publication of this report does not signify that the contents necessarily reflect the views of the States of New York and Vermont, the Lake Champlain Basin Program, or the U.S. Environmental Protection Agency.

BENTHIC PHOSPHORUS CYCLING IN LAKE CHAMPLAIN

Final Report

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July 24, 1999

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Summary

In five sampling trips to Lake Champlain we have successfully carried out pore water and sediment-water exchange studies on Lake Champlain sediments. Six stations were examined in July 1994, October 1994, April 1995 and August 1996, with an additional plus an additional 13 sites in July 1994 or September 1996. The sediment-water exchange of phosphorus in Lake Champlain was successfully measured for the first time in this study.

Soluble reactive P (SRP) fluxes were generally low except where bivalves enhanced the flux rates. The higher rates of SRP flux was found in Missisquoi Bay, St. Albans Bay, and in the southern lake. The N flux and pore water data strongly suggest that nitrification and denitrification are important processes. Sediment pore water were characterized by modest SRP concentrations and very high Fe and Mn concentrations. The rapid disappearance of pore water nitrate and sulfate leads to sediment metabolism dominated by methanogenesis and perhaps metal oxide reduction.

The solid phase chemistry indicates that most sediment P is inorganic and that Fe-P co-diagenesis may be important in controlling P distribution. The cycling of Mn and Fe in Lake Champlain sediments results in metal oxide-enriched sediment layers.. A sediment incubation experiment showed that the highest rates of organic matter decomposition occurred in surficial sediments. The production of inorganic carbon and methane were similar in magnitude, suggesting that methanogenesis is the dominant anaerobic process in the sediments.

Radiometric (^{210}Pb) sedimentation rates in Lake Champlain ranged from ~ 300 to >5500 g dry mass $\text{m}^{-2} \text{y}^{-1}$, with the highest rates observed in the southern lake. Anthropogenic Pb distributions generally showed a mid-1970's peak, consistent with time course for other regions in North America.

The sediment P mass balance suggested somewhat higher rates of P burial than whole system mass balances had predicted. The sediment release of SRP was locally significant in Missisquoi Bay, St. Albans Bay, and in the southern lake, all regions with high water column SRP concentrations. In most other lake areas, the sediment release of P is small compared to sediment burial of P.

Acknowledgments

This research was funded as a subcontract to Hydroqual Inc. with primary funding derived from the Lake Champlain Basin Program sponsored by the U.S. EPA and the states of New York and Vermont. Drs. Lyn McElroy and Robert Fuller of SUNY-Plattsburgh provided essential laboratory space and advice; their assistance with logistics was instrumental to the success of our July 1994 sampling trip. We thank Janet Barnes, Brad Bebout, Dan Boudreaux, Teresa Coley, Karla Heidelberg, Kellie Merrell, Lora Pride, Elise Robinson, and Jen Zelenke for field assistance. Laboratory assistance was provided by Kellie Merrell and Lora Pride. We thank Brad Bebout for the design and development of the in situ chambers. Several reviewer provided comments which have improved this final report. Finally, we thank Dr. Jim Fitzpatrick of Hydroqual Inc. for his encouragement and support.

Chapter I. Introduction

Background

Since the time of Einsele (1936) and Mortimer (1941), there has been considerable interest in the processes controlling the flux of phosphate across the sediment-water interface. Phosphate fluxes are clearly enhanced by reducing conditions at the sediment-water interface, with iron often a major controlling factor in P distribution in non-calcareous sediments (Williams et al. 1971; Carignan and Flett, 1981; Cornwell 1987). Other species, such as sulfur, can strongly affect P cycling by changing the nature of iron oxide minerals (Caraco et al. 1989). The flux of remineralized P across the sediment-water interface is minimized when pore water phosphate encounters a "diffusive barrier" such as iron oxide minerals; the loss of iron oxide surface area can enhance P fluxes. Biological enhancement of P fluxes can occur when benthic macrofauna advect pore water into the overlying water, bypassing adsorptive processes.

The highest concentrations of total water column phosphorus ($> 20 \mu\text{g L}^{-1}$) in Lake Champlain are found in the extreme southern part of the lake, Missisquoi Bay in the northern part of the lake, and in highly eutrophic St. Albans Bay. These latter two bays have been identified as critical areas for understanding sedimentary P cycling. An extensive survey of changes in bottom sediment P concentration showed that in St. Albans Bay, decreased loading from sewage and the ongoing long-term flux of P from the sediment has resulted in decreased solid phase P concentrations (Martin et al. 1994). Vertical profiles of total P in Lake Champlain generally show higher concentrations in near-surface sediments (MacIntosh 1994), indicating either increased P loading in the 20th century or post-depositional mobility (Carignan and Flett 1981). Pore water and sediment-water P exchange data are unavailable for Lake Champlain.

The Lake Champlain Management Conference identified phosphorus sediment-water interaction as a priority area for study. "Internal phosphorus loading" was cited as an area of critical management need, with the emphasis on several lake areas with historically high P loading and potentially high rates of sediment P release. This study was developed to quantify sedimentary P recycling rates and increase understanding of the biogeochemical controls of P release in Lake Champlain.

Objectives

While a number of "recycling" processes are important to the P cycle in lakes, the emphasis of this research program in Lake Champlain is on the importance of sediments to the overall P cycle. The sedimentary P cycle aquatic sediments is controlled by such processes as rates of aerobic and anaerobic organic matter metabolism, water column pH and dissolved oxygen concentrations, the binding capacity of sediments for P and both the rates and forms of P sedimentation. The primary objective of this research was to quantify the rates of sediment-water exchange of P and the processes which control this recycling pathway.

Our research/monitoring work plan had four major elements:

1. Sediment-water exchange in experimental chambers. Sediment-water exchange was carried out in gas-tight flux chambers; sediment fluxes of solutes and gases were determined by their change in concentration during a time course incubation. The most expedient method for measuring fluxes is to bring intact cores to the surface and incubating the sediments at ambient temperature and dissolved oxygen concentrations (Garber et al. 1989). Comparisons of such fluxes to *in situ* chambers has been favorable, plus, the chamber provide a means of modifying overlying water chemistry to examine factors controlling P release. Pore water gradients often give a misleading calculation of sediment-water P exchange because of interfacial adsorptive processes.
2. Pore water profiles of P, Fe and other dissolved constituents plus measurement of reactive solid phase constituents. Pore water profiles of P can be useful in discerning the nature of reactions controlling P regeneration, but adsorptive and advective (i.e. bioturbation) processes at the sediment-water interface can make diffusive flux calculations invalid for measuring sediment-water exchange. By examining solute profiles, it is possible to determine controlling factors that limit or enhance P flux to overlying water (Callender and Hammond 1982; Baccini 1985; Cornwell 1987; Sundby et al. 1992). Profiles of nutrient elements (P, N), and redox sensitive elements (NO_3^- , Fe^{2+} , Mn^{2+} , SO_4^{2-}) provide a sense of the redox regime and when combined with major anion, cation and pH analyses, provide the information for a thermodynamic examination of P solubility (Emerson and Widmer 1978).
3. Solid phase profiles of P, Fe, Mn, C, N, Ca, etc. on ^{210}Pb -dated cores. Profiles of solid phase P, Fe, Mn, Ca and other species provide the information needed for understanding controls of P fluxes. In addition, the burial fluxes of P, organic C and other particulate elements may be calculated using ^{210}Pb -dated cores. These measurements are useful for documenting the recent history of environmental change in the lake, the burial fluxes of P and C for diagenetic modeling, and the first order calculation of P burial needed for a whole lake budget (Evans and Rigler 1980; Whalen and Cornwell 1985). The ^{210}Pb dating technique has been utilized in a large number of lake sediment studies and has been applied successful to Lake Champlain sediments (Wahlen and Thompson 1980).
4. "Diagenesis" experiments to determine rates of sediment metabolism and nutrient regeneration. Anaerobic incubations of sediments have been used to calculate the kinetics of diagenetic reaction in many sedimentary environments (Aller and Mackin 1989 and references therein). In order to construct a model of P recycling in Lake Champlain, understanding the kinetics of organic matter diagenesis is useful.

The design of a sampling scheme to definitively answer the questions asked in the original RFP must take into account both temporal and spatial changes in the sediment P cycle. Bottom water hypoxia in Lake Champlain is limited to Malletts Bay, and this process will likely have little quantitative effect on the lake-wide P cycle. The seasonally variable activities of

bioturbating organisms may have an impact on the flux of P from sediments. Finally, in a system with both point and non-point source nutrient inputs, spatial heterogeneity may be quite high.

Study Approach

Our work in Lake Champlain was designed to provide the first detailed biogeochemical study of sediment processes. Given the resources available, it has been relatively successful. However, as in any study at any level of funding, it is necessary to emphasize the examination of a selective number of study sites and processes.

The original request for proposal requested a suite of work that was not feasible considering the available funding. The rationale for a study was stated: "Research on internal phosphorus processes in the lake is needed to enhance the predictive value of water quality models. Studies at selected sites should be conducted in a manner such that the knowledge gained can be transferred elsewhere in Lake Champlain." In the scope of work it was stated that "major study emphasis should be on the quantification of internal phosphorus loading of internal phosphorus flux rates including sedimentation, chemically or biologically mediated sediment release, and physical resuspension."

In this section, the rationale for the choices made during this study are presented, with the hope of helping the reader understand both the strengths and limitations of this work:

1. ***Study sites.*** A total of 19 sites were sampled in this study. Six sites were chosen for seasonal studies, with an additional 13 examined on a one-time basis. Five of the 6 sites were located in lake segments with highly elevated water column P, with the sixth located at a greater depth (50 m). All of the intensive sites, with the single exception of the Shelburne Bay site, were chosen to correspond to long-term nutrient monitoring sites. This was done to provide sediment data for modeling at sites that already had water column information. In general, the other sites were chosen for geographical balance. While these choices have been good for understanding rates in impacted areas, they are not necessarily optimal for whole lake budget calculations. Such calculations were not a goal of the original project, but are provided as a first order attempt at reconciling major P input and output terms.
2. ***Incubation Techniques.*** There are three approaches to determining sediment-water exchange in aquatic sediments: 1) diffusive calculations based on pore water gradients; 2) incubations of cores in the laboratory and 3) emplacement of chambers on the sediment-water interface. The pore water approach can be problematic because of non-diffusive transport processes such as biorrigation, as well as P adsorption at the sediment-water interface. Core incubations generally work well but may poorly replicate physical processes at the sediment-water interface. The small surface area of incubation may be disadvantageous in systems with high spatial heterogeneity. The chamber approach has

the advantage of larger areas of incubation and better temperature control, but may also poorly replicate physical flow. In our study, we chose core incubations because 1) the gear was available, 2) at many Lake Champlain sites, a remotely operated instrument package would have been necessary, and 3) many sites could be sampled and incubated simultaneously. In summer 1994, we incubated cores at SUNY/Plattsburgh. We switched to incubating cores in Maryland because of 1) better temperature control, 2) substantially lower logistical costs and 3) the low rates of sediment metabolism resulted in minimal transportation artifacts. Our comparison of *in situ* chambers with cores incubated in Maryland showed no measurable problems with our approach.

3. ***Geochronology of P Burial.*** We used ^{210}Pb -dated cores to determine the rate of sediment accretion and the rates of P burial. Estimating the rate of P burial is a difficult process and post-depositional mobility of P can potentially result in incorrect rates. However, given the state of knowledge of sedimentation in the lake, our study is an important advance. Alternative methods of sedimentation rate measurement (i.e. ^{137}Cs dating) were not available at the time of this study; in the future we will carry out analyses on selected cores.
4. ***Choice of Analytes.*** The study of the geochemistry of P in aquatic sediments requires knowledge about oxygen, iron and organic matter cycling in the ecosystem. In this study, we have examined a broad range of solid phase (P, N, C, Fe, Mn, Pb), pore water (P, N, S, Cl, Fe, Mn species) and flux parameters (O_2 , P, N) to provide a better understanding of the processes which control P fluxes.
5. ***Resuspension Studies.*** We carried out simple P release/resorption studies. While these studies clearly indicate a P release with resuspension, a lack of knowledge of the frequency of resuspension, competition between algal/bacterial uptake and adsorption, and depth of resuspension limit the applicability of our data. There is a strong need for descriptive field studies on resuspension.
6. ***Coring.*** The box coring system we used brought up undisturbed cores with intact interfaces. Obvious resuspension or sediment disturbance resulted in rejection of the core.
7. ***Other Factors Affecting P Burial.*** In shallow water environments, the presence of light throughout the water column and at the sediment surface may lead to benthic primary production. Uptake of P by microphytobenthos and submerged plants may result in interception of P that might otherwise be recycled back to the water column. In some cases, plants may "mine" P from the sediments. These processes are unexamined in Lake Champlain and may have a local impact in some shallow-water areas of the lake.

Chapter II. Methods

Sample Collection

The field work utilized the University of Maryland's 21' Outer Banks outboard boat which was trailered to the closest possible launch sites. Station locations were determined using a portable GPS system (Apelco GPS 15). Sediment was collected using a non-contaminating box core system (AC-6, Fabrau Inc., Massena, NY) which was purchased by the Horn Point Laboratory specifically for this project. This system was deployed from small boats and was light enough to be hauled in by hand; a battery-powered rope puller was installed on the boat to facilitate coring at depths greater than 5 meters. Bottom water was collected using a small pump with no exposed metal parts and lengths of PVC hose; this system successfully pumped water bottom water from depths as great as 50 m. Depth was measured with a weighted measuring tape at each site and temperature at each site was measured by inserting a VWR temperature meter probe into surficial sediments.

At each site, cores were collected for sediment-water exchange measurements and for pore water/solid phase analysis. In July 1994, two flux cores, one pore water core and one ^{210}Pb geochronology core were collected for experimentation and analysis, while in October 1994, April 1995, August 1996 and September 1996, three flux cores and one pore water core were collected from each station. Six main stations were selected for seasonal flux measurements, two in Missisquoi Bay, two in the St. Albans Bay area, and two in the southern part of the lake (Figure II-1, Table II-1). In addition, eight additional sites were examined in July 1994. In September 1996, we collected cores from 5 new sites in the main lake area, sampling to depths > 100 m. Table 2 identifies the sampling months and activities.

Table II-1. Station Locations. The station numbering scheme is the same as that for the Lake Champlain Diagnostic-Feasibility Study Final Report (Vermont DEC & NY DEC 1994).

Station ID	Depth (m)	Lake Segment	Latitude (N)	Longitude (W)
Main Stations				
2	5.2	South Lake B	43°42.89'	73°22.98'
7	49.0	Port Henry	44°07.56'	73°24.77'
37	18.6	Northeast Arm	44°45.97'	73°11.20'
41	5.6	St. Albans Bay	44°47.80'	73°09.14'
50	4.1	Missisquoi Bay	45°00.80'	73°10.43'
51	5.0	Missisquoi Bay	45°02.22'	73°06.99'

Station ID	Depth (m)	Lake Segment	Latitude (N)	Longitude (W)
July 1994 Stations				
4	7.6	South Lake A	43°57.10'	73°24.47'
25	9.2	Malletts Bay	44°34.92'	73°16.87'
33	11.7	Cumberland Bay	44°42.07'	73°25.09'
34	51.1	Northeast Arm	44°42.49'	73°13.61'
36	56.4	Isle LaMotte	44°45.37'	73°21.30'
40	6.4	St. Albans Bay	44°47.12'	73°09.73'
48	3.8	Missisquoi Bay	45°00.02'	73°07.55'
52	5.0	Missisquoi Bay	45°02.68'	73°08.60'
Station ID	Depth (m)	Lake Segment	Latitude (N)	Longitude (W)
September 1996 Stations				
SS	5	Shelburne Bay	43°57.10'	73°24.47'
10	122	Main Lake	44°18'00	73°18.02'
12	93	Main Lake	44°21.42'	73°19.79'
19	100	Main Lake	44°28.26'	73°17.95'
21	15	Burlington Bay	44°28.49'	73°13.90'

Table II-2. Sample Collection Time, Location and Type. The collected samples are indicated by "x").

Time	Station ID	Core Fluxes	<i>In Situ</i> Fluxes	Pore Water	Resuspension Experiment	²¹⁰ Pb
July 1994	40	x		x		
July 1994	41	x		x		x
July 1994	48	x		x		x
July 1994	50	x		x		x
July 1994	51	x		x		x
July 1994	52	x		x		x
July 1994	2	x		x		x
July 1994	4	x		x		x
July 1994	7	x		x		x
July 1994	33	x		x		x
July 1994	25	x		x		x
July 1994	34	x		x		x
July 1994	36	x		x		x
July 1994	37	x		x		x
Time	Station ID	Core Fluxes?	<i>In Situ</i> Fluxes?	Pore Water?	Resuspension Experiment?	²¹⁰ Pb?
October 1994	37	x		x		
October 1994	41	x		x		
October 1994	50	x		x		
October 1994	51	x		x		
October 1994	2	x		x		
October 1994	7	x		x		
Time	Station ID	Core Fluxes?	<i>In Situ</i> Fluxes?	Pore Water?	Resuspension Experiment?	²¹⁰ Pb?
April 1995	37	x		x		
April 1995	41	x		x		
April 1995	50	x		x		
April 1995	51	x		x		
April 1995	2	x		x		
April 1995	7	x		x		

Time	Station ID	Core Fluxes?	<i>In Situ</i> Fluxes?	Pore Water?	Resuspension Experiment?	²¹⁰ Pb?
August 1996	2	x		x		
August 1996	4	x		x		
August 1996	7	x		x		
August 1996	37	x		x		
August 1996	41	x		x	x	
August 1996	50	x	x	x	x	
August 1996	51	x		x		
Time	Station ID	Core Fluxes?	<i>In Situ</i> Fluxes?	Pore Water?	Resuspension Experiment?	²¹⁰ Pb?
September 1996	SS	x	x			x
September 1996	10	x				x
September 1996	12	x				x
September 1996	19	x				x
September 1996	21	x				x

Sediment-Water Exchange

Our sediment-water exchange techniques generally follow those of Garber et al. (1989). The 6" square corer box was subcored with 4" inner diameter PVC cores. A magnetic stirring system was used to mix the overlying water in each core (Figure II-2) and the cores were incubated in the dark at *in situ* ($\pm 2^{\circ}\text{C}$) temperatures. Overlying water was replaced with fresh overlying water prior to incubation to minimize coring effects on water chemistry. We had saturated dissolved oxygen conditions at the outset of the experiment. At our detailed stations, we measured time courses of dissolved oxygen, soluble reactive phosphorus (SRP), ammonium, and nitrate. At our 6 intensive sites, we measured fluxes in triplicate (duplicates in July 1994) plus a bottom water blank incubation, with 4 time points per incubation. At less intensive sites (the "synoptic" survey, July 1994), we measured fluxes in duplicate with no blank incubation, allowing the broadest spatial coverage. All 1996 fluxes used triplicate incubation cores. Samples were analyzed for dissolved oxygen analysis using an oxygen meter (Strathkelvin Instrument Model 781). Solute samples were filtered using a 25 mm diameter, 0.45 μm pore size cellulose acetate syringe filter (Nalgene #191-2045). Typically, 20 mL was filtered into vials for analyses of SRP, NH_4^+ , and anions (NO_3^- , Cl^- , SO_4^{2-}). Overlying water volumes were calculated from water height.

In July 1994, sediments were incubated in constant temperature incubators at the State University of New York at Plattsburgh. In subsequent sampling trips, sediments were immediately transported to a constant temperature room at the Horn Point Environmental

Laboratory. Sediments were kept oxygenated during transport. The methods for chemical analysis of solutes and gases are outlined in Table II-3. Sediment flux rates were determined by linear regression of solute concentrations versus time.

In August 1996 and September 1996, we deployed *in situ* benthic chambers at sites in Missisquoi and Shelburne Bay. The purpose of these measurements included: 1) comparison to laboratory flux work, 2) inclusion of a larger area of sediment for fluxes, 3) immediate flux measurements, 4) inclusion of realistic light regimes (i.e. benthic algal effects on fluxes will be accounted for, and 5) fewer sampling artifacts. Chambers were deployed in triplicate in shallow water, with each chamber followed for ~18 hours for dissolved oxygen and nutrients. A peristaltic pump was used to fill sample bottles.

Acrylic chambers similar to those of Glud et al. (1995) were deployed. These chambers are square with rounded corners, with overall side length of 30 cm. We used this design because 1) Glud et al. have calibrated the physical regime in these chambers (vertical and horizontal flow) as well as benthic boundary layer thickness, 2) they cover a much larger area than our other core designs, 3) we had an opportunity to test these in our experimental mesocosm facility at Horn Point, and 4) six units were available at no cost for the Champlain work.

Table II-3. Dissolved Constituent Analysis.

Analyte	Reference	Description
pH	EPA 150.1	A flat combination electrode is directly inserted into fresh sediment. All measurements using pH 4 and 7 buffers. Precision = ± 0.05 pH.
soluble reactive P (SRP)	Parsons et al. 1984 EPA 365.2	
SO ₄ , Cl ⁻ , NO ₃ ⁻	EPA 300.0	Ion chromatography (d.l. < 0.1 mg L ⁻¹)
Fe, Mn, Ca, Mg, K	EPA 236.1, 243.1, 215.1, 242.1, 258.1	Flame atomic absorption spectrophotometry (d.l. < 0.1 mg L ⁻¹)
total CO ₂	Stainton, 1973	Headspace technique, analysis of gas on Shimadzu GC 8-AIT chromatograph with Porapak Q column and thermal conductivity detector. (d.l. < 0.05 mmol L ⁻¹)
CH ₄		Headspace technique similar to CO ₂ analysis on Shimadzu Mini 3 GC with Porapak N column and flame ionization detector. (d.l. < 1 μ mol L ⁻¹)
NH ₄ ⁺	Parsons et al. 1984	Phenol/hypochlorite colorimetry (d.l. < 0.1 mg L ⁻¹)

Pore Water Chemistry

Pore water chemistry was determined on single cores at each sampling for sediment-water exchange. We used 3" diameter acrylic core tubing for subcoring and sectioned the sediments in 0.5 cm intervals in the top 2 cm, with 1 and 2 cm sections deeper within the core. All sediment handling was carried out in nitrogen-filled glove bags to minimize oxidation artifacts (Bray et al. 1974). Sediment was sectioned into 50 mL centrifuge tubes and centrifuged for 20 minutes at 4000 rpm. The water was filtered through a 0.4 μ m syringe filter. The pore water sample was divided into separate vials for each analysis immediately after filtration. pH was measured using "punch-in" electrodes.

Solid Phase Chemistry/Geochronology

We used dried sediment for the chemical analysis of solid phase components. Analytes are listed in Table II-4. Sediment dating was via ^{210}Pb (Robbins 1978; Sugai 1990).

Table II-4. Solid phase analyses.

Analyte	Reference	Description
Total C, N		Control Instruments Elemental Analyzer
Total P	Aspila et al. 1976	1.0 N HCl extraction of ashed sediment, colorimetry
Inorganic P	Aspila et al. 1976	1.0 N HCl extraction of unashed sediment, colorimetry
HCl-Fe, Mn and Ca		Analysis of 1.0 N HCL extract by flame AAS
Trace Metals	Evans and Rigler 1980b; Cornwell 1986	HNO ₃ /HCl digestion to dryness; dissolution in 10% HCl; flame AAS analysis of Mn, Fe, Pb, Cu, Zn
^{210}Pb	Sugai 1990	HCl-HNO ₃ extraction, ^{210}Po alpha counting

Decomposition Rate Constants

Sediments collected in October at the 6 main sites were sectioned at 3 depth intervals (0-1 cm, 4-6 cm, 8-10 cm). Homogenized sediments (6 ml) from each treatment were placed in 30 ml serum bottles with 10ml of anoxic water and sealed. All sediment manipulations including sampling were conducted in a nitrogen filled glove bag. The sediments were incubated in darkness as a slurry with an anoxic headspace at 12 °C. Serum bottles were destructively sampled on 0, 21, 98, and 143 days for pore water NH_4^+ , ΣCO_2 , soluble reactive P (SRP) and CH_4 concentrations. Duplicate vials were sacrificed at each time of sampling and the rates of organic decomposition were calculated from linear regressions of the time course incubation data.

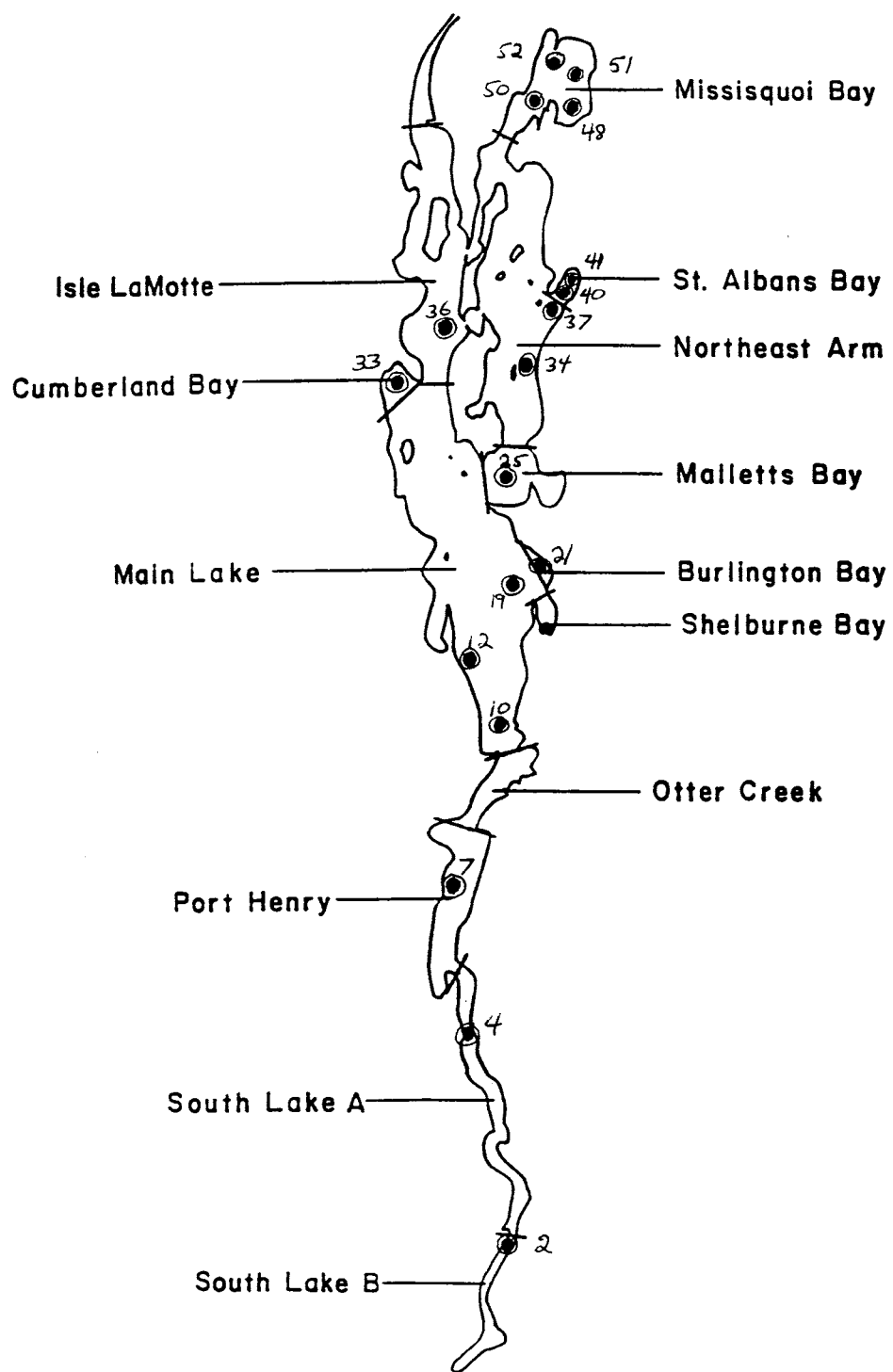
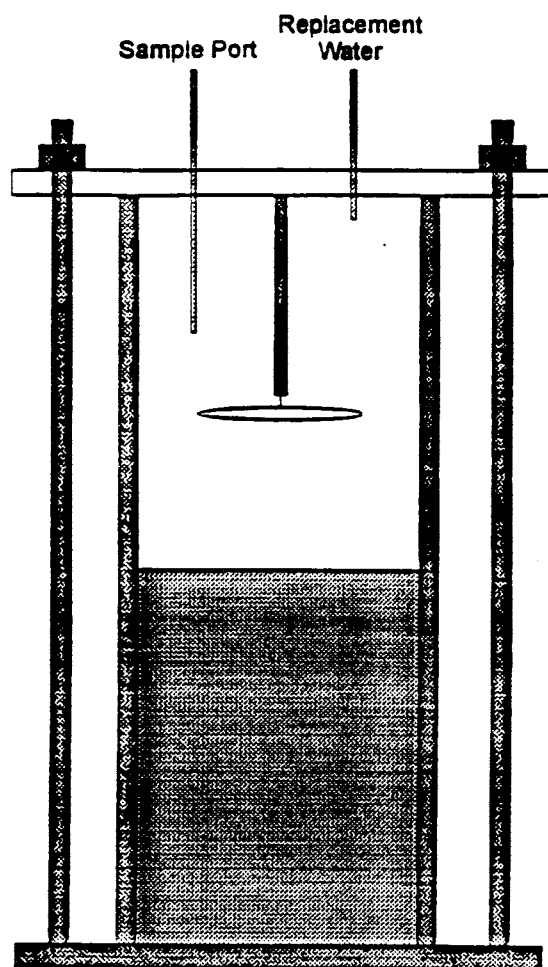


Figure II-1 Location of sampling stations.



Inner Diameter = 10.2 cm
Height = 30 cm

Figure II-2 Diagram of sediment incubation chamber

Chapter III. Sediment-Water Exchange

Nutrient and Oxygen Fluxes -- Main Stations

The highest sediment oxygen demand rates were measured at almost all stations in August of 1996; in some cases these rates are more than twice the rates measured in the summer of 1994 (Figure III-1). The sediment temperature in August of 1996 was actually $\sim 5^{\circ}\text{C}$ lower on average than in July of 1994 at all stations except 7 which showed an increase of $\sim 10^{\circ}\text{C}$. The increase in summer sediment oxygen demand rates at station 7 could be explained by the increase in sediment temperature. The lower sediment temperature at stations 2, 37, 41, 50, and 51 makes the disparity between the summer sediment oxygen demand rates even greater. Missisquoi Bay and St. Albans Bay exhibited a degradation in water quality in August of 1996 evident by intense bloom conditions. Higher flow and a subsequent increase in nutrients may have been the cause of the bloom as well as the elevated sediment oxygen demand rates. In general temperature appears to have a large influence on sediment oxygen demand.

The SRP flux rates vary from a high of $12\ \mu\text{mol m}^{-2}\text{ h}^{-1}$ at station 51 during summer months down to undetectable fluxes at several stations during the cooler months (Figure III-1). Rates of SRP flux rise dramatically in August of 1996 in Missisquoi Bay and St. Albans Bay with SRP fluxes 3 to 5 times greater in August of 1996 than the maximum rates measured two years previously. This increase in SRP flux is greater than would be predicted by the increase in sediment oxygen demand using Redfield Ratio, suggesting another source of dissolved P from the sediments other than organic matter degradation. The increase in SRP flux in August is probably a result of an increase in organic matter degradation and a subsequent shallowing of the sediment oxygen penetration causing the sediments to be less retentive of phosphorus. High flow conditions prior to our sampling in August of 1996 and increased carbon deposition may be responsible for the elevated SRP flux. Station 7 is anomalous in that it has the lowest sediment temperature throughout the year but the second highest SRP flux and does not have an elevated SRP flux in 1996. Station 2 has overall the lowest rates of SRP flux particularly at lower temperature and despite a doubling of the sediment oxygen demand from July 94 to August 96 there is no apparent change in the SRP flux. Station 2 appears to be more retentive of phosphorus than the other shallow water stations. The flux of SRP at station 37 correlates well with temperature but is elevated in 1996 showing the same general pattern as inner St. Albans Bay and Missisquoi Bay.

The flux of NH_4^+ at most sites reveals a pattern consistent with temperature effects, with the highest fluxes in summer and minimum fluxes in winter (Figure III-2). Station 7 shows very little or no exchange of NH_4^+ even in summer, probably resulting from lower temperatures and higher rates of coupled nitrification/denitrification. Uptake of NH_4^+ at stations 37, 50 and 51 in April suggest an increase in nitrification which could result from increased O_2 penetration in the sediment at that time. Station 2 shows no seasonal pattern with high fluxes of NH_4^+ through the year except for April. Surprisingly, the anomalously high sediment oxygen demand and SRP fluxes in August 1996 do not coincide with elevated NH_4^+ fluxes. The lack of increased NH_4^+ fluxes further suggest that the increase in SRP flux is being controlled by a mechanism other

than increased organic matter decomposition. Conversely, bacterial uptake of N may be another sink for N at this station. Stations 2 and 7 show some uptake of NO_3^- through most of the year, with a flux of NO_3^- out of the sediment in the cooler months indicating an increase in nitrification activity. St. Albans Bay and Missisquoi Bay have seasonally-variable fluxes of NO_3^- directed out of the sediment.

Spatial Patterns in Nutrient and Oxygen Fluxes

This study included 19 stations in Lake Champlain for measurements of sediment/water exchange including 14 stations sampled in July of 1994 and 5 from August of 1996. Our survey of 14 sites in July 1994 showed that the highest rates of SRP flux occur mainly in shallow water regions of Missisquoi Bay, St. Albans Bay, and South Lake B (Figure III-3). These sites also have the highest sediment oxygen demand, NH_4^+ flux and the highest sediment temperature (Figure III-4). The SRP flux rates varied from a high of $7 \mu\text{mol m}^{-2} \text{h}^{-1}$ at station 41 down to less than $2 \mu\text{mol m}^{-2} \text{h}^{-1}$ at station 4 with no measurable flux recorded at many of the deep water sites. Station 48 was the only shallow water site which did not show a SRP flux in July. Low sediment oxygen demand and low rates of nutrient release from deep water sites ($>20 \text{ m}$) in July are probably a result of low sediment temperatures ($< 10^\circ\text{C}$) limiting rates of decomposition. High rates of nitrate uptake at stations 2, 50, 51, 52 in July suggest high rates of sediment denitrification (Figure III-4).

Selection of our 6 main sites was partially based on the presence of high SRP concentrations in the water column, and included 5 shallow water sites (stations 2, 37, 41, 50, and 51) and one deep water site (station 7). The survey of 5 additional sites in August of 1996 included 3 deep water ($> 90 \text{ m}$) sites (stations 10,12,19) in the main stem of the lake. This area represents the deepest part of Lake Champlain and a large spatial area which was not represented in our previous survey. The SOD of stations 10, 12, and 19 was higher (Figure III-3) than the other deep water stations measured in July of 1994. The narrowing of the lake in this region could cause organic matter to be focused into this deep region, resulting in higher rates of sediment metabolism. This deep region has relatively low SRP fluxes and no apparent NH_4^+ flux (Figure III-4) despite the higher sediment oxygen demand. High rates of NO_3^- uptake at the deep water stations suggest high rates of nitrification/denitrification are controlling the flux of NH_4^+ derived from organic matter remineralization. Stations 21 and SS have sediment oxygen demand rates comparable to the other shallow water sites in St. Albans Bay and Missisquoi Bay but have much lower SRP fluxes and no NH_4^+ fluxes.

Bivalves and SRP Fluxes

St. Albans Bay and Missisquoi Bay have the highest SRP fluxes of any areas sampled in our survey. These shallow water areas (stations 50-52 and 41) also have the highest densities of bivalves which were excluded in our flux incubations when possible. Occasionally cores with numerous bivalves would be visible in our cores which could not be removed without disturbing the sediment/water interface. Relative to cores which contain very few or no bivalves, nutrient fluxes were significantly increased by the presence of bivalves. Cores with large numbers of

bivalves were excluded from data shown previously because of the high variability between cores. While rates of sediment oxygen demand tended to increase $< 50\%$ with bivalves present, SRP and NH_4^+ fluxes showed a dramatic increase when bivalves were present during incubation (Figures III-5, III-6). These results suggest that bivalves could play a major role in nutrient cycling in St. Albans Bay and Missisquoi Bay. The bivalves could be recycling both SRP and NH_4^+ back to the water column, circumventing subverting biogeochemical process which might otherwise limit the flux of these nutrients from the sediment. The flux of NO_3^- into the sediment is also enhanced with bivalves present which might suggest a decrease in sediment O_2 penetration caused by increased organic matter deposition near the bivalves. A linear increase in SRP and NH_4^+ concentrations during incubation suggests that decreasing O_2 concentrations are not responsible for the enhanced fluxes. Our sediment flux incubations, having relatively small surface area are not well suited for sampling a heterogeneous distribution of bivalves. The present study does not give enough definitive evidence that bivalves are a major factor controlling nutrient flux; however the evidence presented here along with the high density of bivalves in Missisquoi Bay and St. Albans Bay suggest that further study of the effect of bivalves may be warranted.

In situ Chambers versus Core Incubations

Our sediment/water flux cores are transported to our laboratory and incubated at bottom water temperatures. This method works well allowing us to have excellent control over temperature and the duration of the flux by monitoring O_2 levels over a detailed time course. A concern with the current study is whether or not cores transported to Maryland could provide the same rates as cores incubated immediately. To address this question, *in situ* benthic chambers were used at two sites in 1996 to collect flux data. After the *in situ* flux the benthic chambers were carefully removed and cores were collected by diver from the area under the benthic chambers and transported back to our laboratory for incubation. A comparison of sediment oxygen demand, SRP, and NH_4^+ flux data for the two modes of incubation is shown in Figure III-7. The flux data shows very good agreement between flux rates of *in situ* cores and those cores held for several days before incubation. The small differences that do exist appear to be within the natural variability of the system. These results are very encouraging considering the difficulties in deploying and sampling *in situ* benthic chambers.

Sediment Resuspension

Steep pore water gradients of phosphorus near the sediment/water interface at many sites would indicate higher fluxes of SRP than were generally found in our incubations. The flux of SRP is probably limited by interactions with iron oxides near the sediment-water interface. In the shallow regions of the lake, resuspension of bottom sediments could be a major mechanism for releasing SRP to the water column during strong wind events.

In order to assess the effects of resuspension, cores were incubated under our normal incubation conditions and then surface sediments were resuspended. The average flux rates of sediment oxygen demand, SRP, and NH_4^+ for triplicate cores from stations 2, 41, and 50 are

shown in Figure III-8 . The sediment oxygen demand rates were slightly higher in cores after resuspension at stations 41 and 50 but showed no difference at station 2. The pattern of NH_4^+ flux follows sediment oxygen demand except for station 41 which shows an uptake of NH_4^+ with resuspension, indicating a possible increase in nitrification activity. The SRP flux decreased dramatically with resuspension with no consistent increase of SRP with time after resuspension.

Linear flux rates do not represent the actual short term release of SRP after resuspension. Figure III-9 shows the average release of SRP measured via accumulation in the overlying water 2 hours before and after resuspension. Resuspension causes a large initial release of SRP at stations 2 and 41 and only a slight increase in station 50. After the first 2 hours, cores without resuspension continue to release SRP while the resuspended cores show a significant reduction in SRP release. The resuspension may have exposed high levels of pore water phosphorus to the overlying water, rapidly increasing the release of SRP. This mechanism would explain the higher release at station 41 which had a steeper upward pore water SRP gradient compared to the other sites. After 2 hours after resuspension, SRP may be sequestered by rapidly settling particulates, with a diminished SRP gradient at the interface resulting in a decreased SRP flux. The overall magnitude of the SRP flux with resuspension could be a function of the duration of resuspension and the water depth. Resuspension of sediments in a deep water column may allow a physical separation between SRP released upon resuspension and the particulates which might bind SRP in the water column. The disturbance of surface sediments during a resuspension event clearly can enhance the release of SRP from the sediments on a short term basis, but this short term release may be offset by a reduction in SRP flux as sediments settle out and pore water SRP gradients are reestablished.

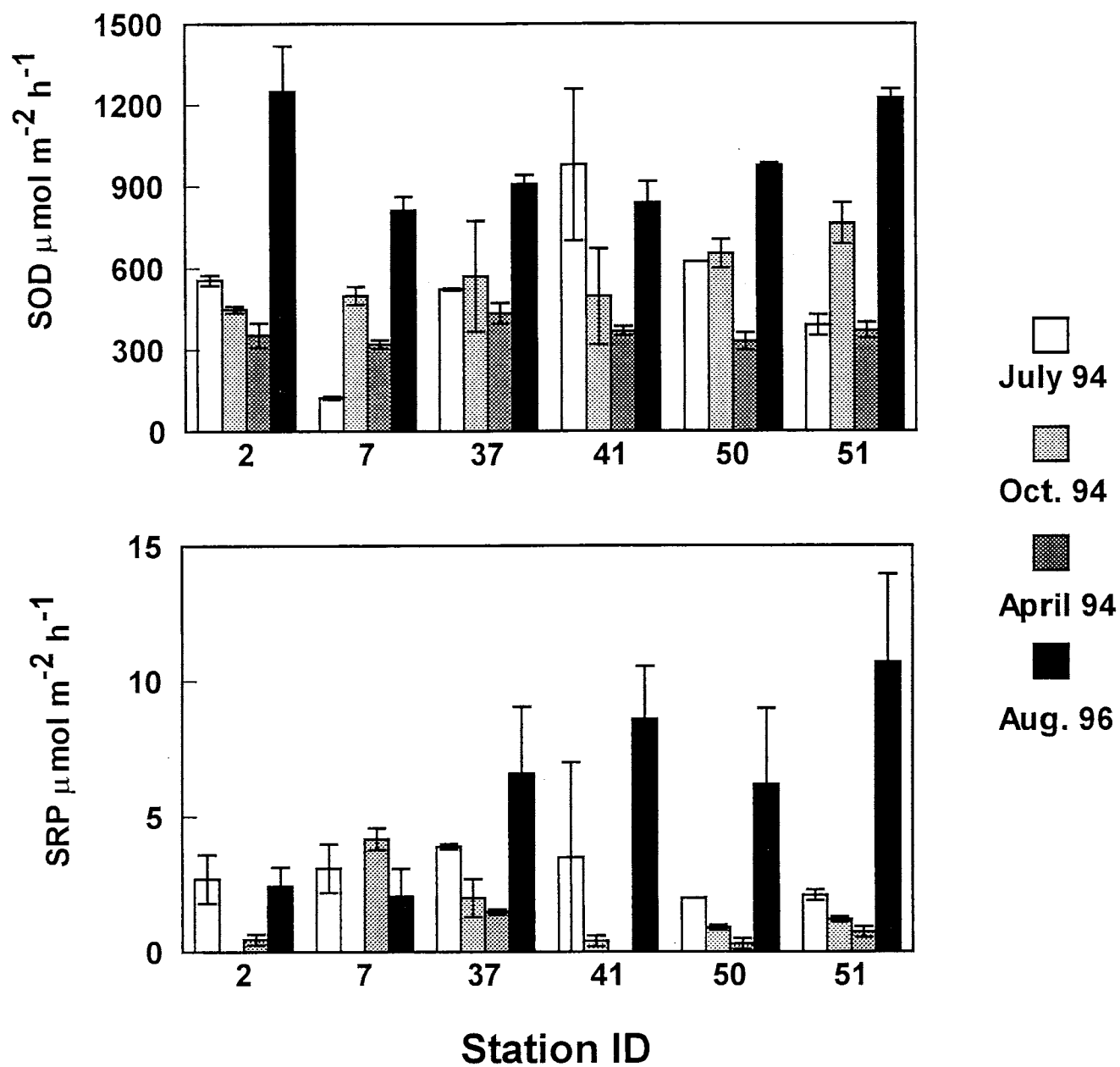


Figure III-1. Seasonal sediment oxygen demand and SRP fluxes at the six main stations. Error bars indicate the standard deviation of three replicates (only 2 in July 1994). Cores with bivalves were excluded from these data.

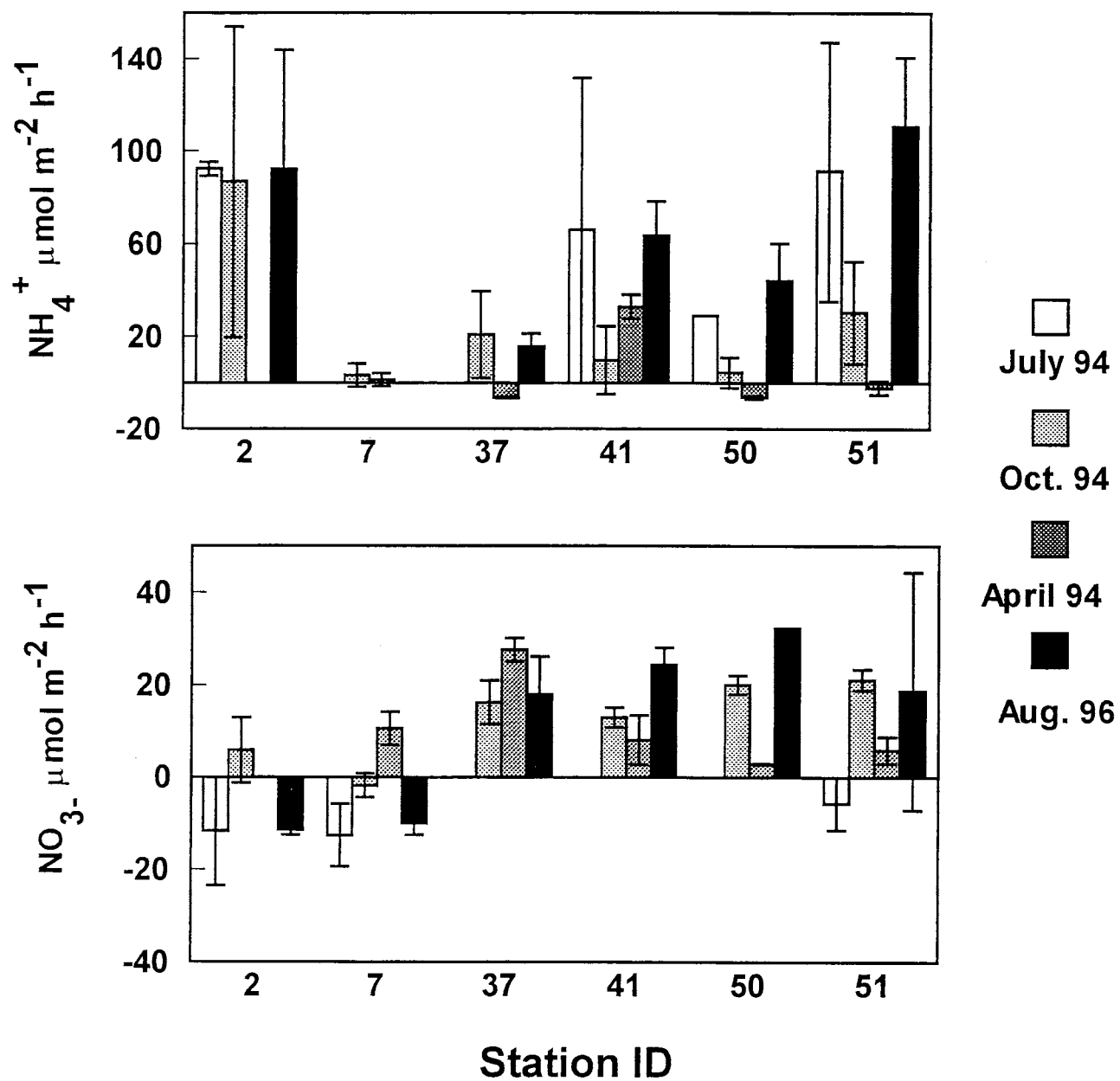


Figure III-2. Seasonal ammonium and nitrate fluxes at the six main stations. Error bars indicate the standard deviation of three replicates (only 2 in July 1994). Cores with bivalves were excluded from these data.

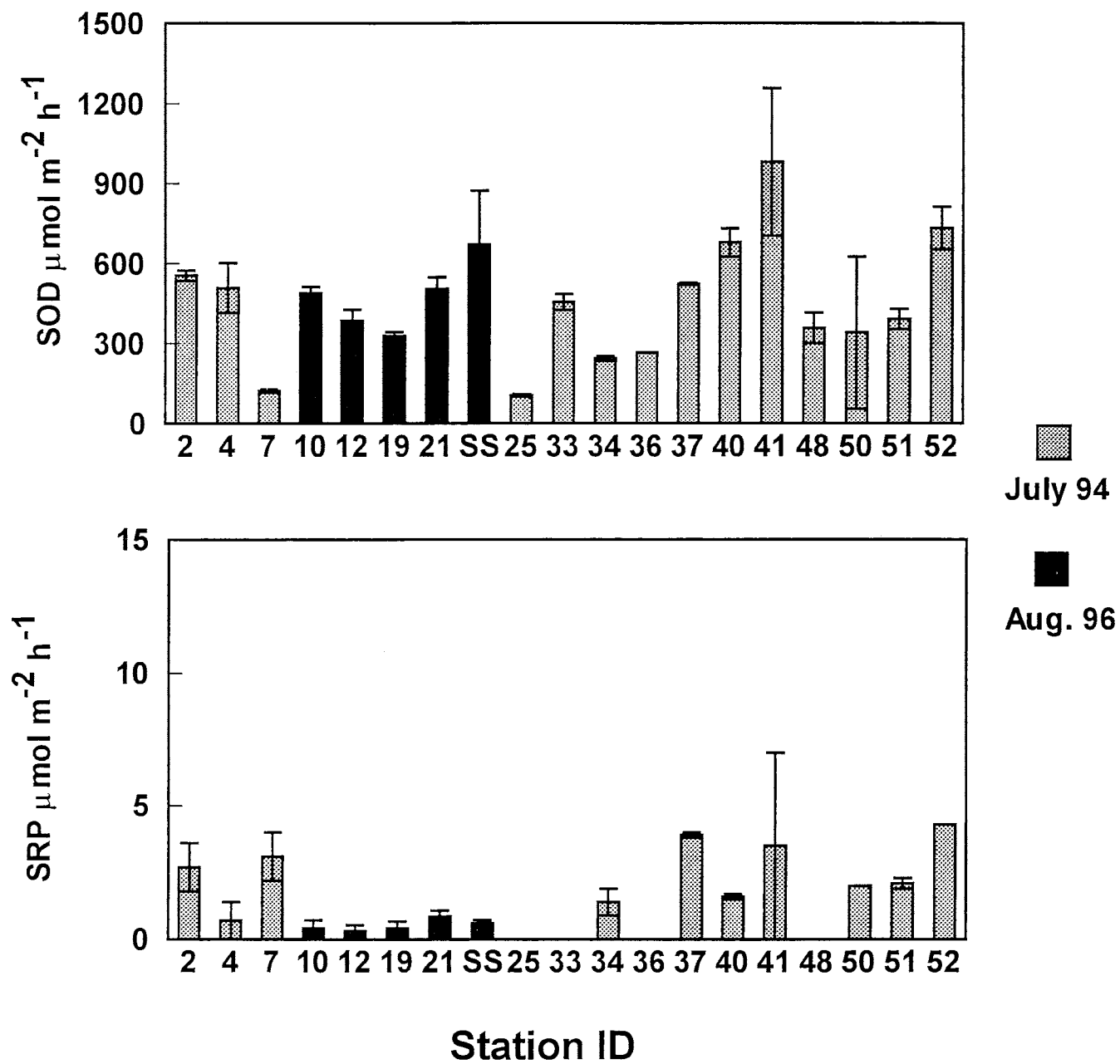


Figure III-3. Summer sediment oxygen demand and SRP fluxes at all stations. Error bars indicate the standard deviation of three replicates (only 2 in July 1994). Cores with bivalves were excluded from these data.

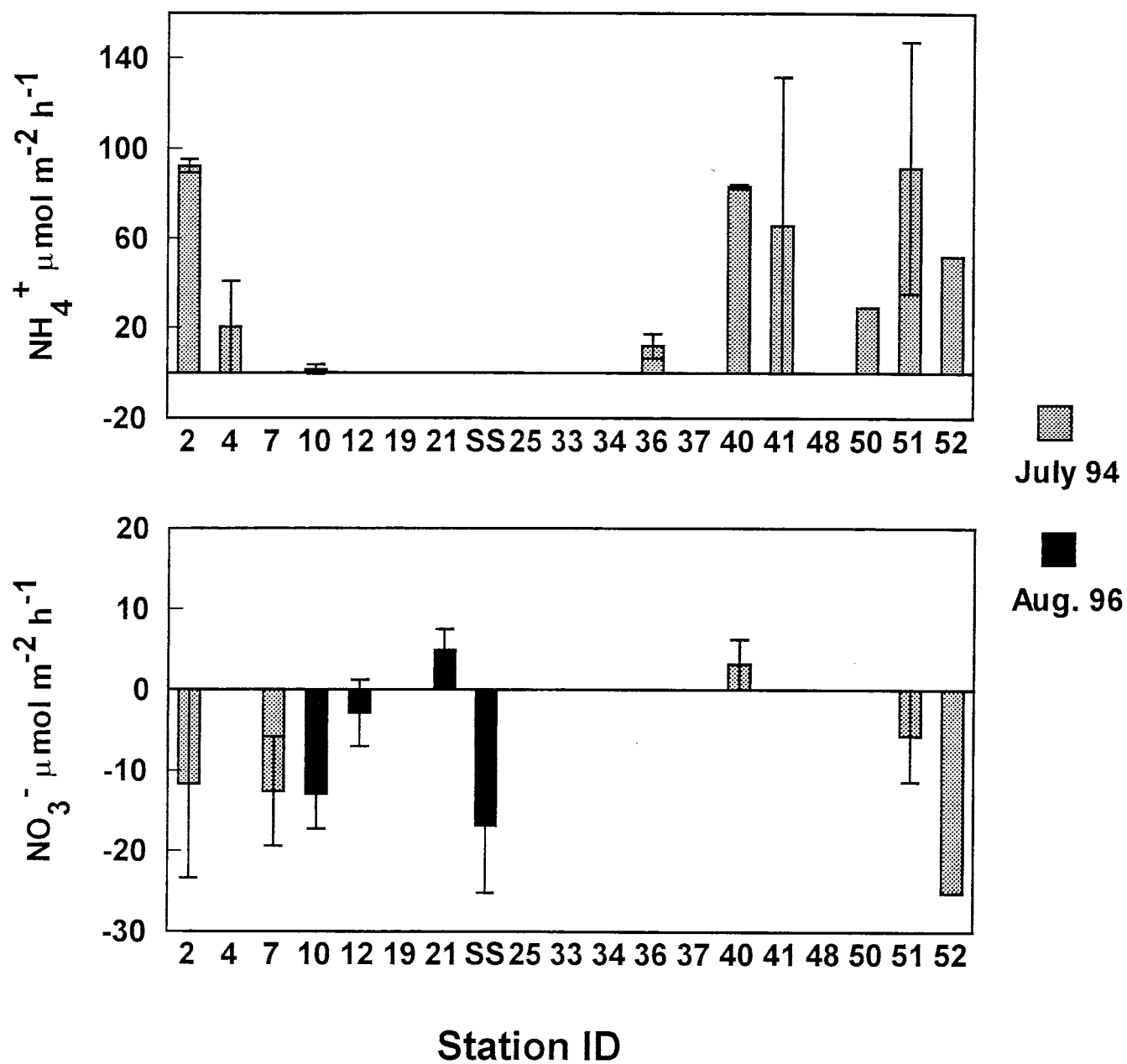


Figure III-4. Summer ammonium and nitrate fluxes at all stations. Error bars indicate the standard deviation of three replicates (only 2 in July 1994). Cores with bivalves were excluded from these data.

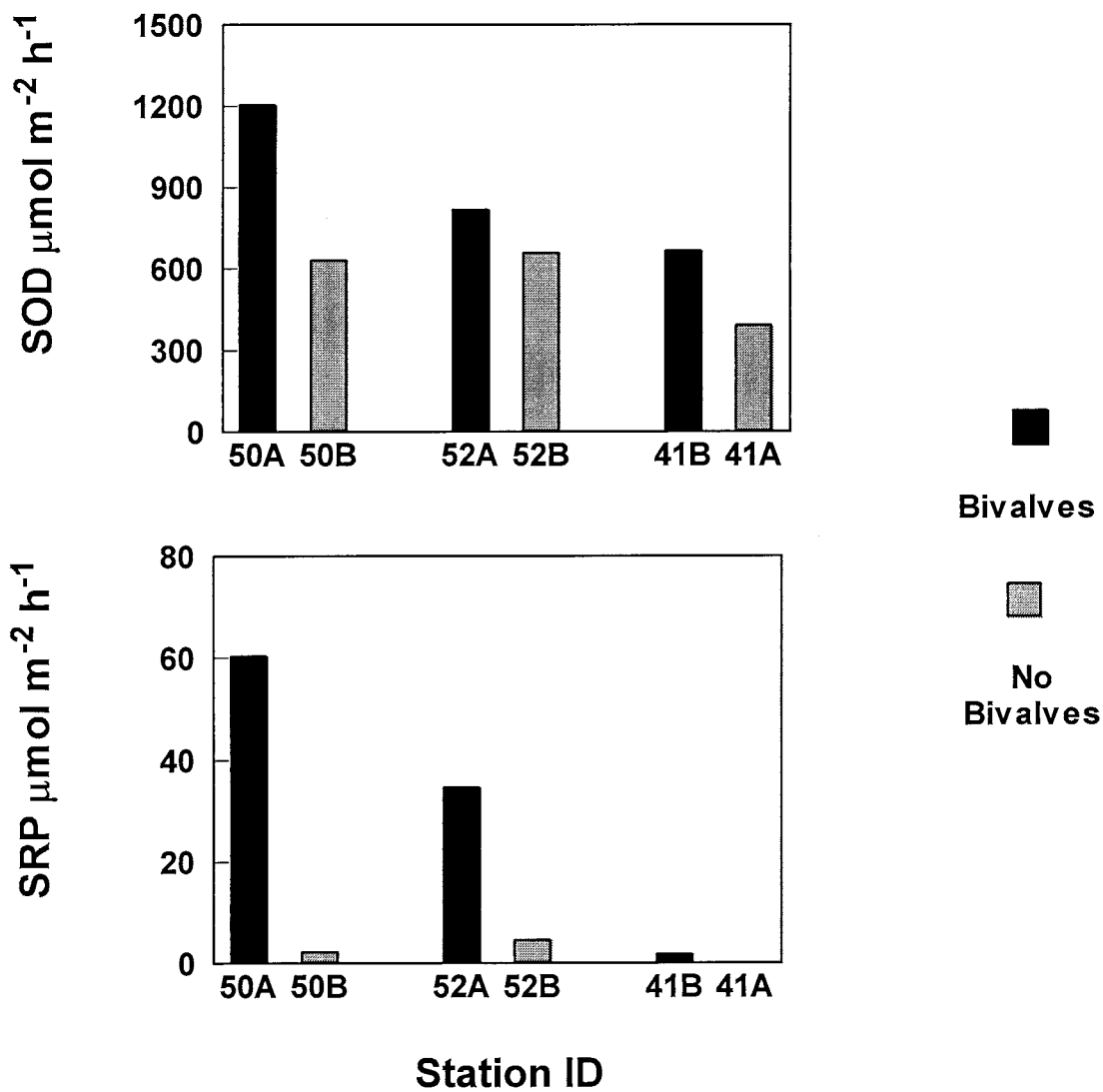


Figure III-5. Comparison of sediment oxygen demand and SRP fluxes in cores with and without bivalves, August 1994. Core 41A had no measurable SRP flux. These are single core comparisons at stations 50, 52 and 41, with inadvertent incorporation of bivalves in the flux cores.

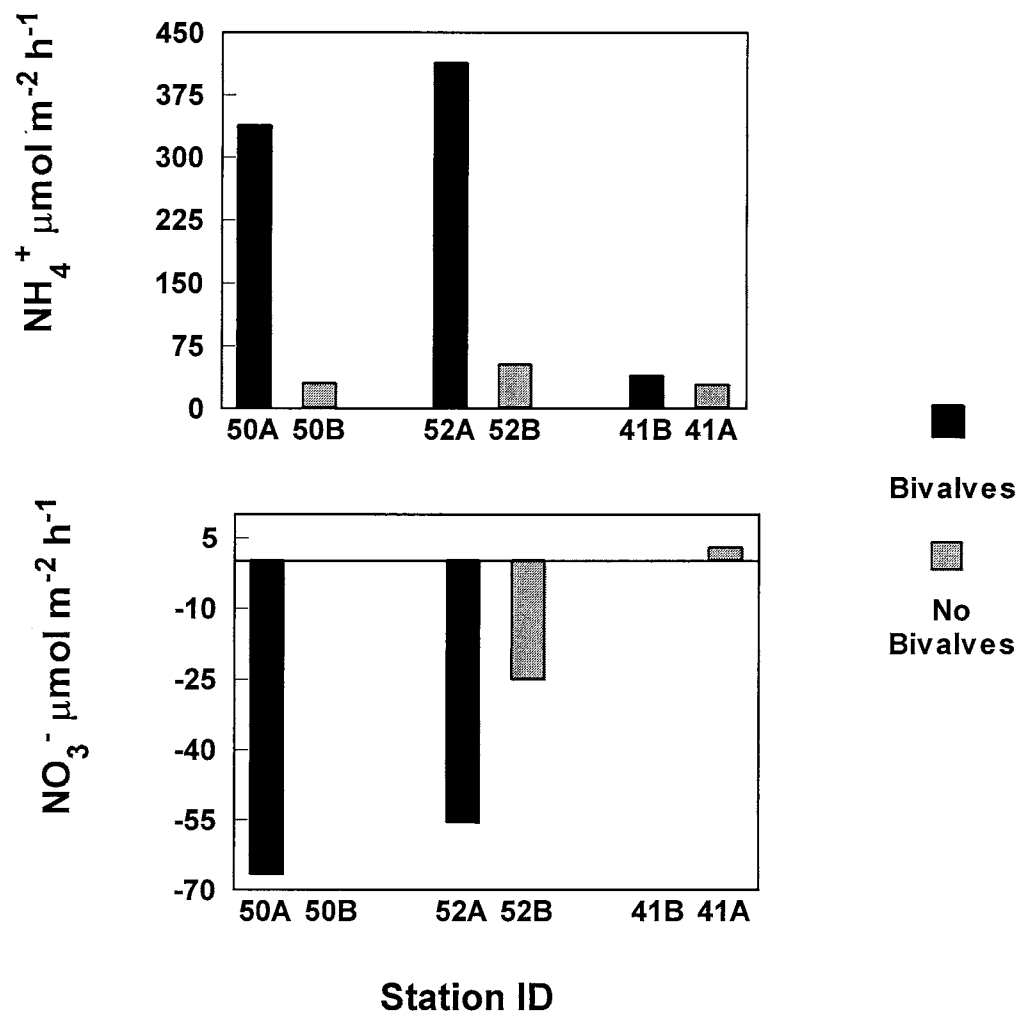


Figure III-6. Comparison of ammonium and nitrate fluxes in cores with and without bivalves, August 1994. These are single core comparisons at stations 50, 52 and 41, with inadvertent incorporation of bivalves in the flux cores.

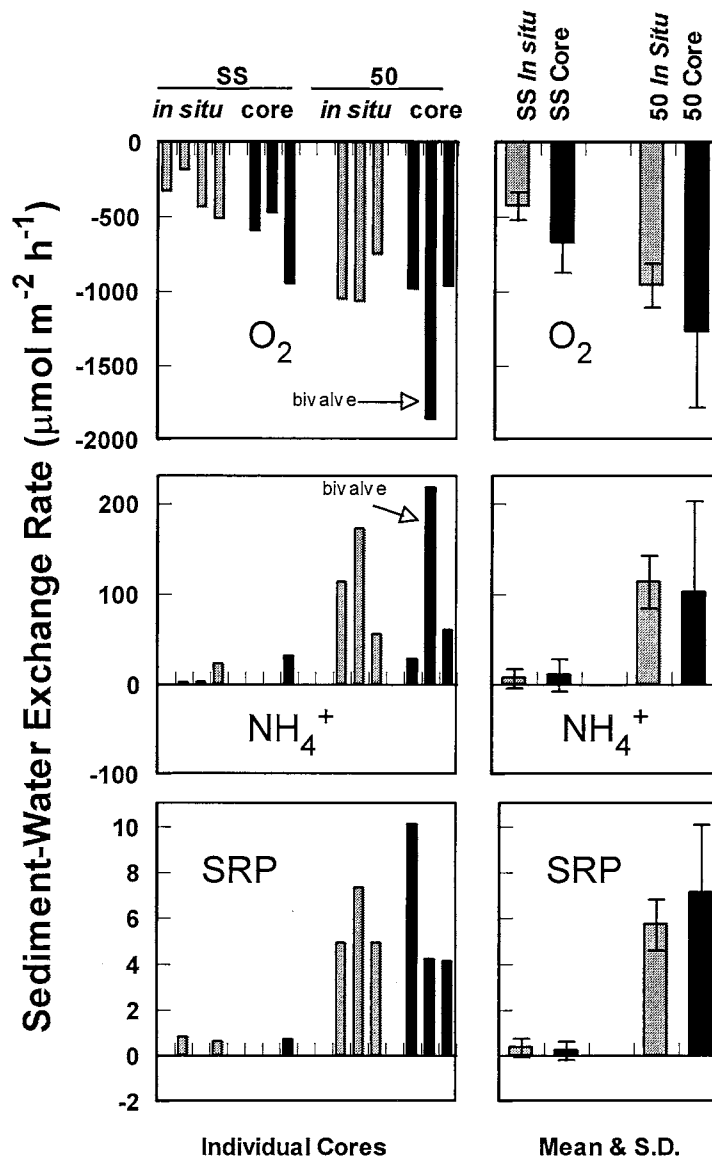


Figure III-7. Comparison of in situ sediment incubation chambers and core incubations for flux measurements. Stations 50 and SS sediments were compared in August and September 1996 respectively. The left figure of each pair shows the individual core data while the right panel shows the mean and standard deviation. At a confidence level of $P < 0.05$, no significant difference are found for these means (t test). The differences in oxygen flux at SS would be significant at $P < 0.08$ for a one tail test. The presence of a bivalve in one site 50 core results in high oxygen and ammonium fluxes.

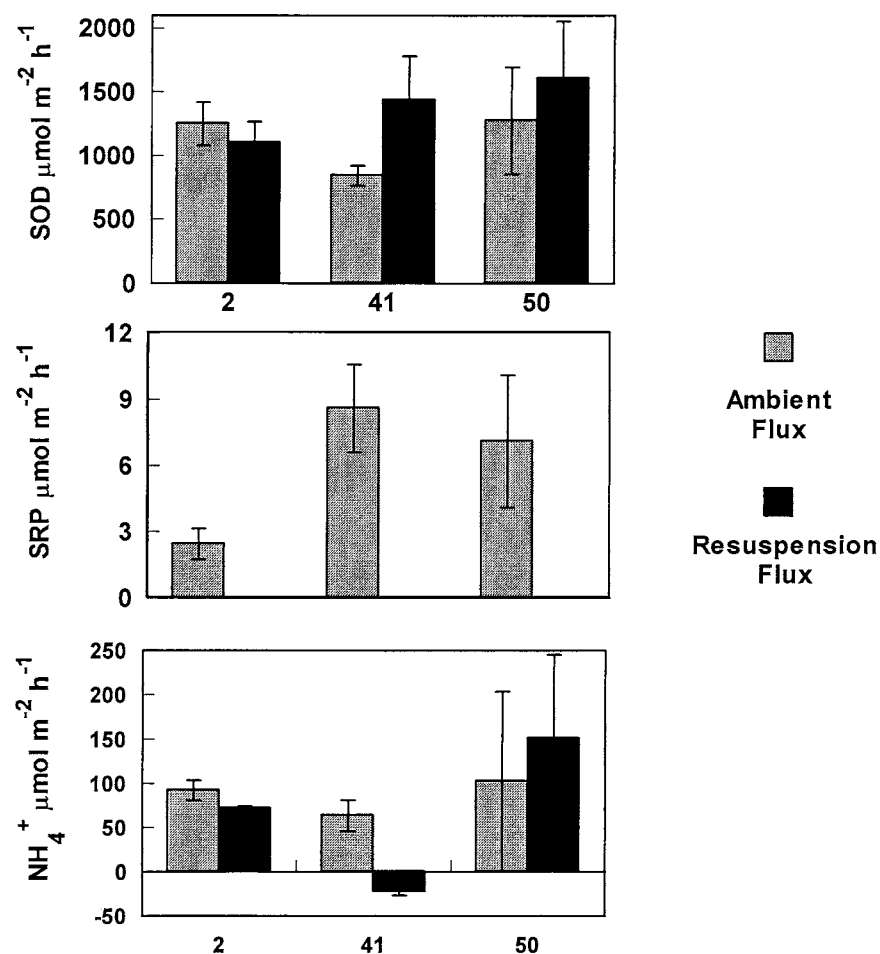


Figure III-8. Sediment flux comparison of sediment oxygen demand, SRP flux and ammonium flux in cores before and after resuspension of surface sediments. Error bars indicate the standard deviation of three replicate incubation cores, though in several cases changes in concentration were not clear enough to calculate a precise rate. Significant differences ($P < 0.10$, one-tailed t test) were noted between ambient and resuspension flux data for all of the SRP data, station 41 ammonium fluxes, and station 41 oxygen flux data. A bivalve in one station 50 core resulted in high standard deviations, especially for ammonium.

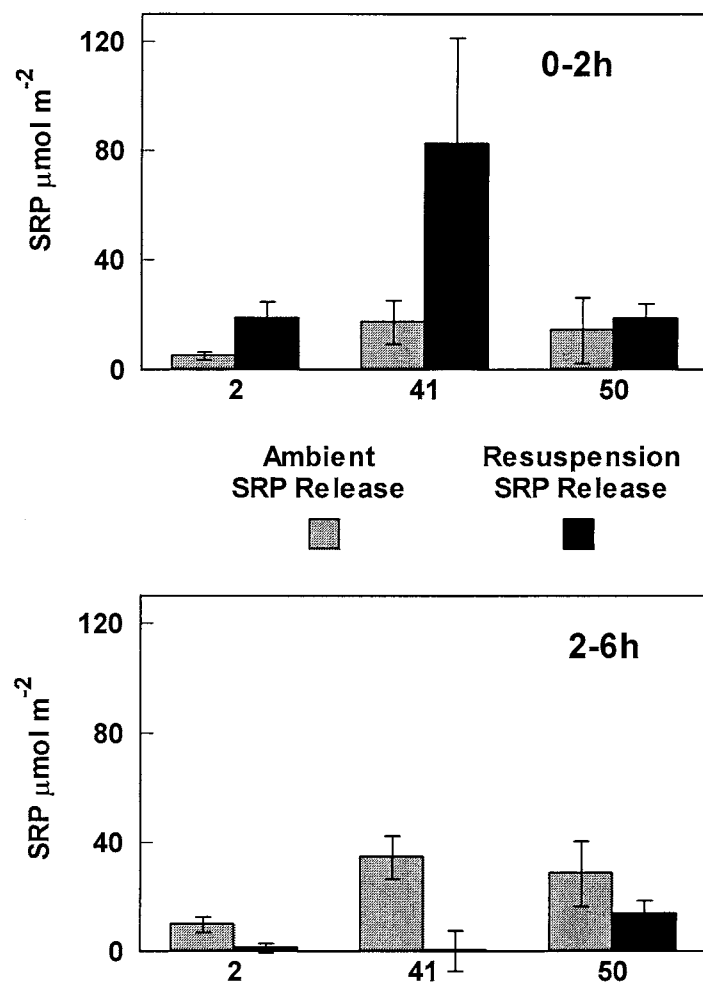


Figure III-9. Comparison of the total mass of SRP released from cores with and without resuspension of surface sediments. The top panel shows the total release two hours after resuspension. The bottom panel shows the release between 2 and 6 hours after resuspension. Error bars are for triplicate cores.

Chapter IV Pore Water Chemistry

Pore water profiles were generated at a total of 19 sites through the course of this study, with seasonal coverage at the six main flux sites; a total of 37 profiles have been analyzed, with 7 different analytes measured. The fine scale resolution (0.5 cm sections) in the top 2.0 cm of sediment was particularly useful for comparison to the sediment-water exchange and solid phase data. For most pore water analytes, high spatial and moderate temporal variability was observed.

The vertical profiles shown in Figure IV-1 are illustrative of the kind of information that these profiles provide. At station 7, a down core increase in Cl^- indicates a deeper source of this ion. In contrast, rapid downcore depletion of both NO_3^- and SO_4^{2-} in the top few cm indicates that the reduction of these species occurs rapidly. With a rapid downcore increase of Mn and deeper increase in Fe, the expected redox sequence of NO_3^- , Mn(IV), Fe(III) and SO_4^{2-} reduction is observed. Microelectrode profiles of dissolved O_2 at main lake sites (Luther et al., unpublished data) suggest that typical Lake Champlain O_2 penetration depths are ~ 0.5 cm or less, suggesting a rapid shift to anaerobic metabolism within these sediments. Low gradients of pore water phosphate at the sediment-water interface suggest relatively low rates of flux across the sediment-water interface; higher gradients within the sediment suggest a P cycle that is tied into Fe cycling, with coprecipitation and adsorption controlling phosphate concentrations just below the sediment-water interface (Cornwell 1987).

In this chapter, we will examine each pore water analyte individually, examining spatial and temporal patterns in the data. Using pore water gradients for some analytes, diffusive flux calculation can be undertaken to demonstrate the quantitative use of these data. In a concluding section, the soluble reactive phosphorus (SRP) data will be put in a broader perspective.

Pore Water Chloride Distributions

The pore water chloride distributions (Figure IV-2) at the six main sites for this program generally show very little structure. Upward fluxes of Cl^- into bottom water occur at site 7, and diffusive fluxes may be calculated using the following equation:

$$J = \Delta[\text{Cl}^-]/\Delta x * D_s * \phi$$

where J is flux in units of mass per area per time, x is depth (cm) and ϕ is sediment porosity. The diffusion coefficient D_s is calculated from tabulated tracer diffusion coefficients (Li and Gregory 1974) corrected for temperature (D_t), with a correction for sediment tortuosity following Ullman and Aller (1982):

$$D_s = D_t * \phi^2$$

At site 7, the average measured porosity (ϕ) was 0.90, the average 1994/5 Cl gradient was 42 ± 5 nmol cm^{-4} , and the tracer diffusion coefficient at 10°C was estimated at $1.4 * 10^{-5}$. Using these data, one can calculate an annual Cl^- flux of $4.8 \text{ g Cl}^- \text{ m}^{-2} \text{ y}^{-1}$. This compares to a standing stock

of $540 \text{ g Cl}^- \text{ m}^{-2}$ at this 50 m deep site. It is unlikely that sediment Cl^- fluxes from sites such as station 7 will have a large impact on water chemistry in Lake Champlain.

Pore Water Nitrate Distributions

At the six main sites in this study (Figure IV-3) and the other 13 auxiliary sites, there is a rapid depletion of NO_3^- , with measurable concentrations generally occurring only in the top 0.5 or 1.0 cm of sediment. This rapid downcore depletion of NO_3^- within pore water indicates that the process of denitrification is limited to relatively shallow sediment depths. If there is a depletion of $10 \text{ } \mu\text{mol L}^{-1} \text{ NO}_3^-$ in pore water over a depth interval of 0.50 cm ($T = 10^\circ\text{C}$, $\phi = 0.90$), an influx of $\sim 7 \text{ } \mu\text{mol NO}_3^- \text{ m}^{-2} \text{ h}^{-1}$ across the sediment-water interface is predicted. We have observed higher and lower gradients that this at the sediment-water interface, and this calculated flux number plus or minus a factor of 3 is similar to the observed NO_3^- fluxes.

The absence of subsurface maxima in NO_3^- does not indicate that nitrification is unimportant in these sediments. Both NO_3^- uptake from the water column and nitrification are likely to be important NO_3^- sources for denitrification in these sediments.

Pore Water Manganese Distributions

Pore water Mn concentrations increase rapidly with increasing depth at most sediment sites (Figures IV-4, IV-5, IV-6), with the sharpest gradients near the sediment-water interface. Maximum concentrations in pore water ranged from < 50 to $> 500 \text{ } \mu\text{mol L}^{-1}$. The buildup of Mn in pore water results from the reductive dissolution of Mn(IV) oxides; as these oxides are buried into reducing horizons in the sediments, they serve as terminal electron acceptors for organic matter diagenesis (Burdige 1993). Pore water Mn gradients result in a net upward flux of this reduced Mn(II) into oxidizing sediments, where Mn(IV) oxides are reprecipitated and the cycle starts again (Froelich et al. 1979). This results in the formation of Mn oxide-enriched sediment zones near the sediment-water interface, such as those observed in this study and that of McIntosh (1994). Clear decreases in pore water Mn at greater depths (especially at sites 37, 50 and 51) may indicate solubility control through the formation of Mn minerals such as rhodochrosite (MnCO_3); this has been suggested previously by Robbins and Callender (1975).

Pore Water Iron Distributions

Pore water iron concentrations increased below the sediment water interface, exceeding $500 \text{ } \mu\text{mol L}^{-1}$ at site 10 (Figures IV-5, IV-6, IV-7). When examined in conjunction with Mn profiles, pore water Fe tended to increase after pore water Mn concentrations increased; this is in accordance with the expected redox sequence for these metals (Froelich et al. 1979). While some cores showed a peak in pore water Fe with lower concentrations both above and below the peak, most pore water Fe profiles seemed to increase rapidly in the top 5 cm to near asymptotic concentrations. No easily identifiable temporal trends were observed in the pore water data at the six main stations. Strong upward gradients, combined with low surficial sediment

concentrations suggest that upward fluxes of Fe are higher than rates of sediment-water Fe exchange. Dynamic reduction, diffusion and oxidation processes result in considerable mobility of sediment Fe, without much involvement with the overlying water (Cornwell 1987). Enrichment of Fe oxides at the sediment-water interface likely result from such mobility.

Pore Water Sulfate Concentrations

Sharp gradients of sulfate are observed in Lake Champlain sediments (Figures IV-5, IV-6, IV-8), indicating net uptake of sulfate by these sediments. The depth of sulfate penetration is an indicator of when a switch between sulfate reduction and methanogenesis would occur. In general, there is a $> 100 \mu\text{mol L}^{-1}$ decrease in sulfate in the top 2 cm of sediments; diffusive flux calculations (as for Cl^- and NO_3^- ; $T = 10^\circ\text{C}$, $\phi = 0.90$) would suggest net sulfate uptake rates of approximately $10 \mu\text{mol m}^{-2} \text{h}^{-1}$; this rate is considerably lower than O_2 fluxes and may suggest that sulfate reduction may not be a quantitatively important terminal electron accepting process. However, the reoxidation of reduced sulfur to sulfate within these profiles may be the major source of sulfate for sulfate reduction, thus increasing the relative importance of sulfate reduction (Roden and Tuttle 1993; Urban et al, 1994).

Pore Water Ammonium Distributions

Pore water ammonium profiles are typical of those in many sedimentary environments, with relatively smooth downcore increases at many sites (Figures IV-5, IV-6, IV-9). Pore water NH_4^+ concentrations generally were highest during summer months (Figure IV-7), both at and below the sediment-water interface. The highest concentrations were found at sites 10, 12 19 and 34, with the lowest at sites SS, 19, 21, 33 and 36.

Pore Water P Distributions

Pore water phosphate or SRP concentrations (Figures IV-5, IV-6, IV-10) were considerably higher than water column concentrations, with the highest concentrations at or above $75 \mu\text{mol L}^{-1}$ (2.3 mg P L^{-1}). Concentrations in the 0.0-0.5 cm pore water section were generally only a few $\mu\text{mol L}^{-1}$ or less, suggesting that despite readily observable P gradients within the sediment, P fluxes should be low. Upward P fluxes would result in both 1) P fluxes to overlying water or 2) P enrichment in near-surface Fe-rich sediment horizons. We will explore the relative importance of these mechanisms later in Chapter VIII.

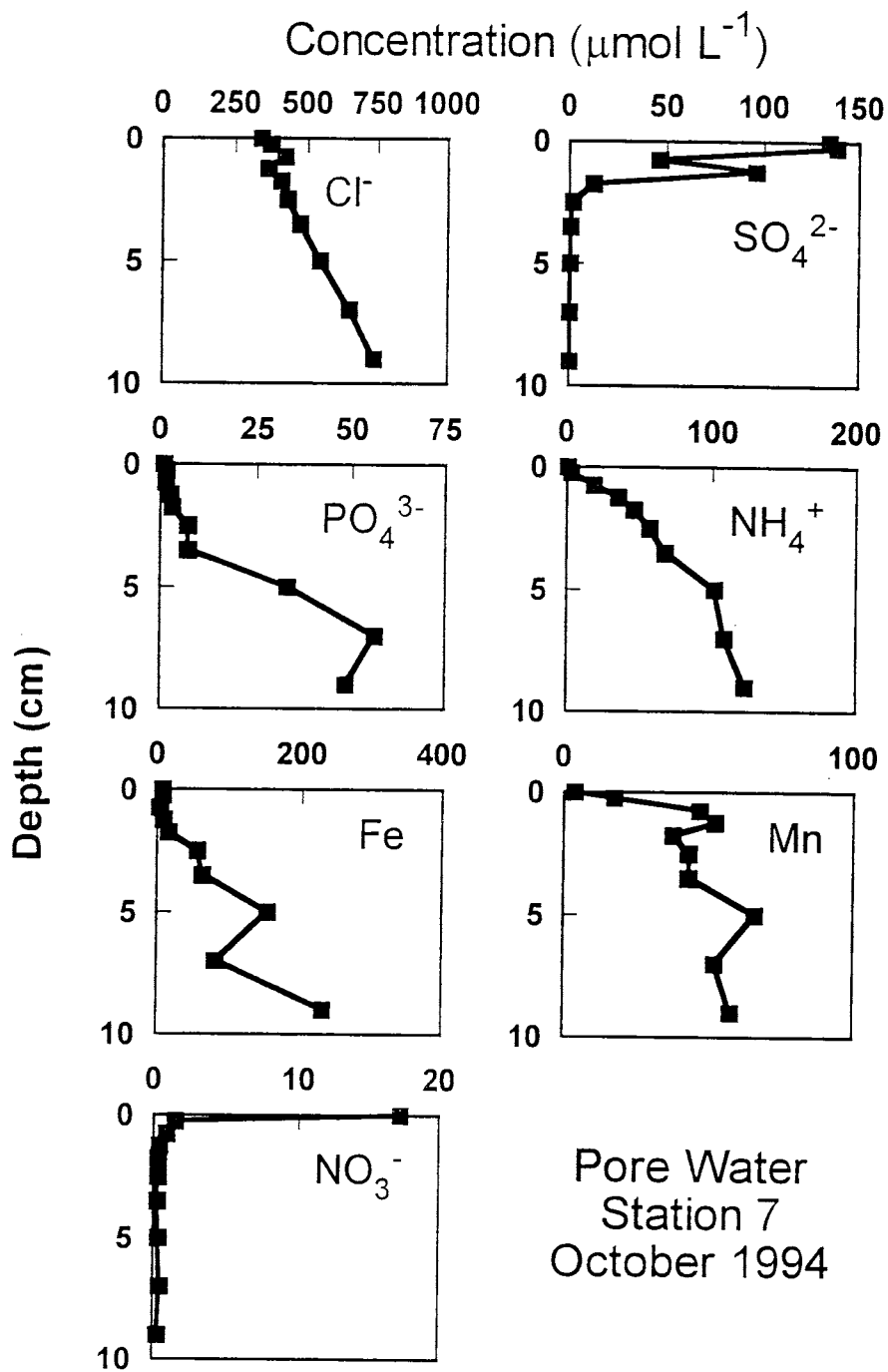


Figure IV-1. Pore Water Profiles For Station 7

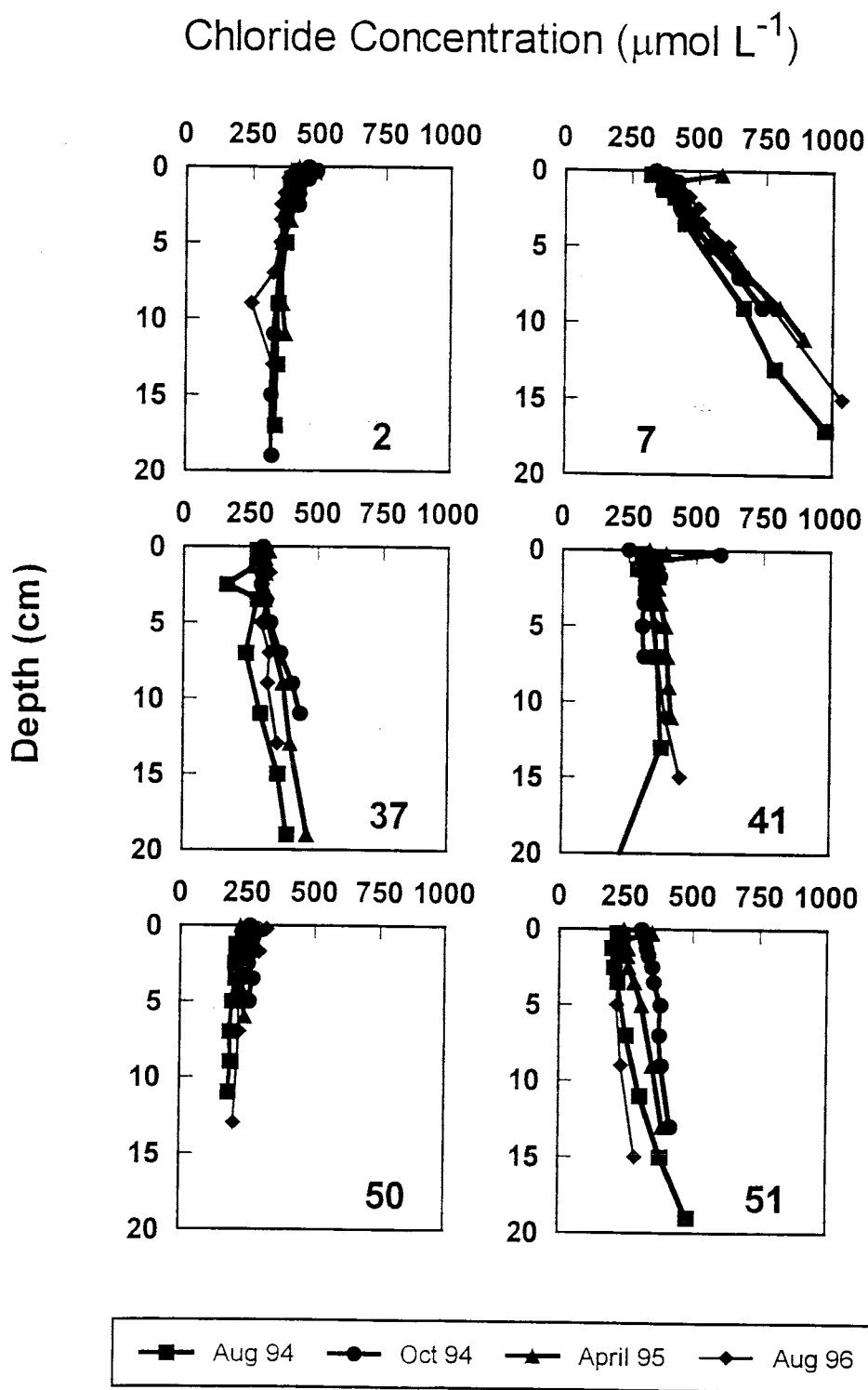


Figure IV-2. Pore water chloride concentrations at the 6 main study sites.

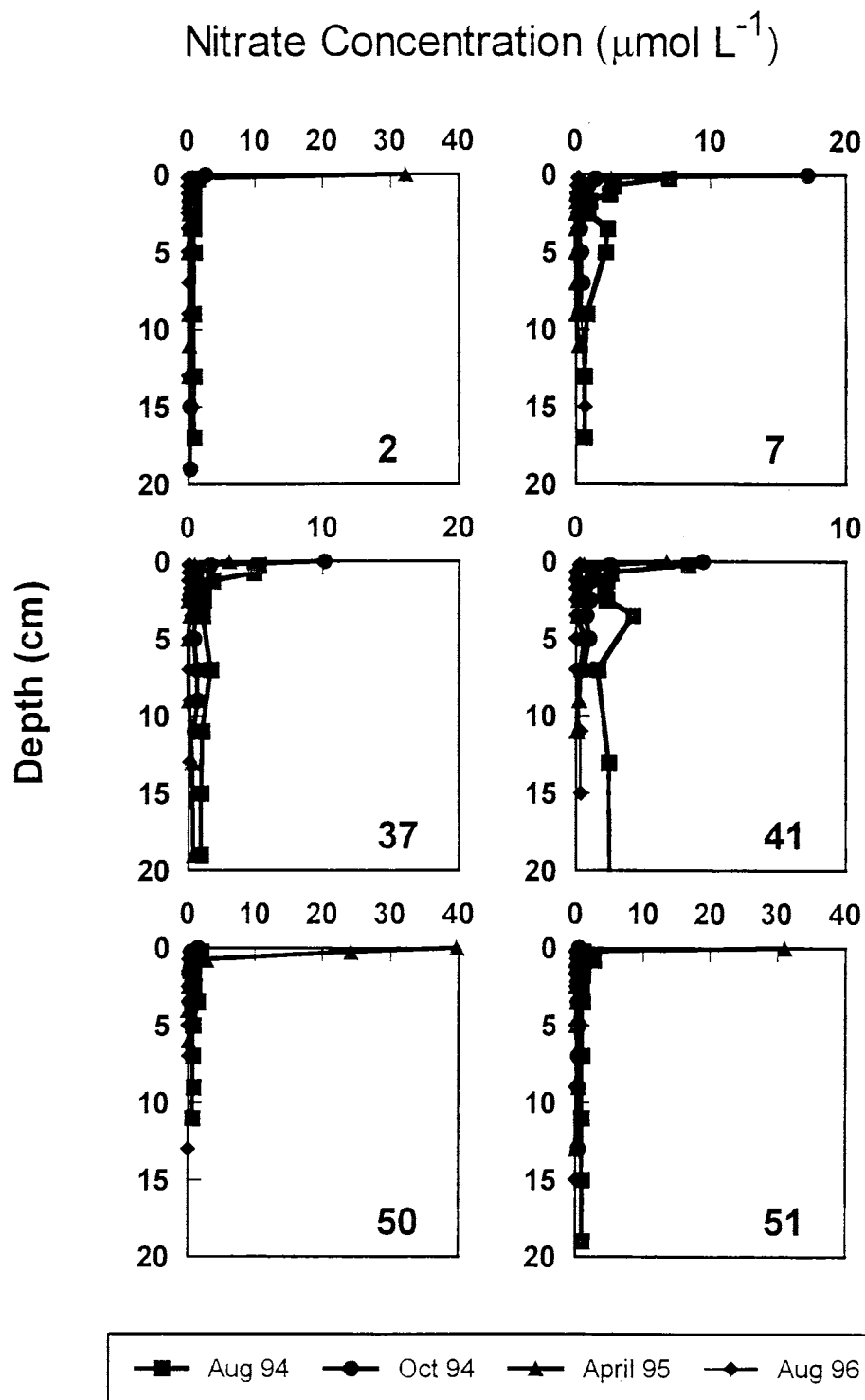


Figure IV-3. Pore water nitrate concentrations at the 6 main study sites.

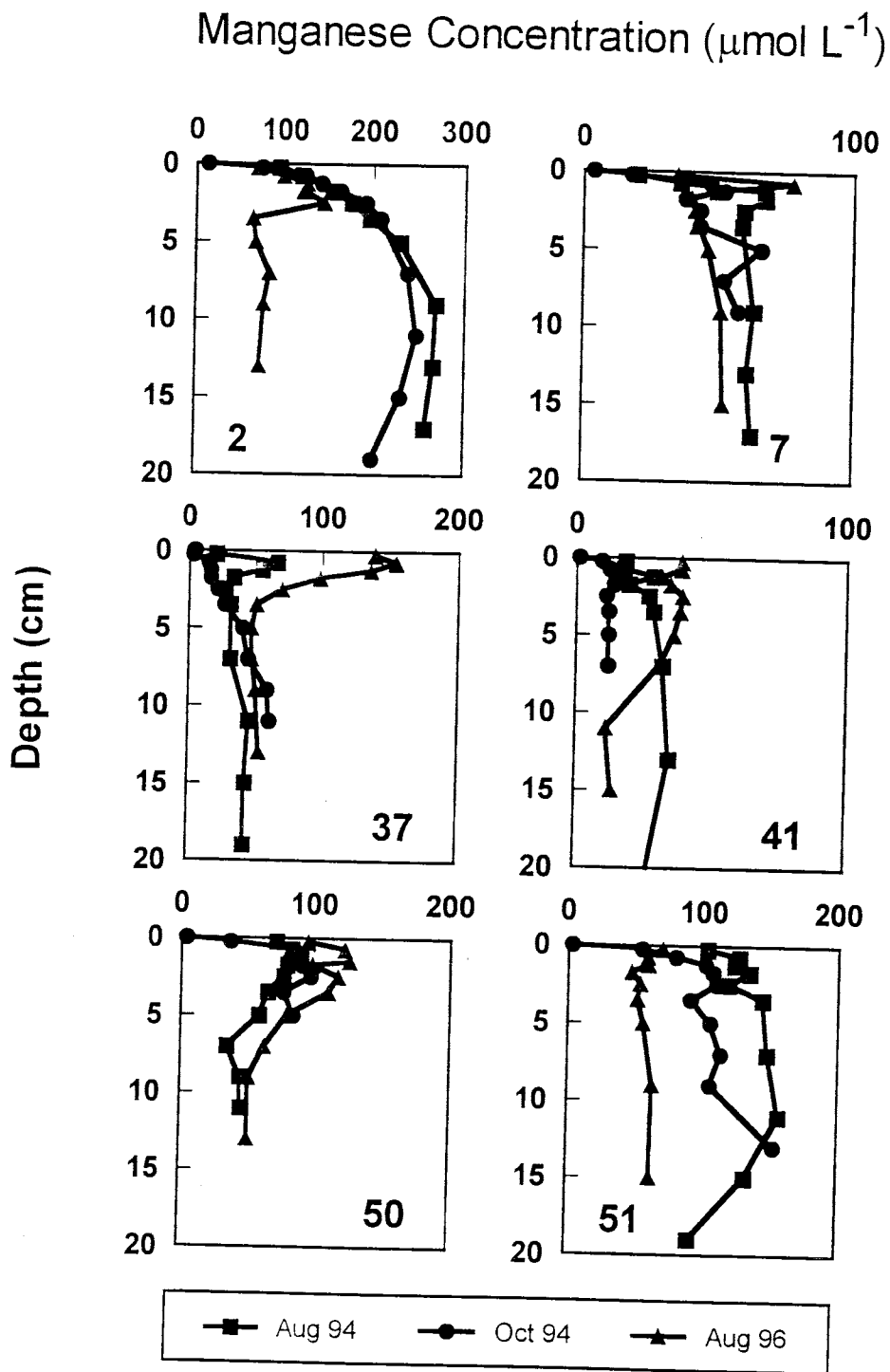


Figure IV-4. Pore water manganese concentrations at the 6 main study sites

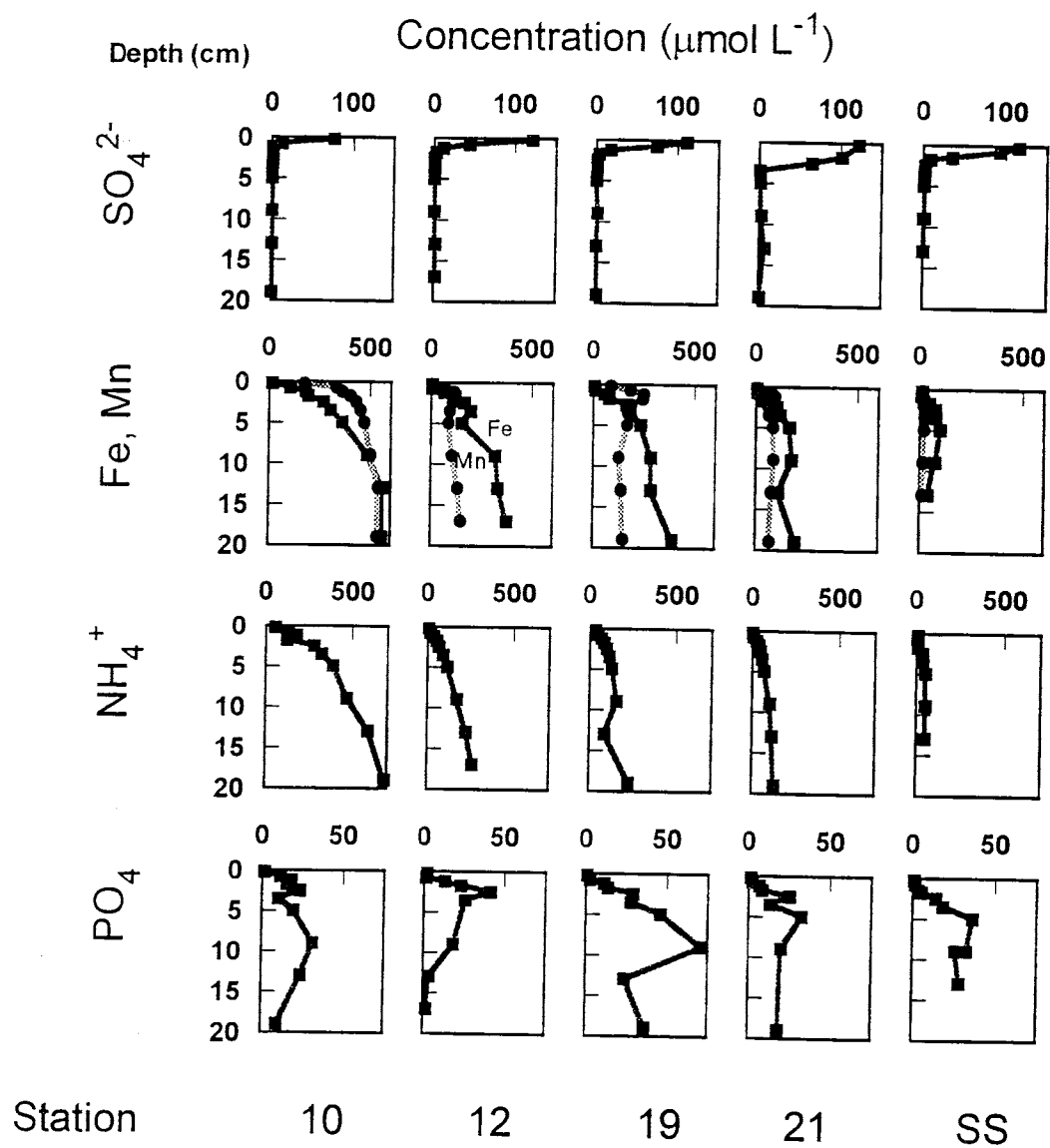


Figure IV-5 Pore water chemistry at the 1994 auxiliary sites

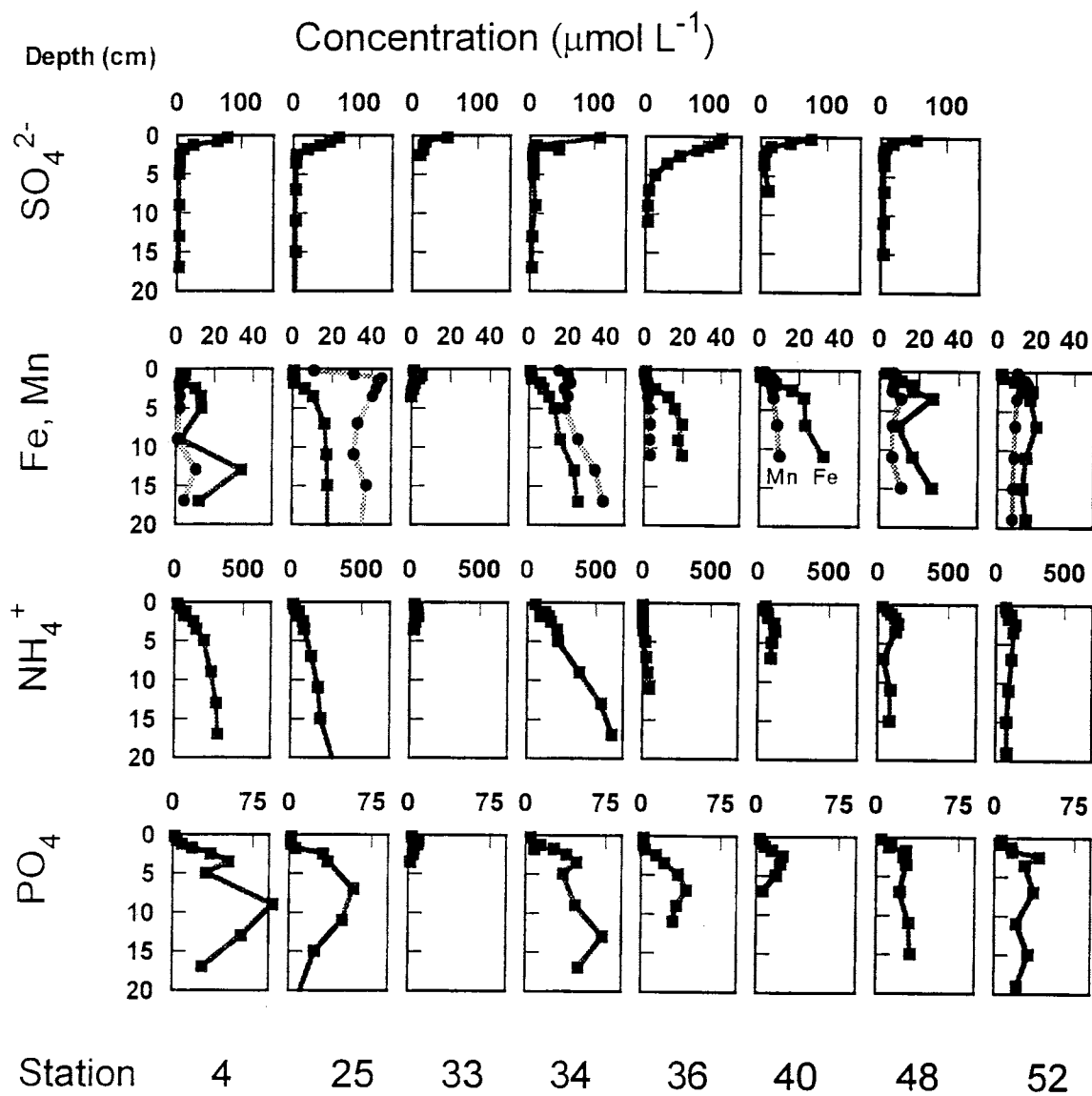


Figure IV-6 Pore water chemistry at the 1996 auxiliary sites

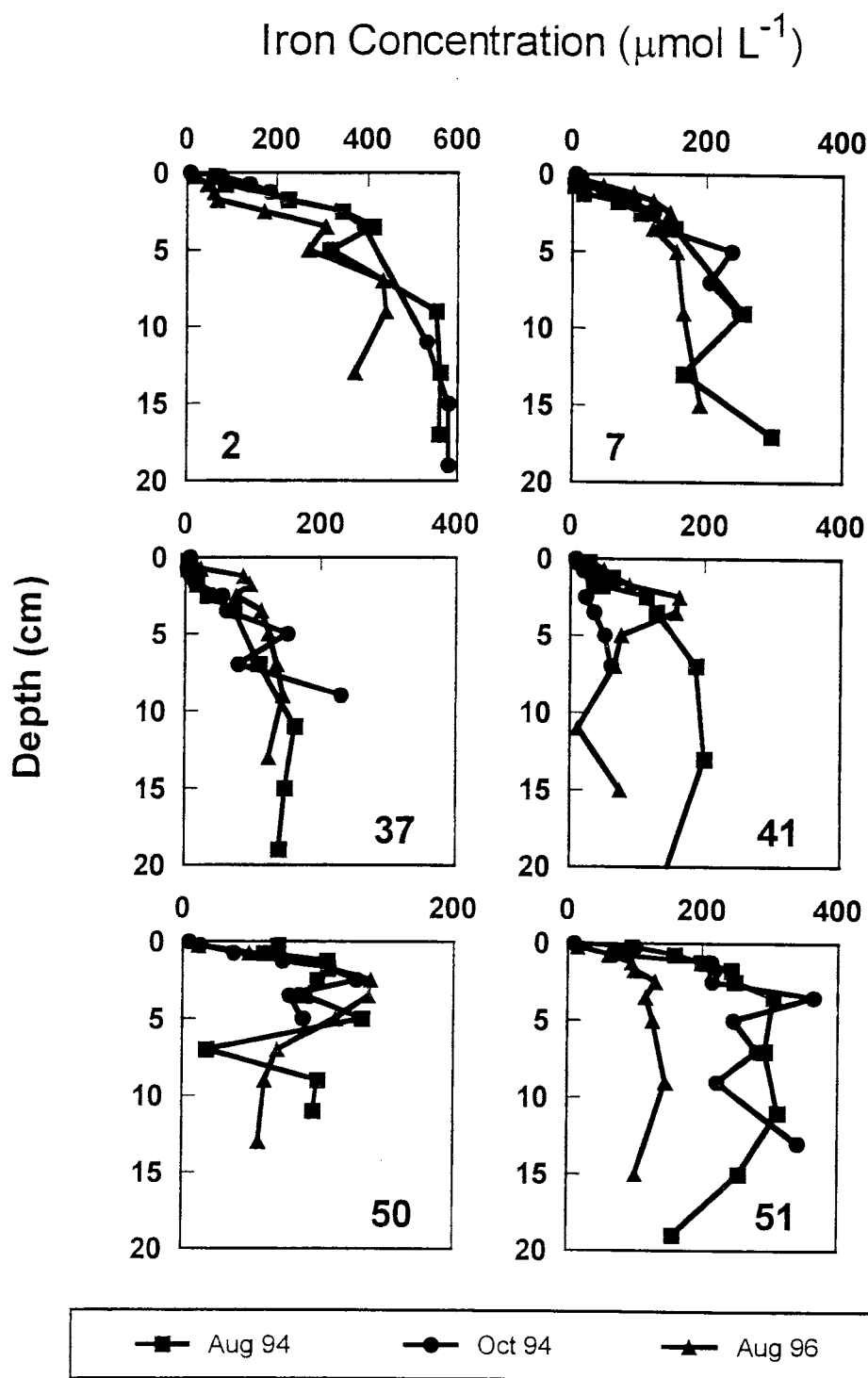


Figure IV-7 Pore water iron concentrations at the 6 main study sites

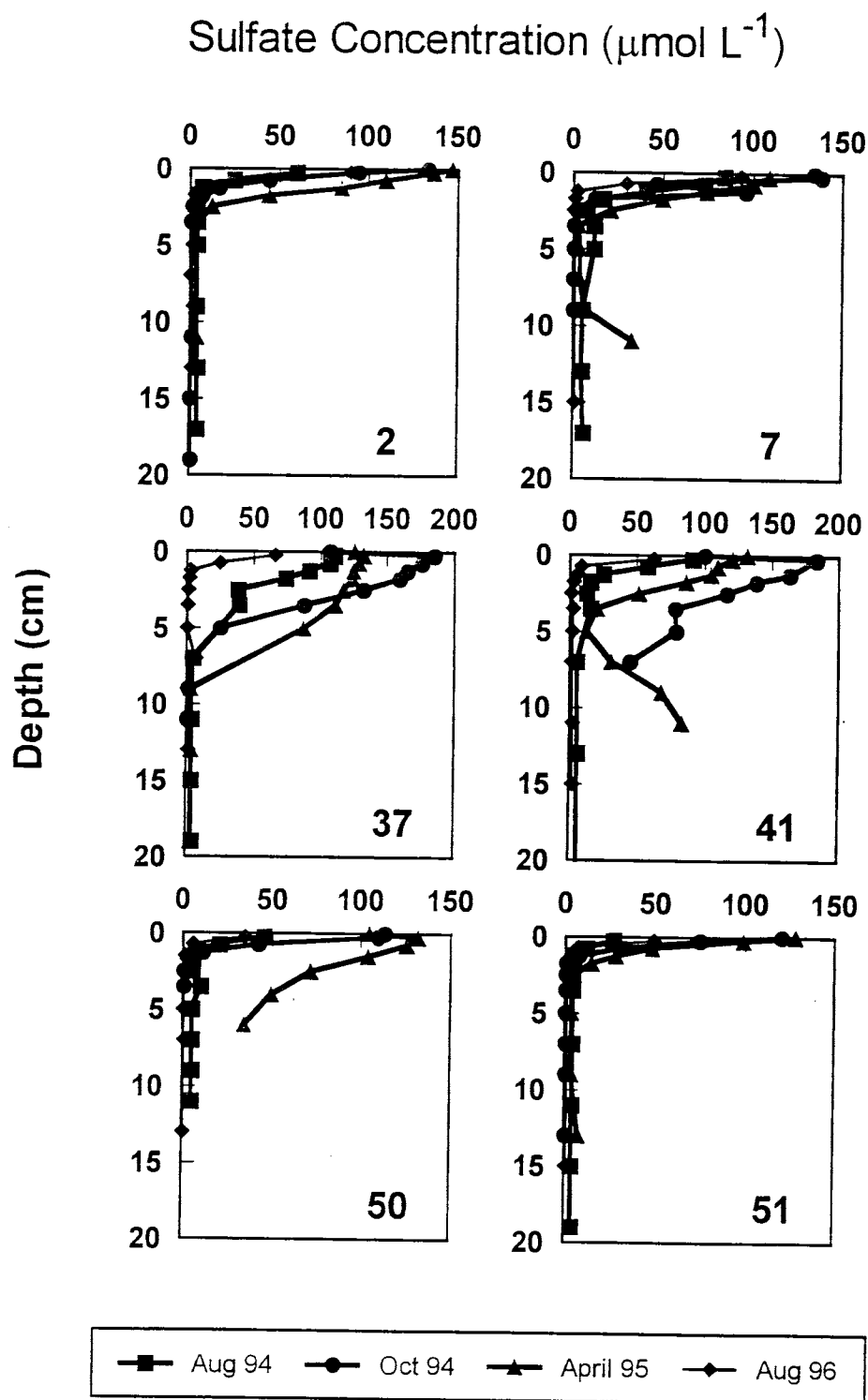


Figure IV-8 Pore water sulfate concentrations at the 6 main study sites

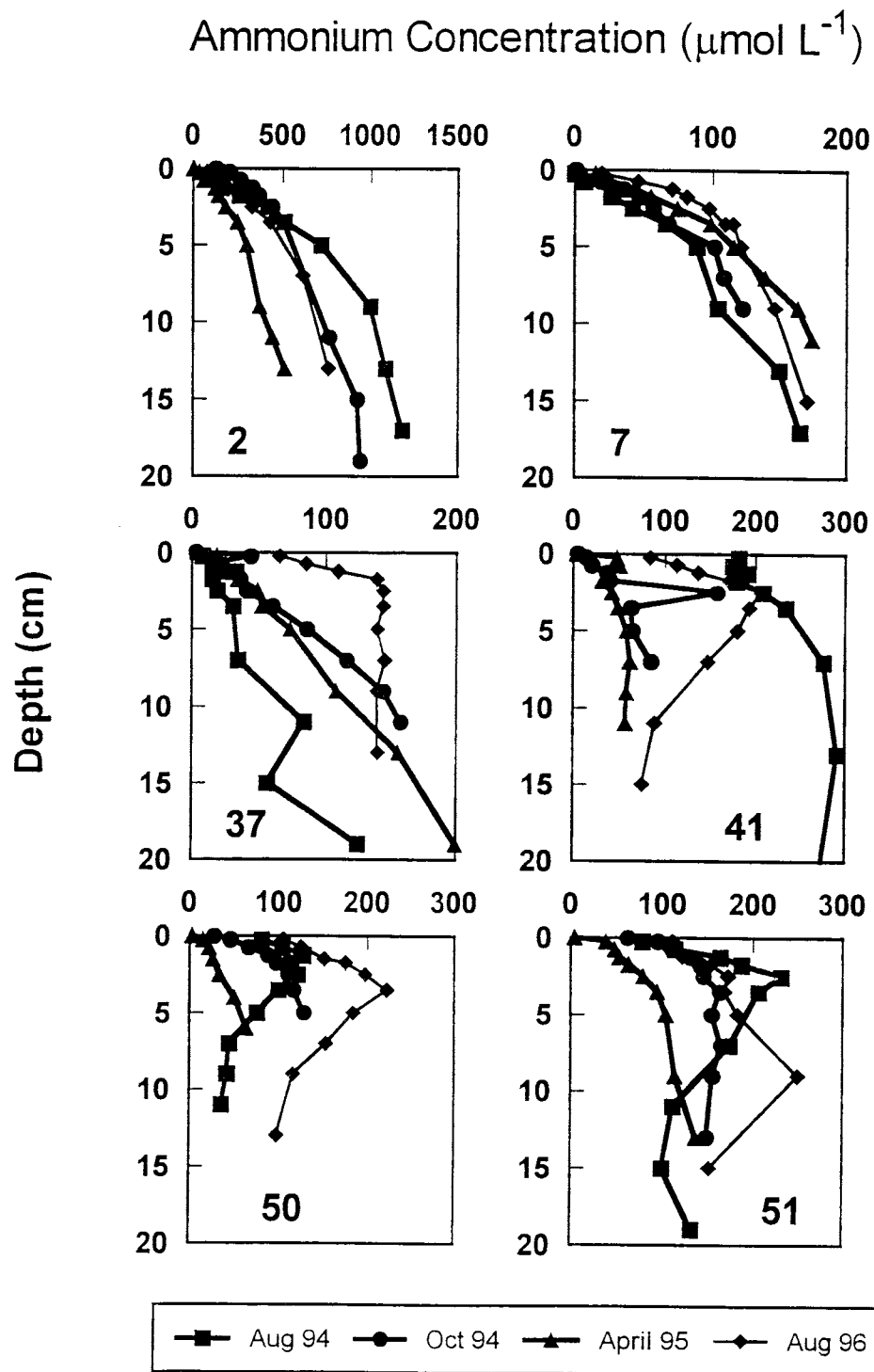


Figure IV-9 Pore water ammonium concentrations at the 6 main study sites

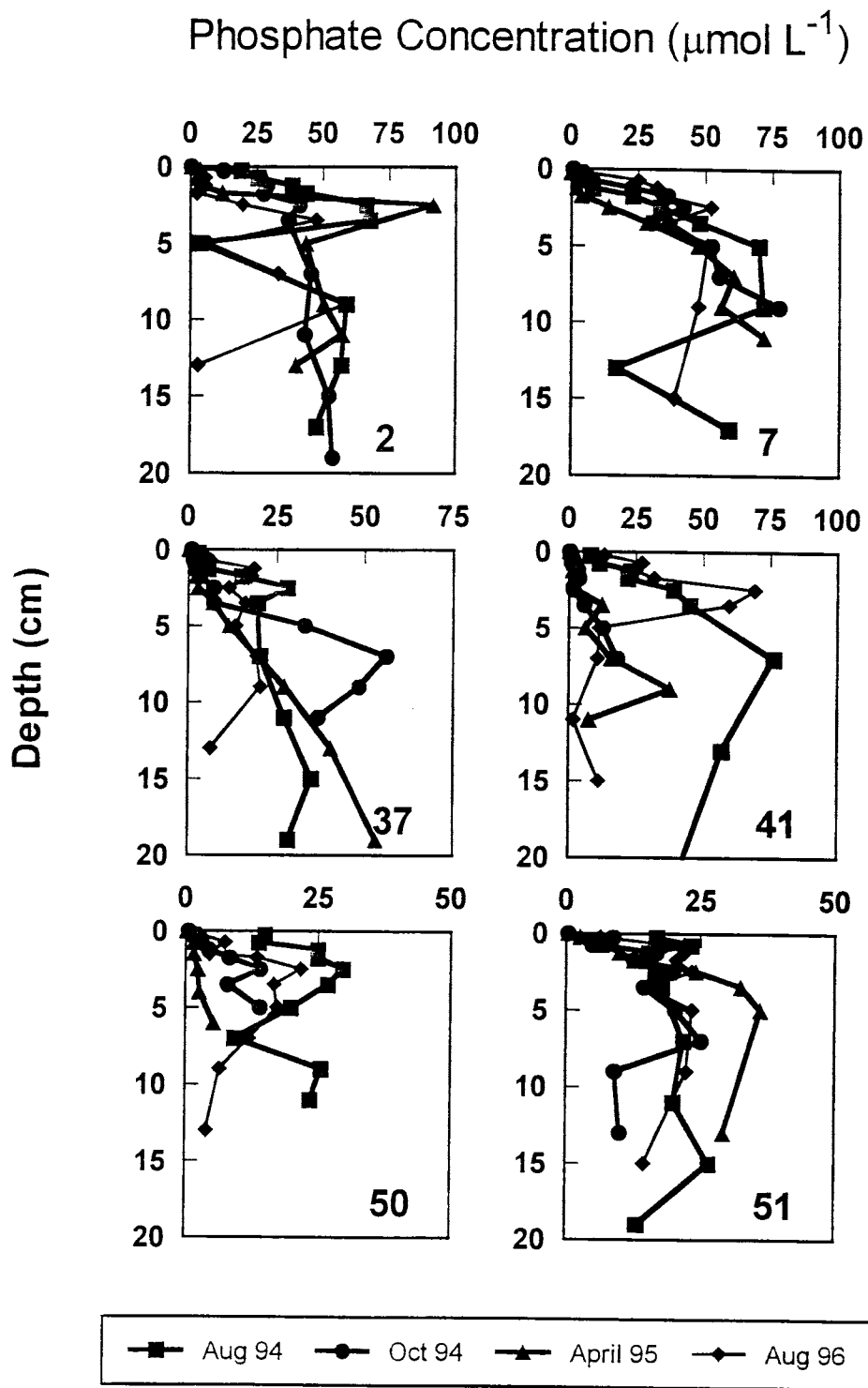


Figure IV-10 Pore water SRP concentrations at the 6 main study sites

Chapter V. Decomposition Rate Constants

The sediment diagenesis experiment worked exceptionally well, with significant production rates of ΣCO_2 , CH_4 , and NH_4^+ . These experiments are useful in determining decomposition rates, but because they are closed systems, they are not perfect measures of decomposition pathways. For example, rapid sulfate depletion without sulfate replenishment from overlying water results in the eventual loss of this important decomposition pathway, most likely increasing apparent methanogenesis. Additional concerns include the importance of NH_4^+ adsorption processes which decreases apparent NH_4^+ production rates. Finally, the buildup of pore water SRP and Fe can lead to the precipitation of Fe-P minerals, potentially leading to unreasonably low rates of P production. Conversely, anaerobic incubations of surficial sediments may artificially increase P production rates by increased release of inorganic P from Fe(III)-P complexes.

Table V-1. Sediment decomposition results. The results are expressed relative to the volume of the original sediment.

Station	Depth	ΣCO_2 Flux	CH_4 Flux	NH_4 Flux
	cm	$\text{nmol cm}^{-3} \text{ h}^{-1}$		
2	0-1	1.35	1.39	0.343
	2-4	0.93	1.62	0.253
	8-10	1.17	1.67	0.249
7	0-1	2.87	2.45	0.422
	2-4	2.20	1.58	0.171
	8-10	0.87	1.17	0.072
37	0-1	2.65	1.18	0.257
	2-4	2.15	2.05	0.162
	8-10	0.74	1.27	0.167
41	0-1	1.28	2.14	0.132
	2-4	0.98	1.17	0.197
	8-10	0.77	1.16	0.165
50	0-1	4.81	3.50	1.264
	2-4	1.94	1.63	0.245
	8-10	0.77	1.68	0.044
51	0-1	2.69	2.80	0.668
	2-4	1.39	1.47	0.143
	8-10	1.41	1.26	0.181

Surficial sediment sections (0-1 cm) always had the highest ΣCO_2 production rates (Figure V-1), consistent with the occurrence of more recent labile organic matter in this horizon. Methane production rates (Figure V-II) were of a similar magnitude to the ΣCO_2 rates, but maximum production rates were not at the sediment-water interface at stations 2 and 37. Total

decomposition rates are represented by the sum of $\sum \text{CO}_2$ and CH_4 flux rates (Figure V-III). In a comparison of rates of pore water NH_4^+ increase at different stations (Figure V-4), the same pattern as the sum of $\sum \text{CO}_2$ and CH_4 rates is observed, suggesting a relatively uniform organic matter composition.

The rates of pore water SRP increases are high relative to the expected rates based on assumed stoichiometric relationships ($\text{C:P} = 106:1$; $\text{N:P} = 16:1$) to carbon and nitrogen fluxes (Figure V-5). The SRP production rates are a result of both the decomposition of organic P as well as the dissolution of Fe-P complexes, and these experimental results may be of little value in understanding P diagnosis in Lake Champlain sediments.

If the average rate of the top 10 cm of sediment for total metabolism (i.e. $\sum \text{CO}_2 + \text{CH}_4$) was $2.0 \text{ nmol C cm}^{-3} \text{ h}^{-1}$, the estimate of oxygen demand would be $\sim 2,000 \text{ } \mu\text{mol m}^{-2} \text{ h}^{-1}$. This rate is considerably higher than that estimated by sediment oxygen demand in the flux experiments and may reflect an artifact of the sealed incubation experiments.

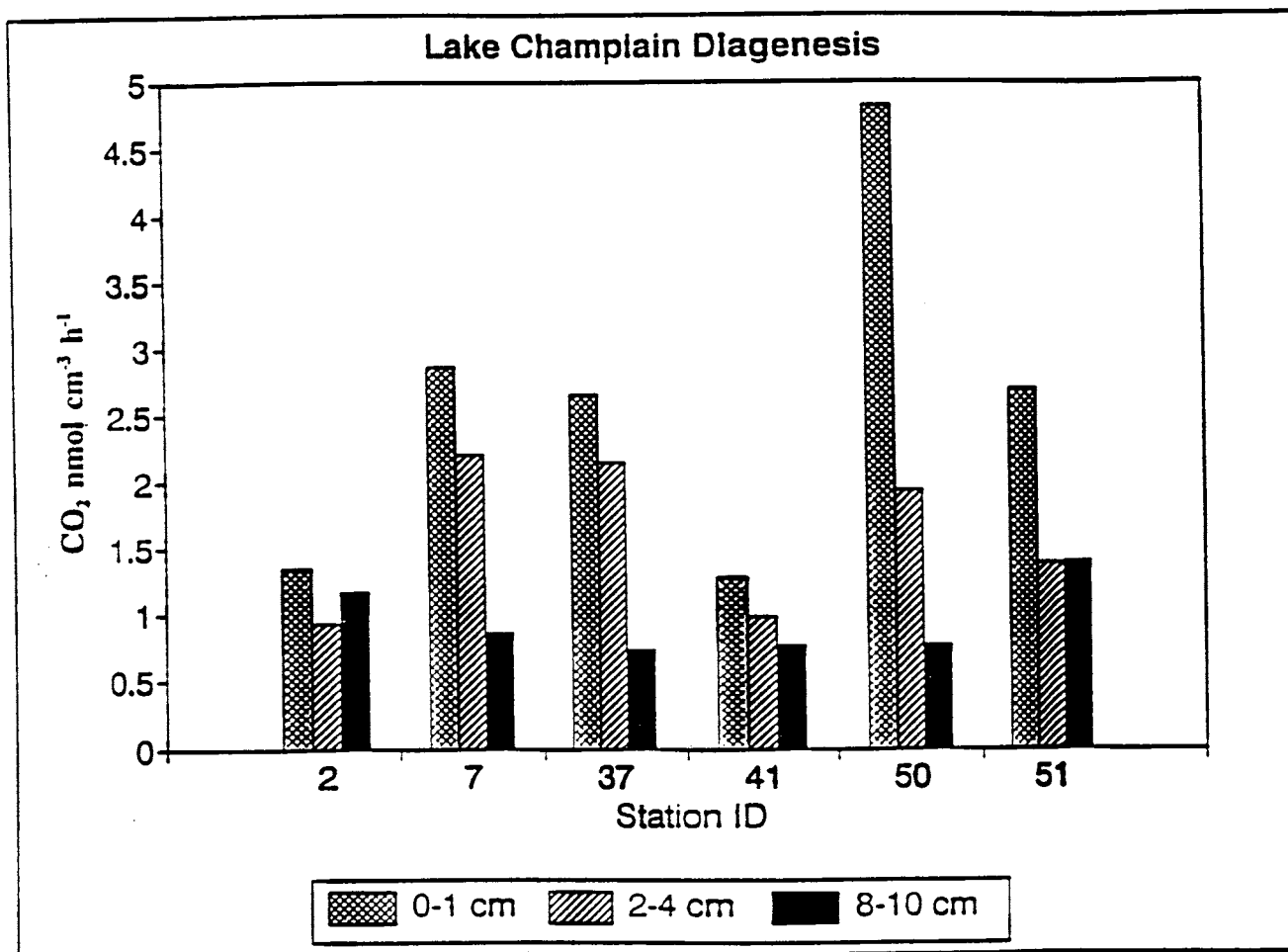


Figure V-1 Lake Champlain decomposition rate experiment: $\sum \text{CO}_2$ results. The rates are expressed on the basis of the original volume of sediment that was slurried.

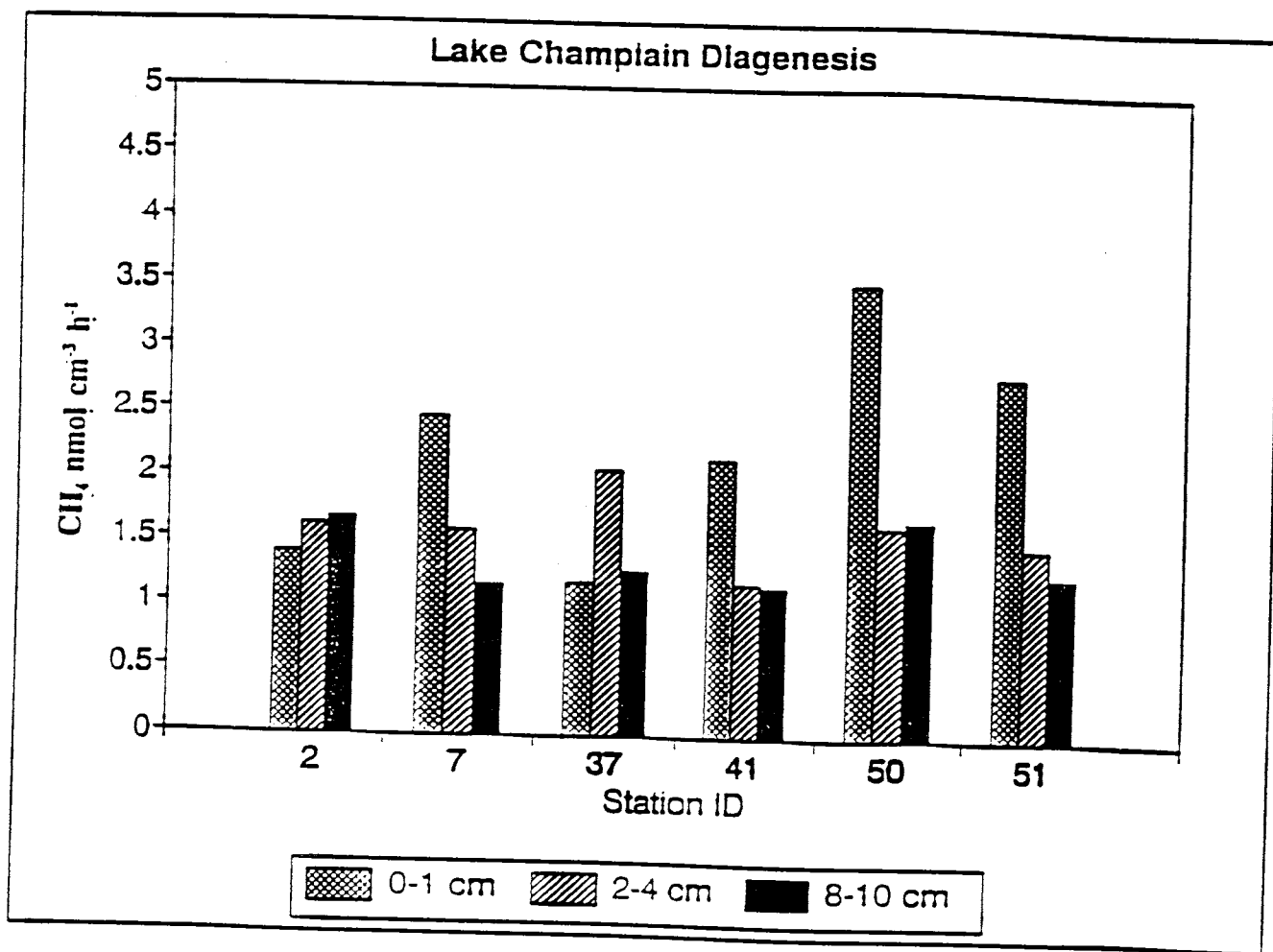


Figure V-2 Lake Champlain decomposition rate experiment: methane results. The rates are expressed on the basis of the original volume of sediment that was slurried.

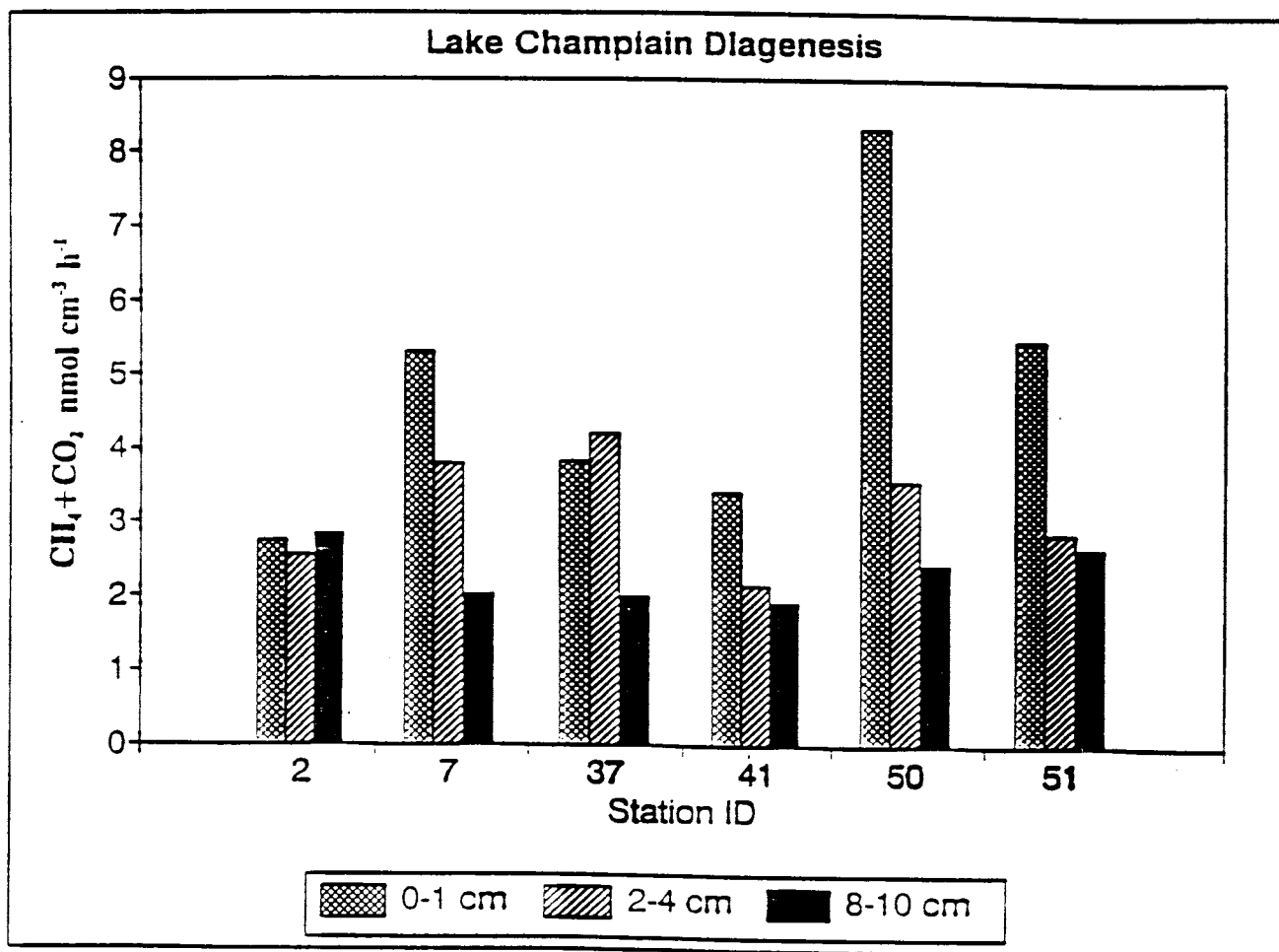


Figure V-3 Lake Champlain decomposition rate experiment: methane + $\sum \text{CO}_2$ results. The rates are expressed on the basis of the original volume of sediment that was slurried.

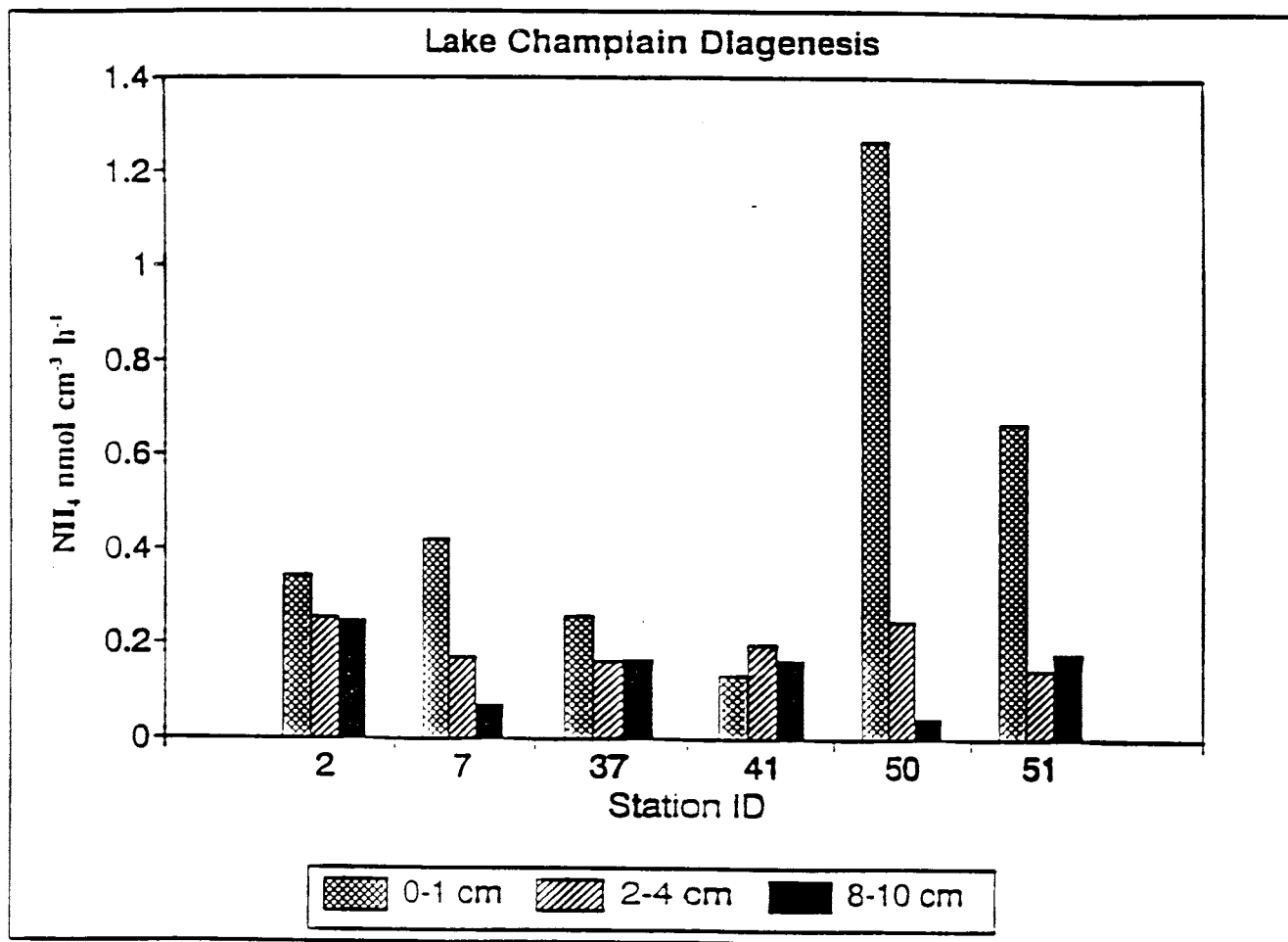


Figure V-4 Lake Champlain decomposition rate experiment: ammonium results. The rates are expressed on the basis of the original volume of sediment that was slurried.

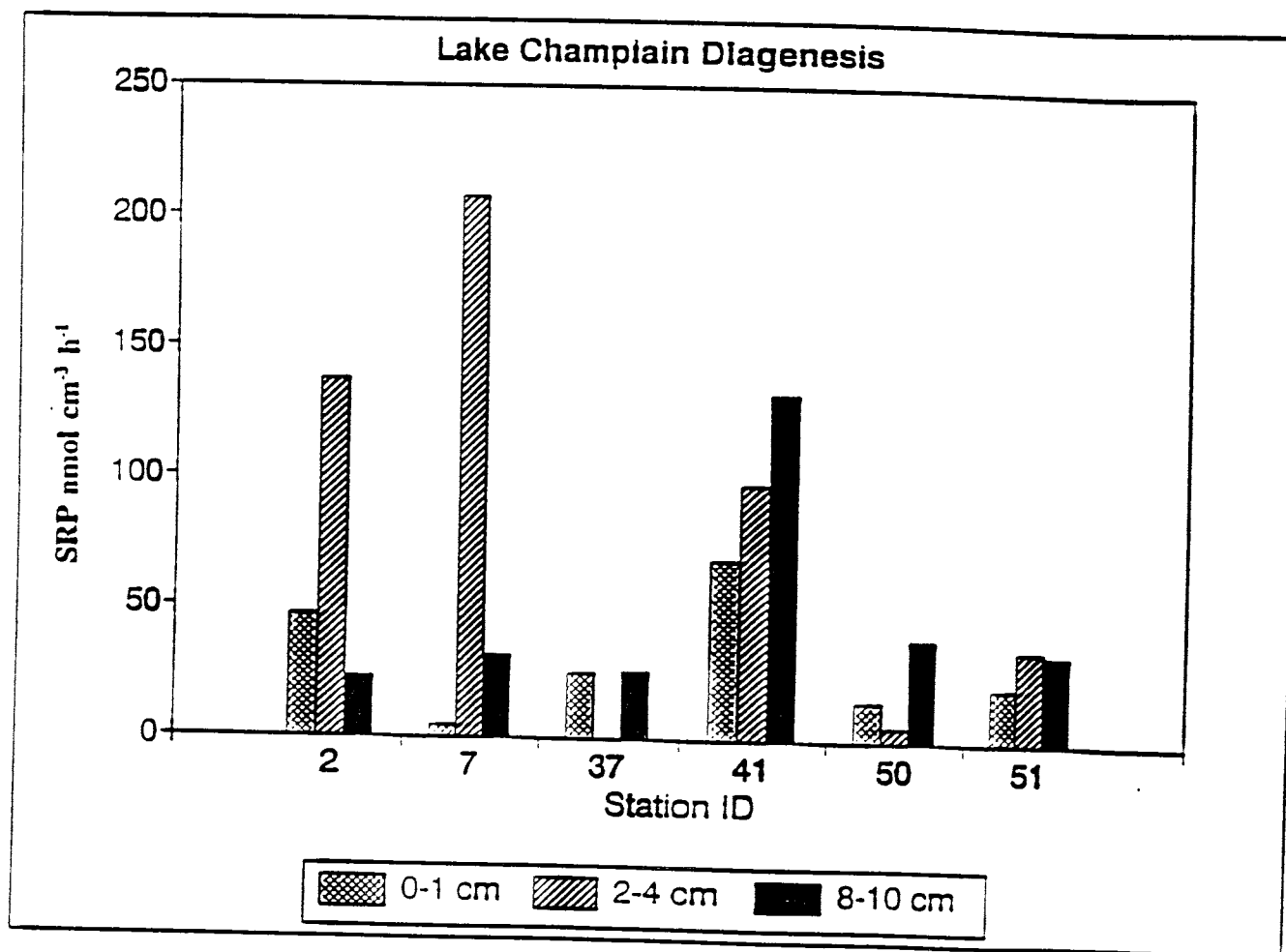


Figure V-5 Lake Champlain decomposition rate experiment: SRP results. The rates are expressed on the basis of the original volume of sediment that was slurried.

Chapter VI Sediment Composition

Introduction

The measurement of the solid phase concentrations of C, N, Fe, Mn and P can 1) provide a comparison of biogeochemical pools at different sites within and between systems, 2) when combined with sediment accretion data, provide estimates of elemental retention in systems, and 3) help establish relationships between different elemental cycles. In this chapter, we present the basic distribution of these solid phase pools in Lake Champlain; in subsequent chapters, we will use these data in conjunction with sedimentation rates, pore water and sediment-water exchange data to provide a more complete picture of P cycling in Lake Champlain sediments.

Two major studies of sediment composition in Lake Champlain have been carried out: 1) The Martin et al. (1994) study in St. Albans Bay looked at the distribution of P forms in sediment and calculated changes in P pools relative to an earlier study (Ackerly 1983). The contaminant-oriented study of McIntosh (1994) presents profiles of C, N, Fe, Mn and P at 9 sites located throughout Lake Champlain. The concentrations and vertical profiles of these elements in our 1994-1996 sampling program are generally consistent with the data generated by these previous studies. This chapter is organized into a data presentation of 1) surficial sediment (0-1 cm) chemistry, 2) examination of all vertical profile data from a single site, station 7, and 3) presentation of all vertical profile data from the study.

Surficial Sediment Data

The variability of surficial sediment chemical concentrations vary considerably for the different biogeochemical parameters (Table VI-1). Carbon concentrations averaged $37.5 \pm 9.9 \text{ mg g}^{-1}$ (mean \pm standard deviation), showing a modest coefficient of variation (26%) while HCl-extractable Mn concentrations averaged $7.13 \pm 10.16 \text{ mg g}^{-1}$, a coefficient of variation of 142%. The concentrations of C, N and organic P are likely reflective of the inputs of these elements, while the distribution of Fe, Mn and inorganic P are strongly affected by post-depositional migration. The molar C/N ratio (9.43 ± 0.87) is did not vary as much as the other parameters.

The latitudinal distribution of these surficial sediment parameters reveals both the local and regional variability in these parameters (Figure VI-1). The highest HCl-extractable Fe concentrations are found in the southern lake cores and in Missisquoi Bay, while the highest carbon concentrations are found the deep Main Lake, the Northeast Arm, and St. Albans Bay. Manganese concentrations appeared to be somewhat lower in the southern and northern parts of the lake. The highest concentrations of Mn in this study were found at Outer Malletts Bay (Station 25); these data are similar to other data from that site (McIntosh 1994). Iron concentrations were highest in the three most southern sites and within Missisquoi Bay ($> 35 \text{ mg g}^{-1}$); HCl-extractable Fe concentrations in the deep water Main Lake area were a very uniform $26.0 \pm 0.3 \text{ mg g}^{-1}$ ($n=3$).

Table VI-1. Surficial sediment (0-1 cm) data in mg g^{-1} for 17 Lake Champlain sites. The site SS data are from a 1-2 cm sediment section. The C/N ratio data are in molar units.

Station	C	N	IP	OP	TP	HCl-Mn	HCl-Fe	C/N
2	23.1	2.7	0.84	0.18	1.02	1.36	38.76	9.98
4	22.9	3.4	1.10	0.20	1.30	3.14	44.63	7.86
7	34.3	4.8	2.33	0.37	2.70	9.82	49.18	8.34
10	41.6	5.5	1.21	0.47	1.68	13.88	25.90	8.82
12	38.3	4.7	1.38	0.43	1.81	8.11	25.70	9.51
SS	33.9	4.0	0.84	0.24	1.08	0.48	16.30	9.89
19	41.6	5.6	1.30	0.46	1.76	9.84	26.30	8.67
21	31.3	3.9	1.90	0.46	2.36	6.49	32.40	9.36
25	48.9	5.1	1.41	0.31	1.72	45.27	25.88	11.19
34	63.9		2.52	0.70	3.22	8.40	28.58	
36	36.6	4.4	1.13	0.51	1.64	1.08	13.53	9.70
37	40.5	5.1	1.57	0.46	2.03	2.05	19.37	9.26
41	48.0	6.1	1.08	0.22	1.30	0.45	10.82	9.18
48	32.8	3.7	1.37	0.38	1.75	1.44	15.90	10.34
50	29.3	3.2	1.02	0.30	1.32	3.66	37.09	10.68
51	32.4	4.0	1.35	0.30	1.65	2.11	52.11	9.45
52	37.6	5.1	1.37	0.45	1.82	3.58	51.51	8.60
Mean	37.5	4.5	1.40	0.38	1.77	7.13	30.23	9.43
S.D.	9.9	1.0	0.47	0.13	0.57	10.61	13.40	0.87
Median	36.6	4.6	1.35	0.38	1.72	3.58	26.30	9.41

Total P concentrations averaged $1.77 \pm 0.57 \text{ mg g}^{-1}$, with inorganic P averaging $1.40 \pm 0.47 \text{ mg g}^{-1}$. No large latitudinal trends in total and inorganic P were noted (Figure VI-1). Inorganic P is significantly correlated with total P and HCl-Fe (Figure VI-2, for both P, 0.01). The average organic P, determined by difference between total and inorganic P, was $0.38 \pm 0.13 \text{ mg g}^{-1}$.

A number of parameters are significantly correlated; several of these are shown in Figure VI-2. The correlation between C and N is commonly found in most aquatic sediments, with these ratios consistent with those expected when algae is a major sediment organic matter source. Similarly, the significant correlation between carbon and organic P suggests that a common source of both components is found in the lake. The correlation between HCl-Fe and inorganic P, although significant at the $P < 0.01$ level, is not as strong as observed in some other lake studies (i.e. Cornwell 1987).

While there was no lake-wide trend in the surficial sediment C/N ratio (Figure VI-3), the ratio of inorganic P to Fe tends to increase from south to north, with a large decrease in

Missisquoi Bay. A simple interpretation would be that the normalized inorganic P concentration increases because of closer proximity to population centers; an examination of the inorganic P to Fe ratio (Figure VI-3) suggests that the changes in the concentration of Fe drive this latitudinal distribution.

Station 7 Profile Data

Figure VI-4 shows the vertical profiles of solid phase chemistry for monitoring station 7, collected in August 1994. There is a pronounced decrease in the concentration of C and N in these cores that is consistent with previous work (McIntosh 1994). A simple interpretation of increased C and N loading to the sediments is not consistent with general principles of organic matter diagenesis; although profiles such as these can arise from increased loading, they may also be interpreted as steady state diagenesis, with higher concentrations at the sediment-water interface primarily reflecting the occurrence of more labile organic matter (Cornwell et al. 1996). Of interest is the apparent increase in the C:N ratio in these cores; a simplified explanation would be an increasing proportion of planktonic organic matter versus terrestrial organic matter. Without further biogeochemical evidence for such a change, the C:N ratio change cannot be readily interpreted.

Higher Mn and Fe concentrations at the sediment-water interface are consistent with pore water migration and enrichment in more oxidizing sediment layers (Robbins and Callendar 1975; Froelich et al. 1979; Cornwell and Kipphut 1992). Strong gradients in pore water Mn and Fe concentration at this site support such migration. Such migration can have important consequences for the distribution of trace metals (Cornwell 1986) and P (Carignan and Flett 1981; Cornwell 1987).

The profiles of total P and inorganic P are similar to each other, with the difference being an estimate of organic P. A strong inorganic P and total P correlation is found (Figure VI-4). A relatively constant 2 mg g⁻¹ organic P value is found in this core. As with C and N, any explanation of increased P concentrations in recent sediment horizons must consider both changes in P loading and post-depositional migration. A significant correlation between inorganic P and HCl-extractable Fe (Figure VI-4) suggests that P distributions are at least partially related to the diagenesis of Fe. Increased loadings of P from human activities are not readily determined from these profiles.

Carbon and Nitrogen

In general, there are down core decreases in the concentrations of C and N in Lake Champlain cores (Figure VI-5). High sedimentation sites (i.e. stations 2, 4 10) often don't exhibit such characteristic decreases. As described above for station 7, the question of diagenetic versus depositional control of C and N concentrations in the upper parts of these cores remains an open question.

Iron and Manganese

Manganese and iron are both redox-reactive metals, with changes in their vertical distribution usually related to post-depositional migration (Burdige 1993). Manganese enrichments (Figure VI-6) are most pronounced at most of the deep-water sites (Stations 7, 10, 12, 19, 36) plus Mallets Bay (25) and Burlington Bay (21). In Mallets Bay, the subsurface Mn concentration maxima is similar to that observed by McIntosh (1994), while at all other sites, the surficial (0-1 cm) sediment sample was the highest.

At all sites with Mn enrichments near the sediment-water interface, there are large pore Mn concentration gradients. The process of Mn oxide reduction leads to upward diffusion of pore water Mn(II) and the reprecipitation of Mn oxides near the sediment-water interface (Robbins and Edgington 1975; Froelich et al. 1979; Cornwell and Kipphut 1992). In fine-grained lacustrine sediments, this mechanism is the usual cause of solid phase Mn enrichment near the sediment-water interface.

Pronounced Fe enrichments are found in cores 7, 12, 19, 21, 25, 50 and 51, with smaller enrichments found at other sites. As with Mn, the post-depositional migration of Fe(II) in pore water can result in the enrichment of solid-phase Fe oxides at or below the sediment-water interface.

Inorganic and Total Phosphorus

Vertical profiles of inorganic and total P in Lake Champlain sediments mirror each other very closely (Figure VI-7), with most of the total P consisting on inorganic P. The relatively high variability of inorganic within the cores indicates P mobility. The simple pattern of near-surface P enrichment is observed in some cores, but in many cores, a more complex pattern is found. Large changes in inorganic P concentration often are associated with the diagenesis of Fe (Carignan and Flett 1981; Baccini 1986), and strong correlations between Fe and P within cores are observed (Cornwell and Kipphut 1992). Upward fluxes of both SRP and Fe may be a major cause of variability within these profiles.

Strong Fe-P correlations ($P < 0.01$) are found in 7 Lake Champlain cores (Figure VI-8), particularly those with large changes in P and Fe concentration within the core. This kind of association is commonly found in lacustrine sediments and illustrates the strong relationship between P and Fe cycling. Because of this P-Fe association, it is difficult to use the profiles of sediment P in Lake Champlain cores as any sign of temporal changes in P loading.

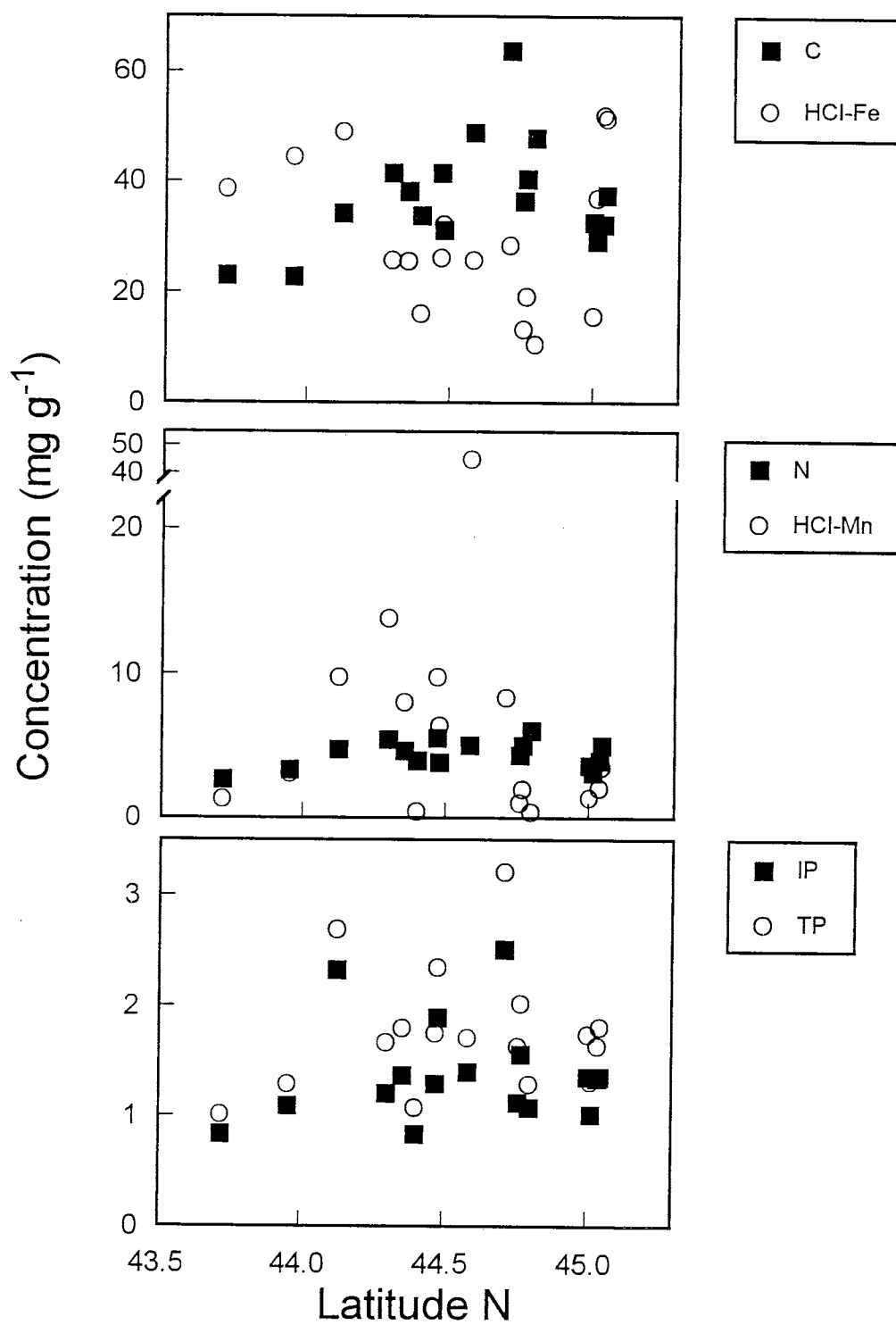


Figure VI-1 Latitudinal plots of solid phase parameters for Lake Champlain surficial (0-1 cm) sediments.

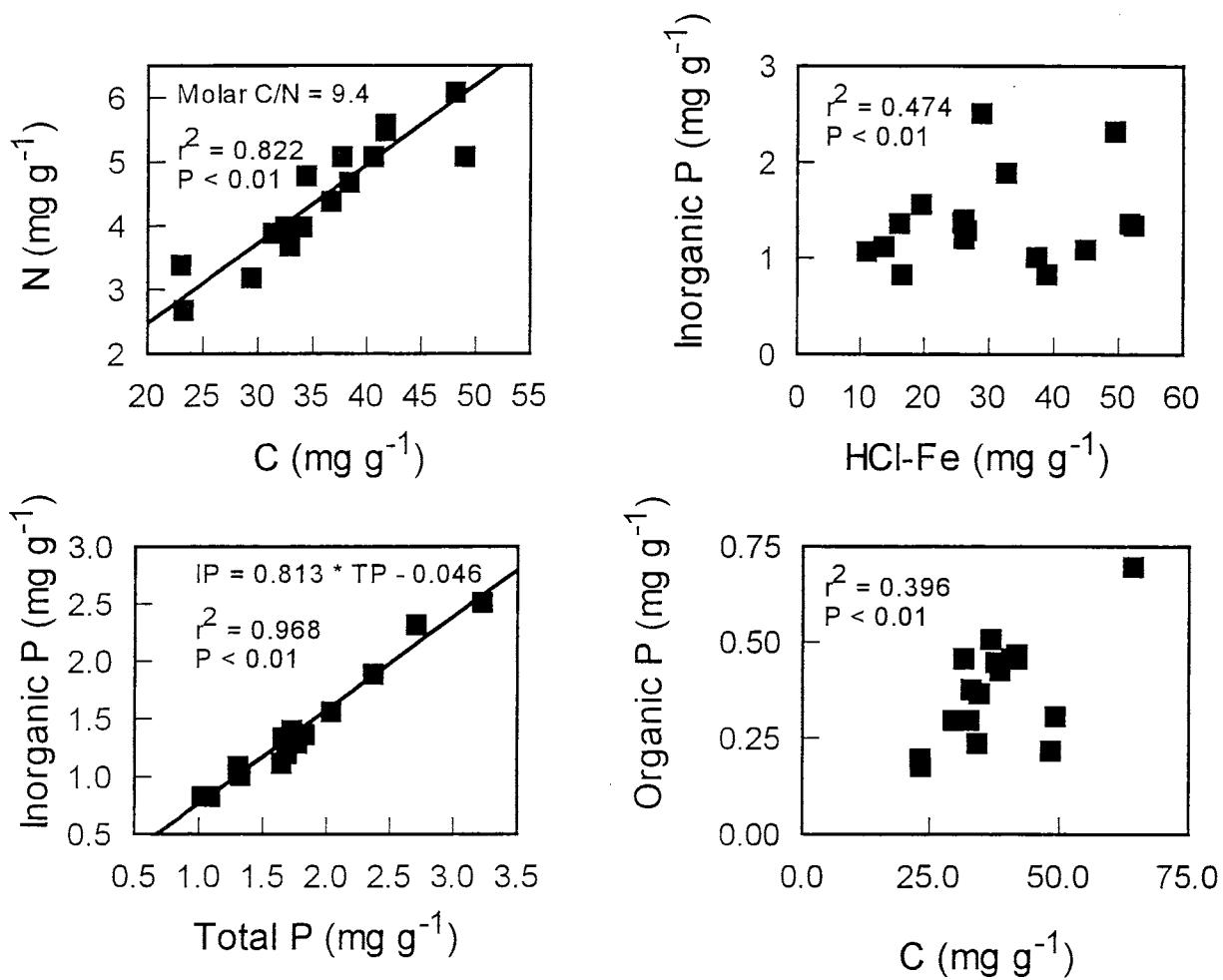


Figure VI-2 Property-property lots of sediment properties from Lake Champlain surficial (0-1 cm) sediments.

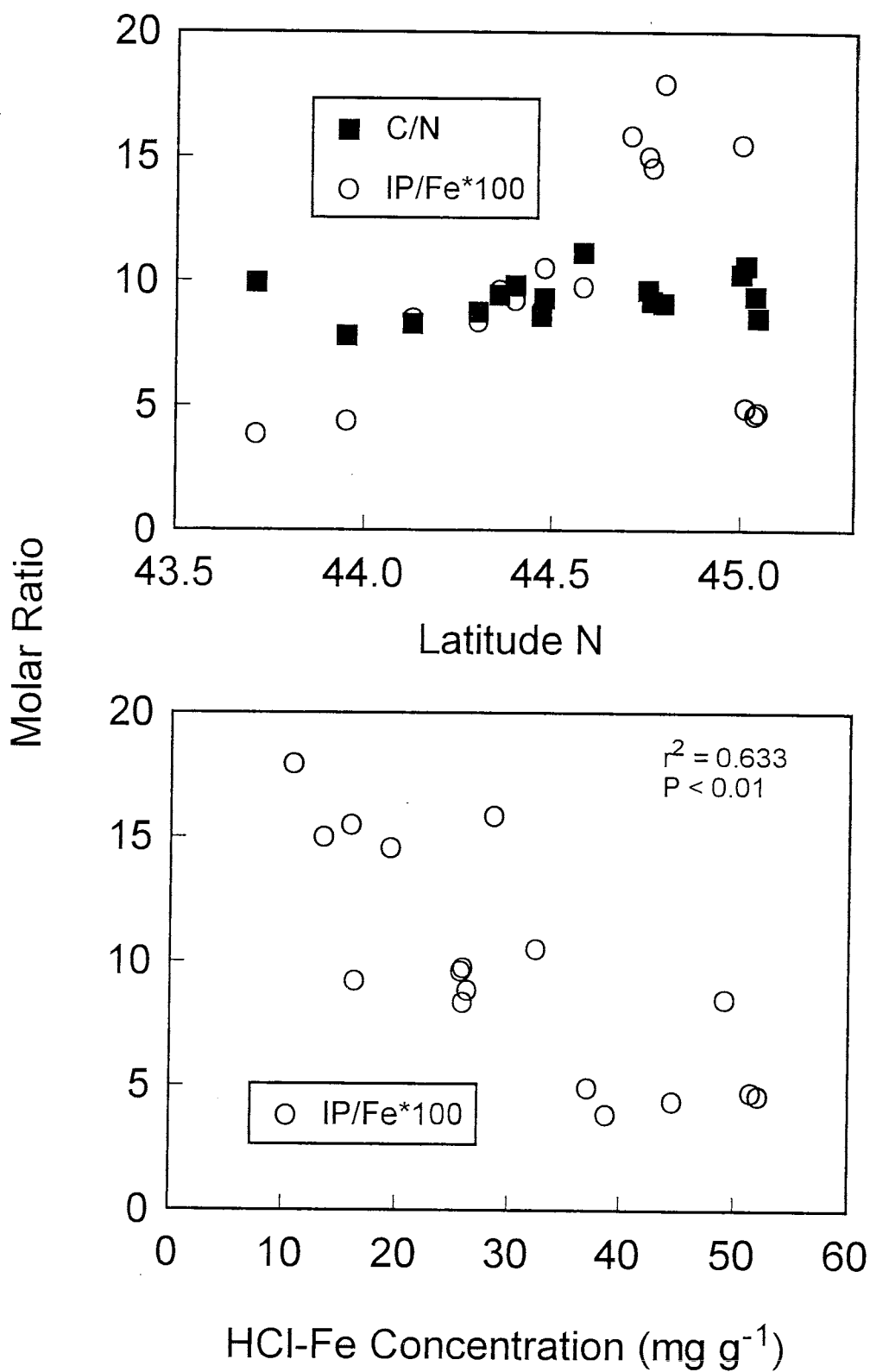


Figure VI-3 Latitudinal plots of the molar C/N ratio and inorganic P/Fe ratio (*100) in surficial (0-1 cm) Lake Champlain sediments.

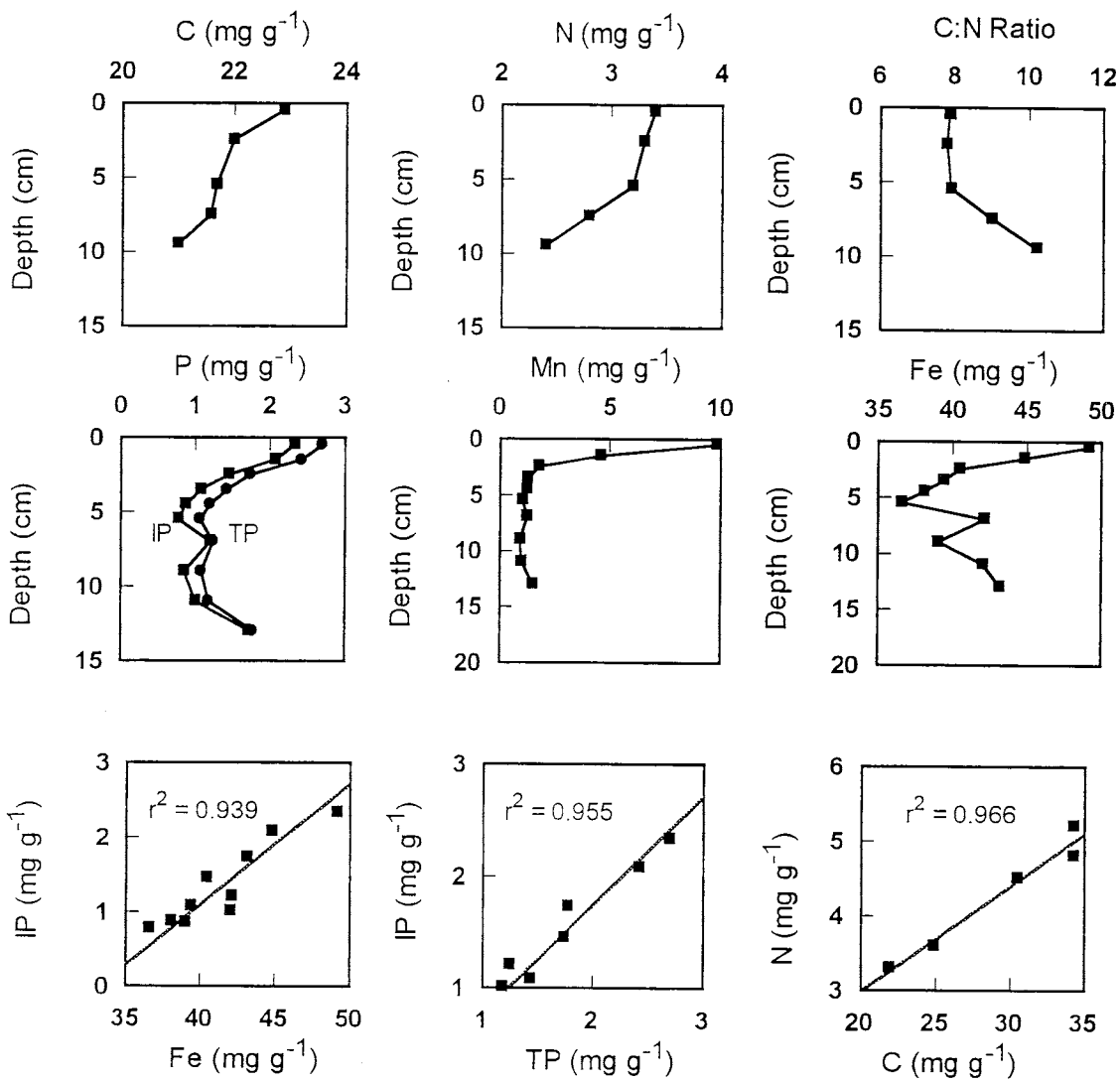


Figure VI-4. Profiles of sediment biogeochemical parameters and property plots from Station 7.

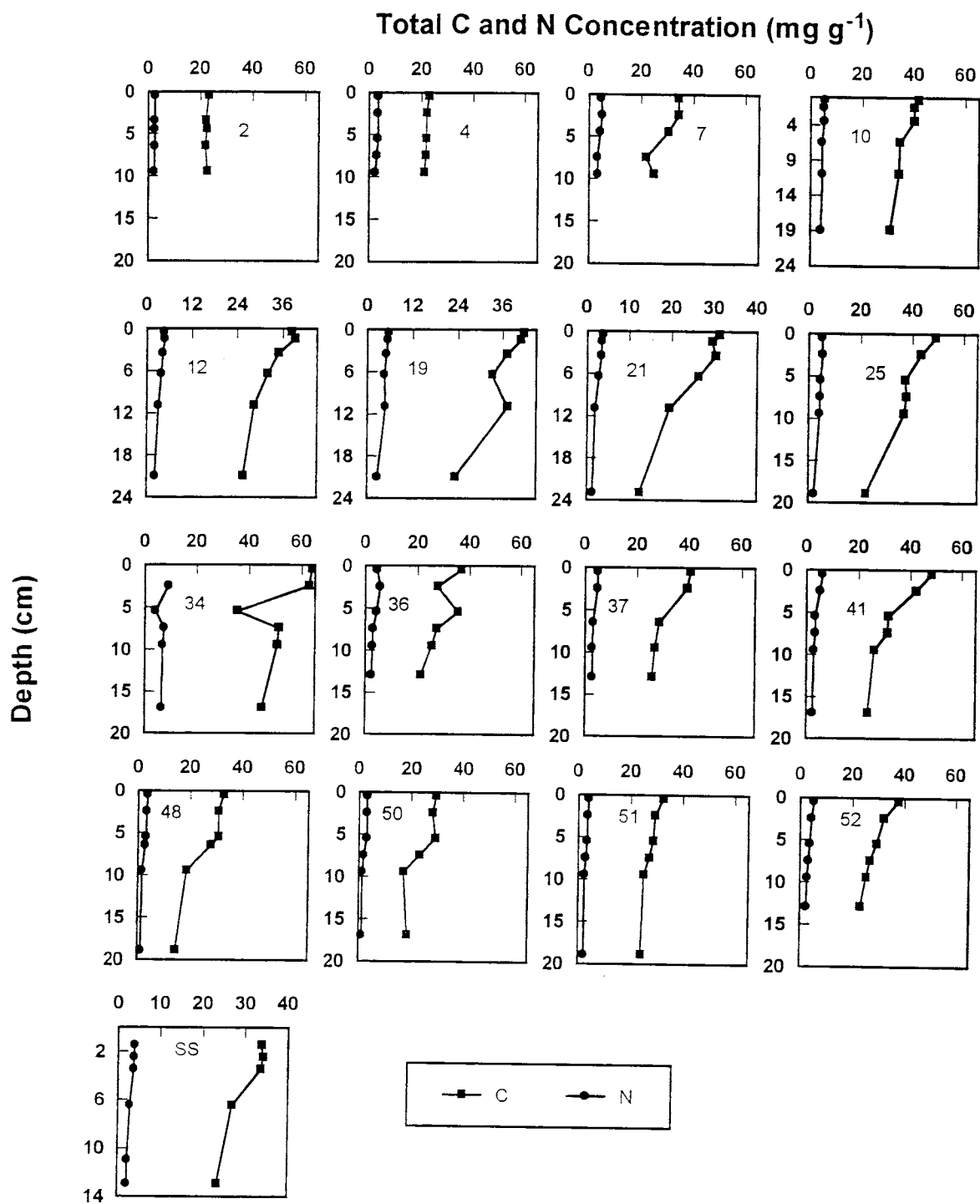


Figure VI-5. Carbon and N concentration profiles in Lake Champlain sediments

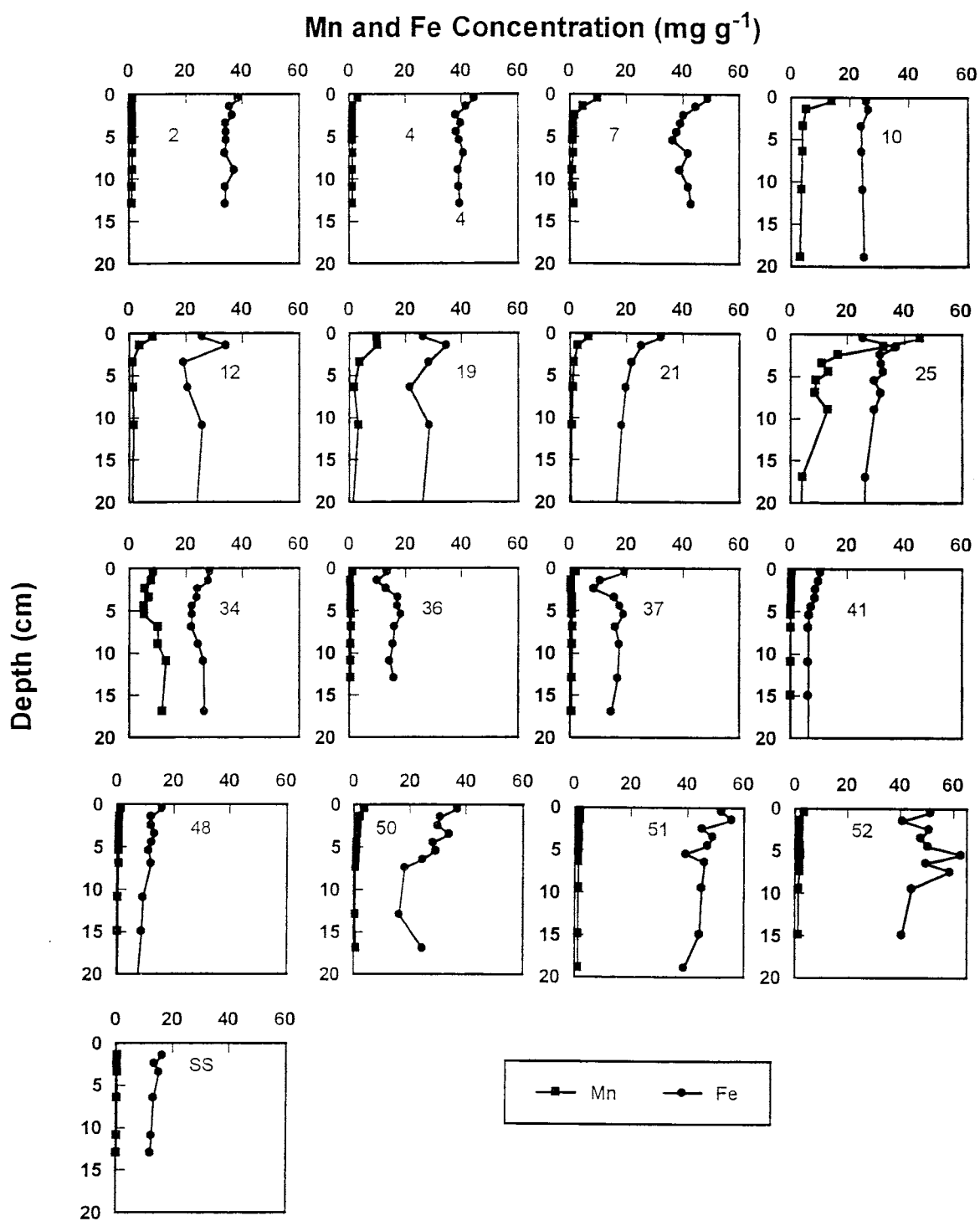


Figure VI-6 HCl-extractable Mn and Fe concentration profiles in Lake Champlain sediments

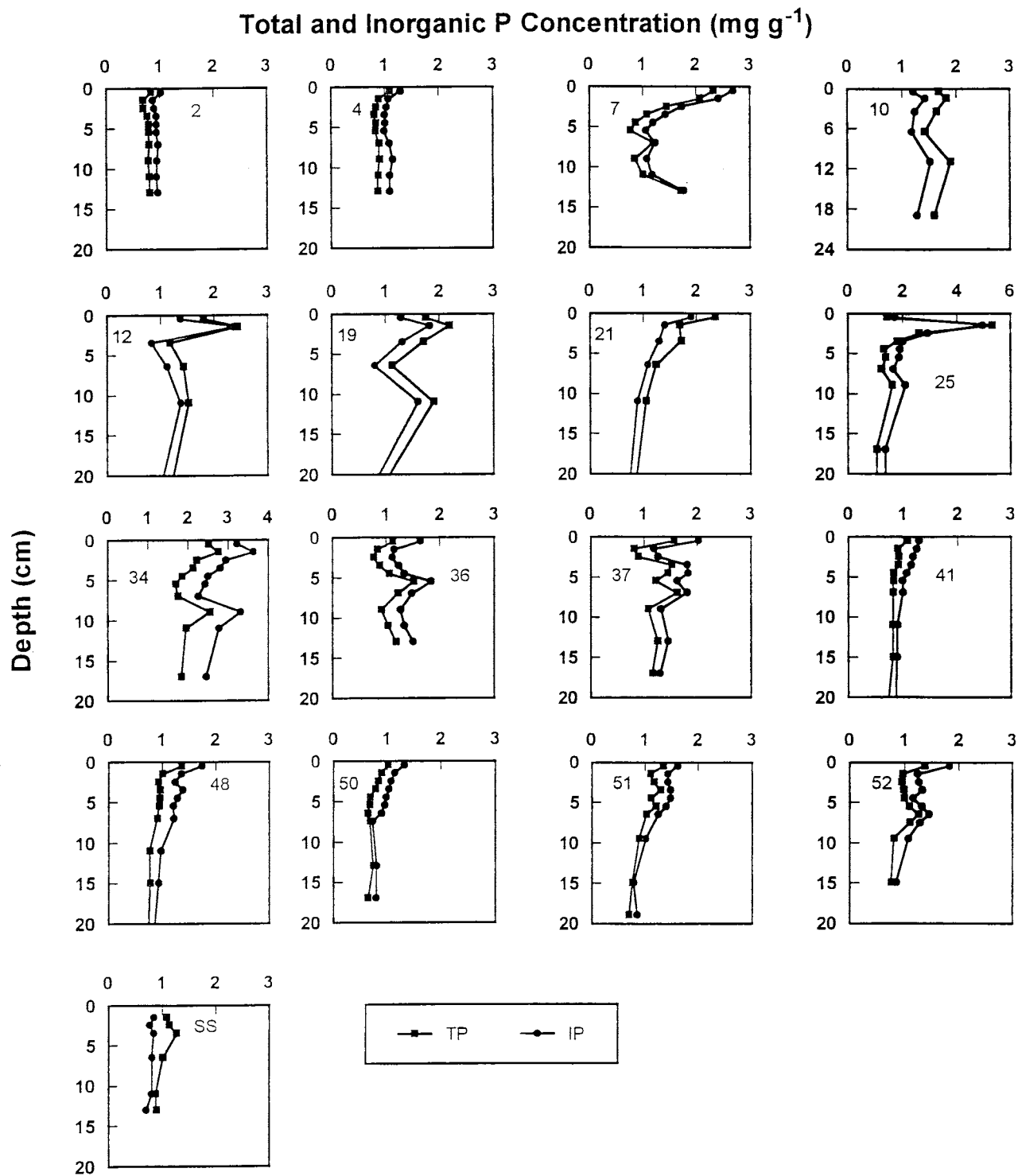


Figure VI-7. Total and inorganic P profiles in Lake Champlain sediments

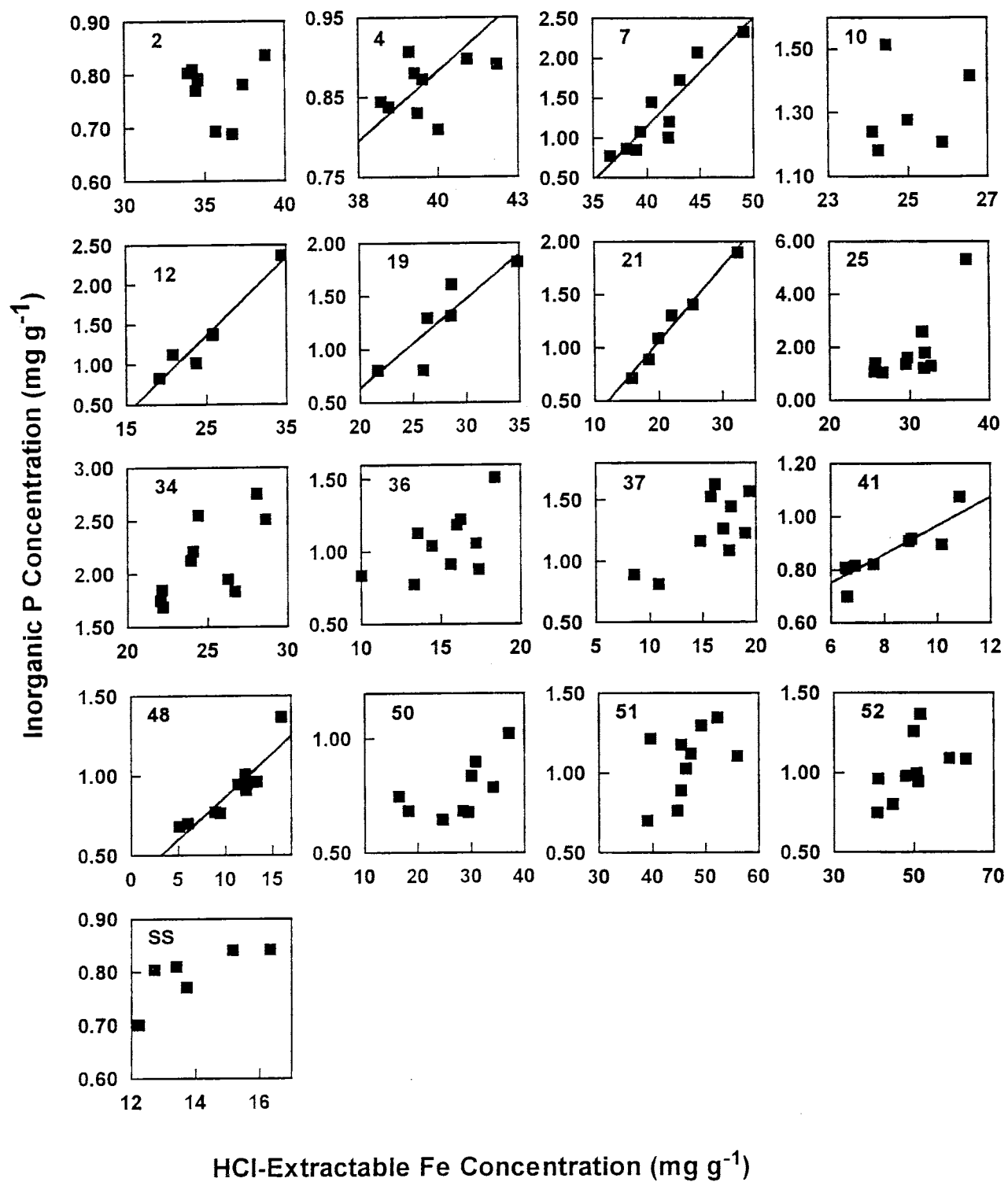


Figure VI-8. Plots of inorganic P as a function of HCl-extractable Fe for all study sites. For all cores with highly significant ($P < 0.01$) correlations, the regression line is included.

Chapter VII Lake Champlain Geochronology

Background

The ^{210}Pb dating technique has been applied to the determination of lacustrine sedimentation rates since the 1970's (Robbins and Edgington 1975; Krishnaswami and Lal 1978). With a 22.3 year half-life, this nuclide can provide sedimentation rates valid for up to 100 yr. There are numerous successful examples of studies in both large and small lakes, but in all studies, it is necessary to consider the assumptions and potential artifacts associated with the technique. Core shortening using gravity cores can result in a compromised sample (Baxter et al. 1981; Nevissi et al. 1989), and box coring (as in this study) or diver collection of cores are considered better approaches. Additional problems with the mobility of ^{210}Pb , its daughter ^{210}Pb or its parent ^{226}Ra have been demonstrated (Cornwell 1985; Anderson et al. 1987; Benoit and Hemond 1990). The mixing of sediments by organisms (Robbins 1978) and changing rates of sediment input (Appleby and Oldfield 1978) can require the use of different calculation models. Overall, the technique generally is robust and has provided good sedimentation estimates in many lakes.

There is a published sedimentation rate for a single Lake Champlain site, with a $^{210}\text{Pb}/^{137}\text{Cs}$ based rate of $\sim 1500 \text{ g m}^{-2} \text{ y}^{-1}$ (Wahlen and Thompson 1980). This rate compares favorably with the data from our study. A recent sediment contaminant/geochronology study has developed sediment accumulation rates at a number of sites, but the data were not readily available from the report (McIntosh 1994). The sedimentation rate data in this report were generated in parallel with sediment-water exchange experiments, pore water geochemical profiles, and a number of solid phase analyses. Our main purposes in collecting these data were 1) to assess the rates of P burial in Lake Champlain and 2) provide a burial term helpful in understanding the diagenesis P, Mn and Fe in these sediments.

Validation of ^{210}Pb -based sedimentation rates can be difficult. We were not able to provide ^{137}Cs dating in this study, but the analyses of total Pb and other trace elements relate our geochronology with general continental patterns of Pb inputs into aquatic systems. We expected to see a peak of Pb input in the mid 1970's; the change from leaded to unleaded gas has resulted in rapid decreases of Pb concentrations in sediments (e.g. Owens and Cornwell 1995).

Profiles of ^{210}Pb (or ^{210}Po) in aquatic sediments consist of two main components: 1) "excess" or "unsupported" ^{210}Pb and 2) "supported" or background ^{210}Pb . Excess ^{210}Pb is that component of ^{210}Pb that is in excess of the ^{210}Pb generated *in situ* via the decay of ^{226}Ra (Robbins 1978). In this study, the concentration of ^{226}Ra was not measured and ^{226}Ra concentrations are estimated from the asymptotic ^{210}Po concentrations at depth; where asymptotes were not reached, we assigned a value of 1.5 dpm g^{-1} , a good average value of supported ^{210}Pb for this lake.

The decay of radionuclides is a first order process described by the equation:

$$1) \quad A = A_0 e^{-\lambda t}$$

where A is the activity at time t, A_0 is the activity at time zero and λ is the decay coefficient (0.03114 for ^{210}Pb). This equation may be modified for sediments:

$$2) \quad A = A_0 e^{(-\lambda x/\omega)}$$

where A is the activity (dpm g^{-1}) at depth x (cm) and ω is the sediment accretion rate (cm yr^{-1}). This formulation is the constant initial concentration model ("CIC") of ^{210}Pb -based sedimentation. It depends on 1) constant input fluxes of both sediment and excess ^{210}Pb , 2) no post-depositional mobility of ^{210}Pb relative to sediment particles, and 3) no sediment mixing by biota or physical processes. In the ideal situation, excess ^{210}Pb is described by equation 2 and provides an exponential decrease in excess ^{210}Pb activity with depth. To apply this model, equation 2 is log transformed:

$$3) \quad \ln A = \ln A_0 - (\lambda x/\omega)$$

This calculation approach is illustrated in Figure VII-1, with an exponential decrease in ^{210}Pb evident in this core from site 21. The linear regression of the natural log of activity versus cumulative mass provides a mass sedimentation rate. The top two points were not used in the regression; in many cores, either mixing near the sediment-water interface or tracer migration result in the top 1-3 data points being excluded from regressions.

^{210}Pb -Based Sedimentation Rates in Lake Champlain

In general, the ^{210}Pb activity in Lake Champlain sediments appeared to have an exponential decrease down core (Figure VII-2). Core 2 had a mostly vertical profile, either a result of mixing or very rapid sedimentation. Cores 2, 4, 7, 10, 34, and 52 did not reach supported ^{210}Pb levels and where possible, supported levels from sites closest to them were used for an estimate. Only core 25 exhibited a deeper "mixing" profile. Maximum ^{210}Pb activities were observed below the sediment-water interface for cores 7, 10, 12, 19 and 21 and SS. Explanations for this subsurface maxima may include post-depositional mobility of ^{210}Pb or ^{210}Po (Benoit and Hemond 1990) associated with Mn and/or Fe cycling. Because cores 10, 12, 19, 21 and SS were analyzed within several months of collection, while all other cores were analyzed over 1 year after collection, we reanalyzed ^{210}Po on core 12 down to the 9-10 cm section. This analysis was after a year of additional ^{210}Po ingrowth, and while most analyses generated similar activities, there was a clear increase in ^{210}Po in the surface two samples (Figure VII-3). This is strongly suggestive of post-depositional migration of ^{210}Po ; this site has near-surface Mn/Fe redox cycling (as evidenced in pore water and solid phase chemistry) that may be a driving force for ^{210}Po mobility. These data suggest that such mobility mainly occurs near the sediment-water interface; it is unlikely that there is a large effect on sedimentation calculations based on deeper sediments.

Sedimentation rates were calculated using the CIC model, with excess ^{210}Pb regressed against cumulative sediment mass. In cores with subsurface ^{210}Po maxima, regressions did not utilize the data above the maxima; given the evidence for post-depositional mobility, this appears

to be a justifiable exclusion. Sedimentation rates ranged from 333 to 5567 g m⁻² y⁻¹ (Table VII-1), averaging 1212±1223 g m⁻² y⁻¹ (n = 17; median = 784 g m⁻² y⁻¹). The highest rates were found at sites 2 and 4 in the southern lake, while the lowest rates were found at sites 25, 36 and 37; simple depth versus sedimentation rate relationships found in some studies (Evans and Rigler 1983) are not likely to be found in a morphometrically complex system like Lake Champlain. Typical sediment accretion rates were 2-4 mm y⁻¹ (Table VII-1).

Table VII-1. Sedimentation Rates For University of Maryland Sites. The range used for the sedimentation rate is derived from the standard error of the regression.

Station	Sedimentation Rate (g m ⁻² y ⁻¹)	Sedimentation Rate -- Range (g m ⁻² y ⁻¹)	# Data Points Used For Regression	r ²	Accretion Rate (cm y ⁻¹)	²¹⁰ Pb Inventory (dpm cm ⁻²)
2	5567	4508-7276	9	0.721	1.07	33.9
4	2118	1818-2537	10	0.821	0.58	32.4
7	784	729-847	9	0.962	0.34	40.8
10	1690	1518-1907	10	0.907	0.75	100.3
12	664	594-753	11	0.889	0.24	41.4
SS	1100	1008-1211	8	0.952	0.20	24.7
19	707	623-819	10	0.871	0.28	60.0
21	525	509-542	8	0.994	0.20	29.3
25	479	465-493	12	0.992	0.32	36.6
34	811	722-924	14	0.846	0.70	99.8
36	333	261-460	6	0.767	0.10	9.2
37	485	464-508	7	0.990	0.18	22.0
41	612	557-677	7	0.955	0.13	17.8
48	1255	1105-1452	6	0.931	0.21	21.5
50	1470	1227-1832	7	0.836	0.25	20.4
51	1106	1007-1226	10	0.928	0.18	37.7
52	1394	1322-1474	9	0.978	0.36	55.5

Sediment ²¹⁰Pb Inventories

The main source of "excess" ²¹⁰Pb in lakes is from the atmosphere, with the flux of ²²²Rn from soils to the atmosphere leading to the production of ²¹⁰Pb which is subsequently deposited at the lake surface and eventually incorporated into sediments (Robbins 1978). One of the primary assumptions of the ²¹⁰Pb dating technique is that ²¹⁰Pb input fluxes are constant;

however, that does not require that inputs from site to site within a lake have identical inputs. The steady-state input assumption requires that there is one atom of ^{210}Pb added to the site for each atom that decays; this implies that the inventory of ^{210}Pb activity in the sediment is equal to the input of ^{210}Pb . Deviations from the expected inventory may indicate that sediments are "focused" either to a site or away from a site.

Calculating the inventory of excess ^{210}Pb is relatively simple, but when the supported ^{210}Pb activity is not reached, it is difficult to estimate the inventory. At a number of Lake Champlain sites, we cannot directly estimate the inventory because supported ^{210}Pb activities were not reached. If we use the inventory at a specific depth, and independently know the age at that depth, we can estimate the entire inventory:

$$4) \quad I_{\text{total}} = I_x / (1 - e^{-\lambda t})$$

where I_{total} is the total inventory (dpm cm^{-2}), I_x is the inventory at depth x (dpm cm^{-2}), and t is the time (yr) at depth x calculated from the CIC model. The ^{210}Pb inventories in Table VII-1 are calculated from equation 4. The expected inventory throughout most of the eastern United States is $\sim 32 \text{ dpm cm}^{-2}$; lower inventories are found at higher latitude (Robbins 1978; Cornwell 1985).

Lake Champlain ^{210}Pb inventories vary greatly, from 9.2 dpm cm^{-2} at station 36 to $\sim 100 \text{ dpm cm}^{-2}$ at stations 10 and 34. This range is from ~ 30 to 300% of expected inventories suggesting that some stations are poorly retentive of both ^{210}Pb and sediment, and that others "focus" sediment and ^{210}Pb . Such focusing of sediment and radionuclides has been observed in numerous lake and estuarine studies (Evans et al. 1986; Dibb and Rice 1989). A relationship between focusing and depth may be expected in lakes, with sediments at greater depth capturing more sediment and ^{210}Pb . In Lake Champlain, there is no apparent simple correlation between the inventory of ^{210}Pb and water depth, though most sediments from deep sites are higher than the average of shallow water sediments (Figure VII-4).

If particles are uniformly labeled with ^{210}Pb in the water column, it is possible to normalize sediment and pollutant input/burial rates to an unfocused flux. This flux may be more applicable to the regional flux than that of the non-normalized burial fluxes. For the sedimentation rates in Lake Champlain, there are moderate changes in apparent sedimentation rates when we normalize for focusing (Figure VII-5). For some stations, large increases in apparent sedimentation rate are noted (SS, 36, 48, 50) while at others, large decreases are found (10, 19, 34, 52).

Comparison to Contaminant Profiles

Selected trace metal contaminants were analyzed on these cores to confirm or reject the general rates of sedimentation estimated by the ^{210}Pb technique. Contaminant profiles in aquatic sediments often have characteristic regional or continental concentration profiles; in general, many metals increased in concentration until the 1960's or 1970's, with decreases after that time due to environmental regulation (Vallette-Silver 1993). In particular, Pb inputs have had a major

decrease since the phasing out of leaded gasoline in the 1970's, with the sedimentary record showing a decrease in recent years (i.e. Owens and Cornwell 1995).

The deep water sediment site closest to Burlington, station 19, shows a distinct subsurface enrichment of Cu, Pb and Zn, with all of these enrichments apparently unrelated to the distribution of Mn and Fe (Figure VII-6). The post-depositional mobility of Mn and Fe can be a large influence on the distribution of metals in sediment profiles (Cornwell 1986), but in most Lake Champlain cores, the main peaks in trace metal concentrations do not correspond to the horizons that are Mn- or Fe-enriched. The Fe enrichment at 18-20 cm within the station 19 core corresponds with slight enrichments in Cu, Pb and Zn (Figure VII-6); such deep enrichments do not mask major increases and decreases in trace metal concentrations in the last 60 years.

Subsurface Pb peaks are observed in 13 of the 17 cores analyzed (Figure VII-7). Such peaks are readily observed in aquatic sediments and terrestrial ecosystems (Ragsdale and Berish 1988) throughout North America (Vallette-Silver 1993). The removal of alkyl lead in gasoline and the use of electrostatic precipitators in power plants is generally thought to be the cause of the recent decline. In many locations, the rapid decline in Pb started in the mid-1970's. Steady increases in Pb above background concentrations generally commence in the early part of the 20th century. In some cores (e.g. 48, 52, SS), an apparently lower rate of decline in Pb may indicate sediment bioturbation.

The profiles of Zn and Cu were determined for 5 cores (Figure VII-8). The Zn profile showed distinct subsurface maxima at stations 21 and 37, with the other sites showing less enrichment. Copper enrichments were not as obvious.

The time course of Pb concentration was examined at all dated sites (Figure VII-9). In all cores with distinct subsurface Pb maxima, the middle of the 1960-1980 time frame is the time of greatest sediment Pb concentration. As in other locations (Owens and Cornwell 1995), Pb concentration increases occurred near the beginning of the century. Despite the relative complexity in many of these Pb profiles, there appears to be a good deal of agreement in the time frames of Pb increase and decrease in cores collected throughout Lake Champlain.

These contaminant results indicate:

- 1) We have found the same general time courses of Pb input as shown in the McIntosh (1994) study. Peaks in the mid-1970's at many stations are consistent with the general pattern of Pb concentration changes in aquatic and terrestrial environments throughout North America.
- 2) Our ^{210}Pb dating results are consistent with other independent markers (i.e. Pb).

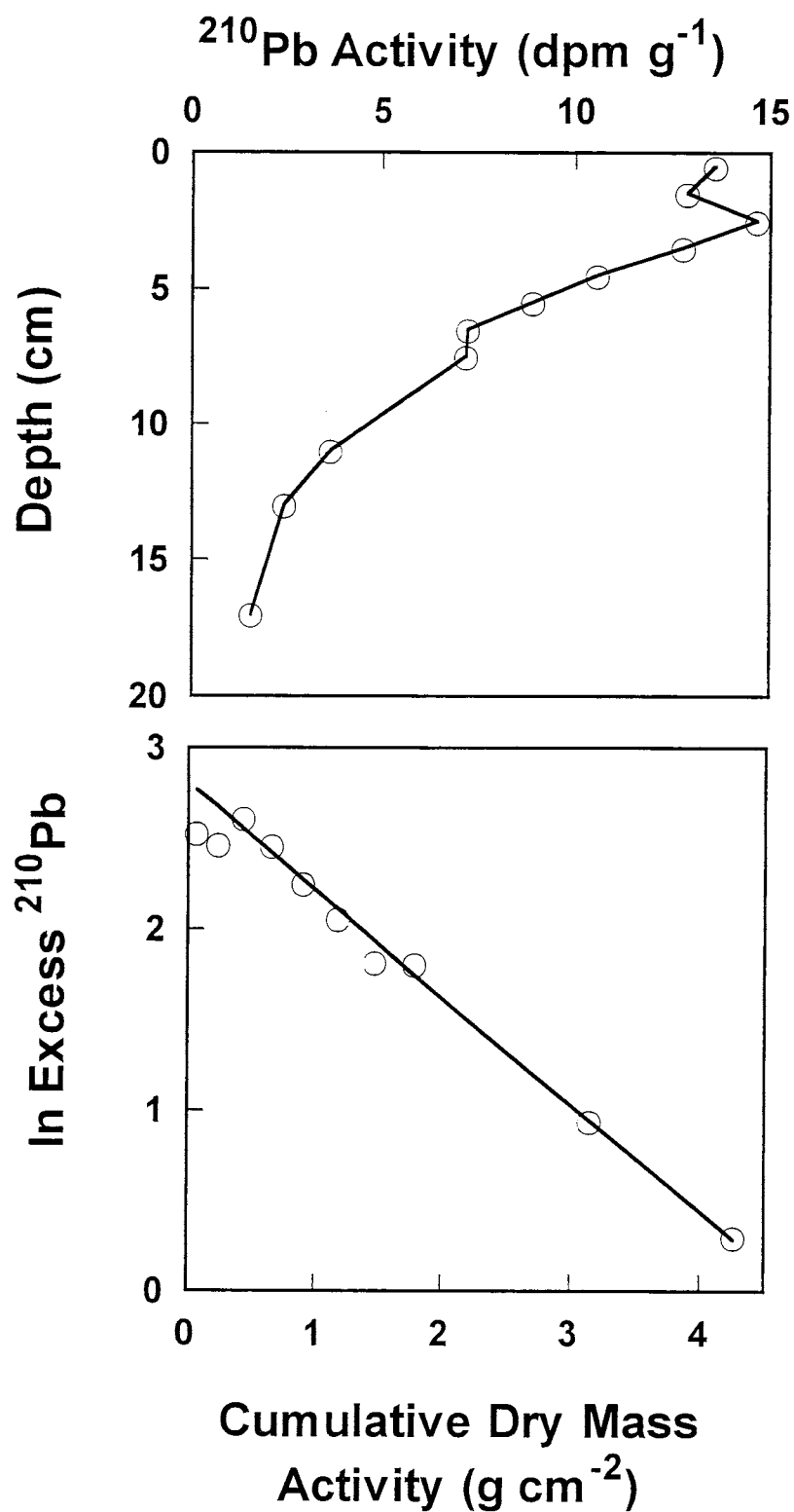
Summary

The ^{210}Pb dating technique appears to be applicable to a wide range of sediment locations in Lake Champlain. The range of sedimentation rates ($333\text{--}5567\text{ g m}^{-2}\text{ y}^{-1}$) is quite broad, with an average rate of $1212\pm1223\text{ g m}^{-2}\text{ y}^{-1}$ ($n=17$). The highest rates of sedimentation were found in the southern-most part of the lake (Stations 2, 4) and in the northernmost part of the lake (Missisquoi Bay). The wide range of ^{210}Pb inventories suggests that preferential deposition of ^{210}Pb and sediment occurs in some sites, at the expense of others.

Contaminant profiles, particularly anthropogenic Pb, are consistent with those observed in other aquatic systems. Management actions in the 1960's have resulted in lower contaminant inputs in recent years; this is reflected in lower contaminant concentrations. Our Pb geochronologies are consistent with those developed in Lake Champlain (McIntosh 1994) and elsewhere; while not a rigorous test of the ^{210}Pb dating procedure, they lend some assurance that our sedimentation rates are reasonable.

The calculation of lake-wide sedimentation averages is difficult, especially when only 17 cores are used. The average rate of all the rate data ($1212\pm1223\text{ g m}^{-2}\text{ y}^{-1}$) is remarkably similar to the ^{210}Pb inventory-generated "normalized" sedimentation rates ($1202\pm1206\text{ g m}^{-2}\text{ y}^{-1}$). Given the relatively small areal coverage that should be assigned to the higher sedimentation north and south sites, these averages may be high. If we assign the normalized core data to the model section areas in the NY/VT DEC report, we can calculate a whole system input of $790\text{ g m}^{-2}\text{ y}^{-1}$. We did not have any data for segments that represent 20% of total lake area; average lake data was assigned to those segments. Additionally, some segments had only one core available. The lower whole lake rate reflects the relatively larger areal importance of medium to low sedimentation sites.

The sedimentation rate data generated here provide the first Lake Champlain-wide look at rates; better sediment budgets will require considerably more analyses. However, for the purposes of developing a first-order understanding of P burial and recycling, these rates are sufficient.



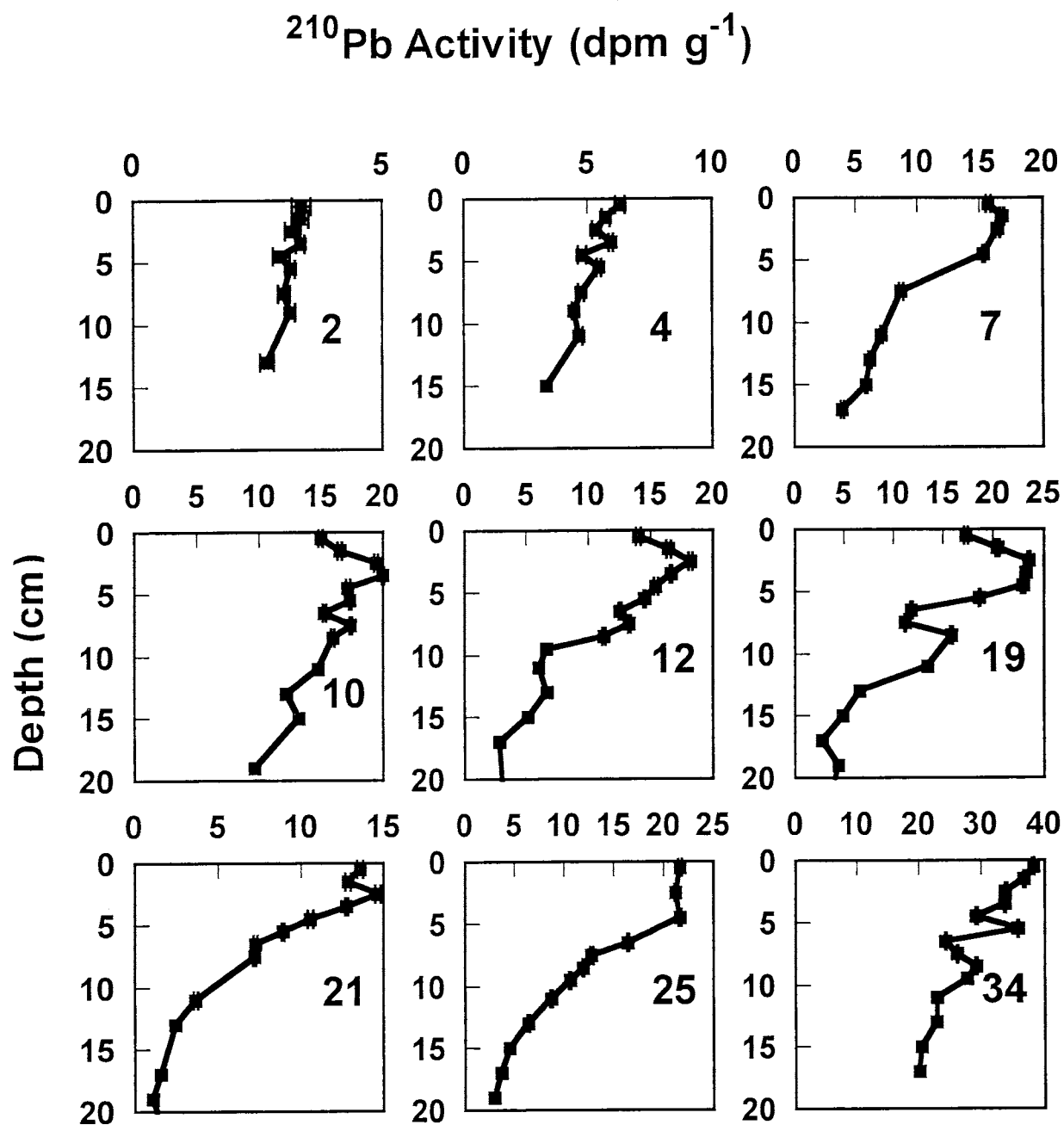


Figure VII-2. Vertical profiles of ^{210}Po in Lake Champlain sediments.

^{210}Pb Activity (dpm g^{-1})

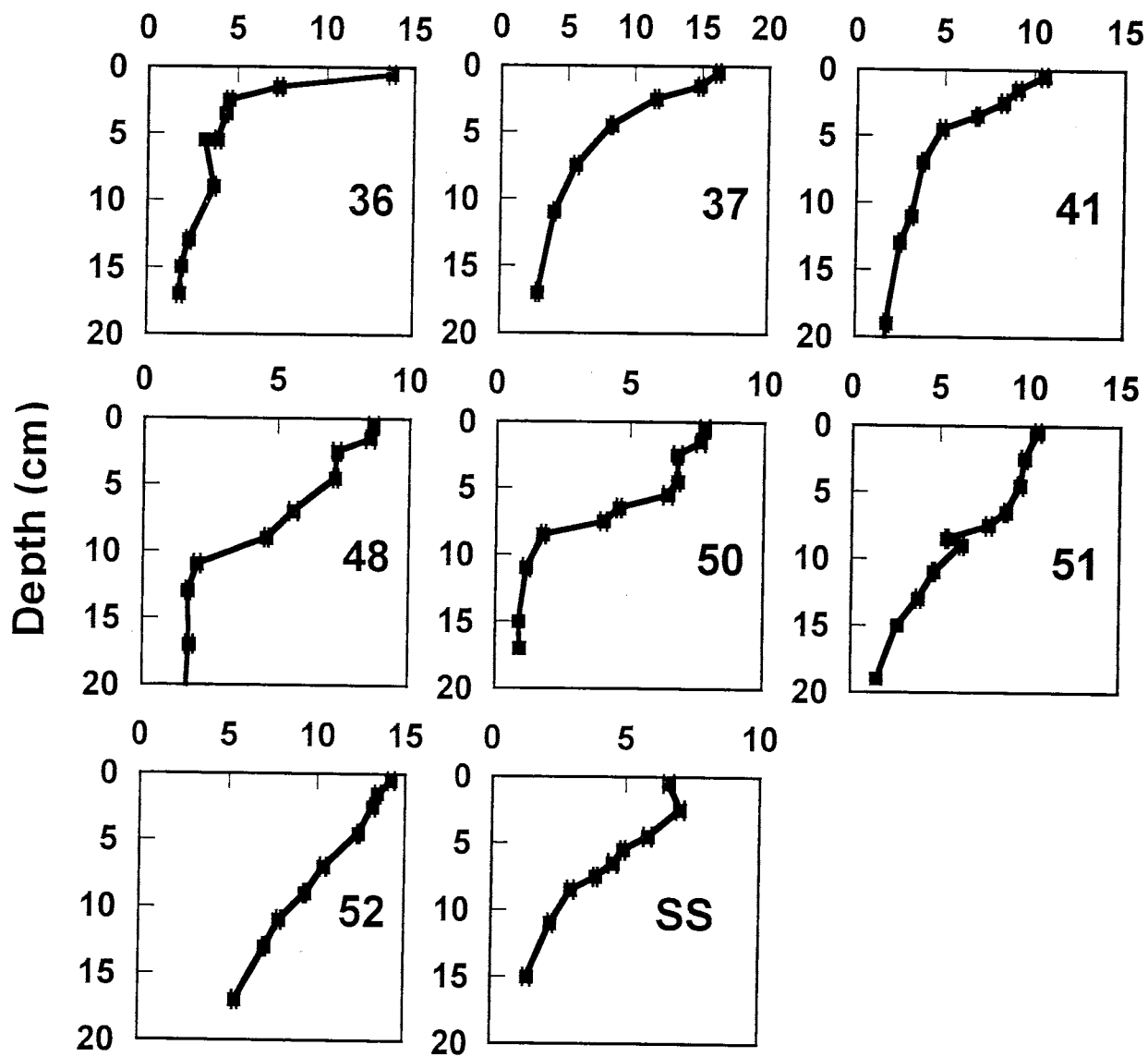


Figure VII-2. Continued, vertical profiles of ^{210}Po in Lake Champlain sediments

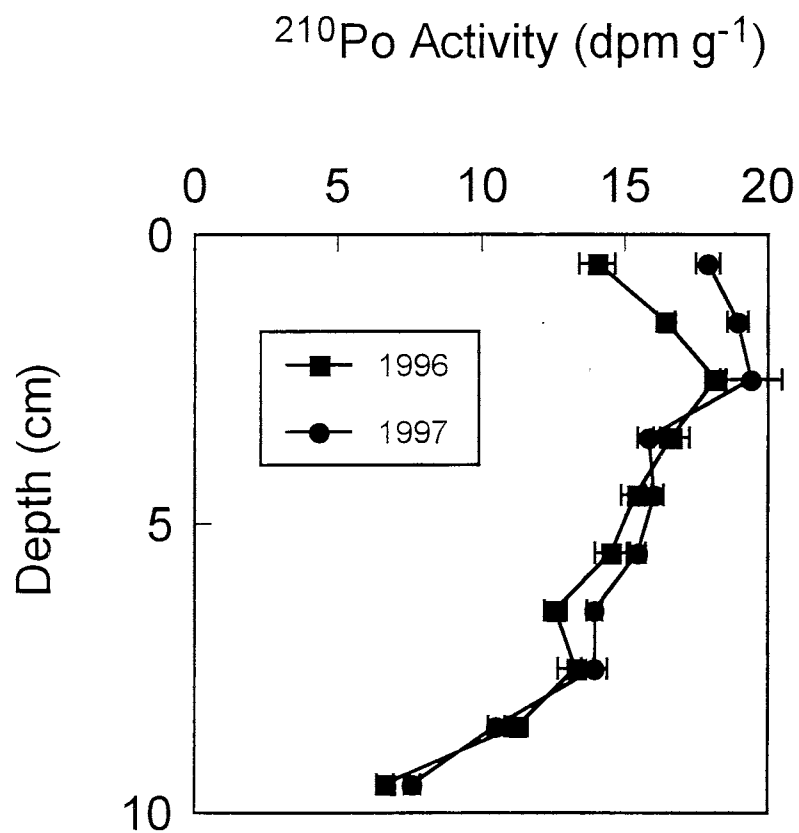


Figure VII-3. Replicate analyses of ²¹⁰Po at site 12. The 1996 analyses were carried out 30-40 days after sediment collection; the 1997 analyses were 450 days after sediment collection and were carried out on the same samples.

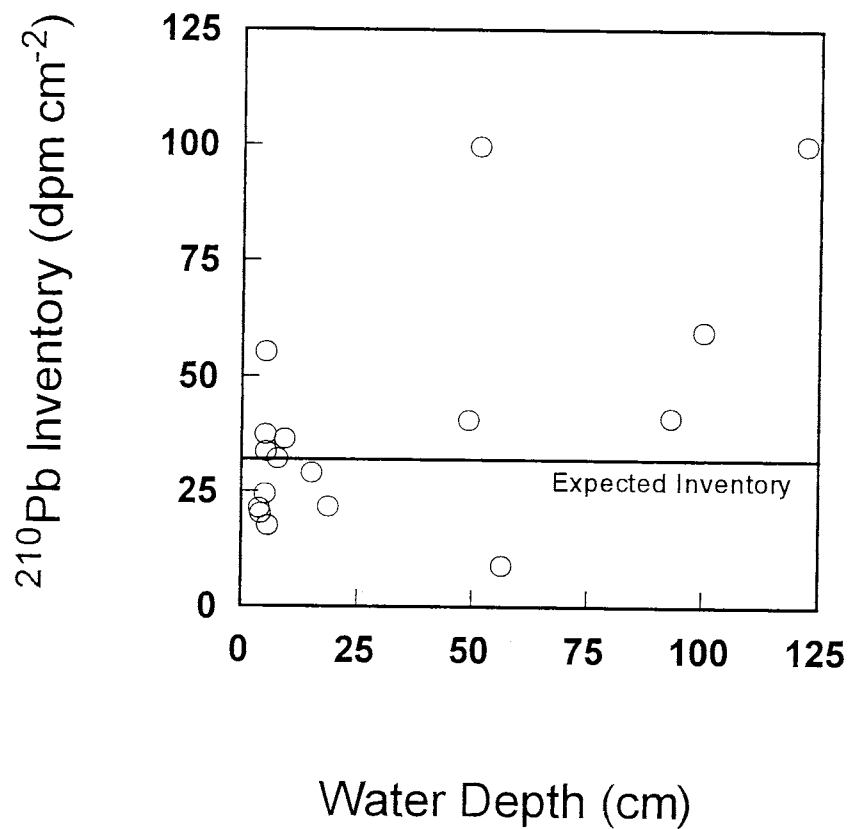


Figure VII-4. Calculated ^{210}Pb inventories in Lake Champlain plotted as a function of water depth. Inventories greater than the expected atmospheric input are indicative of sediment focusing; lower inventories indicated that sediment is focused away from the site.

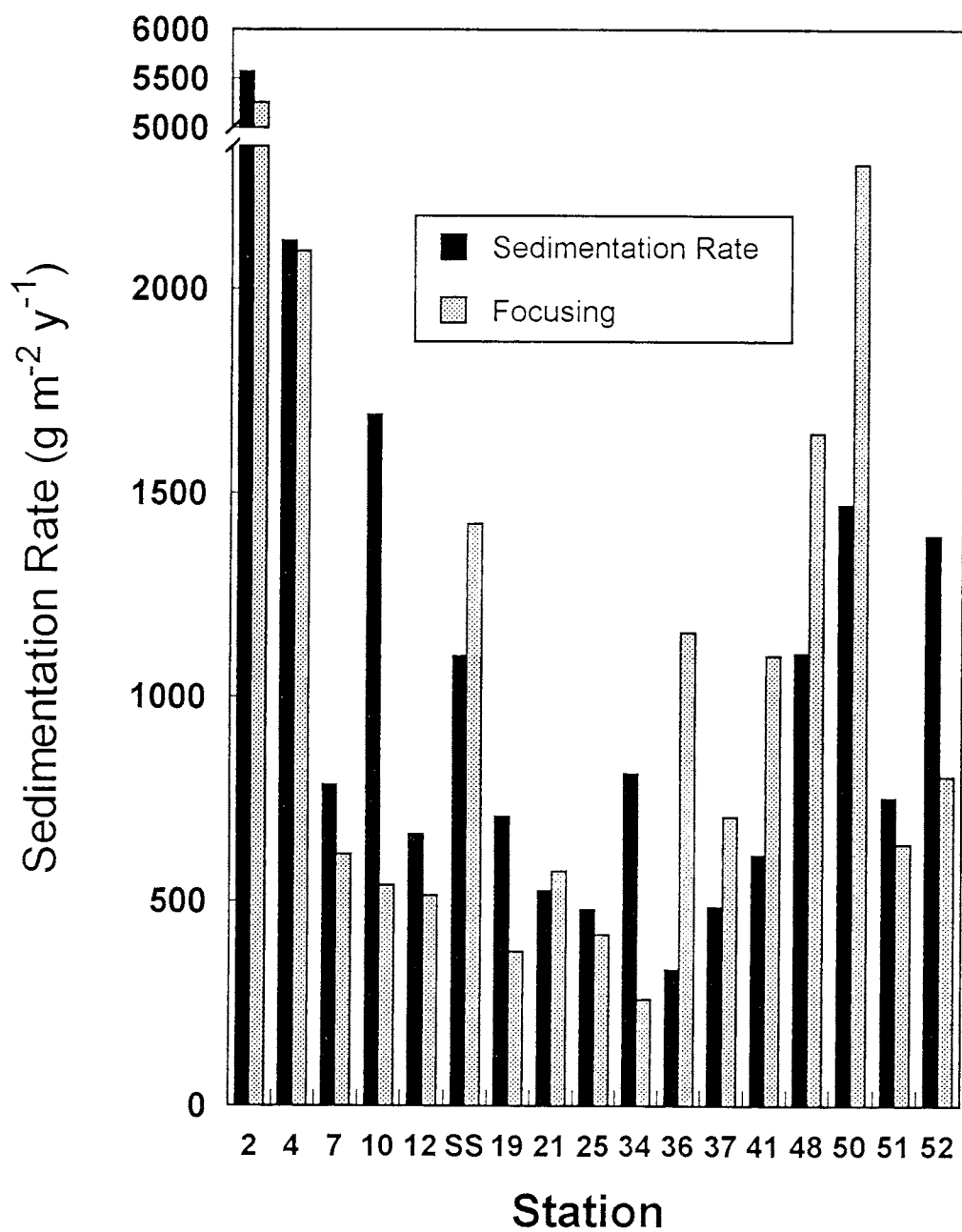


Figure VII-5. Bar graph showing ^{210}Pb -estimated sedimentation rates and the focusing-normalized rate.

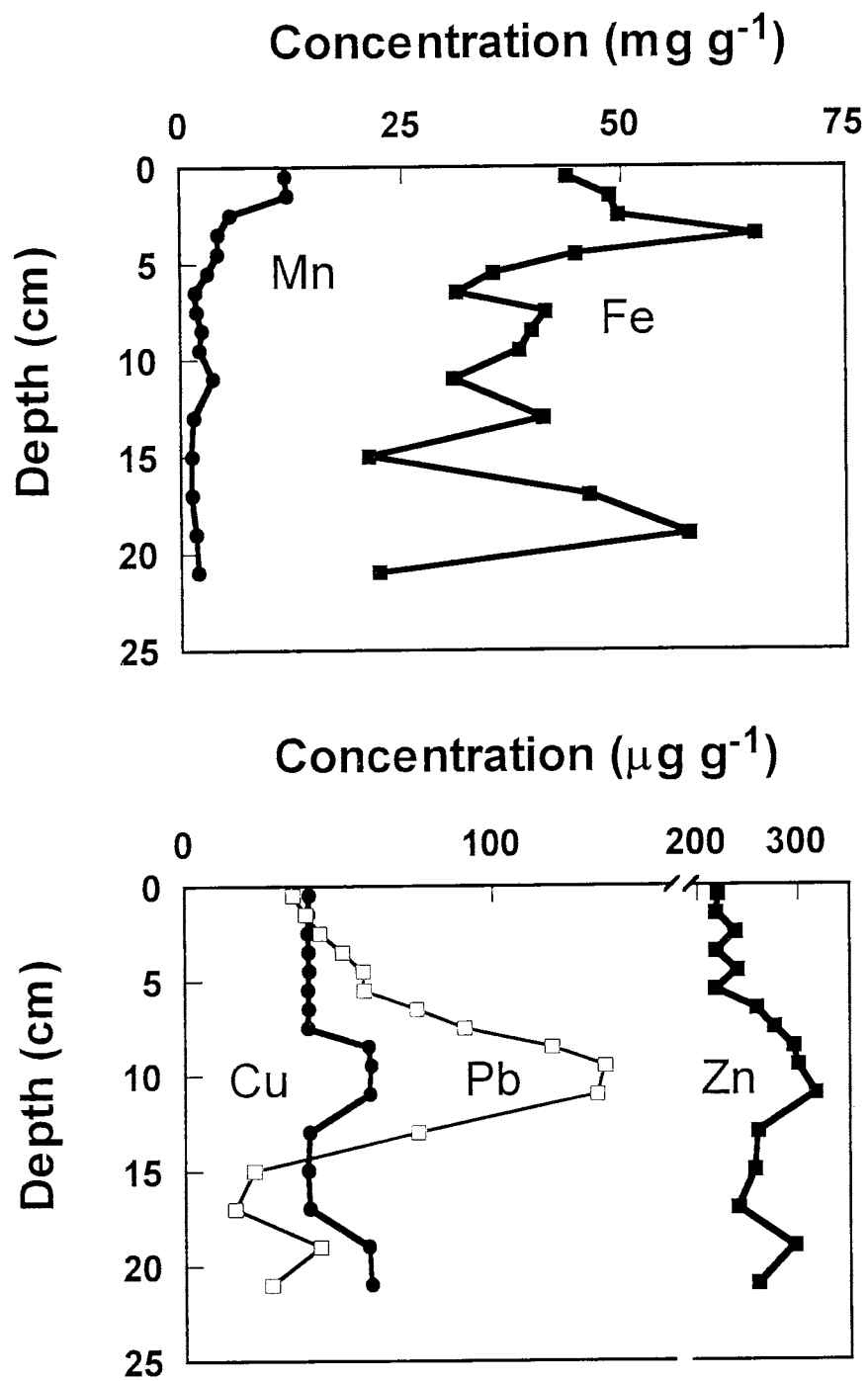


Figure VII-6. Vertical profiles of Mn, Fe, Cu, Pb and Zn at station 19.

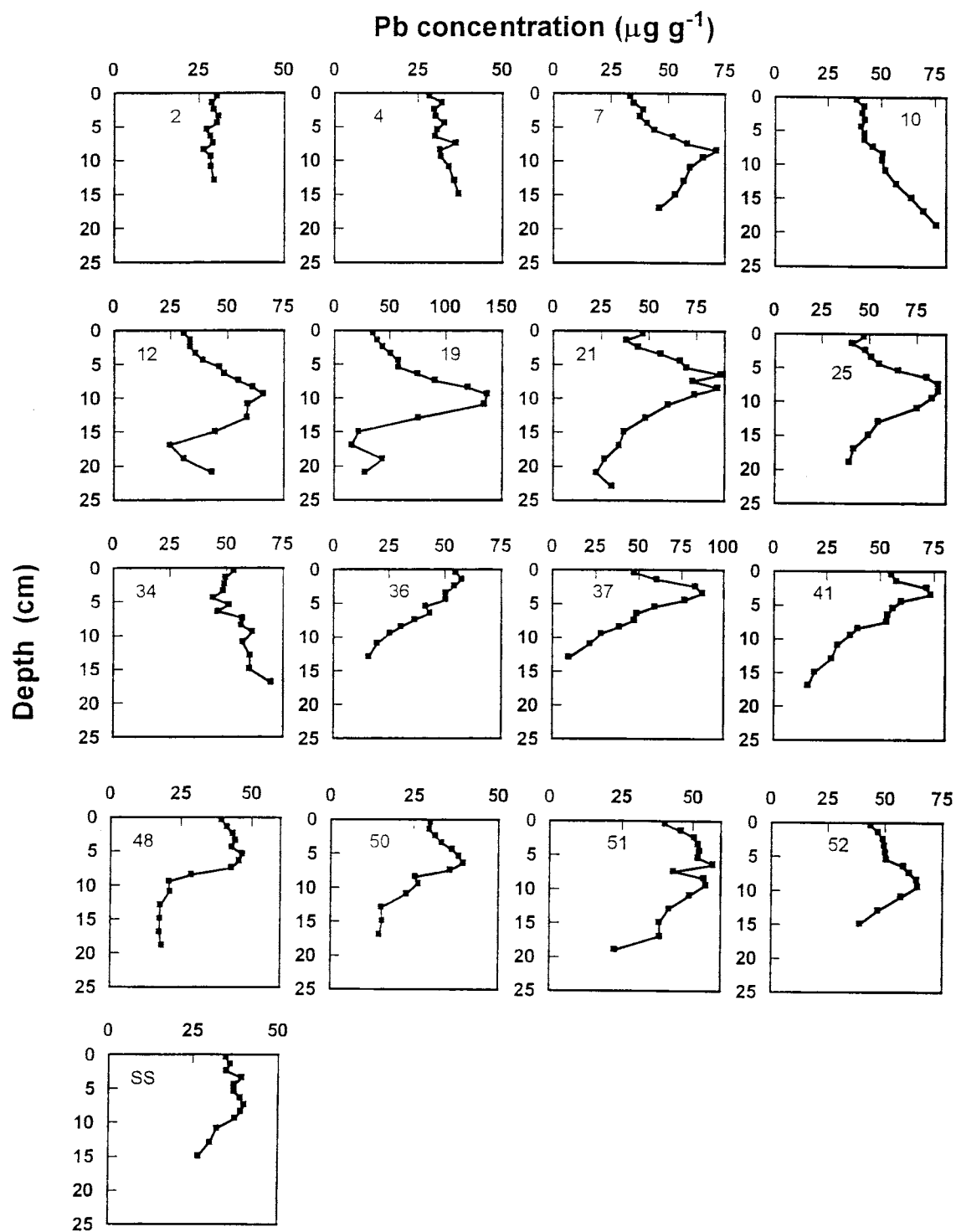
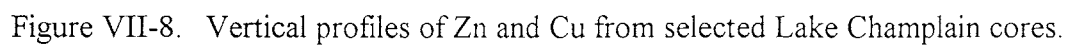


Figure VII-7. Vertical profiles of Pb from all Lake Champlain ^{210}Pb -dated cores.



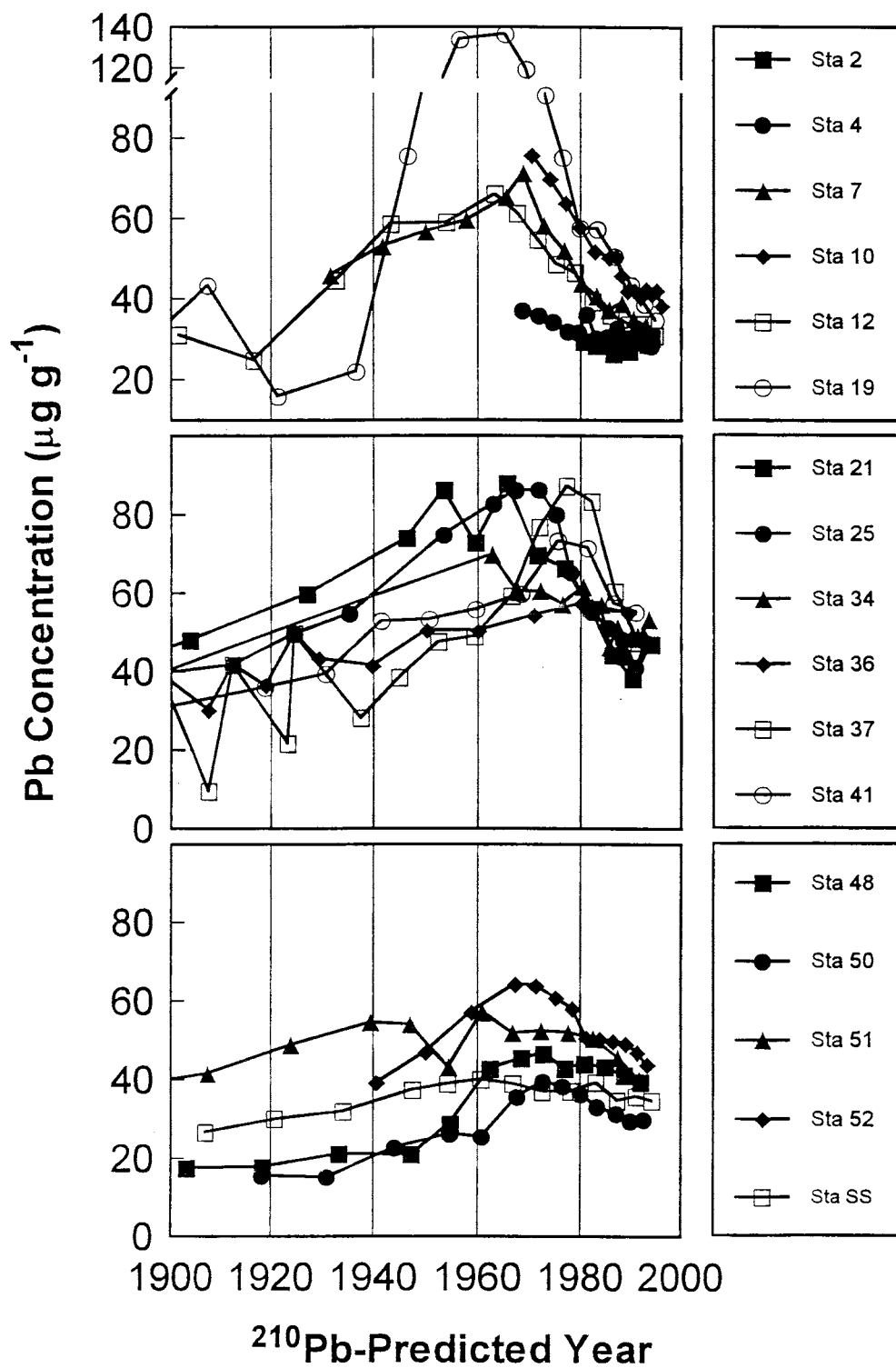


Figure VII-9. Concentration of total sediment Pb plotted as a function of ^{210}Pb -estimated year.

Chapter VIII The Role of Sedimentary Processes in the Lake Champlain P Cycle

The treatment of pools and rates in the previous chapters of this report has been largely qualitative, with an emphasis on spatial and temporal variability in the data. The goal of this chapter is to use these data to address three key questions on the role of sediment P cycling processes in the overall Lake Champlain P cycle. These questions are:

1. At what rate is phosphorus being buried in Lake Champlain sediments? The spatial pattern of such burial is of considerable interest to understanding the P cycle, and a whole lake burial estimate can be compared to mass balance estimates of P retention in the lake.
2. Do pore water-estimated phosphorus fluxes compare well with direct sediment-water exchange measurements? Does our data indicate what processes control SRP fluxes and solid phase P distributions?
3. Is sediment recycling of P to the water column an important process in Lake Champlain?

A considerable amount of data on the distribution of metal oxides (Mn, Fe) and nitrogen has been generated as part of this study. For the purposes of this chapter, the focus will be upon the fluxes of P in Lake Champlain, and these other data will be used only to set the stage for a better understanding of P cycling.

Phosphorus Burial In Lake Champlain Sediments

Calculation of Phosphorus Burial Rates

At each site, the estimation of P burial rates can be calculated simply as:

- 1) Burial rate ($\text{mg P m}^{-2} \text{ y}^{-1}$) = mass sedimentation rate ($\text{g m}^{-2} \text{ y}^{-1}$) * P concentration (mg g^{-1})

This should be a simple calculation, but it is complicated by considerable difficulty in choosing a P concentration. In many cores, there are large changes in P concentration within the top 10 cm of sediment below the sediment-water interface. The influence of Fe cycling on solid phase inorganic P distribution has been shown to be considerable in many cores (Chapter VI). In lake ecosystems unperturbed by anthropogenic inputs, choosing a P concentration below the most active zone of P diagenesis can provide a reliable estimate of P burial (Cornwell 1987). In lakes with increased P inputs from anthropogenic sources, P burial calculated from horizons with lower P concentrations may not effectively reflect these recent (20th century) inputs. This approach would yield a P burial estimate lower than the "true" current rate. Inclusion of the higher P concentrations near the sediment-water interface may result in a large overestimate of the P burial rate, with diagenetic enrichments being included in the burial rate. Several different calculation approaches are shown in Table VIII-1.

Table VIII-1. Phosphorus burial rates. The sedimentation rate data has both the direct site estimate and the "focusing"-corrected rate. Phosphorus concentrations are the minimum, maximum and mean (0-10 cm) P concentrations within each profile, the standard deviation is also presented. The P burial rates and focus-corrected P burial rates are calculated from mass sedimentation rates times the maximum, minimum or average P concentrations.

Station	Sedimentation Rate		P Concentration				P Burial Rates			Focus-Corrected P Burial Rates	
	Sed Rate	Focus	Max	Min	Ave	S.D.	Max	Min	Ave	Ave.	Min
	$\text{g m}^{-2} \text{y}^{-1}$	$\text{g m}^{-2} \text{y}^{-1}$	mg g^{-1}	mg g^{-1}	mg g^{-1}	mg g^{-1}	$\text{g m}^{-2} \text{y}^{-1}$	$\text{g m}^{-2} \text{y}^{-1}$	$\text{g m}^{-2} \text{y}^{-1}$	$\text{g m}^{-2} \text{y}^{-1}$	$\text{g m}^{-2} \text{y}^{-1}$
2	5567	5255	1.02	0.69	0.78	0.05	5.68	3.84	4.34	4.10	3.63
4	2118	2092	1.30	0.99	0.89	0.08	2.75	2.10	1.89	1.86	2.07
7	784	615	2.33	0.78	1.34	0.54	1.83	0.61	1.05	0.82	0.48
10	1690	539	1.89	1.42	1.67	0.17	3.19	2.40	2.82	0.90	0.77
12	664	513	2.37	0.83	1.60	0.47	1.57	0.55	1.06	0.82	0.43
SS	1100	1425	1.28	0.88	1.05	0.15	1.41	0.97	1.16	1.50	1.25
19	707	377	1.82	0.80	1.61	0.46	1.29	0.57	1.14	0.61	0.30
21	525	573	2.36	0.83	1.48	0.55	1.24	0.44	0.78	0.85	0.48
25	479	419	4.97	1.35	1.88	1.29	2.38	0.65	0.90	0.79	0.57
34	811	260	3.64	2.26	2.84	0.45	2.95	1.83	2.30	0.74	0.59
36	333	1158	1.84	1.12	1.40	0.23	0.61	0.37	0.47	1.62	1.30
37	485	705	1.57	0.82	1.26	0.28	0.76	0.40	0.61	0.89	0.58
41	612	1100	1.30	0.86	1.06	0.16	0.80	0.53	0.65	1.17	0.95
48	1106	1646	1.75	0.76	0.93	0.18	1.94	0.84	1.03	1.53	1.25
50	1470	2306	1.32	0.64	0.76	0.12	1.94	0.94	1.12	1.75	1.48
51	752	638	1.35	0.70	1.07	0.22	1.02	0.53	0.80	0.68	0.45
52	1394	804	1.37	0.75	1.02	0.20	1.91	1.05	1.42	0.82	0.60
Ave.	939	948	2.03	0.99	1.37	0.35	1.72	0.92	1.20	1.08	0.85
S.D.	501	622	1.00	0.40	0.51	0.30	0.79	0.63	0.64	0.42	0.49
Med	784	705	1.75	0.83	1.26	0.22	1.83	0.65	1.06	0.89	0.60

The sedimentation rates are the direct ^{210}Pb calculated mass burial rate as well as the focusing-corrected mass burial rate; the latter rate may be more representative of the regional rate at each site. In some cases, this correction may considerably reduce the rate of sedimentation (e.g. stations 10, 34) while in others, the rate increases (e.g. 36, 41). The lake-wide average rate is largely unchanged with this normalization procedure.

The phosphorus concentrations represent the maximum, minimum and average (0-10 cm) concentration within the sediment profile. The minimum and maximum concentrations are almost certainly underestimates and overestimates of the modern P burial rate. The average rate may be more representative, but in cores with considerable P mobility, average concentrations may overestimate the concentration of P that is buried. A lake-wide average estimate of average sediment total P concentration is $1.37 \pm 0.51 \text{ mg g}^{-1}$, about 38% higher than the lake-wide minimum concentration average and about 67% of the lake-wide maximum P concentration average. Several stations (7, 12, 19, 21, 25, 48, 50) have maximum P concentrations that exceed

the minimum concentrations by 2 fold.

The overall effect of choosing different P concentrations is illustrated in Figure VIII-1 and Table VIII-1. While the choice of P concentration can make a difference at some sites, considerable differences exist for many sites. The maximum concentration-based P burial rates are probably the least realistic of the estimates. Phosphorus burial estimates based on average P concentrations averaged $1.20 \pm 0.64 \text{ g m}^{-2} \text{ y}^{-1}$. When the average P concentrations are used with focusing-corrected sedimentation rates, the P burial rate drops to $1.08 \pm 0.42 \text{ g m}^{-2} \text{ y}^{-1}$.

The lake-wide pattern in P burial shows high burial rates in the south lake and no clear pattern in the rest of the lake (Figure VIII-2). Compared to the non-normalized P burial rates, the focusing-based rates tend to have fewer extreme rates, but higher variability on the local scale (Missisquoi Bay).

Comparison to Whole-Lake Phosphorus Mass Balances

Whole-lake P burial rates are based upon the estimates at each site, which can be quite variable. Taking the average burial rates for each calculation approach can be problematic, since some lake segments are over-represented (e.g. Missisquoi, St. Albans) while many others have single or no data points. In Table VIII-2, the mean rates from Table VIII-1 are presented with whole lake estimates based on spatial normalization and whole lake mass balances (NY/VT 1994). The spatially-normalized data are based upon the surface areas for different lake model segments (NY/VT 1994), with focusing-normalized mean P burial rates calculated for each segment. We had no cores for ~20% of the lake area. The calculation using lake segment areas yielded a P burial rate that is 87% of the average rate for all cores, a modest difference.

Table VIII-2. Lake Average P Burial Estimates. The mass balance data is from the 1994 NY/VT phosphorus budget.

Overall Approach	Calculation Based Upon:	Lake-Wide P Burial Estimate ($\text{g P m}^{-2} \text{ y}^{-1}$)
Lake-Wide Flux Average (All Cores)	Maximum P Concentration	1.72 ± 0.79
	Minimum P Concentration	0.92 ± 0.63
	Average P Concentration	1.20 ± 0.64
	Focusing, Minimum P Concentration	0.85 ± 0.49
	Focusing, Average P Concentration	1.08 ± 0.42
Spatially-Normalized Burial Flux	Focusing, Average P Concentration, 13 Lake Segments	0.94
Published Lake Wide Mass Balance	Difference between all measured P inputs and output	0.63

The spatially-normalized estimate is about 50% higher than the mass balance estimate. This difference between burial estimates and the mass balance estimate is not particularly alarming considering:

1. The sediment estimate is based on only 17 cores. Considering that a number of the cores were collected to emphasize high water column P lake segments, and that these segments do not comprise a large proportion of the lake area, this is a very minimal number of cores for a 170 km long lake.
2. Sedimentation estimates are generally long-term estimates, recent improvements in waste water treatment and the phosphate detergent ban should result in recent decreases in P burial. Such changes might not be identifiable in these cores.
3. There is considerable uncertainty in estimating the amount of P buried in each core. It is easy to construct scenarios of changing P inputs that would result in either high or low estimates of P retention in the lake.
4. The whole lake mass balance estimates are for a single year and have the potential for error.

Overall, the level of agreement is generally encouraging. Given the uncertainties of calculating P burial in a single core, refinement of this estimate with more sample sites may require a relatively large effort with only a modest potential for improvement. This study is consistent with the sediment retention of a high proportion of Lake Champlain P inputs. The NY/VT (1994) study estimated a P retention of ~80%; this study would predict a retention of 120%. A higher sediment-based estimate has been observed in mass balance studies in other lakes (Dillon and Evans 1993).

Linking Pore Water Chemistry and Sediment-Water Phosphorus Exchange

The pore water SRP data can be used qualitatively as an indicator of the SRP that is remineralized or remobilized; it can also be used quantitatively to calculate the flux of P within pore water (i.e. Baccini 1986; Cornwell 1987; Klump et al. 1997):

$$J = \Delta[\text{SRP}] / \Delta x * D_s * \phi$$

where J is flux in units of mass per area per time, x is depth (cm) and ϕ is sediment porosity. The diffusion coefficient D_s is calculated from tabulated tracer diffusion coefficients (Li and Gregory 1974) corrected for temperature (D_t), with a correction for sediment tortuosity following Ullman and Aller (1982):

$$D_s = D_t * \phi^2$$

We have ignored the effects of ion pairing on diffusion coefficients and have used the mean D_t 's of $H_2PO_4^-$ and HPO_4^{2-} . The influence of the benthic boundary layer on diffusion is not included in this calculation.

Two pore water flux estimates are present in Table VIII-3. The maximum fluxes are those calculated from the maximum pore SRP gradient, regardless of the depth at which it occurs. The interfacial flux calculation is based on the flux from the 0.0-0.5 cm pore water horizon to overlying water. For consistency with the flux data, pore water fluxes have units of $\mu\text{mol m}^{-2} \text{h}^{-1}$. The gradient used in this interfacial flux calculation may be expressed:

$$\Delta[\text{SRP}]/\Delta x = \Delta[\text{SRP}]/0.25 \text{ cm}$$

where $\Delta[\text{SRP}]$ has units of nmol cm^{-3}

Table VIII-3. Estimates of P diffusion in Lake Champlain pore waters. The interfacial rate is based on the gradient between surficial (0.0-0.5 cm) pore water concentrations and overlying water concentrations; the maximum pore water flux is the maximum section-to-section flux within the core and in some cases, the maximum flux is the interfacial flux. The fluxes from the sediment-water exchange experiments are also presented.

Station	Month	Pore Water	Pore Water	Sediment-Water Exchange	Station	Month	Pore Water	Pore Water	Sediment-Water Exchange
		Interface	Maximum				Interface	Maximum	
		$\mu\text{mol m}^{-2} \text{h}^{-1}$					$\mu\text{mol m}^{-2} \text{h}^{-1}$		
2	April 95	1.2	10.0	0.5	2	Oct 94	5.0	5.0	0.0
7	April 95	0.0	1.5	4.2	7	Oct 94	1.0	3.6	0.0
37	April 95	0.7	0.7	1.5	37	Oct 94	0.4	2.1	2.0
41	April 95	1.0	1.0	0.0	41	Oct 94	0.1	0.6	0.4
50	April 95	0.5	0.5	0.3	50	Oct 94	0.5	0.6	0.9
51	April 95	0.8	1.5	0.7	51	Oct 94	3.9	3.9	1.2
2	July 94	10.1	10.1	2.7	2	Aug 96	1.1	4.1	2.5
4	July 94	0.9	0.9	0.7	7	Aug 96	3.7	4.1	2.1
7	July 94	1.0	3.7	3.1	37	Aug 96	3.4	5.5	6.6
25	July 94	1.0	5.0	0.0	41	Aug 96	9.4	9.4	8.6
33	July 94	2.7	2.7	0.0	50	Aug 96	1.4	2.5	6.2
34	July 94	3.3	4.5	1.4	51	Aug 96	3.7	3.7	10.7
36	July 94	1.1	1.5	0.0					
37	July 94	1.7	1.7	3.9	SS	Sept 96	0.5	1.2	0.6
40	July 94	2.6	2.6	1.6	10	Sept 96	0.8	2.7	0.4
41	July 94	5.7	5.7	3.5	12	Sept 96	1.0	3.0	0.3

48	July 94	3.0	5.0	0.0		19	Sept 96	0.4	2.1	0.4
50	July 94	9.3	9.3	31.1		21	Sept 96	0.8	1.6	0.9
51	July 94	11.0	11.0	2.1						
52	July 94	5.0	6.4	4.3						

The maximum pore water flux rates often occur at the sediment-water interface for the six main stations (Figure VIII-3). On most sample dates, the maximum upward SRP flux rates are found below the sediment water interface at station 7. A high upward flux of SRP within the core would be a strong indication of inorganic P remobilization within the core; the station 7 solid phase data shows a strong Fe-P correlation and upward fluxes of both Fe and P result in their enrichment near the sediment-water interface.

Estimates of pore water fluxes often do not correspond with measured fluxes. When the apparent diffusion-driven fluxes across the interface are higher than the measured fluxes, SRP adsorption near the sediment-water interface is indicated (Cornwell 1987). When sediment-water exchange rates are higher than interfacial diffusion-driven fluxes, there may be 1) a high rate of P production in interfacial flocculent material that supplies SRP with minimal interaction with pore water (see discussion in Callender and Hammond 1982), 2) the direct influence of organism (bivalves) on SRP fluxes (Chapter III), or 3) an advective process such as bioirrigation (Krezoski et al. 1982) or methane ebullition (Kipphut and Martens 1982) which exchanges water and solutes at rates in excess of diffusion.

A comparison of the P fluxes estimated from interfacial pore water diffusion, maximum pore water diffusion and sediment water exchange experiments is shown in Figure VIII-4; the data presented are for July 1994 and September 1996 surveys. In general, surficial pore water SRP flux estimates equal or exceed those from the sediment-water exchange experiment; exceptions are stations 7, 37, and 50. For stations, 4 10, SS, 19, 21, and 52, the pore water and flux experiment estimates are virtually identical; the use of pore water data would thus provide good estimates at 6 stations, provide underestimates at 3 stations, and provide overestimates at 10 stations.

The surficial diffusive P fluxes exceed the experimental flux rates (Figure VIII-5) most of the time; most of the points in which the experimental flux rates exceed the pore water diffusive fluxes are from the main stations in July 1994 and August 1996. Interestingly, these sites are all characterized by relatively high water column SRP concentrations.

Is Sediment Recycling of Phosphorus an Important Process in Lake Champlain?

This question posed by this section heading is really the key question of this entire measurement program. All of the analyses of P burial, pore water chemistry and sediment water exchange were designed to address this question. As with the estimates of P burial, it is possible to make only a first-order whole lake P recycling estimate.

While it is clear that sediment burial in Lake Champlain is a major part of the phosphorus cycle, the importance of P recycling fluxes is somewhat harder to evaluate. Examining the main stations, annual average SRP release from sediments averaged $46 \pm 11\%$ of P deposition (Table VIII-4; Figure VIII-6). This is a relatively high percentage of release, especially considering the considerable recycling of adsorbing metal oxides, particularly Fe, in surficial sediments. Summer P release at the main stations averaged $58 \pm 11\%$ of deposition, while the average of all other stations was considerably lower ($11 \pm 13\%$). The main stations were chosen because of a concern that sediments could be a relatively important P source at these sites; in comparison to the other sites located throughout the lake, these sites have relatively high recycling rates.

Table VII-4. Annual and summer sediment water SRP exchange, sediment P burial, P deposition and percent P recycling for the main stations and "extra" stations in this study. Phosphorus deposition is calculated as the sum of P burial and SRP sediment-water exchange rates.

Station	Average SRP Sediment-Water Exchange	P Burial (From Average P in Top 10 cm)	P Deposition (Exchange + Burial)	Percent Recycled
	$\mu\text{mol m}^{-2} \text{h}^{-1}$			
2	7.36	16.00	23.36	32
7	3.02	3.70	6.72	45
37	2.12	2.25	4.37	48
41	3.05	2.39	5.44	56
50	2.32	4.12	6.43	36
51	4.24	2.97	7.20	59
Ave. \pm S.D.	3.68 ± 1.95	5.24 ± 5.32	8.92 ± 7.14	46 ± 11
July 1994, August /September 1996 Data				
Main Stations	6.91 ± 5.98	5.27 ± 5.31	12.18 ± 6.77	58 ± 26
"Extra" Stations	0.81 ± 1.23	5.01 ± 2.59	5.83 ± 3.08	11 ± 13

The summer P exchange rates have considerable variability throughout Lake Champlain (Figure VIII-7), with the lowest rates in the mid-lake region. If annual rates are expressed on an hourly basis, both the absolute rate of P sediment-water exchange and the proportion of P deposition that is recycled clearly is highest in the more northerly sites. The relative estimate of

recycling rate is considerably higher in summer than in annual rates for the main stations, reflecting the importance of temperature as a control of sediment processes. It is also likely that water filtration and nutrient recycling by bivalves in the shallow water main sites may also increase the efficiency of recycling.

On average, the summer percent recycled P averaged $28 \pm 29\%$ of annual P deposition. With 1) higher sediment-water exchange rates in the summer and 2) a spatially over-represented number of stations with a high proportion of sediment P recycling, this value is undoubtedly represents an upper limit. Sediment-water exchange in the summer averages $2.97 \mu\text{mol m}^{-2} \text{h}^{-1}$, while annual P inputs expressed on an areal basis are $2.88 \mu\text{mol m}^{-2} \text{h}^{-1}$. If one considers the "extra" stations, the average sediment water exchange averages $0.81 \mu\text{mol m}^{-2} \text{h}^{-1}$. The lower value is probably more realistic for a whole lake estimate; using this lower value results in a sediment P source that is 28% of terrestrial and atmospheric sources. The previous mass balance comparison between whole lake estimates and P burial suggested our P burial estimates may be high. Similarly, the whole system P recycling estimates may be high.

The high rates of sediment P recycling at the shallow water main sites clearly contribute to the higher concentrations of water column SRP observed at all of these sites. Sediment recycling of P at these sites is generally more "efficient", while retention and permanent burial is less efficient.

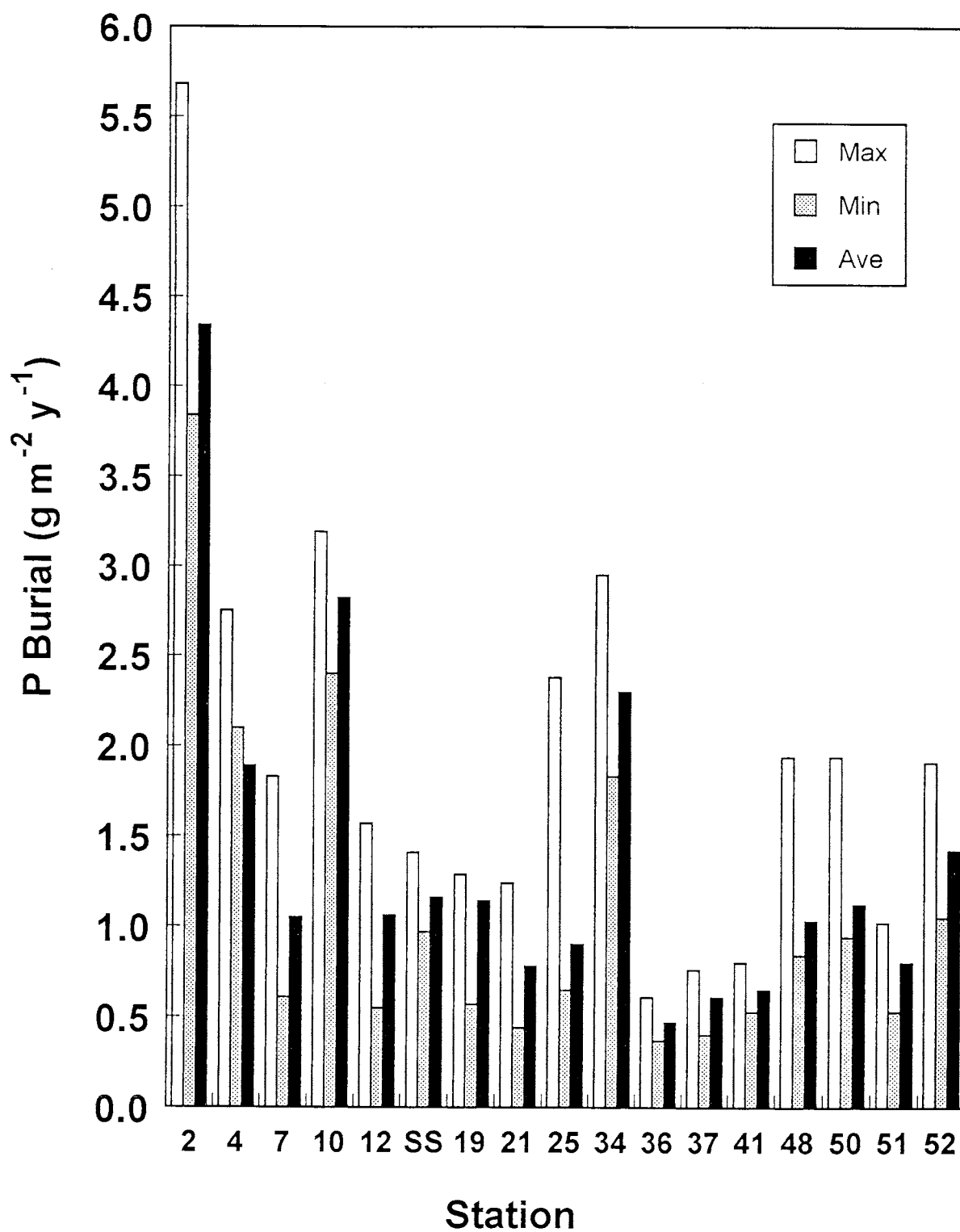


Figure VIII-1 Lake-wide P burial by station. Rates are based on the maximum, minimum and average (0-10 cm) P concentrations found in each core.

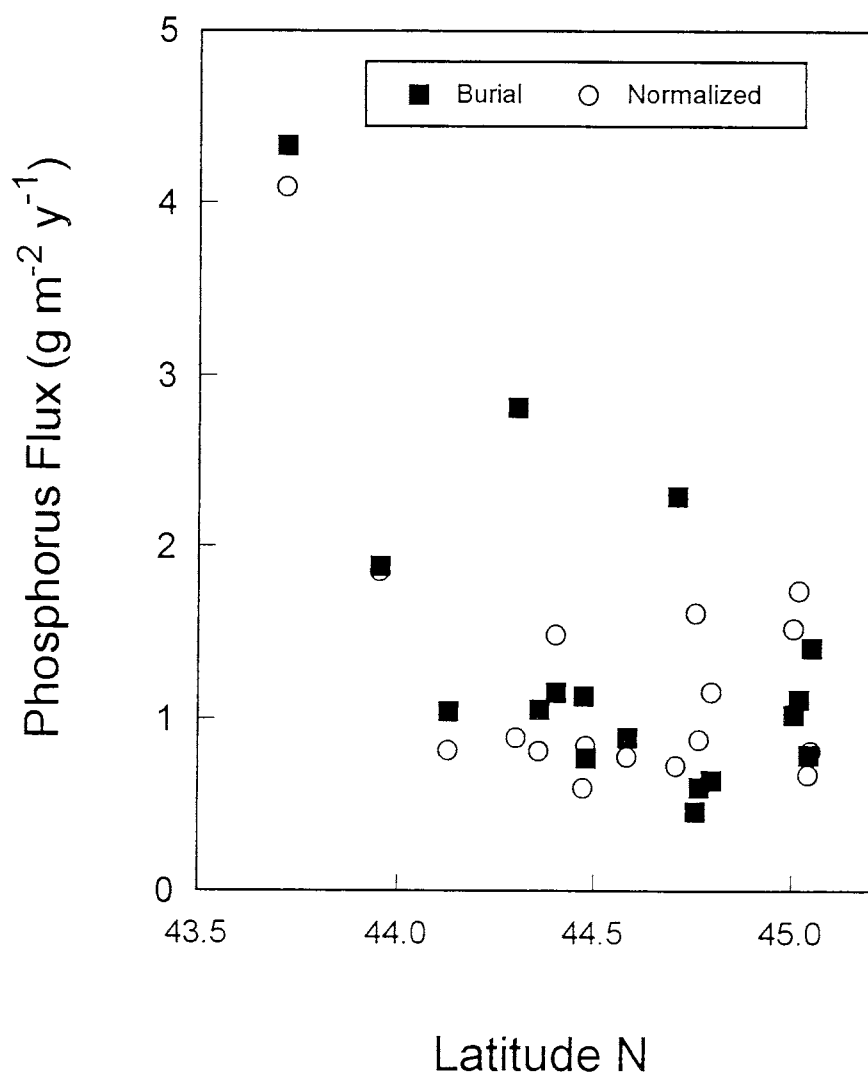


Figure VIII-2 Phosphorus burial rates as a function of latitude. “Normalized” rates take into account ^{210}Pb -based focussing estimates.

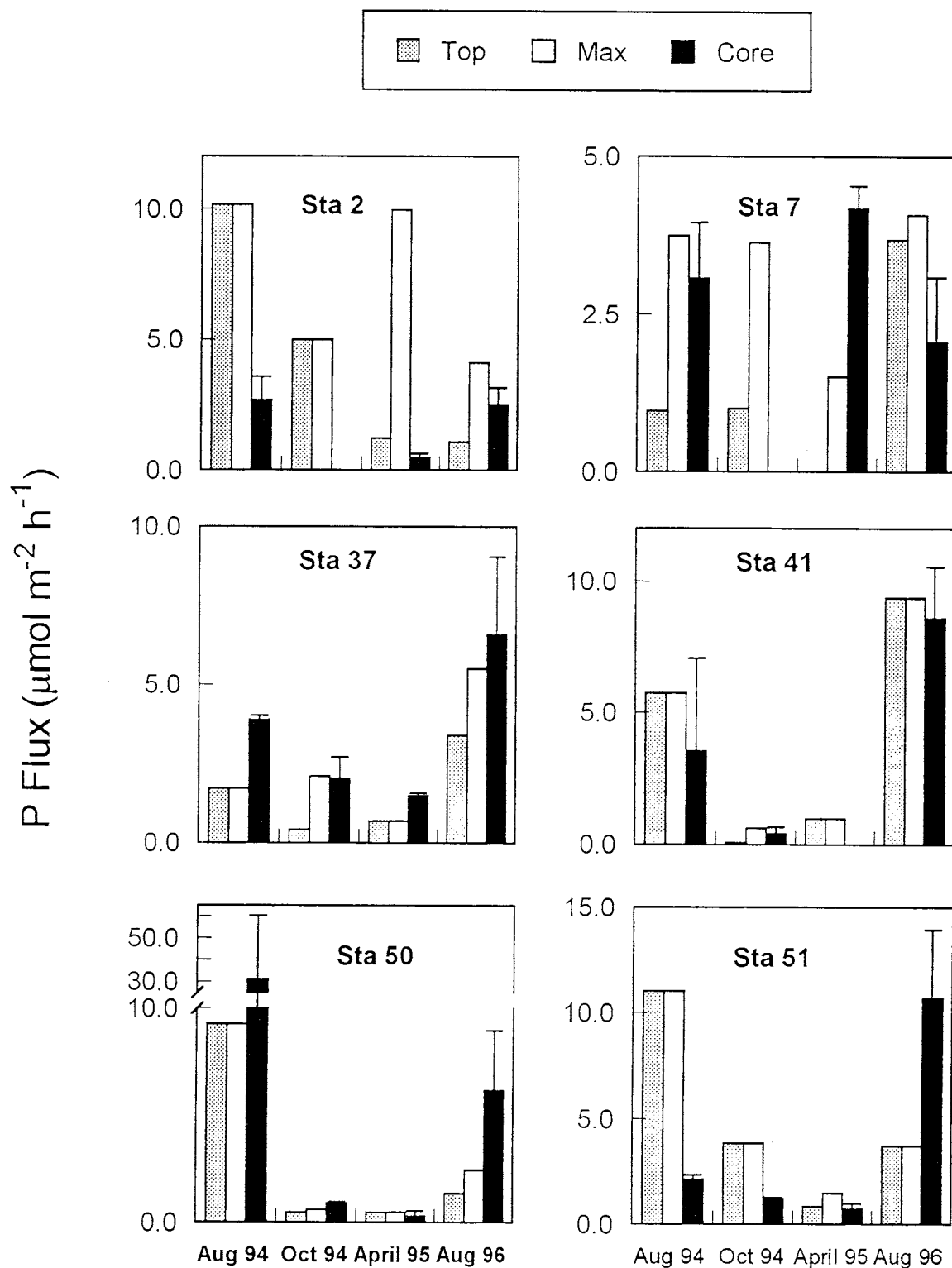


Figure VIII-3 Fluxes of SRP in the 6 main stations. Top and Max fluxes correspond to the pore water diffusive fluxes calculated from 1) pore water gradients at the sediment-water interface and 2) the maximum pore water gradient in the core, regardless of depth. Core fluxes are the incubated sediment-water exchange numbers.

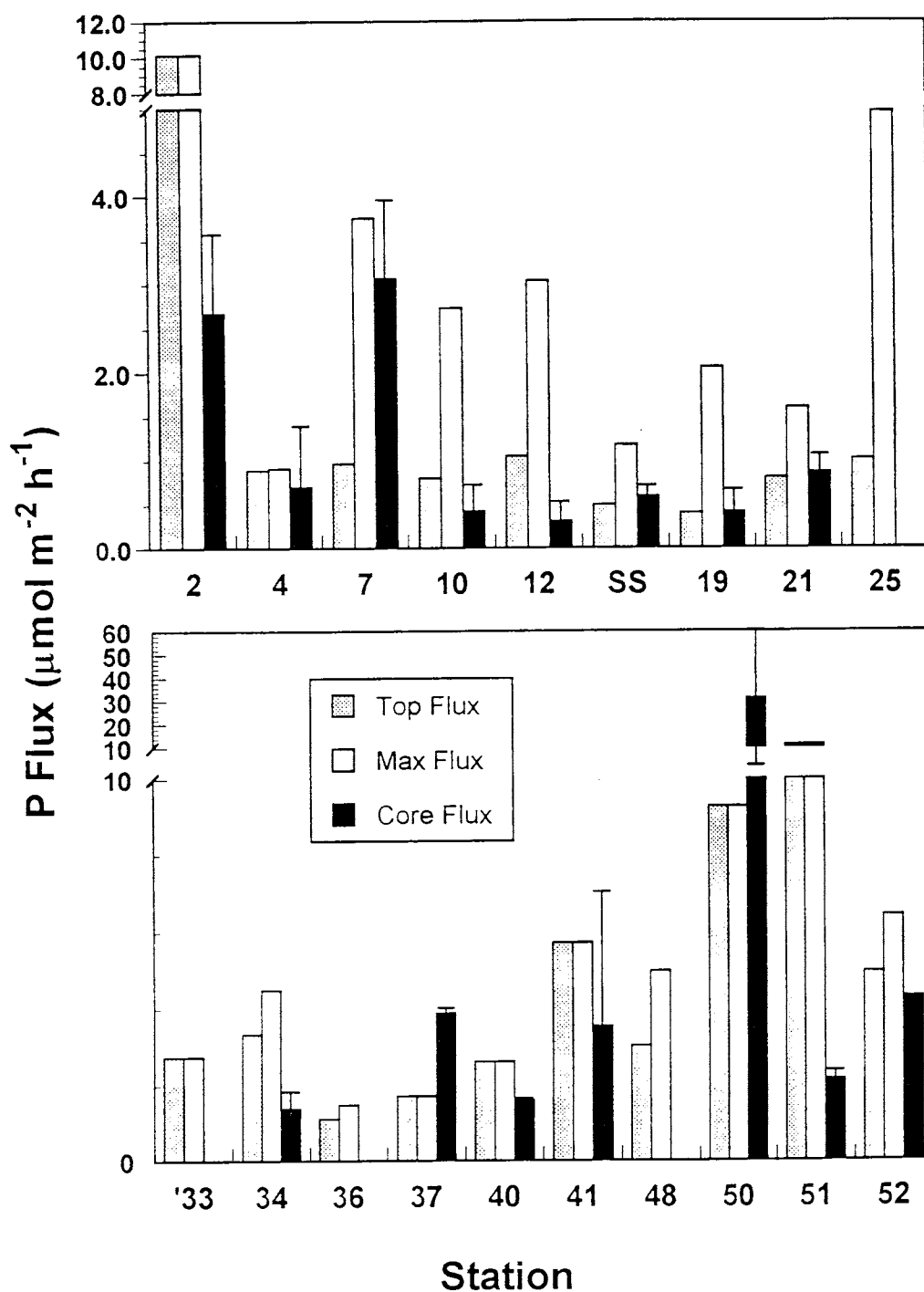


Figure VIII-4 Summer fluxes of SRP at all stations. Most of the data are from July 1994; stations SS, 10, 12, 19 and 21 are from September 1996. Top and Max fluxes correspond to the pore water diffusive fluxes calculated from 1) pore water gradients at the sediment-water interface and 2) the maximum pore water gradient in the core, regardless of depth. Core fluxes are the incubated sediment-water exchange numbers.

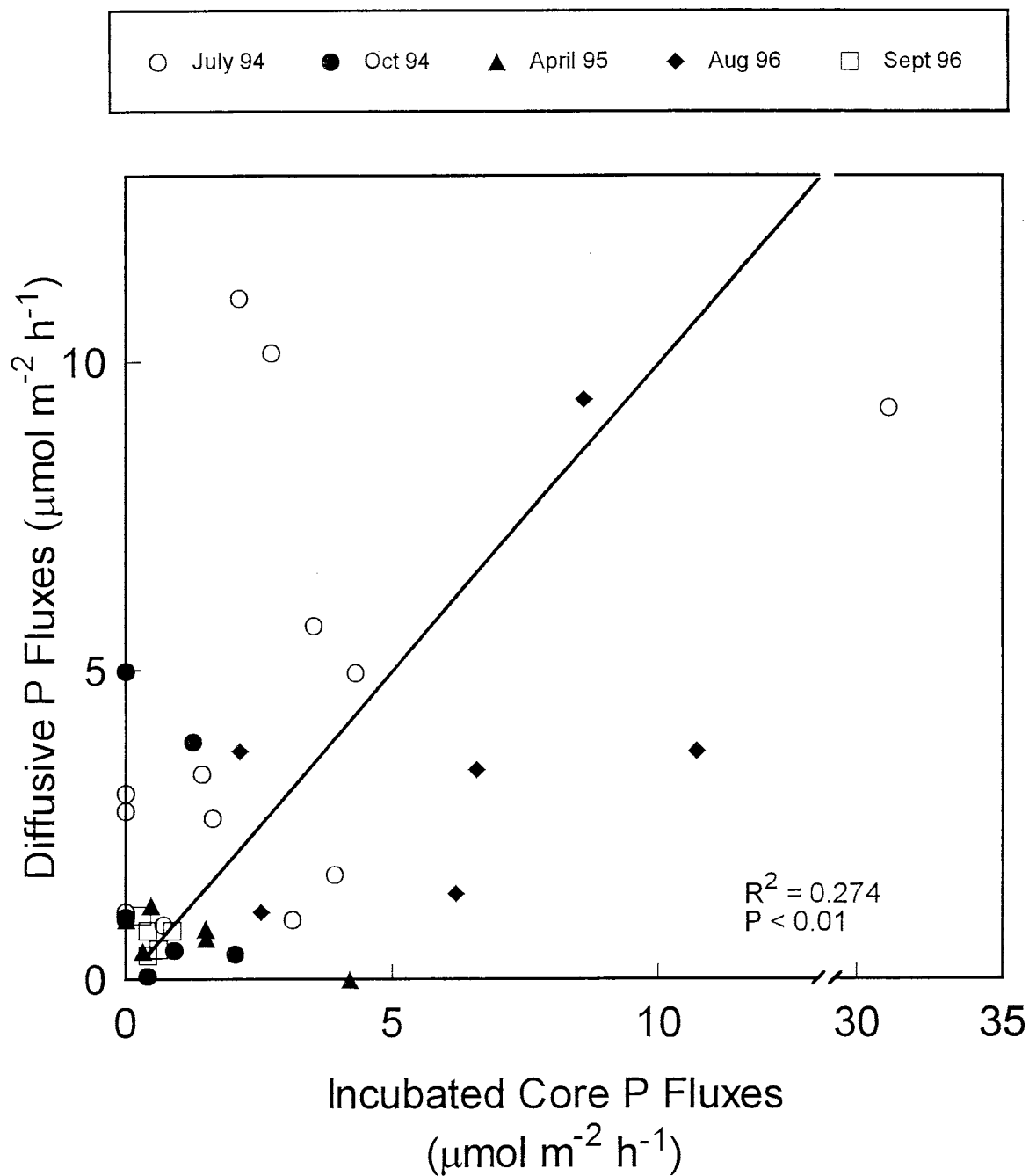


Figure VIII-5 Sediment-water exchange P fluxes versus the fluxes calculated from surficial sediment pore water gradients. The line represents equal fluxes for each technique.

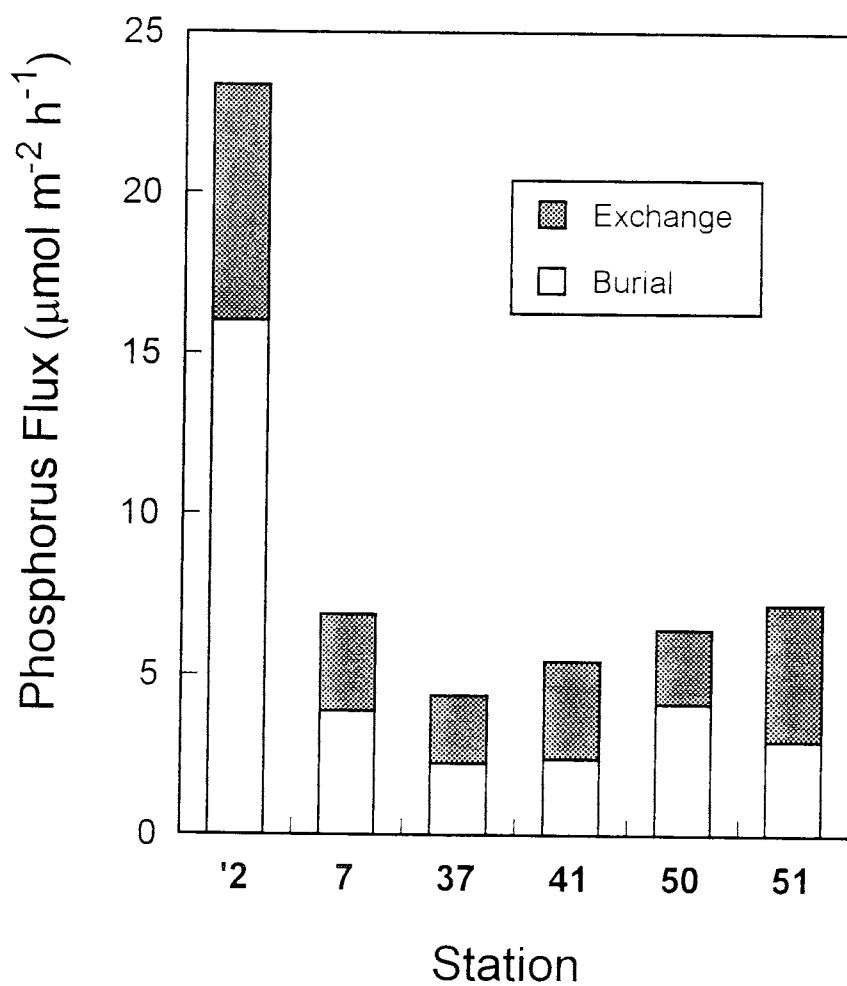


Figure VIII-6 Annual sediment-water exchange estimates and burial estimates for P at the 6 main sites. The sum of exchange and burial rates is the rate of P deposition to the sediments. The exchange rates are annual means of summer (July 1994, August 1996), fall (October 1996) and spring (April 1995) flux rates.

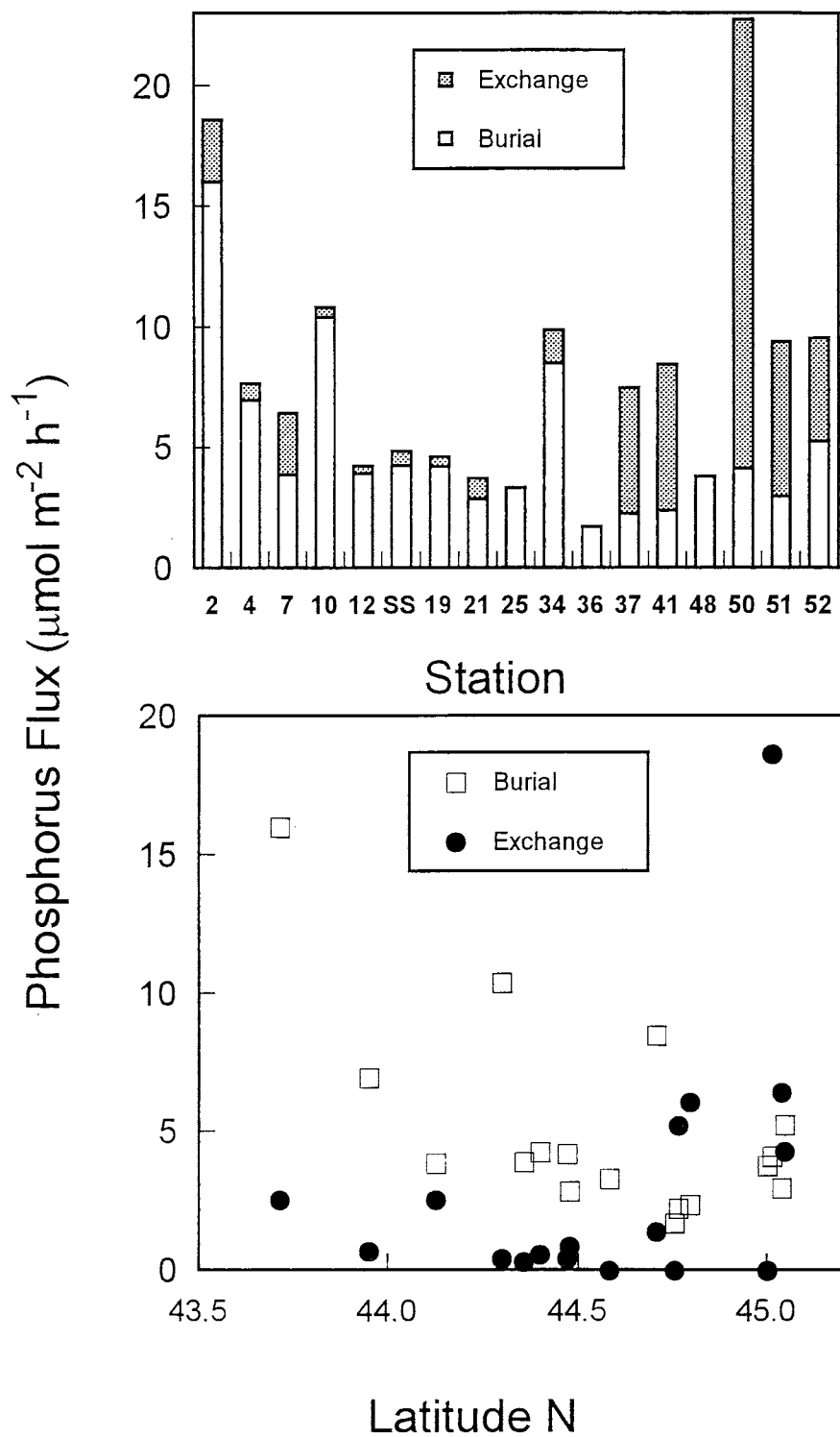


Figure VIII-7 Annual P burial rates and summer P fluxes for the main stations, plotted as a function of station ID and latitude. For the main sites (2, 7, 37, 41, 50, 51), summer rates are the average of data from July 1994 and August 1996; all other data are from July 1994 (4, 25, 34, 36, 48, 52) or September 1996 (SS, 10, 12, 19, 21).

Chapter IX Conclusions and Recommendations

This research program has generated a considerable amount of new information on Lake Champlain sediments, and has provided a first order understanding of sediment phosphorus burial and recycling fluxes. The data generally hang together very well, and identify a system with generally low rates of sediment organic matter and P cycling. Some of the main conclusions are:

- 1) The rate of sediment-water P exchange is generally low throughout most of the lake; in Missisquoi Bay, St. Albans Bay, and the South Lake segment, the rates are higher than in other parts of the lake.
- 2) On average, about half of the P that is sedimented in our intensive eutrophic stations was recycled back to the water column; the average throughout the rest of the lake was 11%. Clearly, the sediment P retention efficiency in the eutrophic parts of the lake is poor.
- 3) Sediment dating using ^{210}Pb appears to provide reasonable sedimentation rates, predicting very well the continental temporal pattern of lead inputs.
- 4) The calculated P burial rates are slightly higher than those predicted by the whole lake P mass balance study.

Our recommendations for further study primarily involve a need for a better spatial view of the Lake Champlain sediment P cycle. Specific recommendations include:

- 1) While Missisquoi Bay has enough sediment stations, a spatially detailed study of sediment-water P exchange and burial in St. Albans Bay would provide a better understanding of the future of the P cycling in a system with decreased P inputs.
- 2) Some areas of the lake were not studied at all (e.g. Isle LaMotte) or with very few sites (the northern main lake segment, the south lake areas) and this study may not be representative of the actual rates in those areas.
- 3) Bivalves may have a profound impact on P recycling in St. Albans Bay and Missisquoi Bay; our study indicates they may be important, but we cannot estimate their importance.
- 4) Differences in the main station fluxes between 1994 and 1996 suggest that substantial interannual variability in P fluxes may occur, perhaps driven by changing nutrient inflow rates. Longer-term records of sediment fluxes at reference sites may prove to be a useful gauge of environmental improvement.

Chapter X References

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Appendix XI Data

Included in this data listing are:

1. Tabular data of the rates of sediment-water exchange.

Notes: The positive values reflect the fluxes directed out of the sediments. The standard deviations are based on 3 cores (2 in July 1994), with each individual core rate determined from a four point time course.

The detailed time course data has been supplied previously and we will make it available on electronic media to any interested parties.

2. All pore water data profiles

Notes: The top 4 sections were 0.5 cm depth intervals, the next two were 1.0 cm intervals, with the remainder being 2.0 cm intervals.

3. All solid phase profiles. The HCl-Mn and the HCl-Fe analyses are from the overnight 1.0 N HCl extraction; the other Fe and Mn analyses are on the HNO₃-HCl trace metal extracts.

Other Notes:

The diagenesis experimental data was supplied in a previous report.

Sediment-Water Exchange Data Summary

Station	O ₂ Flux	O ₂ S.D.	SRP Flux	SRP S.D.	NH ₄ Flux	NH ₄ S.D.	NO ₃ Flux	NO ₃ S.D.
$\mu\text{mol m}^{-2} \text{ h}^{-1}$								
July 1994								
2	-555.7	19.2	2.7	0.9	92.2	3.0	-11.7	11.7
4	-508.7	94.3	0.7	0.7	20.4	20.4	0.0	0.0
7	-122.7	6.6	3.1	0.9	0.0	0.0	-12.6	6.8
25	-104.9	5.0	0.0	0.0	0.0	0.0	0.0	0.0
33	-454.1	29.6	0.0	0.0	0.0	0.0	0.0	0.0
34	-244.4	9.1	1.4	0.5	0.0	0.0	0.0	0.0
36	-265.7	1.2	0.0	0.0	11.9	5.4	0.0	0.0
37	-523.4	4.2	3.9	0.1	0.0	0.0	0.0	0.0
40	-677.9	52.6	1.6	0.1	83.0	1.0	3.1	3.1
41	-981.2	277.7	3.5	3.5	65.8	65.8	0.0	0.0
48	-357.2	56.6	0.0	0.0	0.0	0.0	0.0	0.0
50	-339.7	285.7	31.1	29.1	182.8	153.8	-33.4	33.4
51	-390.5	37.2	2.1	0.2	91.3	56.0	-5.7	5.7
52	-732.8	79.3	4.3	0.0	231.9	180.2	-40.4	15.2
Oct 1994								
2	-449.3	12.2	0.0	0.0	86.9	67.2	5.8	7.1
7	-499.3	33.4	0.0	0.0	3.3	5.0	-1.8	2.6
37	-570.8	203.8	2.0	0.7	20.8	18.7	16.2	4.7
41	-496.4	177.1	0.4	0.2	9.8	14.6	12.9	2.2
50	-653.7	52.3	0.9	0.1	4.4	6.6	20.0	2.0
51	-765.6	74.8	1.2	0.1	30.3	22.1	21.1	2.3
April 1995								
2	-354.1	45.0	0.5	0.2	0.0	0.0	0.0	0.0
7	-320.8	16.7	4.2	0.4	1.4	2.9	10.5	3.6
37	-435.2	38.3	1.5	0.1	-6.5	0.4	27.5	2.5
41	-369.4	17.4	0.0	0.0	32.9	5.3	8.0	5.4
50	-330.2	32.4	0.3	0.2	-6.3	0.6	2.8	0.1
51	-371.0	29.0	0.7	0.2	-2.2	3.1	5.8	2.9
August 1996								
2	-1249.0	169.5	2.5	0.7	92.2	51.7	-11.4	1.1
7	-813.2	49.4	2.1	1.0	0.0	0.0	-10.0	2.5
37	-908.6	33.2	6.6	2.5	15.7	5.6	18.0	8.1
41	-841.5	77.7	8.6	2.0	63.5	14.6	24.4	3.7
50	-1273.3	419.9	6.2	2.8	102.0	83.1	32.2	0.0
51	-1224.9	33.8	10.7	3.3	110.5	30.4	18.6	25.7
Sept 1996								
10	-487.9	24.6	0.4	0.3	1.5	2.1	-12.9	4.3
12	-385.2	42.4	0.3	0.2	0.0	0.0	-2.9	4.1
19	-329.1	13.7	0.4	0.3	0.0	0.0	0.0	0.0
21	-504.8	43.6	0.9	0.2	0.0	0.0	4.8	2.6
SS	-671.2	201.8	0.6	0.1	0.0	0.0	-16.9	8.3

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
2	July 1994	0.25	18.8	413	1.42	59.8	134.7	65.4	93.0	
		0.75	25.1	388	0.89	24.5	161.1	85.5	119.0	
		1.25	38.1	385	0.85	6.6	154.5			
		1.75	43.3	388	0.85	4.3	258.5	225.3	153.5	
		2.5	66.4	375	0.81	3.8	414.5	343.1	175.5	
		3.5	67.5	370	0.86	3.9	506.9	411.7	196.1	
		5	3.2	370	0.88	4.0	713.2	317.2	229.3	
		9	58.8	343	0.77	3.8	993.9	552.2	269.2	
		13	56.9	339	0.87	4.4	1082.6	561.3	266.5	
		17	47.4	332	0.81	4.0	1179.8	559.3	257.9	
2	Oct 1994	BW	0.1	454	2.56	133.1	124.4	7.2	12.7	
		0.25	12.3	484	1.29	94.2	199.3	75.2	73.7	
		0.75	25.9	454	0.38	44.1	259.0	139.7	122.9	
		1.25	28.5	415	0.45	16.0	324.1	184.4	141.1	
		1.75	27.3	414	0.28	6.6	363.4	221.1	162.0	
		2.5	41.0	415	0.35	1.4	436.3	341.1	191.1	
		3.5	36.7	363	0.27	0.5	503.5	391.2	207.5	
		7	45.4				761.1	530.0	237.5	
		11	43.0	326	0.27	0.8	920.3	579.3	247.6	
		15	52.2	316	0.24	0.3	937.5	579.3	230.3	
		19	53.6	319		0.5	876.2	537.2	200.2	
2	April 1995	BW	0.4	420	32.23	146.9	1.8			
		0.25	3.6	426	1.04	136.5	35.0			
		0.75	2.6	412	0.36	110.1	60.4			
		1.25	3.1	419	0.18	85.0	121.9			
		1.75	11.9	401	0.08	44.2	141.3			
		2.5	91.6	403	0.18	12.3	179.7			
		3.5		387	0.20	3.7	246.9			
		5	43.5	357	0.08	3.4	296.8			
		9	50.4	358	0.05	3.4	369.8			
		11	57.2	370	0.12	3.7	440.5			
		13	39.6	368	0.09	3.5	507.7			
2	Aug 1996	0.25	1.8	400	0.05	90.1	76.4	16.3	68.6	2.5
		0.75	5.3	379	0.00	43.4	127.5	45.7	98.1	4.6
		1.25	5.3	392	0.00	11.8	191.1	62.1	125.6	4.0
		1.75	2.4	366	0.06	2.7	259.5	68.6	121.0	4.1
		2.5	19.5	353	0.00	1.3	326.5	173.0	144.7	5.1
		3.5	47.5	352	0.00	1.2	427.7	307.1	64.3	6.7
		5	6.6	350	0.00	1.7		269.5	67.2	7.5
		7	33.0	326	0.00	0.3	610.7	433.8	83.0	8.6
		9	58.3	24	0.00	1.7		439.6	76.6	9.6
		13	2.8	32	0.00	1.2	758.0	371.1	72.3	7.6

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
7	July 1994	0.25	2.0	320	6.87	83.8	0.0	7.3	19.5	
		0.75	2.7	366	2.76	72.6	6.9	3.5	35.4	
		1.25	7.8	368	2.48	40.4	27.3	16.8	66.6	
		1.75	22.9	410	1.04	16.9	25.8	68.6	67.1	
		2.5	33.1	441	0.88	7.5	41.4	102.9	59.2	
		3.5	47.6	447	2.33	11.8	65.4	152.8	58.5	
		5	69.9	944	2.16	11.8	88.2			
		9	71.6	667	0.79	5.5	103.8	254.4	63.1	
		13	16.8	784	0.62	5.0	149.4	166.4	60.5	
		17	58.8	974	0.62	6.0	165.0	296.5	62.5	
7	Oct 1994	BW	0.7	336	17.18	133.9	0.7	5.4	3.6	
		0.25	2.6	370	1.43	138.0	3.1	12.5	17.3	
		0.75	7.7	418	0.87	46.1	18.7	18.8	46.4	
		1.25	22.5	362	0.38	95.7	35.3	57.3	51.9	
		1.75	35.6	405	0.31	12.4	46.1	90.4	37.3	
		2.5	41.5	429	0.29	1.6	56.7	120.9	42.8	
		3.5	29.9	472	0.26	0.5	67.4	135.2	42.8	
		5	52.2	543	0.33	0.5	101.3	236.9	65.5	
		7	55.1	647	0.44	0.3	108.3	205.0	51.9	
		9	77.4	735	0.29	0.3	122.3	248.0	57.3	
7	April 1995	BW								
		0.25	0.0	584	2.63	109.0	15.1			
		0.75	2.3	415	0.19	100.6	26.1			
		1.25	2.0	403	0.05	74.0	42.9			
		1.75	3.8	434	0.06	49.6	55.1			
		2.5	14.1	455	0.02	20.9	74.2			
		3.5	28.1	515	0.01	3.1	98.5			
		5	47.3	573	0.01	3.6	115.9			
		7	60.5	684	0.02	3.6	139.1			
		9	56.1	802	0.01	6.2	163.5			
		11	71.8	894	0.24	33.0	173.9			
7	Aug 1996	0.25	5.5	380	0.21	93.2	19.5	5.9	34.4	2.8
		0.75	25.0	406	0.13	29.6	45.7	46.9	77.4	3.7
		1.25	32.0	428	0.07	2.3	70.6	92.6	49.0	3.8
		1.75	33.7	462	0.14	1.0	81.0	121.6	39.7	4.0
		2.5	51.9	498	0.16	0.2	97.3	146.5	41.0	4.7
		3.5	36.5	445	0.19	0.5	109.3	136.4	41.7	4.7
		3.5	36.6	513	0.14	2.0	115.2	121.0	42.4	5.0
		5	50.8	610	0.29	0.7	121.2	156.3	45.9	5.3
		9	47.2	775	0.44	0.8	146.5	166.2	50.8	5.8
		15	38.3	1036	0.66	1.1	170.3	190.9	51.9	

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
37	July 1994	0.25	2.6	271	5.24	110.4	7.5	3.9	19.9	
		0.75	2.7	275	4.93	106.9	14.7	3.9	65.8	
		1.25	5.4	268	1.84	91.5	32.7	12.3	54.5	
		1.75	14.9	633	1.12	73.5	15.0	17.5	33.2	
		2.5	27.9	160	1.16	38.0	18.6	33.0	26.6	
		3.5	19.4	273	1.05	38.7	30.6	73.3	30.7	
		7	20.1	232	1.66	4.7	34.2	110.1	31.2	
		11	27.0	285	1.01	3.9	83.4	163.1	45.3	
		15	34.8	352	0.95	3.8	55.8	148.9	43.2	
		19	28.1	387	0.91	4.2	124.2	140.5	42.5	
37	Oct 1994	BW	0.2	282	3.03	125.8	3.9			
		0.25	1.8	317	0.50	132.7	18.5			
		0.75	2.0	304	0.23	129.1	24.9			
		1.25	2.0	307	0.29	125.1	27.2			
		1.75	2.3	307	0.09	124.3	34.2			
		2.5	2.8	295	0.01	117.0	48.7			
		3.5	6.9	302	0.11	111.2	52.2			
		5	11.4	315	0.02	87.2	73.0			
		9	27.1	371	0.04	3.1	107.8			
		13	40.4	398	0.29	3.4	155.3			
37	April 1995	BW	0.9	293	10.10	106.9	2.9	7.2	3.6	
		0.25	1.6	304	1.59	184.7	43.4	7.2	2.7	
		0.75	1.4	295	0.57	175.7	15.4	2.7	13.7	
		1.25	2.6	295	0.60	165.0	26.2	8.1	15.5	
		1.75	3.0	289	0.61	159.1	35.9	15.2	15.5	
		2.5	7.1	287	0.45	132.4	40.6	54.6	20.9	
		3.5	7.1	305	0.52	87.4	59.9	61.8	28.4	
		5	32.8	321	0.43	25.0	85.7	151.3	40.0	
		7	56.1	360	0.65	4.4	115.8	79.7	44.6	
		9	48.3	405	0.67	1.0	143.8	229.2	59.2	
37	Aug 1996	11	36.7	435	0.41	0.3	157.2		61.0	
		0.25	3.8	293	0.03	65.8	65.3	7.9	139.2	2.3
		0.75	6.2	296	0.04	24.9	85.1	23.8	154.7	3.5
		1.25	18.4	302	0.00	3.0	109.3	87.2	136.5	4.0
		1.75	17.7	319	0.13	2.1	139.0	96.7	98.7	4.7
		2.5	11.5	294	0.00	1.1	143.5	76.1	69.7	6.6
		3.5	16.0	310	0.25	0.8	143.5	113.5	50.6	4.8
		5	13.3	287	0.04	0.4	139.0	124.6	46.8	4.4
		7	19.3	320	0.04	6.3	145.0	136.3	47.3	4.9
		9	20.3	313	0.07	0.5	139.0	145.6	50.4	5.3
37	Aug 1996	13	6.3	351	0.07	1.5	139.3	125.0	53.5	4.4

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
41	July 1994	0.25	7.7	297	4.16	91.1	180.3	28.5	17.94	
		0.75	11.3	314	1.27	57.5	173.7	27.8	17.28	
		1.25	22.9	280	1.13	25.3	191.1	63.0	28.31	
		1.75	21.7	311	1.07	15.7	178.2	47.9	19.27	
		2.5	38.6	310	1.12	12.6	208.2	113.3	26.58	
		3.5	44.8	331	2.10	15.7	233.4	128.4	28.31	
		7	76.1	356	0.80	5.2	275.3	187.7	31.90	
		13	56.9	372	1.20	6.1	290.9	200.7	34.56	
		21	40.7	201	1.25	5.9	270.5	138.5	25.92	
		29	25.3	420	1.53	10.1	253.7	123.0	26.58	
41	Oct 1994	BW	0.1	248	4.69	99.7	4.9	8.1	0.9	
		0.25	0.6	587	1.23	183.3	13.8	9.0	9.1	
		0.75	0.9	343	0.59		19.7	18.8	12.0	
		1.25	3.3	339	0.54	163.0	35.9	33.1	14.6	
		1.75	3.5	363	0.30	138.4	38.6	34.9	13.7	
		2.5	1.6	334	0.50	116.1	156.7	23.3	10.9	
		3.5	5.5	304	0.36	78.3	62.6	35.8	11.8	
		5	12.5	300	0.48	79.0	64.2	51.9	11.8	
		7	17.8	306	0.27	45.0	84.6	61.8	11.8	
41	April 1995	bw	0.3	326	3.35	131.3	4.1			
		0.25	2.5	388	0.30	120.6	47.5			
		0.75	1.8	359	0.02	109.7	50.4			
		1.25	1.3	363	0.19	104.8	41.2			
		1.75	1.6	362	0.12	86.5	31.3			
		2.5	2.5	360	0.08	51.3	41.7			
		3.5	12.3	368	0.06	20.0	48.7			
		5	6.1	387	0.30	12.6	58.0			
		7	15.9	393	0.17	31.4	61.4			
		9	37.4	401	0.12	68.3	58.0			
41	Aug 1996	11	7.5	410	0.03	83.3	56.8			
		0.25	13.2	323	0.14	62.3	83.5	30.6	38.8	1.7
		0.75	27.0	322	0.00	8.9	112.7	50.9	38.6	1.9
		1.25	24.8	336	0.00	6.2	136.0	67.7	31.5	1.9
		1.75	31.6	329	0.00	3.2	170.3	89.0	34.6	2.7
		2.5	69.1	333	0.00	1.3	206.0	163.3	39.1	3.6
		3.5	59.7	341	0.00	2.7	192.6	157.6	38.2	3.1
		5	11.2	353	0.00	2.4	179.2	76.6	36.0	3.6
		7	10.6	358	0.00	1.7	146.5	67.0	30.4	4.0
		11	1.7	387	0.15	2.4	88.4	11.8	11.3	3.4
41		15	11.1	441	0.17	2.8	75.0	75.6	13.5	3.3

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
50	July 1994	0.25	14.8	245	2.01	45.0	80.1	70.6	71.1	
		0.75	13.6	229	0.83	20.2	102.9	60.2	83.1	
		1.25	24.8	206	0.81	6.9	126.9	106.2	89.7	
		1.75	24.8	206	0.75	5.5	113.4	106.8	79.8	
		2.5	29.6	202	0.89	5.2	120.6	99.0	77.1	
		3.5	26.7	203	1.47	10.0	99.0	89.3	65.1	
		5	19.8	192	0.73	5.1	75.0	132.1	58.5	
		7	9.2	185	0.71	5.1	43.8	18.1	34.6	
		9	25.5	188	0.73	5.3	41.4	99.7	44.5	
		11	23.4	179	0.64	5.1	35.4	96.5	45.2	
50	Oct 1994	BW	0.5	257	1.42	113.2	26.9	4.5	3.6	
		0.25	1.6	280	0.42	109.5	45.0	12.5	36.4	
		0.75	2.8	271	0.75	42.2	65.4	37.6	84.6	
		1.25	4.3	262	0.31	11.2	86.4	73.4	81.9	
		1.75	8.1	260	0.30	3.6	96.1	107.4	91.0	
		2.5	13.9	250	0.26	0.7	109.4	128.0	97.4	
		3.5	7.8	268	0.24	0.7	115.8	79.0	77.0	
		5	13.9	255			127.7	88.6	84.6	
50	April 1995	bw	0.2	223	39.72	104.5	3.0			
		0.25	1.6	288	24.13	131.8	15.1			
		0.75	1.6	248	2.75	125.6	21.4			
		1.5	1.6	234	0.24	103.9	25.5			
		2.5	2.3	218	0.10	71.6	33.0			
		4	2.5	223	0.04	49.4	49.8			
		6	5.2	240	0.10	34.3	62.6			
50	Aug 1996	0.25	2.5	321	0.25	34.6	104.3	12.0	95.7	4.2
		0.75	7.3	234	0.11	5.6	124.6	49.8	122.9	4.4
		1.5	4.4	247	0.04	1.3	150.9	106.2	126.5	
		1.75	13.3	294	0.00	2.3	174.7	106.5	99.2	4.6
		2.5	21.7	213	0.00	0.4	197.0	138.6	118.1	3.7
		3.5	16.6	241	0.00	0.9	222.3	136.8	110.7	5.6
		5	17.3	218	0.00	0.7	183.6	112.6	79.7	5.5
		7	11.8	219	0.08	0.9	152.4	70.4	63.0	4.8
		9	6.4				115.2	61.4	51.1	4.0
		13	3.9	199	0.00	0.5	97.3	56.9	50.8	4.4

Lake Champlain Pore Water Chemistry

Station	Month	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	mmol/L
51	July 1994	0.25	16.7	218	1.08	26.4	77.1	95.8	102.4	
		0.75	23.1	236	2.61	11.7	112.5	159.1	126.2	
		1.25	15.3	199	1.05	4.1	162.9	198.7	123.0	
		1.75	15.1	520	1.01	4.6	186.6	242.8	134.3	
		2.5	16.5	206	0.86	3.9	231.0	247.9	118.3	
		3.5	17.7	219	1.01	4.0	205.8	305.6	143.6	
		7	21.7	251	0.89	4.0	173.4	293.3	147.5	
		11	19.8	305	0.85	3.9	111.0	312.0	156.2	
		15	26.5	382	0.91	3.8	99.0	254.4	131.6	
		19	13.2	482	0.91	3.9	131.4	157.6	90.6	
51	Oct 1994	BW	0.3	308	0.45	120.2	61.1	9.0	2.7	
		0.25	8.6	320	0.50	74.4	94.5	100.3	53.7	
		0.75	4.7	324	0.38	31.7	109.0	68.0	79.2	
		1.25	16.6	327	0.37	7.3	129.4	212.2	101.0	
		1.75	12.5	336	0.37	0.7	140.2	217.6	106.5	
		2.5	19.7	350	0.30	0.3	143.8	214.0	109.2	
		3.5	14.3	356	0.30	0.2	162.1	364.2	90.1	
		5	20.2	381	0.34	0.2	153.5	246.2	104.7	
		7	25.0	377	0.32	0.2	164.2	281.1	112.9	
		9	9.0	384	0.31	0.2	154.6	222.0	104.7	
		13	10.0	419	0.32	0.2	148.1	341.1	152.9	
51	April 1995	bw	0.4	244	31.10	127.9	4.1			
		0.25	2.5	350	0.13	98.8	37.7			
		0.75	6.7	244	0.04	48.3	47.5			
		1.25	9.9	259	0.03	28.1	52.7			
		1.75	12.6	257	0.12	14.7	62.6			
		2.5	24.1	261	0.03	4.8	78.2			
		3.5	32.5	283	0.15	3.6	93.9			
		5	36.1	311	0.06	3.3	103.2			
		9		353	0.48	3.5	113.0			
		13	29.3	391	0.01	7.5	136.2			
51	Aug 1996	0.25	6.3	236	0.04	49.0	110.3	15.0	69.5	1.7
		0.75	18.5	216	0.22	6.7	108.2	61.8	58.6	1.6
		1.25	22.0	221	0.09	3.2	121.2	96.3	59.0	2.0
		1.75	20.4	227	0.05	2.7	152.4	99.9	46.8	1.6
		2.5	23.3	213	0.03	1.7	171.7	130.7	53.0	1.8
		3.5	14.8	221	0.15	1.0	167.3	116.4	51.0	1.9
		5	23.3	218	0.03	0.6	182.2	127.3	55.3	1.1
		9	22.3	235	0.00	1.3	249.1	146.7	62.6	2.3
		15	14.5	288	0.00	0.8	150.9	102.1	61.3	2.2

Month	Station	Depth cm	SRP umol/L	Cl umol/L	NO3 umol/L	SO4 umol/L	NH4 umol/L	Fe umol/L	Mn umol/L
July 1994	4	0.25	1.7	271	5.83	78.0	23.1		
		0.75	3.6	346	5.65	63.5	35.9	47.5	30.3
		1.25	8.4	349	1.60	25.8	80.1	34.9	23.9
		1.75	18.4	379	1.30	10.4	67.8	35.8	14.7
		2.5	35.5	367	0.95	5.0	136.2	100.3	16.5
		3.5	52.1	374	0.90	4.6	161.4	129.8	20.2
		5	31.2	361	0.84	3.8	215.4	134.3	22.1
		9	93.2	471	0.86	3.8	266.9	24.2	8.3
		13	64.2	491	0.84	3.8	306.5	341.1	105.7
		17	27.9	515	0.84	3.8	317.3	123.6	46.0
July 1994	25	0.25	1.7	265	2.72	68.6	15.3	8.1	110.3
		0.75	1.3	267	1.71	54.7	27.3	3.6	307.9
		1.25	1.8	263	1.80	39.5	57.3	9.8	450.4
		1.75	5.8	252	1.14	21.8	55.8	9.0	432.9
		2.5	30.8	258	1.05	5.0	84.6	61.8	421.9
		3.5	35.0	284	0.89	3.9	94.2	103.9	402.6
		7	58.3	292	0.87	4.1	147.0	162.9	330.0
		11	48.3	290	0.92	3.8	195.0	173.7	311.6
		15	23.6	292	0.91	3.9	213.0	179.1	375.0
		21	8.2	302	0.79	3.8	316.1	181.7	348.4
July 1994	33	0.25	3.2	371	1.31	53.7	32.1	14.3	8.3
		0.75	9.3	338	0.96	20.0	51.3	52.8	19.3
		1.25	8.4	313	1.40	17.0	55.5	38.5	21.1
		1.75	5.4	317	1.27	16.7	58.2	17.7	9.9
		2.5	4.2	303	1.19	11.9	40.2	9.7	3.3
		3.5	1.8				30.6		
July 1994	34	0.25	4.7	733	2.10	108.4	60.9	7.2	155.3
		1.75	8.1	279	1.41	44.5	93.9	12.5	201.3
		1.25	13.9	273	0.93	10.5	129.3	15.2	201.3
		1.75	26.5	271	0.87	5.8	155.4	57.3	215.1
		2.5	38.1	265	0.97	4.9	172.2	75.2	182.9
		3.5	47.6	267	0.85	5.7	216.6	104.8	202.2
		5	34.8	287	1.21	5.4	222.6	134.1	190.3
		9	46.7	336	5.31	9.0	380.9	162.9	254.6
		13	72.1	254	0.82	3.7	539.2	236.4	347.4
		17	49.5	281	1.16	4.2	620.8	257.8	388.8
July 1994	36	0.25	2.6	490	8.95	119.9	0.0	7.2	0.9
		0.75	2.1	343	5.87	114.3	0.0	4.5	0.9
		1.25	2.5	347	0.75	98.6	0.0	5.4	9.2
		1.75	3.9	343	1.23	81.9	0.0	13.4	17.5
		2.5	14.1	424	0.83	54.3	0.0	58.2	15.6
		3.5	22.0	357	0.84	34.0	4.2	127.1	19.3
		5	35.0	354	0.82	15.1	18.6	159.4	25.7
		7	42.9	430	0.93	5.3	24.6	198.8	31.3
		9	33.4	410	0.86	4.1	36.6	178.2	29.4
		11	30.0	424	0.93	4.2	51.0	199.7	31.3
July 1994	40	0.25	3.5	362	2.88	76.2	56.1	3.6	33.1
		0.75	5.6	319	0.89	44.7	60.3	5.4	57.0
		1.25	8.2	314	0.84	16.1	72.3	32.2	70.8
		1.75	14.4	302	0.72	7.6	72.6	78.8	58.8
		2.5	23.9	273	0.70	5.6	114.6	163.8	67.1
		3.5	22.2	294	0.66	5.2	124.2	224.7	72.6
		5	18.4				100.2	232.8	89.2
		7	6.1	362	2.35	12.2	93.0	321.4	102.9
July 1994	48	0.25	4.6	207	1.28	53.4	34.5	34.0	68.9
		0.75	13.6	196	0.99	18.2	70.5	77.0	74.5
		1.25	11.8	209	0.97	7.9	96.3	106.5	95.6
		1.75	27.0	208	0.66	5.4	121.8	165.6	70.8
		2.5	25.1	200	0.67	5.1	143.4	170.1	66.2
		3.5	27.4	221	0.71	5.2	127.8	268.6	108.5
		7	21.5	193	0.76	5.2	41.4	94.9	68.0
		11	29.6	196	0.63	5.0	91.8	166.5	66.2
July 1994	52	15	31.0	189	0.84	5.1	85.8	265.9	110.8
		0.25	6.5				70.5	20.6	103.9
		0.75	6.4				78.3	26.9	114.9
		1.25	16.0				113.1	91.3	142.5
		1.75	16.9				91.8	128.9	157.2
		2.5	41.9				143.4	180.0	124.1
		3.5	28.4				127.8	171.0	101.1
		7	36.5				115.8	201.4	91.9
		11	20.8				94.2	149.5	87.3
		15	31.7				79.8	130.7	81.8
		19	21.3				82.2	149.5	80.9

Lake Champlain Pore Water Chemistry

Date	Station	Depth	SRP	Cl	NO3	SO4	NH4	Fe	Mn	pH	DIC
		cm	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L	umol/L		mmol/L
Sept 1996	10	0.25	1.5	362	0.93	76.25	54.3	16.1	172.9	7.22	1.83
		0.75	11.5	362	0.06	12.05	126.5	104.0	329.5	7.40	2.82
		1.25	17.9	345	0.07	1.24	177.7	179.2	358.6	7.38	2.94
		1.75	15.4	352	0.04	1.26	119.6	190.7	398.6	7.33	3.98
		2.5	23.2	248	0.06	1.22	276.0	267.7	429.6	7.13	4.05
		3.5	10.2	364	0.07	0.90	319.8	300.4	451.4	7.25	4.00
		5	19.4	359	0.10	0.75	386.5	359.9	469.6	7.20	4.32
		9	31.4	377	0.12	0.75	467.0	486.1	502.4	7.20	6.46
		13	23.9	368	0.60	0.62	591.3	558.7	540.6	7.04	6.12
		19	9.7	389	0.29	0.87	686.8	557.8	537.0	7.05	6.30
Sept 1996	12	0.25	2.0	397	1.60	121.08	6.9	5.0	8.6	7.00	1.18
		0.75	1.2	365	0.86	43.91	14.9	5.6	66.6	7.18	1.38
		1.25	13.0	346	4.61	11.07	34.5	67.1	113.8	7.25	1.59
		1.75	22.9	350	0.04	2.56	51.7	118.7	117.2	7.41	1.99
		2.5	41.4	358	0.07	0.73	66.6	164.6	106.3	7.19	4.43
		3.5	25.7	349	0.08	0.73	89.6	195.9	92.3	7.12	2.50
		5	2.5	354	0.06	0.67	113.8	154.0	88.3	7.14	2.25
		9	18.4	362	0.09	0.93	170.2	321.0	104.7	7.18	3.02
		13	3.5	377	0.38	1.65	223.1	334.4	133.3	7.04	3.21
		17	2.0	387	0.16	1.82	262.2	377.4	148.8	6.99	3.89
Sept 1996	19	0.25	0.7	437	2.11	111.43	35.0	4.5	88.1	7.36	0.57
		0.75	2.5	390	1.01	74.56	46.5	9.8	187.5	7.44	1.19
		1.25	11.5	360	0.52	18.26	68.4	55.2	251.2	7.42	1.14
		1.75	13.7	354	0.58	3.52	82.8	80.8	245.7	7.45	1.33
		2.5	29.4	344	0.29	1.20	100.0	165.6	189.3	7.30	1.29
		3.5	27.9	356	0.46	1.60	115.0	186.2	172.9	7.13	1.34
		5	45.8	233	0.28	0.47	131.1	236.4	171.6	7.33	1.46
		9	70.8	342	0.20	2.08	158.7	287.9	128.3	7.09	1.32
		13	24.4	189	0.29	0.71	89.6	286.5	141.5	7.08	0.48
		19	36.6	322	0.06	1.05	230.6	390.8	151.1	7.11	1.84
Sept 1996	21	0.25	1.2	354	5.02	122.26	0.0	4.7	11.5	7.08	0.36
		0.75	2.2	349	0.60	27.48	5.7	7.0	73.7	7.07	0.44
		1.25	6.7	337	0.33	6.01	24.1	27.6	92.8	7.57	0.53
		1.75	8.5	354	0.87	101.17	37.3	43.7	67.0	6.87	0.56
		2.5	24.9	352	0.50	64.61	47.1	104.9	61.9	7.05	0.77
		3.5	13.2	335	0.72	1.27	56.3	120.9	64.1	6.87	0.77
		5	32.4	348	2.40	1.80	67.8	164.0	84.3	6.88	0.93
		9	19.9	367	1.01	3.17	101.1	176.2	88.3	6.69	0.80
		13	3.0	426	1.69	7.17	113.8	111.2	77.7	6.29	1.19
		19	18.4	279	0.05	1.06	127.0	193.2	68.1	6.96	1.69
Sept 1996	SS	0.25	1.0	589	0.76	115.72	9.5	10.0	12.0	7.46	0.45
		0.75	1.7	621	1.42	93.56	6.3	6.6	13.8	7.21	1.45
		1.5	3.2	611	0.76	35.14	9.7	17.9	15.1	7.30	0.59
		1.75	5.2	600	0.52	8.72	8.0	45.3	18.9	7.20	0.49
		2.5	14.0	577	0.92	2.94	33.3	74.0	24.0	7.38	0.75
		3.5	18.4	590	1.46	1.69	37.9	78.2	22.8	7.28	0.99
		5	36.4	345	1.45	1.23	54.0	99.6	20.4	7.41	1.30
		9	32.4	393	0.85	2.17	51.7	75.0	16.9	7.45	0.61
		13	25.9	361	2.39	0.91	51.7	71.4	20.4	7.44	
			28.9	341	0.59	0.86	51.7	38.9	12.9	7.45	

Lake Champlain Solid Phase Data

Station	Depth	%H ₂ O	Inorganic	Total	HCl-Mn	HCl-Fe	HCl-Ca	C	N	Pb-210	Pb-210	Fe	Mn
			P	P							S.D.		
	cm		mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	dpm/g	dpm/g	mg/g	mg/g
2	0-1	72.8%	0.84	1.02	1.36	38.76	9.48	23.1	2.7	3.37	0.19	40.4	1.38
	1-2	64.5%	0.69	0.87	1.06	35.62	8.77			3.34	0.17	27.4	1.02
	2-3	61.1%	0.69	0.90	1.12	36.70	10.64			3.20	0.16	35.0	1.05
	3-4	59.8%	0.77	0.94	1.10	34.41	7.66	22.0	2.5	3.35	0.09	29.8	1.11
	4-5	60.6%	0.79	0.93	1.13	34.52	7.95	22.3	2.5	2.97	0.17	38.6	1.13
	5-6	58.8%	0.79	0.93	1.12	34.55	8.92			3.15	0.09	36.1	1.13
	6-7	58.9%	0.80	0.97	1.11	33.91	8.44	21.9	2.5			30.2	1.12
	7-8	59.0%	0.78	0.95	1.17	37.35	9.32			3.02	0.12	34.9	1.10
	8-9	54.7%	0.80	0.94	1.07	34.20	10.69					33.4	1.07
	9-10	54.3%	0.81	0.96	1.03	34.20	8.23	22.5	2.3	3.14	0.09	32.2	1.11
	10-12	54.1%										36.3	0.99
	12-14	52.4%								2.67	0.14	26.8	4.86
4	0-1	86.5%	1.10	1.30	3.14	44.63	8.43	22.9	3.4	6.32	0.27	39.7	1.54
	1-2	73.8%	0.89	1.08	1.35	41.85	7.20			5.74	0.23	49.3	1.62
	2-3	66.8%	0.84	1.04	1.04	38.21	5.94	22.0	3.3	5.36	0.34	40.2	1.06
	3-4	70.6%	0.81	1.00	1.09	40.00	6.59			5.96	0.20	33.3	1.01
	4-5	70.4%	0.84	1.01	1.08	38.45	6.60			4.79	0.27	41.8	1.10
	5-6	69.2%	0.83	0.99	1.14	39.34	7.07	21.7	3.2	5.46	0.20	40.2	1.16
	6-7	63.3%	0.90	1.09	1.22	40.90	7.03					40.1	1.18
	7-8	67.7%	0.91	1.16	1.17	39.10	5.72	21.6	2.8	4.75	0.28	48.0	1.31
	8-9	70.3%	0.88	1.10	1.13	39.26	5.82					43.1	1.14
	9-10	64.2%	0.88	1.08	1.10	39.56	6.54	21.0	2.4	4.46	0.17	33.0	1.14
	10-12	74.9%								4.66	0.24	45.2	1.05
	12-14	75.1%										35.7	1.08
	14-16	72.0%								3.34	0.11	40.2	1.07
7	0-1	86.5%	2.33	2.70	9.82	49.15	8.88	34.3	4.8	15.72	0.36	40.1	10.34
	1-2	82.7%	2.08	2.43	4.59	44.80	7.64			16.79	0.49	39.5	5.30
	2-3	84.0%	1.45	1.74	1.77	40.44	6.92	34.3	5.2	16.45	0.50	47.4	1.88
	3-4	82.6%	1.08	1.43	1.26	39.37	6.52					42.2	1.40
	4-5	82.4%	0.87	1.20	1.23	38.07	6.17	30.5	4.5	15.33	0.38	42.7	1.29
	5-6	79.5%	0.78	1.07	1.03	36.56	6.05					41.4	1.09
	6-7	77.3%	1.21	1.24	1.24	42.12	6.86					45.1	1.29
	7-8	73.7%	0.86	1.09	0.92	39.00	5.85	21.9	3.3	8.70	0.25	39.7	0.97
	8-9	73.4%	1.01	1.18	0.98	42.04	6.90					31.9	0.94
	9-10	77.4%	1.73	1.78	1.48	43.08	7.98	24.9	3.6			40.7	1.43
	10-12	74.7%								7.09	0.22	45.4	1.14
	12-14	74.1%								6.17	0.21	52.3	1.12
	14-16	72.8%								5.86	0.20	43.2	1.23
	16-18	68.2%								3.90	0.15	46.6	1.03
10	0-1	89.3%	1.68	1.21	13.88	25.86	5.06	41.6	5.5	14.95	0.46	45.7	21.43
	1-2	84.7%	1.81	1.42	5.23	26.55	4.24	40.0	5.1	16.50	0.51	39.7	7.31
	2-3	85.1%								19.45	0.57	37.9	8.12
	3-4	83.3%	1.63	1.24	4.12	24.08	3.96	40.0	5.3	20.00	0.48	30.9	4.96
	4-5	82.5%								17.15	0.22	46.5	5.73
	5-6	82.2%								17.33	0.28	42.9	4.66
	6-7	80.1%	1.42	1.18	3.88	24.24	3.87	34.4	4.5	15.24	0.58	34.9	5.02
	7-8	81.9%								17.37	0.50	42.5	5.97
	8-9	82.5%								15.93	0.32	43.0	5.07
	9-10	80.4%										41.4	4.45
	10-12	79.6%	1.89	1.52	3.69	24.44	3.35	34.0	4.6	14.72	0.55	43.8	4.82
	12-14	78.1%								12.16	0.29	47.3	4.16
	14-16	79.1%								13.17	0.32	43.5	4.42
	16-18	77.6%										43.4	4.30
	18-20	74.7%	1.59	1.28	3.11	24.98	3.66	30.8	4.0	9.64	0.33	43.9	3.70

Lake Champlain Solid Phase Data

Station	Depth	%H ₂ O	Inorganic	Total	HCl-Mn	HCl-Fe	HCl-Ca	C	N	Pb-210	Pb-210	Fe	Mn	Zn	Cu	Pb
			P	P							S.D.					
	cm		mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	dpm/g	dpm/g	mg/g	mg/g	ug/g	ug/g	ug/g
12	0-1	88.1%	1.81	1.38	8.11	25.70	5.89	38.3	4.7	14.02	0.64	43.6	14.77	178.9	39.7	31.0
	1-2	85.7%	2.44	2.37	3.61	34.38	4.82	39.2	4.8	16.44	0.31	48.8	4.66	179.1	39.8	33.8
	2-3	83.1%								18.19	0.35	32.9	1.65	198.5	39.7	33.7
	3-4	79.2%	1.18	0.83	1.15	19.08	4.11	34.9	4.3	16.64	0.64	30.2	1.13	198.4	39.7	36.1
	4-5	79.2%								15.42	0.53	33.5	1.21	196.9	39.4	39.4
	5-6	79.5%								14.51	0.57	34.3	1.82	217.0	39.5	46.6
	6-7	78.7%	1.44	1.13	1.28	20.71	3.76	32.0	3.9	12.56	0.38	35.2	1.38	198.2	39.6	48.8
	7-8	79.0%								13.28	0.62	36.3	1.43	218.5	39.7	54.8
	8-9	77.2%								11.26	0.36	31.4	1.05	239.1	39.9	61.4
	9-10	75.6%								6.66	0.30	39.3	1.15	238.9	39.8	66.1
	10-12	74.0%	1.53	1.38	1.61	25.75	3.74	28.4	3.2	6.03	0.20	34.6	1.55	218.0	39.6	59.1
	12-14	70.8%								6.68	0.28	30.2	1.08	238.0	39.7	58.7
	14-16	71.0%								5.15	0.21	77.8	1.10	219.3	39.9	44.7
	16-18	59.2%								2.83	0.20	25.8	0.77	157.4	19.7	24.8
	18-20	61.7%										28.0	0.95	179.4	39.9	31.1
	20-22	63.5%	1.21	1.02	1.05	23.67	3.11	25.6	2.3	3.07	0.12	42.7	1.16			43.6
19	0-1	88.1%	1.76	1.30	9.84	26.34	4.79	41.6	5.6	17.31	0.47	43.8	11.78	220.0	40.0	34.8
	1-2	85.7%	2.19	1.82	9.97	34.84	4.53	40.8	5.3	20.44	0.40	48.7	11.99	218.0	39.6	38.8
	2-3	83.1%								23.52	0.75	49.7	5.61	237.2	39.5	43.5
	3-4	79.2%								23.24	0.44	65.0	4.27	217.8	39.6	50.7
	4-5	79.2%	1.71	1.32	3.65	28.55	3.80	37.1	5.0	22.96	0.45	44.8	4.20	239.2	39.9	57.4
	5-6	79.5%								18.65	0.47	35.5	3.04	217.4	39.5	57.7
	6-7	78.7%	1.13	0.80	1.87	21.67	3.52	33.1	4.4	11.83	0.41	31.2	1.67	258.1	39.7	75.1
	7-8	79.0%								11.21	0.31	41.4	1.82	276.0	39.4	90.7
	8-9	77.2%								15.89	0.53	39.8	2.38	295.6	59.1	119.4
	9-10	75.6%								13.45	0.36	38.4	2.11	299.6	59.9	136.6
	10-12	74.0%	1.90	1.61	3.26	28.57	3.55	37.2	4.7	6.58	0.21	30.8	3.61	317.3	59.5	134.1
	12-14	70.8%								4.88	0.29	41.1	1.44	259.5	39.9	75.4
	14-16	71.0%								2.78	0.14	21.1	1.25	256.4	39.4	22.1
	16-18	59.2%								4.43	0.07	46.3	1.22	239.4	39.9	16.0
	18-20	61.7%										57.4	1.72	295.9	59.2	43.4
	20-22	63.5%	1.00	0.80	1.22	25.96	2.94	23.3	2.6	3.65	0.14	22.2	1.91	259.9	60.0	27.6
21	0-1	87.1%	2.36	1.90	6.49	32.35	4.67	31.3	3.9	17.31	0.47	49.4	5.18	220.4		46.9
	1-2	82.6%	1.69	1.41	2.71	25.34	3.86	29.6	3.6	20.44	0.40	35.6	3.16	218.8		38.2
	2-3	81.3%								23.52	0.75	24.4	1.87	238.9		44.2
	3-4	79.7%	1.72	1.30	1.45	22.01	3.49	30.4	3.5	23.24	0.44	38.1	1.64	237.1		56.1
	4-5	77.3%								22.96	0.45	31.4	1.45	258.0		66.3
	5-6	75.9%								18.65	0.47	31.4	1.47	238.8		69.6
	6-7	73.8%	1.25	1.09	1.10	19.85	3.12	26.2	2.9	11.83	0.41	42.3	1.34	255.2		87.9
	7-8	73.2%								11.21	0.31	17.3	1.26	258.7		72.8
	8-9	73.2%								15.89	0.53	78.5	1.53	278.2		86.2
	9-10	69.3%								42.4	1.23	554.0				74.0
	10-12	61.3%	1.05	0.89	0.69	18.37	2.87	19.4	2.0	13.45	0.36	24.8	0.91	255.9		59.8
	12-14	55.2%								6.58	0.21	33.5	0.75	237.8		48.0
	14-16	54.5%								4.88	0.29	32.5	0.67	198.3		36.9
	16-18	53.9%								2.78	0.14	35.8	0.67	199.6		34.3
	18-20	52.3%								4.43	0.07	37.4	0.70	179.5		26.7
	20-22	53.4%								3.65	0.14	35.8	0.64	176.6		22.4
	22-24	54.2%	0.83	0.72	0.33	15.74	2.84	12.5	1.4			43.8	0.62	157.5		30.7
25	0-1	92.7%	1.41	1.72	45.27	25.58	7.73	48.9	5.1	21.63	0.97	38.9	34.39			47.3
	1-2	90.2%	5.32	4.97	32.68	37.14	5.23					58.0	30.68			41.0
	2-3	88.7%	2.61	2.91	16.80	31.56	3.81	43.2	5.4	21.20	0.61	49.4	21.90			48.0
	3-4	86.8%	1.79	2.00	11.09	31.89	4.04					63.4	17.29			51.1
	4-5	86.1%	1.31	1.90	13.32	32.61	4.39			21.63	1.03	50.3	14.66			55.1
	5-6	82.4%	1.38	1.86	9.03	29.49	4.08	37.3	4.6			62.0	10.55			65.3
	6-7	87.1%	1.22	1.65	8.65	31.76	4.31			16.44	0.48	52.2	14.53			80.0
	7-8	85.4%	1.61	2.09	13.22	29.63	4.09	37.1	4.4	12.76	0.38	54.3	10.35			86.3
	8-9	80.6%								11.91	0.52	55.8	14.78			86.3
	9-10	81.6%								10.62	0.34	62.5	16.53			82.7
	10-12	80.0%								8.73	0.43	54.8	11.96			74.9
	12-14	65.8%	1.04	1.35	4.20	26.54	3.70			6.40	0.27	57.6	7.10			54.7
	14-16	77.6%								4.56	0.21	58.6	5.84			49.6
	16-18	75.0%								3.69	0.18	55.5	5.76			41.7
	18-20	71.4%	1.09	1.35	3.08	25.46	3.17	22.1	2.3	2.98	0.24	52.5	4.48			39.5

Lake Champlain Solid Phase Data

Station	Depth	%H ₂ O	Inorgani	Total	HCl-Mn	HCl-Fe	HCl-Ca	C	N	Pb-210	Pb-210	Fe	Mn	Zn	Cu	Pb
			P	P							S.D.					
	cm		mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	dpm/g	dpm/g	mg/g	mg/g	ug/g	ug/g	ug/g
34	0-1	90.6%	2.52	3.22	8.40	28.58	6.01	63.9		38.24	1.36	48.8	12.86			53.3
	1-2	91.6%	2.76	3.64	7.72	28.05	5.44			36.75	0.66	43.2	13.45			49.6
	2-3	90.9%	2.22	2.94	5.53	24.05	4.71	62.7	9.3	33.85	0.99	34.7	10.63			49.2
	3-4	89.5%	2.13	2.81	6.86	23.91	5.30			33.73	0.74	41.1	12.29			48.5
	4-5	90.3%	1.85	2.50	5.05	22.14	4.56			29.22	1.22	40.0	10.10			43.9
	5-6	90.1%	1.69	2.43	5.19	22.17	4.12	35.3	4.2	35.79	0.80	40.1	9.12			51.1
	6-7	88.3%	1.75	2.26	10.04	22.06	4.87			24.35	0.72	24.6	10.24			46.2
	7-8	87.3%	2.55	3.32	9.98	24.37	4.11	51.3	7.5	26.21	0.66	32.3	14.36			57.1
	8-9	86.7%	1.95	2.78	12.94	26.24	4.04			29.21	0.98	39.1	14.69			56.7
	9-10	86.7%						50.8	7.1	27.79	0.75	50.1	20.29			61.6
	10-12	84.9%								22.98	0.67	40.4	20.87			57.2
	12-14	84.3%	1.88	2.46	11.54	26.60	4.31			22.91	0.83	43.7	20.67			60.5
	14-16	84.1%								20.50	0.51	25.3	13.11			60.3
	16-18	81.8%								20.11	0.54	32.5	6.61			69.8
36	0-1	84.0%	1.13	1.64	1.08	13.53	5.97	36.6	4.4	13.73	0.51	28.7	1.15			54.9
	1-2	74.1%	0.84	1.16	0.30	10.00	4.68			7.32	0.31	27.2	0.51			57.4
	2-3	73.8%	0.77	1.12	0.36	13.29	4.58	27.5	5.4	4.51	0.27	37.1	0.57			54.3
	3-4	70.3%	0.88	1.24	0.42	17.34	4.28			4.36	0.22	38.7	0.67			50.4
	4-5	72.7%	1.06	1.35	0.51	17.17	4.32					49.2	0.84			50.5
	5-6	71.2%	1.51	1.84	0.63	18.39	4.44	35.3	4.2	3.90	0.24	50.3	0.91			41.4
	6-7	71.6%	1.23	1.49	0.53	16.21	4.02					37.6	0.79			43.3
	7-8	71.1%	0.91	1.27	0.41	15.58	3.91	27.1	2.8	3.70	0.23	41.9	0.64			36.4
	8-9	68.9%										39.9	0.68			30.2
	9-10	68.4%	1.04	1.34	0.39	14.40	4.10	25.3	2.7	2.31	0.11	42.2	0.64			25.5
	10-12	65.8%								1.91	0.15	45.4	0.70			19.6
	12-14	66.1%	1.27	1.62	0.43	16.42	3.74	21.1	2.4	1.82	0.10	41.7	0.66			16.0
37	0-1	85.4%	1.57	2.03	3.88	49.85	7.23	40.5	5.1	16.16	0.58	44.4	2.57	239.1	39.9	47.4
	1-2	80.4%	0.82	1.20	0.82	27.20	5.37			14.84	0.61	23.3	0.62	255.6	59.0	60.4
	2-3	80.4%	0.89	1.28	0.87	30.75	5.27	39.1	4.9	11.57	0.35	26.9	0.64	297.9	59.6	83.4
	3-4	79.0%	1.53	1.82	1.25	36.09	4.55					45.1	0.88	319.6	59.9	87.3
	4-5	77.7%	1.45	1.84	1.29	39.36	4.26			8.28	0.19	39.3	0.92	279.2	59.8	76.8
	5-6	77.2%	1.23	1.63	1.36	43.07	4.35					43.2	0.93	258.2	59.6	59.3
	6-7	71.4%	1.63	1.81	1.44	36.99	4.01	28.4	3.2			39.3	1.00	237.9	39.7	48.9
	7-8	72.0%	1.09	1.33	1.30	41.20	4.20			5.65	0.18	42.0	0.85	239.3	39.9	47.5
	8-9	70.2%										46.2	0.91	237.0	39.5	38.5
	9-10	70.4%	1.27	1.46	1.30	41.67	3.91	26.7	2.8	4.03	0.16	44.4	0.93	236.2	39.4	28.1
	10-12	71.5%										45.0	0.81	200.0	40.0	21.7
	12-14	68.8%	1.17	1.31	1.23	42.94	4.40	25.7	2.8	2.84	0.09	41.3	0.76	179.2	39.8	9.5
41	0-1	79.6%	1.08	1.30	0.88	29.86	5.16	48.0	6.1	10.54	0.20	28.9	0.64			55.2
	1-2	77.1%	0.90	1.25	0.74	34.70	5.12			9.09	0.21	23.8	0.49			57.4
	2-3	73.2%	0.92	1.18	0.49	24.84	4.33	42.1	5.1	8.30	0.20	24.7	0.45			71.5
	3-4	70.5%	0.91	1.15	0.48	28.94	4.77			6.81	0.27	26.9	0.37			73.3
	4-5	65.5%	0.82	1.06	0.39	24.98	4.44			4.87	0.24	22.3	0.32			59.8
	5-6	59.5%	0.82	0.99	0.38	24.59	4.45	31.4	3.4			23.0	0.31			55.8
	6-7	58.9%	0.81	0.99	0.33	22.90	4.23			3.79	0.21	20.0	0.30			53.3
	7-8	57.9%						31.1	3.4			24.8	0.30			52.8
	8-9	53.1%	0.81	0.89	0.30	20.72	3.89			3.15	0.20	16.6	0.23			39.4
	9-10	48.8%						25.9	2.7	2.52	0.17	19.5	0.25			36.0
	10-12	49.4%	0.81	0.89	0.31	24.33	4.48					23.3				29.8
	12-14	49.6%										21.5	0.25			27.1
	14-16	46.8%	0.72	0.89	0.28	20.69	3.90	23.5	2.4	1.78	0.13	19.6	0.24			19.2
	16-18	48.3%								1.53	0.13	16.4	0.22			16.3

Lake Champlain Solid Phase Data

Station	Depth	%H ₂ O	Inorganic	Total	HCl-Mn	HCl-Fe	HCl-Ca	C	N	Pb-210	Pb-210	Fe	Mn	Zn	Cu	Pb
	cm		P	P							S.D.					
			mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	dpm/g	dpm/g	mg/g	mg/g	ug/g	ug/g	ug/g
48	0-1	74.2%	1.37	1.75	2.36	39.98	5.37	32.8	3.7	8.60	0.35	72.4	2.22			39.4
	1-2	69.8%	1.01	1.36	1.38	32.35	3.94			8.50	0.36	41.6	1.16			41.2
	2-3	66.5%	0.93	1.24	1.19	34.05	3.88	30.8	3.3	7.23	0.17	38.2	0.91			43.2
	3-4	65.4%	0.96	1.39	1.16	34.29	3.64			7.18	0.17	45.3	0.95			44.0
	4-5	65.6%	0.95	1.28	1.19	32.75	3.54					41.0	0.90			42.9
	5-6	63.9%	0.95	1.21	1.10	32.17	3.56	30.7	3.1			36.3	0.88			46.6
	6-7	62.9%	0.91	1.22	1.17	35.10	3.77	27.8	2.7	5.60	0.14	44.1	0.91			45.6
	7-8	52.0%								4.61	0.14	41.4	0.78			42.7
	8-9	43.7%	0.76	0.98	0.70	27.44	3.19			2.02	0.09	45.8	0.69			28.8
	9-10	44.9%						18.7	1.7	1.69	0.07	43.9	0.68			20.9
	10-12	47.6%	0.77	0.93	0.80	27.26	3.36					42.2	0.56			21.1
	12-14	44.3%								1.74	0.14	31.7	0.56			17.8
	14-16	44.3%										31.4	0.57			17.5
	16-18	43.8%										33.8	0.57			17.5
	18-20	40.4%	0.69	0.76	0.49	17.58	2.78	14.7	1.3	1.41	0.14	32.2				18.3
50	0-1	74.0%	1.02	1.32	3.66	37.09	4.68	29.3	3.2	7.76	0.29	39.4	2.52	199.6	39.9	29.9
	1-2	68.3%	0.90	1.15	2.18	30.79	3.67			7.62	0.23	38.5	17.83	199.5	20.0	29.5
	2-3	66.3%	0.84	1.08	1.47	30.01	4.19	28.0	3.1	6.75	0.22	30.4	0.96	198.5	39.7	31.4
	3-4	58.7%	0.79	1.04	1.22	34.12	4.59					33.5	0.82	219.7	40.0	33.2
	4-5	62.8%	0.68	0.99	0.90	28.33	3.74			6.76	0.24	41.9	0.78	219.6	39.9	36.3
	5-6	60.8%	0.68	0.96	0.96	29.38	4.02	29.2	3.0	6.40	0.33	36.8	0.76	219.7	40.0	38.4
	6-7	57.0%	0.64	0.90	0.80	24.60	3.49			4.61	0.18	26.4	0.66	219.5	39.9	39.5
	7-8	49.2%						23.1	1.9	4.04	0.16	23.5	0.54	198.4	19.8	35.7
	8-9	37.1%	0.68	0.74	0.54	18.20	2.98			1.77	0.12	23.5	0.45	158.5	19.8	25.4
	9-10	41.9%						17.0	1.4			28.6	0.50	159.1	19.9	26.3
	10-12	46.7%								1.15	0.11	22.7	0.50	139.5	19.9	22.7
	12-14	39.1%	0.75	0.82	0.43	16.41	3.24					19.6	0.37	100.0	20.0	15.2
	14-16	39.8%								0.88	0.09	21.7	0.40	119.5	19.9	15.5
	16-18	42.2%	0.65	0.80	0.70	24.53	3.66			0.93	0.07	25.8	0.48	119.1	19.9	14.7
51	0-1	79.6%	1.35	1.62	2.11	52.11	5.42	32.4	4.0	10.45	0.48	41.1	1.44			40.0
	1-2	73.1%	1.11	1.44	2.12	55.84	5.29					42.2	1.39			45.7
	2-3	70.3%	1.18	1.43	1.63	45.27	4.13	29.3	3.5	9.70	0.35	46.8	1.33			50.5
	3-4	69.4%	1.30	1.49	1.76	49.10	4.72					41.9	1.30			51.9
	4-5	67.7%	1.12	1.49	1.61	47.14	4.10			9.49	0.51	49.1	1.27			52.4
	5-6	66.8%	1.21	1.40	1.40	39.51	3.86	28.5	3.3			44.6	1.20			51.9
	6-7	65.4%								8.71	0.30	51.0	1.25			57.1
	7-8	62.1%	1.03	1.26	1.40	46.14	4.07	27.0	2.9	7.77	0.22	43.8	1.15			43.2
	8-9	58.3%								5.41	0.39	48.6	1.04			54.0
	9-10	57.8%	0.89	1.02	1.41	45.23	3.91	25.1	2.5	6.25	0.19	46.6	1.18			54.5
	10-12	56.7%								4.69	0.20	47.2	1.07			48.8
	12-14	54.5%								3.83	0.16	36.9	1.00			41.6
	14-16	54.0%	0.77	0.79	1.29	44.57	3.99			2.65	0.17	46.9	0.99			38.2
	16-18	53.8%										48.3	1.20			38.4
	18-20	52.1%	0.70	0.86	1.30	38.91	3.99	24.2	2.2	1.49	0.09	31.5	0.94			22.7
52	0-1	81.8%	1.37	1.82	3.58	51.51	5.56	37.6	5.1	14.20	0.46	51.5	2.86			43.9
	1-2	76.0%	0.96	1.24	1.76	40.84	4.13			13.43	0.43	48.1	1.90			47.0
	2-3	73.4%	0.95	1.26	1.82	50.91	4.44	32.1	4.2	13.14	0.42	50.3	1.70			49.2
	3-4	70.8%	0.98	1.33	1.70	47.78	4.20					46.4	1.57			49.8
	4-5	70.3%	1.00	1.16	2.03	50.53	4.64			12.34	0.43	46.5	1.80			50.3
	5-6	70.2%	1.09	1.32	2.21	62.95	4.89	29.2	3.7			36.7	1.63			50.7
	6-7	68.6%	1.26	1.44	1.84	49.81	4.09			10.38	0.41	46.4	1.70			58.1
	7-8	64.1%	1.09	1.28	1.89	58.78	4.49	26.6	3.2	9.36	0.20	47.1	1.32			60.8
	8-9	58.6%								7.89	0.19	46.9	1.16			63.9
	9-10	58.3%	0.80	1.07	1.32	44.52	3.67	24.0	2.6	7.09	0.31	38.1	1.18			64.3
	10-12	56.4%										41.6	1.06			57.1
	12-14	55.4%								5.46	0.27	40.7	0.99			47.0
	14-16	52.9%	0.75	0.84	1.32	40.64	4.09					37.8	1.00			39.2

Lake Champlain Solid Phase Data

Station	Depth	%H2O	Inorgani	Total	HCl-Mn	HCl-Fe	HCl-Ca	C	N	Pb-210	Pb-210	Fe	Mn	Zn	Cu	Pb
			P	P							S.D.					
	cm		mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	dpm/g	dpm/g	mg/g	mg/g	ug/g	ug/g	ug/g
SS	0-1	76.2%	1.08	0.84	0.48	16.32	4.92			6.59	0.33	21.6	0.66			34.7
	1-2	71.7%	1.13	0.77	0.38	13.71	3.68	33.9	4.0	7.02	0.32	28.8	0.50			35.9
	2-3	67.2%						34.2	3.9			24.0	0.46			34.8
	3-4	63.4%	1.28	0.84	0.43	15.15	3.90	33.6	3.8			29.4	0.50			39.3
	4-5	58.6%								5.83	0.29	26.5	0.44			37.1
	5-6	55.2%								4.91	0.29	25.2	0.41			37.0
	6-7	54.5%	1.02	0.81	0.30	13.40	3.34	26.9	2.9	4.55	0.22	29.6	0.43			39.0
	7-8	51.8%								3.90	0.21	23.0	0.38			40.1
	8-9	50.6%								2.97	0.23	22.7	0.37			39.0
	9-10	48.7%										22.4	0.36			37.4
	10-12	49.0%	0.88	0.80	0.27	12.70	3.08		2.3	2.22	0.12	22.0	0.34			32.0
	12-14	48.7%	0.89	0.70	0.21	12.23	3.10	23.5	2.2			20.4	0.34			30.0
	14-16	47.8%								1.36	0.05	21.1	0.33			26.6