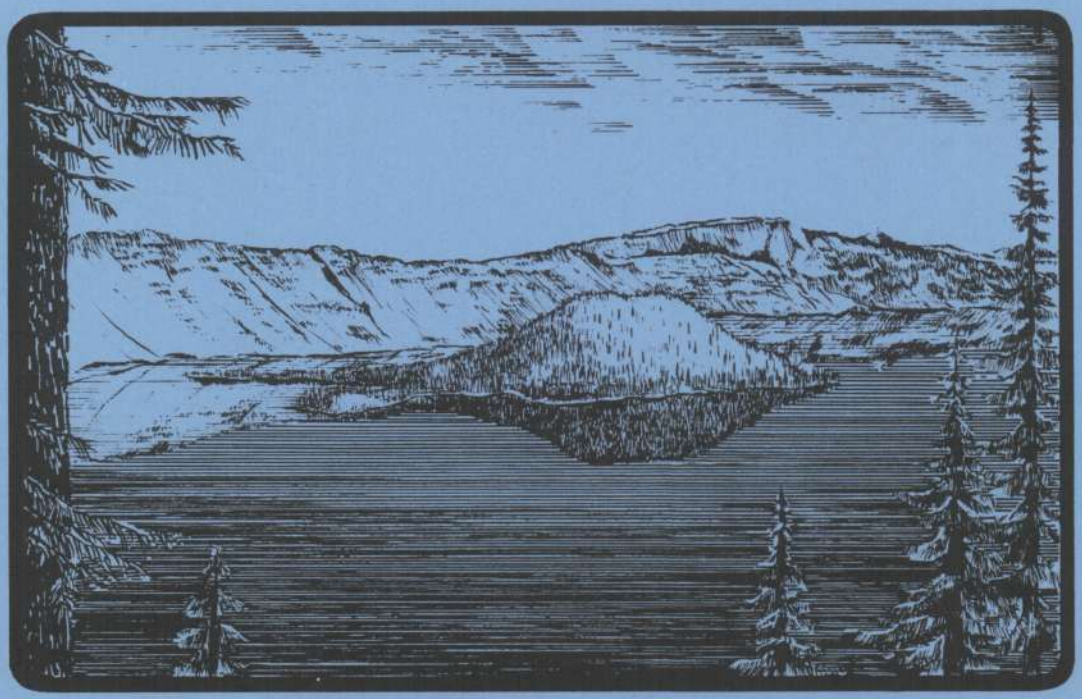
Geochemistry and Phytoplankton Studies of Crater Lake

Robert Collier and Jack Dymond
College of Oceanography

and

C David McIntire and Mary K. Debacon
Department of Botany and Plant Pathology

Oregon State University



National Park Service
Cooperative Park Studies Unit
College of Forestry
Oregon State University
Corvallis, Oregon 97331

CPSU/OSU 88-5

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Final Report

CA-9000-3-0003

Subagreement 13

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Biogeochemistry of Crater Lake

by

Robert Collier and Jack Dymond
College of Oceanography

Oregon State University

INTRODUCTION

Since the summer of 1983, we have been studying the biogeochemistry of Crater Lake. Our work primarily focuses on descriptions of elemental cycles driven by physical, biological, hydrothermal and anthropogenic processes. The primary efforts fall into three general categories: 1) trace metal distributions and cycles; 2) hydrothermal activity in the lake; and 3) present and historical fluxes of particulate matter in the lake and its sediments. The primary results of these sub-projects are summarized below. Nonetheless, we are continuing our studies at the lake such that this "final" report, which covers the last four years of work, will be augmented in the future.

METHODS

Water sampling and analyses.

We collected a variety of water samples for this program with the operational assistance of NPS personnel. At various times during the program, samples were analyzed for major cations, trace metals, Radon-222, and helium isotopes. All samples were collected with oceanographic samplers specifically designed (or modified) for trace metal work. These included 30-liter Niskin™ samplers (General Oceanics), as well as 5- and 20-liter GOFLO™ samplers (General Oceanics). All sampling, handling, storage and analysis was carried out using a strict contamination control "consciousness" which can be essential for certain trace metal analyses on environmental samples (see Bruland, 1983). A portable conductivity, temperature, and depth probe (CTD) was deployed in 1984 to identify hydrothermal signals.

Trace metal samples were collected directly into hot-acid cleaned polyethylene bottles. The samples were filtered within 8 hours at the park chemistry laboratory using acid-cleaned, 0.4µm Nuclepore™ filters. The samples were acidified to pH 2 using 6N HCl which was prepared by sub-boiling redistillation in all-teflon apparatus. Samples for radon gas analysis were collected directly into evacuated 20-liter glass carboys. Samples for He analyses were stored in copper tubes after cold-weld sealing (Young and Lupton, 1983).

Analyses of major cations were carried out by standard flame atomic absorption spectrometry using direct aspiration (EPA-600/4-79-020, 1979). Trace metal concentrations also were determined by atomic absorption using graphite furnace atomization. Samples for furnace analysis were either directly injected (with matrix modification) or preconcentrated by a cobalt-APDC coprecipitation technique (Collier, 1984). Radon-222 was measured by stripping the radon gas onto a cryogenic support column followed by beta-induced scintillation counting. These methods were developed at Lamont-Doherty Geological Observatory and have been applied to other hydrothermal systems (Dymond et al., 1983). Helium concentrations and He-3/He-4 isotope ratios were determined by J. Lupton at U.C. Santa Barbara on a 21 cm radius mass spectrometer (Lupton and Craig, 1975).

Sediment trap collections and analyses.

Particles settling through the water column were collected in an inverted funnel sediment trap designed at OSU (Moser, Dymond and Fischer). This trap collects and concentrates particles into a small sample cup that contains preservative (formalin). These devices have been used for many years in the ocean and in lakes to collect large-diameter, rapidly-settling suspended

material which dominates the total vertical rain flux of particulate matter in most natural aquatic systems.

Traps were deployed in Crater Lake on non-contaminating nylon rope moorings. Since 1983, eight deployments have been made (see Table 1) - the first two at Station 13 and the remaining deployments at Station 23 (Fig. 1). Typically, a mooring was deployed during the summer (July-September) and again over the winter (September-July). The first two years (CL1-4, Table 1) used paired traps deployed at two depths. Moorings since CL-5 used larger single cone traps deployed at three depths. The mooring deployed in September 1986 (CL-8) used a multi-cup sample collector which will collect 5 subsamples during the winter.

Sediment core collection and analyses.

Sediment cores were collected using a standard oceanographic gravity core and using a small "box core" developed in New Zealand for lake work. The core samples were taken back to OSU for opening, description, archival and subsampling. A total of 15 sediment cores have been collected to date. The unanalyzed portions of these cores are archived at the OSU Oceanography Core Laboratory facility.

Table 1. Crater Lake Field Programs -- "Geochemistry and Limnology of Crater Lake"
Cooperative Agreement No. CA-9000-3-003
Subagreement # 13 parts a. and c.

Date	Sample description		Location	Depth (meters)	# samples
7/11/1983	Trace element water samples		Stn. 23	0-300	15
	Radon/Mn water samples		Stn. 13	integrated	2
7/12	Sediment trap deployment	[CL-1]	Stn. 23		
7/13	Radon/Mn water samples		Stn. 23	integrated	3
9/12	Sediment trap recovery	[CL1]	Stn. 23	2x200, 2x456	4
	Radon/Mn water samples		Stn. 23	integrated	2
9/13	Sediment trap deployment	[CL2]	Stn. 23		
	Radon/Mn water samples		Miriam cone	integrated	2
7/10/84	Sediment trap recovery	[CL2]	Stn. 23	2x200, 2x456	4
7/11	Sediment trap deployment	[CL3]	Stn. 13		
8/8	Coring stations GC84-1, 2, 3, 4, 5				
8/9	Trace element water samples		Stn. 13	surface to 580	14
	Trace element water samples		Stn. 23	surface to 455	12
	Spring water samples				8
	Surface water samples				5
8/10	CTD stations 1 & 2				
9/17	Sediment trap recovery	[CL3]	Stn. 13	2x200, 2x580	4
9/18	Sediment trap deployment	[CL4]	Stn. 13		
7/10/85	Sediment trap recovery	[CL4]	Stn. 13	2x200, 2x580	4
7/11	Sediment trap deployment	[CL5]	Stn. 13		
	Coring stations GC85-1b, 2, 3, 4				
9/4	Radon/Mn/He water samples		Stn. 23		4
	Multiple near-bottom water samples				15
9/5	Sediment trap recovery	[CL-5]	Stn. 13	200, 390, 580	3
9/6	Sediment trap deployment	[CL-6]	Stn. 13		
7/7/86	Radon/Mn water samples		Stn. 23		4
7/8	Sediment trap recovery	[CL-6]	Stn. 13	200, 390, 580	3
	Radon water samples		Stn. 23		4
7/9	Radon water samples		Stn. 23		4
	Sediment trap deployment	[CL-7]	Stn. 13		
7/10	Radon water samples		Stn. 23		8
	Small box cores CL86-1, 2		Stn. 23, Stn. 13		
9/3	Sediment trap recovery	[CL-7]	Stn. 23	200, 390, 580	3
	Small box cores CL86-3, 4				
9/4	Sediment trap deployment	[CL-8]	Stn. 23		
	Small box cores CL86-5, 6				

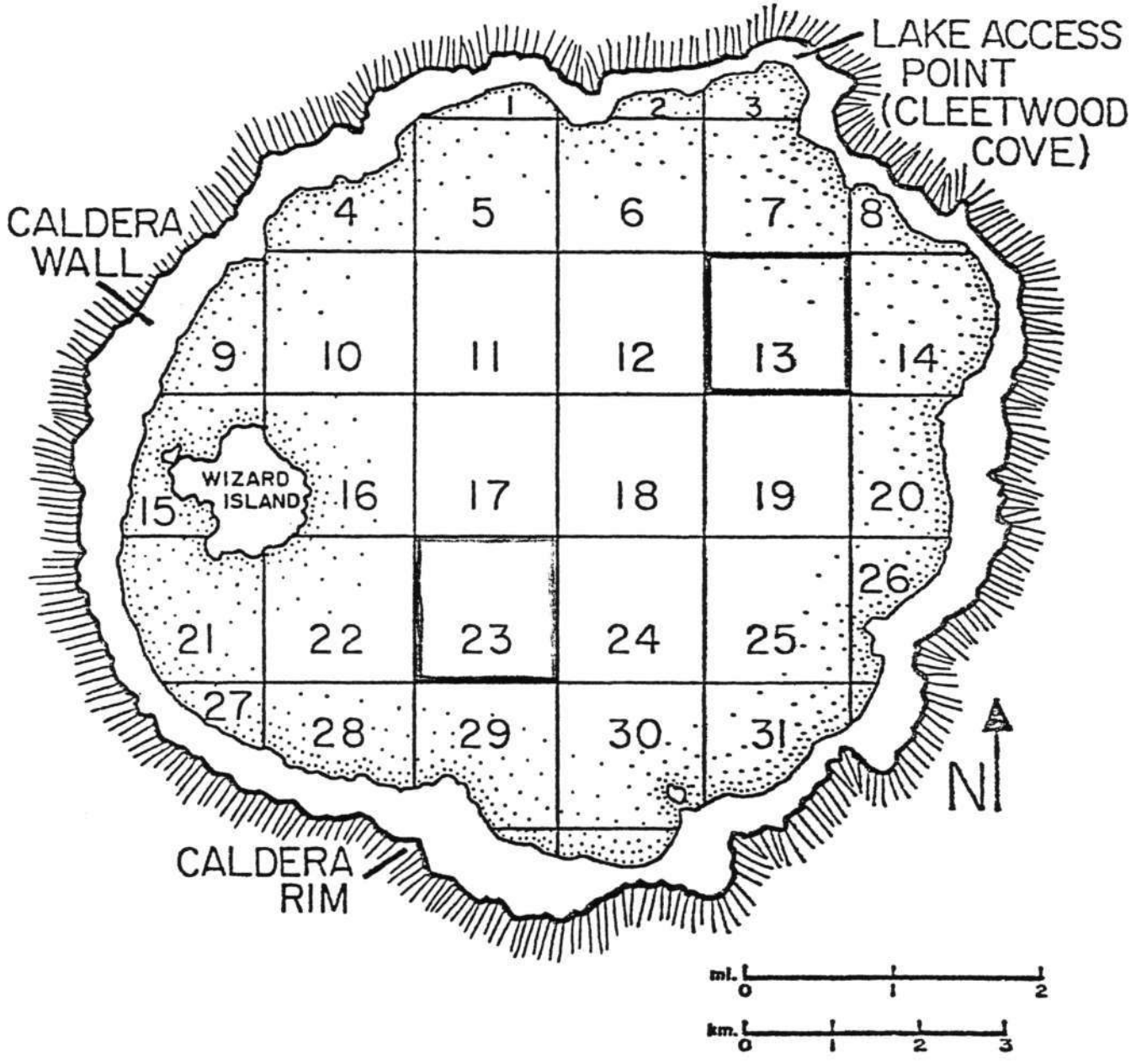

Figure 1. Crater Lake grid system showing the locations of stations 13 and 23.

TECHNICAL FINDINGS

Trace metal distributions.

Water sample collection for trace metals started in 1983 and has continued through the 1986 field season. These samples included several vertical profiles, numerous near-bottom profiles related to hydrothermal investigations, samples from a transect of surface waters between Phantom Ship and Cleetwood Cove, and a set of samples from several of the caldera springs collected in 1984 (see Table 1). The analytical results from the 1983 and 1984 data are given. The results from 1985 and 1986 are primarily related to the hydrothermal investigation (see below).

The concentrations of many of the metals are below those commonly found in seawater (Bruland, 1983). The vertical profiles of concentrations for many of the metals showed a clear surface maximum (see Figs. 2 and 3) which decreased rapidly below 75 meters (into the thermocline). Significant surface inputs of these metals must exist in order to maintain these maxima. Analyses of the major cation concentrations in these profiles suggest that the spring snowmelt runoff event is probably not the major source of these metals (Tables 2,3,4 and 5). The compositions of the caldera springs also appear to be insufficient to account for these metal maxima (Table 6). Atmospheric deposition of metals remains as a likely source for these surface features. The presence of a significant lead maximum suggests anthropogenic input from local sources or long-range transport of aerosols.

These data were discussed at the AGU Ocean Science - ASLO meeting in January 1986 (Holbrook et al., 1985) and a manuscript is currently in preparation for submission to the journal Limnology and Oceanography.

TABLE 2

1983-Stn.23

Sample ID#	depth (m)	Mg (mM)	Na	Al-F* (μM)	Al-U	Mn-F (nM)	Mn-U	Fe-F	Fe-U	Cu-F	Cu-U	Ni	Pb	Mo	V	Zn-F	Zn-U
CL-1	10	0.111	0.453	99.5	173.4	4.37	5.90	6.5	36.1	5.96	6.61	2.00	0.69	2.01	42.4	3.29	4.17
CL-2	20	0.110	0.448	82.8	146.1	2.86	4.71	3.1	32.6	2.31	2.84	1.90	0.11	2.09	43.1	1.28	
CL-3	30	0.110	0.453	79.2	128.1	1.21	5.34	2.3	28.8	2.41	3.20	0.70	0.11	1.91	43.1	1.24	3.45
CL-4	40	0.111	0.453	54.8	114.0	0.95	4.40	2.7		2.05		1.00				0.62	1.13
CL-5	50	0.110	0.445	49.1	120.8	0.73	4.33	1.9		1.33			0.12	1.94	43.8	0.27	0.25
CL-6	75	0.110	0.450	42.0	113.0	0.45	3.96			1.23							0.19
CL-7	100	0.109	0.448	42.9	99.6	0.40	3.90						0.10	1.95	44.1	0.25	0.16
CL-8	125	0.109	0.451	36.5	110.3	0.17	4.01	0.8		1.21		0.29	0.13	1.88	43.9		0.07
CL-9	150	0.110	0.449	38.6	104.3	0.05	3.84	1.0		1.98			0.05	1.81	43.8		0.03
CL-10	175	0.110	0.453	32.5	103.0	0.06	3.54	1.1		1.57			0.02			0.27	0.08
CL-11	200	0.110	0.452	28.4	111.3		3.73	0.9		1.13		0.42	0.05	1.84	44.6	0.07	0.25
CL-12	225	0.110	0.456	34.7	113.3	0.57	3.74			1.51						0.37	0.11
CL-13	244	0.108	0.453		106.2	0.41	3.77			1.40			0.02	1.80	43.5	0.20	0.26
CL-14	269	0.109	0.457	29.8	111.4	0.12	3.92	1.4		1.32			0.02	1.83	43.8		0.26
CL-15	294	0.112	0.457	41.9	118.5	0.18	3.98	0.8		1.60				1.85	43.7		0.09
CL-16	294	0.110	0.449	34.8	69.2	0.08	2.05	0.7		1.36						0.43	0.58
CL-17	264	0.110	0.450	48.1	72.2	0.08	2.22	1.9		1.58			0.06	1.83	43.0	0.34	0.48
CL-18	100	0.109	0.450	44.1	80.6	0.01	2.99	1.1		1.09			0.11	1.82		0.01	0.18
CL-19	130	0.109	0.447	38.5	73.7	0.03	2.97			1.47			0.06			0.03	

* The designation "-F" and "-U" used in Tables 2-6 refers to filtered and unfiltered samples.

TABLE 3

1984-Stn.13

Sample ID#	depth (m)	Ca (mM)	K	Mg	Na	Al-F (μM)	Al-U	Mn-F (nM)	Mn-U	Fe-F	Fe-U	Cu	Ni	Cd	Pb	Mo	V
CL168	4	0.066	0.042	0.11	0.49	0.13	0.38	3.94	5.69	5.36	88.3	2.38	9.0	0.041	0.410	2.33	41.9
CL156	10	0.066	0.040	0.10	0.43	0.14	0.33	2.16	3.42	2.94	50.9	1.21	5.4	0.011	0.074	2.20	40.1
CL150	20	0.065	0.040	0.12	0.43	0.11	0.20	1.88	2.44	1.52	26.4	1.18	1.6	0.016	0.021	2.27	41.1
CL172	30	0.067	0.041	0.10	0.50	0.12	0.20	1.61	2.46	2.08	19.5	1.34	2.0	0.021	0.260	2.18	40.2
CL166	40	0.066	0.040	0.10	0.49	0.10	0.21	0.96	2.69	1.66	18.5	2.16	1.2	0.014		2.18	40.0
CL157	50	0.064	0.040	0.10	0.43	0.12	0.24									2.41	43.2
CL170	74	0.066	0.040	0.11	0.48	0.13	0.47	0.42	2.25	2.04	12.7	1.94			0.021	2.26	43.0
CL159	100	0.062	0.040	0.11	0.49	0.13	0.18	0.43	2.13	2.03	12.3	1.73	0.8	0.005	0.049	2.60	47.9
CL158	150	0.063	0.040	0.12	0.44	0.12	0.22	0.43	2.04	2.07	14.8	1.75	0.6	0.007	0.023	2.32	44.0
CL154	200	0.067	0.040	0.10	0.43	0.12	0.29	0.48	1.76	1.08	12.3	1.26	1.5	0.003	0.003	2.31	41.8
CL161	250	0.063	0.040	0.11	0.48	0.10	0.26	0.34	1.81	1.68	14.5	1.73	1.5	0.011	0.033	2.29	41.1
CL153	300	0.064	0.040	0.11	0.44	0.09	0.18	0.35	1.63	0.75	10.2	1.23	0.6	0.014	0.004	2.31	39.4
CL162	350	0.064	0.041	0.11	0.49	0.11	0.23	0.26	2.20	1.89	15.1	1.73	1.2	0.012	0.013	2.48	42.3
CL174	400	0.066	0.042	0.11	0.51	0.10	0.31	0.29	2.91	1.26	23.1	1.58	0.7	0.007	0.001	2.37	41.9
CL167	450	0.064	0.041	0.11	0.50	0.15	0.38	0.38	4.23	10.10	66.0	1.38	1.0	0.012	0.013	2.32	40.0
CL171	500	0.065	0.040	0.11	0.50	0.10	0.45	0.37	4.85	13.75	64.7	1.98	1.0	0.007	0.013	2.41	43.0
CL176	540	0.065	0.041	0.11	0.51	0.16	0.23	0.69	5.44	6.30	46.3		1.2	0.007	0.021	2.43	42.8
CL152	580	0.065	0.041	0.12	0.45	0.12	0.51	0.53	5.50	3.41	39.2	2.04	1.6	0.008	0.001	2.50	44.5

TABLE 4

1984-Stn.23

Sample ID#	depth (m)	Ca (mM)	K	Mg	Na	Al-F (μM)	Al-U	Mn-F (nM)	Mn-U	Fe-F	Fe-U	Cu	Ni	Cd	Pb	Mo
CL173	5	0.065	0.040	0.10	0.40	0.09	0.33	1.96	3.77	16.54	59.4	0.99	0.63	0.028	0.061	1.96
CL175	10	0.064	0.040	0.10	0.40	0.10	0.30	1.69	3.40	9.44	49.2	0.91	0.66	0.005	0.070	1.95
CL151	20	0.067	0.040	0.10	0.41	0.07	0.16	1.63	2.37	9.12	22.6	0.69	0.80	0.005	0.077	1.91
CL160	30	0.066	0.040	0.10	0.41	0.08	0.16	1.29	2.41	8.31	17.7	1.08	1.22	0.019	0.068	2.14
CL165	40	0.066	0.040	0.10	0.41	0.04	0.13	0.51	2.35	8.54	15.0	0.82	0.87	0.004		1.95
CL163	50	0.066	0.040	0.10	0.40	0.04	0.09	0.27	2.10	7.79	14.0	0.82	0.73	0.003	0.032	2.13
CL164	75	0.066	0.039	0.10	0.41	0.10	0.13	0.32	2.24	8.01	12.8	1.73	1.01	0.019	0.010	1.95
CL169	100	0.069	0.040	0.10	0.41	0.06	0.13	0.25	1.95	7.16	13.7	1.15	0.89	0.015	0.031	1.81
CL205	150	0.067	0.039	0.10	0.43	0.11	0.07	0.36	1.75	5.41	10.2	1.23	1.66	0.023	0.010	1.79
CL195	200	0.066	0.040	0.10	0.43	0.08	0.11	0.44	1.76	8.28	12.6	1.42		0.019		1.91
CL207	250	0.064	0.040		0.43	0.07	0.13	0.22	1.55	9.51	9.4	1.27	1.80	0.015	0.016	1.87
CL181	300	0.065	0.039	0.10	0.41	0.02	0.11	0.21	1.44	5.14	10.3	1.30	1.82		0.039	2.29
CL184	350	0.069	0.040	0.10	0.44	0.04	0.14	0.06	1.42	4.26	10.5	1.42	0.86	0.014	0.053	2.72
CL180	400	0.066	0.041	0.10	0.41	0.05	0.15	0.72	2.65	4.15	14.3	1.41	1.28	0.016		2.04
CL197	430	0.065	0.040	0.10	0.43	0.07	0.16	1.28	2.56	14.11	25.5	2.68	4.84	0.030	0.078	1.95

TABLE 5 1984-surface water transect

Sample ID#	depth (m)	Ca (mM)	K	Mg	Na	Al-F (μM)	Al-U	Mn-F (nM)	Mn-U	Fe-F	Fe-U	Cu	Ni	Cd	Pb	Mo	V
CL193	5	0.066	0.041	0.093	0.48	0.12	0.23	2.78	4.28	3.46	51.3	1.27	1.00	0.528	0.780	2.00	42.7
CL203	6	0.067	0.040	0.118	0.48	0.05	0.23	2.40	3.66	5.93	46.8	1.22	4.60	0.068	0.132	2.13	44.2
CL192	5	0.062	0.040	0.093	0.48	0.19	0.25	2.41	3.86	2.00	48.8	0.98	0.90	0.238	0.112	2.21	45.2
CL200	4	0.064	0.041	0.099	0.49	0.13	0.21	2.70	4.20	2.60	54.8	1.88	0.50	0.418	0.112	1.92	43.3
CL206	6.5	0.065	0.041	0.094	0.49	0.10	0.22	2.40	3.61	1.96	46.4	1.07	0.50	0.128	0.242	1.86	43.0

TABLE 6 1984-springs

Sample ID#	(spring#)	depth (m)	Ca (mM)	K	Mg	Na	Al-F (μM)	Al-U	Mn-F (nM)	Mn-U	Fe-F	Fe-U	Cu	Ni	Cd	Pb	Mo	V
CL188	(24)	[42]* -	0.032	0.034	0.024	0.11	1.46	3.00	1.95	8.80	177.0	533	1.77	3.02	0.013	0.026	2.13	
CL191	(21)	[39] -	0.016	0.011		0.03	0.52	49.00	15.40	273.00	27.8	7802	4.10	1.92	0.041	0.132	0.67	18.4
CL190	(19)	[38] -	0.050	0.022	0.530	0.12	0.60	12.40	4.30	71.50	41.8	2535	5.57	3.01	0.019	0.112	1.28	28.9
CL204	(9)	-	0.163	0.020	0.249	0.32	0.17	0.62	0.15	2.70	1.9	125	0.28	0.28	0.000	0.030	3.25	102.6
CL201	(51)	-	0.069	0.012	0.076	0.12	0.24	1.00	2.26	6.00	51.9	253	1.20	0.54	0.024	0.000	1.63	56.4
CL183	(52)	-	0.529	0.018	0.152	0.13	0.58	39.90	20.20	271.00	5.8	6985	1.19	22.20	0.048	0.000	1.79	6.1
CL202	(63)	-	0.017	0.022	0.049	0.15	0.30	0.62	0.37	2.10	46.2	101	0.45	0.80	0.002	0.000	2.69	10.8

* The numbering system with the parentheses areound spring numbers, e.g. (24) is an older numbering system which has been replace. The current numbers are those in brackets, e.g. [42].

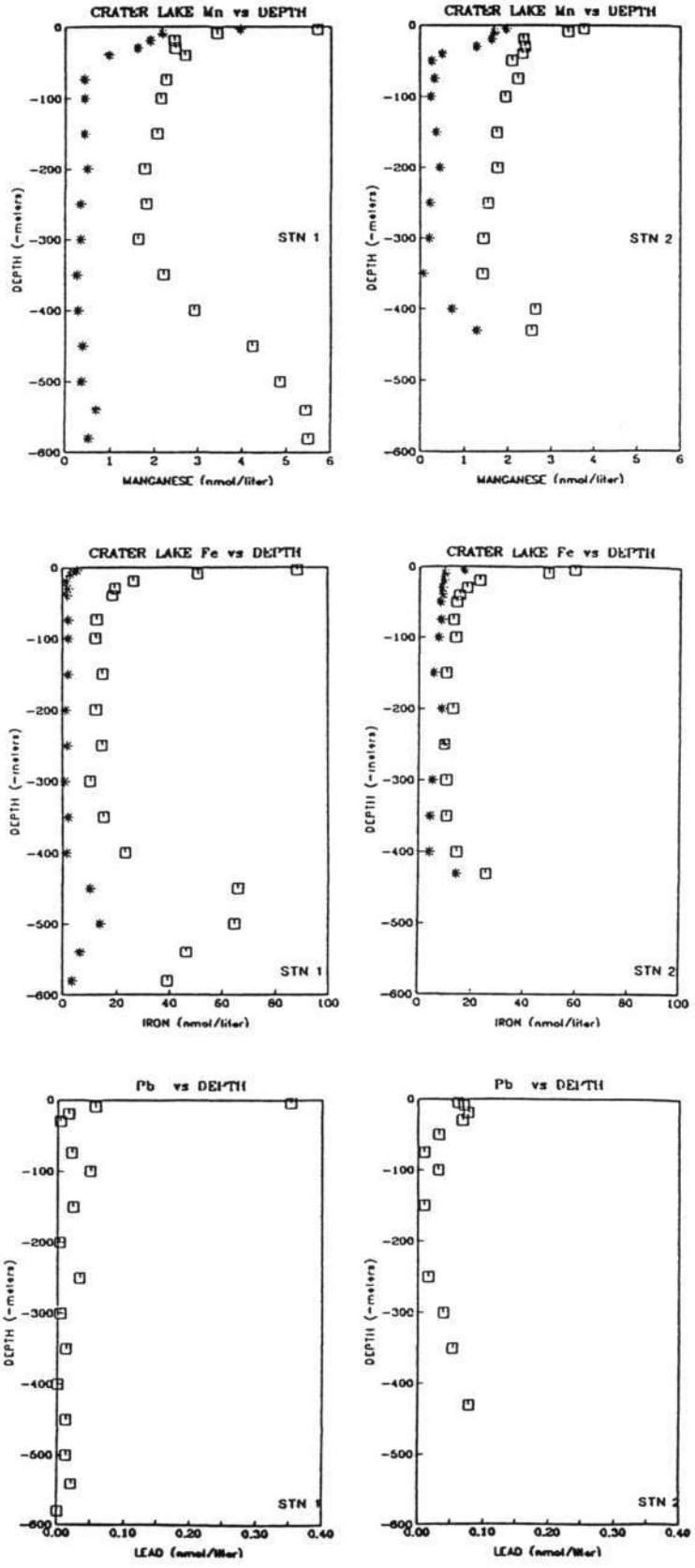

Figure 2. Depth profiles of trace metals at stations 13 (STN 1) and station 23 (STN 2), Crater Lake. Boxes represent total and asterisks, dissolved concentrations.

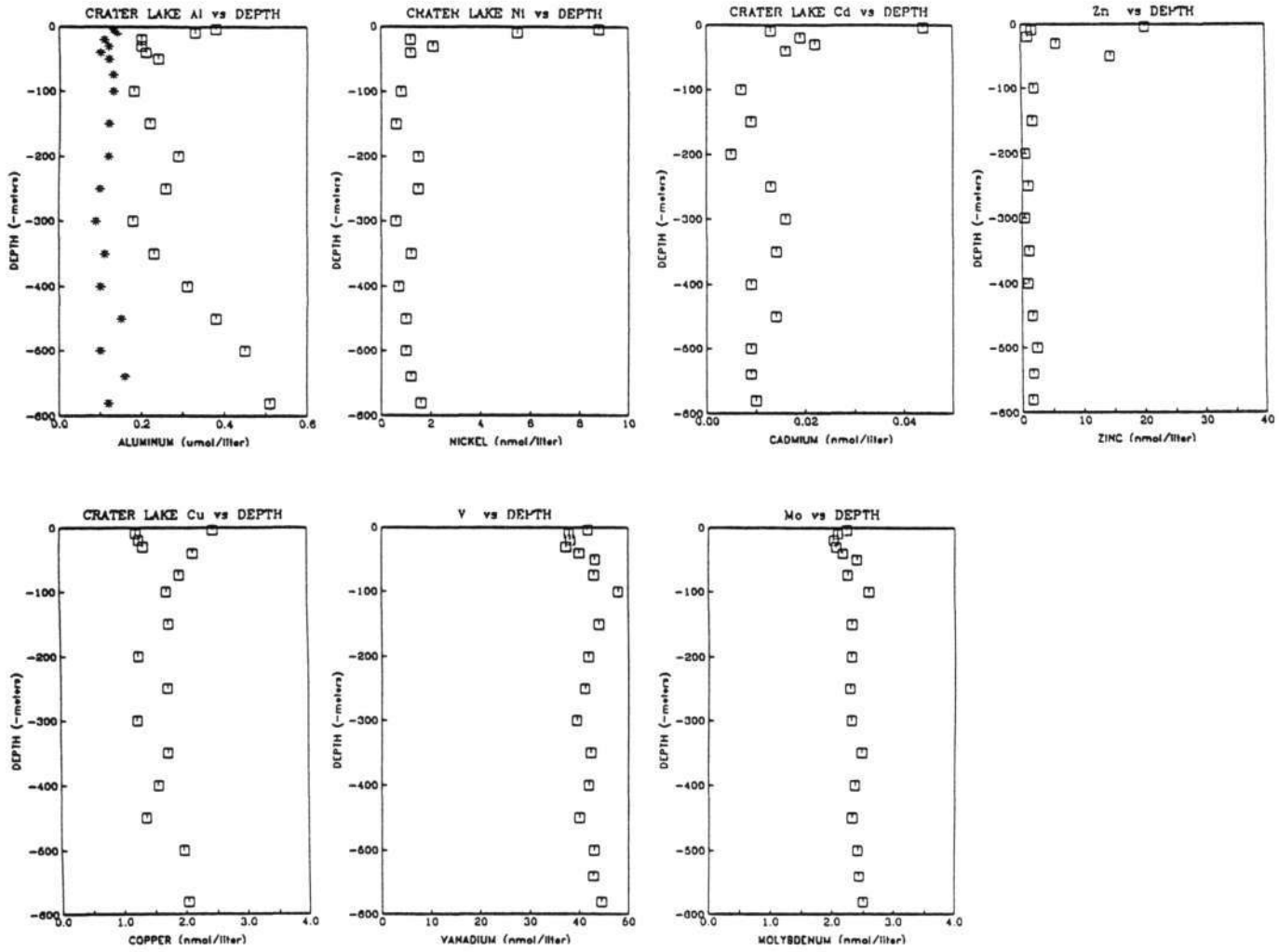

Figure 3. Depth profiles of trace metals at station 13, Crater Lake.

Hydrothermal chemical tracers.

More recent efforts have focused on analysis of hydrothermal chemical tracers deep in the lake. The results of our work to date are summarized below and a manuscript is in preparation for Nature. This work is still in progress and a major research effort is planned to continue over the next several field seasons.

From the data of Williams et al. (1983) and from the major ion composition of the lake, it is clear that hot spring inputs have played a role in determining the composition of the lake in the recent past. In order to locate and study the composition of these springs, we have applied several chemical determinations which have been used in the marine environment to locate active hot springs on the seafloor. These analyses included: the dissolved trace elements Mn and Fe; the dissolved radioactive gas Rn-222 (half-life = 3.6 days); and the dissolved inert gas Helium (both isotopes He-3 and He-4 were analyzed by Dr. John Lupton, UCSB).

In 1984, very high and variable concentrations of Rn-222 and Mn were found deep in the lake suggesting the active input of hydrothermal solutions (Fig. 4). Although Rn can be transferred through a vapor phase, dissolved ions like Mn and Na can not. The following year, we added He analyses to the data set and clearly demonstrated the presence of high concentrations of "mantle" helium in the lake (Collier, Dymond and Lupton, Nature, in prep.). From the tritium data of Simpson (1970), gas exchange rate with the atmosphere appears to occur on a time scale of a few years. This suggests that the strong helium anomaly found in the deep lake must be <u>actively</u> maintained over this same time scale. We believe this data demonstrates the existence of some form of active hydrothermal circulation in the lake. A more extensive field

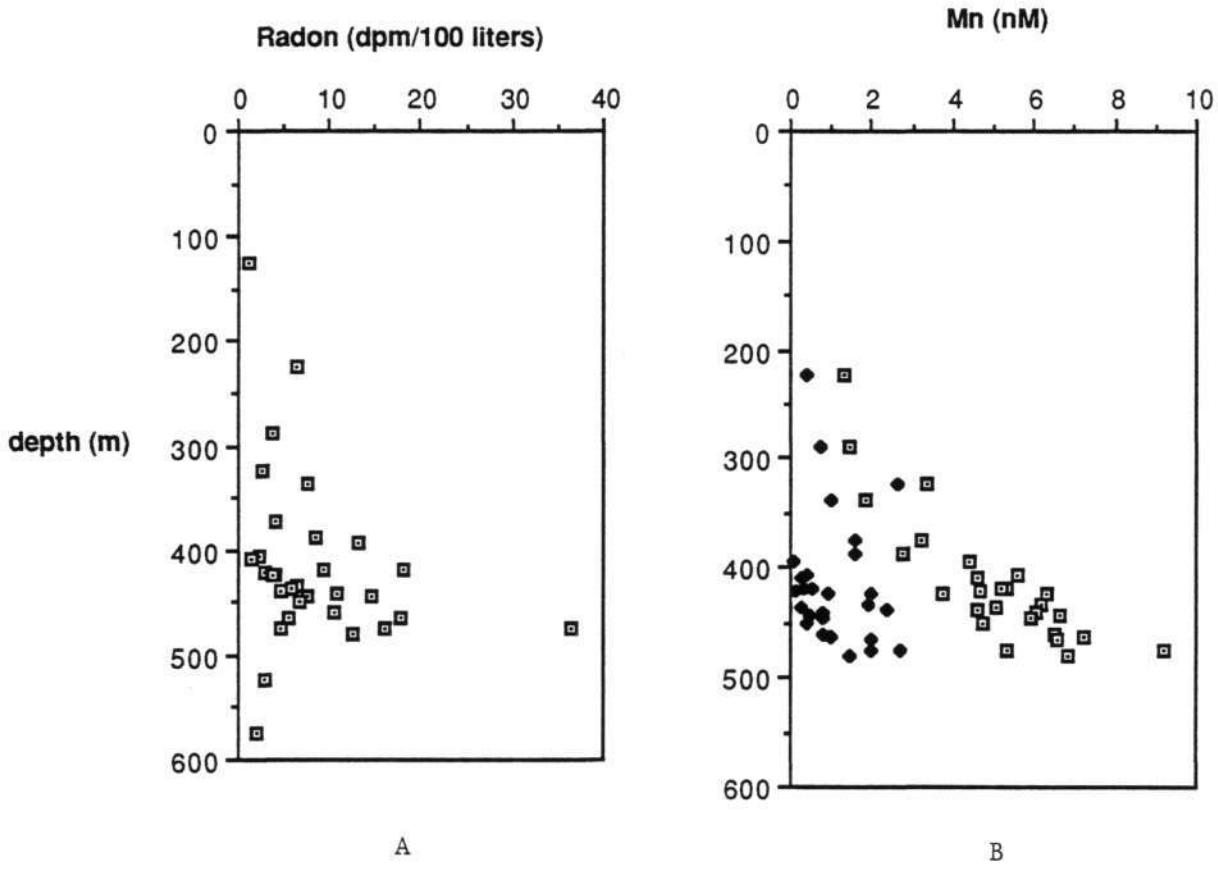

Figure 4. Depth profiles of (A) dissolved randon-222 activities and (B) dissolved (diamond) and total (unfiltered-boxes) manganese at station 23, Crater Lake.

sampling program to address this question is currently planned for 1987 - 1989.

Sediment traps and sediment cores.

The sediment trap program and sediment core analyses are also part of an ongoing effort. Our eighth sediment trap is currently in the lake and will be recovered this July (1987). We currently plan to redeploy the trap for the summer (1987) and again for the winter (1987-1988). At this point we feel that we will have acquired a sufficient data record to estimate average fluxes and variance among several seasons and years. Preliminary core analyses also exist and demonstrate long-term variations in biogenic and hydrothermal accumulation rates (Fig. 5).

Comparisons of trap fluxes to estimates of primary production suggest that greater than 90% of the total primary production is recycled within the euphotic zone, greater than 60% of the organic matter that settles out of the euphotic zone is decomposed before it reaches the lake floor, and greater than 80% of this is regenerated before final burial in the sediments. Some portion of the manganese enrichment seen deep in the lake basin is probably supported by the regeneration of particulate Mn at the lake floor before burial. When the final trap data are acquired and all of the cores analyzed, we will be able to finalize these elemental cycles with a box model of the lake (Fig. 6).

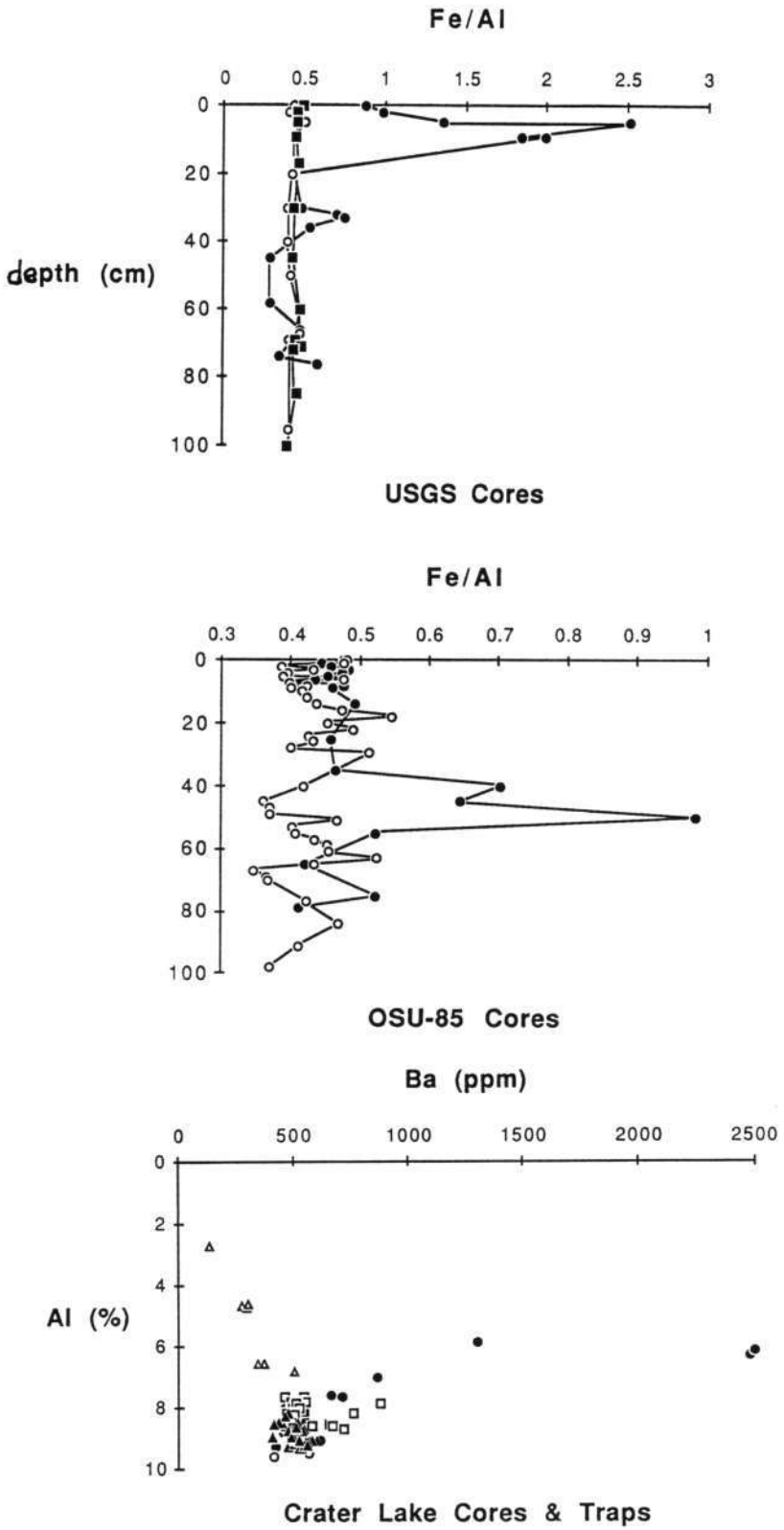

Figure 5. Composition of several cores (including OSU analyses of a USGS core series) showing variations in Fe/Al ratios related to hydrothermal inputs at different places and times at the lake floor. Variations in Ba and Al demonstrate three end members present in the lake particles: diamonds - sediment trap material with a biogenic influence; lithogenous material; and high-Ba hydrothermal materials.

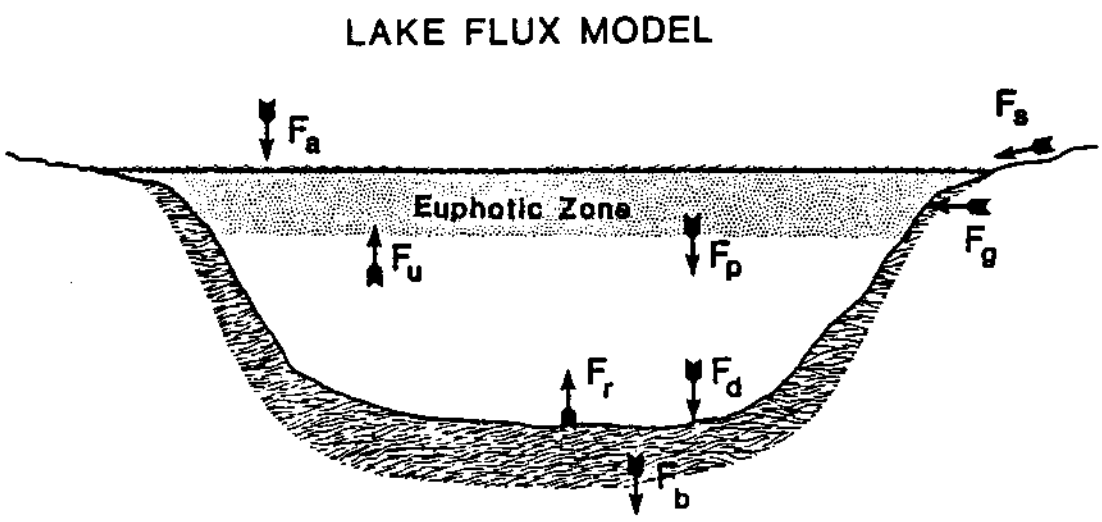

Figure 6. Schematic box model with major fluxes noted: F_a - atmospheric inputs; F_s - net surface water inputs (inflow - outflow); F_g - ground water inputs; F_u - net upward flux from the hypolimnion due to mixing; F_p - settling flux of particulate matter out of the euphotic zone; F_d - settling flux of particulate matter to the sediment surface ($F_p - F_d$ = flux recycled within the hypolimnion); F_r - flux of material recycled through the sediment/water interface; F_b - flux of material permanently buried (at steady state $F_r = F_d - F_b$).

CONCLUSIONS

Our conclusions for the work completed are generalized below. Again, since much of this work is still in progress, these conclusions will be updated and modified as new results are available.

The trace metal concentrations in Crater Lake are extremely low - in some cases lower than equivalent concentrations in seawater. There is a surface maximum in concentration for many of the metals which we attribute to atmospheric inputs. Some of these atmospheric inputs may be anthropogenic (e.g. Pb) and others are probably natural (e.g. Mn). There are elevated concentrations of Mn and Fe deep in the lake that appear to be partly related to hydrothermal activity.

The chemical composition deep in the lake is consistent with other data suggesting that there is active hydrothermal circulation at the lake floor. These anomalies include Fe, Mn, Rn-222, and He, and isotopic composition. These data, when combined with bulk chemical properties of the lake and the previously measured temperature anomalies, demonstrate recent active hydrothermal inputs of some as-yet unknown magnitude.

The vertical flux of biogenic and lithogenic particulate matter in the lake demonstrates that the "winter" sample period (actually 10 months) is as significant to particle fluxes as is the summer period. The fluxes of biogenic material through each vertical "layer" of the lake system (both spatial and trophic) decreases towards the bottom and the sediments demonstrate a high degree of recycling in this efficient, oligotrophic ecosystem. The burial of biogenic and hydrothermal materials in the lake sediments offers a wealth of information about the paleolimnology of the lake.

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ACCESS INFORMATION FOR DATA

Further information on these data can be acquired through the principal investigators at the College of Oceanography, Oregon State University, Corvallis, OR 97331 (503-754-2296).

Three journal articles are currently in various stages of preparation and will discuss these data more fully:

"Trace element distributions in Crater Lake, OR," Collier, Dymond et al., for Limnol. and Oceanogr. (end of summer, 1987).

"Chemical evidence of hydrothermal inputs to Crater Lake, OR," Dymond, Collier and Lupton, for Nature (by summer 1987).

"Nutrient cycles and vertical fluxes of particulate matter in Crater Lake, OR," Dymond and Collier, for Limnol. and Oceanogr.

TAXONOMY AND ECOLOGY OF THE PHYTOPLANKTON OF CRATER LAKE

submitted to

THE NATIONAL PARK SERVICE

PACIFIC NORTHWEST REGION

final report in relation to

COOPERATIVE AGREEMENT NO. CA-9000-3-0003

SUBAGREEMENT NO. 13

prepared by

C. David McIntire

and

Mary K. Debacon

Department of Botany & Plant Pathology

Oregon State University

Corvallis, Oregon 97331

INTRODUCTION

This report has been prepared primarily for the information of persons having the responsibility of evaluating the progress of an ongoing study of the phytoplankton of Crater Lake. Although scientists interested in the vertical and seasonal distribution and abundance of phytoplankton in the lake may find this report an informative summary of our field and laboratory studies, it is not intended to be a definitive publication and should not be evaluated as such. The information included in the report covers the period from March 19, 1985 through November 30, 1986. During this period the research was primarily concerned with the identification of phytoplankton species, the development of counting methods, the counting of 1985 and some 1986 phytoplankton samples obtained by the Park Service, the development of statistical methods, and a preliminary analysis of data obtained from the 1985 samples.

The report is organized into four major parts: Introduction, Methods, Species Composition of Crater Lake Phytoplankton, and Distribution and Ecology of Crater Lake Phytoplankton. In the introduction, we provide general background information and restate the objectives of the ongoing project. The Methods section is concerned with the description of procedures for counting the phytoplankton samples, an outline of our approach to data management, and a summary of an approach to the statistical analysis of the data. The third section is concerned with a brief description of the taxonomic composition of the flora; we have also included a complete list of taxa, along with species code numbers, a food resource classification category, and factors for converting cell counts to biovolumes. The final section presents distributional patterns and some corresponding relationships for data collected in 1985 and in March 1986.

Objectives of the Project

The general objective of this project is to describe the dynamics of phytoplankton assemblages at an intensive study site in Crater Lake, and to generate hypotheses that could account for the vertical and seasonal distribution and abundance of the constituent populations in the water column. Specific objectives include: (1) the identification of organisms in plankton samples obtained from Park Service personnel; (2) the development of laboratory and statistical procedures for the analysis of the samples; (3) the quantitative evaluation of the absolute and relative abundance of phytoplanktonic species in the samples; (4) the multivariate analysis of the data obtained during the 1985-86 sampling period; (5) if possible, a quantitative analysis of the data obtained during an earlier sampling program (1981-84); and (6) the interpretation of the distributional patterns in the phytoplankton relative to patterns of chlorophyll and nutrient distribution in the water column and surrounding springs, and relative to other physical, chemical, and biological variables under investigation (e.g., thermal stratification, zooplankton density, patterns of light attenuation, etc.). Because this is an ongoing project, the work associated with Subagreement No. 13 and reported here was confined to the activities stated above in the second paragraph of this introduction.

METHODS

Analysis of Phytoplankton Samples

Phytoplankton samples were obtained as part of a 10-year limnological research and monitoring program conducted by the National Park Service. During the period covered by this report, samples were taken from different water depths at Station 13, a location approximately 3 km south of Cleetwood Cove. Table 1 summarizes the date and depth of each sample and indicates whether or not the sample was processed during the time supported by Subagreement No. 13.

For the quantitative analysis of species composition, 1-liter subsamples of each plankton collection were fixed with Lugol's solution and concentrated by allowing the seston to settle for at least 50 hr. After decanting the supernatent water, a concentrated subsample of 50 ml was transferred to a plexiglass settling chamber. The chamber then was mounted on a Wild inverted microscope, and approximately 300 algal units were identified and counted at a magnification of 1250X (Utermohl 1958). In this case, an algal unit was an individual cell or diatom valve, if the taxon was a unicellular form, or an individual filament in the case of multicellular taxa. To aid in the identification of some diatom taxa, it was sometimes necessary to use the modified Utermohl method (Taylor et al. 1986) to help clear the cells of organic material.

Cell densities were estimated from the expression:

$$\text{algal units/liter} = \text{count} \times [A/(W \times L)] \div [V/1000\ \text{ml}] \times CF$$

where A is the area of the chamber (cm^2), W is the field width (cm), L is the total length of the transects (cm), V is the volume of the chamber (ml) times 1 liter, and CF is the volume of the concentrated sample divided by the volume of the original sample. Biovolume conversion factors were determined for each taxon using appropriate geometric formulae. These

conversion factors were multiplied by the densities of algal units to obtain estimates of biovolumes expressed as $\mu m^3/l$.

Data Structure and Management

Raw data obtained from the microscopic examination of plankton samples were recorded on computer coding sheets according to a standard format required by the programs selected for data analysis (AID1, AIDN, and CLUSB3). During the period supported by Subagreement No. 13, the following data files were created: CRATER1.685, CRATER2.785, CRATER3.885, CRATER4.985, CRATER5.386, CRATER6.586, CRATER7.686, and CRATER8.786, corresponding to sets of samples taken on 6/26/85, 7/23/85, 8/20/85, 9/18/85, 3/5/86, 5/28/86, 6/25/86, and 7/23/86, respectively (Table 1). Each data file was organized into a series of blocks, each of which represented the counts of species occurring in a sample from a particular depth. For example, if 12 species occurred in a particular sample, the corresponding block of data would have twelve lines of information. Each line in the file provides ten fields of information:

Field	Column Number	Description
1	1 - 3	block number
2	4 - 10	sampling date
3	11 - 14	station
4	15 - 25	depth
5	26 - 33	species code number
6	34 - 38	number of algal units in a total of ca. 100
7	39 - 45	algal units per liter based on a total of ca. 100
8	46 - 58	number of algal units in a total of ca. 300
9	59 - 65	algal units per liter based on a total of ca. 300
10	66 - 80	biovolume expressed as cubic micrometers per liter

The format of the eight data files is also compatible with the files created from earlier research (1980 - 1984). Because the earlier work generated counts of 100 algal units for each sample, the data obtained during the period of Subagreement No. 13 also included counts for each taxon after 100 algal units had been observed. Consequently, the newer file can be pooled with the older files for a combined analysis, if research objectives in the future require an examination of long-term trends.

Data Analysis

During the period supported by Subagreement No. 13, it was possible to complete a preliminary analysis of patterns in CRATER1.685, CRATER2.785, CRATER3.885, CRATER4.985, and CRATER5.386. Since this research is an ongoing project, these files eventually will be analyzed in combination with the rest of the files created from all of the 1986 data.

Our general approach to the quantitative analysis of distributional patterns in the phytoplankton involves: (1) estimation of community composition parameters (AID1 program); (2) estimation of niche breadth for individual taxa (AIDN program); (3) calculations of a similarity measure for comparing the species compositions of sample pairs (AIDN program); (4) calculations of a similarity measure for comparing the species compositions of pooled sample pairs (AIDN program); (5) a cluster analysis which generates discrete groups of samples (CLUSB3 program); (6) a detrended correspondence analysis, an ordination procedure that orders samples and species along axes (DECORANA program); (7) and a correlation analysis of selected biological, chemical, and physical variables. For this report, some output from the AID1 and AIDN programs is presented; the other analyses will be performed after the 1986 data become available.

In the last section of this report, two indices of species diversity,

Table 1. Summary of samples obtained during the period from March 1985 through November 1986. An X-mark indicates that the sample was processed during the time supported by Subagreement No.13. Other symbols refer to the samples obtained but not processed (O) and missing observations (N).

Date	0	5	10	20	40	60	80	100	120	140	160	180	200	225	250	275	300	350	400	450	500	550
6/26/85	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7/23/85	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O
8/20/85	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O
9/18/85	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	N	N	N	N
3/5/86	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	N	N	N	N	N
5/28/86	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O
6/25/86	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7/23/86	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	O	O
8/20/86	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
9/17/86	O	N	N	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

the information measure and Simpson's index, are used to express community structure:

$$H'' = -\sum_i (n_i/N)\log_e(n_i/N), \quad \text{and}$$

$$SDI = 1 - \sum (n_i/N)^2 \quad ,$$

where n_i is the number of algal units in the i-th species, and N is the number of algal units in the sample. Both indices are biased, but consistent, and bias is negligible at a sample size of 300, the size used with these data.

Along with the diversity measure, we have also included a measure of dominance and a measure of niche breadth for selected taxa. In this case,

$$R = (H''_{max} - H'')/(H''_{max} - H''_{min}) \quad ,$$

where H''_{max} and H''_{min} are the maximum and minimum possible values for H", respectively, given the number of taxa in the sample; H" is the measured diversity of the sample; and R is a measure of dominance. The niche breadth of a selected taxon is measured by the expression

$$B_i = \exp[-\sum_j (p_{ij}/R_i)\log_e(p_{ij}/R_i)] \quad ,$$

where B_i is the niche breadth of the i-th taxon, p_{ij} is the proportional abundance of the i-th taxon in sample j, and R_i is the summation of the p_{ij} values for the i-th taxon over all samples. B_i can vary from 1 when a taxon is present in just one sample to k when it is equally common in k samples.

The measure of similarity used in the report is

$$SIMI(a,b) = (\sum_i p_{ai}p_{bi})/[(\sum_i p_{ai}^2)(\sum_i p_{bi}^2)] \quad ,$$

where SIMI(a,b) is the taxonomic similarity between samples a and b, and

p_{ai} and p_{bi} are the proportional abundances of the i-th taxon in samples a and b, respectively. SIMI can vary from zero when the samples have no species in common to one when they have the same species with corresponding relative abundance values.

SPECIES COMPOSITION OF CRATER LAKE PHYTOPLANKTON

Table 2 presents a list of the 132 taxa found in the phytoplankton samples processed during the period supported by Subagreement No. 13. In most cases, organisms were identified to species. When such an identification was not possible, the organism was given a unique number so that it could be recognized and counted in other samples. The list of taxa includes 49 diatoms (Bacillariophyceae), 45 chrysophytes (Chrysophyceae), 2 xanthophytes (Xanthophyceae), 19 chlorophytes (Chlorophyta), 3 blue-green algae (Cyanophyta), 10 dinoflagellates (Pyrrhophyta), and 4 cryptomonads (Cryptophyta).

Table 2 also includes computer coding numbers, taxonomic acronyms, food class acronyms, and a factor for converting algal units per liter to biovolume expressed as cubic micrometers per liter. The coding system provides a unique identification number for each taxon which is necessary for the calculation of similarity values, an output from the AIDN program. The taxonomic acronym refers to the division or class of each taxon. The food class acronym was derived for the benefit of personnel involved in the interpretation of Crater Lake zooplankton data, and was based on measurements of individual cells and on information in the literature. These acronyms indicate food class (nannoplankton or netplankton), food size (7 categories from 1 µm to > 150 µm), and potential use as a food resource.

Table 2. List of phytoplankton species found in samples from Crater Lake during the period from March 19, 1985 through November 30, 1986. The table also includes computer coding numbers, taxonomic acronyms, food class acronyms, and a factor for converting algal units per liter to biovolume expressed as cubic micrometers per liter.

KEY:

Taxonomic Acronyms: CHR (Chrysophyceae); XAN (Xanthophyceae); BAC (Bacillariophyceae); CHL (Chlorophyta); CYA (Cyanophyta); PYR (Pyrrhophyta); CRY (Cryptophyta)

Food Class: NA (Nannoplankton); NE (Netplankton)

Food Size: 1 µm - 10µm (1); 10 µm - 20 µm (2); 20 µm - 50 µm (3); 50 µm - 70 µm (4); 70 µm - 90 µm (5); 90 µm - 150 µm (6); > 150 µm (7)

Resource Utility: E (edible); I (inedible); F (flagellated)

* Could be eaten by grasping cladocerans

CODE	ACRONYM	FOOD	FACTOR	TAXON
100	CHR	NA1E	17.2	Chrysophyta, unidentified
101	XAN	NE5I	1853.0	Tribonema affine G.S. West
102	XAN	NE4E	424.0	Tribonema CL1
103	BAC	NA1E	226.0	Stephanodiscus hantzschii Grun.
104	BAC	NE7I	920.0	Asterionella formosa Hass
105	BAC	NA2E	540.0	Fragilaria construens (Ehr.) Grun.
106	BAC	NE7I	3114.0	Synedra acus Kütz.
107	BAC	NE7I	5000.0	Synedra delicatissima W. Smith
108	BAC	NE5I	1460.0	Synedra rumpens var. familiaris (Kütz) Hust.
109	BAC	NA3I	495.0	Synedra mazamaensis Sov.
110	BAC	NA3I	276.0	Achnanthes minutissima Kutz.
111	BAC	NA3I	780.0	Navicula cryptocephala var. veneta (Kütz.) Rabh.
112	BAC	NA3I	480.0	Gomphonema olivaceum var. calcarea
114	BAC	NA4I	1100.0	Fragilaria vaucheriae var. capitellata (Grun.) Patr.
115	BAC	NA3I	640.0	Fragilaria vaucheriae (Kütz.) Peters
116	BAC	NE4I	998.4	Synedra rumpens Kütz
117	BAC	NE6I	1210.0	Synedra radians Kütz.
119	BAC	NA2E	65.0	Navicula sp. 1
120	BAC	NA3I	367.0	Gomphonema heidinii Hust.
121	BAC	NA5I	1300.0	Nitzschia palea (Kütz.) W.Smith
122	BAC	NE5I	380.0	Nitzschia bacata Hust.
123	BAC	NA3E*	315.0	Nitzschia perminuta Grun.
124	BAC	NA3E	276.0	Nitzschia frustulum Kütz.
125	BAC	NE7I	9342.0	Nitzschia linearis W. Smith
126	BAC	NE7I	4000.0	Nitzschia vermicularis (Kütz) Grun.
127	BAC	NE6I	2820.0	Nitzschia serpenticula Arch.
128	BAC	NA2E	207.4	Nitzschia CL1
129	BAC	NA2E	174.1	Nitzschia CL2

Table 2. (cont.)

CODE	ACRONYM	FOOD	FACTOR	TAXON
130	BAC	NE5E*	473.0	Nitzschia gracilis Hantzsch
131	CHR	NA1F	207.5	Kephyrion CL1
132	CHR	NA1F	36.0	Kephyrion asper
133	CHR	NA2F	73.0	Calycomonas sp.
134	CHR	NA1F	38.6	Chromulina CL1
135	CHR	NA1F	17.2	Chromulina-like sp.
136	CHR	NA2F	924.0	Pseudopedinella CL1
137	CHR	NA1F	384.8	Ochromonas CL1
138	CHR	NA1F	100.5	Ochromonas CL2 [O. ovalis, Dolf.]
139	CHR	NA1F	226.2	Ochromonas CL3 [O. elegans, Dolf.]
140	CHR	NA1F	137.0	Ochromonas CL4
141	CHR	NA1F	40.4	Ochromonas-like sp.
142	CHR	NA2F	399.0	Dinobryon sertularia Ehr.
143	CHR	NA1F	50.0	Chrysolykos planctonicus Mack.
144	CHR	NA1F	58.0	Pseudokephyrion CL1
145	CHR	NA1F	69.0	Pseudokephyrion CL2
146	CHR	NA1F	48.0	Pseudokephyrion CL3
147	CHR	NA1F	80.4	Pseudokephyrion CL5
148	CHR	NA1E	172.0	Diplomitella socialis (Kent) Silva
149	CHR	NA1F	92.0	Chrysochromulina sp. 1
150	CHR	NA1I	56.5	Chrysophyte statospore CL1
151	CHR	NA1I	904.0	Chrysophyte statospore CL5
152	CHR	NA1I	65.0	Chrysophyte statospore CL4
153	CHR	NA1I	147.0	Chrysophyte statospore CL3
154	CHL	NA1E	524.0	Chlorophyta, unidentified
156	CHL	NA1E	101.5	Chlorophyta, unidentified CL 1
157	CHL	NA1E	92.0	Chlorophyta, unidentified CL 2
158	CHL	NA1E	10.5	Chlorophyta, unidentified Cl 3
159	CHL	NA1E	6.2	Chlorophyta, unidentified CL 4
160	CHL	NA1E	327.0	Oocyctis pusilla Hansgrig
161	CHL	NA2E	110.0	A.falcatus v. acicularis (A. Braun) G.S. West
162	CHL	NA2E	30.0	Ankistrodesmus spiralis (Turner) Lemm.
163	CHL	NA1E	9.0	Kirchneriella contorta (Schmidle) Bohlin
164	CHL	NA1E	144.0	Planktosphaeria glatinosa G.M. Smith
165	CHL	NA1E	88.0	Scenedesmus bijuga (Turp.) Lagerh
166	CHL	NA1E	22.0	Selenastrum minuta (Naeg.) Collins
167	CHL	NE7E	33757.0	Mougeotia sp.
169	CYA	NA1E	71.7	Anabaena CL1
170	PYR	N34I	14137.0	Pyrrophyta, unidentified
171	PYR	NA2I	963.0	Cryptochrysis polychrysis Pascher
172	CRY	NA2E	823.0	Rhodomonas minuta Skuja
173	CRY	NA2E	1042.0	Rhodomonas lacustris Pascher et Ruttner
174	CRY	NA1E	254.0	Rhodomonas minuta var. nannoplantica Skuja
175	CRY	NA1E	452.4	Rhodomonas sp. 1
176	PYR	NA1F	346.4	Amphidinium lutem Skuja
177	PYR	NE4F	33000.0	Gymnodinium fuscum (E.) Stein
178	PYR	NA3I	5440.0	Gymnodinium inversum Nygaard
179	PYR	NA3I	6750.0	Peridinium inconspicuum Lemm.
180	PYR	NA3I	9425.0	Peridinium aciculiferum (Lemm.) Lemm.

Table 2. (cont.)

CODE	ACRONYM	FOOD	FACTOR	TAXON
181	BAC	NA2E	339.3	Cyclotella kutzingiana Thwaites
182	BAC	NA3I	820.0	Fragilaria leptostauron (Ehr.) Hust.
183	BAC	NA3I	675.0	Achnanthes lanceolata (Bréb.) Grun.
184	BAC	NE4I	143.5	Nitzschia acicularis W. Smith
185	BAC	NE7I	42000.0	Nitzschia tryblionella Hantzsch
186	CHR	NA1F	35.0	Kephyrion spirale (Lack.) Conr.
187	CHR	NA2F	77.0	Dinobryon bavaricum Imhoff.
188	CHR	NA1F	65.0	Pseudokephyrion conicum (Schill) Schm.
189	CHR	NA2F	82.0	Calycomonas sp.
190	CHL	NE5E*	177.0	Ankistrodesmus falcatus (Corda) Ralfs.
191	PYR	NE3I	811.0	Pyrrophyte statospore
192	CHR	NA1I	87.0	Chrysophyte statospore CL2
193	BAC	NE6I	1228.5	Fragilaria crotonensis var. oregona Sov.
194	BAC	NA1I	260.0	Fragilaria construens var. veneta (Ehr.) Grun.
195	CHR	NA1F	26.5	Chromulina-like sp. 2
196	CHR	NA2F	124.0	Dinobryon sociale Ehr.
197	CHR	NA1F	40.4	Pseudokephyrion CL6
198	CHR	NA1I	137.0	Bicoeca petiolatum (Stein) Pringsheim
200	CHL	NA1E	72.0	Chlorophyta, unidentified
201	CHR	NA2F	221.0	Chrysophyta, unidentified
202	BAC	NE6I	1050.0	Synedra tenera W. Smith
203	PYR	NA3I	687.0	Pyrrophyte, unidentified
204	CHL	NA1E	11.0	Chlorophyta, unidentified
205	CHL	NA1E	95.0	Chlorophyta, unidentified
206	CHR	NA1I	78.0	Chrysophyte endocyst
207	BAC	NE4I	840.0	Rhoicosphenia curvata (Kütz.) Grun. ex Rabh.
208	CHR	NA1E	103.2	Chrysocapsa planctonica
210	CHR	NA1F	33.5	Ochromonas miniscula Conrad
211	CHL	NA1E	56.0	Chlorophyta, unidentified
212	BAC	NA3I	600.0	Gomphonema parvulum Kütz.
213	BAC	NE5I	143.5	Nitzschia closterium
214	PYR	NA3I	1767.0	Pyrrophyta statospore
216	BAC	NA1E	28.6	Nitzschia dissipata (Kütz.) Grun.
217	BAC	NA1E	155.5	Nitzschia, sp.
219	CHR	NA2F	268.0	Chromulina grandis Dolf.
220	CHR	NA1F	9.4	Pseudochromulina asymmetrica Dolf.
221	CHR	NA1F	29.0	Ochromonas verrucosa Skuja
222	CHR	NA1F	72.0	Chromulina spectabilis Scherffel
223	BAC	NA3I	294.4	Achnanthes lanceolata var. dubia Grun.
224	BAC	NA3E	462.0	Nitzschia innominata
225	CHR	NA3I	4189.0	Dinobryon sertularia statospore
226	CYA	NA1E	8.6	Spirulina major Kütz.
227	CHR	NA1F	14.1	Kephyrion cupriloforme Conr.
228	CHL	NA1E	697.0	Crucigenia quadrata Morren
229	BAC	NA2E	300.0	Fragilaria pinnata Ehr.
230	BAC	NA1E	63.0	Colonial diatom
231	BAC	NA3E	120.0	Nitzschia fonticola Grun.
232	CHR	NA2F	113.0	Ochromonas granulosa H. Meyer
233	BAC	NE6I	1905.0	Nitzschia acuta Hantzsch

Table 2. (cont.)

CODE	ACRONYM	FOOD	FACTOR	TAXON
234	CYA	NA1E	9.0	Cyanophyta
235	BAC	NE7I	7800.0	Epithemia sorex Kützc.
236	BAC	NE6I	2160.0	Cymbella turgida Greg.
237	BAC	NA1E	176.0	Navicula seminulum Grun.
239	BAC	NE4I	1021.0	Cocconeis rugosa Sov.
240	CHR	NA1F	29.0	Chromulina minor Pasch.

DISTRIBUTION AND ECOLOGY OF CRATER LAKE PHYTOPLANKTON

Species Diversity

Mean species diversity in the water column as expressed by Shannon's index (H") ranged from 1.60 on 8/20/85 to 2.34 on 6/26/85 (Table 3); the corresponding range for Simpson's index was 0.61 (8/20/85) to 0.84 (6/26/85). Simpson's index gives most weight to dominant taxa, while values for Shannon's index are influenced slightly more by rarer taxa. Lowest species diversity was found in the upper 10 meters during July and August when Nitzschia gracilis was a dominant organism. Apparently, this species was able to generate a relatively large biovolume under conditions of relatively high temperature, high light energy, and low nutrient supply. The greatest vertical variation in species diversity (see standard deviations in Table 3) occurred during late summer (8/20/85) when N. gracilis was dominant in a well developed epilimnion. In contrast, species diversity was relatively uniform from the water surface to a depth of 250 meters in June 1985 and March 1986, when there was no evidence of thermal stratification.

Seasonal Abundance

The summation of the biovolumes of all phytoplankton taxa in each sample was calculated, and a mean of these values for all samples collected on a particular date was used as an indication of phytoplankton abundance in the water column (Figure 1). Mean biovolume ranged from a minimum of 52,185 $\mu m^3/l$ on 9/18/85 to a maximum of 111,070 μm^3 on 8/20/85. Maximum values occurred in July and August when Nitzschia gracilis was a dominant organism in the upper 20 m. Biovolumes in March and June were similar, which corresponded to times when the taxa were more evenly distributed

Table 3. Community composition parameters for phytoplankton samples obtained from June 1985 through March 1986. Values include Shannon's information measure to the log base e (H") and Simpson's diversity index (SDI).

DATE	DEPTH	H"		SDI	
6/26/85	0	1.89		0.74	
	5	2.09	$\bar{H}$" = 2.34	0.82	$\overline{SDI}$ = 0.84
	10	2.40		0.86	
	20	2.54	s = 0.234	0.89	s = 0.046
	40	2.40		0.88	
	60	1.98		0.76	
	80	2.14		0.82	
	100	2.22		0.83	
	120	2.26		0.84	
	140	2.51		0.88	
	160	2.45		0.86	
	180	2.59		0.90	
	200	2.65		0.88	
	225	2.58		0.88	
	250	2.43		0.85	
7/23/85	0	1.01		0.53	
	5	0.99	$\bar{H}$" = 1.67	0.56	$\overline{SDI}$ = 0.69
	10	1.34		0.60	
	20	1.62	s = 0.358	0.69	s = 0.090
	40	1.93		0.73	
	60	1.44		0.55	
	80	1.76		0.75	
	100	2.18		0.82	
	120	1.74		0.70	
	140	1.89		0.73	
	160	2.15		0.76	
	180	1.86		0.70	
	200	1.90		0.78	
	225	1.69		0.75	
	250	1.53		0.65	
8/20/85	0	0.47		0.17	
	5	0.59	$\bar{H}$" = 1.60	0.23	$\overline{SDI}$ = 0.61
	10	0.66		0.25	
	20	1.44	s = 0.583	0.56	s = 0.219
	40	2.12		0.82	
	60	2.00		0.78	
	80	2.23		0.82	
	100	2.23		0.81	
	120	1.93		0.71	

Table 3. (cont.)

DATE	DEPTH	H"		SDI	
8/20/85	140	1.89		0.72	
	160	1.72		0.67	
	180	1.89		0.72	
	200	1.46		0.60	
	225	1.69		0.65	
	250	1.68		0.67	
9/18/85	0	2.21		0.85	
	5	2.22	$\bar{H}$" = 1.81	0.85	$\overline{SDI}$ = 0.71
	10	2.05		0.83	
	20	2.37	s = 0.395	0.88	s = 0.135
	40	1.52		0.71	
	60	1.68		0.69	
	80	2.18		0.83	
	100	1.96		0.72	
	120	1.89		0.75	
	140	1.72		0.64	
	160	1.60		0.62	
	180	1.68		0.63	
	200	1.01		0.44	
	225	1.22		0.50	
3/5/86	0	1.74		0.66	
	5	1.63	$\bar{H}$" = 1.75	0.63	$\overline{SDI}$ = 0.64
	10	1.76		0.64	
	20	2.00	s = 0.268	0.73	s = 0.095
	40	1.85		0.66	
	60	1.95		0.71	
	80	1.94		0.70	
	100	2.00		0.71	
	120	1.97		0.71	
	140	2.15		0.77	
	160	1.67		0.59	
	180	1.44		0.54	
	200	1.17		0.41	
	225	1.53		0.56	
	250	1.46		0.54	

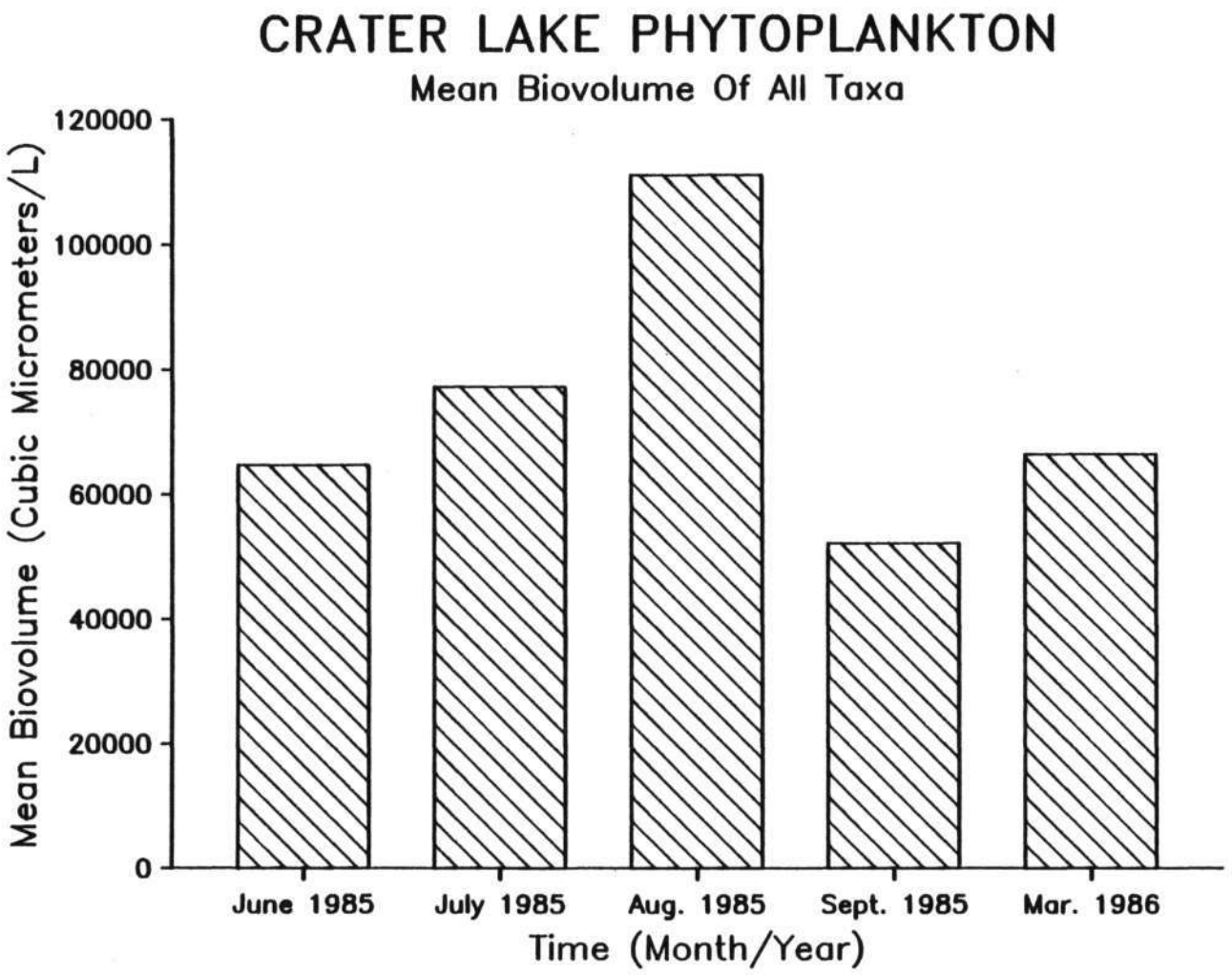

Figure 1. Mean cell biovolume (um^3/l) of all phytoplankton taxa found in samples obtained between June 1985 and March 1986.

throughout the water column.

The seasonal abundances of some taxa were more variable than others (Figure 2). In particular, Nitzschia gracilis exhibited mean biovolumes greater than 30,000 $\mu m^3/l$ in July and August 1985, but was much less abundant in June 1985, September 1985, and March 1986. Synedra rumpens v. familiaris followed a pattern similar to N. gracilis, while Asterionella formosa reached its maximum abundance in September. Stephanodiscus hantzschii was the dominant taxon in March 1986, but was relatively rare in samples collected during the summer and fall. Of the more abundant taxa, Gymnodinium inversum exhibited the least seasonal variation.

Vertical Distribution of Selected Taxa

The vertical distributions of five selected taxa (Nitzschia gracilis, Stephanodiscus hantzschii, Ankistrodesmus spiralis, Tribonema CL1, and Gymnodinium inversum) are illustrated in Figures 3 and 4. These graphs contrast the late summer pattern when the epilimnion is well defined with the pattern during late winter and early spring when thermal stratification is not present. In August 1985, Nitzschia gracilis was dominant in the upper 20 m, while Gymnodinium inversum was more evenly distributed throughout the water column down to a depth of about 120 m. At this time of year, Stephanodiscus hantzschii is restricted to depths below 100 m. In early March 1986, S. hantzschia was the dominant species and was evenly distributed throughout the water column down to a depth of 250 m. N. gracilis also exhibited a more even vertical distribution in March than in the late summer, although it was considerably more abundant during the summer months than at other seasons of the year (Figure 2).

Niche breadth values corresponding to each sampling date for 15 of the most abundant taxa also are indicative of vertical distribution (Table 4). In this case, a relatively high value corresponds to a more even

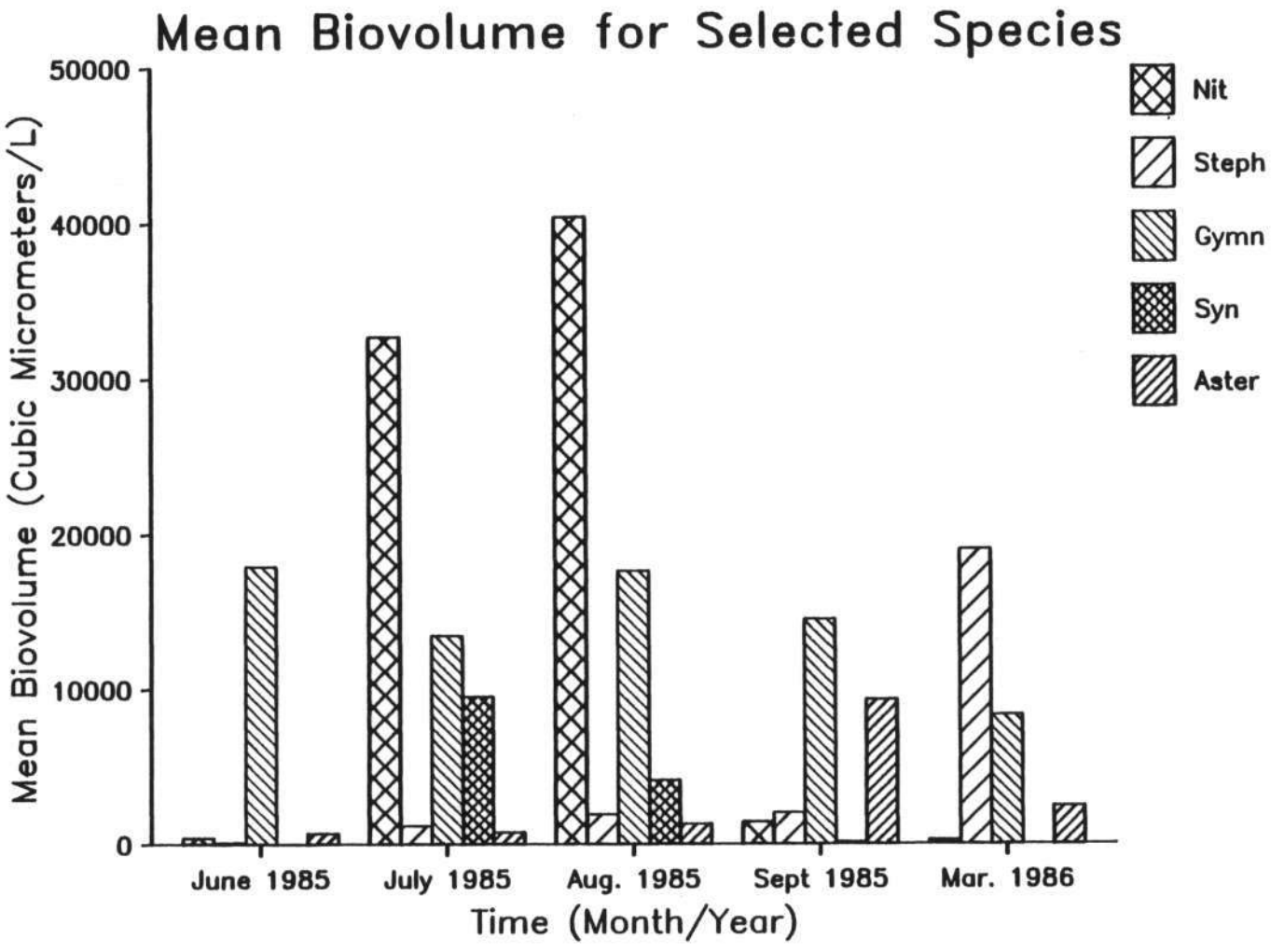

Figure 2. Mean cell biovolume (um^3/ml) of selected phytoplankton species found in samples obtained between June 1985 and March 1986. The species are Nitzschia gracilis (Nit), Stephanodiscus hantzschii (Steph), Gymnodinium inversum (Gymn), Synedra rumpens var. familiaris (Syn), and Asterionella formosa (Aster).

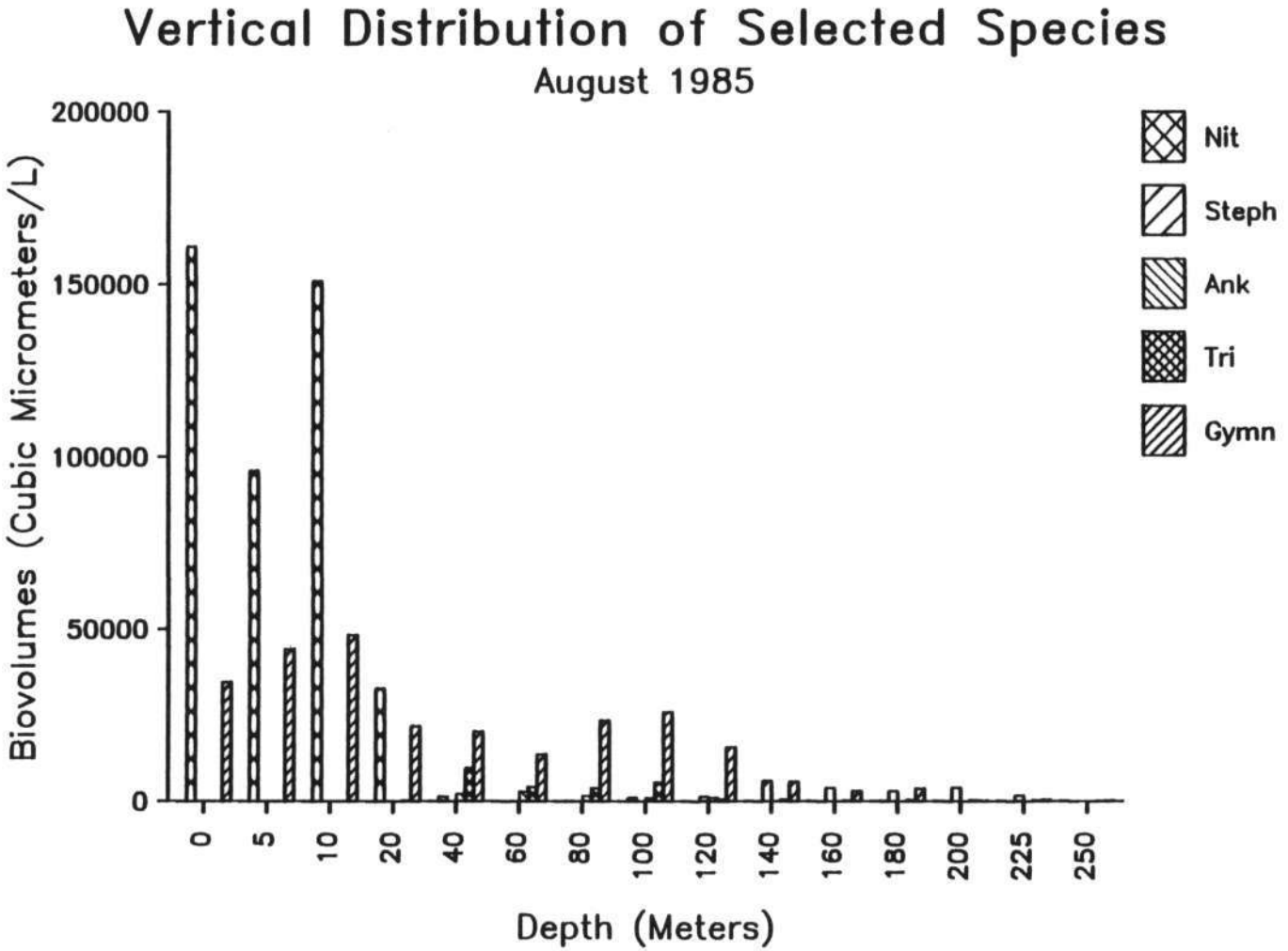

Figure 3. Vertical distribution of selected species of phytoplankton found in samples obtained in August 1985. Abundance is expressed as cell biovolume (um^3/ml). The species are Nitzschia gracilis (Nit), Stephanodiscus hantzschii (Steph), Ankistrodesmus spiralis (Ank), Tribonema CL1 (Tri), and Gymnodinium inversum (Gymn).

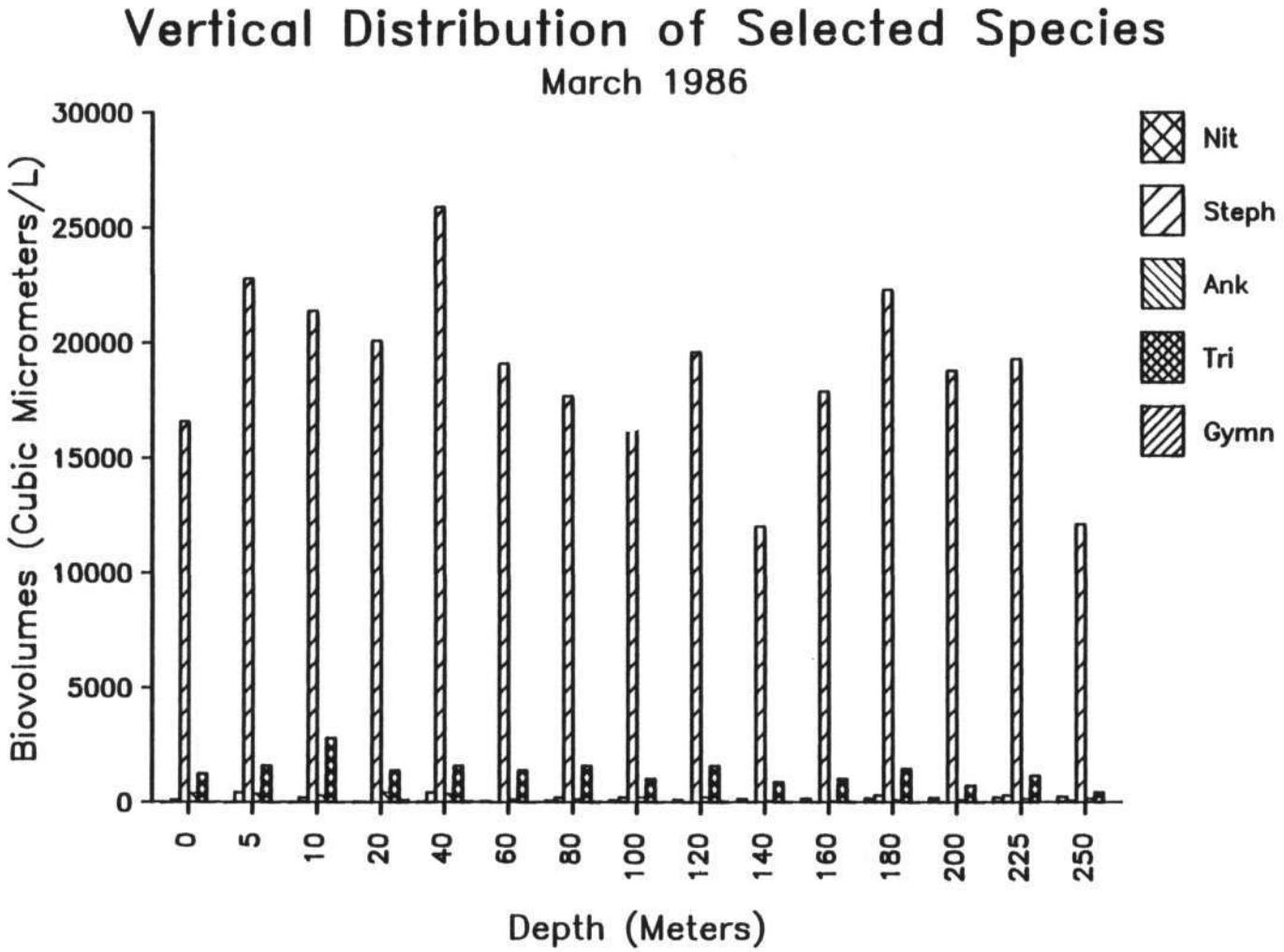

Figure 4. Vertical distribution of selected species of phytoplankton found in samples obtained in March 1986. The abundance measure and species acronyms are the same as in Figure 3.

Table 4. Niche breadth values for 15 dominant taxa from the Crater Lake phytoplankton samples. Values are expressed as percentage of the maximum possible value, which is equal to the total number of samples collected on each sampling date.

TAXON	6/26/85	7/23/85	8/20/85	9/18/85	3/5/86
Chrysophyta, unidentified	77.7	31.8	42.5	26.8	47.9
Tribonema affine	58.3	58.2	30.1	22.5	65.2
Stephanodiscus hantzschii	24.3	35.6	31.4	35.5	99.2
Asterionella formosa	50.4	31.1	35.9	15.4	85.9
Synedra rumpens v. familiaris	4.5	25.0	9.7	5.9	-
Nitzschia serpenticula	51.0	30.7	23.3	26.2	34.2
Nitzschia gracilis	24.0	24.9	21.4	28.1	55.5
Dinobryon sertularia	66.7	27.7	22.0	18.6	66.3
Chlorophyta, CL 1	65.3	17.0	26.2	46.7	68.1
Ankistrodesmus spiralis	71.5	59.2	47.6	58.3	91.8
Rhodomonas lacustris	45.6	13.8	19.3	21.2	66.8
Gymnodinium inversum	51.9	42.3	60.5	48.5	70.3
Peridinium inconspicum	10.5	27.2	14.2	5.9	5.9
Pseudokephyrion conicum	31.7	19.3	8.0	34.2	60.8
Ankistrodesmus falcatus	67.5	56.6	39.5	50.6	85.6

distribution throughout the water column than a lower value. Of the 15 taxa, all but 4 of these were more evenly distributed in March 1986 than during the summer and early fall 1985. Synedra rumpens v. familiaris had the lowest niche breadth values and was confined to the near surface waters where it cooccurred with Nitzschia gracilis in the summer. The most conspicuous seasonal differences in niche breadth were observed for Stephanodiscus hantzschii, Asterionella formosa, Dinobryon sertularia, Pseudokephyrion conicum, Ankistrodesmum falcatus, and an unidentified chrysophyte. In all of these species, maximum values corresponded to either the March or June samples, and values for July, August, and September were relatively low.

Vertical Distribution of Cell Biovolume and Chlorophyll a

Phytoplankton samples obtained in July, August, and September 1985 and in March 1986 indicated that there was little correspondence between the vertical distributions of total cell biovolume and chlorophyll a. Figures 5 - 8 illustrate these values plotted on a relative scale for comparative purposes. Maximum biovolumes were found in the upper 20 m during July and August when Nitzschia gracilis exhibited its maximum abundance in the near-surface waters (Figures 5 and 6). In contrast, the corresponding maximum chlorophyll a concentrations occurred between 100 m and 150 m, a phenomenon that has also been observed in Lake Tahoe during the summer months. The closest correspondence between chlorophyll a and total cell biovolume was observed in September when the maximum for both variables occurred between 80 m and 120 m below the water surface (Figure 7). Chlorophyll a and cell biovolume were more evenly distributed throughout the water column in March than in July, August, or September (Figure 8).

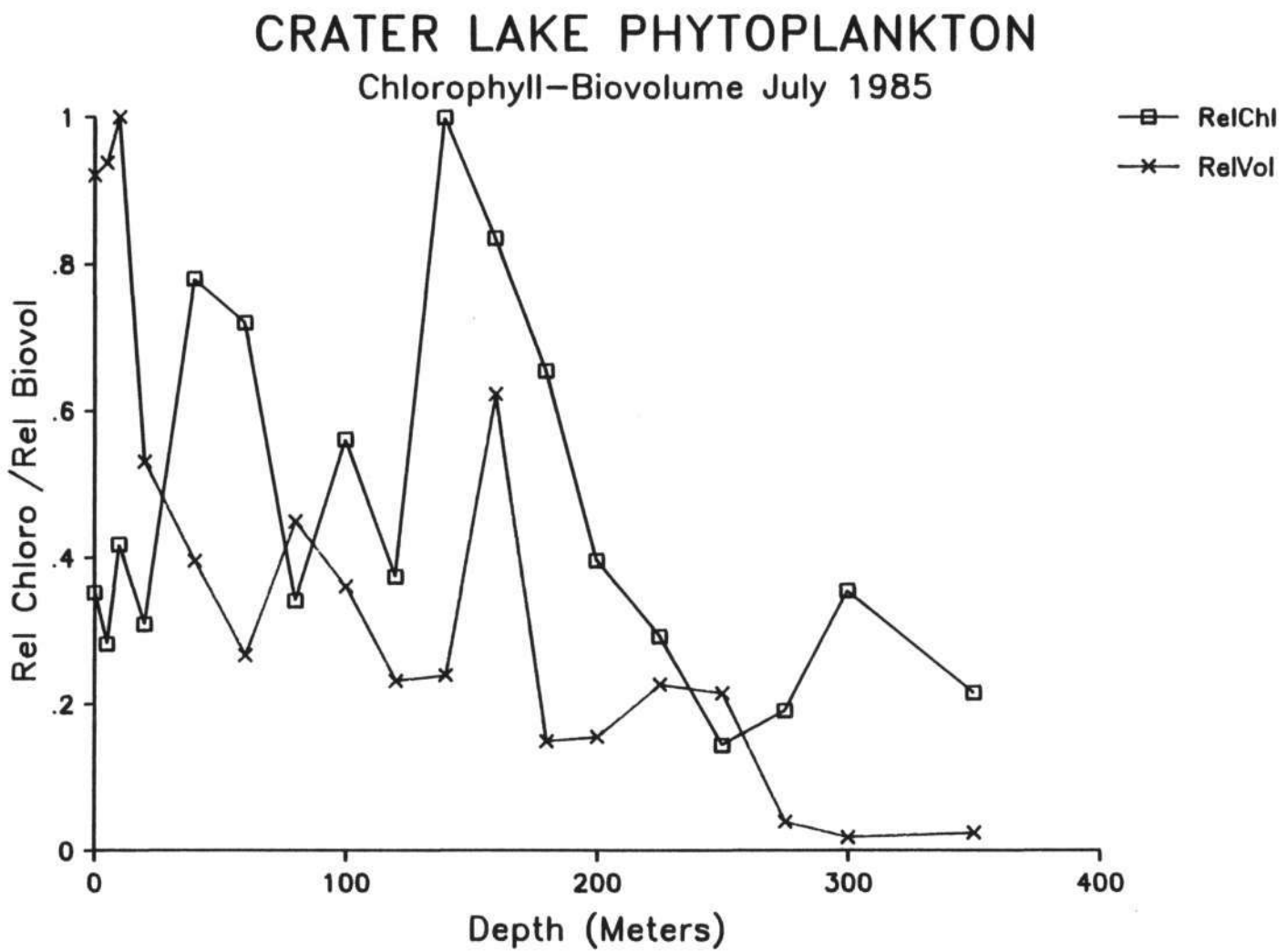

Figure 5. Vertical distribution of chlorophyll a and phytoplankton cell biovolume for samples obtained in July 1985. Values are relativized and expressed as a proportion of the maximum concentration.

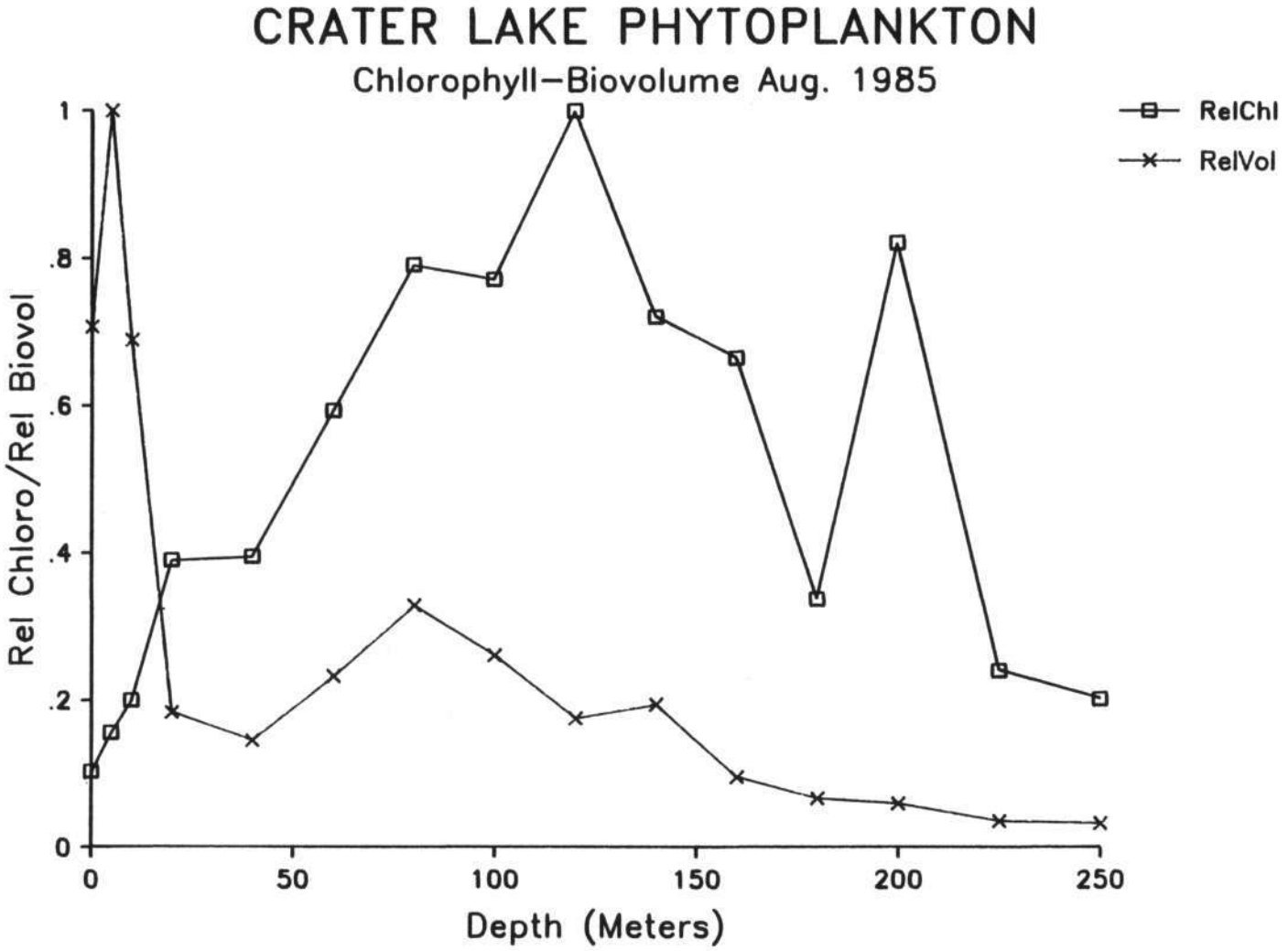

Figure 6. Vertical distribution of chlorophyll a and phytoplankton cell biovolume for samples obtained in August 1985. Values are relativized and expressed as a proportion of the maximum concentration.

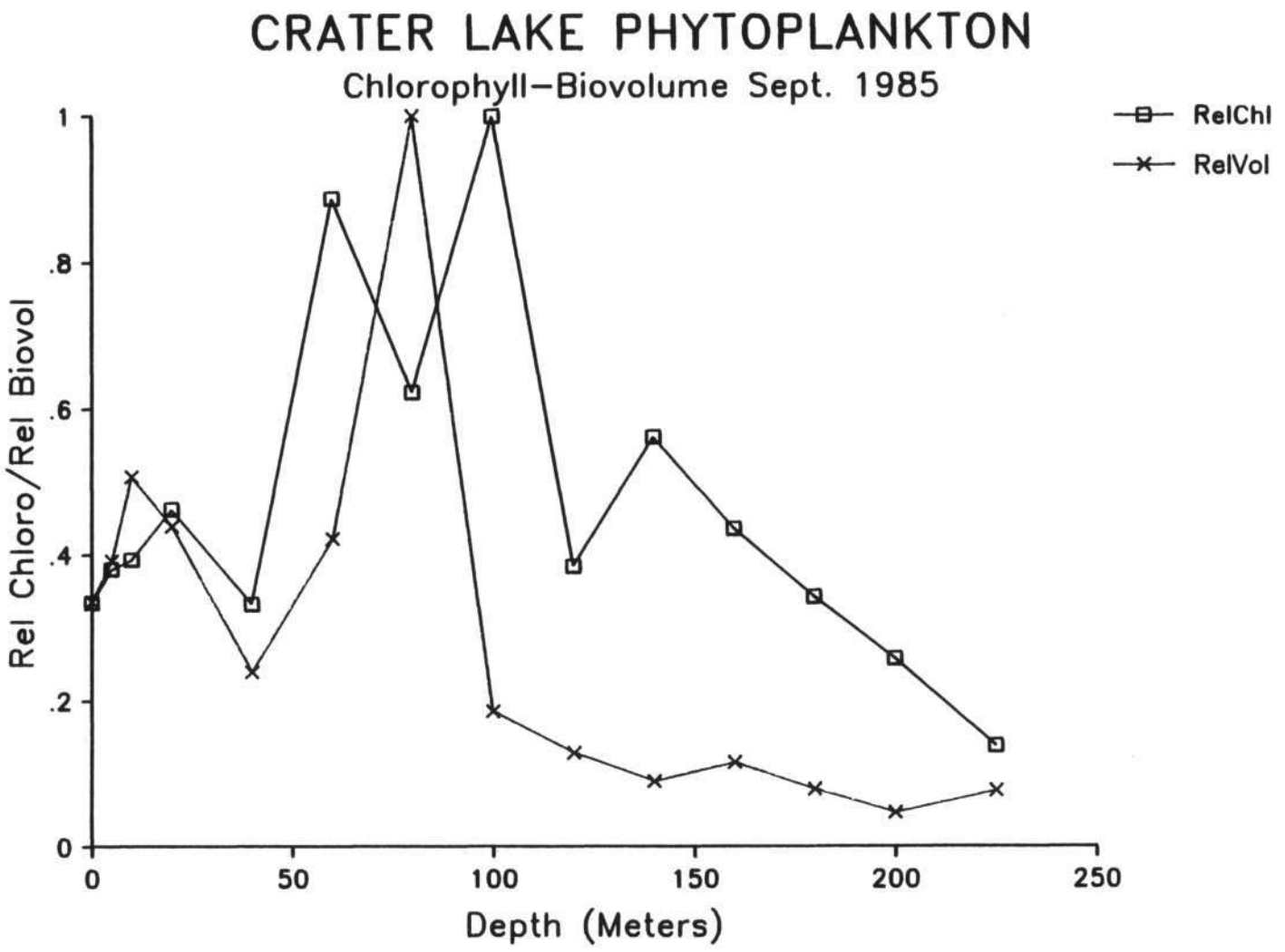

Figure 7. Vertical distribution of chlorophyll a and phytoplankton cell biovolume for samples obtained in September 1985. Values are relativized and expressed as a proportion of the maximum concentration.

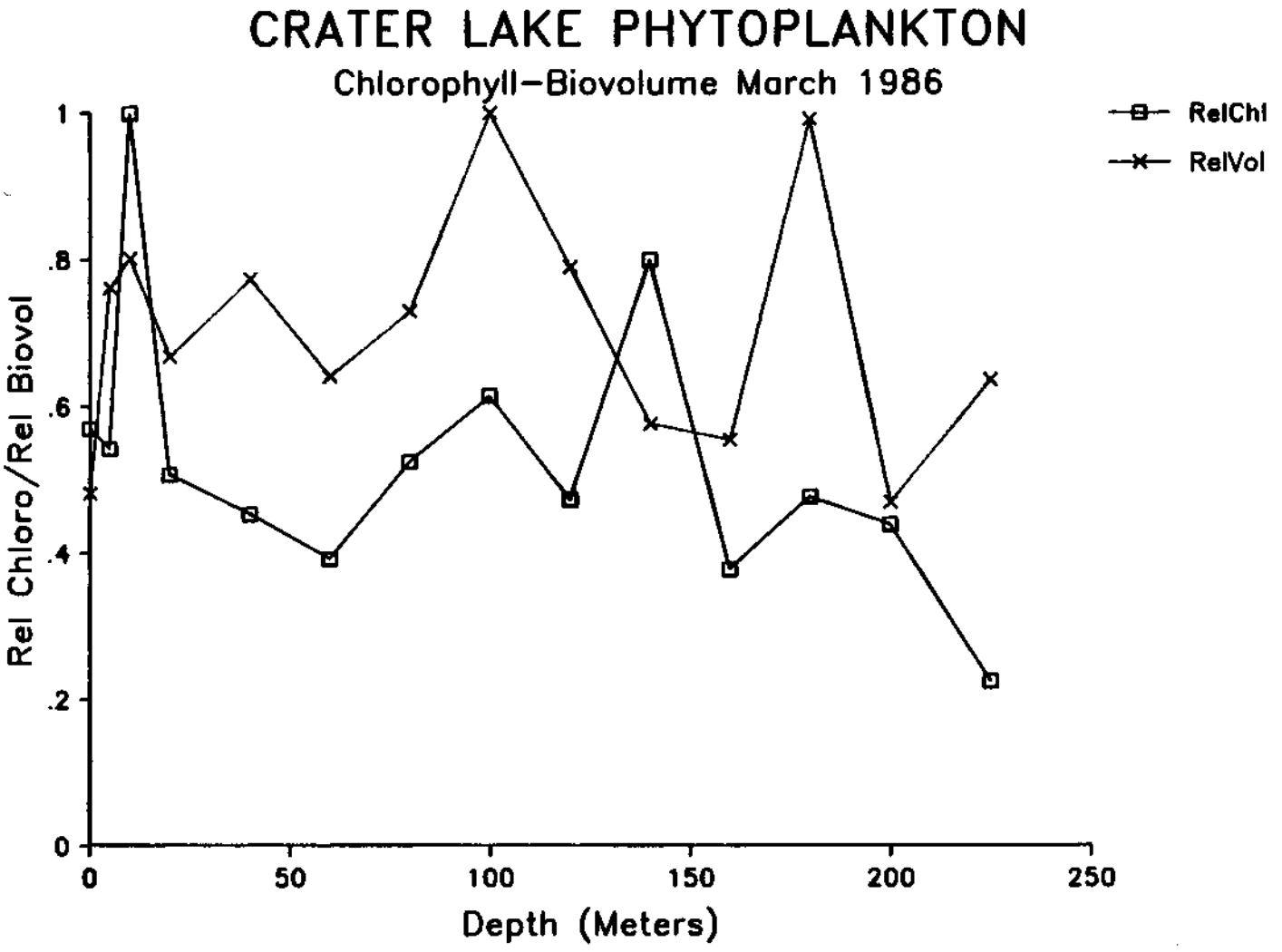

Figure 8. Vertical distribution of chlorophyll a and phytoplankton cell biovolume for samples obtained in March 1986. Values are relativized and expressed as a proportion of the maximum concentration.

Seasonal Similarities at the Community Level of Organization

Along with an autecological view of individual taxa, it was also interesting to examine seasonal similarities at the community level of resolution. For this purpose, data from all samples collected on a particular date were pooled and treated as one sample for comparisons with pooled samples collected at other times. Consequently, the matrix of SIMI values with all possible comparisons of samples obtained on 6/26/85, 7/23/85, 8/20/85, 9/18/85, and 3/5/86 contained 10 values (Table 5).

Table 5 indicates that there was a relatively large change in the taxonomic structure of the phytoplankton in early July 1985. This transition period was characterized by a rapid increase in the biovolume of Nitzschia gracilis in the upper 20 m of the water column. After late July, the SIMI values indicated that there was a gradual change in the flora from August 1985 through early March 1986. The lowest SIMI value (0.112) corresponded to the comparison between the 6/25/85 samples and the 3/5/86 samples. Whether or not such patterns occur repeatedly from year to year cannot be determined without an integrated analysis of the 1981 - 1987 data sets.

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Table 5. A matrix of similarity values (SIMI) comparing pooled phytoplankton samples obtained on selected dates between June 1985 and March 1986.

	7/23/85	8/20/85	9/18/85	3/5/86
6/26/85	0.543	0.414	0.486	0.112
7/23/85		0.820	0.692	0.344
8/20/85			0.819	0.642
9/18/85				0.781