AN ABSTRACT OF THE THESIS OF

ROGER DEAN MEYERHOFF for the degree of MASTER OF SCIENCE

in FISHERIES presented on June 17, 1976

Title: SEDIMENT CHARACTERISTICS AND THE TROPHIC STATUS OF FOUR OREGON LAKES

Abstract approved: Redacted for Privacy
Gerald E. Davis

There is evidence that recent ecological changes in lakes and their watersheds can be detected from analysis of lake sediments. This study was initiated to correlate changes in some sediment characteristics of four Oregon lakes with past cultural developments of the lakes and their watersheds. The lakes chosen for this study were Waldo, Odell, and Diamond Lakes located in the Cascade mountains and Devils Lake located on the Oregon coast. Percentage dry weight, percentage organic matter, sedimentary chlorophyll degradation products (SCDP), total phosphorus, total organic nitrogen, and diatom assemblages were used as indices of sediment changes through time. To evaluate the usefulness of the sediment record for showing changes in lake productivity, sediment cores were taken from lakes that exhibit present day differences in trophic status.

Profiles of selected characteristics of the sediment cores reflected the events unique to each lake and its watershed. The characteristics measured in cores from Waldo Lake sediments indicated that the lake has always been ultra-oligotrophic. The sedimentation rate was very low and the diatom assemblages revealed the unchanging water quality of the lake. Odell Lake responded to enrichment of its waters by shifting from its original oligotrophic condition to a more productive status. When the enrichment was ended, the lake responded by returning to a new intermediate productivity level. This was revealed by changes in profiles of percentage dry weight, percentage organic matter, SCDP, and diatom assemblages. Diamond Lake appears to have increased in productivity as a result of human activities in its watershed. This was shown also by shifts in SCDP, percentage organic matter, percentage dry weight and diatom assemblages. Although many changes occurred in the watershed of Devils Lake, sediment analysis showed changes only in profiles of total phosphorus and total organic nitrogen. Many factors in this lake may have combined to destroy the fine layer stratigraphy of the sediments. Meaningful successions of events were described with the aid of the sediment characteristics.

The most useful sediment characteristics measured in this study were SCDP, diatom assemblages, percentage dry weights, percentage organic matter, and total phosphorus.

Increases in SCDP and the percentage of organic matter seemed to indicate increases in the productivity of the lakes. Large decreases in the percentage of dry weight seemed to represent increases in rates of sedimentation. Changes in the diatom community undoubtedly indicated shifts in the trophic status of the lakes. Shifts in total phosphorus concentrations probably represented disturbances in the watersheds. Total organic nitrogen was the only sediment characteristic that was not very useful.

Sediment Characteristics and the Trophic Status of Four Oregon Lakes

by

Roger Dean Meyerhoff

A THESIS

submitted to

Oregon State University

in partial fulfillment of the requirements for the degree of

Master of Science

June 1977

APPROVED:

Redacted for Privacy

Professor of Fisheries
in charge of major

Redacted for Privacy

Head of Department of Fisheries and Wildlife

Redacted for Privacy

Dean of Graduate School

Date thesis is presented June 17, 1976

Typed by Deanna L. Cramer for Roger Dean Meyerhoff

ACKNOWLEDGEMENTS

I wish to express my sincere appreciation to Drs. Gerald E. Davis, Gary L. Larson, and H.K. Phinney who served as members of my graduate committee. Special thanks go to Dr. Gerald E. Davis for serving as my major professor and for his advice and help throughout the course of this project. Special thanks also go to Dr. Gary L. Larson for his help, direction and advice concerning all aspects of this project.

I am most indebted to Linda, my wife, for her patience, encouragement, and support, both financial and moral.

I would like to offer my appreciation to the staff and graduate students at Oak Creek Laboratory of Biology for creating a stimulating environment in which to work.

For specific information, I would like to thank Mr. E. Atkinson; Dr. M.E. Harward, Department of Soil Science - O.S.U.; J. Bull, U.S. National Forest Service - Deschutes; D. Larson, U.S. National Forest Service - Deschutes; S. Lewis, Oregon Department of Fish and Wildlife; J. Lyford, Department of General Science - O.S.U.; D. Martin, U.S. National Forest Service - Umpqua; C.F. Powers, U.S. Environmental Protection Agency - Corvallis; S. Radke, U.S. National Forest Service - Umpqua; W.D. Sanville, U.S. Environmental Protection Agency - Corvallis; and G. Schuytema, U.S. Environmental Protection Agency - Corvallis.

A number of people have helped me to complete various aspects of this project. I wish to thank L. Lamperti, E. Robinson-Wilson, and F. Hutchinson for their conscientious assistance in the field. Special thanks go to F. Hutchinson for designing and building a very reliable coring device.

I wish to thank C.D. McIntire for confirming the identities of a number of diatom species.

Support for this study was provided under Public Law 88-379, administered by the Office of Water Research and Technology, U.S. Department of the Interior, contract A-027-OREGON.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

SEDIMENT CHARACTERISTICS AND THE TROPHIC STATUS OF FOUR OREGON LAKES

INTRODUCTION

For many years limnologists have studied the physical, chemical and biological features of lakes to develop a workable understanding of the fundamental mechanisms that determine the ecological character of lakes. From these studies it is evident that the trophic status of lakes is influenced by a number of factors. Some important ones are lake morphometry, watershed fertility, rates of inflowing water, and climate (Hutchinson, 1957). Also, evidence indicates that lakes change through a natural aging process whereby they can become more productive. However, this eutrophication process is not necessarily continuous. A balance may be achieved between the relatively constant nutrient supply characteristic of the watershed, the physical factors which effect production, and production itself. Hutchinson (1973) points out that such a trophic equilibrium, if undisturbed, can continue for a very long time. The rate of eutrophication is often greatly accelerated in lakes whose watersheds are subjected to cultural development. The cause of the increase is frequently suspected to be from increased nutrient loads.

Although limnologists have developed techniques for estimating the productivity of lakes, they still have difficulty distinguishing between the effects of the natural aging process and the effects of human activities on present-day productivity levels of lakes. Limnologists have turned to paleolimnology to compare the past and present ecological condition of lakes. Many of these studies have been concerned with long term changes in lakes (Hutchinson and Wollack, 1940; Cowgill and Hutchinson, 1970).

Some paleolimnology studies have been directed toward measurement of changes that have occurred in lakes during the last few hundred years. Since many cultural developments began during this period, the study of recent lake sediments has the potential for revealing how lakes have responded to cultural developments in their watersheds.

There is evidence from several studies that recent ecological changes in lakes and their watersheds can be detected from analysis of lake sediments. However, changes cannot be detected unless measured parameters are interpretable. That is, of the large number of parameters that could be measured in the sediments, only a small percentage convey any meaning. Diatom assemblages in lake sediments have been analyzed by Stockner and Benson (1967), Stockner (1971), Stockner (1972), and Nipkow (1927) to show recent changes in lake trophic status. Phosphorus measurements have been used by Shapiro *et al.* (1971), Bortleson and Lee (1972), Wentz and Lee (1969), and Larson (1975) to indicate changes in lake productivity and watershed development. Likewise, nitrogen has been used as a marker by Shapiro et al. (1971) and Bortleson and Lee (1972). Measurements of chlorophyll degradation products have been used by Wunderlich (1974) to show recent lake productivity trends. Sediment organic matter, often used as a parameter to show long term change in the trophic status of a lake, has been used in studies of recent sediments by Bortleson and Lee (1972), Shapiro et al. (1971), Wentz and Lee (1969), Ohle (1972) and others. A shift in lake sediment characteristics has been interpreted as representing a change in lake trophic status. In many cases, changes in sediment characteristics have been shown to coincide with shifts in lake productivity.

The objective of this study was to correlate changes in some sediment characteristics of four Oregon Lakes with the past cultural developments of the lakes and their watersheds. To evaluate the usefulness of the sediment record for showing changes in lake productivity, lakes of different present day trophic status were chosen.

STUDY AREAS

Waldo Lake

Waldo Lake is a large ultra-oligotrophic water body located near the crest of the Oregon Cascade Mountain Range. The lake has no permanent influent streams. The principal source of water for the lake is snowmelt and subsurface runoff. Waldo Lake serves as a headwater of the middle fork of the Willamette River.

Waldo Lake basin, 10,000 to 12,000 years old, is a glacial depression bordered by terminal and lateral moraines (Larson and Donaldson, 1970). A bathymetric chart of Waldo Lake is presented in Figure 1. True firs, pine and hemlock are common in the watershed of the lake. Huckleberry is the principal ground cover (Curtis, personal communication, 1975). The soil mantle in the watershed consists mainly of weathered volcanic ash and glacially rounded boulders (Malueg *et al*., 1972). Depth to hard basalt bedrock is no more than two meters (Larson and Donaldson, 1970). The soil mantle of the watershed is porous and provides for rapid percolation of groundwater.

Physical, chemical, and biological measurements reflect the ultra-oligotrophic nature of the lake. According to Malueg *et al*. (1972), extremely low concentrations are found for total phosphorus (less than 0.003 mg/L), total nitrogen (0.1 mg/L), total carbon (less than 1 mg/L), total alkalinity (1 mg/L), calcium (0.36 mg/L), and magnesium (0.05 mg/L). The lake has an oxygen profile that is orthograde. This dimictic lake stratifies in the summer and the thermocline is located nearly ten meters below the surface (Larson and Donaldson, 1970). Phytoplankton consist mostly of dinoflagellates and direct counts of total bacteria average less than 200/100ml of water (Malueg et al., 1972). Chlorophyll a averages 5.3 mg/m^2 for the summer growing season and zooplankton are low in abundance. Data on some important features of Waldo Lake are presented in Table 1.

Until recently, this pristine lake was accessible only by trail or off-the-road vehicle. In 1969, the U.S. Forest Service completed construction of three large campgrounds on the east shore as well as a paved road to the lake (Curtis, personal communication, 1975). The improved accessibility did not cause the high visitor use originally expected. Less than 20 percent of the campground capacity was utilized in the summer of 1975 (Curtis, personal communication, 1975).

Odell Lake

Oligotrophic Odell Lake is located near Willamette Pass in the Cascade Mountains of Oregon. Rain and snowmelt provide water to the lake through at least two permanent tributaries, over twenty temporary tributaries, and

Table 1. Some important features of Waldo Lake.

Location	latitude 43° 43' N,[a] longitude 122° 03' W
Elevation	1650 m (above mean sea level)[a]
Watershed Area	52 km^2 [b]
Average Precipitation	180 cm/year[b]
Lake Surface Area	27 km^2 [b]
Maximum Depth	127 m [b]
Mean Depth	35.6 m [b]
Volume	0.95 km^3 [b]
Shoreline Length	40 km [d]
Light Transmittance (1%)	75 m [a]
Volume Replacement Time	30 years[c]
Total Dissolved Solids	3 mg/L [d]
pH	5.5 [a]
Mean Summer Primary Production	36 mg C/M^2/day [d]

[a]Malueg _et_ _al_. (1972)

[b]Powers _et_ _al_. (MS, 1975)

[c]Calculated from data obtained from the U.S. Dept. of Interior (1974)

[d]Larson and Donaldson (1970)

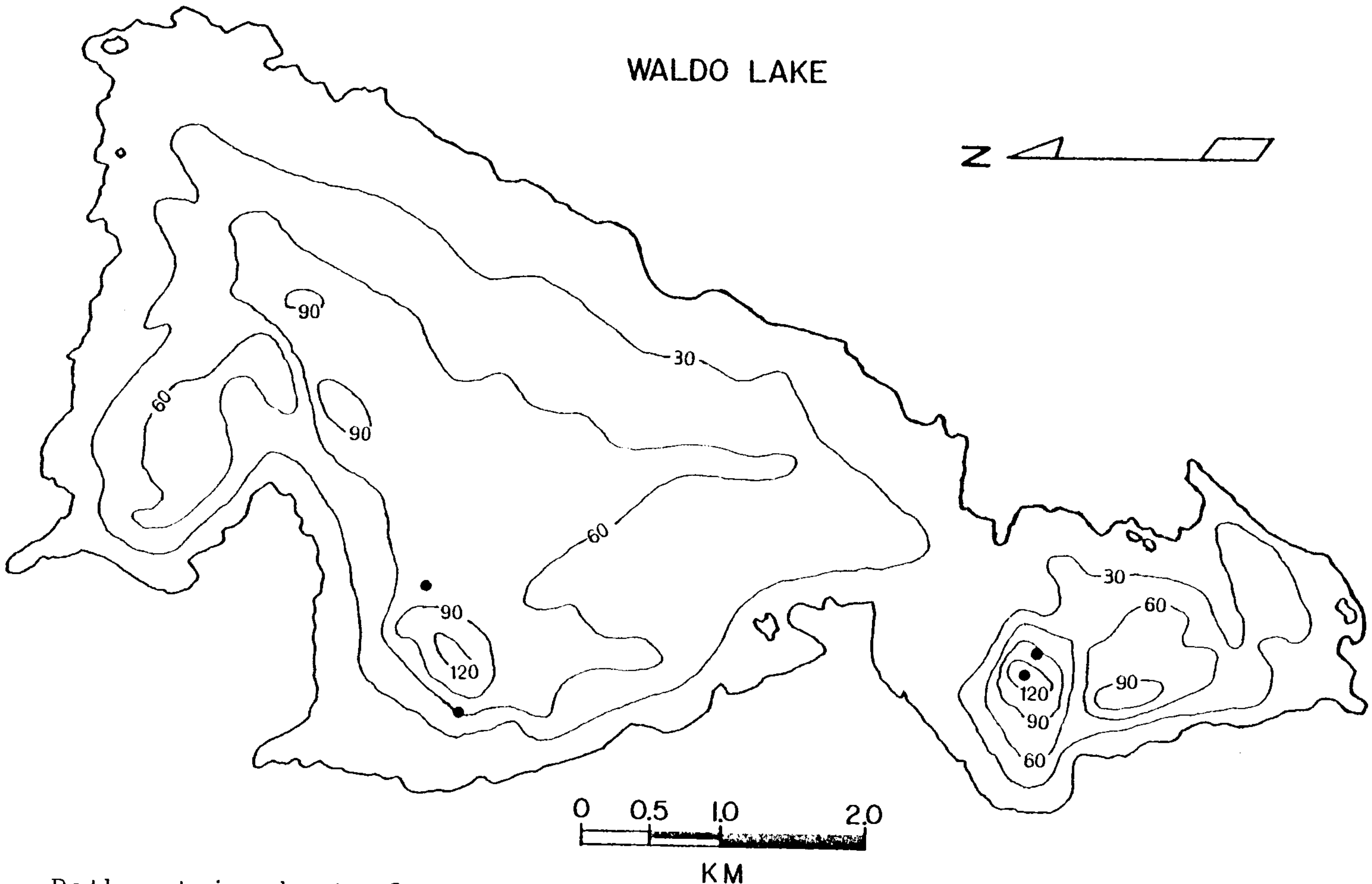

Figure 1. Bathymetric chart of Waldo Lake, Oregon. Map based on 1958 survey by the State of Oregon Game Commission, Portland, Oregon (map no. 1014). Contour interval, 30 meters. Sample locations are shown (●).

permanent subsurface runoff. The outlet of the lake supplies water to the Deschutes River system.

Odell Lake basin, formed 10,000 to 12,000 years ago, is thought to be a glacial trough closed at one end by a terminal moraine (Larson, 1970a). A bathymetric chart of Odell Lake is included in Figure 2. The watershed of the lake is forested predominantly with Douglas fir, pine, and mountain hemlock. Ground cover is principally huckleberry, sedges, and mosses (Larson, MS, 1976). Soils of the watershed are derived from pumice, volcanic ash, and glacial till (Larson, MS, 1976). Gravel, sand, hard basalt, and red cinders are found below the soils (U.S.N.F.S., 1976). This combination results in moderate to very high water permeability (Larson, MS, 1976).

Physical, chemical, and biological characteristics of Odell Lake provide ambiguous evidence of its oligotrophic status. This dimictic lake stratifies in early summer with a thermocline established near 20m by August (Larson, 1970a). Oxygen is never depleted from the hypolimnion, reaching a minimum of 60 percent saturation (Lewis, personal communication, 1976). Values of total alkalinity and total hardness were reported by Larson (1970a) to be 16.5 mg/L $CaCO_3$ and 10.6 $CaCO_3$, respectively. These low values were typical of the concentrations of other chemical constituents. Yet, biological measurements have shown Odell Lake to be very productive. Algal blooms have occurred and zooplankton have reached densities of 170,000/ m^3 (Larson, 1970a). The lake supports populations (Lewis, 1975) of mountain whitefish (Prosopium williamsoni), tui chub (Gila bicolor), rainbow trout (Salmo gairdneri), lake trout (Salvelinus nomaycush), Dolly Varden (Salvelinus varden), Atlantic salmon (Salmo salar), and kokanee (Oncorhyncus nerka). The lake could be considered oligotrophic on the basis of its morphometry and chemistry, but values of primary production recorded for the lake would place it on the eutrophic end of the Rodhe scale (Kavanagh, 1973). Data on some important features of the lake are presented in Table 2.

Odell Lake has been visited regularly by tourists since about 1925. In 1929, permits were issued for two small resorts. There are presently sixty-six private cabins, one resort, and four large campgrounds in the watershed (U.S.N.F.S., 1976). The lake is accessible throughout the year by an all-weather highway and visitor use has increased steadily since the late 1940's (Atkinson, personal communication, 1976). Odell Lake supports multiple use, including boating, water-skiing, and one of the most popular kokanee fisheries in Oregon.

Table 2. Some important features of Odell Lake.

Location	latitude 43° 34' N,[a] longitude 122° 00' W
Elevation	1459 m (above mean sea level)[a]
Watershed Area	101 km^2 [b]
Average Precipitation	127 cm/year [c]
Lake Surface Area	14.4 km^2 [d]
Maximum Depth	86 m [d]
Mean Depth	41 m [d]
Volume	0.59 km^3 [d]
Shoreline Length	21.5 km [d]
Light Transmittance (1%)	22 m [d]
Volume Replacement Time	8.1 years [b]
Total Dissolved Solids	28 mg/L [d]
pH	7.9 [d]
Mean Summer Primary Production	1700 mg C/M^2/day [d]

[a]Calculated from U.S. Dept. of the Interior (1963)

[b]Calculated from data obtained from the U.S. Dept. of the Interior (1974)

[c]Calculated from data obtained from the U.S. Dept. of Commerce (1969-1973)

[d]Larson (1970a)

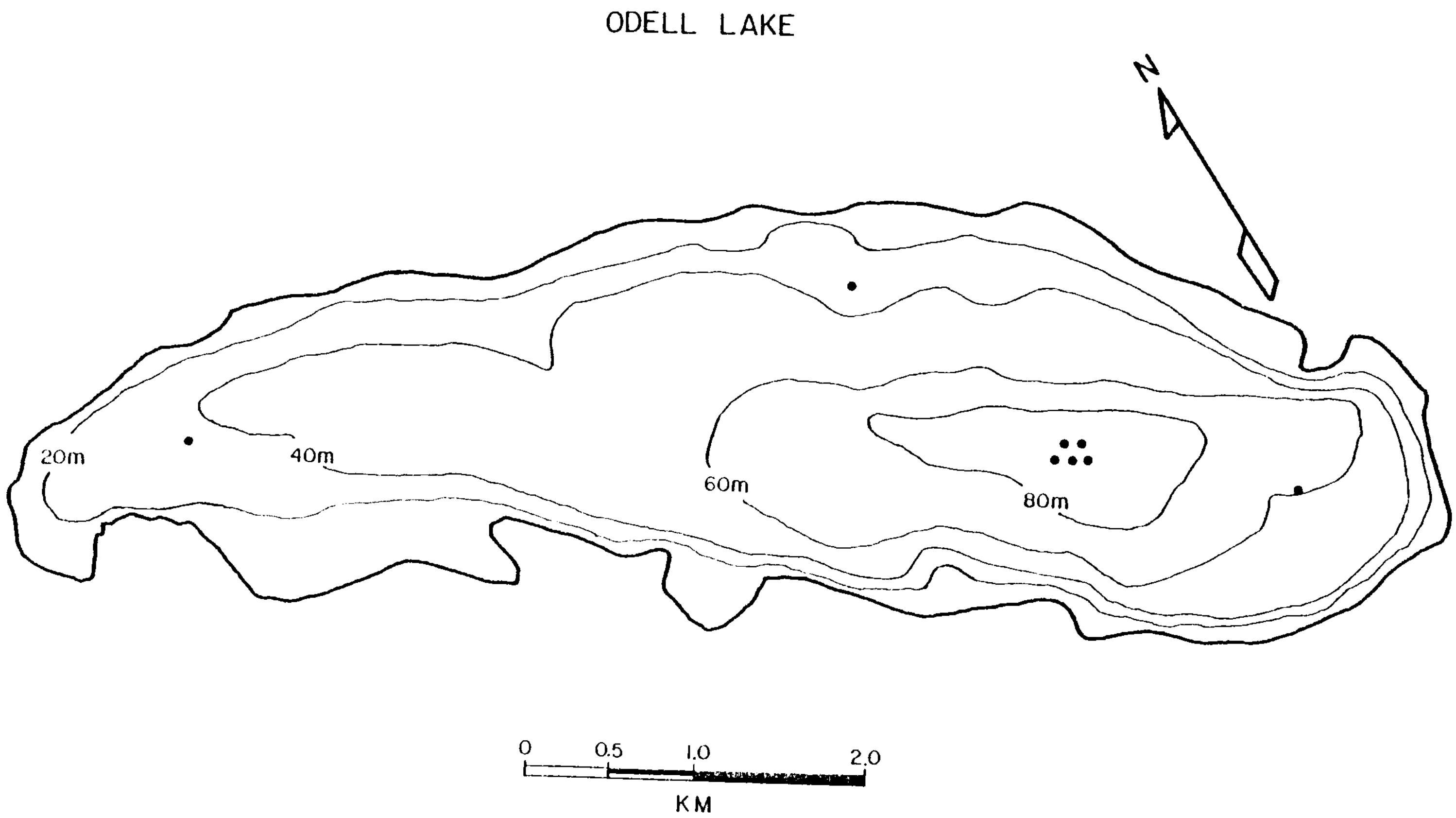

Figure 2. Bathymetric chart of Odell Lake, Oregon. Map based on 1964 survey by the State of Oregon Game Commission, Portland, Oregon (map no. 1274). Contour interval, 20 meters. Sample locations are shown (●).

Diamond Lake

Diamond Lake is a eutrophic high mountain water body located near the crest of the Oregon Cascade Mountain Range. With less than two meters of snowfall yearly, the principal source of water in the watershed is rain. The lake has at least ten permanent and temporary tributaries and probably receives a large amount of subsurface runoff (Radke, MS, 1976). Diamond Lake is a headwater of the Umpqua River System.

The watershed of Diamond Lake was scoured by glacial action. The glacier which formed the lake basin probably retreated up nearby Mt. Thielsen some 8,000 to 10,000 years ago (Radke, personal communication, 1976). A bathymetric chart of Diamond Lake is shown in Figure 3. Lodgepole pine, mountain hemlock, and fir predominante in the watershed. Ground cover consists of huckleberry, grasses, sedges and some manzanita (Radke, MS, 1976). Surface soils are mostly composed of pumice, loamy sand, and cobbles (Radke, MS, 1976). Subsurface pumice layers are no more than two meters deep and bedrock is hard basalt (Radke, MS, 1976). The soil mantle of the watershed provides for high to very high water permeability and soil drainage.

The eutrophic nature of Diamond Lake can be identified from its physical, chemical, and biological characteristics. The dimictic lake develops a thermocline that may extend to near the bottom, leaving the hypolinmion only in the deepest portion of the lake (Sanville and Powers, 1971). Oxygen depletion occurs in the summer near the bottom of the lake, reaching a minimum of 0.2 mg/L (Sanville and Powers, 1971). Some surface water areas are supersaturated with oxygen (Sanville and Powers, 1971). Summer hypolimnetic concentrations of total phosphorus reached 0.25 mg/L. Yearly algal blooms are almost exclusively diatoms in the early spring and are dominated by coccoid and filamentous blue-green algae in the late summer (Sanville and Powers, 1971). Primary production measurements (Sanville, personal communication, 1976) show that Diamond Lake is well established at the "eutrophic-polluted" end of the Rodhe scale (Rodhe, 1969). Data on some important lake features are presented in Table 3.

Diamond Lake has been visited by vactioners since the late 1920's. Presently, one-hundred and two summer homes, three campgrounds, one resort, and one trailor park are located along the lake shore (U.S.N.F.S., 1974). The lake is accessible by an all-weather highway which parallels the eastern shore. Diamond Lake supports multiple use, including boating, swimming, and one of the most popular trout fisheries in Oregon.

Table 3. Some important features of Diamond Lake.

Location	latitude 43° 09' N,[a] longitude 122° 09' W
Elevation	1580 m (above mean sea level)[a]
Watershed Area	142 km^2 [a]
Average Precipitation	127 cm [b]
Lake Surface Area	10.5 km^2 [c]
Maximum Depth	16 m [c]
Mean Depth	8.9 m [c]
Volume	9.3 x 10^{-2} km^3 [a]
Shoreline Length	13.7 km [c]
Average Summer Secchi Disc Depth	4.2 m [d]
Volume Replacement Time	1.84 years [a]
Average Summer Total Carbon	5.75 mg/L [d]
pH	8.1 [d]
Mean Summer Primary Production	2460 mg C/M^2/day [e]

[a]Calculated from data obtained from the U.S. Dept. of Interior (1974)

[b]Calculated from data obtained from the U.S. Dept. of Commerce (1969-1973)

[c]Calculated from Oregon State Game Commission Map (1946)

[d]Calculated from data obtained from Sanville and Powers (1971)

[e]Calculated from data obtained from Sanville (personal communication, 1976) using techniques of Vollenweider (1965) and Platt and Irwin (1968)

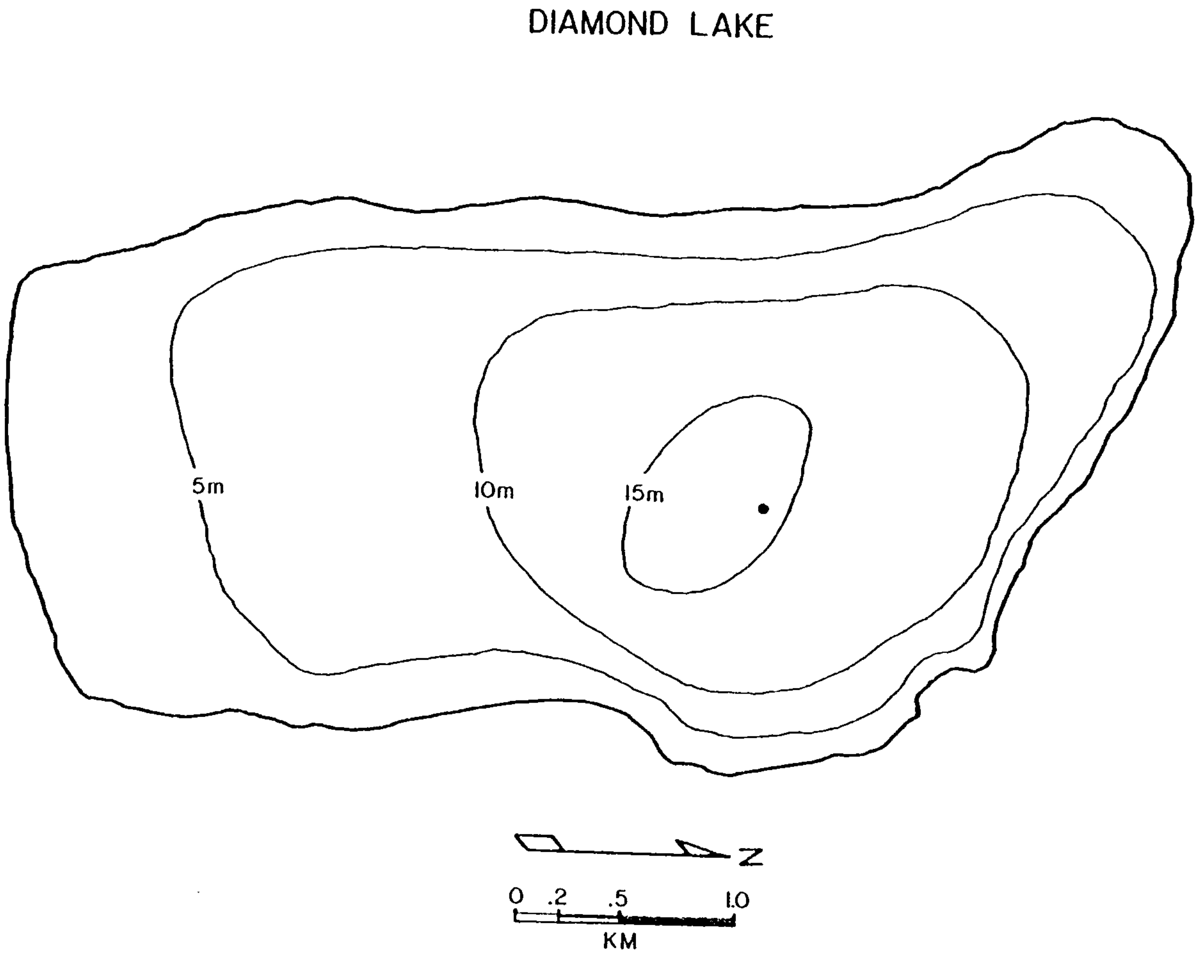

Figure 3. Bathymetric chart of Diamond Lake, Oregon. Map based on 1946 survey by the State of Oregon Game Commission, Portland, Oregon (map no. 400). Contour interval, 5 meters. Sample location is shown (●).

Devils Lake

Eutrophic Devils Lake is located on the Oregon coast near Lincoln City. Water is supplied to the lake through two permanent tributaries and drains from the lake directly into the Pacific Ocean which is less than two-hundred meters away.

Like much of the Oregon coast, physical features of Devils Lake basin were probably extensively modified by shifting sand dunes, stream alluviation, and a rise in sea level during the late Pleistocene. The formation of Devils Lake most likely resulted from a drowned river valley partially blocked by changing coastal features (Kavanagh, 1973). On the basis of morphology, this lake would be classified as a dendritic maritime coastal lake (Hutchinson, 1957). A bathymetric chart of Devils Lake is shown in Figure 4.

The watershed of Devils Lake is only partially forested. Most of the watershed has been developed for human use. Housing units, boat houses, an organizational camp, and public areas crowd about sixty percent of the shoreline and the lake borders a city. Lake tributaries run through pastures and across a golf course. Devils Lake probably receives nutrient input from septic tank drainfields and run-off from fertilized lawns and gardens (McHugh, 1972). Until 1970, poorly treated sewage was released directly into the lake (McHugh, 1972). Devils Lake is a very popular recreational area and supports multiple use, including boating, swimming, water-skiing, and a popular trout fishery.

Biological evidence points toward the eutrophic nature of Devils Lake. The lake is holomictic, has an orthograde oxygen profile, and supports life throughout the water column (Kavanagh, 1973). Large numbers of freshwater bivalves (*Andota oregensis* and *Andota nataliana*) are found in the sediments. Extensive mats of aquatic macrophytes were identified by McHugh (1972) as *Myriophyllum* and *Potamogeton*. Large stands of *Elodea densa* also grow in the lake. Emergent water plants such as *Nuphar*, *Typha*, *Scirpus*, *Carex* and *Juncus* were found near the shoreline (McHugh, 1972). The blue-green alga *Oscillatoria princeps* has been found in the lake (McHugh, 1972). The yearly mean planktonic production ranks well into the "natural-eutrophic" end of the Rodhe scale (Kavanagh, 1973). Devils Lake supports a variety of fish, including coho salmon, cutthroat trout, steelhead trout, largemouth bass, white crappie, black crappie, yellow perch, channel catfish, sculpin, and stickleback (Smith and Smith, 1972). Some important features of Devils Lake are presented in Table 4.

Table 4. Some important features of Devils Lake.

Location	latitude 45° 59' N,[a] longitude 124° 01' W
Elevation	5 m (above mean sea level)[b]
Watershed Area	21 km^2 [a]
Average Precipitation	198 cm [c]
Lake Surface Area	2.8 km^2 [b]
Maximum Depth	6.4 m [b]
Mean Depth	3.0 m [b]
Volume	8.4×10^{-3} km^3 [b]
Shoreline Length	17.2 km [b]
Light Transmittance (1%)	4.5 m [b]
Volume Replacement Time	0.37 year [d]
Total Dissolved Solids	60 mg/L [b]
pH	7.0 [b]
Mean Yearly Primary Production	400 mg C/M^2/day [b]

[a]Calculated from Oregon State Water Resources Board (1964)
[b]Kavanagh (1973)
[c]Calculated from data obtained from the U.S. Dept. of Commerce (1969-1973)
[d]Calculated from data obtained from Wheeler (1974)

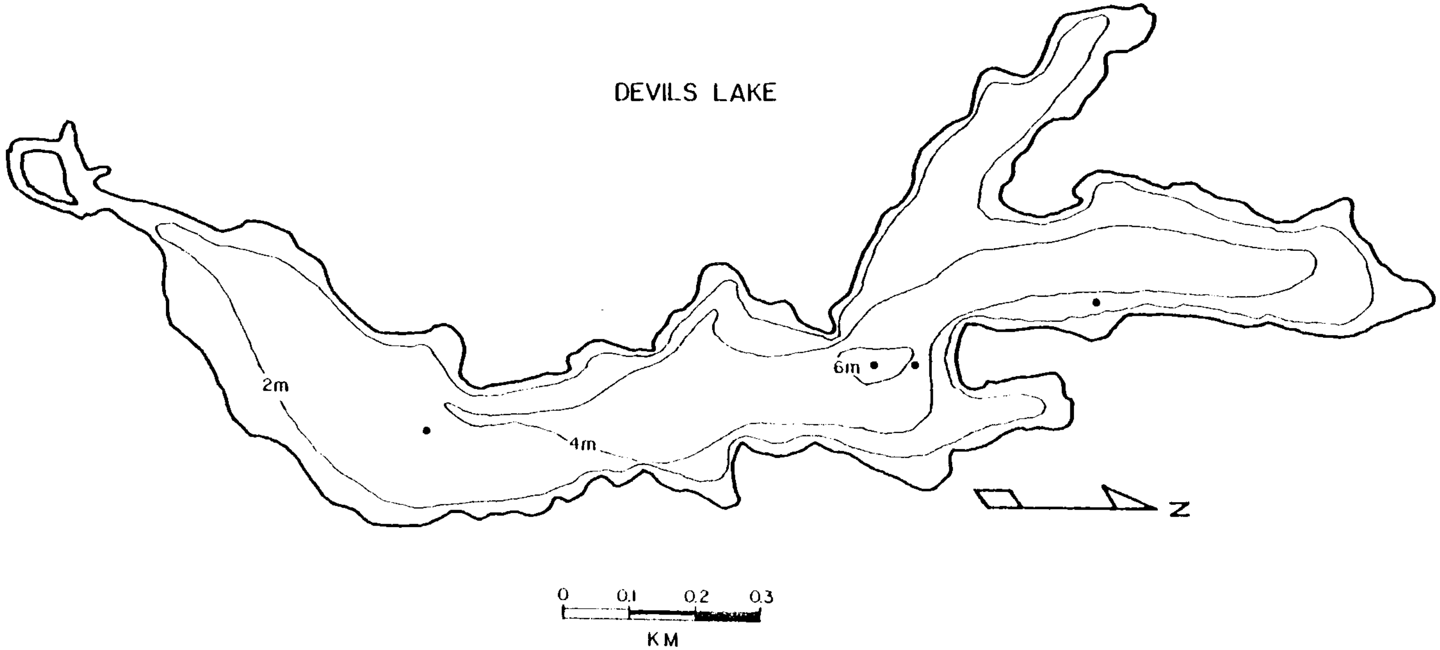

Figure 4. Bathymetric chart of Devils Lake, Oregon. Map based on 1953 survey by the State of Oregon Game Commission, Portland, Oregon (map no. 920). Contour interval, 2 meters. Sample locations are shown (●).

MATERIALS AND METHODS

Each study area was selected on the basis of the following criteria: the availability of recent limnological information, documentation of the development of recreational and/or residential facilities in the watershed, and the value of the lake as a resource.

Three to eight cores were taken from each lake. Sediment samples were taken in plastic tubes (36mm I.D.) driven into the lake bottom by a piston coring device similar in design to that described by Edmondson and Winberg (1971). Each core was visually inspected and many were X-ray photographed to detect varves or layers of unique material useful for dating those layers of the core. The upper 50cm of sediments were then extruded from the plastic tubes and sectioned into 0.5cm or 1cm layers. Each layer was stored in a plastic vial until the analyses could be performed.

Various sediment layers were analyzed for sedimentary chlorophyll degradation products (SCDP), percentage dry matter, percentage organic matter, total phosphorus, total organic nitrogen, and diatom assemblages. SCDP, corrected for turbidity (Strickland and Parsons, 1968), were extracted from wet sediment with 90 percent acetone and measured on a Beckman Model DB-G spectrophotometer according to the methods of Vallentyne (1955). Samples were dried at 70C for 48hrs to determine the percentages of dry matter and ashed at 550C for 5hrs to determine the percentages of organic matter (milligrams lost on ignition per gram dry weight). Total phosphorus was determined spectrophotometrically after perchloric acid digestion and color development with ammonium molybdate and ascorbic acid (Strickland and Parsons, 1968). Total organic nitrogen values were calculated from concentrations of ammonia. The concentration of ammonia was determined with an Orion Ammonia Electrode after Kjeldahl digestion (APHA, 1971) and subsequent treatment with a concentrated solution of sodium iodide and sodium hydroxide (Orion Research Incorporated, 1974).

Replicate determinations for physical and chemical characteristics were made in a number of sediment layers. The ranges of values for the different characteristics were: dry matter ±5 percent, organic matter ±2.5 percent, total organic nitrogen ±2 percent, total phosphorus ±5 percent, and SCDP ±2 percent.

Diatom assemblages were determined for a single deep water core from each lake. Approximately 0.1gm (dry wt.) of sediment from each sample stratum was prepared for analysis by boiling in a solution of fifty percent nitric acid. When the solution reached half volume, the diatom slurry was diluted with distilled water and allowed to settle. The solution was alternately decanted and diluted until a pH value of seven was obtained. An aliquot of the diatom slurry was dispersed on a #1½ coverslip (22mm x 22mm) and dried on a hotplate. The coverslips were permanently mounted on glass slides using Hyrax mounting medium (refractive index 1.63). Microscopic examination (950X) was done on random transects of each slide. For each sample stratum, between 400 and 600 frustules were identified as to genera and percent relative abundance was calculated. Species identification, based on Hustedt (1930) and Patrick and Reimer (1966), was made for the surface sediment layers from each lake core. The three diatom species that were dominant in a single stratum were recorded for various layers throughout each core.

RESULTS AND INTERPRETATIONS

Waldo Lake

Two cores from depths of 127 meters and 105 meters in the south basin, and two cores from depths of 77 meters and 60 meters in the north basin, were extracted from the sediments of Waldo Lake (Figure 1). All sediments were light brown. The deep water cores from each basin (127m and 77m) contained an extensive matrix of the moss *Hygrohypnum* (Lyford, personal communication, 1975). Lacustrine sediments were packed between the strands of the moss. The core from 105m contained a moderate amount of moss and the 60m core had none. Almost no macrobenthos (one small *Oligochaeta*) was found in the cores. Physical and chemical data are presented for the south basin core from 105m (Figure 5). Variations in profiles of the other cores are described.

The profile of percentage dry weight in Figure 5 showed two maximum points. The increase in percentage dry weight near a sediment depth of 18cm was due to a volcanic ash layer, probably from an eruption of Mt. Mazama some 6,600 years ago (Harward, personal communication, 1976; and Harward and Youngberg, 1969). The other cores showed this volcanic ash layer in different positions in their profile. However, for the two cores that contained an extensive

WALDO LAKE

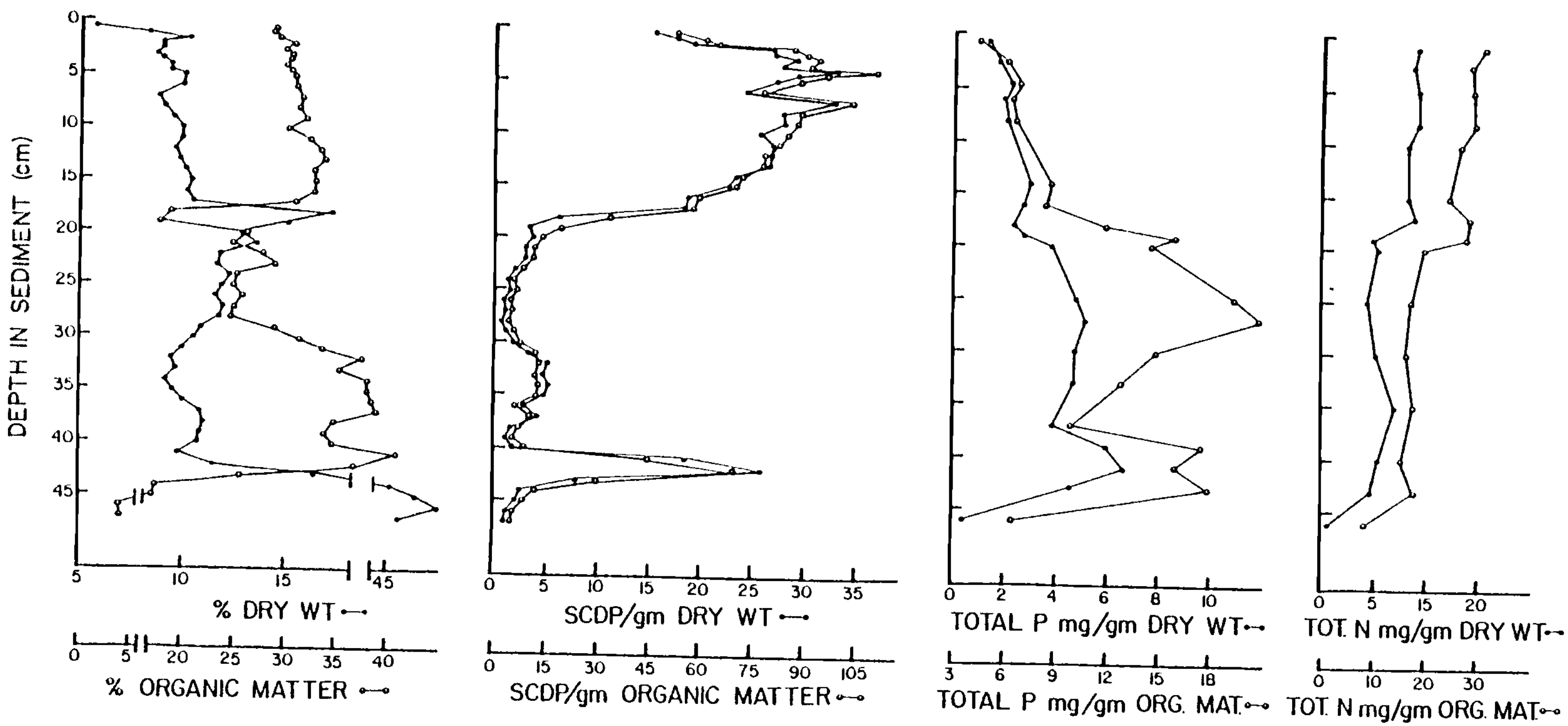

Figure 5. Physical and chemical profiles of a Waldo Lake sediment core taken at a depth of 105 meters.

amount of moss, the volcanic ash layers were at exactly the same stratum, 24cm. The second increase in dry weight occurred between the 42cm and 47cm strata (Figure 5). This increase corresponded to another layer of unique material, silt. The silt particles, which were smaller than 20µ, appeared near 42 cm and expanded to a thick layer encompassing the remainder of the core. The silt layer probably resulted from the deposition of glacial flour from the meltwater of retreating glaciers. This silt layer was only encountered in the cores with little or no moss. The 60m core from the north basin of the lake showed the silt band starting at 42cm. The volcanic ash and silt layers were clearly shown in X-ray photographs of the cores.

Profiles of two cores taken from Waldo Lake probably span the entire history of the lake. Sedimentation rates were calculated using the unique layers as markers of approximate dates. Up to the volcanic ash layer, the rate was 0.055mm per year, and from that layer to the surface the rate was 0.027mm per year. The average sedimentation rate for the entire history of the lake was 0.038mm per year. This figure seems reasonable considering the ultra-oligotrophic nature of the lake.

Profiles of percentage organic matter varied between cores. However, the two cores with little or no moss, possibly best reflecting the planktonic history of the lake, showed a similar downward trend in percent organic matter

(Figure 5). Large decreases in percent organic matter near 18cm and 43cm were due to the relative increases in dry matter (the volcanic ash layer and the silt layer). The amount of organic matter in cores with an extensive moss matrix ranged from 60 percent to 35 percent. One of these cores showed a slight decreasing trend in percent organic matter with decreasing depth, the other showing no obvious trends.

The sedimentary chlorophyll degradation products (SCDP) profile (Figure 5) graphically displayed the difference between sediments that do and do not contain strands of moss. Only slight amounts of moss were found from 0.5cm to 18cm and from 41cm to 43cm, yet SCDP increased up to five times that measured for other strata. The profile of SCDP per gram dry weight for the core containing no moss showed a slight downward trend and reached, at most, six SCDP units per gram dry weight near the deepest portion of the core. The SCDP records suggest that the attached moss, when present, may have contributed substantially to primary production.

The profile of total phosphorus concentrations showed a trend toward decreasing values with decreasing sediment depth (Figure 5). Below 15cm, large variations were seen in the total phosphorus per gram organic matter whereas the total phosphorus per gram dry weight slope was relatively constant. The large fluctuation in total phosphorus per gram organic matter was probably due to the corresponding changes in the organic matter profile. If the total phosphorus measured was bound to inorganic substrates, as was apparently the case, then the total phosphorus per gram dry weight profile probably mirrors watershed fertility. Changes in total phosphorus per gram dry weight in a core with an extensive matrix of moss were similar to those described for Figure 5.

The total organic nitrogen records (Figure 5) indicated little change throughout the history of the lake. Profiles from the three other cores were nearly vertical with perturbations corresponding only to volcanic ash and silt layers. Values for total organic nitrogen profiles closely match between cores.

The core taken from the deepest location (127m, south basin) in Waldo Lake was analyzed for relative abundance of diatoms. This core contained an extensive mat of moss. The diatoms in this core were much better preserved than they were in sediment without the moss matrix. Although this core did not cover as great a time span as two other cores, it still covered approximately eighty percent of the history of the lake.

There were very few planktonic species found in the sediments. The periphytic diatoms never numbered less than 88 percent throughout the entire core. Even in sediment samples without moss, a quick survey showed no more than

20 percent planktonic diatoms. Diatoms found in the water column include *Fragilaria*, *Synedra* and *Surirella* (Larson, 1970b); *Melosira distans*, *Cyclotella atomus*, *Stephanodiscus astraea*, *Eunotia*, *Achnanthes*, *Navicula*, *Cocconeis*, *Gomphonema*, *Rhoicospenia*, *Cymbella*, *Nitzschia*, *Frustulia*, *Tabellaria*, *Neidium*, *Peronia fibula*, *Amphora*, *Diploneis*, and *Meridion* (Schuytema, personal communication, 1976); and *Pinnularia* (McHugh, 1972). A number of these genera were not found in the core sample analyzed. A list of diatom species identified from the surface (1cm) sediments of Waldo Lake is presented in Table 5. The range in relative abundance of the genera for all strata and the percent occurrence of each genus in the core profile are also listed. Some genera and species in Table 5 have not been previously recorded from Waldo Lake.

Nearly all the diatom species identified in the surface sediments occur typically in oligotrophic waters. *Melosira distans*, an acidophil, is found in oligotrophic or dystrophic waters and may be periphytic (Lowe, 1974). The other planktonic forms were not abundant. The attached forms dominated the diatom community. The *Eunotia* species, most abundant among the periphytic diatoms, are found in fresh acid waters with low mineral content (Patrick and Reimer, 1966). Many are normally associated with moss (Patrick and Reimer, 1966). Others are indicative of oligosaprobic waters (Lowe, 1974). According to Patrick

Table 5. Species of diatoms recorded for the surface (1 cm) sediments and the distribution and abundance of genera in a Waldo Lake core.

Fragilariales

Fragilaria construens* (0-0.9,35)[a]
Meridion sp. [1][b] (0-0.2,4)

Tabellaria flocculosa (0-0.2,4)

Eupodiscales

Melosira distans (0.6-10.9,100)
Melosira sp. [1]

Stephanodiscus astraea (0-0.2,4)

Eunotiales

Eunotia bractriana* (64.5-78.7, 100)
E. curvata*
E. elegans
E. exigua*
E. incisa*
E. maior*
E. nymanniana*
E. pectinalis*
E. serra*
E. tenella*
E. trinacria*
E. vanheurckii*
Eunotia spp. [2]

Peronia fibula (1.3-6.9,100)
var. fibula
var. [2]
P. intermedium var. intermedium*

Achnanthales

Achnanthes marginulata (0-4.7,96)
var. austriaca*
Achnanthes spp. [2]

Naviculales

Anomoeneis serians (0-2.8,90)
var. brachysira
var. [1]

Cymbella ventricosa (0-3.9,98)
Cymbella sp. [1]

Frustulia rhomboides (3.9-16.6, 100) var. saxonica
var. capitata

Gomphonema gracile* (0-1.9,79)
Gomphonema sp.

Navicula ludloviana* (0.5-7,100)
N. mutica var. cohnii*
Navicula sp. [1]

Neidium iridis (0-0.2,8)
var. amphigomphus*

Pinnularia braunii (0.4-6,100)
var. amphicephala*
P. subcapitata*
P. sudetica*
Pinnularia spp. [2]

Stauroneis sp. [1] (0-0.2,2)

Bacillariales

Bacillaria sp.* [1] (0-0.2,2)

Nitzschia Hantzschiana* (0-0.7,21)

Surirellales

Surirella linearis (0-0.2,4)
var. constricta*

[a] Range in percent relative abundance of genus for all strata, percent occurrence of the genus in all strata ( ).

[b] Number of species or varieties that could not be identified [ ].

*Not previously recorded from this lake.

and Reimer (1966), *Eunotia incisa* is often found in clear, cool water with low mineral content, especially calcium, and is many times found in association with moss. *Eunotia vanheurckii* is normally found in characteristically oligotrophic waters (Patrick and Reimer, 1966). Again, *Eunotia tenella* prefers somewhat acid, soft waters. Almost all of the remaining species, especially those of the orders *Acnanthales* and *Naviculales*, are normally found in fresh, sometimes acidic, water with low mineral content (Patrick and Reimer, 1966). The water quality requirements reported in the literature for the species found in the surface sediments closely correspond to the physical and chemical data from the lake.

Although the A/C (*Araphidineae*/*Centrales*) ratio of Stockner and Benson (1967) was developed for sediments of lakes where planktonic diatoms dominate, this ratio satisfactorily represented the trophic status of Waldo Lake (Figure 6). Values of the A/C ratio rank lakes as oligotrophic (0 to 1), mesotrophic (1 to 2) and eutrophic (2 or greater). In most strata of the Waldo Lake core the A/C ratio was zero. The A/C ratio was greater than zero in several strata only because of the occurrence of a few frustules of *Fragilaria*. The peaks in the A/C ratio near the surface sediment were due to the presence of several frustules of *Araphidineae* and a concomitant decrease in the abundance of *Melosira*.

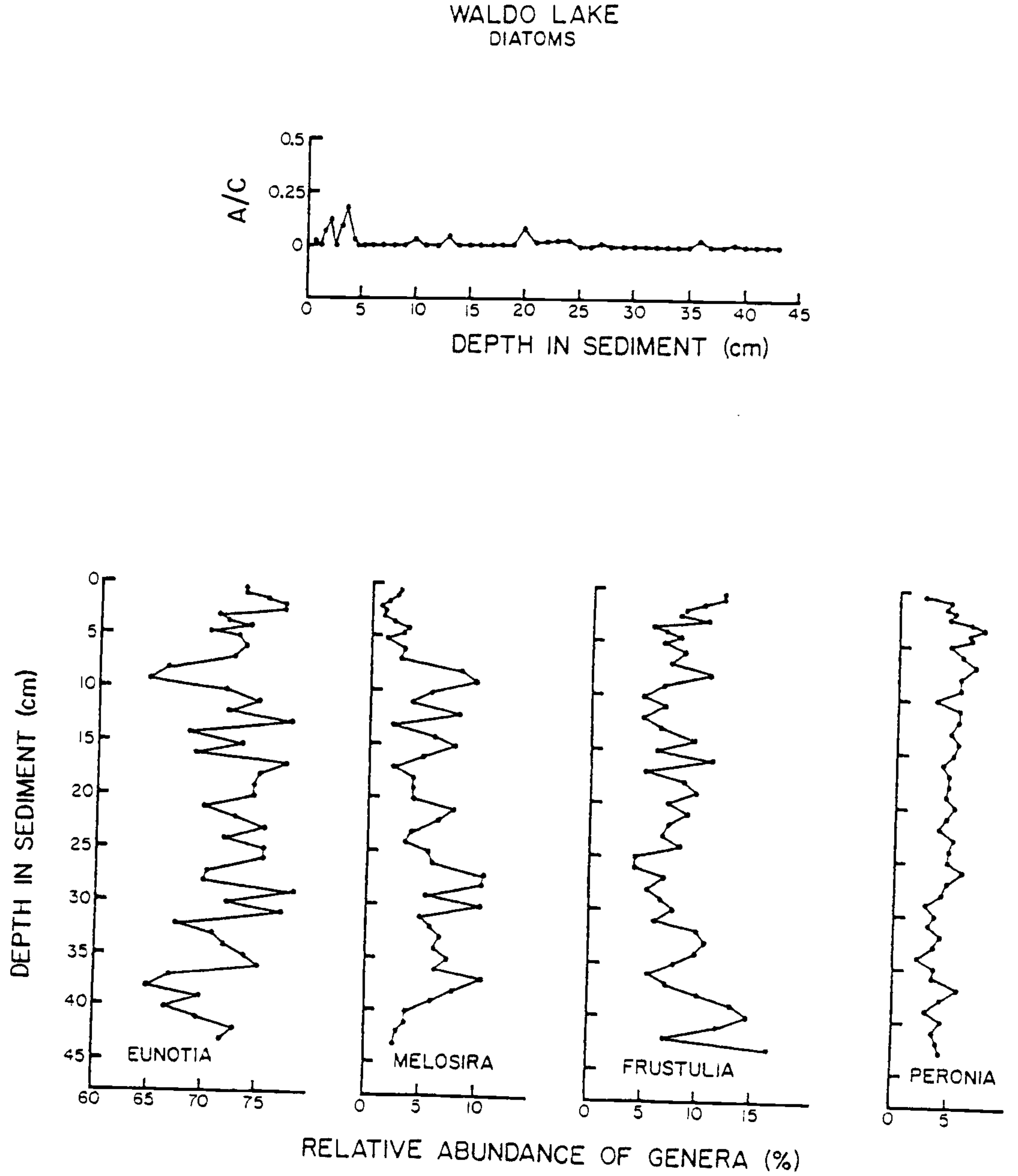

Figure 6. A/C (Araphidineae/Centrales) ratio of Stockner and Benson (1967) and relative abundance of some important genera in a sediment core taken at a depth of 127m in Waldo Lake.

Profiles of diatom genera and species indicated that oligotrophic diatoms were common throughout the core (Figure 6 and Table 6). These profiles demonstrated that periphytic diatoms dominated the assemblages. Eunotia was the most abundant diatom genus in the lake.

The parameters measured in cores from Waldo Lake sediments demonstrated that the lake has always been ultra-oligotrophic. The sediments contained very high concentrations of organic matter and total phosphorus, but on the basis of the sedimentation rate, annual accumulation of these materials was small. When moss was not present, SCDP values were very low and probably reflected the amount of algal production in the lake. Requirements of diatom types and their profiles showed the oligotrophic nature of the lake.

If the lake changed at all, it became less productive. This is indicated by the declining trend in percentage organic matter (Figure 5) and the reduced sedimentation rate. This reduction in productivity may be a direct result of diminished leaching of minerals from the watershed over geological time. This is reflected in the total phosphorus per gram dry weight profile (Figure 5).

Table 6. The three dominant species of diatoms, listed in order of abundance, in different strata of a Waldo Lake sediment core.

Depth from sediment surface (cm)	1	2	3
0.5	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides
5	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides
10	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides
15	Eunotia vanhuerckii	Eunotia incisa	Eunotia tenella
20	Eunotia vanhuerckii	Euntoia incisa	Frustulia rhomboides
24	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides
25	Eunotia vanhuerckii	Eunotia incisa	Eunotia tenella
30	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides
40	Eunotia vanhuerckii	Eunotia incisa	Frustulia rhomboides

Odell Lake

The most extensive documentation was made of Odell Lake sediments. Eight cores (five at 86m, one at 61m, one at 33m and one at 27m) were taken from the sediments of Odell Lake in October, 1974 and in August, 1975 (see Figure 2 for locations). The cores extracted in August, 1975 were from 86m. The sediment in all cores was light brown. All of the cores were analyzed for percentage dry weight, organic matter, and were X-ray photographed. Values of total organic nitrogen and SCDP were recorded for two cores taken at a depth of 86m. Total phosphorus and diatom assemblages were determined for one core from 86m. All data presented in figures and tables are from one 86m core taken in August, 1975. Variations in appropriate profiles of other cores will be described.

Percentage dry weight generally decreased from the bottom to the top of the deep water cores (Figure 7). Above 10cm there was a marked decrease in percentage dry weight followed by a small increase above the 4.5cm level. There was little change between the 3.5cm and 1.5cm strata. The surface (1cm) sediment was not consolidated. This pattern was present in all of the cores taken from 86m.

Cryptic laminations between 3.5cm and 11cm were revealed in X-ray photographs of the deep water cores. The laminations were alternately light and dark. One pair of

ODELL LAKE

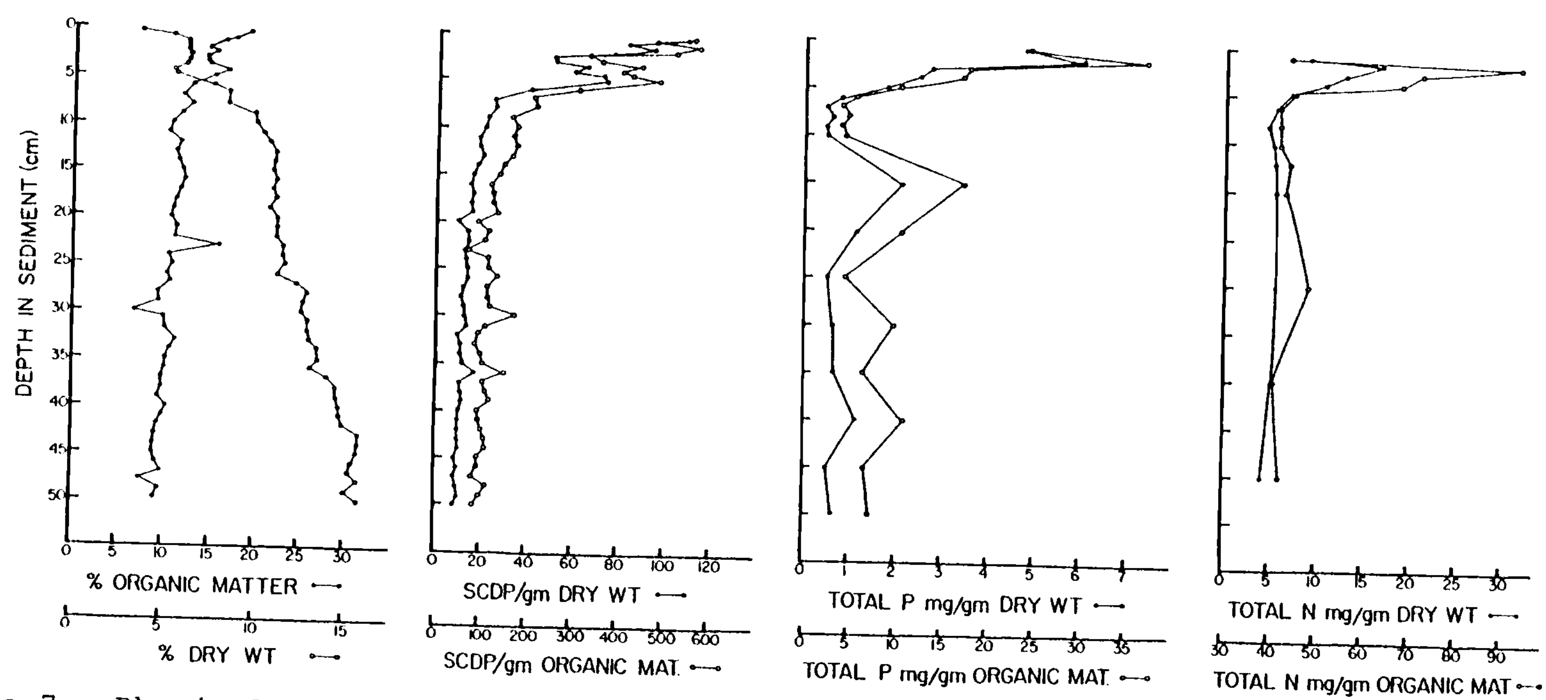

Figure 7. Physical and chemical profiles of an Odell Lake sediment core taken at a depth of 86 meters.

light and dark laminations was assumed to be autochthonus material (Edmondson, 1975) and allochthonus mineral matter, deposited during one growing season and the following winter. A wide (8mm) light band occurred near the 4.5cm stratum in the profile of the sediment core. Laminations in the 86m core were measured to estimate yearly sedimentation rates. A set of light and dark layers was considered to represent one year. The average sedimentation rate was considered to be constant from the surface to the first set of identifiable laminations. Since percentage water content of the core varied within the top 10cm, lamination widths were adjusted so that values of percentage dry matter were equal, 16 percent. With this adjustment the sedimentation rates became comparable. Sedimentation rates near 10cm and 4.5cm, when adjusted to 16 percent dry weight, were double the average. With these adjustments the 4.5cm stratum and the 10cm stratum were assigned ages of approximately 8 years and 21 years, respectively.

Cores from 33m and 27m were different from the deep water cores in that the change in percentage dry weight was essentially constant from the bottom to the top of the cores. No laminations were detected in X-ray photographs of shallow water cores. Fine layering might have been absent from these cores because of mixing by turbulent water currents and internal seiches (Larson, 1970b).

In all of the deep water cores, the percentage organic matter was essentially constant below the 10cm level. The percentage organic matter increased between the 10cm and 4.5cm strata and then decreased (Figure 7). The second core taken in 1975 mirrored this profile. Profiles of percentage organic matter for deep water cores taken in 1974 showed a steady increase above 10cm with only a small change at the 4.5cm stratum. The percentage of organic matter changed little in the shallow water cores; values ranged from 13 percent to 15 percent.

SCDP concentrations were relatively constant below the 15cm stratum, but increased above this stratum. Below 15cm, SCDP per gram dry weight was approximately 10 units and SCDP per gram organic matter was approximately 100 units. Above 15cm, SCDP concentrations increased slightly to 9cm. SCDP concentrations increased between the 9cm and 4.5cm strata and then decreased. The SCDP profile of the other core taken in 1975 mirrored the described profile.

Both total phosphorus and total nitrogen increased above the 6cm stratum (Figure 7). The concentration of total phosphorus increased and then decreased between the 25cm and 10cm strata. Only small changes in concentrations occurred below the 25cm level. Total organic nitrogen was nearly constant below the 6cm stratum.

Planktonic types comprise the bulk of the diatom assemblages found in the sediment core (Table 7). Larson

Table 7. Species of diatoms recorded for the surface (1 cm) sediments and the distribution and abundance of genera in an Odell Lake core.

Fragilariales

Asterionella formosa (0-11.2, 89)[a]

Diatoma sp.* [1][b] (0-0.6,4)

Fragilaria construens* (0.7-39.7, 100)
F. crotonensis var. crotonensis
F. brevistriata var. brevistriata*
F. pinnata var. pinnata*
F. vaucheria var. vaucheria*

Synedra cyclopum (0-0.7,60)
var. robustum*
S. delicatissima*
S. rumpens var. rumpens*

Tabellaria fenestrata (0-5.6,38)

Eupodiscales

Cyclotella comta* (0-0.7,22)

Melosira granulata* (5.2-74,100)
M. granulata var. angustissima*
M. italica

Stephanodiscus astraea* (11.4-52.4,100)
S. astraea var. intermedia*
var. minutula*
S. niagarae

Achnanthales

Achnanthes exigua* (0-2.8,89)
var. [1]
A. lanceolata var. lanceolata*
var. omissa*
Achnanthes sp. [1]

Cocconeis placentula (0.6-4.5, 100)
var. placentula*
var. euglypta*
C. rugosa var. rugosa*

Rhoicosphenia curvata (0-0.2, 2)

Naviculales

Amphora ovalis* (0-1.1,11)

Cymbella cistula* (0-1.7,84)
C. turgida*

Diploneis sp.* (0-0.4,10)

Gomphonema longiceps* (0-1.4, 56)

Navicula pseudocutiformis* (0-4.1,96)
N. radiosa*
Navicula spp. [3]

Bacillariales

Bacillaria sp.* [1] (0-0.6,2)

Epithemia turgida* (0-0.9,40)

Hantzschia sp.* [1] (0-0.4,2)

Nitzschia microcephala* (0-4.7,91)
Nitzschia spp. [2]

Surirellales

Suriella sp. [1] (0-0.2,2)

[a] Range in percent relative abundance of genus for all strata, percent occurrence of the genus in all strata ( ).

[b] Number of species or varieties which could not be identified [ ].

*Not previously recorded from this lake.

(1970b) and McHugh (1972) have listed some diatom types found in the water column. The small percentage (no more than 20 percent) of periphytic forms (Achnanthales, Naviculales, Bacillariales, and Surirellales) suggest their shallow water origin.

Analyses of the trophic preferences of the diatom species yield a complex picture. Asterionella formosa (Stockner and Benson, 1967; Lowe, 1974; and Patrick and Reimer, 1966), Fragilaria construens (Lowe, 1974), Fragilaria crotonensis (Stockner and Benson, 1967); Lowe, 1974; Rawson, 1956; and Patrick and Reimer, 1966), and Fragilaria pinnata (Lowe 1974) have all been correlated to mesotrophic and/or eutrophic conditions. Tabellaria fenestrata is listed by Patrick and Reimer (1966) as existing in mesotrophic to eutrophic conditions and was reported to appear in abundance preceding massive growths of Oscillatoria rubescens (Nipkow, 1927). Cyclotella comta, although not at all abundant in Odell Lake sediments, is probably a true oligotrophic species (Stockner and Benson, 1967; and Rawson, 1956). More abundant was Melosira granulata which has been classified as an index of oligotrophic waters (Rawson, 1956) to eutrophic waters (Lowe, 1974) but probably grows best in mesotrophic to eutrophic conditions. Melosira italica, another abundant species in Odell Lake sediments, is more representative of oligotrophic (Stockner and Benson, 1967) and oligosaprobic

(Lowe, 1974) waters. A number of forms of the genus Stephanodiscus were found. The predominant type throughout the core was S. astraea variation minutula. Only few S. astraea, S. astraea variation intermedia, and S. niagarae were found. S. astraea variation minutula, and S. niagarae are common in oligotrophic waters (Stockner and Benson, 1967; and Rawson, 1956). The same dichotomy in trophic preference exists when considering periphytic forms. However, the coexistence of both eutrophic and oligotrophic indicator species provides the basis for a biologically meaningful ratio derived from average yearly contribution of species to the sediment (Stockner and Benson, 1967). That is, any ratio of trophic types in the sediments automatically subsumes the relative importance even of blooms of different diatoms throughout the year.

Coexistence of diatoms with different trophic preferences in the sediments of the Odell Lake substantiates the use of the A/C ratio proposed by Stockner and Benson (1967). The A/C ratios were recorded for different strata of a core from Odell Lake (Figure 8). The value of the ratio increased slightly near 25cm and remained relatively stable in strata between 25cm and 10cm. Between the 10cm and 4.5cm strata, the value of the ratio increased markedly. Above this level the index declined to an intermediate value in the surface sediments. Although this index sacrifices information by grouping diatoms, the ratio has been

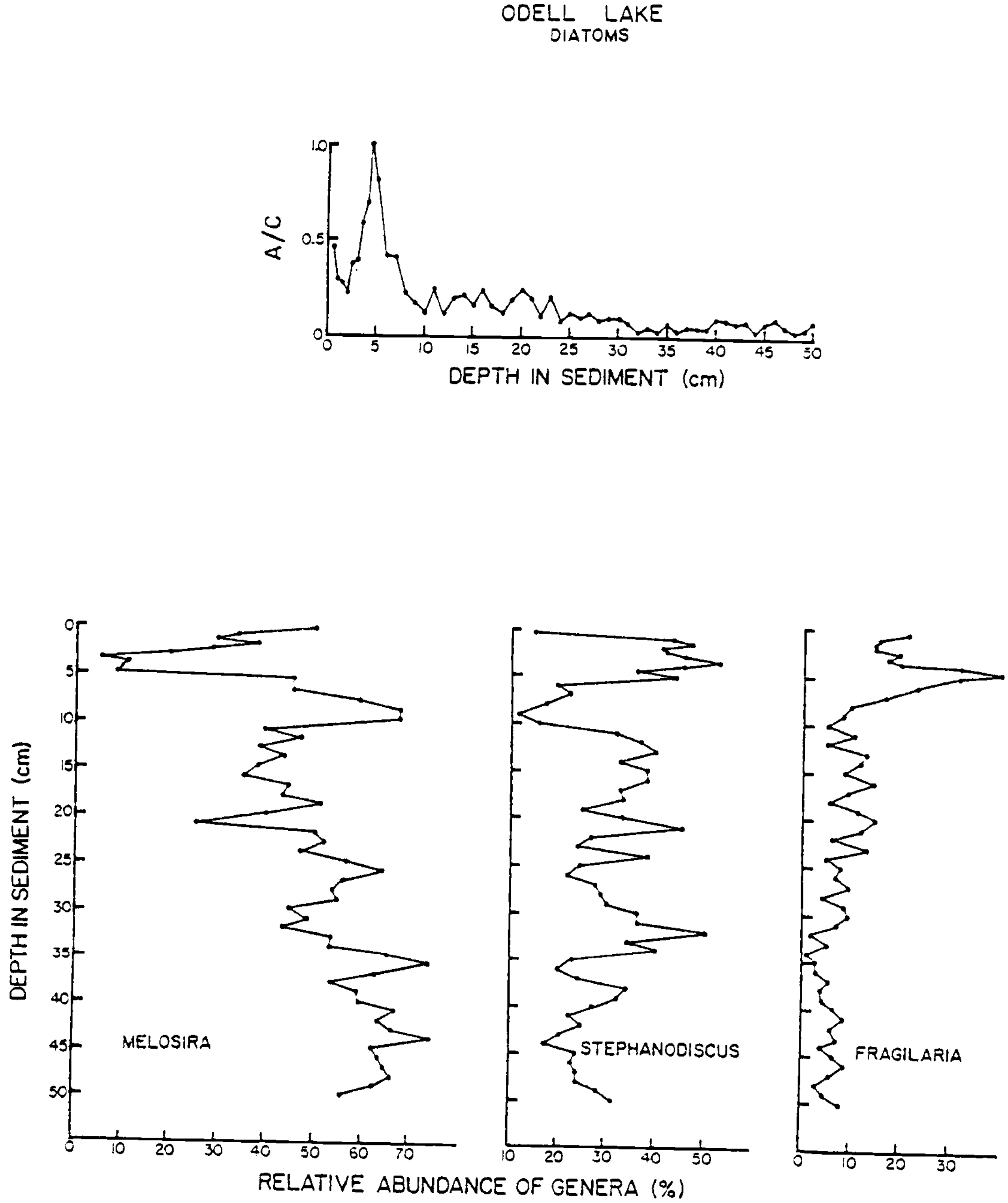

Figure 8. A/C (Araphidineae/Centrales) ratio of Stockner and Benson (1967) and relative abundance of some important genera in a sediment core taken at a depth of 86m in Odell Lake.

shown to be closely correlated to trophic changes in lakes. The index for Odell Lake sediments suggest that the lake has increased in productivity, peaked in trophic status, and recovered to an intermediate level. According to the scale assigned to this index, Odell Lake has only barely reached mesotrophic status (A/C=1).

Information concerning the changes in the diatom community were provided by analyses of the relative abundance of genera (Figure 8). The planktonic fossil diatoms were dominated by three genera, Melosira, Fragilaria, and Stephanodiscus. Melosira showed an overall decline in relative abundance up to the 10cm stratum, an increase to the 9cm level, and then a decrease to a minimum near the 3.5cm stratum. Above this level Melosira increased in abundance. The abundance of Stephanodiscus increased to the 13cm stratum and then decreased to a minimum at 9cm. Above this stratum, the abundance of Stephanodiscus increased and peaked at 3.5cm. The abundance of Fragilaria maintained a stable profile up to the 10cm layer but then it increased to the 4.5cm stratum. Above 4.5cm, the abundance of Fragilaria declined to an intermediate level. Not shown in Figure 8 are profiles for Asterionella and Tabellaria. The abundance of Asterionella increased gradually from 25cm and reached a maximum near 3.5cm. Above this stratum its abundance declined. Tabellaria appeared for the first time at 22cm and was found sporadically up to 7cm. Above 7cm, this genus consistently occurred and its abundance peaked at 4.5cm. Profiles of periphytic genera show these diatoms are evenly distributed throughout the core and are not involved in any major fluctuations.

Concurrent with shifts in genera were changes in species dominance (Table 8). Melosira granulata, Stephanodiscus astraea, and Melosira italica were almost equally dominant in strata below 12cm. Above this layer, there was a substantial increase in abundance of Melosira granulata, a mesotrophic to eutrophic species. Accompanying this increase was a decrease in abundance of Stephanodiscus astraea, primarily the oligotrophic variation minutula, and Melosira italica, another oligotrophic species. The relative abundance of Melosira decreased with concurrent increases in the relative abundance of Fragilaria and the larger form of Stephanodiscus. Fragilaria crotonensis, which was not abundant below the 10cm stratum, is a mesotrophic to eutrophic species which probably responded to enrichment of Odell Lake. Also responding were Asterionella formosa and Tabellaria fenestrata. The drop in nutrient status of this lake is indicated above 4.5cm. The rapid decline in Fragilaria crotonensis and Asterionella formosa and return to dominance of Melosira italica and Stephanodiscus astraea variation minutula above the 4.5cm stratum suggests a drop in the trophic status of the lake.

Table 8. The three dominant species of diatoms, listed in order of abundance, in different strata of an Odell Lake sediment core.

Depth from sediment surface (cm)	1	2	3
0.5	Melosira italica	Melosira granulata	Stephanodiscus astraea
1	Stephanodiscus astraea	Melosira italica	Melosira granulata
3	Stephanodiscus astraea	Melosira italica	Fragilaria crotonensis
4	Stephanodiscus astraea	Fragilaria crotonensis	Asterionella formosa
4.5	Fragilaria crotonensis	Stephanodiscus astraea	Asterionella formosa
5	Stephanodiscus astraea	Fragilaria crotonensis	Asterionella formosa
7	Melosira granulata	Stephanodiscus astraea	Melosira italica
10	Melosira granulata	Melosira italica	Stephanodiscus astraea
12	Stephanodiscus astraea	Melosira granulata	Melosira italica
15	Stephanodiscus astraea	Melosira granulata	Melosira italica
20	Stephanodiscus astraea	Melosira granulata	Melosira italica
25	Melosira granulata	Stephanodiscus astraea	Melosira italica
30	Stephanodiscus astraea	Melosira granulata	Melosira italica
35	Melosira granulata	Stephanodiscus astraea	Melosira italica
40	Melosira granulata	Stephanodiscus astraea	Melosira italica
50	Melosira granulata	Stephanodiscus astraea	Melosira italica

Information concerning the physical, chemical, and biological characteristics of the sediment cores becomes even more meaningful when related to human activities in the watershed and records of lake productivity. The first cabins were built at the lake in the late 1920's, and by 1937, the majority of the cabins had been built. In 1925, Southern Pacific Railroad layed tracks along the south-west side of the lake. By 1937, Trapper Creek Campground had been constructed (U.S.N.F.S., 1976). An all weather road, which connected the lake with the Willamette Valley (Newcomb, 1941), was completed by 1940. In 1940, the pH of Odell Lake was circumneutral, the oxygen profile was orthograde, and bottom fauna were not abundant (Newcomb, 1941). Newcomb (1941) rated the lake as oligotrophic.

Use of the lake increased after World War II and the lake became very popular in the early to middle 1950's (Atkinson, personal communication, 1976). By that time, Sunset Campground had been constructed (U.S.N.F.S., 1976). The campgrounds, two resorts, and sixty-seven cabins around the lake had only pit toilets and septic tanks with drainfields. Although all toilet facilities were at least thirty meters from the shoreline, substantial quantities of nutrients undoubtedly leached through the highly permeable soil into the lake.

Sediment characteristics below the 20cm stratum indicate a period of trophic stability. Increased phosphorus content of strata between 15cm and 10cm (Table 7) may have resulted from increased soil erosion associated with construction of the railroad and highway. Calculations of the age of the 10cm stratum indicated the eutrophic diatoms increased in abundance (Table 8 and Figure 8) in the middle 1950's.

In the 1960's visitor use increased (Atkinson, personal communication, 1976) and the number of toilets per campground was increased (U.S.N.F.S., 1976). Consequently, the amount of nutrients reaching the lake presumably increased. A program to vault all of the campground pit toilets was initiated in 1965 and all vaults were pumped after 1969 (U.S.N.F.S., 1976). In the 1960's, algal blooms were observed for the first time (Larson, 1970a). "Heavy" blooms were observed in 1967 (Atkinson, personal communication, 1976) and 1968 (McHugh, 1972). The 1968 bloom consisted almost entirely of Anabaena spiroides (McHugh, 1972). Algal production was probably greatest during the summers of 1967 and 1968.

Corresponding to these apparent changes in productivity were changes in the characteristics of the sediments. Percentages of dry weight decreased possibly because detritus from algal blooms was unconsolidated. Percentage organic matter and SCDP may have increased because detritivores, and bacteria were able to only partially degrade these materials. Diatom changes showed that the algal community responded to the shifts in nutrient input (Figure 8 and Table 8). All indices, except total phosphorus and total organic nitrogen, showed maxima near the 4.5cm stratum, a layer dated around 1967. Increases in concentrations of sediment characteristics in the top two centimeters probably can be attributed to incomplete diagenesis (Shapiro et al., 1971).

Lake productivity appears to have declined since 1968, presumably because of the vaulting of toilets and the consequent reduction in the availability of nutrients. Transparency of the lake water has increased progressively and zooplankton abundance has declined steadily in recent years (Lewis, 1974). The recent reduction in the trophic status of the lake was mirrored in the characteristics of the sediments. There have been increases in percentage dry weight and decreases in percentage organic matter, SCDP, and the A/C ratio. Furthermore, species of oligotrophic diatoms have increased in abundance in the surface sediments (Table 8).

Diamond Lake

Percentage dry weight, percentage organic matter, SCDP, total phosphorus, total organic nitrogen and diatom assemblages were recorded for the core taken from the deep portion (15m) of the lake. The sediment was light brown.

Percentage dry weight declined between 30cm and 22cm (Figure 9). The dry matter per unit volume at the 22cm stratum was only two-thirds of that found at the 30cm stratum. The decrease in percentage dry weight coincided with an increase in organic matter. This may reflect a reduction in sediment consolidation associated with an increased sedimentation rate and decreased compaction of frustules and detritus. Direct evidence for assigning dates to particular sediment layers was not available. Volcanic ash, forest fire ash, and cryptic laminations were not found in the sediment.

Concurrent to the increase in percentage organic matter was an increase in SCDP, total organic nitrogen and total phosphorus (Figure 9). Below the 30cm level, values of these characteristics remained relatively constant. Above 30cm, the percentage of organic matter increased to almost 25 percent near the sediment surface. Between the 30cm and 20cm strata, both SCDP measures increased to relatively stable levels. Total nitrogen values also increased above 30cm. Values of total phosphorus showed a slight increase above 30cm.

The species of diatoms found in surface (1cm) sediments and the distribution and abundance of genera were recorded for the Diamond Lake core (Table 9). The planktonic forms of diatoms were most abundant in all strata, never comprising less than 79 percent. Nitzschia, Navicula,

DIAMOND LAKE

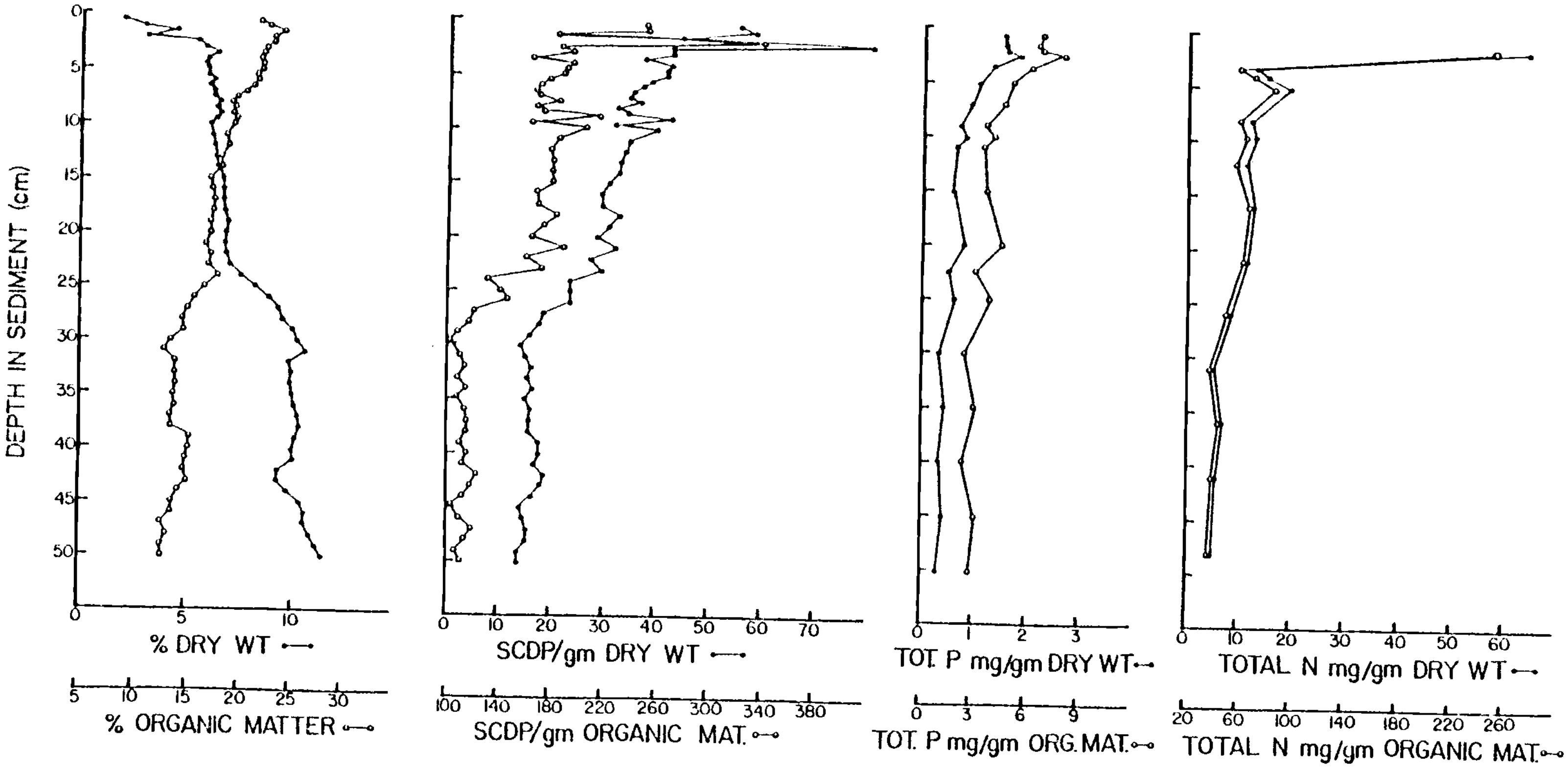

Figure 9. Physical and chemical profiles of a Diamond Lake sediment core taken at a depth of 15 meters.

Table 9. Species of diatoms recorded for the surface (1 cm) sediments and the distribution and abundance of genera in a Diamond Lake core.

Fragilariales

Asterionella formosa (0-3.8,73)[a]

Diatoma sp. [1][b] (0-0.2,2)

Fragilaria brevistriata (57-86.9,100)
var. capitata*
F. capucina var. mesolepta
F. construens var. construens
var. venter*
F. crotonensis var. oregona
F. leptostauron var. dubia*
F. pinnata var. lancettula

Meridion sp. [1] (0-0.2,2)

Opephora martyi (0-1.4,25)
var. martyi

Synedra cyclopum (0-1.1,35)
robustum*
S. mazamaensis var. mazamaensis
S. parasitica
var. subconstricta*
S. ulna var. ulna
var. danica

Eupodiscales

Melosira granulata (0-4.6,67)
M. granulata var. angustissima

Stephanodiscus astraea (0.9-23.1,100)
S. astraea var. intermedia*
var. minutula*
S. niagarae

Achnanthales

Achnanthes exigua (0-3.9,84)
var. [1]
A. lanceolata var. lanceolata

Cocconeis placentula (0-1.9,85)
var. euglypta
C. rugosa

Rhoicosphenia curvata (0-1.5, 20)

Naviculales

Amphora ovalis (0-0.4,16)

Cymbella cuspidata (0-1.5,71)
C. turgida

Diploneis sp. [1] (0-0.2,6)

Gomphonema rhombicum (0-0.6,27)

Navicula aurora (1.1-10,100)
N. cuspidata var. cuspidata*
N. pupula var. rectangularis*
N. radiosa
Navicula spp. [2]

Neidium iridis* (0-0.2,6)

Pinnularia braunii* (0-1.5,75)
Pinnularia sp. [1]

Stauroneis anceps (0-0.2,2)
var. gracilis*

Bacillariales

Epithemia zebra (0-0.9,22)
var. porcellus*

Nitzschia amphibia (1.6-13.5, 100)
N. frustulum
N. lancettula
Nitzschia sp. [2]

Surirellales

Cymatopleura sp. [1] (0-0.2,4)

[a] Range in percent relative abundance of genus for all strata, percent occurrence of the genus in all strata ( ).

[b] Number of species or varieties which could not be identified [ ].

*Not previously recorded from this lake.

and *Achnanthes* were the only abundant periphytic diatoms. Only a few species and variations listed (Table 9) were not previously recorded for this lake. Sovereign (1958) has published a much more complete list of diatoms found in Diamond Lake.

Information on the trophic requirements of the kinds of diatoms found in the surface sediments of Diamond Lake indicate that this lake was mesotrophic or eutrophic. *Fragilaria* was more abundant than other genera in the sediment core. The species *F. crotonensis*, *F. construens*, and *F. pinnata* are commonly found in mesotrophic to eutrophic waters (Lowe, 1974; Patrick and Reimer, 1966; and Stockner and Benson, 1967). *Fragilaria capucina* was listed by Palmer (1969) as being tolerant of pollution. *Fragilaria construens* variation *venter* was reported by Lowe (1974) to prefer mesotrophic to oligotrophic waters. Other planktonic diatom forms, *Asterionella formosa*, *Synedra ulna* variation *ulna*, and *Melosira granulata* and variation *angustissima*, are also listed as preferring or tolerant of mesotrophic and/or eutrophic waters (Lowe, 1974; Patrick and Reimer, 1966; Palmer, 1969; and Stockner and Benson, 1967). Only *Stephanodiscus astraea* variation *minitula* and *S. niagarae* can be considered truly oligotrophic plankton (Rawson, 1956; and Stockner and Benson, 1967). The attached forms were dominated by the genus *Nitzschia*, commonly considered to prefer eutrophic waters (Lowe, 1974) and to be pollution tolerant (Palmer, 1969).

Profiles of the A/C ratio and the abundance of diatom genera (Figure 10) indicate that the lake has remained at an advanced trophic state throughout its recent history. Fragilaria was dominant in all strata of the core and partially accounted for the change in the A/C ratio between the 25cm and 21cm strata. The abundance of Fragilaria was greatest near the 18cm stratum and decreased slightly above 4cm. The abundance of Stephanodiscus generally fluctuated at moderate levels in strata below 25cm. Its abundance decreased above this stratum. The abundance of Navicula and Nitzschia decreased somewhat above the 25cm stratum.

Changes in the order of abundance of the three dominant species of diatoms (Table 10) helped to document changes that occurred in the trophic conditions of the lake. The eutrophic diatom Fragilaria crotonensis was never found below the 37cm stratum and was ranked as a dominant species above the 25cm stratum. Another eutrophic species, Fragilaria construens, was ranked as a dominant species in many strata. The oligotrophic diatom Stephanodiscus astraea, mostly the variation minutula, was not recorded as a dominant species above the 25cm stratum.

Changes in characteristics of the Diamond Lake sediment strata become more meaningful when they are correlated with records of human activities in the watershed. Stable

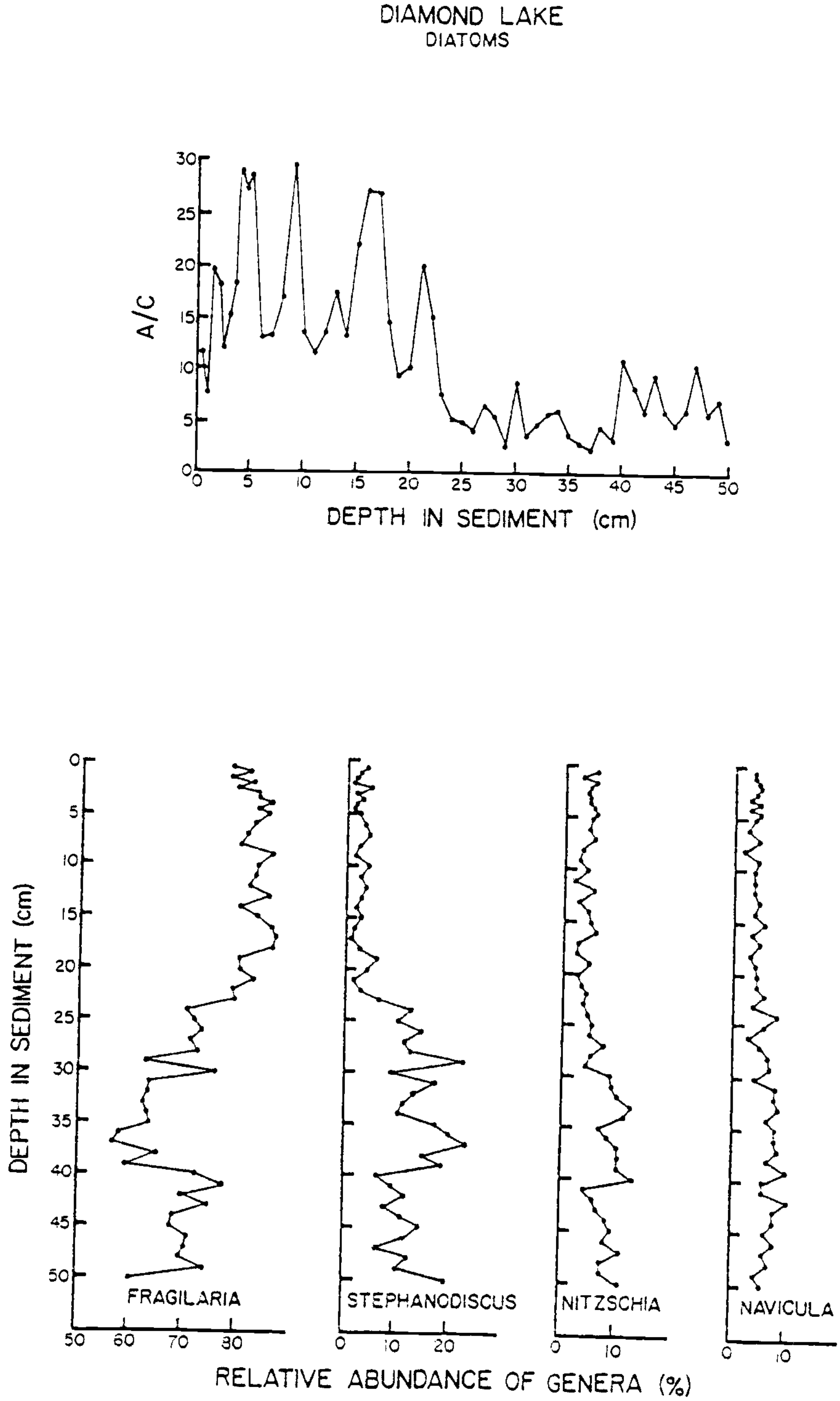

Figure 10. A/C (Araphidineae/Centrales) ratio of Stockner and Benson (1967) and relative abundance of some important genera in a sediment core taken at a depth of 15m in Diamond Lake.

Table 10. The three dominant species of diatoms, listed in order of abundance, in different strata of a Diamond Lake sediment core.

Depth from sediment surface (cm)	1	2	3
0.5	Fragilaria leptostauron	Fragilaria crotonensis	Fragilaria construens
5	Fragilaria leptostauron	Fragilaria crotonensis	Fragilaria construens
10	Fragilaria leptostauron	Fragilaria crotonensis	Fragilaria construens
15	Fragilaria leptostauron	Fragilaria crotonensis	Fragilaria construens
20	Fragilaria leptostauron	Fragilaria crotonensis	Fragilaria construens
25	Fragilaria crotonensis	Fragilaria leptostauron	Stephanodiscus astraea
30	Fragilaria leptostauron	Fragilaria brevistriata	Stephanodiscus astraea
35	Fragilaria leptostauron	Fragilaria brevistriata	Stephanodiscus astraea
40	Fragilaria leptostauron	Fragilaria construens	Stephanodiscus astraea
50	Fragilaria leptostauron	Fragilaria construens	Stephanodiscus astraea

values of percentage dry weight, percentage organic matter, and SCDP for strata below the 30cm stratum suggest the lake has been in trophic equilibrium. Because of the lack of any other evidence to date layers of the core, it shall be assumed that human activities in the watershed were the direct cause of the initial changes, near 30cm, in physical chemical, and biological profiles. Use of the 30cm stratum as a marker for the first date (around 1930) of significant human activity in the watershed permitted calculation of the sedimentation rate. Adjustment of the rate on the basis of changes in dry weight resulted in a value of 4.3mm per year. Pennington (1973) reported sedimentation rates greater than 5mm per year in a eutrophic English lake.

The first major human activity in the watershed of Diamond Lake was probably initiated in the late 1920's and early 1930's when a resort and private cabins were built (Martin, personal communication, 1976). Public use of the lake steadily increased to many hundreds of thousands of visitor days by the middle 1950's (Martin, personal communication, 1976). By this time most of the 102 summer homes and cabins in the watershed had been built. Since then, visitor use has remained comparably high (Sanville and Powers, 1971). In 1966, a project was undertaken to construct a sewage interceptor system and treatment facility (Sanville and Powers, 1971). Until this time and for some time thereafter, pit toilets and septic tanks with drainfields were common (Bauer, personal communication, 1976). The treatment facility, which is not located in the watershed, and the sewage collector system were partially functional by 1971 (Sanville and Powers, 1971) and completed in 1975 (Powers, personal communication, 1976). This new facility was not designed to serve the complex of summer homes and personal residences on the western shore of the lake. There, unimproved septic systems still exist (Martin, personal communication, 1976; and McHugh, 1972).

Evidence for an increase in the productivity of Diamond Lake was a decrease in the percentage dry weight and increases in SCDP and total organic matter. The increase in abundance of diatoms indicating eutrophic conditions and in the A/C ratio also provide evidence of change. Sedimentation rate presumably increased as a result of increased production. This is reflected in the larger percentage change of SCDP per gram _dry weight_ as compared to the percentage change of SCDP per gram _organic matter_. Autochthonus material comprised a greater proportion of the sediment and, in effect, diluted the allochthonus material. Although it may be speculated that detritivores and bacteria may not have been capable of reducing the SCDP per gram organic matter to levels observed in deeper strata of the core, a larger percentage change was measured for SCDP per gram _dry weight_ than per gram _organic matter_. Decreases in the abundance of the littoral genera _Nitzschia_ and

Navicula, add evidence for an increase in the sedimentation rate.

During the period before the sewage facility was completed, large amounts of nutrients were presumably leached from toilet facilities through extremely porous soils into the lake. High phosphorus concentrations in the oxygen-depleted hypolimnion probably also insured high limnetic production after each overturn. Release of phosphorus from the sediment would account for the high hypolimnetic phosphorus concentration reported by Sanville and Powers (1971) and would explain the relatively minor increase in the concentration of phorphorus in the strata above 30cm.

Considering the rapid response to cultural enrichment and the rapid rate of "volume replacement" (Table 3), the productivity of the lake might have been expected to decline even before completion of the sewage interceptor system. However, dramatic decreases probably will not occur. Considerable cultural enrichment still exists. Flocks of sheep are grazed in the watershed (Martin, personal communication, 1976). It has been estimated that as much as 900 kilograms of soft cheese (fish bait) is thrown into Diamond Lake in less than a week during fishing season (McHugh, 1972). Also, unimproved toilet facilities still exist in many residences. Eventually, lake productivity will presumably decrease as a result of the sewage treatment and a new intermediate trophic status may be reached.

The decrease noted in the A/C ratio in surface sediments (Figure 10) may indicate the beginning of this trend.

Devils Lake

Four cores were taken from the sediments of Devils Lake at depths of 6m, 5m, 3.5m, and 3m. Sample locations are given in Figure 4. All sediment in the cores was dark brown and left rust colored stains on the plastic coring tubes. All of the cores were X-ray photographed and their strata analyzed for percentage dry weight and percentage organic matter. The strata of the 6m and 5m cores were analyzed for SCDP. Total phosphorus and total organic nitrogen were measured in the strata of the 6m core. Sediments from the 6m core were prepared and mounted on microscope slides for analysis of diatom assemblages. All data presented are based upon the 6m core (Figure 11). Variations between cores for appropriate profiles will be discussed.

There were only small variations between most cores in percentage organic matter and percentage dry weight. Percentage dry weight in all the cores was approximately 15 percent. There was a decrease in percentage dry weight near the sediment surface (Figure 11). Profiles of percentage organic matter were vertical (Figure 11) and ranged from 22 percent to 25 percent in three cores.

DEVILS LAKE

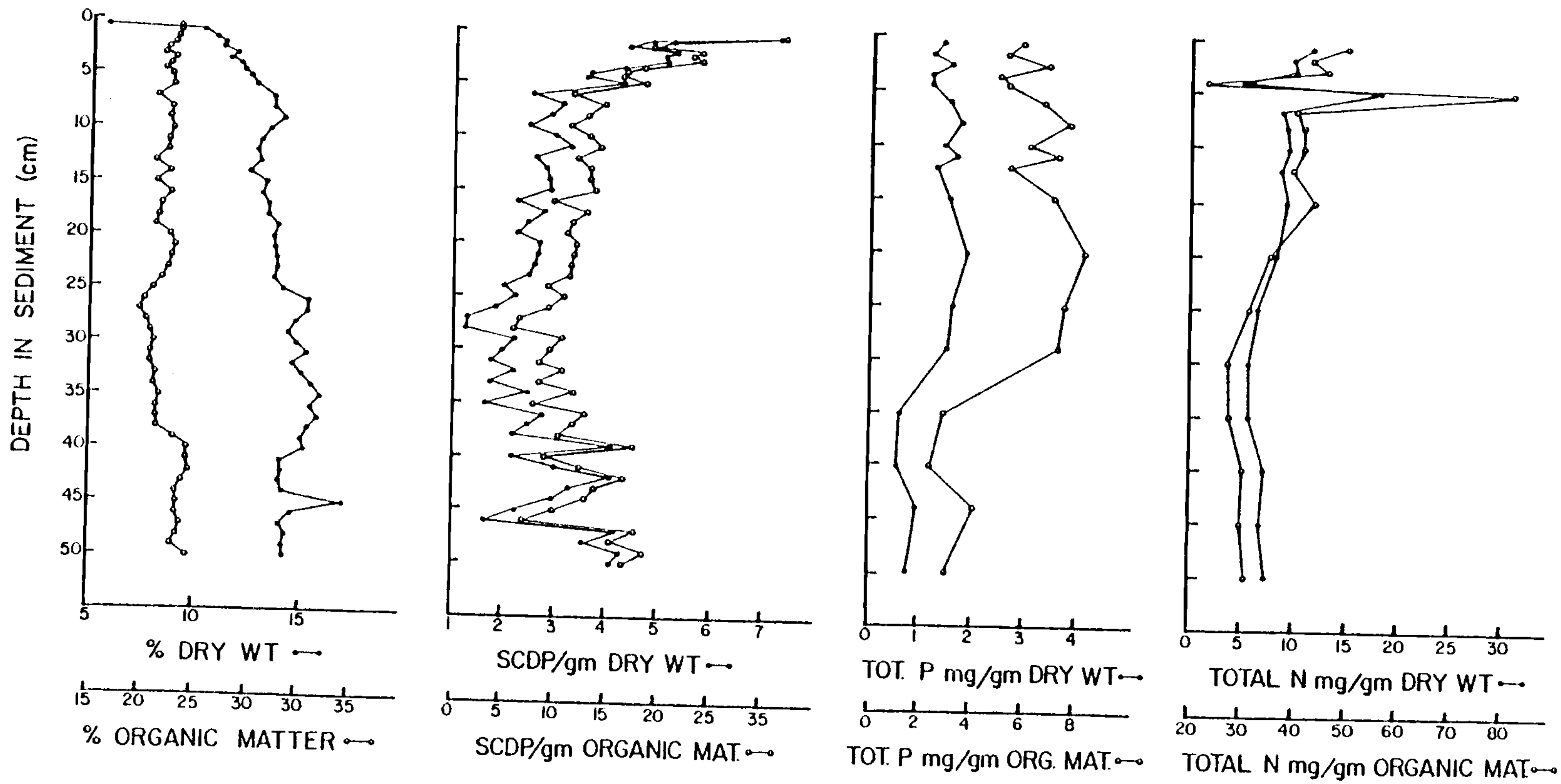

Figure 11. Physical and chemical profiles of a Devils Lake sediment core taken at a depth of 6 meters.

Percentage organic matter in the 3.5m core was constant at 10 percent. This large difference cannot be explained satisfactorily.

Specific strata in these cores could not be dated. Visual inspection revealed no obvious layers of foreign material. X-ray photographs showed no cryptic laminations.

Profiles of SCDP per gram dry weight and per gram organic matter varied little. Only near the sediment surface did values of SCDP increase significantly (Figure 11). SCDP profiles from the 5m core were vertical, showed no perturbations, and closely matched the values of the profiles in Figure 11.

Profiles of total phosphorus and total organic nitrogen showed differences not apparent in profiles of other characteristics. Total phosphorus increased in strata between 35cm and 30cm. Total organic nitrogen increased above 30cm. These increases may have resulted from the presence of refractory materials in the sediments.

Only a few diatoms were found in the 6m core. The surface (1cm) sediments contained the greatest number of whole and fragmented diatom frustules (197 were found on the prepared slides). Most of these frustules were *Stephanodiscus dubius*, a eutrophic species (Lowe, 1974). Only fragments of frustules of *Melosira granulata*, *Cocconeis*, *Fragilaria*, *Navicula*, *Raphoneis*, *Asterionella*, and *Opephora* frustules were found in subsurface portions of the core. Melosira granulata, Melosira varians, and Surirella guatemalensis were found in the water column by McHugh (1972).

The combination of mixing, continuous oxidizing conditions, and rapid diagenesis may account for the extremely vertical organic matter profile and the low SCDP values in the sediments. Wind induced currents and the presence of large numbers of freshwater bivalves and other benthic organisms probably contribute to the mixing of the sediment. Although the organic matter in the sediment could have been derived from submerged vegetation, the SCDP profiles do not support this contention.

Profiles of total phosphorus and total organic nitrogen provide the only evidence that the watershed has been disturbed. Concentrations of these materials generally increased above the 35cm stratum. Yet it is impossible to interpret whether these changes were responses to the first settlement of the watershed, personal residences being built on the shoreline, a golf course being built in the watershed, livestock grazing in the watershed, or release of poorly treated sewage directly into the lake. No change in these sediment characteristics was found to correspond to the date when this sewage disposal practice was stopped, 1970.

The watershed of Devils Lake has undergone many changes, yet surprisingly little can be interpreted from the profiles of sediment characteristics. This may be a result of lake features such as the high rate of volume replacement (0.37 year), extensive benthos, large community of bacteria (McHugh, 1972), continuous mixing, and large stands of submergent vegetation. All of these factors may significantly influence the sediment stratigraphy. Although the lake is now eutrophic (Kavanagh, 1973; and McHugh, 1972), total phosphorus and total organic nitrogen profiles indicate that the lake may have received a smaller nutrient load in the past.

DISCUSSION

Study of sediment profiles can reveal the magnitude and the rate of changes in the trophic status of lakes. By correlating profiles of sediment characteristics with historic information on lakes and their watersheds, direct comparisons of sediment characteristics between lakes can be made. Also, judgements can be made concerning the value of each characteristic.

The organic content of the sediments of the lakes in this study did not appear to be as closely related to the trophic conditions of the lakes as did the sedimentation rate of organic matter. Sedimentation rates of organic matter for Waldo Lake, Odell Lake, and Diamond Lake were estimated to be 1.5 $gm/m^2/year$, 48 $gm/m^2/year$, and 108 $gm/m^2/year$, respectively. These rates characterize well the differences between the ultra-oligotrophic, oligotrophic-mesotrophic, and eutrophic lakes. This comparison may be tenuous to the extent that the origins of the organic matter are unknown. Mackereth (1965) regarded lake sediments as the accumulated debris derived from the soil drainage system with minor additions from the lake biota, whereas Frey (1974) stated that organic matter found in the sediments can originate within or from outside lakes.

Most organic matter in the sediments of lakes in this study may have originated autochthonously. This is supported by similarities in profiles or organic matter, SCDP, and diatom assemblages for the mountain lakes. Poor soils in the watersheds of the mountain lakes also suggest autochthonous origin of the organic matter. The origin of the organic content of Devils Lake sediments cannot be deduced. However, contributions of macrophytes to the organic content of the sediments may have been significant.

Analysis of concentrations of organic matter in sediments of the lakes of different trophic status is revealing. Organic content per gram dry weight of sediment is by far the highest in the ultra-oligotrophic Waldo Lake. This lake is very deep and its waters have a high oxygen content so any labile organic matter produced in the lake presumably would be oxidized to insignificant amounts. High concentrations of organic matter may be related to the very low water temperature in that bacterial activity is directly correlated to temperature (Hargrave, 1969). In addition, the numbers of bacteria in the water column are very small. Therefore, degradation of autochthonous material could be incomplete. Also, the volume replacement time of Waldo Lake is slower than that of the other lakes in this study. Because of this, the loading rate of allochthonous mineral matter may have been reduced resulting in an increased concentration of organic matter.

Odell Lake is deep, well oxygenated and slightly warmer than Waldo Lake. It is much more productive than Waldo Lake and probably supports a larger bacterial population. Odell Lake sediments have been degraded to a much lower concentration of organic matter than those in Waldo Lake. Also, the volume replacement time for Odell Lake is almost four times faster than for Waldo Lake resulting in a greater loading rate of silt.

The organic content of Diamond Lake sediments is only slightly greater than that of Odell Lake in the sediment strata predating human activities (presumably 50cm to 30cm). Diamond Lake has a larger watershed and faster volume replacement time than Odell Lake presumably resulting in a greater loading rate of silt. The sediments of the more productive Diamond Lake contain slightly more organic matter than do the sediments of Odell Lake presumably because there is a greater dilution of the silt load with organic materials.

Odell Lake and Diamond Lake responded differently to human activities and increased nutrient loading. Although Odell Lake showed increases in productivity, the concentration of organic matter in the sediments remained at low levels. This may have resulted from the oxidation of this material in the deep oxygen rich lake. Productivity of the shallow Diamond Lake also increased but because of a decreased supply of oxygen, organic materials were not fully degraded and accumulated in the sediments.

Percentage dry weight of the sediments, another qualitative indicator, changed with changes in productivity. Percentage dry weight decreased with increased productivity in both Odell Lake and Diamond Lake. Pennington (1943) made the same observation for the deep water sediment of the north basin of Lake Windermere. She noted that a decrease in percentage dry weight corresponded to an increase in the abundance of *Asterionella*, an event correlated to human activities in the watershed.

Concentrations of SCDP showed a varying ability to indicate trophic changes in the lakes studied. In holomictic Devils Lake, changes in concentrations of SCDP could not be correlated to changes in any other sediment characteristics, whereas changes in concentrations of SCDP in Odell Lake and in Diamond Lake reflected those of other sediment characteristics. High concentrations of SCDP in Waldo Lake were related to the occurrence of moss in the sediments.

Changes in profiles of total phosphorus and total organic nitrogen, under some circumstances, may be related to watershed disturbances and lake productivity. An increase in total phosphorus concentration in the sediments of Odell was probably a result of the construction of a railroad and highway. Concentrations of total organic nitrogen in the sediments of Diamond Lake increased as the productivity of the lake apparently increased. Increases in concentrations of total phosphorus and total organic nitrogen in the sediments of Devils Lake could not be related to specific watershed disturbances or trophic changes of the lake. Certainly the decline in total phosphorus per gram dry weight in the Waldo Lake core profile appeared to represent a drop in watershed fertility.

Diatom indicator species and the A/C ratio may be the most sensitive to trophic changes of all parameters measured in this study. Shifts in species dominance and abundance of genera gave clear indications of trophic changes in Odell Lake and Diamond Lake. Waldo Lake fossil diatoms showed this water body to have a stable oligotrophic history. Diatom records are not always found. Very few diatoms were found in Devils Lake sediments. Possibly the absence of diatoms is as informative as their presence, but further study of such situations is necessary.

Trophic equilibrium, as indicated in the sediments, is determined by the nutrient supply characteristic of the watershed, physical factors which effect production, and production itself. Furthermore, the equilibrium indicated in the sediments incorporates loading of resistant mineral matter and diagenic efficiency. Changes in any of these equilibrium conditions may be indicated in lake sediments. Yet these changes may be recorded at different rates. In

Odell Lake, shifts in the composition of the sensitive diatom community occurred before changes in organic matter. In shallow Diamond Lake, increased concentrations of organic matter occurred in the sediments even before the composition of the sensitive diatom community changed. For lakes with watersheds of similar edaphic characteristics, it may be surmised that the capacity of the lakes to process organic matter is indicative of their trophic stability.

When consideration is given profiles of sediment characteristics, a meaningful succession of events can be described. Powerful explanation can be found when paleolimnological data are combined with certain limnological data and historical records of watershed disturbances. With all this information for a particular lake system, it is not only possible to determine the trophic history of a lake, but it may be possible to estimate future trends in productivity.

BIBLIOGRAPHY

Atkinson, E. 1976. Marina owner for 37 years at Odell Lake. Retired. Personal communication. Odell Lake, Oregon. April 8.

American Public Health Association. 1971. Standard methods for the examination of water and wastewater. 13th edition. New York. APHA. 874 p.

Bauer, J. 1970. Fishery biologist for Oregon Department of Fish and Wildlife. Personal communication. Roseburg, Oregon. April 2.

Bortleson, G.C. and G.F. Lee. 1972. Recent sediment history of Lake Mendota, Wisconsin. Environmental Science and Technology 6:799-808.

Cowgill, U.M. and G.E. Hutchinson. 1970. Chemistry and minerology of the sediments and their source materials. (In) Ianula: An account of the history and development of the Lago di Monterosi, Latium, Italy. Transactions of the American Philosophical Society 60:37-101. (cited in Hutchinson, 1973).

Curtis, J. 1975. Willamette National Forest Ranger. Personal communication. Oakridge, Oregon. November 7.

Edmondson, W.T. 1975. Microstratification of Lake Washington sediments. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 19: 770-775.

Edmondson, W.T. and G.G. Winberg. 1971. A manual on methods for the assessment of secondary productivity in fresh waters. IBP Handbook no. 17. International Biological Program. 358 p.

Frey, D.G. 1974. Paleolimnology. Mitteilungen Internationale Vereinigung für Theoretische and Angewandte Limnologie 20:95-123.

Hargrave, B.T. 1969. Epibenthic algae production and community respiration in the sediments of Marion Lake. Journal of the Fisheries Research Board of Canada 26:2003-2026.

Harward, M.E. 1976. Soils scientist at Oregon State University. Personal communication. Corvallis, Oregon. March 24.

Harward, M.E. and C.T. Youngberg. 1969. Soils from Mazama ash in Oregon: Identification, distribution and properties. Pedology and Quarternary Research Symposium. University of Alberta, Edmonton, Alberta Canada. 163-178 p.

Hustedt, F. 1930. Bacillariophyta (Diatomeae). (In) A. Pascher (editor) Die Süsswasser-flora Mitteleuropas. Volume 10. Gustav Fischer. Jena. 466 p.

Hutchinson, G.E. 1957. A treatise on limnology. Volume 1. John Wiley and Sons, Inc. 1015 p.

Hutchinson, G.E. 1973. Eutrophication: The scientific background of a contemporary practical problem. American Scientist 61:269-279.

Hutchinson, G.E. and A. Wollack. 1940. Studies on Connecticut Lake sediments. II. Chemical analysis of a core from Linsley Pond. American Journal of Science 238: 493-517. (cited in Hutchinson, 1973).

Kavanagh, R.C. 1973. A comparative analysis of four Oregon coastal lakes on the basis of description, trophy, and density-dependent functions. M.S. thesis. Oregon State University. Corvallis, Oregon. 117 p.

Larson, D. 1976. Soils of the Deschutes National Forest. U.S. National Forest Service. (photocopy-manuscript).

Larson, D.W. 1970a. On reconciling lake classification with the evolution of four oligotrophic lakes in Oregon. Ph.D. thesis. Oregon State University. Corvallis, Oregon. 145 p.

Larson, D.W. 1970b. Limnological studies on lakes in the Deschutes National Forest, Oregon: Odell Lake. Water Resources Research Institute Publication. 34 p.

Larson, D.W. and J.R. Donaldson. 1970. Waldo Lake, Oregon: A special study. Water Resources Research Institute Publication. 21 p.

Larson, G.L. 1975. Sand content of the sediments in three sand dune lakes in Oregon, U.S.A. Archiv für Hydrobiologie 75:240-252.

Lewis, S. 1974. Population dynamics of kokanee salmon in Odell Lake. Oregon Wildlife Commission Report. Project no. F-71-R. 31 p.

Lewis, S. 1975. Evaluation of the kokanee fishery and hatchery releases at Odell Lake, 1964-1975. Oregon Department of Fish and Wildlife Report. Project no. F-71-R. 26 p.

Lewis, S. 1976. Fishery biologist for the Oregon Department of Fish and Wildlife. Personal communication. Corvallis, Oregon. March 23.

Lowe, R.L. 1974. Environmental requirements and pollution tolerance of freshwater diatoms. U.S. Environmental Protection Agency Report no. EPA-670/4-74-005.

Lyford, J. 1975. Professor of biology at Oregon State University. Personal communication. Corvallis, Oregon. September 28.

Mackereth, F.J.H. 1965. Chemical investigation on lake sediments and their interpretation. Proceedings of the Royal Society of Britain 161:295-309.

Malueg, K.W., J.R. Tilstra, D.W. Schults, and C.F. Powers. 1972. Limnological observations on an ultra-oligotrophic lake in Oregon, U.S.A. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 18:292-302.

Martin, D. 1976. U.S. National Forest Service Ranger, Umpqua National Forest. Personal communication. Corvallis, Oregon. April 10.

McHugh, R.A. 1972. An interim study of some physical, chemical, and biological properties of selected Oregon lakes. State of Oregon Department of Environmental Quality Report. 109 p. (mimeographed).

Newcomb, H.R. 1941. A biological investigation of forty lakes of the upper Deschutes River watershed in Oregon. State of Oregon Game Commission Lake Survey Report no. 1. 207 p. (mimeographed).

Nipkow, F. 1927. Über das Verhalten der Skelette Planktischer Kieselalgen im geschichteten Tiefenschlamm des Zurich und Baldenggersees. Schweiz Z. Hydrol. 4:71-120. (cited in Stockner and Benson, 1967).

Ohle, W. 1972. Die Sedimente des GroBen Plöner Sees als Dokumente der Zivilisation. Jahrb. f. Heimatkunde (Plön) 2:7-27. (cited in Frey, 1974).

Oregon State Game Commission. 1946. Diamond Lake: Lake survey map no. 400. Portland, Oregon.

Oregon State Game Commission. 1953. Devils Lake: Lake survey map no. 920. Portland, Oregon.

Oregon State Game Commission. 1958. Waldo Lake: Lake survey map no. 1014. Portland, Oregon.

Oregon State Game Commission. 1964. Odell Lake: Lake survey map no. 1274. Portland, Oregon.

Oregon State Water Resources Board. 1964. Middle-coast drainage basin map no. 18.8. Salem, Oregon.

Orion Research Incorporated. 1974. Orion ammonia electrode manual. Orion Research, Inc. Cambridge, Massachusetts. 24 p.

Patrick, R. and C.W. Reimer. 1966. The diatoms of the United States. Philadelphia Natural Academy of Science Monograph no. 13. 688 p.

Pennington, W. 1943. Lake sediments: The bottom deposits of the north basin of Windermere, with special reference to diatom succession. New Phytologist 42:1-26.

Pennington, W. 1973. Observations on lake sediments using fallout ^{137}Cs as a tracer. Nature 242:324-326.

Platt, T. and B. Irwin. 1968. Primary productivity measurements in St. Margaret's Bay, 1967. Fisheries Research Board of Canada Technical Report no. 77. 123 p. (cited in Larson, 1970a).

Powers, C.F. 1976. Scientist at the U.S. Environmental Protection Agency, Corvallis. Personal communication. Corvallis, Oregon. March 24.

Powers, C.F., W.D. Sanville, and F.S. Stay. 1975. Waldo Lake, Oregon. (manuscript). U.S. Environmental Protection Agency. Corvallis, Oregon. 19 p. (photocopy).

Radke, S. 1976. Soils of the Umpqua National Forest. (manuscript). U.S. National Forest Service.

Radke, S. 1976. Soils scientist for the U.S. National Forest Service, Umpqua National Forest. Personal communication. Roseburg, Oregon. April 2.

Rawson, D.S. 1956. Algal indicators of trophic lake types. Limnology and Oceanography 1:18-25.

Rohde, W. 1969. Crystallization of eutrophication concepts in northern Europe. (In) Eutrophication: Causes, consequences, correctives. Proceedings of a symposium of the National Academy of Sciences. Washington, D.C.

Sanville, W.D. 1976. Eutrophication and lake restoration branch, U.S. Environmental Protection Agency scientist. Personal communication. Corvallis, Oregon. March 24.

Sanville, W.D. and C.F. Powers. 1971. Diamond Lake studies: Progress report no. 1. Working paper no. 8. National Eutrophication Research Program. U.S. Environmental Protection Agency Publication. 22 p.

Schuytema, G. 1976. Research scientist for the U.S. Environmental Protection Agency. Personal communication. Corvallis, Oregon. March 26.

Shapiro, J., W.T. Edmondson, and D.E. Allison. 1971. Changes in the chemical composition of sediments of Lake Washington, 1958-1970. Limnology and Oceanography 16:437-452.

Sovereign, H.E. 1958. The diatoms of Crater Lake, Oregon. Transactions of the American Microscopic Society 77:96-134.

Smith, A.K. and J.E. Smith. 1972. Fish and wildlife resources of the middle coast basin, Oregon, and their water requirements (revised): A report with recommendations to the Oregon State Water Resources Board. Oregon State Game Commission Report. 87 p.

Stockner, J.G. 1971. Preliminary characterization of lakes in the Experimental Lakes Area, northwestern Ontario, using diatom occurrences in sediments. Journal of the Fisheries Research Board of Canada 28:265-275.

Stockner, J.G. 1972. Paleolimnology as a means of assessing eutrophication. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 18:1018-1030.

Stockner, J.G. and W.W. Benson. 1967. The succession of diatom assemblages in the recent sediments of Lake Washington. Limnology and Oceanography 12:513-532.

Strickland, J.D.H. and T.R. Parsons. 1968. A practical handbook of seawater analysis. Bulletin no. 167. Fisheries Research Board of Canada. 203 p.

U.S. Department of Commerce. 1969-1973. Climatological data: Oregon. Environmental Data Service 75(1)-79 (13).

U.S. Department of the Interior. 1963. U.S. Geological Survey map: Odell Lake. Map no. N4330-W12152.5/7.5.

U.S. Department of the Interior. 1974. Water resources data for Oregon: Part I, surface water records. Geological survey. 400 p.

U.S. National Forest Service. 1974. Map and facility descriptions of Diamond Lake campground. (brochure).

U.S. National Forest Service. 1976. Deschutes National Forest regional office official records. Personal review. Gilcrest, Oregon. April 8.

Vallentyne, J.R. 1955. Sedimentary chlorophyll determination as a paleobotanical method. Canadian Journal of Botany. 33:304-313.

Vollenweider, R.A. 1965. Calculation models of photosynthesis-depth curves and some implications regarding day rate estimates in primary production measurements. (In) Primary productivity in aquatic environments. C.R. Goldman (editor). University of California Press. Berkeley, California. p. 428-457. (cited in Larson, 1970a).

Wentz, D.A. and G.F. Lee. 1969. Sedimentary phosphorus in lake cores: Observations on depositional pattern in Lake Mendota. Environmental Science and Technology 3:754-759.

Wheeler, C.L. 1974. Surface water records and precipitation records of Oregon. State of Oregon Engineer. 264 p.

Wunderlich, R.C. 1974. Evaluation of lake pollution by analysis of sediments. M.S. thesis. Colorado State University. Fort Collins, Colorado. 66 p.