1964

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Recommended Citation

Callender, Edward, "The physical limnology and sedimentology of Miller Lake, Martin River Glacier, south-central Alaska" (1964). *Theses and Dissertations*. 45.
https://commons.und.edu/theses/45

THE PHYSICAL LIMNOLOGY AND SEDIMENTOLOGY OF MILLER LAKE, MARTIN RIVER GLACIER, SOUTH-CENTRAL ALASKA

by

Edward Callender

B. S. in Geology, The Colorado College, 1962

A Thesis
Submitted to the Faculty
of the
Graduate School
of the
University of North Dakota
in Partial Fulfillment of the Requirements
for the Degree of
Master of Science

Grand Forks, North Dakota

June
1964

This thesis submitted by Edward Callender in partial fulfillment of the requirements for the degree of Master of Science in the University of North Dakota is hereby approved by the committee under whom the work has been done.

Wilson M. Laird
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CONTENTS

ILLUSTRATIONS

TABLES

THE PHYSICAL LIMNOLOGY AND SEDIMENTOLOGY OF MILLER LAKE, MARTIN RIVER GLACIER, SOUTH-CENTRAL ALASKA

Edward Callender

ABSTRACT

Miller Lake is an ice-walled lake located on the terminus of the Martin River Glacier, south-central Alaska. It has an area of 1.36 km.^{2} and a mean depth of 25 meters. The lake basin was formed by the coalescence of several ice sinkholes and is characterized by extremely uneven bottom topography.

Analysis of detailed thermal data obtained during the summer of 1963 indicates that the lake is never permanently thermally stratified but does develop some stratification during periods of warm, calm weather. This stratification is easily destroyed by stormy weather. Miller Lake is classified as a subpolar lake due to the fact that the thermal gradient is small and the surface temperature is above 4°C for only a relatively short time in the summer. The calculated annual heat budget is 8873 cal/cm.^{2}.

The general sediment distribution of Miller Lake is characterized by a band of sand, gravel, and coarser material surrounding a large area composed mainly of silty clay located in the center of the lake. There are several areas of anomalous sediment distribution which are difficult to explain in the light of the physical setting of Miller Lake. Generally, deposition of sediment is controlled by the bathymetry of the lake. Finer sediment is deposited in basins where the effects of currents and

waves are small, while coarser material is concentrated on higher areas where finer particles are winnowed out by wave action currents.

The sediments of Miller Lake may generally be classified as a glaciolacustrine diamicton deposit. These sediments are deposited by the glacier and ice bergs which dump phenoclastic material into the lake.

INTRODUCTION

Location

Miller Lake is located in the extreme southern part of the terminus of the Martin River Glacier in south-central Alaska at an approximate elevation of 122m. (400 ft.) above mean sea level. The Martin River Glacier (144° 20' to 144° 00' West Longitude by 60° 35' to 60° 25' North Latitude) is located 80 km. (50 mi.) east-southeast of Cordova, Alaska (Fig. 1).

Description of lake

Miller Lake is an ice-walled glacial meltwater lake formed by the coalescence of several ice "sinkhole" lakes. The lake is 2.19 km. long (1.36 mi.), 0.71 km. wide (o.44 mi.), and has a maximum depth of 70 m. (230 ft.) with a subcircular or kidney-shaped outline and is fed almost exclusively by glacial meltwater.

Purpose

The purpose of this investigation was to study, both qualitatively and quantitatively, the hydrography, physical limnology, and sedimentology of an aquatic environment poorly understood by geologists and limnologists alike. An attempt has been made to be quantitative as well as descriptive with the data gathered, but this attempt has been necessarily limited by the lack of continuous data obtained from observations made over long periods of time.

Previous work

The glacial geology of the Martin River Glacier area has been briefly described by Martin (1908, p. 50-52, Pl. 5) and Tarr and Martin (1914, p. 463). Clayton (1964) and Reid and Clayton (1963) have described several interesting aspects of the glacial geology of the area. Tuthill

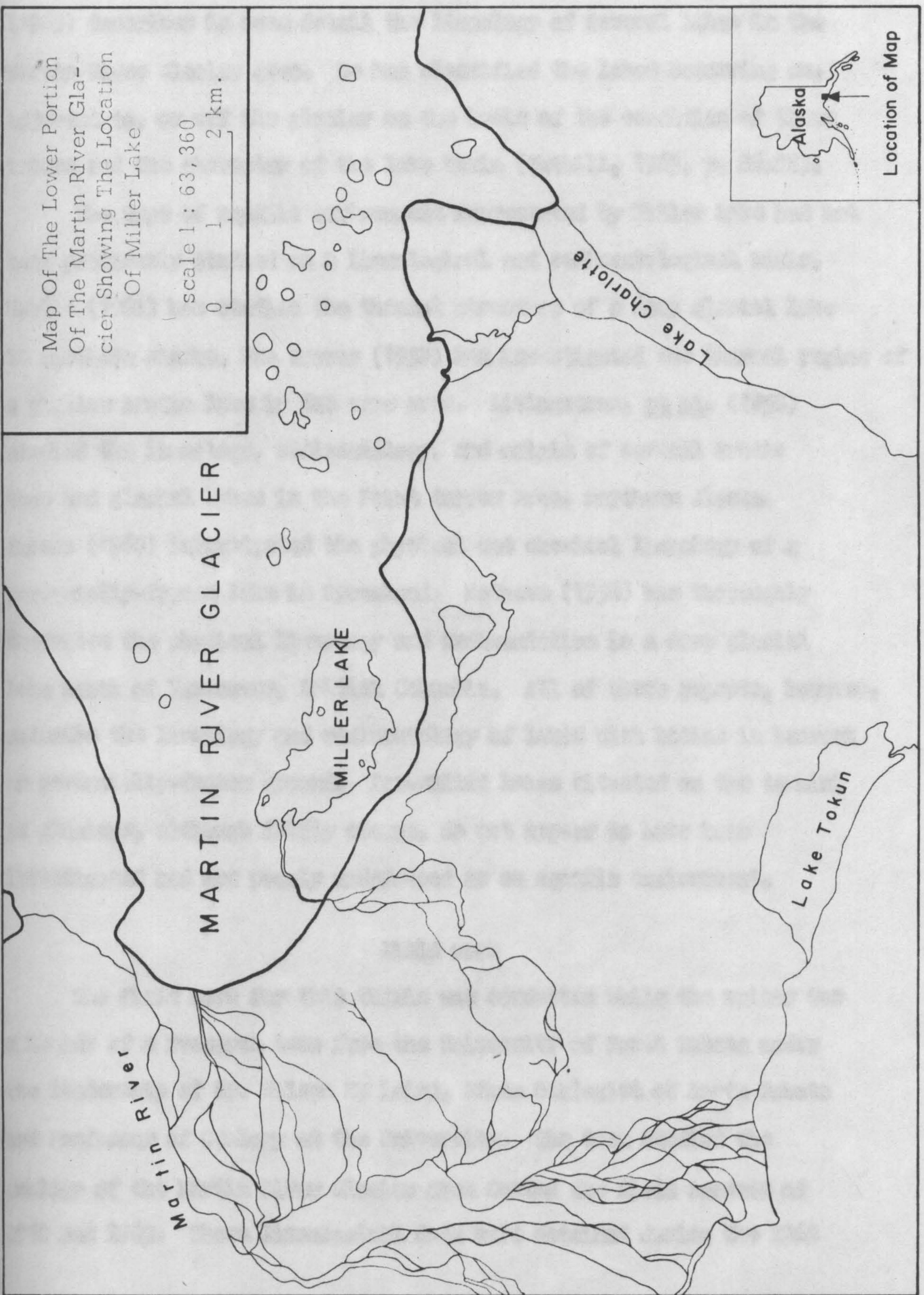


FIGURE 1. Map of lower portion of the Martin River Glacier showing location of Miller Lake.

(1963) describes in some detail the limnology of several lakes in the Martin River Glacier area. He has classified the lakes occurring on, adjacent to, or off the glacier on the basis of the condition of their waters and the character of the lake basin (Tuthill, 1963, p. 86-88).

The type of aquatic environment represented by Miller Lake has not been previously studied on a limnological and sedimentological basis. Hobbie (1961) has studied the thermal structure of a deep glacial lake in northern Alaska, and Brewer (1958) has investigated the thermal regime of a shallow arctic lake in the same area. Livingstone, *et al.* (1958) studied the limnology, sedimentology, and origin of several arctic thaw and glacial lakes in the Point Barrow area, northern Alaska. Barnes (1960) investigated the physical and chemical limnology of a perennially-frozen lake in Greenland. Mathews (1956) has thoroughly described the physical limnology and sedimentation in a deep glacial lake north of Vancouver, British Columbia. All of these reports, however, describe the limnology and sedimentology of lakes with basins in bedrock or perennially-frozen ground. Ice-walled lakes situated on the termini of glaciers, although fairly common, do not appear to have been investigated and are poorly understood as an aquatic environment.

Field work

The field work for this thesis was conducted while the writer was a member of a research team from the University of North Dakota under the leadership of Dr. Wilson M. Laird, State Geologist of North Dakota and Professor of Geology at the University. The team studied the geology of the Martin River Glacier area during the field seasons of 1962 and 1963. These limnological data were obtained during the 1963 field season at which time the investigation of Miller Lake was conducted. The team operated out of a permanent base camp located on the southern shore of the lake. The limnological and sedimentological investigations were conducted using a 5.2 m. (17 ft.) aluminum canoe stabilized by an outrigger and pontoon (Callender, 1964).

Acknowledgments

The field work for this investigation was supported by the National Science Foundation (Grant Number NSF-G22016) awarded to the Geology Department of the University for the study of the Martin River Glacier area in south-central Alaska with Dr. Wilson M. Laird, Principal Investigator.

I wish to thank the many people who have assisted me with this study. Dr. Wilson M. Laird, State Geologist of North Dakota and Chairman of the Geology Department of the University of North Dakota gave his support and help in the field, aided in the construction of equipment, and critically read this manuscript. Mr. Samuel J. Tuthill, fellow graduate student who studied the limnology and geology of several lacustrine environments in the Martin River Glacier area, gave his support and help in the field as well as in the laboratory. His suggestions and discussions concerning the problems encountered throughout the duration of this investigation were of great help to the writer. Dr. John R. Reid and Dr. Walter L. Moore of the University of North Dakota made many helpful suggestions and critically read this manuscript. Dr. Reid also rendered valuable assistance in the field. Mr. Bruce Switzer and Mr. Frank Schulte, summer field assistants, assisted the author in the field. Without their help completion of the project would have been impossible. My wife, Penny, critically read the manuscript and offered

many valuable suggestions concerning its style. I am most grateful to these people for their help and support during the preparation and completion of this investigation.

GEOGRAPHY AND GEOLOGY

Climate

The climate of the Martin River Glacier area is characterized by heavy rainfall with moderate winter and low summer temperatures. This climate is classified as a temperate rainy climate with cool, short summers (Cfc Köppen symbol /Strahler, 1960, p. 191/), or a marine west coast climate (Strahler, 1960, p. 191).

Meteorological records made at Katalla in 1907 (Martin, 1908, p. 17) are presented in table 1.

The United States Weather Bureau has summarized the weather data for Cordova, Alaska from 1931 to 1960 (United States Weather Bureau, 1962). These data are presented in table 2.

Reid (1963a, p. 3) summarized meteorological observations taken by him throughout the summers of 1962 and 1963 at the Miller Lake and Lake Charlotte base camps (see table 3).

Clear weather generally occurred with west and southwest winds, while rainy weather accompanied east winds.

Vegetation

There are three major types of vegetation in the Martin River Glacier area. Muskeg, consisting predominantly of swamp and meadow grass, occupies the lowland area between the margin of the glacier and the Martin River. Dense growths of alder cover a large part of the outwash plain of the Martin River.

A spruce forest occurs adjacent to the southern margin of the glacier while spruce-alder forests occupy a position immediately adjacent to and on the stagnant margin of the glacier. Alder is the predominant vegetation farther out on the glacier. Spruce-alder forests grow on

Table 1. Meteorological records made at Katalla, Alaska in 1907.

	Temperature (°F)			Cloudiness (no. days)				Precip. (in.)	
	Max.	Min.	Mean	Clr	ptly Cldy	Cldy	Rain	Rain	Snow
April	50	23	35.8	8	10	12	12	7.5	2.0
May	67	30	44.2	11	6	14	17	4.85	-
June	80	41	50.0	6	9	15	16	8.29	-
July	78	42	55.0	1	8	22	23	14.95	-
Aug.	84	44	59.4	5	11	15	17	11.41	-
Sept.	76	37	52.0	8	11	11	19	12.34	-
Oct.	54	22	41.7	1	7	23	29	25.52	1.25

Table 2. Summary of weather data for Cordova, Alaska (1931 - 1960).

Measurement	Jan.	Feb.	March	April	May	June	July	Aug.
Max. temp.	31.6	35.2	38.2	44.2	51.7	58.1	60.3	60.5
Min. temp.	14.5	17.1	19.9	28.1	35.6	42.3	46.1	44.2
Av. temp.	23.1	26.2	29.1	36.2	43.7	50.2	53.2	52.4
Precip. (in.)	6.10	4.64	3.84	4.32	5.06	3.48	6.27	8.06

Measurement	Sept.	Oct.	Nov.	Dec.	Annual
Max. temp.	56.0	47.7	38.5	32.9	46.2
Min. temp.	39.1	31.9	23.6	18.2	30.1
Av. temp.	47.6	39.8	31.1	25.6	38.2
Precip. (in.)	12.51	11.90	8.02	6.78	80.98

Table 3. Summary of meteorological observations taken at the base camps during the summers of 1962 and 1963.

			Total rain	Average temperature
June	1962	(16 days)	7.19 inches	52.3°F
July	1962	(31 days)	7.45 inches	50.0°F
August	1962	(14 days)	1.07 inches	51.8°F
Total	1962	(61 days)	15.71 inches	

June	1963	(20 days)	6.68 inches	47.3°F
July	1963	(31 days)	7.89 inches	51.2°F
August	1963	(10 days)	5.10 inches	47.1°F
Total	1963	(61 days)	19.67 inches	

the lower slopes of the hills to an approximate elevation of 364 m. (1200 ft.) which is the elevation of the tree line in this area.

The third type of vegetation in the Martin River Glacier area is alpine flora which is characterized by heath and meadow grass. Alpine flora usually occurs above the tree line where it is occasionally interspersed with stunted alder and spruce growth.

The lower margin of the glacier is covered by a 1.6 to 2.4 km. wide (1 mi. to 1½ mi.) band of dense alder (Alnus) growth. The southern margin between Lake Charlotte and Deadwood Lake (Fig. 2) is covered by a mature Sitka spruce (Picea sitchensis [Bong.] Carr.) forest which extends about 0.8 km. onto the stagnant part of the glacier (Tuthill, 1963). Lichens appear initially on the superglacial debris and are the hardiest flora. They are followed by Lupin (Lupinus Nootkatensis Donn.) and fireweed (Epilobium latifolium Linne.) which invade the drift covered parts of the glacier. These are followed by alder, willow (Salix), and sitka spruce. The presence of vegetation on the glacier is determined by the amount of superglacial debris which provides an insulating effect enabling stable slopes to be established.

Topography

The topography of the Martin River Glacier area is characterized by rugged mountains and moderately high hills with glaciers, outwash plains, moraines, and muskeg occupying the areas in between. The glacier is bounded on the west by the outwash plain of the Martin River, on the north by the Chugach Mountains with a maximum elevation here of approximately 1820 m. (6000 ft.), on the east by the Bering Glacier and the Bagley Ice Field, and on the south by the foothills of the Chugach Range having a maximum elevation of 606 m. (2000 ft.).

There are many lakes in the area, several of which contain abundant aquatic life (Tuthill, 1963). The larger lakes (area greater than 2 km.^{2}), all of which are rock basin lakes, are dammed by glacial ice, glacial moraines, or glacial outwash. There are numerous smaller ice-contact lakes located on the terminus of the Martin River Glacier. Miller Lake is the largest of these.

The streams of this area derive their water from local rainfall and glacial meltwater. Both of these sources are large and consequently the streams, such as the Martin River and the Bering River, are large in proportion to their length and drainage area and are subject to severe flooding.

Regional bedrock geology

Payne (1955) describes three tectonic provinces in the Martin River Glacier area. These provinces, which occur in an east-west zone north of the Gulf of Alaska, are known as the "Chugach Mountains geosyncline" and the "Mesozoic greenstone-graywacke-slate sequence" north of the glacier, and the "Yakataga geosyncline" south of the Martin River Glacier.

Chugach Mountains geosyncline

The east-west trending Chugach Mountains geosyncline consists of a series of tightly folded and metamorphosed graywackes and slates. These rocks have been studied only outside the Martin River Glacier area and have been described in the Prince William Sound region west of the Martin River Glacier (Moffit, 1954, p. 242-247) and in the Chitina valley north of the glacier (Moffit, 1938, p. 89-128).

In the Prince William Sound region these rocks are represented by the Valdez Group of Late Cretaceous age (Moffit, 1954). They are composed mostly of graywacke, argillite, and slate. The graywacke is gray or bluish-gray and contains quartz, feldspar, and quartzite and slate rock fragments. Conglomerate and dark, impure limestone are occasionally found interbedded with the slates and graywackes. The beds show the effect of metamorphism which has been so intense as to alter the rocks to phyllite and schist in some places. The graywackes and slates have been intruded by felsic dikes and sills and granitic and dioritic batholiths. The rocks are commonly permeated with quartz veins ranging from a fraction of a centimeter to a meter thick.

The graywacke-slate sequence is intensely folded and faulted, with a total thickness measured in thousands of feet.

Gold is the principal economic mineral found in the rocks of the Chugach Mountains geosyncline. This gold occurs as placer and quartz lode deposits in the Prince William Sound region (Moffit, 1954, p. 302-308).

Mesozoic greenstone-graywacke-slate sequence

The rocks represented by this sequence are very similar to those of the Valdez Group, the main difference being the presence of altered mafic extrusive and intrusive rocks commonly called greenstones. These rocks, which border the Gulf of Alaska, are represented in the Prince William Sound region by the Orca Group (Moffit, 1954, p. 247-250) of probable Lower Cretaceous age (Payne, 1955). They crop out in the Chugach Mountains north of the Martin River Glacier.

The most dominant part of this sequence consists of slate and graywacke, with the characteristic greenstone making up a subordinate portion of the rocks. The greenstones are altered dense basalts and massive diabase occurring as lava flows, dikes and sills that commonly exhibit pillow structure. Agglomerates, argillites, quartzites, conglomerates, and some limestones and cherts are associated with this sequence.

The rocks are tightly folded and greatly faulted, but exhibit minor metamorphic effects. Locally, contact metamorphism has resulted from minor igneous intrusions. The strata and faults dip steeply to the north-northwest.

Copper deposits are commonly found associated with the greenstone. Gold and silver deposits are also present in this sequence (Moffit, 1954).

Yakataga geosyncline

The rocks of the Yakataga geosyncline compose the Chugach Mountains foothills and extend under the Martin River Glacier south to the coast, and from the Copper River Delta southeast to Mt. Fairweather. These rocks, which have been studied by Martin (1908, p. 27-43), Taliaferro (1932, p. 757-777), and Miller (1957), consist of well-lithified Tertiary continental and marine sandstones, shales, and coals. They are generally complexly folded and exhibit few signs of metamorphism.

The Eocene Kushtaka and Stillwater Formations and the Tokun Formation (Eocene-Oligocene) are exposed immediately south of the Martin River Glacier, while the Katalla Formation (Oligocene-Miocene) is located several miles farther south. Table 4 is a stratigraphic section showing the relationship of these units in the Martin River Glacier area. The Kushtaka Formation extends from the crest of Kushtaka Ridge (see Fig. 2) west throughout the valley of Carbon Creek (Martin, 1908, p. 31) and interfingers with the Stillwater Formation (MacNeil and others, 1961, p. 1807). It consists of dominantly non-marine coarse arkose, shale, and a large number of coal beds. The thickness exceeds 600 m. (2000 ft.), but the exact thickness is not known. The Kushtaka Formation contains all the coal of the Bering River coal field which occurs as anthracite, semianthracite, and semibituminous coal and is found in beds ranging from

Table 4. Stratigraphic section of rocks of the Yakataga geosyncline in the Martin River Glacier area. From Taliaferro, (1932, p. 774), Martin (1908, p. 20), and MacNeil and others (1961, p. 1803).

S	Fm.	Member	Lithology	Thick.
MIOCENE	Katalla Formation	Puffy	Sh with thin ss layers and many sh-matrix congl beds; in part glacial drift (?)	4000+
		Pt. Hey Ss	Ss ans congl with thin sh beds; congl at top	1100
OLIGOCENE		Burls Cr. Sh	Sh, concretionary ("cannonballs")	1700
			Organic sh; glauconitic horiz; oil seeps	400
			Dark sh; in parts organic; with thin hard ss beds	700
		Split Cr. Ss	Ss	800
			Sh; base not exposed	
	Tokun Fm.		Ss	500
EOCENE			Sh	2000+
	Stillwater Formation	Sh and ss; marine	1000± Kushtaka Formation Crs arkose, coal, sh, and ss; continental	2500±

FIGURE 2. Map of the southern margin of Martin River Glacier and adjacent areas.

a few cm. to 15 m. (1 in. to 50 ft.) in thickness.

The Stillwater Formation, which consists of predominantly marine shale and sandstone, interfingers with the Kushtaka Formation and is the marine equivalent of that unit.

The Tokun Formation crops out along the margin of the Martin River Glacier in this area (Martin, 1908, p. 35) where it consists mainly of more than 750 m. (2500 ft.) of marine shales and sandstones which conformably overlie the Kushtaka Formation.

The Katalla Formation crops out south of the Martin River Glacier area adjacent to the Gulf of Alaska. It consists mainly of marine shales with scattered limestone concentrations which contain fossils of marine mollusks, echinoderms, and crustaceans (Martin, 1908, p. 28). Two massive sandstones are present, one below and one above the most prominent shale bed.

There are two other upper Cenozoic marine formations in the Martin River Glacier area. These are the Poul Creek Formation (Oligocene and Miocene) and the Yakataga Formation (Miocene and Pliocene). They consist of approximately 910 m. (3000 ft.) of siltstone, sandstone, and conglomerate (Miller, 1957). Small dikes and sills and laccoliths of basalt and diabase are common in this area, with the dikes and sills being especially abundant north and east of Stillwater Creek.

The Cenozoic rocks of this area have a general northeast strike and dip steeply to the northwest. The rocks of the Yakataga geosyncline are brought in contact with the greenstone-slate-graywacke sequence by the Chugach-Mt. St. Elias overthrust which extends from the Copper River Delta under the Martin River Glacier to Yakutat Bay. Deformation of rocks in the Yakataga geosyncline varies from gentle, open folds in the south to complex, tight folds with steep dips and numerous thrust faults in the north. Most of the deformation took place during the Pliocene but continued into the Quaternary (Payne, 1955).

Glacial geology

General

Many of Alaska's glaciers border the Gulf of Alaska, and this coastal region is covered with valley and piedmont glaciers. Fiords are common throughout much of this region except in an area from the Copper River Delta southeast to Yakutat Bay. This area, which has a relatively straight coastline, is occupied in part by piedmont glaciers, the two largest of which are the Malaspina and Bering Glaciers. Piedmont glaciers occupy broad lowlands located at the base of steep mountain slopes.

The piedmont glaciers of the Gulf of Alaska originate as valley glaciers in the Chugach and St. Elias Mountains which coalesce and expand in the foothills to form broad piedmont glaciers. A band of stagnant ice occupies the terminal part of many of these glaciers and is generally covered by superglacial drift which varies from a few cm. to 7.5 m. (1 in. to 25 ft.) in thickness. The glacial surface is relatively stable in places where the superglacial drift is moderately thick (1 to 3 m.), but in areas where the drift is only 0.4 to 1 m. (1.5 ft. to 3.3 ft.) thick, the surface of the glacier is unstable and exhibits a great deal of local relief.

Commonly, the stagnant margin of these glaciers is drift covered. This drift or ablation till may possibly have been formed by the concentration of subglacial debris carried up into the glacier along shear planes in the ice (Flint, 1957, Fig. 5-14; and Clayton, 1964, p. 108).

These shear or thrust planes result from active ice overriding stagnant ice. Subglacial debris is dragged into the upper part of the glacier and concentrated there through ablation. Superglacial drift may also be formed by lateral diffusion of medial moraines. This ablation till insulates the ice beneath thereby causing this area of the glacier to melt more slowly than areas covered by little or no drift. A forest often grows on the more stable (1 to 3 m. of drift [3 to 10 ft.]) stagnant margin of the glacier, whereas the less stable part (0.4 to 1 m. of drift) of the stagnant margin supports little vegetation and is characterized by a very hummocky surface with high local relief.

The stagnant part of many of these glaciers is occupied by many solution features which result in a type of karst topography developed on ice (Clayton, 1964). The most significant feature of this karst topography is the presence of numerous superglacial funnel-shaped ice sinkholes. These sinkholes are commonly 67 to 400 m. (220 to 1320 ft.) across, 17 to 100 m. (55 to 330 ft.) deep, and often contain water. These sinkholes are common on the stagnant part of the Malaspina Glacier (Russell, 1901, p. 115-117), the Bering Glacier, and the Martin River Glacier (Clayton, 1964). The lakes are filled with debris that slides down the steep walls which melt more rapidly due to poor insulation. Eventually the lake bottom, after draining, stands above the surrounding ice and becomes an ice-cored cone, thereby completing an inversion of topography. Russell (1901, p. 117) believes that these sinkhole lakes are the result of widening of crevasses. This conclusion is also supported by Renaud (1936). Superglacial sinkhole lakes, high local relief, abundant superglacial drift, and lack of surface meltwater streams (along with many other features characteristic of karst topography) seem to be diagnostic of stagnant ice.

Martin River Glacier

The Martin River Glacier is intermediate between a valley glacier and a piedmont glacier. It begins at the western edge of the Bagley Ice Field and is approximately 39 km. (26 mi.) long, 8 km. (5 mi.) wide, and terminates 32 km. (20 mi.) east of the Copper River Delta. The glacier descends some 2000 m. (6600 ft.) from an elevation of 2120 m. (7000 ft.) at the western edge of the Bagley Ice Field, to 120 m. (400 ft.) at the terminus of the glacier. The glacier, which originates in the Bagley Ice Field, is fed by several tributary glaciers. It differs from the Bering and Malaspina piedmont glaciers in that it is confined to a broad valley instead of debouching onto a broad flat plain at the base of the mountains. The Martin River Glacier is bordered on the north by the Chugach Mountains, on the south by the Chugach foothills, on the east by the Bagley Ice Field and the Bering Glacier, and on the west by the outwash plain of the Martin River. There are two lobes along its southern margin, one extending into the valley of Kushtaka Lake, and the other descending into Lake Charlotte Valley.

The southern part of the stagnant margin of the glacier is covered with drift and is moderately forested. This stagnant margin is 1 to 3 km. (0.5 to 2 mi.) wide (Clayton, 1964, p. 108). The superglacial drift ranges in thickness from more than 8 m. (26 ft.) to a few cm. (1 in.). The more active part of the glacier exhibits medial moraines, primary stratification and ogives, with crevasses being present on all but the most stagnant parts of the glacier.

A terminal moraine crosses the Martin River Valley approximately 1 km. (0.6 mi.) west of the terminus of the glacier. There are 18 successive lateral moraines which may be traced along the sides of the hills in the area. The highest moraine is located 230 m. (760 ft.) above the present surface of the glacier. By comparing the elevation of the present surface of the glacier with that of the moraine corresponding in age to the Little Ice Age (1729-1824), Reid (1963a) has estimated that the glacier surface has ablated vertically some 25 m. (82 ft.) since that time. He believes that present ablation rates approximate this figure.

A valley train 4 km. (2.5 mi.) long and 1 to 2 km. (0.6 to 1.2 mi.) wide extends from the terminus of the glacier westward where it eventually joins the Copper River Delta some 7 km. (4.3 mi.) from the margin of the glacier. The surface of the valley train has aggraded above the mouths of tributaries to the Martin River thereby forming Martin Lake, Little Martin Lake, and Lake Tokun (Martin, 1908).

Although the exact recent history of the Martin River Glacier has not yet been determined, some tentative conclusions may be drawn from the preliminary analysis of tree ring studies conducted during the summer of 1963 (Reid, 1963b). These dendrochronological studies of trees on and adjacent to the glacier suggest that there have been two recent glacier advances in the Lake Charlotte area. The most recent advance occurred around 1910, while the earlier advance took place during the "Little Ice Age" which is dated between 1729 and 1824. These dates correspond to the ages (determined by tree ring studies) of the two most recent lateral moraines of the Martin River Glacier (Reid, 1963a) and are recorded by two end moraines located at the southern end of Lake Charlotte. No distinct end moraine exists at the main terminus of the glacier which corresponds to the 1910 advance in the Lake Charlotte area (Reid, 1963b). A minor advance of the glacier may have occurred during 1959 (Tuthill, oral communication, University of North Dakota). This conclusion is based on a cursory examination of aerial photographs. It appears that while the Martin River Glacier has experienced several readvances, or periods where recession was at a standstill in the last 250 years, the margin of the glacier is now thinning rapidly and is presently receding.

MORPHOMETRY, MORPHOLOGY, AND ORIGIN

The morphometry of a lake is the quantitative expression of the form of the lake basin, while the morphology describes the shape of the lake and the relation of that shape to its origin and history.

Bathymetry

General bathymetry

The general topography of the bottom of Miller Lake was measured while obtaining samples of the bottom sediments. A line attached to the Ekman sampler was marked in meters and depth to the bottom was recorded at 150 stations located by triangulation, using a Brunton compass, from control points of the lake shore. More detailed bathymetry was constructed from fathograms representing 37 traverses of the lake.

The bathymetric map was constructed using some 600 depth measurements and contoured on a 10 meter interval in order to show reasonable detail. The bathymetric map is presented in Plate 1.

The bottom of Miller Lake is quite irregular and marked by steep-sided depressions and hills, which in turn contain smaller similar hills and depressions. The most striking bathymetric feature is the presence of several elliptical to subrectangular basins, many of which contain isolated hills. The entire northern half of the lake basin is characterized by these elongate depressions and hills. The southwestern part of the lake basin exhibits a fairly extensive, gently sloping littoral shelf. This gently sloping shelf is in striking contrast to the subcircular, steep-sided, sublacustrine depressions and hills found in the northern part of the lake basin.

Detailed bathymetry

A detailed bathymetric map and several bathymetric profiles are presented in Plate 1. The following description of the bathymetric features of Miller Lake basin relies entirely on this map and the accompanying profiles.

Northern and eastern part of the lake: The elongate, steep-sided depressions which are so characteristic of this part of the Miller Lake basin are found within a long, relatively narrow arcuate basin. This basin occupies the greater part of the lake basin and has fairly steep walls in its eastern, northern, and western parts and more gently sloping walls in the southern part where it grades into a littoral shelf.

Many of the elongate depressions contain steep-sided hills rising tens of meters above the basin floor. Profile 2 shows such a situation wherein a basin, designated by site no. 1, contains a hill, site no. 2, which rises 20 m. (65 ft.) above the basin floor. The bathymetric map illustrates several such features scattered throughout the lake basin.

Many of these hills, in turn, exhibit depressions located on the tops of the hills that extend several meters (20 m. in one case) below the crests of these hills. Profile 2 shows this feature where a depression, site no. 3, lies on top of the hill (2) described in the preceding paragraph. Many of these sublacustrine hills contain such depressions (see Plate 1).

As will be noted later, the formation of these unusual bathymetric features is directly related to the presence of ice beneath a large part, if not all of the lake basin.

The elongate, steep-sided depressions occurring in the northern part of the lake basin are separated from one another by a sill or sublacustrine ridge. The walls of the basins and depressions have a very steep slope, ranging between 26° and 52°, with an average of 38°.

There appears to be a rough arcuate alignment of steep-sided basins in the lake (see Plate 1). This is most certainly related to the origin of the lake basin and is probably controlled, in whole or in part, by differential flow in the ice (Reid and Callender, in preparation).

Southwestern part of the lake: The southwestern part of the Miller Lake basin is characterized by a fairly extensive gently sloping littoral shelf (see Plate 1) which occupies a large part of the southern half of the lake basin and lies only 10 to 30 m. (33 to 100 ft.) below the surface of the lake. This is in contrast to the "hilly" topography of the northern part of the basin where features lie from 30 to 70 m. (100 to 230 ft.) below the lake surface. Several elongate hills are present on this shelf. Profile 3 shows such a hill (1) rising 20 m. (66 ft.) above the shelf surface. These hills possess a rough arcuate alignment which is probably related to the origin of the lake basin. Hill (1) contains a depression (2) which extends 15 m. (50 ft.) below its crest.

The slope of the littoral shelf is quite gentle compared to that of the sublacustrine basins and hills. The shelf has an average slope of 11° to the north and ranges from 2° to 25° (see profiles in Plate 1).

Morphometric parameters

The morphometric parameters and the respective symbols which are used in this paper are those outlined by Hutchinson (1957, p. 165-167). The reader is referred to this work for a complete explanation and derivation of these parameters.

Maximum depth: The maximum depth of Miller Lake (Z_m) will vary slightly depending upon the water level, and in this regard the accuracy of the maximum depth measurement of Miller Lake is within ±1 m., as the water level varied from day to day throughout the summer. The maximum depth of the lake is 70 m. (230 ft.).

Mean depth: The mean depth ($\bar{z}$) of any lake is obtained by dividing the volume of a lake by its area. Miller Lake has a mean depth of 25 m. (82 ft.).

Maximum length: The maximum length (l) of any lake is the shortest distance along the water surface between the two most distant points on the lake shore. Miller Lake has a maximum length of 2.19 km. (1.35 mi.).

Breadth: Breadth (b) is defined as the length of a line, drawn at right angles to a line defining the length of a lake, connecting two points on the lake shore. Miller Lake has a maximum breadth of 0.77 km. (0.5 mi.). Mean breadth ($\bar{b}$) is obtained by dividing the area of a lake by its maximum length. Miller Lake has a mean breadth of 0.62 km. (0.4 mi.).

Area: The area (A) of a lake is obtained by planimetry using a map of the outline of the lake. Miller Lake has an area of 1.36 km.^{2} (0.6 mi.^{2}).

Volume: The volume (V) of a lake is given by the formula $V_1 = 1/3\ (A_1 + A_2 + \sqrt{A_1A_2}\ )h$. The area enclosed by each 10 m. contour was measured with a compensating polar planimeter. The volume under each 10 m. contour was computed using the equation given above and the entire volume of the lake was obtained by totaling the individual volumes. The resulting volume of Miller Lake is 0.034 km.^{3} (0.0107 mi.^{3}).

Length of shore line: Length of the shore line (L) is commonly measured on a map by means of a rotometer. Miller Lake has 6.99 km. (4.34 mi.) of shore line.

Development of shore line: The development of shore line (D_L) is the ratio of the length of the shore line to the circumference of a circle which has an area equal to that of the lake. The shore line development may be obtained using the following formula: $D_L = \frac{L}{2\sqrt{\pi A}}$. Shore line development obviously cannot be less than unity and the figure derived is regarded as a measure of the effectiveness of littoral processes on the lake, providing the area is relatively constant (Hutchinson, 1957, p. 166). Miller Lake has a shore line development value of 1.69.

Development of volume: Development of volume (D_V) is a morphometric parameter which is an expression of the form of the lake basin. It is defined as the ratio of the volume of a lake to that of a cone which has a basal area A (the area of the lake) and height Z_m (the maximum depth of the lake). In this report the development of volume is defined as the ratio of the mean depth to the maximum depth ($\bar{Z} : Z_m$) following the practice of Hutchinson (1957, p. 166). Miller Lake has a development of volume of 0.357 which is quite close to that of a cone (0.33). This parameter will be discussed in more detail in a later section.

Relative depth: The relative depth (Z_r) of a lake is determined using the maximum depth as a percentage of the mean diameter of the lake and is obtained using the following equation: $Z_r = 50\, Z_m \sqrt{\pi}\, (\sqrt{A})^{-1}$. Miller Lake has a relative depth of 5.33%.

Insulosity: The insulosity (A_i) of a lake is the area within the shore line that is occupied by islands. Two of the three islands in Miller Lake are ice-cored islands, while the third is a rock island (which may be ice-cored) that has remained fairly stable for at least the past 7 years. The area of these islands within the shore line is 12,442 m.^{2} (136,862 ft.^{2}).

Morphology

Outline of the lake

Miller Lake exhibits a general subcircular outline which is distinctly kidney-shaped. In detail, however, the outline is fairly irregular and is probably directly related to the origin of the lake basin. Such irregular outlines are generally characteristic of lakes whose basins formed by fusion of several basins, or by glacial scouring of shattered bedrock (Hutchinson, 1957, p. 171). The irregular outline of Miller Lake is due to the coalescence of several ice-sinkhole basins and the presence of crevassed ice along a large part of the lake shore.

The development of the shore line of Miller Lake (D_L= 1.69) is indicative of the nature of the lake basin and its origin. This low value is characteristic of a lake basin that formed from several circular basins, either kettle holes or sinkholes (Hutchinson, 1957, p. 172).

Islands

The insulosity of a lake is the area within the shore line that is occupied by islands. Miller Lake has quite a low insulosity (A_i=12,442 m.^{2}). At the time of this study (June-August 1963) there were three islands in the lake, two of which were ice-cored islands covered with debris, while the third was a pile of boulders. The ice islands are unstable features and are subject to a brief existence. Analysis of air photos taken in 1959 indicates that these particular ice islands were not present as islands at that time (see Fig. 5). The formation of these ice-cored islands is probably related to the ablation till present on top of the ice cliff (Reid and Callender, in preparation). Both these islands occupy positions only a few meters from the ice cliff. The ablation till slides down the ice slope due to ablation of the ice cliff and is deposited along the base of this slope in various localities. The debris acts as an insulator and inhibits the ablation of the underlying ice. As more and more debris slides down the slope, the protected area beneath the debris is expanded. At the same time, the ice cliff melts and recedes. The protected area is eventually transformed into an ice-cored island when the adjacent ice cliff has melted back a sufficient distance.

The third island was probably also ice-cored at one time but achieved a stable state sometime between 1950 and 1957. The island was not present in 1950 (see Fig. 3), but was present in 1957 (see Fig. 4). It is assumed that the island has been fairly stable since 1957 as it appears on aerial photos taken in 1957, 1959, and 1963 with very little evident change in shape. This island was probably formed in a manner similar to that of the other islands described above and acheived its present stable condition either when the ice in the core of the island completely melted, or if it is still ice-cored it became so well insulated that its rate of melting became extremely slow.

Shore processes

The modifications that occur in the form of a lake basin are due to both internal and external processes acting upon that basin (Hutchinson, 1957, p. 176). The effects of waves and currents, as well as the melting of ice, modify Miller Lake from within, while the calving of ice along its margin alters the lake from without.

The prevailing winds in the Miller Lake area come from the east-northeast. The velocity of the wind from this direction exceeded an estimated 10 mph on 25 days during the 1963 field season. Commonly the wind velocity at these times approached 20 mph. There were several days during this period on which the wind velocity attained a peak value in

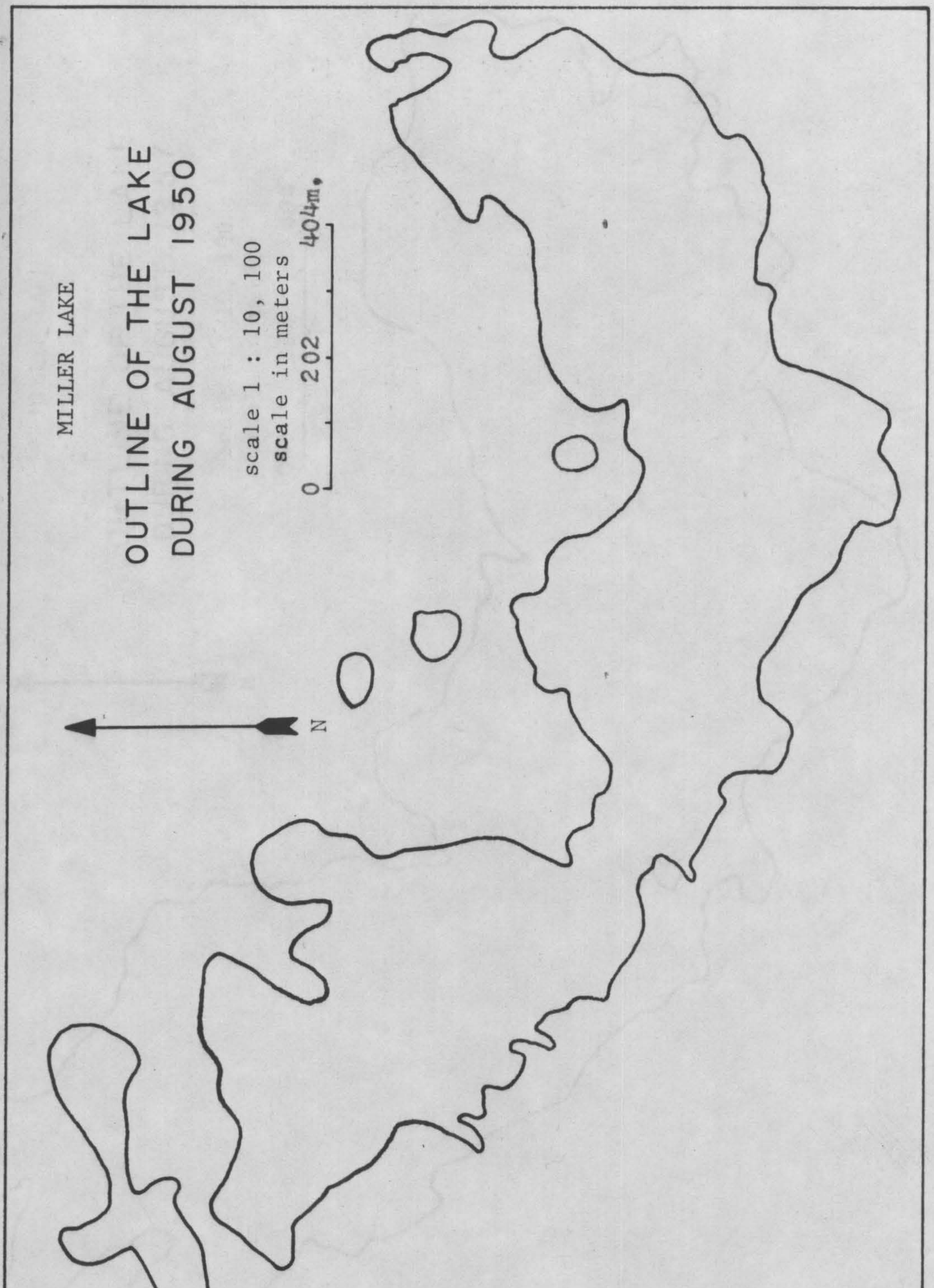


FIGURE 3. Outline of Miller Lake during August 1950.

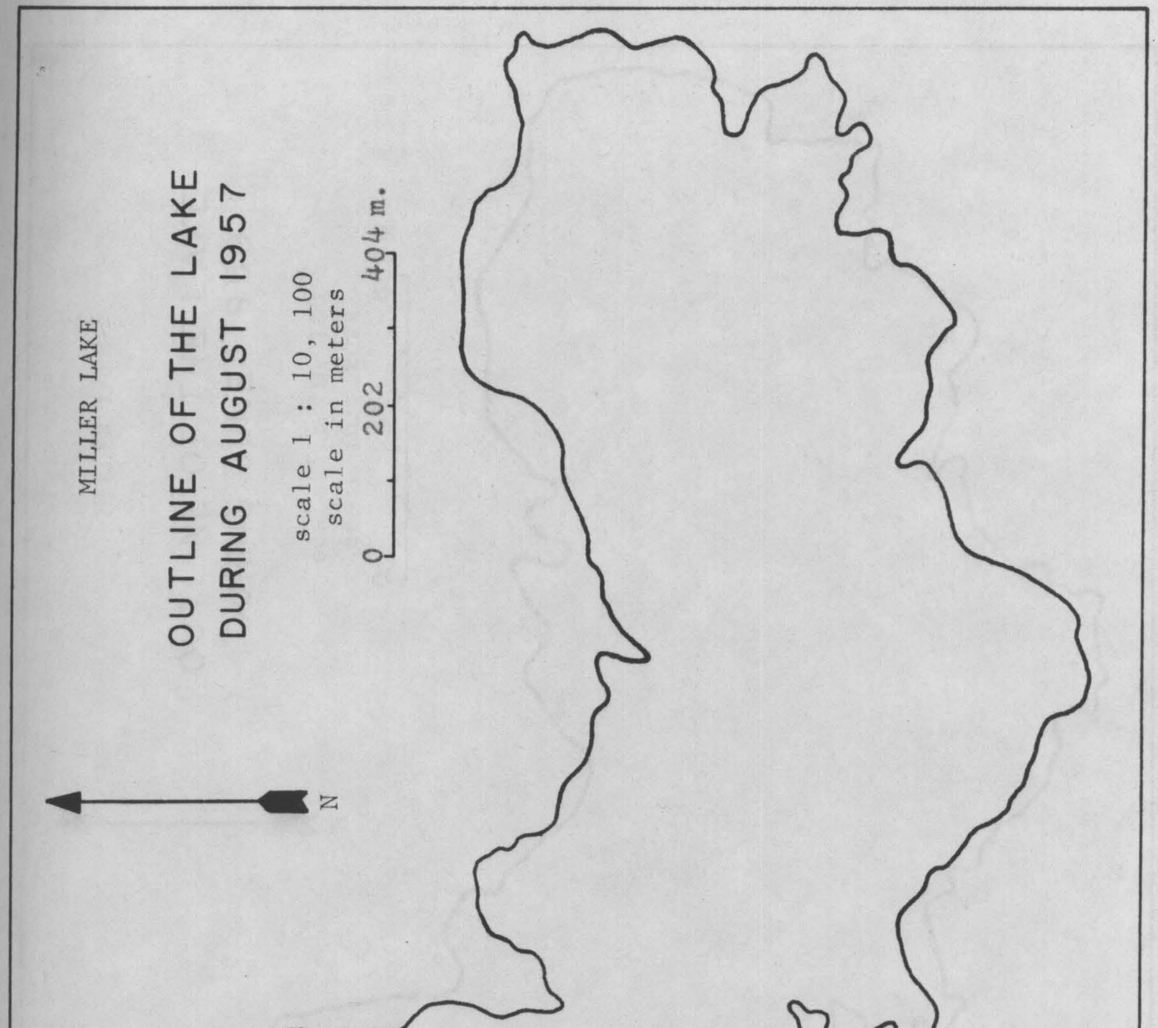


FIGURE 4. Outline of Miller Lake during August 1957.

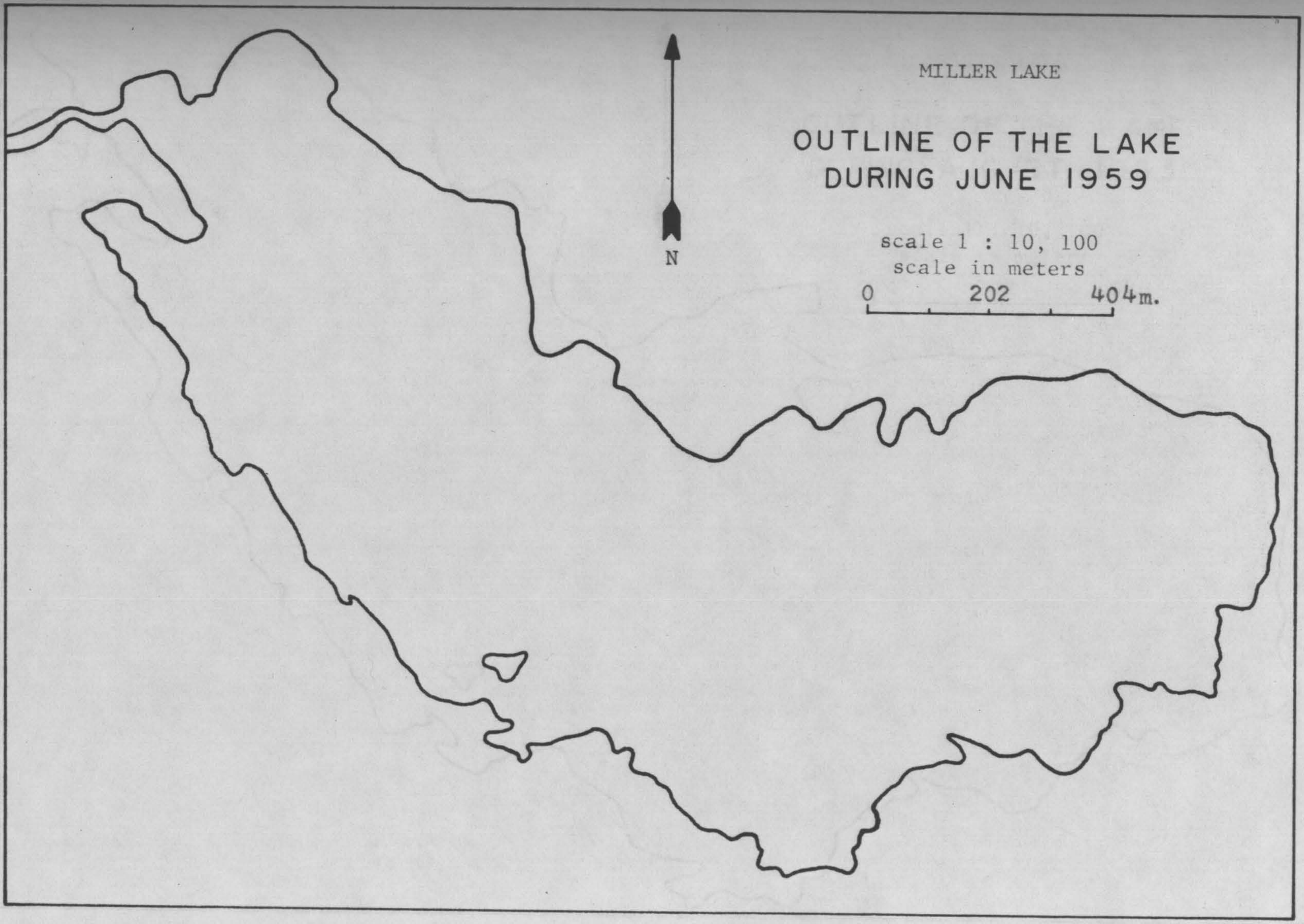


FIGURE 5. Outline of Miller Lake during June 1959.

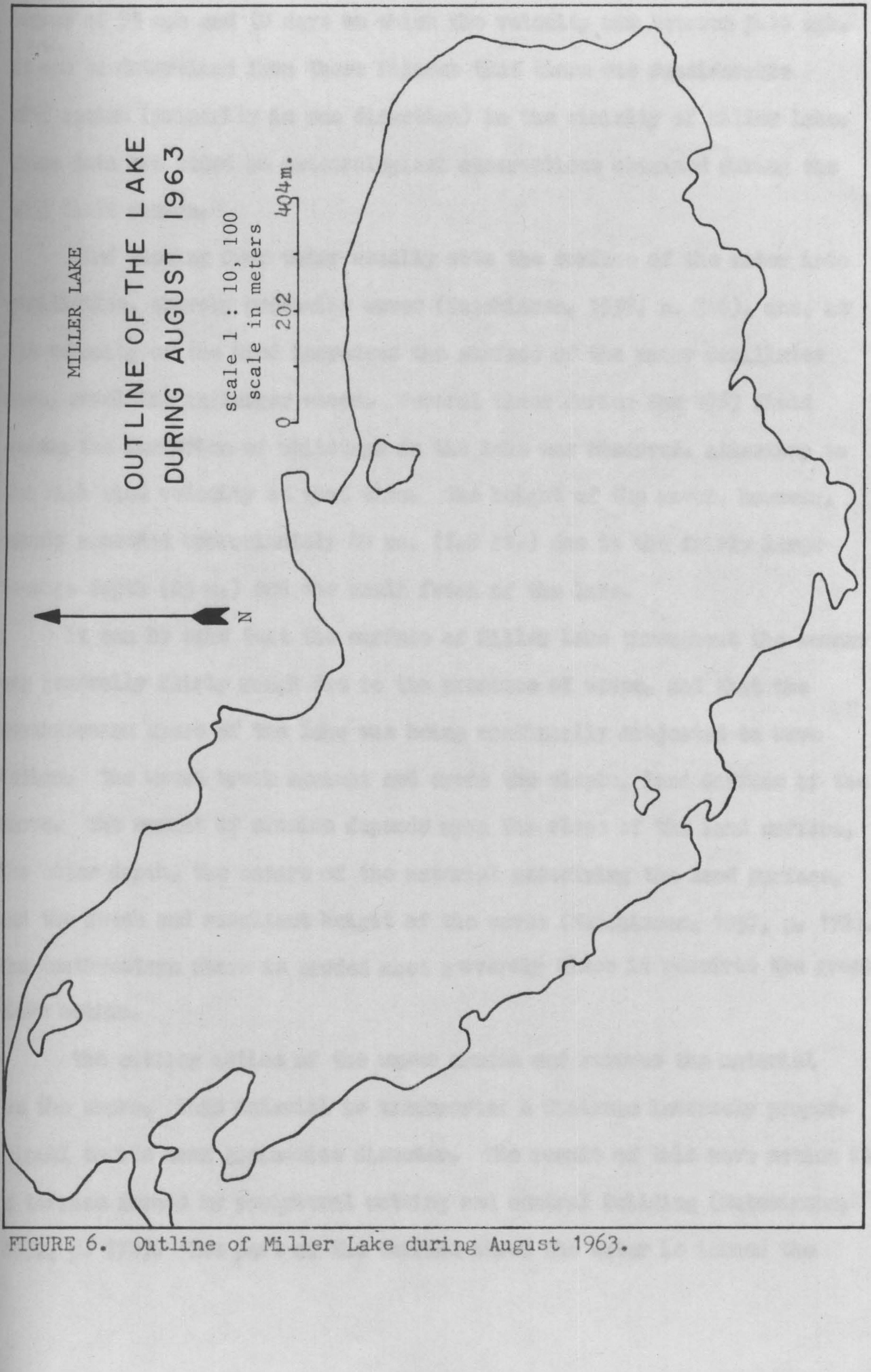


FIGURE 6. Outline of Miller Lake during August 1963.

excess of 35 mph and 10 days on which the velocity was between 5-10 mph. It can be determined from these figures that there was considerable wind action (primarily in one direction) in the vicinity of Miller Lake. These data are based on meteorological observations obtained during the 1963 field season.

Wind blowing over water usually sets the surface of the water into oscillation, thereby producing waves (Hutchinson, 1957, p. 346), and, as the velocity of the wind increases the surface of the water oscillates more, resulting in larger waves. Several times during the 1963 field season the formation of whitecaps on the lake was observed, attesting to the high wind velocity at that time. The height of the waves, however, rarely exceeded approximately 40 cm. (1.2 ft.) due to the fairly large average depth (25 m.) and the small fetch of the lake.

It can be said that the surface of Miller Lake throughout the summer was generally fairly rough due to the presence of waves, and that the southwestern shore of the lake was being continually subjected to wave action. The waves break against and erode the sloping land surface of the shore. The amount of erosion depends upon the slope of the land surface, the water depth, the nature of the material underlying the land surface, and the fetch and resultant height of the waves (Hutchinson, 1957, p. 178). The southwestern shore is eroded most severely since it receives the greatest wave action.

The cutting action of the waves erodes and removes the material on the shore. This material is transported a distance inversely proportional to its mean grain-size diameter. The result of this wave action is a terrace formed by peripheral cutting and central building (Hutchinson, 1957, p. 178). The part of the terrace above the water is termed the beach, while the part below water is called the littoral shelf. There is a fairly extensive littoral shelf being formed in the southwestern part of Miller Lake (see Plate 1).

Generally, there is a straightening of the shore line along most of the margin of the lake. Along the southern shore this straightening is accomplished by wave action. The waves act particularly strongly on projections in the shore line and tend to erode these more quickly than the areas in between. In fact, while the projections are being eroded, material is being deposited in the coves and areas between these points. The overall effect of this erosion and deposition is to straighten the shore line. The straightening of the southwestern shore (consisting of drift-covered stagnant ice) is aided by its relative stability in this region which allows the action of the waves to modify the shore line without interruption by melting ice.

The shore line around the rest of Miller Lake is generally more irregular due to the presence of active ice which is found either on the surface or lying only a few centimeters (several inches) below the surface. An ice cliff is present along the western, northern, and eastern shores of the lake (see Figs. 7 and 8). In most localities this cliff has very steep walls rising nearly straight up from the water surface (see Fig. 7). The height of this cliff ranges from 12 to 41 m. (39 to 134 ft.) and averages 25.5 m. (84 ft.). It is generally not as high or as steep along the extreme western margin of the lake.

The shore line in these areas where the margin of the lake consists predominantly of ice is modified by ice calving from the ice cliff. This calving from the cliff is controlled primarily by the crevasse pattern in the ice near the margin of the lake. Figure 9 shows this crevasse

FIGURE 7. Photograph of ice cliff along northern margin of Miller Lake.

FIGURE 8. Photograph of ice cliff along northern margin of Miller Lake.

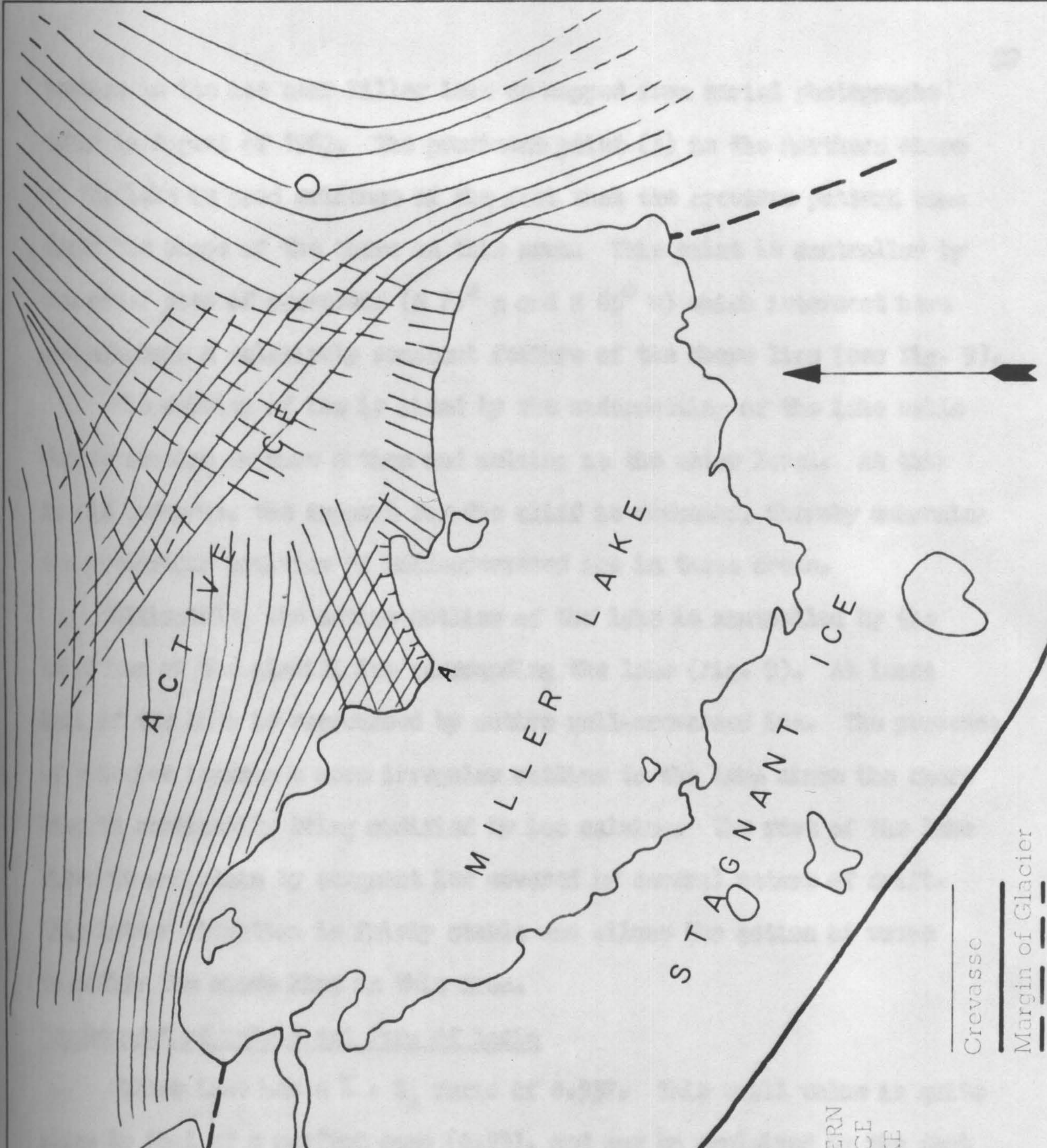


FIGURE 9. Crevasse pattern and condition of the ice surrounding Miller Lake.

pattern in the ice near Miller Lake as mapped from aerial photographs taken in August of 1963. The prominent point (A) in the northern shore of the lake is good evidence of the fact that the crevasse pattern controls the shape of the shore in this area. This point is controlled by two major sets of crevasses (N 70° E and N 65° W) which intersect here and maintain a relatively constant feature of the shore line (see Fig. 9).

The calving of ice is aided by the undercutting of the lake walls due to erosion by wave action and melting at the water level. As this ice is undercut, the support for the cliff is weakened, thereby enhancing the precarious position of well-crevassed ice in these areas.

Ultimately, the entire outline of the lake is controlled by the condition of the glacial ice surrounding the lake (Fig. 9). At least half of the lake is surrounded by active well-crevassed ice. The presence of this ice imparts a more irregular outline to the lake since the shore line is continually being modified by ice calving. The rest of the lake shore is underlain by stagnant ice covered by several meters of drift. This latter situation is fairly stable and allows the action of waves to modify the shore line in this area.

Development of volume and form of basin

Miller Lake has a $\bar{Z} : Z_m$ ratio of 0.357. This small value is quite close to that of a perfect cone (0.33), and may be explained by the fact that the lake basin is characterized by several deep holes, representing sinkholes, occupying a larger, more shallow basin. At one time, when the lake basin consisted essentially of three adjoining sinkholes, the $\bar{Z} : Z_m$ ratio for the lake probably more nearly approached 0.33. The ideal shape, (a conical basin) exemplified by the original sinkholes, has been modified by wave action, melting and calving of ice, movement of the glacial ice in this area, and sedimentation.

Origin

Origin of the lake basin

Miller Lake basin originated as several ice depressions that were located adjacent to one another. These depressions were formed by the melting action of glacial meltwater which percolated downward along joints and crevasses, especially in areas of intersecting joints where the meltwater encountered least resistance. These joints and crevasses were slowly enlarged by solution (melting of the ice) into holes whose shapes were controlled by the minor structural features of the ice (Sparks, 1960, p. 155; Renaud, 1936).

There are two main types of solution holes formed in the above-mentioned manner: funnel-shaped depressions with a hole in the center (sinkholes); and shaft-like holes (moulins). It seems possible that with continued melting a moulin could eventually attain a more funnel-like shape and thereby be classified as a sinkhole. In any case, Miller Lake basin originated as several adjoining sinkholes that enlarged due to continued melting and eventually coalesced to form a compound sinkhole which may or may not be equivalent to an uvala. Even though Miller Lake does not presently have a major surface influent, it might possible have a major underground (englacial and subglacial) influent and therefore at one time had a stream flowing through the compound sinkhole, a situation which would justify the usage of the term "uvala" in describing this basin. In order to avoid speculation concerning the exact origin of Miller Lake basin, the term "compound sinkhole" will be applied to this feature. Many smaller ice-sinkhole lakes located farther up on the glacier have an origin similar to that of Miller Lake.

Origin of features within the lake basin

The steep-sided depressions described in an earlier section probably originated in one of two different ways. Some are remnants of the original sinkholes that coalesced to form the compound sinkhole or new sinkholes that have formed due to continued melting of ice in the basin. Others may be depressions left by huge blocks of ice having broken away from the floor and sides of the lake basin. One such depression (the 55 m. deep rectangular basin located in the extreme northwestern part of the lake basin) originated in this latter fashion during the summer of 1963.

On July 14, 1963, a large block of ice broke away from the floor of the lake and rose to the surface where it remained as an iceberg (Reid and Callender, in preparation). This iceberg was approximately 350 m. (1150 ft.) long and 30 m. (100 ft.) wide. Subsequent depth soundings in the area revealed a depression 360 m. (1180 ft.) long, 60 m. (200 ft.) wide, and 20 m. (65 ft.) deeper than soundings taken in the same area earlier in the season.

The steep-sided hills located in many of these depressions are probably the sublacustrine equivalent of the "prairie mounds" found in glacial deposits of late Wisconsin age in the northern Great Plains of North America (Gravenor, 1955; Gravenor and Kupsch, 1959). These hills were probably formed by the mass movement of superglacial drift down the sides of the lake basin into the sinkholes and subsequent inversion of topography due to the insulating effect of this material protecting the bottom of the depression and allowing the sides to melt more rapidly, thereby forming a hill surrounded by a depression.

The depressions occupying the top of several sublacustrine hills probably formed as a result of the more rapid melting of ice on the tops of these hills. As these hills are formed, debris slides down their sides and accumulates around the lower part of the hill. The top of the hill becomes exposed and the ice begins to melt more rapidly in this area. Continued melting will eventually produce a depression extending below the crest of the hill.

Evolution of the lake

As noted previously, it is postulated that Miller Lake basin was formed by the coalescence of several adjoining ice sinkholes. Since this occurred, the area of the lake has been steadily increasing as a result of melting and calving of ice along the shore of the lake and shore processes (mainly wave action) which have eroded the shore line.

An analysis of aerial photos of the Miller Lake area taken in 1950, 1957, 1959, and 1963 indicates that the rate at which the lake is enlarging is not uniform. The approximate areas of the lake during these years were obtained by planimetry using the outline of Miller Lake as it appeared on the aerial photos. Figures 3, 4, 5, and 6 show the outline of the lake during these periods . The area of the lake during 1950 was 0.73 km.^{2}. During 1957 it was 1.20 km.^{2}; the area was 1.22 km.^{2} during 1959; and during 1963 it was 1.30 km.^{2}. The rate of change during the first 8 years was 0.06 km.^{2}/year, 0.01 km.^{2}/year during 1957-1959, and 0.035 km.^{2}/year during the last 4 years. These different rates can probably be attributed to differing climatic conditions from year to year which caused changes in the rate of ablation and movement of the Martin River Glacier.

The volume of the lake is probably increasing with time due to the melting of ice beneath the lake basin. This is contrary to the situation in non-ice-controlled lake basins in which the volume of a lake decreases with time because of sedimentation and/or lowering of the water level.

In addition to an increase in the volume, the maximum depth of the lake is probably also being increased by melting of the lake bottom. Eventually, when the bottom of the lake is on solid ground, or when the thickness of the lake sediments becomes great enough to materially retard melting of the ice beneath the basin, the volume and maximum depth of the lake will begin to decrease due to sedimentation and possible cutting at the effluent, unless the rate of increase in area exceeds the rate of sedimentation.

Correspondingly, the mean depth of the lake is probably becoming larger due to the increase in volume, although this does not necessarily follow as the area is also increasing.

A factor useful in discussing the evolution of a lake outline is the ratio of the shore length (L) to the area (A). A steady decrease in the value of this ratio indicates that shore processes are straightening the shore line and changing the outline of the lake over a given period of time. The L : A value steadily decreases from 9 : 6 in 1950 to 6 : 1 in 1957; 5 : 7 in 1959; and 4 : 7 in 1963. This decrease indicates that the irregular shore line, so typical of compound sinkholes, is being straightened and that the outline of the lake is being changed from a subrectangular elongate shape to a more circular shape by the action of shore processes, melting, and ice calving from the shores of the lake.

PHYSICAL LIMNOLOGY

Physical limnology deals with the physical nature of a lake and generally includes the water balance, the hydromechanics, and the thermal properties of a lake. The investigation of Miller Lake, however, could not encompass a detailed study of the water balance nor determine the exact nature of waves, currents, and seiches in the lake because the project was not equipped to measure such phenomena. Consequently the discussion of these topics will be considerably more generalized than the discussion concerning the thermal properties of the lake which were studied extensively during the 1963 field season.

Water balance

Miller Lake is located in an exoheric region where rivers arising in this area reach the sea. The lake lies within a drainage basin whose surface area is very small and is probably no more than twice the area of the lake. This lake, however, may drain a much larger area by receiving many englacial streams originating farther up the glacier. A few englacial streams were observed entering the lake. These streams may be only a fraction of the englacial influents as most of these streams probably enter the lake below water level. Therefore, the area that Miller Lake drains is impossible to estimate accurately.

The water balance of a lake is the relationship between the amount of incoming water from all sources and the amount of water loss (Hutchinson, 1957, p. 231). Miller Lake has several sources of incoming water, many of which are impossible to determine with any amount of accuracy. One of these is precipitation upon the lake surface. This source of water is large due to the location of Miller Lake in an area receiving yearly precipitation in excess of 80 inches. The largest source of incoming water for Miller Lake is glacial meltwater which enters the lake as either surface meltwater or englacial and subglacial streams. The amount of this meltwater source is impossible to determine, a fact which drastically hinders the estimation of the water balance of the lake.

Miller Lake may be classified as a drainage or open lake because it exhibits an outlet or effluent (Hutchinson, 1957, p. 231). Although the lake most certainly fills by sublacustrine channels, it may or may not drain by similar channels. Since such an occurrence was not witnessed during the past field season, it seems unlikely that this is the major mechanism of water loss for the lake. There are several ice sinkhole lakes located farther up on the glacier that do fill and drain by sublacustrine channels (Reid and Clayton, 1963). The main modes of water loss for the lake are discharge at the effluent, which appeared to be fairly large, and evaporation, which is probably fairly low in this area due to the low air and water temperatures.

Variations in lake level

Although there is probably an annual variation in the level of Miller Lake, this variation cannot be determined as no water level data were available. However there were pronounced daily and periodic fluctuations in the lake level. These fluctuations were recorded by a guage installed below the base camp by Dr. John R. Reid.

Figure 10 shows the daily variation in the lake level from June 24 to August 7, 1963. There is generally a significant rise in the level of the lake following a period of prolonged rain. During the period July 16 to 18, 3.88 inches of rain fell in the vicinity of Miller Lake. During a five-day period from July 16 to 20, 1963, the lake level rose nearly 40 cm. (15.7 inches). A similar but smaller rise in level

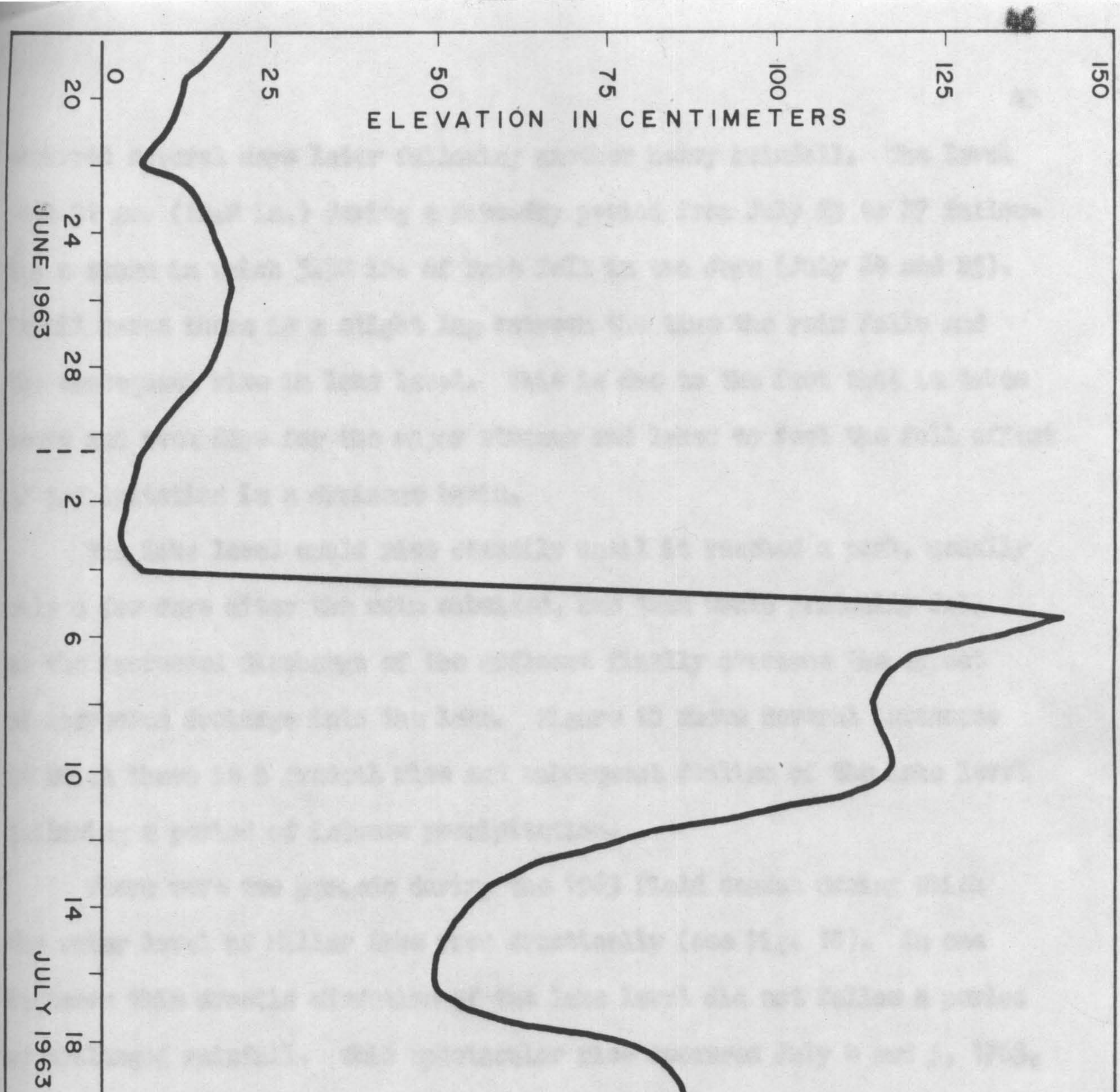


FIGURE 10. Fluctuations of the water level in Miller Lake June 18-Aug. 7, 1963.

occurred several days later following another heavy rainfall. The level rose 31 cm. (12.2 in.) during a five-day period from July 23 to 27 following a storm in which 3.32 in. of rain fell in two days (July 24 and 25). In all cases there is a slight lag between the time the rain falls and the consequent rise in lake level. This is due to the fact that it takes hours and even days for the major streams and lakes to feel the full effect of precipitation in a drainage basin.

The lake level would rise steadily until it reached a peak, usually only a few days after the rain subsided, and then would gradually fall as the increased discharge of the effluent finally overcame the effect of increased drainage into the lake. Figure 10 shows several instances in which there is a gradual rise and subsequent decline of the lake level following a period of intense precipitation.

There were two periods during the 1963 field season during which the water level of Miller Lake rose drastically (see Fig. 10). In one instance this drastic elevation of the lake level did not follow a period of prolonged rainfall. This spectacular rise occurred July 4 and 5, 1963, when the level of the lake rose 138 cm. (54.3 in.). The greater part of this rise occurred in 12 hours (from 12 noon to 12 midnight on July 4th) when the level rose 120 cm. (47.2 in.).

This spectacular rise was probably caused by the sudden draining of an ice sinkhole lake (or lakes) farther up the glacier. This phenomenon of rapid draining of ice sinkhole lakes was observed by several members of the research team during the summer of 1962 (Reid and Clayton, 1962). It has been estimated that one of these lakes drained at a rate of approximately one million gallons per minute (Reid and Clayton, 1962).

On the same day as the above-mentioned rise in level occurred, several members of the research party observed an event which indicated that one or more ice sinkhole lakes had in fact recently drained. A supraglacial stream, which had been barely more than a trickle several days earlier (Reid, oral communication, University of North Dakota), was discharging a large volume of muddy water. It seems quite likely that this large volume of water was a result of the rapid draining of one or more ice sinkhole lakes situated farther up on the glacier.

Currents and waves

Currents are movements of water maintained by the action of external forces, while seiches are periodic movements which tend to develop when the external forces cease to act (Hutchinson, 1957, p. 259). These water movements could not be measured directly, thus all evidence for the existence of such phenomena in Miller Lake is based upon thermal data. Although these thermal data are fairly complete, they are perhaps not detailed enough to detect discrete water movements. A few words, however, may be said concerning the possibility (indeed probability) of the general movement of water in the lake during the 1963 field season.

It seems probable that there were currents in Miller Lake at various times during the summer. These currents were probably wind-generated. When wind blows over a lake surface, it exerts a shearing stress at the air-water interface, resulting in the acceleration of the water. During periods of prolonged wind action, the water movement will result in the piling up of water in one part of the basin and a lowering of the water level in another part. The slope of the water surface produced by this wind denivellation will cause a gradient current to begin flowing (Hutchinson, 1957, p. 265).

These currents are normally measured by means of a current meter, but since such a device was not available to the expedition, another technique to indicate the existence of such currents must be relied upon. If such a current is produced whereby wind denivellation piles up water in one part of the lake basin and consequently depresses the water level upwind, then water will flow from the higher to the lower level resulting in a return current moving in an upwind direction. As this current returns to the surface of the lake, it brings deeper water (which is sometimes several degrees colder) to the surface. Thus, the resultant temperatures in the upper part of the lake will be noticeably lower in this upwind direction.

Such a situation is exhibited by Figure 11 which is a temperature profile across Miller Lake for July 23, 1963. Throughout the day a fairly strong wind (15-20 mph from the northeast) was blowing across the lake. As a result, water was piled up in the southern part of the lake and a current was created which flowed from the south to the north across the lake basin and returned to the surface with colder water brought from deeper parts of the lake. The temperature of the water in the upper 10 m. was 1-1.5°C warmer in the southern part of Miller Lake than in the northern part. Although this temperature cross-section is by no means absolute proof of a current, these data indicate some type of water movement in the lake during this period. These data, coupled with the observed wind action at this time, provide significant evidence for the existence of currents in the lake during July 23, 1963. Many such currents were generated by continuous wind action that occurred throughout the summer in the Miller Lake area.

These gradient currents will continue as long as the wind produces an uneven water level. After the wind has subsided the water level will

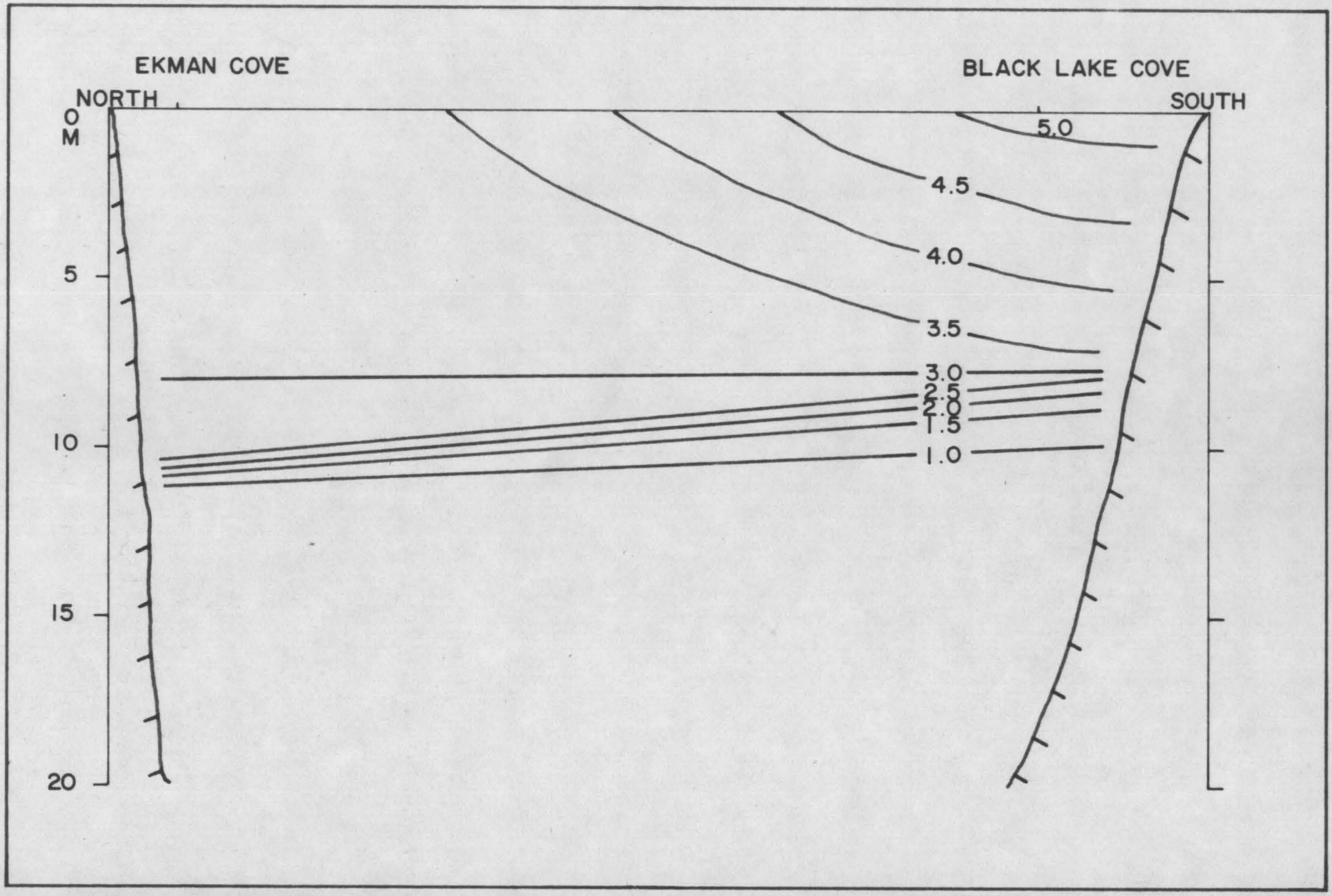


FIGURE 11. Temperature profile across the middle of Miller Lake, July 23, 1963, showing upwelling of colder water in the northern part of the Lake. Isotherms are in degrees centigrade.

tend to return to equilibrium; this is accomplished by gradient currents. Water flows from the leeward area to the windward area and, since little momentum is lost in this process, a new flow starts from the former windward end to the former leeward end (Hutchinson, 1957, p. 365). Thus a periodic rocking motion or seiche is produced. Seiches can be measured by simultaneous recordings of the lake level at various localities around the lake or by vertical temperature measurements taken simultaneously at two opposite points on the lake. The periodic rocking motion of the seiche will vertically displace the isotherms (lines of equal temperature) in the lake. Although simultaneous vertical temperature readings could not be taken on Miller Lake, readings were taken approximately 10-15 minutes apart at two stations located on opposite sides of the lake. This procedure was followed several times during the month of July. Figure 12 shows a temperature profile (constructed from these thermal records) for Miller Lake on July 24, 1963. This profile shows the displacement of isotherms (generally 4 to 10 m.) during that time. There had been a fairly strong wind (15-20 mph blowing from the northeast across the lake on the previous day, and there was a moderate wind blowing on the day on which these readings were taken. The existence of currents in the lake at this time may modify the position of the isotherms in the upper 10 m., but the position of the lower isotherms seems to indicate vertical displacement of the water body in the lake basin. Many such seiches were caused by wind denivellation during the 1963 field season.

The size of waves on Miller Lake depends largely upon the fetch (distance over which the wind has blown) and the velocity of the wind (Hutchinson, 1957, p. 352). The waves on the lake were never very large; the highest probably not over 45 cm. (1.5 ft.) and the wave length not

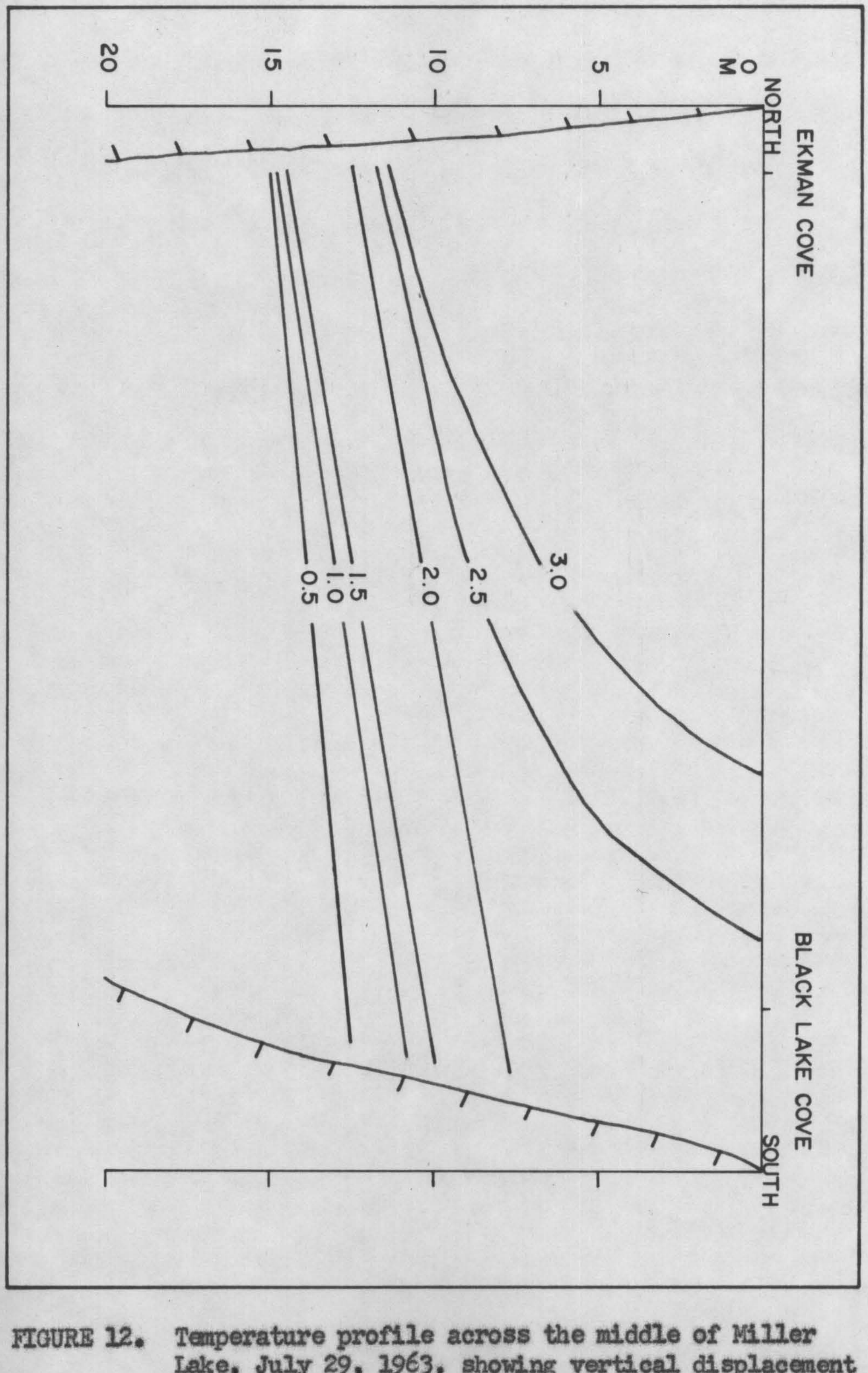


FIGURE 12. Temperature profile across the middle of Miller Lake, July 29, 1963, showing vertical displacement of isotherms. Isotherms are in degrees centigrade.

more than 5-6 m. (17-20 ft.). There were only three times throughout the 1963 field season when whitecaps were observed on the lake. They occurred during storms when the wind reached moderate gale force (30-40 mph). The waves generated during these storms are sufficiently large to erode material to a depth of approximately 3 m. (Kuenen, 1950, p. 81). The erosion of the projections and associated central deposition between these projections caused by this wave action have resulted in the formation of a beach and littoral shelf along the relatively stable southwestern shore.

Thermal properties of the lake water

Methods of study

The thermal structure of Miller Lake was investigated using a Whitney Thermometer, a thermistor resistance-type thermometer. This thermometer enables continuous vertical temperature readings to be taken and accurate temperature curves for the lake to be constructed. Vertical temperature measurements were made, usually at several stations, throughout the 1963 field season. There were a total of 18 days when measurements were not made as the thermometer was not available, but this gap in the thermal data did not seriously affect the reconstruction of the thermal structure of Miller Lake.

On several days during the 1963 field season the vertical temperature distribution within the lake was measured at 10 localities and the data obtained were used to make an isothermal analysis of Miller Lake.

Mean temperature curves were constructed for Miller Lake using values obtained from electronic computer reduction of the entire thermal data collected during the 1963 field season. The mean temperatures and standard deviation from these means for the upper 30 m. of the lake are presented in Table 5. There are five basic mean temperature curves representing five thermal periods for Miller Lake during the 1963 field season. These mean temperature curves are important in determining the thermal history of the lake during that period.

Thermal stratification

The temperature of water in moderately deep lakes during the winter is relatively uniform from top to bottom (Reid, 1961, p. 110). If the lake is covered by ice the temperature of the water directly beneath the ice is somewhat lower than that below this layer. In the spring increased solar radiation and warmer air temperatures accompanied by winds melt the ice and warm the surface waters. Convection currents and wind circulate and mix the water resulting in a uniform temperature from surface to bottom (usually at the temperature of maximum density, 4°C.). This vernal process of mixing and circulation is called spring overturn.

Continued heating of the surface waters during the spring and early summer results in the division of the lake into an upper region of warm, circulating water which is relatively uniform in temperature, the epilimnion, and a deep, cold, relatively undisturbed region termed the hypolimnion (Hutchinson, 1957, p. 428). The region of rapid temperature decrease separating the relatively warm epilimnion from the relatively cold hypolimnion is called the metalimnion, and contains the zone in which the temperature gradient is steepest, the thermocline. This type of thermal distribution is most characteristic of moderately deep to deep lakes situated in temperate regions (Reid, 1961, p. 110). The thermal condition of the lake exhibited by this distribution is called summer thermal stratification.

There has been considerable disagreement concerning the concept of the thermocline. Birge (from Hutchinson, 1957, p. 428) defined it as that layer in which the fall in temperature exceeds $1^{\circ}C$ per meter. Modern limnologists consider the thermocline a plane of maximum rate of decrease in temperature (Reid, 1961, p. 112). This plane, or very narrow zone is considered a zone of shear where an infinite number of minute water particles slide over one another as a result of large density differences between adjacent minute planes. The thermocline constitutes an effective barrier between the epilimnion and the hypolimnion, preventing the mixing of heat, currents, and nutrients throughout the lake.

The intensity of thermal stratification is a measure of the stability of the lake. The stability of stratification is the expenditure of energy necessary to destroy an existing stratification allowing complete mixing of the whole water mass (Ruttner, 1963, p. 32). The idea of stability gives a value for the resistance of a given thermal stratification to the mixing effect of the wind. Thus a lake that exhibits a well developed thermal stratification will have a large thermal resistance to mixing, while a lake that has a poorly developed stratification will exhibit a low resistance to mixing by the wind.

Thermal structure of Miller Lake

The density of the water in Miller Lake is controlled not only by temperature, but also by the concentration of suspended material. This suspended material is composed wholly of inorganic particulate matter of clay and colloid size. Since thermal stratification results from density differences, this fact is of the utmost importance. Although good thermal stratification may not form due to low temperatures in the lake, this stratification may be aided by large density differences caused by significant vertical changes in the concentration of suspended material.

The presence of ice beneath most of the lake basin has a pronounced effect upon temperatures within Miller Lake. The cooling effect is reduced somewhat by the insulating effect of the lake sediments. However, the insulating effect is probably not too significant throughout most of the lake basin.

During the month of June the lake waters were essentially homiothermal. Figure 13 shows the mean temperature curve for Miller Lake during the period June 5 to July 1, 1963. This curve shows that the temperature of the water was fairly uniform from top to bottom, cooling 0.5°C one meter above the bottom. This period represents warming of the lake from the winter minimum temperature which was probably near 0°C. Increased solar radiation and day length, accompanied by warmer air temperatures, warm the surface waters of the lake during the spring and early summer. As the surface waters warm up they become more dense and a slight temporary stratification is produced that sets up convection currents. These currents, aided by the wind, mix the lake water throughout the basin until the water is essentially homiothermal. Figure 14 shows a temperature curve for Miller Lake on June 7, 1963. The mean temperature of the water at that time was approximately 1.7°C. Figure 15, the temperature curve for Miller Lake on June 15, 1963, shows a mean water temperature near 1.9°C. This curve also exhibits some incipient stratification at 16 m., but this stratification is so slight that there will be essentially no thermal resistance to mixing. These two curves indicate that the lake was warming up slowly. This slow rate of warming is due to the fact that the average temperature for June, 1963, was relatively low (47°F) and that the insolation for that period was also quite low.

During the first two weeks in July, Miller Lake warmed up considerably and developed some incipient thermal stratification which was

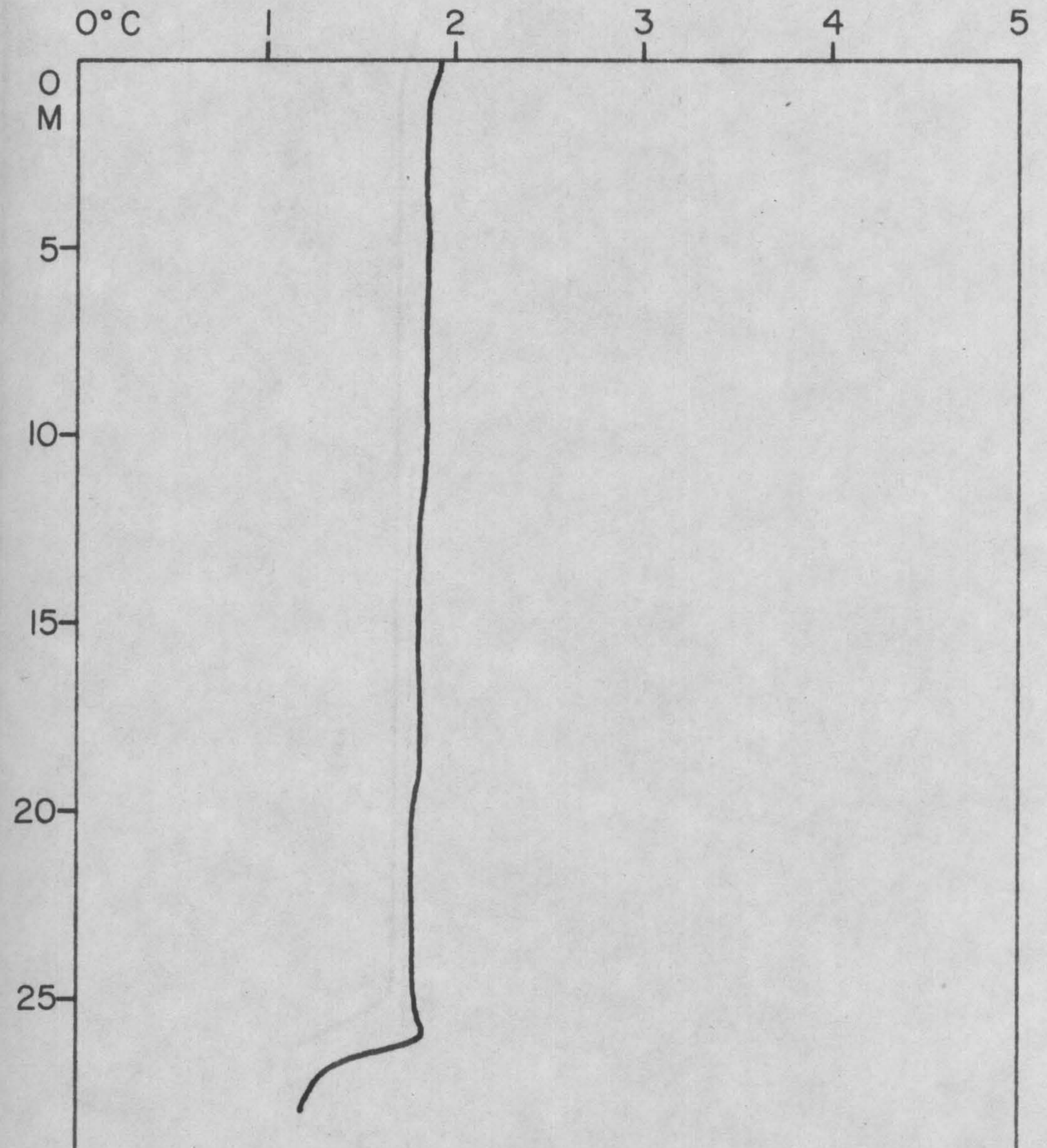


FIGURE 13. Mean temperature curve for Miller Lake during the period June 5 to July 1, 1963.

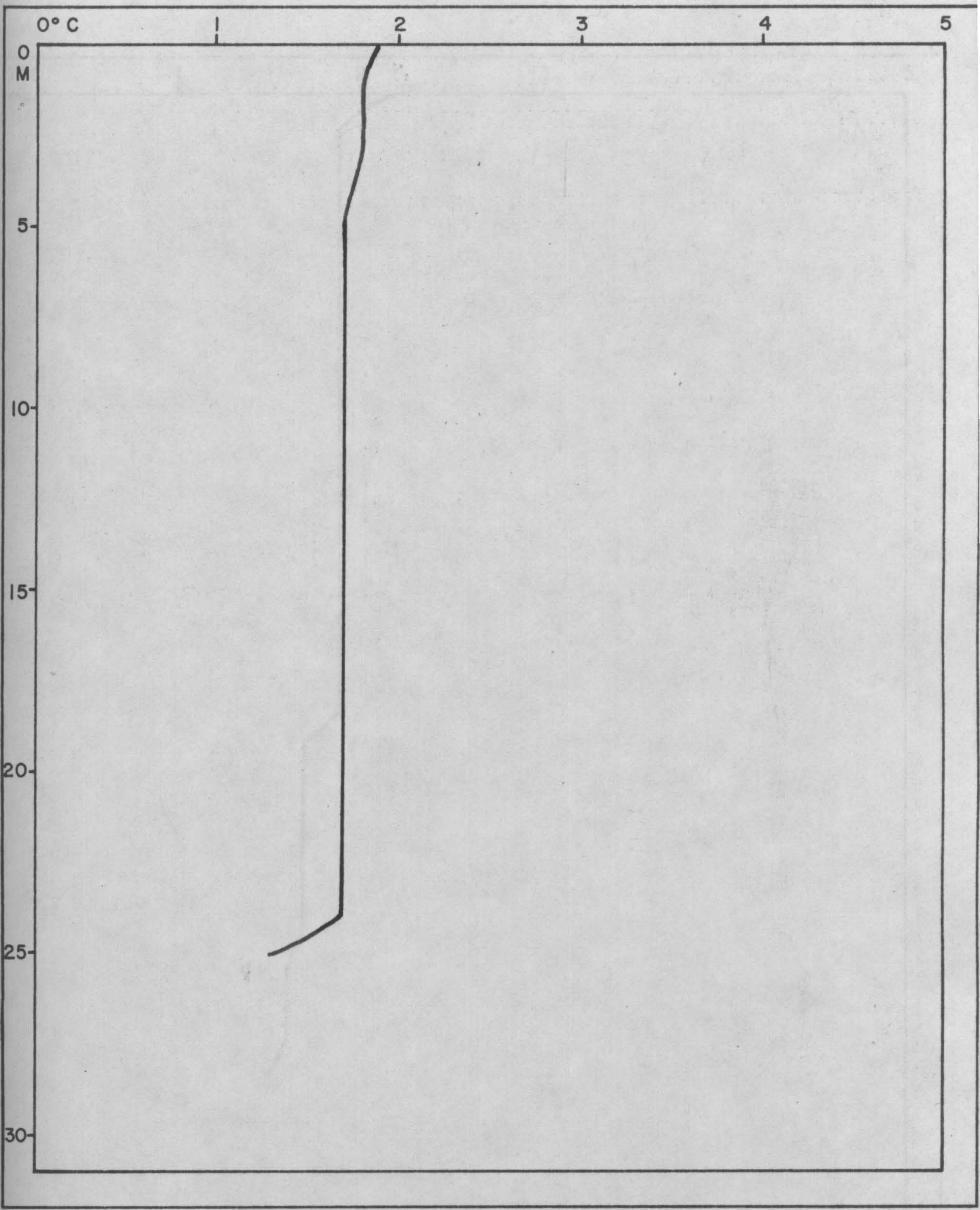


FIGURE 14. Temperature curve for Miller Lake, June 7, 1963; note homiothermal condition.

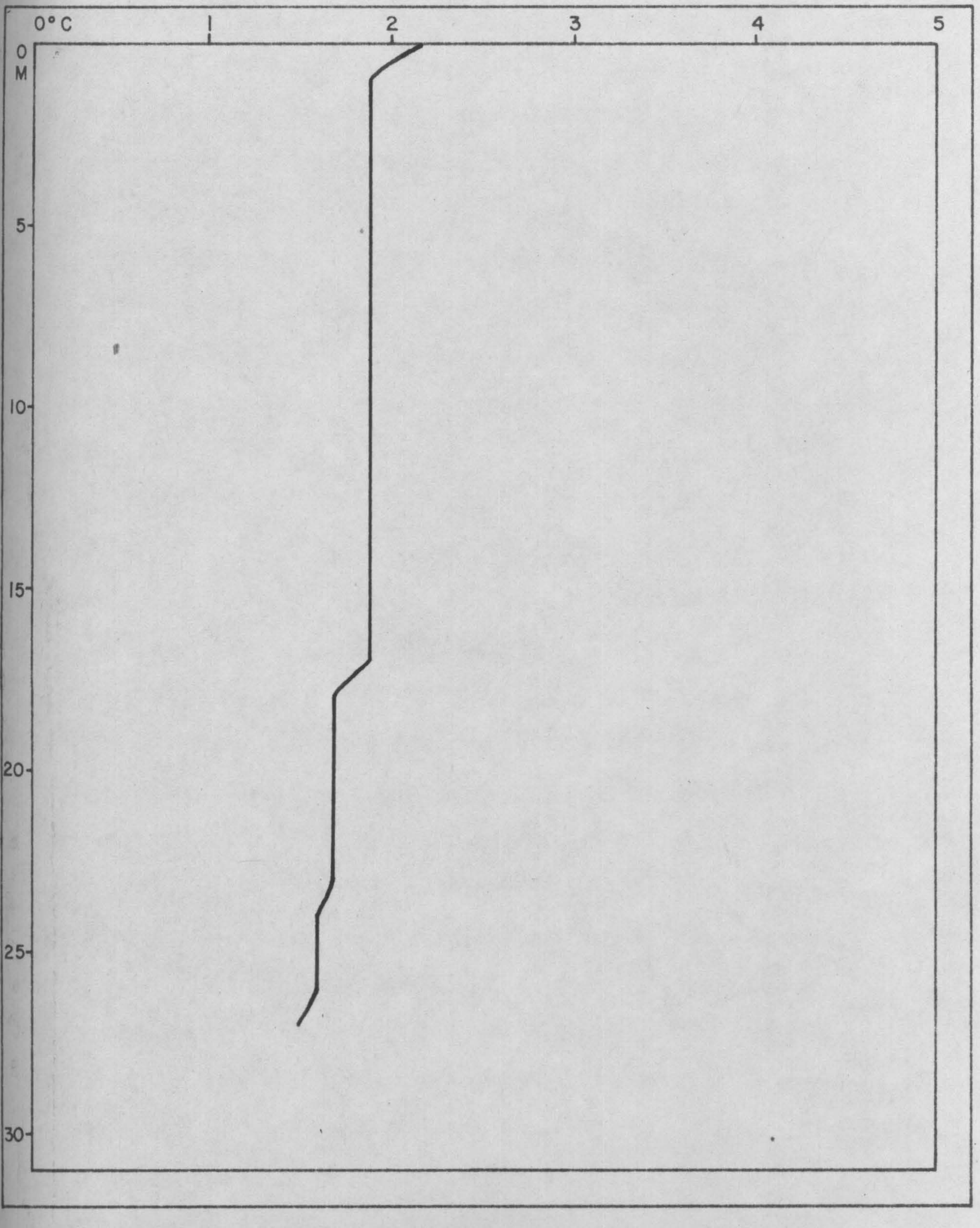


FIGURE 15. Temperature curve for Miller Lake, June 15, 1963; note homiothermal condition.

often destroyed by the wind. Generally, however, the lake still exhibited a more or less homiothermal condition as illustrated by Figure 16, which shows that the upper 20 m. of water has a relatively uniform temperature near 3.2°C. This represents an overall warming of 1.3°C in the upper 20 m. of water. This increase of 1.3°C represents the 3715 x 10^{11} calories of heat income necessary to raise the mean temperature of Miller Lake by this increment. This heat income is approximately one fourth the annual heat income for the lake. The warming is due mostly to higher air temperatures in the Miller Lake area and greater insolation (average temperature for July, 1963, is 51°F).

The presence of a deep metalimnion (shown in Figure 17) indicates that the lake was beginning to stratify thermally. The thermocline was originally at a higher position in the lake, but continuous wind action drove this zone down to a relatively deep position.

During the middle part of July, 1963, the upper 10 m. of the lake continued to warm. As the upper layers of water are warmed, the density difference becomes greater between adjacent layers and the resistance to mixing subsequently increases. Figures 18 and 19 are mean temperature curves for Miller Lake during the middle part of July. These curves illustrate the poor stratification of the lake and show that no real thermocline exists. In fact, there is a more or less gradual decrease in temperature with depth in the upper 15 m. of the lake. The following 15 m. of water, however, exhibit an essentially homiothermal condition, the temperature approaching a uniform 0.1°C. This extremely low temperature indicates that the water at these depths is affected by the presenceof ice beneath the lake basin and sublacustrine influents bringing icy meltwater into the lake.

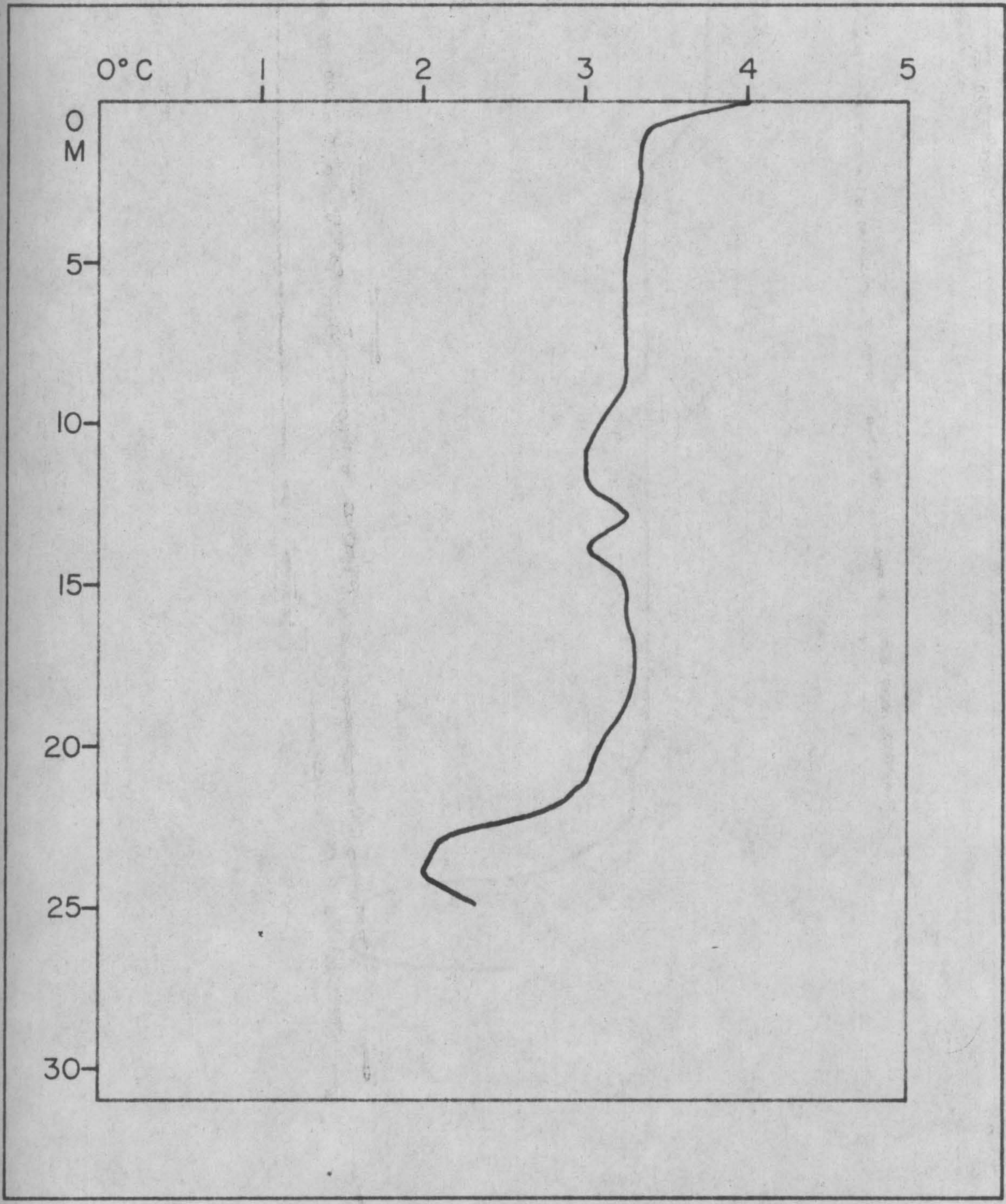


FIGURE 16. Mean temperature curve for Miller Lake during the period July 1 to July 15, 1963.

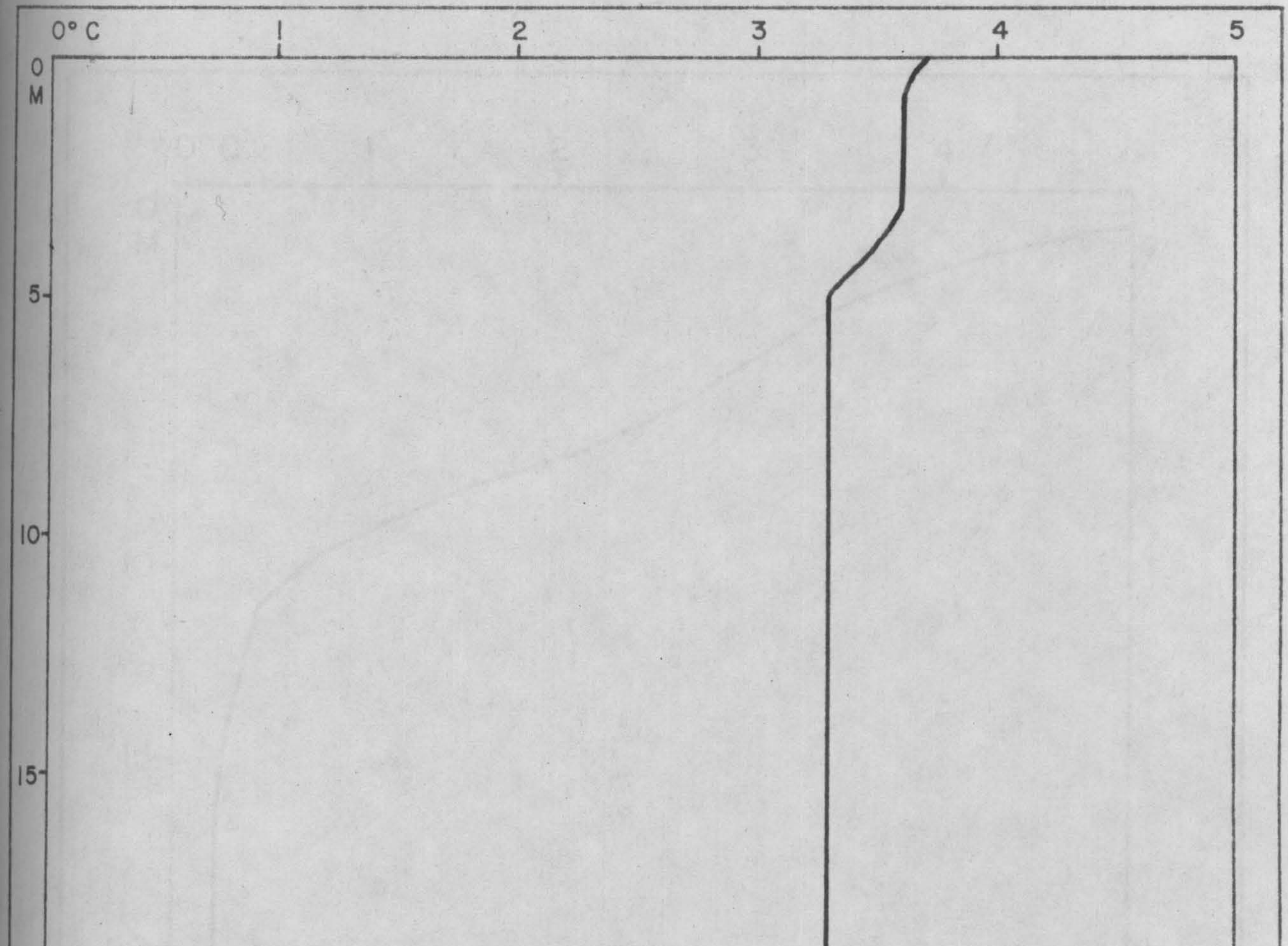


FIGURE 17. Temperature curve for Miller Lake, July 5, 1963; note deep thermocline.

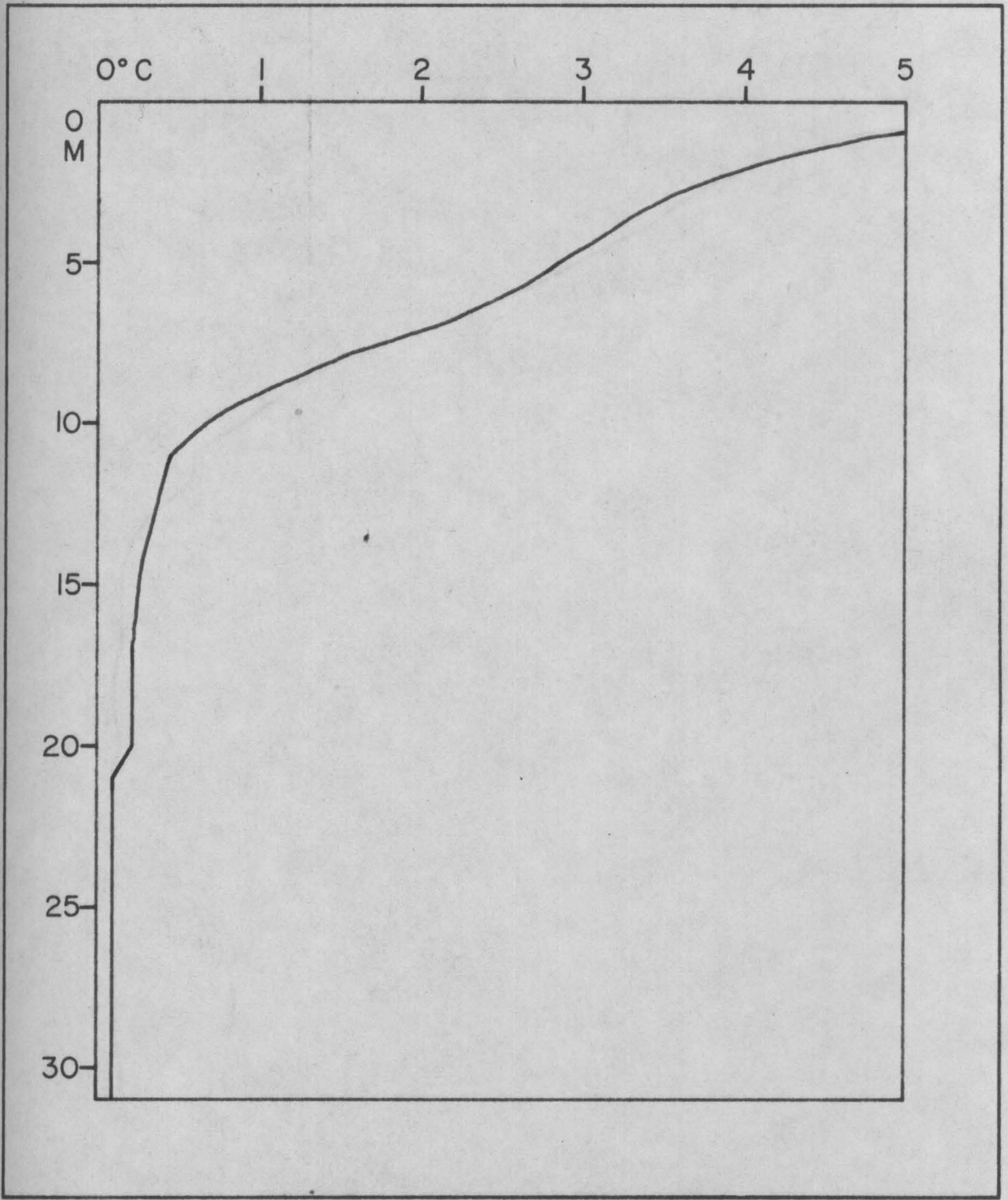


FIGURE 18. Mean temperature curve for Miller Lake during the period July 15 to July 20, 1963.

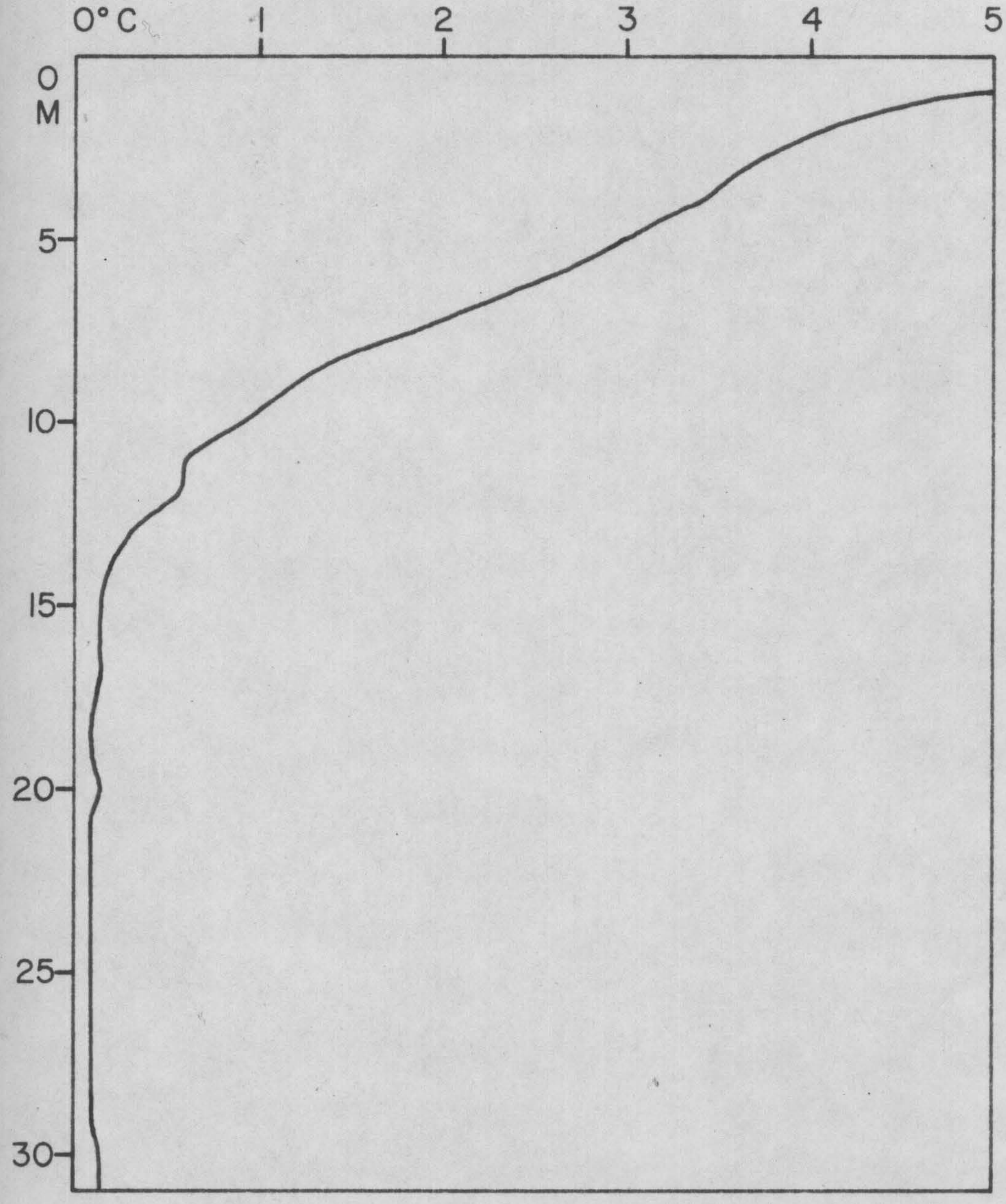


FIGURE 19. Mean temperature curve for Miller Lake on July 20, 1963.

There were, however, several days on which Miller Lake was thermally stratified, but subsequent stormy weather accompanied by strong winds and lower air temperatures partially destroyed this stratification. Figure 20 shows a temperature curve for the lake on July 18, a day on which the skies were partly cloudy and there was essentially no wind. A brief glance at this curve shows that the lake is relatively well stratified with a moderately warm (at least for Miller Lake) epilimnion, a 2 m. thick thermocline, and a very cold homiothermal hypolimnion.

Figure 21 shows the mean temperatures for Miller Lake during the period July 20 to August 5, 1963. This curve is quite similar to Figure 18 except that the overall temperature of the upper 15 m. of water was nearly 1°C warmer during the end of July to the first of August than during the middle of July. This is due to the general increase in air temperature and insolation throughout the month of July and the first part of August. The lake is still poorly stratified with a relatively warm upper zone, approximately 15 m. thick, and a very cold lower zone. There were many days during this period when Miller Lake was somewhat thermally stratified. Figure 22 shows a temperature curve taken in the middle part of the lake on July 22, 1963. This curve shows that the lake is relatively well stratified at this time. The weather on this day was mild with partly cloudy skies, a slight breeze, and a maximum temperature of nearly 58°F. Figure 23 shows another temperature curve for July 22, which was taken in a cove on the south-central shore of the lake. As shown by these two figures, the water in this area was even better thermally stratified than throughout the rest of the lake.

The values for standard deviation from the mean temperature of each 1 m. stratum of water in Miller Lake (down to 31 m.) indicate the

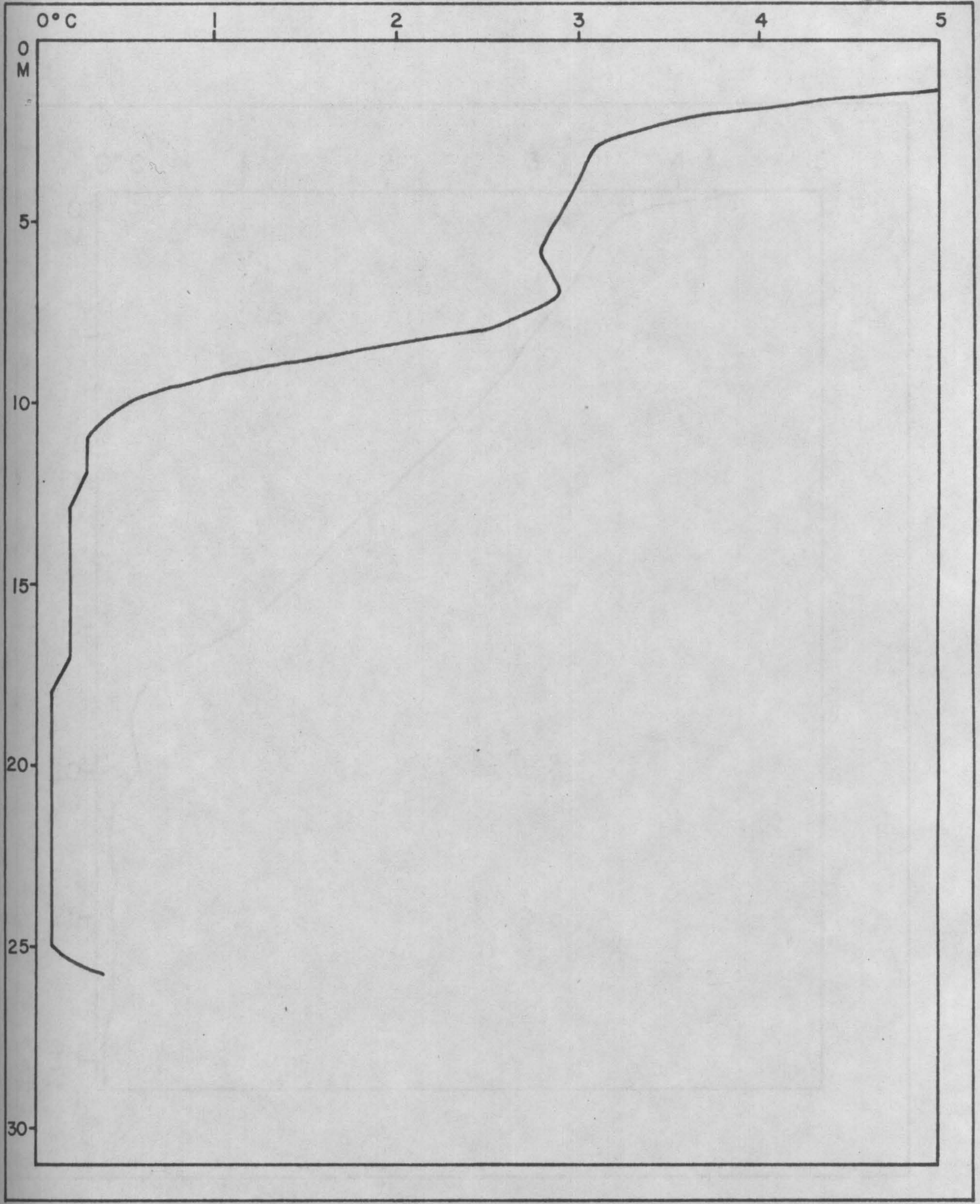


FIGURE 20. Temperature curve for Miller Lake, July 18, 1963; note thermal stratification.

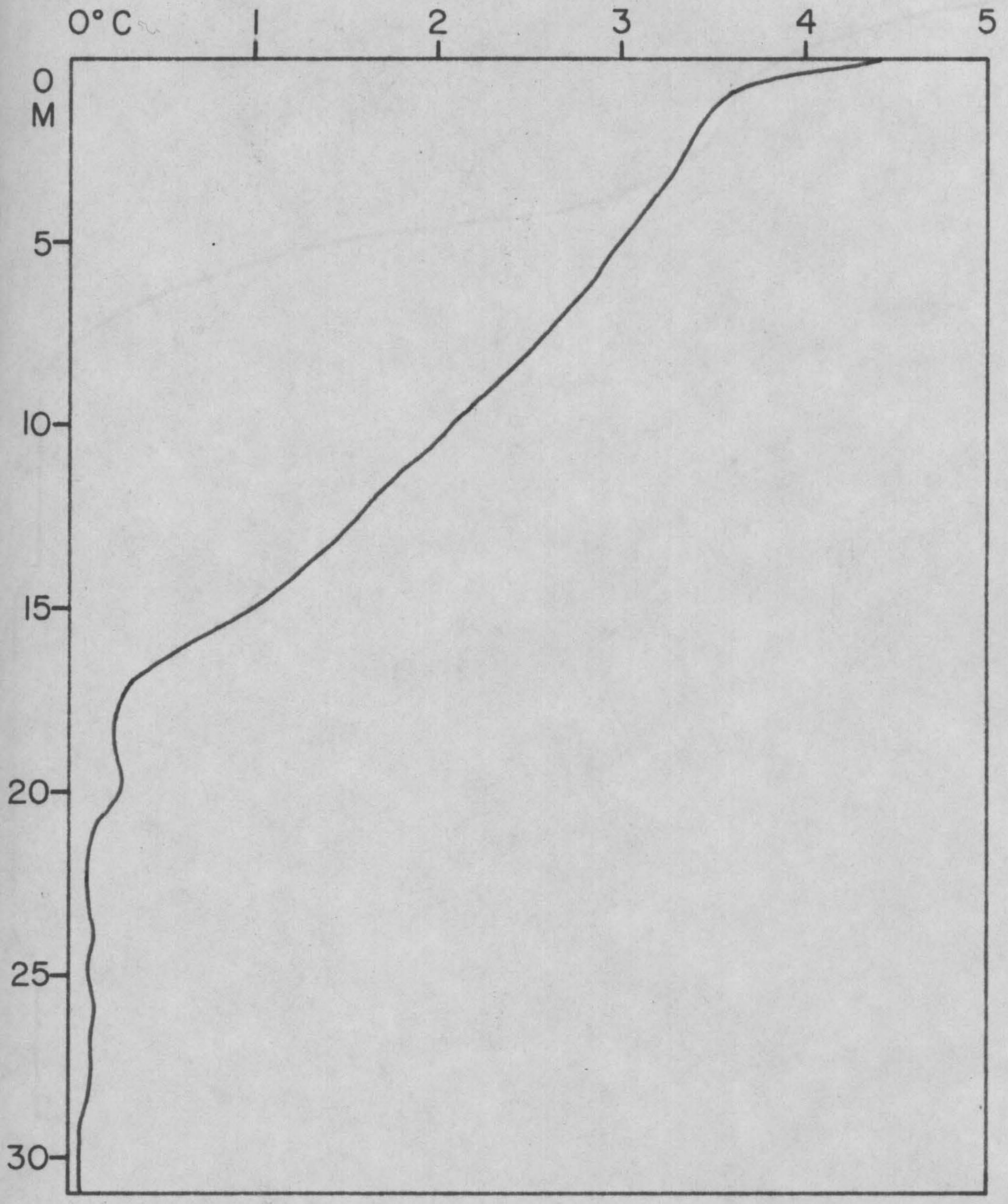


FIGURE 21. Mean temperature curve for Miller Lake during the period July 20 to August 5, 1963.

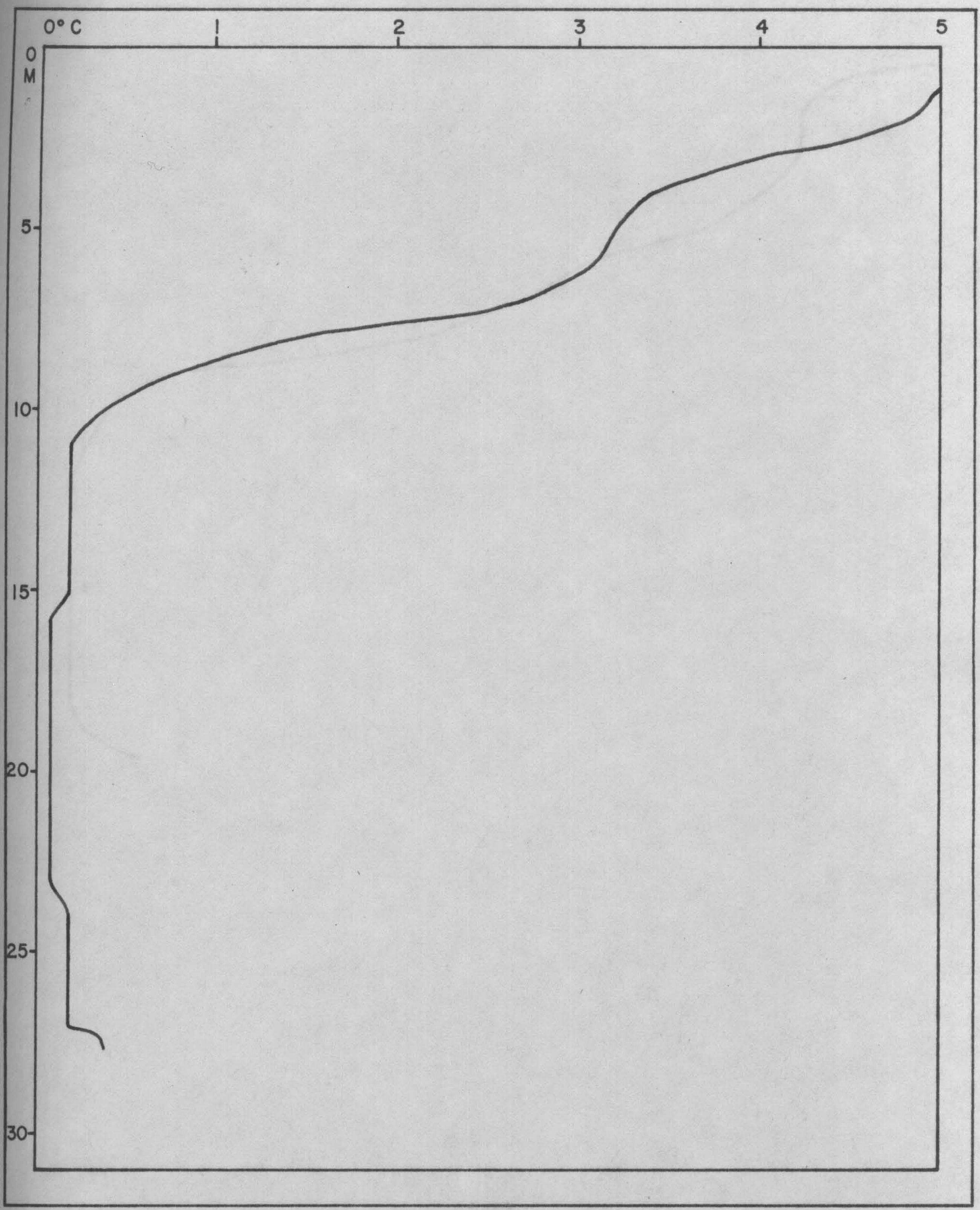


FIGURE 22. Temperature curve for the west-central part (A) of Miller Lake, July 22, 1963; note good thermal stratification.

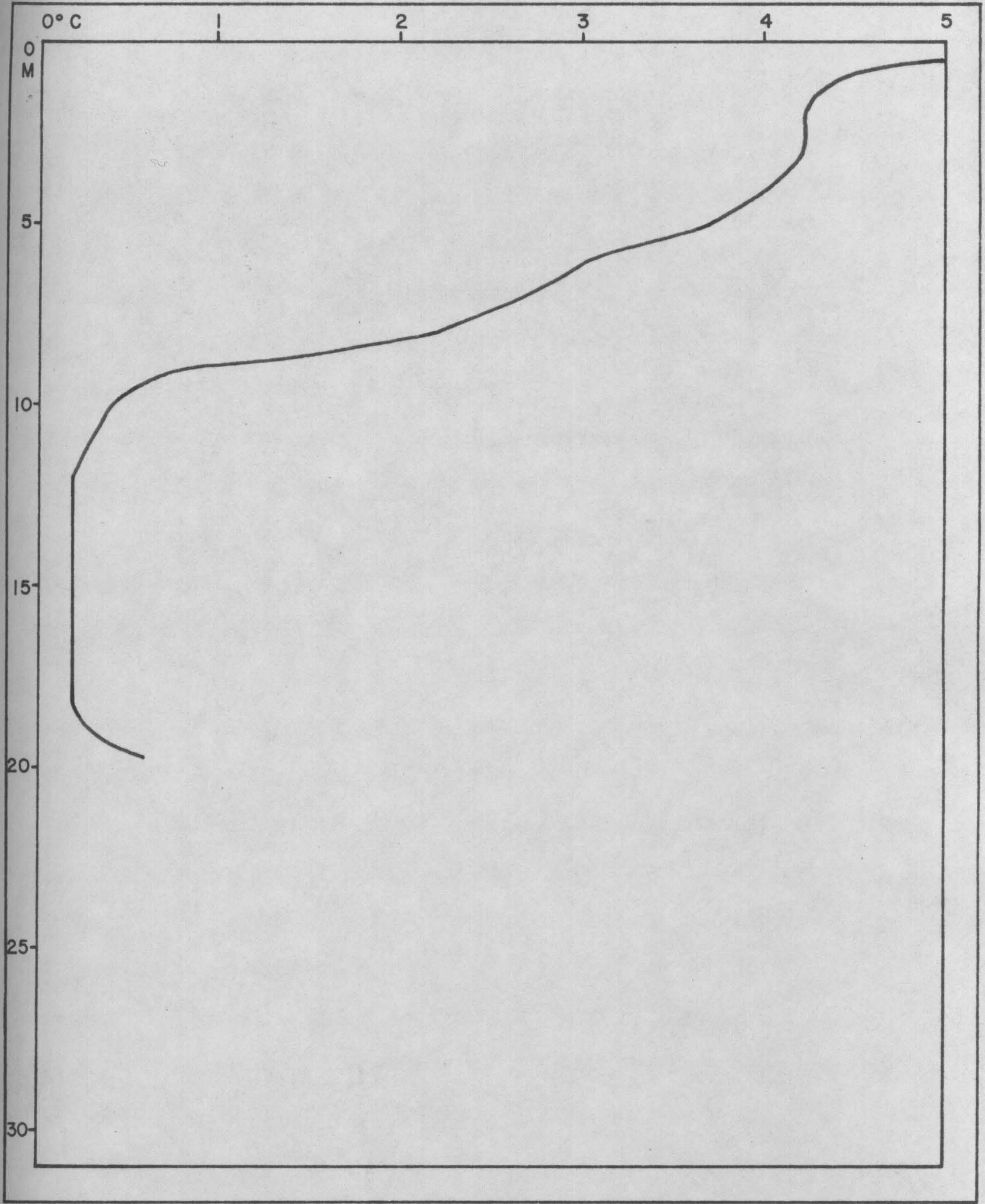


FIGURE 23. Temperature curve for the south-central part of Miller Lake, July 22, 1963; note thermal stratification.

variability of the thermal structure for July and the first part of August (see Table 5). The standard deviation from $\bar{X}$, the mean temperature of each meter of water stratum, during the latter part of June is, in most cases, quite small, usually less than 0.1700. This situation reflects the essentially homiothermal condition of the lake during that period.

The standard deviation from mean temperatures increased somewhat for thermal measurements made during the first two weeks in July. This increase reflects the formation of incipient thermal stratification during that time. There is, however, a substantial increase in the value of SD $\bar{X}$ (standard deviation from the mean temperature) obtained from 53 vertical thermal measurements taken during the last part of July and the first week in August. This increase is restricted to the upper 15 m. of water, the epilimnion. There appears to be only a small deviation for the lower 16 m. This is attributed to the fact that the lower part of Miller Lake (below 15 m.) is essentially homiothermal (see Fig. 21). This lower part corresponds to the hypolimnion. The increase of SD $\bar{X}$ for the upper 15 m. of the lake reflects the widely divergent thermal conditions during this period. There are several diagrams that will illustrate this divergence.

Figure 22 is a curve representing a vertical sequence of temperatures taken in the west-central part of the lake (A in Fig. 25) on July 22, 1963. The lake appears to be relatively well stratified at this time. On this day the skies were partly cloudy, there was a slight breeze blowing from the east-northeast, and the maximum temperature was near 58°F. Figure 24 is a temperature curve taken in the same area on July 24 when a storm was occurring in the Miller Lake area. This storm was accompanied by heavy rain, strong winds, and cool temperatures (approximately 44°F). It is readily apparent that the thermal stratification exhibited by the

Table 5. Mean temperatures and standard deviations for the upper 30 meters of Miller Lake.

	June 5–July 1, 1963			July 1–July 15, 1963			July 20–Aug. 5, 1963		
Depth in meters	$\bar{X}$	SD$\bar{X}$	N	$\bar{X}$	SD$\bar{X}$	N	$\bar{X}$	SD$\bar{X}$	N
0	1.97	.168	21	4.2	1.497	10	4.5	2.488	53
1	1.90	.130	21	3.4	.282	10	3.6	.775	53
2	1.89	.124	21	3.4	.288	10	3.4	.679	53
3	1.90	.118	21	3.3	.241	10	3.3	.591	53
4	1.90	.118	21	3.3	.203	9	3.2	.593	53
5	1.90	.110	21	3.2	.167	9	3.0	.638	53
6	1.90	.116	21	3.2	.173	9	2.8	.688	53
7	1.89	.112	21	3.2	.172	9	2.7	.700	53
8	1.89	.114	21	3.2	.156	9	2.5	.762	53
9	1.88	.111	21	3.2	.240	9	2.3	.799	52
10	1.90	.117	20	3.1	.238	8	2.1	.919	52
11	1.88	.115	20	3.0	.497	5	1.9	.970	52
12	1.85	.162	18	3.0	.451	4	1.7	.988	52
13	1.84	.203	17	3.2	.255	3	1.5	.987	51
14	1.86	.154	15	3.0	.252	3	1.3	.936	49
15	1.87	.153	14	3.2	.071	2	1.0	.782	47
16	1.86	.155	14	3.2	.071	2	.6	.533	46
17	1.82	.204	14	3.2	.000	2	.4	.250	46
18	1.85	.173	12	3.3	.000	2	.3	.144	45
19	1.82	.253	12	3.2	.071	2	.3	.096	40
20	1.79	.168	12	3.1	.141	2	.3	.181	33
21	1.80	.180	9	3.0	.212	2	.1	.055	17
22	1.78	.252	9	2.8	.141	2	.1	.048	15
23	1.77	.228	9	2.1	.283	2	.1	.052	12
24	1.81	.248	7	2.0	.283	2	.1	.121	12
25	1.78	.376	7	2.4	.354	2	.1	.055	10
26	1.86	.339	6				.1	.086	8
27	1.32	.110	5				.1	.075	6
28	1.20	.173	3				.1	.097	5
29							.1	.029	3
30							.1	.029	3

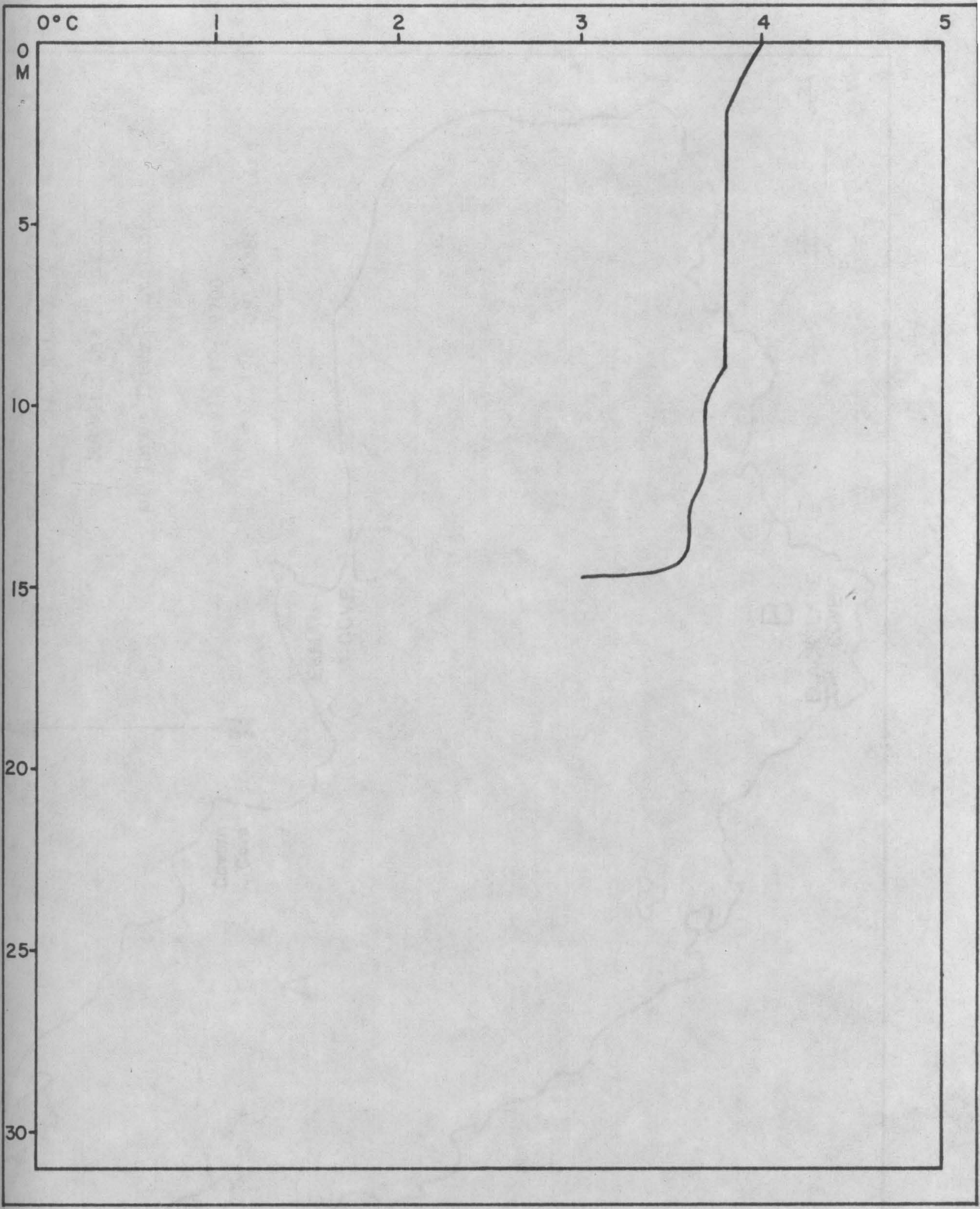


FIGURE 24. Temperature curve for the west-central part of Miller Lake, July 24, 1963; note homiothermal condition.

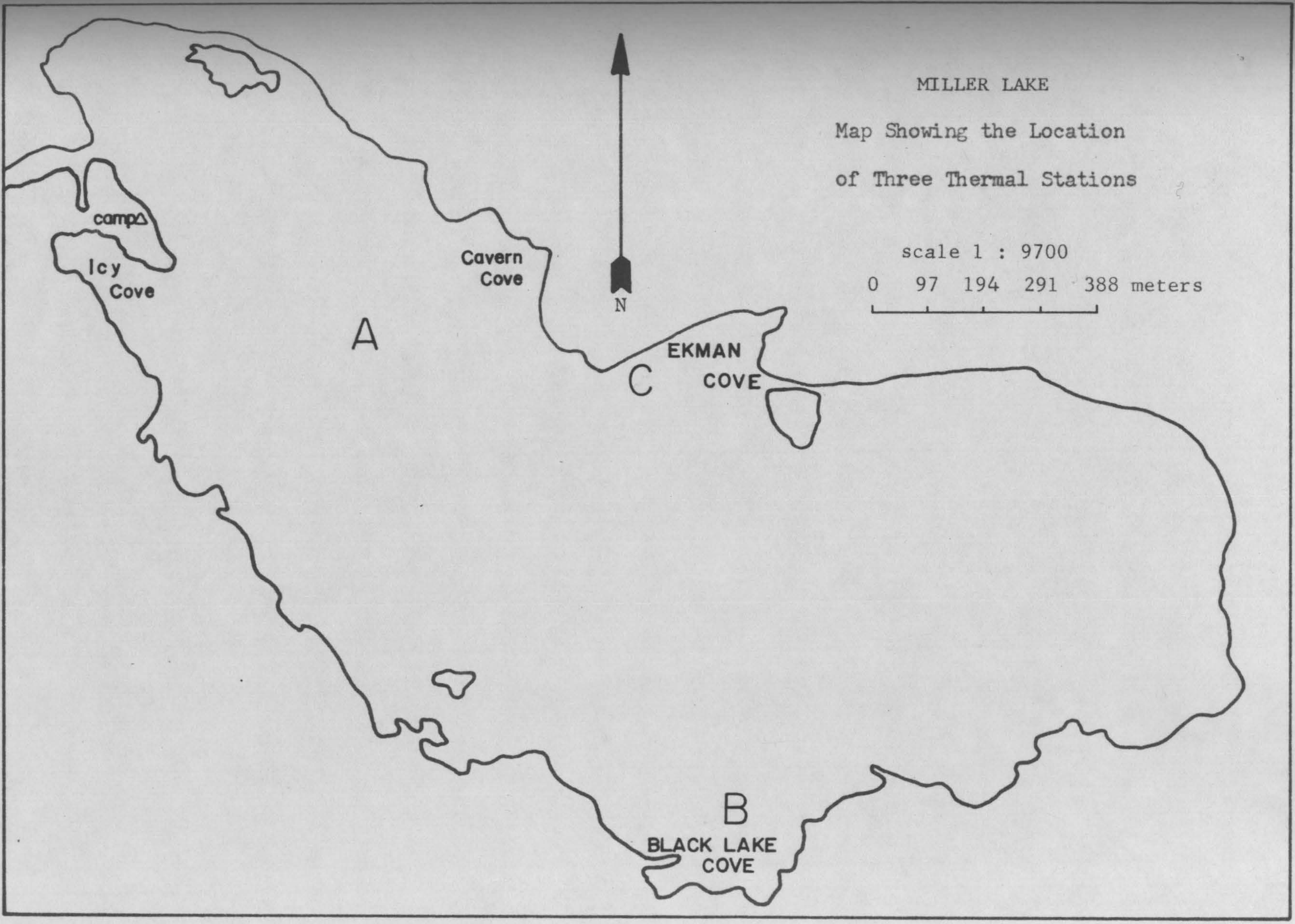


FIGURE 25. Location of important thermal stations on Miller Lake.

lake on July 22 had been completely destroyed and replaced by an essentially homiothermal condition, a situation which indicates that Miller Lake had undergone fairly complete mixing (at least in the upper 15-20 m.) in this area. This mixing, of course, is a result of high winds and cool air temperatures. There was, however, another area which did not experience such complete destruction of thermal stratification. Figure 26 is a temperature curve taken in Black Lake cove along the south-central shore (B in Fig. 25) on July 24, 1963. The lake appears to be nearly stratified in this area with a relatively warm homiothermal epilimnion, a small metalimnion (1.1°C drop in 2 m.), and a cold homiothermal hypolimnion. These three figures illustrate the variability of the thermal condition of the lake during the latter part of July and the first week in August.

The great difference in thermal characteristics exhibited between Figures 24 and 26 needs explanation. These differences are presumed to be due to varying degrees of exposure of the lake to the wind. The curve in Figure 24 was taken at station A in the west-central part of Miller Lake. The prevailing winds in this area are from the northeast. Station A was so situated that this area felt the full effect of the winds which created currents and thus mixed the lake waters. Station B was in a protected cove, Black Lake Cove, and the water in this area did not receive the force of the wind. Even the currents produced by wind action on the exposed part of the lake did not thoroughly mix the entire column of water in protected areas such as Black Lake Cove.

The ease with which the wind destroys thermal stratification within Miller Lake is reflected by the low value for thermal resistance to mixing. This thermal resistance to mixing is the resistance of a given state of stratification to the stirring effect of the wind and is in reality a

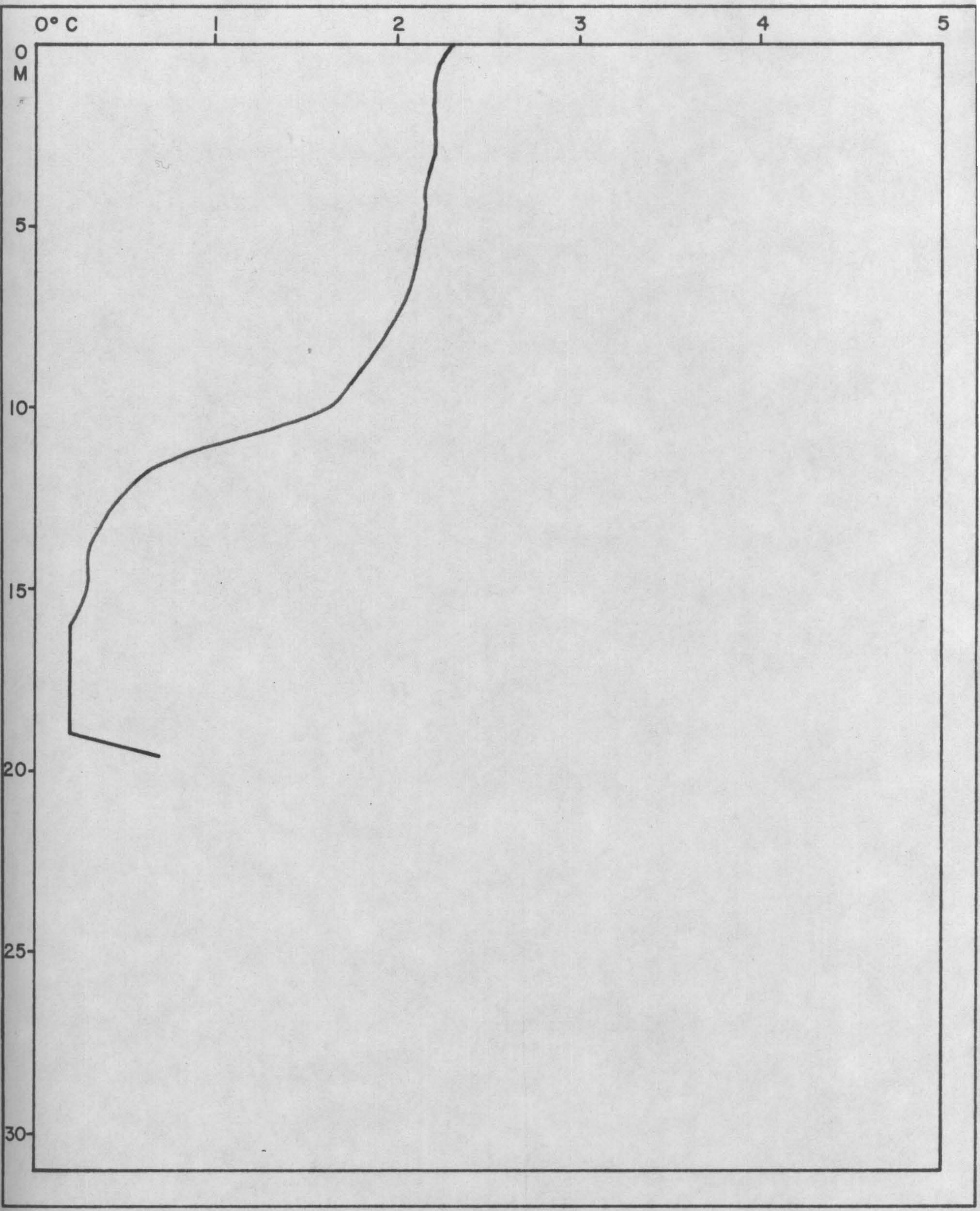


FIGURE 26. Temperature curve for Miller Lake in Black Lake Cove, July 24, 1963; note thermal stratification.

measure of the stability of stratification of the lake (Ruttner, 1963, p. 32). Using the method outlined by Welch (1948, p. 123), the value of the thermal resistance to mixing for Miller Lake was found to be 125 x 10^{10} ergs. This value is quite low, especially when one considers that it takes 98 x 10^{10} ergs of work to lift a weight of one metric ton a distance of 10 meters against the force of gravity. Thus it is not difficult to see why a moderate wind can almost completely destroy thermal stratification in Miller Lake. Even in tiny Lunzer Untersee in the central European Alps which has a surface area of 0.68 $km.^2$ and a volume of 13.6 x $10^6 m.^3$, the value of the thermal resistance to mixing reaches 30 x 10^6kg. - m. during midsummer (Ruttner, 1963, p. 34). This figure represents the work required to raise thirty ten-ton cars a distance of 100 m. against the force of gravity. By comparison, the thermal resistance of Miller Lake is quite small.

Analysis of temperature curves for Miller Lake during the latter part of the 1963 field season indicates that multiple thermoclines formed on several days during this period.

Figure 27 is a temperature curve for Miller Lake on July 26, 1963, which shows the formation of a multiple thermocline. A storm, bringing high winds, rain, and low air temperatures, had been present in the area for two days previous to July 26. This storm drove the thermocline deeper in the lake (15 m.) and partially destroyed it. The storm subsided during the evening of July 25, and on July 26 the skies were cloudless, the winds nil, and the air temperatures warm (56°F). This period of calm and relatively warm weather set up a shallow thermocline at 10 m. During a period from July 24-30, 1963, alternately stormy-cold and calm-warm spells of weather resulted in the formation of several multiple thermoclines.

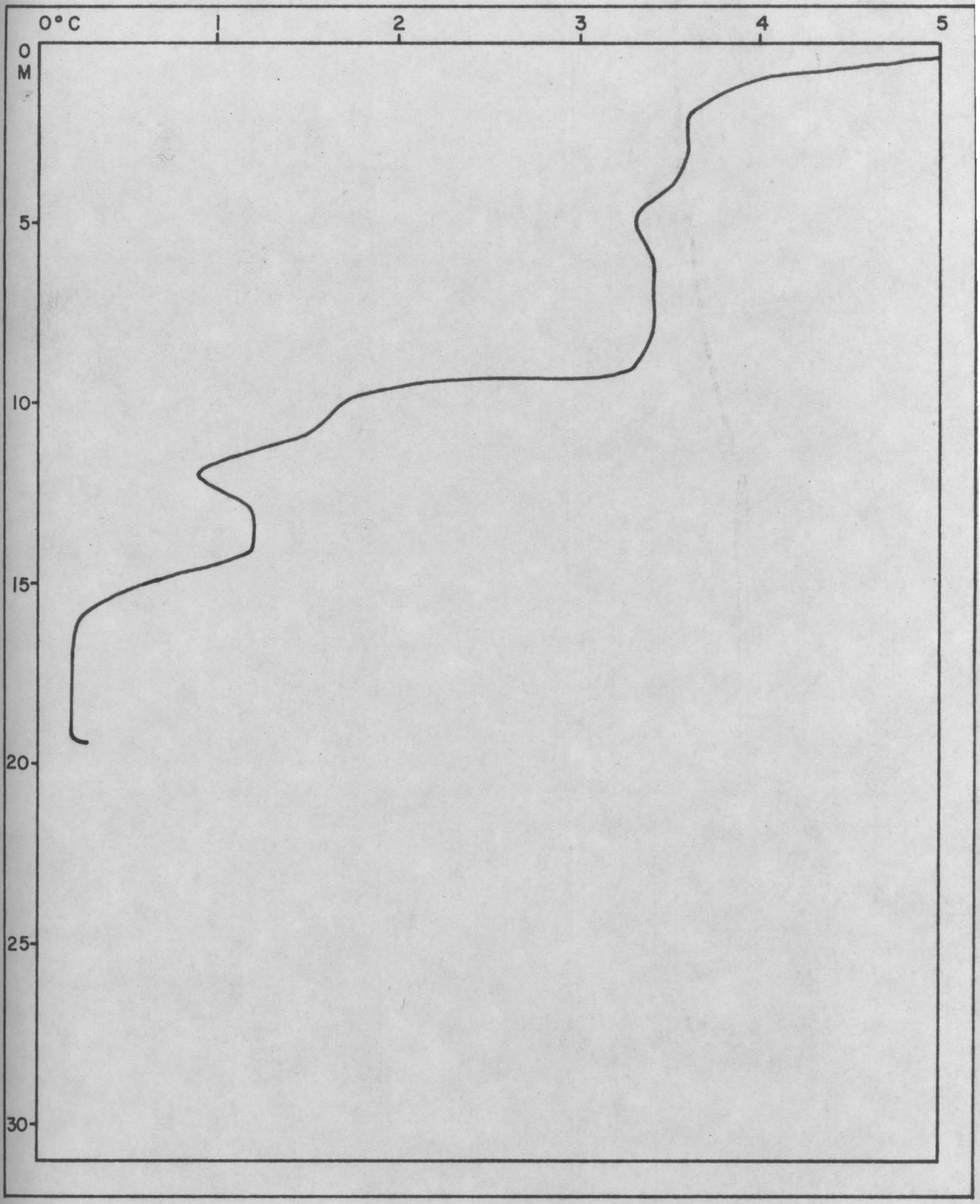


FIGURE 27. Temperature curve for Miller Lake in Black Lake Cove, July 26, 1963; note multiple thermocline.

On July 29, following a day of stormy weather, another secondary thermocline was produced by a period of warm-calm weather which overlaid the shallow thermocline, produced on July 26, that had been driven down to 14 m. by the storm (see Fig. 28). A subsequent storm during the following day (July 30) drove both thermoclines farther down in the lake (from 8 m. to 13 m. and from 14 m. to 17 m.) and produced a relatively deep circulating epilimnion (see Fig. 29). Figure 30 shows a temperature curve taken near the ice cliff on July 30, 1963, showing a deep, homiothermal epilimnion and the depressed well-delineated thermocline. These three curves show thermal stratification only because the temperatures were measured at stations located in protected areas on the lake (B and C on Fig. 25).

The reversal of many of these temperature curves at the bottom of the curve represents a warming in the bottom muds. This phenomenon is probably due to the decomposition of organic material (flora) present around the lake shore.

The thermal structure of Miller Lake is affected by numerous factors. Some of the less important are the latitude, the mean air temperature, and the mean depth of the lake. The most important factors, however, are the effect of cold influents and the presence of ice beneath the lake basin. The cold influents, consisting of glacial meltwater, serve to cool the entire lake; the surface influents cool the epilimnion and the sublacustrine influents cool the deeper waters. The ice that lies only a short distance beneath much of the lake basin also cools the lake waters. The moderate to large amount of wind action in the area mixes the lake water constantly and continually destroys the thermal stratification.

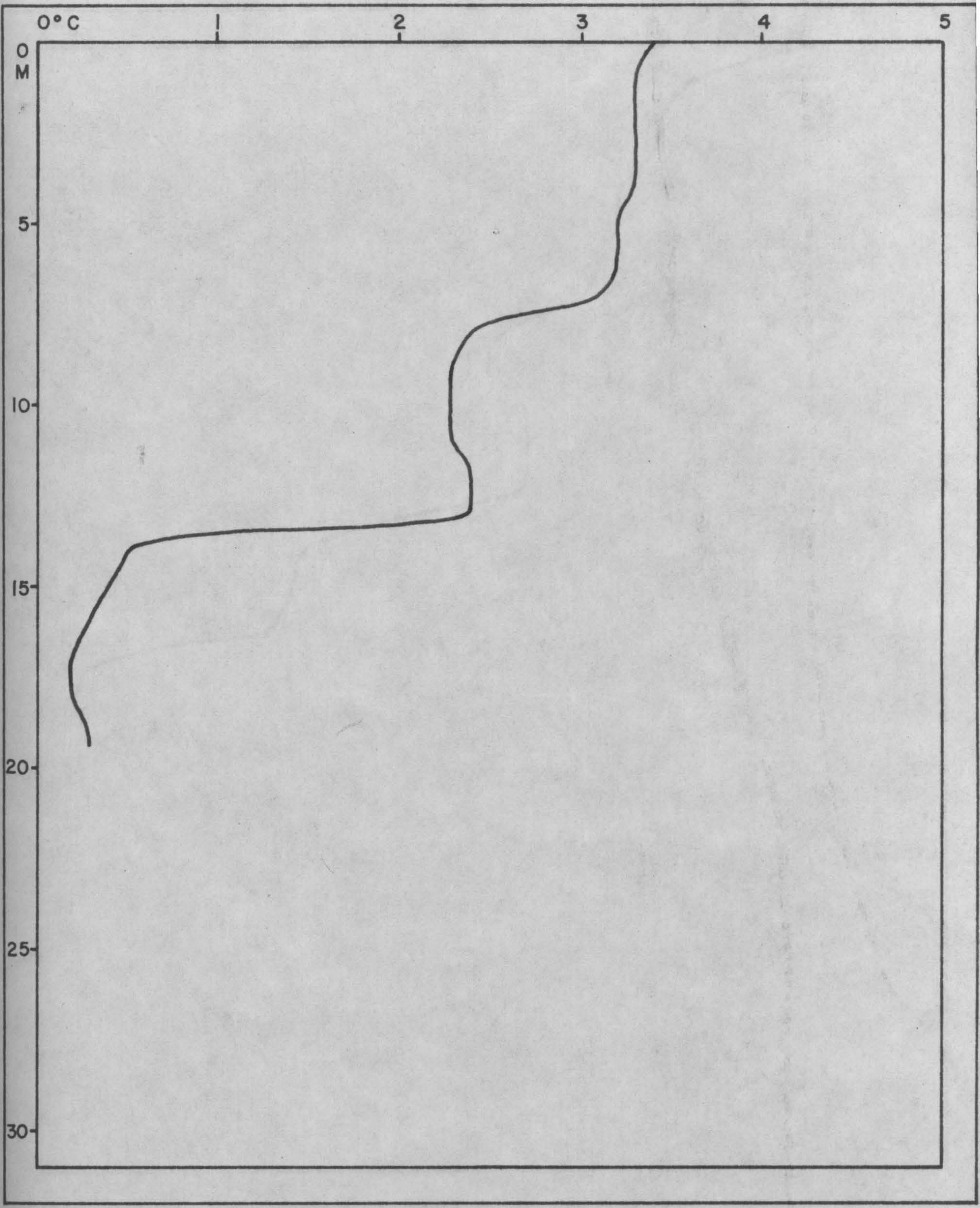


FIGURE 28. Temperature curve for Miller Lake in Black Lake Cove, July 29, 1963; note multiple thermocline.

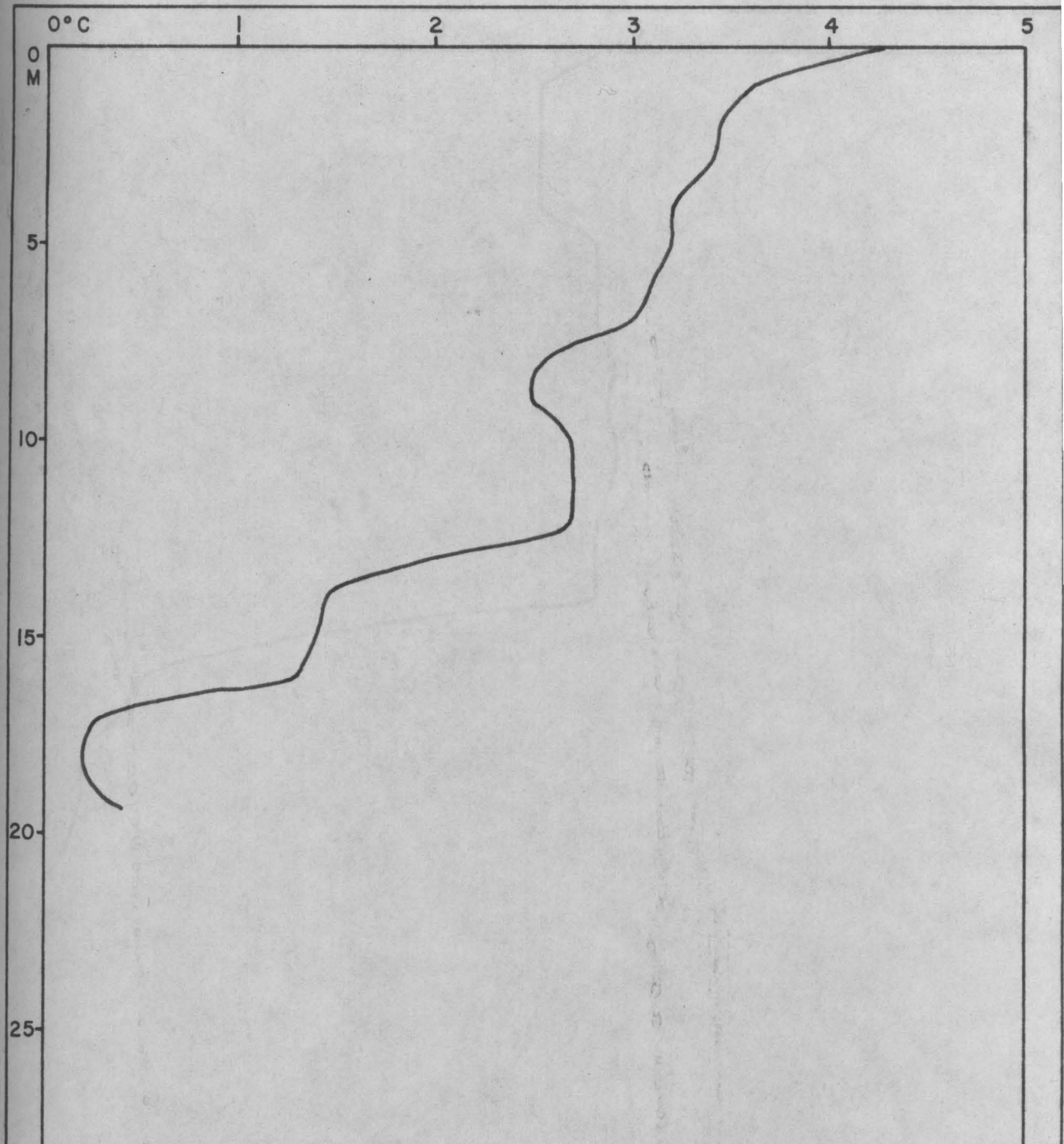


FIGURE 29. Temperature curve in Miller Lake in Black Lake Cove, July 30, 1963; note multiple thermoclines.

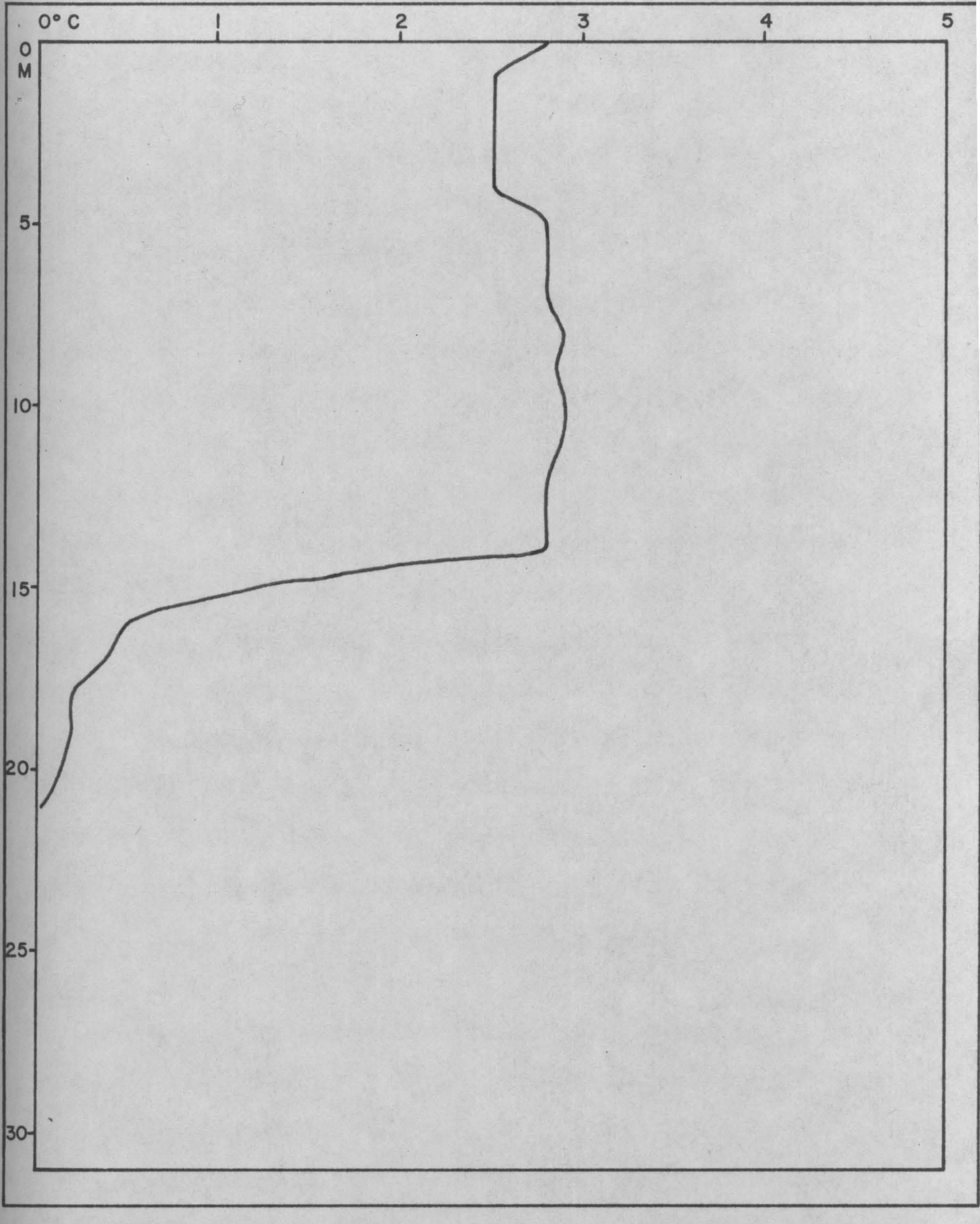


FIGURE 30. Temperature curve for Miller Lake in Ekman Cove, July 30, 1963; note good thermal stratification.

Thermal classification of Miller Lake

Miller Lake is classed as a temperate lake according to the classification of Forel (in Hutchinson, 1957, p. 437). This thermal classification, however, is not really suited to Miller Lake because the lake generally circulates more than twice a year.

A much improved thermal classification of the lake is subpolar, using the classification of Yoshimura (in Hutchinson, 1957, p. 437). A subpolar lake is one in which the surface temperature is above 4°C for only a short time in the summer and the thermal gradient is small. The thermocline, if present, is poorly developed and generally near the surface. There are two circulation periods in a subpolar lake, in the early summer and early fall, but temporary cooling throughout the summer accompanied by winds generally causes fairly frequent mixing (Hutchinson, 1957, p. 437). This description appears to be a very close approximation of the thermal structure of Miller Lake. Theoretically though, it may be considered a dimictic lake using the classification of Hutchinson (1957, p. 438). Since the lake probably circulates completely more often than twice each year, the term dimictic is not strictly applicable and should not be used. Miller Lake, therefore, is classified as a subpolar lake.

Heat budget

The annual heat budget of a lake is the total quantity of heat absorbed by the lake to warm the waters from the lowest winter temperature to the maximum summer temperature (Reid, 1961, p. 118). The easiest way of determining this budget is to multiply the difference between the winter and summer temperatures at a particular depth Z by the area of that stratum of water, integrate these values for the whole lake, and divide by the surface area of the lake (Hutchinson, 1957, p. 494). Although no winter temperatures are available for Miller Lake, it seems quite reasonable (due to the high winds, the effect of cold influents, and the effect of ice beneath the basin) that the water temperature approaches 0°C. Also, some assumption should be made concerning the thickness of ice on the lake in order to account for the heat needed to melt the ice. For this reason, the thickness of the ice has been arbitrarily placed at 1 foot.

Using these two reasonable assumptions, the annual heat budget of Miller Lake is calculated to be 8873 cal./cm.^{2}. The summer heat income (the quantity of heat needed to warm a lake from the homiothermal spring condition to the summer maximum temperature), or wind distributed heat, is 882 cal./cm.^{2}, only 1/10 the annual heat budget. This is a very small percentage in comparison with most other lakes for which the summer heat income is the largest item in the heat budget. It is, in fact, considerably smaller than that of a northern Alaska Lake (Chandler Lake) whose summer heat income is only 1/5 of the total heat income (Livingstone, et al., 1958, p. 198).

The work of the wind in warming Miller Lake from 4°C to the mean maximum summer temperature is 513 gm. - cm./cm.^{2}. This small value is due to the low summer temperature of the lake water.

Color and turbidity

The apparent grey color of the water in Miller Lake is due to the large amounts of inorganic clay-size material suspended in the water.

Turbidity is the degree of opaqueness produced in water by suspended particulate matter (Reid, 1961, p. 103). Figure 31 shows the vertical distribution of turbidity in ppm silica units for Miller Lake on August 7, 1963. It is readily apparent that the turbidity of this lake is very high. The turbidity of the surface water increased throughout the

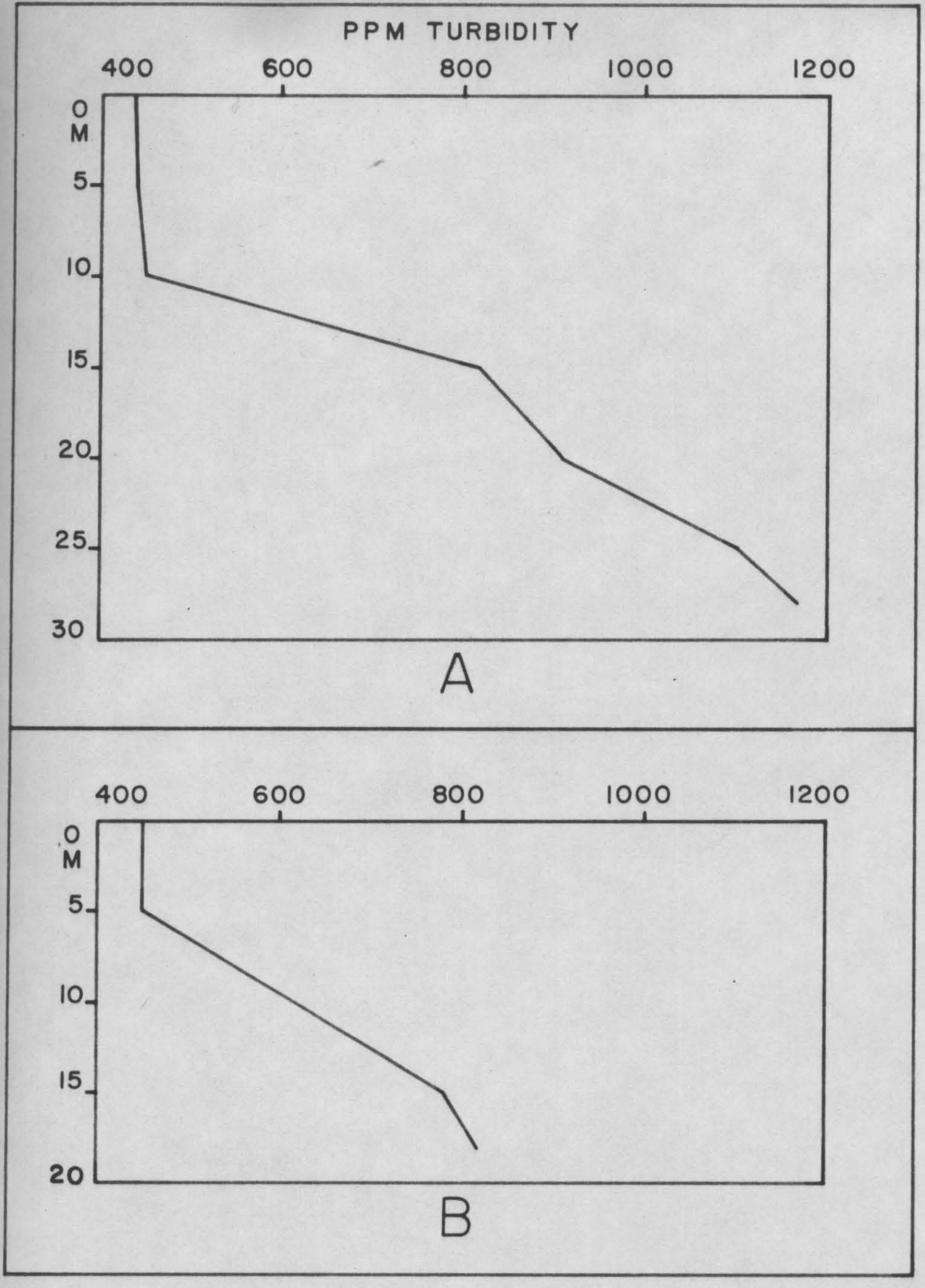


FIGURE 31. Vertical distribution of turbidity (in ppm silica units) in the east-central (A) and southeastern (B) parts of Miller Lake, August 7, 1963.

summer. It also increased a significant amount following storms or periods of strong wind when the lake underwent fairly good mixing.

This high turbidity has a pronounced effect upon the heating of the lake. The suspended particles absorb light which produces a great warming effect in the surface waters to a depth of a few decimeters. Figure 32 shows this large warming effect in the top three decimeters of the lake on three warm, clear to partly clear days in July.

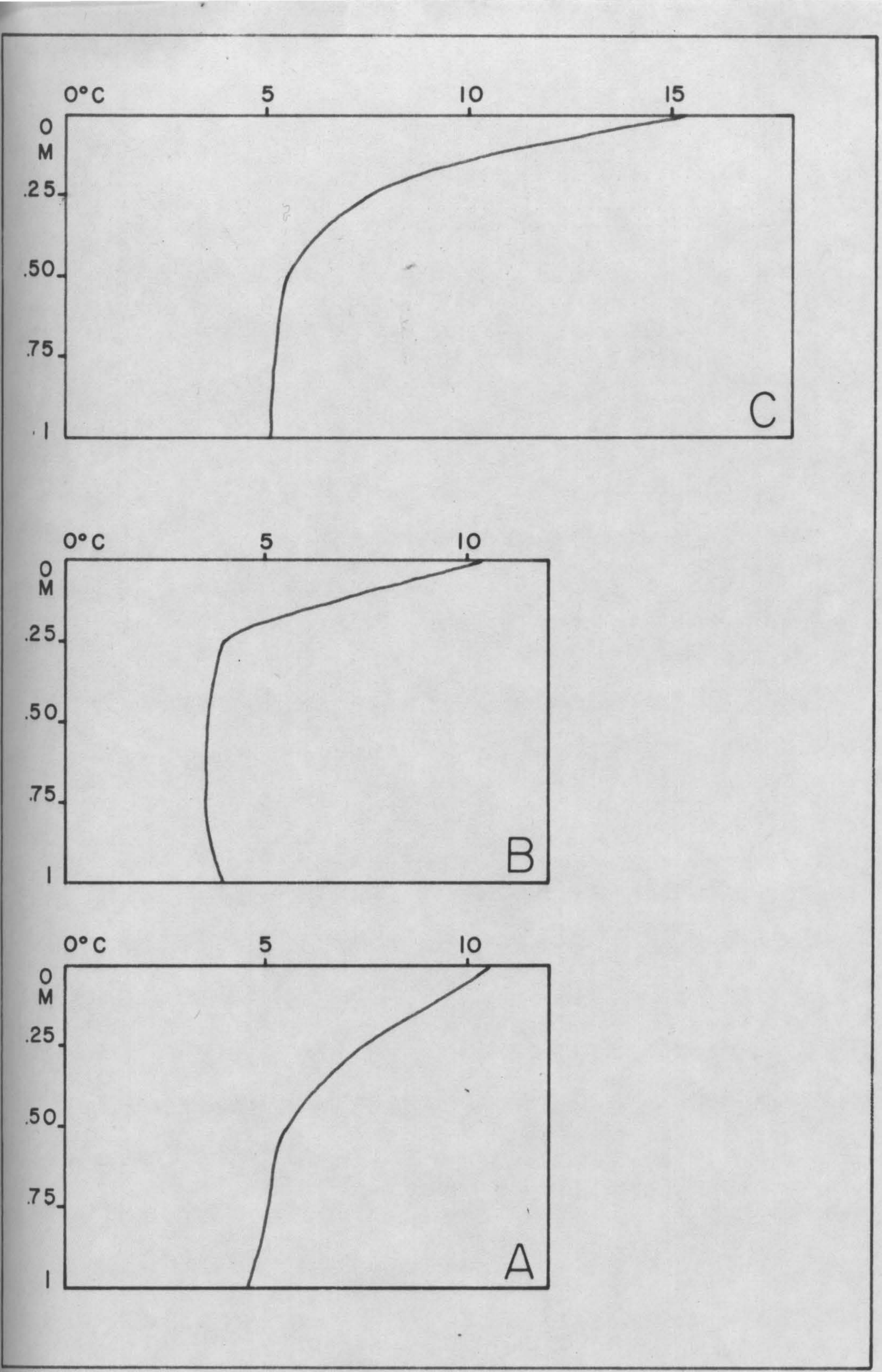


FIGURE 32. Heating the top few decimeters of Miller Lake; (A)-August 18, (B)-August 19, and (C)-August 20, 1963.

CHEMICAL LIMNOLOGY

Methods of Study

All water samples, except those taken at the surface, were collected with a Kemmerer water sampler. Dissolved free CO_2 was determined by titrating phenolphthalein indicator with N/44 sodium hydroxide. The alkalinity (normal carbonate, bicarbonate, and hydroxides) was measured by titrating phenolphthalein and methyl orange indicators with N/50 sulfuric acid. Both of these procedures are outlined by Welch (1948, p. 213-216). The pH was measured by means of a Beckman pocket pH meter. The major dissolved ions and turbidity (total particulate matter) were determined using standard analytical procedures and a Hellige colorimeter (Aqua Analyzer, model no. 950A).

Results

A relatively complete chemical analysis was done on two water samples taken from 10 m. and 20 m. depths in Miller Lake. The results of these analyses are presented in Table 6. One surprising value is the pH, which seems to be quite high. This value may be erroneous, however, due to fluctuations in the pH meter. Anomalous readings with this instrument were experienced continually during the latter part of the 1963 field season and therefore these values are not entirely accurate. Miller Lake is rather high in sulfate. The source of this sulfate is unknown, but is probably contributed by local bedrock. It is evident from the table that the water chemistry of Miller Lake is not extraordinary.

Figures 33, 34, and 35 are curves showing the observed vertical distribution of CO_2 and pH in Miller Lake on two days in August, 1963. These curves show a general increase in CO_2 accompanied by a consequent decrease in the pH value with an increase in depth. Generally, however,

Table 6. Chemical analyses of Miller Lake (in ppm) of water samples collected on August 8, 1963.

	10 meters	20 meters
Dissolved CO_2	2.0	3.0
HCO_3	30.0	31.0
Cu	0.0	0.0
Fe	0.3	0.2
NO_3	0.0	0.0
PO_4	0.0	0.0
SiO_2	14.8	14.5
SO_4	11.7	14.2
Turbidity	621	910
pH	8.9	9.0

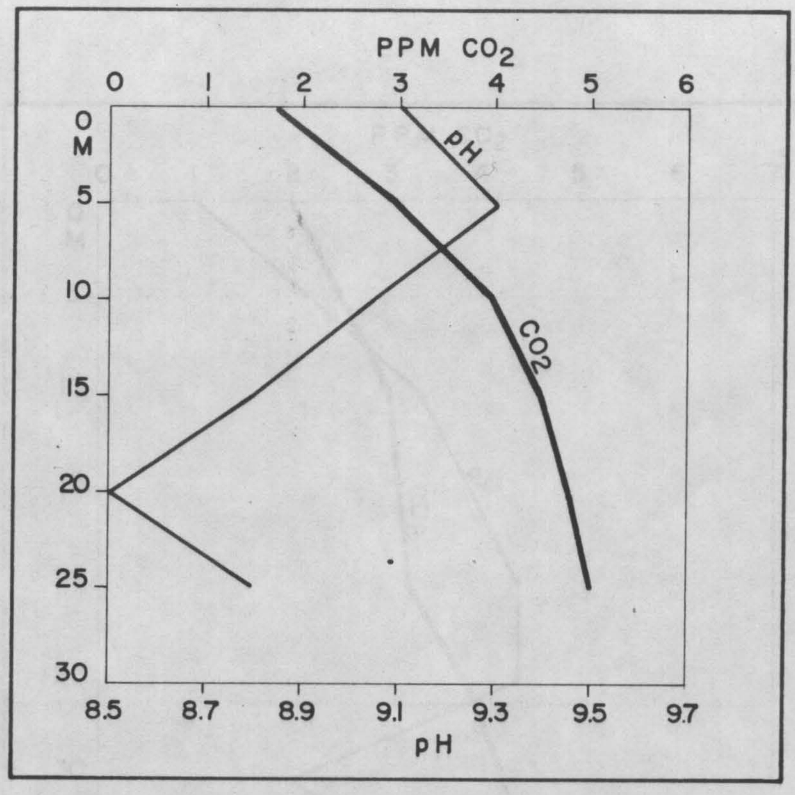


FIGURE 33. Vertical distribution of CO_2 and pH in Miller Lake, August 10, 1963.

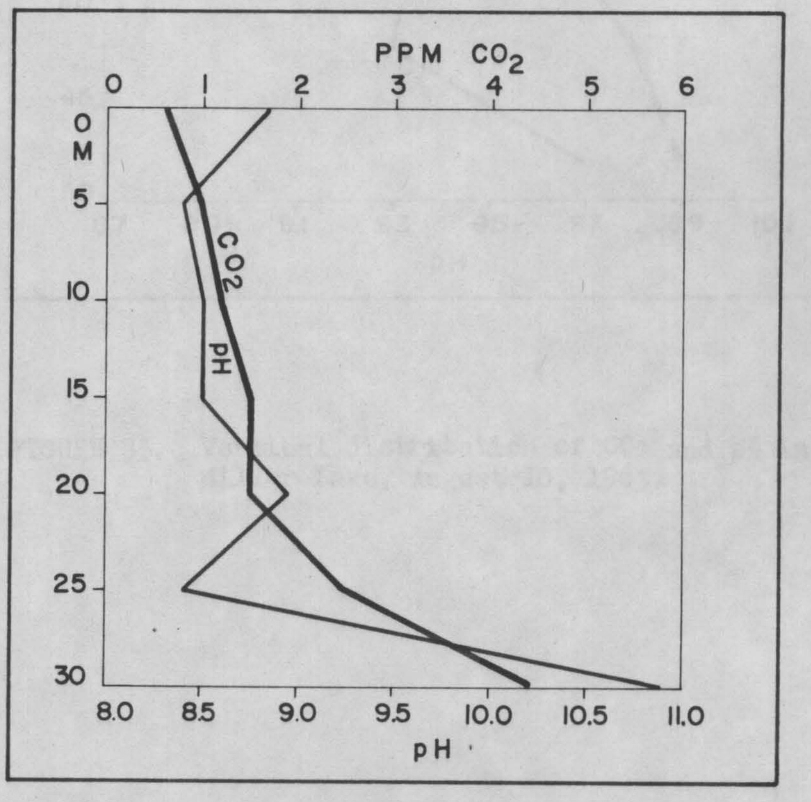


FIGURE 34. Vertical distribution of CO_2 and pH in Miller Lake, August 7, 1963.

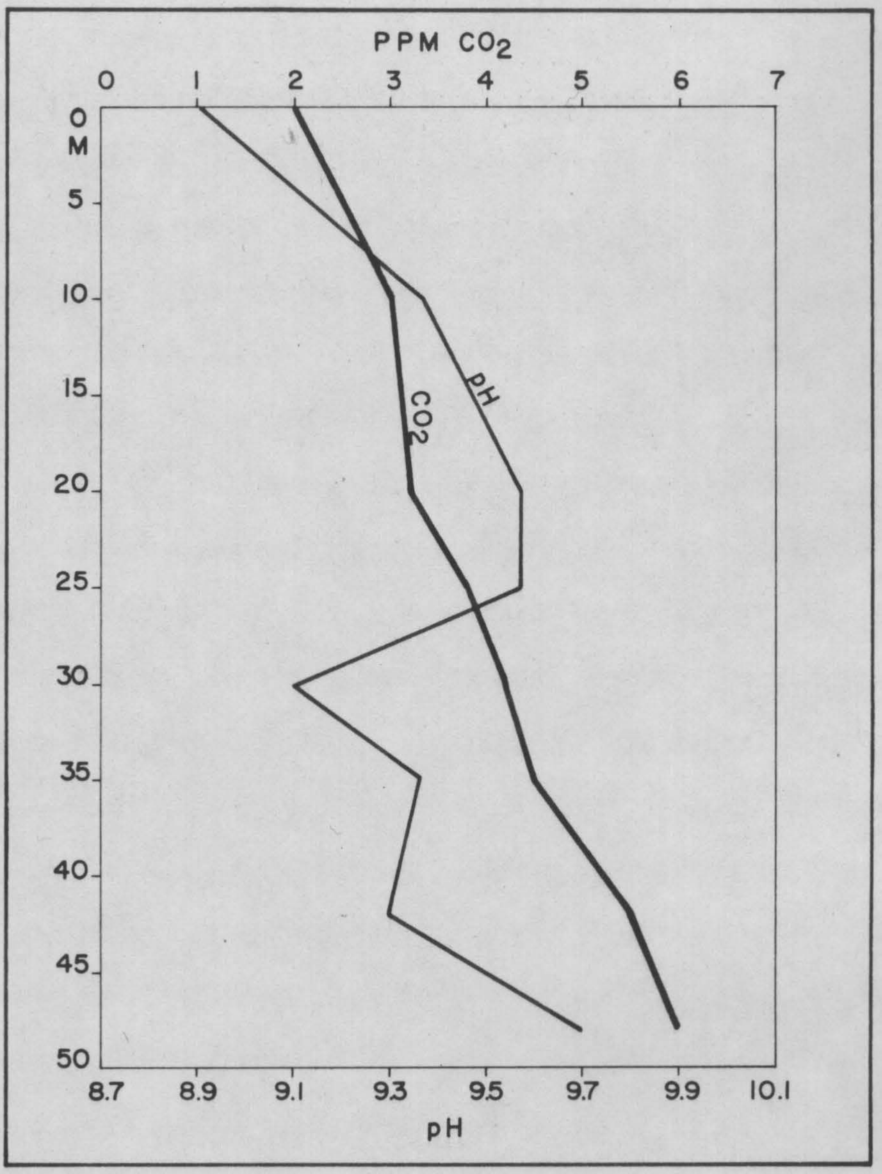


FIGURE 35. Vertical distribution of CO_2 and pH in Miller Lake, August 10, 1963.

these curves show a gradual change in these values and reflect the low biological productivity of the lake (at least the absence of any significant photosynthesis). In fact, Miller Lake could probably be classified as an oligotrophic lake; one which is poor in nutrients.

Figures 36 and 37 are graphs showing the 24-hour variations in temperature, pH, and turbidity of the surface water offshore from the camp, in a protected cove behind the camp, and in the lake's effluent during August 6 and 7, 1963. These graphs show a minimum pH value in the early afternoon and a maximum value around midnight. This increase in pH during the night may result from the loss of free CO_2 to the atmosphere, although this seems unlikely since the solubility of CO_2 increases as the temperature decreases (Reid, 1961, p. 157). The increase may result from the fact that the incoming glacial meltwater has a lower pH value and during the day, when temperatures are higher, there is a greater volume of this meltwater entering the lake than at night when the air temperatures are lower. In one instance of water samples taken offshore from the camp, the concentration of undissolved solids (turbidity) also increases to a maximum during the middle of the night and then decreases to a minimum in mid-afternoon. This also may be due to the fluctuation volume of meltwater flowing into the lake. Generally, however, the turbidity varies relatively little throughout the 24-hour period.

Daily analysis of turbidity of Miller Lake water at the three localities mentioned previously indicates that the concentration of undissolved material increased throughout the summer. Although there were local decreases in the turbidity due to rain water dilution, the turbidity generally increased from approximately 270 ppm during the middle of June, to nearly 300 ppm during the middle of July, and to approximately 420 ppm

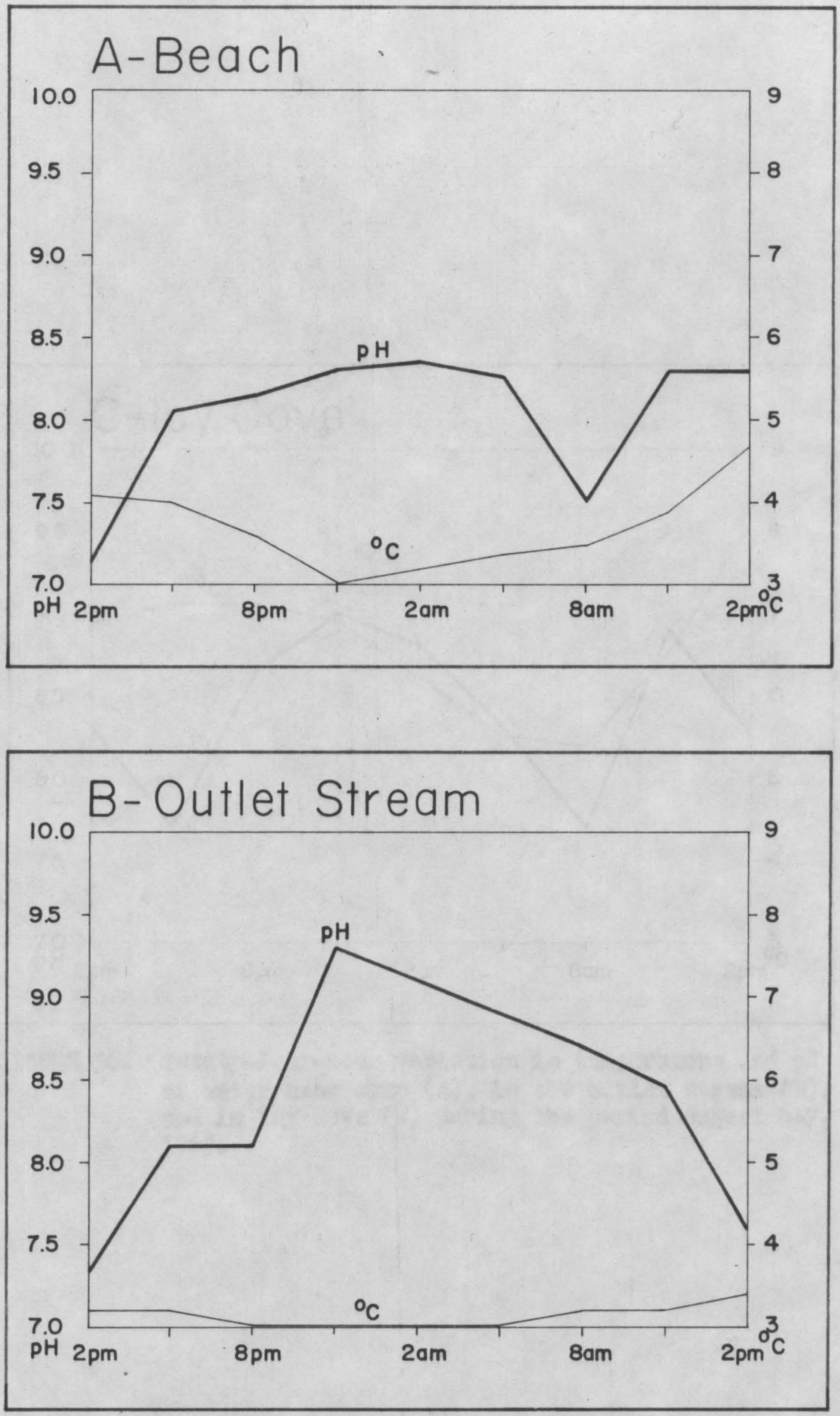


FIGURE 36. (See following page).

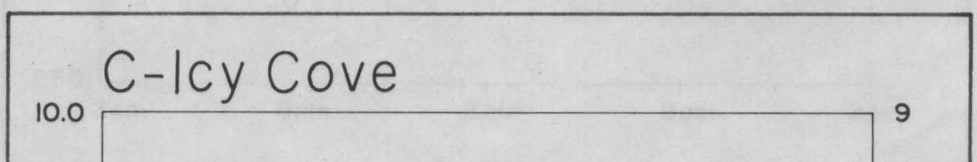


FIGURE 36. Twenty-four-hour variation in temperature and pH of water near camp (A), in the outlet stream (B), and in Icy Cove (C) during the period August 6-7, 1963.

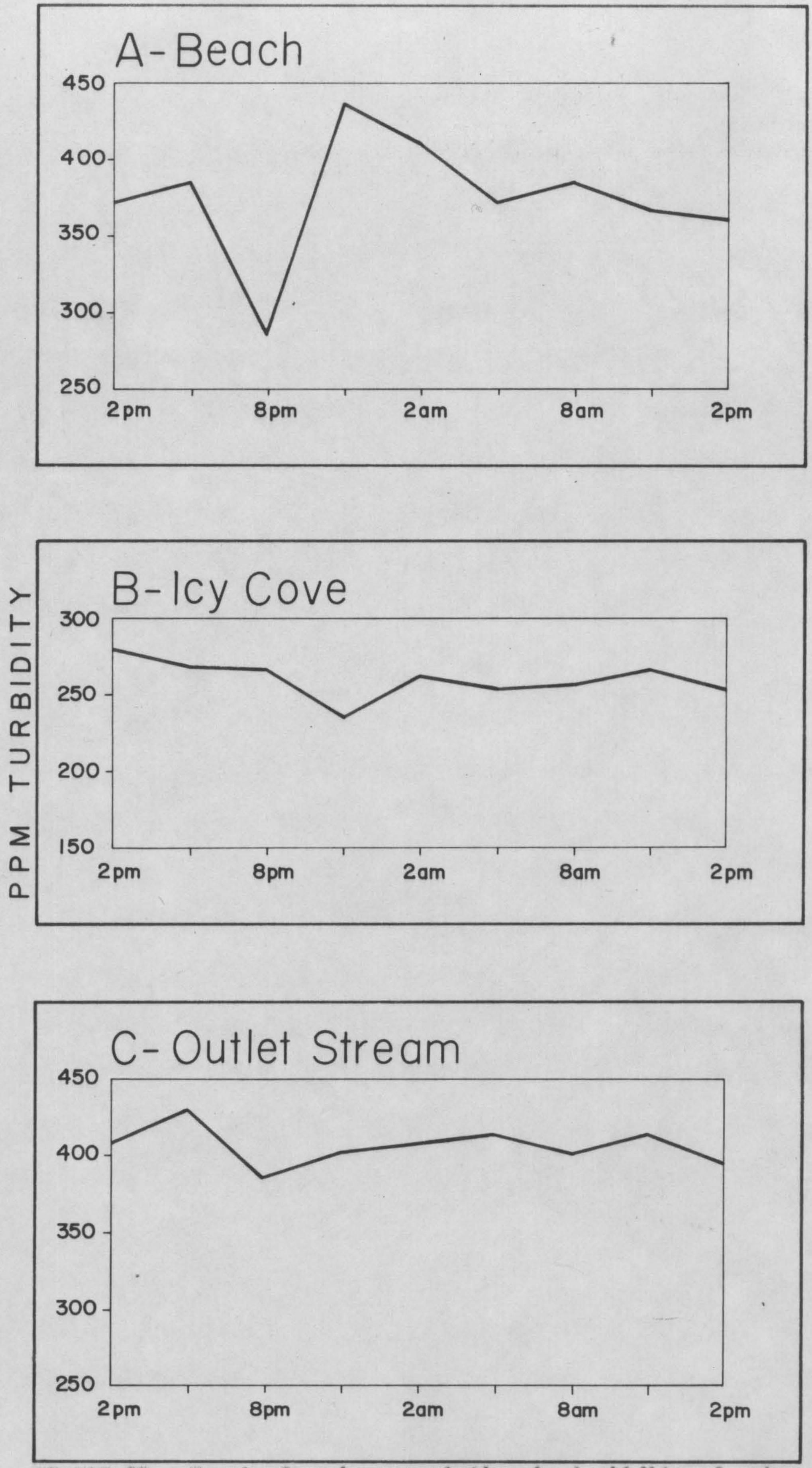


FIGURE 37. Twenty-four-hour variation in turbidity of water near camp (A), in Icy Cove (B), and in the outlet stream (C) during the period August 6-7, 1963.

during the first week in August. This general increase is due to the greater volume of glacial meltwater entering Miller Lake throughout the summer.

SEDIMENTOLOGY

Procedures

Field

A total of 150 sampling stations were occupied on Miller Lake. A rough grid system was employed and the stations were located by triangulation from several known stations on the lake shore using a Brunton Compass. Samples were obtained by means of a grab sampler, the Ekman Dredge, and stored in sealed plastic containers. The samples, when brought to the surface, were placed in a bucket and a representative sample was put into a container. After the sample was described and the percentage of coarse material estimated, the bucket was emptied over the side of the canoe and washed out.

Pebble counts were made by Callender and Schulte at 12 localities around the lake. Approximately 200 pebbles were counted within a two-meter-square area; the rock type of each pebble was recorded.

Laboratory

In the laboratory, only the primary textural properties (percentages of gravel, sand, silt, and clay) of the bottom sediment samples were determined. Size analyses were made on weighed samples of wet sediment taken directly from the sealed containers. Gravel and sand were separated by wet-sieving and the washings, consisting of silt and clay, were retained for hydrometer analysis. The gravel and sand fractions were dried and weighed.

A representative wet sample of silt and clay (10-20 grs.) was weighed, dried, and weighed again so that the equivalent dry weight of the analyzed sample could be determined. Each wet sample for analysis (approximately 50 grs. equivalent dry weight) was soaked for 24 hours in

125 ml. of Calgon standard solution in order to thoroughly disperse the sample. After soaking, each sample was stirred with distilled water in an electric mixer for approximately 2 minutes and then poured into a liter graduate. Distilled water was added to the 1 liter mark.

Mechanical analysis was then made on the silt and clay fraction using a modification of the A.S.T.M. hydrometer method (The Asphalt Institute, 1961). The mixture in the graduate was stirred, temperature recorded, and time noted. The length of time needed to reach the silt-clay boundary was calculated using Stokes' Law. The hydrometer reading was taken at the proper time and recorded. Calculations gave the percentages of gravel and sand, determined by sieve analysis, and silt and clay, determined by hydrometer analysis, for each sample.

Approximately 50 grams of sample (granule-size material) was examined under the binocular microscope and the individual grains were analyzed for petrologic differences. The petrologic type of nearly 250 grains was noted and recorded for each of 15 bottom sediment samples spaced more or less evenly throughout the lake.

From 3 to 6 grams of sample (diameter between 0.125 and 0.250 mm.) were poured into a funnel containing Tetrabromoethane (specific gravity 2.96) and allowed to separate for 1 hour. Residues of both light and heavy minerals were washed and dried. The dried samples were weighed and the percentages of light and heavy minerals calculated. The heavy minerals were mounted on slides for microscopic study.

Statistical Treatment of the Data

Pebble counts

The data obtained from pebble counts were tabulated and plotted as petrologic type against percent frequency on a bar diagram (see Fig. 47).

Sediment size analyses

Because Miller Lake contains such a wide range of sediment sizes (boulders, cobbles, pebbles, granules, sand, silt, clay), it has been found desirable to reduce the number of these components to five basic groups based on particle size. These are: Boulders, Gravel, Sand, Silt, and Clay. The term "Boulders" is used for particles larger than 32 mm., "Gravel" applies to particles between 32 and 1 mm., "Sand" is used for those particles whose diameters are from 1 to 0.062 mm., "Silt" denotes particles between 0.062 and 0.005 mm. Boulders include both cobbles (32 - 128 mm.) and boulder-size material (greater than 128 mm.) This component was determined from the field descriptions, while the other four basic components were determined by mechanical analyses.

The phi scale of particle size is used in this report. A phi unit is the negative logarithm to the base two of the diameter in millimeters. A full discussion of this scale is found in Inman (1952). The Wentworth grade scale and a table for converting phi units into millimeters is presented in Table 7. The use of phi units gives size classes in whole number integers with smaller grain sizes corresponding to larger phi units.

A table giving the sample number, sample depth, percentages of the four basic components (gravel, sand, silt, and clay), the sediment type, and a field description for each sample is presented in Appendix A. Figure 38 shows the location of the sediment samples.

A series of three triangular diagrams was applied to show the textural relations among the sediments (Figures 39, 40, and 41). Nearly all the analyzed sediment samples had less than 10% of one of the basic four components, and in many cases the amount was closer to 5% (see

Table 7. Table for converting from phi units into particle diameter in millimeters with the sediment size class according to the Wentworth scale (from Inman, 1952).

Phi Unit	mm.	Size Class
-8	256	boulder
-7	128	
-6	64	cobble
-5	32	
-4	16	pebble
-3	8	
-2	4	granule
-1	2	
-0	1.0	very coarse sand
+1	0.5 (1/2)	coarse sand
+2	0.25 (1/4)	medium sand
+3	0.125 (1/8)	fine sand
+4	0.06 (1/16)	very fine sand
+5	0.03 (1/32)	coarse silt
+6	0.016 (1/64)	medium silt
+7	0.008 (1/128)	fine silt
+8	0.004 (1/256)	very fine silt
+9	0.002 (1/512)	coarse clay
+10	0.001 (1/1024)	medium clay

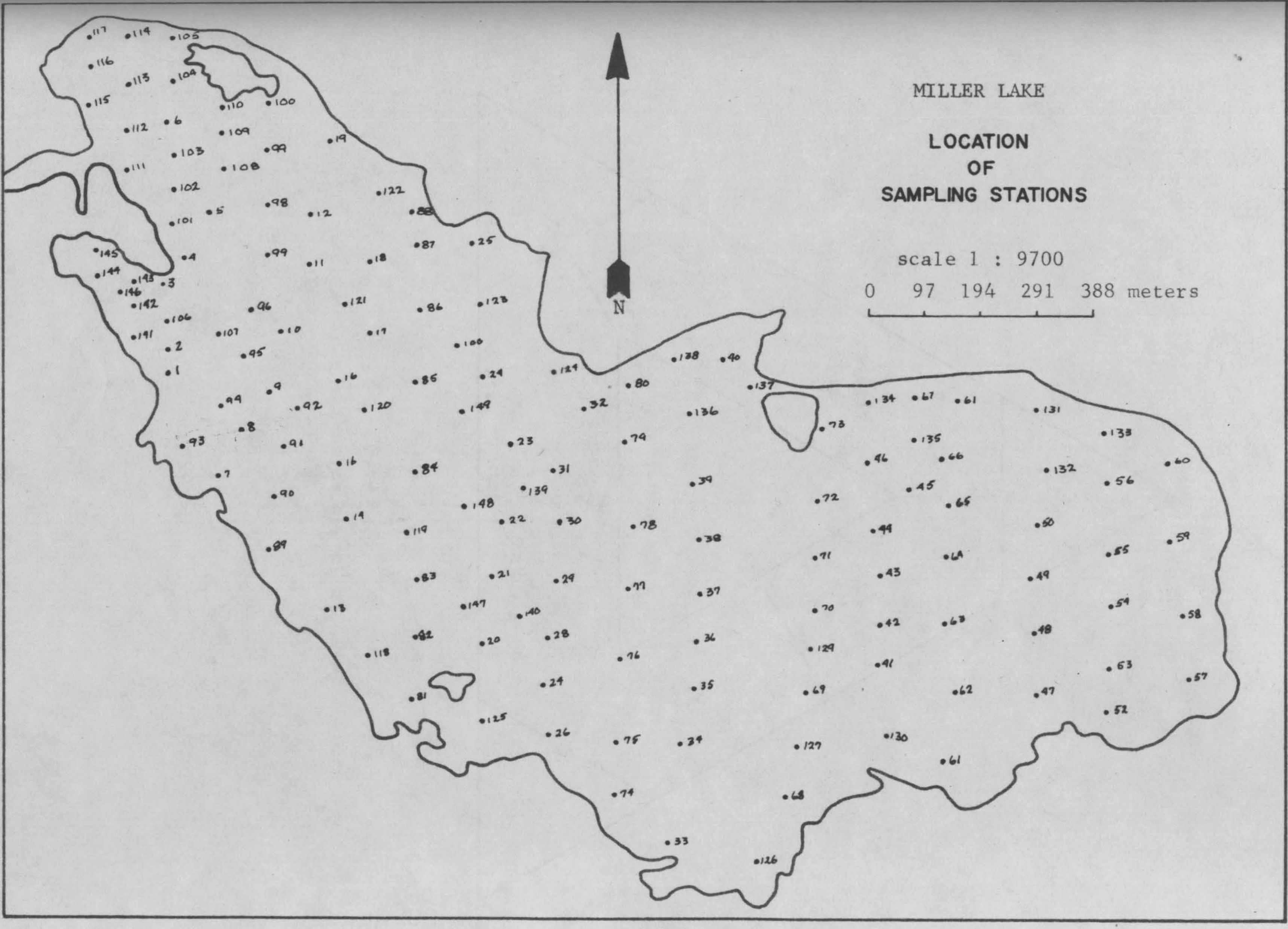


FIGURE 38. Locations of sediment samples in Miller Lake.

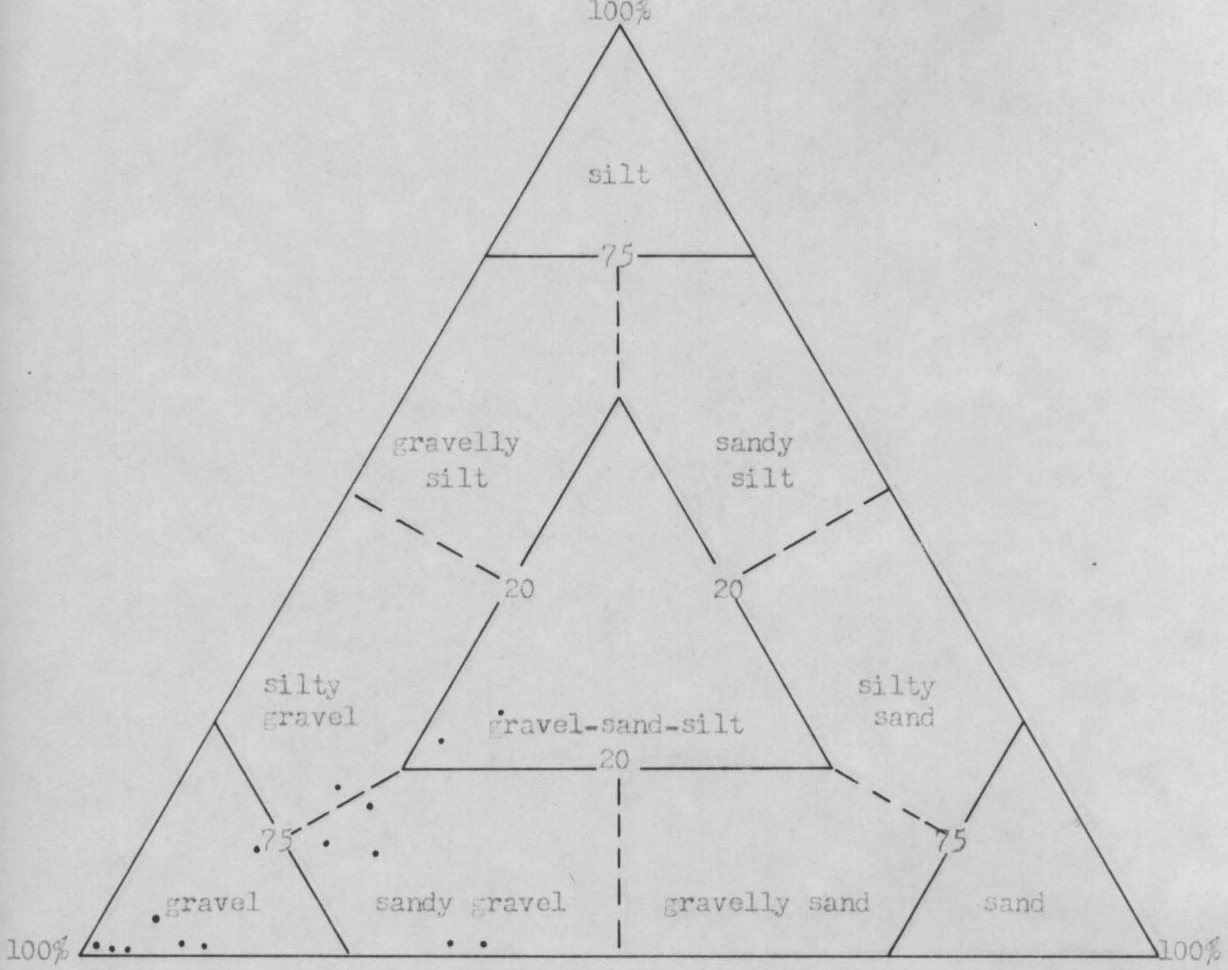


FIGURE 39. Triangular diagram showing distribution of sediments in the "gravel-sand-clay" group.

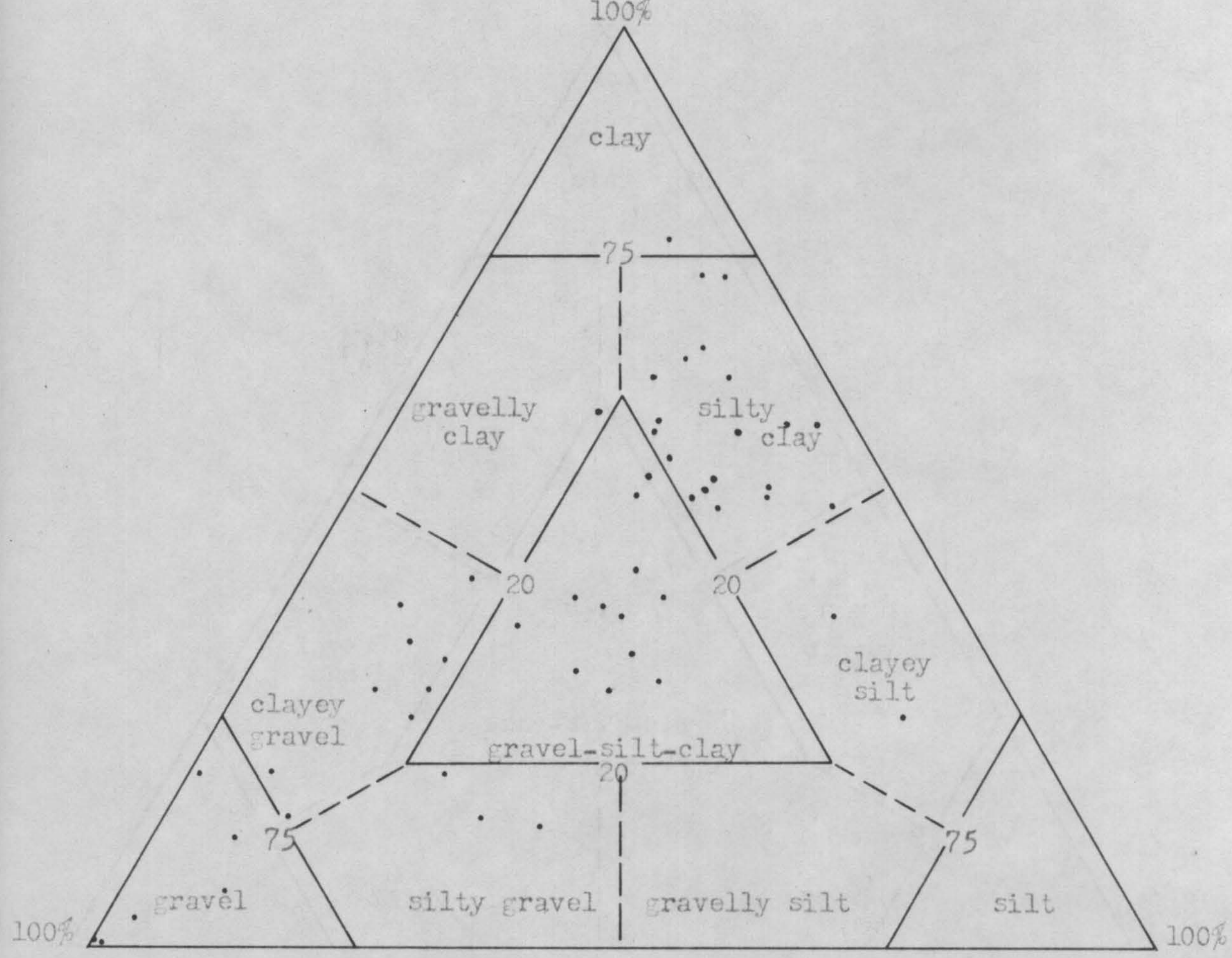


FIGURE 40. Triangular diagram showing distribution of sediments in the "gravel-silt-clay" group.

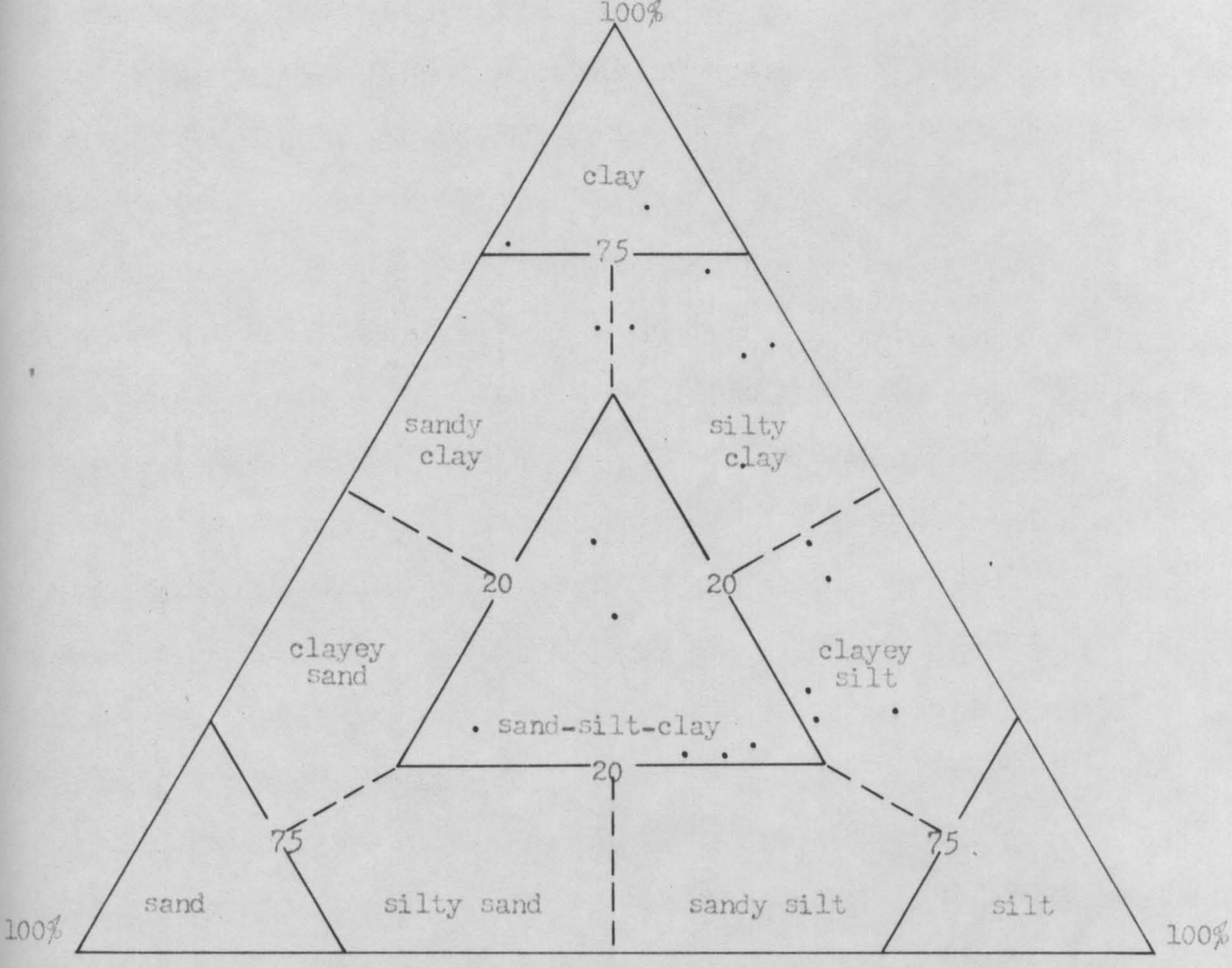


FIGURE 41. Triangular diagram showing distribution of sediments in the "sand-silt-clay" group.

Appendix A). It is felt that since one component was so small it could be ignored as the component would have no bearing on the sediment type. In essence, most of the samples had only three major grain size components. These components were plotted on a triangular diagram to show the textural relations among the sediments. In those few cases where there were four major components all greater than 10%, two adjacent components were combined as one with the resultant component depending upon which grade size exhibited the largest percentage. The vertices of the three triangular diagrams were arranged in the following manner: Gravel-sand-silt; Sand-silt-clay; and Gravel-silt-clay. These components located at the vertices of the diagrams provided a basis for dividing the three triangular faces into a number of textural classes. The arrangement of class lines and the resultant sediment types (class names) followed the recommendations of Shepard (1954, p. 157), but were modified to include the gravel component.

The data obtained from heavy mineral and petrological analyses were tabulated and plotted as rock or mineral type against percent frequency on a bar diagram (see Figs. 49 and 50). The ratio by weight of heavy minerals to light minerals was computed from the heavy mineral data.

Results of analyses

Distribution of sediment components

In drawing the isopleths of Figures 42, 43, and 44, consideration was given to the field descriptions of samples inadequate for analysis or so similar to adjacent analyzed samples that their analysis was deemed unprofitable.

Sand and gravel: Figure 42 shows the percentage distribution of sand and gravel. The general dominant feature is the gradual decrease

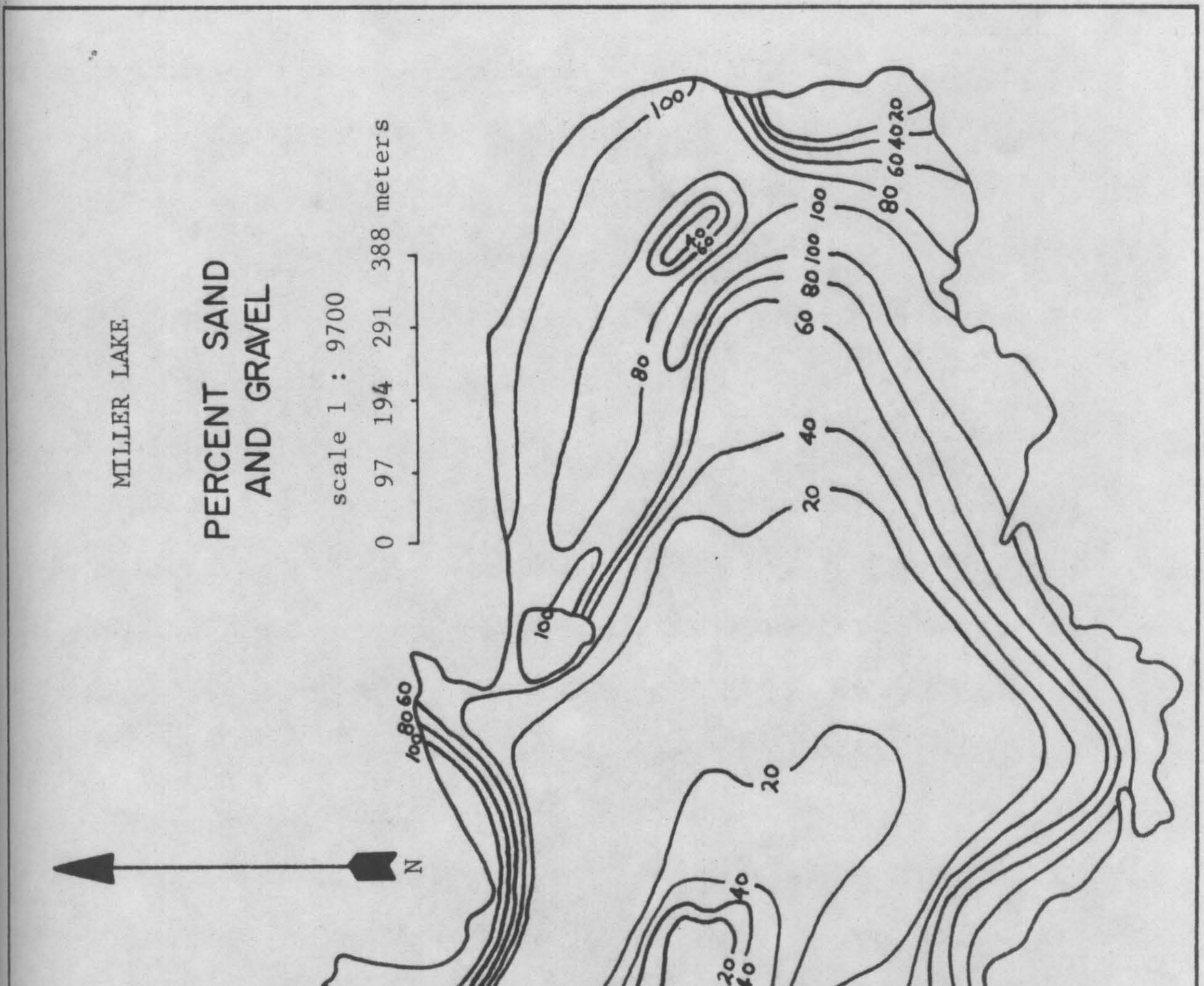


FIGURE 42. Percent sand and gravel in Miller Lake sediments.

in the percentage of coarse sediment from the margin to the center of Miller Lake basin. It should be remembered that this map shows only the surface distribution of sand and gravel throughout the basin and gives no indication concerning the size of sediment located a few centimeters below the bottom surface. The overall picture presented by the map does suggest, however, that the sediments located near the shore of the lake are considerably more coarse than those in the middle of the basin.

There are several areas within the basin that exhibit anomalous percentages of sand and gravel. The inner part of Eman Cove (informal name) has a relatively low percentage of coarse material and a high percentage of finer material (Fig. 42). This may be explained by the fact that the basin slopes very steeply in this region and the coarser material is masked by finer material present in greater amounts since it is relatively unaffected by wave action. However, as the entire northern basin wall exhibits a steep slope, this would not seem to be an adequate explanation. It is possible that the rate of ablation may be slower in this area than in others and therefore less coarse material is being contributed to the lake. It seems improbable that the rate of ablation of the ice cliff would differ enough from area to area to produce significant changes in the amount of material supplied to the lake. The ice in this area may contain material that is generally finer than that in other areas. Lastly, this area is located within a cove which may be protected from currents that would tend to remove the finer material. At the present time no plausible explanation can be offered to account for this low amount of coarse material in Eman Cove. The above suggestions are offered only as very tentative possibilities.

There is a similar area of low sand and gravel content located

Cavern Cove (Fig. 25). The central part of this cove lies within the 20% isopleth. The possible explanations for this distribution correspond to those offered for the anomalous sand and gravel distribution in Emman Cove. A third area of anomalous sand and gravel percentages is located in the extreme southeastern corner of the lake where the area adjacent to the shore lies within the 20% isopleth. The detrital material in and on the ice adjacent to the area is definitely finer than that of most other areas along the ice cliff. This finer source material is probably a major factor controlling the fineness of the bottom sediment in this area.

There is a large area in the west-central part of the Miller Lake basin in which the percentage of sand and gravel becomes greater toward the middle of the lake. This area corresponds to a gentle sublacustrine rise located on the littoral shelf (see Plate I). The water depths in this area are relatively shallow, with much of the basin floor lying only 10 m. (ranging from 5-15 m.) below the water surface. During times of extreme wave action the higher parts of this sublacustrine ridge may be subject to some erosion by the waves, resulting in the removal of finer material from this region. This ridge acts as a barrier to icebergs which are quite numerous on Miller Lake (see Fig. 45). The prevailing northeast winds blow the bergs across the lake where they become grounded on this ridge. Subsequent melting of the ice deposits sediment from the berg on the basin floor. A large amount of this sediment consists of sand and gravel. These two factors explain the high percentage of coarse material in this area.

Directly southeast of this sublacustrine ridge is a small semi-rectangular area which has a region of small sand and gravel content surrounded by one of significantly higher content. This area corresponds to a sublacustrine hill, the top of which is occupied by a smaller depression. The higher percentages correspond to the crest of the hill, while the lower percentages fall within the depression. This distribution is to be expected since finer material is more easily eroded by wave action at shallow depths.

Silt: Percentage of silt tends to attain its high values in areas low in sand and gravel and low-to-moderate in clay. Figure 43 indicates that areas of approximately 60% silt are located in Ekman Cove and in the extreme southeastern part of the lake basin. Both of these areas are very low in sand and gravel and have moderate amounts of clay. The large area of moderate silt content corresponds to the extensive region, situated in the central part of the lake, of low sand and gravel content (less than 20%). A narrow rectangular area of low silt percentage is situated in the west-central part of Miller Lake. Areas devoid of silt are located adjacent to much of the shore line (Fig. 43).

Clay: There are several areas with sediments high in clay (Fig. 44). There is one small area which contains greater than 80% clay and two relatively large areas with more than 60% clay. These three areas of high clay content are located in the central part of the basin (Fig. 44), and correspond roughly to the areas of low sand and gravel content. Areas devoid of clay are found in locations with 100% sand and gravel; in a relatively narrow zone around much of the margin of Miller Lake. There is a relatively high (greater than 40%) amount of clay within the inner part of Icy Bay (Fig. 25) and a low clay value (0%) near the entrance to the Bay. There appears to be a small sill at the entrance of this bay which protects the inner part of the bay and deters removal of finer

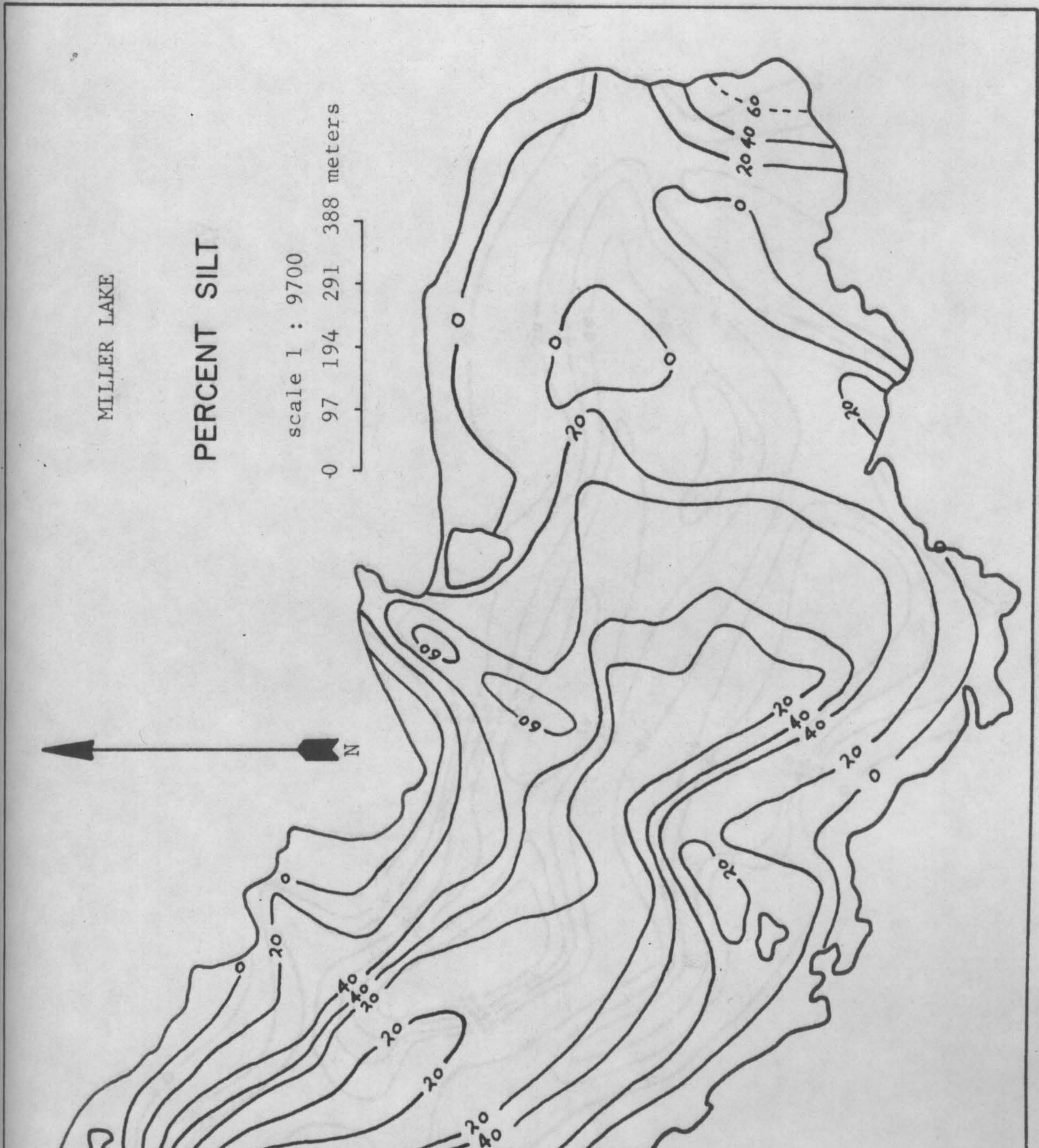


FIGURE 43. Percent silt in Miller Lake sediments.

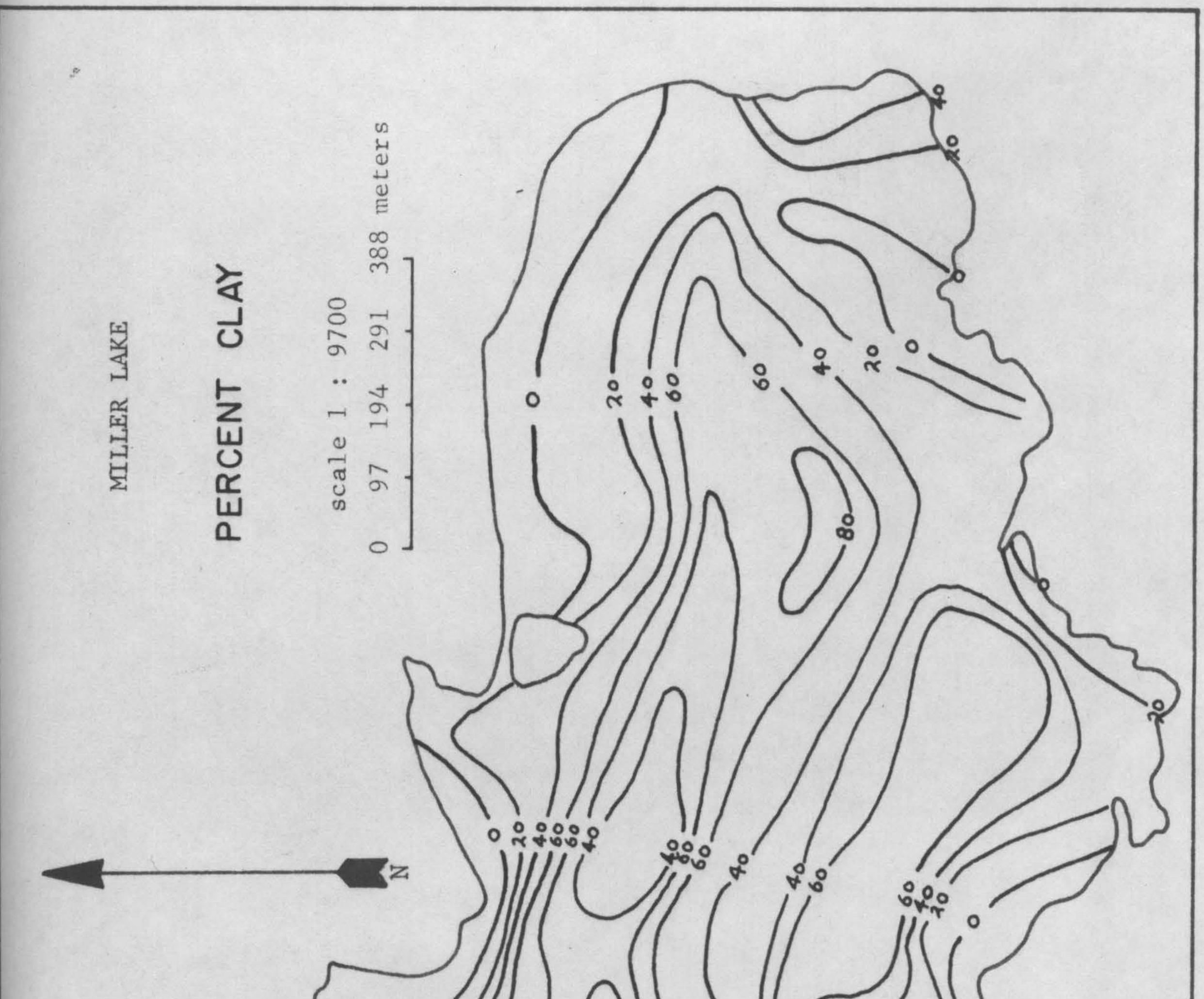


FIGURE 44. Percent clay in Miller Lake sediments.

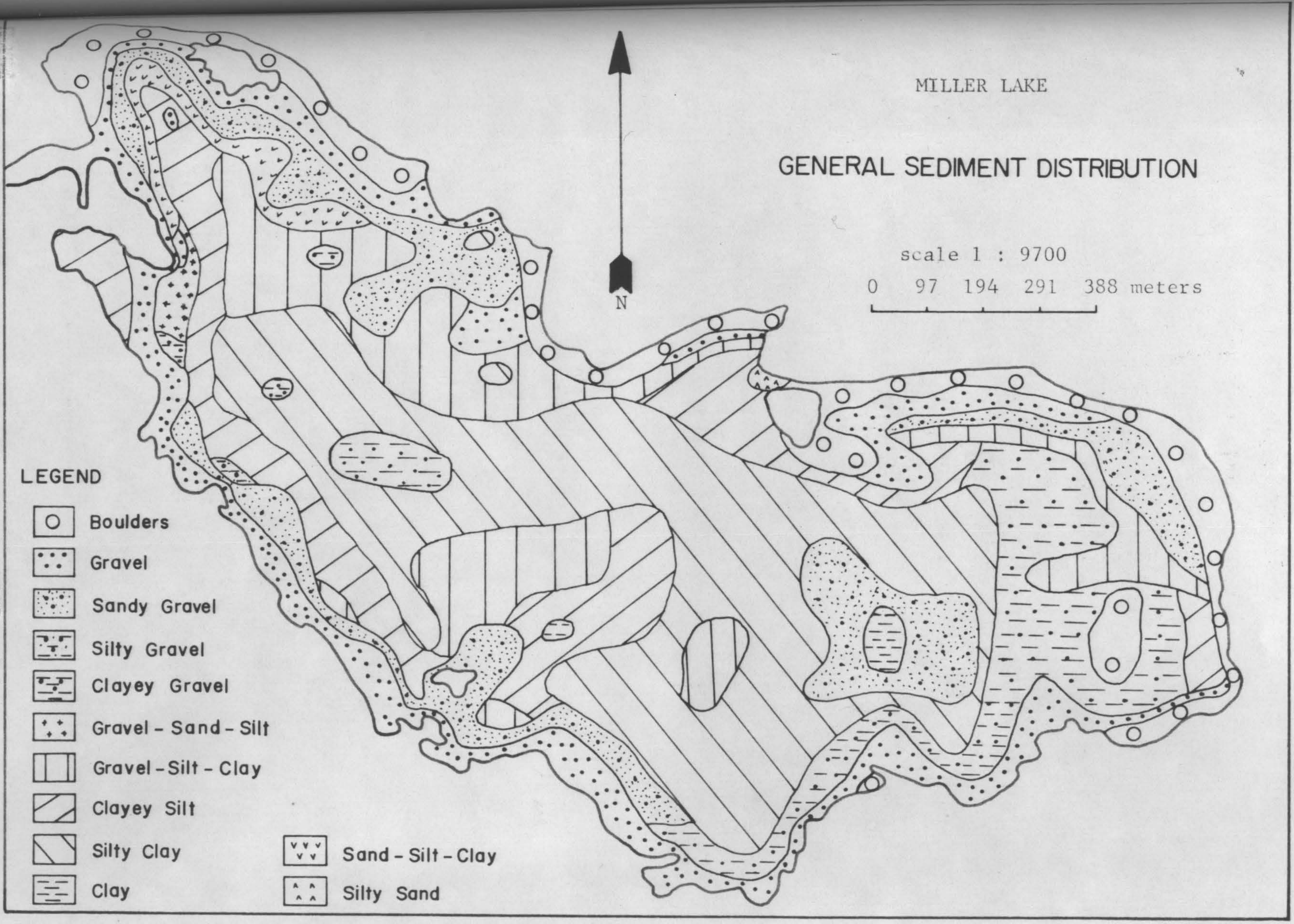
sediment (silt and clay) from this area by wave action. The other areas of anomalous clay content have already been discussed under "Sand and gravel".

Distribution of sediment types

In order to determine the type of sediment represented by each sample, the percentages of gravel, sand, silt, and clay have been plotted on triangular diagrams and classified according to the nomenclature recommended by Shepard (1954, p. 157). Figures 39, 40, and 41 are triangular diagrams showing the sediment classes and the number of samples falling into these classes. There are 11 major sediment types in Miller Lake: Boulders, gravel, sandy gravel, silty gravel, clayey gravel, gravel-sand-silt, gravel-silt-clay, clayey silt, silty clay, clay, and sand-silt-clay. Figure 46 shows the distribution of these sediment types in Miller Lake. Although the sample density was sufficiently uniform throughout the lake, this map represents only the general distribution of sediment type. This is due to the fact that directly adjacent to one station analyzed as one type of sediment (silty clay, for example) may lie a completely different sediment type (such as a boulder). This situation results from the erratic mode of sediment deposition in Miller Lake.

It is readily apparent from Figure 46 that silty clay is the dominant sediment in Miller Lake. Silty clay occurs throughout a large part of the central area of the lake. The areas of clayey gravel, sandy gravel, and gravel-silt-clay occurring within the silty clay region are associated with sublacustrine ridges and hills which, due to shallower depths (see Plate I), are subject to more erosion by wave action than is the rest of the central part of the lake. The main silty clay region is bounded in several places by areas of clayey silt. In many cases the difference

FIGURE 45. Photographs showing icebergs on Miller Lake.



IGURE 46. General distribution of sediments in Miller Lake.

between silty clay and clayey silt is so slight that the two classes of sediment can be treated as one in this report.

Most of the margin of Miller Lake exhibits a band of coarse material extending a short distance out in the basin. Along the north side of the lake there is a band of cobbles and boulders, a band of gravel, and one of sandy gravel. In this area there seems to be a rough gradation from coarse to fine material toward the deeper parts of the lake. Along the southern shore there is a band of gravel adjacent to a band of sandy gravel. Throughout most of Miller Lake there is a general gradation from coarser to finer material toward the middle of the lake.

A band of gravel extending across the mouth of Icy Cove seems to reflect the small sublacustrine sill in this area. The eastern part of the lake appears to exhibit a larger area of coarse sediment than the western part. There are several anomalous areas of sediment distribution throughout the basin, an explanation for the occurrence of these areas was suggested in the previous section.

Pebble counts

Figure 47 shows the results of twelve pebble counts taken around the lake shore at the stations whose locations are shown on Figure 40. It is readily apparent from these bar diagrams that granite and slate are the dominant rock types in the Miller Lake area. Samples numbered 1, 2, and 3 exhibit a much higher percentage of granite than slate, while the remaining samples have high percentages of granite and slate and low percentages of granite gneiss, quartz diorite, and greenstone. This distribution results from the fact that there is a high percentage of granite pebbles in the superglacial till which occurs west of

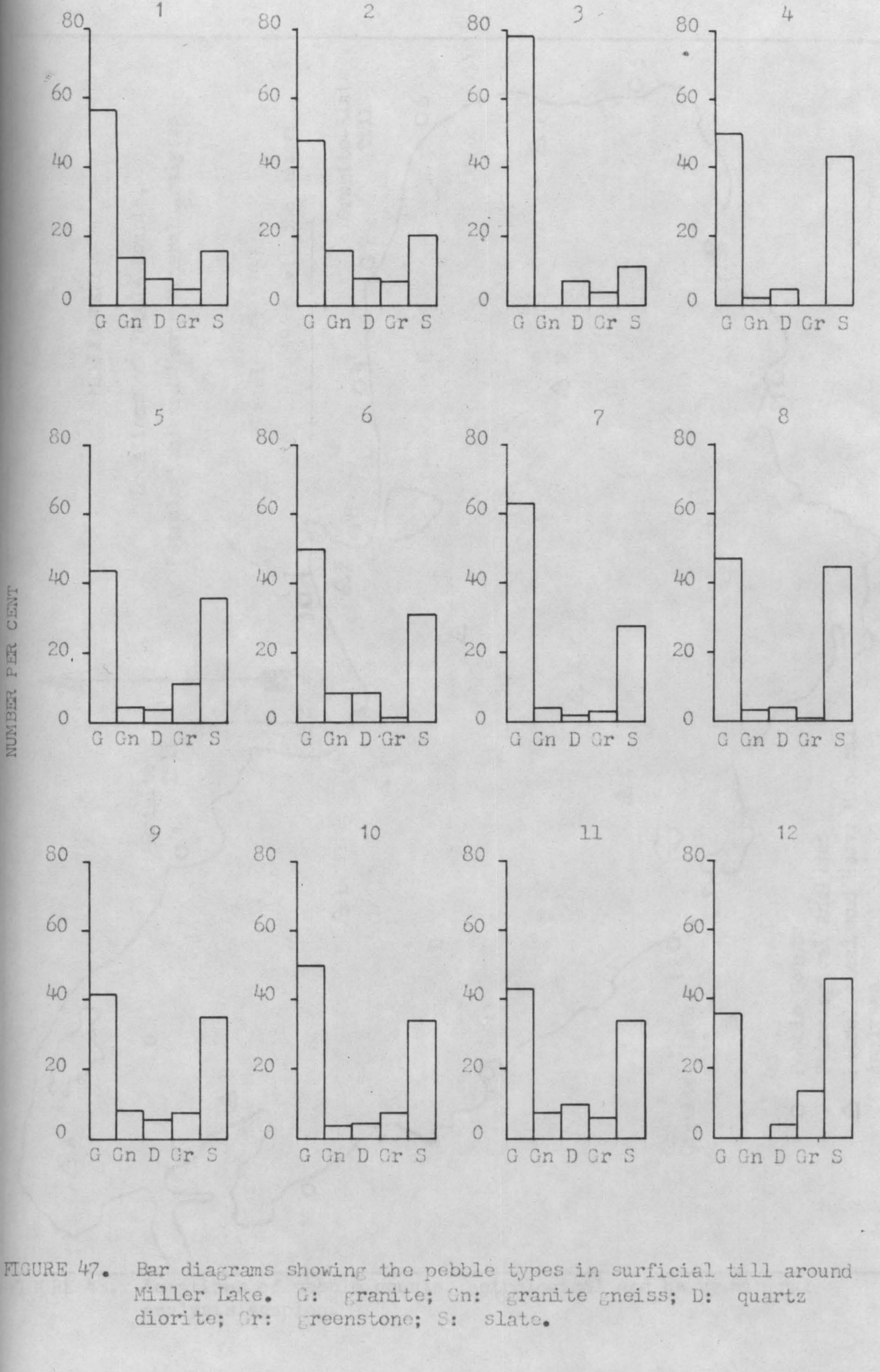


FIGURE 47. Bar diagrams showing the pebble types in surficial till around Miller Lake. G: granite; Gn: granite gneiss; D: quartz diorite; Gr: greenstone; S: slate.

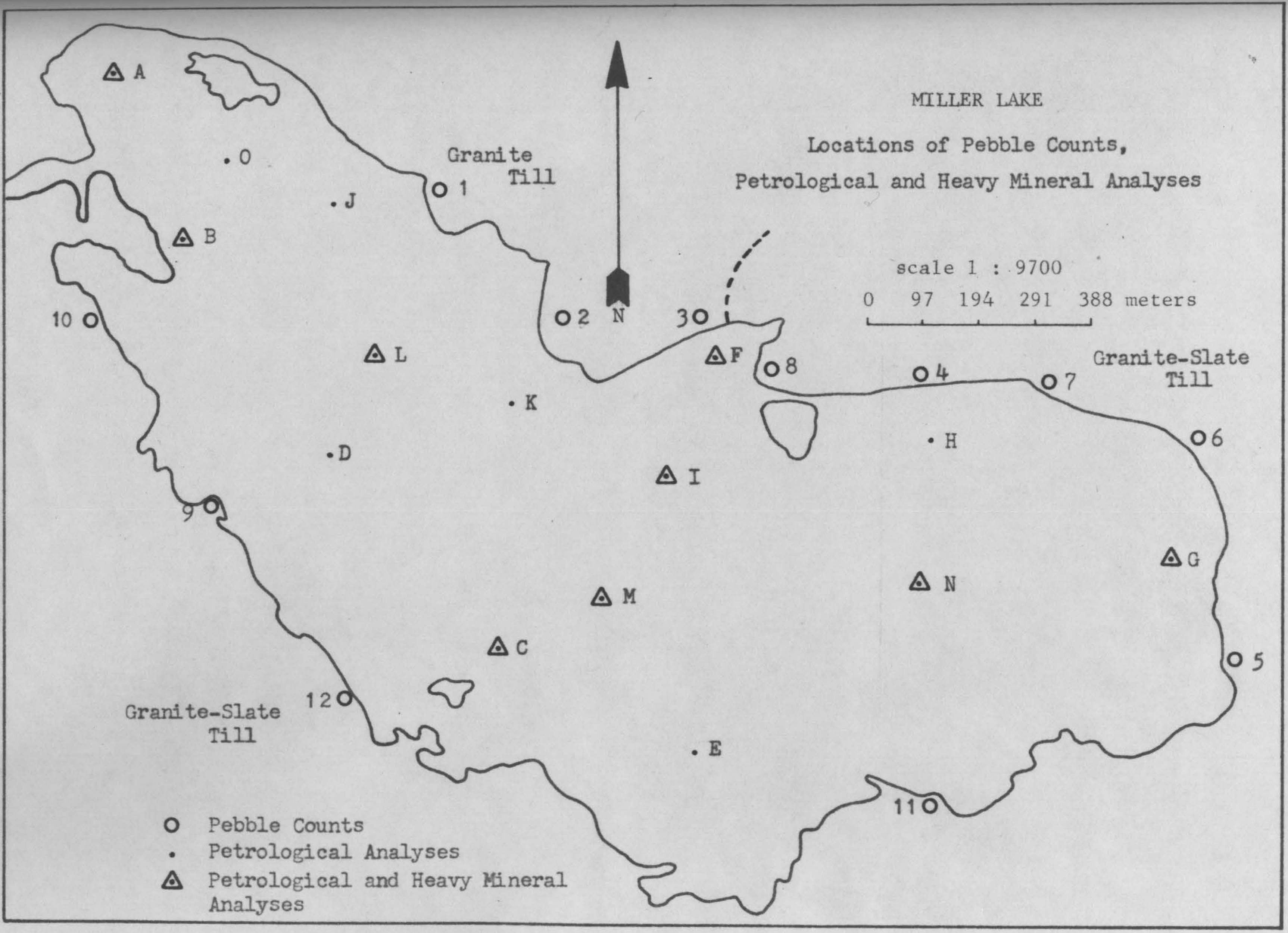


FIGURE 48. Locations of pebble counts, petrological and heavy mineral analysis samples.

location number 2 on the north shore of Miller Lake, while the till around the rest of the lake has relatively equal granite and slate components. This distinction between light and dark till is readily noticeable from the air where one can observe a sharp contact between tan granite-rich till and grey slate-granite till. The dashed line in Figure 46 marks the approximate position of this contact.

Petrological analyses

The results of the petrological analyses presented in Figure 49 appear to be quite similar to the results of the pebble counts. The main differences are the greater percentage of slate in relation to granite and the general increase in the percentages of granite gneiss, quartz diorite, and greenstone in relation to granite and slate. This figure indicates that the coarse fraction (gravel and larger) of the sediments in Miller Lake generally contains higher amounts of slate and more nearly equal but smaller amounts of granite, granite gneiss, quartz diorite, and greenstone.

Heavy mineral analyses

Heavy mineral studies were conducted on nine sand samples from Miller Lake. The locations of these sampling stations are shown in Figure 46. There are five minerals or mineral groups that composed the majority of the samples. Epidote is by far the most abundant mineral (see Fig. 50) except in samples A and I. Sample A is located adjacent to the granite-rich till area and sample I is located near the contact between the granite-rich and granite-slate till. The other major heavy minerals are hornblende (generally of the common variety), chlorite-serpentine minerals, biotite, and a little augite. Hornblende is second in abundance to epidote, reflecting the granitic rocks and the quartz diorite that comprise a good part of the till in the Miller Lake

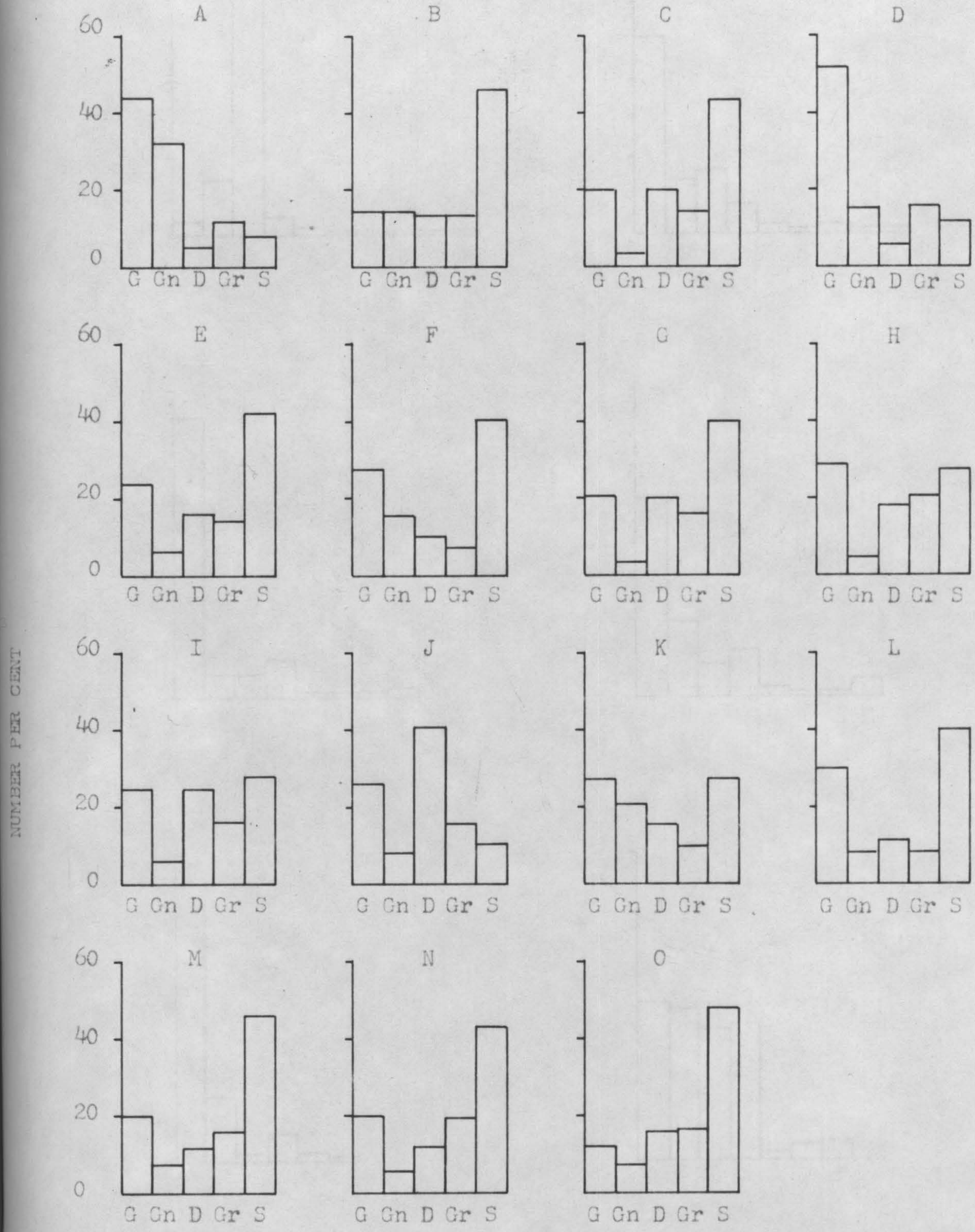


FIGURE 49. Bar diagrams showing the distribution of rock types in Miller Lake as determined by petrological analyses. G: granite; Gn: granite gneiss; D: quartz diorite; Gr: greenstone; S: slate.

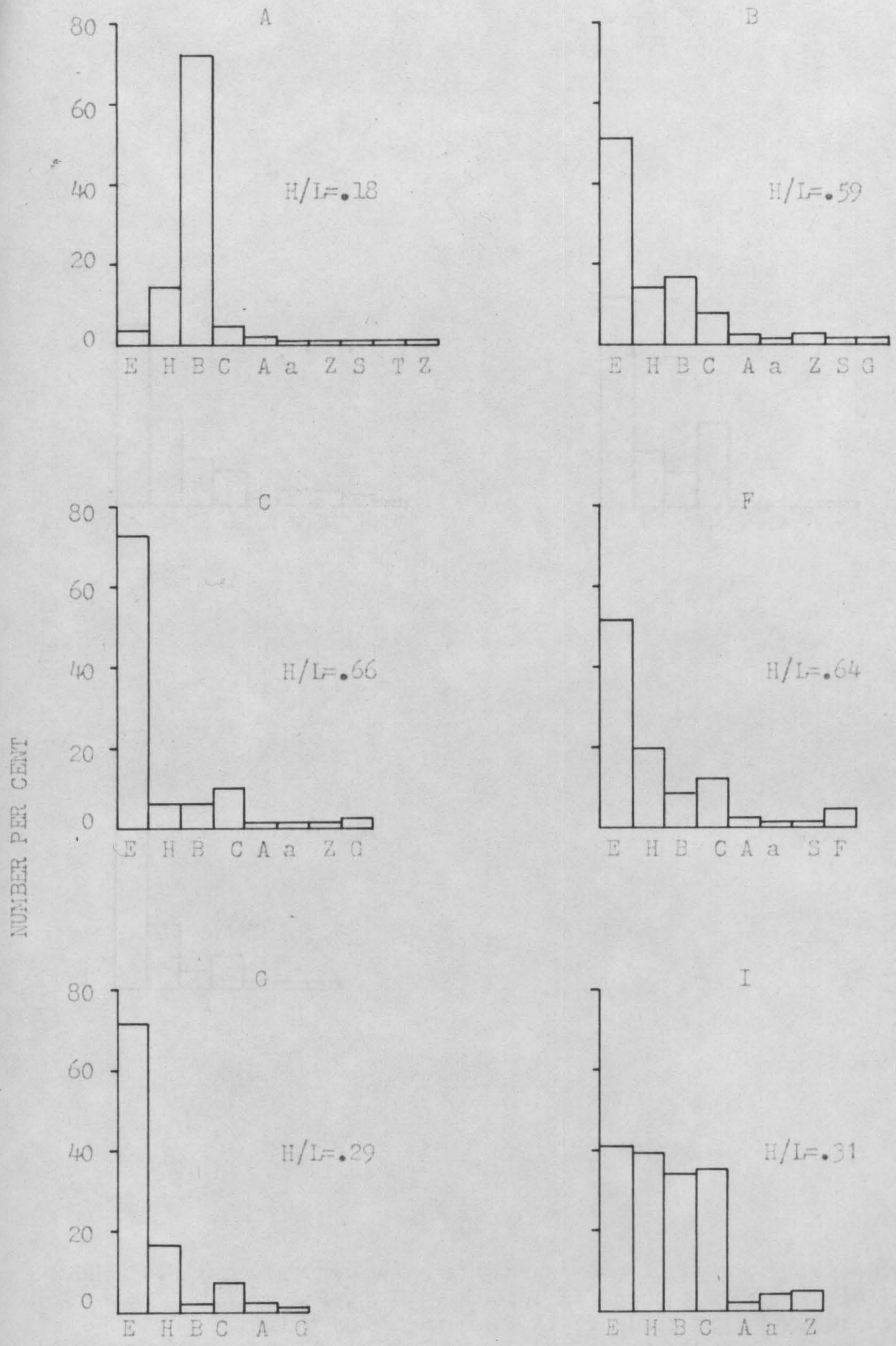


FIGURE 50. (See following page.)

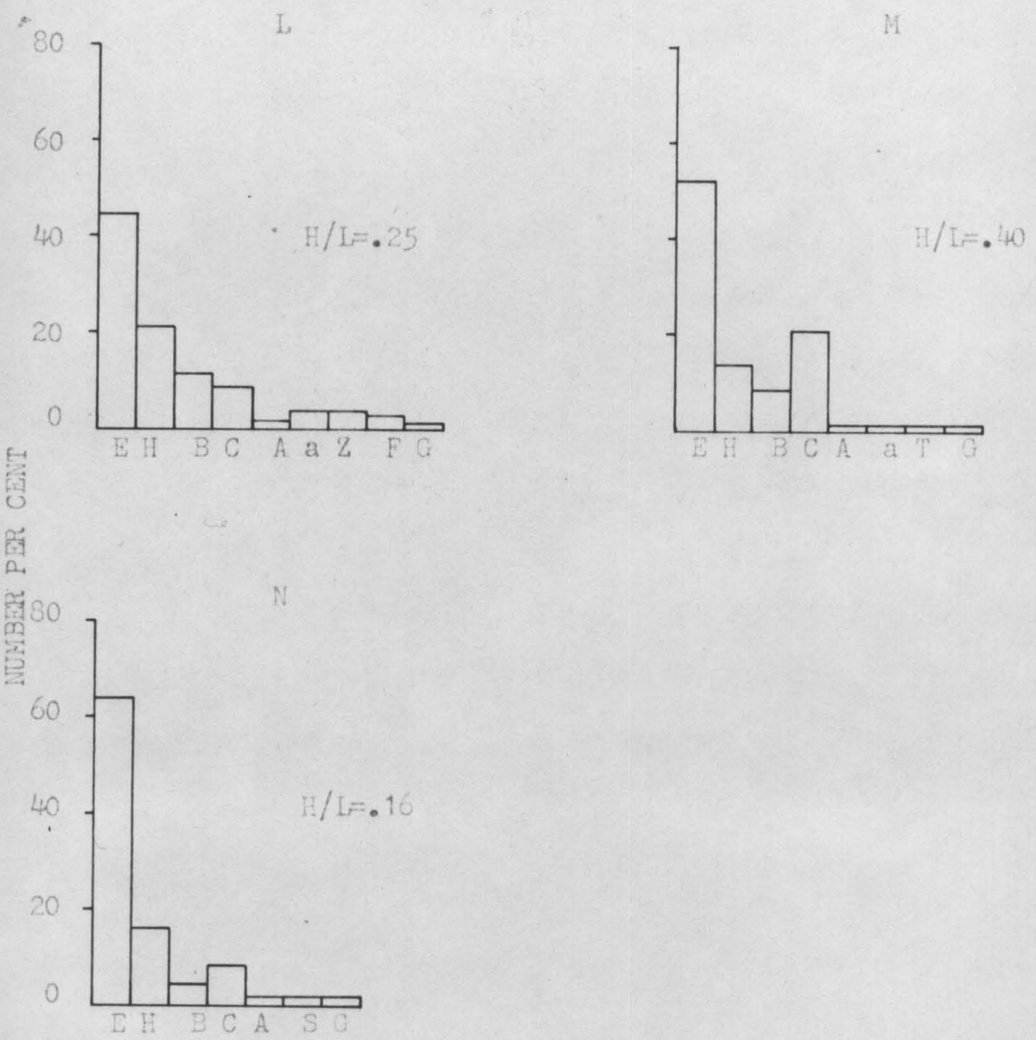


FIGURE 50. Bar diagrams showing mineral composition of sediments in Miller Lake. E: epidote; H: hornblende; B: biotite; C: chlorite-serpentine; A: augite; a: apatite; Z: zircon; F: fluorite; S: sphene; T: tourmaline; G: garnet.

area. Biotite and chlorite-serpentine occur in more or less equal abundance (Fig. 50), biotite reflecting the granite source and chlorite-serpentine, the greenstone-slate components of the till. Biotite comprises 72% of the minerals in sample A (Fig. 50). This is probably due to the close proximity of granite-rich till.

The accessory heavy minerals found in the samples rarely comprise more than 10% (Fig. 50). The more abundant accessory minerals are apatite, zircon, and garnet; sphene, fluorite, and tourmaline are rare.

The ratio by weight of heavy minerals to light minerals generally reflects the composition of the sediments. The samples with high ratios contain more mafic minerals (epidote, chlorite-serpentine, augite) than those with low ratios. The source of these mafic minerals is the greenstone and slate components of the till occurring in the Miller Lake area.

Discussion

There are several mechanisms by which sediment is deposited in Miller Lake. The chief mechanisms are associated with ice and pertain to material situated on top of or within ice. Figures 51 and 52 show the amount of material on top of and in the ice along the northern shore of Miller Lake. This material ranges from boulders the size of a small house, to clay size particles. When chunks of ice calve from this ice cliff the debris on top of the ice is dumped into the lake. Much of this debris remains near the base of the cliff due to its large size.

There were numerous icebergs on Miller Lake during the 1963 field season, and aerial photographs indicate that there were numerous bergs

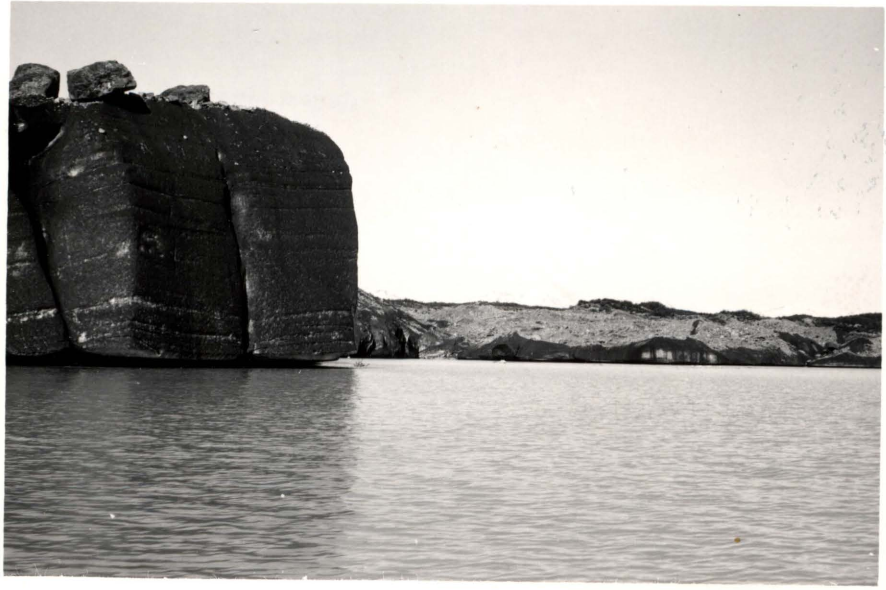


FIGURE 51. Photographs showing amount of material on top of and in the ice along the northern shore of Miller Lake.

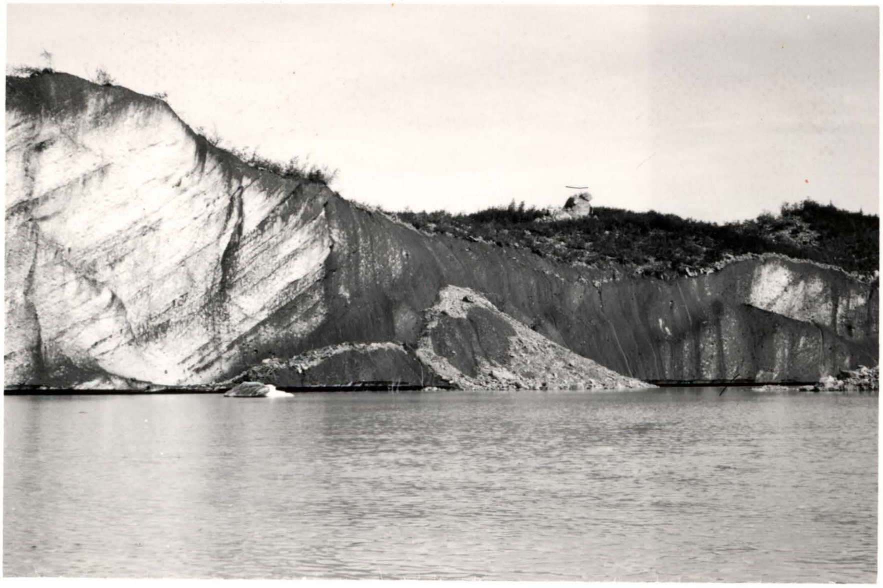


FIGURE 52. Photographs showing amount of material on top of and in the ice along the eastern shore of Miller Lake.

during the last 15 years. Many of these icebergs have large amounts of debris (Fig. 45) on or within them. Subsequent melting of these bergs deposits this debris in the lake. This ice rafting process deposits coarse material in areas where such material would not ordinarily be deposited by normal modes of sediment deposition.

Finer sediment (silt and clay) is supplied to the lake via water entering the lake in the form of surface meltwater, englacial streams, and sublacustrine influents. This water is quite turbid where observed, indicating the high concentration of suspended particulate matter composed of sand, silt, and clay-size particles.

Most of the coarser material (sand, gravel, cobbles, and boulders) is deposited during the late spring, summer, and early fall when melting and calving of the ice is most severe. The frequent mixing experienced by the lake during this period stirs up the finer material and puts it into suspension. Therefore, not as much silt is deposited during this time. The water samples collected at 30 - 40 m. depths in Miller Lake contained nearly 1500 ppm suspended material, approximately 40% of which was silt-size material.

Very little clay-size sediment is actually deposited during the summer. As previously noted, frequent mixing of the lake water during this period keeps this material in suspension. In fact, fine material which was deposited during the previous winter may be suspended again.

Probably the only time when fine material (especially clay-size material) is deposited in Miller Lake in any sizeable quantities is during the winter months when the lake is sealed off from the winds by ice. During the winter the amount of melting is negligible and it is doubtful whether Miller Lake receives any substantial inflow at this time. Thus the lake is relatively undisturbed during this period and the fine suspended material is able to settle out and accumulate on the floor of the lake basin.

Source of sediment

Results of the pebble counts and of the petrological and heavy mineral analyses indicate that there is essentially one source for the sediments in Miller Lake. Rocks composed of slate, greywacke, and greenstone, intruded by biotite granite and diorite (rocks of the Chugach Mountains geosyncline and the greenstone-greywacke-slate sequence), occur in the mountains to the north and east of the Miller Lake area. This material is eroded by the action of glacial ice and is entrained by the ice and transported down the glacier. A glance at the analyses mentioned above will indicate that these rocks are the source for the sediments in Miller Lake.

Rate of sedimentation

Due to the lack of accurate information concerning the amount of sediment entering Miller Lake as a result of melting ice both around the shore and in icebergs, or material transported by influents, it is impossible to accurately estimate the rate of sedimentation. An attempt was made during the 1963 field season to determine the rough rate of deposition of fine sediment. Three five-pound coffee cans were lowered to the bottom in the southern part of Miller Lake. They remained in place for two months. When they were raised to the surface in the middle of August, the cans were found to be nearly full of silty clay. Since the height of the containers was 15.2 cm., this means that approximately 15 cm. of sediment was deposited over the entire basin in two months. Projecting this figure over seven months, during which time material is entering the lake, and allowing for the settling out of fine material during the winter, the calculated yearly sedimentation in Miller lake is 5½ cm./year. This figure is high! This figure should probably be much lower since most of the sediment in the cans does not represent new material deposited, but is, in reality, old sediment previously deposited on the lake floor which has been taken into suspension by currents produced by wind action and redeposited during calm periods. In any case, the above figure applies only to silt and clay and completely disregards the deposition of coarser sediments, a major constituent of the overall sedimentation in Miller Lake. The annual rate of sedimentation in Miller Lake is probably quite high, but there are no accurate data upon which to base any estimate.

CONCLUSIONS

Miller Lake exhibits a dynamic and often erratic lacustrine environment due to its location on the terminus of the Martin River Glacier. Glacial ice is situated around the shore of the lake and probably beneath the lake basin. Many of the unusual limnological and geological features in Miller Lake are a result of its location.

At the present time the area and mean depth of the lake are increasing. This increase results primarily from melting and calving of ice around and beneath the lake. Shore processes, such as wave action and ice calving, are modifying the lake margin resulting in a straighter shore line.

The low maximum summer temperatures exhibited by the water in Miller Lake allow the winds to frequently circulate the waters. This frequent mixing keeps a large quantity of finer material in suspension, thus increasing the turbidity of the lake.

The distribution of sediment in Miller Lake is more regular than would be expected in such an erratic environment. Coarser sediments predominate around the margin, while finer material is found in the middle. There are, however, many exceptions to this general pattern (Fig. 46). Generally, sedimentation in the lake is controlled by the bathymetry. Finer sediment is deposited in basins where the effects of currents and waves are small, while coarser material is concentrated on higher areas where the finer particles are winnowed out by wave action and currents. The zone of coarse sediment corresponding to a sublacustrine ridge in the south-central part of the lake (Fig. 46) is an excellent example of this process.

The sediments in Miller Lake may generally be classified as glacio-

-lacustrine diamicton deposits similar to those described by Ferrians (1963). The term "diamicton" as proposed by Flint and others (1960 a,b) to designate "nonsorted or poorly sorted terrigenous sediment that consists of sand and/or larger particles in a muddy matrix" is quite applicable to the sediments in Miller Lake. Figure 53 is a series of three photographs showing a two-foot-long core taken from the middle of the lake. It is readily apparent from these photographs that the material is poorly sorted, with pebbles and cobbles occurring in a muddy matrix. This sediment was deposited by the glacier and icebergs that dumped phenoclastic material into Miller Lake. If such a deposit were encountered in the outcrop, it would undoubtedly be classified as a glacial till. The fact that this sediment was deposited in a body of standing water might well escape notice by the investigator. It is felt that there are probably numerous such water-deposited tills to be found in glaciated areas, but that the recognition of such water-laid tills is difficult due to their striking similarity to "normal" tills deposited by glaciers.

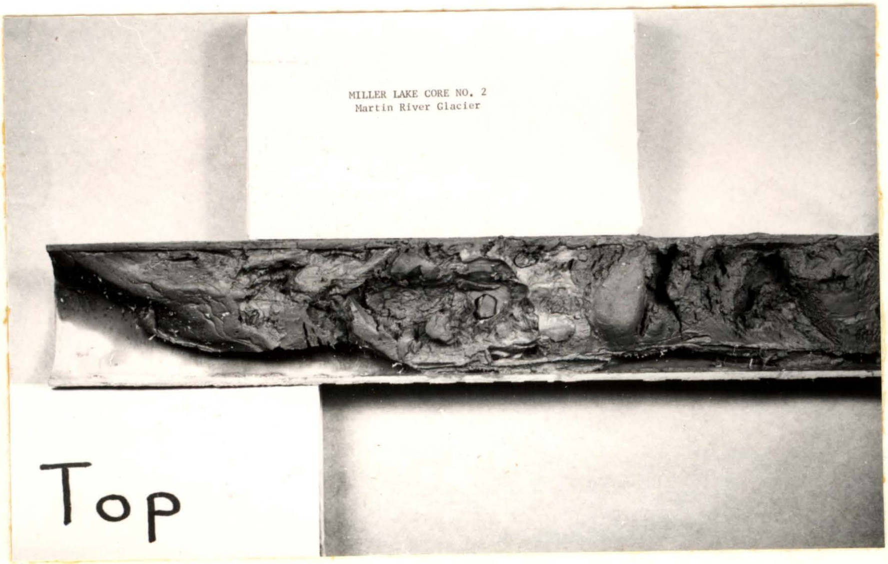


FIGURE 53. Photographs of a 2-foot core taken from the center of Miller Lake. Scale: 1 inch = 2.2 inches.

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APPENDIX A

This appendix contains the description of the sediment samples from Miller Lake. The water depths are given in meters. The columns "Gravel", "Sand", "Silt", and "Clay" are percentages of these components obtained from mechanical analysis of the sample.

The sediment-type column indicates the classification into which the sediment fell when plotted in triangular diagrams (Figures and). Abbreviations used in the sediment-type column and in the field descriptions are:

B	Cobbles and Boulders
G	Gravel
SG	Sandy gravel
SiG	Silty gravel
CG	Clayey gravel
G-S-Si	Gravel-sand-silt
G-Si-C	Gravel-silt-clay
CSi	Clayey silt
SiC	Silty clay
C	Clay
S-Si-C	Sand-silt-clay

The sediment-type enclosed by parentheses was inferred from the field description.

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Descriptions
U-1	10.5	74	6	8	12	G	Grey silty gravel.
U-2	11.5	42	9	18	31	CG	Grey silty gravel.
U-3	6.5	48	26	16	10	G-S-Si	Grey silty sand, pebbles.
U-4	4.3	44	12	30	14	SiG	Grey silty sand, pebbles.
U-5	13.5	2	11	63	24	CSi	Grey clayey silt.
U-6	13	98	.5	1.0	.5	G	Sand and pebbles.
U-7	8.5	41	10	36	13	SiG	Grey silty sand, pebbles.
U-8	13	8	3	64	25	CSi	Grey clayey silt; some cohesiveness.
U-9	13	46	8	18	28	CG	Grey clayey silt, pebbles.
U-10	14	11	5	33	51	SiC	Grey silty clay; some cohesiveness.
U-11	21	57	4	14	25	CG	Grey silt, sand, and pebbles.
U-12	49.5	9	20	50	21	S-Si-C	Grey silt and sand.
U-13	12.5	33	10	35	22	G-Si-C	Grey silt and clay, pebbles.

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Descriptions
U-14	15	8	4	24	64	SiC	Grey silty clay.
U-15	17	44	3	13	40	GC	Grey silty clay, pebbles.
U-16	17	15	2	35	48	SiC	Grey silty clay, some pebbles.
U-17	18	84	6	4	6	G	Pebbles, some grey sand-silt-clay.
U-18	32	28	5	30	37	G-Si-C	Grey silt and clay, pebbles.
U-19	45	-	-	-	-	-	Cobbles and pebbles.
U-20	10.5	67	22	5	6	SG	Light grey sand and gravel, cobbles.
U-21	18	42	6	17	35	G-Si-C	Grey silt and clay, pebbles.
U-22	27.5	16	3	25	56	SiC	Grey silty clay, some gravel.
U-23	41	2	1	40	57	SiC	Grey silty clay; dark streaks in sample.
U-24	42	8	3	39	50	SiC	Grey silty clay; dark streaks in sample.
U-25	46	15	4	28	53	SiC	Grey clayey silt; some cohesiveness.
U-26	18.5	-	-	-	-	-	Cobbles and pebbles.
U-27	30	14	4	15	67	SiC	Grey silty clay, pebbles.
U-28	30.5	1	1	22	76	C	Grey silty clay; dark streaks.
U-29	25	27	5	39	29	G-Si-C	Grey sand, silt, and clay, pebbles.
U-30	39	4	2	46	48	SiC	Grey silt and clay; dark material.
U-31	35	16	3	32	49	SiC	Grey silty clay, pebbles.
U-32	51	2	3	22	73	SiC	Grey silty clay; dark material.
U-33	12	59	-	13	28	GC	Grey silt and gravel, pebbles.
U-34	16	3	1	23	73	Sic	Grey clayey silt; some cohesiveness.
U-35	19.5	22	11	19	58	GC	Grey silty clay, pebbles.
U-36	14.5	35	13	14	38	G-Si-C	Grey gravel, sand, silt and clay, pebbles.
U-37	33.5	11	-	33	56	SiC	Grey silt and clay; dark material streaking sample.
U-38	34.5	14	4	25	57	SiC	Grey clayey silt, few pebbles.
U-39	43.5	5	7	36	52	SiC	Grey silt and clay; dark material.
U-40	39	6	20	52	22	S-Si-C	Grey silt and sand, few pebbles; some dark material.

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Descriptions
U-41	25.5	5	2	16	77	C	Grey silty clay; some dark streaks.
U-42	26.5	1	6	13	80	C	Grey silty clay; some dark streaks.
U-43	28	16	8	14	62	SiC	Grey clay and silt; some dark streaks.
U-44	39.5	8	1	29	62	SiC	Grey silt and clay; few dark streaks.
U-45	45	94	-	3	3	G	Gravel
U-46	48	-	-	-	-	-	Boulders, cobbles, and pebbles: No sample retained.
U-47	27.5	-	-	-	-	G	Pebbles.
U-48	31.5	58	1	8	33	CG	Grey silty clay, pebbles.
U-49	50	24	8	19	49	G-Si-C	Grey silty clay and gravel; some dark streaks.
U-50	54	-	-	-	-	G	Gravel.
U-51	64	-	-	-	-	G	Gravel.
U-52	16	70	12	9	9	SiG	Grey sand and gravel, some silt.
U-53	5.5	-	-	-	-	-	Boulders and cobbles; no sample retained.
U-54	27	-	-	-	-	-	Cobbles and pebbles.
U-55	34	22	9	18	51	G-Si-C	Grey gravel, silt and clay, some sand.
U-56	51	69	19	7	5	SG	Grey sand and gravel, pebbles.
U-57	43	1	18	56	25	CSi	Grey sand and silt.
U-58	25	7	5	39	49	SiC	Grey clayey silt.
U-59	31	71	17	7	5	SG	Grey sand and gravel.
U-60	29.5	-	-	-	-	-	Boulders, cobbles, and pebbles.
U-61	18.5	5	1	21	73	SiC	Grey silty clay, fair cohesiveness.
U-62	10.5	-	-	-	-	-	Boulders and cobbles; no sample retained.
U-63	31	-	-	-	-	(SiC)	Grey silty clay, pebbles.
U-64	35	-	-	-	-	(SiC)	Grey silt and clay, some dark streaks.
U-65	39	-	-	-	-	(SiC)	Grey silt and clay, some dark streaks.
U-66	47	-	-	-	-	(SiC)	Grey silty clay, pebbles, dark streaks.
U-67	50	-	-	-	-	-	Boulders and cobbles; no sample retained.
U-68	11.5	2	2	32	64	SiC	Grey silty clay; good cohesiveness.
U-69	24	44	8	11	37	CG	Grey silt and clay, pebbles.

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Description
U-70	33	88	12	-	-	G	Pebbles, little silt and clay.
U-71	41	-	-	-	-	(SG)	Gravel, little silt and clay.
U-72	49	4	2	37	57	SiC	Grey silt and clay, few pebbles.
U-73	58	-	-	-	-	(G)	Gravel, little silt and clay.
U-74	14	90	10	-	-	G	Gravel.
U-75	32	-	-	-	-	(SiC)	Light and dark grey silt and clay.
U-76	31	6	4	25	65	SiC	Grey silt and clay, few pebbles, dark streaks.
U-77	37	-	-	-	-	(G)	Gravel.
U-78	39	9	3	52	36	CSi	Light and dark grey silt and clay; sample shows stratification; dark streaks.
U-79	43.5	-	-	-	-	(CSi)	Light and dark grey silt and clay; sample shows stratification; dark streaks.
U-80	19	-	-	-	-	-	Boulders; no sample retained.
U-81	4.5	43	14	24	19	SiG	Grey silt, sand, and gravel.
U-82	12.5	6	1	40	53	SiC	Grey silt and clay, pebbles; fair cohesiveness.
U-83	16.5	28	4	27	41	G-Si-C	Grey silty clay, pebbles; dark streaks.
U-84	23	66	7	8	19	CG	Gravel, some silt and sand.
U-85	25	-	-	-	-	(G-Si-C)	Grey gravel, silt, and clay.
U-86	34	1	5	30	64	SiC	Light and dark grey silt and clay; sample shows stratification.
U-87	43	-	-	-	-	(SG)	Grey sand and gravel.
U-88	25	99	1	-	-	G	Gravel, cobbles.
U-89	5.5	78	11	7	4	G	Grey sand and gravel.
U-90	14.5	-	-	-	-	(G-S-Si)	Grey silt, sand, and gravel.
U-91	14	-	-	-	-	(SiC)	Grey silty clay, few pebbles.
U-92	16	-	-	-	-	(SiC)	Grey silty clay, pebbles.
U-93	5.5	-	-	-	-	(SG)	Dark grey sand and gravel.
U-94	14	-	-	-	-	(SiC)	Grey silty clay.
U-95	13.5	12	5	33	50	SiC	Grey silty clay, few

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Descriptions
							pebbles; sample shows stratification.
U-96	10.5	-	-	-	-	(G-Si-C)	Grey silt, sand, and gravel.
U-97	13.5	18	9	35	38	G-Si-C	Light and dark grey sand, silt, and clay, pebbles; dark streaks.
U-98	24	-	-	-	-	(SG)	Dark grey sand and gravel.
U-99	48.5	11	22	46	21	S-Si-C	Dark grey sand, silt, and clay, pebbles, dark streaks.
U-100	31.5	91	9	-	-	G	Gravel.
U-101	9	3	51	25	21	S-Si-C	Dark grey sand, silt, and clay.
U-102	18	-	10	46	44	CSi	Light and dark grey sand and clayey silt; shows stratification.
U-103	33	-	-	-	-	(SSi)	Dark grey sandy silt.
U-104	9	-	-	-	-	(SG)	Grey sandy gravel.
U-105	2	-	-	-	-	-	Boulders; no sample retained.
U-106	13	-	-	-	-	(G-S-Si)	Grey clayey silt, sand, pebbles.
U-107	12	-	-	-	-	(CSi)	Grey clayey silt, pebbles.
U-108	25	33	4	35	28	G-Si-C	Grey clayey silt and gravel; some cohesiveness and stratification.
U-109	26	-	-	-	-	(SG)	Dark grey sandy gravel.
U-110	9	-	-	-	-	(G)	Gravel.
U-111	19.5	93	7	-	-	G	Gravel.
U-112	28	-	-	-	-	(SG)	Dark grey sandy gravel.
U-113	15	5	30	21	44	S-Si-C	Grey silt and clay.
U-114	8	-	-	-	-	(SG)	Boulders, sand, and gravel.
U-115	13.5	-	-	-	-	-	Boulders; no sample retained.
U-116	14	-	-	-	-	-	Boulders; no sample retained.
U-117	8.5	-	-	-	-	-	Boulders; no sample retained.
U-118	12	-	-	-	-	(G)	Gravel.
U-119	19	-	-	-	-	(CSi)	Dark grey clayey silt, little gravel.
U-120	18	-	-	-	-	(SiC)	Grey silty clay, few pebbles.
U-121	30	-	-	-	-	(SG)	Grey sandy gravel.
U-122	46.5	-	-	-	-	-	Cobbles.
U-123	46	63	37	-	-	SG	Grey sand and gravel.
U-124	27	-	-	-	-	-	Boulders; no sample retained.

Sample	Depth	Gravel	Sand	Silt	Clay	Type	Field Descriptions
U-125	9	24	15	31	30	(G-Si-C)	Grey sand, silt, clay, and pebbles.
U-126	13	-	-	-	-	(SiC)	Grey silty clay, few pebbles; some cohesiveness.
U-127	18	-	-	-	-	(SiC)	Grey silty clay; sample soupy.
U-128	3	-	-	-	-	-	Boulders and wood.
U-129	16.5	-	-	-	-	(SiC)	Light and dark grey silt and clay.
U-130	8	-	-	-	-	(SG)	Grey sandy gravel.
U-131	54	-	-	-	-	(G)	Gravel, boulders.
U-132	70	46	28	12	14	SG	Grey sand and fine gravel.
U-133	21	62	38	-	-	SG	Grey sandy gravel.
U-134	25.5	-	-	-	-	(G)	Gravel, few cobbles.
U-135	52.2	55	22	10	13	G-S-Si	Grey sand, silt, and gravel.
U-136	51.5	2	16	54	28	CSi	Grey clayey silt; some stratification.
U-137	51	-	-	-	-	(SiS)	Grey silty sand.
U-138	29	97	3	-	-	G	Grey gravel.
U-139	28.5	-	-	-	-	(SiC)	Grey silty clay.
U-140	20	-	-	-	-	(CSi)	Grey clayey silt, few pebbles.
U-141	6	91	5	2	2	G	Grey sandy gravel.
U-142	4	-	-	-	-	(G)	Gravel and little sand, cobbles.
U-143	2.5	-	-	-	-	(G)	Gravel, little sand.
U-144	4	-	-	-	-	(CSi)	Light and dark grey clayey silt, few pebbles.
U-145	2	-	-	-	-	(CSi)	Grey clayey silt, few pebbles.
U-146	3	4	6	50	40	CSi	Grey clayey silt, few pebbles.
U-147	16	-	-	-	-	(G-Si-C)	Grey clayey silt and gravel.
U-148	25	-	-	-	-	(CSi)	Grey clayey silt, pebbles.
U-149	37	24	8	32	36	G-Si-C	Light and dark grey silt and clay, gravel; dark streaks.
U-150	41	-	-	-	-	(G-S-Si)	Light and dark grey silt and sand, gravel.

BATHYMETRIC MAP
OF
MILLER LAKE

MARTIN RIVER GLACIER, SOUTH-CENTRAL ALASKA

DATUM PLANE IS LAKE LEVEL: 110 METERS ABOVE MEAN SEA LEVEL

SCALE IN METERS

0 48 96 144 192 METERS

SCALE 1:2400

CONTOUR INTERVAL 10 METERS

EDWARD CALLENDER

PLATE 1