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Geologic and limnologic history of Glovers Pond, northwestern New Jersey

J. Mark Erickson
University of North Dakota

GEOLOGIC AND LIMNOLOGIC HISTORY OF GLOVERS POND, NORTHWESTERN NEW JERSEY

by

J. Mark Erickson

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This thesis submitted by J. Mark Erickson 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.

F. D. Holland Jr.
Chairman

Alan M. Cvancara

Wilson M. Laird

A William Johnson
Dean of the Graduate School

Permission

Title Geologic and Limnologic History of Glovers Pond, Northwestern New Jersey

Department Geology

Degree Master of Science

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ABSTRACT

Glovers Pond is a temperate, dimictic lake, 1¼ miles southwest of the town of Johnsonburg, Blairstown 7.5' Quadrangle, northwestern New Jersey. The Paleozoic Kittatinny, Jacksonburg, and Martinsburg Formations, in fault contact with each other, crop out in the vicinity of the lake. The lake has a maximum depth of 9.5 meters and occupies a glacially modified and dammed fault valley currently being infilled concentrically by four types of sediment. Basinward these are: (1) peat, (2) marl, (3) "transitional", calcareous, organic-rich silt, and (4) gyttja. Glovers Pond is thermally and chemically stratified. The hypolimnion is undersaturated with $CaCO_3$; this prohibits deposition of calcium carbonate in the profundal zone. Marl is deposited on a shallow shelf by chemical and biochemical precipitation of $CaCO_3$ caused primarily by blanketing growths of _Chara_; these provide a habitat for several of the nine species of gastropods and the three species of bivalves which live in the lake.

Five cores from the lake and contiguous bogs present a stratigraphic record from late Wisconsinan time to the present. Wood from the base of the marl gave a radiocarbon age of approximately 11,560 years B.P.; the youngest peat was deposited 2,080 ±100 radiocarbon years B.P., indicating an average rate of horizontal infilling of 2.9 cm per year. Chemical analyses of sediments show that twice in the past $CaCO_3$ was deposited in the deepest part of the lake implying two periods of warmer, drier climate in the past. The second of these changes may represent the Hypsithermal Interval.

INTRODUCTION

Purpose of the Study

The primary purpose of this study was to interpret the geologic and limnologic history of Glovers Pond, from the time of its origin to the present, using as many parameters as reasonable within the limits of time and equipment available. The writer feels that a complete interpretation of the environment can be made only when physical, chemical, geological, and biological data are evaluated synchronously. Thus it was hoped that environmental changes recorded in the lake basin could be defined and interpreted to make clear the conditions of environmental evolution so that the information might be applied to similar geologic problems in other areas.

Location and Land Use

Glovers Pond is a small lake located at lat 40°56'30''N., long 74°53'30'' W., 1¼ miles southwest of Johnsonburg in northwestern New Jersey. The lake is on property owned by the Synod of New Jersey of the United Presbyterian Church. Thesis research was confined to this property which is presently used by the Synod as a summer camp. The land lies in Warren County within the Blairstown 7.5' Quadrangle. It is accessible from county road 519 between the towns of Johnsonburg and Hope.

The land in this part of New Jersey is hilly with discontinuous bedrock outcrops covered by shrubs and mixed hardwood forest which limit exposures. Open areas, the result of clearing forests from the more level regions are largely underlain by glacial deposits. The lake lies in a bedrock basin bordered by peat bogs and marshes on the southwest, south and northeast. The north and northwest shore lies against a bedrock escarpment. An intermittent stream flows through a northeastern bog into the lake, and an equally ephemeral flow leaves the lake through a bog at the southwest end.

This part of New Jersey was originally settled by Moravian farmers in 1769. They tilled the land or planted apple orchards. Where land was unsuitable for farming, the forest was left until the late 1700's when a small sawmill and millpond were established by damming the outlet stream from Glovers Pond. Much, but not all, of the timber was then harvested. Since that time the forest has regrown and the apple orchards and fields are returning to natural conditions.

In the 1920's the Stevens Institute of Technology, Hoboken, New Jersey, began to purchase portions of the present property from various farmers in the area. The land was used by Stevens Institute as a summer study area for civil engineering students until 1953 when it was rented to the YMCA for use as a summer camp for two years. The property, now encompassing 356 acres, was purchased from the Stevens Institute by the Synod of New Jersey in 1959 for continued use as a camp.

Previous Work

The bedrock lithology, structure, and stratigraphy of northern New Jersey have been described in detail in early publications dating back to Cook in 1868. Kummel and Weller (1901) discussed the

Paleozoic stratigraphy of the Kittatinny Valley, and Kummel (1900) made a thorough study of the Middle Ordovician limestones of the valley, including the area around Johnsonburg in an attempt to locate limestone deposits suitable for use as cement rock. In 1905 Kummel (p. 176-177) described some "white crystalline limestones" of possible Precambrian age from Sussex and Warren Counties.

Later work on the stratigraphy of the Ordovician rocks, particularly the Jacksonburg Limestone, was carried out by Miller (1937). This related New Jersey sections to those of eastern Pennsylvania. The stratigraphy of the Cambrian section of eastern Pennsylvania that has direct bearing on the rocks of New Jersey was discussed by Howell, et al., (1950). Prouty (1959) showed sections of Jacksonburg equivalents in Pennsylvania but did not trace them into the area under consideration. Sherwood (1964) made a thorough study of the structure of the Jacksonburg Formation in Northampton and Lehigh Counties in eastern Pennsylvania, making many interpretations which may be applied equally well to structural relationships in New Jersey.

The paleontology of the region was summarized by Weller (1903). Some additions to his faunal lists for the Jacksonburg Limestone were made by Miller in 1937.

The general geology of New Jersey was described by Widmer (1964) in connection with the state's tercentenary observation. The most recent geologic map of the state is the revision by Johnson in 1950.

A most complete survey of the surficial deposits and glacial geology of the region was given by Salisbury (1902). He gave detailed descriptions of glacial sediments and geomorphic features resulting from the presence of Wisconsin ice, including features near Johnsonburg and Southtown. Little major revision or addition to this work has been undertaken since.

Herpers (1961) reported deposits of the Ogdensburg-Culvers Gap recessional moraine in Sussex County. MacClintock (1940) described tills south of the Wisconsinan moraine in northern New Jersey. These, however, do not appear in the area of this study.

The most useful work on the lakes of the area was that of Smith (1957). In this, chemical and sedimentological conditions in several lakes in Warren County were discussed but no mention was made of Glovers Pond. Frey (1963, p. 224) gave a brief synopsis of some New Jersey lakes, referring to White Lake in Warren County as, "one of the uncommon marl lakes of the state." Glovers Pond falls in this group of lakes.

The surface water characteristics for New Jersey were most recently described in detail by Anderson and George (1966). They listed conditions in the major drainage basins in northwestern New Jersey including that of the Pequest River into which Glovers Pond water eventually drains. Representative wells in the area were also sampled for water quality.

Peat deposits were recognized early as a source of income in the state. They were surveyed extensively by Parmelee and McCourt (1905). They gave chemical analyses of some peats sampled in the area of Johnsonburg with no specific reference to those of Glovers Pond. Kummel (1900) mentioned the bog and marl deposits of White Lake as a possible source of calcium carbonate while making his search for suitable cement rock locations.

Further intensive studies of the peat and related sediments were made by Waksman (1942) and Waksman, et al. (1943). They showed many stratigraphic sections of the bogs sampled, several of which are in Warren County, New Jersey. They discussed peat and marl deposition and included pollen diagrams from bogs, of which the nearest to Glovers Pond was White Lake.

A complete pollen study of bogs in High Point State Park in the northwestern corner of the state was made by Niering in 1953. This summarized the post-glacial plant succession of the area.

Field Work

Research was begun in December of 1965 when a temperature and precipitation gauging station was established at the home of the camp Resident Manager. Readings were taken at this station throughout the year of 1966 and into April of 1967. The area was visited briefly in early April, early June and early August of 1967, as well.

Field work in residence was begun during the last week of June and continued to the first week in September, 1966. During this time a reconaissance of the bedrock lithology, structure, and glacial geology was made. The main effort was concentrated in taking cores of the bogs and the lake bottom, collecting grab samples of lake sediments, examining the present molluscan fauna of the lake, and studying the present physical and chemical conditions of the lake water.

A chemical laboratory was established near the lake for analysis of lake water. Samples were analyzed promptly after they were taken from the lake. Water and air temperatures were taken daily.

Three cores were taken in the bogs and two were taken from the lake bottom. Those in the lake were made from a floating platform anchored firmly at all four corners. When coring in the lake, the first one or two meters of the hole were cased to prevent loss during installation of new core liner. To augment the cores, posthole auger samples to a depth of five feet were taken in the bogs at numerous localities.

Upon completion of field work all samples were taken to the University of North Dakota where they were analyzed for chemical, sedimentological, and paleontological factors. Details of the analytical methods employed will be discussed in Appendix A of this report.

GEOLOGIC SETTING

Physiography

Glovers Pond is located on the southern edge of the Appalachian Valley and Ridge Province in northern New Jersey (Figure 1). This is an area of low hills and broad valleys which trend northeast-southwest across the state and are governed by the bedrock structure of the province. The Kittatinny Valley and Kittatinny Mountain, a resistant ridge of Silurian conglomerate and quartzite, are the most important physiographic features of the region.

Because the lake is located almost on the very edge of this province near the foot of Jenny Jump Mountain, a crystalline outlier from the Reading Prong of the New England Highland Province, the landscape immediately surrounding it is more hilly and irregular than many portions of the Kittatinny Valley. More complex structure has produced numerous truncated bedrock ridges, some of which are aligned contrary to the general northeast-southwest trend of the province. The ridges have been steepened and modified by glacial erosion and the lowlands between them have been scoured and then partly filled by glacial action to produce the present topography. The structure and its glacial modifications control the drainage pattern locally.

As indicated on the drainage map of central Warren County (Figure 2), Glovers Pond is the origin of one of the tributaries of Trout Brook. This flows eventually into the Pequest River and then to the Delaware River. The surface flow from Glovers Pond has been intermittent for the

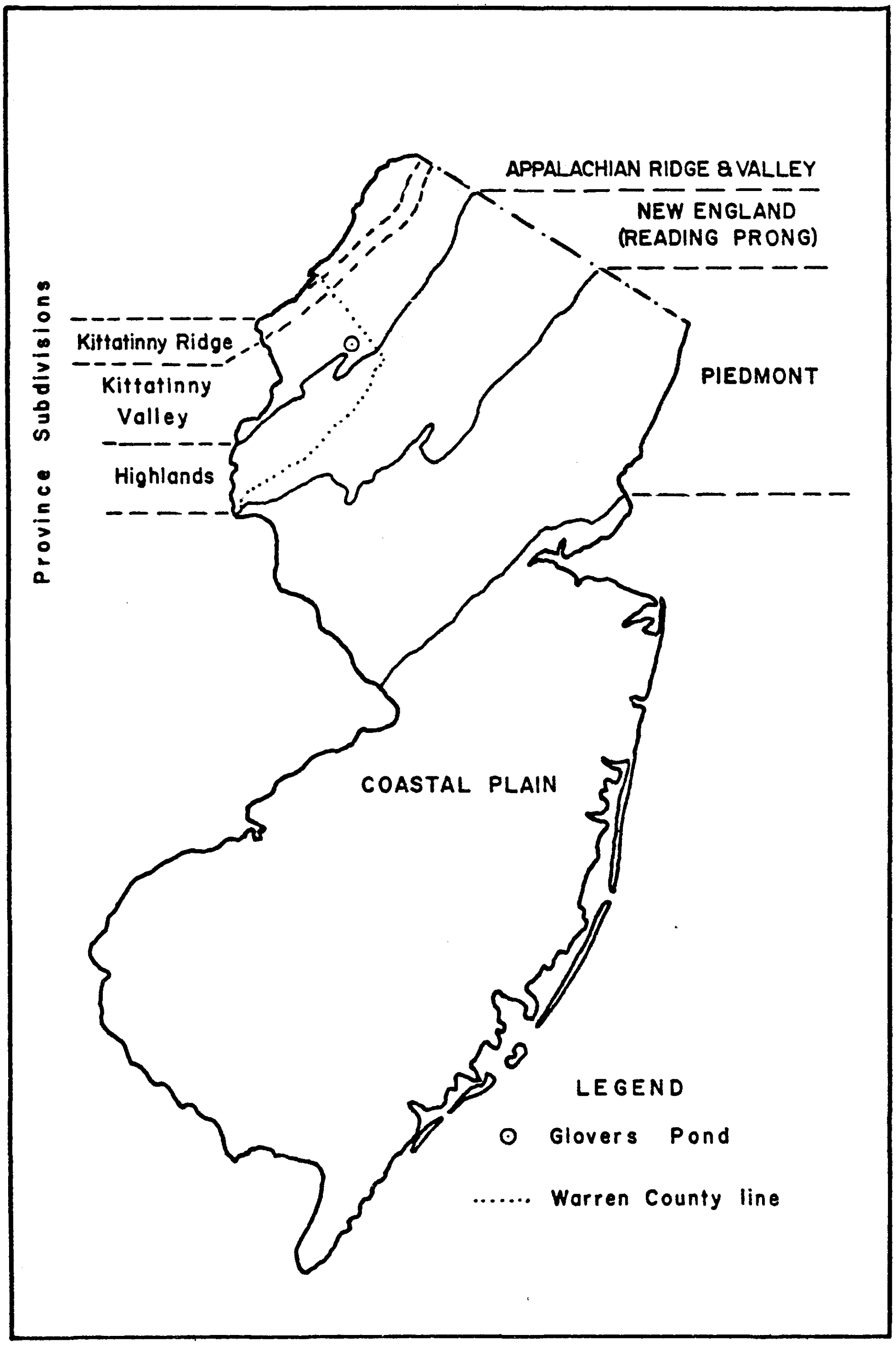


Figure 1.--Physiographic provinces of New Jersey showing the location of Glovers Pond and the Warren County line (partly after Kennedy, et al., 1963).

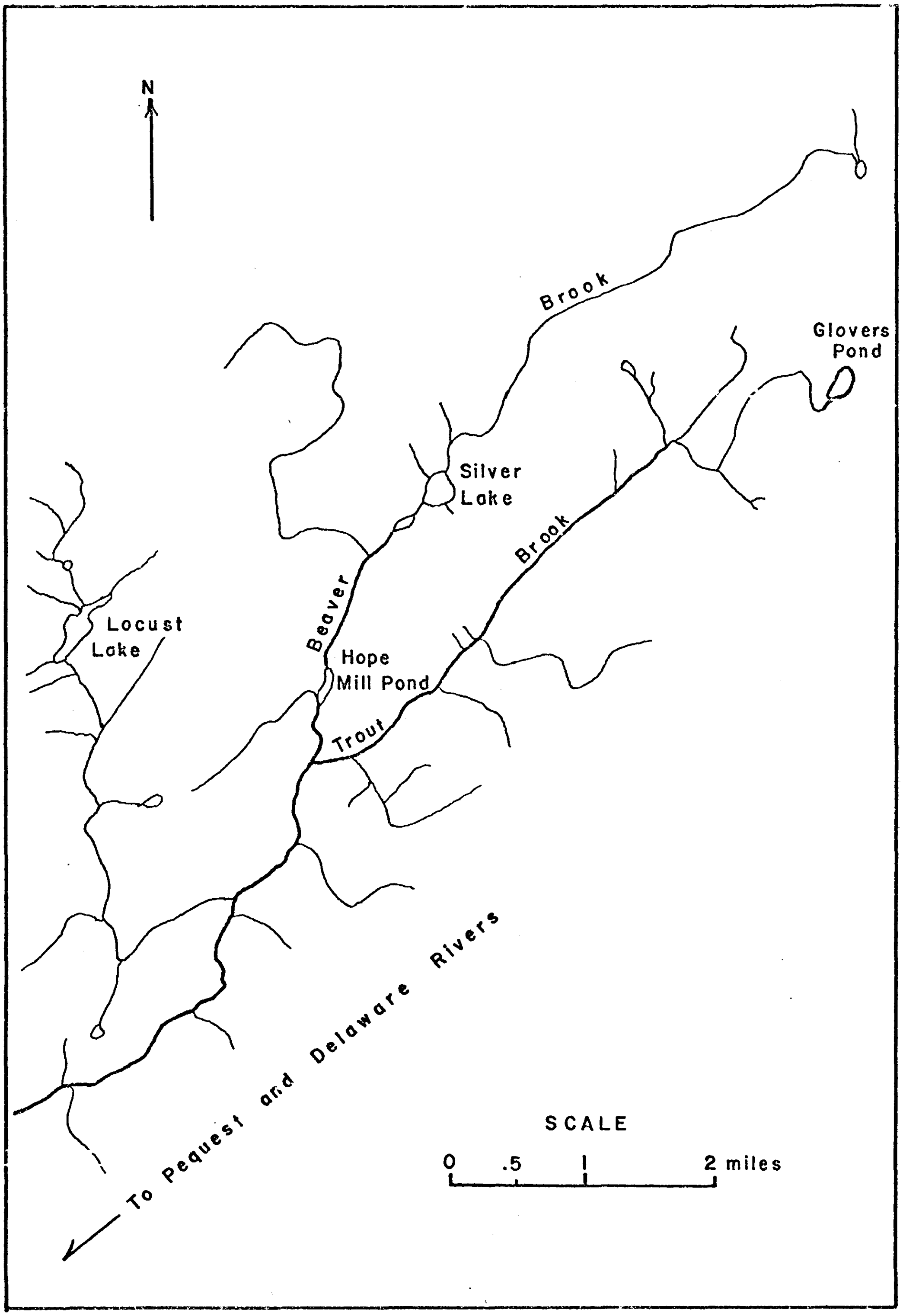


Figure 2.--Drainage map of central Warren County, New Jersey.

last few years and has not supplied sufficient water to maintain the tributary, thus it is not a major source of surface water for Trout Brook.

Stratigraphy

Three formations crop out within the area of this study, and all are of early Paleozoic age. The outcrop pattern is one of truncated ridges and isolated ledges surrounded by till which, accompanied by thick forest growth, obscures the structural and stratigraphic relationships of the units. The formations which crop out around Glovers Pond are (in descending order):

Ordovician	Martinsburg Shale
	Jacksonburg Limestone
Cambrian	Kittatinny Limestone

Kittatinny Limestone.--The oldest formation in the area, the Kittatinny Limestone, was named by H. D. Rogers in 1840 for exposures of limestone and dolostone in the Kittatinny Valley of northern New Jersey. As mapped by the New Jersey Geological Survey (Johnson, 1950) the formation is of Cambrian and Ordovician age and is divided into three units as described generally below.

The lower unit is designated as massive blue to blue-gray limestone with yellowish or silvery shale and is early Cambrian in age. This is said to be uncomformably overlain by upper Cambrian "light and dark, medium bedded limestones with cryptozoon heads." Above this, again unconformably, lie thin and thick bedded, gray or blue, cherty, magnesian limestones of early Ordovician age.

At Glovers Pond the Kittatinny Formation is medium to thick bedded (Gray, 1955), medium gray, N5, to dark gray, N3, (Goddard, 1948) dolostone. Frequently thin to medium beds of black chert occur interbedded with the dolostone. Several outcrops contain numerous 0.5 to 1.0 cm beds of chert appearing at regular intervals in the dolostone. Thick dolostone beds are predominantly fine to medium grained, crystalline dolomite. They weather to yellowish gray, 5Y8/1 color. Differential weathering exposes very thin bedding planes within the more massive units. These are generally not visible on fresh surfaces.

Several localities show thin, medium or thick beds of fine to medium grained calcareous sandstone within the Kittatinny Formation. These beds are more resistant and may have as much as six inches of relief above the surrounding dolostone

There are no fossiliferous outcrops of Kittatinny Limestone on the property. The contacts between this and the other formations are not exposed. On the basis of lithologic characteristics alone, rock of the Kittatinny Formation at Glovers Pond is placed in the upper unit, lower Ordovician cherty dolomitic limestone sequence, of the New Jersey Geological Survey terminology.

Jacksonburg Formation.--The Jacksonburg Formation of Middle Ordovician age is a gray to black, silty, fine to coarse, crystalline limestone, argillaceous limestone, calcareous shale, and calcite-cemented, dolostone conglomerate.

Although the name Jacksonburg Limestone was first applied to these rocks by Kummel, et al. in 1908, it is obvious that because of the diversity of lithologies the term "Limestone" should be dropped from formal usage in this connection, and the unit be called the Jacksonburg Formation. The section at Jacksonburg, New Jersey, which Kummel designated as the type section, had been measured and described earlier by Weller (1903, p. 18) as part of his study of New Jersey paleontology. Though originally surveyed thoroughly for its potential as a cement rock and designated simply as "Trenton limestone" (Kummel, 1900), Weller's faunal studies (as interpreted by Miller, 1937, p. 1695) showed that an unconformity exists between the lower 58 feet and the upper 77 feet at the type locality.

Miller completed a detailed analysis of the stratigraphy of the Jacksonburg Formation in eastern Pennsylvania and northwestern New Jersey. He described the occurrence of beds of conglomerate containing, predominantly, clasts of dolostone in a calcium carbonate matrix. These units are found locally in New Jersey, and Pennsylvania. They are not restricted to the basal Jacksonburg, but rather occur at various positions within the formation.

Exposures of the conglomerate along county road 519 between Johnsonburg and Hope, and outcrops on the southern edge of the town of Hope, were visited during the 1966 field season. There the clasts were pebbles and cobbles, primarily of dolostone, in a calcium carbonate matrix. The unit had been jointed and many of the joints were filled with secondary calcite. These usually cut across clasts and matrix alike. Beneath the conglomerate at Hope was a bed of undetermined thickness of medium to coarse crystalline limestone in which many of the coarser grains were altered pelmatogoan columnals. According to Miller, the base of the formation is marked by conglomerates with clasts that are more angular than in the local, higher conglomerates.

At Glovers Pond rocks referred to the Jacksonburg Formation consist of grayish black, N2, to medium light gray, N6, crystalline limestones, argillaceous limestones, and subangular dolostone conglomerates with calcite cement. In all cases the outcrops of this formation are so badly distorted by subsequent tectonism that description of bedding characteristics is not feasible. Nowhere was there more than fifteen feet of this formation exposed.

Fossils were found at location 2 on the geologic map (Figure 5) at the northeastern end of Glovers Pond. The strong cleavage developed on the limestone at this location is shown in Figure 3. Preservation of the fossils at this outcrop was poor because of this distortion and no identifications of the fossils could be made. This same outcrop was visited by Kummel (1900, p. 89). Due to masking by glacial debris he was not able to determine the type of contact between the Jacksonburg and adjacent formations. The same holds true in this study, though some probable conclusions regarding the nature of the contacts will be considered later. No attempt is made herein to assign these rocks to upper or lower portions of the Jacksonburg Formation.

Martinsburg Shale.--The thick beds of shale which underlie large portions of the Kittatinny Valley in New Jersey were early assigned to the Martinsburg, named by H. R. Geiger and A. Keith in 1891 for exposures near Martinsburg, West Virginia, and were mapped as such by Kummel (1908). These shales overlie the Jacksonburg Formation and are of middle and late Ordovician age (Twenhofel, et al., 1954). Miller noted that though most previous workers had considered the Jacksonburg-Martinsburg contact to be transitional, he could find no evidence for this conclusion in New Jersey. On the contrary, the single good exposure of the contact which he found appeared to indicate a disconformity between the two formations. The contact was not visible at Glovers Pond.

The Martinsburg Shale crops out in isolated patches a few feet in the northeastern part of the study area. The shale is (medium dark

Figure 3.--Outcrop of the Jacksonburg Formation at the northeast end of Glovers Pond (location 2 in Figure 5). A slaty cleavage is shown here well developed on limestone.

gray, N4,) strongly cleaved, fissile, and slightly calcareous. Most of the shale was mapped on the basis of shale fragments brought up from the till by posthole auger. At most, only six feet of this formation are exposed at the surface in the area. Because of the limited exposures, no attempt was made to estimate what part of the formation is represented at Glovers Pond. Shale exposures are shown on Figure 4.

Structural Geology

Structural relationships in the Paleozoic sequence of northern New Jersey and eastern Pennsylvania have long puzzled geologists. Miller (1937, p. 1691), in discussing the various conclusions drawn by other workers in the area, stated that "much of the region is structurally so complex and paleontologically so barren that it would be surprising if some conflicting interpretations had not arisen." In the same vein he quoted (p. 1691) this description given by Frederick Prime some fifty years earlier:

> "Level as the general surface may be, it is the planed-off section of as gnarled and twisted a piece of the earth's crust as can be found in any country. Although these plications are comparatively small they are of the same nature as the gigantic overthrown anticlines of the Alps and Apennines."

This regional complexity has made interpretation of one small area more difficult than might be expected otherwise.

The north shore of Glovers Pond is bordered by a southeast-facing fault-line scarp on the Kittatinny Limestone. To the northwest of this fault the Kittatinny beds show a general, though consistent, strike ranging from N. 63° E. to N. 86° E. with readings of N. 73° E. being common. The beds dip to the north-northwest at angles of 50.5° to 67.5°. Dips of 52° are frequent. Outcrops are discontinuous ridges or

Figure 4.--Martinsburg Shale, poorly exposed in a field northeast of the lake (location 6 of Figure 5). Fissle character of the rock is evident.

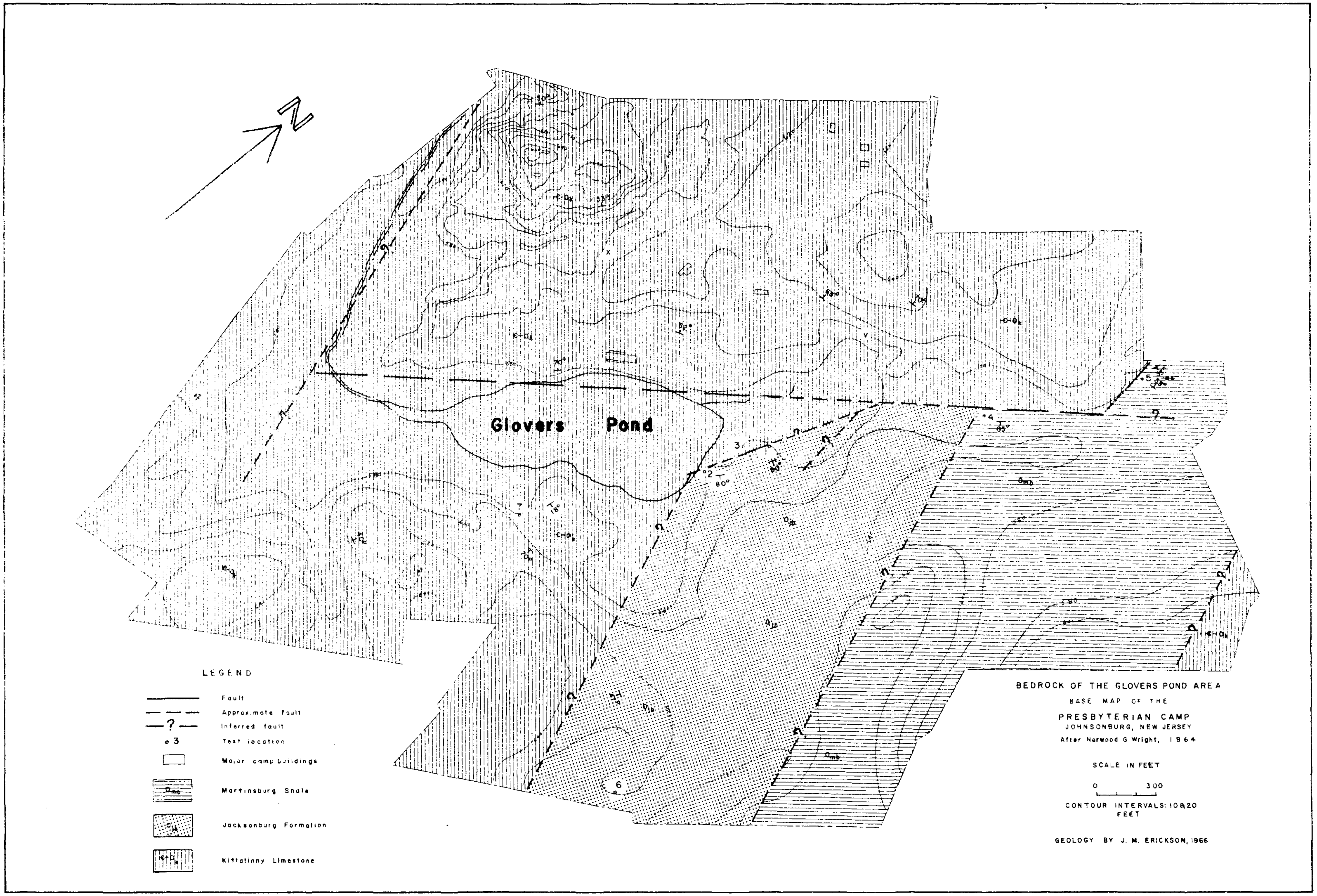


Figure 5.--Paleozoic bedrock map of Johnsonburg Presbuterian Camp surrounding Glovers Pond.

isolated dolostone remnants surrounded by till. Some effort was made to determine whether or not the Kittatinny section was repeated on the northwest side of the lake but no evidence of repetition was observed.

All three formations which occur in the vicinity are brought to the surface by faulting northeast of the lake. None of the contacts is visible because of till and forest cover. Similarly the Jacksonburg and Martinsburg Formations here have been so badly cleaved and distorted, as already pointed out in Figures 3 and 4, that they lack the resistance to glacial erosion possessed by the more competant dolostone beds of the Kittatinny. For this reason significant outcrops are difficult to find. All relationships shown in Figure 5 are therefore inferred.

The fault contact between the Jacksonburg and Kittatinny Formations at location 1 may be placed within five feet, but the actual fault is buried beneath an old, tree-covered rock wall and glacial till. This is the same fault which formed the scarp already discussed. North of location 2, the outcrop of Jacksonburg Formation seen in Figure 3, the shoreline swings northeastward for about 150 feet with no outcrops; it then turns northward again. At location 3, about 60 feet from this turning point, there is an outcrop of Kittatinny dolostone in which a large dead cedar tree stump is rooted (Figure 6). This is the beginning of a discontinuous ridge which extends to location 1 where the Kittatinny and Jacksonburg Formations have been described as almost in visible contact. The trend of the fault between the two has been taken as a line drawn from location 1 to location 2. This line bears N. 31 E.

At both location 1 and 3 distortion has obscured the bedding of

Figure 6.--Outcrop of Kittatinny Limestone (here dolostone) at location 3 (Figure 5), the beginning of a ridge which extends to the concealed contact with the Jacksonburg Formation at location 1.

the Jacksonburg Formation even in polished hand specimens. The cleavage surfaces at location 1 strike about N. 20° E and dip 80° to 85°. Those at location 3 are nearly vertical and strike about N. 30° E, nearly parallel to the inferred strike of the major fault. Sherwood (1964, p. 39) found the bedding increasingly more difficult to distinguish the higher he worked in the Jacksonburg. The tendency to cleave also increased farther up the section. This may be one indication that these rocks are in the upper part of the formation. If these rocks have cleaved along bedding planes, the formation here must be nearly vertical; if not, the beds are probably steeply dipping.

Outcrops become sparse farther eastward from the lake where till masks the bedrock. Auger holes indicated that the rock changes from limestone to shale as shown on Figure 5. The Martinsburg Shale underlies most of the unused fields in this immediate vicinity. It crops out only toward the northern edge of the property where it nears the major northeast trending fault. At location 4 it was seen at the surface. There the cleavage is nearly vertical and trends approximately N. 35° E.

The contact between the Martinsburg and Kittatinny Formations is hidden. It lies in a low area formerly used as a farm road but which is now only a foot path. If this slight valley is followed northward to a narrow gully at location 5, the shale and dolostone may be seen only fifteen feet apart. The cleavage on the shale is dipping about 35° E. and N. The strike of the shale swings from N. 37° W. to N. 50° E. in the space of thirty feet giving the appearance of a synclinal nose in the shale butted against the dolostone and having its axis plunging north-northeast. Because the outcrop is so badly cleaved and weather-ed, bedding was not determined. Thus the true attitude of the structure is here left to question.

Southeast of the lake at locality 6, the Jacksonburg is represented by one outcrop of conglomerate with angular dolostone clasts in a calcium carbonate matrix. This has been highly distorted so that the outcrop has very little appearance of conglomerate. Polished sections easily revealed the nature of the rock.

Just west of this point the Jacksonburg is again in contact with the Kittatinny although the contact is not visible. From here to the southwest corner of the property all bedrock is the Kittatinny Formation. The structure of these rocks is quite different from the Kittatinny on the opposite side of the lake. Here the beds show no consistent strike or dip trends between various outcrops. Rather there are numerous changes of dip indicating the presence of many minor structures within the formation. At location 7 a distorted anticlinal fold with a radius of ten or twelve feet may be seen apparently disconnected from surrounding structures.

There are probably many small faults and folds within the formation on this side of the lake. These would account for the difficulty in correlating sections even a few tens of feet apart. It would require highly detailed mapping if at all possible, to interpret all the minor structures, and this was not the primary aim of the present work.

In Figure 5 all formations have been shown with fault contacts. As indicated these faults are evident in some cases, as at locations 1 and 4, and must exist, though they are hidden. In others there are no outcrops nearby and the relations are open to greater question. The contact of the Jacksonburg with the Martinsburg need not be a fault in order for these formations to be positioned as shown. Kummel (1900, p. 86) and Johnson (1950) showed it as an inferred depositional contact. There is no direct visual evidence to support either opinion. It is probable, however, that, because of the obvious magnitude of tectonic activity in the area, and because of the demonstrated relative incompetence of these two formations, and because of the way the areal exposure of the Jacksonburg as mapped appears to pinch and thin against the Martinsburg near location 5, the contact is again a fault plane. The same holds true for the Kittatinny-Jacksonburg contact in the same area east of the lake.

Due to the concealed faults and the discontinuous outcrop pattern, no definition of the type of faulting has been made. Sherwood (1964, p. 34) found mainly high and low angle thrust faults, and "cross faults" with undetermined movement to be most commonly associated with the Jacksonburg belt. He found normal faults to be rare. These findings are probably equally valid in New Jersey.

The only estimate of the amount of throw on these faults that can be made from relationships in the area is taken where the Martinsburg and Kittatinny Formations are in juxtaposition at location 5. Here the Jacksonburg Limestone is completely absent. At its type section the Jacksonburg is at least 135 feet thick though the top and bottom there are inferred. In Pennsylvania, Sherwood indicates as much as 1000 feet of Jacksonburg Limestone may be present. At Glovers Pond there appear to be at least 200 feet of this formation at the surface (though this may, and probably does, include some repetition of section). To bring the Kittatinny and Martinsburg formations into juxtaposition would require faulting out at least 135 feet, at most 1000 feet, or locally 200 feet of the Jacksonburg Limestone.

As demonstrated, the structural relationships at Glovers Pond are indeed as complicated as any in the surrounding area. Their concealment by glacial deposits and forest, and the irregular distribution of outcrops make greater evaluation of structure imprudent at present.

Glacial Geology

Glovers Pond lies five miles north of the youngest terminal moraine, taken to mark the farthest advance of Wisconsin ice in New Jersey, as mapped by Salisbury in 1902. Older dissected tills and boulder fields exist south of this moraine. These have been discussed by Salisbury, MacClintock (1940), and Flint (1957) and are thought to be pre-Wisconsinan. They, however, do not occur in the study area.

Local glacial features.--Glacial features and deposits for the locale are described adequately by Salisbury (1902, pp. 340-1, 322-3, 399, 400, and 447). He found that the valley of Bear Creek which flows through Johnsonburg and east of Glovers Pond is occupied by "stratified drift" and kame deposits. He attributes the present course of the stream to a "line of sinks" caused by melting of covered, or partially covered, blocks of stagnant ice. This stream passes Glovers Pond about 0.6 miles to the northeast making a semi-circle around the lake. It is not directly related to any features there. The stratified sediment filling this valley is at least 40 feet thick as shown by data from the water well drilled at the Johnsonburg Hotel.

Salisbury (p. 340-1) gives some trends of glacial striae taken near Johnsonburg. The location nearest Glovers Pond is 1½ miles southeast of Johnsonburg on a limestone outcrop where the striations trend

S. 15° E.

Glacial features at Glovers Pond.--Till at the lake is clayey with pebbles and cobbles of Jacksonburg Limestone and Martinsburg Shale, and with less numerous cobbles and boulders of Kittatinny Limestone, Shawangunk Conglomerate, and assorted crystalline and metamorphic rocks of unknown source. In most cases the upper three to five feet have been thoroughly oxidized.

No striae were seen in the area; however, the effects of ice movement south-southeast are manifest by the over-steepened appearance of many of the bedrock outcrops. The north-northwest dip of the Kittatinny Limestone allowed plucking to occur easily on the southeast-facing outcrops causing many to have roche moutonnee configurations. This is especially true along the northern shore of the lake and bog where several of these apparently plucked surfaces may be seen. The steep face on the Jacksonburg outcrop (Figure 7) is interpreted as the result of this ice activity.

The most prominant feature of glacial deposition is a low, linear hill of glacial debris which lies along the landward side of the bog at the southwest end of the lake. This feature forms a broad, partially tree-covered rise as viewed from the lake (Figure 8). It is composed of clay, sand, gravel, cobbles, and boulders and resembles till. The boulders are up to three feet in diameter. Cobbles and boulders represent all lithologies previously mentioned. Locally derived lithologies predominate, though the largest boulders and cobbles are generally igneous and metamorphic erratics, obviously transported some distance.

Apparently this is the same feature which Salisbury (p. 447) des-

Figure 7.--Glacially plucked hill of Jacksonburg Formation at location 2 (Figure 5) on the northeast end of Glovers Pond.

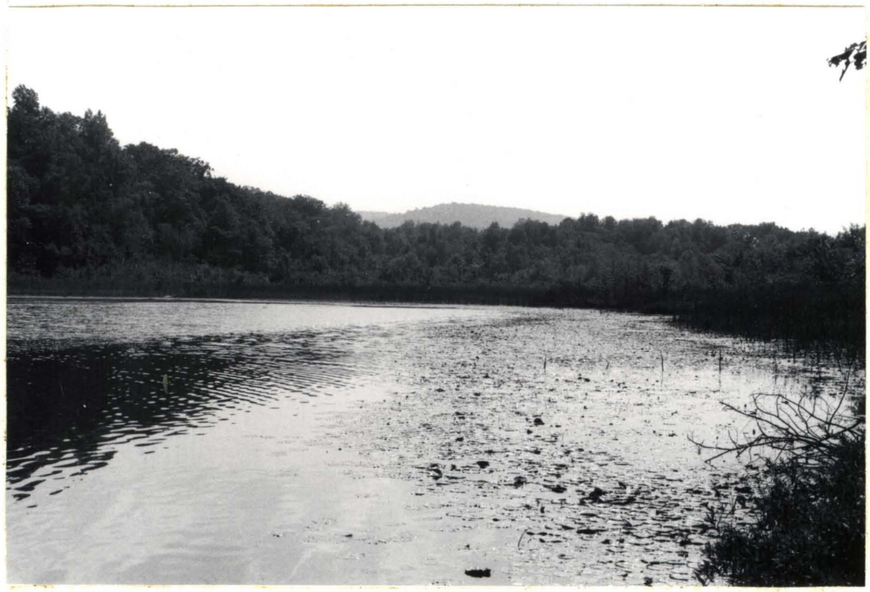


Figure 8.--View of the southeast end of Glovers Pond. The heavily tree-covered ridge is interpreted to be a crevasse filling or kame. The hills behind are part of the Jenny Jump Mountain crystalline outlier.

cribed as one of the rare eskers in New Jersey. In his words the esker lies:

> "...north of Southtown and southwest of Glovers Pond. Its length is 350 to 400 yards, its width 40 to 50 yards, and its height 5 to 15 feet. To the north it ends sharply at the swamp [Glovers Pond bog?]; southward it fades away on the hillside. Its surface is cobble strewn."

This is one of four supposed eskers described for New Jersey.

Examination of this deposit in a borrow pit used by the camp as a source of road material shows that the deposit lacks distinguishable stratification. Upon close inspection, however, a visual impression of alignment in the clays and an orientation of the long axes of elongate shale and limestone pebbles suggests that the deposit does have some water-laid or compaition characteristics. There is absolutely no indication of sorting, winnowing, or transport from the original site of deposition unless this occurred by mass movement. These characteristics are not consistent with the interpretation that this body is an esker.

There are two other possible explanations of the origin of this deposit: 1) a recessional moraine, and 2) a crevasse filling or kame.

Recently Herpers (1961, p. 45) described the "Ogdensburg-Culvers Gap Moraine", a recessional moraine in Sussex County, New Jersey. The moraine was said to be a ridge, chiefly of sand, gravel, cobbles, and boulders, from a few to fifty feet high, and a few hundred feet to two miles wide. It has a hummocky surface and is frequently discontinuous against rock ridges which run contrary to its course. The feature is said to contain little true till though its lithology is variable. This work significantly points out that both recessional (active) and stagnant ice features are to be expected in New Jersey where primarily stagnant ice features have been described previously.

It is possible, then, that the ridge at Glovers Pond may be a poorly developed recessional moraine. It was, however, not traced by Salisbury any farther than the bog. The short extent and relative narrowness of the body tend to make its origin as a recessional moraine doubtful. They suggest, rather, that the feature is a crevasse filling or a related kame-like deposit that has been collapsed, or let down, into place thus destroying any superficial stratification that may have existed due to periodic deposition.

Finally, it should be noted that the entire shore of Glovers Pond is ringed by erratic boulders such as those shown in Figure 9. In most instances these are masked by dense vegetation, but they are present around the entire lake shore. Their significance is discussed under the section entitled Origin and Glacial History of the Glovers Pond Basin.

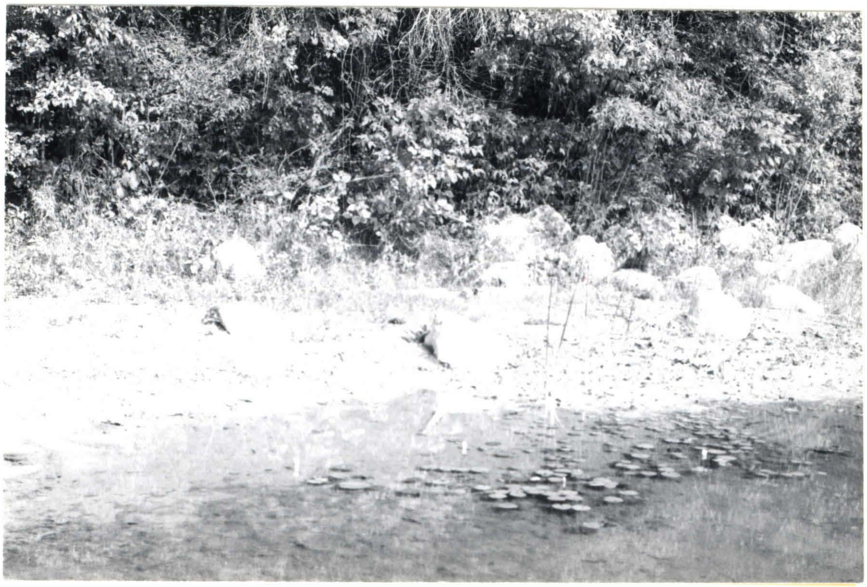


Figure 9.--Lag deposit of glacial erratic boulders at the northeast end of Glovers Pond. Erratics of this type encircle the lake basin and indicate erosion of the shore during a higher stand of the lake.

PRESENT ENVIRONMENT OF GLOVERS POND

Meteorology

The climate of northern New Jersey was described by Trewartha (modified from Köppen in Goode, 1953) as a humid continental forest climate with warm summers. The mean annual temperature and the average annual precipitation at Newton, New Jersey, about 10 miles northeast of Johnsonburg, are 49.6 °F, and 44.79 inches respectively (U.S. Weather Bureau, 1962). The mean winter temperature for this part of the state is about 27 °F, whereas the normal summer temperature is about 70 °F, as interpreted from isothermal maps (Visher, 1954). This part of the state has an average annual frost-free period of 120 days, (Kennedy, 1963).

Because the area surrounding Johnsonburg is a hilly upland region, individual valleys among the hills may undergo climatic isolation which, to a small extent, establishes local "microclimates" during some parts of the year. Glovers Pond is such an isolated area and is subject to slight variations from the "normal" weather of the region. This is particularly true with regard to summer precipitation.

In order to investigate the effects of local precipitation on Glovers Pond a rain gauging station was established on the property during the year 1966. The total precipitation for Glovers Pond in 1966 was 32.1 inches. The greatest accumulations occurred during the months of February, May, and September, whereas June, July and November had the smallest accumulations. A comparison of the monthly precipitation at

Glovers Pond with the ten year average (Figure 10) given by the U. S. Weather Bureau (1962) shows that only May and October could really be considered normal for the area. However during 1966 and for the four years preceeding 1966, New Jersey and the surrounding states had been undergoing a rather severe drought. This accounts for the low figures during the summer months, but it does not account for the very uneven distribution of precipitation during the rest of the year. This is better explained by variations in the ability of precipitation-producing storms to reach the area.

During the summer months, most of the rain falls from thunderstorms, some of which are quite violent. Because of its topographic position and shelter by mountains on the north and northwest where most thunderstorms originate, Glovers Pond is often left untouched by these summer rain producers although areas only a few miles away may receive several inches of rain. It is possible that to a lesser extent, similar conditions cause abnormalities in the precipitation throughout the year and thus are partially responsible for the deviation from the pattern in the immediate area.

This "microclimate" has a distinct bearing on the level and trophic conditions of the lake since precipitation on the drainage basin controls the water level to a great extent. This is shown by the fact that the lake lost almost a foot of water in 1961 that was not regained until the summer of 1967 when heavy rains fell. The lake fluctuated another 10 to 12 inches each summer during this period depending on local rainfall conditions. The drought thus had a marked effect on the condition of the lake and surrounding land.

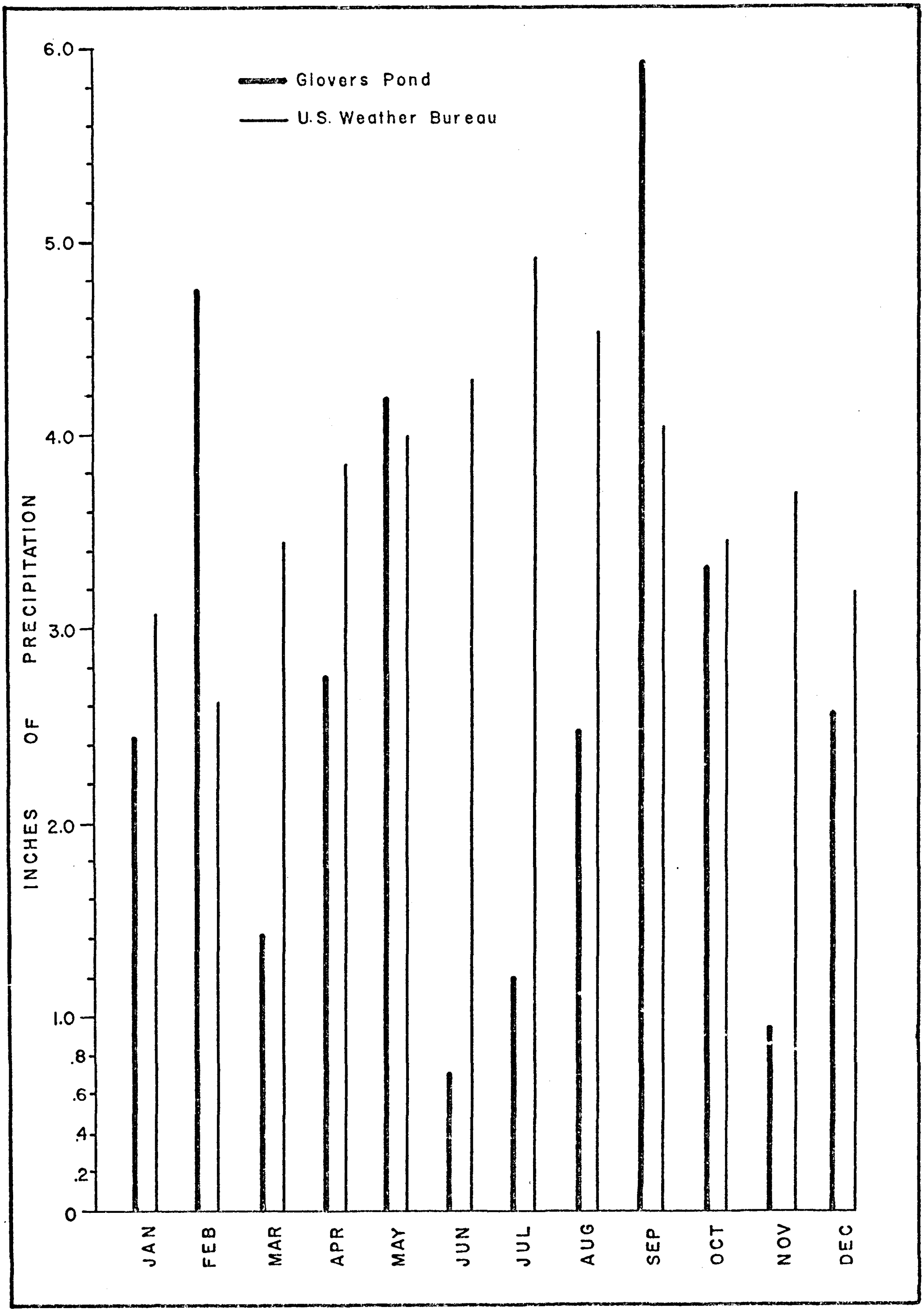


Figure 10.--Precipitation data for Glovers Pond, 1966, compared with 10-year mean of U. S. Weather Bureau (Newton, New Jersey station).

Morphometry

Bathymetric studies of Glovers Pond were made with a Bendix DR-2 transistorized depth recorder and with line soundings taken during the process of sampling bottom sediments. The depth recorder produced continuous profiles of the bottom of the lake. These profiles and soundings were used to construct a bathymetric map (Figure 11).

The lake is partially bordered by a shallow shelf (Figure 12) which generally reaches a depth of 1.5 meters before dropping off steeply into the deeper basin. Where the shelf is not present, as along the north shore, the basin slopes away steeply from the waters edge. Much of the shoreward edge of the shelf was subaerially exposed during the summer of 1966 due to the lowered lake level.

From the shelf edge the bottom drops off abruptly to a depth of 4 or 5 meters. From the base of the shelf to the center of the basin the bottom slope is much more gentle. The maximum depth of the basin is 9.5 meters. Other morphometric parameters are given in Table 1.

About 14,550 square meters, or more than one quarter of the surface area of the lake, is underlain by the shelf as shown by the hypsograph in Figure 13. This large proportion of shallow water is of prime significance to the biologic and sedimentologic processes currently taking place in the lake, and the evolution of the shelf has been a major part of the sedimentologic history of the lake.

Another useful morphometric parameter is the shoreline development, D_L (where $D_L = \frac{L}{2\sqrt{\pi A}}$, Hutchinson, 1957, p. 166) is an approximation of the configuration of the shoreline relating the length of the shoreline to the circumference of a circle of the same area as the lake. A circular lake thus approaches a value D_L=1 whereas more irregular

TABLE 1

MORPHOMETRIC DATA FOR GLOVERS POND

Parameter	Value
Surface area	54,343 sq m
Shoreline length	1,360 m
Mean depth	4.8 m
Maximum depth	9.5 m
Maximum length	426 m
Mean breadth	127 m
Maximum breadth	183 m
Volume	264,260 cu m

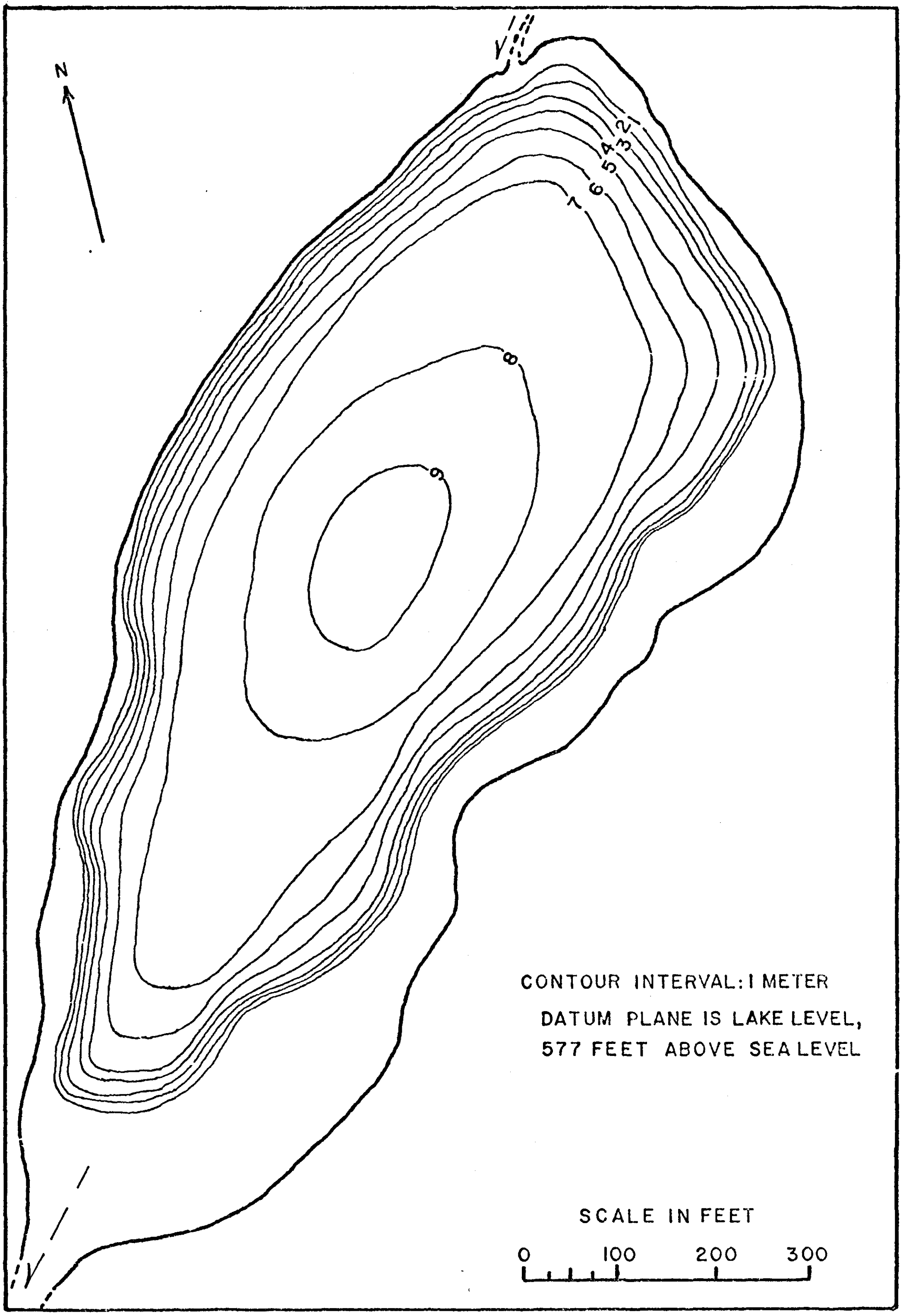


Figure 11.--Bathymetric map of Glovers Pond.

Figure 12.--Looking northeast at the shoreward edge of the shallow shelf exposed during the dry summer of 1966. A white stake indicates the position of station Lk-2 (Figure 23) where water and sediment samples were taken.

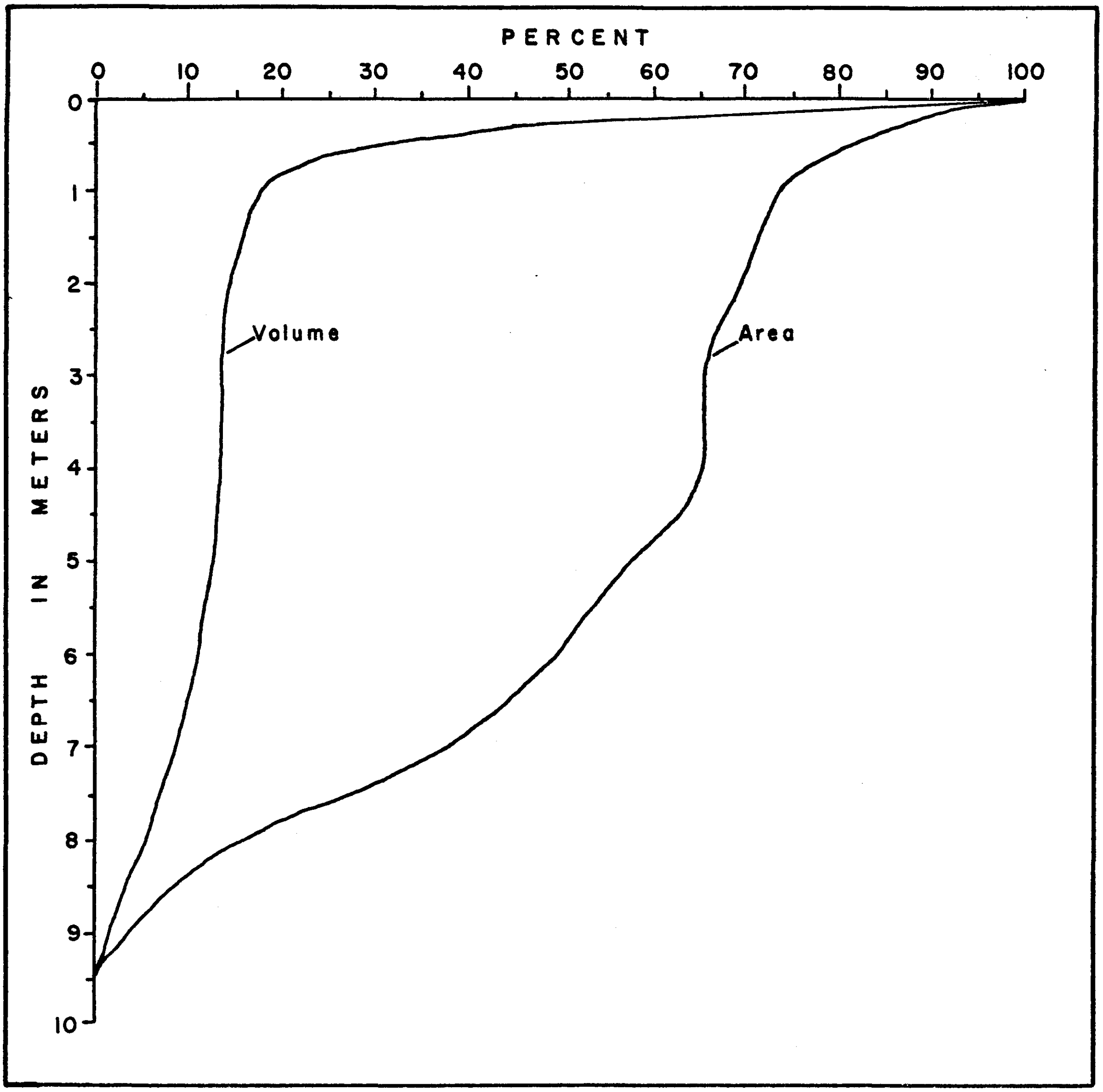


Figure 13.--Hypsograph showing what percent of the total area and total volume of the lake basin is represented by the area and the volume of each one-meter interval of depth in Glovers Pond, New Jersey.

lakes have higher values of D_L. The shoreline development of Glovers Pond at the present time is 1.65. This is a quantitative statement of the fact that the present lake has a smooth shoreline nearly devoid of embayments. Such a shoreline is in an advanced stage of development, (Reid, 1965, p. 34).

Physical Limnology

Wind, waves, and currents.--No quantitative values for wind velocity were obtained at Glovers Pond. Estimates of velocity and direction were made, however, each time that samples were taken for water analysis.

Because the lake basin lies between forested bedrock ridges it is protected from wind action to a great extent. Wind can produce significant action only when it blows from the less sheltered southwestern end of the lake. During June, July, and August the wind begins to blow from the southwest at about 11:00 A.M. each day as a slight breeze. This increases until the velocity has reached 3, or occasionally 5, miles per hour by 3:00 or 4:00 P.M., at which time the wind dies and the lake becomes calm. Only during summer thunderstorms does the wind velocity greatly exceed 5 mph.

This predominant summer breeze from the southwest has the full fetch of the lake and is strong enough to produce some slight wave action. Waves of a few inches in height are generated under these conditions. Such wave action does cause some water to pile up at the northeast end of the basin, and this may, in turn, initiate a return current beneath the surface. Such a current was never identified or measured directly, but it may have been responsible for some of the irregularities in the temperature curves which will be discussed later.

Sources of water.--There are two principal sources of water for Glovers Pond. One source is ground water entering the system through springs; the other is precipitation falling on the surface of the lake. Little of the summer precipitation reaches the lake as runoff. Spring melt water, however, does reach the lake.

Water supplied by springs is the most important constant water supply. Several springs emerge in the bog at the northeast end of the lake, and these produce a small brook which flows into the lake at the surface when the water table is high enough to permit (Figure 14). At other times the same springs serve to maintain the water table in the bog and to supply water to the lake by subsurface flow. There is also evidence for the existence of other springs along the north wall of the lake itself. This will be discussed later.

The spring brook ceased flowing at the surface on July 11 during 1966. Cores and auger holes taken in the bog during the remainder of the year continued to strike water at 0.3 to 0.8 meters below the surface. This water was flowing slowly through the bog. The water level of the lake dropped slowly during the summer due to the drought, but flow continued from the bog to the lake throughout the summer as ascertained in shallow auger holes. No measure of volume of flow to the lake was made, however.

During the year 1966 a total volume of 44,452 cubic meters of precipitation fell on the lake surface. Rain during the three months of June, July, and August, however, contributed only 5,978 cubic meters of water to the lake surface, while, in the same period, the lake level dropped about 0.30 meters (Figure 15). A water level change of this amount would equal a volume of about 14,100 cubic meters of water evapo-

Figure 14.--The spring brook flowing into the northeast end of Glovers Pond during December, 1966.

Figure 15.--The northeast shoreline of Glovers Pond showing the former high-water mark of the summer on plant stems and the low water stand in late August, 1966.

rated from the lake.

These conditions, which had prevailed since 1963, were not repeated in 1967, however. During the summer of that year rain was more frequent, and the lake level actually rose almost 12 inches. Early in July of 1967 a single storm produced nearly 6 inches of rain. This was followed 2 days later by another of about 4 inches. When the writer visited the area on August 23, 1967, these two storms along with average rainfall for the summer had contributed enough water so that the former millpond along the outlet stream held more than 4 feet of water, and the stream was draining it through the old earth dam. At this time approximately .57 cubic feet per second (cfs) were flowing out the stream as measured where the water flows through a metal culvert under the road 300 yards below the dam. This is the first time in at least five years that any flow has been measured from the millpond.

If I assume that spring water was the only source of inflow at this time, it is reasonable to suggest also that the springs were supplying more than 0.57 cfs into the lake. Naturally some of the water input was lost by evaporation and by infiltration to the surrounding shore areas. It is probable that springs actually supply more than 1.0 cfs to the water system, but this is distributed to the water table in the bogs as well as to the lake; from the bogs it is rapidly transpired into the atmosphere by plants and is thus removed from the system rather quickly. The water table at the periphery of lake basin is undoubtably not part of a closed groundwater system; however, no extensive studies of subsurface flow were made, and therefore no more elaborate discussion of water gain or loss can be made at this time.

Thermal properties.--Glovers Pond is a temperate, dimictic lake in the classification of Hutchinson (1957). The lake turns over in the spring and fall and maintains strong thermal stratification during the summer. In the winter the lake is weakly stratified.

In 1966 the spring overturn came during the third week of March when the ice left and temperature inversion began. On March 6 the surface temperature was 3.3°C while the bottom temperature was 5.0°C. On March 20 the temperature at the surface was 7.7°C while that at the bottom was 6.6°C. Overturn began shortly before March 20. In March of 1967 the lake was still frozen and snow covered due to late snow storms. (Data taken in early 1967 is used here to produce a continuum as an illustration of the seasonal thermal conditions since such data are not available for spring, 1966.) The thermal curve for the lake at this time appears in Figure 16 a. Because of this late snow the lake did not melt until April, and the overturn was probably considerably later.

Wind continued to mix the lake through May and into June when the thermocline began to strengthen. Three thermal curves for May of 1967 (Figure 16 b, c, and d) indicate that the lake had already lost the holothermal character of the overturn and was beginning to warm in the upper layers. The upper one meter of water was well mixed while the metalimnion was beginning to stabilize below this depth, extending to a depth of about 2 meters where the gradient became less steep again.

Three thermal curves for mid-June 1967 (Figure 17 a, b, and c) indicate that the water body as a whole was still warming, but the upper one or two meters were warming at a faster rate, as would be expected. The top of the metalimnion was now firmly established at one meter depth. Its base was at about 4 meters. These data for May and June of 1967 probably represent the normal formation of thermal stratification for

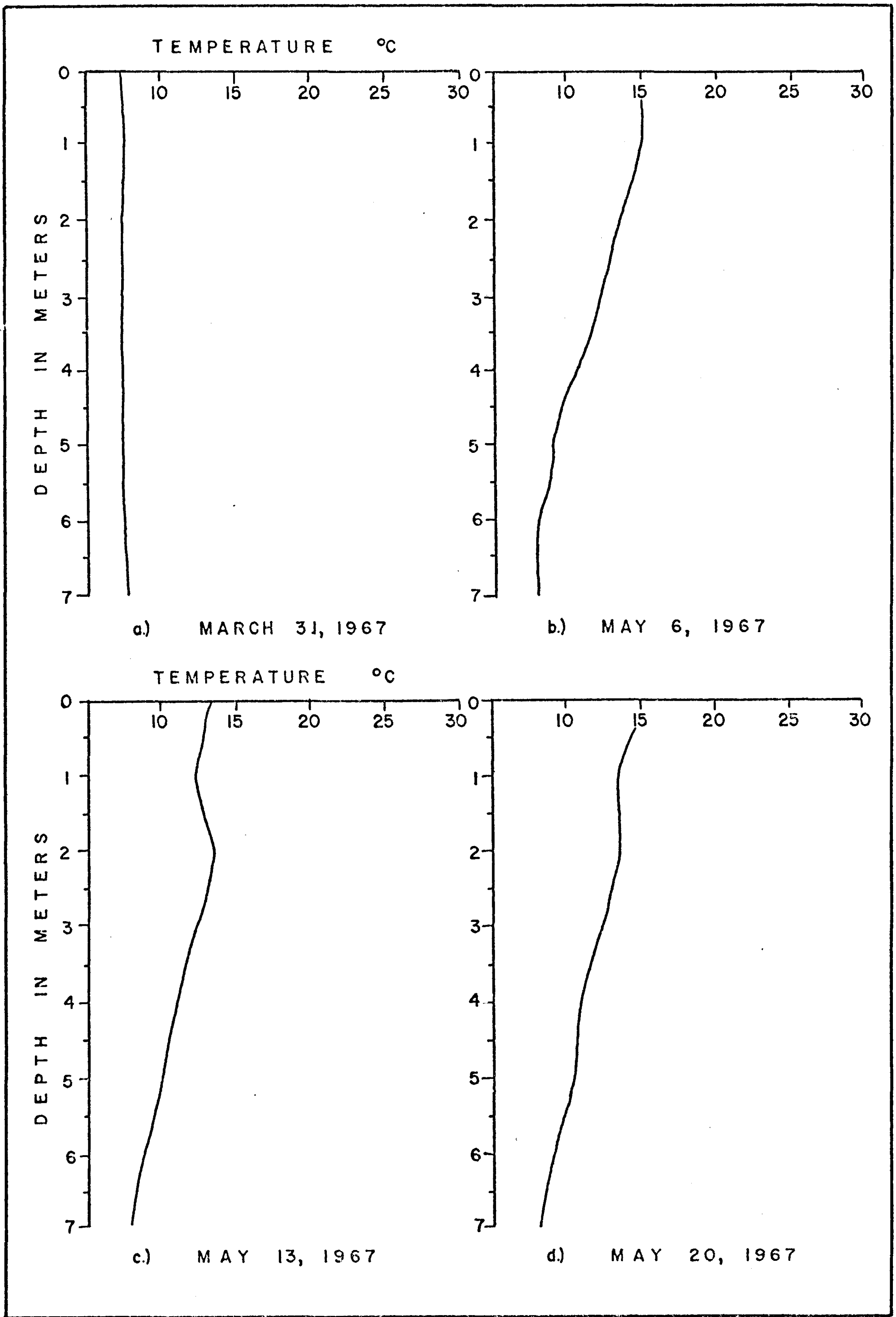


Figure 16.--Thermal conditions at station Lk-1, spring, 1967.

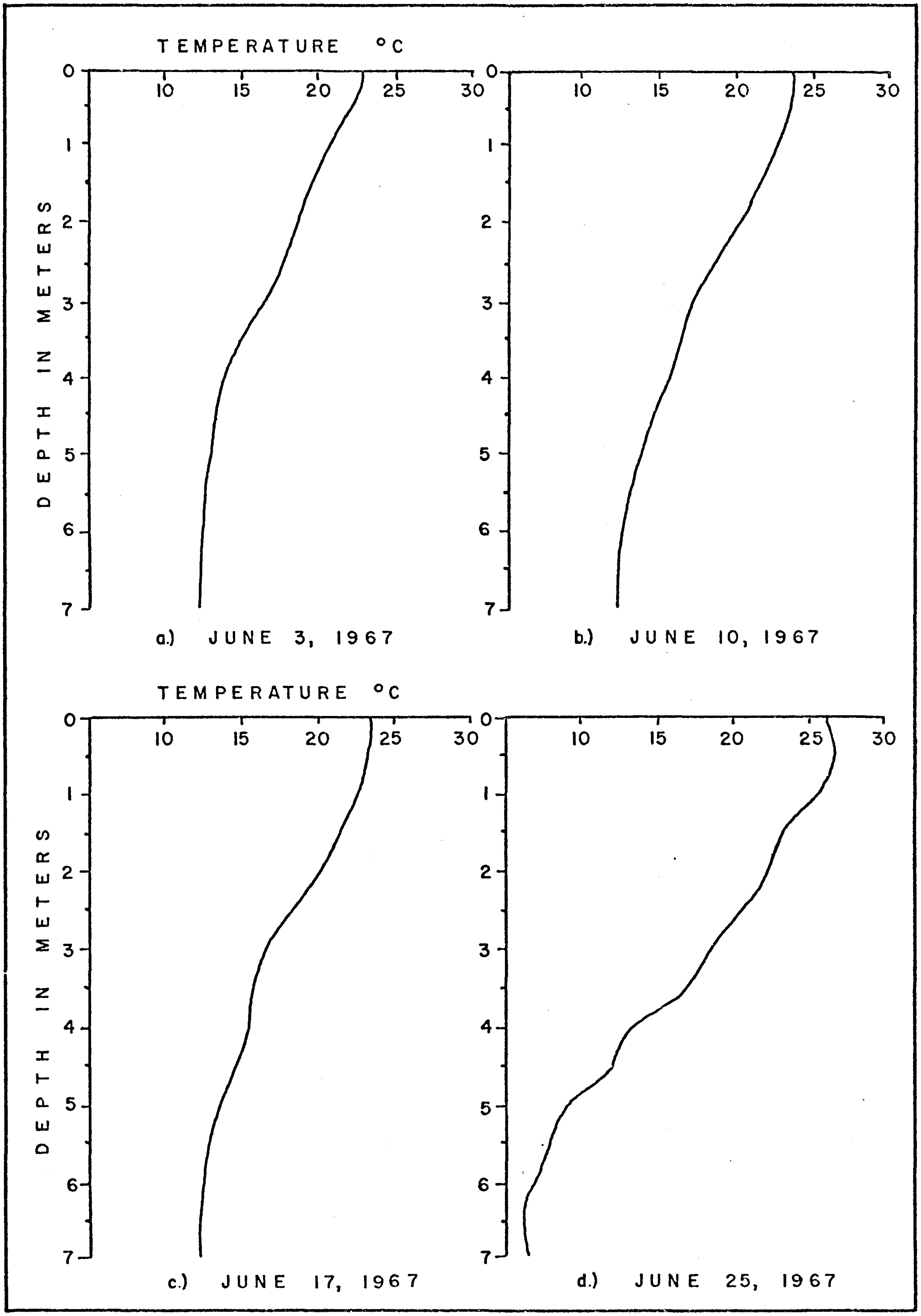


Figure 17.--Thermal conditions at station Lk-1, summer, 1967.

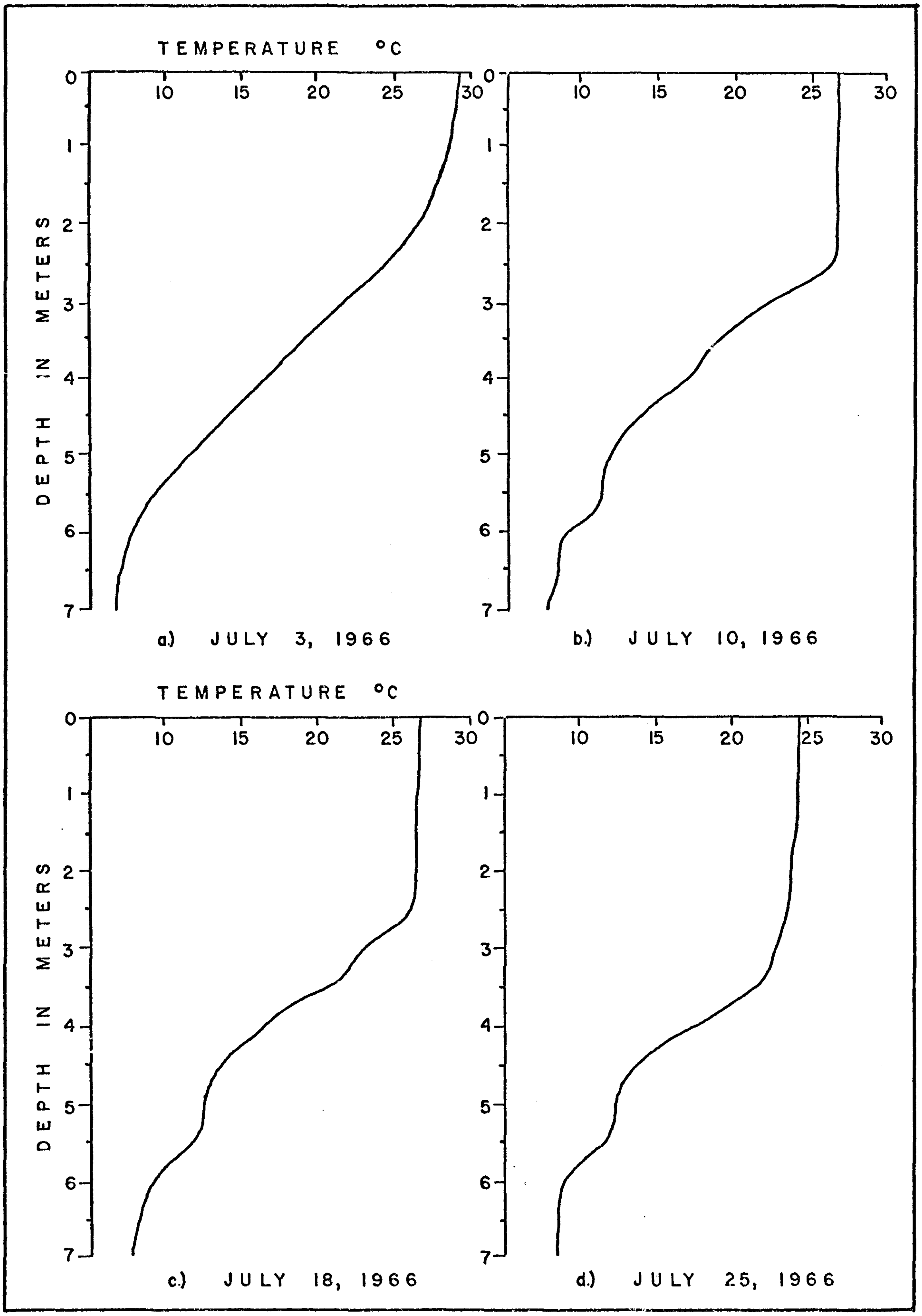


Figure 18.--Thermal conditions at station Lk-1, July, 1966.

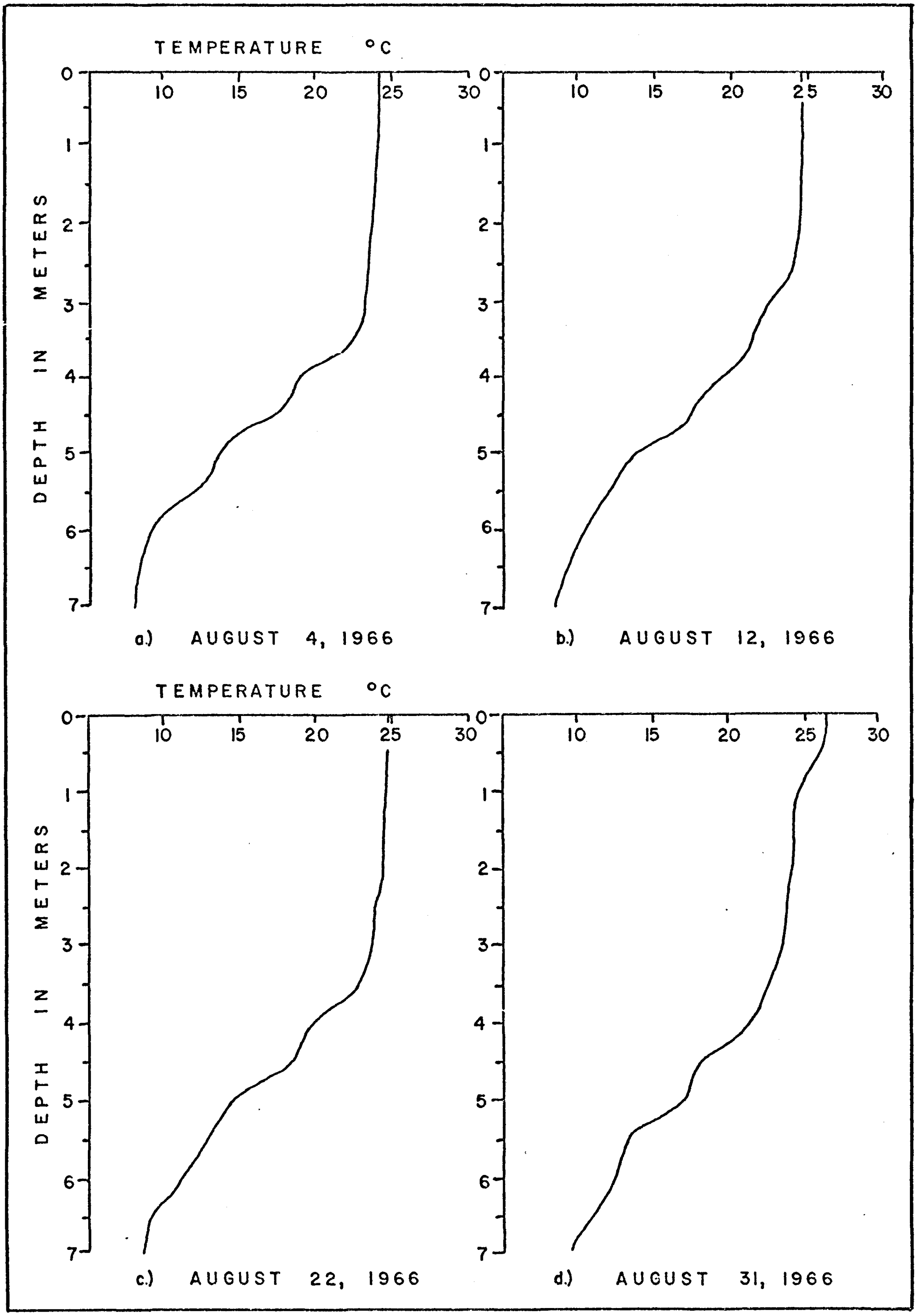


Figure 19.--Thermal conditions at station Lk-1, August, 1966.

Glovers' Pond.

In 1966 the maximum surface temperature of 29 C occurred on July 3 when the air temperature reached a high of 40 C. From this time the top of the metalimnion moved steadily downward until it reached the 4-meter mark in early August. The thermocline did not extend much below 6.0 meters.

The thermocline produces a very stable barrier against circulation of epilimnitic waters with the hypolimnion in Glovers Pond. By the end of the summer the epilimnion had a volume of approximately 158,250 cubic meters, whereas the hypolimnion had been reduced to about 43,211 cubic meters. This uniformly warm upper strata provides good living conditions for the biologic community of the lake. Complete stagnation probably takes place only in the bottom two meters of the lake.

The thermal properties were not studied during the fall so no data are available for the time of the fall overturn. The mean date of the first fall frost in the area is October 12 (Kennedy, et al., 1963, p. 92). The temperature during the fall of 1966 remained warm during the daylight hours until November 4. It is probable that the thermocline did not begin to disintegrate until this lasting cold weather set in. The fall overturn, therefore, probably occurred during the second or third week of November.

The writer visited Glovers Pond in late December of 1966 and found only a thin (1 to 2.5 cm) layer of ice present. The lake did not freeze permanently until December 13. The temperature during the day of December 31 reached 55 F. This was part of a warm trend that spanned the last several days of 1966. Heavy ice formation was impeded by this warm weather until January of 1967.

Several variations in the thermal data from Glovers Pond require further explanation. It will be noted that on all of the thermal curves (Figures 18 and 19) presented here for July and early August of 1966 (excepting that of July 3 which is measured in whole meter intervals) there is an elevation of the temperature at the 5.5 meter depth which causes a slight concavity in the curve for that depth. If the slope of the graph held constant, the temperature at the 5.5 meter depth would be about 10.1 C, whereas it was actually 11.9 C.

At first glance this trend does not appear to continue in the curves after August 12; however, on inspection it will be seen that the temperature is still about 12 C on those curves as well. The reason that the concavity of the curve is lost lies in the fact that the warmer water at the base of the thermocline has reached almost to the 5.5 meter depth and has incorporated the relatively high temperature of that depth into its structure thereby changing the overall slope of the graph at this depth.

This slight deviation from the normal trend of the temperature curve is interpreted by the writer to be caused by an influx of spring water into the lake below the level of the thermocline. The consistency of this temperature (about 11.9 or 12 C) at this particular depth is reliable evidence that springs do enter the lake proper at some depth below the surface along the north shore. More than one such spring probably exists.

A second variation in the thermal distribution appears in Figure 20, 21 and 22. These variations are discrete with time. They do not repeat in any regular pattern, but they do have reflections vertically on the graphs on particular days. Some of these flucuations correlate

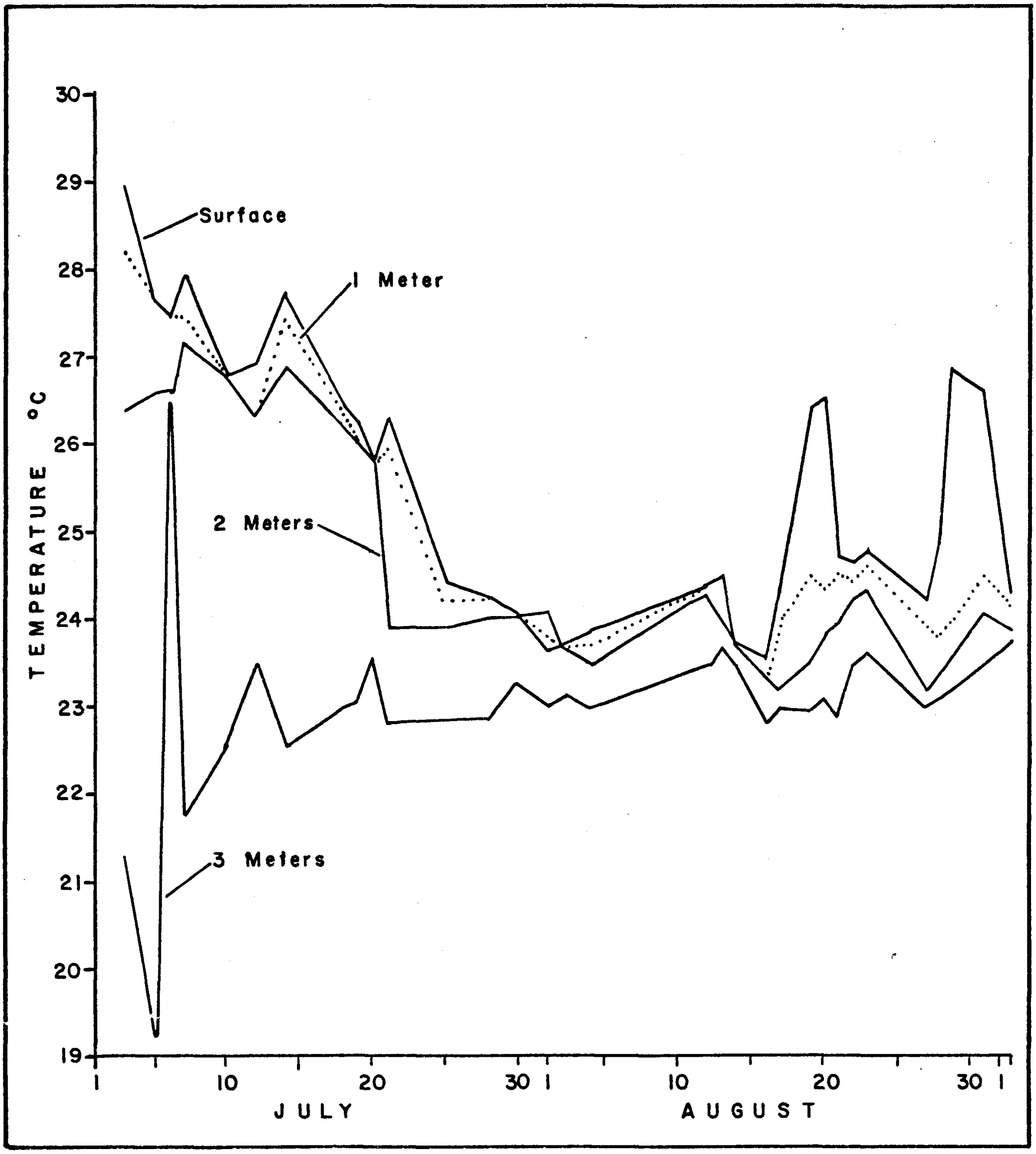


Figure 20.--Temperature variations in the upper three meters at station Lk-1 in Glovers Pond during July and August, 1966.

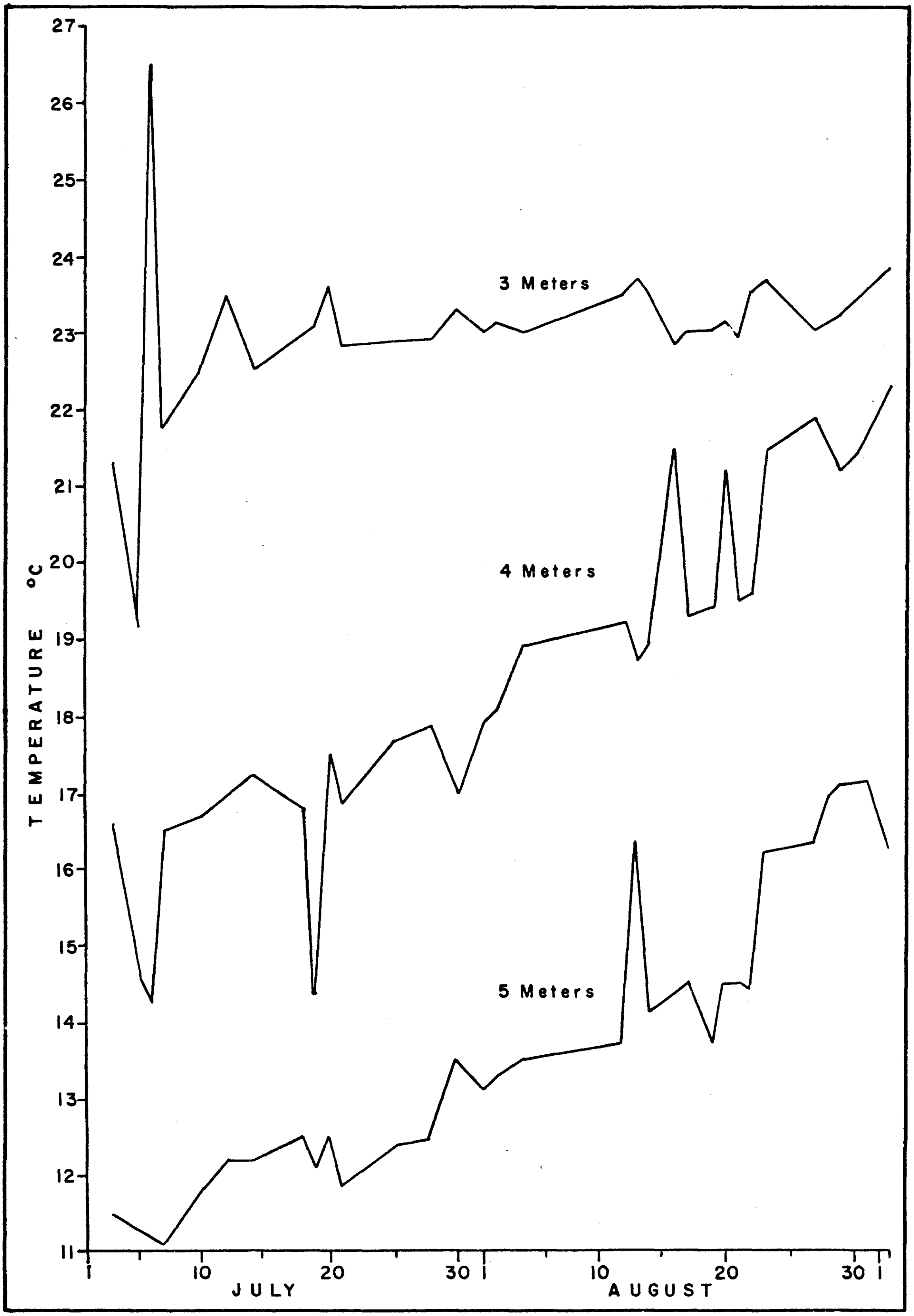


Figure 21.--Temperature variations at three, four, and five meter depths at station Lk-1 in Glovers Pond for July and August, 1966.

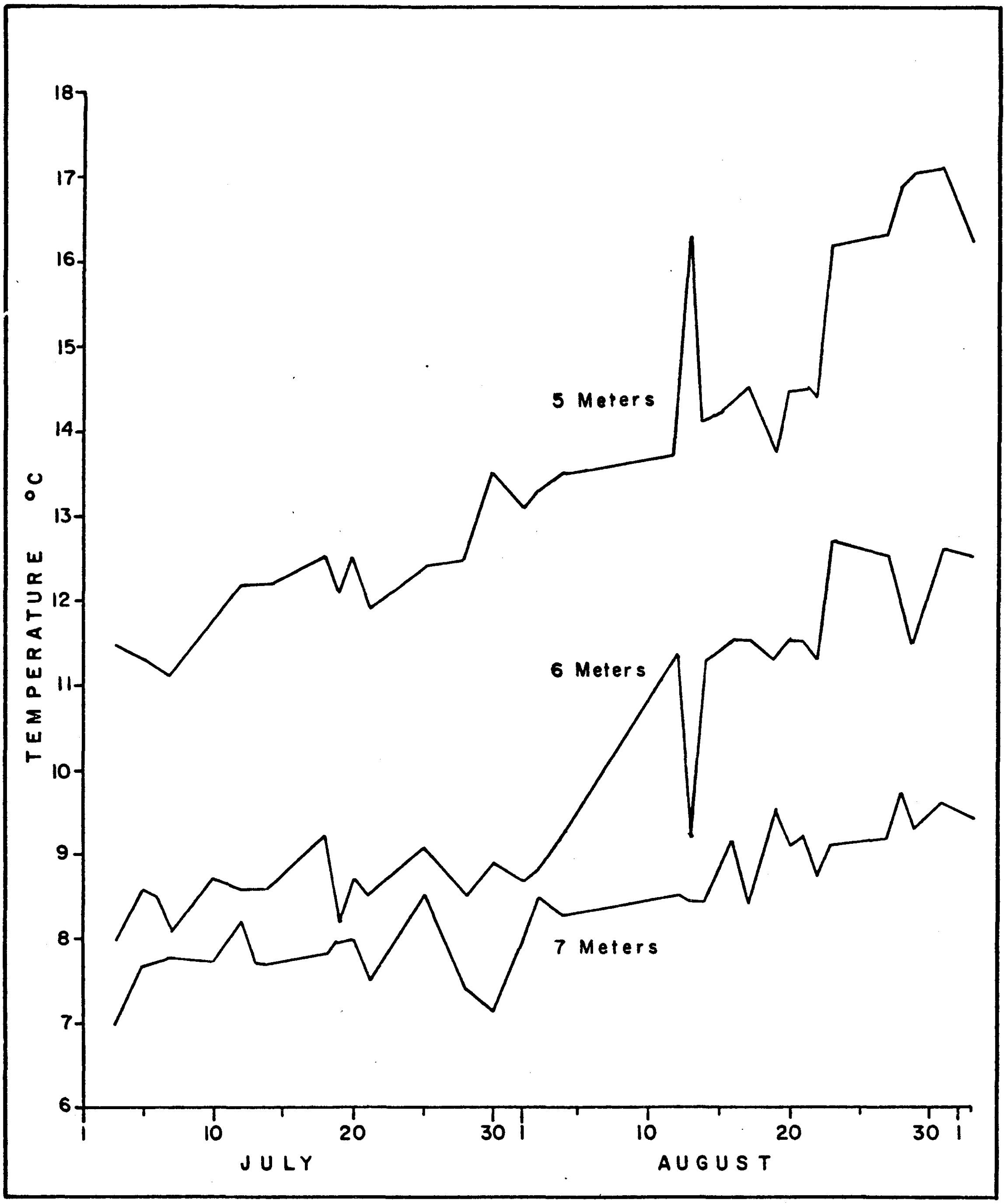


Figure 22.--Temperature variations at five, six, and seven meter depths at station Lk-1 in Glovers Pond, July and August, 1966.

with extremes of daily temperature as is the case of the high on July 2 and 3 when the air temperatures were near 100 °F (40 °C). The other extremes occurred on days when heavy rain fell. This rain water, settling in the lake to a depth commensurate with its density, caused variations in the thermal curves of the lake at various depths. This is the case, for example, on July 6, 7, 15, 19, 28, 29 and August 11, 12, 15, 16, 17, and 23. Most of this rainfall was only a few tenths of an inch, but on August 15, 16, and 17 produced a total of 2.4 inches and caused longer lasting deviations in the curve. These deviations thus represent daily fluctuations in the climate of the area.

The final variation is that shown on the thermocline for August 12 (Figure 19, b). Here the metalimnion is broken up into a series of smaller thermoclines. This structure may be attributed to relatively high (about 15 mph) winds which disturbed the lake during that day. Rain occurring at the same time also had an effect on the thermocline, but most of this disturbance is attributed to wind action.

The thermal properties discussed here for Glovers Pond are usual for a dimictic lake (Ruttner, 1963). The thermocline provides a density barrier strong enough to inhibit the mixing action of the wind, and allows the bottom few meters of the lake to become relatively stagnant during the summer. Ice in the winter also protects the water body from the wind. This permits only the two regular periods of overturn in the spring and the fall.

Chemical Limnology

General chemical conditions.--The chemistry of Glovers Pond was studied during 1966 in order to characterize the chemical properties of the lake. Alkalinity, pH, calcium and magnesium hardness, chloride concentration, and oxygen content were considered to be the factors best suited to characterize the lake, and at the same time, they were readily measured with the equipment and time available. Techniques were used to measure these factors are discussed in Appendix A of this report.

The portion of New Jersey in which Glovers Pond lies is described by Anderson and George (1966, p. G14) as having water with a moderate (90-250 ppm) content of dissolved solids, particularly calcium and magnesium, due to the fact that water is flowing through the Valley and Ridge province where limestone, dolostone, and shale bedrock prevail. The median turbidity is described by these workers as 5-10 Jackson candle units (p. G41). The values for hardness, alkalinity, and chloride concentration as given by these workers agree well with the data obtained by the writer. Glovers Pond is chemically compatible with other surface waters of the region.

Water samples for analysis were taken primarily from two locations in the lake. Station Lk-1 (Figure 23) was in 7 meters of water at the end of the swimming area of the camp while station Lk-2 was on the shallow shelf at the southwest corner of the lake. Two other stations were occasionally occupied to contrast and compare data with results from the first stations. Of these, Lk-3 was located in the center of the northeastern half of the lake in 9.5 meters of water, and Lk-4 was at the former location of the fire pumping line on the edge of the lake just southwest of the boating area.

There are two principal chemical provinces in Glovers Pond. The first is the deep lake, or profundal zone. This, in turn, is subject to subdivision because of stratification of chemical factors by the action of the thermocline. The second chemical zone is the

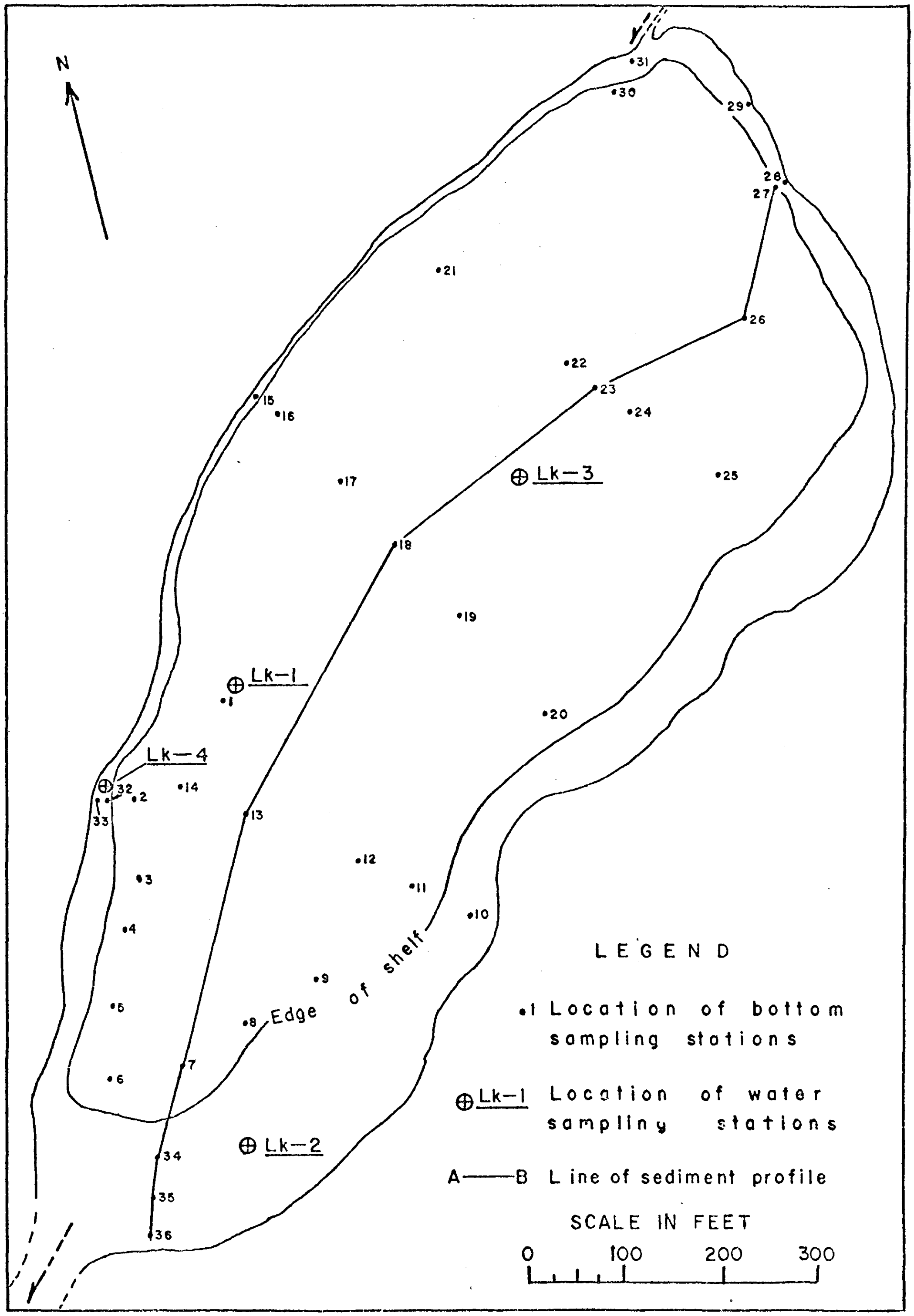


Figure 23.--Location of sampling stations and line of chemical profile (Figure 25) in Glovers Pond.

water overlying the shelf area. There are significant differences in the water chemistry of the two zones which, in part, reflect differences in the physical conditions already mentioned. Because of this dual aspect of water chemical values, the two provinces will be discussed separately.

A complete investigation of the water chemistry of this lake would take two years of constant sampling, including detailed work with the biological productivity which has a very strong influence on the present environment in the two provinces. There are important biological differences between the open lake and the shelf, but a complete analysis of the chemical and biochemical relationships was beyond the scope of this study.

Station Lk-1.--Station Lk-1 was located at the end of a floating boardwalk in the swimming area above 7.0 meters of water. Because of the depth, water there is subject to thermal stratification and, to a lesser extent, to chemical stratification. The formation of thermal density layers restricts water circulation to such an extent that independent chemical gradients are formed. Such a gradient is known as the chemocline. The chemocline may be seen in Figure 24 from data taken on July 2. On this date the top of the thermocline was at 1.8 meters depth and the base was at 6.0 meters.

Discussion of chemical data from station Lk-1 will concentrate on information obtained from the epilimnion (the upper one or two meters of water) because this is the zone in which biologic activity is most significant and with which the values obtained in the shallow water above the shelf can best be compared. All values obtained for the summer of 1966 appear in Appendix B.

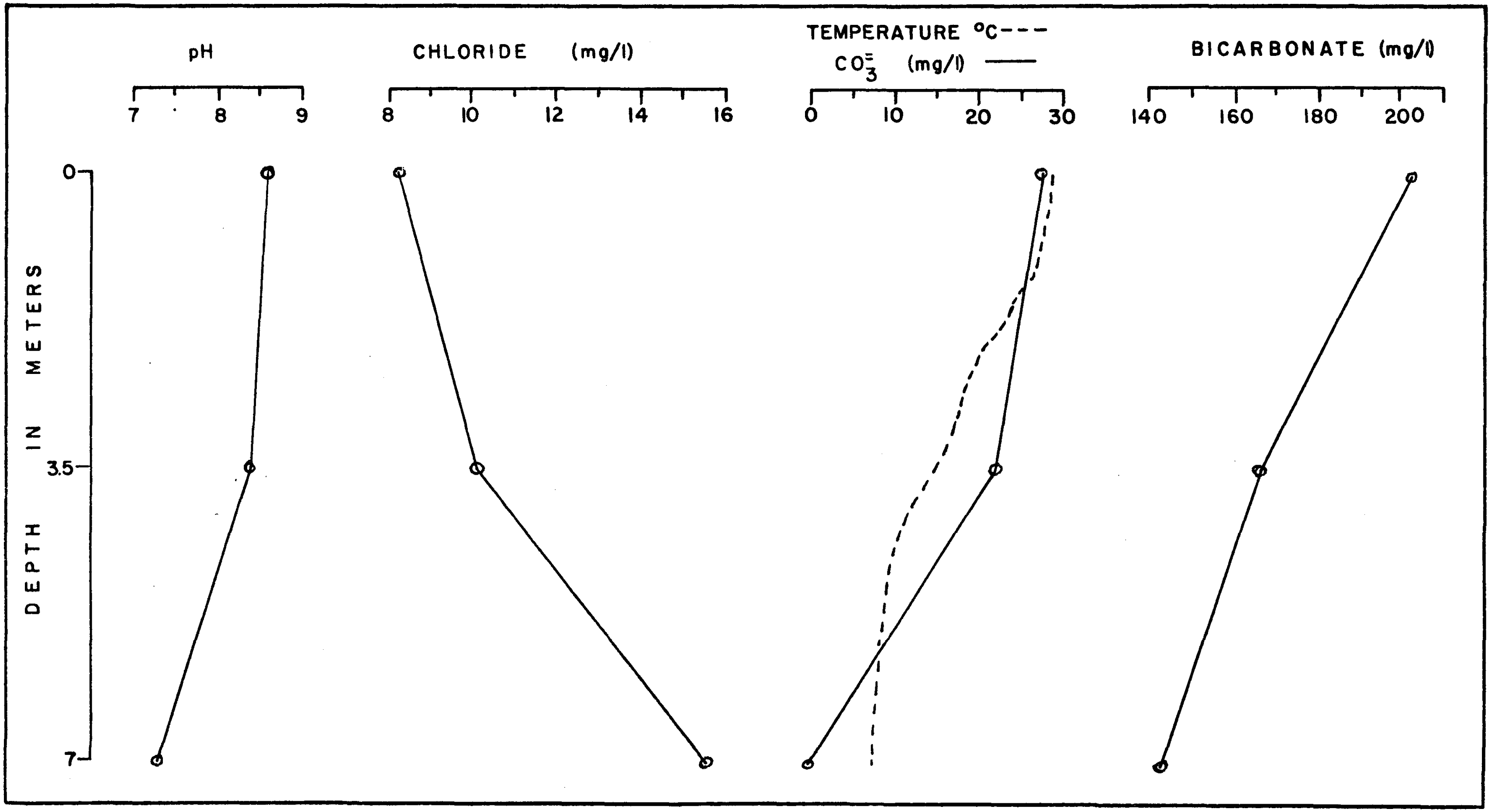


Figure 24.--Chemical values showing the development of slight chemocline at station Lk-1, July 2, 1966.

Chloride concentration (calculated as milligrams per liter of Cl^-) varied, in the epilimnion, from 11.6 mg/l to 15.6 mg/l during the summer. This small amount of chloride does not have significant influence on the major chemical processes to be considered in this discussion. During July and August the pH of the water varied from 8.3 to 8.6.

The content of dissolved oxygen in Glovers Pond was measured periodically. Measurements were not taken during the first week of July when a plankton bloom was occurring, so there are no data available for comparison of dissolved oxygen values during periods of high and low biologic productivity. Oxygen values taken at noon in the epilimnion generally ranged between 9.0 ppm and 11.0 ppm. These figures are in close agreement with those found by Smith (1957, p. 194) in Silver Lake, a similar lake, three miles west of Glovers Pond.

In lakes of this type the strong density differences caused by the thermocline frequently inhibit mixing of the water sufficiently so that the hypolimnion becomes highly undersaturated or even devoid of dissolved oxygen. (Ruttner, 1963, p. 74; Welch, 1952, p. 183) This was most certainly the case in Glovers Pond (as already shown such a chemocline does exist) just as it was in Silver Lake where at 32 feet no oxygen was found late in August. At 23 feet in Silver Lake on the same day only 1.05 ppm oxygen were found (Smith, 1957, p. 194).

Water samples from the hypolimnion usually gave off a strong hydrogen sulphide odor. This is a good indication that circulation to the lower reaches of the lake was limited causing reducing conditions to prevail in the absence of dissolved oxygen.

Tables 2 and 3 give some values for carbonate, bicarbonate, calcium, and magnesium taken at station Lk-1. During July and August, carbonate content varied from 5.4 mg/l to 27.6 mg/l and bicarbonate ranged from

TABLE 2

CHEMICAL VALUES FOR GLOVERS POND
STATION Lk-1 ON JULY 12, 1966

Factor	Depth		
	Surface	3 meters	7 meters
Carbonate (mg/l)	10.8	10.8	none
Bicarbonate (mg/l)	143.4	157.4	185.4
Calcium (mg/l)	43.2	42.4	50.4
Magnesium (mg/l)	21.6	21.1	19.7
Chloride (mg/l)	11.6	10.1	10.1
pH	8.4	8.3	7.5

TABLE 3

CHEMICAL VALUES FOR THE EPILIMNION
AT STATION Lk-1 (1 METER DEPTH) IN GLOVERS POND

Factor	Date - 1966				
	7/2	7/5	7/6	7/14	8/14
pH	8.6	8.5	8.5	8.4	8.3
Carbonate (mg/l)	27.6	22.2	5.4	22.2	10.8
Bicarbonate (mg/l)	140.3	140.3	151.9	142.7	247.6
Calcium (mg/l)	-	-	44.0	-	-
Magnesium (mg/l)	-	-	18.9	-	-

140.3 mg/1 to 247.6 mg/1 during the same period. Calcium and magnesium were measured only twice at this station. Calcium concentration was about 44 mg/1 while magnesium was about 19 mg/1 during early July.

As mentioned previously station Lk-3 was sampled periodically as a comparison for data from Lk-1. Due to its greater depth there are some variations in chemical parameters. Values for one day during the plankton bloom are listed in Table 4. In most cases the chemical factors did not vary a great deal between the two stations except for effects of the thermocline and the related chemocline.

Station Lk-2.--Station Lk-2 was located in the littoral zone on shelf (30cm deep) 5.0 meters from the lakeward edge (Figure 23). Chemical values in this shallow area were found to vary significantly from those of the profundal zone as well as from the epilimnion of the deep lake. The water over the shelf is usually less than one meter deep. It is bottomed primarily by deposits of marl and by the aquatic plant, *Chara*. The sun easily warms this shallow water and heats the sediments which in turn radiate heat back into the water from below. Shelf temperatures as high as 33.5 °C (92.3 °F) were recorded while temperatures of 26 °C to 28 °C were common. Some chemical values for the shelf are given in Table 5.

The pH there was always higher than that of the main lake as would be expected for an area of higher alkalinity. Values on the shelf varied from a low of 8.5 to a high of more than 9.2 with the most common value approximately 8.8. Chloride content of the water was not significantly different from that of the main lake. It was about 9 mg/1 most of the summer.

TABLE 4

CHEMICAL VALUES FOR GLOVERS POND
STATION Lk-3 ON JULY 4, 1966

Factor	Depth		
	Surface	3.5 meters	9 meters
pH	8.6	8.5	7.0
Carbonate (mg/l)	22.2	22.2	none
Bicarbonate (mg/l)	151.3	162.9	189.1
Calcium (mg/l)	44.0	47.2	62.4
Magnesium (mg/l)	129.6	20.6	13.4

TABLE 5

CHEMICAL VALUES FOR GLOVERS POND
STATION Lk-2 ON JULY 5, 1966
AT A DEPTH OF 10 CM

Factor	Value
pH	8.9
Carbonate (mg/l)	27.0
Bicarbonate (mg/l)	87.2
Calcium (mg/l)	36.0
Magnesium (mg/l)	155.0
Chloride (mg/l)	9.2

Measurements of dissolved oxygen taken at noon during August resulted in values of 8.6 mg/l to 13.6 mg/l. As would be expected, these values are slightly higher than those of the main lake since the water is shallower and is constanly being mixed by the wind. Also, thick plant growth enriches this water by photosynthesis during the daylight hours causing higher values.

The important factors of carbonate and bicarbonate alkalinity and calcium and magnesium concentration at station Lk-2 show some variation from those at station Lk-1 (Table 2). The bicarbonate content is slightly lower than at Lk-1; however, the carbonate content is higher. This is caused by the greater biological and chemical activity occurring here.

Chemistry of Source Waters.--Since the primary source of water for Glovers Pond is ground water from springs, samples from the spring brook and from one of the camp water wells were also analyzed. Water well no. 1 (location "X" on Figure 5) pumps from limestone and dolostone aquifers at 90 feet. (J. D. Taylor, personal communication). Samples of the well water were drawn from the line before the water was chlorinated so that no contamination would occur.

The spring water was sampled from the brook flowing through the northeast bog where the water flowed under a small footbridge, about 80 feet from the spring itself.

The samples are comparable in all aspects except for pH (Table 6). The higher pH of the spring water is probably due to the fact that the spring source is well below the bog surface so that the water must flow upward through alkaline sediments before emerging. Also, plants growing in the spring box and brook raise the pH by withdrawing carbon dioxide from the water. These factors serve to raise the pH considerably above

TABLE 6

CHEMICAL VALUES FOR WATER WELL NO. 1
AND THE SPRING BROOK JULY 5, 1966

Factor	Well No. 1	Spring Brook
pH	7.4	9.0
Carbonate (mg/l)	none	none
Bicarbonate (mg/l)	258.0	305.6
Calcium (mg/l)	66.4	68.8
Magnesium (mg/cl)	20.2	31.2

that of the well water. As would be expected (Ruttner, 1963, p. 62) in ground water, all the alkalinity present was in the form of bicarbonate ions.

Effects of Biological Activity.--The ions Ca^{++}, Mg^{++}, $CO_3^{=}$, and HCO_3^- are closely interrelated with each other as well as with the biological activity of the upper stratum of the lake. This layer of water, being closest to the surface, receives the majority of the light and heat energy supplied to the surface by the sun. It is in this region that photosynthetic production is carried on causing important changes in chemical equilibria. These stresses in turn affect the above mentioned ions.

Such a region of photosynthetic activity is called the trophogenic zone of the lake and is separated from the lower, tropholytic zone of respiration, or no photosynthesis, by a boundary defined (Ruttner, 1963, p. 72) at the point where the uptake of CO_2 in photosynthesis is exactly balanced by the output of O_2 in respiration.

In the chemical system of Glovers Pond, calcium, carbonate, and bicarbonate ions are present according to delicate equilibria. Free CO_2 gas is dissolved in the lake water in varying amounts which may or may not be in equilibrium with the atmosphere at any one time. At all times, minimum concentrations of dissolved CO_2 are necessary in order to maintain balance in the equilibrium system described below.

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \quad (1)$$

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \quad (2)$$

$$2HCO_3^- \rightleftharpoons CO_2 + H_2O + CO_3^{=} \quad (3)$$

If free CO_2 is removed from the system a stress results and the equilibrium shifts to remove that stress as in equation 3.

During periods of increased phytoplanktonic activity in the trophogenic zone rates of photosynthesis increase. This removes free CO_2 from the water first according to equation 4.

$$6CO_2 + 6H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 \qquad (4)$$

Removal of free CO_2 introduces a stress to the system causing the half-bound CO_2 to be released according to equation 3.

If, at the same time, the calcium ion is present in the system, the release of the half-bound CO_2 will progress by the following reaction (5).

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3 \text{ (solid)} + CO_2 \text{ (gas)} + H_2O \qquad (5)$$

Due to this reaction, solid calcium carbonate will be precipitated from the system. These reactions will occur only if the respective ions are present at proper saturation levels, and only if the free CO_2 is depleted sufficiently in the system. These equilibria are discussed in detail by Ruttner (1963, p. 58-73). They are the most important reactions affecting Glovers Pond.

Early in July in 1966, very warm air temperatures, up to 27 °C (106 °F), heated the epilimnion to 29 °C and stimulated growth of plankton causing a bloom to occur. The water became murky green cutting light penetration, as measured by Secchi disk, to less than one meter, whereas normal values generally exceeded three meters. This was the largest bloom seen by the writer in five summers at the lake and it undoubtedly shifted the chemical equilibria in the lake water.

First approximations of saturation values for calcium carbonate indicate that the epilimnion is supersaturated continuously during the summer months. The hypolimnion is barely saturated (about 120%) at 7 meters and is probably even less so at 9.5 meters in the deepest part of the lake during the same time period.

These saturation differences indicate that much of the calcium carbonate formed in the epilimnion during such a plankton bloom as mentioned above will begin to redissolve when it reaches the less saturated hypolimnion as Ruttner (1963, p. 193) showed. This effect will be more pronounced in the fall and winter when the temperature of the entire water mass has been lowered to about 8 °C and mixed by the fall overturn. This allows the water to hold more carbon dioxide in solution. Whether any calcium carbonate that may be deposited at depth during the summer is actually redissolved from the bottom sediments during the winter or not is a question debated by some writers according to Ruttner (1963); in Glovers Pond there is a strong possibility that because of its depth some is again placed in solution due to the overturn.

The same plankton effects described for the main lake (stations Lk-1 and Lk-3) will hold for the shelf area (station Lk-2). One additional factor must be added. As noted, plankton blooms play an important regulatory role in alkalinity concentrations at station Lk-1. These blooms are short lived and occur only once, or at most twice, a year. The littoral zone is subject to the same plankton growths, but it is also strongly influenced by very dense growths of Chara which blanket the outer shelf and the sublittoral slope to the limit of light penetration (3 to 3.5 meters).

Chara (stonewart or muskgrass) is a large multicellular alga with a cylindrical stem and whorled branches. It occurs in water of high alkalinity, where its stems become coated with encrustations of calcium carbonate precipitated from the water during photosynthesis.

On the shelf, high water temperatures and these blanketing growths of Chara serve almost as a continual plankton bloom, thus keeping the water continually depleted in free CO_2 and continually supersaturated with calcium carbonate according to the above equilibrium reactions. Chara is the most important biological-chemical agent acting on the lake. It is a prime cause of the differences between the chemistry of the trophogenic zone at Lk-1 and the water of the shelf area of Glovers Pond. As will be seen, this in turn, affects the present sedimentary environment.

Present Sedimentary Environment

The lake was sampled for bottom sediments by means of an Ekman dredge at 36 stations, 11 of which were on the shelf and 25 in the deeper lake, as shown in Figure 23. The stations were chosen so that a good representation of both deep and shallow water sediments would be obtained.

Color and texture of sediments.--Deposits from the profundal zone are entirely organic, gelatinous oozes containing a few larger decayed leaf fragments of terrestrial origin. These sediments are very dark brown (10YR2/2) to very dark grayish brown (10YR3/2) when wet and dark grayish brown (2.5Y4/2) to very dark grayish brown (2.5Y3/2) when dry (Munsell, 1954). This finely divided, silt-sized, organic sediment is classified as sapropel (Pettijohn, 1957, p. 488), or, in the particular case of lacustrine sediment, as gyttja (Ruttner, 1963, p. 195). deposits of this type were found at stations 13, 17, 18, 19, 22, 23, and 24 (Figure 23).

Sediments taken from the sublittoral zone on the slope are composed of silt-sized particles in an organic rich, semi-gelatinous matrix containing needles and grains of calcium carbonate and numerous gastropod shells that have been swept of the shelf. On the slope a mixing or transition between profundal and littoral types of sediment occurs. Organic constituents decrease, whereas calcium carbonate content increases in progressively shallower samples. This may be seen from chemical profile data in Figure 25.

These shelf slope deposits have a wider color and textural variation than do the profundal deposits due to the fact that they lie on the interfingering margins of littoral and profundal deposition. This gives such sediments a unique physical and chemical composition which is a transitional mixture of both environments. Most of the wet sediment is dark grayish brown (2.5Y4/2) whereas the most common color of the dry sediment is light gray (5Y6/1). Some of these sediments, if sufficiently organic, may still be classified as gyttja though they have been modified by additions of calcium carbonate. They will be referred to in this discussion as "transitional sediments" because of the dual origin (littoral and profundal) of their components. Deposits of this type were found at stations 1, 2, 3, 4, 5, 6, 7, 8, 14, 16, 20, 21, and 25.

The shelf is the place of most active sedimentation. Here, sediments are of silt-sized particles, or aggregates of these particles, composed almost entirely of calcium carbonate into which are mixed numerous mollusk shells and some plant remains. The wet sediment is

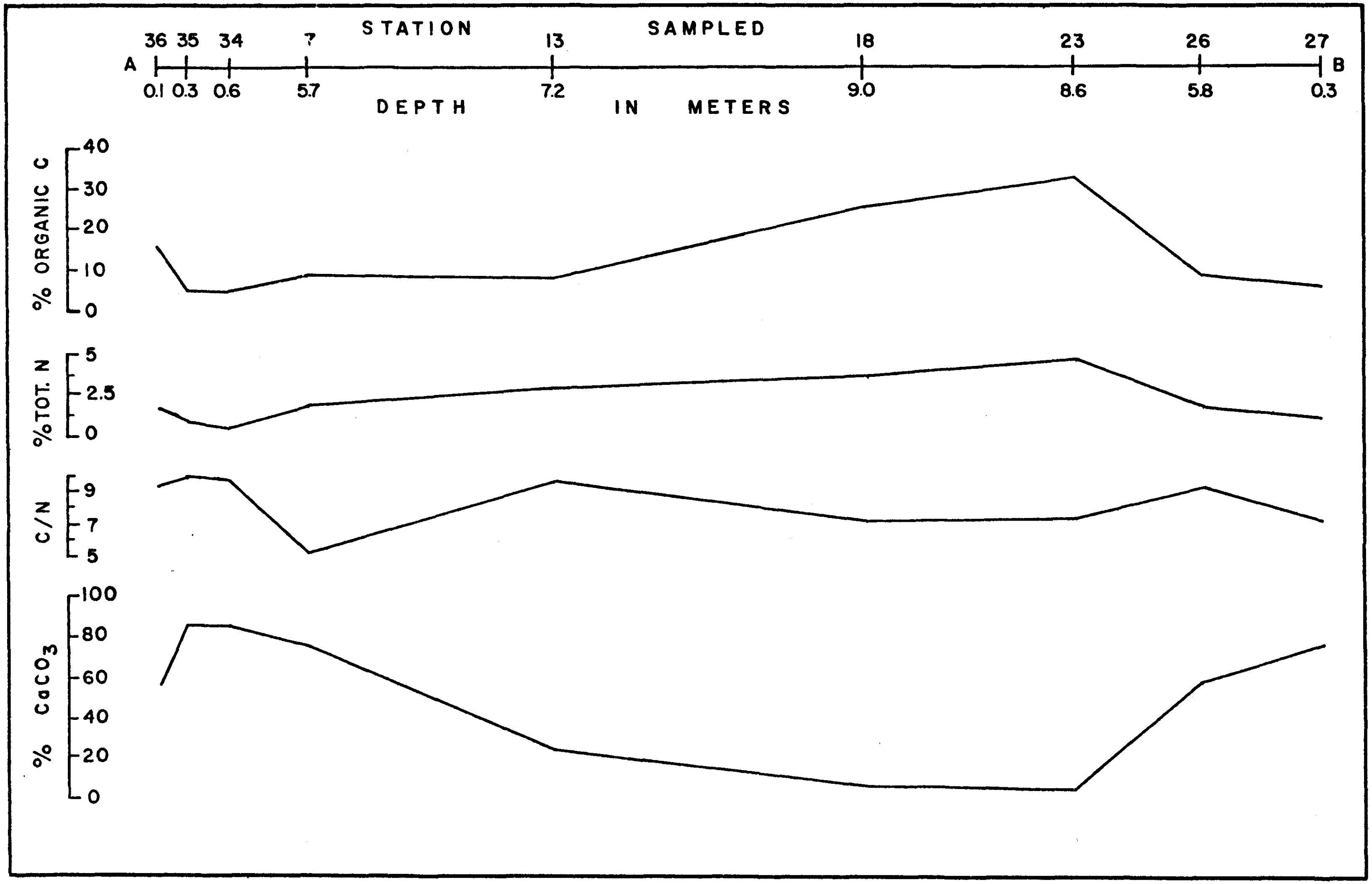


Figure 25.--Chemical profile of bottom Sediments in Glovers Pond.

light gray (10YR7/2); dry samples are generally white (5Y8/1). Sediments of this type are pure marl and were collected at stations 10, 27, 28, and 34.

On the shelf the upper three inches of this marl is nearly a suspension. It flows freely when disturbed by the slightest movement of the water. This fluid condition decreases quickly below the three-inch level to sediment of a more solid, muddy consistency which is the case to at least four feet below the surface. The entire body of marl is well saturated with water.

On the rare occasions when the wind blows strongly from the southwest, waves of sufficient depth to erode the marl may be produced. At these times (usually during storms) the littoral material is swept from the shelf and deposited on the slope to produce the transition sediments.

The littoral zone is rimmed by sediments deposited as water levels recede each summer. These deposits are organic, consisting mainly of plant stems and leaves of shallow aquatic plants or marginal terrestrial vegetation. They are very dark grayish brown (10YR3/2) when wet and gray (10YR5/1) when dry.

This organic sediment is often thinly spread over the marl, only to be removed when high water returns to the lake in the fall. Such thin organic layers are of little import at any one instant during sedimentation at Glovers Pond. In one area only are they more developed than a one or two cm. thick bed. There, on the east edge of the lake (and to a lesser extent on the western margin), large beds of the white water lily, Nymphaea tuberosa Paine, have taken root on the marl. Their thick tuberous root systems have intertwined to form a mat which in turn serves to collect further organic material. This mat has extended over the shelf edge due to the prolonged low water levels. It may be easily punctured with an oar yet it is a firm substrate that may even be walked upon.

This is the beginning of a typical bog succession. From a sedimentological viewpoint the plants here serve to secure the shoreward edge of the shelf from erosion and, additionally, form an organic-rich sedimentary stratum which is a successor to the marl and which is terminal in the lake sediment sequence. Water level strongly influences the rate of this incipient peat deposition.

This mat serves as a rooting medium for lake-margin plants such as Typha (Cattail) and Scirpus (Bull rush) which grow along the shore. When the lake is low, seeds of these and other marginal aquatics root in this border of organic sediment and bind it together so that higher water will not erode it. This foreshadows the advancing of zones of fringing marsh and bog vegetation which continually seek to establish viable communities on the littoral shelf. Thus, prolonged periods of drought and related low water levels have affected the sedimentation markedly by permitting shore vegetation to grow farther out on the shelf than is usual under present conditions. Samples of this marginal, highly organic sediment were taken at stations 35. and 36.

At three places along the north and northwest shore sediment texture and composition varied from the pattern described.

The first of these anomalies is at stations 32 and 33. Here, the shelf sediments are usually of the marginal highly organic type, but at this spot higher amounts of marl were found with the organic matter. This was caused by the fact that a fire pumping line was established in the lake and material was dredged from the shelf for location of the pipe. In the process marl that had been covered by organic sediment was brought up and mixed with that upper layer to produce unusual mixtures of the two. This is best shown in Figure 27.

Another variation was found at station 15, the only station where large quantities of terrestrially derived sediment may presently be found. These sediments consisted of silt, sand, and gravel that had been eroded from till on the steep lake shore by water running from the downspouts of the camp dining hall roof. This deposition has produced a delta having a five-foot radius. This is a minor source of sediment, but because of its composition and for the sake of completeness it is noted.

The final variation was found in sediments at stations 30 and 31. There, the spring brook flows from the bog into the lake carrying with it entrained particulate organic matter of both large and small size. Some of this is derived from peat deposits in the bog, and some is from leaves and twigs fallen into the brook from bog vegetation. This material is not carried far into the lake; rather, it is gradually distributed along the sublittoral slope at the northeast tip of the lake by wind and wave action. This is only a minor source of sediment for the lake.

Chemistry of the sediments.--The gelatinous texture of the gyttja and marl made quantitative physical description of the sediments difficult and useless. In order to understand exact sedimentary regimes within the basin, quantitative chemical analysis for percent total carbon, percent total nitrogen, and percent calcium carbonate content of each sample was made according to the methods used successfully by Callender (1968). These analytical techniques are described in Appendix A.

Approximately 120 analyses were required.

Some samples of marl were analyzed by X-ray diffraction. The results showed that no dolomite or high-magnesium calcite are being deposited. This permitted marl to be analyzed for carbonate with the assumption that essentially all of this was in the form of calcium carbonate.

The amount of carbon attributable to organic processes (e.g., decaying plants) was obtained by subtracting the percent of inorganic carbon in the $CaCO_3$ from the percent total carbon (both organic and inorganic) measured in the sediments. This value and the percent total nitrogen in the sediment were used to indicate the amount and character of the organic matter in the deposit.

Some additional values of chemical analyses are given in Appendix B. Calcium carbonate content varied from essentially zero 1.6% to 89.4%. The total nitrogen values ranged from 0.51% to 4.96%, whereas total carbon content ranged from 14.35% to 39.88%. The C/N value varied from 4.9 to 12.7.

Sediment distribution.--By contouring these chemical values of sediment in the lake basin a clear illustration of sediment distribution can be produced. Figures 26 and 27 show that the basin is being filled by concentric bands of sediment, some of which look physically alike but which are actually quite different chemically and therefore have different origins.

The profundal zone, particularly in the deepest section, is receiving almost entirely organic sediments. Calcium carbonate values are extremely low as predicted for the hypolimnion where the water is undersaturated or barely saturated with $CaCO_3$ most of the year.

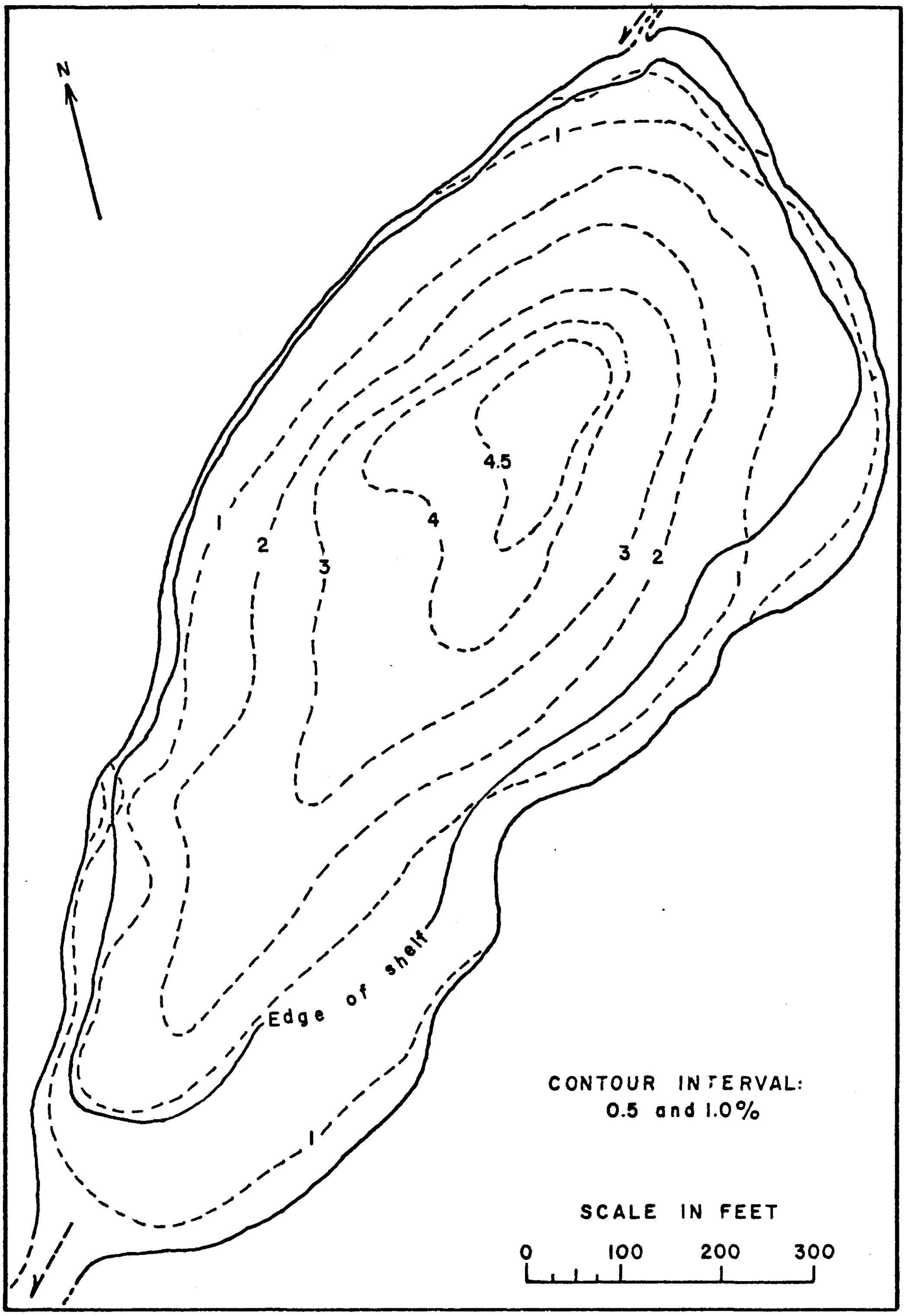


Figure 26.--Distribution of total nitrogen in bottom sediments of Glovers Pond.

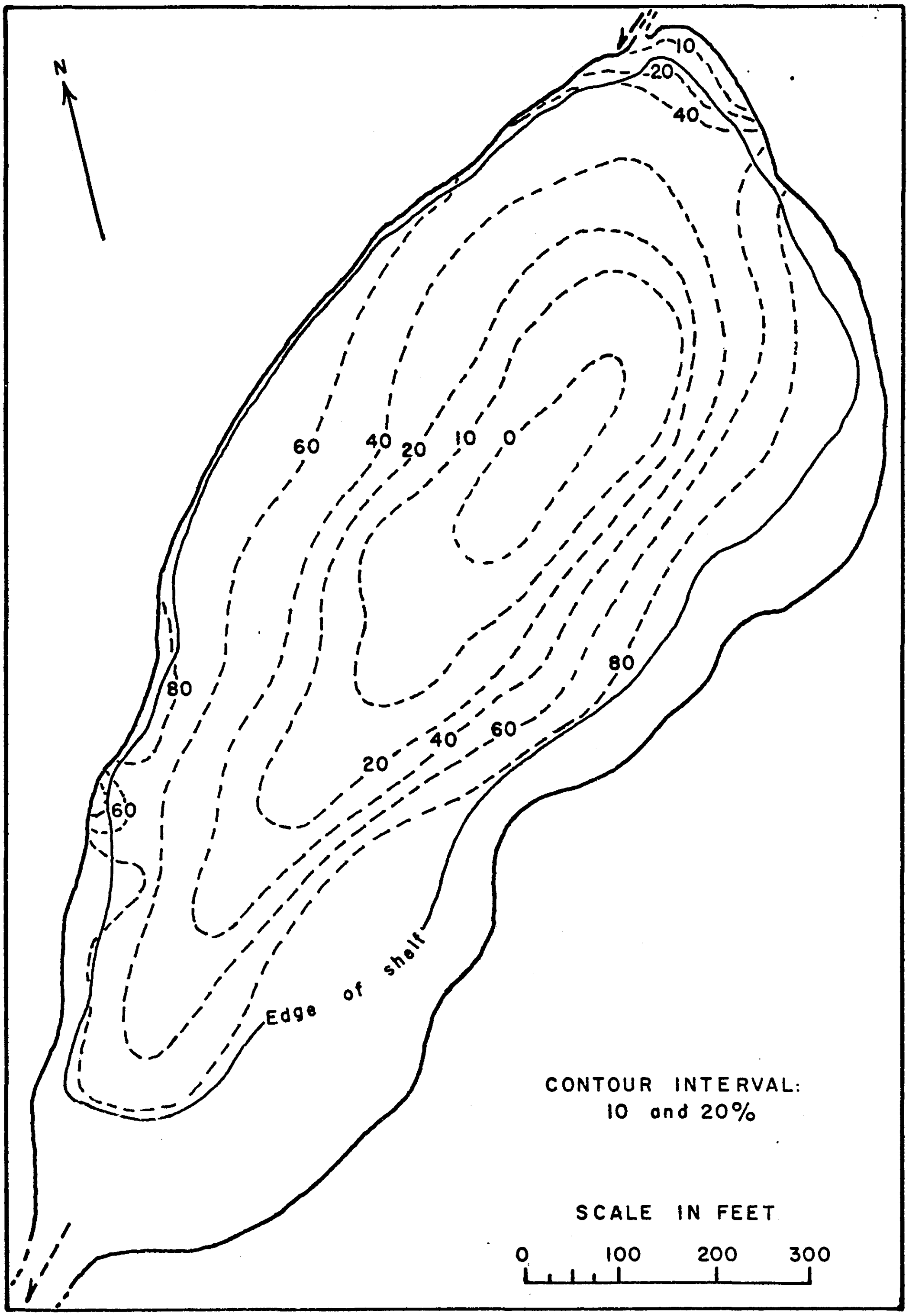


Figure 27.--Distribution of calcium carbonate in bottom sediments of Glovers Pond.

As one approaches shallower water, $CaCO_3$ content is found to increase while the percent nitrogen decreases. On the shelf at the northeast end of the lake, however, the percent nitrogen increases shoreward; there the C/N values are high, indicating that the sediment is derived from terrestrial bog vegetation rather than from aquatic vegetation.

In order to make the sediment distribution map in Figure 28, arbitrary values for percent calcium carbonate and percent nitrogen content were picked to define the various types of sediments, since the sediment system is actually continuous and gradational. Gyttja was mapped where the sediment contained less than 40% calcium carbonate or more than 3% total nitrogen. The "transitional sediments" were those having from 40% to 80% $CaCO_3$ or between 3% and 1% total nitrogen. Sediments with greater than 80% $CaCO_3$ were mapped as marl. The marginal, highly organic sediments were mapped on the basis of C/N values exceeding 9.

Origin of the sediments.--It is clear from the descriptions already given that there are four main types of sediment presently being deposited in Glovers Pond. These deposits indicate that markedly different environments of deposition exist within the basin. A discussion of sediment origins is thus important for complete understanding of the present environment and is a necessity before interpretation of the paleo-environment can be made.

Gyttja is now being deposited in the area of deepest water. This organic matter originates as phytoplankton and zooplankton, primary producers, living in the warm waters of the trophogenic zone, often in its uppermost region. These microscopic organisms

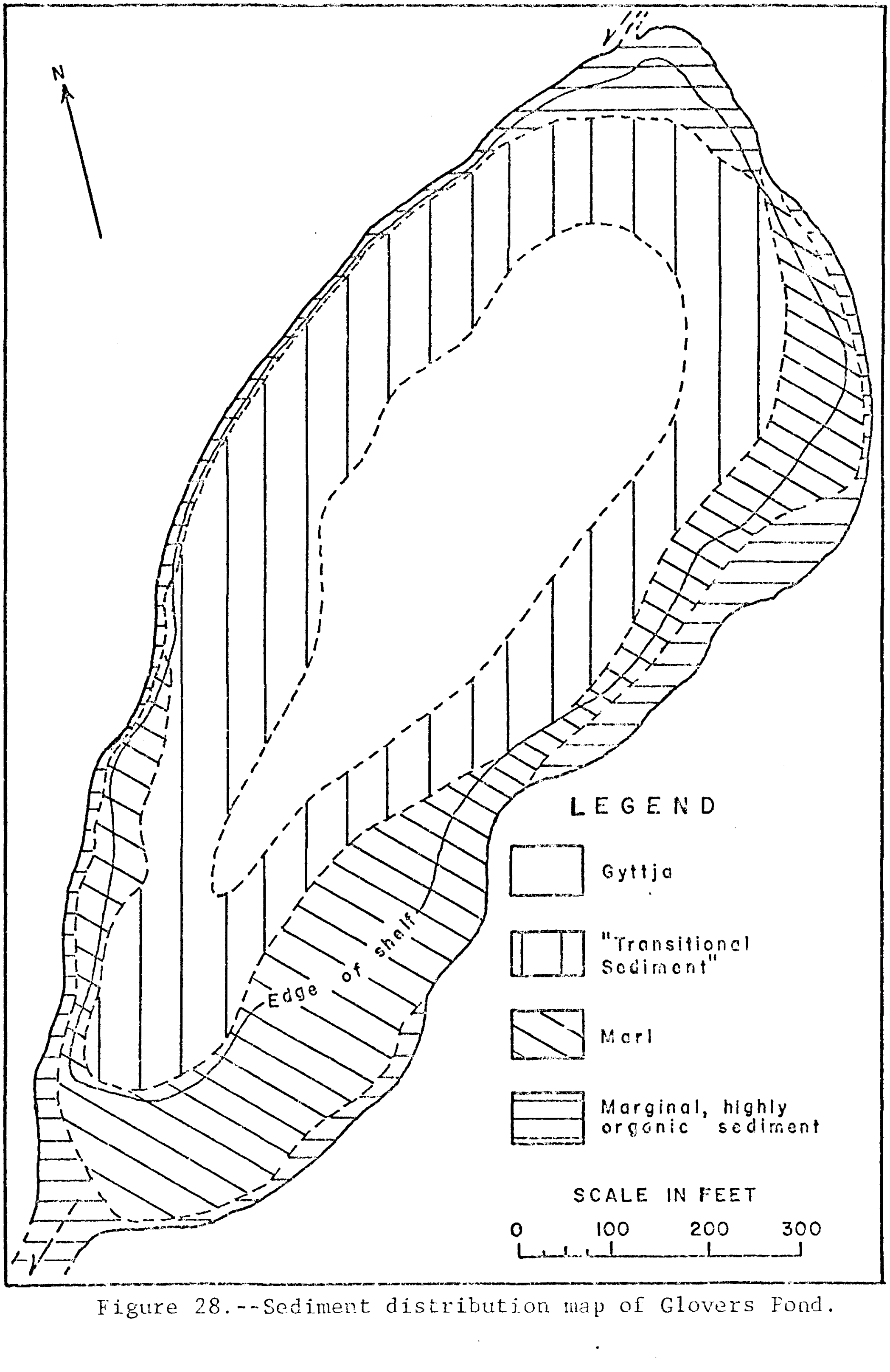


Figure 28.--Sediment distribution map of Glovers Pond.

grow in vast quantities during optimum "bloom" conditions, but quickly use up nutrients necessary to sustain such teeming life in the uncirculating epilimnion. When they exceed this limit they die and settle slowly through the thermocline to the bottom to form organic ooze.

At the same time, the plankton bloom causes shifts in the carbonate equilibria of the trophogenic zone by using all the free CO_2. This causes stress in the system as previously described and $CaCO_3$ is precipitated. This too settles toward the bottom. When it passes into the hypolimnion, however, much of it is again dissolved by the colder, less saturated water of this layer. Only in the shallower portions of the profundal zone can calcium carbonate settle without being greatly affected. Clearly the gradual shallowing of the basin, coupled with depth-controlled organic and carbonate deposition, causes a complete gradation between true gyttja and true marl.

Little terrestrially derived material reaches the deepest portion of the basin. Wind-blown silts and clays might be transported from the shore, but they lack a source and are not found in the gyttja. Snail shells which would have to be transported from the littoral or sublittoral zones are nearly non-existent in the gyttja, indicating that there is little transport of marginal sediment to the center of the lake. It is apparent, then, that the gyttja is a product of, and therefore reflects, physical and chemical conditions in the profundal region of the lake.

At the other extreme is deposition of marl on the shelf. The marl has three components, all of which contribute calcium carbonate.

These are: 1) primary $CaCO_3$ deposited by direct precipitation from the water; 2) mollusk shells which are extremely numerous on the shelf; 3) biochemically derived $CaCO_3$ which covers the stems of Chara growing on the shelf. Of these the Chara is the most important and is the reason for the existence of the shelf at present.

As mentioned, Chara borders the entire shelf and blankets the slope to the maximum depth of photic penetration. An example of this growth may be seen in Figure 29. These plants annually grow and die back according to the season. When Chara dies, plant remains fall to the bottom and decay leaving their tubular carbonate crusts as part of the sediment.

Chemical analysis of living Chara taken from the shelf and allowed to decay showed that the remains contain an average of 87.9% $CaCO_3$. These remains have an elongate shape and a striated appearance under magnification. They are often preserved and are found to be numerous in samples of both surface and subsurface marl.

The Chara not only serves to deposit marl on the shelf, but it also stabilizes the shelf and maintains the steep slope which is stabilized because Chara is rooted, though loosely, in the sediment. The thick growth thus acts, just as terrestrial vegetation covering a slope, to hold the sediment in place and minimize movement of large quantities by wave action or sub-lacustrine slumping. At the same time it is an aid in the lakeward migration of the shelf.

This migration occurs slowly. Though the Chara is stable, some storms or high winds do manage to transport sediment to the shelf edge and beyond. This material rapidly settles and is trapped in the thick Chara bed on the slope. This sediment, plus that derived

Figure 29.--Foreground shows a thick growth of Chara blanketing the shelf at the northeast end of Glovers Pond.

from *Chara* decaying *in situ*, forms a new layer always parallel to the shelf profile, yet advancing ever farther into the lake. This is not to imply that sediments would not advance into the lake if this plant were absent. They would, and perhaps more rapidly, but they probably would not maintain the steep slope and shelf which are so characteristic of present conditions.

In this sense the *Chara* is analogous to coral in a marine reef. If the stems of *Chara* were more durable, it is probable that analogous back reef carbonate, reef core, and fore reef talus sediments would be present.

The "transitional sediments" originate where overlapping of the profundal and littoral environments occurs beginning at the maximum depth of *Chara* growth. Here planktonic, organic sediments and calcium carbonate precipitated from the epilmnion mix with dying *Chara* at the base of the slope. The water in this zone is usually incorporated into the thermocline during the summer months. As discussed, it is supersaturated with $CaCO_3$, thus making primary deposition of this mineral possible. These sediments are, therefore, of several different origins and their deposits precede the advancing shelf. They may be found presently in 4 to 7½ meters of water in Glovers Pond.

Marginal, highly organic sediments owe their origin to lakeward migrating zones of shore vegetation, first in the form of *Potamogeton*, *Nymphaea*, *Sagittaria*, *Typha*, and *Scirpus*, and later as *Carex*, grasses, alder, swamp maple, sumac, and other sedges and shrubs which prefer soil of high moisture content. The lake shore has several typical vegetational zones, as would be expected, which are a source of the organic rich sediments with high C/N values.

When the lake level is lowered, these deposits thicken and migrate lakeward according to the process described earlier. As much as one meter of the littoral zone was covered in this manner during the mid 1960's due to the drought. Peat deposition, begun by this means, is currently in progress in bogs at the north, northeast, and southwest corners of the lake in areas previously occupied by open water.

As has been shown, each sediment type owes its origin to a restricted environment within the lake. By understanding this pattern of deposition and how it changes, interpretations regarding past depositional environments may be made more accurately.

Present Molluscan Fauna

During the course of sediment sampling and collecting of water samples, note was made of the occurrence of aquatic mollusks in Glovers Pond. Terrestrial gastropods were also collected from the surrounding woodlands. These notes show that at least nine species of aquatic gastropods, nine species of terrestrial gastropods, and three species of bivalves inhabit the lake and surrounding land at present. The following is a list of the species as tentatively identified:

Aquatic gastropods

- Helisoma companulatum (Say)
- Helisoma anceps (Menke)
- Gyraulus parvus (Say)
- Fossaria obrussa (Say)
- Physa sp.
- Lymnea sp.
- Stagnicola sp.
- Amnicola limosa Say
- Valvata tricarinata (Say) (acarinate form)

Terrestrial gastropods

Triodopsis albolabris (Say)
Triodopsis tridentata (Say)
Stenotrema hirsutum (Say)
Stenotrema fraternum (Say)
Anguispira alternata Say
Succinea? sp.
Cionella lubrica Muller
Discus cronkhitei catskillensis (Pilsbry)
Retinella electrina (Gould)

Bivalves

Anodonta cataracta Say
Sphaerium rhomboideum? (Say)
Pisidium ferrugineum? Prime

Distribution of the aquatic species definitely reflects certain ecologic factors prevailing in the lake. Amnicola limosa and Valvata tricarinata (acarinate form) were taken exclusively among clumps of living Chara growing on the edge of the shelf. Physa, Helisoma companulatum, Helisoma anceps, and Gyraulus parvus were taken both among the Chara and in shallower water from filamentous algae and from the underside of waterlily pads. Fossaria obrussa and Lymnea were taken only from the bottom of the waterlily leaves. Stagnicola was found only in the colder water flowing in the spring box in the northeast bog. It was accompanied by large specimens of Physa.

The specimens of Amnicola, Helisoma, and Valvata found in the Chara beds were always pale, nearly white, and appeared to be almost clear when wet. None of these was ever seen on the marl itself.

The freshwater mussel Anodonta cataracta was collected alive on only two occasions although numerous empty shells on the shelf bottom suggested that it is fairly common in the lake. Originally this was thought not to be the case. Daily searches were made for mussels during early June, July and early August with no success. Frequently a canvas raft which could float in only a few inches of water was used with a diving mask to allow close inspection of the bottom and still none was seen.

On August 16 a heavy rainstorm (1.7 inches of precipitation) raised the lake level appreciably. Up to that time much of the shelf had been exposed due to the drought. The sediment below water level contained a high amount of hydrogen sulfide as evidenced by the strong smell and by the fact that a silver ring on the writer's hand was rapidly blackened by a coating of silver sulfide while being run through the sediment in search of the mussels. This deleterious condition could not have been easily tolerated by mollusks.

Following the rain, many trails were noted and a mussel was taken on August 17, presumably indicating migration of the mussels toward shallower water. On August 18 four mussels were taken within a radius of ten feet, and many trails were noted; most trails were more than twenty feet long, indicating that a great deal of movement was taking place.

Because of the fluid nature of the marl it is impossible for the mussels to dwell at, or even near, the surface as most would do in more compact sediment. They apparently live well below the sediment surface where the substrate is more firm. When the lake level recedes, they migrate toward the edge of the shelf under the Chara mat where they lie until the heavy rain raises and freshens the water. At this time they migrate rather rapidly back to the shallower water. Perhaps in this way, they avoid the high H_2S content of the stagnating shallows.

These mussels have been identified as Anodonta cataracta Say by comparison of width/height and height/length ratios of living and dead specimens with those given by Clarke and Berg (1959, p. 39) for several species of Anodonta inhabiting the Atlantic drainages. These data are compared in Tables 7 and 8. Although the specimens have a H/L ratio similar to that of A. imbecilis the overall fit of both ratios was deemed closer to that of A. cataracta.

Sphaerium rhomboideum? and Pisidium ferrugineum? have been tentatively identified. Both of these species were collected only suspended within masses of intertwined living Chara in association with Amnicola and Valvata. They appeared pale as were gastropods. This method of growth in, or on, algal masses was mentioned by Herrington (1962, p. 25) as common for Sphaerium rhomboideum. Pisidium ferrugineum was mentioned (p. 40) as occurring in marl lakes.

Samples of marl contained hundreds of dead shells of all of these Chara-associated mollusks, but no living specimens were ever included in such samples. The very fluid marl substrate makes it impossible for any of these smaller mollusks to survive on the open bottom. Without support above the marl ooze by beds of Chara, they could not live on the shelf. The importance of Chara as a substrate on which mollusks can live is a prime ecologic conclusion to be drawn from the conditions on the shelf of Glovers Pond.

TABLE 7

SHELL SIZES (IN MM) AND RATIOS FOR SPECIMENS OF *ANODONTA CATARACTA* TAKEN FROM GLOVERS POND, NEW JERSEY

Length	Height	Width	H/L	W/H
Living Specimens				
97.0	48.0	36.5	.495	.760
91.0	44.0	34.5	.483	.784
98.0	49.5	39.0	.505	.787
86.0	45.0	33.0	.523	.733
98.0	49.0	39.0	.500	.796
Dead Shells				
104.0	53.0	41.0	.509	.773
102.0	55.0	40.5	.539	.736
102.0	49.0	38.0	.480	.775
Range of shell ratios			(.48-.54)	(.73-.79)

TABLE 8

COMPARISON OF ATLANTIC DRAINAGE SPECIES LISTED BY CLARKE AND BERG (1959) WITH RATIOS OF *ANODONTA CATARACTA* FROM GLOVERS POND

Species	H/L	W/H
Anodonta grandis	.45-.55	.68-.88
Anodonta implicata	.46-.58	.78-.88
Anodonta imbecilis	.48-.55	.62-.72
Anodonta cataracta	.45-.56	.62-.76
Glovers Pond species	.48-.54	.73-.79

PAST ENVIRONMENTS OF GLOVERS POND

Glacial and Post-glacial Sediments

Five cores, three from bogs and two from the open lake, were taken during the summer of 1966 at Glovers Pond, New Jersey. These were augmented by about two dozen posthole auger samples from areas around the periphery of the lake basin. The locations of core and important auger sampling stations are shown on Figure 31. Cores were located so as to provide a reliable cross-section of sediments along the long axis of the lake basin. Those from the open lake were taken from a floating coring platform (Figure 30).

The only problem in coring was the foreshortening of the cores due to sediment compaction when the core barrel was pushed into the strata. This problem is frequently encountered in coring (Piggot, 1941; Emery and Deitz, 1941), particularly where poorly compacted sediments with high water content are involved. Peat, and gyttja units were most susceptible to this distortion whereas deeper silts were not distorted appreciably. An adjustment of 0.2 meter per meter cored was made for compaction. This is a conservative estimation of the amount of compaction and a larger correction would not be out of order in some cases.

Stratigraphy of the lake deposits.--Due to differences in the types of sediments, the cores have been divided into two groups for stratigraphic description. First the bog stratigraphy will be discussed, followed by stratigraphy indicated by cores taken from

Figure 30.--Coring at station C-Lk-1 (8.5 meters deep) using the floating core platform. Location of this station is given on Figure 31.

the open lake. Detailed physical descriptions of the units are given in Appendix B. Strata are correlated in Figure 31.

Six major stratigraphic units, designated units A through F, can be recognized in the bogs on the basis of similar lithology, texture, color, and chemical composition. Four of these units have depositional counterparts in the present sedimentary environment of the lake.

The basal unit, unit A, is, in all cases, gray clayey silt containing pebbles and cobbles of varying lithologies. One such small cobble, about three inches in diameter, was recovered jammed in the cutting head of the corer. Coring was halted when cobbles or boulders large enough to stop penetration were encountered. This sediment is interpreted to be till.

Above this, in the southwestern bog, is a uniform gray or dark gray layer of slightly calcareous silt, although in the northern bog the till is overlain by sand which grades upward from coarse to very fine sand within about two meters. This sand represents an areally restricted facies of deposition and is, in turn, overlain by silt. This silt and sand, collectively designated unit B, is of glacial and peri-glacial origin.

Over the silt in both bogs is unit C, a very dark gray to dark olive gray, organic-rich silt. This sediment is believed to mark the beginning of true post-glacial sedimentation. No material was being actively contributed by glacial or peri-glacial mechanisms, although erosion of surrounding glacial sediments was a factor contributing to this deposition.

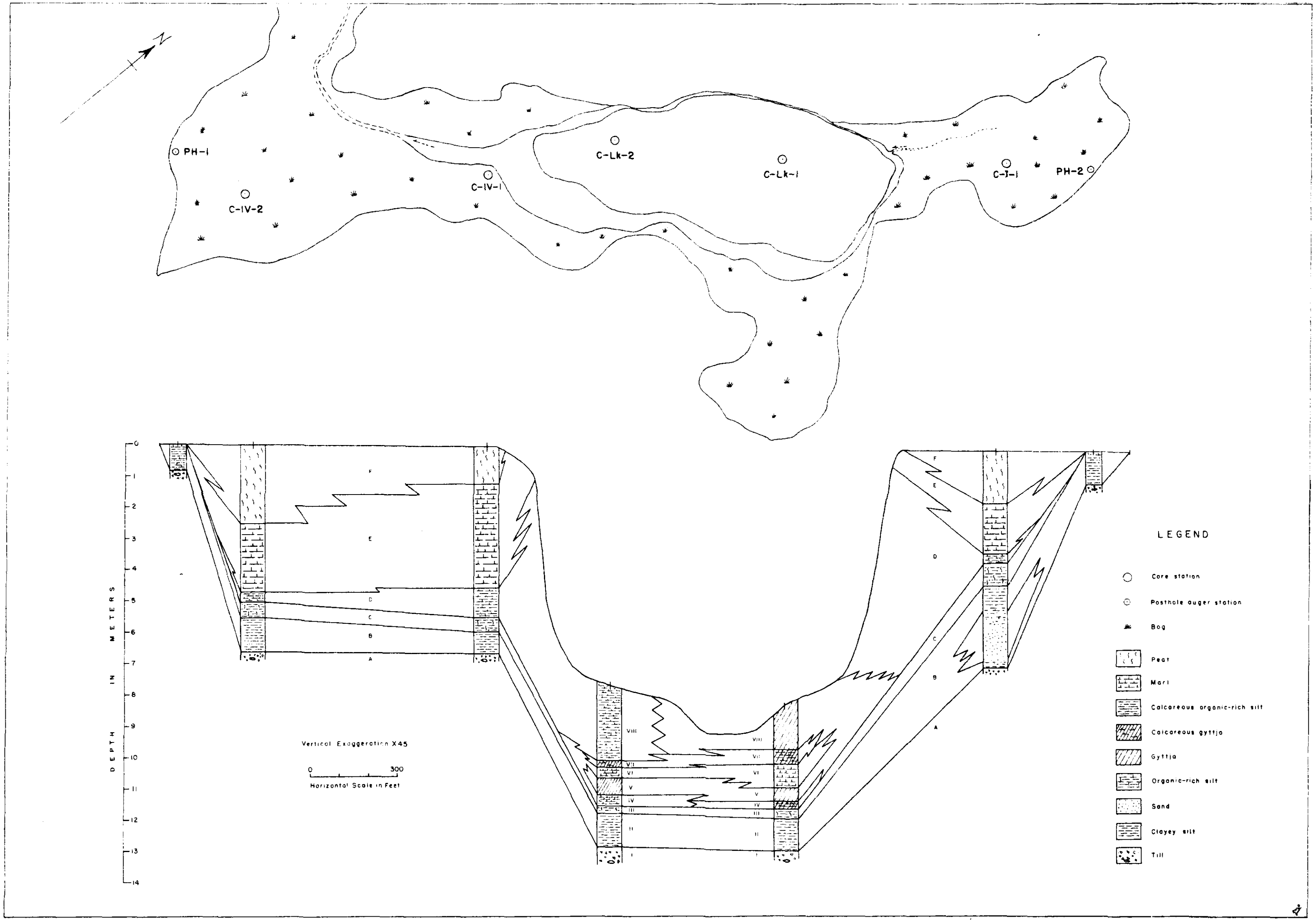


Figure 31.--Lithofacies relationships of Glovers Pond sediments.

A layer of calcareous, organic-rich silt (unit D) overlies unit C. This bed contains many shell fragments, plant stems, and Chara oögonia and is distinctly laminated due to accumulations of this material on bedding planes. Sediments of this type are analogous to those presently being deposited in the transitional zone at the base of the shelf in Glovers Pond.

Light gray marl of unit E overlies the "transitional sediments". Occasional layers of Chara stems and numerous mollusk shells mark bedding planes within the marl. This unit becomes increasingly more water saturated and more poorly compacted toward the top.

Unit F consists of dark brown sedge and reed peat above the marl. In some instances the peat becomes woody, but sedge peat is the more common form of bog deposit.

At least eight units are discernable in the two cores (C-Lk-1 and C-Lk-2; Figure 31) from the open lake. Sediments in these cores represent continual deposition in the lake basin from the time of its origin to the present. Because this deposition took place in the central part of the basin, these sediments are markedly different from those of the bogs. Lake core units have been designated as units I through VIII.

Both lake cores terminated in till. Designated unit I, this till is correlated with till in the bog cores described previously as unit A. Silt and clayey silt, designated as unit II, overlie the till and are correlated with unit B in the bogs.

This non-organic silt is overlain by dark gray to dark olive gray silt containing organic material. Termed unit III, this organic-rich silt is, seemingly, the lithologic and chronologic equivalent of unit

C in the bog sequence. It represents the beginning of post-glacial deposition in the basin.

Overlying this is a more complex sequence of calcareous and non-calcareous gyttja. In core C-Lk-2, this reaches the composition of marl in the upper portion (unit VIII). Units IV, V, VI, and VII are differentiated on the basis of calcium carbonate content. They represent related forms of deposition with slight environmental variations.

Conditions differ slightly in core C-Lk-1 where slightly calcareous gyttja (unit IV) and non-calcareous gyttja (unit V) are overlain by a rather thick (1.2 m) unit of very calcareous (almost marl) gyttja. This has been designated as unit VI and marks a major environmental change which is masked to some extent in core C-Lk-2; that core was taken closer to the shore and was thus influenced more by littoral shelf-slope forms of sedimentation. Unit VII encompasses a gradational change upward from highly calcareous sediment toward the nearly non-calcareous gyttja of unit VIII, which is essentially the same as sediment now being deposited at the site.

Facies Relationships at Glovers Pond.--It is apparent that correlation of stratigraphic units at Glovers Pond is complicated by the existence of several environments of deposition within the lake basin. Units deposited after unit C (= III) have a typical facies relationship with each other as indicated on Figures 31 and 32.

The three lowest units of all cores conform to the shape of the lake basin and deposition of similar sediments under similar environmental conditions at essentially synchronous intervals of time. They may be equated lithologically and time-stratigraphically.

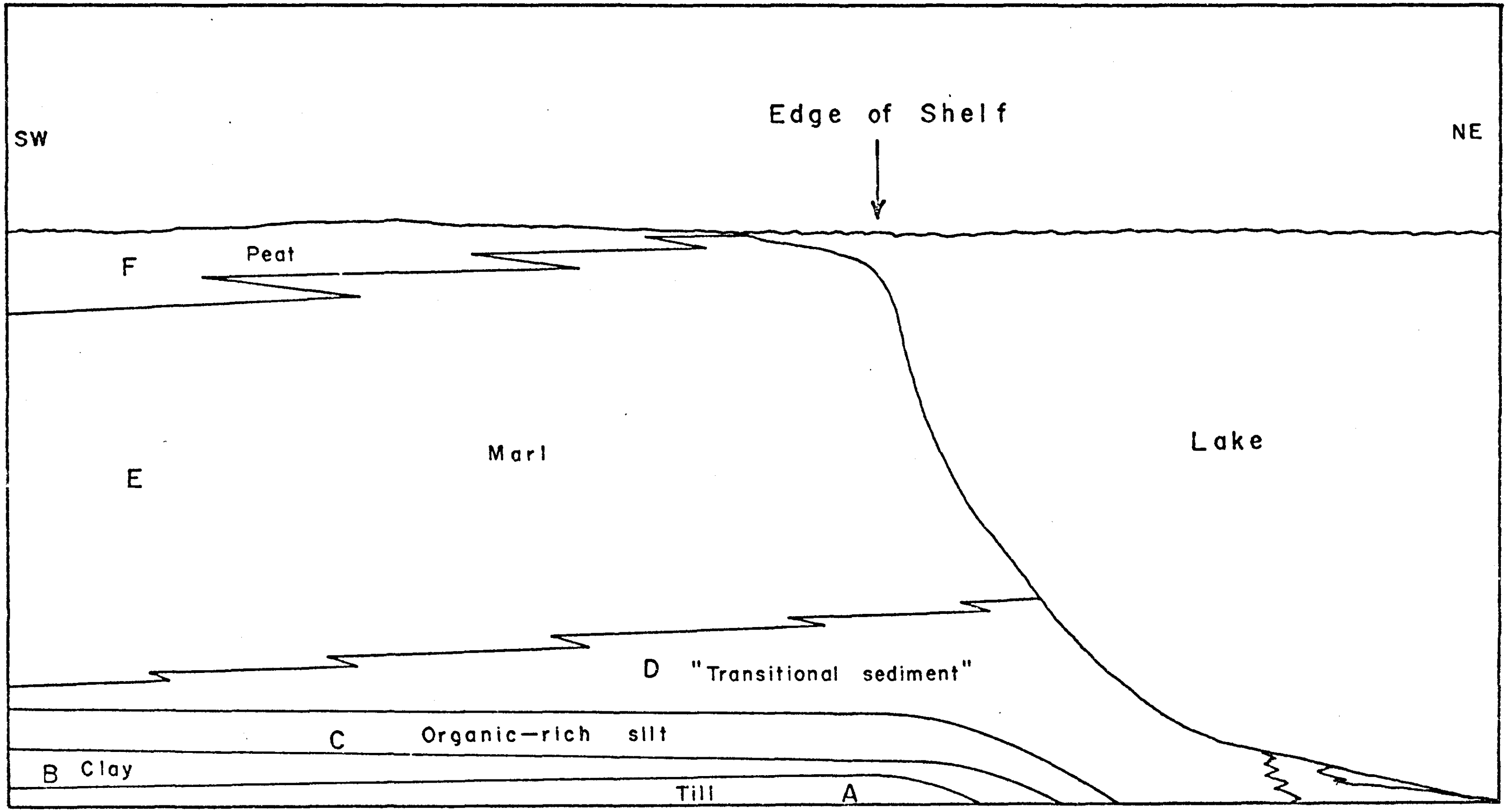


Figure 32.--Diagramatic facies relationships of the southeast bog of Glovers Pond.

Generally, they do not have interfingering relationships (excepting the sand zone in unit B) and their contacts may be assumed to be time planes.

No certain correlation can be made above unit C (= III) without accessory fossil evidence or absolute dating. This is due to the migratory movement of the shelf as shown schematically in Figure 33 for relationships in the southeast bog. Marl deposited at the base of core C-IV-2 has no marl time equivalent in core C-IV-1, although a zone of wood fragments indicates that it is time equivalent to the marl in the base of unit E in core C-I-1. Rather, when marl deposition began at station C-IV-2, transitional sediments may have been deposited at station C-IV-1 and gyttja was deing deposited in the open lake. When peat was first deposited at station C-IV-2, marl was being deposited at station C-IV-1 and gyttja was forming in the profundal zone of the lake.

This shelf, shelf-slope, and profundal sequence of sedimentary environments is strikingly similar to the Unda, Clino, and Fundo classification of sedimentary environments proposed by Rich (1951). His lithologic terms undathem, clinothem, and fundathem could easily be applied to the marl, "transitional sediments" of the shelf slope, and the profundal gyttja that I have described.

It may be seen that the plane of synchronous deposition is curved and has essentially the same shape as the present surface of deposition. In Figure 33 these planes of contemporaneity are shown schematically by the curved lines which represent various positions of the migrating shelf slope. The relations of the facies are, on a very small scale, the same as magnafacies and parvafacies (Caster,

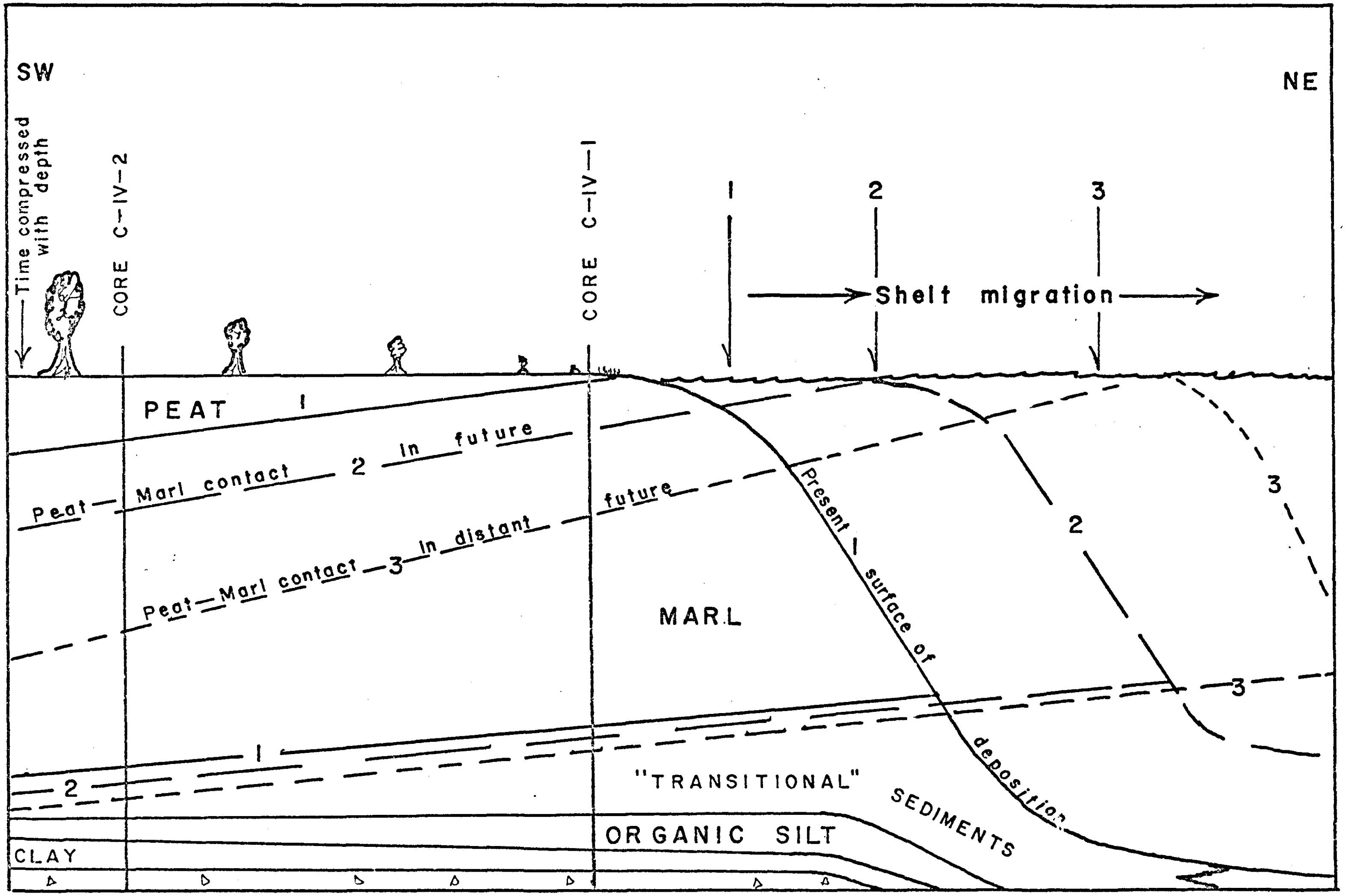


Figure 33.--Schematic diagram of time and time-stratigraphic relationships in the southeast bog of Glovers Pond. Surfaces of deposition, lithologic contacts, and relative shelf positions are indicated for the present (1), future (2), and distant future (3).

1934, p. 19). Each of the major lithologic units (D, E, and F) of the bog sequence transgresses time and represents a magnafacies, whereas the bodies of sediment within each major lithologic unit deposited between the various surfaces of deposition (lines 1, 2, and 3 on Figure 33), the "planes of contemporaneity" of Caster, are parvafacies.

Complicating this is the factor of compaction, which may be causing warping (compression) of stratigraphic as well as time surfaces in the older sediments. Furthermore, there are positions in the bog or on the shelf at which continuously deposited sediments do not reflect varying environmental episodes. This is true because not all deposits, or depositional environments, are equally sensitive to environmental changes of the same magnitude. Thus, lithologic changes (indicating environmental episodes) detected only in deep lake sediments are not reflected as changes of lithology within the continuously deposited marl or peat sequence. Therefore, interpretation of a single core taken in the present bog might well preclude recognition of such an environmental episode. Also, this evidence of an environmental episode is impossible to interpret from physical data alone. Eventually, radiometric dating methods must be used to establish proper time-stratigraphic relationships between the units. The import of the facies effects and the environmental episodes here discussed will become clear during discussion of the sedimentary history of the lake.

Description of the Cores

Cores from Glovers Pond have been described using physical, chemical, and paleontological characteristics. In most cases chemical analysis seemed more significant than particle size or paleontological analysis. A combination of these parameters was used to make the final correlations shown on Figure 31.

Physical Description of Cores.--Analysis of various physical characteristics of the sediments such as color, texture, and particle size were attempted for each unit of the cores. It soon became evident that, because of the high organic content of the gyttja, particle size analysis would not be practical for sediments from the open lake cores. The gelatinous ooze continually clogged sieves and flocculated in the settling columns. In this case, color and texture alone were described.

Size analysis of glacial, and peri-glacial sediments, and marl was not difficult. These were wet sieved into settling tubes and sampled according to a schedule of prearranged settling times. Results are presented in Figure 34. According to the classification here utilized (Shepard, 1954) most of the sediment, (including the marl units), is silt or clayey silt. The only variations from this are the two samples taken from the sandy zone of unit B in core C-I-1. These show the gradational trend from sand in the lowest part, to sandy silt in the middle, and finally the upper part becomes pure silt and is indistinguishable from silt units in the other cores.

Color and composition of coarse fractions proved to be useful physical factors for describing the sediments. Color of both wet and dry samples was described and appears in the descriptions in Appendix B. Much of the coarse fraction of the upper units consisted of plant fragments and mollusk shells.

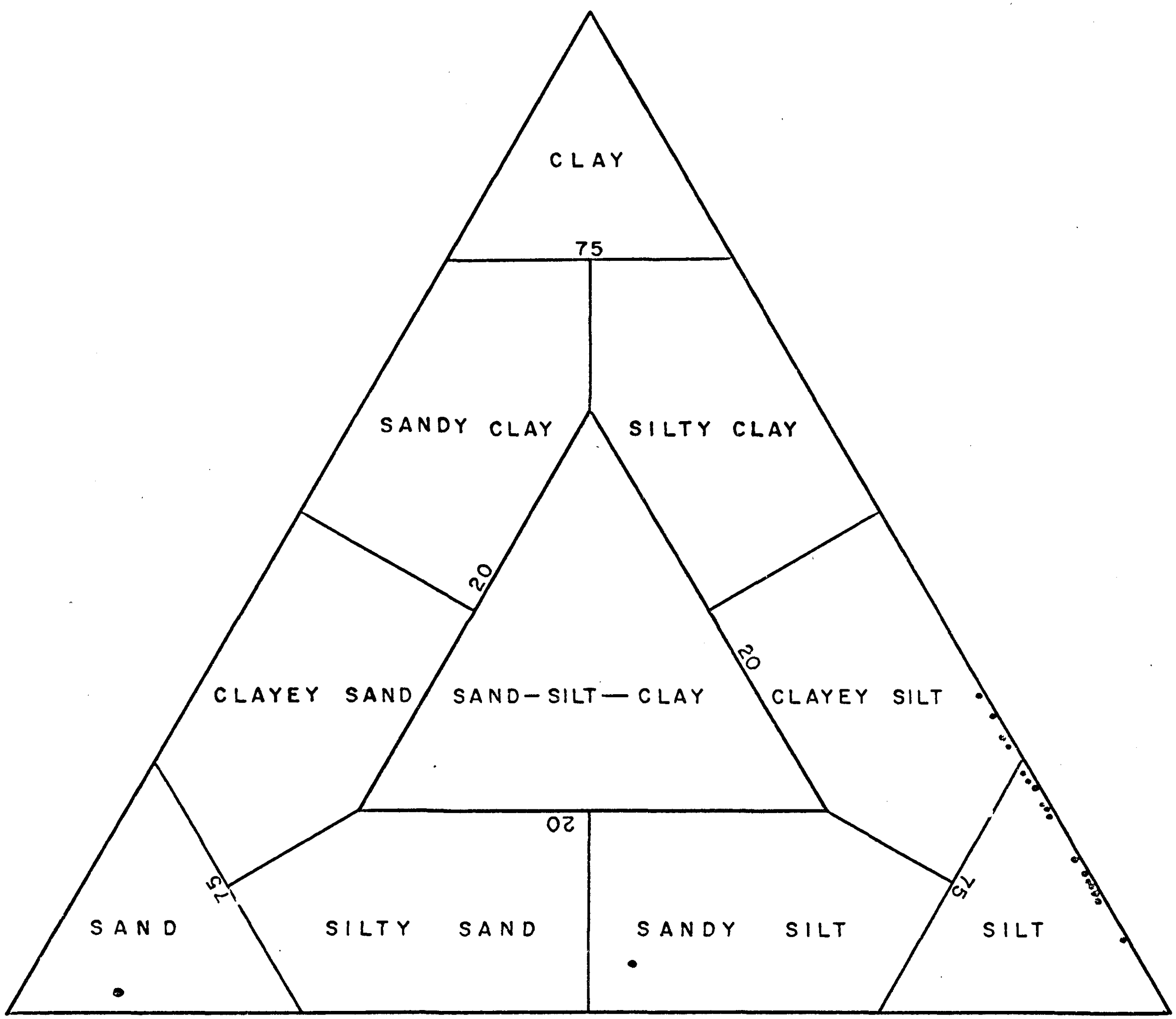


Figure 34.--Classification of Glovers Pond core sediments by size distribution (Shepard, 1954).

Some characteristic features were also useful in correlation of units. Lower portions of gyttja in the open lake cores have been so compacted that the sediment has a very low moisture content and has developed a "rubbery" quality which is more apparent in the slightly calcareous gyttja than in the non-calcareous gyttja. It is a gradational feature decreasing toward the surface.

A second characteristic feature occurs on the bedding planes in unit D, and unit VI of core C-Lk-2. This is a crisscross pattern of compressed calcareous tubes, impressions of these tubes, and some associated plant fibers. These are the remains of calcareous coverings of *Chara* stems lying on bedding planes. Frequently associated with this checkered pattern are *Chara* oogonia and sparse, fragmentary snail shells. These characters indicate deposition similar to that occurring at present in the transition zone of the shelf slope.

Finally, unit E in cores C-I-1 and C-IV-2 has a basal zone containing numerous wood fragments and probably logs. A large piece of wood was recovered from the core barrel in this zone provided sufficient material for a radiocarbon date. This zone is significant in that it provides a datum traceable, at least in part, in both bogs. It is essentially the only link between sedimentation in the northern and southeastern bogs. Hopefully, future work will link this zone with correlative sediments in the open lake cores.

Chemical description of cores.--Due to the varied character of Holocene sedimentation in Glovers Pond, it was found that some sedimentologic changes, not otherwise discernable, were clearly differentiated by chemical analysis. The same factors analyzed in present sediments were analyzed in the cores.

The littoral zone of Glovers Pond is sensitive to some conditions which do not affect the profundal zone during any one period of general environmental uniformity. On the other hand, the profundal sediments reflect some major environmental changes which are apparently not recorded by littoral or transitional sediments, although deposition in the littoral zone may be continuous. If only one core from the edge of a lake were used to describe the post-glacial environmental and sedimentological history of a lake, a major environmental change could easily be overlooked. A sequence of similar sediments representing a depositional continuum could contain a climatic change or environmental discrepancy of great pertinence to the geologic history of a region. An interpretation is here made that such a climatic change did occur during deposition of the bog sediments of Glovers Pond. It is recognized by comparison of chemical analyses of sediments from both bog and lake cores.

Figures 35, 36, 37, 38, and 39 show the chemistry of Glovers Pond cores. In Figures 35, 36, and 37 the general configuration of the curves indicate similar chemical changes in each of the three bog cores, although unit thickness may vary from one core to the other. These chemical similarities indicate that like units were deposited under like conditions but not at the same time.

In like manner similarities exist between cores C-Lk-1 and C-Lk-2, but they do not agree in their upper portions. This is

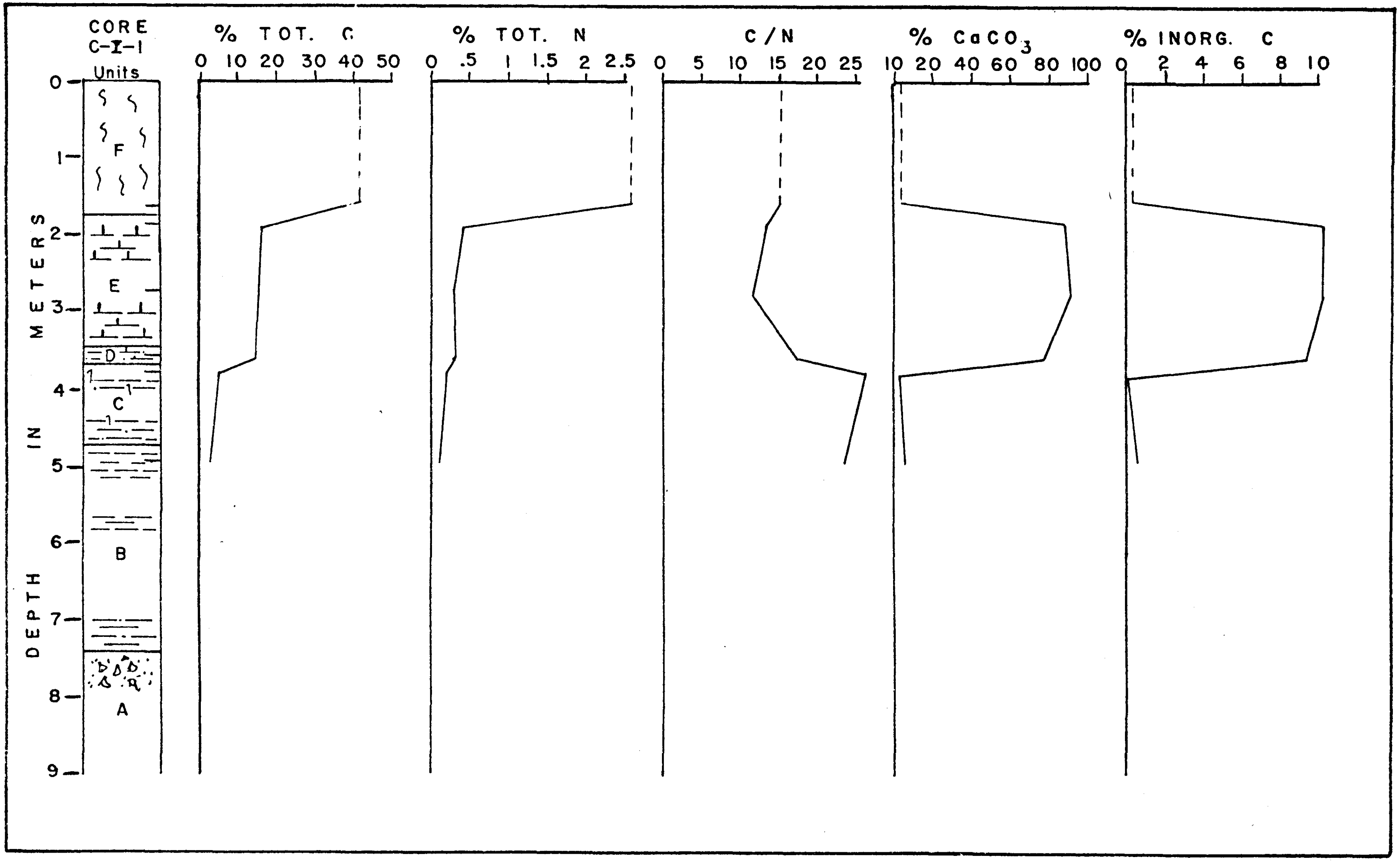


Figure 35.--Chemical analyses of core C-I-1.

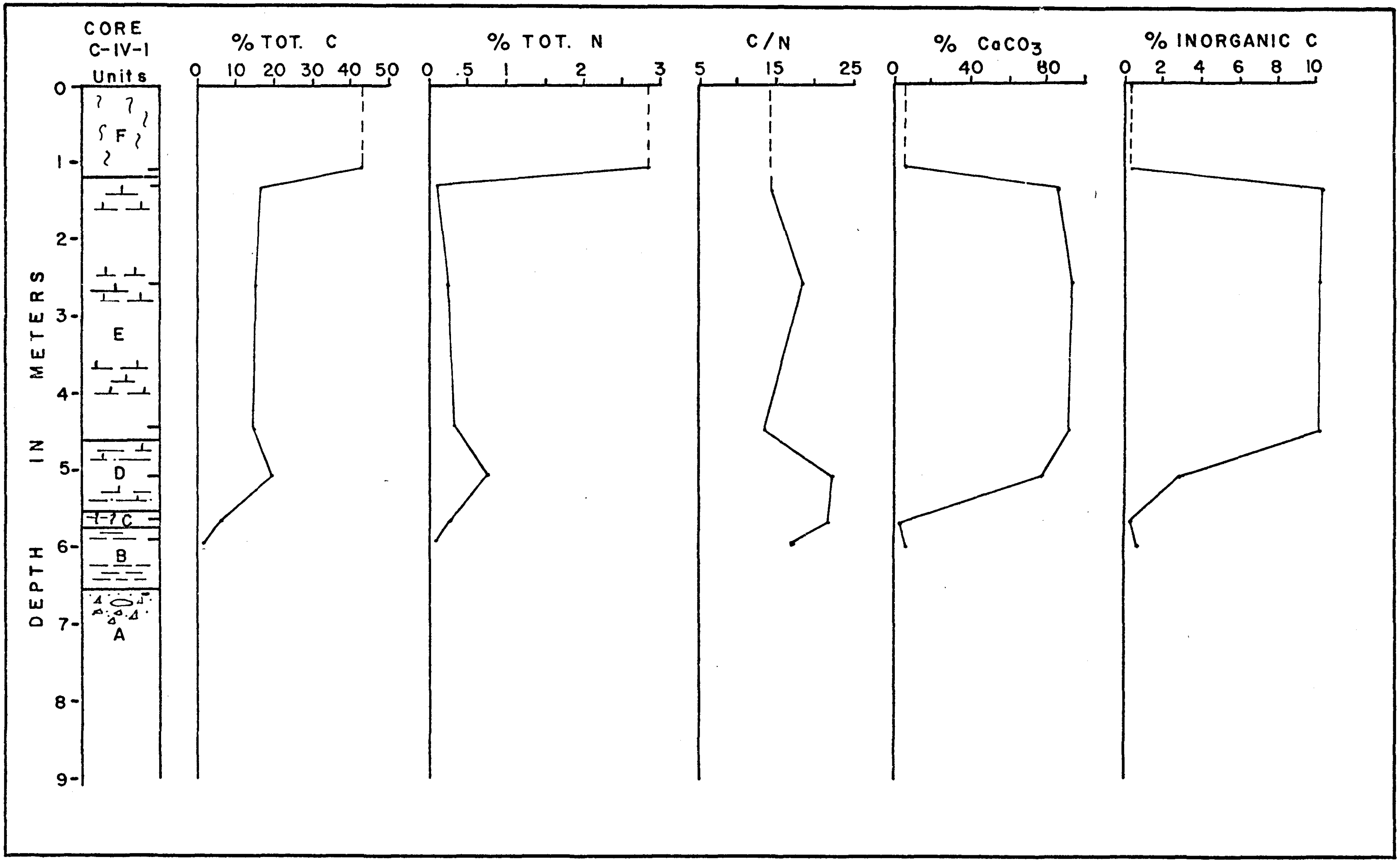


Figure 36.--Chemical analyses of core C-IV-1.

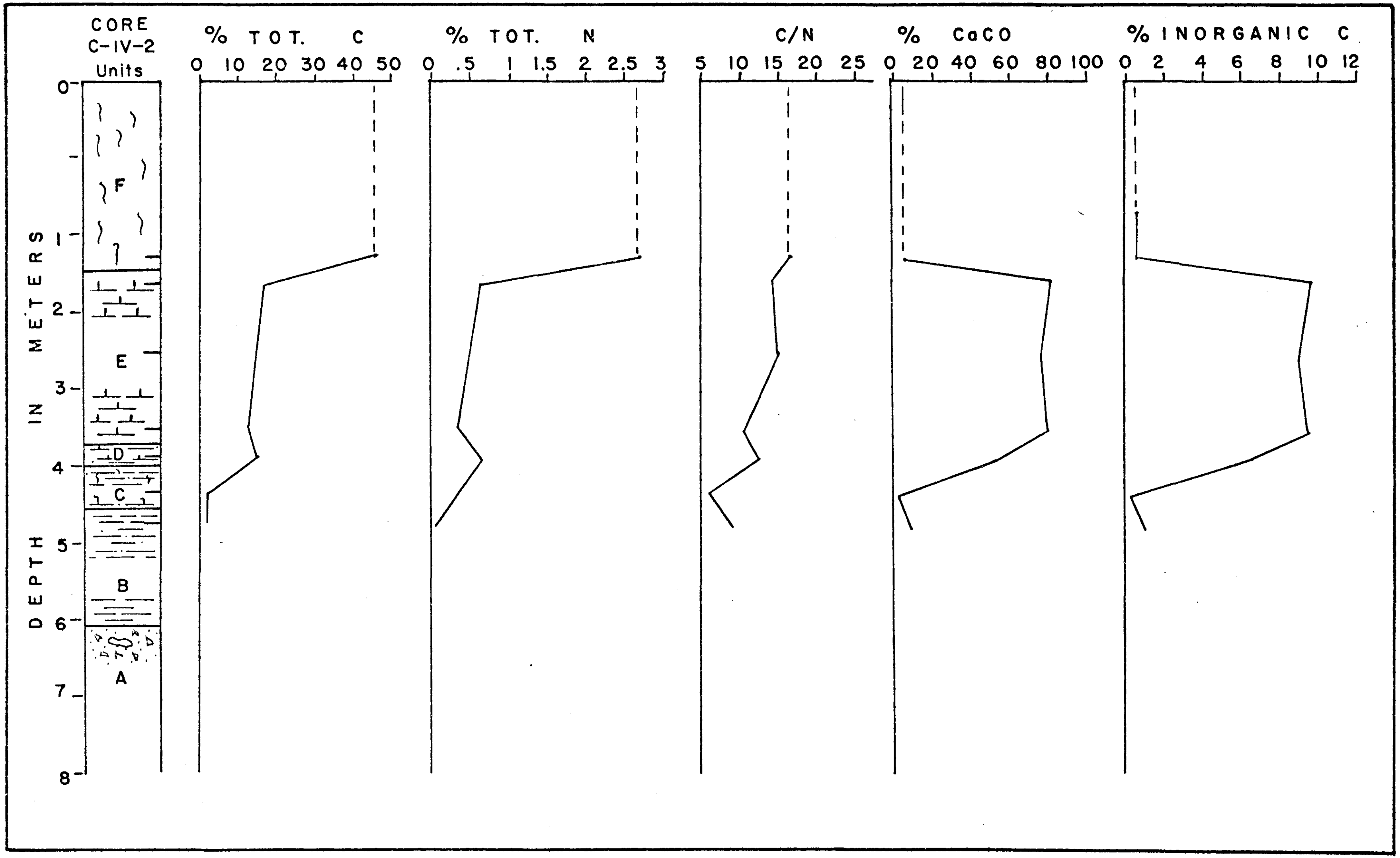


Figure 37.--Chemical analyses of core C-IV-2.

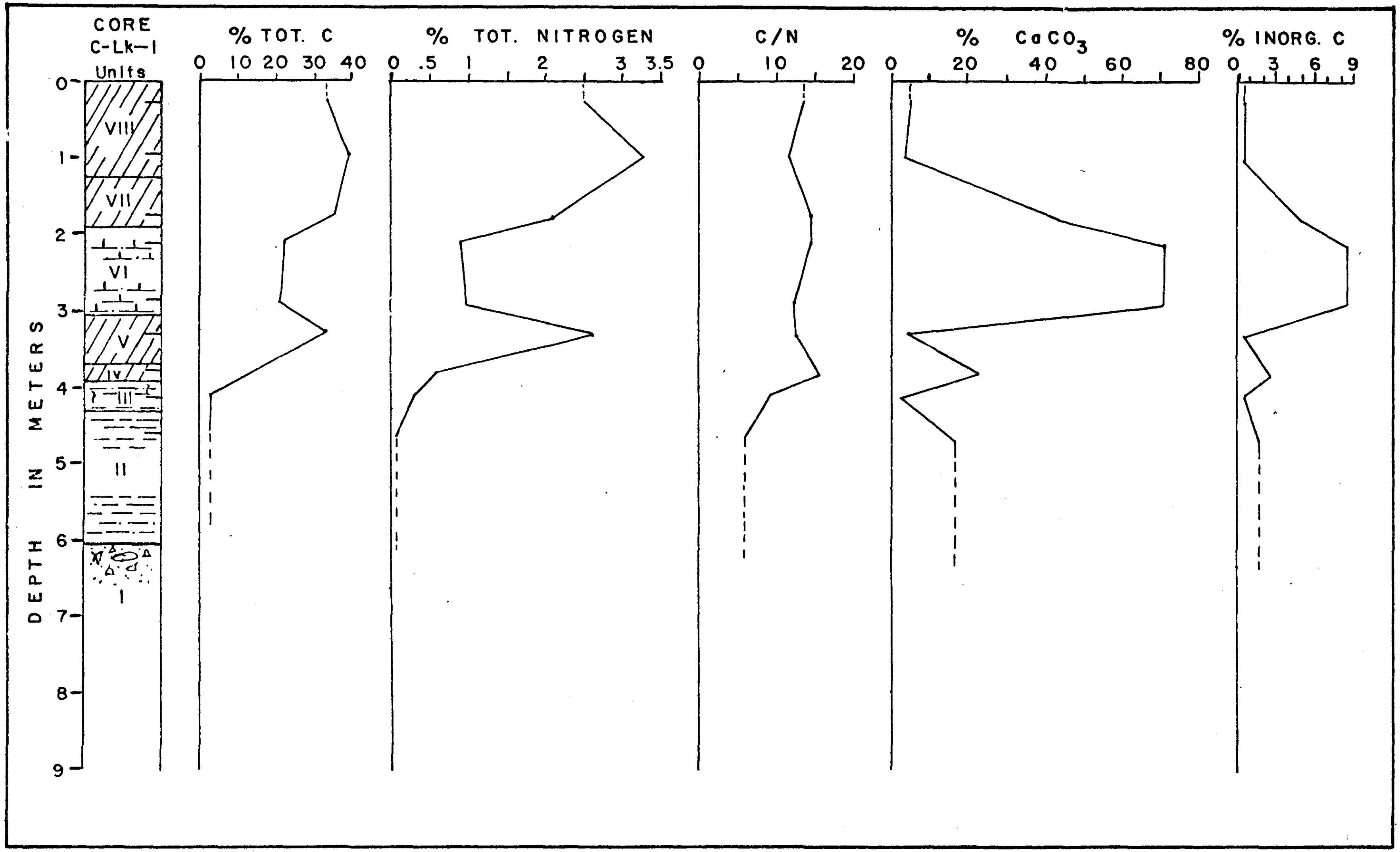


Figure 38.--Chemical analyses of core C-Lk-1.

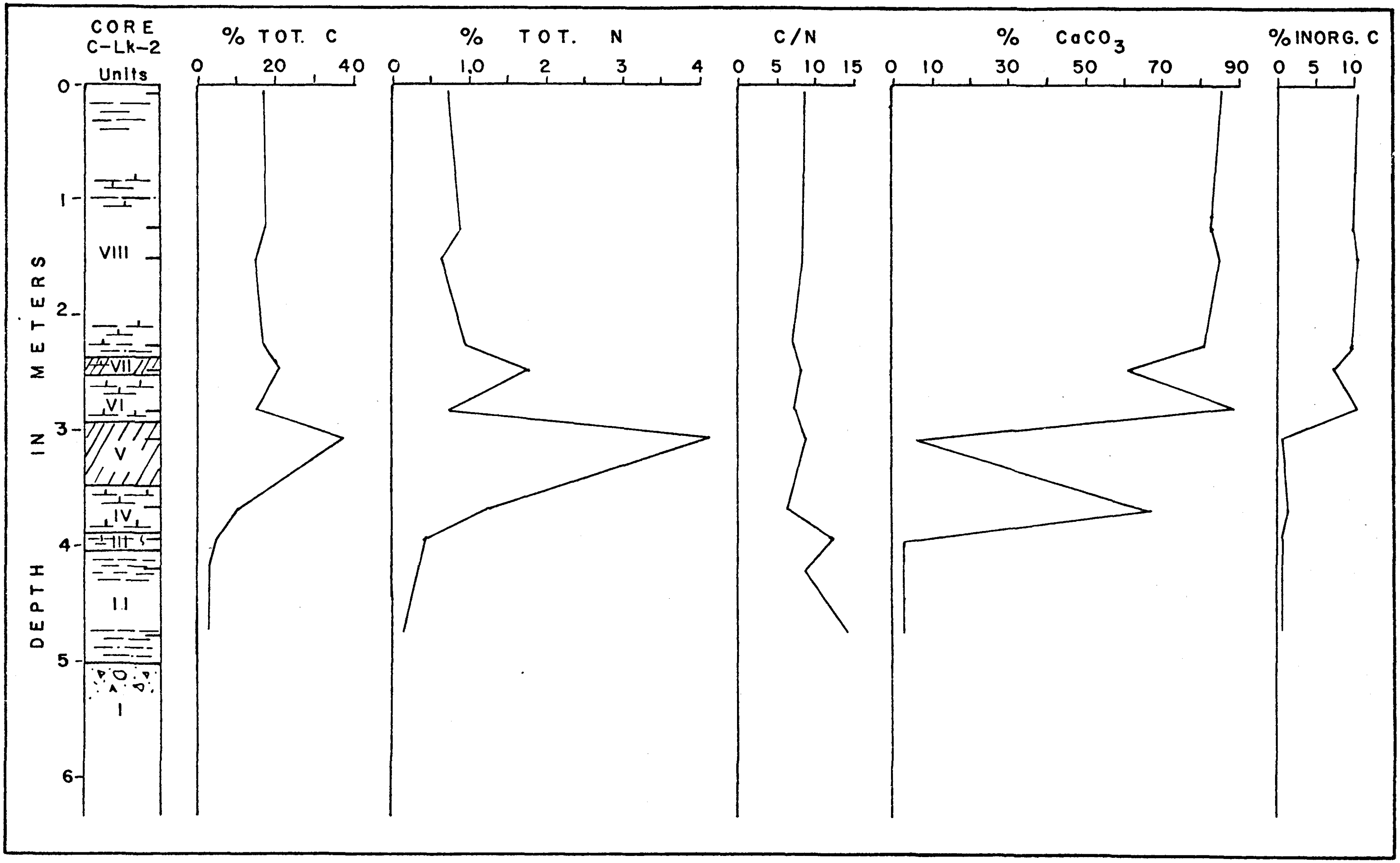


Figure 39.--Chemical analyses of core C-Lk-2.

because core C-Lk-1 was taken farther from shore than C-Lk-2 and was not influenced by the advance of the "transitional sediment" zone of higher carbonate.

The major environmental change is recorded in unit VI of core C-Lk-1 where high (greater than 70%) carbonate values are found at a station where present carbonate deposition totals but a few percent. It is thought that this change is caused by lowered water levels at some time during the history of the lake. It is marked in core C-Lk-2 by higher carbonates in unit VI. Figure 39 indicates that this condition is not prolonged upward in the core; instead, the carbonate values drop slightly and then increase toward a second maximum rather than continuing a gradual decrease in carbonate content as is the case in core C-Lk-1 (Figure 38). This decrease is masked by the advance of the base of the shelf slope into the area of core station C-Lk-2 shortly after the carbonate decrease began. The true picture of conditions is recorded only in core C-Lk-1 from the profundal zone.

At first, one would expect this lowered water level to appear as an influx of organic matter in the bog cores. It would be recorded by higher values of percent total nitrogen. This condition probably is present somewhere between stations C-IV-1 and C-IV-2, but neither of these stations showed such an influx, perhaps because peat deposition had already begun at the latter station while marl deposition had hardly begun at the former. The lowered lake level simply served to stimulate marl deposition in the area of station C-IV-1. Thus an environmental discrepancy was created in the bog sediment sequence. Without utilization of chemical analyses of sediments from both bog and lake cores this climatic change would not be so readily apparent.

Paleontology of the cores.--The post-glacial units, particularly the marl, in the bog cores contain numerous macro- and microfossils representing both plants and animals. Some of these are useful stratigraphic indices within the basin. *Chara* oögonia and *Fontinalis* can be used as indices of post- and pre-marl deposition. The primary macrofossils are mollusks found almost exclusively in the marl unit E.

A detailed study was made to determine whether the mollusks, particularly the gastropods, could be used to delineate periods of environmental change not recorded by sedimentary change in the area of marl deposition. It was hoped that some gastropods would be sensitive to such changes as higher water temperatures or increased alkalinity, and would thus indicate environmental discrepancies by variations in the numbers of each species with respect to the total number of individuals present. With this in mind the following fauna was identified from core samples:

Aquatic gastropods

- *Helisoma companulatum* (Say)
- *Helisoma anceps* (Menke)
- *Gyraulus parvus* (Say)
- *Fossaria obrussa* (Say)
- *Physa* sp.
- *Amnicola limosa* Say
- *Valvata tricarinata* (Say) (tricarinate, bicarinate, and unicarinate forms)
- *Valvata lewisi* Currier
- *Ferrissia* sp.

It will be noted that this fauna is similar in most respects to that given for the present lake. However, *Valvata tricarinata* and its bicarinate and unicarinate forms were not found alive at present.

Valvata lewisi was not recorded alive either, although the surface sediments contain many shells of this form, indicating that perhaps it was overlooked. Ferrissia was also not found in the lake presently and is represented in the core fauna by only one specimen.

In order to interpret fossil data in unit E, the marl was subdivided into 15 or 30 cm sections, all of 4.5 cm diameter, and the number of adult, or nearly adult, individuals of each species was counted in each section. Numbers of specimens of each species were tabulated as percent of the total number of individuals for each section. This process was carried out for transitional sediment units as well. In all, more than 2,872 individuals were examined from the three bog cores. Representatives of the fossil fauna are shown in Plate 1.

Data from these analyses are presented in Figures 40, 41, and 42. At present no correlations within the marl units have been made on the basis of these data. Of significance is the shell morphology of the Valvata complex. Changes seem to indicate that Valvata passes from a tricarinate to a bicarinate to a unicarinate and finally (if the present fauna is considered) to an acarinate form from the bottom to the top of unit B. As has been mentioned, the marl units represent a lithofacies and not a unit of contemporaneous deposition throughout; thus unit B in cores C-IV-2 and C-I-1 is older than in core C-IV-1 (as shown by absence of the wood layer in core C-IV-1). Consequently, the data in Figures 40, 41, and 42 must be combined vertically in order to present a complete sedimentary sequence. When examined in this manner the gradual decrease of the tricarinate form, and eventually of the bicarinate form, becomes apparent. These are

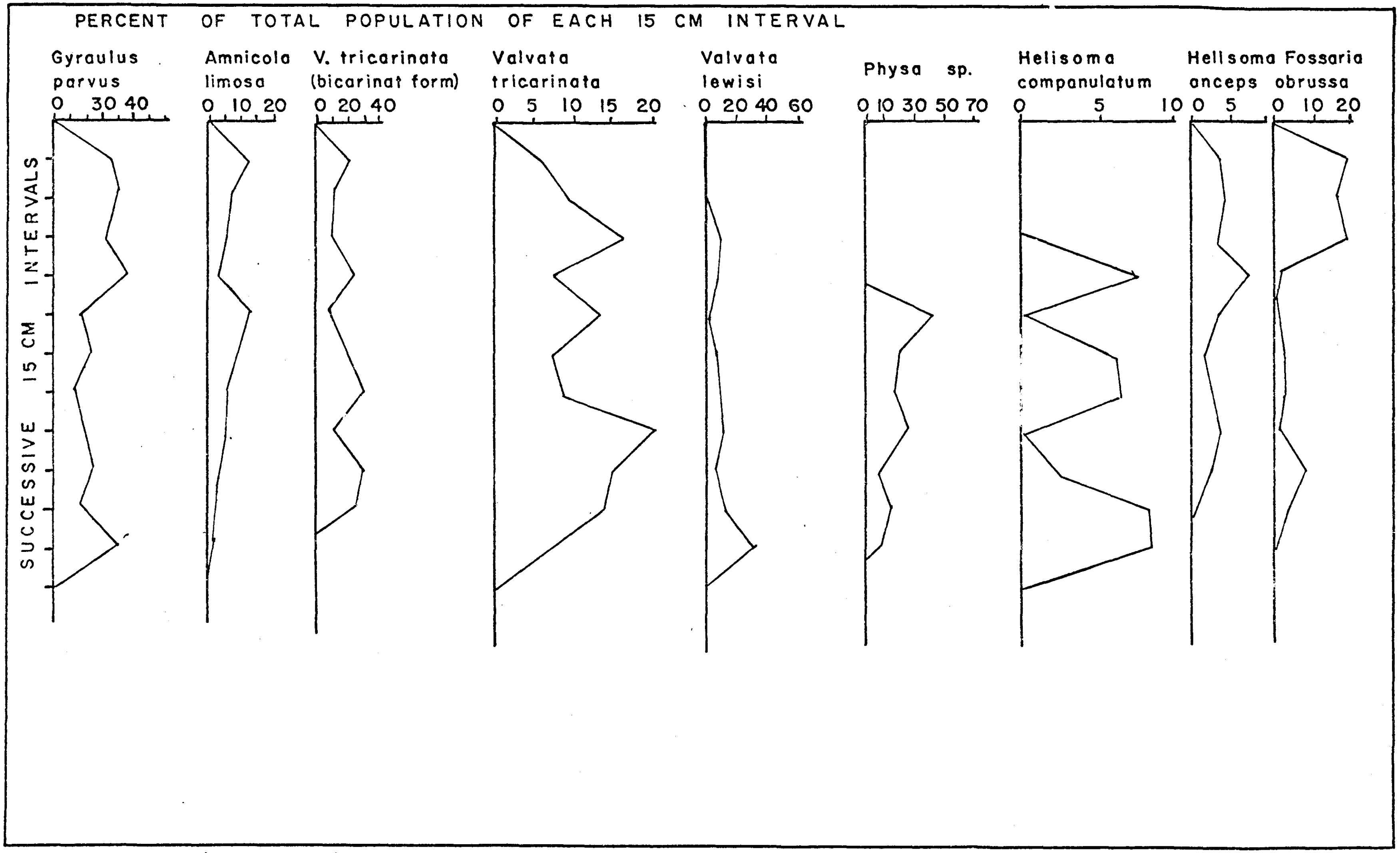


Figure 40.--Fossil percentages in unit E (Marl), core C-I-I.

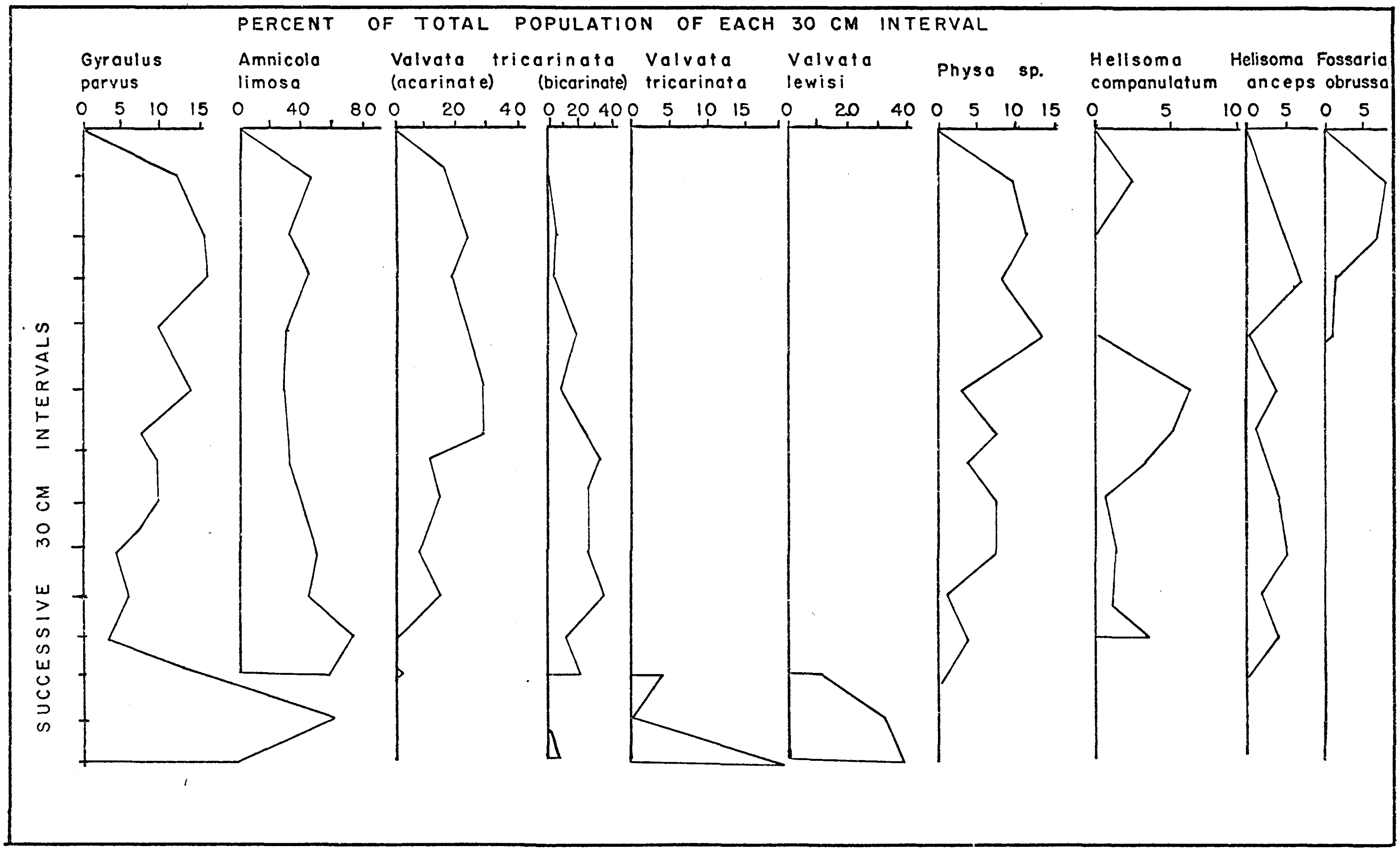


Figure 41.--Fossil percentages in unit E (Marl), core C-IV-1.

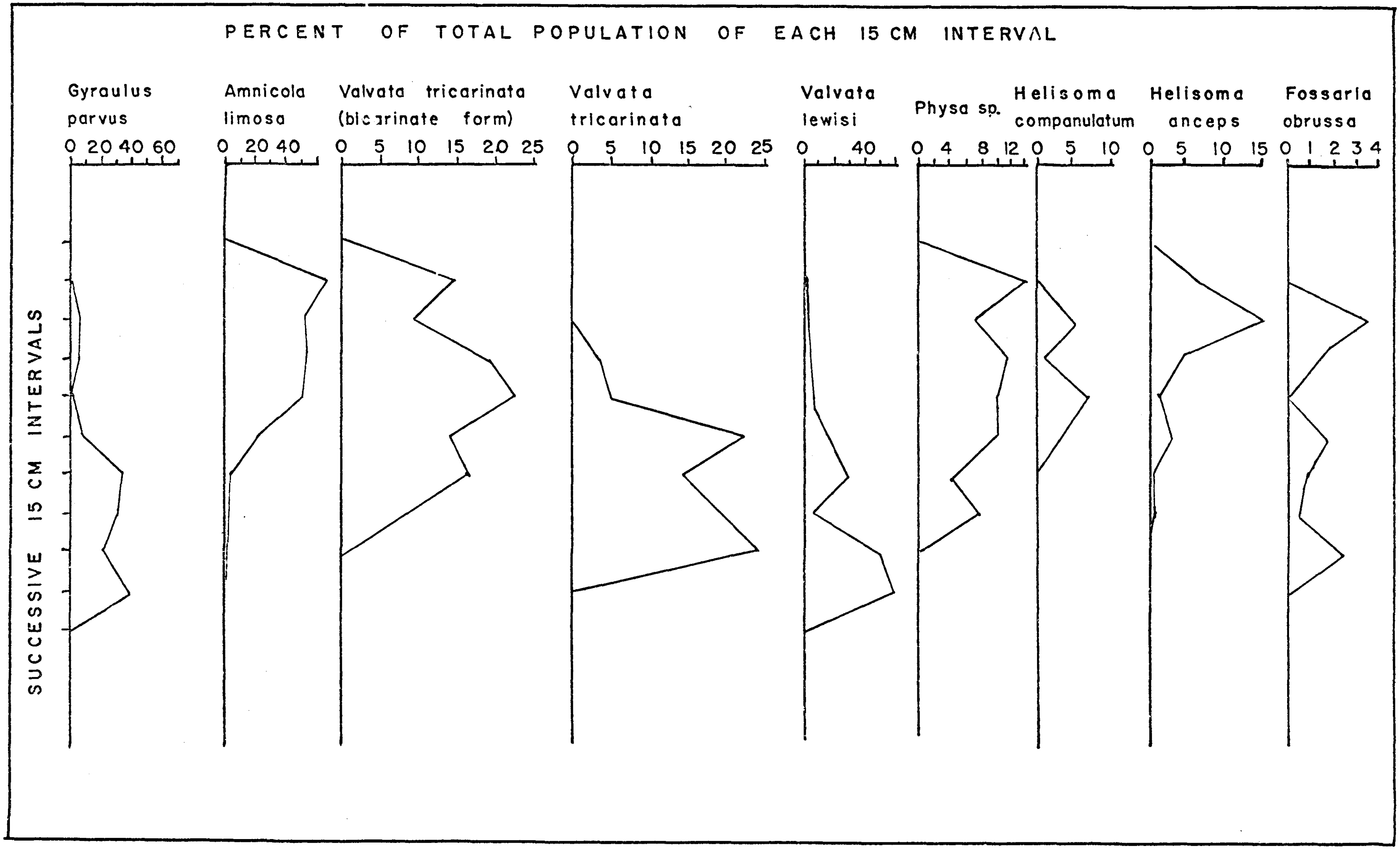


Figure 42.--Fossil percentages in unit E (Marl), core C-IV-2.

PLATE I

POST-GLACIAL MOLLUSCA FROM
UNIT E (MARL) OF CORES C-I-1 and C-IV-2,
AT GLOVERS POND, JOHNSONBURG, NEW JERSEY
(ALL SPECIMENS ENLARGED APPROXIMATELY 3¼X)

Figures 1 and 2. *Gyraulus parvus* (Say). C-IV-2, 3.2 meters deep, UND Nos. 13,110 and 13,111, respectively.

Figures 3 and 4. *Valvata lewisi* Currier. C-I-1, 2.8 meters deep, UND Nos. 13,112 and 13,113, respectively.

Figures 5 and 6. *Valvata tricarinata* (Say). (bicarinate form). C-I-1, 2.9 meters deep, UND Nos. 13,114 and 13,115, respectively.

Figures 7 and 8. *Valvata tricarinata* (Say). (tricarinate form). C-IV-2, 3.8 meters deep, UND Nos. 13,116 and 13,117, respectively.

Figures 9 and 10. *Amnicola limosa* Say. C-IV-2, 3.2 meters deep, UND Nos. 13,118 and 13,119, respectively.

Figures 11 and 12. *Fossaria obrussa* (Say). C-IV-2, 3.2 meters deep, UND Nos. 13,120 and 13,121, respectively.

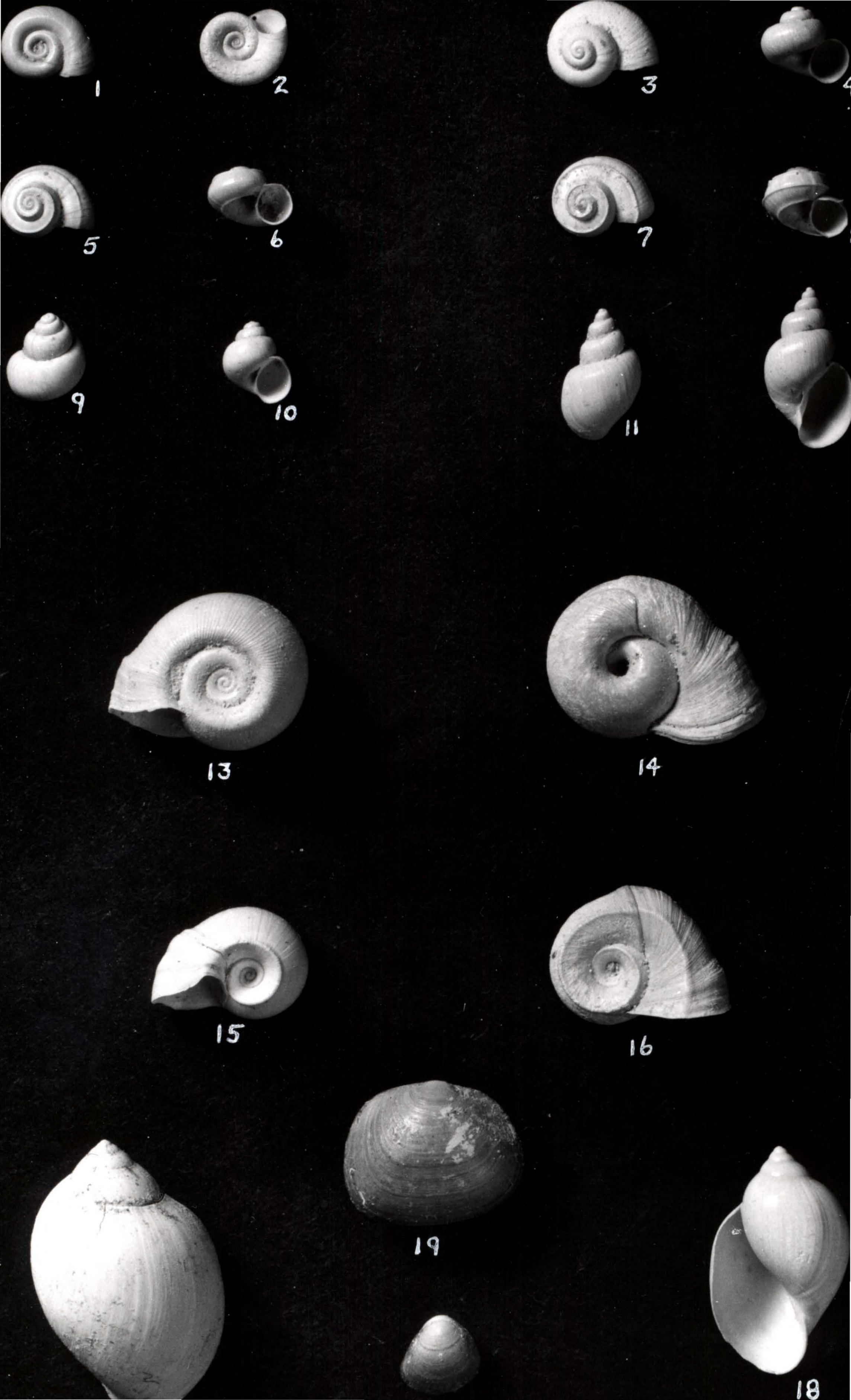
Figures 13 and 14. *Helisoma companulatum* (Say). C-I-1, 2.9 meters deep, UND Nos. 13,122 and 13,123, respectively.

Figures 15 and 16. *Helisoma anceps* (Menke). C-I-1, 2.9 meters deep, UND Nos. 13,124 and 13,125, respectively.

Figures 17 and 18. *Physa* sp. C-IV-2, 3.0 meters deep, UND No. 13,126.

Figure 19. *Sphaerium rhomboideum*? (Say). C-IV-2, 3.2 meters deep, UND No. 13,127.

Figure 20. *Pisidium ferrugineum*? Prime. C-I-1, 2.8 meters deep, UND No. 13,128.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replaced by a unicarinate form which grades to the acarinate form found in the present environment. This change may be an artifact of the counting method used though, at present, I do not believe that to be the case. These results (if, in fact, they represent real changes) are interpreted to be local and environmental, but at the same time evolutionary, since they probably reflect changes within a population that is a breeding continuum of Valvata tricarinata.

Further work at a later date with various paleontological factors at Glovers Pond will undoubtedly provide useful environmental and perhaps chronologic data. Diatoms have been examined sparingly by the writer and will be studied further at a later time. They may, when coupled with pollen data, give important environmental information from unit C and the lake units which are barren of macrofossils. Only one undetermined species of ostracod was recorded from the cores indicating that ostracods probably are not of paleontological significance at Glovers Pond. It is hoped that future work can be done on the fossil forms that have been only briefly mentioned here.

Origin and Glacial History of the Glovers Pond Basin

Initially, the basin now occupied by Glovers Pond originated by erosion of a fault zone in the Kittatinny Limestone to form a valley greater than 70 feet (probably greater than 100 feet) deep. Successive glaciations scoured the valley and helped to enlarge side embayments by removal of less resistant bedrock such as the Jacksonburg units in the northern part of the basin. This pre-Wisconsinan valley probably followed the southwest trend of the fault prior to glacial modification, a course which is not reflected in the current drainage outlet of the lake.

Wisconsin glaciers covered the area to a thickness estimated by Salisbury (1902, p. 64-67) to have been between 2,100 and 2,600 feet. Theoretically the ice covered Jenny Jump Mountain, 1,134 feet high, about 2 miles south and west of the lake. It is the writer's interpretation that after the ice began to thin, but while the front was still active beyond Glovers Pond, crevassing and shearing occurred in the glacier, particularly near the southern end of what is now the lake basin. Thick till accumulated in this crevasse as indicated in Figure 43.

When the ice front had melted back to the vicinity of Glovers Pond, this accumulation of till was left as a crevasse filling or kame-like ridge, across the southern end of the basin. At the same time the central portion of the lake basin was occupied by a block of stagnant ice. Salisbury (1902, p. 400) indicated that such stagnant blocks were common in the more isolated valleys of the area. Sediment sloughing off the edge of this ice block was deposited along the present lake shore. Finer sediments have been winnowed from these deposits leaving only the larger cobbles and boulders ringing the basin (Figure 9). This slumped-off material may have taken the form of a thin kame deposit when it was first deposited.

At the time that the ice block lay in the lake basin, streams of glacial meltwater were flowing into the basin from the north and northeast. These deposited the restricted sand facies (unit B, core C-I-1) found in the northeast bog. The course of the stream supplying this sand is marked by a small hanging valley on a dolostone ledge with the remnant of a plungepool at its base on the north edge of this

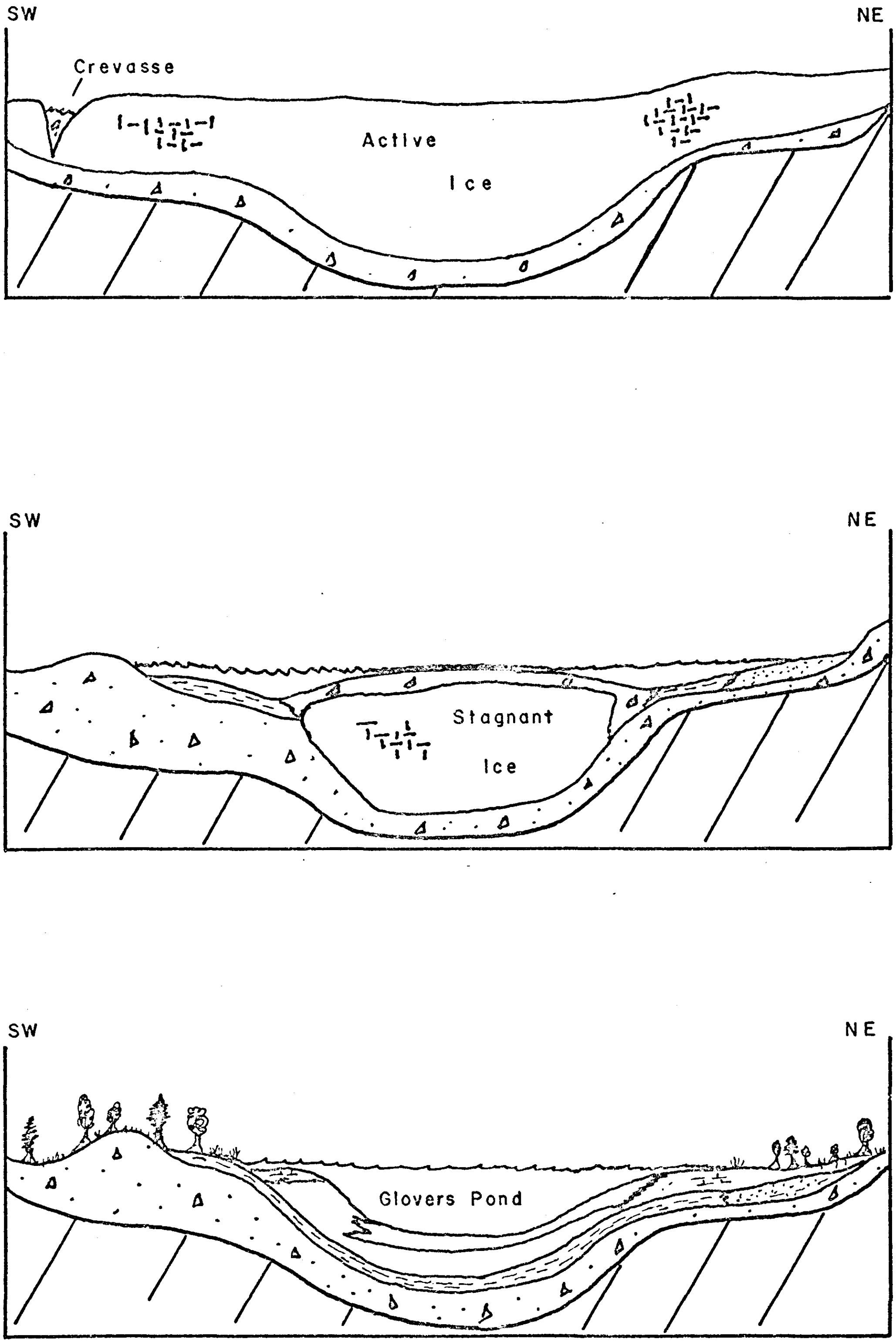

Figure 43.--Diagramatic interpretation of late glacial history of the Glovers Pond basin.

bog (location "V", Figure 5).

The crevasse filling served as a dam and diverted drainage water northwestward out of the basin. This course was also followed by melt-water leaving the basin as indicated by a lag pavement of cobbles and boulders which underlies the mud deposited in the old millpond during historic times. A similar cobble pavement also lies along a valley to the southeast of the basin, indicating that a second, slightly higher drainage may have been used by meltwater. Because of the presence of the ice block and large quantities of meltwater, lake levels were higher in glacial times. This is proved by the presence of glacial clay found in an auger hole only two feet below peat and soil on the very edge of the lake basin (Figure 31).

Glacial influences on the basin ceased when the stagnant ice finally melted, a process that may have taken one or two thousand years to complete as demonstrated (Clayton and Freers, eds., 1967, p. 36) in the case of stagnant ice in North Dakota. Ther period of melting likely was shorter at Glovers Pond since supra-glacial drift, insulating the ice, was probably not as thick as in North Dakota. Melting left a kettle hole within the larger basin of the lake.

History of Post-glacial Sedimentation

After the ice melted, the water level dropped because of a lack of source water. Springs and rainfall became the only water sources. The lake bottom was covered by a uniform deposit of glacial silt and clay, and the lake was probably oligotrophic. Sedimentation during this stage is represented by units C and III (Figure 31), the dark, organic-rich silt bed found throughout the lake basin. Erosion of surrounding glacial deposits was the source of the silt. The lake water was well mixed and cooler much of the summer. The presence of *Fontinalis* in the silt shows that the water was clearer than at present, allowing light penetration to greater depth since this plant requires more light than currently reaches the bottom. This plant requires a good supply of free CO_2 which supports the interpretation that the lake was mixing better than at present. *Fontinalis* was not found in the present lake. Because of the general lack of fossil remains (other than *Fontinalis*) it is believed that few members of the present flora and fauna were then living in the lake. Silt deposition in the oligotrophic lake was slower than sediment deposition in the present eutrophic environment. This condition may have lasted 300 to 500 years although there is no evidence at present to substantiate this estimate.

More complex patterns of sedimentation, similar to the present, began after the post-glacial silt (units C and III) was deposited. Water in the lake became stratified due, perhaps, to climate warming, decrease in wind velocity, growth of thicker and taller forests, or some combination of these factors. The climatic warming caused the lake to become eutrophic.

Marl deposition then began around the edge of the basin while gyttja deposition started in the profundal zone. Aquatic plants and animals, similar to those present, now were inhabiting the lake at that time. Facies relationships between marl, transitional calcareous silts, and gyttja were formed. Eutrophic sedimentation began approximately 11,560 years (+850 or -750 years) B.P. as shown by a radiocarbon date from the wood zone in the base of unit E of core C-I-1 (I-2793-S, Isotopes, Inc.). A date of this age would be considered

Two Creekan (Frye and Willman, 1960, p. 2). This new deposition was more rapid than the former organic silt deposition.

Stimulated by some periods of warmer climate, marl spread over and eventually filled the more restricted, shallow embayments of the basin. A radiocarbon date from the base of the youngest peat, that found in core C-IV-1, gives an age of 2,080±100 years B.P. (I-2792, Isotopes, Inc.) for the beginning of peat deposition at that spot.

Some estimates of the time required to fill the southwest bog may be made from these data. The areal distance from station C-IV-1 to station C-IV-2 (where the wood zone in unit E can be found) is approximately 274 meters. The shelf has migrated this distance in 9,480 years, or it has migrated lakeward at a rate of 2.9 cm per year. This rate has little practical meaning except as an average figure, since shelf migration has probably been faster during times of low water, and slower during times of high water.

Although the pattern of sedimentation has remained stable during most of post-glacial time, several anomalous units are present in the open-lake cores. These may be summarized here from previous sections of this chapter. Unit VI in core C-Lk-1 (Figure 31) is one such anomaly. Presently, essentially no calcium carbonate is being deposited in this region of the lake, although, in the past, sediment deposited in the profundal zone contained as much as 70% $CaCO_3$ as shown by the chemical data presented in Figure 38.

The same anomaly is also shown in unit VI of C-Lk-2 (Figure 39). Such a high carbonate phase was probably caused by a lowering of the lake level at which time the entire lake became supersaturated with calcium carbonate. This condition was gradually lessened as the chemical curves show, but a second increase occured shortly thereafter in core C-Lk-2.

The second increase occurred when the "transitional" calcareous silts from the shelf slope began to encroach on this portion of the lake. Any further changes in lake level would be masked by this sediment just as the change here described was masked in the bog cores. Since this influx of carbonate, post-glacial sedimentation has continued without much change.

Peat succession has reached the woody stage in the northeast bog although the southwest bog is still being covered with sedge and reed peat. This indicates that the tree covered bog is older than the sedge covered bog. An attempt was made to determine by dendrochronology the age of forest growth on the bog. These efforts proved somewhat frustrating in that no very old dates were obtained contrary to my expectations. Red cedars on the bog gave ages of 55 and 70 years and this is thought to be a reliable estimate for first encroachment of cedar into the bog. Cores from larch gave ages of 17 to 20 years. These are probably not reliable ages for first growth larch and may indicate that these are second or third generation trees on the bog, or improper ring counting by the writer. It will suffice to say that tree growth similar to that at present has been going on for at least 70 years on the northeast bog whereas the tree succession is only now beginning on the southwest bog.

Changes in Morphology

Some morphologic changes in the lake caused by post-glacial sedimentation can be described. The present lake occupies an area of approximately 54,343 square meters. In the past, the maximum surface area of the basin was 169,917 square meters when the lake was at its highest level. The present shoreline length of 1,360 meters is only 32.3% of the former maximum length of 4,230 meters.

Formerly the shoreline development (D_L) was 2.69 indicating that the shape of the lake deviated a great deal more from a perfect circle (D_L=1) than does the present shape (D_L=1.65). Most of the former irregularities have been filled with sediment. The profound effects of the largely biochemical sediment as a basin-filling agent at Glovers Pond are evident from this comparison.

Paleoclimatic Interpretations

Chemical analysis of core sediments indicates that climatic fluctuations have occurred several times in the past 12,000 years. Because these climate changes have not been dated by radiocarbon techniques, no absolute chronology of post-Wisconsinan climatic intervals can be proposed. Estimates of relative lake levels (as affected by climate) are shown in Figure 44. The best single climatic interpretation for northern New Jersey is that of Niering (1953) who based it upon pollen profiles.

Cary glaciers began to retreat between 13,000 and 14,000 (Flint, 1957) years ago. For perhaps 1,000 years after this retreat, Glovers Pond was oligotrophic, indicating a cool, moist climate with high lake levels.

Climatic amelioration and lower lake levels are shown by the first influx of carbonate (unit III). Deevey (1951, p. 197) has used such carbonate layers to infer climatic changes. When this first occurred in Glovers Pond the lake became eutrophic. This probably represents the beginning of full-scale marl deposition in the shallower

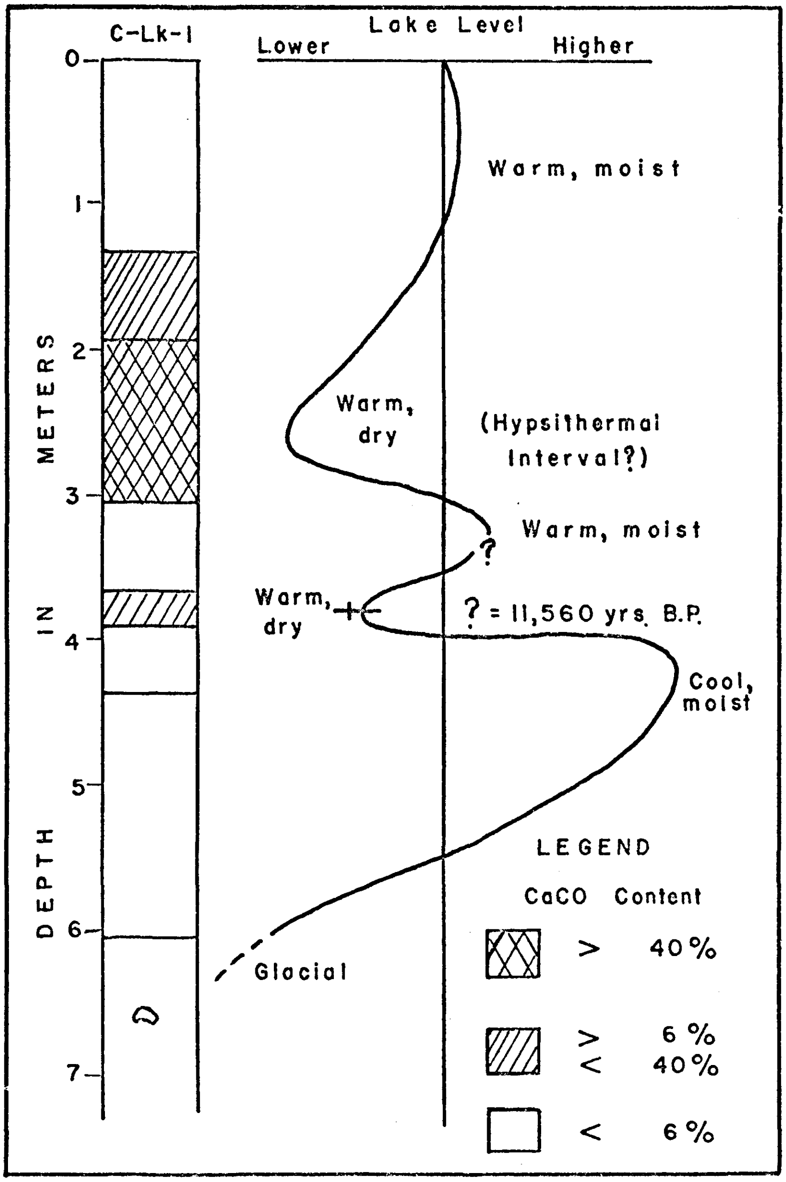

Figure 44.--Diagramatic interpretation of high and low water levels in Glovers Pond based on chemical analyses of core C-Lk-1.

areas. If so, the warming took place around 11,500 to 12,000 years ago based on the dated wood in unit E.

A decline in carbonate once again (unit V, Figures 38 and 39) indicates more moist, perhaps cooler, conditions and higher lake levels.

A large climatic fluctuation is shown by the high (greater than 70%) influx of carbonate in unit VI of core C-Ik-1 where such deposition is currently restricted by the undersaturated condition of the hypolimnion. This marl deposition in the profundal zone is caused by lowering lake levels at least 10 to 12 feet below those of the present. Such sediments may record events of the Hypsithermal Interval of sustained warm climates beginning between 9,000 and 6,000 years ago (Flint and Deevey, 1957).

The lake rose gradually to a level a few feet below that of the present about 2,000 years ago when peat deposition began at the site of core C-IV-1. Since that time no major fluctuations have been recorded.

Historically, the lake must have been about two feet higher when the millpond was dammed in the late 1700's. Recently, drought has caused lake levels to fluctuate as much as two feet during a single summer. Such local effects lend credence to the idea that changes recorded by sediments in the lake have been of a larger scale, since the smaller recent changes have not had major effects on the type of sediment being deposited in the profundal zone. Dating of unit VI in core C-Ik-1, as well as pollen analysis, should show that the sediments of Glovers Pond record a clear history of the post-glacial climate of northern New Jersey. This should be explored in greater detail.

SUMMARY OF CONCLUSIONS

The following conclusions regarding the geology and limnology of Glovers Pond are offered:

1. Glovers Pond is a temperate, eutrophic, dimictic lake, strongly stratified during the summer and weakly stratified during the winter. The lake has a maximum depth of nine meters.

2. The water supply of the lake comes from precipitation and from springs entering the basin along the northern edge.

3. Within the basin there are presently four distinct zones of sediment type. From shore to basin these are: peat, marl, calcareous silt ("transitional sediments"), and gyttja. These zones interfinger at their edges and become gradational from one to the next.

4. Primary deposition of calcium carbonate occurs on a shallow shelf by chemical and biochemical precipitation on the alga, Chara. This plant is of prime importance in $CaCO_3$ deposition, maintenance of the shelf slope by stabilization, and as a habitat for mollusks and other organisms.

5. Nine species of aquatic gastropods and nine species of terrestrial gastropods inhabit the lake and surrounding woodland at present. Three bivalves also inhabit the lake.

6. The gastropods Valvata lewisii, Valvata tricarinata (tricarinate, bicarinate, and unicarinate forms) and Ferrissia sp. were found in core sediments but were not taken from the living fauna.

7. The lake lies in a glacially modified fault valley, once more than 70 feet deep. The deepest part of the basin held a block of stagnant ice for some length of time during deglaciation in late Wisconsinan time.

8. Six stratigraphic units are recognized in the bog sediments and eight in the lake sediments. The oldest marl unit has a radiocarbon age of approximately 11,560 years B. P., whereas the youngest peat unit has a radiocarbon age of 2,080±100 years B. P.

9. The lake is being encroached upon by marl from the shelf at an average horizontal rate of 2.9 cm per year. This is only an average rate and actual filling occurs more rapidly at times of lower water and more slowly when water levels are high.

10. Post-glacial morphologic changes in the shape of Glovers Pond are due primarily to infilling of the basin by sediments which are largely of biochemical origin. This indicates the importance of biochemical relationships as the major sediment producing factors in this, and perhaps other, "marl lakes" of northern New Jersey.

11. At least two intervals representing climates warmer and drier than that of the present are indicated by high calcium carbonate values in the sediment of core C-Lk-1 in the profundal lake basin. One interval represents a major climatic amelioration that may mark the Hypsithermal Interval in northern New Jersey.

Future work on the sediments of Glovers Pond will perhaps reveal further environmental data for the post-glacial of New Jersey if sufficient age determinations can be obtained.

REFERENCES

Anderson, P. W., and George, J. R., 1966, Water quality characteristics of New Jersey streams: U.S. Geol. Survey Water-Supply Paper 1819-G, 48 p.

Callender, Edward, 1968, Post-glacial sedimentology of Devils Lake, North Dakota, Unpub. Doctoral Dissertation, North Dakota Univ.

Caster, K. E., 1934, The stratigraphy and paleontology of northwestern Pennsylvania: Bull. Amer. Paleontology, v. 21, no. 71, pt. 1, 185 p.

Clarke, A. H., Jr., and Berg, C. O., 1959, The freshwater mussels of central New York: Cornell Univ. Agricultural Experiment Station Mem. 367, p. 79.

Clayton, Lee, and Freers, T. F., editors, 1967, Glacial geology of the Missouri Coteau and adjacent areas: North Dakota Geol. Survey Misc. Ser. 30, p. 170.

Colenvaux, P. A., 1964, Sampling of stiff sediments of an ice-covered lake: Limnology and Oceanography, v. 9, p. 262-264.

Davis, C. A., 1913, Origin and formation of peat, in White, David, and Thiessen, Reinhardt, The origin of coal: U.S. Bur. Mines Bull. 38, p. 165-186.

Deevey, E. S., Jr., 1951, Late-glacial and post-glacial pollen diagrams from Maine: Am. Jour. Sci., v. 249, no. 3, p. 177-207.

Emery, K. O., and Deitz, R. S., 1941, Gravity coring instrument mechanics of sediment coring: Geol. Soc. Amer. Bull., v. 52, p. 1685-1714.

Fasset, N. C., 1966, A manual of aquatic plants: new ed., Madison, Wisconsin Univ. Press, 405 p.

Flint, R. F., 1957, Glacial and Pleistocene geology, New York, John Wiley and Sons, p. 553.

Flint, R. F., and Deevey, E. S., Jr., 1957, Post-glacial hypsithermal interval: Science, v. 105, no. 3240, p. 182-184.

Frey, D. G. (editor), 1963, Limnology in North America: Madison, Wisconsin Univ. Press, 734 p.

Frye, J. C., and Willman, H. B., 1960, Classification of the Wisconsinan stage in the Lake Michigan glacial lake: Illinois Geol. Survey, Circ. 285, 16p.

Goddard, E. N., et al., 1948, Rock-color chart: National Research Council, Washington, D.C.

Goode, J. P., 1953, World atlas: ninth ed., E. B. Espenshade, Jr., ed., New York, Rand McNally, 287 p.

Gray, H. H., 1955, Thickness of bedding and parting in sedimentary rocks: Geol. Soc. Amer. Bull., v. 66, no. 1, p. 147-148.

Hach Chemical Co., 1966, Water and sewage analysis procedures: Catalogue No. 9, Ames, Iowa, 108 p.

Herpers, Henry, 1961, The Ogdensburg-Culvers Gap recessional moraine and glacial stagnation in New Jersey: Geol. Rept. Ser. No. 6, New Jersey Geol. Survey, 16 p.

Herrington, H. B., 1962, A revision of the Sphaeriidae of North America (Mollusca: Pelecypoda): Michigan Univ. Mus. Zool. Misc. Pub. 118, 74 p.

Howell, F. B., et al., 1950, Subdivision and dating of the Cambrian of eastern Pennsylvania: Geol. Soc. Amer. Bull., v. 61, no. 12, pt. 1, p. 1355-1367.

Hutchinson, G. E., 1957, A treatise on limnology, v. 1: New York, John Wiley and Sons, p. 1015.

Johnson, Merideth, (revisor), 1950, Geologic map of New Jersey: Dept. of Conservation and Economic Development, Trenton, New Jersey.

Kennedy, S. M., et al. (editors), 1963, The New Jersey almanac: New Jersey Almanac and Trenton Evening Times, Upper Montclair and Trenton, 768 p.

Kummel, H. B., 1900, Report on the portland cement industry: New Jersey Geol. Survey Annual Rept., pt. 2, p. 9-101.

_______, H. B., 1905, Chemical composition of the white crystalline limestones of Sussex and Warren Counties: Ann. Rept. of the State Geologist; New Jersey Geol. Survey, p. 175-191.

Kummel, H. B., and Weller, Stuart, 1901, Paleozoic limestones of the Kittatinny Valley, New Jersey: Geol. Soc. Amer. Bull., v. 12, p. 147-64.

Kummel, H. B., et al., 1908, Description of the Franklin Furnace quadrangle, New Jersey: U.S. Geol. Survey Atlas, Folio 161.

MacClintock, Paul, 1940, Weathering of the Jerseyan till: Geol. Soc. Amer. Bull., v. 51, p. 103-115.

Miller, R. L., 1937, Stratigraphy of the Jacksonburg Limestone: Geol. Soc. Amer. Bull., v. 48, no. 11, p. 1687-1717.

Munsell Soil Color Charts, 1954, Baltimore, Munsel Color Co.

Niering, W. A., 1953, The past and present vegetation of High Point State Park, New Jersey: Ecological Monographs, v. 23, p. 127-48.

Parmeke, C. W., and McCourt, W. E., 1905, A report on the peat deposits of northern New Jersey: Ann. Rept. of the State Geologist, pt. 5, New Jersey Geol. Survey, p. 223-307.

Pettijohn, F. J., 1957, Sedimentary rocks: New York, Harper and Brothers, 719 p.

Piggot, C. S., 1941, Factors involved in submarine core sampling: Geol. Soc. Amer. Bull., v. 52, p. 1513-1523.

Pilsbry, H. A., 1948, Land mollusca of North America (north of Mexico): Philadelphia, Acad. Nat. Sci., Mon. 3, v. 2, pt. 2, 1113p.

Prouty, C. E., 1959, The Annville, Myerstown, and Hershey Formations of Pennsylvania: Pennsylvania Geol. Survey Bull. G31, 47 p.

Rainwater, F. H., and Thatcher, L. L., 1960, Methods for collection and analysis of water samples: Geol. Survey Water-Supply Paper 1454, p. 301.

Reid, G. K., 1961, Ecology of inland waters and estuaries, New York, Reinhold Pub. Co., 375 p.

Rich, J. L., 1951, Three critical environments of deposition, and criteria for recognition of rocks deposited in each of them: Geol. Soc. Amer. Bull., v. 62, p. 1-20.

Ruttner, Franz, 1963, Fundamentals of limnology: third edition, transl. D. G. Frey and F. E. J. Fry, Toronto, Toronto Univ. Press, 295 p.

Salisbury, R. D., 1902, The glacial geology of New Jersey: New Jersey Geol. Survey, Final Rept. 5, 802 p.

Shepard, F. P., 1954, Nomenclature based on sand-silt-clay ratios: Jour. Sed. Petrology, v. 24, p. 151-158.

Sherwood, W., 1964, Structure of the Jacksonburg Formation in Northampton and Lehigh Counties, Pennsylvania: Pennsylvania Geol. Survey Bull. G45, 64 p.

Smith, R. F., 1957, Lakes and ponds: New Jersey Dept. Conserv. and Econ. Devel., New Jersey Fisheries Survey Rept. 3, 198 p.

Twenhofel, W. H., et al., 1954, Correlation of the Ordovician formations of North America: Geol. Soc. Amer. Bull., v. 65, p. 247-298.

United States Weather Bureau, 1962, Climatography of the United States, no. 81-24 (New Jersey): U.S. Gov't. Printing Office, Washington, 4 p.

Visher, S. S., 1954, Climatic atlas of the United States: Harvard Univ. Press, 403 p.

Waksman, S. A., 1942, The peats of New Jersey and their utilization: New Jersey Dept. of Conservation and Development Bull. 55, pt. A, Geol. Ser., 155 p.

Waksman, S. A., et al., 1943, The peats of New Jersey and their utilization: New Jersey Dept. of Conservation and Development Bull. 55, pt. B, Geol. Ser., 278 p.

Welch, P. S., 1952, Limnology: New York, McGraw-Hill Book Co., 538 p.

Weller, Stuart, 1903, Report on paleontology, v. 3, The Paleozoic faunas; Geol. Survey of New Jersey, 462 p.

Widmer, K., 1964, The geology and geography of New Jersey: New Jersey Historical Ser., v. 19, Princeton, New Jersey, D. Van Norstrand Co., p. 193.

APPENDIX A: METHODS OF STUDY

Sampling Methods

Water samples

Samples of water from the open lake were taken by a Kemmerer sampler having a volume of 1200 cubic centimeters from the epilimnion, metalimnion, and hypolimnion. Most samples were taken at station Lk-1 (Figure 23), but some were occasionally drawn from station Lk-3. Samples were placed in one-pint polyethylene bottles for transport to the laboratory. At stations Lk-2 and Lk-4 water samples were collected from depths of 10 to 30 cm directly in polyethylene bottles. Samples were analyzed within 2 hours (usually within 20 minutes) after collection.

Bottom samples

Samples of the present lake sediments were taken by means of an Eckman Dredge or grab sampler having a cross-sectional area of 196 square centimeters. Sixteen ounce heterogeneous samples were put in Nasco "Whirl Pac" plastic bags and sealed to exclude air moisture until they could be analyzed at the University of North Dakota. The depth-to-bottom was recorded at each of the 36 stations to be used as an aid in bathymetric mapping.

Bathymetry

Basic profile data were gathered with a Bendix DR-2 sonic depth recorder which produced a continuous bottom profile across the lake basin. These data were supplemented by control data from grab sampling as already discussed.

Temperature

Thermal conditions in Glovers Pond were measured daily (when possible) using a thermistor made by Whitney Underwater Instruments, Inc. (San Luis Obispo, California). This instrument recorded accurately temperature changes of 0.1°C and may be read to units of 0.01°C with some confidence. Temperatures were measured at intervals of 0.5 meter, primarily at stations Lk-1 and Lk-2. Readings were generally made at 4:00 P.M.

Turbidity

The depth of light penetration in Glovers Pond was measured with a secchi disk having a 10-inch diameter. Penetration was recorded as meters of depth to which the disk could last be seen. Readings were taken at 12:30 P.M. about once a week.

Precipitation

A rain guage was stationed in an open area behind the home of the Resident Manager of the camp. A tubular rain guage with a 3-inch diameter catch basin and calibrated to read in tenths of inches was used. Precipitation as snow was recorded by catching the snow in the guage and allowing it to melt then reading the guage as with rain. While readings may not always be precise, they are felt to be accurate enough to provide a first approximation of values for Glovers Pond during 1966.

Auger samples

Where it was necessary to study shallow sub-surface sediments, a hand-operated posthole auger able to penetrate five feet of sediment was used. This instrument brought up good, unmixed samples from bogs and fields. Many of these were saved for later analysis, and for use in correlation of lake and bog strata.

Cores

Five cores with penetrations of 20 to 28 feet were taken; three in the bogs, and two in the open lake. Cores were made with a modified Colinvaux (1964) corer (as described by Callender, 1968), a hand-injected, piston device, which takes one-meter or two-meter lengths of core at each injection as desired. Core passes through a cutting head into a 1½ inch (outer diameter) clear plastic core-liner. This plastic tube is then removed from the core barrel and corked shut and sealed with tape to retain sediment and exclude air. Some compaction of sediment was caused during coring but this may be corrected for during logging of the sediments.

Cores from the open lake were made from a floating platform with a work area of 81 square feet buoyed up by two 9 X 3 foot sections of 6 inch thick styrofoam. This platform was very sturdy (even in 30 feet of water) when anchored firmly by all four corners. In the open lake it was necessary first to case the hole with 4 inch diameter plastic, electrical conduit so that the hole would not be lost during installation of new core-liner. This system proved to be very satisfactory.

Three cores were extruded, logged, and bagged at the camp; two were returned to the University of North Dakota intact and later extruded in the laboratory.

Analytical Methods

Physical analyses

Twenty-gram samples of sediments suitable for particle-size analysis were dispersed in Calgon (sodium hexametaphosphate) for two months, wet sieved on a 4-phi (62 microns) sieve into one-liter cylinders, and mixed thoroughly. Aliquots of this mixture were taken at prearranged times during the settling of the sediment. Times were chosen according to Wadell's modification of Stoke's Law. The aliquots were dried and weighed to the nearest milligram. Sediments coarser than 4-phi were dried and sieved mechanically on Tyler Standard screens arranged in whole-phi intervals from +4 to 0 phi. These size fractions were also weighed as above. These data were subjected to computer analysis by the program utilized by Callender (1968). Results were plotted on the basis of percentage content of sand, silt, and clay according to the method of Shepard (1954).

Color and texture

Color of sediments was examined for both wet and dry samples. Values given for color are those of the Munsell (1954). Rock colors were taken from the rock-color chart (Goddard, et al., 1948). Samples were examined stereoscopically at magnifications of 20X, 40X, and 80X for analysis of coarse fractions, fossils, and sedimentary textures and fabrics. At this time macro- and microfossils were picked from the sediment.

Chemical analyses

Water chemical values were measured at a laboratory established on the camp property. Alkalinity was measured by titrating 50 ml samples with .023 N sulfuric acid to the phenolpthalein and methyl purple endpoints. Alkalinity was calculated as mg/l $CO_3^=$ and $HCO_3^=$.

Chloride concentration was measured by titrating 50 ml samples with $AgNO_3$ using $K_2Cr_2O_4$ as an indicator. At the endpoint the solution changes from yellow to a salmon-pink color.

Measurement of pH was made with a Taylor comparator which could be extrapolated to the nearest 0.1 pH unit.

Hardness and oxygen concentration measured using the techniques and reagents described in the manual of water and sewage analysis procedures published by the Hach Chemical Company, Ames, Iowa. Hardness was measured as calcium and magnesium content in milligrams per liter. Oxygen measurements were calculated as part-per-million dissolved oxygen and were later converted to mg/l. Oxygen titrations were taken, usually at 12:00 noon.

Chemical analyses of grab samples and core sediments were carried out at the University of North Dakota during the six months following the field season. Each of 67 samples were analyzed for total nitrogen, total carbon, and calcium carbonate. Calcium carbonate content was measured by acidifying samples with a known volume of H_2SO_4 and back-titrating with NaOH to determine the amount of acid that had been reacted with the carbonate. Generally one-gram samples of dry sediment were used for this procedure.

The values of total nitrogen and total carbon were measured using the technique described by Callender (1968, p. 283-297). This method required only a few milligrams (generally 18 to 30) of the dried sample which had previously been powdered in a Spex ball mill. Powdered sample was reacted for 3 hours in evacuated flasks with an excess of chromic acid to oxidize organic and inorganic constituents.

The CO_2 evolved was collected in absorption tubes containing NaOH and back titrated for values of total carbon. Organic carbon content was calculated from this value by subtracting the value obtained for inorganic carbon in the calculation of $CaCO_3$ content. The residue from the oxidation of the sample was analyzed by the Kjeldahl method for calculation of total nitrogen content. Several of the refinements of these techniques were developed by Callender (1968); he estimated oxidation to be 85 to 90% complete in total carbon analysis. He found precision of the method to be ± 2% of the mean value when run on duplicate sediment samples (Callender, 1968, p. 287). He found precision on the nitrogen values to be within ±5% of the mean value (p. 288). The writer found his accuracy to be ±2% and ±6% of the mean values for total carbon and total nitrogen respectively.

Finally samples for radiocarbon dating were wrapped in aluminum foil and refrigerated until they could be used. These were eventually sent to Isotopes, Inc. in Westwood, New Jersey, for analysis.

APPENDIX B: SUPPLEMENTAL PHYSICAL AND CHEMICAL DATA

Additional physical data are given as descriptive lithologic sections of the cores. Compositional values for present lake sediments are listed by station (Figure 23) in Table 9. These data provide sufficient information for characterization of the present sedimentary environment.

The past environments have been characterized on the basis of chemical values which are presented in Tables 14 through 18.

Present water chemical values for station Lk-1, in the open lake, and station Lk-2, on the shelf, are presented in Tables 10 through 13.

TABLE 9

CHEMICAL VALUES FOR BOTTOM SAMPLES

Station	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
1	18.39	1.94	5.87	58.30
2	17.03	1.07	7.95	71.00
3	15.84	.78	7.77	81.40
5	19.45	1.34	8.66	65.65
6	19.78	1.37	8.80	64.40
7	17.36	1.71	4.91	74.80
8	15.95	1.16	5.47	80.00
9	15.34	.51	10.73	82.30
10	15.22	.58	7.74	89.40
11	14.57	.79	7.20	74.05
12	21.26	1.22	11.72	58.05
13	29.20	2.75	9.70	21.10
14	25.81	2.00	7.63	87.95
15	16.37	.99	7.96	70.80
16	17.01	.71	11.96	70.20
18	63.76	3.49	16.24	59.05
19	37.40	4.24	8.74	3.00
20	18.31	2.03	5.46	60.70
22	39.88	4.96	8.02	3.15
23	33.08	4.57	7.20	1.60
24	31.30	3.73	8.30	2.85
25	19.22	.99	10.06	77.20
26	22.19	1.67	9.29	55.60
27	15.33	.87	7.06	76.65
28	14.35	.60	8.87	75.25
29	31.71	2.59	12.10	2.95
30	22.77	1.60	10.36	51.65
31	31.72	2.69	10.98	18.15
32	17.52	1.17	8.41	64.00
33	35.72	2.72	12.77	8.15
34	14.41	.44	9.52	85.15

TABLE 10

WATER CHEMICAL VALUES FOR THE EPILIMNION AT STATION LK-1, 1966, IN MG/L

Date	$CO_3^{=}$	HCO_3^{-}	Ca^{++}	Mg^{++}	pH
7/2	27.6	140.3	-	-	8.6
7/5	22.2	140.3	-	-	8.5
7/6	5.4	151.9	44.0	18.9	8.5
7/12	10.8	143.4	43.2	21.6	8.3
7/14	22.2	142.7	-	-	8.4
8/14	10.8	247.6	-	-	8.3

TABLE 11

WATER CHEMICAL VALUES FOR THE METALIMNION AT STATION LK-1, 1966, IN MG/L

Date	$CO_3^{=}$	HCO_3^{-}	Ca^{++}	Mg^{++}	pH
7/2	22.1	167.8	-	-	8.4
7/5	16.6	156.7	-	-	8.4
7/12	10.8	157.4	42.4	21.1	8.3
7/14	None	185.4	-	-	8.1

TABLE 12

WATER CHEMICAL VALUES FOR THE HYPOLIMNION AT STATION LK-1, 1966, IN MG/L

Date	$CO_3^{=}$	HCO_3^{-}	Ca^{++}	Mg^{++}	pH
7/2	None	201.3	-	-	7.3
7/5	None	190.0	-	-	7.2
7/12	None	185.4	50.4	19.7	7.5
7/14	None	190.9	-	-	7.3
8/14	None	192.2	-	-	7.3

TABLE 13

WATER CHEMICAL VALUES FOR STATION LK-2, 1966 IN MG/L

Date	$CO_3^{=}$	HCO_3^{-}	Ca^{++}	Mg^{++}	pH
7/2	22.2	128.7	-	-	8.8
7/5	27.0	87.2	36.0	155.0	8.9
7/14	33.0	106.7	44.0	18.7	9.0
7/19	27.6	129.3	40.8	20.2	8.9
7/20	27.6	134.8	36.8	18.2	9.2+
7/21	33.0	87.20	33.6	16.1	9.2+
7/25	22.2	112.2	32.0	21.1	8.7
7/28	27.6	134.8	58.4	8.64	8.5
8/1	24.8	98.2	-	-	9.2
8/12	22.2	120.8	-	-	8.9
8/4	41.4	92.1	-	-	9.0
8/10	24.8	111.6	-	-	9.1
8/12	27.6	129.3	43.2	15.4	8.5
8/13	27.0	109.8	-	-	8.9
8/16	19.2	95.8	-	-	8.9
8/19	16.2	164.1	-	-	-
8/23	16.8	123.2	-	-	8.7
8/29	16.8	123.2	-	-	8.5

TABLE 14

CHEMICAL VALUES FOR CORE C-I-1

Unit	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
F	41.09	2.62	15.52	3.60
E	16.49	.43	13.40	89.40
	14.50	.31	11.65	90.75
D	14.62	.30	17.60	77.85
C	5.54	.21	26.90	1.30
B	2.86	.10	23.40	4.35

TABLE 15

CHEMICAL VALUES FOR CORE C-IV-1

Unit	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
F	42.20	2.81	14.93	5.90
	17.00	.09	14.45	95.60
E	15.78	.24	18.54	94.45
	15.44	.32	13.31	93.95
D	19.99	.76	22.21	77.80
C	6.09	.28	21.54	1.55
B	1.61	.08	17.01	6.35

TABLE 16

CHEMICAL VALUES FOR CORE C-IV-2

Unit	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
F	44.83	2.70	16.43	3.90
	18.56	.62	14.16	81.55
E	16.77	.51	14.86	76.65
	13.55	.35	10.57	82.10
D	15.41	.67	13.34	53.85
C	2.42	.39	6.00	.65
B	1.95	.07	9.00	11.00

TABLE 17

CHEMICAL VALUES FOR CORE C-Lk-1

Unit	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
VIII	33.63	2.50	13.23	4.65
	39.22	3.29	11.81	3.20
VII	35.16	2.10	14.24	43.85
VI	22.07	.92	14.64	71.70
	20.64	.95	12.83	70.30
V	32.97	2.61	12.40	5.05
IV	11.99	.59	15.66	23.05
III	2.99	.30	9.00	2.50
II	2.53	.09	6.11	16.50

TABLE 18

CHEMICAL VALUES FOR CORE C-Lk-2

Unit	% Total Carbon	% Total Nitrogen	C/N	% $CaCO_3$
VIII	16.26	.72	8.4	85.05
	17.24	.90	8.2	82.25
	15.54	.68	8.0	84.10
	16.55	.97	7.0	81.45
VII	21.21	1.71	8.1	63.30
VI	15.87	.73	7.3	88.05
V	36.91	4.18	8.8	7.05
IV	10.80	1.23	6.6	67.05
III	4.95	.44	10.20	3.75
	3.77	.39	8.9	2.45
II	3.09	.19	14.4	3.05

LITHOLOGIC DESCRIPTION OF CORE C-I-1

F 1.7 meters	Wood and sedge peat; wet color, very dark brown, 10YR2/2; dry color, 10YR2/2; sedge peat becoming woody in the upper portion; contact with marl marked by a 6 cm gradational zone containing snails.
E 1.5 meters	Marl; wet color, light gray, 10YR7/2 (upper) to light gray, 2.5Y7/2 (lower); dry color, white, 10YR8/2; poorly compacted near top to well compacted near base, primarily silt sized particles of $CaCO_3$; contains many snails, one mussel shell, plant fibers, *Chara* stems and oogonia, ostracods, diatoms, and unidentified seeds; zone near the base contains wood fragments which gave a C^{14} age of 11,560 +850 or -750 years B. P.; lower contact abrupt.
D 0.2 meters	Calcareous, organic silt ("transitional sediment"); wet color, dark gray, 10YR4/1; dry color, light gray, 5Y7/1; compact, "rubbery", calcareous silt; contains numerous shell fragments, much organic matter, diatoms; shows crisscrossed pattern of *Chara* stems which mark bedding planes. Lower contact fairly abrupt.
C 0.6 meters	Organic-rich silt; wet color, black, 5Y2/1; dry color, gray, 5Y5/1; compact, cohesive, non-calcareous silt; contains numerous plant fragments, many of *Fontinalis* (water moss); no mollusk shells; bedding marked only by plant remains. Lower contact abrupt.
B 2.5 meters	Sandy silt, silty sand, and silt; wet color, dark gray, 5Y6/1; dry color, gray, 5Y4/1; unit divisible into upper sandy silt (.5 m) and lower sand and silty sand (2.0 m); sand grades upward from medium to fine and very fine. Lower contact gradational.
A ?	Till; wet color, dark gray, 5Y4/1; dry color, gray, 5Y6/1; very compact silt and clay with pebbles.

LITHOLOGIC DESCRIPTION OF CORE C-IV-1

F 1.3 meters	Sedge peat; wet color, very dark brown, 10YR2/2; dry color, very dark brown, 10YR2/2; reed and sedge peat with gradational lower contact; base of this peat gives C^{14} age of 2,080 years B. P.
E 3.3 meters	Marl; wet color, light gray, 2.5Y7/2; dry color, white, 2.5Y8/2; poor to well compacted, silt sized particles of $CaCO_3$; plant fragments, <u>Chara</u> stems, seeds, and diatoms present; many mollusk shells mark the bedding planes. Lower contact rather abrupt.
D 1.0 meters	Calcareous, organic-rich silt ("transitional sediment"); Wet color, 2.5Y5/2, grayish brown; dry color, light gray, 5Y7/1; compact, calcareous, "rubbery", silt, containing many shell fragments; shows laminations marked by crisscrossed accumulations of <u>Chara</u> stems; oogonia and diatoms present. Lower contact rather abrupt.
C 0.3 meters	Organic-rich silt; wet color, very dark gray, 5Y3/1; dry color, gray, 5Y5/1; well compacted, non-calcareous cohesive, clayey silt; contains <u>Fontinalis</u>; no mollusk remians present. Lower contact abrupt.
B 1.0 meters	Sandy silt; wet color, gray, N5/0; dry color, gray, 5Y6/1; cohesive; contains no mollusks or organic matter. Lower contact gradational.
A ?	Till; wet color, 5Y4/1, dark gray; dry color, gray, 5Y6/1; very compact clayey silt containing gravel, pebbles, and cobbles.

LITHOLOGIC DESCRIPTION OF CORE C-IV-2

F 2.7 meters	Sedge peat; wet color, very dark brown, 10YR2/2; dry color, very dark brown, 10YR2/2; reed and sedge peat; Lower contact slightly gradational.
E 2.0 meters	Marl; wet color, gray, 2.5Y6/2; dry color, white, 2.5Y 8/2; silt sized grains of $CaCO_3$; poorly to well compacted; many mollusk shells, <u>Chara</u> oogonia, seeds, and ostracods present; base contains a zone of wood fragments. Lower contact rather abrupt.
D 0.2 meters	Calcareous, organic-rich silt; ("transitional sediment"); wet color, light olive gray, 5Y6/2; dry color, light gray, 5Y7/1; compact, calcareous, "rubbery", silt; contains scattered fragments of mollusk shells, criss-crossed tubes of <u>Chara</u> stems, and oogonia; Lower contact abrupt.
C 0.5 meters	Organic-rich silt; wet color, dark olive gray, 5Y3/2; dry color, gray, 5Y5/1; compact, cohesive, non-calcareous silt and some fine sand; contains few plant remains of <u>Fontinalis</u>; no mollusk shells. Lower contact abrupt.
B 1.5 meters	Silt; wet color, gray, 2.5YN5/0; dry color, gray, 5Y6/1; compact, cohesive, clayey silt with some fine sand; no snails or organic matter. Lower contact gradational.
A ?	Till; wet color, dark gray, 5Y4/1; dry color, gray, 5Y6/1; very compact clayey silt with gravel, pebbles, and cobbles.

LITHOLOGIC DESCRIPTION OF CORE C-Lk-1

VIII 1.2 meters	Gyttja, wet color: 5Y2/1 black; dry color: 10YR2/2 very dark brown, gelatinous organic ooze; no mollusks, contains fragments of oak leaf; lower contact gradational.
VII 0.70 meters	Gyttja calcareous, wet color: 5Y3/2 dark olive gray; dry color 2.5Y5/2, gelatinous organic ooze; slightly calcareous, slightly compacted, mottled color pattern, contains some snails. Lower contact rather abrupt.
VI 1.2 meters	Marl (organic-rich), wet color: 2.5Y3/2 very dark grayish brown; dry color: 2.5Y6/2 light brownish gray, slightly compacted, very calcareous, organic-rich gyttja. Contains some snails, lower contact abrupt.
V 0.7 meters	Gyttja, wet color: 5Y2/1 black; dry color: 2.5Y3/2 compact, noncalcareous, gyttja; contains no snails. Lower contact abrupt.
IV 0.3 meters	Gyttja (calcareous), wet color: 2.5Y3/2 very dark grayish brown; dry color: well compacted, slightly calcareous, organic gyttja. No snails present, lower contact rather abrupt.
III 0.4 meters	Silt (organic-rich), wet color: 5Y3/2 dark olive gray; dry color 5Y5/2 olive gray, very compact, noncalcareous, clayey silt with some fine sand. Contains much organic matter including stiff plant fibers of unknown affinities; no snails, lower contact abrupt.
II 1.5 meters	Clayey silt and fine sand, wet color: 2.5YN5/0 gray; dry color: 5Y6/1 gray, compact, cohesive, calcareous, clayey silt, no organic matter of mollusk shells present, lower contact gradational.
I ?	Till, wet color: 5Y4/1 dark gray; dry color: 5Y6/1 gray, very compact, clayey silt with pebbles and cobbles, no organic matter. Thickness unknown.

LITHOLOGIC DESCRIPTION OF CORE C-Lk-2

VIII 2.5 meters	"Transitional", wet color: 2.5Y5/2 grayish brown; dry color: 10YR8/1, silt-sized calcareous grains with organic matter and *Chara* stems, poorly to moderately well compacted; contains deciduous leaf fragments and some snails. Lower contact rather abrupt.
VII 0.3 meters	Gyttja (calcareous), wet color: 2.5Y4/2 dark grayish brown; dry color: 2.5Y5/2 calcareous gyttja, "rubbery". Contains *Chara* oogonia, snails, and unident seeds. Lower contact abrupt.
VI 0.5 meters	"Transitional" sediment (calcareous organic-rich silt), wet color: 2.5Y5/2, grayish brown; dry color: 2.5Y7/2 compact, rubbery, silt-sized $CaCO_3$ grains with organic matter; has crisscrossed pattern of *Chara* stems on bedding plane; *Fontinalis*-like plant present; many snails. Lower contact abrupt.
V 0.6 meters	Gyttja, wet color: 5Y2/1 black; dry color: 5Y3/1; very compact, noncalcareous, "rubbery", gyttja, no mollusk shells. Lower contact gradational.
IV 0.3 meters	Calcareous gyttja, wet color: 2.5Y3/2 very dark brown, no snails, well compacted, lower contact abrupt.
III 0.5 meters	Silt (organic-rich), wet color: 5Y4/2 olive gray; dry color: 5Y5/1, compact, calcareous, clayey silt, with much fine organic matter, lower contact abrupt.
II 1.2 meters	Clayey silt, wet color: 5Y4/1 dark gray; dry color: 2.5Y5/2 compact cohesive, clayey silt; no organic matter, poorly calcareous, becoming slightly more calcareous toward base; unfossiliferous, lower contact gradational.
I ?	Till, wet color: 3.5YN5/0 gray; dry color: 2.5Y2/2, very compact, clayey silt, water pebbles and cobbles; thickness unknown.