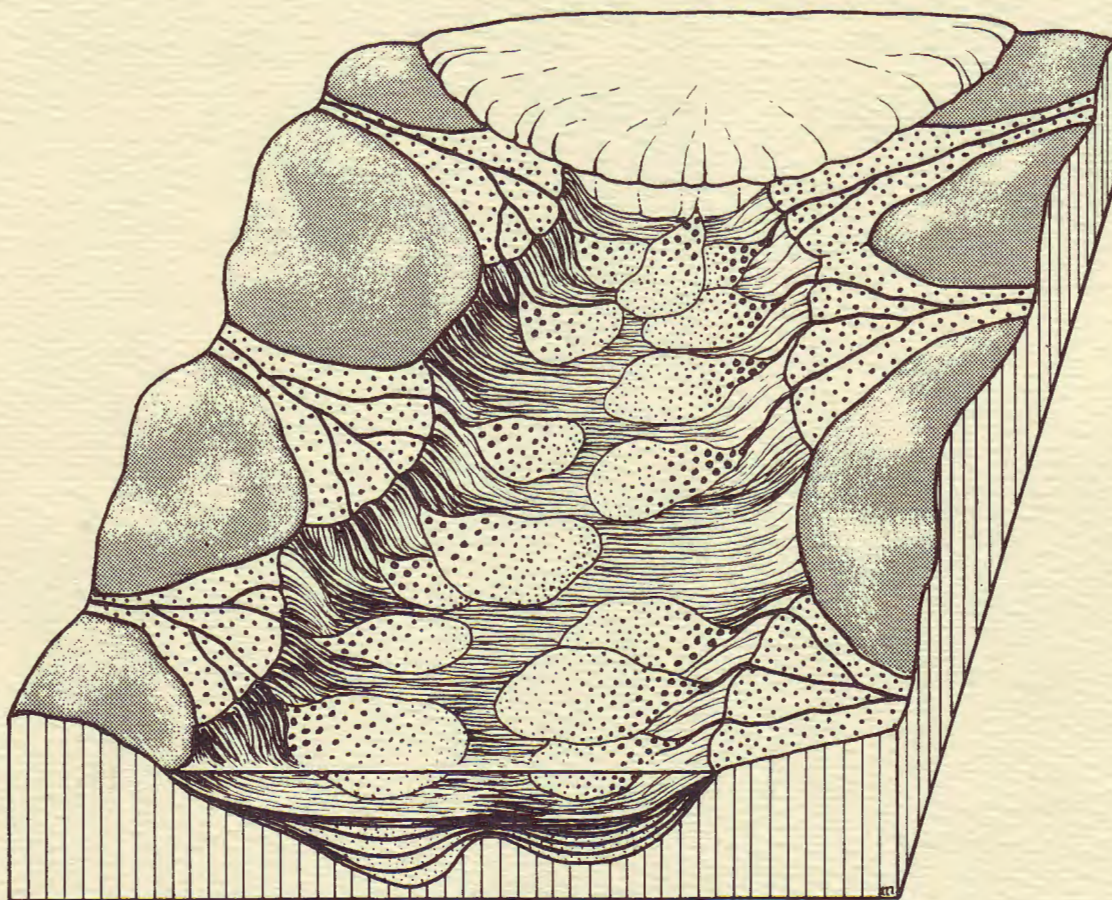


# **RHYTHMIC SEDIMENTATION IN GLACIAL LAKE HITCHCOCK, MASSACHUSETTS-CONNECTICUT**

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RHYTHMIC SEDIMENTATION IN GLACIAL LAKE HITCHCOCK,

MASSACHUSETTS-CONNECTICUT

By

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Abstract: Most of the fine-grained bottom sediments of proglacial Lake Hitchcock are rhythmites composed of silt and clay couplets that occur in three textural groups:

Group I - clay thickness greater than silt thickness

Group II - clay thickness approximately equal to silt thickness

Group III - clay thickness less than silt thickness

Thin sections from impregnated sediments show flat bedding with a maximum of 40 graded laminae in one 2-inch layer. Erosional contacts and ripple crossbedding are common in Group III, but rare in Groups I and II. The contact between silt and the overlying clay layer in any one varve is gradational in less than 50 percent of the samples. Other sedimentary structures include two distinct types of lebenspuren. Mean grain size of the silt layers ( $5.5\phi$  to  $8.5\phi$ ) depends upon the environment of deposition of the silt within the lake. Mean grain size of the clay layers is much the same everywhere (averaging  $10.5\phi$ ).

Data from 34 localities suggest that the rhythmites are annual (i.e., varves), and the following depositional mechanism is proposed. Sediment was transported by streams from the glacier and from nearby deglaciated uplands. Gravel and sand was deposited on deltas, whereas the finer fraction was carried out into the lake mainly by density underflow. Incoming sediment contained a significant amount of clay that settled out continually but became dominant only during the winter when coarse material was less available.

Varves belonging to Groups I and II generally were formed in water away from inflowing rivers, where little sediment was received

directly from density currents. Conversely, Group III varves were formed in water relatively near delta fronts, in a position to receive abundant sediment as it entered the lake.

## INTRODUCTION

Early recognition of the fact that a large fresh-water body once occupied the Connecticut Valley was made by Smith (1832). Emerson (1898) found field evidence of relic strandlines that increased in altitude toward the north. He envisioned a great swollen river containing wide areas to explain these features.

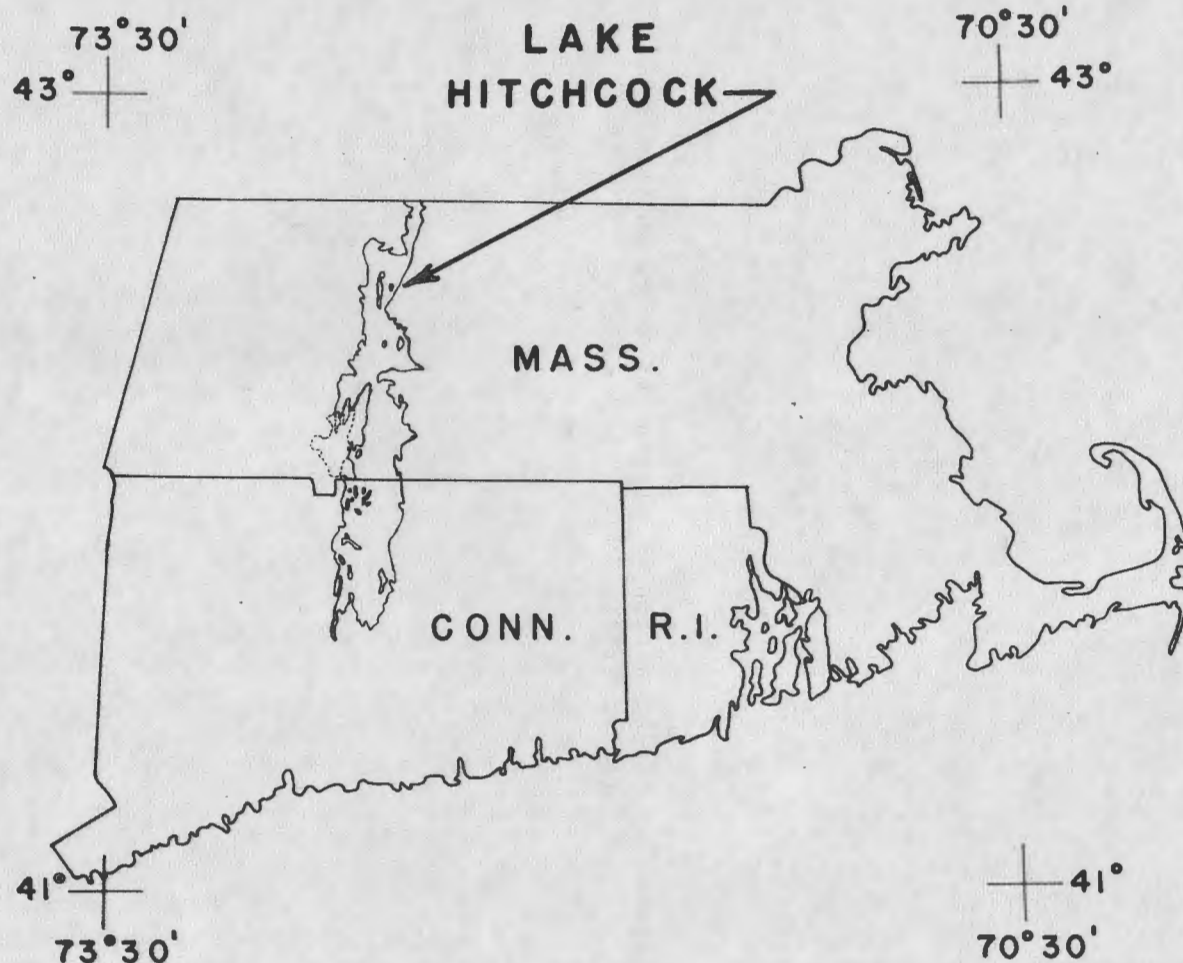
Although lake sediments have been the subject of local engineering studies (Sangrey, 1964; Leach, 1967) and mentioned in all surficial quadrangle maps of the valley, the only previous detailed study was made by Antevs (1922). Antevs' attempt to work out Pleistocene chronology was welcomed, because New England has few recognizable recessional moraines. He worked out a varve chronology of 4,100 years from Rocky Hill, Conn., to St. Johnsbury, Vt., with only one break at Claremont, N.H.

Figure 1 shows the area covered in this study. Within this area, Lake Hartford (Flint, 1933), and Lake Springfield, Lake Hadley, and Lake Montague (Emerson, 1898) are names that have been used for the southern to northern portions, respectively. Lougee (1939) first used the term Lake Hitchcock to apply to the water body that extended from Rocky Hill, Conn., to Lyme, N.H. This name includes the four interconnected lakes mentioned above as well as the lake occupying the valley north of the Massachusetts border (Fig. 2). Lake deposits in the valley north of Lyme were considered by Lougee to be part of a lower level younger glacial lake, named Lake Upham (Lougee, 1939).

"Rhythmite" and "varve" are terms used interchangeably in this report, even though there is the following important distinction



Figure 1. Location map of the portion of glacial Lake Hitchcock covered in this study.



LAKE  
HITCHCOCK

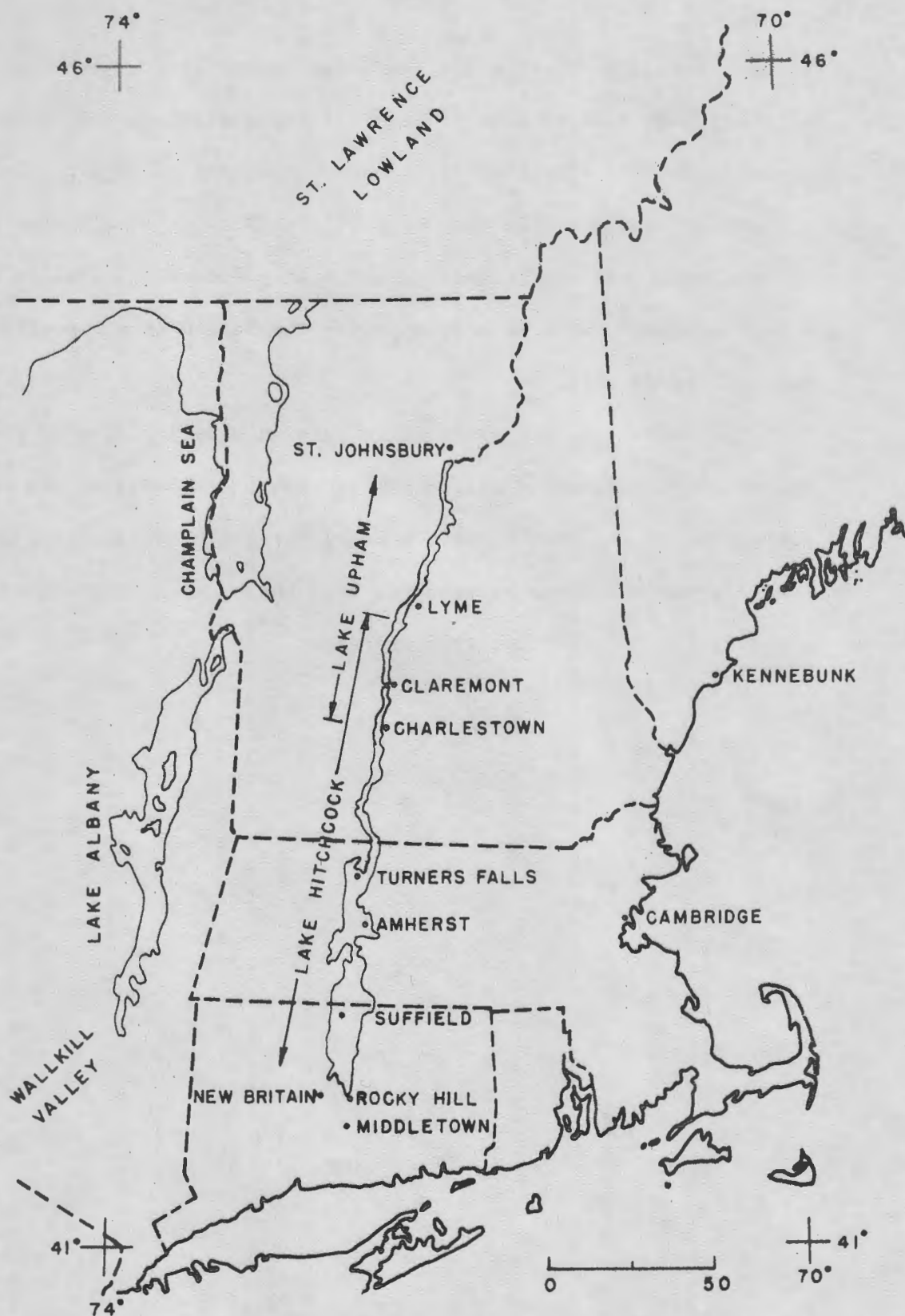
MASS.

CONN.

R.I.

Figure 2. Map of pertinent places mentioned in this study  
(after Flint, 1959).





between them: rhythmites are individual units (i.e., couplets) of rhythmic beds with no time or seasonal connotation (A.G.I. Glossary, p. 246), whereas varves are couplets, regardless of origin, that represent an annual period (De Geer, 1912). Although the annual nature of Lake Hitchcock rhythmites has not been proved conclusively, the common usage of varve as a synonym for the lake-bottom deposits justifies its usage here.

The intent of this study is to gain an understanding of the mechanism of sediment distribution in the lake as well as the method of deposition of the rhythmites. A model for sedimentation in glacial Lake Hitchcock can now be proposed from the studies of grain-size distribution and sedimentary structures.

## ACKNOWLEDGEMENTS

Funds for this project were obtained from a Grant-in-aid of Research from the Society of Sigma Xi and from the Department of Geology and Geography, University of Massachusetts. Special thanks are extended to Professor Joseph H. Hartshorn, supervisor of the project. Professors John F. Hubert and Leo M. Hall read the manuscript and made many helpful suggestions. Discussions with Professor Miles O. Hayes, as well as with many of the graduate students involved in Pleistocene research at the University, were particularly helpful. Eugene G. Rhodes wrote the computer program used in determining the grain-size parameters. Appreciation is extended to Bruce Tiffney for identification of the plant fossils and Professor Stephen E. Haggerty for assistance in mineral identification using the x-ray diffractometer.

For development of the process of impregnation of unconsolidated sediments, the author is grateful to Dr. David E. Hill (Connecticut Agricultural Experimental Station), who provided information for the basic technique and to Professor Thomas R. Stengle, who advised on the selection of laboratory equipment. The completion of this project would have been impossible without the support of Mrs. Ida E. Wright as well as the drafting and continued encouragement of my husband, Stuart Ashley.



## GEOLOGIC HISTORY

The latest glacial maximum of the Laurentide Ice Sheet in northeastern United States took place approximately 25-20,000 years ago. Ice recession is thought to have taken place predominantly by stagnation-zone retreat (Currier, 1941; Flint, 1971). Moraines, indicating solid-front retreat, are few and generally occur in areas of fairly low relief. MacDonald (1968) suggests that difference in topographic relief is responsible for the two basic patterns of deglaciation.

Evidence for the presence of a specific ice front or of a glacial readvance has been reported from various areas (Fig. 3). Both the radiocarbon dates and the estimated dates are approximate within 400 to 900 years. Many minor readvances probably took place during ice retreat. These may have been local ice-margin fluctuations and not readvances of the entire ice sheet. Thus two areas, each with evidence for a readvance, are not necessarily correlative, although the evidences might indicate ice-front positions. Summarizing dated ice-front positions from Figure 3, it appears that the glacial margin occupied central Connecticut between 14,000 and 13,500 B.P.

During deglaciation of the Connecticut Valley, temporary proglacial lakes developed, commonly dammed by the ice itself or by drift deposits. Into one such lake south of Rocky Hill, Connecticut, a large concentration of stratified drift was deposited and filled a narrow portion of the valley (Schafer and Hartshorn, 1965). This mass of debris acted as a dam for glacial melt water during the continued ice-front retreat in the valley. The beginning of the lake has been

Figure 3. Dates relevant to the geologic history of glacial Lake Hitchcock. See Figure 2 for geographic locations.

Location	Date	Explanation	Reference
Wallkill Valley, N.Y.	<15,000 B.P.  Rosendale readvance	Pollen analyses with correlations to dated <u>sequences</u> -----	Connally and Sirkin, 1970
	>12,400 $\pm$ 200 B.P. (L-3199)	Date taken from a bog (Pine Log Camp) north of the valley means the glacier had already retreated from the area.	Connally, 1968
Middletown, Conn.	13,500 B.P. readvance	Till over disturbed lake sediments. Est- imate based on older dates to the south.	Flint, 1956
	13,000 B.P.	Pollen analyses indicates ice had retreated from southern Conn.	Deevey, 1958
	12,200 $\pm$ 350 B.P. (W-828)	Suffield, Conn.; base of bog on the Farm- ington River delta of Lake Hitchcock.	Colton, 1961
Cambridge, Mass.	14,250 $\pm$ 250 B.P. (W-735)	Fresh Pond Moraine deposited over clay containing barnacle plates.	Chute, 1959
	13,800 $\pm$ 300 B.P. (L-598A)		Kaye and Barg- hoorn, 1964
	11,600 $\pm$ 300 B.P. (W-1802)	Peat from kettle on top of till.	Marsters and others, 1969
	Glacial advance  12,275 $\pm$ 300 B.P. (W-1801)	Peat on top of marine clay at base of till.	
Southeastern Maine	12,800 $\pm$ 450 B.P. (W-1011) -----	Shell date taken from esker. This glacial feature indicates presence of ice as a source.	Borns, 1963
	11,800 $\pm$ 240 B.P. (W-737)	Shell date from marine sediment deformed by ice movement. Sediments are of mixed glacial and marine origin.	Bloom, 1960

arbitrarily given the date of 13,700 B.P., because it was in the approximate time period of 14-13,500 B.P. that the glacier stood in central Connecticut (Flint, 1956).

Elevations taken from beaches and from topset/foreset contacts in deltas show that Lake Hitchcock had at least three stable lake levels south of the Mt. Holyoke Range (Hartshorn and Colton, 1967). But by the time ice had retreated north of the range, the southern outlet at New Britain had apparently stabilized and only one water level is observed for the remaining lake to the north.

The weight of the Laurentide Ice Sheet created a crustal downwarping which increased in magnitude to the north. Due to this isostatic depression, the waters of Lake Hitchcock always were in direct contact with the glacier front. The lake was able to grow northward and still have its level controlled at the southern end by the New Britain spillway. Rapid drainage, and thus the end of the lake, occurred when the dam was breached at Rocky Hill (Schafer and Hartshorn, 1965). A topographic high near Charlestown, N.H., limited southern drainage (Fig. 4). Consequently, a lake (Lake Upham of Lougee, 1939) formed to the north of the high and a river flowed away to the south. The river was the ancestral Connecticut River and was graded to a bedrock dam (the Lily Pond barrier) near Turners Falls, Mass. (Jahns and Willard, 1942).

The following field evidence indicates the presence of the glacier front when the lake drained. Lake Hitchcock deposits end at Lyme, N.H., and are overlain by a thick sand unit. On top of the sand is another

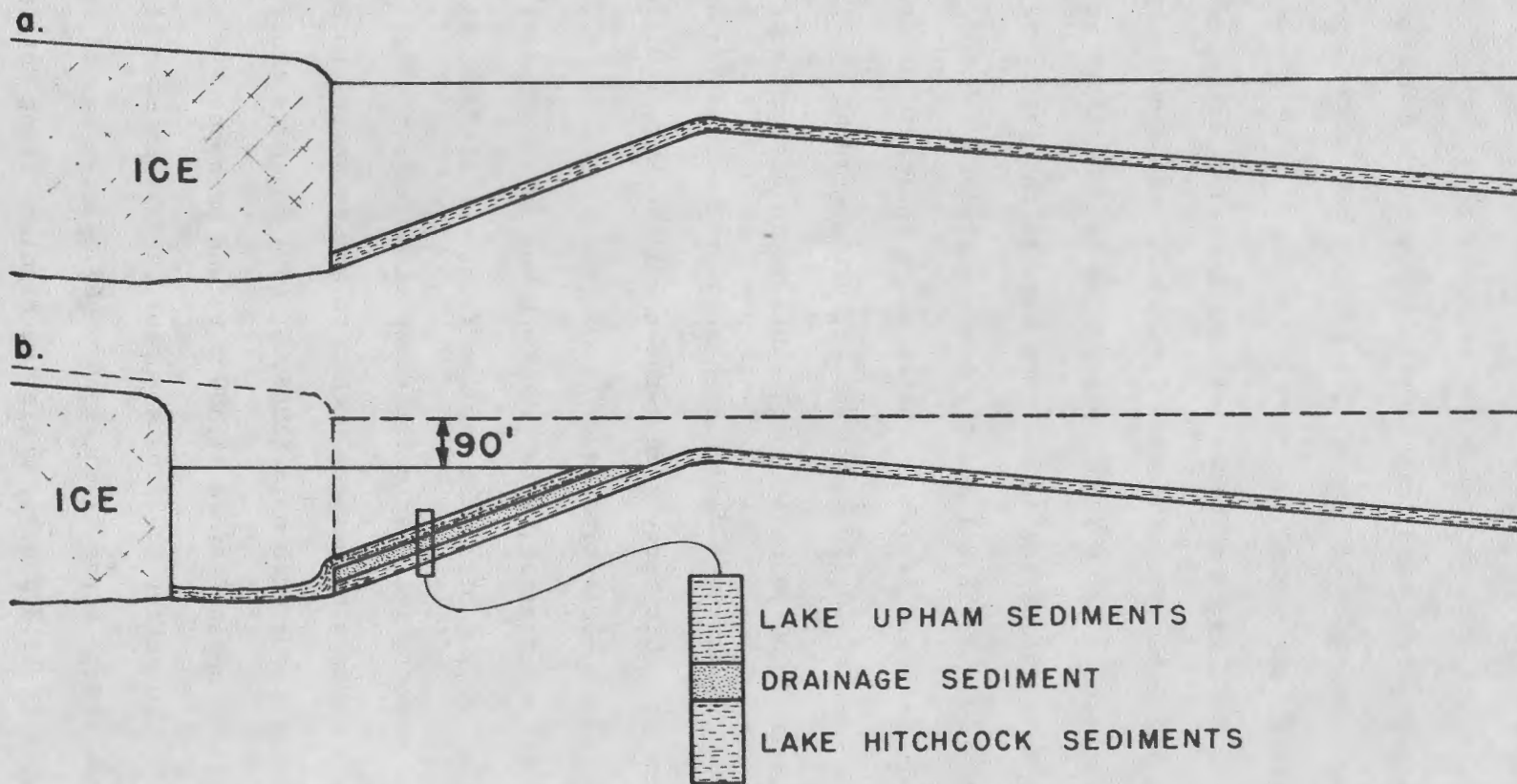


Figure 4. Drainage of Lake Hitchcock and the commencement of Lake Upham. a. Lake Hitchcock      b. Lake Upham

LYME, N.H.

CHARLESTOWN, N.H.

MASS./N.H.  
BORDER



(NOT TO SCALE)

sequence of lake clays, which overlap Lake Hitchcock sediments to the south and are continuous to the north (Fig. 4b). Lougee (1939) interpreted the sand unit as a Lake Hitchcock drainage deposit and the overlying clays as those of a younger but lower level lake, which he called Lake Upham.

The length of time that Lake Hitchcock lasted should be known in order to interpret the sediments accurately and to understand the sedimentary processes. Flint (1956) placed the lake drainage at 10,700 B.P., based on two radiocarbon dates. One date is thought to be pre-lake drainage ( $10,700 \pm 330$  B.P.) and the other post-lake ( $10,650 \pm 320$  B.P.). The only estimate of lake duration using radiocarbon dating is based on this one date of  $10,710 \pm 330$  B.P. Thus, according to Flint, Lake Hitchcock lasted 3,000 years at most. This is in disagreement with the varve count by Antevs (1922), which suggested a duration of 4,100 years. Later in this study some reasons will be suggested for the discrepancy between these estimates.

To summarize, Lake Hitchcock was an ice-contact lake, which drained about 10,700 B.P. when the ice front was situated in Lyme, N.H. If this is correct, ice was in the Connecticut Valley about 1,000 years after Lake Champlain had been opened to marine waters through the St. Lawrence lowland, for MacDonald (1968, p. 675) suggests that the Champlain Sea episode began "before 11,500 B.P. and perhaps as early as 12,000 B.P."

Two active ice fronts appear to have existed at approximately the same time. Borns (1963, 1966, 1967) places an ice front in southeastern Maine at 12,800 B.P., while the Highland Front Moraine was thought to

have been deposited around 12,600 B.P. (MacDonald, 1968, p. 676). In addition, abundant evidence exists for zonal stagnation occurring in New England (Schafer and Hartshorn, 1965, p. 120) and perhaps for widespread stagnation occurring in portions of New England (Maine) (Borns, 1963, p. 739).

To reconcile the above evidence, it has been suggested in papers by MacDonald (1967) and Borns (1963), and on isochrone maps (Prest, 1969; Bryson and others, 1969), that as the ice retreated it thinned, and a reentrant developed in the St. Lawrence Lowland (Fig. 5). A large mass of ice situated over northern New England separated from the Laurentide Ice Sheet to the north and became independent. Nourished from the White Mountains, this ice mass might have been responsible for indications of ice being present as late as 11,000 B.P. at Kennebunk, Maine (Bloom, 1960), and at Boston, Mass. (Marsters and others, 1969).

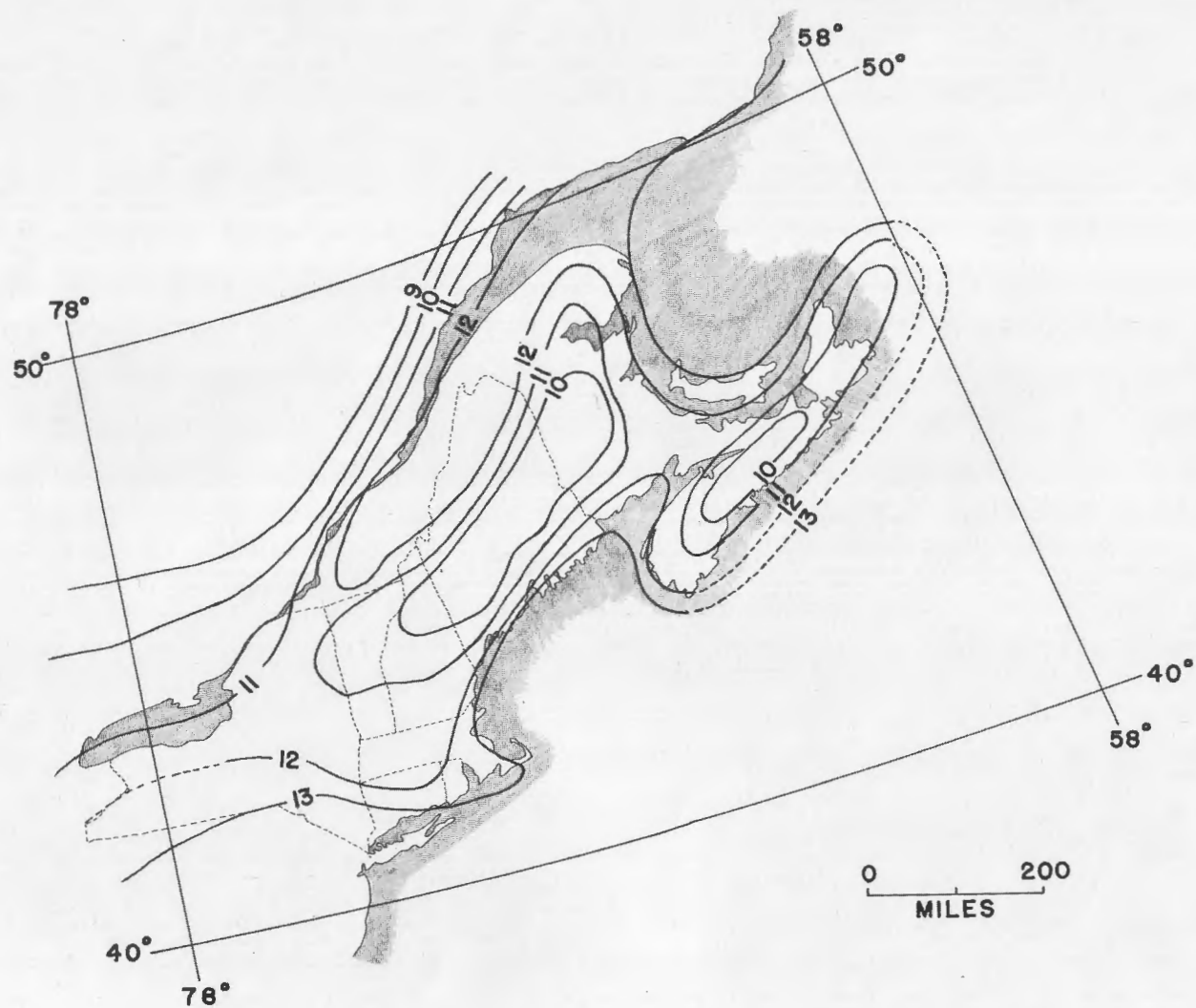
What effect this ice mass would have had on Lake Hitchcock can only be conjectured. But its presence might have been a deterrent to vegetation and thus explain the paucity of organic remains in the lake deposits as a whole. The small amounts found, to discussed later, occur near the top of the lake sediments and have been identified by Emerson (1898) and in this study as arctic-alpine flora.

#### METHODS AND PROCEDURES

Even though lake clays underlie a considerable portion of the Connecticut River valley, they are seldom exposed. Only construction sites or actively eroding streams provide vertical faces for



Figure 5. Radiocarbon isochrones of the retreat of the Laurentide Ice from New England show that as the ice thinned a reentrant developed in the St. Lawrence lowland. A large area of ice situated over northern New England separated and became independent (after Bryson and others, 1969).



observations and sampling. The 34 localities used in this study represent most of the outcrops available during the summer of 1969. Wells drilled in lake sediments show that in places the clay is over 250 feet thick. The study samples were taken mostly from the top half of the section and thus are temporally biased (Fig. 6). Interpretations made hold only for that time during the lake history when these sediments were being deposited.

#### Sampling procedure

The outcrops were scraped to produce vertical faces. Oriented slab samples were removed and allowed to dry for several days before detailed observations and photographs were made. A couplet (a silt layer and overlying clay layer) from each sample was divided for grain-size analysis into 2, 3, or 4 parts parallel to the silt-clay contact. Five unusually thick clay layers from different localities were cut horizontally into 4 parts to determine any change in grain size within the layer. A total of 153 samples were pipetted using the method described by Folk (1968). Three samples which had more than 5 percent coarser than  $4\phi$  were dry sieved. Statistical analyses were done both by the method of moments (Folk and Ward, 1957) and by graphical methods using the IBM 3600 computer.

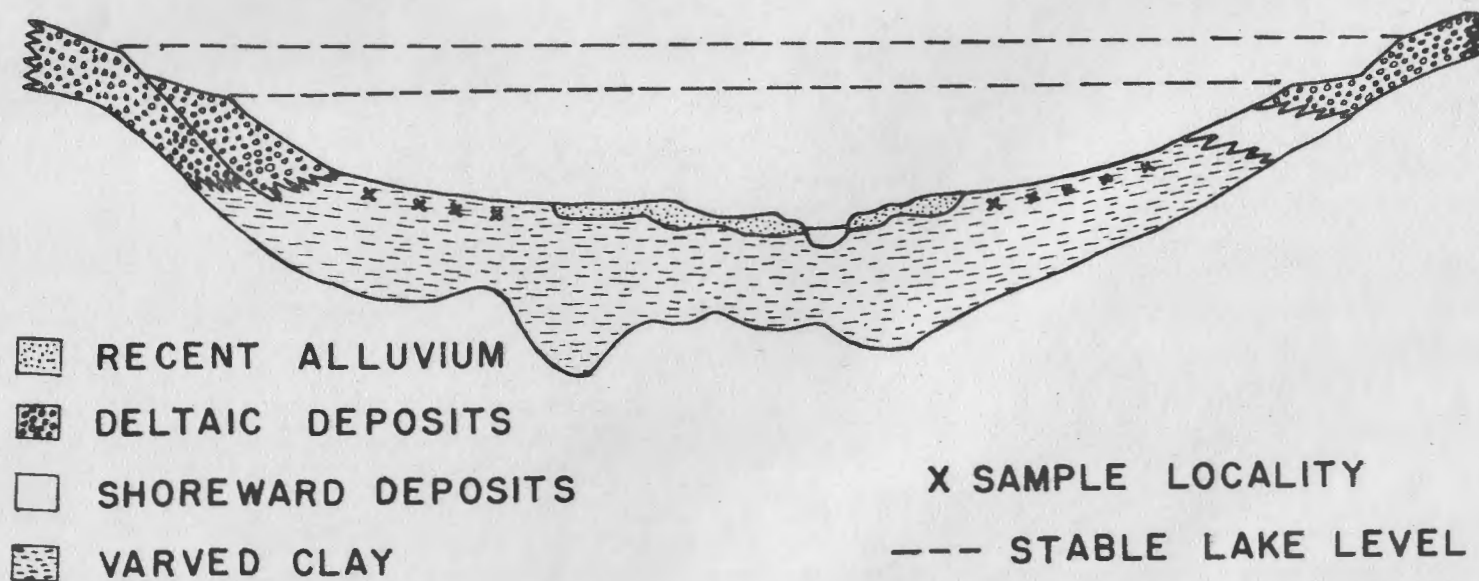
#### Impregnation process

In order to study adequately the small-scale sedimentary structures in the silt layers, 19 samples were impregnated with a polyester resin to facilitate thin-sectioning. The method was a modification

Figure 6. Generalized facies distribution diagram.



# SEDIMENT FACIES DISTRIBUTION OF GLACIAL LAKE HITCHCOCK



after Altemuller (1962), using the laboratory apparatus shown in Figure 7a. Samples (approximately 60 cc) are thoroughly dried and placed in tin containers in the dessicator. A Y-tube is arranged so that the containers can be repeatedly filled with formula while under continuous vacuum. To prevent pump damage, a system should be set up to trap styrene vapors as they are drawn from the dessicator. A glass trap immersed in a mixture of dry ice and acetone will create temperatures low enough to solidify the styrene vapor as it passes through.

Table I. Formulas used in the impregnation process.

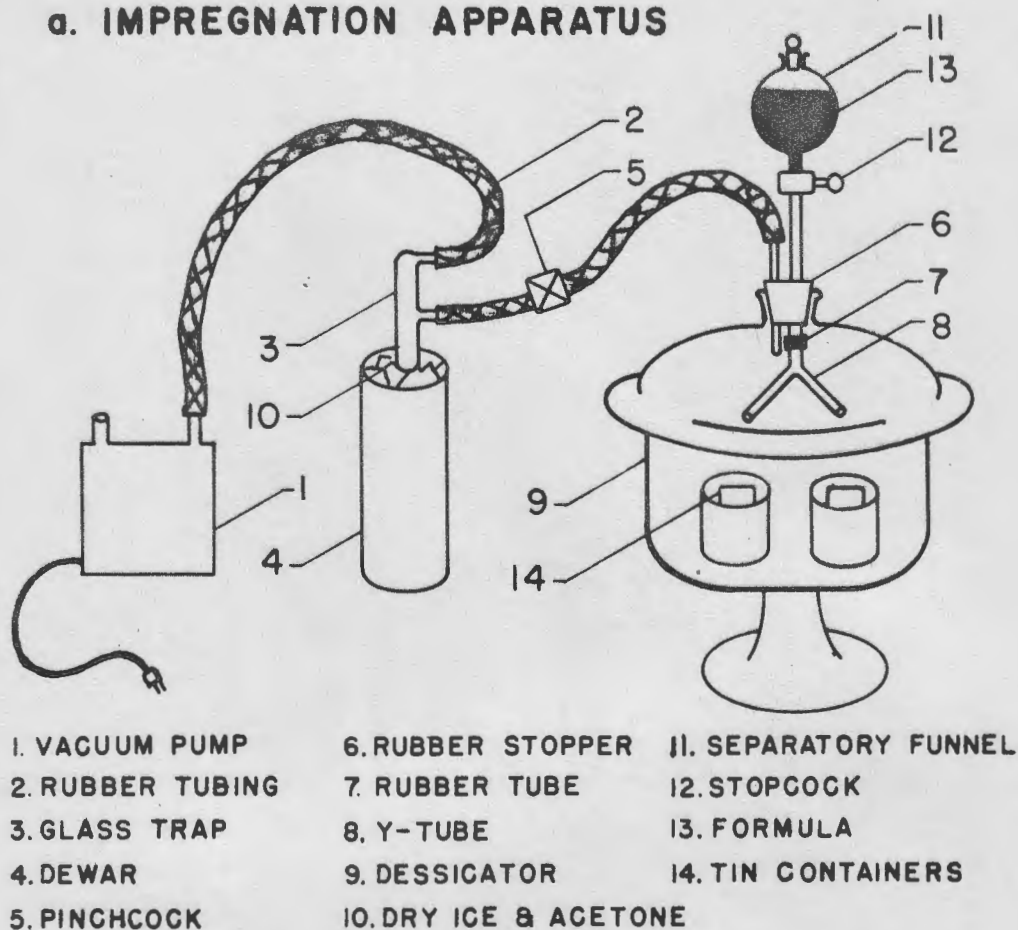
<u>Formula I</u>	<u>Formula II</u>	<u>Formula III</u>
300 ml Vestopal H	100 ml of Formula I	100 ml Vestopal H
250 ml styrene	.3 ml cyclohexanone- peroxide (85% solution)	.3 ml cyclohexanone- peroxide (85% solution)
.8 ml cobalt naphthenate (6% solution)		5 drops cobalt naphthenate (6% solution)

Formula I (Table I) should be mixed and stored as stock solution in a dark-colored bottle. Formula II is the working solution and once mixed must be used immediately. Formula III is used only if complete encasement of the sample in resin is desired.

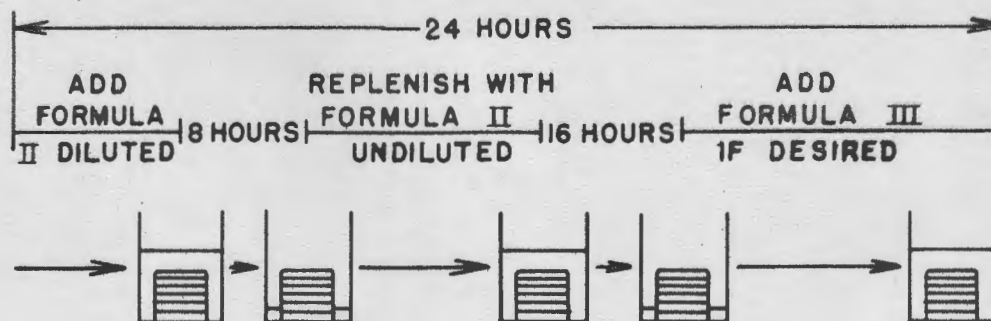
To impregnate the samples, Formula II is added to the separatory funnel with stopcock closed (Fig. 7b). The pump is started and allowed to run 15 minutes after reaching equilibrium (at least 15 mm Hg) to insure that all air has been removed from sediment pores before any formula is added. Following the timing procedure suggested in Figure 7b, the vacuum is maintained for 24 hours. Formula is drawn into the

Figure 7. a. Laboratory apparatus used in impregnation of  
varved clays.  
b. Timing of formula additions.

## a. IMPREGNATION APPARATUS



## b. TIMING



tin containers by periodically opening the stopcock until the sample is saturated. For the first addition, the suggested ratio of Vestopal H to styrene in Formula I is changed from 6:5 to 3:4 because it facilitates penetration into the minute pores of the silt layer. Once capillaries are wetted, passage is easier for subsequent additions of undiluted formula. It is important that undiluted Formula II be used to finish the impregnation process, because the solidified end product has sufficient strength for grinding and is stable against solvents.

After 24 hours the samples are removed and allowed to dry slowly at room temperature for several days before thin-sectioning.

#### GENERAL FEATURES OF THE LAKE SEDIMENTS

Sediments consisting of alternating coarse- and fine-grained layers were deposited over almost the entire lake bottom. Individual couplets have been traced laterally 100 feet with no significant change in thickness, but thickness of lake deposits as a whole varies noticeably. The lake-bottom sediments are thickest in depressions and thinnest over highs (Figs. 8, 9, 10, and 11). In fact, clay is completely absent on some topographic highs on the lake bottom (Hartshorn, Campbell, oral commun.). Figure 11 shows an example of a subaqueous high where Campbell saw no obvious evidence of subsequent erosion. Along the shore, sediments probably were reworked by waves in the summer and disturbed during the winter by ice rafting. This disturbed material has been referred to as shoreward deposits (Jahns and Willard, 1942) and lies



Figure 8. Index map of glacial Lake Hitchcock shows sample and cross-section localities (Hartshorn, oral commun.). The dashed shoreline west of the Mt. Tom Range is the projected strandline of the lowest stable lake level. Latest findings indicate that only local, discontinuous, high-level lakes existed in the area and not a large continuous water body connected to the main part of glacial Lake Hitchcock (Larsen, oral commun.).

# GLACIAL LAKE HITCHCOCK - SAMPLE LOCALITIES

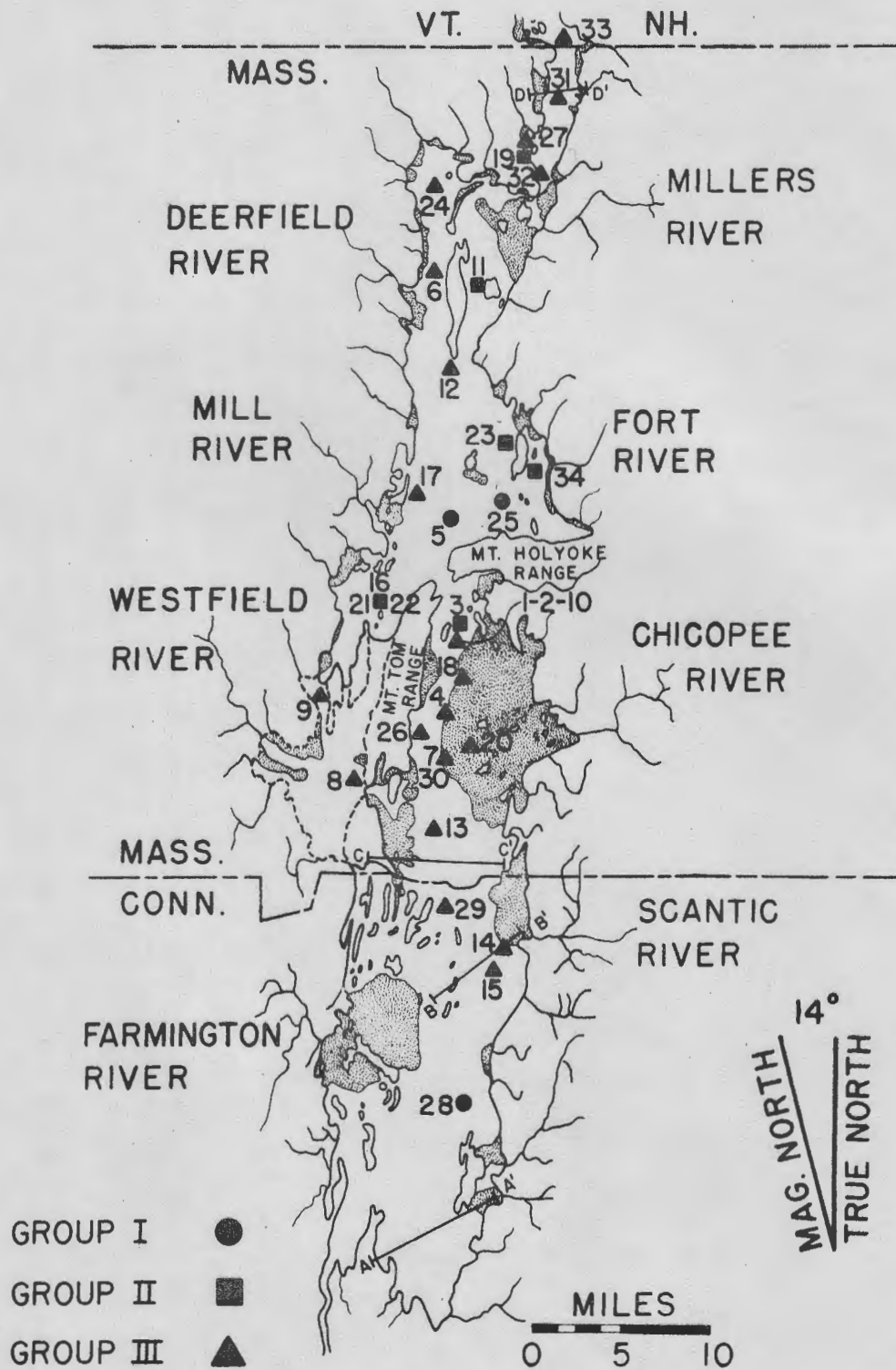
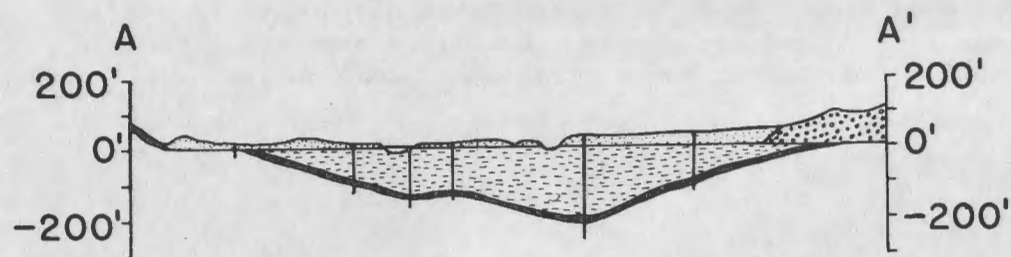
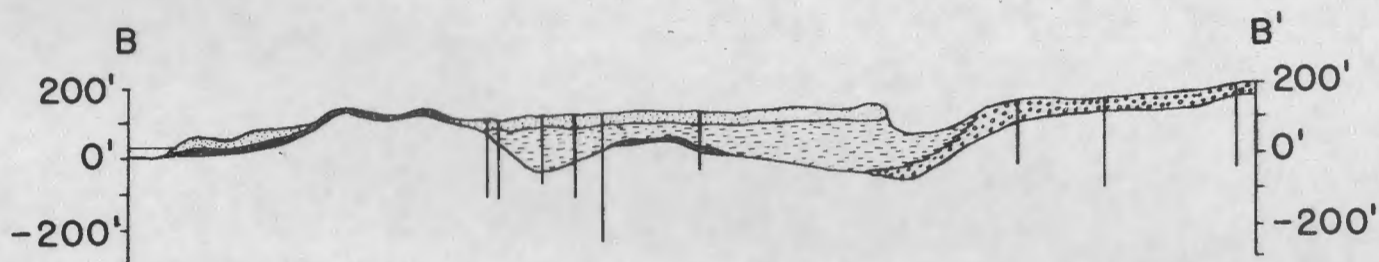






Figure 9. Cross sections, a few miles in width, show a thickening of lake sediments in low areas and thinning over highs (Cushman, 1964).

# CONNECTICUT



200'  
1/2 mi.

VE = 10 X

-  RECENT ALLUVIUM
-  DELTAIC DEPOSITS
-  VARVED CLAY
-  TILL

AFTER WATER-SUPPLY PAPER 1752  
ROBERT V. CUSHMAN

Figure 10. Information from seven wells shows till to be continuous under the lake sediments; varved clay is thickest in the low areas and thinnest over high areas. Data from Moser (oral commun.).



# SOUTHERN MASSACHUSETTS

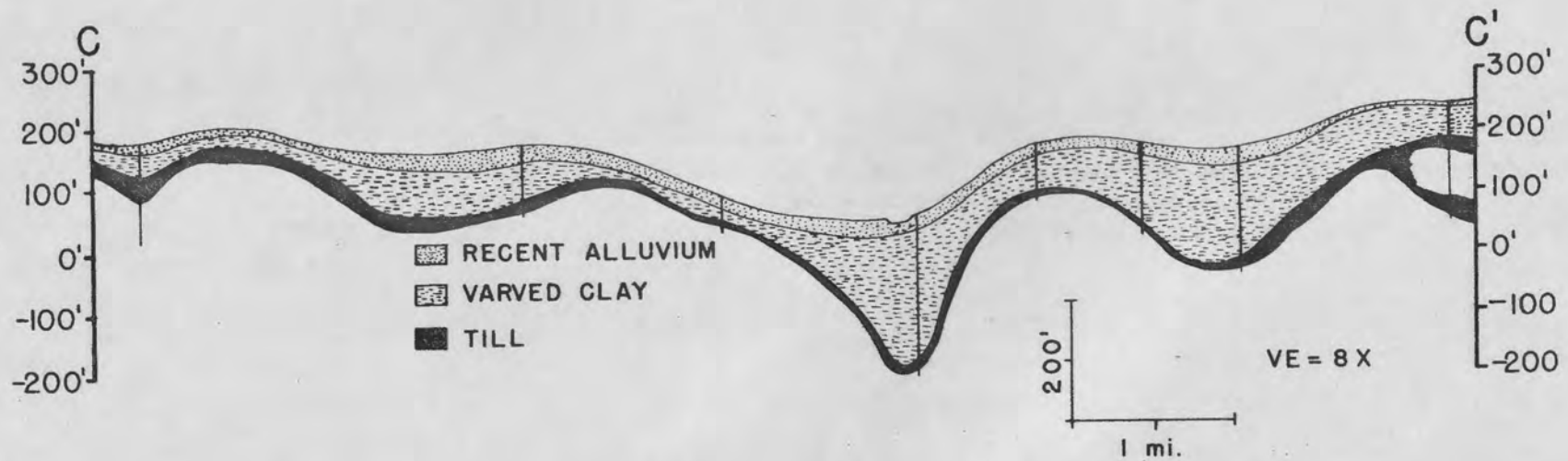
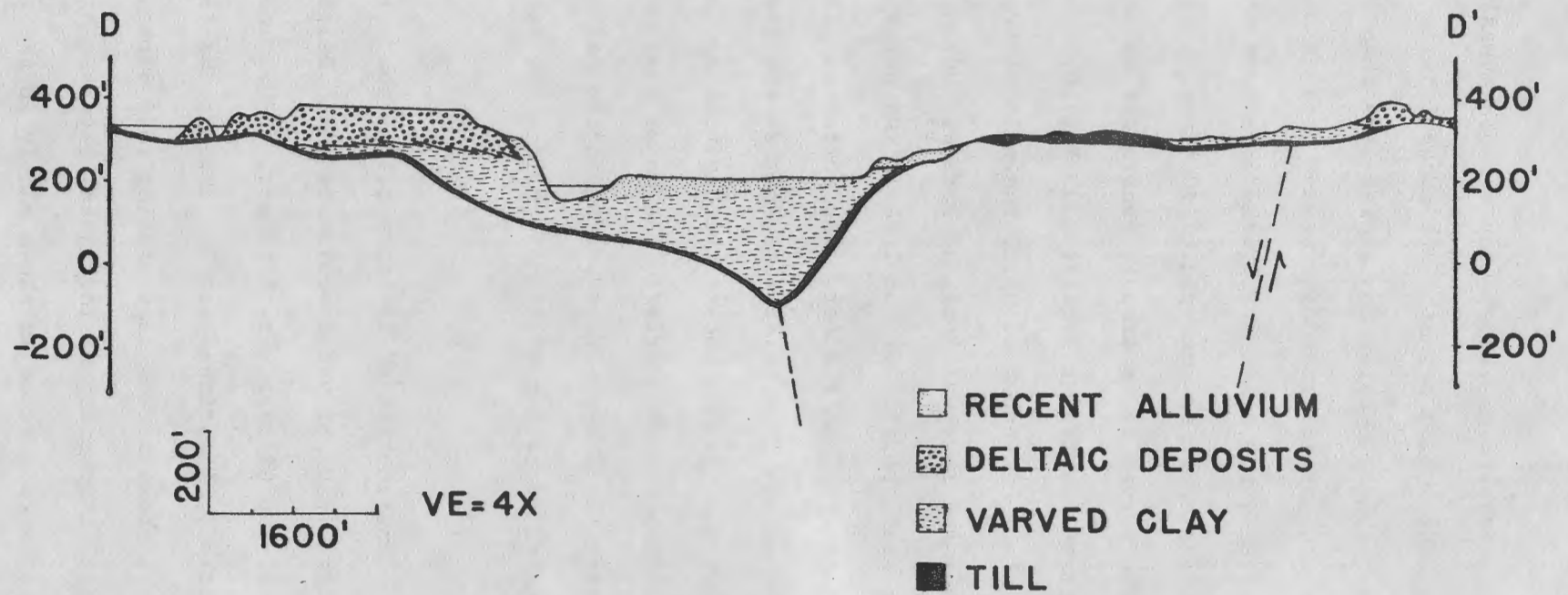


Figure 11. Clay is thickest in the low areas and thin to absent over the high areas. The section between the eastern fault and the preglacial river valley has no clay even though it was subaqueous and there is no obvious evidence of subsequent erosion (Campbell, oral commun.).

# NORTHFIELD, MASS.



laterally between varved clay and beach sediments (Fig. 6).

Lake-bottom deposits are exceptionally fine grained, with silt-clay couplets usually containing less than 2 percent fine sand. They are easily eroded and seldom present a vertical exposure of any magnitude, but seismic and well data have shown them to be more than 250 feet thick in some places (Cushman, 1964). The rhythmic nature of the varves is remarkably consistent as demonstrated by the 625 couplets counted at locality 30 (Fig. 8).

Lake Hitchcock occupied the natural trough of a preglacial river valley and thus was long and narrow. During glacial retreat, only that small portion of the lake at the north end was ever in direct contact with the glacier. The bottom or oldest sediments were derived mainly from valley ice, but as the glacier receded northward ice on the uplands became the dominant sediment source and supplied large amounts of debris to the major east- or west-flowing rivers feeding the lake. Crossbedding in the silt layers corroborates the inferred direction of transport from the bordering highlands.

#### Deltas

Construction of the many deltas that fringed the lake was an integral part of varve sedimentation. Deltas, commonly very large, are of the Gilbert type (Gilbert, 1890), indicating fresh-water deposition. A vertical section through the largest delta, the Chicopee delta, shows varved clay grading into varved deltaic deposits by a gradual thickening of individual layers. At any one depositional site, delta advance is shown mainly in the thickening of fine sand

and silt layers. Dimensions of the clay layers remain relatively constant (Table II).

Table II. Individual layer thickness at Locality 4.

	Proximal portion of delta	Distal portion of delta
Winter	.5 in.	.3 in.
Summer	30.0 in.	.6 in.

The encroachment of the delta is also shown in the different sedimentary structures within a silt layer. Multiple graded beds are common at the distal end of the prodelta slope, whereas festoon ripples, ripple-drift, and an undulating ripple form dominate the proximal end. These sedimentary structures indicate that during most of delta construction there was abundant sediment and rapid deposition. This, in turn, implies that the bulk of delta building occurred when glacial ice occupied the drainage basin of a particular delta. The nearby ice may have limited the vegetation and thus allowed more sediment to be transported to the lake.

The time needed to construct a large lacustrine delta can be determined from the Farmington River delta (Fig. 8). A date of 12,200 B.P. was obtained from a bog developed on the delta when it was no longer active (Colton, 1961). Assuming that the lake commenced about 13,700 B.P. and the delta shortly afterwards, fairly rapid deposition is indicated.

Retardation of delta building is probably related to the disappearance of glacial ice from the environs of the delta, as discharge and the necessary sediment supply would decrease without the ice as a



source. This relationship can be extended to most of the other Lake Hitchcock deltas, which probably continued to grow as long as the lake existed, but at a slower rate.

During construction of the large deltas, sedimentation probably occurred on only a small segment at one time, although this locale would change often. For instance a particularly sharp increase in varve thickness was observed at three localities in the Chicopee delta. Within a few vertical feet, the silt layer doubles in size while the clay layer thickness remains about the same. The change occurs at about the same elevation at localities 30 and 7 (Fig. 8), which are close to each other and probably the same horizon. A similar change occurs at locality 4, but 35 feet above the other horizon, and it is assumed to be unrelated. The feature is interpreted as a record of change in direction of the stream building that part of the delta.

A pattern of active deltaic sedimentation, followed by decreased deltaic sedimentation, apparently was characteristic of Lake Hitchcock, and is recorded in a group of closely spaced localities (1, 2, 3, and 10), as well as at locality 30. The changing growth pattern is interpreted from the gradual increase and decrease in silt-layer thickness and mean grain size (Fig. 12) as well as from fluctuations in other statistical parameters (Fig. 13). These trends reflect diminishing sediment supply as the glacier retreated northward.

#### Lake stratigraphy

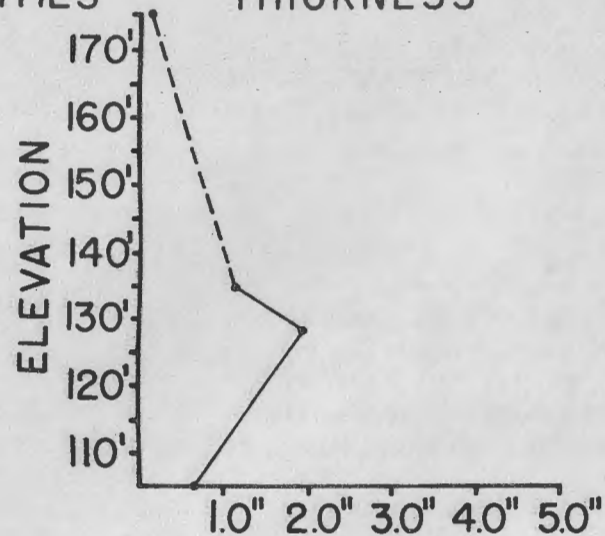
Lake Hitchcock sample localities occur in all stratigraphic positions from basal to uppermost varves, with most of the sites in

Figure 12. Average silt-layer thickness within each one-foot thick sample and the mean grain size (computed graphic mean) of the coarsest silt layer within the sample were plotted against elevation of the sample site. A gradual increase and then decrease of silt-layer thickness and mean grain size is interpreted as reflecting active delta building and then diminishing sediment supply as ice disappeared and vegetation encroached into the Chicopee drainage area.

# SILT LAYER

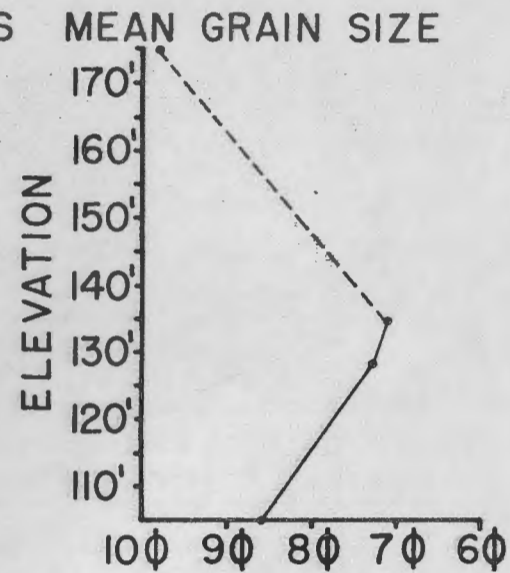
LOCALITIES

1, 2,  
3, 10



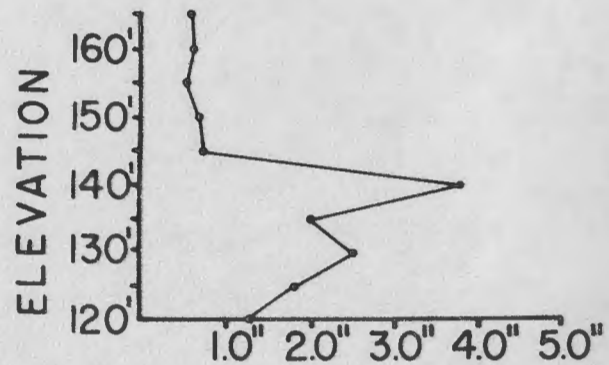
LOCALITIES

1, 2,  
3, 10



LOCALITY

30



LOCALITY

30

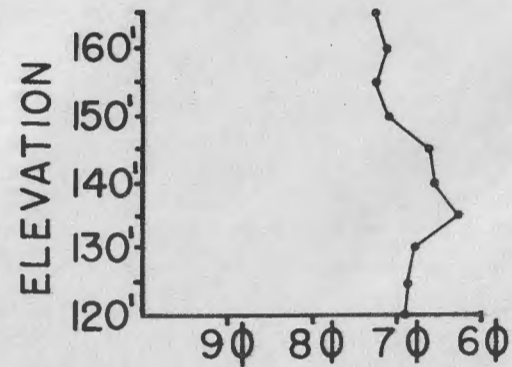
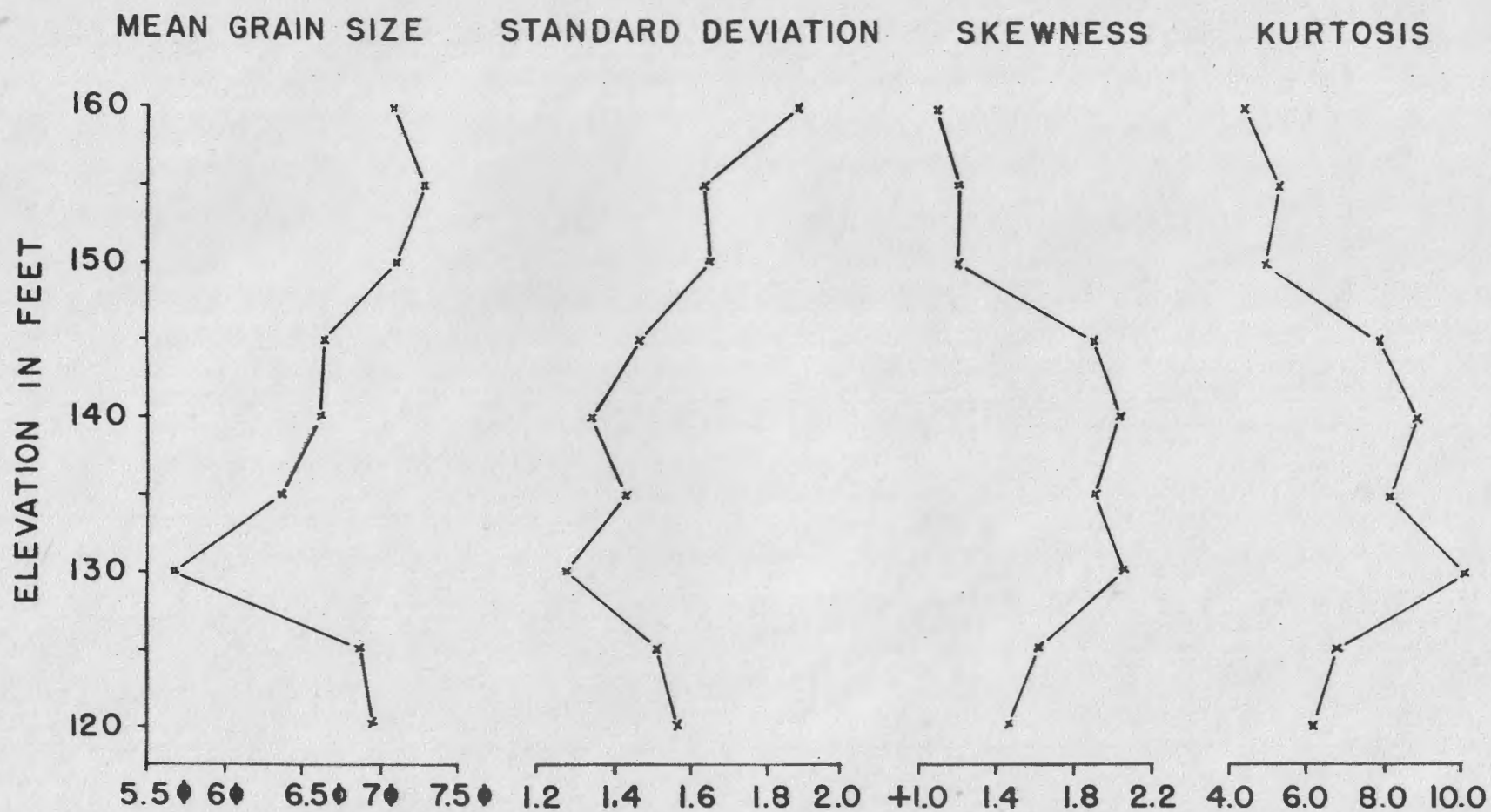


Figure 13. Data (computed by method of moments) from the coarsest portion within the silt layer of one couplet is plotted to show change occurring in a 45-foot section of varves located in the Chicopee delta. These trends reflect diminishing sediment supply as the glacier retreated northward.





the top half of the section. A general summary of lake stratigraphy has been compiled from the study of all localities.

Basal varves are usually thicker than other couplets in the column (Fig. 14), and it is assumed that this is due to the nearby glacier. With a decrease in direct inflow of melt water from the ice, the thickness of succeeding varves depends on how close the locality is to an actively building delta. Active delta growth followed by decreasing growth is shown by a corresponding change in varve thickness and mean grain size. A section of varved clay in Lake Hitchcock that was not influenced by nearby delta building would consist of gradually thinning varves capped with alluvium or with a thin layer of sand deposited during final lake drainage.

Once the glacier had retreated into New Hampshire and Vermont and vegetation had become established, sedimentation was limited to the slow settling of clay, except in areas off deltas where moderate amounts of nonglacial sediment were brought from the many drainage basins surrounding the lake. The end of lake sedimentation is recorded near the top of every undisturbed section, but the type of contact varies depending on position in the lake. I have found this upper contact to be of three kinds (Table III). Jahns and Willard (1942, p. 286), in their work in the Connecticut Valley, described the upper contact as normally gradational. In this study, the gradational type was found associated only with deltas. In some localities the upper contact of the varve was an erosional unconformity overlain by river alluvium.

Figure 14. Basal varve at locality 29. a. Couplets with thick silt layers are assumed to be due to the nearby glacier. b. Till (below arrow) overlain by varved clay.

a.



b.



0 CM 3

Table III. Three kinds of upper contacts found in glacial Lake Hitchcock.

Upper contact	Explanation
Thinning varves, capped with a thin layer of sand (2-5 ft).	Areas not influenced by deltas: sands deposited during drainage of glacial lake.
Thickening and coarsening of silt layers changing gradually to sand. Clay eventually disappears.	Building out of delta until clay no longer accumulated on pro-delta slope to define yearly sedimentation.
Top varve contorted, capped with sands.	Post-drainage disturbance with no obvious erosion. Sands deposited during drainage of glacial lake.

Lake Hitchcock was drained by downcutting through the drift at Rocky Hill. The lake lowered 90 ft (the observed amount at Lyme, N.H., Fig. 4) and only small water bodies remained in isolated basins that may or may not have been interconnected by an ancestral glacial Connecticut River. The change in base level caused rivers draining into the lake to incise their valleys and deltas and spread sand and silt on the newly exposed lake floor. Jahns (1967) estimated that an isolated lake in central Massachusetts (Lake Hadley) existed for at least 60 years before the Connecticut River completely drained the valley.

#### Grain-size distribution

Mean grain sizes of the clay layers are relatively constant (averaging 10.5 $\phi$ ) throughout the lake, whereas mean grain size in the

silt layers varies according to environment of deposition. The coarsest sediments ( $M\phi = 5.5\phi$ ) occur in the silt layers of Group III and are usually associated with deltas; the finest sediments ( $M\phi = 8.5\phi$ ) are found in Group I in areas distant from the larger rivers.

On a scatter plot of standard deviation ( $s\phi$ ) versus  $M\phi$ , samples from Lake Hitchcock show a nearly complete separation of classical summer and winter deposits in the sense of De Geer (1912) (Fig. 15). On the average, summer samples are both coarser and better sorted than winter samples. Summer layers with crossbedded units were plotted separately; they are coarsest and best sorted of all samples taken. The samples containing crossbeds plot in a cluster around  $6\phi$ , showing that the occurrence of crossbedding is at least partly controlled by grain size. Folk and Ward (1957) found that when a  $s\phi/M\phi$  plot was made of a sediment sample containing sand, silt, and clay a sinusoidal trend results. They attributed the trend to the basic populations of grain sizes created during mechanical and chemical rock weathering. Figure 15 shows the fine end of such a trend, although the apex centers between  $9\phi$  and  $10\phi$  rather than at  $8\phi$  as found by Folk and Ward. The shifting of the curve toward the finer grain sizes might be related to glacial processes of rock disintegration that produce slightly finer populations. A more likely explanation may be found in the sorting processes occurring between the glacier and the depositional site within the lake.

A distinct trend results when skewness ( $sk$ ) vs.  $M\phi$  of both classical summer and classical winter samples is plotted (Fig. 16). The



Figure 15. Scatter plot (mean grain size versus standard deviation) of analyses of glacial Lake Hitchcock samples. Analyses of composite samples (containing both silt and clay layers) were not plotted. Dashed lines enclose the range of  $s\phi/M\phi$  values for the crossbedded units and for the classical "summer" silt and "winter" clay layers.

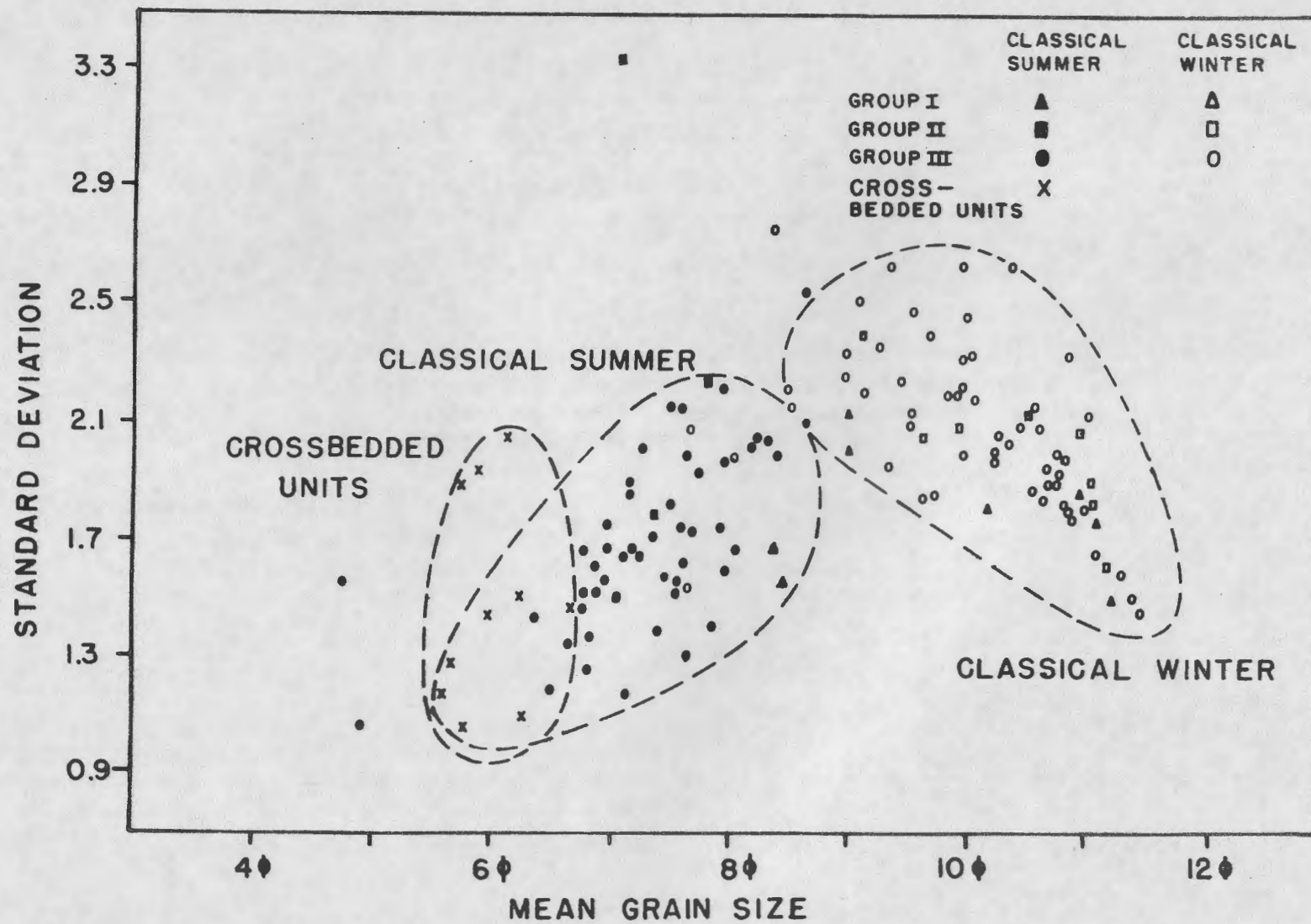
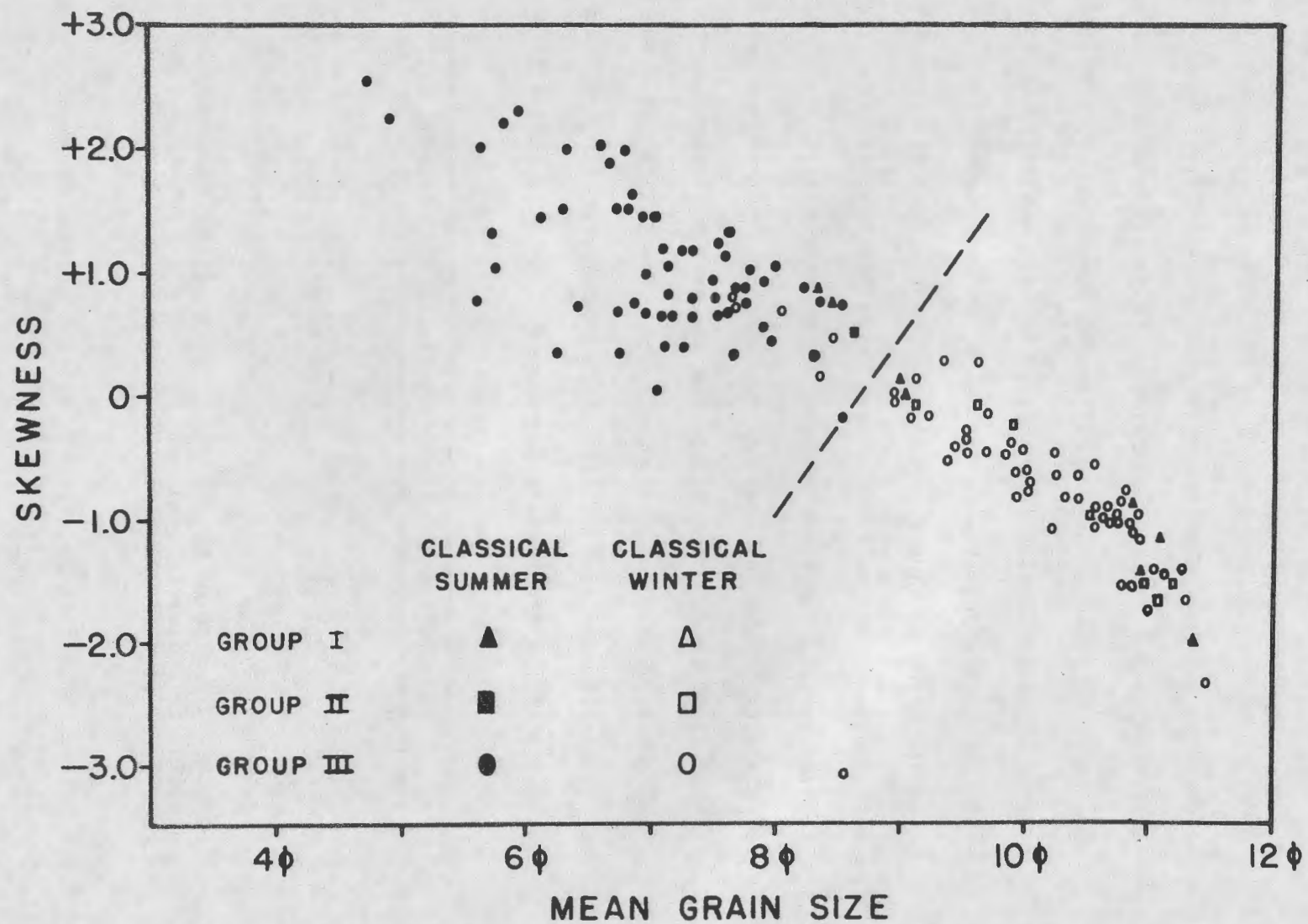


Figure 16. Scatter plot (mean grain size versus skewness) of analyses of glacial Lake Hitchcock samples. Dashed line separates classical summer from classical winter samples.



summer samples are coarser and positively skewed, while the winter samples are finer and negatively skewed. Bimodality is commonly the cause of pronounced skewness (Folk and Ward, 1957). Thus during the process of sedimentation clay probably was incorporated into the silt layer and silt into the clay layer. The positive skewness of the summer layer could be due either to continuous settling of clay interrupted by periodic silt influxes, or to clay contained in density underflows and deposited in situ with the silts, or both. The negative skewness shown by winter layers could result from silt being brought in through the action of burrowing organisms or accidental incorporation of silt in clay layers during laboratory analyses. A third possibility is that silt as well as clay settled through the water column of 50 to 200 feet during the winter period when ice covered the lake surface. The following calculation (Table IV) shows that the settling velocity of a 6 $\phi$  silt grain in water at 4°C undisturbed by currents is .05 centimeters per second. It would take a silt grain

Table IV

Calculation of settling velocity of a 6 $\phi$ silt grain.	
Stoke's Law	
$V = \frac{2/9 (d_p - d_l) gr^2}{n}$	$V = \text{cm/sec}$
For particle size of 6 $\phi$ settling in sediment-laden lake water at 4°C:	$d_p = \text{particle density of } 2.7$
	$d_l = \text{liquid density (water at } 4^\circ\text{C} = 1.0 \text{ combined with an estimated sed. conc. of } .25 \text{ gms/liter)}$
$V = \frac{2/9 (2.7 - 1.0025)(780.66)(.00156)^2}{.016}$	$g = \text{gravity} = 780.66 \text{ cm/sec}^2$
$V = .05 \text{ cm/sec}$	$r = \text{particle radius in cm}$
	$n = \text{absolute viscosity of liquid}$

this size 1.15 days to settle 50 meters (approximately 160.5 feet) and so a relatively short time would be needed to clear the lake water of silt completely. The fact that some silt is found throughout all winter clay layers implies either that lake currents prevented silt from settling or that sediment was continually introduced into the lake all year round. Since samples occurring near inflowing rivers do not exhibit a more negative skewness than samples from other locations, lake currents would seem a more logical answer.

The range of grain sizes for silt and clay layers is approximately the same ( $3.5\phi$  to  $14\phi$ ). However, grain-size distribution varies and each has a decidedly different mode (i.e., the silt layer has a mode of  $7.5\phi$ , the clay layer  $10.5\phi$ ). Composite samples (combined silt and clay layers which could not be divided with precision) show an intermediate third mode which appears to be artificially created by the overlap in grain-size distribution of the individual layers (Fig. 17b).

Grain-size distribution plotted as cumulative curves show a bump or deviation from the normal curve in the medium to fine silt range (Fig. 18). Large bumps occur more often in the finer samples; that is, more often in clay layers rather than in silt layers. This pronounced change in slope could represent a mode, reflect an error in the method of laboratory analysis, or both. Using the same laboratory method, but on glacial outwash sediments, plotted grain-size analyses show a similar distribution problem (Boothroyd, oral. commun.).

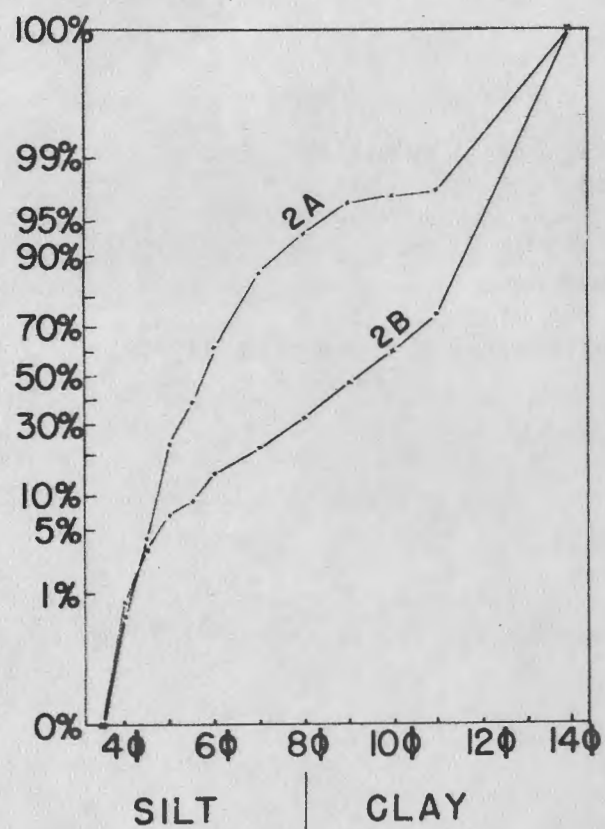
All samples in this study were processed in the same manner, but the bumps occur only in some. Two conclusions can be drawn from this



Figure 17. Group III grain-size analyses. a. Channel sample through thick silt layer (7-2A) is positively skewed with mean grain size of  $6\phi$ . Clay layer (7-2B) is negatively skewed with mean grain size of  $9.1\phi$ . b. Plot of composite sample (combined silt and clay layers which could not be accurately divided) shows modes at  $4.5\phi$ ,  $7\phi$ , and  $11\phi$ . The  $7\phi$  mode probably is composed of material from both layers.

## GROUP III VARVES

a. SAMPLE 7



b. SAMPLE 30-10

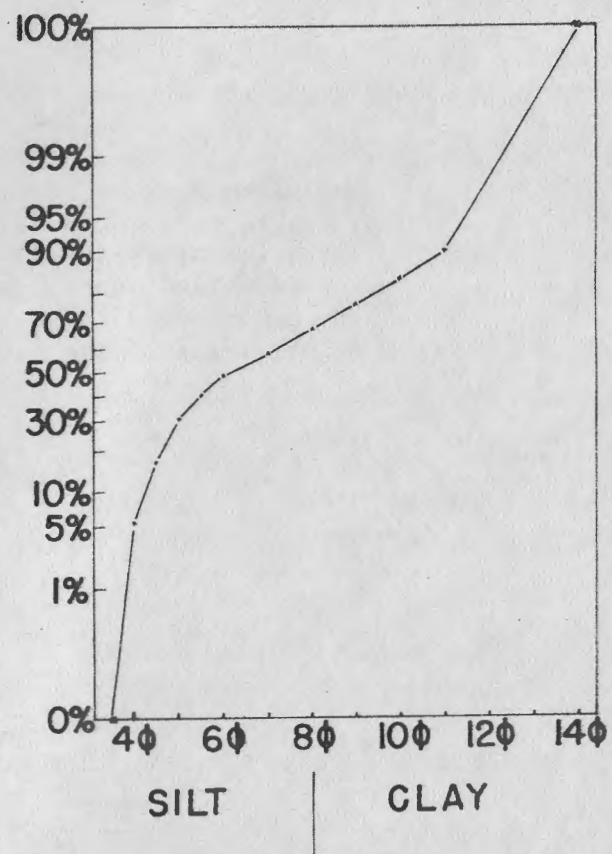
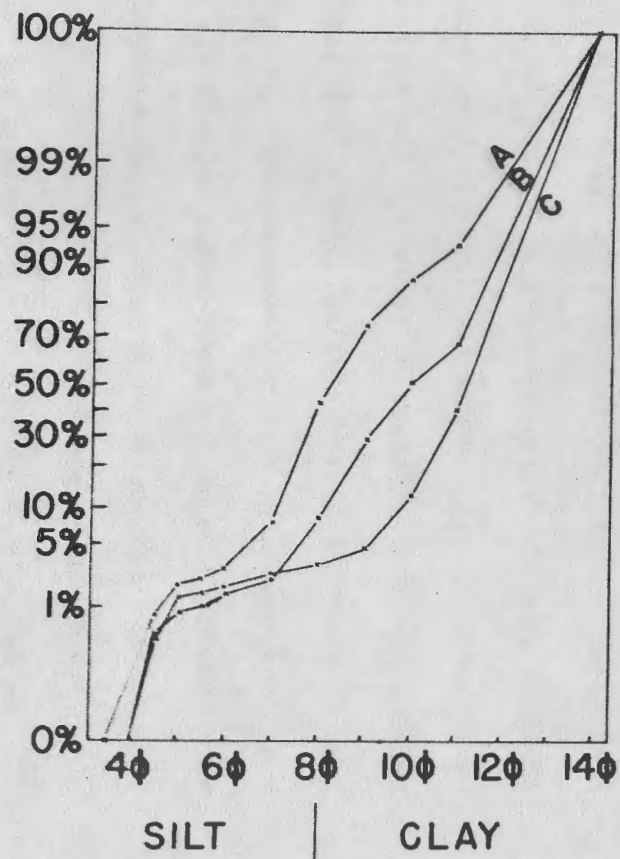


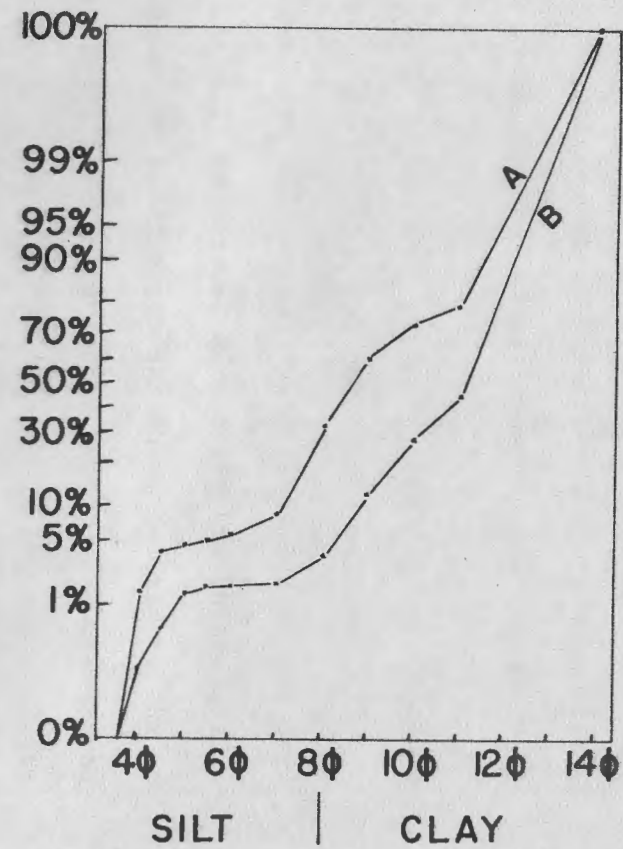
Figure 18. Group I grain-size analyses. All curves show the inflection in the medium silt range discussed on page 52. Mean grain size of A, the bottom section of a varve (i.e., "summer" layer) is in the clay range (sample 5-2,  $M\phi = 8.5\phi$ ; sample 25,  $M\phi = 9.0\phi$ ). Mean grain size decreases in succeeding sections B and C (i.e., "winter" layer).

## GROUP I VARVES

a. SAMPLE 5-2



b. SAMPLE 25



apparently conflicting evidence: 1) an error in laboratory procedure affects correct analyses for grains in the medium silt range, and 2) a silt mode is present in the finer samples, but the inflection in the graph is probably accentuated by the laboratory procedure.

#### Sediment color

All samples were dried for 5 to 7 days before colors were read with the Munsell Rock Color Chart. The two dominant colors of both silt and clay are olive gray (averaging 5Y 4/1), generally thought to be due to mineralogy of the crystalline and metamorphic uplands, and dark yellowish brown (averaging 10YR 4/2), suggesting the influence of Triassic rocks.

Localities 8, 9, and 29 (Fig. 8) exposed varves that have both silt and clay layers colored dark yellowish brown. Localities 8 and 9 consist of varves laid down in high-level temporary local lakes, and locality 29 shows basal varves. All three localities represent sedimentation occurring soon after deglaciation, and the color appears to reflect the local (Triassic) bedrock. The rest of the lake sediments have couplets of olive-gray clay layers with light (5Y 6/1) olive-gray and, less commonly, dark yellowish-brown silt layers. In general the metamorphic rocks on the surrounding uplands are the dominant source for the lake sediments and generally mask mineralogies from locally occurring Triassic rocks.

An informative record of color change was found in the Chicopee delta sediments. The oldest sediments observed have dark yellowish-brown summer silt with olive-gray winter clay, but in succeeding varves



both the summer and winter are dark yellowish brown. Higher in the section, laminations of olive gray appear and then dominate the silt layer, and the clay suddenly changes to olive gray. The sequence of color changes indicate that an area of Triassic sediments was uncovered in the Chicopee drainage area and for a short time became the dominant source locally for lake sediments. Subsequently other sediments became available, and the Triassic material was diluted until varves became totally olive gray in color.

#### Dropstones and concretions

Dropstones were found at all localities. They range in size from very coarse sand grains to cobbles and appear to have been dropped into the lake after deposition of an undisturbed clay layer. This can best be explained by melting of lake ice or icebergs during the warm season.

Concretions are found in some areas of the lake, but are abundant where they do occur. Not enough concretions were found to determine a pattern to their occurrence. Most contain a pebble or sand grain as a nucleus and grow radially parallel to the bedding plane. No evidence was found to indicate how long after deposition of the varves the concretions were formed.

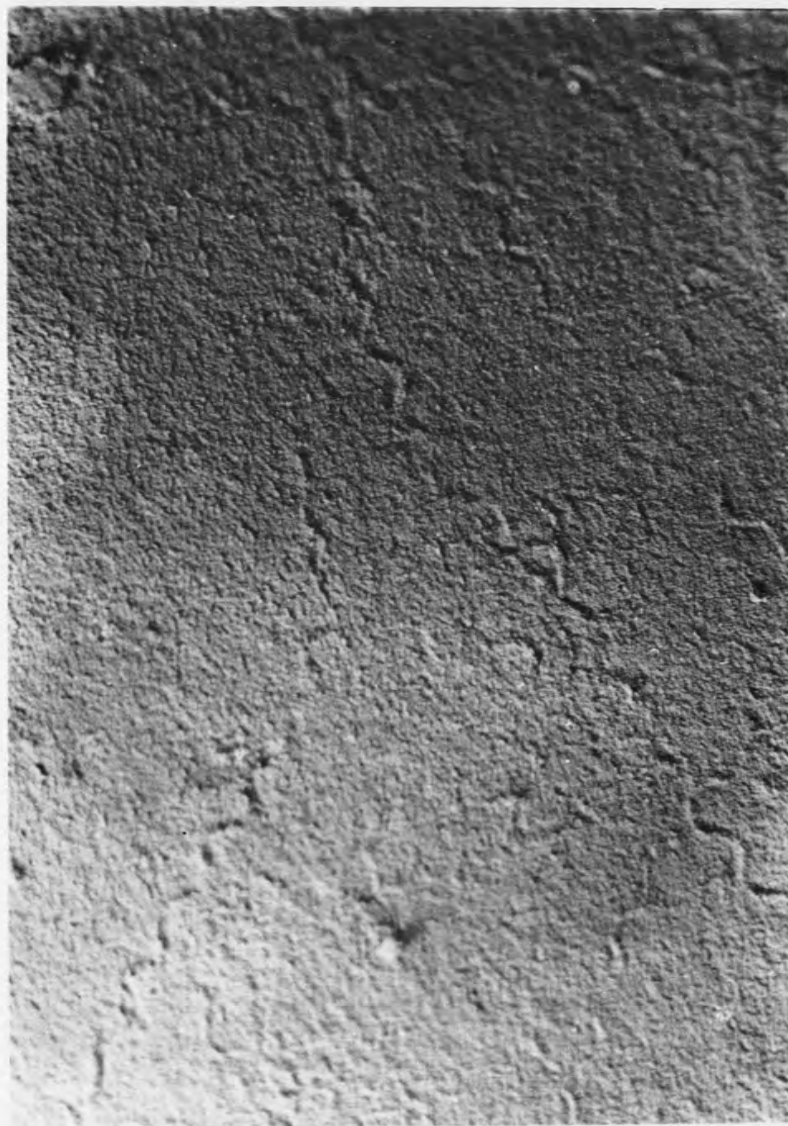
#### Lebenspuren

Two distinct types of trace fossils occur in Lake Hitchcock sediments (Fig. 19) with no apparent restrictions as to water depth or geographical location for either type. They occur together and



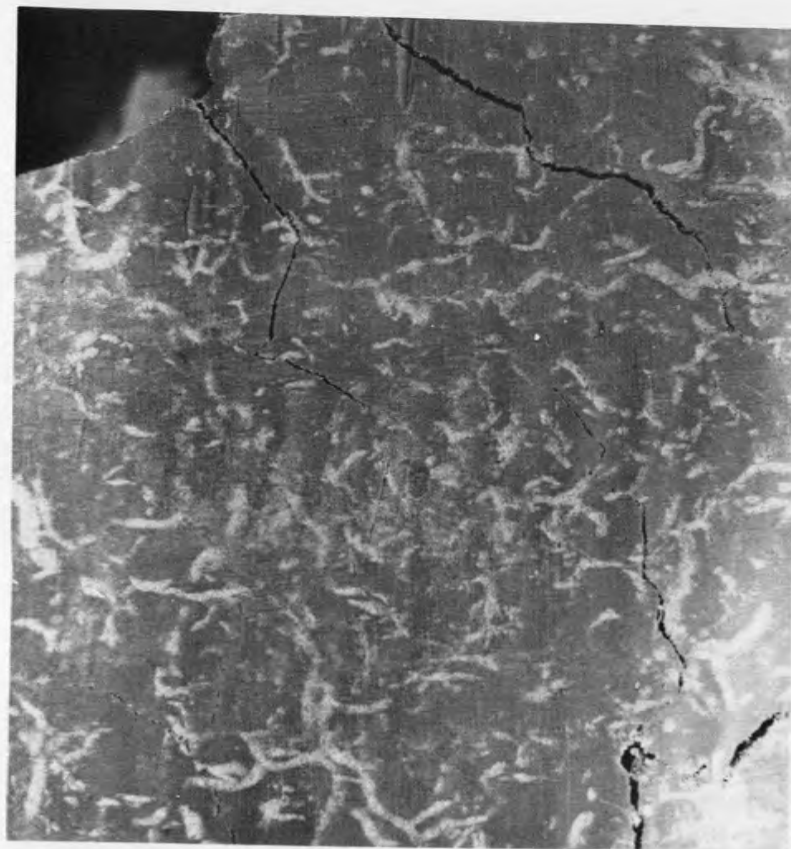
Figure 19. Lebenspuren a. Casts of distinctive tracings are found on bedding planes between silt layers and between silt and clay layers. b. Burrows in top of clay layer were later filled by silt from above.

a.



0 CM 1

b.



separately in all parts of the lake, though not at every locality. They are best seen on the top surfaces of clay layers, because silt from the overlying layer later filled in the burrows. But they have been seen within the silt layer as well. One organism burrowed horizontally (Fig. 19a), leaving an "S" shaped tracing, the other burrowed both horizontally and vertically, leaving random discontinuous tracings (Fig. 19b).

Emerson (1898) speculated that these "tracks" were produced by a dipterous insect that spent only the larval stage of its life cycle feeding on organic matter contained in the clay. This theory is reasonable, because there is no obvious biogenetically disturbed sediment, expected of permanent bottom dwellers. Fossil traces are rare in varves containing thick silt layers, and none occur in the only basal varve exposure (locality 29).

#### Plant remains

Plant fossils are extremely rare and occur parallel to bedding in small isolated patches in the varves. Although sparse, they probably are distributed in all parts of the lake, and a systematic detailed search might produce a more complete record of vegetation surrounding the lake than was obtained in this study.

Small amounts of fossil leaves were collected at localities 15, 13, and 18, but localities 5, 25, and 34 in the large embayment near Amherst produced the most fragments. The only genus positively identified (by Bruce Tiffney, Boston University, Boston, Mass.) was *Vaccinium* (*uliginosum*?) (Fig. 20), which is an arctic-alpine plant occurring

Figure 20. Photomicrograph of a leaf of the only identified plant remains found in this study of glacial Lake Hitchcock sediments. *Vaccinium (ulignosum?)*, Schlossman photo. 60X





today on summits of mountains in New England, mainly above timberline.

### Organic matter

Thin sections revealed opaque material assumed to be organic matter occurring as finely disseminated particles and clumps throughout the summer silt. Because the dark upper portion of the winter clay is commonly attributed to high organic content, each sample was ashed at 600°C to determine weight percent of organic matter. Weight loss varied from 1 percent to 25 percent. A brief study of clay mineralogy was carried out to determine if this loss was due primarily to mineral dehydration, oxidation of organic matter, or a combination of both.

Four winter clay samples with grain sizes finer than 11 $\phi$  and from different parts of the lake were examined with an x-ray diffractometer both before and after ashing. Quartz, chlorite, and illite were positively identified.

Differential thermal analysis curves of chlorites generally have an endothermic peak at about 600°C, which may correspond to dehydration of the "brucite" layers of the structure. Since most chlorites have between 11 percent and 14 percent water, the high weight loss incurred during ashing can be attributed at least in part to mineral dehydration. To avoid this problem, other methods, such as treatment with 30 percent H<sub>2</sub>O<sub>2</sub>, are recommended for determining concentration of organic matter in lake clays.

## PHYSICAL PROPERTIES OF GLACIAL LAKES

Exceptionally few documented studies of proglacial lake

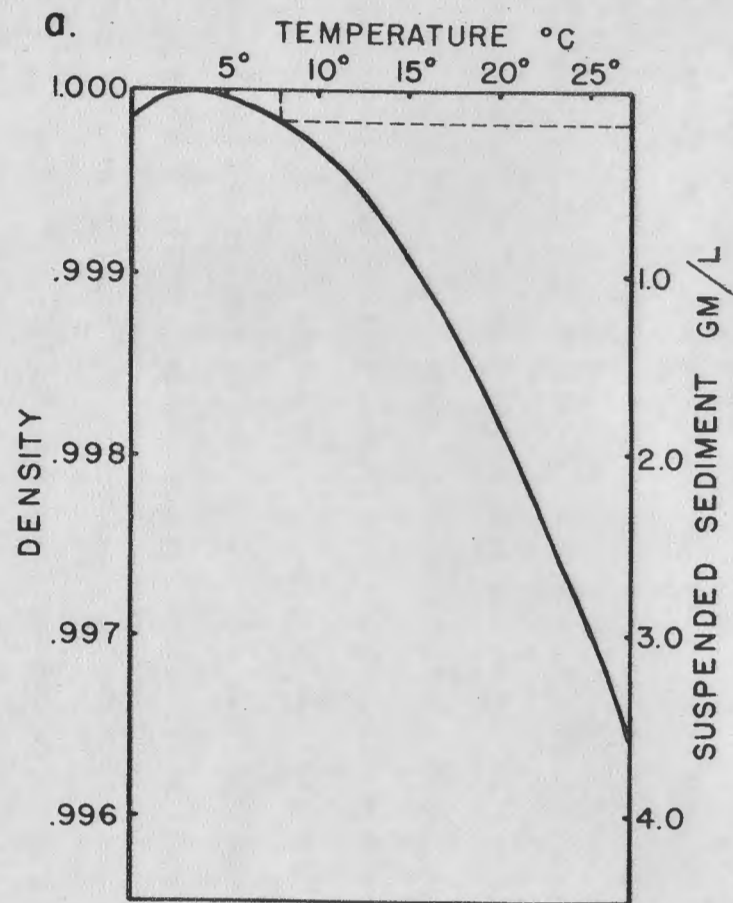


sedimentary processes exist. Thus delineation of physical properties and their effects on sedimentation in a lake that no longer exists becomes very difficult. Using theories derived from basic limnology (Hutchinson, 1957), in conjunction with observations by others of present-day glacial lakes, an outline of the physical conditions that may have existed in glacial Lake Hitchcock is proposed.

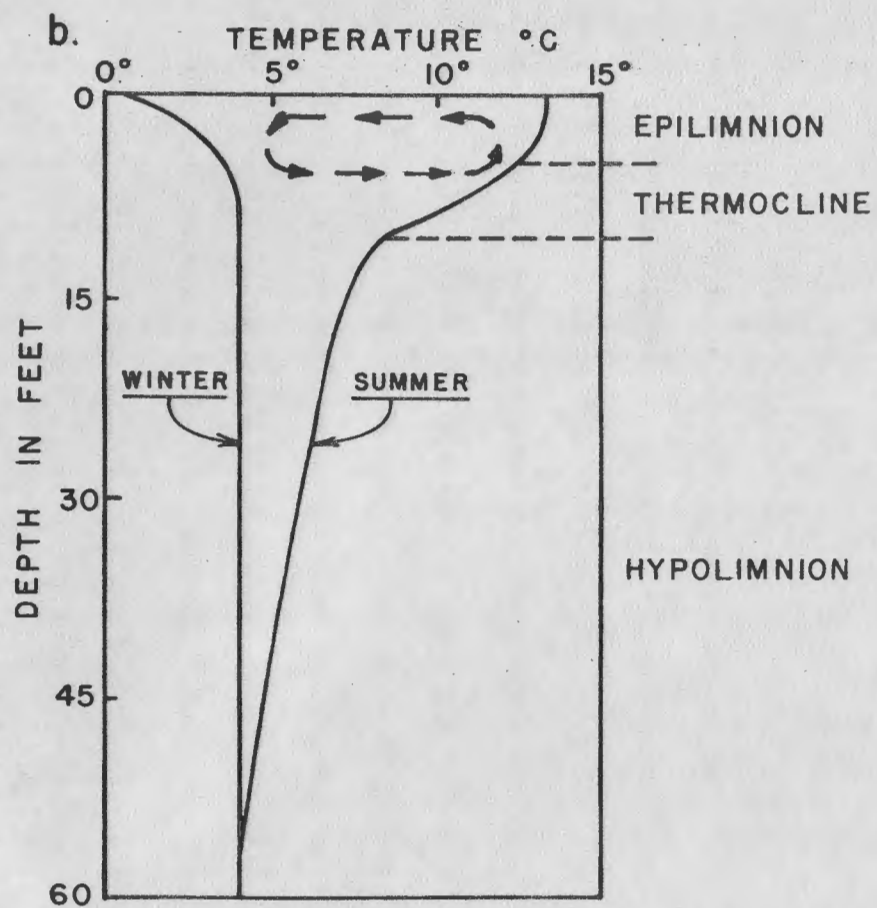
#### Thermal properties

The following factors are among those used in classifying lakes: seasonal range of water temperatures, vertical water-temperature profile, and changes in temperature profile with seasons. Profiles often show a development of thermal strata. The epilimnion is an upper layer stirred by wind-generated currents. The hypolimnion is colder and commonly stagnant. Separating these two zones is the thermocline, a stratum showing rapid temperature change with depth (Fig. 21a). Most proglacial lakes are thermally classified as subpolar (Yoshimura, 1936), although they may be temperate or polar depending upon size, elevation, shape, proximity to glacier, and geographical location. Fluctuations in daily atmospheric temperature and mean annual temperature will depend in part upon nearness to the glacier, and these fluctuations, in turn, affect temperature variations in the lake. Thus the physical environment at any one location will vary through time as the glacier recedes. Glacial Lake Hitchcock probably did not fit into a simple thermal category but varied in thermal characteristics with the retreating ice front.

Figure 21. a. Density of distilled water as a function of temperature. Figures on the right show amount of suspended sediment in gms/liter needed to return water at any given temperature to a density of 1 (Gustavson, oral commun.). For example, water at 8°C containing .15 gms/liter of suspended sediment would have a density of 1. b. Summer and winter thermal gradients. Thermal stratification that develops only during summer allows wind-generated circulation near the surface.



MODIFIED FROM VALLENTYNE (1957)



### Circulation

The following is a discussion of four of the more important factors involved in lacustrine circulation:

(1) To mix fluids of differing density, physical work must be performed; the amount of work required, among other things, depends upon density contrast between the two fluids. Since the density of distilled water is a function of temperature (Fig. 21a), in general, the greater the temperature difference between two fluids, the more difficult they are to mix. This fact is the main cause for the development of a thermocline. In the spring when the surface waters begin to warm above 4°C, a weak thermocline develops. With increased warming, the density contrast increases and the thermocline becomes better developed. This self-perpetuating situation, probably aided by katabatic winds, would allow good circulation in the surface waters, but would not encourage much movement in the hypolimnion. Thus a well-developed thermocline would enhance surface circulation and aid in distributing suspended sediments.

(2) If excess pressure is exerted on the lake surface by local barometric variations or by strong winds, or if a large stream discharge disturbs the equilibrium of the lake, then standing waves (external seiches) occur. In a lake containing strata of differing densities, such as the lighter epilimnion and the heavier hypolimnion, an internal seiche results (Rutner, 1969). The rhythmic oscillations that occur during a seiche set off currents that help disperse fine-grained sediments throughout the lake.

(3) Spillway drainage can be a factor in the development of lake currents. To maintain a fairly constant lake level, approximately the same volume of water that drained into a lake must also flow out. In Lake Hitchcock, spillway drainage probably generated slight southward flowing currents.

(4) In temperate lakes or temperate portions of a thermally complex lake, fall and spring overturns also aid in mixing the lake water.

Combining the possible effects of the four factors, there was probably enough circulation to distribute fine silt and clay to all parts of Lake Hitchcock, even though sediment entered at discrete points around the lake perimeter (Fig. 8).

#### Water density

The two classical theories of sediment distribution in glacial lakes may be termed the hyperpycnal or underflow theory and the hypopycnal or overflow theory (Fig. 22). The critical factor determining whether overflow or underflow will occur is the relative densities of the lake water and the entering stream.

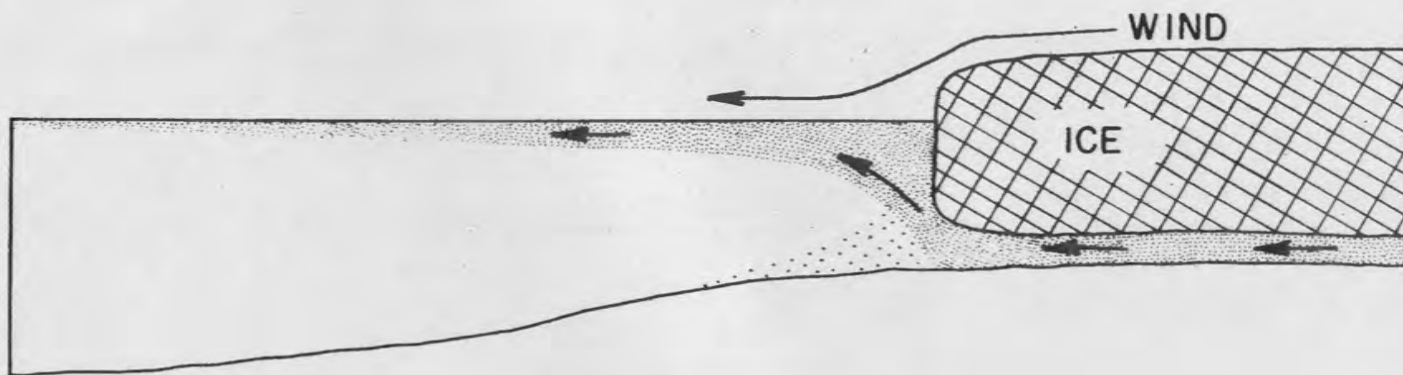
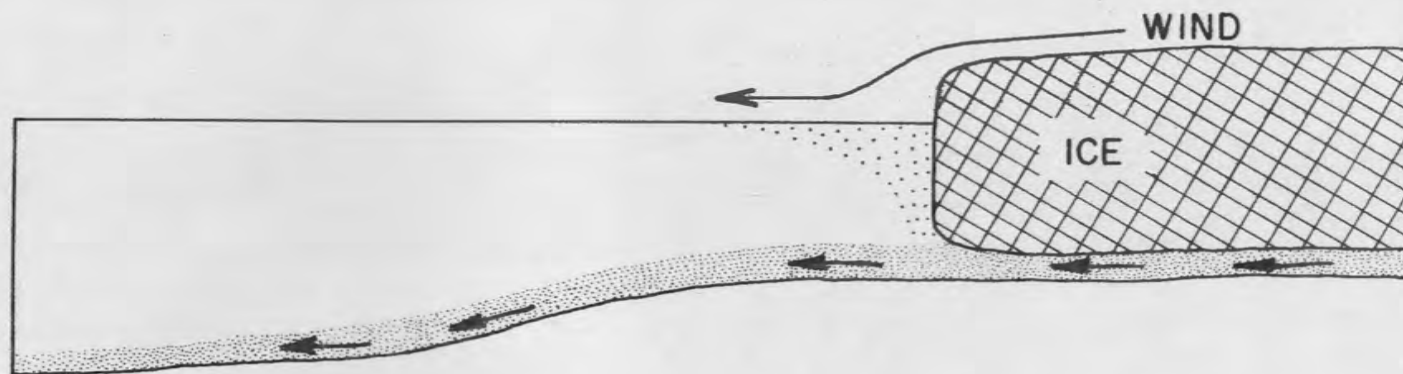
Figure 21a shows that water density increases to a maximum of 1.000 with a temperature increase from 0° to about 4°C. Further increase in temperature results in a decrease in water density. The figures on the right show the amount of suspended sediment in grams/liter needed to return water at any given temperature to a density of 1.000 (Gustavson, oral commun.). For example, one could take 8°C as an extreme temperature for an overland stream entering a glacial lake, which is assumed to be at 4°C. Density underflow will occur as long

Figure 22. The two classical theories of sediment distribution in proglacial lakes are: a) Hyperpycnal inflow, the method favored by De Geer (1912), and b) Hypopycnal inflow, the method suggested by Antevs (1951).



## METHODS OF SEDIMENT DISTRIBUTION

### a. HYPERPYCNAL INFLOW



### b. HYPOPYCNAL INFLOW

as the entering stream has a .15 grams/liter of suspended sediment more than the lake. Thus the concentration of suspended sediment is the most important factor affecting water density, differences in temperature being negligible by comparison.

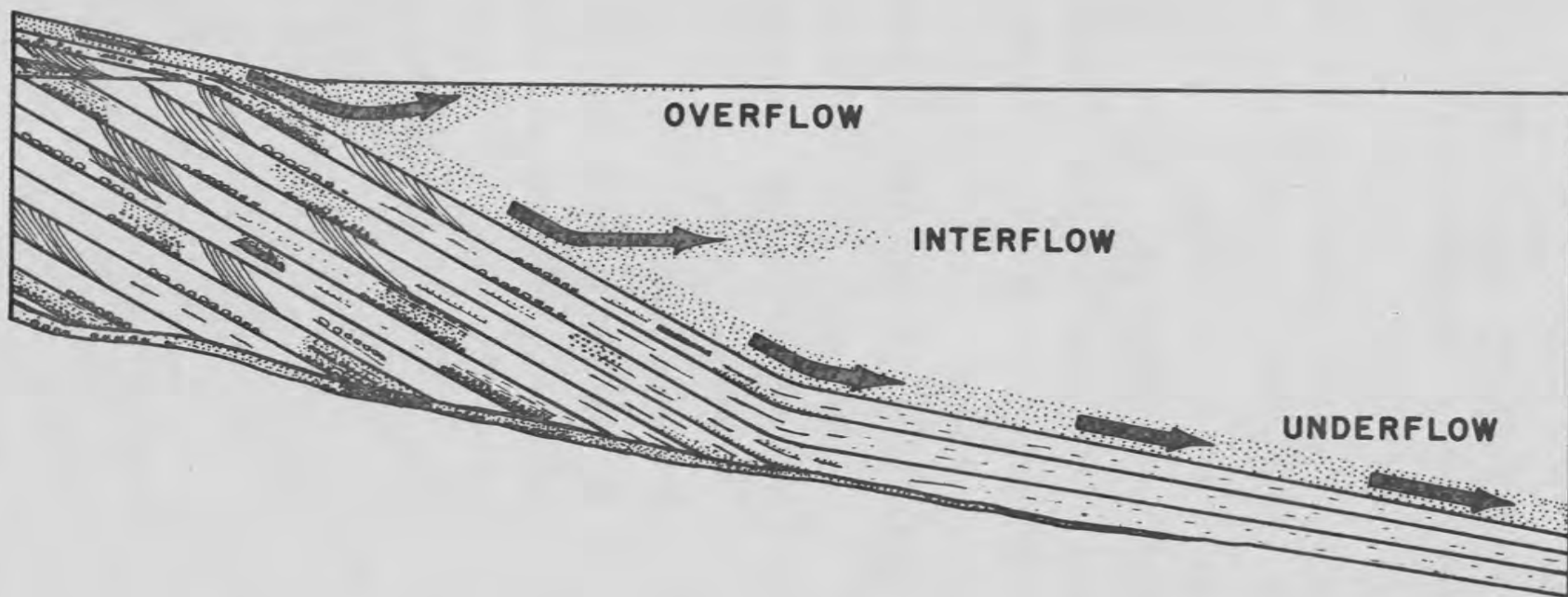
Data from one proglacial lake (Malaspina Lake, Alaska; Gustavson, 1971) and from a lake served by short glacier-derived overland streams (Garibaldi Lake, B.C.; Mathews, 1955) show that, in general, entering streams carry more sediment in gms/liter than is contained in the lake. Thus, density underflow would be the major mechanism of sediment distribution. However, sediment content of streams probably fluctuates diurnally and certainly fluctuates over the entire summer season. Conceivably the suspended sediment concentration of entering streams could be reduced to such an extent that they would be of equal density or even less dense than the lake. Stream water would enter the lake and flow at a level determined by the positive or negative difference between its density and that of the lake (Fig. 23). "Inter-flow" is the term used to describe all levels of flow intermediate between underflow and overflow.

#### Probable physical processes in Lake Hitchcock

As Lake Hitchcock grew during ice retreat, many differences developed between the northern and southern parts of the lake. As the lake lengthened these differences became more pronounced so that the environment of deposition varied with both location and time.

Based on the principles discussed above, the following physical

Figure 23. Proposed method of sediment distribution. Three types of flow that can occur in a glacial lake are underflow, interflow, and overflow. The critical factor determining type of flow is the density contrast between melt water and lake water.



environment of varve deposition in glacial Lake Hitchcock can be postulated. For streams entering the lake, the major mechanisms of sediment distribution would be underflow, interflow, and overflow. The type that would predominate is dependent upon the density contrast between lake and stream water. Probably there would be a difference in the density of inflowing streams coming from deglaciated highlands around the southern part of the lake compared to those streams coming directly from the glacier. Streams that drained valleys supplied only with precipitation and not with melting glacial ice would not have as much readily available sediment. These streams would probably enter the lake as an interflow or overflow. Glacial melt-water streams heavily laden with silt would enter as density underflow, depositing coarse material on the delta and continuing out onto the lake floor. In any flow the amount of mixing between it and surrounding lake water is inversely proportional to the density contrast of the two fluids. Continuous sedimentation during the flow decreases the density contrast and allows continued mixing in increasing proportions until finally the energy of the flow is spent. Suspended clay close to the lake bottom would then begin settling and continue to accumulate until disturbed by another flow.

Once sediment is in the water it would be continually dispersed by lake currents. In the portions of the lake farthest from the glacier, wind-generated circulation above the thermocline would distribute sediments in the surface waters. Internal seiches and fall and spring overturns would continue to mix material throughout the water column.

Only a guess can be made of the environment of deposition which

existed in the lake area in contact with the glacier. Glacial melt water at a temperature less than 4°C probably flowed into the lake all year round, but in much reduced amounts in the winter. The area probably never would reach an isothermal state and overturn. It would be the site of active sedimentation of coarse material in the summer, but during the winter it probably would be quiet enough for clay deposition (i.e., the formation of varves).

#### CLASSIFICATION OF VARVES

Varves are a rather unique phenomenon because the process that forms them is repeated with such precision that only minor textural changes may occur within several hundred couplets (Fig. 24). This rhythm has led most geologists to believe that the couplets are controlled by the annual climatic cycle.

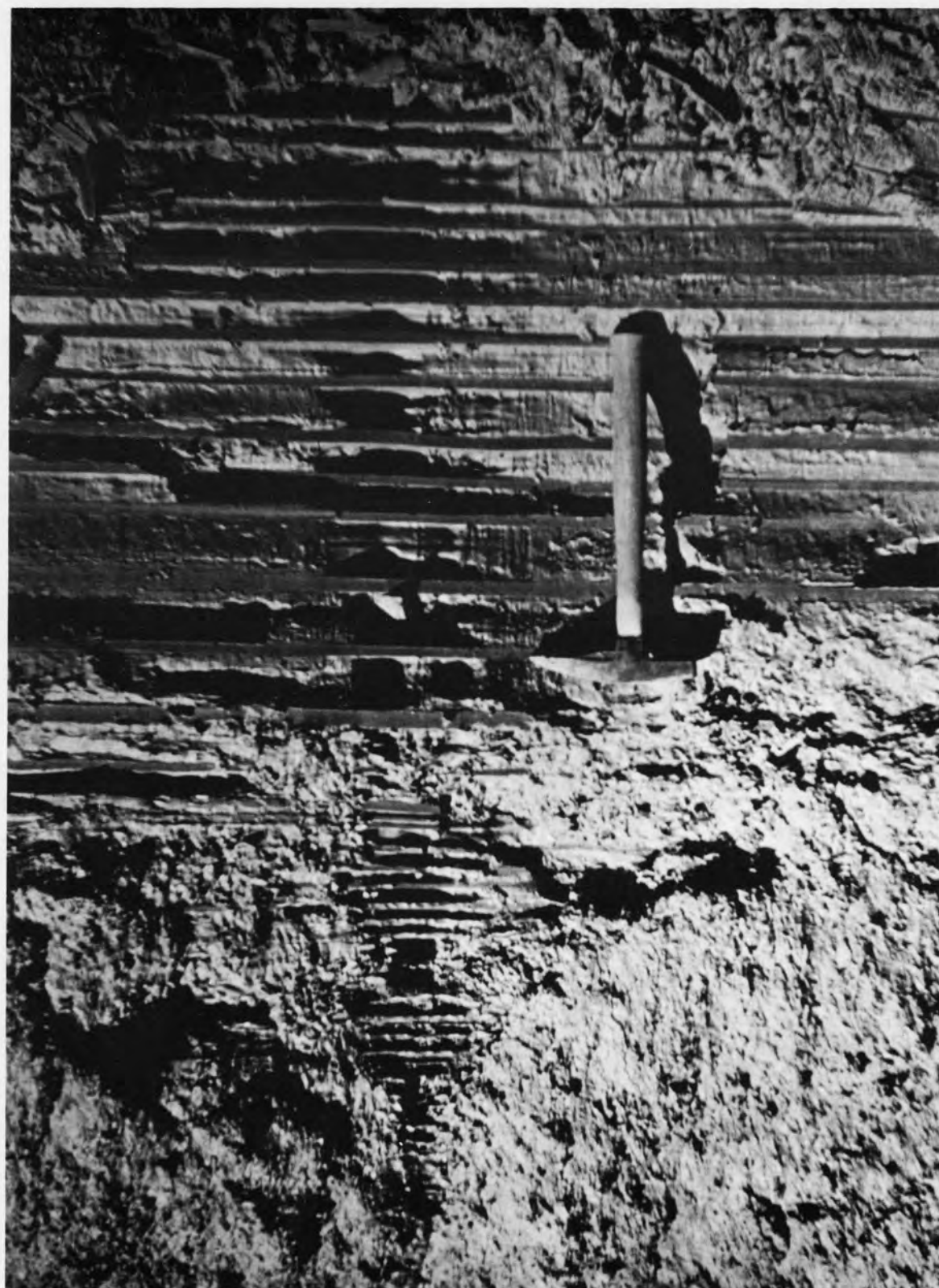
Glacial Lake Hitchcock sediments are remarkably similar in texture and structure to the varves of southern and central Sweden. The varve chronology worked out in Sweden and corroborated with radiocarbon dates (E.H. De Geer, 1952) strongly suggests that the Swedish varves are annual. Based on this similarity, and on several other lines of evidence enumerated at the end of this chapter, I believe that Lake Hitchcock rhythmites are also annual deposits.

The most natural grouping of varves is provided by the relative thicknesses of silt and clay layers. Each varve locality was assigned to one of the three following groups:

Group I - clay thickness greater than silt thickness



Figure 24. Differential erosion emphasizes the rhythmic nature of the lake sediments (locality 4).  
Hartshorn photo.



Group II - clay thickness approximately equal to silt thickness;  
and

Group III - clay thickness less than silt thickness.

The symbol for the group was then plotted on a base map (Fig. 8). Major streams that drained into the lake were also plotted, on the assumption that streams presently crossing the relic strandline of glacial Lake Hitchcock also drained into the lake.

A direct correlation is apparent between varve groups and the proximity of a varve locality to rivers of significant size. Although this correlation holds true for this study, one must remember that the samples were collected mostly from the top half of the sediment column and thus are not representative of the lake's entire history (Fig. 6). During deposition of the oldest varves at the base of the section, the glacier, rather than inflowing rivers, was probably the dominant influence.

Although successive couplets from any one locality are quite similar, there is commonly a great deal of variation in varve characteristics between localities. Therefore, although the fundamental winter-summer cycle controlled the occurrence of silt and clay layers, marked variations occur within the silt and clay layers due to their relative environmental positions in the lake.

The chronological relationship between the three groups is suggested in Figure 25 through the use of time-lines (T0 - T4). The classical division into summer and winter layers is based on the silt-clay contact. It is proposed that the environment of deposition varied throughout the lake so that while clay began to accumulate in areas of

Figure 25. Proposed chronological relationship between varves of Groups I, II, and III. Time-lines T0 through T4 enclose one varve.

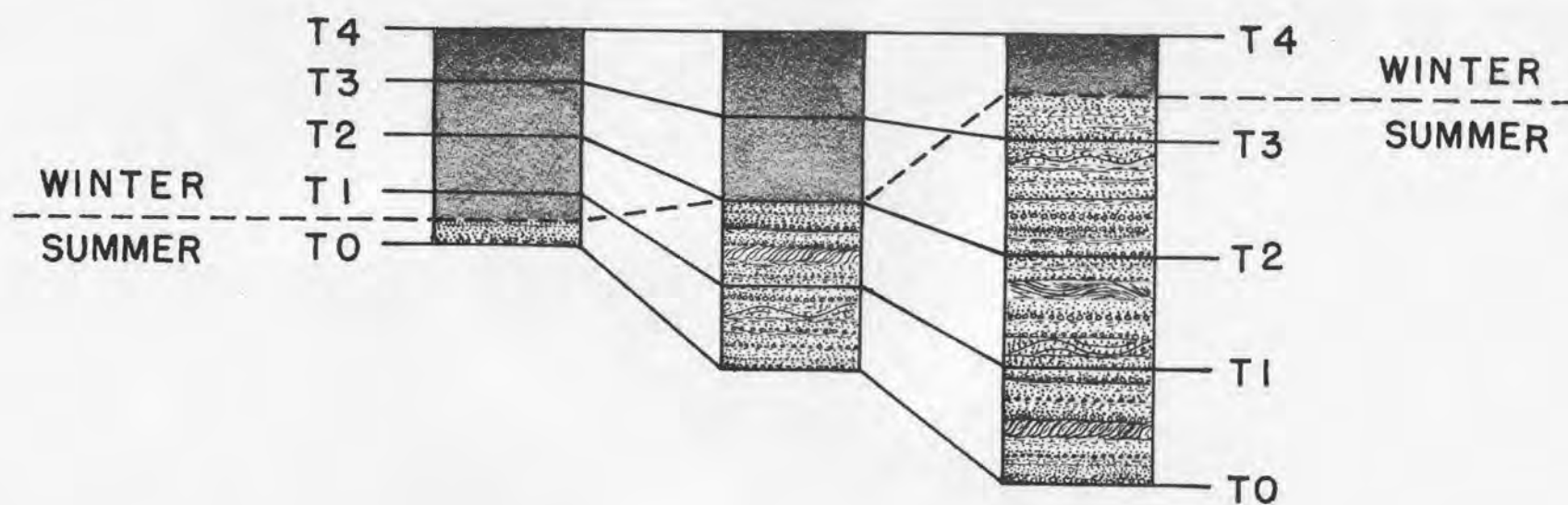
INCREASING DISTANCE FROM INFLOWING RIVERS



I

II

III



Group I varves, active silt deposition was still occurring at Group III localities. Thus, as shown by T2, the clay layer of a Group III varve is only in part time-equivalent to the clay layer of a Group II or Group I varve.

The original depositional site of each varve sample within the glacial lake is determined by its distance from shore and depth of water during deposition. Water depth was determined by subtracting the elevation of the sample from the elevation of the lowest stable lake level at that locality (Appendix II). The position of the water plane was determined by connecting accordant lake shores and deltas (Jahns and Willard, 1942; Hartshorn and Colton, 1967). The strandline rises northward at a rate of 4.2 feet per mile due to isostatic rebound.

Correlation of varve sections by detailed measurements (i.e., varve tapes) assumes that variations in varve thickness reflect only fluctuations in climate, or more specifically, regional ablation rates (De Geer, 1912). However, in Lake Hitchcock additional factors, discussed below, may have affected varve thickness and thus invalidated the method of varve measurement that is so successful in Sweden.

Lake Hitchcock was a long narrow lake fed by numerous large streams. The silt layers vary substantially in thickness, grain size, and sedimentary structures due to lake-bottom irregularities and nearness to stream drainage basins. Drainage basins themselves are variable in hydrologic conditions. Among streams, size of drainage area, amount of stagnant ice left in the drainage area, concentration of sediment in the ice, and the time lapse between disappearance of



ice and revegetation would contribute to differences in sediment concentration and discharge. The silt layers then are not solely the result of uniform regional ablation rates.

Serious doubt has been cast by radiocarbon dates on the accuracy of the varve chronology in New England worked out by Antevs (1922) (Flint, 1957, p. 297). He has defended his work by maintaining that there is more error inherent in radiocarbon dating than in the counting of varves (Antevs, 1951, 1962). In my opinion, the method of visually matching curves drawn from varve tapes, which was so successful in Sweden, is unreliable for the Connecticut Valley. The marked variation in silt layer thickness appears to reflect local rather than regional conditions. This might be a factor in causing the discrepancy between the radiocarbon estimate of the duration of Lake Hitchcock and Antevs' varve chronology.

#### Group I varves

Group I varves are composed of a thin silt layer (.05 - .3 inch) and a much thicker clay layer (.1 - .5 inch), with the total varve thickness in the three localities sampled averaging .4 inch or from 30 to 40 varves per foot. Grain-size analyses show that the couplets, on the whole, are extremely fine. The "silt layer" is more than half clay, with a mean grain size between  $8.4\phi$  and  $9\phi$ . Clay layers have a mean grain size of  $11\phi$  (Fig. 18; Appendix I).

When wet, each varve shows a change in color (a decrease in value) from bottom to top, and thus the couplet appears to be a graded bed. Microscopic examination of thin sections reveals two distinctive sedimentary units (Fig. 26). The contact between the two

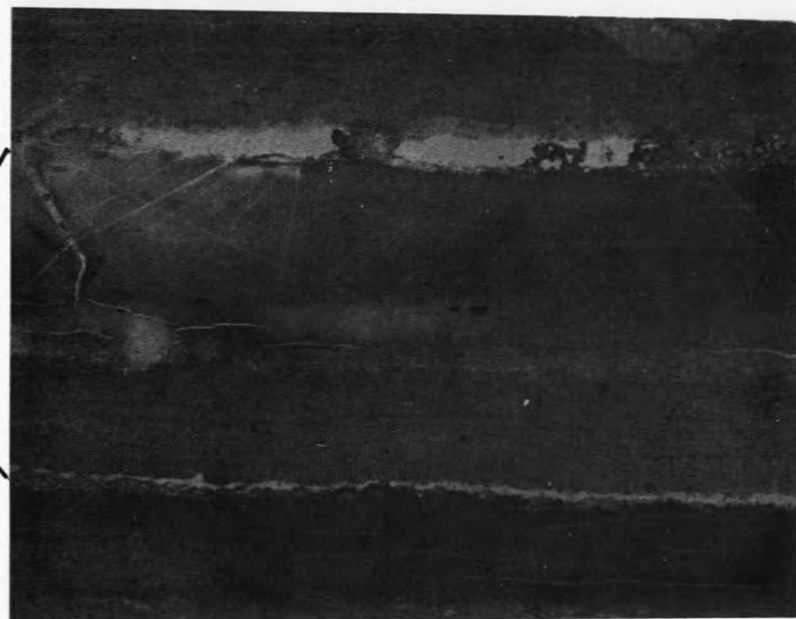
Figure 26. Group I varves. a. Sample 28-3. Inconsistent couplet thickness shown here may present a problem in varve counting. It is difficult to determine which silt laminae represent the commencement of a yearly deposit and which are the result of a chance influx of silt into an area where only clay deposition usually occurs. b. Thin section (sample 28-3) shows that a varve as a unit is not a graded bed, but consists of two distinct layers. Both the silt/clay and the clay/silt contacts are relatively sharp. White areas are dessication cracks.

a.



0 CM 3

b.



0 MM 4

units is usually sharp and not gradational as is often assumed. The lower unit consists of silt laminations of varying grain sizes containing some minute graded beds. The upper (clay) unit becomes darker near the top, which is generally attributed to decreasing grain size or increasing organic matter. The top of the clay is usually uneven, due to burrowing organisms and subsequent filling of the cavities by silt.

Localities 5 and 25 are in the large embayment in central Massachusetts, and locality 28 is in central Connecticut (Fig. 8). All three localities are in areas that receive little sediment from the unusually few streams draining into that part of the glacial lake. Deep water at the time of deposition does not appear to be a necessity for formation of Group I varves (Table V).

TABLE V

Average water depth at each location for Group I samples.	
Locality	Water Depth
5	156 feet
25	141 feet
28	65 feet

The source for relatively large amounts of clay to be deposited year after year with relatively little associated silt presents a problem. Melting glacial ice releases all grain sizes from boulders to clay, but concentrations of any size are due to a sorting process; the following one is suggested. Clay, together with other sediment, entered at some point in the lake removed from the depositional site.

The coarsest material was deposited on the delta while the finer fraction continued as a density flow out into the lake. Upon dissipation of the flow, clay became suspended in the lake water and subsequently was dispersed by currents.

The thicker clay layer is probably due to two factors. One is that the location of deposition was far distant from rivers of significant size. Thus silt only reached the area by density flow during the periods of highest runoff. Except for these influxes, clay in suspension in the lake and moved by lake currents was the major sediment source. The other reason for a thick clay layer is the length of time required for clay deposition. Because of the environment of deposition, settling clay could accumulate unhindered almost all year round. This proposed process for deposition of Group I varves also explains the ungraded nature of the silt layer and the graded nature of the clay.

Any change in the above proposed pattern would explain the common occurrence of thin clay laminae in the silt layers and thin silt laminae in the clay layers (Fig. 27).

#### Group II varves

Varves composed of silt and clay layers of similar thickness are found in eight localities in the lake (Fig. 8). These localities are neither directly off major deltas nor distinctly removed from obvious river sources. Although layers are of equal thickness, the total varve varies considerably in magnitude. Based on this dimension, varves are divided into three subgroups (Table VI), with each defining a

Figure 27. Group I varves. a. Locality 5. Ratio of clay thickness to silt thickness is higher here than at any other locality sampled. X is a thin clay lamination in a silt layer; Y is a thin silt lamination in a clay layer. b. Arrows point to irregular contacts which are due to burrowing organisms feeding on top of the clay layer (Sample 25-2).

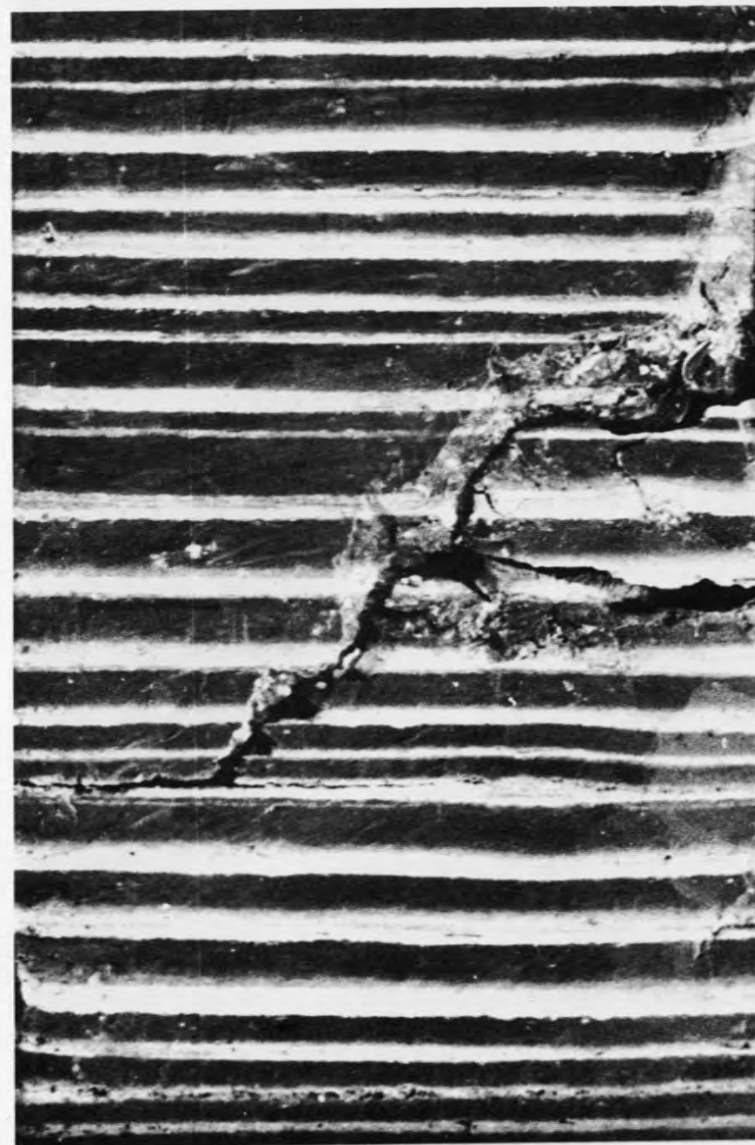


a.



0 CM 3

b.



0 CM 3

slightly different environment of sedimentation. Subgroup IIa varves are .1 inch thick, or less. Subgroup IIb couplets are approximately .2-.3 inch thick and Subgroup IIc varves are .5 inch thick, or greater.

Table VI. Group II measurements

Subgroup	Locality	Ave. M $\phi$	Water depth in feet	Ave. varve thickness in inches
Subgroup IIa	34	9.7 $\phi$	100	.10
Subgroup IIb	3	9.2 $\phi$	63	.20
	16		93	.20
	21		85	.20
	22		95	.30
	23		130	.20
Subgroup IIc	19	8.8 $\phi$	95	.50
	11		190	.70

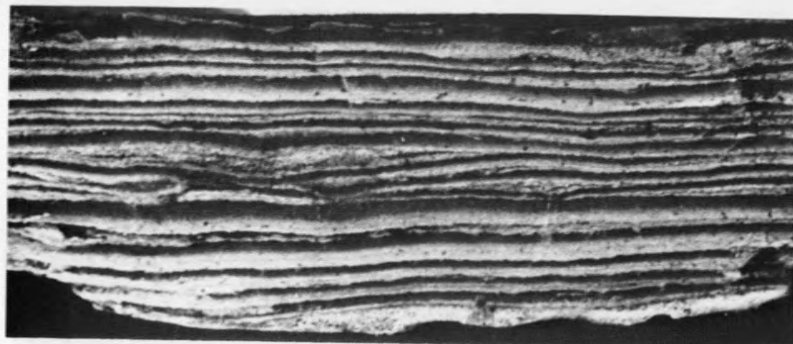
Apparently the depth of water at time of deposition had no influence on the thickness of individual layers, that is, which subgroup formed. Features of the three subgroups and an interpretation of their mode of deposition are summarized below.

Subgroup IIa. Although layers are of equal thickness in Subgroup IIa, they are very thin, and the couplets have been termed "microvarves" (Jahns and Willard, 1942) (Fig. 28b). In this study, they have been found only at locality 34, but have been observed elsewhere in the lake sediments by other workers (Emerson, 1898; Lougee, 1939; Jahns and Willard, 1942).

The varves appear structurally similar to recent lake sediments (Ludlam, 1967), but they are composed entirely of mineral grains and not of chemical precipitates as are often found in modern temperate lakes.

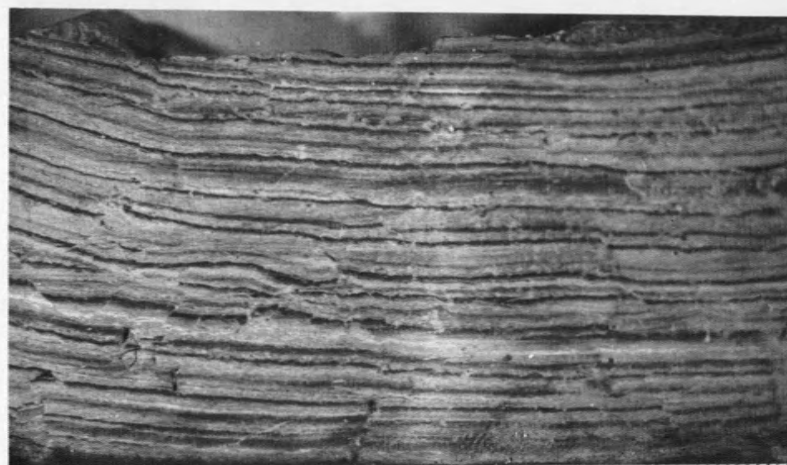
Figure 28. Group II varves. a. Sample 3. Sediment at base of silt layer appears to have been brought by density underflow while material for top of silt layer and entire clay layer probably was brought by interflow or overflow and settled through the water column. b. Subgroup IIa. Microvarves (Sample 34-2) represent either the final stage in Lake Hitchcock sedimentation or deposition in the small basin lakes that existed for a period after Lake Hitchcock drained. Grain-size analysis in Fig. 30b.

a.



0 CM 3

b.



3 4 5 6 7 8 9 10

The clay layer averages only .05 inch in thickness and is commonly disturbed by burrowing organisms. Exceptionally thin couplets imply that little sediment was entering the lake annually at time of deposition. Since Subgroup IIa varves occurred only at the top of the lake section, final Lake Hitchcock sedimentation was probably in a sediment-starved environment. These microvarves also might represent sedimentation in the isolated lake basins that existed after the main body of Lake Hitchcock had drained (Jahns and Willard, 1942).

Subgroup IIb. Subgroup IIb is considered the "normal" Group II type. This subgroup was not formed as the bottomset beds of a delta, nor in a sediment-starved area of the lake, but in an intermediate depositional environment.

Multiple graded beds, ripples, usually composed of fine sand, and erosional contacts indicating deposition by currents are common in the silt layer. Thus, the lower part of the silt layer was deposited mainly by a bottom current (i.e., density underflow). A gradational contact usually occurs between the upper portion of the silt layer and the overlying clay layer (Fig. 29a). Sediment for this upper section appears to have been brought to the area by another process (perhaps overflow) and to have settled through the water column.

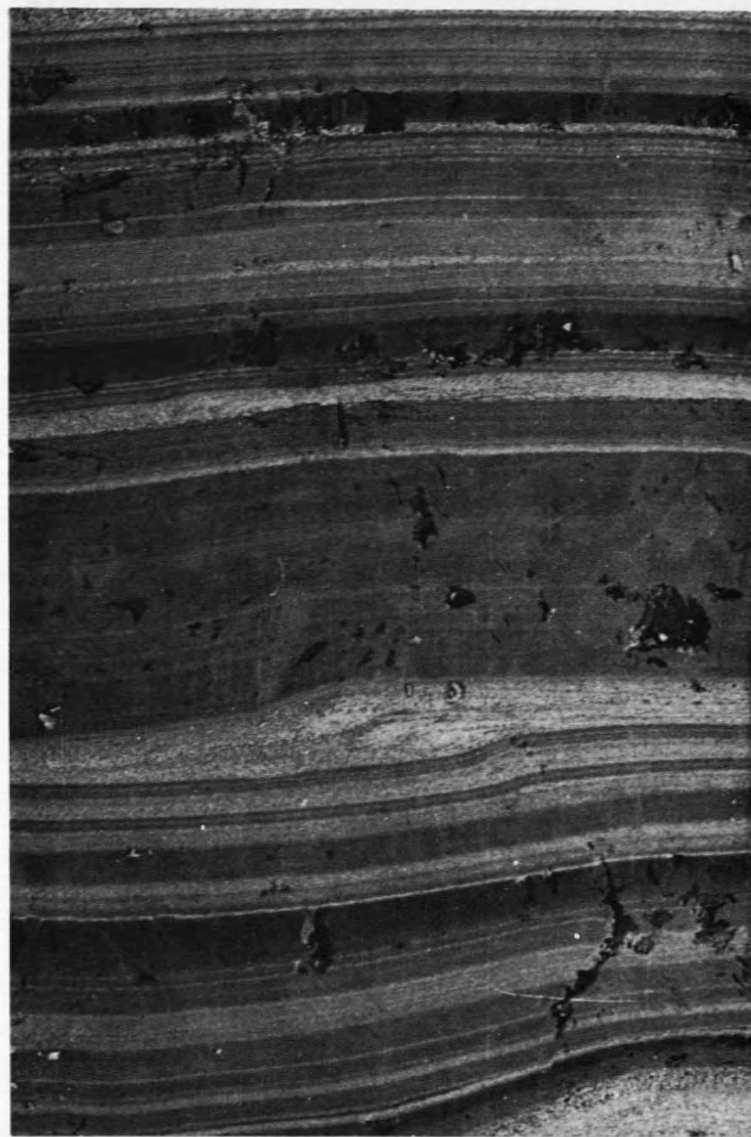
Subgroup IIc. Varves with equal but unusually thick layers are found at only two localities. Both occur in a topographic trough-like depression at least a mile from a delta. Locality 11 is between highs that once were islands, while locality 19 is in a low area between what was the shore and an island. Density underflow coming off a



Figure 29. Group II varves. Silt layer and clay layer approximately equal in thickness. a. Subgroup IIc: layers are exceptionally thick. Grain-size analyses of clay layer are shown in Figure 30a. Sample shows coarse sand beds probably representing influx by density underflow. b. Subgroup IIb. Varves were deposited in 85 feet of water and over 2 miles from shore. Isolated ripples (wavelength is 7 cm), erosional contacts, and multiple graded beds suggest deposition by density underflow.

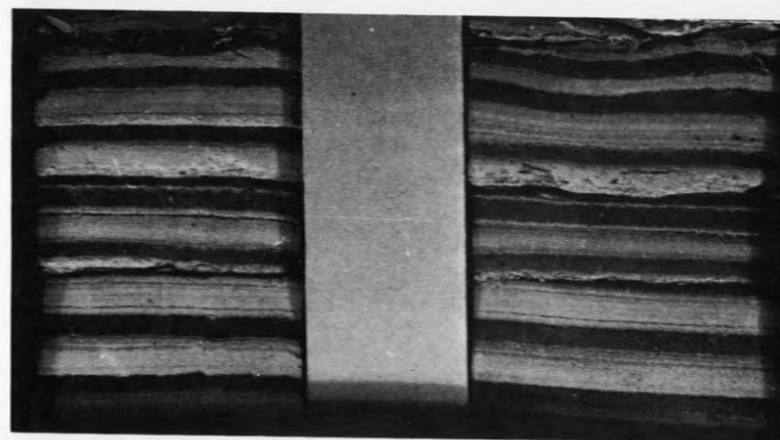


a.



0 CM 3

b.



0 CM 3

nearby delta would be funneled through the trough and thicker deposits could be expected there.

The source for the large volume of fine sediment needed every year to form these varves appears to be different for the two areas. Locality 11 is in the bottom half of the lake section and the varves sampled were probably deposited during the early stages of delta building. During the early stages a greater distance (2-3 miles) existed between the point where streams entered the lake and the depositional site. The coarse fraction was deposited before reaching the locality. The occasional sand layer that occurs in the summer layer (Fig. 29) can be explained by an exceptionally dense and far-reaching underflow.

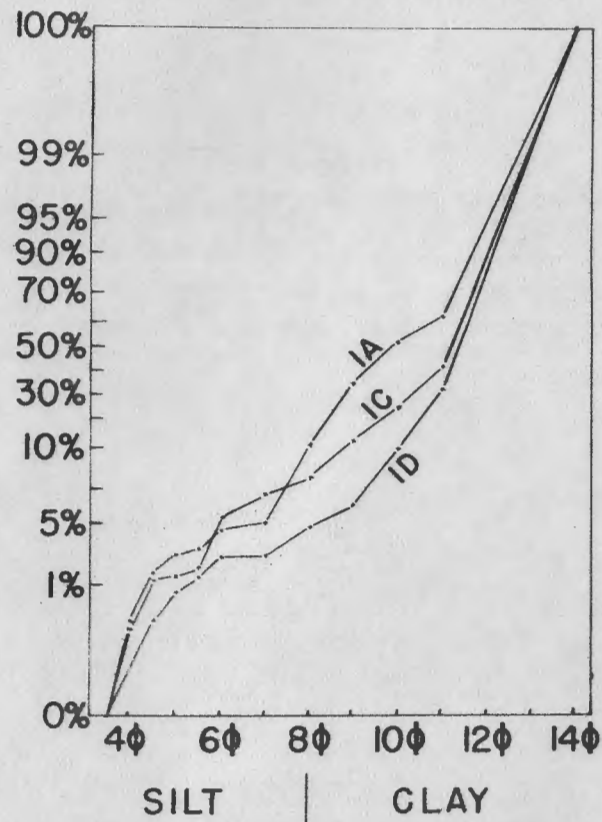
The clay-rich sample of locality 19 was deposited about a mile from a delta, and the silt and clay probably came from this river source. Erosion of surrounding drumlin islands of clay-rich till, however, also could have supplied some sediment.

Generally in Group II, grain-size analyses (Figs. 30, 31; Appendix I) show that the couplets are composed of sediment slightly coarser than that in Group I varves. Some varves were too thin to split accurately: analyses of the whole varve show an average grain size of  $9\phi$  (Fig. 30b). In varves thick enough to divide horizontally, the mean grain size of the silt layer varies from  $7\phi$  to  $8.6\phi$  (averaging  $7.7\phi$ ), while the clay layer averages  $10.5\phi$ . A clay layer from locality 11 split horizontally shows a consistent decrease in mean grain size from bottom to top ( $9.61\phi$ ,  $10.52\phi$ ,  $11.18\phi$ ) (Fig. 30a).

Figure 30. Group II grain-size analyses. a. Clay layer of a Subgroup IIc varve shows a decrease in mean grain size from bottom to top (11-1A to 11-1D). b. Distribution of a Subgroup IIa sample (microvarve).

## GROUP II VARVES

a. SAMPLE II



b. SAMPLE 34-2

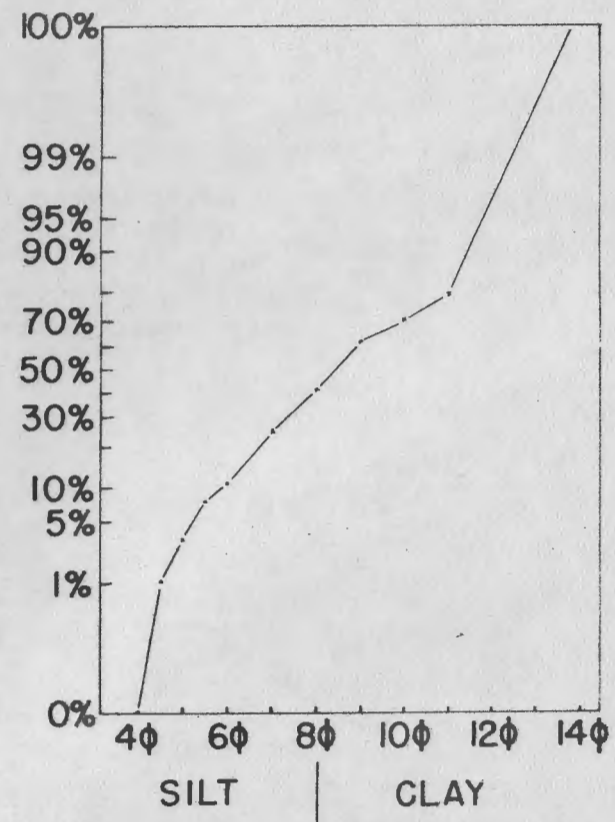
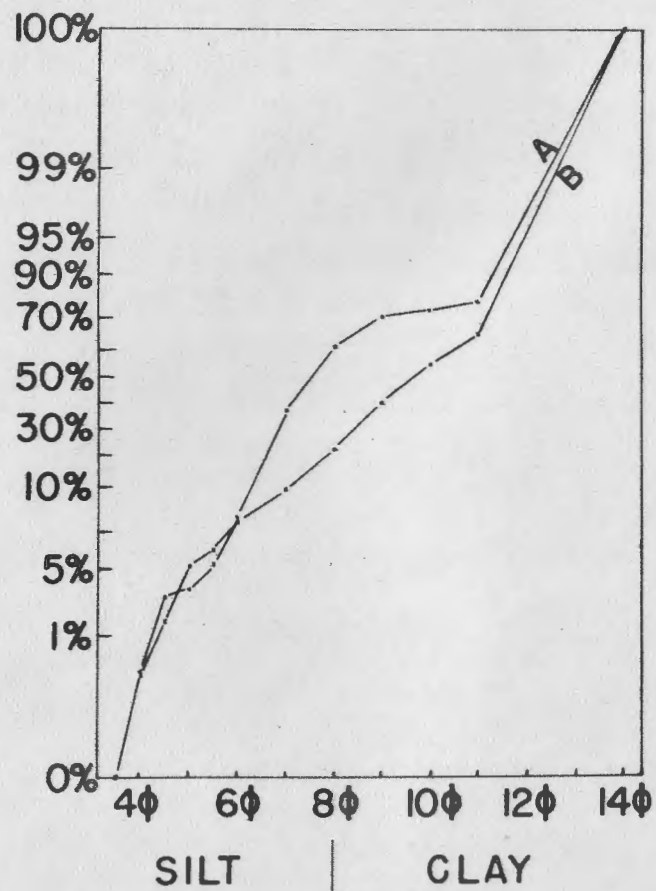


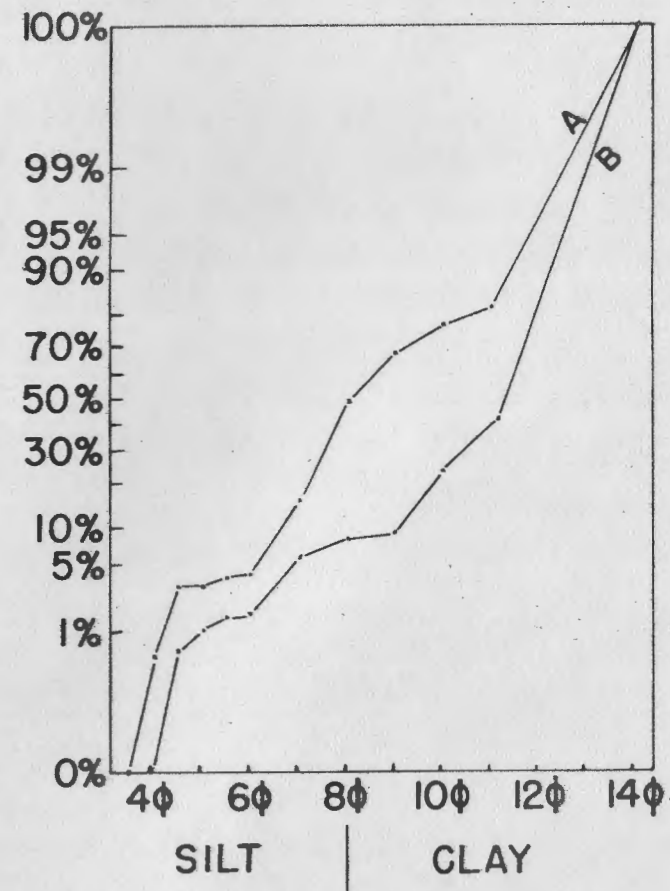
Figure 31. Group II grain-size analyses. a. Subgroup IIb; 21-A is the silt layer, 21-B is the clay layer.  
b. This example of a Subgroup IIc varve shows a pronounced inflection (discussed on page 52) in both the silt layer (19-A) and clay layer (19-B).

## GROUP II VARVES

a. SAMPLE 21



b. SAMPLE 19





### Group III varves

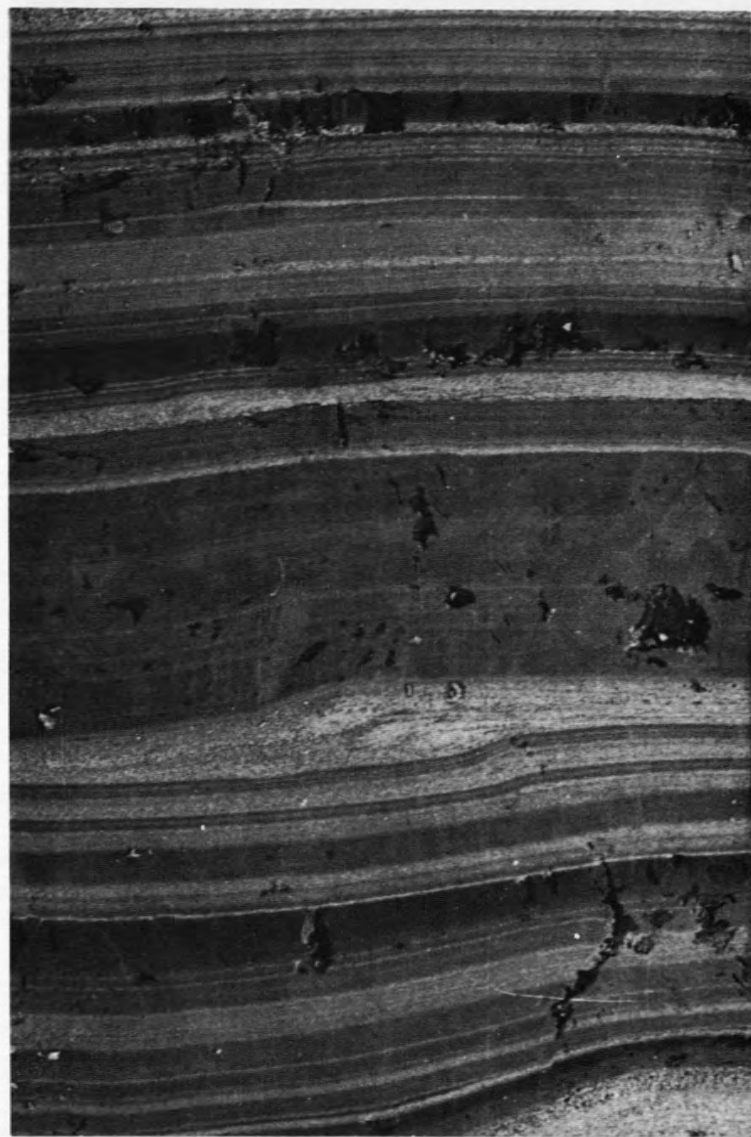
Couplets in which silt layers are consistently thicker than clay layers have been classified as Group III varves. Total varve thickness in the samples studied varies from 1 inch to 30.5 inches with most of the thickness in the silt layer. Within a limited vertical range, silt layers are fairly constant in thickness and any increase in this thickness occurs gradually. An exception to this generalization is shown in Figure 32a, but here it can be seen that even though the silt layer thickness varies considerably, the clay thickness remains relatively constant (seldom thicker than .5 inch).

Locally, layers, do not appear to thicken or thin laterally. Figure 32b shows two samples, taken 100 feet apart, that are very similar. On the other hand, cross sections through lake sediments (Figs. 9, 10, and 11) show considerable thickening and thinning over irregular topography. Inadequate exposures prevent determination of whether this large-scale variation is due to slumping or to a variation in thickness within individual layers. Most slumping phenomena observed in this study and by other workers (Emerson, 1898; Antevs, 1922), except for an occasional thin zone (Fig. 33a), are found at the top of the section and probably are contemporaneous with final drainage. But extensive sections of lake deposits, especially near the base of the varves, have never been observed and should not be interpreted by features seen near the top.

Two localities, 15 and 30, were examined to detect vertical change in layer thickness. Figure 34 shows that the total varve

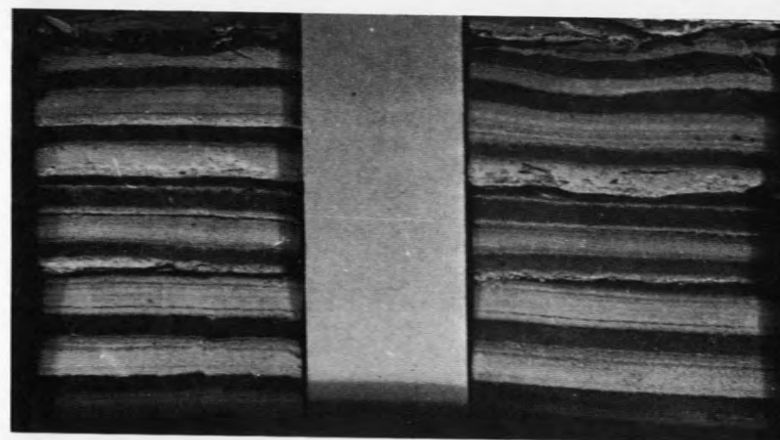
Figure 32. Group III varves. a. Sample 26-2. Silt layers vary considerably in thickness throughout the lake, while clay layer thickness remains relatively constant. This suggests different modes of deposition for the two layers. b. Samples 15-6A and 15-6B. The two samples were collected 50 feet apart laterally and demonstrate that varves, and even thin laminations within silt layers, are locally continuous.

a.



0 CM 3

b.

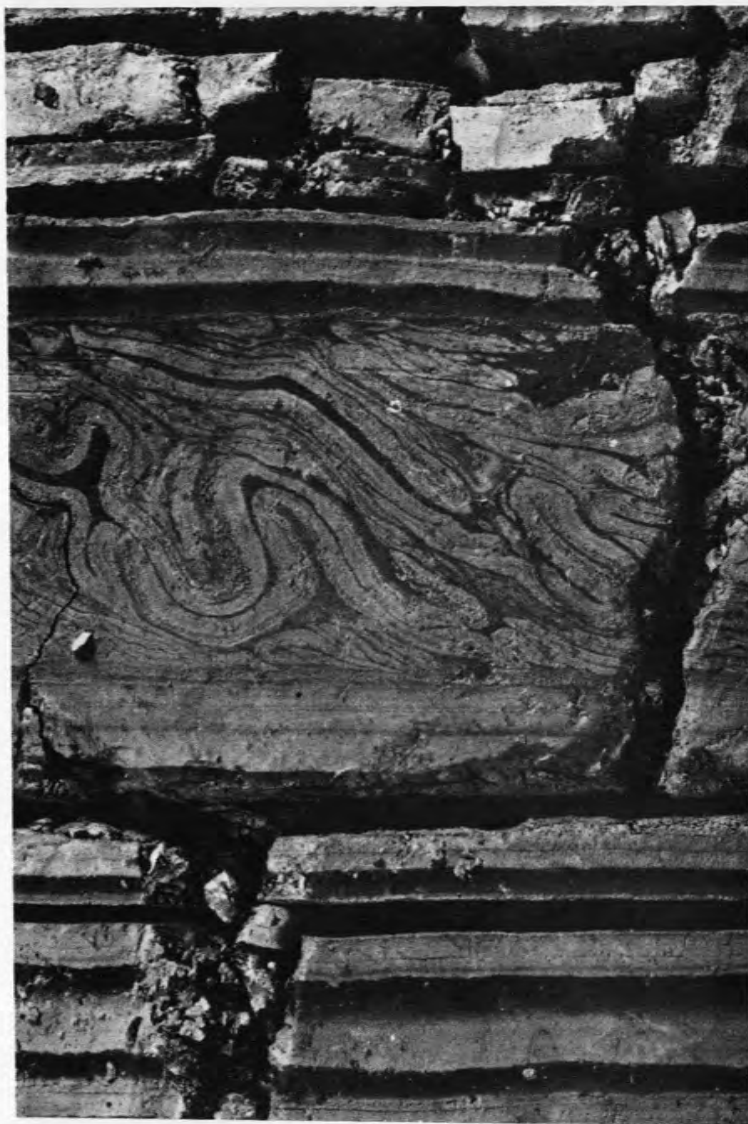


0 CM 3

Figure 33. Group III varves. a. Sample 32-1. A disturbed zone involving about 5 couplets separates sequences of regular varve sedimentation. b. Arrow points to a clay drape separating silt layers which here are crossbedded. This feature suggests the process of settling clay is interrupted by periodic current deposition of silt (Sample 14-1).

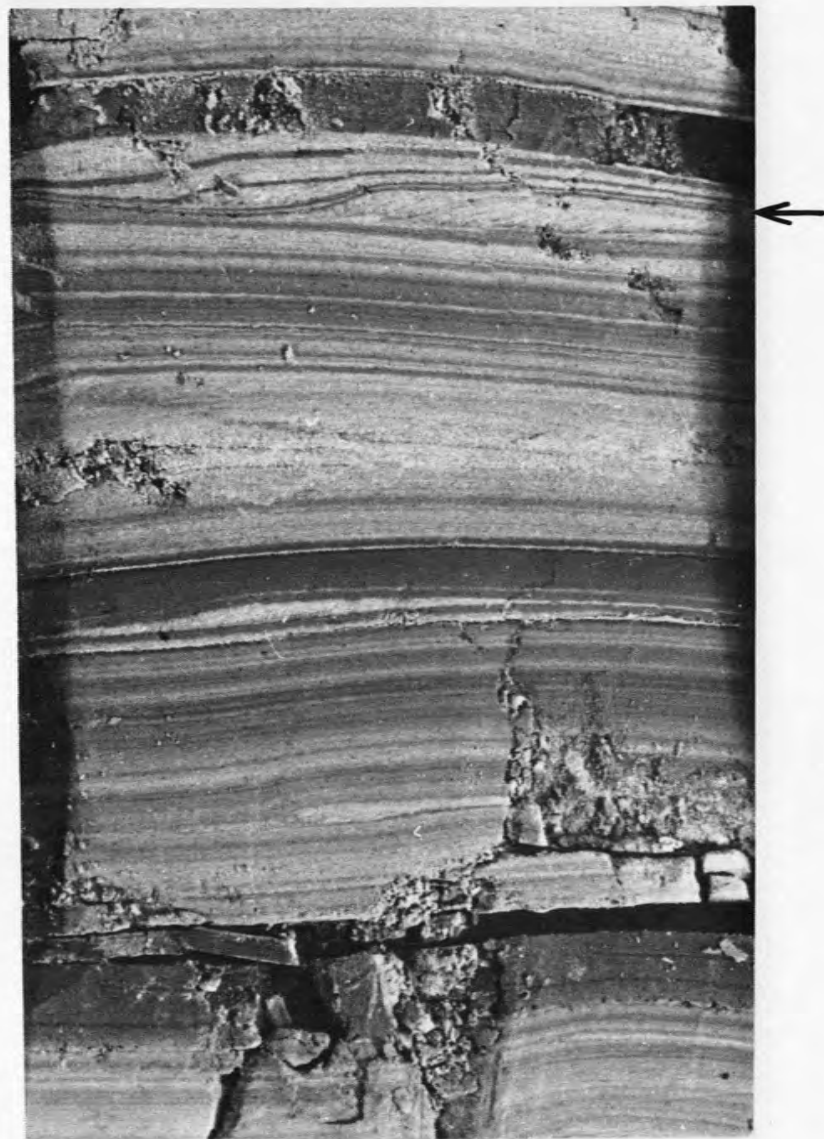


a.



0 CM 3

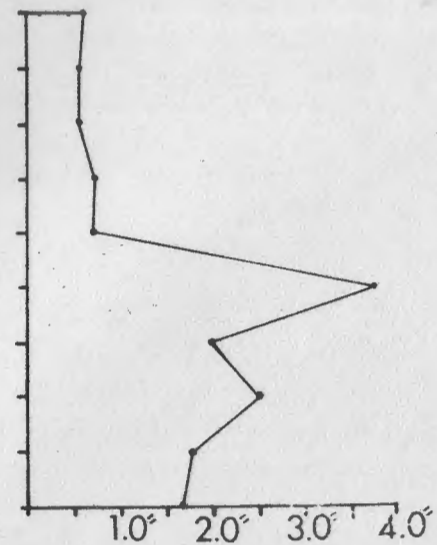
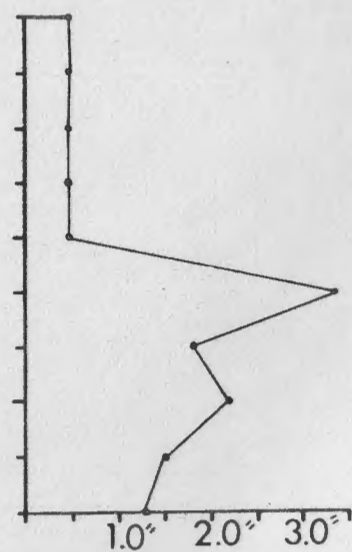
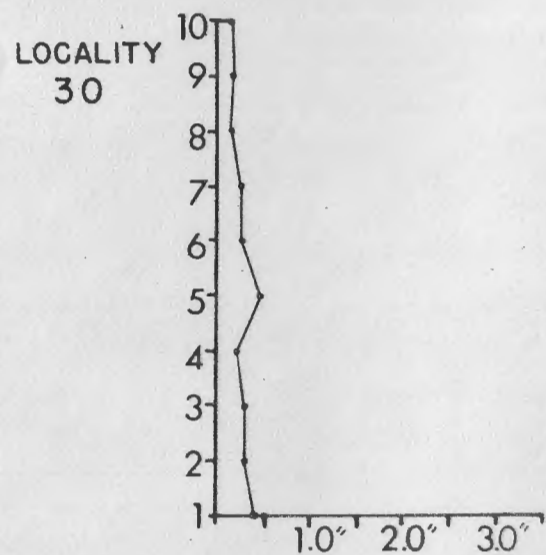
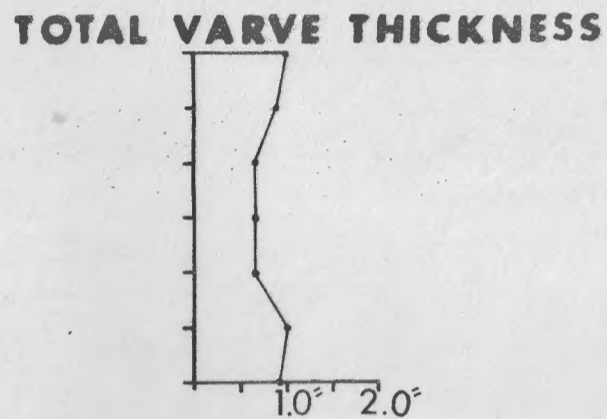
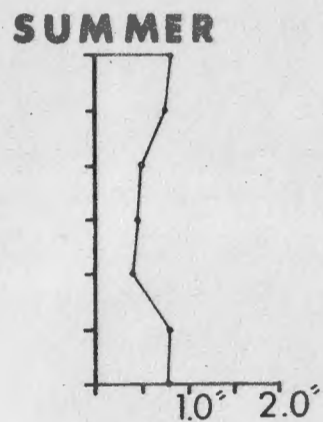
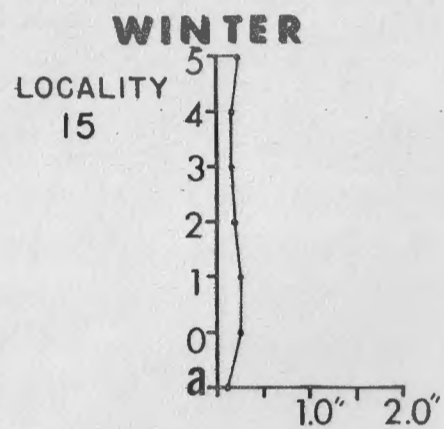
b.



0 CM 3

Figure 34. Position of varve samples (designated by sample number) collected every 5 feet are plotted on the ordinate. The average layer thickness within one-foot samples is plotted on the abscissa. Total varve thickness varies as summer thickness varies; winter thickness remains relatively constant. This implies that the mode of deposition for the two layers is different.





thickness varies as silt thickness varies and that clay thickness remains relatively constant. This suggests that the mode of deposition is different for the two layers. That is, a couplet is not the result of only one sedimentation pulse. The key to these modes of deposition lies in correct interpretation of sedimentary structures and grain-size analyses.

Grain-size distribution. Silt layers are positively skewed, coarser, and better sorted than the negatively skewed clay layer (Figs. 15, 16). As in all varves there is a sharp change in grain size between the clay layer and overlying silt layer, although this contact is sometimes uneven due to burrowing organisms.

The silt layer is composed of laminations of varying grain size, mineralogy, and thickness (Figs. 35a, 36a, 37a), and when these laminations are magnified, many are seen to be micrograded beds (Figs. 35b, 36b, 37b). Even though the silt layer is composed mostly of multiple graded beds, as a unit it does not always fine upward (Figs. 38b, 39a). Almost every silt layer studied is composed of laminations too thin to be analyzed individually for grain-size distribution. Thus analyses were of samples containing several sedimentary units and represent a composite of grain-size distributions. Nevertheless, general trends can be seen.

Some silt layers show a coarse layer at the base with a finer but fairly constant mean size for the remainder of the varve (Fig. 38a). Others show a decrease or an essentially similar mean grain size for the entire silt layer (Figs. 38b, 39a). Clay layers, on the other

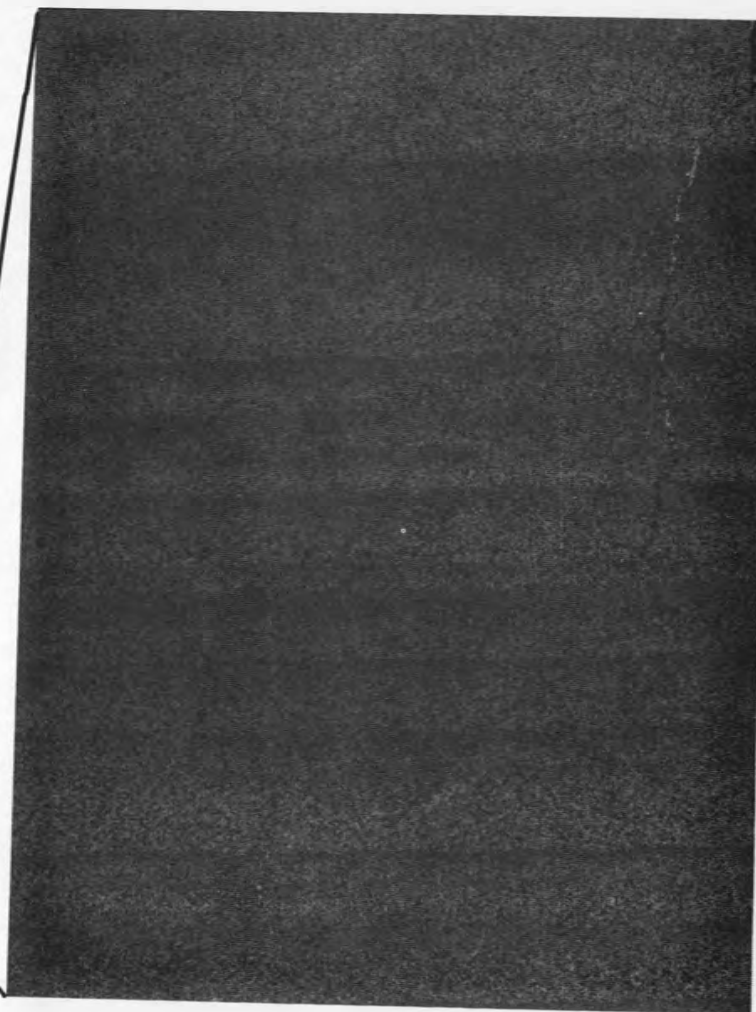
Figure 35. Group III varves; Sample 30-5. a. Thick silt layers are composed of many sedimentation units. Grain-size analyses are shown in Figure 39a. b. A thin section of a portion of the middle of a silt layer shows the units to be micrograded beds. 15X

a.



0 CM 3

b.

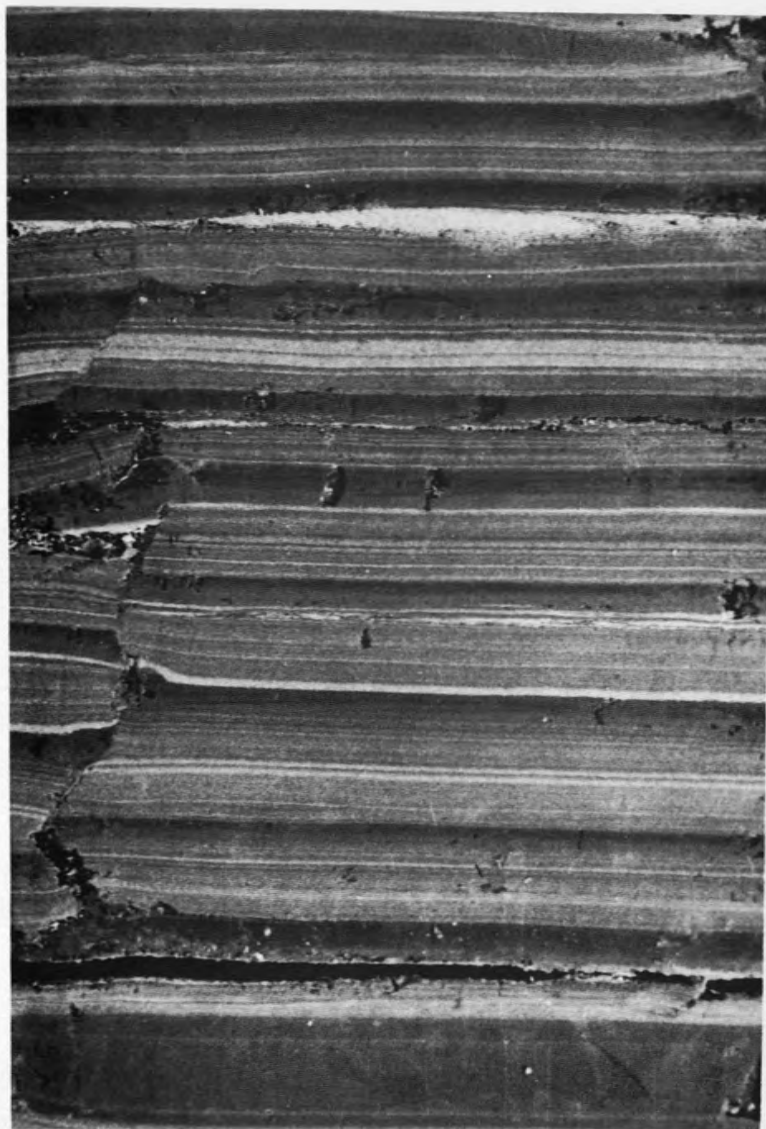


0 MM 3

Figure 36. Group III varves; Sample 30-7. a. This sample is located 10 feet above sample 30-5 (Fig. 35). Varves from the two sites have the same sedimentary structures, but the couplets are thinner in 30-7. This decrease in thickness going up the section is attributed to a decrease in rate of delta building. b. A thin section from a portion of a silt layer shows multiple graded beds. 15X



a.



b.

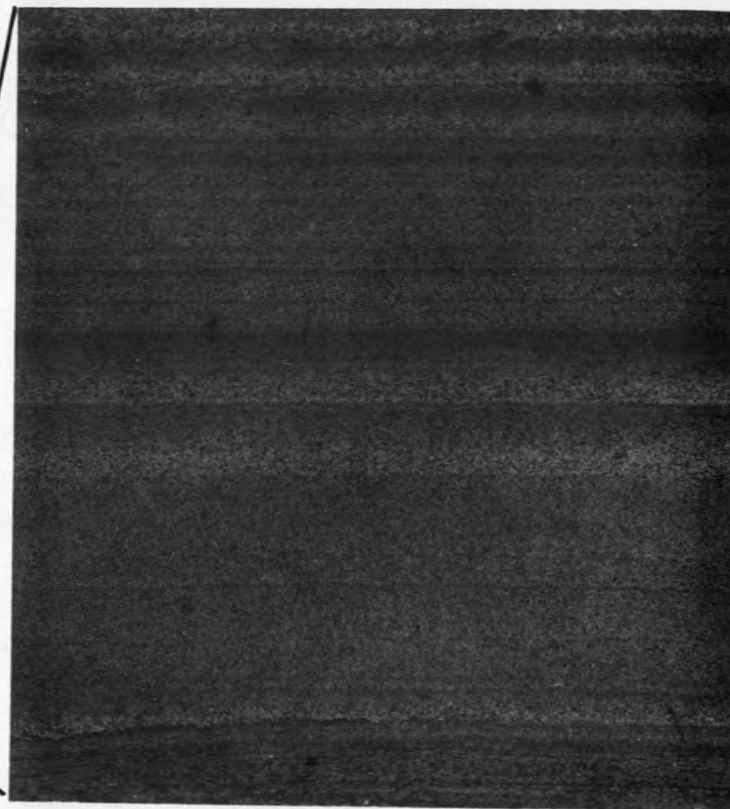
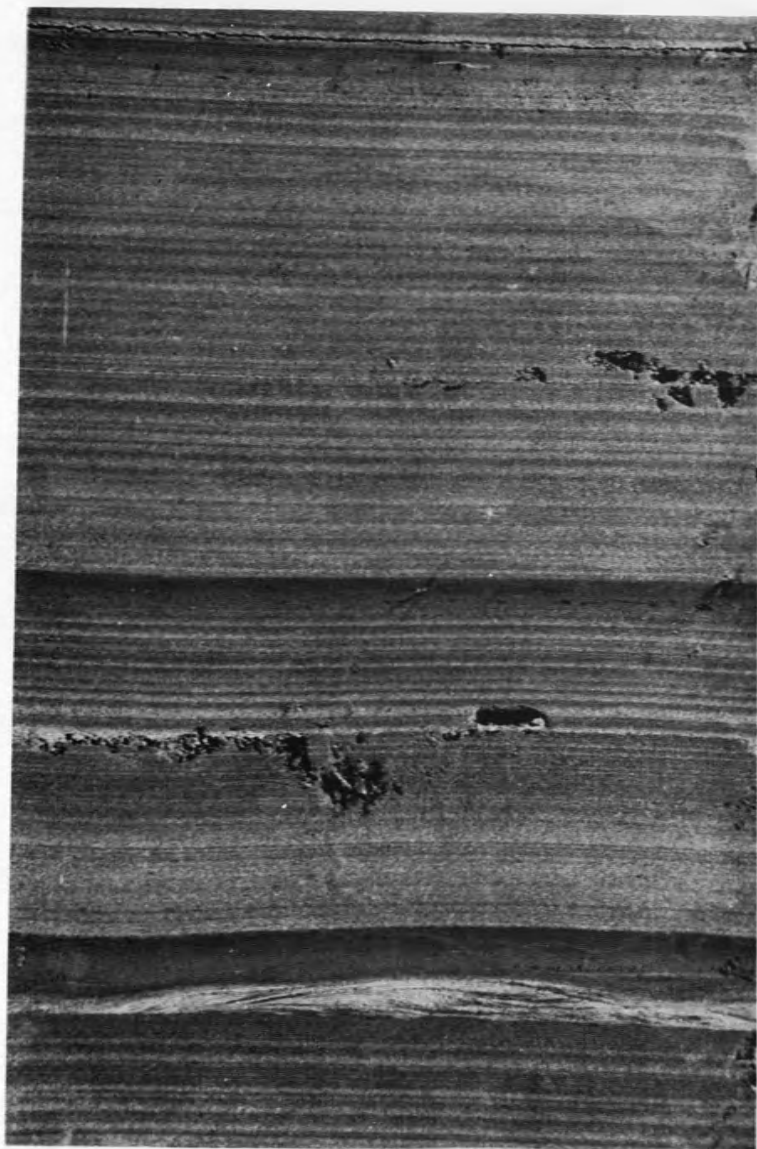




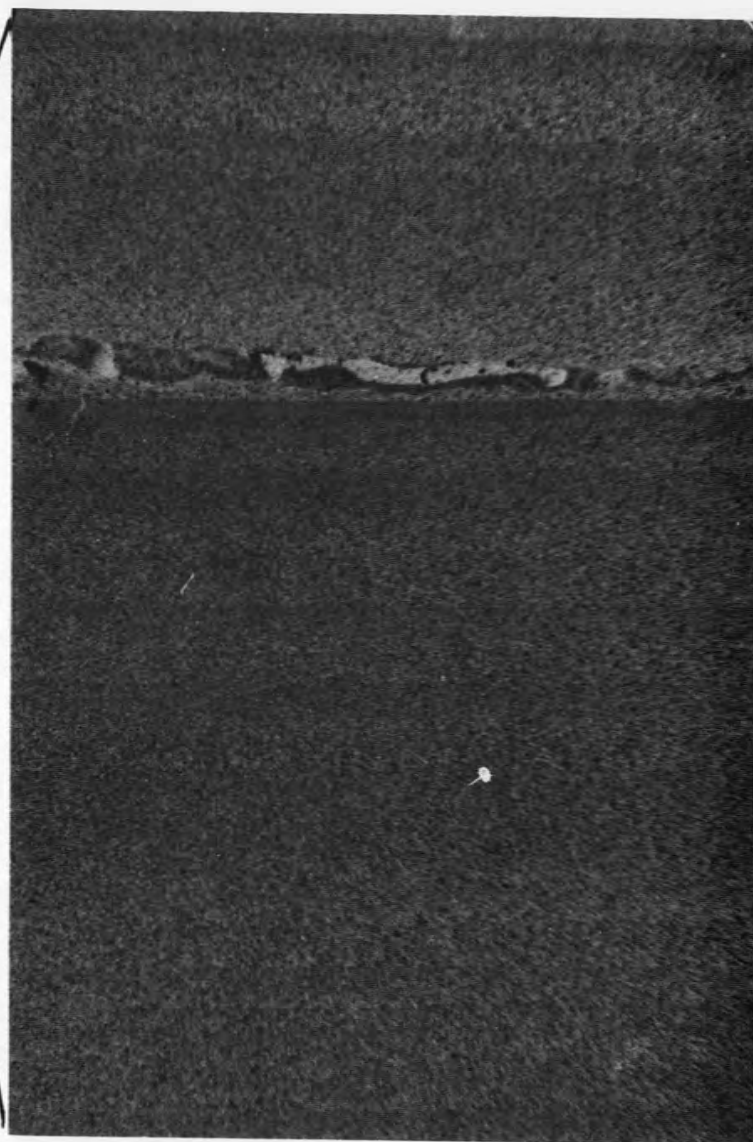
Figure 37. Group III varves; Sample 7-2. a. The uppermost silt layer here is composed of over 40 micrograded beds. These laminations probably reflect fluctuations in suspended sediment concentration of streams that flowed into the lake and continued along the lake bottom as density underflow. Grain-size analyses are shown in Figure 17. b. Thin section of a portion of the uppermost silt layer shows multiple graded beds. 15X

a.



0 CM 3

b.

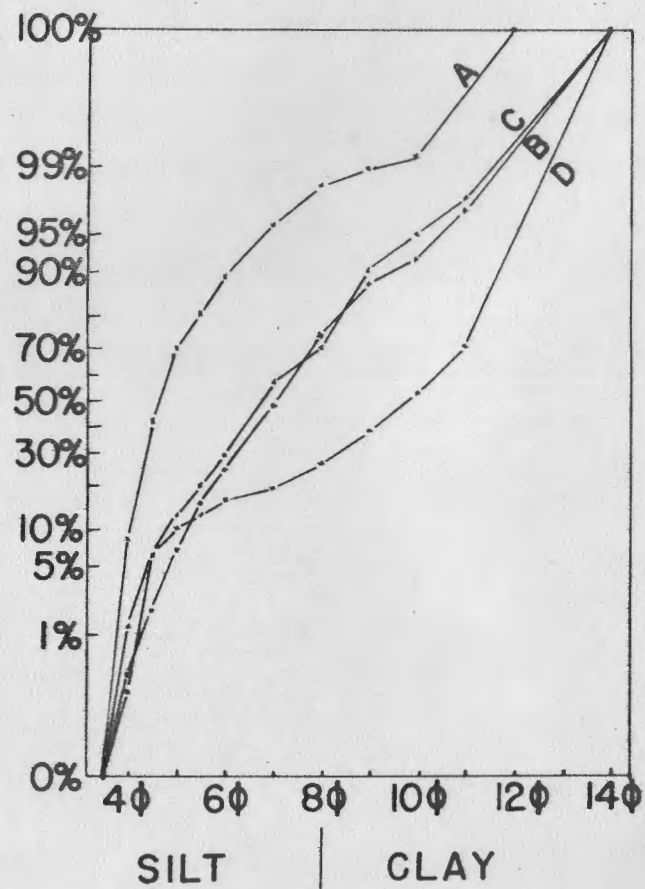


0 MM 3

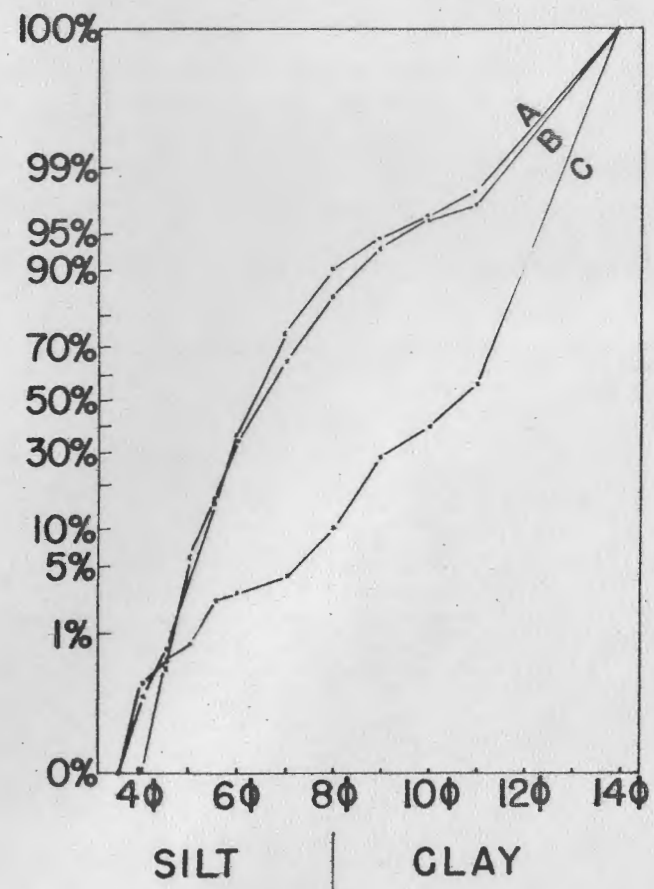
Figure 38. Group III grain-size analyses. a. A divided silt layer shows bottom section (30-5A) to be much coarser than the remainder (30-5B and 30-5C), which have essentially the same mean grain size. 30-5D is the clay layer. b. Silt layer sections (15-4A and 15-4B) show little change in mean grain size though they are composed of multiple graded beds. 15-4C is the clay layer.

## GROUP III VARVES

a. SAMPLE 30-5



b. SAMPLE 15-4



hand, always show a constant decrease in mean grain size from bottom to top (Fig. 39b). This gradation within the clay layer suggests that flocculation was not significant in clay sedimentation. The pronounced difference in grain-size distribution between the two layers suggests that conditions governing their deposition were different.

Sedimentary structures. Figure 40a clearly shows graded beds in the fine-grained laminations, while crossbedding occurs only in the thicker coarse-grained beds. At several localities crossbeds in the form of ripples have been found with wavelengths of 7 cm (Fig. 29b), 14 cm (Fig. 40a), and 21 cm (Fig. 40b). It can be safely said that the graded beds and crossbeds found in the silt layers were deposited from a current, but the type formed, as well as the wavelength of the ripples, is dependent on many variables. Factors such as grain size, current velocity, thickness of current, and the density contrast between the density flow and the surrounding lake waters would be important. Erosional contacts, best seen under magnification, are additional evidence of current action (Fig. 41b). Disturbed zones of limited vertical extent (Fig. 33a, 41a) may or may not have been generated by an underflow.

Genesis. Group III varves were found to be closely associated with the formation of lacustrine deltas. All sample sites, except the basal-varve locality 27, were in a delta or on the periphery of one. Water depth at time of deposition ranged from 50 to 130 feet. The close proximity to inflowing rivers explains the current-formed sedimentary structures and the thick silt layers characteristic of the group.

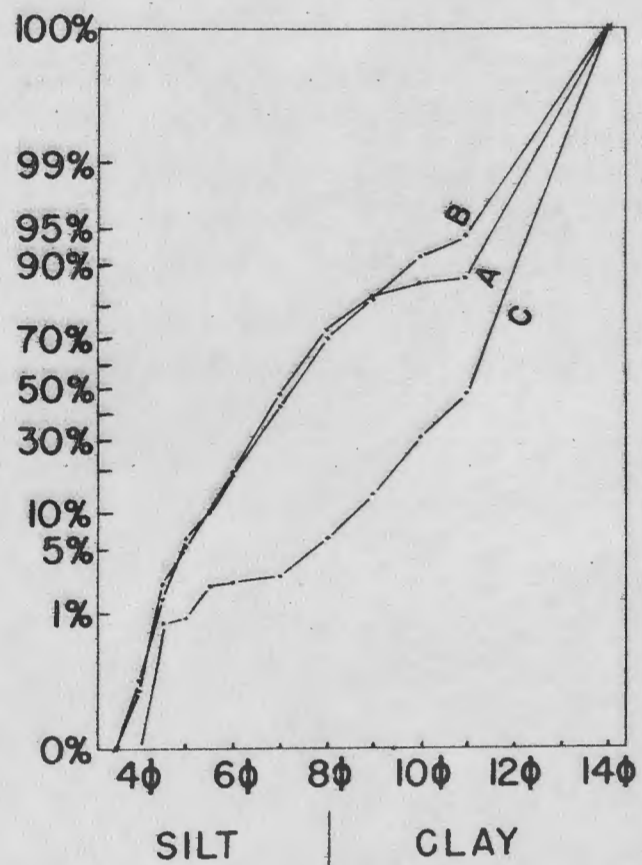


Figure 39. Group III grain-size analyses. a. Silt layer does not fine upward; bottom half (20-A) is only slightly finer than top half (20-B). Mean grain size of clay layer (20-C) is  $10.9\phi$ . b. A thick clay layer divided in vertical section into four equal parts shows a fining upward (20-1A to 20-1D).



# GROUP III VARVES

a. SAMPLE 20



b. SAMPLE 20

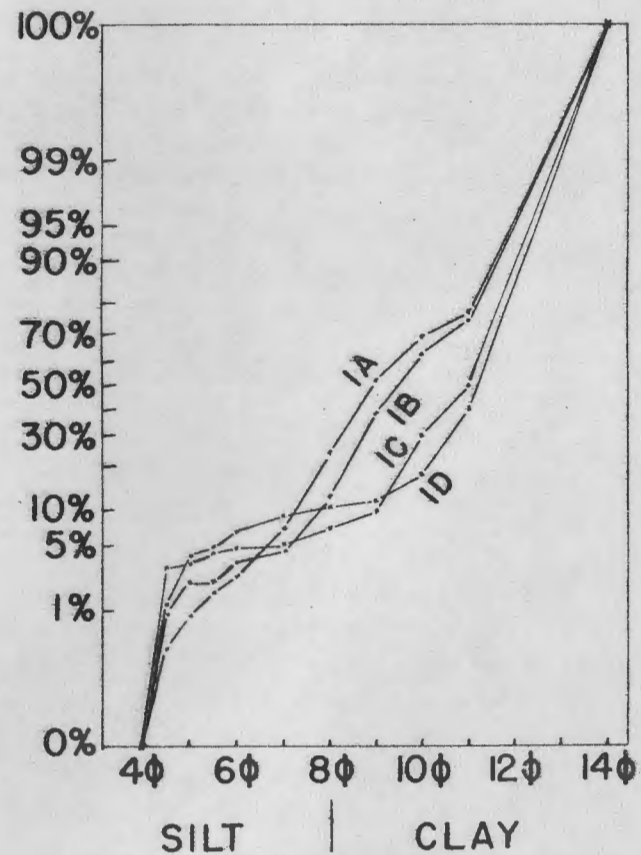
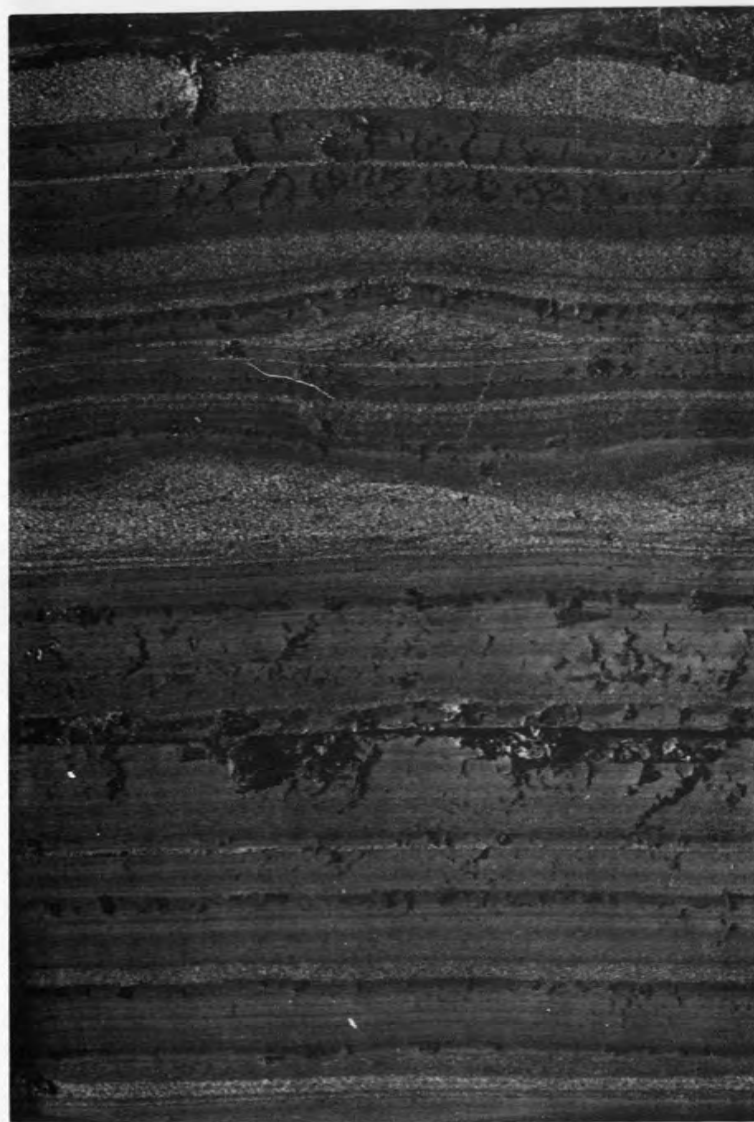


Figure 40. Group III varves. a. Varves (deposited in 80 feet of water) demonstrate that multiple graded beds are found in fine-grained laminations, while ripples (here, wavelength is 14 cm) occur in the coarse-grained units. Grain-size analyses are shown in Figure 38b. b. Varves (deposited in 70 feet of water) show festoon crossbedded silt layers (here, wavelength is 21 cm). Winter clay is draped over bedforms from the previous summer deposit.

a.



0 CM 3

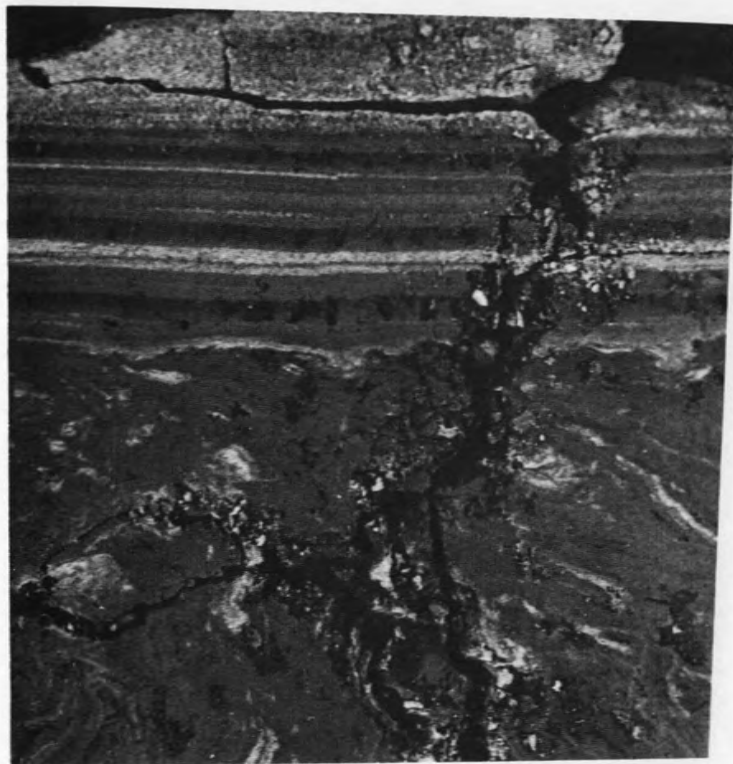
b.



0 CM 3

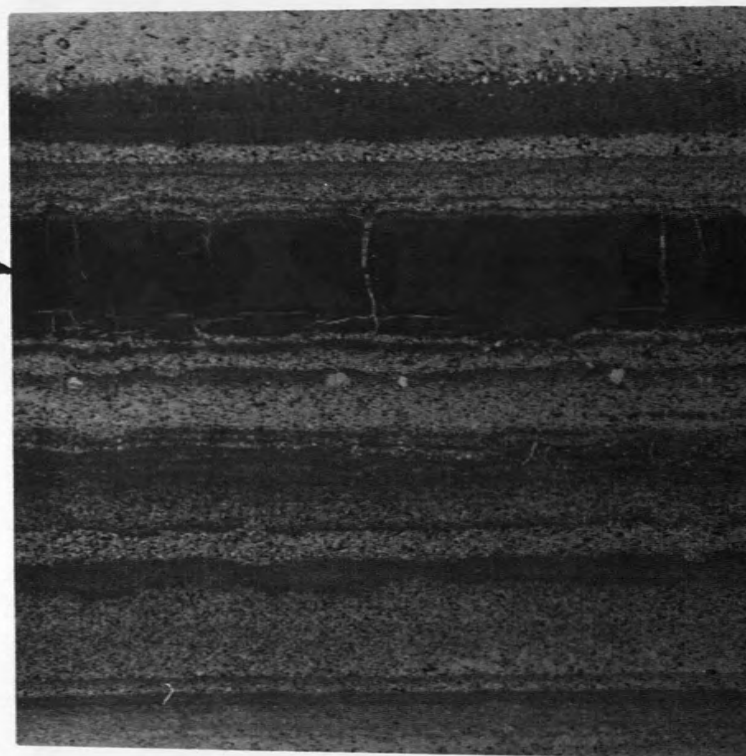
Figure 41. Group III varves; Sample 30-10. a. The bottom section was apparently disturbed when in a thixotropic state. Above the contorted zone are the final varves of the section (locality 30). Sample is located 15 feet above sample 30-7 (Fig. 36). Grain-size analyses are shown in Figure 17. b. A thin section shows a sharp change in grain size between laminations. This is interpreted as being due to the process of slowly settling clay interrupted by periodic silt influxes. Erosional contracts can be seen at arrows. 15X

a.



0 CM 3

b.



0 MM 3



The following mechanism for the formation of Group III varves is proposed. Sediment-laden streams entering lake water of lower density would continue along the bottom at a lesser velocity as an underflow. Sediment dispersed in the stream contained a significant amount of clay, most of which later became dispersed by lake currents. Particles settled continuously throughout the year from this widely dispersed clay supply. Clay sedimentation was interrupted periodically, during the melt season, by additional underflows (Fig. 33b). Although rivers flowed continuously during the summer, suspended sediment content in them would certainly fluctuate. Laminations of varying thickness and grain size, characteristic of Group III, probably reflect these fluctuations.

With the beginning of winter, the ground surface became frozen and glacier melting decreased. Both factors made sediment less available and allowed clay suspended in the lake to be the dominant sediment source for the varves. This change in source occurred rapidly, as evidenced by the usually sharp contact between the silt and overlying clay.

In summary, the main mechanism of deposition of the multi-laminated summer layer appears to be periodic influxes of silt brought by density underflows that interrupted the continuous settling of silt and clay dispersed in the lake. The mode of deposition for the winter layer was unimpeded clay sedimentation, normally resulting in a graded bed.



### Annual nature of rhythmites

No direct evidence was discovered in this study to prove conclusively that Lake Hitchcock rhythmites are annual deposits (i.e., varves). However, several indirect lines of evidence suggest that their rhythmic nature is due to sedimentation controlled by the yearly climatic cycle.

A dominant rhythmic pattern prevails throughout the lake sediments even though they vary in couplet thickness, relative thickness of silt and clay layers, sedimentary structures, and grain size. At any one location only minor textural changes occur in a section of several hundred rhythmites. Six hundred and twenty-five couplets with little significant change in character were observed at locality 30, indicating consistent repetition of depositional processes.

Thickness and sedimentary structures of the silt layers vary between localities while clay layer thickness remains relatively constant. Silt layers are positively skewed, coarser, and better sorted than the negatively skewed clay layer. These differences indicate that a couplet is not a uniformly graded bed, but consists of two distinctive layers having different modes of deposition. Thus a rhythmite is not a turbidite resulting from one sedimentation pulse but was deposited by two alternating processes. Considering the amount of sediment involved with lake-wide deposition of each couplet, the consistent repetition of sedimentological processes is best explained by the annual climatic cycle rather than by the diurnal cycle or by haphazard storms.

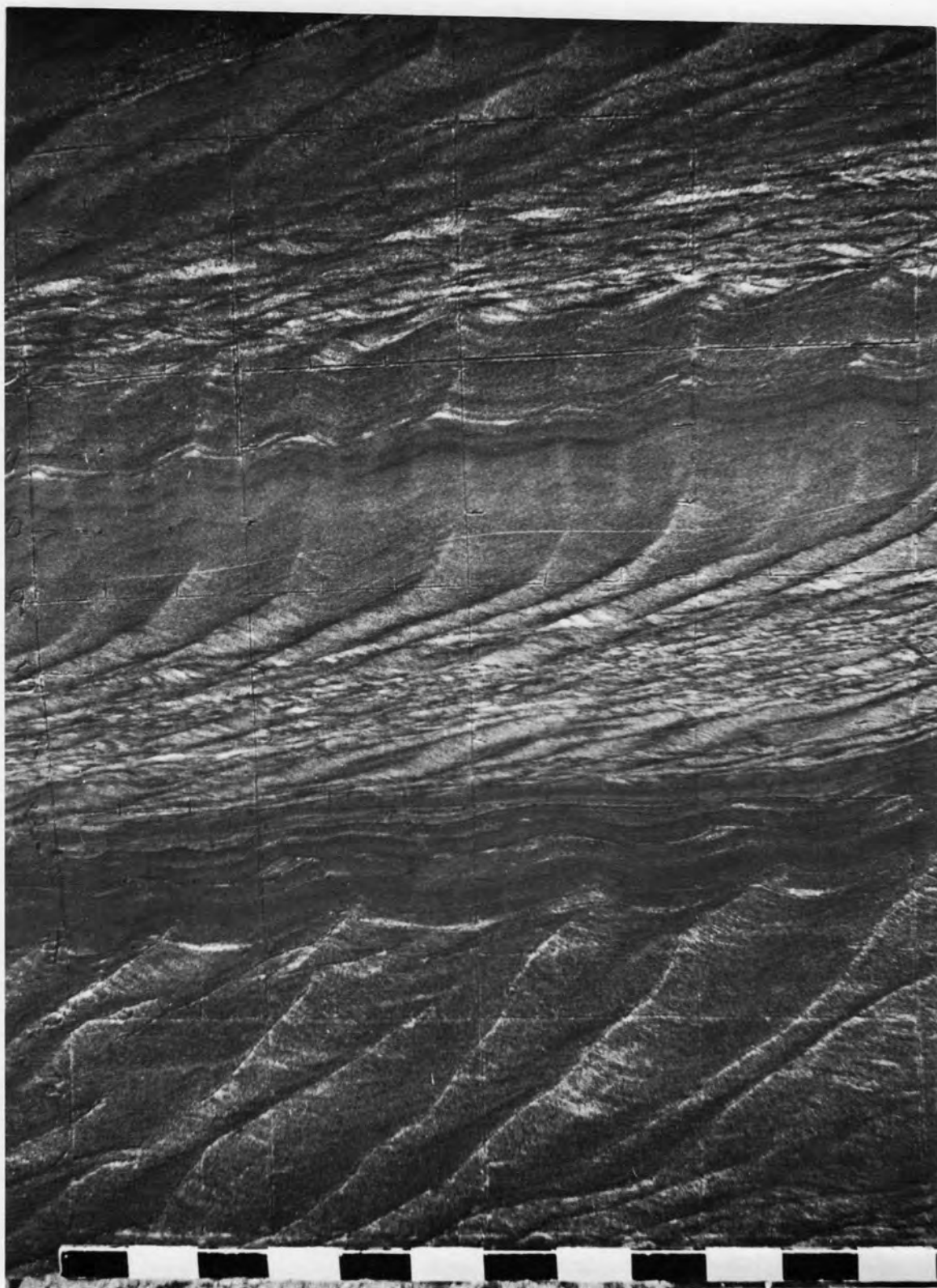
## DELTAIC SEDIMENTATION

Almost all theories of varve formation include as an important part the direct contact between glacial ice and the proglacial lake (De Geer, 1940; Sauramo, 1923; Antevs, 1951). In Lake Hitchcock, the section of lake perimeter in direct contact with ice was small in comparison to the length of lakeshore bordered by land. Thus the delta and not the glacial front was the point where most of the sediment entered the lake, and deltaic deposits can be considered the proximal equivalent of the more distal varved clays.

A rhythmic sequence of bedforms, similar to one observed in a kame delta by Jopling and Walker (1965), was seen in the fine-grained portions of the prodelta slope of several Lake Hitchcock deltas (Fig. 42). Such a sequence begins above a clay or silt layer with ripple-drift, generally consisting of fine to medium sand. The angle of climb of ripple crests usually steepens and sometimes recurves, eventually changing to an undulating ripple form. With continued sedimentation on this ripple form, crests can then build downcurrent, vertically, or even upcurrent. A sequence is usually completed with a lamination of silt or clay draped over the ripple form. This form when exposed in three dimensions has linear crests that appear to be in an echelon pattern (Fig. 43).

Jopling and Walker (1965) attributed the deposition of the ripple-drift cross-lamination in their study to density underflows of sediment-laden melt water into a glacial lake. They postulated that different types originated from fluctuations in current velocity and

Figure 42. Rhythmic sequence of deltaic bedforms. The top of one sequence (1), one complete sequence (2), and nearly all of a third sequence (3) were exposed in a fine-grained lobe of a Lake Hitchcock delta. Divisions on the rod are 10 cm. Gustavson photo.

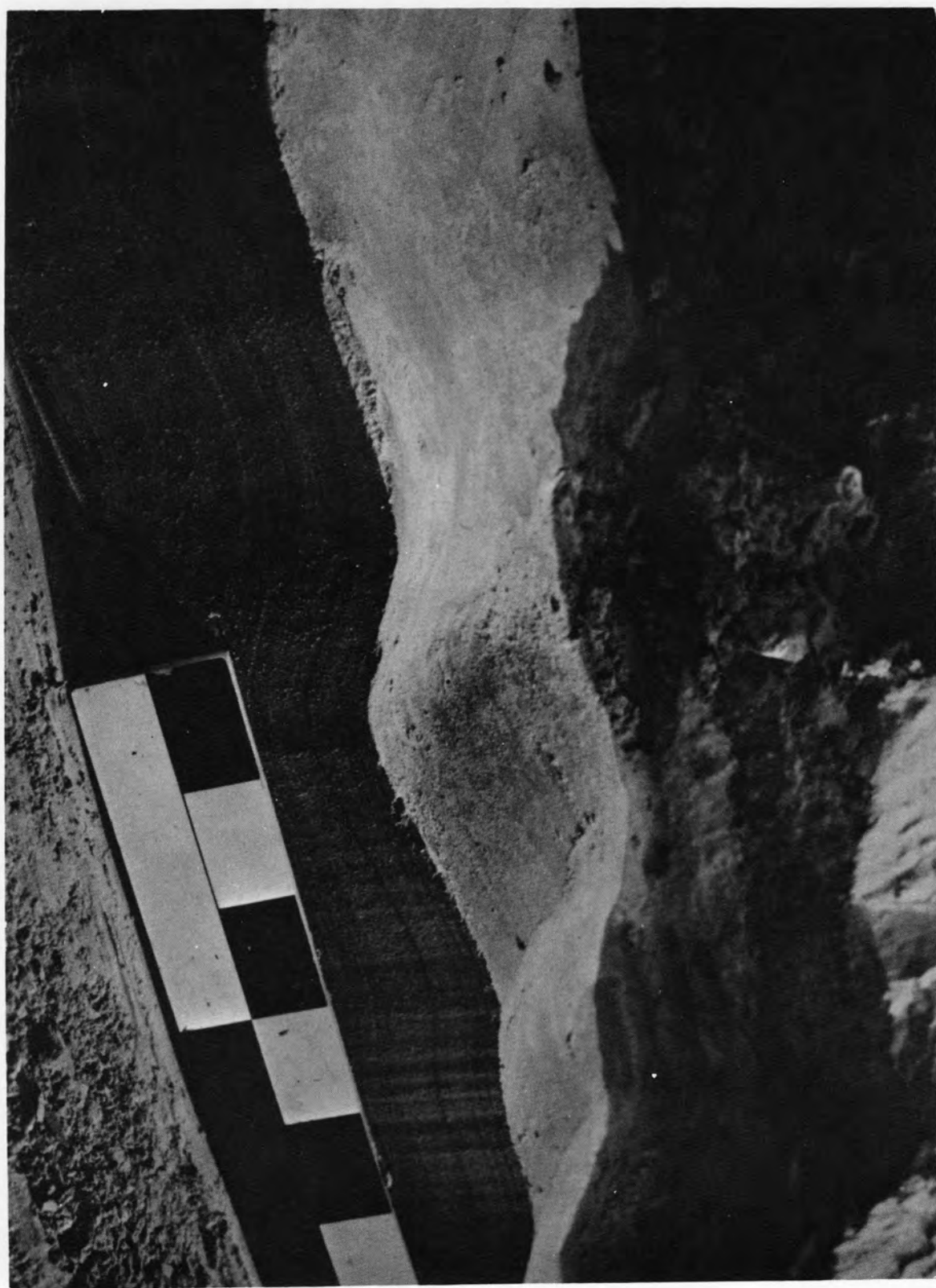


3

2

Figure 43. The undulating ripple form has linear crests  
that appear to be in an en echelon pattern.  
Scale is 30 cm.







from variations in composition and concentration of suspended sediment within the flow. Because of the similarity of environment of deposition and bedform types between their study area and Lake Hitchcock deltas, a similar origin is assumed.

In glacial Lake Hitchcock, the distal equivalents (varved clay) of the rhythmic deltaic deposits contain two forms of rhythmic sedimentation: multiple graded beds commonly occurring in the silt layer and repeated couplets. The deposition of a couplet probably involves an alternation of two distinct processes while multiple graded beds in the silt layer result from repetition of one process only. Since the deltaic sequence of bedforms also results from the repetition of one process, deltaic sequences and the graded beds probably are genetically related. That is, each deltaic sequence, or portion of the sequence, is the proximal equivalent of a graded bed within the silt layer.

#### CONCLUSIONS

The following is a summary of the important physical properties of the Lake Hitchcock sediments and the processes involved in their deposition.

(1) A rhythmic pattern prevails even though the varves vary between localities in relative thickness of individual layers, total couplet thickness, grain size, color (mineralogy), and sedimentary structures.

(2) Varved clays fill topographic irregularities. Deposits are thickest in the depressions and thinnest over high areas.

(3) Generally, deltas show active growth followed by decreasing growth. Decrease in growth is interpreted to reflect diminishing sediment supply as ice disappeared from each respective drainage basin.

(4) Rhythmic sedimentation occurred in the deltas as well as in the lake deposits.

(5) Near inflowing rivers, varved clays grade shoreward into varved deltaic deposits by gradual thickening of individual silt layers.

(6) Thickness of the silt layers varies considerably and appears to be directly related to proximity of inflowing rivers, while clay layer thickness is relatively constant throughout the lake. This difference implies that the depositional mechanism is different for each layer.

(7) A varve, as a unit, is not a graded bed but consists of two texturally and genetically distinct layers. A couplet is not the result of only one sedimentation pulse.

(8) The silt layer is composed of thin laminations that are commonly graded. Forty graded beds were observed in one 2-inch layer.

(9) Silt layers do not always fine upward, while clay layers do. This gradation within the clay layer suggests that flocculation was not significant in clay sedimentation.

(10) The silt-clay contact varies according to the environment of deposition. Less than 50 percent of the varves have gradational contacts. Groups I and III varves rarely have gradational contacts; Group II varves commonly do.

(11) Small scale crossbedding is common in Group III but rare in Groups I and II.

(12) Sedimentary structures within the silt layer appear to be related to grain size: multiple graded beds occur in fine-grained laminations, while crossbedding is found in the coarse-grained beds.

(13) Thin silt laminae sometimes occur in the clay layers; thin clay laminae occasionally occur in the silt layers.

(14) In general, grain size of the silt layer ( $M\phi$  varies from  $5.5\phi$  to  $8.5\phi$ ) depends upon location in the lake. Grain-size distribution of clay is much the same everywhere (average  $M\phi = 10.5\phi$ ).

(15) The range of grain sizes for the silt and clay layers is approximately the same, but each has a decidedly different mode. The positively skewed silt layer is coarser and better sorted than the negatively skewed clay layer.

(16) The clay-silt contact is sharp, though commonly uneven due to burrowing organisms.

(17) Many contacts appear macroscopically regular, but microscopically are erosional.

(18) Lebenspuren were created by two different species of insect larvae, both of which appeared to have lived only part-time in the lake. No evidence of extensive burrowing of permanent infauna has been observed.

(19) The only identified plant remains found in the lake were arctic-alpine species washed in from adjacent land.

(20) The two dominant colors of both silts and clay are olive

gray (averaging 5Y 4/1), generally thought to be due to mineralogy of the crystalline and metamorphic uplands, and dark yellowish brown (averaging 10YR 4/2), suggesting the influence of Triassic rocks.

#### Lacustrine sedimentation

As the glacier retreated up the Connecticut Valley, the large ice mass became a decreasing influence on the southern portions of the elongate lake. Lake Hitchcock probably was not homogeneous in physical characteristics related to seasonal variations in lake water temperature. Most lacustrine circulation is directly related to thermal conditions within a lake. A well-developed thermocline enhances surface circulation. Fall and spring overturns are dependent upon significant annual fluctuations in lake temperature. Overturns and the thermocline are important factors in temperate lakes but are of less importance in subpolar and polar lakes. Although some lake currents probably existed in all parts of Lake Hitchcock, the best circulation occurred in areas farthest from the glacial front.

Concentration of suspended sediment is the most important factor affecting water density, differences in temperature being negligible by comparison. In glacial lake sedimentation, the absolute density of the lake water is not as important as the density contrast between the lake and the inflowing streams. By analogy with modern glacial streams, streams coming directly from the glacier would have a much higher sediment concentration (i.e., were more dense) than streams draining ice-free valleys around the southern end of the lake. Depending upon their relative densities, the major means of sediment

distribution would be grouped into underflow, interflow, and overflow.

Using the above suggested limnological conditions as a framework the following mode of deposition is proposed. Sediment was carried to the lake from the glacier or from stagnant ice masses, first directly from the glacier and later by overland streams. Sand and gravel was deposited on the deltas while the finer fraction continued into the lake and flowed at a level determined by its density and that of the lake.

Sediment entered Lake Hitchcock at a number of discrete points. This incoming sediment contained clay that eventually was distributed throughout the lake by currents. The clay settled continuously, unless interrupted by currents, but accumulated in significant amounts only during the winter when coarser material was made less available. The extremely fine-grained winter layer permits the inference that the lake, which was over 200 feet deep in some places, was not cleared of suspended sediment during the winter. Thus the clay composing a winter layer does not necessarily represent the same volume of clay brought in the previous summer. Thickness of the clay layer would be more likely related to concentration of suspended sediment near the lake bottom and length of settling time. Because clay layers tend to be relatively constant in thickness, both of the above factors must have been fairly consistent from year to year.

Most of the sedimentary structures found in the silt layer, such as erosional contacts, crossbedding, and multiple graded beds, are best explained by a bottom current (density underflow). As a stream heavily laden with suspended sediment entered the lake, it flowed



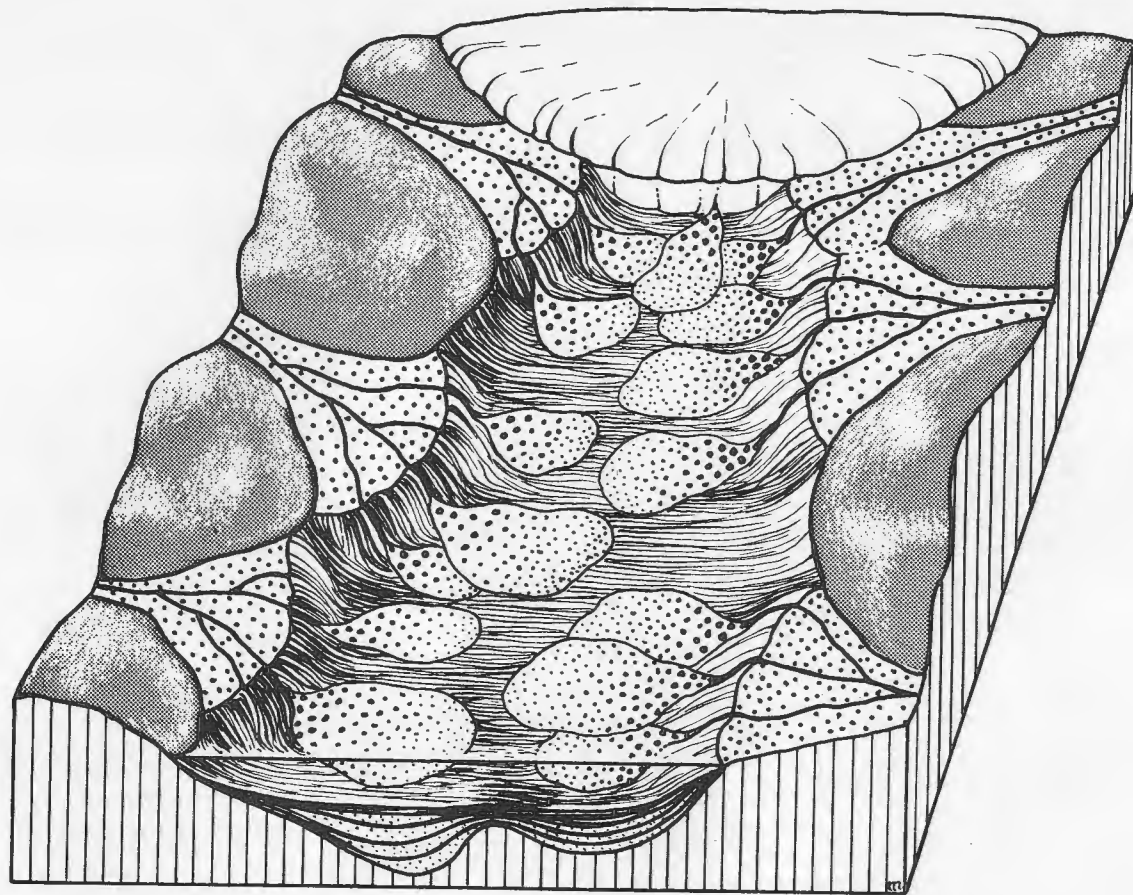
down the prodelta slope and out onto the lake floor, depositing sediment as it went. Since streamflow is usually continuous, one can expect that underflow would also be continuous and not like a single-pulse marine turbidity flow. Although flow is continuous, sediment content would certainly vary; multiple graded beds might be explained best by fluctuations in sediment content of the entering stream. Two reasons for these fluctuations could be the diurnal melt cycle or varying runoff due to storms.

Figure 44 shows the postulated density underflow pattern for a portion of one summer. During the rest of the summer and in succeeding years these various flows overlapped and interfingered as deposition occurred on different areas of the deltas, causing bottom currents to flow in a new direction. A flow pattern such as this would tend to fill in low areas and perhaps flow around highs. Groups I and II varves are found in areas seldom reached by the density underflow, while Group III varves are found in areas reached regularly by underflow.

The summer layer varies greatly in physical characteristics between localities. The clay layer deposited each winter blanketed this complex silt deposit and imprinted a rhythmic nature on the otherwise very diverse sediments.



Figure 44. The density underflow pattern suggested here is for a portion of one summer. During the rest of the summer and in succeeding years, fans would overlap and interfinger with each other.



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## APPENDIX I

## Grain-size statistics of 153 Lake Hitchcock samples

S Classical summer, bottom to top (S1-S3)

W Classical winter, bottom to top (W1-W4)

C Composite

Sample		Mean ( $\phi$ )	Standard Deviation	Skewness	Kurtosis
1-B	W	10.25	1.99	-.67	3.07
1-C	C	8.58	1.84	.23	2.98
1-D	S	7.16	1.89	.65	3.26
1-E	S	7.76	1.93	.87	3.35
2-1	S	7.12	1.16	.40	3.32
2-2	W	10.04	2.33	-.80	2.87
3-1	C	9.81	2.47	-.67	2.55
3-2A	S	7.04	3.33	.09	1.74
3-3	W	10.93	2.07	-1.52	4.79
4-0A	S1	7.54	1.54	.79	5.11
4-0B	S2	8.22	2.02	.62	2.89
4-0C	W	10.64	1.84	-1.01	4.04
4-1A	S	7.55	1.51	1.25	5.51
4-1B	W	10.22	1.97	-0.48	2.59
4-2A	S	7.63	1.99	.66	3.46
4-2B	W	9.52	2.48	-.49	2.42
5-1A	S	9.01	2.00	.10	2.89
5-1B	W	10.83	1.80	-.86	3.01
5-2A	S1	8.47	1.55	.75	4.28
5-2B	S2	10.18	1.81	-.23	2.43
5-2C	W	11.37	1.50	-2.00	8.47
5-3A	S	8.37	1.65	.87	4.19
5-3B	W	10.95	1.87	-1.47	5.25
6-1A	W1	8.53	2.16	3.10	2.34
6-1B	W2	10.58	2.16	-1.07	3.38
6-10	W4	10.87	2.33	-1.55	4.33
6-1	W	11.23	1.50	-1.44	5.22
6-2	S1	6.47	1.18	.71	4.68
7-1A	S	7.48	1.57	.52	3.92
7-1B	W	10.74	1.98	-1.04	3.46
7-2A	S	5.97	1.44	2.31	10.34
7-2B	W	9.09	2.52	-.19	1.95

## APPENDIX I (cont'd.)

Sample		Mean ( $\phi$ )	Standard Deviation	Skewness	Kurtosis
8-1	C	7.19	1.65	.42	3.54
8-2	C	8.04	1.50	.28	4.05
8-A	S	6.71	1.36	1.11	6.42
8-B	W	9.98	2.32	-.47	2.18
9-1	C	7.64	.81	.71	8.59
9-2X	W	8.48	2.02	.49	2.60
9-2Y	S	6.26	1.03	.08	2.85
9-3	S	6.26	1.08	.34	3.15
10-A	S	7.34	1.38	.64	3.17
10-B	W	10.76	1.92	-1.02	3.47
11-1A	W1	9.61	2.05	-.10	2.44
11-1C	W3	10.52	2.15	-.96	3.04
11-1D	W4	11.18	1.62	-1.54	5.80
11-2A	S1	7.34	1.77	.79	4.43
11-2B	S2	7.77	1.40	.74	5.59
11-2C	W1	9.93	2.08	-.25	2.21
11-2D	W2	11.04	1.90	-1.68	5.63
13-A	S	5.86	1.92	2.21	7.91
13-B	W	10.90	1.77	-1.01	3.69
15-AA	S1	7.68	1.30	.32	3.36
15-AB	S2	8.00	1.59	1.04	4.57
15-AC	W1	10.32	2.03	-.73	3.14
15-AD	W2	11.48	1.45	-2.35	10.58
15-0A	S	8.53	1.68	.76	3.95
15-0B	W	10.53	1.87	-.57	2.46
15-1A	S1	7.90	1.73	.54	4.31
15-1B	S2	8.54	2.53	-.19	2.40
15-1C	W	11.10	1.66	-1.48	5.69
15-2A	S1	7.27	2.01	.38	3.05
15-2B	S2	7.97	1.97	.43	3.38
15-2C	W	10.64	1.83	-1.05	4.15
15-3A	S1	5.72	1.89	1.32	5.10
15-3B	S2	7.59	1.74	.62	4.09
15-3C	S	4.73	1.55	2.55	10.33
15-3D	W	9.94	2.62	-.81	2.57
15-4A	S1	4.91	1.05	2.26	11.16
15-4B	S2	7.17	1.66	.83	4.09
15-4C	S3	6.95	1.75	.66	3.58
15-4D	W	9.37	2.63	-.52	2.19
15-2	S1	4.46	.92	4.89	36.79

## APPENDIX I (cont'd.)

Sample		Mean ( $\phi$ )	Standard Deviation	Skewness	Kurtosis
15-5A	S1	5.60	1.17	.79	3.88
15-5B	S2	6.75	1.46	.08	3.64
15-5C	W	7.66	2.08	.69	2.97
16-1	C	8.91	2.46	.001	1.99
17-2A	S	7.92	2.22	.43	2.77
17-2B	W	10.66	1.94	-.91	3.37
18-1A	S	6.76	1.65	1.52	5.52
18-1B	W	9.44	2.24	-.44	2.58
18-2A	S	6.88	1.60	.76	3.97
18-2B	W	9.84	2.19	-.48	2.69
18-2AA	S	7.37	1.71	1.18	4.98
18-2BB	W	9.51	2.09	-.37	2.79
18-3A	S	6.29	1.50	1.53	6.55
18-3B	W	10.37	2.63	-1.12	3.14
19-A	S	8.64	2.10	.51	2.67
19-B	W	11.05	1.83	-1.45	4.71
20-A	S1	7.60	2.15	1.13	3.53
20-B	S2	7.50	1.81	.92	3.95
20-C	W	10.89	1.81	-1.14	4.07
20-1A	W1	9.35	1.95	.27	2.29
20-1B	W2	9.71	1.87	-.16	2.89
20-1C	W3	10.81	1.97	-1.52	5.45
20-1D	W1	11.01	2.13	-1.75	5.25
21-A	S	7.81	2.23	1.09	3.13
21-B	W	9.12	2.39	-.09	2.05
22	C	9.29	2.31	-.08	2.03
23-1	C	9.68	2.26	-.28	2.30
23-2	C	9.60	2.13	.01	2.00
23-3	C	9.17	2.66	-.46	2.38
23-4	C	9.29	2.27	-.03	2.21
23-5	C	9.54	2.40	-.26	2.09
24-1A	S1	8.41	1.99	.75	3.00
24-1B	W	10.81	1.81	-.88	3.15
25-A	S	9.00	2.13	.11	2.77

## APPENDIX I (cont'd.)

Sample		Mean ( $\phi$ )	Standard Deviation	Skewness	Kurtosis
25-B	W	11.10	1.77	-1.15	4.22
26-1A	S	6.98	1.68	.98	4.62
26-1B	W	9.92	2.20	-.63	2.81
26-2A	S	6.13	2.05	1.46	5.13
26-2B	W	8.36	2.75	.14	1.78
26-1CA	W1	7.64	1.52	.74	4.71
26-1CB	W2	9.61	1.82	.26	2.05
26-1CC	W3	10.05	2.18	-.75	2.72
26-1CD	W4	10.43	2.09	-.83	2.75
27-1A	S	7.05	1.50	1.46	6.3
27-1B	W1	10.22	2.07	-.61	2.72
27-1C	W2	11.30	1.59	-1.68	6.24
27-A	S1	3.83	1.57	3.12	15.87
27-B	S2	6.67	1.33	.34	3.46
30-1A	S	6.94	1.56	1.47	6.17
30-1B	W	8.98	2.26	.07	2.12
30-2A	S1	6.87	1.51	1.62	6.75
30-2B	S2	8.29	2.03	.30	2.91
30-2C	W	10.74	1.89	-1.12	4.00
30-3A	S1	5.66	1.27	2.06	9.89
30-3B	S2	6.80	1.26	1.98	9.44
30-3C	W	9.90	2.19	-.41	2.23
30-4A	S	6.35	1.43	1.91	8.06
30-4B	W	9.23	2.36	-.15	2.03
30-5A	S1	6.61	1.34	2.03	8.76
30-5B	S2	6.77	1.51	1.51	6.24
30-5C	W	10.46	1.98	-.65	2.58
30-6A	S	6.69	1.46	1.88	7.71
30-6B	W	8.99	2.33	.03	2.00
30-7A	S	7.12	1.65	1.19	4.77
30-7B	W	9.53	2.12	-.34	2.52
30-8A	S	7.27	1.63	1.19	5.03
30-8B	W	9.12	2.2	.11	1.98
30-9A	S	7.15	1.87	1.07	4.19
30-9B	W	9.69	2.40	-.48	2.26
30-10	C	6.94	2.59	.74	2.44
31-1A	S	7.61	1.61	1.34	5.34
31-1B	W	10.73	1.89	-.86	3.06
31-2A	S	7.68	1.73	.82	4.45
31-2B	W	10.57	2.07	-.96	3.31

## APPENDIX I (cont'd.)

Sample		Mean ( $\phi$ )	Standard Deviation	Skewness	Kurtosis
32-1A	S	8.24	2.03	.86	3.19
32-1B	W	9.99	2.46	-.62	2.26
32-2A	S	7.53	2.15	.63	3.39
32-2B	W	8.03	1.98	.86	3.53
33	S	5.77	1.05	1.09	5.09
34-1	G	8.79	2.46	.04	2.12
34-2	C	8.75	2.32	.26	2.04

## APPENDIX II - Water depths of Lake Hitchcock samples.

Local- ity	Altitude of lake level in feet	Altitude of samples in feet	Water depth in feet	Local- ity	Altitude of lake level in feet	Altitude of samples in feet	Water depth in feet
1	233	105-125	108-128	18	210	148-158	52-62
2	237	135	102	19	348	253	95
3	240	177	63	20	205	130	75
4	218	135-150	83-68	21	240	155	85
5	262	94-100	162-168	22	240	145	95
6	318	185	133	23	278	115-135	143-163
7	210	112-125	85-98	24	335	205-208	127-130
8*	200	200	--	25	268	141	127
9*	215	204-09	--	26	215	136-145	70-79
10	235	128	107	27	355	270	85
11	320	125	195	28	110	50-66	44-60
12	305	215	90	29	173	60	113
13	190	111	79	30	210	120-165	45-90
14	165	95	70	31	362	240-247	115-122
15	160	78-108	52-82	32	341	213-217	124-128
16	240	147	93	33	373	262	111
17	270	143	127	34	275	175	100

\* Samples from a higher-level lake.



