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CONTROL OF SEDIMENTATION AND BOTTOM CONFIGURATION BY CONVECTION CURRENTS, LAKE WASHINGTON, WASHINGTON[1]

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ABSTRACT

Lake Washington near Seattle occupies a deep narrow trough sculptured by the Vashon ice sheet, the last continental glacier to invade the Seattle area. Extending along the center of the trough is a broad ridge that stands 5 to 30 feet above narrow valleys on either side. Thus, the trough in cross-section is W-shaped rather than U-shaped, as are most glacial valleys. The sediments in the trough consist of blue clay, locally more than 100 feet thick, overlain by limnic peat or gyttja 5 to 55 feet thick. The blue clay consists of rock flour of meltwater origin and the limnic peat consists of planktonic organisms that began to accumulate following the meltwater stage. Within the limnic peat are a layer of volcanic ash and an overlying layer of varved peat, each about 2 inches thick. Radiocarbon analyses place the age of the ash at 6,700 years and that of the blue-clay peat contact at 13,650 years. The estimated age of the varved layer is 5,000 years. Core profiles across the lake show that the trough was U-shaped at the close of blue-clay deposition and that the W-shaped profile had approximately its present configuration at the time of the ash fall. Investigations of the lake-temperature structure, together with certain distinctive features of the lake topography and sediments, point to convection currents as being the agents responsible for the observed inequalities in limnic-peat sedimentation which, in turn, account for the unusual W-shaped configuration of the trough floor.

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INTRODUCTION

Lake Washington, a deep elongate body of water that borders Seattle on the east (Fig. 1), is 18.5 miles long, averages 1.5 miles in width, and has a mean depth of 108 feet. In its southern part is Mercer Island. The lake stands 20.6 feet above mean low low tide in Puget Sound, to which it is connected via Lake Union and the man-made Lake Washington Ship Canal. This canal, approximately 8 miles long, is terminated at its western end by a dam and two locks.

Prior to completion of the canal in 1916, the lake stood 9 feet higher than it is now (U.S. Army Corps of Engineers, 1939). At that time the only appreciable inflow into it was from the Sammamish River on the north. The only outflow was through the Black River on the south, which, after receiving the drainage of the tributary Cedar River about one-half mile south of the lake, discharged its water through the Duwamish River into Puget Sound. With completion of the canal and a lowering of the lake surface to its present level, Black River was left dry and Cedar River was diverted into Lake Washington. Thus the lake now has two principal sources of inflow, Sammamish and Cedar Rivers. All discharge is controlled through the Ship Canal.

Lake Washington, like Puget Sound and neighboring Lake Sammamish, lies in an unfilled remnant of a relict drainage system sculptured and modified by the Vashon ice sheet, the last continental glacier to invade the Seattle area (Bretz, 1913; Stark and Mullineaux, 1950). The lake basin lies entirely within glacial drift and outwash except in the vicinity of Bailey Peninsula west of Mercer Island where marine sediments of Oligocene age are exposed (Weaver, 1916). Except where indented by modern streams or remnant glacial valleys, the glacial deposits rise in precipitous cliffs from the lake shore to altitudes of 300 feet or more.

Bretz (1913) concluded that, with the withdrawal of the Vashon ice sheet from western Washington, Lake Washington and Puget Sound were connected first as part of a large glacial lake and later as an arm of the sea. The latter event was occasioned by clearing of ice from the Strait of Juan de Fuca which permitted invasion of both Puget Sound and the Lake Washington basin by marine waters.

To investigate whether the lake had in fact undergone such a marine phase in postglacial time and to develop the stratigraphy

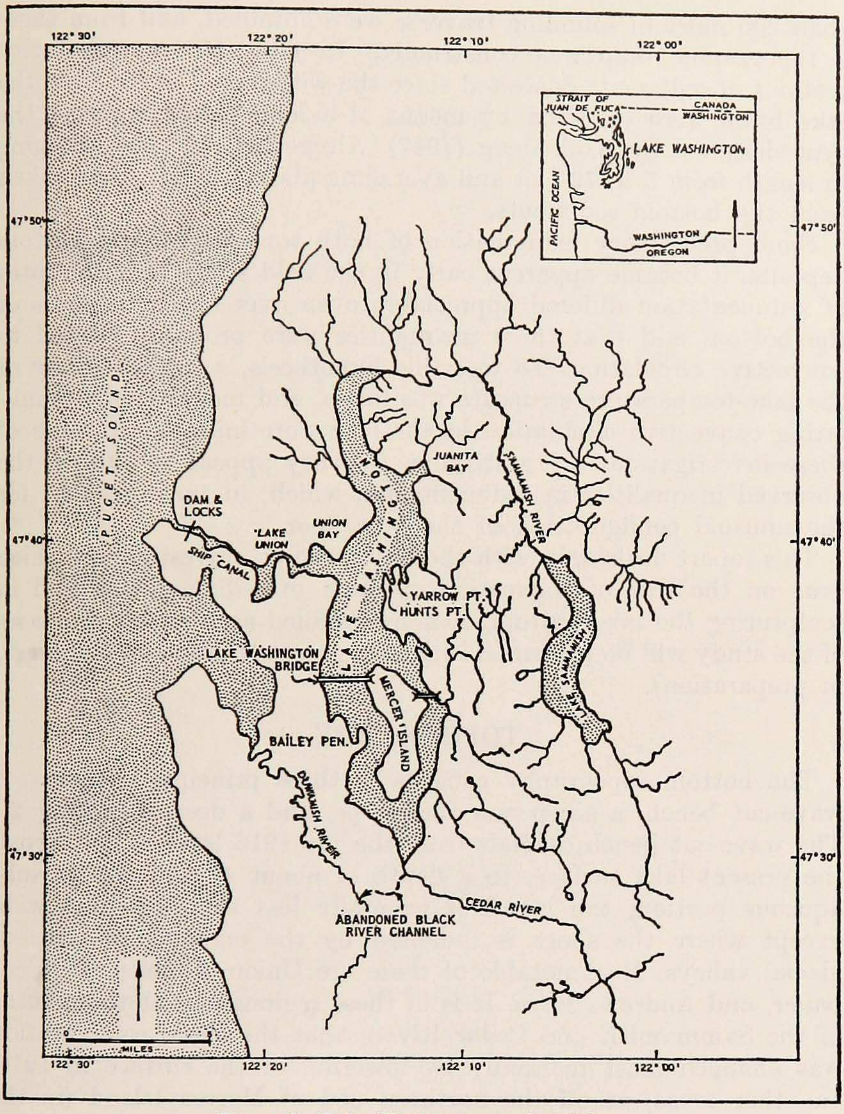

Figure 1. Lake Washington and vicinity.

in a region of continuous deposition following the retreat of Vashon ice, an intensive study was made of the lake topography and bottom sediments. In the course of this work, echograms over more than 200 miles of sounding traverse were obtained, and from these a topographic map was constructed. In addition, representative sections of sediments deposited since the withdrawal of ice from the lake basin were collected by means of a long piston corer of the type designed by Kullenberg (1947). Altogether, 30 cores, ranging in length from 5 to 72 feet and averaging about 29 feet, were taken from the bottom sediments.

From preliminary examination of both topography and bottom deposits, it became apparent early in the field study that the rates of sedimentation differed appreciably even over short distances of the bottom and that these inequalities were probably related to convective circulation. To test this hypothesis, a limited study of the lake-temperature structure was made, and model studies simulating convective circulation in the lake were initiated. Results of these investigations are gratifying, for they appear to explain the observed inequalities in sedimentation which, in turn, account for the unusual configuration of the lake floor.

This report deals only with those parts of the investigation which bear on the role of convection currents in sedimentation and in sculpturing the lake bottom. A more detailed account of all phases of the study will be presented in a later report (Gould and Budinger, in preparation).

TOPOGRAPHY

The bottom topography consists of three principal elements: a wave-cut bench, a steep marginal slope, and a deep floor (Fig. 2). The wave-cut bench extends from the pre-1916 level, 9 feet above the present lake surface, to a depth of about 40 feet. In its subaqueous portion, the bench is generally less than 600 feet wide except where the shore is indented by the embayed mouths of glacial valleys. Most notable of these are Union, Juanita, Meydenbauer, and Andrews Bays. It is in these regions and at the mouths of the Sammamish and Cedar Rivers that the shore configuration was changed most markedly by lowering of the surface in 1916. In other areas, as off the northern end of Mercer Island (in the Fairweather-Yarrow Point region) and south of Juanita Point, glacially sculptured ridges and intervening valleys which continue underwater for appreciable distances add to the shallow areas of the lake.

At its outer edge, the bench and associated shallow areas are

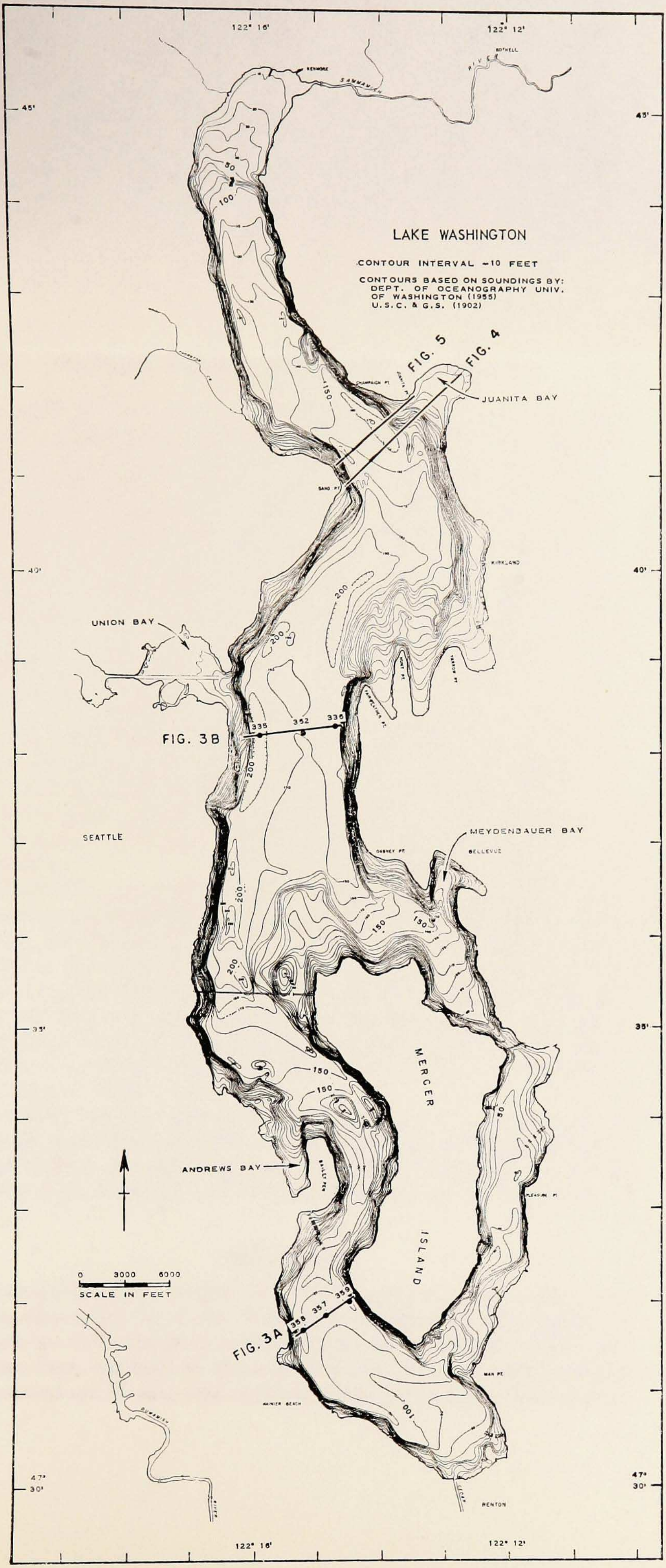

Figure 2. Lake Washington bottom topography. All depths are referred to the lake surface which lies 20.6 feet above mean low low water in Puget Sound.

terminated by the steep marginal slope that descends abruptly to the trough floor, which in places exceeds 200 feet in depth and averages about a mile in width. The declivity of this slope ranges from 6 to 24 degrees and averages about 14 degrees.

Extending along the deep floor of the lake is a broad ridge that extends to more than 30 feet above narrow valleys which lie at the base of the steep marginal slopes. Thus, the lake bottom in cross-section has a subdued W-shape rather than the U-shape which is characteristic of most glacial troughs. This unusual configuration is a feature also of the deep tributary arm between Mercer Island and Meydenbauer Bay.

The echogram, Fig. 5, depicts a typical cross-section of the lake bottom. The W-shape characterizes not only the present bottom but also a sub-bottom reflecting layer about 20 feet beneath the lake floor; upon subsequent coring this was found to consist of a 2-inch bed of white volcanic ash. It is apparent from the W-shape of the ash layer that the deep lake floor, except for its greater depth, had approximately its present configuration at the time of ash deposition.

Within the marginal valleys are several closed depressions with bottoms lying generally less than 10 feet below sill depths. Significantly, the largest depressions lie adjacent to steep side slopes bordering the most extensive shallow areas of the lake, including Union Bay, the Fairweather Point area, Juanita Bay, Meydenbauer Bay, and the area northwest of Mercer Island. The depressions off Union Bay, Meydenbauer Bay, and possibly off Fairweather Point appear to be continuations of small canyons that indent the slope and head in these shallow areas.

The only interruption of the central ridge in the main body of the lake occurs east of Bailey Peninsula where the marginal valleys merge to form isolated basins, the deepest of which lies 43 feet below the top of the sill and 190 feet beneath the water surface.

SEDIMENTS

Since preliminary studies have indicated that most of the sediments deposited in Lake Washington following withdrawal of Vashon ice lie in the deep central trough, investigation of the deposits has been confined to those of this area. The 30 cores obtained are located on 11 east-west sections which lie between Sammamish

River on the north and Cedar River on the south. In most sections, one core was taken from the central ridge and one from the valleys on either side. Although no cores were collected from the shallow margins and steep slopes bordering the trough, it is apparent from studies of Stark and Mullineaux (1950) and from borings made available by the State of Washington Toll Bridge Authority that these areas are underlain chiefly by pre-Vashon sediments into which the Lake Washington basin was cut. Thus the post-Vashon deposits occur as valley fill flanked by these older beds.

Except for deltaic deposits encountered near the mouths of the Sammamish and Cedar Rivers, the sequence of sediments in all sections is essentially the same. This sequence consists of glacial blue clay at the base overlain by limnic peat (Voss, 1934) or gyttja (Twenhofel, 1939), which, in the sections of Fig. 3, ranges from 17 to 41 feet in thickness. Elsewhere the thickness of the limnic peat ranges from 5 to 55 feet. Although the blue clay was penetrated by our borings to a maximum depth of 35 feet below the base of the limnic peat and to a depth of 100 feet in borings of the State of Washington Toll Bridge Authority, its base was not reached.

The blue clay consists of glacial rock flour of meltwater origin, whereas the limnic peat consists of freshwater planktonic organisms, (mainly diatoms) and decomposable organic matter which began to accumulate following the meltwater stage.

In two cores a thin layer of marine molluscs and foraminifers contained within the blue clay at depths of 4 to 13 feet beneath the base of the limnic peat provides the only evidence of an early postglacial marine phase for Lake Washington. The association of this fauna with thin lenses of sand within the clay suggests that both the fauna and the sand were displaced by slumping from shallower depths. Whether slumping occurred during marine occupancy of the basin or at some later time is unknown. A search of the clay for fauna above and below the marine fossil bed sheds little light on the problem. The clay below the fossil zone is barren, whereas the clay above contains a sparse freshwater diatom assemblage. Uniform low salinities of interstitial water in the clay both above and below the marine shell layer suggest, however, that freshwater conditions prevailed in the basin at the time of slumping and that marine occupancy preceded deposition of the deepest clay penetrated, which, as previously stated, lies 100 feet beneath the base of the limnic peat sequence.

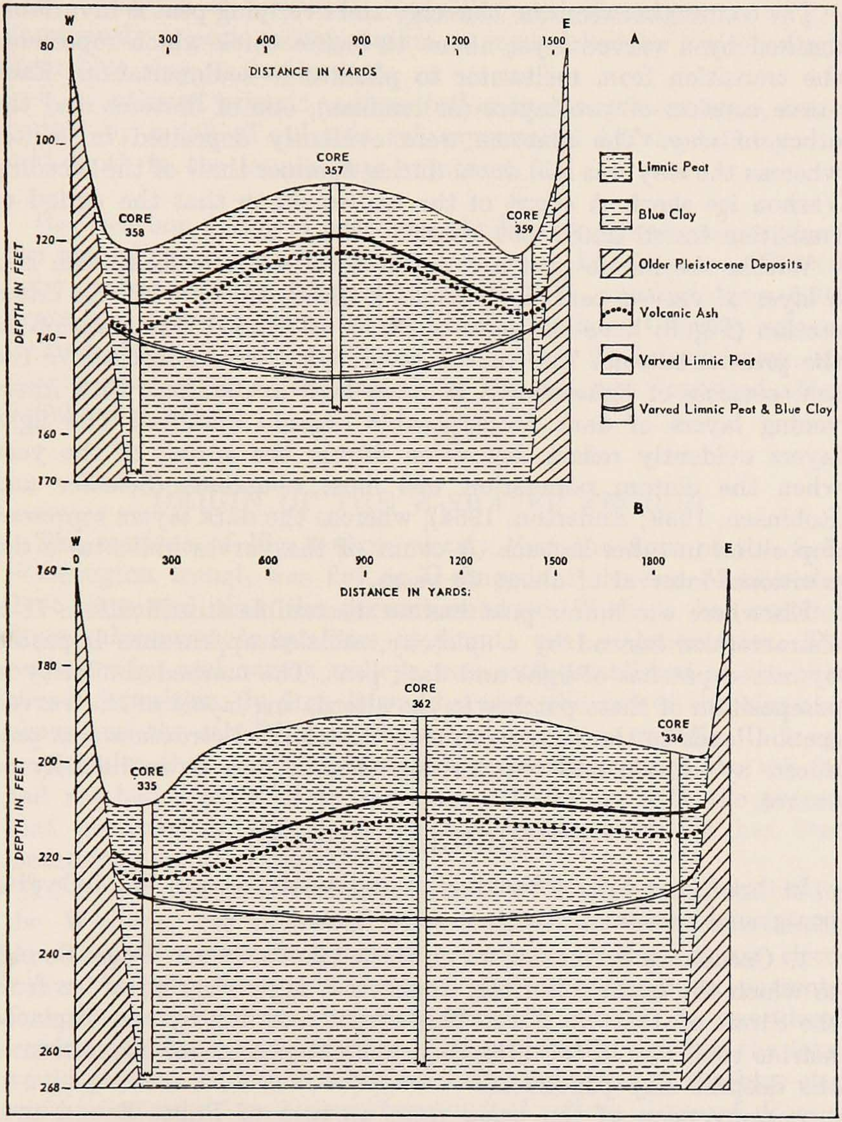

Figure 3. Cross-sections showing stratigraphic sequence of the trough fill. Thickness of ash and varved layers not to scale. For location of sections, see Fig. 2.

The contact between the blue clay and overlying peat is invariably marked by a varved layer about 12 inches thick which represents the transition from meltwater to planktonic sedimentation. Each varve consists of two layers (or laminae), one of diatoms and the other of clay. The diatoms were evidently deposited in winter whereas the clay was laid down during summer thaw of the receding Vashon ice sheet. A count of the varves shows that the period of transition lasted about 200 years.

Within the limnic peat are the layer of white volcanic ash and a layer of varved peat, each about 2 inches thick, which in cross-section (Fig. 3) have the same subdued W-shaped configuration as the present bottom. The varved layer, lying 3 to 4 feet above the ash, consists of light-colored laminae high in diatoms, with intervening layers of dark decomposable organic material. The light layers evidently reflect deposition during the spring of the year when the diatom population was most abundant (Scheffer and Robinson, 1939; Anderson, 1954), whereas the dark layers represent deposition in other seasons. A count of the varves indicates a depositional interval of about 60 years.

Elsewhere the limnic peat has no discernible stratification. It is characterized instead by a splotchy, mottled appearance imparted by mixed patches of light and dark peat. The marked similarity in composition of these patches to the alternating layers of the varved section leads to the conclusion that the mottled structure was produced by erosion and redeposition of peat laid down initially as varves.

POSTGLACIAL HISTORY

In brief, the Lake Washington sediments record the following postglacial events:

1. Occupancy by marine water of the lake basin and Puget Sound, to which the basin was freely connected, upon clearing of ice from the Strait of Juan de Fuca. This event, recorded by the displaced marine shell bed in the blue clay, evidently preceded deposition of the deepest clay penetrated.

2. Conversion of the basin from an arm of Puget Sound to a freshwater lake in which the meltwater blue-clay sequence was deposited. Isolation of the lake basin from Puget Sound presumably resulted from damming of the basin at its southern end by delta building.

3. Cessation of meltwater deposition and the beginning of predominantly organic sedimentation as represented by the transition from blue clay to limnic peat.
4. Continued organic sedimentation to the present time, interrupted by a fall of volcanic ash represented by the ash layer at mid-depth in the limnic peat sequence.

Radiocarbon dating of peat from the blue clay-peat contact places the age of the terminal meltwater stage at 13,650 years. The ash layer, as reported by Rigg and Gould (1957), was laid down 6,700 years ago from an eruption of Glacier Peak, a Cascade volcano located about 63 miles northeast of the lake. By interpolation, the varved peat layer a few feet above the ash was deposited about 5,000 years ago.

ORIGIN OF THE W-SHAPED TROUGH

The sections of Fig. 3 show clearly that the floor of the Lake Washington trough was flat or U-shaped at the end of blue-clay deposition and that the present subdued W-shape has resulted from subsequent inequalities in limnic peat sedimentation. The central ridge and narrow valleys were well established at the time of ash deposition. In fact, it was between the end of the blue-clay phase and the ash fall that the ridge grew most rapidly. It is apparent also that the W-shaped section at the time of the ash fall had reached a state of approximate equilibrium with the process that produced it and that this equilibrium condition has been maintained to the present time.

In an attempt to identify the process or processes responsible for the W-shape, the following three possibilities were entertained: (1) density currents from entering streams, (2) deep rotary circulation resulting from wind action, and (3) convection currents. Density currents from inflowing streams cannot be considered seriously because such currents, if they actually exist in the lake, would produce or follow a central valley like that of the blue-clay surface instead of producing the marginal valleys observed. Rotary wind-induced circulation does not appear a likely explanation either. Such circulation is confined chiefly to the upper surface layers of water, and it is doubtful that wind-induced currents, if they extend to depth, would be of sufficient velocity to produce the valleys.

Of the three possibilities, convection currents appear to provide the most likely explanation. As shown by Scheffer and Robinson (1939), in general terms the water of Lake Washington overturns annually, beginning in December and lasting through February or March. Water cooled at the surface during this period sinks, with some mixing, towards the lake floor and is replaced by warmer water from below. This process of convection takes place to some extent over the entire lake surface; however, a shallow column of water is cooled more quickly than a deep one with the result that water in the bays and along the shallow margins of the lake cools and increases in density more rapidly than the upper layers in midlake. This denser water tends to flow from the periphery to the edge of the steep marginal slope and thence down to the trough floor. As a result, a considerable volume of water at velocities higher than those of convection currents elsewhere in the lake must flow down the marginal slopes.

To determine whether such concentrated flow does in fact take place down the marginal slopes, a study of the lake-temperature structure along a line of section from Sand Point to Juanita Bay was made during a period of intense surface cooling in January 1956. Results of this survey, as illustrated by isotherms in Fig. 4, show clearly that such a flow does occur. At the time of the survey, the coldest water, ranging from 4.4° to about 5.0° C, was situated in the shallow Juanita embayment. Due to intense cooling and to the shallow bottom, this cold water could not be replaced by warmer water from below. Consequently there was a much greater flow of cold water, as shown by the packing of isotherms, down the steep marginal slope leading from Juanita Bay than on the opposite slope off Sand Point where adjacent shallow areas of cooling are more limited.

On the basis of this study, the general conclusion is drawn that a similar convective flow takes place during winter overturn on all steep marginal slopes leading to the basin floor and that the flow down slopes adjacent to the more extensive shallow lake margins is of greater intensity than elsewhere. Furthermore, it is suggested that these currents, upon reaching the basin floor, have eroded sediment from the trough at the base of the slopes and redeposited it to form the medial ridge of the basin floor.

To obtain a qualitative understanding of the effect that such currents might have on the deposition of sediments and on the form-

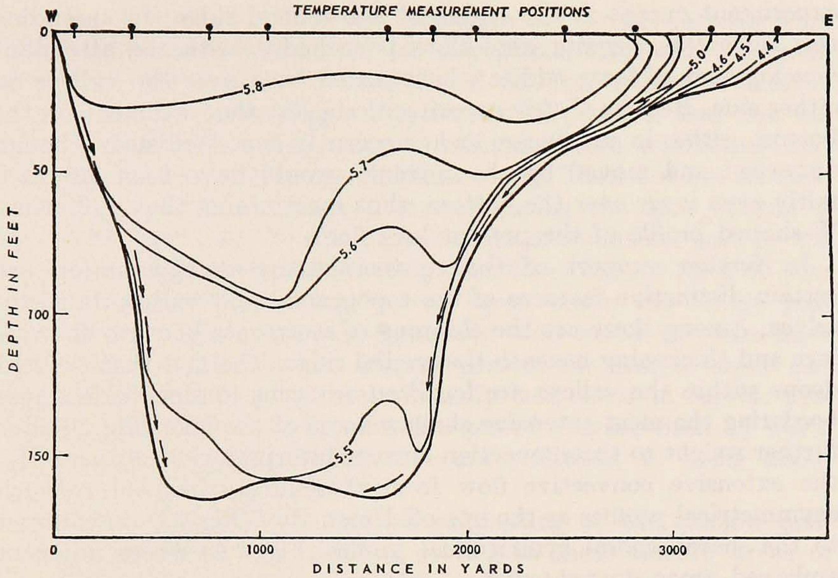

Figure 4. Lake-temperature structure in cross-section from Sand Point to Juanita Bay, showing intense convective flow of cold water down the marginal slopes. The temperature shown by isotherms is in degrees centigrade. See fig. 2 for location of section.

ation of the W-shaped section, a series of simple model experiments was conducted (Fig. 6). In one of the experiments a U-shaped or flat-floored section similar to conditions at the end of the meltwater stage was used. Dense salty water containing blue dye to simulate cold water was introduced simultaneously into the surface water at the two sides. The resulting convection currents (Fig. 6 A–C) produced a rapid flow of water down the slopes and across the bottom to the center of the trough where the two currents collided. Although no sediment was used in this experiment, results indicate that sediments, either suspended in the water near the bottom or lying in a semi-fluid recently-deposited state, would have been carried by the currents to the center of the trough and deposited there. This apparently simulates the condition that prevailed following the meltwater stage which led to the rapid build-up of the central ridge.

In another experiment, a W-shaped section simulating the equilibrium profile of the present lake bottom was used (Fig. 6 D–F). These convection currents behaved similarly to those of the first experiment except in the region of the central ridge; in ascending this ridge the currents were slowed markedly, with the attendant development of large eddies which curled back over the valleys on either side. Results of this experiment suggest that sediment on the bottom, either in suspension or in a recently deposited state, though disturbed and moved by the currents, would have been left in a fairly even layer over the bottom, thus maintaining the equilibrium W-shaped profile of the present lake floor.

In further support of the convection-current explanation are certain distinctive features of the topography and sediments themselves. Among these are the thinning of sediments beneath the valleys and thickening beneath the medial ridge. The fact that isolated deeps within the valleys are localized adjacent to steep side slopes bordering the most extensive shallow areas of the lake (Fig. 2) adds further weight to the convection-current interpretation. Apparently, the extensive convective flow from these areas has led to such asymmetrical profiles as the one off Union Bay (Fig. 3B) in contrast to the more general symmetrical profile (Fig. 3A) where adjacent embayed areas do not exist.

The mottled structure of the limnic peat, apparently produced by erosion and redeposition of sediments laid down initially in annual varves, gives further evidence of the process that produced the W-shaped profile. As each varve requires essentially a year to form, its destruction, if on an annual basis, could be accomplished only by seasonal currents of short duration, such as convection currents. Finally, in response to the possible objection that convection currents may be too weak to erode sediment, it should be pointed out that limnic peat, because of its low density and semifluid state when initially deposited, can doubtlessly be eroded and transported by considerably weaker currents than those required to move most other types of sediment.

SUMMARY

In summary, the sediments and topography of Lake Washington reflect the following changes in postglacial circulation. During the blue-clay phase, the circulation was apparently dominated by rock flour-laden currents issuing from meltwater streams which entered the lake from the north. The U-shape or flat floor of the trough at the end of this phase indicates that these cold dense currents followed the thalweg of the basin. Although convection currents were doubtlessly active during the blue-clay phase, their effect on sedimentation was apparently obliterated by the meltwater-induced circulation. With cessation of meltwater deposition and the beginning of predominantly organic sedimentation, convection currents assumed a much more significant role. Their control on sedimentation and their influence in sculpturing the lake bottom is amply demonstrated by the central ridge of sediments and by the W-shaped configuration of the deep lake floor. Except for a 60-year interval represented by the varved layer within the limnic peat sequence, convection currents associated with winter overturn have apparently extended to the deepest part of the lake to erode and redeposit sediments which were initially laid down as varves. Presumably, this varved layer records a period characterized by warm winters when surface cooling was not sufficient to bring about complete overturn of the lake.

Although cold bottom currents originating at the shallow ends of the lake (either from surface cooling in these shallow areas or from discharge of the Sammamish and Cedar Rivers) may utilize the marginal valleys to reach the deepest part of the trough, there is no conceivable way in which these currents could have produced the valleys.

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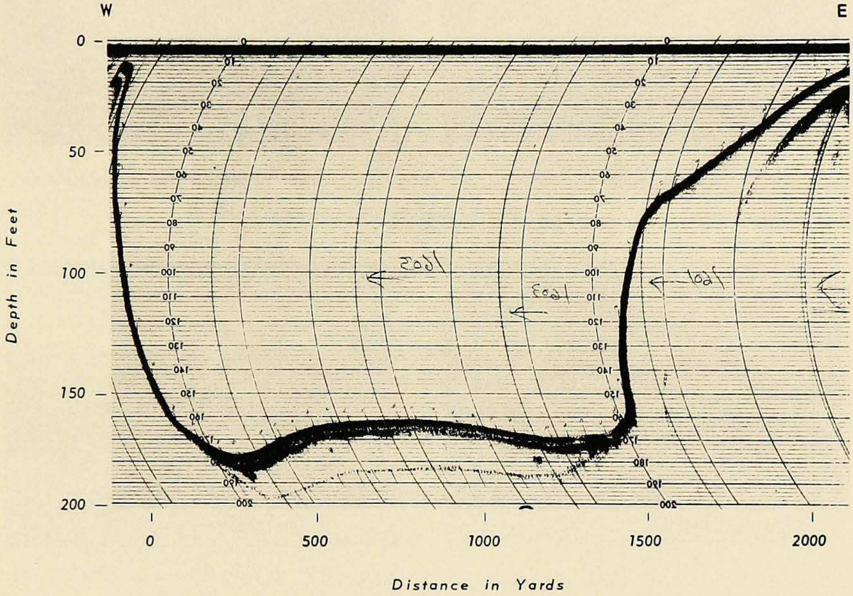

Figure 5. Echogram showing typical W-shaped configuration of the lake floor. The sub-bottom reflection about 20 feet beneath the trough comes from a 2-inch layer of volcanic ash. The record was obtained with a Bendix echo-sounder operating at a frequency of 50 kilocycles. See Fig. 2 for location of section.

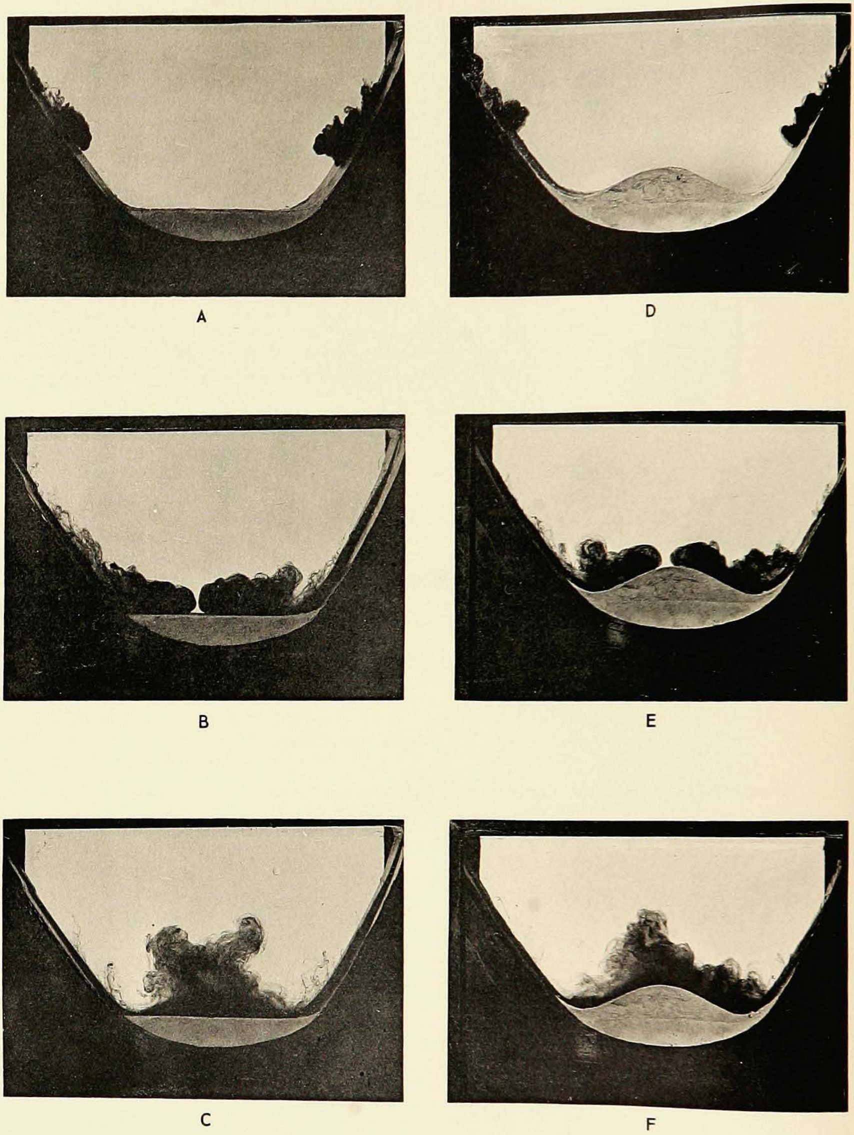

Figure 6. Convection currents produced in model experiments to simulate conditions of convective flow in the lake at the end of the meltwater stage (A-C) and at the present time (D-F).