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Dalwyn R. Davidson
VICE PRESIDENT
SYSTEM ENGINEERING AND CONSTRUCTION

April 21, 1982

A. Schwencer
Chief, Licensing Branch No. 2
Division of Licensing
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

Perry Nuclear Power Plant
Docket Nos. 50-440; 50-441
Supplementary Information -
Geology/Seismology

Dear Mr. Schwencer:

During the staff review of Geology-Seismology, Mr. Harold Lefevre had requested additional material on the Perry site and the surrounding area. The purpose of this letter is to submit to you the items requested by Mr. Harold Lefevre.

Very Truly Yours,

Dalwyn R. Davidson

Dalwyn R. Davidson
Vice President
System Engineering and Construction

DRD: mlb

cc: Jay Silberg
John Stefano
Max Gildner

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TO: Harold Le Fevre

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WALL

ROBERT E. WALL *Lamont Geological Observatory, Columbia University, Palisades, New York*

A Sub-Bottom Reflection Survey in the Central Basin of Lake Erie

Abstract: A geophysical survey of the central basin of Lake Erie was carried out in 1960. The survey track consisted of 18 lines run normally to the lake's axis at five-mile intervals and two lines run parallel to the long axis of the lake. Sub-bottom reflection data show four reflecting horizons extensive enough to be mapped.

The lowest of these reflectors corresponds with Paleozoic bedrock and shows a trough whose axis is displaced somewhat to the south of the present lake's axis. A pronounced spur projecting eastward partially separates this trough from a deeper basin to the northeast.

The reflecting horizon immediately above the Paleozoic bedrock shows two principal topographic features: (1) a lobelike rise centered across the lake's axis, and (2) an elongate east-west trending basin lying to the east of the rise. The lobate rise and its position within the basin indicate a glacial origin during Lake Border time. The elongate basin appears to be an erosional feature. As such, it implies the existence during the Cary-Port Huron interval of a low-lake stage whose eastern outlet was downwarped at least 300 feet by ice loading.

The next highest reflector is widely distributed throughout the basin and generally gives a clear, strong reflection. Its topographic configuration shows a broad ENE-trending valley which leads into a partially closed basin. Within the sediments which fill this valley and basin is found the shallowest sub-bottom reflector. It is nearly level and is buried from 10 to 20 feet by Recent lake muds.

Reflection characteristics and configurations within the basin combined with other lake-study information identify these two horizons as a compact glaciolacustrine clay underlying shallow water deposits. Initiation of shallow water deposition occurred during the retreat of the Port Huron ice and coincided with the formation of Lake Iroquois in the Ontario basin. It was brought to a close as the water level rose in response to isostatic uplift of the eastern outlet at Niagara Falls.

CONTENTS

Geological Society of America Bulletin, v. 79, p. 91–106, 8 figs., January 1968

INTRODUCTION

In the early fall of 1960, the Lamont Geological Observatory of Columbia University and the University of Toronto collaborated in a geophysical survey of the central basin of Lake Erie. The survey used the C.M.S. Porte Dauphine which was made available to the Great Lakes Institute of the University of Toronto by Marine Services, Department of Transport, Canada. The geophysical program included gravity and magnetic measurements and sub-bottom reflection profiling. This paper presents the seismic reflection results and discusses their bearing on the late Pleistocene and Recent history of Lake Erie.

ACKNOWLEDGMENTS

This research was carried out under the supervision of Professor J. Lamar Worzel. His guidance has been invaluable from the survey itself, which he directed, through the reduction and interpretation of the data, to the writing of the manuscript.

The full co-operation of the late Professor R. E. Deane and the Great Lakes Institute of the University of Toronto made possible the survey.

Through critical discussions, the following members of the geology and engineering faculties of Columbia University have contributed to this study: C. L. Drake, J. T. Kuo, J. E. Nafe, A. N. Strahler, and G. H. Sutton.

The additional information provided by Charles Herdendorf, Ohio State Geological Survey, and C. F. M. Lewis, University of Toronto, in correspondence with the author is gratefully acknowledged.

This work was supported in part by the Office of Naval Research Contract Nonr-266(48).

LAKE ERIE AND ITS GEOLOGIC SETTING

Lake Erie, second smallest of the five Great Lakes, separates southwestern Ontario from the states of Michigan, Ohio, Pennsylvania, and New York. Its long axis, trending N. 65° E. is about 240 miles in length with a maximum width of about 57 miles. Lake Erie is the shallowest of the Great Lakes with a maximum depth of 210 feet. The surface stands 572 feet above sea level.

Shoreline features and bottom topography show the lake to be separated physiographically into three distinct basins (Fig. 1). The small eastern basin contains the deepest part of the lake. It is bounded on its western margin by a bottom topographic high which trends approximately S. 30° E. across the lake from the base of Long Point to Erie, Pennsylvania. West of that topographic high, the bottom drops gently down into the broad, flat central basin of typical water depth, 75 feet. The western end of this central basin is marked by a series of islands and shoal areas separating it from the shallow basin to the west.

As with all of the Great Lakes, except Superior, the underlying Paleozoic rocks exert a strong control over the features of the Lake Erie basin. The central and eastern basins lie along the strike of preferentially excavated soft Devonian shales and limestones which dip gently southward under the Appalachian Plateau. The western basin's bottom topography is primarily a result of the variable resistance to erosion of the several Silurian and Devonian formations underlying it (Carman, 1946). The two lines of islands and shoals represent some of the more resistant limestones and dolomites.

The principal outlet from Lake Erie is also structurally controlled and the Lockport dolomite forms the sill of the falls of the Niagara River. This river, with minor exceptions, carries all of the discharge from Lake Erie.

THE LATE- AND POST-GLACIAL GREAT LAKES

Knowledge concerning the history of the glacial and post-glacial Great Lakes has developed from the extensive monograph of Leverett and Taylor (1915), through Hough's book, "Geology of the Great Lakes" (1958), up to the present. Recent investigations in the St. Lawrence Valley and the Lake Ontario basin (Terasmae and Mirynech, 1964; MacClintock and Terasmae, 1960; Mason, 1960; Karrow and others, 1961) have caused a major revision in the chronology and correlation of the glacial Great Lakes (Hough, 1963; Dreimanis, 1964). Even with this revision, and perhaps partly because of it, there exist areas of strong disagreement (Bretz, 1964; Hough, 1966).

A summary of this revised chronology as it applies to glacial Lake Erie follows. Between 14,000 and 15,000 years ago, the waning Wisconsin ice had retreated far enough in the Michigan and Erie drainage basins to form glacial lakes between its margin and drainage divides to the south and west. There followed a succession of different glacial lake stages because the ice front in general retreat, but with re-

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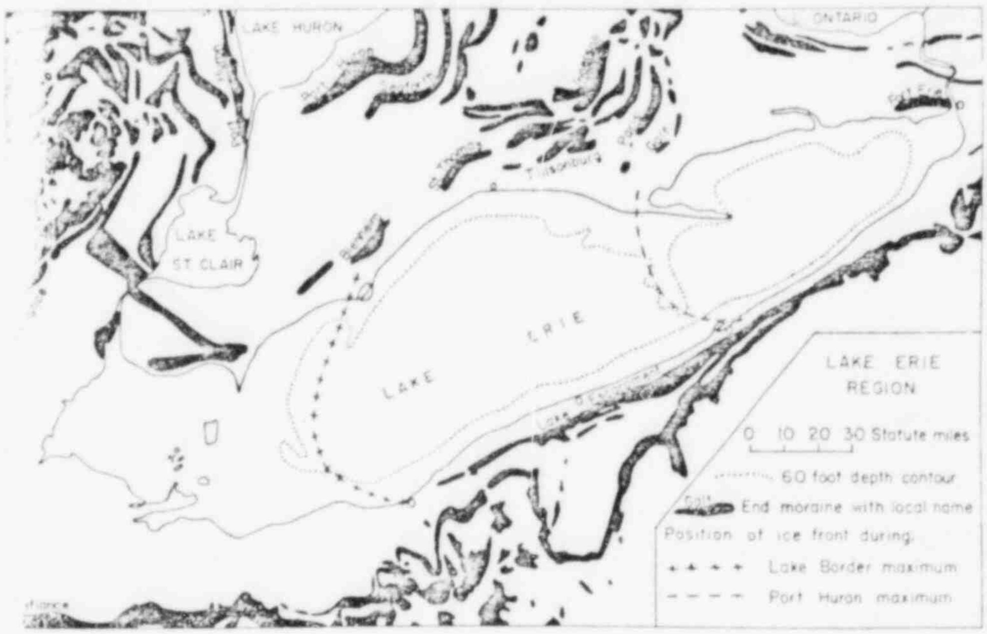


Figure 1. Map of the Lake Erie region. Sixty-foot depth contour from Canadian Hydrographic ervice map 2100. End moraines from "Glacial Map of the United States East of the Rocky Mountains," published by the Geological Society of America. Positions of the Lake Border and Port Huron aximums within Lake Erie from Hough (1963).

dvances and fluctuations of its margin, opened and closed various outlets for the several lakes.

In the Erie basin, the first of these glacial lakes has been named Lake Maumee. From its beginning, until retreat of the Lake Border ice marked the close of the Cary substage, that part of the Lake basin not covered by ice lay under several hundred feet of water. During this time a terminal moraine was deposited across the basin from Erieau to Cleveland (Fig. 1) (Hough, 1963; Fig. 3D). Although not conclusive, the evidence indicates that between the Cary and Port Huron maxima, the ice retreated far enough to allow glacial Lake Erie to drain east to a low level (Hough, 1958, 1963; Kunkle, 1963). With the readvance of the Port Huron ice, water again covered the lake basin to a depth of more than 200 feet and drained into the Huron and Michigan basins. During this Port Huron maximum, a terminal moraine was deposited across the basin from the base of Long Point to the vicinity of Erie, Pennsylvania (Fig. 1) (Hough, 1963; Fig. 4A). Retreat of the ice north and east freed eastern outlets of ice for the final time.

The formation of a separate Lake Iroquois in the Ontario basin about 12,000 years ago initiated the drainage from early Lake Erie over the Niagara escarpment. Because the eastern outlet lies within the area of post-glacial upwarp, it is presumed that the level of early Lake Erie (and of the glacial lake occupying the basin during the Cary-Port Huron interval) was below that of the present lake (Hough, 1963; Figs. 3F, 5C).

The detailed chronology, from which the above summary was taken, is based principally upon studies and correlation of the abandoned beaches, terraces, deltaic deposits, and outlet channels of the glacial lakes, together with information from the contemporaneous glacial deposits. Except for the bottom sediment studies in Lakes Michigan and Huron reported by Hough (1955, 1962), and those in Lake Erie reviewed and discussed in this paper, relatively little information has been obtained from beneath the present Great Lakes.

PREVIOUS STUDIES IN LAKE ERIE

Hartley's (1961a) investigations of sediments beneath Ohio waters of Lake Erie found the predominant bottom sediment to be a soft, deep-lake mud. A band of sand and gravel from 2 to 10 miles wide exists along the south shore-

line. Extensive sands and gra ls overlying a compact clay form the bottor ediments east of long 81° W., and grade laterally to the west into lake mud.

Borings in the island area of Lake Erie (Hartley, 1961b) show, in general, a sedimentary section which includes Recent soft clay and mud with local silt and sand deposits overlying peat and plant-rich clays. These are underlain by a compact clay deposit which lies on glacial till, if present, or directly on the Paleozoic bedrock. Hartley (1961b, p. 10; Table 2) correlated second echoes from echo-sounding records with probable reflecting interfaces observed in the borings. These reflecting surfaces include the tops of (a) the peat or plant-rich clay layer, (b) the compact clay layer, (c) the till layer, and (d) the Paleozoic bedrock.

The presence of peat down to 520 feet above sea level in the island area plus other evidence from borings in the central basin (*See* Sedimentary Section, Horizon "a") led Hartley to conclude that early Lake Erie started at an elevation of about 490 feet.

Morgan (1964, Ph.D. dissert., Univ. Toronto, Toronto, Canada) extended the bottom sediment studies throughout the entire lake. In several cores taken near the north shore of the central basin, he found a relatively stiff, compact, brownish clay forming the bottom sediment. Laboratory measurements of the seismic velocity in this compact clay gave an average velocity of almost 6000 fps while the average velocity in the Recent soft muds was almost the same as that in the water, 5018 fps.

As a part of the same study, Morgan carried out a reconnaissance seismic reflection survey of the entire lake and prepared from the data a generalized contour map of the Paleozoic bedrock surface. The survey also indicated the presence of some intermediate reflectors.

More recently, Lewis and others (1966) have cited further evidence from cores and echo-sounding records which suggests that the water level of early Lake Erie was about 100 feet lower than at present.

THE SEISMIC REFLECTION SURVEY

The sub-bottom reflection system consisted of a sound source, a towed pressure-sensitive hydrophone, and a Precision Depth Recorder (PDR). The sound source used during the survey was a horizontal-plate sonar thumper, type St-8 (Edgerton, Germershausen, and Grier, Inc., 1960). Its towing characteristics limited the speed of the ship to about 5 knots. The thumper-hydrophone separation of about 120 feet was similar in magnitude to the water depth. This resulted in a non-linear print-out on the PDR (Fig. 7).

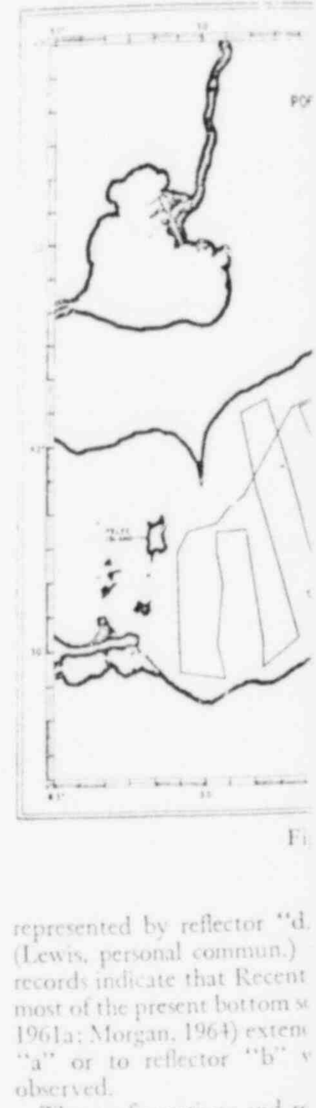
The survey track consisted of a series of crossings of the lake made normal to its long axis and spaced about 5 miles apart. Two long tracks were also made parallel to the long axis of the lake. Comparisons of reflection data at track intersections aided greatly in the correlation of the several reflectors throughout the central basin. Discrepancies in the depths to these reflectors at the intersections were generally less than 6 feet.

Navigation on all crossings was by dead reckoning to within between 15 and 20 miles of shore. At that distance, coastal features came within the range of the ship's radar. As the shore was approached more closely, visual fixes supplemented the radar fixes. The two tracks parallel to the lake's long axis were both made within radar range of shore. The corrected track (Fig. 2) was constructed by determining, with radar and visual fixes, a drift (assumed constant) for each dead-reckoning section of the track. Using these drifts, the dead-reckoning track was corrected to fit the radar and visual fixes.

Although the reflection system was operated almost continuously along the survey track, there were several areas in which no sub-bottom reflections were observed. In these areas, near the south shore and in that part of the central basin lying east of long 81° W., the reflection results showed strong and often multiple bottom reflections. In contrast, the bottom reflections observed over the rest of the basin were generally quite weak. This difference in the reflecting character of the bottom sediment is presumed to be a result of the textural change from a soft, deep lake mud to a more compact silt, sand, or gravel as reported by Hartley (1961a).

DESCRIPTION OF THE REFLECTING HORIZONS

A detailed study and correlation of the reflection records showed four sub-bottom reflectors extensive enough to be mapped. These will be designated reflectors "a," "b," "c," and "d." Reflector "a" represents the top of a layer of sediment herewith designated layer "A." Beneath "A" is a layer of sediment "B" whose top surface is represented by reflector "b." Layer "C" whose top surface is represented by reflector "c" overlies "D" whose top surface is



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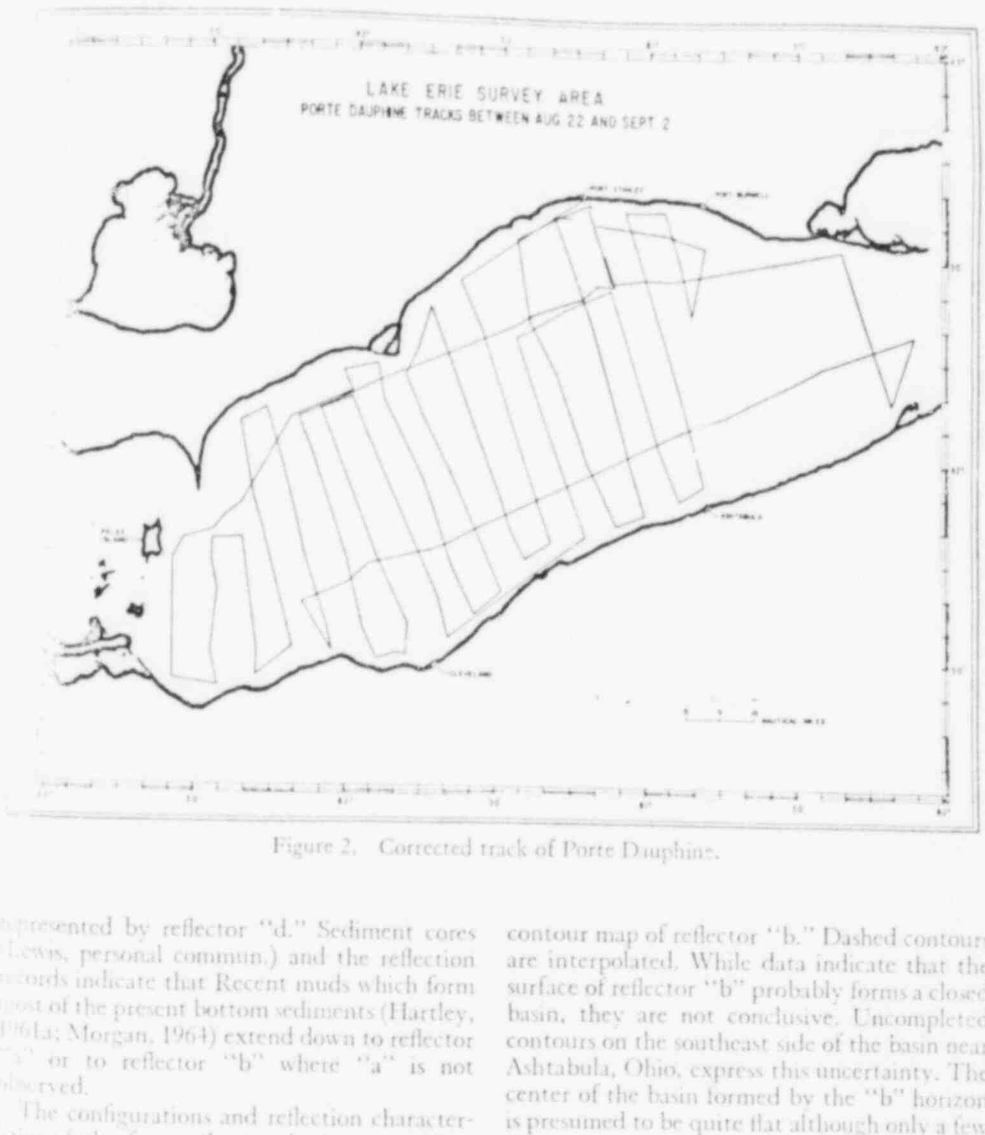

Figure 2. Corrected track of Porte Dauphine.

represented by reflector "d." Sediment cores (Lewis, personal commun.) and the reflection records indicate that Recent muds which form most of the present bottom sediments (Hartley, 1961a; Morgan, 1964) extend down to reflector "a" or to reflector "b" where "a" is not observed.

The configurations and reflection characteristics of the four reflecting horizons are illustrated in Figures 3 through 7. Figures 3, 4, and 5 are contour maps of elevations above sea level of reflectors "b," "d," and "e" respectively. Isopachs of layer "C" are indicated by the dotted lines in Figure 5. Figure 6 shows the three adjacent profiles AA′, BB′, and CC′ indicated on Figures 3, 4, and 5. Figure 7 is a reproduction of a section of an actual reflection record.

Because of its widespread occurrence and the ease with which it could be identified and correlated from profile to profile, reflecting horizon "b" will be the first discussed. Figure 3 is a contour map of reflector "b." Dashed contours are interpolated. While data indicate that the surface of reflector "b" probably forms a closed basin, they are not conclusive. Uncompleted contours on the southeast side of the basin near Ashtabula, Ohio, express this uncertainty. The center of the basin formed by the "b" horizon is presumed to be quite flat although only a few short segments (from 1 to 2 miles long) of "b" reflections were obtained here (Fig. 6).

The elevation of the lake bottom throughout most contoured areas is between 490 and 500 feet. The profiles of Figure 6 show that within 5 to 10 miles of the northern shoreline, reflector "b" rises to become the lake bottom or is covered by less than 2 or 3 feet of Recent lake sediment. On the south, reflector "b" rises more steeply but is so near the shore that it is masked by the increased reflectivity of the bottom sediment.

In the western half and along the northern slope of the basin formed by horizon "b," the

reflections from "b" are very short, sharp, and strong (Fig. 7). Multiple reflections are sometimes observed. In the deeper areas of its basin, even when it is not masked by reflector "a," the "b" reflection is generally not so distinct.

Reflector "a" is found almost continuously within the areas outlined in Figure 3 by the heavy dashed line. The principal area of occurrence lies in the basin defined by the reflector "b" contours. The southern boundary of this region, particularly toward the east, is only approximate. The eastern extension of the area in which "a" is observed is uncertain. In the most easterly profiles, in which typical "a" reflections are observed, the reflections appear only at the north or south boundaries. In the central portions of these profiles, while no "a" horizon is observed, the records indicate arrivals from throughout most of the sediment above "b." South of Erieau, Ontario, "a"-type reflections are also observed in a small, isolated area.

Although small variations in the depth of reflector "a" are present, the horizon lies mostly at elevations of between 475 and 490 feet which correspond to depths from 10 to 20 feet below the lake bottom.

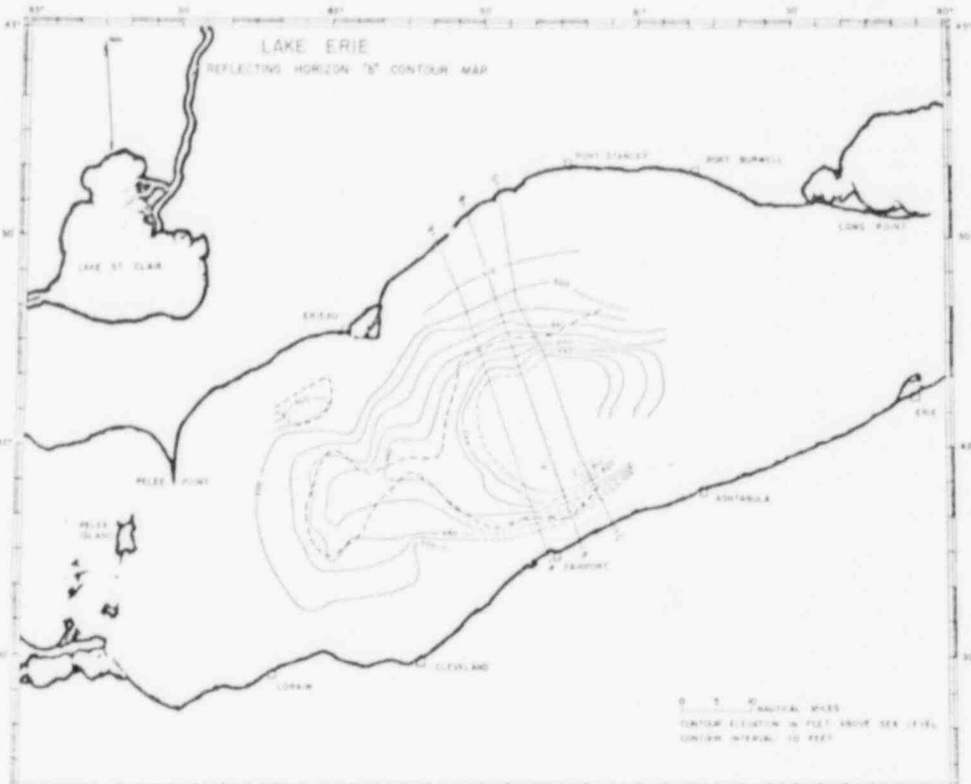

Figure 3. Elevation contours on reflecting horizon "b." Area of occurrence of horizon "a" outlined by heavy dashed line. Profiles along AA′, BB′, and CC′ are shown in Figure 6.

Around the edges of its area of occurrence, particularly the northern and western edges, the "a" reflector is discontinuous. It appears intermittently on the record for a few minutes at a time. This sporadic occurrence of reflector "a" sometimes continues for two or three miles. On the reflection records over these areas, the echogram appears to show side echoes which lead into and become a flat-topped reflector corresponding in elevation and character to the nearby continuous "a" reflections. Figure 7 shows a typical example of the "a" reflection in its boundary region.

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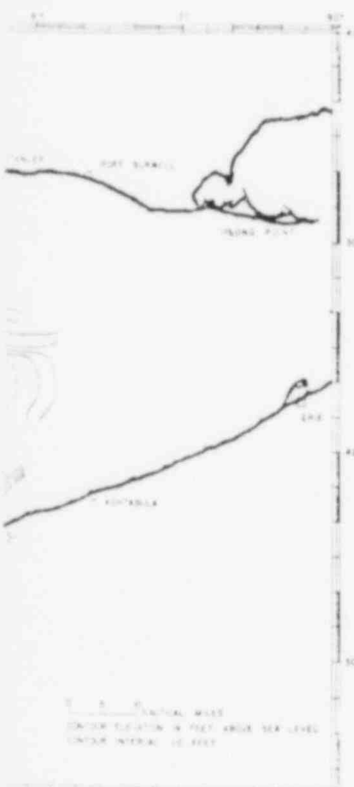

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In contrast to the short and sharp reflection from horizon "b," the echo recorded from "a" does not have a sharp beginning and is very extended. Frequently, the recorded echo from "a" extends down through all the later sub-bottom echoes and tends to mask them. Occasionally, however, where the "a" horizon occurs intermittently, the reflection from horizon "b" appears to be enhanced on the record. This is particularly true beneath the side echo reflections from the "a" horizon and frequently results in multiples of the "b" reflection (Fig. 7). The effect is probably caused by the superposition of the extended "a" echo on the "b" echo.

Of the four reflection horizons, "a" and "b" are quite easily identified and correlated from one profile to the next. Reflectors "c" and "d," while they are easily identified in some areas, are more difficult to correlate with certainty over the entire basin.

In many places both "c" and "d" are composed of two or three fairly distinct reflecting surfaces which diverge, converge, disappear and reappear as they are followed along a profile. On a larger scale the two horizons, "c" and "d," sometimes converge to form one reflector. On the reflection records their echoes generally are relatively weak but extended in time, and do not show a sharp break at their start (Fig. 7). The signal strength of the "d" echo shows considerable variation from one minute to the next. This variation must presumably relate to lateral changes in the reflectivity of "d" or in the attenuation in the overlying sediments.

Echograms of reflector "d" show local relief of from 10 to 20 feet within a mile or two. Frequently, the two or three reflecting surfaces forming this horizon appear to represent thin pockets of sediment which fill the low areas in the local relief.

The configuration of reflecting horizon "d" is shown in the contour map of Figure 4. For the depth determinations used in the contour-

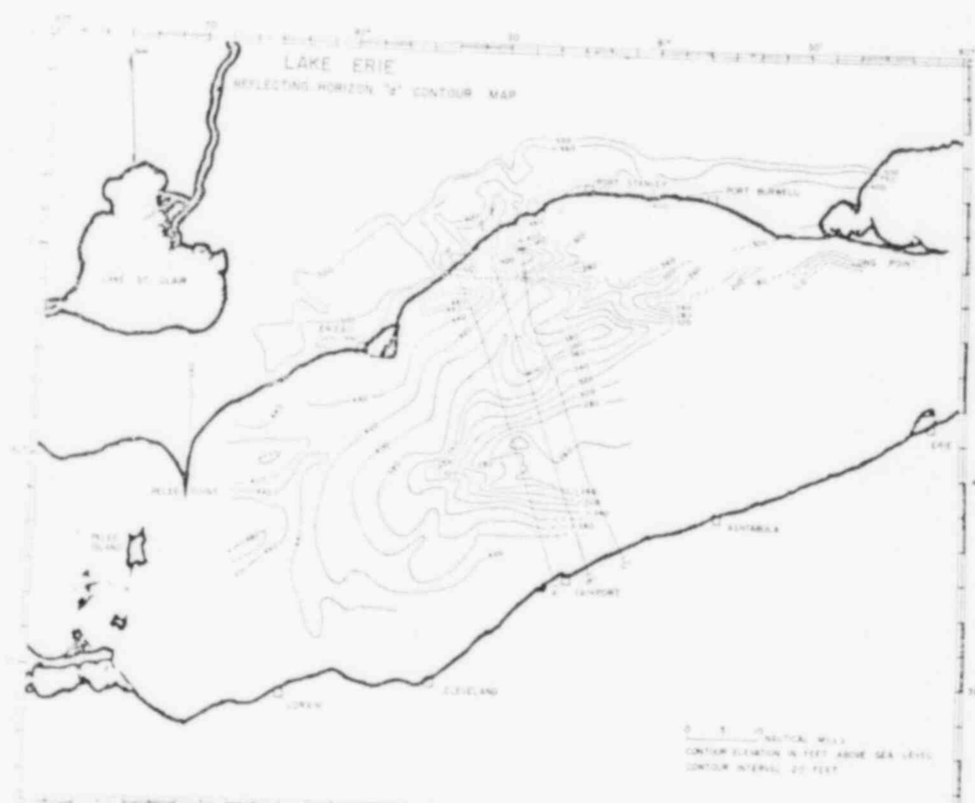

Figure 4. Elevation contours on reflecting horizon "d." Contours in Ontario after Sanford (1953, 1954) and Caley and Sanford (1952a, 1952b). Profiles along AA′, BB′, and CC′ are shown in Figure 6.

d = Paleozoic Bedrock

ing, a velocity of 4800 fps was assumed for the water layer and for the sediments lying above reflector "b." The sediment of layers "B" and "C" representing all of the material between reflectors "b" and "d," was assumed to have an average velocity of 6400 fps (see later section on velocity structure).

Figure 4 shows that the principal feature is a rather deep trough with a minimum elevation of about 240 feet corresponding to a depth below the lake level of 332 feet. Its axis is displaced somewhat south of the central axis of Lake Erie. Probably there is a continuation of this trough into a deeper basin whose northern slope is partially defined by the contours lying offshore from Port Burwell to Long Point. A pronounced spur projects eastward between the south central basin and its extension to the northeast.

Figure 5 contains an elevation contour map of reflector "c" along with an isopach contour map of layer "C." Again a velocity of 6400 fps was assumed for layers "B" and "C" while 4800 fps was used for the sediments above "b" and for the water. The elevation and isopach contour maps indicate a removal of the topographic features of horizon "d" by burial. The deposition of layer "C" has almost completely buried the centrally located valley of horizon "d" as shown by the altered elevation contours and the 120-foot isopach contour over this valley.

Several new features have been added by the deposition (and post-depositional environment) of layer "C." The most obvious of these is indicated by the hachured lines in Figure 5 lying between Erieau and Cleveland. Here reflecting horizon "c" rises on the records until it is lost in the "b" reflections. A second feature is the presence of the two closed 40-foot isopach contours lying just east of the hachured area. A third feature is the very elongate, partially closed basin trending east-west and lying some 10 to 15 miles north of Fairport. The profiles

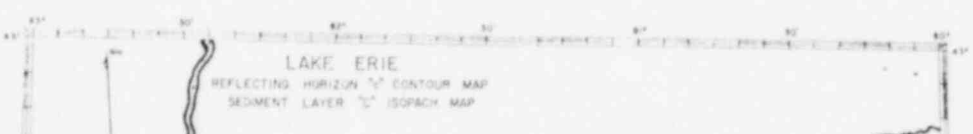

Figure 5. Elevation contours on reflecting horizon "c" and isopachs of layer "C." Profiles along AA′, BB′, and CC′ are shown in Figure 6.

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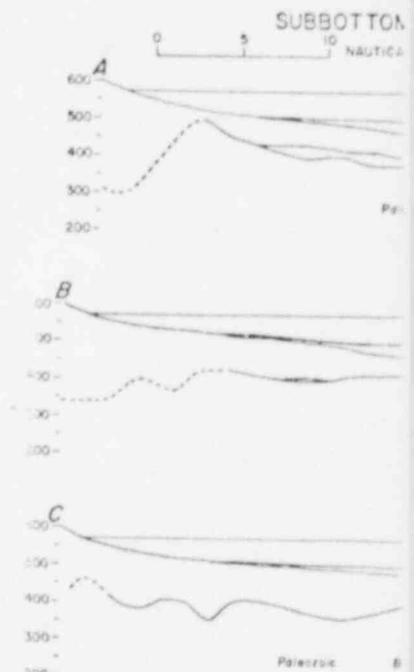

Figure 6. Cross sections al...

central Lake Erie is based upon: (1) ... characteristics and configurations of th... ing horizons, (2) results of recent ... studies in the central basin of Lake ... (3) general knowledge of the late glaci... of the lake and its environs. As migh... pected, the sediments and reflecting ... within the central basin are quite s... those found by Hartley (1961b) in t... area of Lake Erie.

Horizon "a"

The very extended echoes and the s... from horizon "a" imply either that ... locally rough surface capable of stro... scattering or that it is a sequence ...

ned for layers "B" and "C" while
was used for the sediments above "b"
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maps indicate a removal of the topo-
eatures of horizon "d" by burial. The
n of layer "C" has almost completely
e centrally located valley of horizon
own by the altered elevation contours
120-foot isopach contour over this

l new features have been added by the
n (and post-depositional environment)
"C." The most obvious of these is in-
y the hachured lines in Figure 5 lying
Erieau and Cleveland. Here reflecting
"c" rises on the records until it is lost
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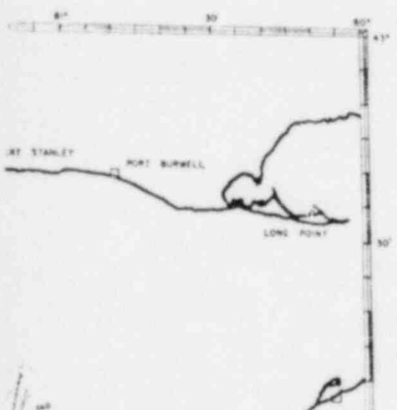
sin trending east-west and lying some
miles north of Fairport. The profiles



isopachs of layer "C." Profiles along AA'.

AA', BB', and CC' (Fig. 6) show this basin quite clearly. Also indicated on the reflector "c" traces in these profiles are several reflecting surfaces which diverge from and lie above "c" and which disappear within a mile or two.

SEDIMENTARY SECTION

The identification of the sediment types and interfaces within the sedimentary section of

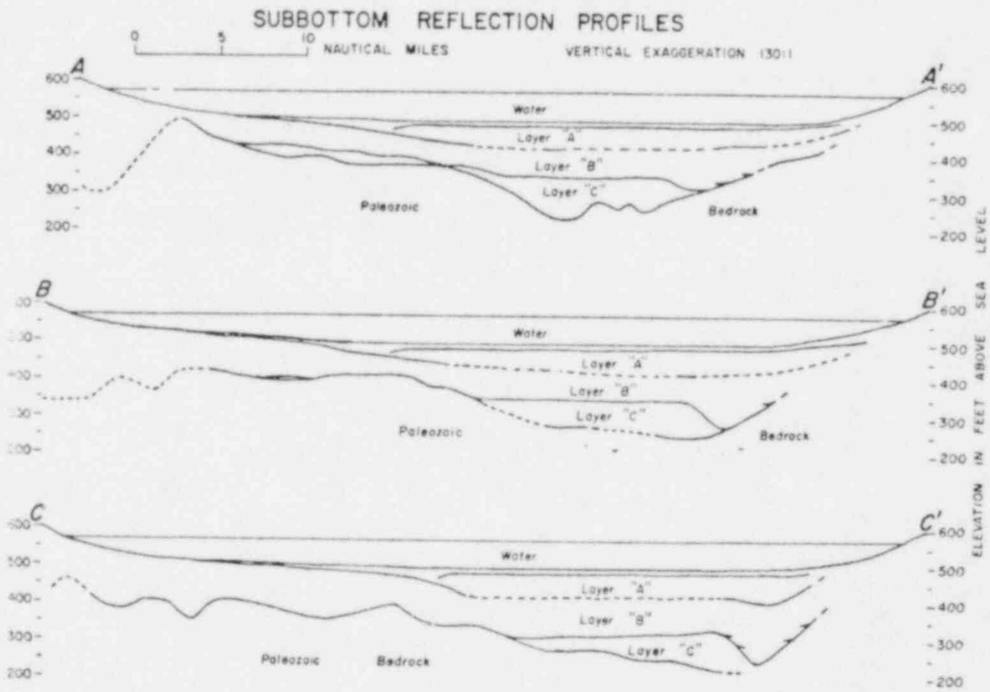


Figure 6. Cross sections along lines AA', BB', and CC' of Figures 3, 4, and 5.

central Lake Erie is based upon: (1) reflection characteristics and configurations of the reflecting horizons, (2) results of recent sediment studies in the central basin of Lake Erie, and (3) general knowledge of the late glacial history of the lake and its environs. As might be expected, the sediments and reflecting horizons within the central basin are quite similar to those found by Hartley (1961b) in the island area of Lake Erie.

Horizon "a"

The very extended echoes and the side echoes from horizon "a" imply either that it has a locally rough surface capable of strong back-scattering or that it is a sequence of layers within which multiple reflections occur.[1] Both of these suggest shallow rather than deep-water deposition. The fact that horizon "a" has very little relief and is observed only in the deeper portions of the basin formed by reflector "b" also supports the view that the deposition of layer "A" occurred in a shallow-water environment.

The peat and plant-rich clay layers in the island area have been found at elevations above 520 feet and indicate the existence of a period during which the lake level was at least this low. Evidence that the lake level was, in fact, lower has been provided by Charles E. Herdendorf (personal commun.). He cites information obtained from borings which indicates the occurrence of a low-water stage of Lake Erie with an elevation of around 490 feet. The evidence

[1] Reflecting horizons with similar characteristics have been observed during reflection studies carried out in Long Island Sound and Chesapeake Bay (Drake, personal commun.; Beckman and others, 1960). A sediment core taken in Chesapeake Bay penetrated this reflecting horizon and showed it to contain a large amount of plant material and gas bubbles.

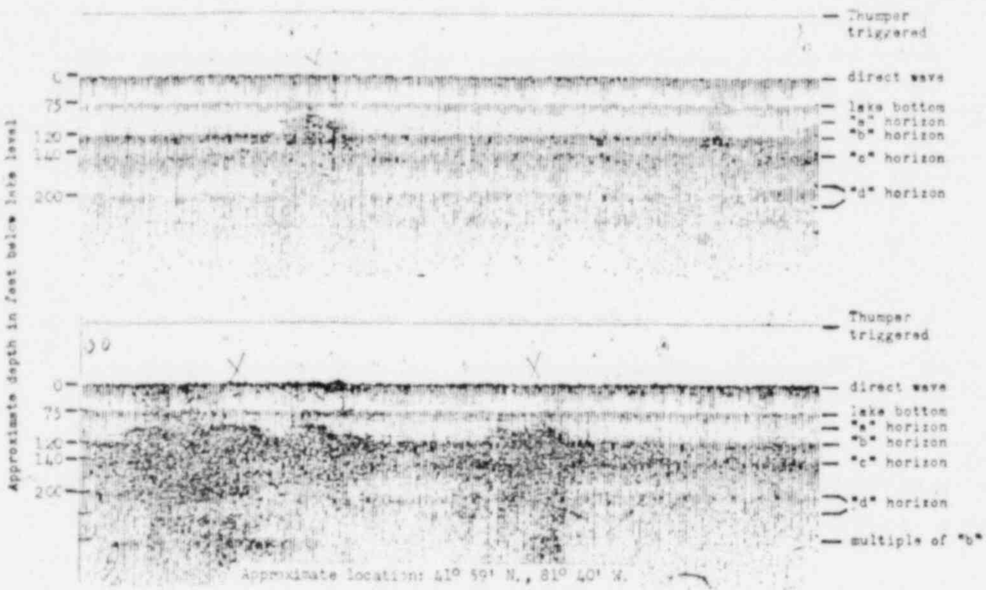


Figure 7. Example of sub-bottom reflection record. Right end of top section is continuous with left end of bottom section. Total horizontal distance shown is 14,000 feet.

includes buried marsh deposits and "the remnants of an ancient soil zone containing plant material" in the central basin west of Lorain, Ohio, and marsh gas at Fairport, Ohio. Herdendorf also reports that several borings north of Ashtabula and Conneaut, Ohio (to the east of Ashtabula), have penetrated peat layers at elevations of 480 to 500 feet. These and other shallow-water deposits found in the area "are generally overlain by deeper water silts and clays."

Although sub-bottom reflection data were not obtained in the area north of Ashtabula, horizon "a" is found at similar elevations farther west and is also overlain by deep lake mud.

C. F. M. Lewis (personal commun.), University of Toronto, has provided the author with data from cores taken in the central basin. Unfortunately, the gravity cores do not penetrate deep enough to reach horizon "a." The pertine piston cores[2] are all located within or near the boundary region of the areas in which "a" reflections are found. Thus, it is difficult to say whether or not layer "A" is present at the coring stations. Logs of these cores frequently show the presence of sand layers or layers containing plant detritus, shells, and shell fragments. These are generally buried by soft Recent mud and are often found to overlie a dense Pleistocene glaciolacustrine clay in which a number of the cores bottom.

It is concluded that reflecting horizon "a" is the surface of buried shallow-water deposits probably containing sand and silt lenses with shells, shell fragments and peat and plant-rich clay layers within which entrapped gas may be present. In summary, this conclusion is based on: (1) the character of the "a" reflections; (2) the presence of reflector "a" only in the deeper portions of the basin formed by the "b" horizon; (3) the fact that the horizon "a" generally lies between the elevations of 475 and 490 feet above sea level; and (4) the presence of buried shallow water sediments at similar elevations in the central basin as shown by cores and borings.

Horizon "b"

Reflector "b" lacks relief, has widespread distribution in the basin, and has a gentle upward slope to the east toward the Port Huron terminal moraine. It is inferred from this description that the sediment of layer "B" was deposited in deep water during and after the

[2] Approximate core locations: lat 42°06' N., long 82°05' W. (9-foot gravity core); lat 42°02' N., long 82°07' W. (piston); lat 41°57' N., long 81°53' W. (piston); lat 41°46' N., long 81°55' W. (piston); lat 41°49' N., long 81°27' W. (piston); lat 41°51' N., long 81°14' W. (piston); lat 42°10' N., long 81°12' W. (piston).

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Horizon "c"

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Horizon "d"

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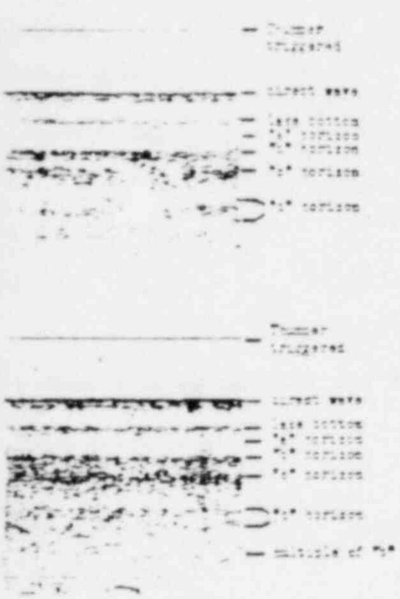

Huron advance. The strong reflections re- :d from the "b" horizon indicate a marked : in acoustic impedance across the inter- Identification of layer "B" as a compact imilar to and correlative with that found : island area is strongly suggested by the : observations.

: cores taken by Morgan (1964) and Lewis :. personal commun.) bear out this identi- on. Both the dense Pleistocene glacio- trine clay noted by Lewis and the stiff, act, brownish clay found by Morgan cor- ond in depth with layer "B." The stiff clay ribed by Morgan, which forms the bottom nent near the north shore of the central .. shows that interface "b" does rise up to me the present lake bottom as the reflec- data suggest.

:e large change in acoustic impedance from Recent soft mud to the compact clay is re- l to their porosities. Morgan (1964, Table 2) gives average porosities of 0.649 and for the Recent and Pleistocene surface nents found in his cores. While it is not ible to determine the original porosity of r "B," Hartley (1961b) suggests that a loss ore water during the low-water stage has tributed significantly to its compaction.

Horizon "c"

The surface configuration of horizon "c" (Fig. 5) suggests that layer "C" is the remnant of a morainal deposit. With such an identifica- tion, the apparently lobate form of the region in which reflector "c" rises into the "b" re- flection is readily explained as are the closed minimum isopachs of 40 feet found on the con- cave side of this rise. Because of the location of this rise within the central basin and its position just below the compact clay, it is presumed that the deposition of the upper sediments of layer "C" took place during Lake Border time (Hough, 1963, Fig. 3D) and contemporane- ously with the Port Stanley till of southwestern Ontario (Goldthwait and others, 1965). The east-west trending basin north of Fairport may be caused by post-depositional erosion. It will be discussed in a later section (History of Lake Erie).

Horizon "d"

The deepest reflecting horizon, "d," is con- sidered to be Paleozoic bedrock. Its configura- tion conforms well with the generalized bed- rock contour map of Morgan (1964). Further corroboration is available as a result of the oil and gas operations in southwestern Ontario. These operations extend out into the lake par- ticularly in the area between Pelee Point and Erieau, Ontario. In this area, the bedrock ele- vations as indicated in well logs (Ontario Fuel Board, 1958; Ontario Department of Energy Research, 1962) compare well with the eleva- tions of horizon "d" (Fig. 4). Several bedrock surface contours in southwestern Ontario, which were obtained originally from well-log data (Sanford, 1953, 1954a; Caley and Sanford, 1952a, 1952b), have been smoothed to a small extent and included in Figure 4 for comparison. The general agreement is quite good along the entire north shore of the central basin. A cor- respondence in detail is indicated between Erieau and Port Stanley.

Summary of the Sedimentary Section

The reflectors "a," "b," "c," and "d" are the surfaces of (a) shallow-water deposits, (b) compact glaciolacustrine clays, (c) glacial till of Lake Border age, and (d) Paleozoic bedrock. It should be kept in mind that, because seismic reflecting horizons and stratigraphic bound- aries are not necessarily coincident or even parallel, this sedimentary section is somewhat oversimplified. For example, the presence of exposed Port Stanley and older tills along the north shore near Port Stanley (Dreimanis, 1958) indicates that horizon "b," as it ap- proaches the north shore, must represent an erosional unconformity cutting across glacio- lacustrine clays and glacial tills. This implies that layer "C," at least in this north-shore area, does not include all of the glacial deposits of Lake Border age. In addition, there is little doubt that sediments of pre-Lake Border time are contained in layer "C." The presence of more than one distinct reflector at the "d" horizon is probably an expression of these older deposits. It is probable that some portions of horizon "d" actually represent more recently formed reflecting surfaces and that the Paleo- zoic bedrock lies somewhere below.

Velocity Structure

Seismic velocity of shallow, quiet water sedi- ments generally differs very little from the velocity of sound in water. Variations with depth of burial are principally controlled by changes in porosity (Nafe and Drake, 1957; Sutton and others, 1957). Hartley (1961b) and Morgan (1964) have shown this to be the case for the Recent soft mud which makes up most of the bottom sediment found in Lake Erie. In laboratory measurements, Morgan found a seismic velocity of 5018 fps in the water. He

found the average velocity at or near the top of the soft Recent sediments to be almost exactly the same.

The velocity of sound in the shallow-water deposits of layer "A" is difficult to assess since the exact nature of these deposits has not been determined. While a section of low or high velocity may exist, its effect on the average velocity for the sediments above horizon "b" cannot be very great. This is required because horizon "b" shows no upward or downward displacement on the reflection records when layer "A" begins or ends abruptly. If sand and silt layers are assumed to give the "a" reflections, they might be expected to have a sound velocity only slightly different from that of the overlying Recent muds and could, therefore, extend down to horizon "b." On the other hand, if the sediments just below horizon "a" are assumed to contain gas, sound velocities as low as several hundred feet per second may be present (Jones and others, 1958; Worzel and Drake, 1959; Levin, 1962). In this case, it would seem reasonable that the low-velocity material forming the top of layer "A" is underlain by soft mud down to horizon "b." Such a situation has been found, on occasion, in the island area (Hartley, 1961b, Pl. 8).

The seismic velocity in the compact clay below horizon "b" has been measured by Morgan (1964). He found an average velocity of just under 6000 fps.

The only remaining layer in whose velocity we are interested is layer "C." While no definite data appear to be available, descriptions of the character of its on-shore counterpart (a mixture of varying amounts of silt, sand, gravel, and boulders within a highly compacted clay matrix) imply a variable velocity averaging somewhat more than that of the overlying compact clay layer.

The seismic velocities used in the conversion of reflection travel times to depths were decided upon before the data of Morgan became available. Therefore, the values of 4800 fps, for which the PDR was calibrated, and 6400 fps were chosen partly as a matter of convenience. Morgan's data, where they apply, are in reasonable accord.

DISCUSSION

Paleozoic Bedrock Surface

It is generally accepted that the Paleozoic bedrock surface in the Lake Erie basin has been formed by erosional processes both glacial and subaerial. However, it is not known which of these two processes predominated.

A good deal of evidence supports the view that subaerial erosion has been the principal factor. Hartley (1961b) indicates the presence of a drainage system in the Paleozoic bedrock of western Lake Erie which has been buried by glacial and lacustrine sediments. Similarly the bedrock contours shown in Figure 4 appear to be more compatible with an origin by fluvial erosion than by glacial scour. In addition, a narrow buried gorge at Cleveland, Ohio, whose bottom is more than 200 feet below the present lake level (Peck, 1954) (and whose extension into the present lake basin is not observed in the reflection data) almost certainly requires a fluvial origin.

On the other hand, there is strong evidence to indicate that the present bedrock basin underlying Lake Erie is closed. Dense well-log data, along the north shore of the eastern basin of Lake Erie give no indication of a buried gorge or valley. This is shown clearly on maps of the bedrock topography of that area compiled from well-log data (Sanford, 1954a, 1954b, 1956). Similar data and bedrock topographic maps of the remainder of southwestern Ontario along the north shore of Lake Erie do not support the possibility of a bedrock channel in these areas.

If we accept that subaerial erosion formed the present bedrock surface configuration under Lake Erie, we would, necessarily, accept that past crustal warping transformed most of the present closed basin into a valley.

History of Lake Erie: Lake Border to Present

The sediments of layer "C" represent morainic deposits of the Lake Border ice lobe in Lake Erie. During the retreat of this ice, the central basin was filled to a depth of almost 400 feet with the water of Lake Arkona which had a surface elevation about 700 feet above present sea level. The east-west trending basin in the drift deposits of layer "C" did not then exist.

Further rapid retreat of the Lake Border ice opened lower and lower outlets to the east until drainage occurred over the Niagara escarpment. At this time, the elongate depression is thought to have been eroded in the Lake Border till by a river which drained the areas to the west and probably, for a time at least, carried the drainage from the Huron basin.

The local reflecting horizons which diverge from both the north and south slopes of the

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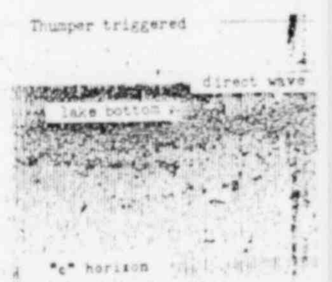

Figure 8. Example of sub-bott
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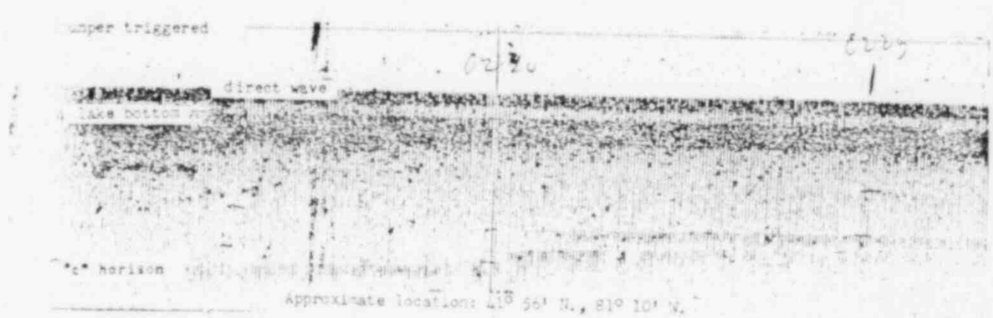
Port Huron low-water stage was the last Lake Maumee, or the several phases of Lake Arkona bracketed the low-water stage. While data are rather incomplete, it is worth noting that in Michigan the upwarp of the Maumee strandlines is about twice that found for the later Arkona strandlines (Leverett and Taylor, 1915, Pl. 20).

The Cary-Port Huron low-lake stage came to a close when the advancing Port Huron ice blocked the eastern outlet. Once again, water



…ure 8. Example of sub-bottom reflection record showing probable buried beach deposit. Total …ontal distance shown is 9000 feet.

…though the data are incomplete, Figure 5 … no indication of a breach in the Lake …der terminal moraine. However, echograms … borings discussed by Hartley (1961a; 1960, … 14, 18) do suggest breaches in both the Lake …der terminal moraine and an older terminal …raine which crosses the lake between Lorain … Pelee Point. In addition, Kunkle (1963) …s found a post-Cary, pre-Port Huron buried …sional surface beneath the Huron River at … west end of Lake Erie. From this he has …rred the existence of a low-lake stage which … called Lake Ypsilanti.

The depth of the eroded valley in the Lake Border till implies that the eastern outlet of the Lake Erie basin must have been depressed about 300 feet. This is a factor of nearly two times the amount of depression indicated by the warped strandlines of Lake Arkona (Leverett and Taylor, 1915, Pl. 18). It is possible that the Lake Arkona strandlines, which were used to determine the upwarp, were formed after the low-lake stage and during the advance of the Port Huron ice. This varies somewhat with the lake-stage chronologies of Leverett and Taylor (1915), Bretz (1951), and Hough (1963). It means either the glacial lake existing within the Erie basin just prior to the Cary-

more than 400 feet deep filled the Lake Erie basin and was forced to drain for a while into Lake Saginaw in the Huron basin. During the formation of the Port Huron terminal moraine, Lake Whittlesey filled the ice-free part of the Erie basin to an elevation of about 740 feet (Hough, 1963).

During this period of deep water in the basin the deposition of glaciolacustrine clay predominated and nearly all of the relief originally present on the bottom was buried. The principal glacial deposit of this age was the pronounced terminal moraine of the Port Huron ice. Its presence in the Lake Erie basin across the lake from the base of Long Point to Erie, Pennsylvania, has been an important factor in the formation of several features of present Lake Erie.

The retreat of the Port Huron ice opened eastern outlets of progressively lower elevations. Opening of the outlet at Rome, New York, some 12,000 years ago, initiated drainage over the Niagara escarpment from the Erie basin into Lake Iroquois in the Ontario basin.

Although the depression of the eastern outlet at that time may have amounted to as much as 150 feet (Fairchild, 1932, Fig. 3), the Port Huron terminal moraine formed a continuous

barrier across the lake and held the water level in the central basin at a higher elevation than that in the eastern basin. The bottom topographic low some ten miles northwest of Erie, Pennsylvania, may represent a partial breaching of this barrier by the outflow from the central basin.

The fine-grained sediments of layer "B," which were mostly uncovered at this time, became more compact through dehydration. The surface of these sediments after modification by erosional processes has become reflecting horizon "b."

Within the basin, sediment deposition was concentrated in the relatively small water-covered area. Locally derived sediments may have been augmented for a time by those brought in from early Lake Algonquin in the Huron basin (Hough, 1963). In addition, the water level in the central basin remained fairly constant for a while, controlled not by the increasing elevation of Niagara area but by the relatively stable elevation of the outlet across the Port Huron terminal moraine. These two factors, the concentration of sediment deposition and a nearly constant water level in the central basin, led to an eventual clogging of the basin with sediment. Extensive marshy conditions developed and the shallow-water sediments of layer "A" were deposited.

Termination of this period of shallow-water deposition in the central basin probably occurred (1) when increasing elevation of the eastern basin Niagara outlet reached the elevation of the outlet across the Port Huron terminal moraine and the central basin began to flood, or (2) when return of drainage from the Huron basin at the end of the Kirkfield stage, about 11,000 years ago, (Hough, 1963, Fig. 7) raised the water level enough so that the formation of shallow-water deposits ceased.

Following the end of shallow-water deposition in the central basin, the water level has continued to rise at a decreasing rate. A number of phenomena observed by other writers are readily explained by the presence of this low-water stage followed by a continuous rise of the eastern outlet and the lake level (Taylor, 1928; Hartley, 1960, 1961a; Lewis and others, 1966).

Peat layers in the western basin and island area have been found from about 520 feet almost up to the present lake level (Hartley, 1961b, Pl. 8; Herdendorf, personal commun.). Because of poor local drainage, their time of formation is probably quite variable. A radiocarbon date of 6550 ± 134 years before the present has been obtained from a piece of wood found in a layer of peat at an elevation of 540 feet (Herdendorf, personal commun.). If this elevation is indicative of the water level at that time, then it seems reasonable to assume that between 7000 and 8000 years ago the water level had risen to about the level of the compact clay surface (530 to 540 feet) in the island area and as Hartley (1961b) states, the "more extensive marsh conditions may have developed." There followed a period of "wide accumulation of plant material and silt mixtures and peat layers." This period presumably was brought to a close, according to Hartley, when "further rise in lake level (with reinforcement by the addition of Lake Nipissing[3] drainage from the Huron basin) out-paced sedimentation and the water became too deep for marsh conditions."

Evidence relating to the rise of the Lake Erie water level in the past 2000 or 3000 years (Taylor, 1928) will not be dealt with here. It is sufficient to state that since the flooding of the western basin, the water level has risen to its present elevation of 572 feet. Modern rates of tilting have been determined using data from pairs of water-level gauges (Gutenberg, 1941; Moore, 1948), but the validity of these rates has been questioned (MacLean, 1963).

CONCLUSIONS

(1) The seismic reflection technique can be a very worthwhile investigative tool in studies of lake sedimentation and history.

(2) In the central basin of Lake Erie, four relatively distinct sub-bottom reflectors have been mapped by this technique. These correspond with the buried surfaces of (a) shallow-water deposits, (b) compact glaciolacustrine clay, (c) glacial till of Lake Border age, and (d) Paleozoic bedrock.

(3) Contours on the Paleozoic bedrock surface (reflector "d") along with other features within the Lake Erie basin seem to favor an origin by fluvial erosion. Proof of this must lie either in the discovery of a buried gorge leading out of the bedrock basin, or in the verification of past crustal warping sufficiently large to remove the necessity of a buried outlet channel.

(4) The presence of what is thought to be a fluvially eroded valley in the Lake Border till

[3] For a period of some 6000 years starting about 10,000 years ago, no discharge from the Huron basin entered Lake Erie. About 4000 years ago this discharge returned due to the uplift of the North Bay outlet of the Huron basin. This initiated the Lake Nipissing phase in the Huron basin.

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while investigative tool in studies of
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e central basin of Lake Erie, four
istinct sub-bottom reflectors have
ed by this technique. These cor-
h the buried surfaces of (a) shallow-
sits, (b) compact glaciolacustrine
icial till of Lake Border age, and
c bedrock.
ours on the Paleozoic bedrock sur-
or "d") along with other features
Lake Erie basin seem to favor an
uvial erosion. Proof of this must lie
discovery of a buried gorge leading
edrock basin, or in the verification
tal warping sufficiently large to re-
cessity of a buried outlet channel.
resence of what is thought to be a
ded valley in the Lake Border till

iod of some 6000 years starting about
go, no discharge from the Huron basin
Erie. About 4000 years ago this discharge
to the uplift of the North Bay outlet of
ron. This initiated the Lake Nipissing
Huron basin.

deposits (layer "C") of the central basin indicates the occurrence of a low-water stage during the Cary-Port Huron interval. A downwarping of the eastern outlet over the Niagara escarpment of some 300 feet is implied by the depth of 300 feet at which this eroded valley is found.

(5) The lacustrine clays of layer "B" were deposited in deep water while Port Huron ice blocked the eastern outlet.

(6) A second low-lake stage, early Lake Erie, occurred following the retreat of the Port Huron ice. Initially early Lake Erie consisted of separate bodies of water in the central and eastern basins with the Port Huron terminal moraine forming a barrier between the two. During this period shallow-water sediments (layer "A") were deposited in the central basin.

(7) The large-scale changes in the level of Lake Erie as inferred from the results of the sediment studies discussed in this paper closely agree with the chronology of Hough (1963).

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Abstract: Magnetic, gravity, and
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* Geophysical and Polar Research C