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CHARACTERIZATIONS OF THE DETROIT, RAISIN, AND MAUMEE SEDIMENT PLUMES IN WESTERN LAKE ERIE USING GRAIN-SIZE AND HEAVY-MINERAL ANALYSES

by

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PREFACE

The following document was prepared by Mark S. Przywara in partial fulfillment for a Master of Science Degree in the Department of Geology, Bowling Green State University. Research conducted for this thesis was supported by Grant Nos. A-032-OHIO and A-045-OHIO from the Office of Water Research and Technology, U.S. Department of Interior. Dr. Lester J. Walters, Jr. served as advisor. Dr. Donald E. Owen and Dr. Jane L. Forsyth served as members of the thesis committee.

On behalf of the Center for Lake Erie Area Research, I am pleased that we are able to reproduce copies of this research report and make them available to other scientists.

Charles E. Herdendorf
Director

ABSTRACT

Grain-size analyses of the bottom sediments of western Lake Erie illustrate the presence of three separate sediment plumes in the basin. These sedimentary features are: the Detroit River sediment plume, which extends southeast into the basin; the Maumee River sediment plume, which enters the lake flowing northeast from Maumee Bay and hugs the Michigan shoreline as it heads north into the basin; and the Monroe-Raisin plume, which is a coarse-sediment feature which seems to emanate from the Raisin River. Because of its high discharge of water, the Detroit River plume is fairly unbroken and consistent, whereas the true character of the Maumee and Monroe-Raisin plumes is constantly being altered by the varying current patterns located in the southwestern portion of the western basin. In addition to these sediment plumes, nearshore-sediment zones are also differentiated along the Ohio, Michigan, and Ontario shorelines. Cores from four cross sections across the western basin were also analyzed to determine the character of the sediments within the various plumes during their most recent depositional history. Variations in sediment distribution and accumulation along these cross sections further illustrate the locations and extents of the depositional zones in the western basin.

Heavy-mineral analyses of the sands within the sediment plumes show a distinct trend with respect to white/pink garnet ratios. The Maumee and Monroe-Raisin plumes possess ratios of greater than 1.0, whereas the Detroit plume contains garnet ratios of less than 1.0.

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INTRODUCTION

The purpose of this thesis is to determine the presence and location of the bedload-sediment plumes of the Maumee and Detroit Rivers in the western basin of Lake Erie. The approximate locations of these fluvial channels are determined by the analyses of core and grab samples collected from throughout the basin. Nearshore deposits derived from the erosion, reworking, and subsequent transportation of glacial till-bluff deposits are also indicated. Heavy-mineral concentrations are additionally used to differentiate between the Maumee, Detroit, and bluff-derived sediments.

Although much research has been performed in efforts to determine various chemical, biological, or other physical trends and zones in the western basin, no attempt has been made to differentiate the bottom sediment "zones" of the entire basin by means of sediment and heavy-mineral analyses. Several grain-size distribution analyses have been carried out by other researchers, but these have generally only dealt with small sections of the basin. The island area, for example, has been intensely studied, but the majority of the basin has not undergone such scrutiny.

The results of this research are intended to be used to further determine the influence of the Detroit and Maumee Rivers on sediment supply and dispersal in the western basin. In addition, any information concerning the dynamics of sediment input from these two rivers will be useful to enviromentalists in their battle to "clean up" this area of Lake Erie.

Location and Physiography

Lake Erie, located between the land areas of Ohio, Pennsylvania, and New York, is the fourth largest of the Laurentian Great Lakes, as well as being the thirteenth largest lake in the world (Federal Water Pollution Control Administration, 1968, p.1). Although researchers have divided the lake into separate physiographic sections, the boundaries, as well as the number, of these sub-basins are open to debate. The morphometric and hydrologic data for Lake Erie is listed in Table I.

Carman (1946, p.279) divided Lake Erie into three basins primarily on the basis of bathymetry. Another tri-basin division was proposed by the Federal Water Pollution Control Administration (1968, p.3). Although these proposals are relatively valid, it is in this writer's opinion that they are too vague to properly describe the entire Lake Erie basin, especially when dealing with deposition and sediment accumulation. For this reason, the four-fold Erie subdivision proposed by several workers, including Lewis et al. (1966), Sly (1976), and Thomas et al. (1976), will be used in this thesis.

This four basin plan, shown in Figure 1, is based on the "natural" subdivisions within the lake which are formed by the presence of the Point Pelee-Lorain and Long Point-Erie Sills. These two low amplitude bathymetric highs originally formed as glacial moraines between 13,500 and 13,000 years ago (Sly, 1976, p. 360). The two sills, as well as the less important Erieau-Cleveland Sill, transverse the Erie basin relatively

Table I. Morphometric and hydrologic data for Lake Erie [1]

Length (straight line)	240 miles
Breadth (right line)	57 miles
Length (coastline including islands)	851 miles
Water Surface (United States)	4,982 sq. miles
Water Surface (Canada)	4,932 sq. miles
Drainage Land (United States)	18,008 sq. miles
Drainage Land (Canada)	4,722 sq. miles
Drainage Land (Total)	22,730 sq. miles
Drainage (land and water)	32,644 sq. miles
Maximum depth	216 feet
Average depth	56 feet
Water volume	110 cubic miles
Mean elevation above sea level (1977)	572 feet
Average annual precipitation	34 inches
Mean outflow	209,776 cfs

[1] after the Federal Water Pollution Control Administration, 1968, p. 2; Chandler, 1964, p. 62; and Hough, 1958, p. 5.

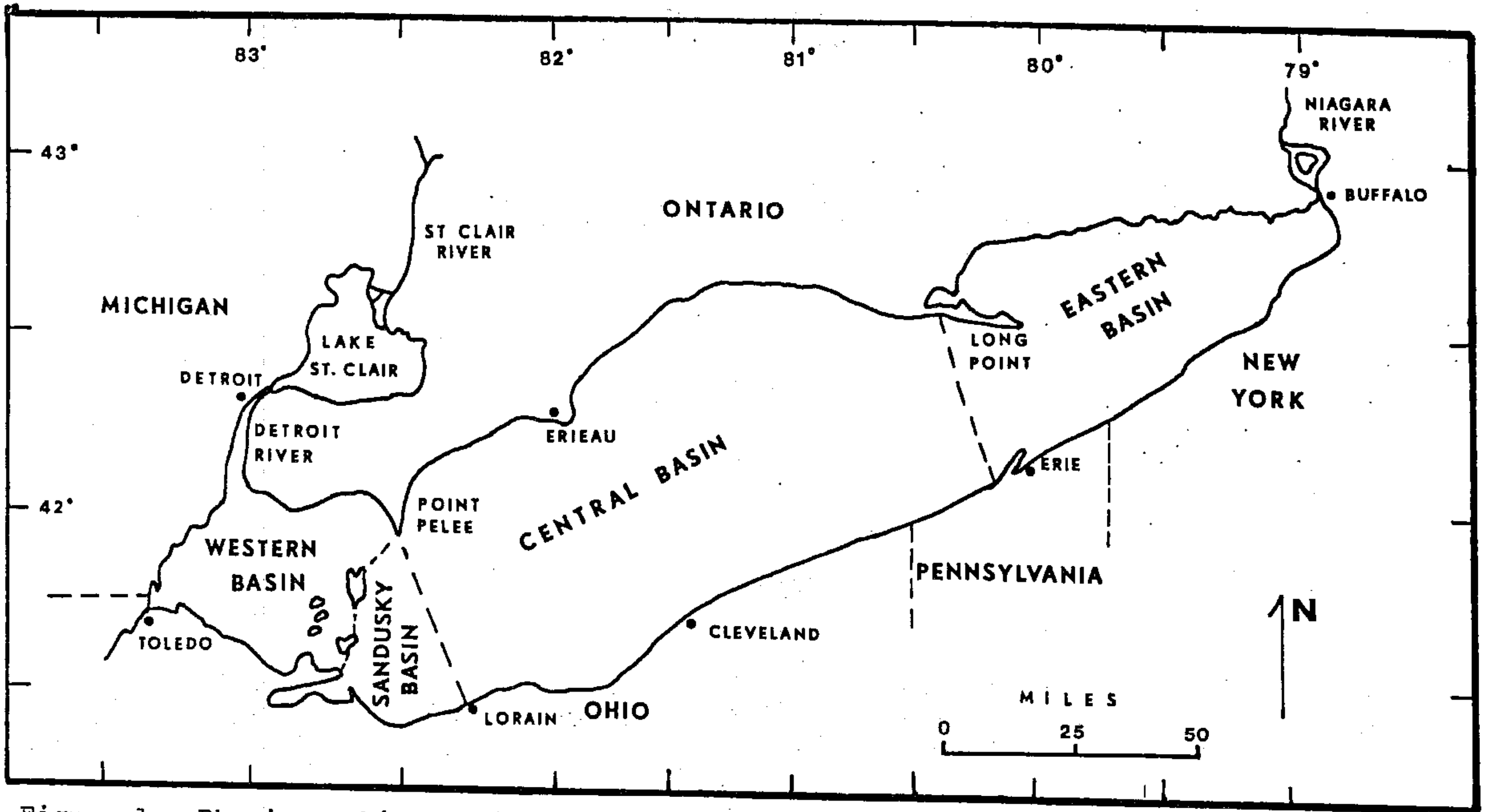

Figure 1. Physiographic subdivisions of Lake Erie (after Lewis <u>et al.</u>, 1966; Sly, 1976; and Thomas <u>et al.</u>, 1976).

perpendicular to the long axis of the lake. The presence of these sills, combined with the depths and underlying topography of various sections within the lake, allows these workers to logically and accurately subdivide Lake Erie into four basins: eastern, central, Sandusky, and western.

The eastern basin, underlain by non-resistant Devonian shales and sandstones, is that part of Lake Erie lying east of the Long Point-Erie Sill. This sill, which is between 17 and 40 kilometers wide, is composed of a till ridge overlain by lag sands and gravels. A more detailed description of this feature is presented by Lewis et al. (1966). The eastern basin covers approximately 2,400 square miles with an average depth of about 80 feet, and a maximum sounding of 216 feet, by far the deepest in Lake Erie (Federal Water Pollution Control Administration, 1968, p. 23).

The central basin is the largest subdivision of Lake Erie, covering over 6,000 square miles with an average depth of 60 feet (Federal Water Pollution Control Administration, 1968, p. 22). This basin is also underlain by non-resistant Devonian clastic bedrock, and is physiographically separated from the remainder of Lake Erie by the Long Point-Erie Sill to the east and the Point Pelee-Lorain Sill to the west.

The Sandusky basin is that portion of Lake Erie which is the subject of debate for many workers. The triangular-shaped basin, located northwest of Sandusky, is bordered to the east by the Point Pelee-Lorain Sill and to the west by a line running from Pelee Point through Pelee and Kelleys

Islands to Marblehead Peninsula (Lewis *et al.*, 1966; Sly, 1976; and Thomas *et al.*, 1976). This line indicates the easternmost extent of the bedrock islands in the Lake Erie basin. The area of this basin is estimated to be about 400 square miles, making this the smallest basin in Lake Erie.

The portion of Lake Erie lying west of Pelee and Kelleys Islands makes up a distinct physiographic unit known as the western basin (Figure 2). The island divide is made up of a series of resistant dolomitic outcrops which completely separate this shallow basin from the deeper portions of the lake. The approximate area of the western basin as shown in Figure 1 is over 800 square miles (Federal Water Pollution Control Administration, 1968, p. 21).

An excellent discussion of the bathymetry of the western basin has been presented in a study of the island and reef area by Herdendorf and Braidech (1972). The following discussion draws heavily from this report.

The mean depth of this basin is only 24 feet, and the lake bottom is relatively flat except for the sharply rising Silurian and Devonian reefs and islands in the eastern part of the basin. The lake bottom slopes gently lakeward from the shoreline with relatively minor gradients. The gradients increase gradually in the island area, with the steepest inclines exceeding 60 feet per mile in the South Passage. The deepest spot in the basin, 62 feet, is located north of Starve Island Reef. Aside from a 54 foot sounding south of Gull Island Shoal, depths in the western basin do not exceed

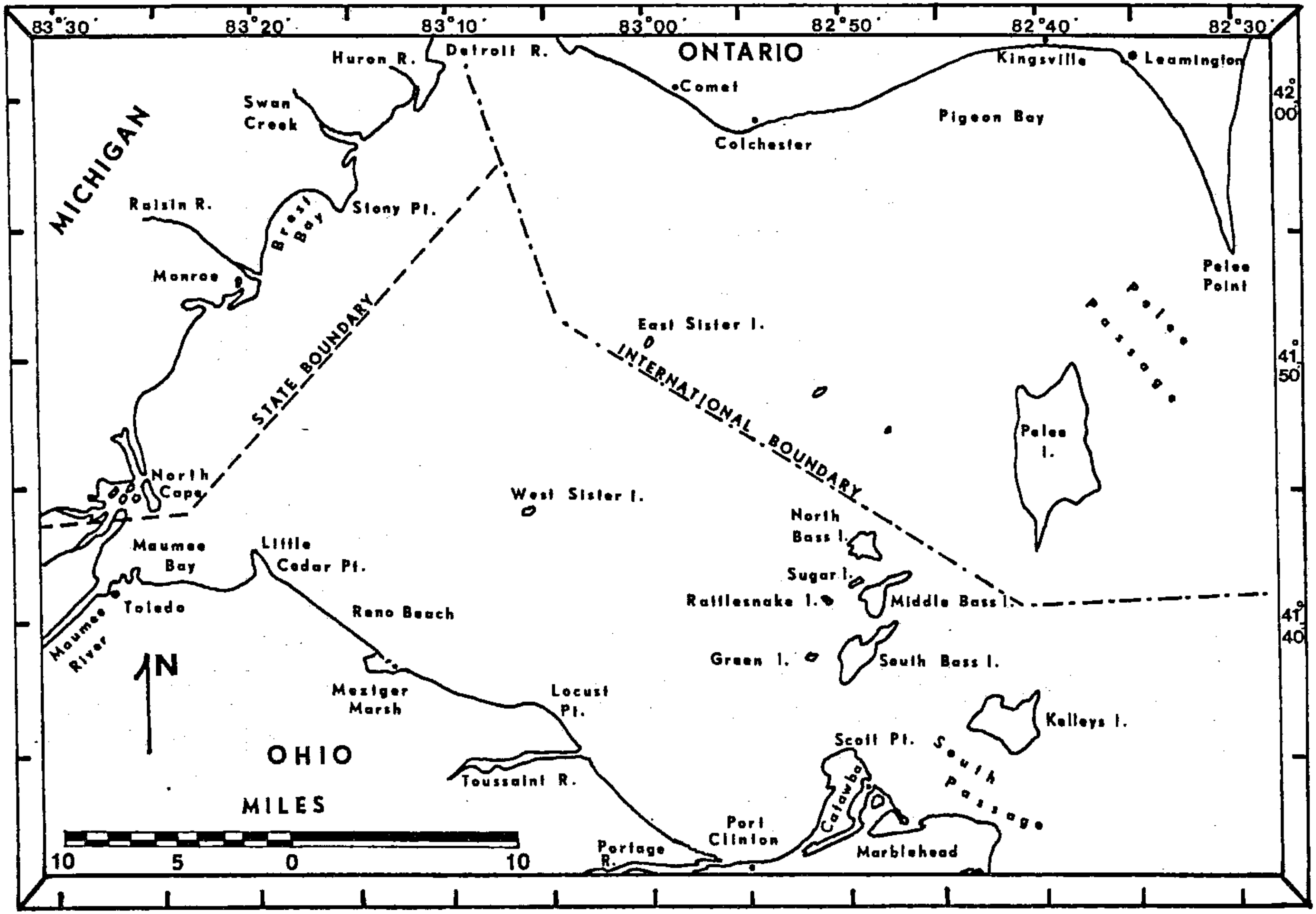

Figure 2. Western basin of Lake Erie (Herdendorf and Braidech, 1972; and the National Oceanic and Atmospheric Administration, 1972).

45 feet. The extreme shallowness in this area is due to the underlying resistant Devonian and Silurian bedrock.

The western basin of Lake Erie was the location of most of the samples used in this thesis research, although some Sandusky basin samples were used. Because of this fact, all additional discussions will deal directly with these two basins and the areas surrounding them, unless otherwise indicated. The morphometric and hydrologic data for the combined Sandusky and western basins is listed in Table II.

Bedrock Stratigraphy and Structural Geology

Figure 3 illustrates the approximate distribution of Paleozoic rocks in the study area. Most of the bedrock underlying the western basin is Silurian and Devonian and was deposited as limy and dolomitic muds in shallow, epicontinental seas between 375 and 410 million years ago. Some Mississippian sandstones and shales are present in the immediate drainage area of the western basin, but these rocks have no actual bearing on the morphology of the basin itself. No evidence exists for the occurence of any sedimentary formations which date from Mississippian to Pleistocene in the area. A generalized stratigraphic section of the western basin of Lake Erie is given in Table III.

During Tertiary and early Quaternary time, it is believed that this portion of the Great Lakes was subjected to subaerial erosion by an extensive fluvial system known as the Erigans river system (Forsyth, 1973, p. 19). This pre-

Table II

Morphometric and Hydrologic Data for the Study Area [1]

Length (straight line)	48 miles
Breadth (right line)	40 miles
Water area	1,265 sq. miles
Drainage area (land)	11,300 sq. miles
Drainage area (total)	12,565 sq. miles
Water volume	5.8 cubic miles
Maximum depth	63 feet
Mean depth	24 feet
Average annual precipitation	33.7 inches
Mean outflow	200,661 cfs

[1] Combined area of the western and Sandusky basins; data from the Federal Water Pollution Control Administration, 1968, p. 21; Chandler, 1964, p. 62; and Limnos, 1972a, p. 10.

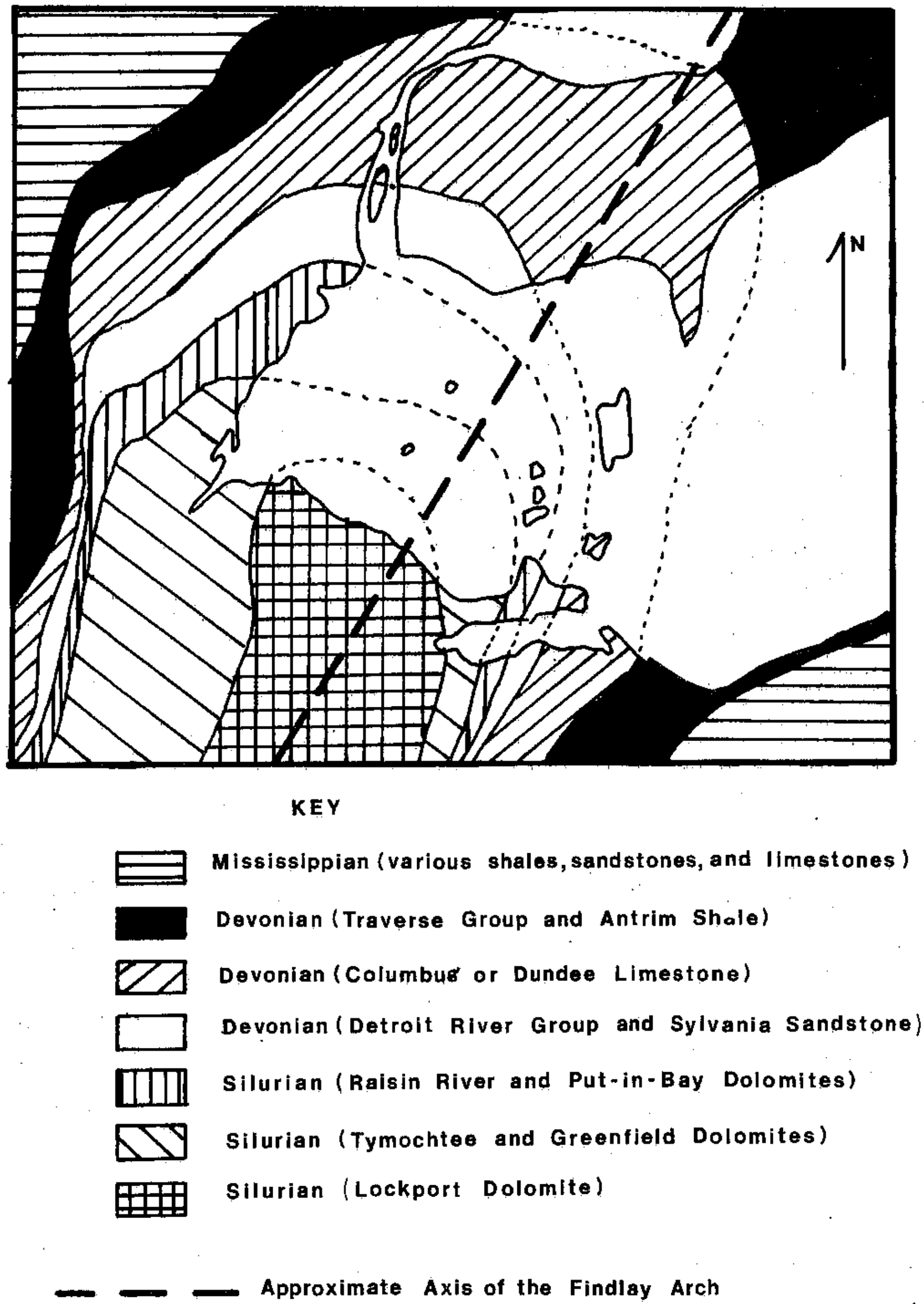

Figure 3. Geologic map of the western end of Lake Erie, with both Paleozoic rock distribution and the location of the Findlay Arch (Carman, 1946, p. 281; Hough, 1958, p. 28; Ehlers, _et al._, 1952, p. 7; and Herdendorf and Braidech, 1972, p. 11).

Table III. Generalized section for the Paleozoic rocks in the western Lake Erie area (after Herdendorf and Braidech, 1972, p. 10; and Ehlers <u>et al.</u>, 1952, p. 8).

System	Group	Formation	Lithology	Thickness
Mississippian		Berea Bedford	sandstone shale	10-50 0-150
Devonian		Ohio [1] Ten Mile Creek Silica Delaware Columbus [2]	shale dolostone shale limestone limestone	100 40 40 35 65
	Detroit River Group	Anderdon Lucas Amherstburg [3] Sylvania	dolostone dolostone dolostone sandstone	15-25 30-120 60-80 40
Disconformity				
	Bass Island Group	Raisin River Put-in-Bay	dolostone dolostone	40-60 35-60
	Salina Group	Tymochtee Greenfield	dolostone dolostone	100 50
		Lockport [4]	dolostone	200-450

[1] known as the Antrim Shale in southeastern Michigan

[2] Dundee Limestone in Michigan

[3] located in southeastern Michigan only

[4] also known as the Guelph Formation

glacial stream valley, with a long axis approximately parallel to the present day axis of Lake Erie, is largely responsible for the over 200 feet of bedrock relief in the western basin (Herdendorf and Braidech, 1972, p. 12).

The western basin is influenced by two major structural elements (Sly, 1976, p. 356). To the south, the Appalachian geosyncline seems to affect the general northeast orientation of the existing lake basin, while to the west, the basin is linked to another major structural feature by the Findlay Arch (Hough, 1958, p. 83). This arch (Figure 3) is the dominant structural feature of the western basin, upwarping the Lower Devonian dolomitic rocks in the area. The nearly north-south axis of the arch almost bisects the basin and plunges slightly to the northeast (Sly, 1976, p. 356). The alignment of this arch gives the overlying Paleozoic bedrock a slight eastward dip.

The bedrock in this area has had a profound effect on the formation and structure of much of the Lake Erie basin. According to Hartley (1962, p. 125), differential weathering of the bedrock controlled the predominant eastward drainage of the pre-glacial Erigans river system. Pleistocene glaciation followed this pre-existing drainage system (Forsyth, 1973, p. 16), and the resultant morphology of the bedrock and glacial deposits enables the lake to be physiographically subdivided into four separate basins.

In addition to the large-scale effects of the bedrock topography on the overall structure of Lake Erie, several other features in the western basin are also related directly to rock structure (Hartley, 1962, p. 125). For example , part of the shoreline of Lake Erie tends to parallel the strike of the underlying bedrock (Carman, 1946, p. 280). The headlands of Point Pelee and Marblehead and the island chain of Pelee, Middle, Gull, Kelleys, and Johnson's Islands all lie along the outcrop of the eastward-dipping Columbus Limestone, whereas Catawba, East Sister, Middle Sister, and the three Bass Islands lie along the outcrop pattern of the Bass Island Group, following a curved pattern induced by the northward plunge of the Findlay Arch (Hartley, 1962, p. 125). The west end and northwest corner of Lake Erie parallel this same outcrop line.

Hartley (1962) has reported that many small-scale structural forms lead to several features in shoreline configuration within the study area. Vertical joint systems in the Columbus Limestone at Kelleys Island have caused the formation of pronounced parallel alignment of bluff faces on the west side of Long Point. Minor thrust faulting has resulted in narrow inlets and embayments in many of the islands. In addition to these two instances, many other morphologic features are also related to structural causes in the western basin (Carman, 1946; Hartley, 1962).

GLACIAL GEOLOGY

The Lake Erie region had undergone a fairly simple history which lasted from the Mississippian, through the Mesozoic, and into Cenozoic time. However, this all changed when Pleistocene glaciation began to infringe on the area about one million years ago. The ice of the Kansan, Illinoian, and Wisconsinan glacial epochs proceeded to scour the western Lake Erie area, as well as the rest of the Great Lakes, into the basic shapes they possess today.

The modern Lake Erie basin was formed "...by glacial erosion of a pre-glacial stream valley, a basin made deeper by the erosion of each successive advance of the ice" (Forsyth, 1973, p. 16). Glacial striae in northwest Ohio are almost parallel to the axis of the lake itself, being generally oriented northeast-southwest. The similar orientation of the glacial striae and Lake Erie basin reinforces the theory that the pre-glacial stream valley governed the direction of the ice flow of the Erie glacial lobe, at least during later Wisconsinan time (Forsyth, 1966, p. 202). Of the five Great Lakes, Lake Erie was eroded the least by this glaciation due to the relative thinness of the ice over the area (Forsyth, 1973, p. 16). In fact, the lake is so shallow, with an average depth of only 60 feet (Federal Water Pollution Control Administration, 1968, p. 1), that it is the only Great Lake whose entire water mass lies above sea level (Hough, 1958, p. vii; and Federal Water Pollution Control Administration, 1968, p. 5).

Wisconsinan glaciation obliterated most pre-existing till deposits from the western basin as it moved over the area (Federal Water Pollution Control Administration, 1968, p. 11). During the ablation of the Erie glacial lobe, a new series of glacial tills were deposited (Dorr and Eschmann, 1970, p. 161). A few end moraines, as well as some outwash sands and gravels, were also constructed during pauses of the glacial retreat, although none are present in northwest Ohio. The median diameter of the particles in these Wisconsinan tills is 0.027 millimeters, with a standard deviation of 4.73 millimeters (Benson, 1971, p. 15). Using Shepps' (1953) glacial-texture data, Benson (1971, p. 6) calculated that the tills in the western basin area are Early Cary in age. This corresponds well with the report of Dorr and Eschmann (1970, p. 161), as well as Goldthwait _et al._'s (1961) glacial map of Ohio; both of which state that all tills located in the western Lake Erie area are Cary, or early Wisconsinan, (16,000-13,500) in age.

The matrix of the till is made up of varying proportions of sand, silt, and clay, with clay predominant in northwest Ohio. In general, mineralogical and grain-size analyses indicate that the till is relatively uniform in composition throughout the study area, although some local variations are present. Benson (1971, p. 30) reports that tills in the island area average approximately 40% silt and 30% clay-sized particles. However, the matrix tends to be very sandy at certain locations. High-sand content in the tills is common in Monroe County (southeastern Michigan) due to the influence of the friable Sylvania Sandstone (Mozola, 1970, p. 8). Coakley (1972, p. 331) reports that sandier tills, which contain about 40% sand and gravel, 40% silt, and 20% clay, are also present between Kingsville and Leamington in southwestern Ontario.

Because of its textural immaturity, grain size in these glacial deposits range from boulders (>256 mm) to clay (<0.0039 mm). The boulders, cobbles, and pebbles present in the till are igneous, metamorphic, and sedimentary in nature. Because the local bedrock is mostly composed of limestone and dolostone, the dominant clasts in the gravels are composed of carbonate rocks, whereas only 5 to 10% of the clasts are non-sedimentary in nature (Forsyth, personal communication, 1977). In a rare exception to this rule, Dreimanis et al. (1957, p. 153) reports the presence of black shale fragments in the tills of southwestern Ontario. The presence of these shale clasts is stratigraphically dependent upon the occurence of Devonian shales cropping-out in the nearby area. In some areas of Monroe County, the tills contain a very high percentage of small pebbles. These inconsistent till zones are termed "hardpan" by drillers because of the extreme difficulty of penetrating this layer (Mozola, 1970, p. 7). Non-sedimentary erratics, which range in size from pebbles to boulders, are also present in the till. Aside from the rock fragments and erratics, the finer fraction within the tills contains quartz, calcite, dolomite, feldspar, illite, kaolinite, chlorite, and minor amounts of mixed-layered clays (Benson, 1971, p. 30), as well as various heavy minerals.

Till deposits in the western basin area vary in color from blue-gray to pink (Hartley, 1961, p.7). Most of the till is blue to blue-gray, but due to oxidation, the tills change to a dull yellow-brown color in the near-surface weathering zone. The depth of oxidation (discoloration) varies depending upon topography and drainage (Hartley, 1961, p. 7). In northwest Ohio, the depth of oxidation is ±12 feet (Forsyth, personal communication, 1977). The density (compaction) of the tills is high due to clay content, but variations do occur, depending on the degree of oxidation. For the most part, unweathered tills are the densest in most samples, whereas weathered tills are generally least dense.

Using core data, Hartley (1961, p. 7) reported till covering two-thirds of the lake bottom with an average thickness of ten feet and a maximum of 68.5 feet. However, the thickness of the till varies widely due to the topography of the bedrock in the western basin of Lake Erie. Glacial deposits are nearly uniform in the western half of the western basin, whereas till occurence is scanty and thin in the island area.

In the drainage basin of western Lake Erie, till thickness varies widely. In Monroe County, glacial deposits range from a few inches to over 150 feet (Mozola, 1970, p. 7). Till bluffs in southwestern Ontario range up to 75 feet in height (Coakley, 1972, p. 331), whereas till thicknesses in northwestern Ohio vary from zero to over 130 feet in accumulation (Nielsen, 1977, p. 33).

Tills are one of the primary sources of fine-grained sediment to the western basin of Lake Erie. Carter (1977, p. 7) reports that about 9.6×10^8 kilograms of silt and clay-sized sediment per year enter the western basin due to erosion of nearshore-till bluffs, as well as 1.75×10^8 kilograms of sand and gravel-sized material. Of the fine-grained sediment, over 54%, or 5.2×10^8 kilograms, is derived from the Michigan shoreline (Carter, 1977, p. 7). In addition to erosion of shoreline bluffs, rivers in the drainage basin are constantly eroding glacial deposits and transporting material. According to Kemp (1975, p. 372), the Maumee River, which drains a combination lake-till plain over almost its entire length, contributes about 1.8×10^9 kilograms of fine-grained, till-derived sediment to the western basin every year. Some of the Detroit River's input of 1.4×10^9 kilograms of fine-grained sediment per year (Kemp, 1975, p. 372) is probably derived from the erosion and subsequent transportation of till material in the drainage basins of the Upper Great Lakes.

According to Forsyth (1973, p. 17), the first of a series of narrow, marginal lakes was formed as the final Wisconsinan glacial lobe retreated from the Fort Wayne End Moraine. These ice-marginal lakes were too short-lived for any significant amounts of bottom sediments to accumulate, although some sandy deltaic deposits are present (Heffner et al., 1965, Ohio Division of Lands and Soil, 1959, 1961, and 1963)..Forsyth (1969, p. 61) has proposed that two or three of these small lakes were formed just north of Lima, Ohio, and that the highest of these lakes had an elevation of about 850 feet. Although these lakes were formed following the retreat of glacial ice, they occurred prior to the formation of glacial Lake Maumee I (Forsyth, 1973, p. 18), which was the first of the classic, Erie basin, post-glacial lakes (Leverett, 1902; Leverett and Taylor, 1915; and Hough, 1958).

In addition to the earlier marginal lakes, erosion was also prevalent in the western Lake Erie area. Tills that were subjected to this erosion were winnowed of their finer components, resulting in the formation of lag or residual sand and gravel deposits on top of the glacial tills. Compositionally, this reworked till is very similar to the underlying glacial material, with the exception of higher concentrations of mixed-layer clays (Benson, 1971, p. 31). The zones of residual coarse materials are especially common in the Pelee-Lorraine Moraine south of Point Pelee (Thomas et al., 1976, p. 387), as well as in various offshore locations.

Lake Maumee I was the first of a series of at least thirteen post-glacial lakes that were formed in the Erie area (Table IV). The lake was bordered on the northeast by the glacier itself, which was still covering the present-day, northeastern part of the Lake Erie basin, and extended south to Van Wert and Findlay (Forsyth, personal communication, 1977). The surface of this lake was about 800 feet above present sea level, and the drainage was westward into the Wabash River in Indiana due to the fact that glacial ice still blocked any eastward drainage outlet (Federal Water Pollution Control Administration, 1968, p. 11). According to Leverett (1902), Leverett and Taylor (1915), Hough (1958), Forsyth (1959),

Table IV. Major Pleistocene lake levels of the Erie basin in Ohio (after Forsyth, 1959, 1966, 1971, and 1973; Lewis, 1966; Hough, 1958; and Dorr and Eschmann, 1970).

Lake Name	Average Elevation (ft.)	Outlet
Modern Erie	570	Niagara River
Early Erie -Great Flood (12,500 BP)	420	Niagara River
Erie (Early Algonquin)	605?	Huron Basin ?
Lundy (Elkton beach)	620	West to Lake Calumet and the Mississippi River
Lundy (Dana beach)	620	West to Lake Calumet and the Mississippi River
Lundy (Grassmere)	640	Mohawk River, or west to Lake Glenwood and the Mississippi River
Warren	680-665	Grand River, Michigan
Wayne	660	Around the north end of the Lower Peninsula of Michigan
Warren	690	
Whittlesey (12,900 BP)	735	Grand River, Michigan, via Ubly
Arkona	710-690	Grand River, Michigan
Maumee III	780	Wabash River, Indiana
Muamee II	760	Grand River, Michigan, via Imlay
Maumee I (present only in western lake basin)	800	Wabash River, Indiana

and Dorr and Eschmann (1970), at least twelve other post-glacial lakes (after Maumee I) occupied the same approximate area of present-day Lake Erie and the area south of it. The locations and elevations of these lakes varied due to the continuing changes in the position of the glacial ice and the available drainage outlets. Most of the lakes drained westward with one major exception, that of Early Lake Erie (Hough, 1958, p. 161; and Lewis et al., 1966, p. 176).

The post-Wisconsinan glacial lakes deposited silty-clay materials which were probably derived from reworked glacial tills. Where glaciolacustrine clays and glacial tills were exposed to erosional energy within the post-glacial lakes, the deposits are capped by a lag sand ranging from one to five inches in thickness (Thomas et al., 1976, p. 389). These glacial-lake sediments have been found to cover most of the western basin (except for the island area) and surrounding drainage basin, and thicknesses range from a few inches to over thirty feet in the Maumee Bay area (U.S. Army Corps of Engineers, 1974, p. 64). Mineralogically, the zone is very similar to the underlying till, except that there are more mixed-layer clays and less chlorite and illite than in the till (Benson, 1971, p. 32).

Aside from the influence on the extent and elevation of the post-glacial lakes, the Erie glacial lobe affected the Lake Erie basin by continuing to retreat and advance in the area. General retreat with minor re-advances from 14,000 to 13,000 years ago caused the construction of the Pelee-Lorraine and Erieau Moraines, as well as the Port Maitland Moraine (Sly, 1976, p. 359). About 13,000 years ago, the ice re-advanced into the eastern basin and formed the Norfolk Moraine, as well as re-excavating the eastern part of Lake Erie (Sly, 1976, p. 359).

About 12,500 years ago, ice which blocked the eastward drainage of the glacial lakes retreated enough to allow a tremendous outlet flow over the still-isostatically low Niagara Escarpment (Thomas et al., 1976, p. 389; Lewis et al., 1966, p. 176; and Sly, 1976, p. 359). The drainage into the Ontario basin, now known as the Great Flood (Forsyth, 1973, p. 22), lowered the level of Early Algonquin Lake Erie to about 490 feet (Lewis, 1969, p. 250), leaving only two very shallow and extremely small residual lakes in the central and eastern basins (Forsyth, 1973, p. 22). These two inter-connected lakes have been termed Early Lake Erie by Hough (1966, p. 104) and Lewis et al. (1966, p. 189), although Forsyth (1971, p. 15) has called the entire feature a "spec-tacle lake." The formation of this Early Lake Erie is significant to the history of the area primarily because it marked the end of glacial influence in the Erie basin (Sly, 1976, p. 361).

During the existence of Early Lake Erie, the western basin was completely drained, with the exception of a few ephemeral ponds and marshes (Herdendorf and Braidech, 1972, p. 16), as well as some extended consequent rivers. This relative draining of the western basin is directly related to the dissection of the bedrock in this area, due to the fact that the Devonian and Silurian rocks were only slightly eroded by the glaciers that extended over the western basin area. Areas of sand lags, peat, plant detritus, bivalve, gastropod, and ostracod shells are a remnant of this marshy period (Lewis et al., 1966, p. 177). The sudden drop in lake level brought the surface of the glaciolacustrine silts and clays above water level (Hartley, 1961, p. 8), and the subsequent de-watering of the sediments probably caused the very high degree of compaction that tends to characterize these lacustrine deposits (Benson, 1971, p. 7).

A highly-compacted, organic-rich zone marks the boundary between glaciolacustrine and modern Lake Erie sediments. Herdendorf and Braidech (1972, p. 16) proposed radiocarbon dates ranging from 4,335 to 9,440 years before present for this layer, which indicates a much later date for the flooding of the western basin than was previously proposed by Lewis et al. (1966). When the range of dates is considered, it is possible that the western basin was dry, with the exception of a few shallow ponds and marshes, for more than 8,000 years. In the western basin, this dark, spongy, highly-compacted, plant-detritus zone occurs about three to fifteen feet below the present-day sediment-water interface, and ranges from one to three inches in thickness (Lewis et al., 1966, p. 179).

From 12,500 to 8,500 years ago, the isostatically low Niagara Escarpment rebounded due to the release of glacial-ice pressure (Lewis, 1969, p. 250). Because of this isostatic rise in elevation, the water level of Lake Erie began to rise and expand over the low drainage area around the basin (Forsyth, 1973, p. 22). According to Lewis (1969, p. 250), this rise in water level was fairly consistent until a slow decrease occurred between 8,500 and 4,000 years ago. According to Forsyth (1973, p. 22), this decrease in the steady rise of Lake Erie water level occurs at about the same time as Sears' (1942, p. 708) Xerothermic Interval, which was the warmest and driest part of the Hypsithermal Interval proposed by Ogden (1965, p. 481). This arid period provided too little precipitation and/or too much evaporation for the water level of Lake Erie to rise as fast as it had been rising, although isostatic rebound continued in the vicinity of the Niagara Escarpment (Forsyth, 1973, p. 23).

Following this slack interval, a period of rapid rise in water level took place from 4,000 to 3,500 years ago (Forsyth, 1973, p. 23). As the water level rose, the lake began to expand into the western basin. When lake level reached 540 feet about 3,000 years ago, water began to penetrate around the bedrock hills that are now known as the Erie Islands (Forsyth, 1973, p. 23). Modern Lake Erie, which was the first of the Great Lakes to be formed (Federal Water Pollution Control Administration, 1968, p. 5), still has a rising water level, which has been calculated to be somewhat less than one inch per century in the entire lake basin (Forsyth, 1973, p. 23).

Much of southeastern Michigan, southwestern Ontario, and northwestern Ohio are covered by the lake plain that was formed due to the presence of the post-glacial lakes (Figure 4). Although these sedimentary deposits are mostly fine-grained in nature, Vagners (1971, p. 102) has reported the presence of several areas of very sandy glaciolacustrine deposits in the proximity of Colchester, Leamington, and Kingsville in southwestern Ontario, as well as both on and south of the Pelee Peninsula. These sandier deposits may be the result of Devonian bedrock highs in the area. Several sand ridges are present on the lake plain that covers the western Lake Erie-drainage basin. In northwest Ohio, these ridges formed as beaches along the margins of glacial Lake Warren about 13,000 years ago, as well as in the middle of the lake as offshore bars (Forsyth, written communication, 1977). However, these sandy deposits are not related to the sandy glaciolacustrine sediments in southwestern Ontario. In addition to these sand bodies in northwestern Ohio, Mozola (1970, p. 8) and Sly (1976, p. 361) have reported the presence of several poorly defined, water-deposited end moraines in Monroe County and southwestern Ontario, respectively.

Drainage Basins and Tributary Supplies

The immediate drainage basin of western Lake Erie covers an area of about 11,300 square miles in Ohio, Michigan, Indiana, and Ontario (Figure 5). The Maumee River is the largest river in the basin (excluding the Detroit River) in terms of both average water supply (4794 cubic feet per second) and

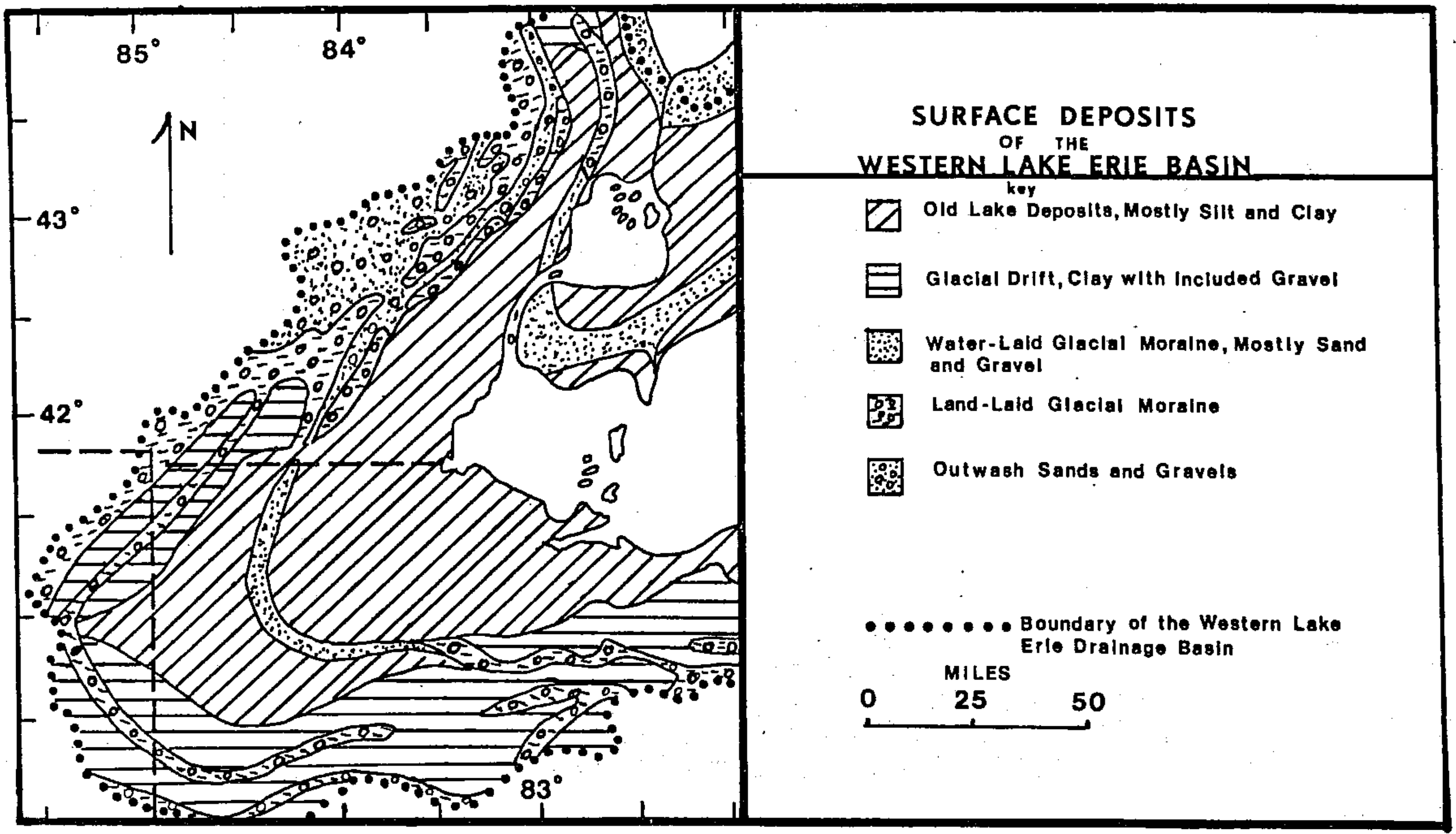

Figure 4. Surficial glacial deposits in the drainage area of the western basin (Dorr and Eschmann, 1970, p. 160; and the Federal Water Pollution Control Administration, 1968, p. 12).

area (6586 square miles), according to the Federal Water Pollution Control Administration (1968, p. 27). The remaining rivers, which cover a total drainage area of about 4,700 square miles, are relatively minor due to their small water discharges. This is especially the case in southwestern Ontario (the St. Clair Clay Plains), where the topography is extremely flat and drained only by a few minor creeks (Ongley, 1976, p. 472). Table V lists the areas of the various drainage basins in the western Lake Erie area, as well as the percentage of precipitation that becomes runoff in each stream basin.

The rivers in the Ohio section of the western Lake Erie drainage basin are similar in all respects except for average water flow. The Maumee, Sandusky, Portage, and Toussaint Rivers all drain highly agricultural and cultivated areas. Runoff into these rivers is relatively low (28 to 29%) due to the flat topography and the compact, semi-permeable clay soils in northwest Ohio (Federal Water Pollution Control Administration, 1968, p. 26). The important streams in Michigan, on the other hand, are all polluted tributaries which pass through highly urbanized and industrialized areas. The Huron and Raisin Rivers both drain rather flat basins which have the lowest precipitation and runoff values for any portion of Lake Erie (Federal Water Pollution Control Administration, 1968, p. 28). In addition, the Huron River is fed by several small natural lakes, while the Raisin is not.

Table V. Drainage-basin areas of western Lake Erie (Federal Water Pollution Control Administration, 1968, p. 27; Herdendorf and Braidech, 1972, p. 8; and Ongley, 1976, p. 478).

River	Area (square miles)	Runoff [1]
Huron	890	27
Raisin	1,125	28
Maumee	6,586	29
Portage	587	28
Toussaint	108	28
Sandusky	1,421	28
Rouge	467	22
Southwest Ontario [2]	116	-
Total	11,300	

[1] percentage of precipitation that becomes runoff in each river's drainage basin.

[2] includes the Sturgeon, Cedar, and Big Creeks

The lower few miles of all the streams in the western basin area are extremely sluggish, due to lake effects. In addition to dredging for navigational purposes, the Raisin River is additionally sluggish due to the presence of several dams near its mouth, which have been constructed in the last few years (Federal Water Pollution Control Administration, 1968, p. 28).

Over 90% of the water supply for the western basin is derived from drainage in Lakes Superior, Michigan, Huron, and St. Clair (Table VI). Although great variations occur in the discharge from these northern lakes, it is still the most uniform of the tributary drainages to Lake Erie (Federal Water Pollution Control Administration, 1968, 24). The actual drainage area of these four lakes is 151,190 square miles in land area, and 77,180 square miles in water-surface area (Table VI). In addition to the outflow from the Upper Great Lakes, the Black, Pine, Belle, Clinton, Rouge, and Thames Rivers all contribute significant amounts of water to western Lake Erie. The outflow from these rivers (Table VII) and the Upper Great Lakes exerts a strong dilutional influence on the western basin, with an average water supply of 193,401 cubic feet per second, or 94.47% of the total basin supply (Federal Water Pollution Control Administration, 1968, p. 34).

The inflow from the Maumee and Detroit Rivers influences the western basin to a much greater extent than the input of the other minor streams and creeks, as well as precipitation and runoff, in the drainage basin. Combined, these two rivers

Table VI. Drainage basins of the Upper Great Lakes (Federal Water Pollution Control Administration, 1968, p. 2).

Lake	Land Area (sq. miles)	Water Area (sq. miles)
Superior	49,180	31,820
Michigan	45,460	22,400
Huron	49,610	23,010
St. Clair	6,940	490
Total	151,190	77,180

Table VII. Water supply to western Lake Erie (Federal Water Pollution Control Administration, 1968, p. 34).

River System	Avg. Water Supply (cfs)	% Total Lake Erie Supply	% Western Basin Supply
St. Clair (Lake Huron outflow)	187,450	79.744	91.562
Black, Pine, Belle	688	.293	.336
Clinton	470	.200	.230
Rouge	235	.100	.115
Thames	1,840	.783	.899
Misc. Runoff	1,799	.776	.879
Precipitation (Lake St. Clair)	919	.391	.449
Subtotal (Detroit River)	193,401	82.307	94.470
Huron (Michigan)	556	.237	.272
Raisin	714	.304	.349
Maumee	4,794	2.040	2.342
Portage	403	.172	.197
Sandusky	1,021	.435	.499
Misc. Runoff	1,271	.541	.621
Precipitation (western basin)	2,564	1.091	1.252
Subtotal (western basin)	11,323	4.820	5.530
Overall Totals	204,742	87.127	100.000

provide 96.81% of the average water supply to western Lake Erie. Because of their large size and water influx, great amounts of sediment are transported by the Maumee and Detroit Rivers, both in suspension and as bedload. The subsequent sediment plumes of the two rivers dominate the bottom deposits of the western basin. The locations and compositions of the sediment plumes as well as further information concerning the Maumee and Detroit Rivers will be dealt with later in this thesis.

Lake Levels, Precipitation, Runoff, and Evaporation in the Western Basin

The water level of Lake Erie varies over short periods of time due to such phenomena as winds, seiches, and lunar and solar tides.. In addition, lake levels also show changes in storage if the levels are averaged over long periods of time. These changes in storage normally reflect precipitation fluctuations over both western Lake Erie and the Upper Great Lakes (Federal Water Pollution Control Administration, 1968, p. 33).

Water levels have been measured by the U. S. Lake Survey, Army Corps of Engineers, since 1860. The mean level for a 110 year test period (1860 to 1969) was 570.4 feet above sea level. The highest average monthly level recorded was 572.8 feet in May of 1952, whereas the lowest monthly average level was 567.5 feet in February of 1936. This represents a change between minimum and maximum lake levels of 5.3 feet - almost nine per cent of the lake's average depth (Federal Water Pollution Control Administration, 1968, p. 33).

The highest and lowest average monthly levels of Lake Erie normally occur in June and February, respectively. The seasonal variation typically ranges from one to two feet. The average monthly levels of the western basin over a period of nineteen years is shown in Figure 6 (Brunk, 1964, p. 207).

Lake level is presently 572 feet above sea level (Forsyth, personal communication, 1977), but this is highly variable, depending on wind direction and seiche effect. Water levels have a greater range of fluctuation at the east and west ends of the lake (Toledo and Buffalo). High water levels coupled with northeast storm winds have produced a maximum fluctuation of 7.1 feet above low water datum at Toledo. Conversely, low levels and southwest winds have lowered the level of the lake to 7.5 feet below datum, which results in a range of 14.6 feet (Herdendorf and Braidech, 1972, p. 21). These wind tides are probably the most common and influential short-term oscillations that affect the western basin. Sun and lunar tides are negligible, resulting in a maximum fluctuation of only 0.11 feet (Verber, 1960, p. 78).

Water levels in the western basin have risen an average of 50 to 60 centimeters over the past 100 years (Lewis, 1969, p. 268). This rising water level is closely associated with the isostatic rebound of the Erie-basin area due to the removal of glacial ice. This effect has been caused by the thickness

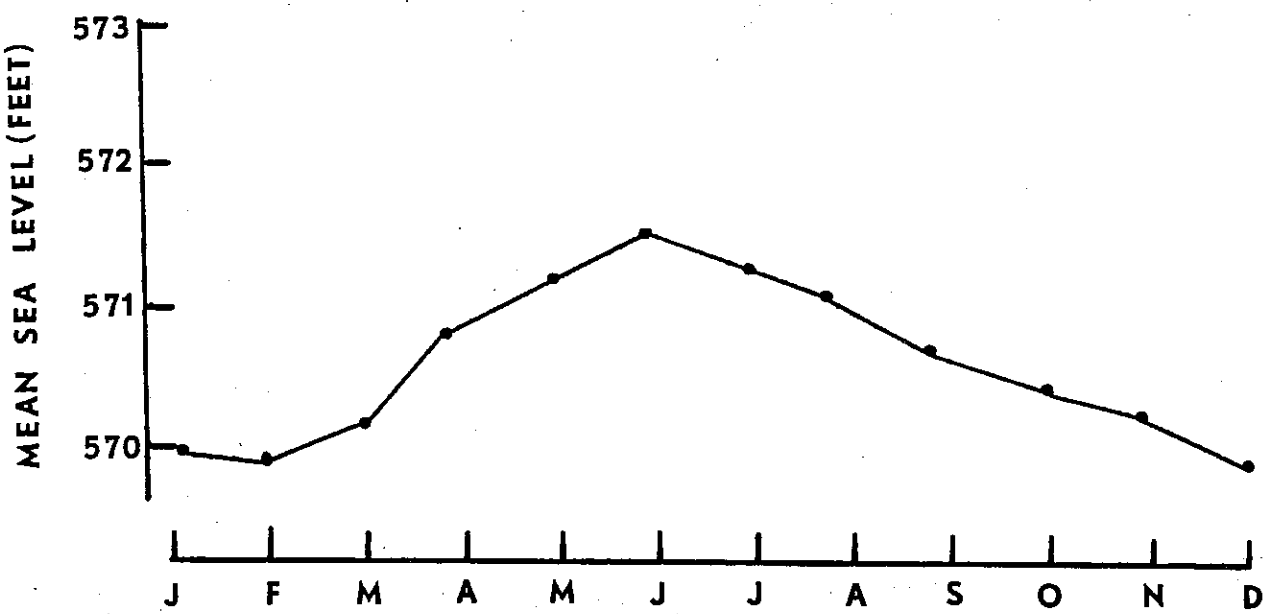

Figure 6. Average levels of Lake Erie from 1940 to 1959 (Brunk, 1964, p. 207).

of the Pleistocene ice sheet, which tended to increase from south to north. The increasing thickness caused varying isostatic depression in the area, and the subsequent glacial retreat caused the areas previously covered by thicker ice to rebound more than those areas covered by thinner ice. This is the case in the Erie basin, where the northern (Canadian) side of the lake is rising more rapidly than the southern (American) side of the lake. This results in a "tilting" of the lake basin, which is closely related to nearshore bluff erosion (Coakley and Cho, 1972, p. 345). Although no noticeable trend is apparent in lake-level records over the past 100 years, the presence of modern, underwater peat deposits offshore of Monroe, stalactites in submerged caves in the Bass Islands, and the abundance of drowned river valleys along the Ohio shore are sufficient evidence of the long-term trend of rising water levels (Liu, 1970, p. 360). The fact that the lake basin is tilting is reinforced by the location of these features, which are all in the southern or down-tilted section of the western basin.

Due to current flow, water in the basin is constantly being flushed into the central and Sandusky basins. Most of this outflow is through the Pelee Passage, although some outflow does occur in the inter-island area, especially in the South Passage (Simons, 1976, p. 384). Burns (1976a, p. 523) has calculated that the mean water-residence time for the western basin is about 0.2 years, which is the lowest for any portion of the Great Lakes.

Precipitation in the western Lake Erie drainage area ranges from 36 to less than 29 inches per year (Sanderson, 1966, p. 276). Rainfall is greatest in the headwaters of the streams that feed the western basin, and decreases the closer one gets to the lake itself. Jones and Meredith (1972, p. 480) calculated lake/land precipitation ratios for both the Canadian and American sides of the Erie basin. These figures are 1.0143 and 0.8644, respectively. Using these figures, the average precipitation for the western basin-drainage area can be calculated. The Federal Water Pollution Control Administration (1968, p. 16) measured the mean rainfall at Put-in-Bay, Ohio, to be 28.99 inches per year, and combined with the lake/land ratio for the American side of the western basin (0.8644), an average precipitation rate of 33.54 inches per year can be postulated. This figure agrees very well with the proposed rainfall average of 33.78 inches per year reported by Limnos (1972a, p. 10).

Of this rainfall, less than 30% becomes runoff into the streams feeding the western basin (Table V). Runoff parallels the aforementioned precipitation patterns with greater values occurring farthest from the lake in the headwaters of the tributary streams. Jones and Meredith (1972, p. 497) proposed that this runoff into Lake Erie is 0.88 cubic feet/second/square mile of surrounding drainage land.

Precipitation on the water mass of western Lake Erie is negligible due to the effect of evaporation. In fact, a slight deficit in the water budget occurs, because rainfall in the basin is less (28.99 inches per year) than the average evaporation rate of 35.52 inches per year (Jones and Meredith, 1972, p. 491).

Water Circulation

The Detroit and Maumee Rivers contribute over 96% of the water supply to the western basin of Lake Erie. As these rivers enter the basin, the size and velocity of their water masses controls the initial distribution of water and the subsequent deposition of sediments and effluents in the area. In an effort to determine the location and extent of these fluvial plumes, Walters and Herdendorf (1975) analyzed numerous core and grab samples from the western basin for variations in heavy-metal concentrations. Using mercury occurences in sediments deposited since 1939, Walters and Herdendorf (1975) constructed a map of sedimentation rates for the western basin (Figure 7).

After studying this map, the plumes of the Detroit and Maumee Rivers can be readily distinguished and their basic flow patterns identified. The Detroit River water mass flows southeast after it leaves the protection of its banks, splitting into two separate flows at about $41^{\circ}57'$ north latitude. This split agrees well with the proposed current bifurcation (Hough, 1958; Hartley et al., 1966; and the Federal Water Pollution Control Administration, 1968) in this part of the lake. The Maumee plume is seen to be a coast-hugging feature which

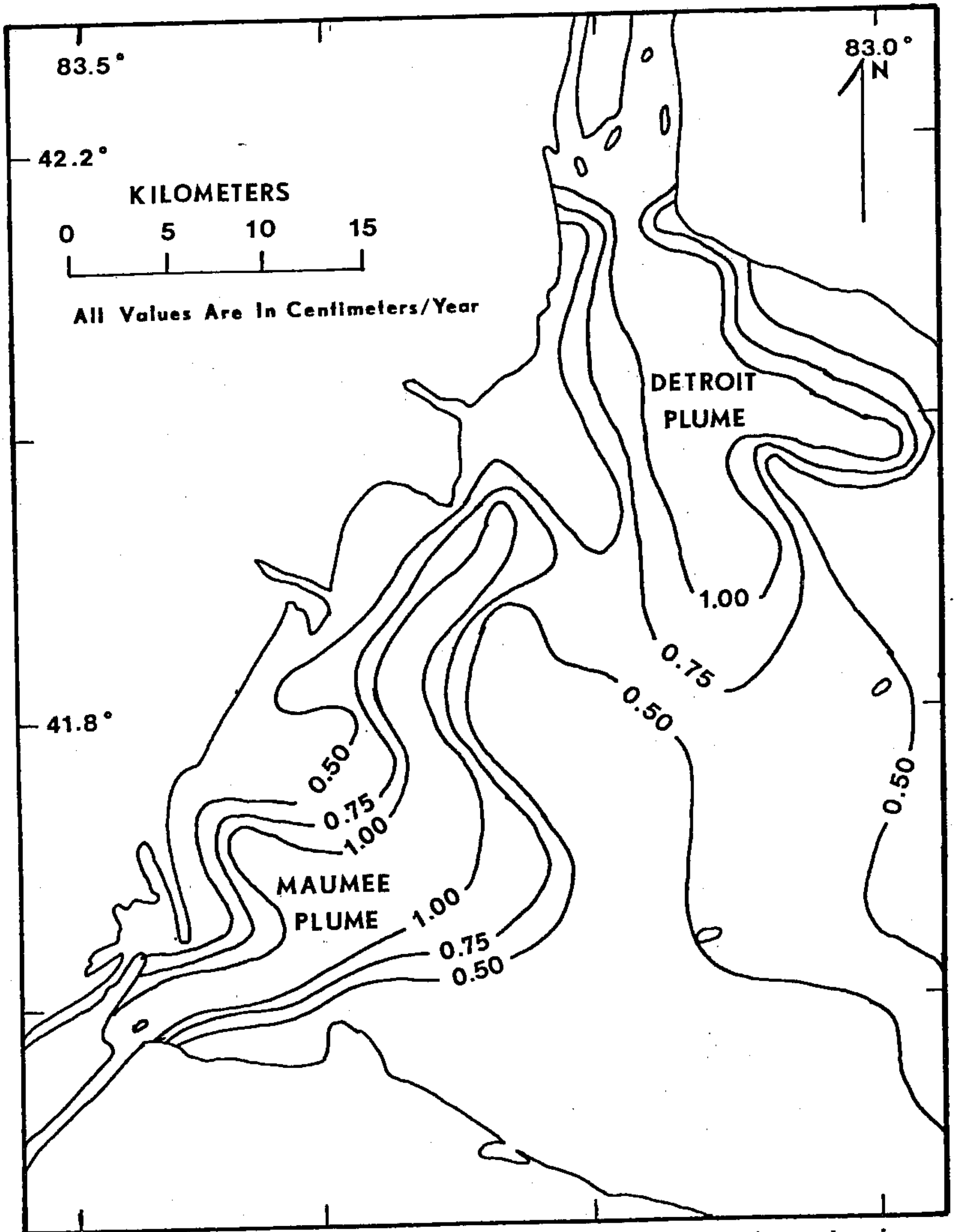

Figure 7. Map of sedimentation rates in the western basin based on mercury concentrations (Walters and Herdendorf, 1975).

stays near the Michigan shore.

Przywara et al. (1977) plotted several chemical parameters for the sediments of the western basin. Their results correspond well with the fluvial plumes proposed by Walters and Herdendorf (1975). Results obtained from grain-size and heavy-mineral analyses of sediments from western Lake Erie pertaining to the presence of these sediment channels will be discussed later in this thesis.

In the western half of the western basin, the water masses exiting the Detroit and Maumee Rivers control the circulation and dispersion of water and sediment. However, after the initial effect of these two fluvial bodies has dissipated and become insignificant, water and sediment circulation in the remainder of western Lake Erie is primarily controlled by wind-related currents. Two main types of currents are present in the western basin: surface and bottom. Surface currents have a relatively minor effect on the distribution of sediments in the basin; their patterns will be analyzed in detail because there is a strong correlation between the surface water flow and the bottom currents.

Harrington (1895) first attempted to interpret the surface currents of the western basin. He originally deduced the bifurcating currents of the Detroit River water mass, as well as the surface-current flow around Pelee and Kelleys Islands. Olson (1950) separated the western basin into seven different water masses, each with a specific drift pattern. Wright (1955) drew no definite conclusions, but discovered that the surface currents are not constant due to the fact that they are highly dependent upon prevailing winds. Verber (1953a, 1953b) concluded that a rotational movement of water existed in the western basin of Lake Erie. Besides also correlating wind movement and surface flow, Verber (1953a, 1953b) calculated that the average current velocity in open lake water was about 6.5 miles per day (0.4 feet per second). Numerous other surficial current studies have also been made, with varying results and conclusions.

Due to its large size and tremendous influx of water into the western basin, the movement of the water mass of the Detroit River and its effects upon western Lake Erie have been the most studied and understood of all the rivers in the Great Lakes. Using synoptic vector methods, O'Leary (1966) analyzed the flow of water from the Detroit River as it entered the western basin. He also documented the effects of various wind directions on the Detroit water mass. Kovacik (1972a, p. 81), using data acquired due to an accidental salt spill at Detroit, proved that some Detroit River water flowed south to a position very close to the northwestern Ohio shore with an average velocity of slightly less than 0.3 feet per second.

Probably the most accurate and efficient current analyses was performed by the Ohio Division of Natural Resources, Division of the Geological Survey, during the summer of 1967. This study was conducted on a physical limnology cruise and the resultant information has been compiled by Herdendorf (1970a). Current and wind direction studies were made along several profile lines, whose locations are given in Figure 8. Most of the following discussion concerning surface flow in the study area is drawn from the limnological data of Herdendorf (1970a).

The resultant direction of all the Lake Erie surface-current measurements is towards the south-southwest at an azimuth of 192°, with an average velocity of 0.37 feet per second. In comparison, the average movement of the surface currents in the western basin is towards the southeast (121°) with an average velocity of 0.66 feet per second. The limnological data of Herdendorf (1970a) also illustrates the tremendous influence of the Detroit River on the current flow in the western basin. Wind and surface currents were measured simultaneously at 49 stations in Lake Erie. When the direction toward which the wind was moving was compared with the surface-current trend for each station, it was found that the average current flowed 16° clockwise to the direction of the wind. When 15 of these stations were omitted because of their proximity to the strong Detroit River inflow, it was discovered that the average direction of the surface currents was 28° clockwise to the wind direction. This 12° variation is due wholly to the influence of the Detroit River water mass on current movements in the western basin. In addition to these readings, it should also be noted that these current deflections are much less than the theoretical 45° clockwise deflection of surface currents from wind direction in the

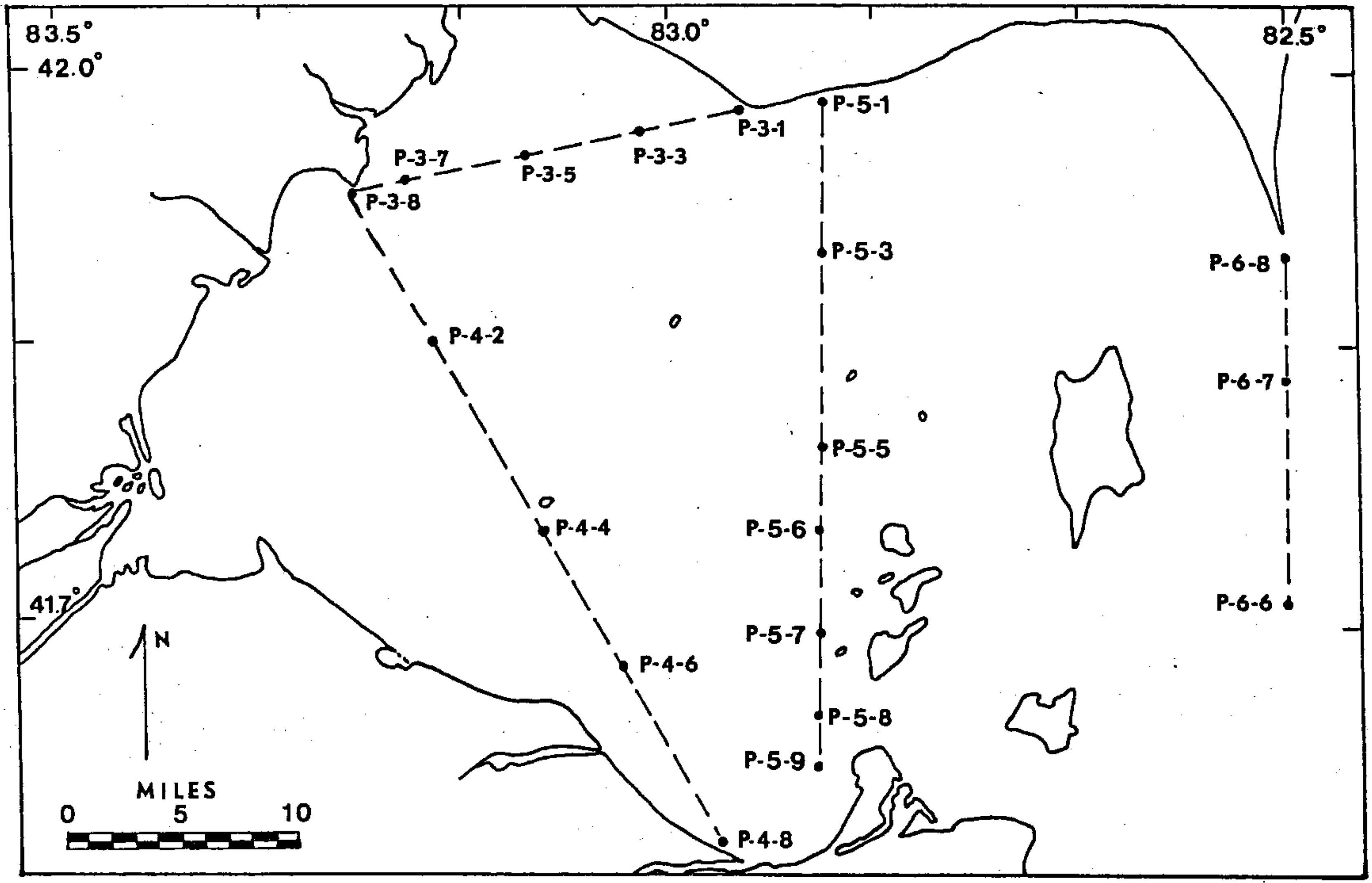

Figure 8. Profile locations for wind and current analyses conducted by Herdendorf (1970a, p. 4).

northern hemisphere (Donn, 1965, p. 431).

Table VIII lists the compass directions and velocities at the profile stations established during the limnological cruise. The Detroit River is the controlling factor for all the readings in profile 3, but measurements along profile 4, 5, and 6 illustrate the influence of northeast-moving winds on surface flow. The surface currents normally move with the wind, whereas bottom currents generally flow in the opposite direction, presumably as subsurface-return flow. The greatest surface velocities in the area were found northeast of Locust Point at P-4-6 (0.80 feet per second) and just west of Catawba Island at P-5-9 (0.50 feet per second). The lowest velocity was found south of West Sister Island at P-4-4 (0.10 feet per second). In a later in-depth study, Herdendorf and Braidech (1972, p. 84-89) also measured the average surface-water velocities in the island area and arrived at a figure of 0.47 feet per second.

Figure 9 shows the dominant movement of both surface and bottom currents in the western basin. As previously stated, however, the surface flow is extremely dependent upon wind direction, and therefore no one map can adequately cover all possible flow patterns. The Federal Water Pollution Control Administration (1968) has constructed maps which illustrate the dominant surface-current movements depending on wind direction. Herdendorf and Braidech (1972, p. 23) have accumulated data dealing with the average annual wind directions

Table VIII. Western Lake Erie surface-current measurements (Herdendorf, 1970a, p. 35).

Station Number	Number of Readings	Average Direction (compass°)	Average Velocity (feet/second)
P-3-1	4	317	0.29
P-3-3	6	170	0.29
P-3-5	7	204	0.29
P-3-7	5	233	0.27
P-3-8	4	360	0.36
P-4-2	7	207	0.30
P-4-4	7	262	0.10
P-4-6	3	262	0.80
P-4-8	3	66	0.32
P-5-1	6	191	0.43
P-5-3	8	148	0.42
P-5-5	7	250	0.48
P-5-6	7	96	0.44
P-5-7	7	92	0.40
P-5-8	6	179	0.41
P-5-9	5	210	0.50
P-6-5	9	140	0.37
P-6-7	8	148	0.48
P-6-8	4	147	0.48

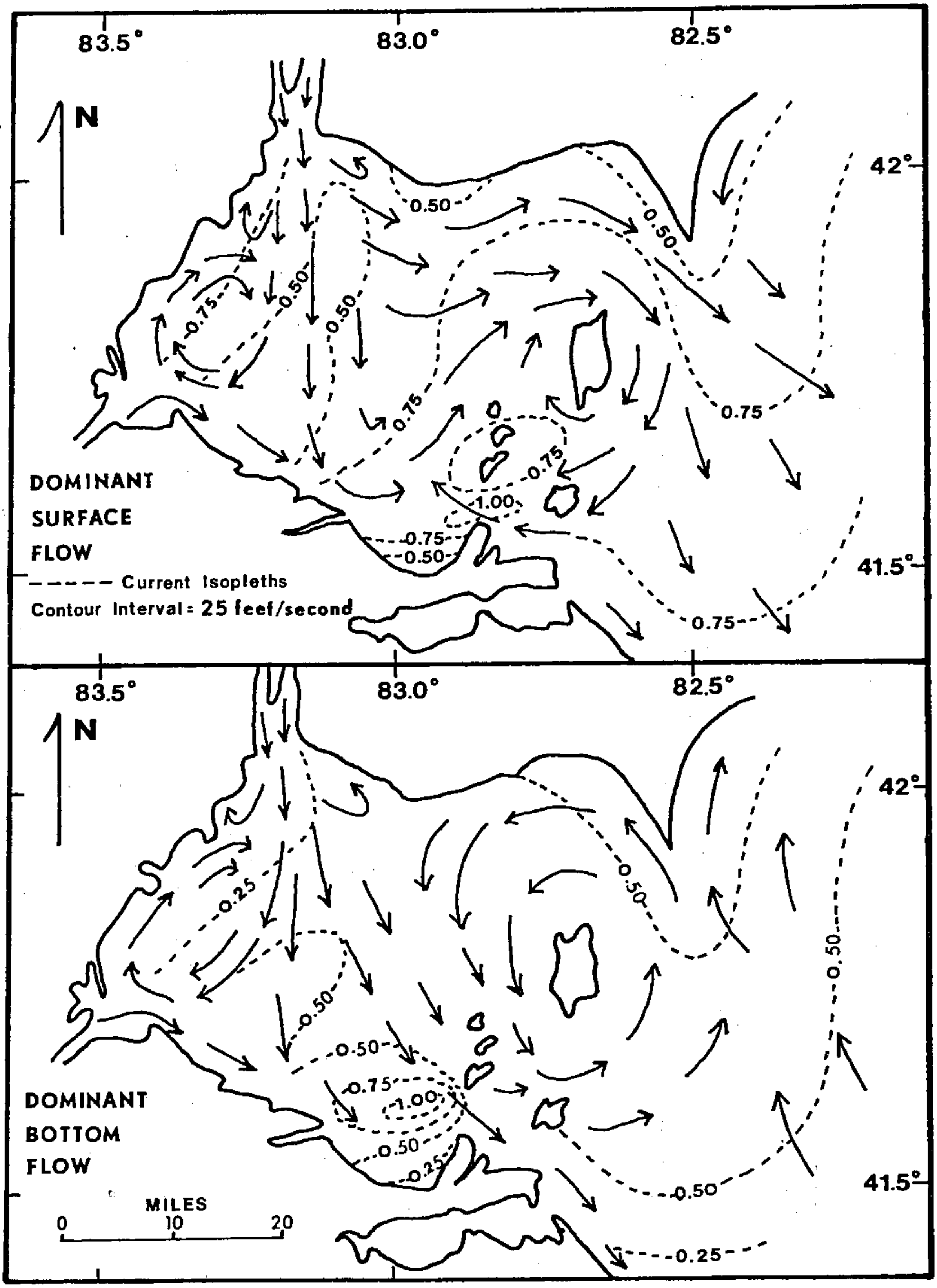

Figure 9. Dominant surface and bottom current flow in the western basin of Lake Erie, including velocity measurements (Federal Water Pollution Control Administration, 1968; Hough, 1958; and Herdendorf, 1970a).

and velocities over a period of several years in the vicinity of Sandusky, Ohio. Herdendorf (1970a, p. 36) also conducted an additional wind study which showed that the mean wind direction in the western basin is out of the southwest at an angle of 45° with an average velocity of 8.3 miles per hour. Although these southwest winds are dominant, six other wind directions are also prevalent, with occurences of thirty days or more.

In summary, the surface currents of the western half of the western basin are dominated by the Detroit River inflow. In the eastern half of the western basin, however, the surface flow becomes more influenced by the prevailing southwesterly winds. This effect produces the clockwise flow around the Erie Islands. The influence of the Maumee River water mass produces an additional clockwise current flow between Toledo and Monroe. Eddy effects along the sides of the Detroit River inflow, which tend to retain water, lead to sluggish movements of surface water west of Colchester, Ontario, and between Stony Point, Michigan, and Toledo. The effect of strong winds on surface circulation is to skim the surface water and move the water in the direction toward which the wind is blowing. One final note concerning surface flow should be made: in the winter, when the western basin is normally iced over, winds have no effect upon surface flow, and the water circulates according to its own dominant flow pattern.

Surface flow, though related, tells almost nothing about bottom circulation. In the summer, bottom currents in much

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of the western basin are similar to surface flow patterns, due to the dominance of the Detroit River inflow. In the island area, however, the bottom currents often flow in the opposite direction of the surface flow (Herdendorf and Braidech, 1972; Simons, 1976). Because of this fact, the bottom currents in the western basin tend to move around the islands in a general counter-clockwise pattern. In late August and into September, however, the bottom flow in the Pelee Passage reverses, and circulation becomes very similar to surface flow (Federal Water Pollution Control Administration, 1968, p. 60). Apparently, lake cooling is important in establishing a top-to-bottom uniformity of dominant circulation at this time of reversal of current directions. A dominant northwest bottom flow is indicated north of Toledo, and this is compatible with the clockwise surface movement in the Toledo-Monroe area.

Herdendorf (1970a, p. 34) has proposed that the mean bottom-current flow in the western basin is to the southwest (218°) with an average velocity of 0.39 feet per second. This velocity is not capable of eroding bottom material, but according to Hjulstrom's Diagram as modified by Postma (1967, p. 158), it is capable of transporting fine sands, silts, and clays once they have been placed into suspension. In addition, Herdendorf and Braidech (1972, p. 84-89) have intensely studied the currents of the island area and arrived at a bottom-current mean of 0.25 feet per second. This mean current velocity is not sufficient to limit the deposition of clay-sized particles within the reef area (Postma, 1967, p. 158). The greatest bottom velocities are found in the restricted areas within the island area, such as inter-island channels, bay mouths, and reef areas. Because the western basin is a high turbidity area (Hartley et al., 1966, p. 305), much sediment is subsequently being dispersed and deposited. During storms, the current velocities are undoubtably much greater, and the bottom currents are then capable of setting larger particles in motion and carrying them farther. Herdendorf and Braidech (1972) also constructed various maps showing bottom current responses to various wind directions, having measured surface, middle, and bottom-current velocities and directions at numerous points throughout the inter-island area. This study is very important due to the complex water and sediment movements in the island area.

Like surface currents, bottom flows can also be changed by prevailing winds, although it probably takes much stronger winds to do so (Federal Water Pollution Control Administration, 1968, p. 60). The most striking feature of this effect is that very strong winds from any direction normally drive surface currents downwind, whereas subsurface currents usually flow in the opposite direction as compensating return flow. This means, for example, that a very strong westerly wind will cause bottom currents to flow towards the west, whereas surface currents move eastward. The western basin water will normally exhibit these responses year-round during the ice-free periods. As previously stated, however, the reverse response of the bottom waters apparently lessens in the fall and winter due to water cooling and ice cover.

Current-meter data from five stations in western Lake Erie were reported by Herdendorf (1970a). The vector graphs illustrate the relationship of surface-to-bottom currents as well as the dominant wind direction at the time that the data was collected. Figure 10 shows these vector graphs, which were chosen because of their importance in describing water flow at various critical positions within the study area.

Station P-3-5 (Figure 10a) illustrates the effect of the Detroit River on lake currents. Flow from surface-to-bottom moves south-southwest in direct opposition to wind direction. Surface currents have the highest velocities and subsurface currents show a slight deflection to the right. Station P-4-2 (Figure 10b), near Monroe, illustrates the "typical" currents of the western basin. Surface flow is forced north-northeast by south-southwest winds, while subsurface currents indicate return flow to the southwest. The greatest current velocity is located at the lake bottom (28 feet), which seems to indicate that this is where most of the return flow is moving.

Station P-5-1 (Figure 10c), near Colchester, Ontario, shows a surface flow moving toward Pelee Passage under the

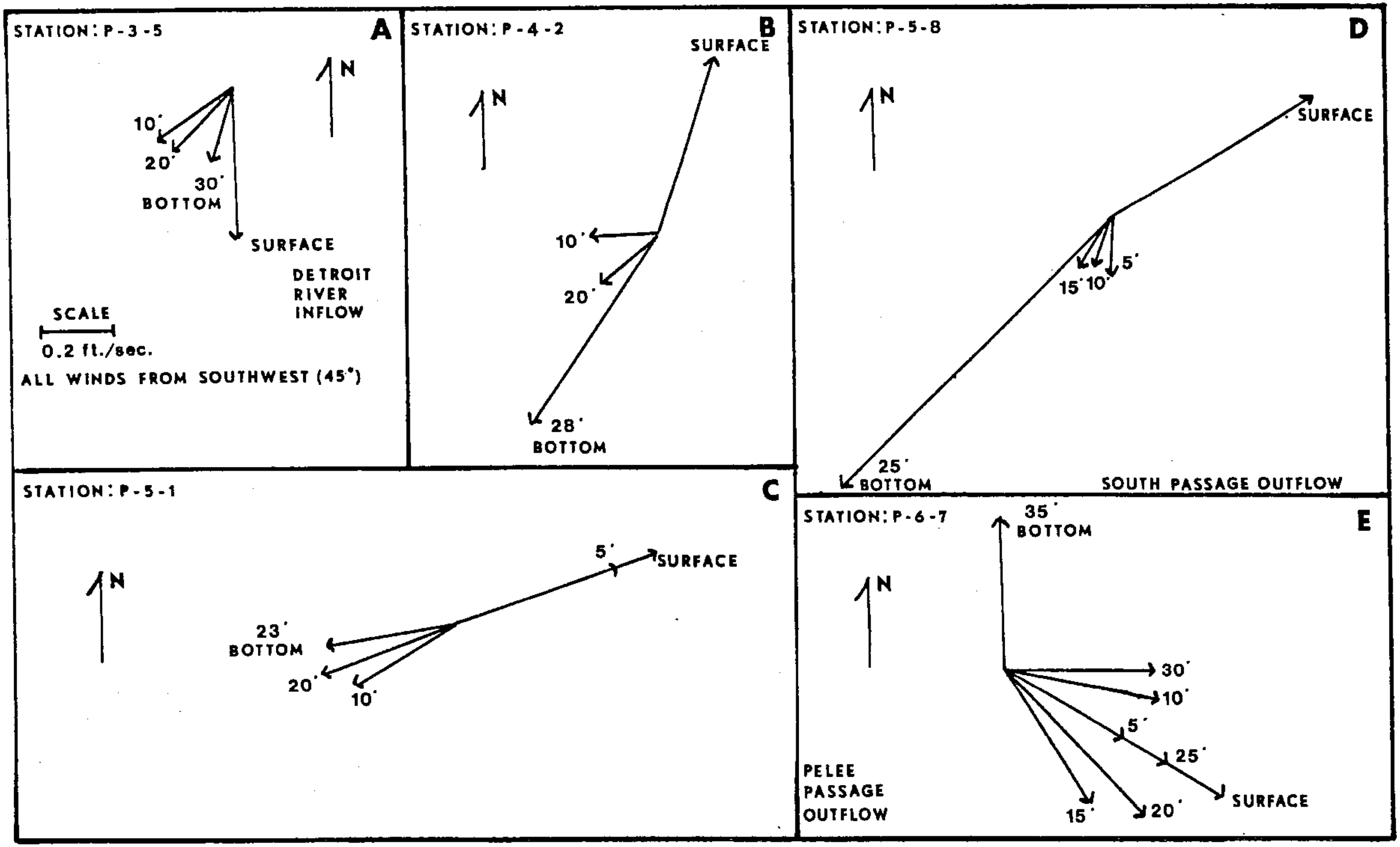

Figure 10. Vector graphs of critical surface-to-bottom currents in the western basin (Herdendorf, 1970a); station locations shown in Figure 8.

influence of the prevailing winds. Subsurface currents oppose the surface flow, indicating an influx of water from the east. The surface currents are shifted 25° clockwise to the direction of the wind and this right-shift increases with depth in the subsurface currents. Station P-5-8 (Figure 10d), north of Catawba Island, illustrates wind-driven currents flowing about 37° clockwise to wind direction. Subsurface flow moves in opposition to wind direction, with progressive clockwise deflection with increasing depth. The bottom currents are the most rapid (1.1 feet per second) in the area, which probably indicates a large volume of water moving into the western basin through the South Passage.

One additional station, P-6-7 (Figure 10e), is included to illustrate the water flow in the area south of Point Pelee. According to Herdendorf (1970a, p. 35) both surface and subsurface currents above the thermocline flow out of the western basin toward the east-southeast at right angles to wind direction. Reverse, northward flow occurs below the thermocline as a possible result of thermocline tilting.

Because of the effect upon shore erosion, littoral drift studies are very important in the understanding of water and sediment circulation within the western basin (Figure 11). From the Detroit River eastward along the Ontario shore, the littoral drift system is fairly simple. A northwest-flowing eddy dominates the shore from the Detroit River to a point just west of Colchester, Ontario. East of this point, littoral drift moves eastward and follows the shoreline

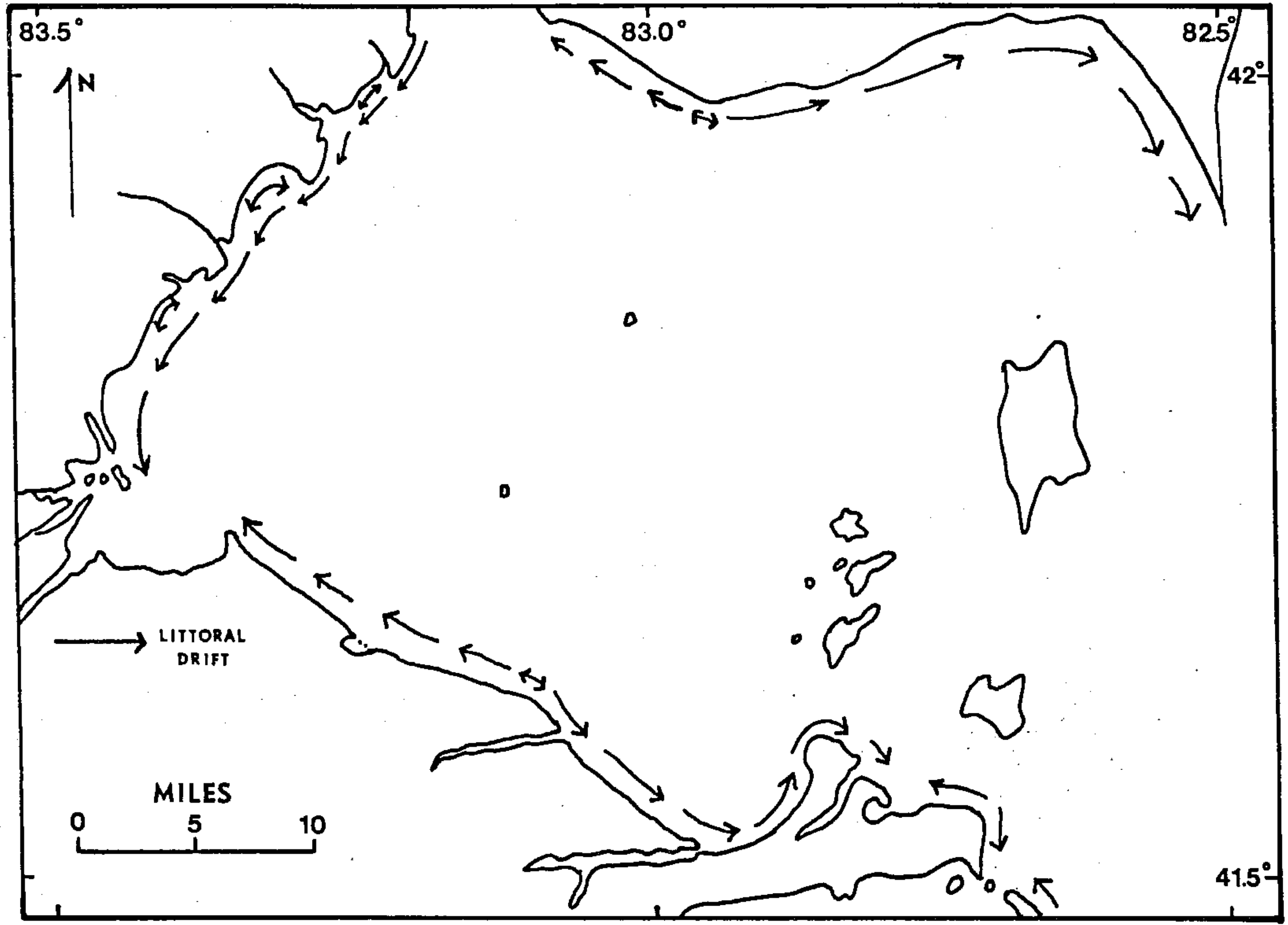

Figure 11. Dominant littoral drift patterns in the western basin of Lake Erie (Herdendorf, 1970a; and Herdendorf and Braidech, 1972).

configuration all the way to Point Pelee (Coakley and Cho, 1972, p. 357).

The Michigan shoreline has a more complex littoral drift system due to a combination of wind and current effects. Eddies between the shore and the Detroit River inflow vary constantly depending on changes in wind direction. Because of the eddy effect, littoral drift is in a back-and-forth motion, and shore-derived material is probably contained in this eddy-controlled "belt" along the Michigan shoreline. The eddying combines with the underlying bedrock to form the scoop-shaped shoreline present in the area, which includes La Plaisance and Brest Bays. Despite this eddy effect, however, there is an overall southwestward littoral drift, which is indicated by the presence of several shoreline features between Monroe and the Michigan-Ohio border.

In the Maumee Bay area, littoral drift swings to the south-southeast along Woodtick Peninsula and North Cape. The drift is then completely obliterated by the inflow from the Maumee River. East of Maumee Bay, a strong north-northwest drift is evident, as illustrated by the presence of Little Cedar Point. The twenty-five kilometer stretch of shoreline from Little Cedar Point southeast to Locust Point is subjected to a much weaker northwestward drift. From Locust Point, which is a nodal zone of diverging currents, to Port Clinton, the littoral drift is to the southeast and is also moderately weak (Herdendorf and Braidech, 1972, p. 24).

A convergence point, is located near Port Clinton, and littoral drift changes from the southeast to the southwest between Scott Point and the Portage River. Currents at this location are very weak and sand is practically absent in the littoral zone due to the presence of dolostone-bedrock bluffs along this stretch of shoreline. Southeast of Scott Point, barrier features are present due to the convergence of opposing littoral drifts originating at Scott Point and the northeast tip of Marblehead Peninsula (Herdendorf and Braidech, 1972, p. 24).

A weak southeast drift carries some sand from Marblehead to Bay Point, whereas a much stronger current flows northwest along Cedar Point. The converging currents subsequently meet at Sandusky Bay. Surface currents in the area average 0.68 feet per second, and bottom currents up to 0.79 feet per second have been reported by Herdendorf and Braidech (1972, p. 24).

In summary, although the currents and water circulation of the western basin are extemely complex and variable, certain dominant patterns can be developed. Through the use of grain-size analyses and the determination of the locations and extents of the Maumee and Detroit River sediment plumes, a more accurate and acceptable pattern for the bottom current circulation in the western basin may be developed.

Sediment Sources in the Western Basin Area

The bottom deposits of the western basin and its surrounding drainage area can be subdivided into three basic types:unconsolidated tills, glacial-lake deposits, and modern Lake Erie sediments. In addition to these deposits, lag sands and gravels formed by the winnowing of pre-existing sediments are also present at various locations within the basin. Using mineralogical analyses, Benson (1971) has reported that the tills, glaciolacustrine sediments, and modern lake deposits are very similar, which seems to indicate that each succeeding series of sediments was derived from pre-existing material within the basin.

The sources of the modern Lake Erie sediments in the western basin have been investigated by numerous researchers. Hartley (1961, p. 1) suggested three possible sources of sediment for the area: the lake bottom itself, the shoreline, and inland areas. With the formation of modern Lake Erie, pre-existing tills and glacial-lake sediments became an important source of sediment within the basin. This is due to the relative shallowness (24 feet average) of the western basin, which allows for the reworking of these older deposits, especially in the nearshore zones. Although bluff erosion along the shoreline of the western basin contributes significant amounts of sediment to the lake, this input represents only nine per cent of the total fine-grained sediment accumulation in the study area (Kemp, 1975, p. 372). Kemp (1975) proposed a fine-grained sediment budget for Lake Erie, which shows that the majority of the sediment being input to the western basin originates from the Maumee and Detroit Rivers.

SAMPLING LOCATIONS AND TECHNIQUES

Sediment samples from the western basin, as well as the Detroit and Maumee Rivers, were selected for the purpose of obtaining the overall sediment-size distribution in the study area. These samples have been collected over the past six years in conjunction with the studies of Kovacik (1972b), Wolery (1973), Walters et al. (1972, 1974), and Walters (1977), and are listed in Table IX. The study area for this research was restricted to the area of Lake Erie west of a line extending from Point Pelee (latitude 41° 54′ N., longitude 82° 30′ W.) south to Cedar Point (latitude 41° 30′ N., longitude 82° 41′ W.) Core and grab samples from 138 locations were selected from materials collected on five separate research cruises. These samples were selected so as to concentrate on the western half of the study area, where the Detroit and Maumee sediment plumes are most critical in the distribution of bottom sediments. The locations of these samples are listed in Table X and shown in Figure 12.

Sediment cores used in this study were collected with gravity-coring devices with 1.5 to 2-inch diameter cellulose acetate butyrate (CAB) plastic core-tube liners. Grab samples were taken with a Petersen sampler in areas where cores could

Table IX. Lake Erie sampling cruises.

Cruise	Stations Sampled and Analyzed				Sample Intervals Analyzed in this Study
	Detroit River	Western Basin	Maumee River	Total	
Cruise 1 RV GS-1 July 19-29, 1971		45		45	163
Cruise 2 RV Inland Seas September 6-13, 1972		8		8	18
Cruise 4 RV GS-1 October 19-22, 1972	4	60	2	66	259
Cruise C RV Hydra September, 1975		17		17	17
Miscellaneous Cruise RV Sandbagger November 14, 1976	1			1	1
Grab Sample MR G. K. Yahney November, 1976			1	1	1
Totals	5	130	3	138	459

Table X. Sampling locations in western Lake Erie.

	Cruise 1	
Location [1]	Latitude	Longitude
4	42°00.00′N	82°45.00′W
5	42°00.00′N	82°40.00′W
6	42°00.00′N	82°35.00′W
8	41°55.00′N	82°35.00′W
9	41°55.00′N	82°40.00′W
10	41°55.50′N	82°45.40′W
11	41°55.00′N	82°50.00′W
12	41°55.00′N	82°55.00′W
13	41°55.00′N	83°00.00′W
14	41°55.00′N	83°05.00′W
15	41°55.00′N	83°10.00′W
16	41°55.00′N	83°15.00′W
17 GS	41°55.30′N	83°18.90′W
18	41°50.00′N	83°20.00′W
19 GS	41°50.00′N	83°15.00′W
20 GS	41°50.20′N	83°10.10′W
22	41°50.00′N	83°00.00′W
23	41°50.00′N	82°55.00′W
24	41°50.00′N	82°50.00′W
25	41°50.30′N	82°45.00′W
26	41°50.00′N	82°40.00′W
27	41°50.00′N	82°35.00′W
28	41°50.00′N	82°30.00′W
29	41°45.00′N	82°30.00′W
30	41°45.00′N	82°35.00′W
31	41°45.00′N	82°45.00′W
32	41°45.00′N	82°50.70′W
33	41°45.00′N	82°55.00′W
34	41°45.00′N	83°00.00′W
35	41°45.00′N	83°05.00′W

Table X. Continued.

Location	Latitude	Longitude
36	41°45.00′ N	83°10.00′ W
37	41°45.00′ N	83°13.60′ W
40	41°40.00′ N	83°15.00′ W
41 GS	41°40.30′ N	83°10.00′ W
42 GS	41°40.50′ N	83°05.00′ W
43	41°40.60′ N	83°00.00′ W
44	41°40.00′ N	82°55.00′ W
45	41°40.00′ N	82°50.00′ W
46	41°40.00′ N	82°45.00′ W
47	41°40.00′ N	82°40.00′ W
48	41°40.00′ N	82°35.00′ W
52	41°34.50′ N	82°40.00′ W
53	41°34.90′ N	82°45.00′ W
55	41°35.30′ N	82°55.00′ W
56	41°35.30′ N	83°00.20′ W
	Cruise 2	
5	41°57.50′ N	82°52.50′ W
6	41°52.00′ N	83°00.00′ W
7	41°50.00′ N	83°05.00′ W
9	41°42.00′ N	83°00.00′ W
10	41°40.30′ N	82°51.00′ W
11	41°41.00′ N	82°45.00′ W
12	41°38.50′ N	82°42.00′ W
37	41°57.50′ N	82°42.50′ W
	Cruise 4	
2	42°03.00′ N	83°07.24′ W
3	42°03.00′ N	83°08.00′ W

Table X. Continued.

Location	Latitude	Longitude
5	42°03.00′N	83°10.00′W
11	42°09.00′N	83°10.25′W
15	42°09.00′N	83°07.17′W
17	42°01.00′N	83°10.00′W
18	42°01.00′N	83°08.00′W
19	42°01.00′N	83°06.00′W
21 GS	42°01.00′N	83°02.00′W
23	41°59.00′N	83°00.00′W
24	41°59.00′N	83°02.00′W
25	41°59.00′N	83°04.00′W
26	41°59.00′N	83°06.00′W
27	41°59.00′N	83°08.00′W
28	41°59.00′N	83°10.00′W
29	41°59.00′N	83°12.00′W
30	41°59.00′N	83°14.00′W
31	41°57.00′N	83°14.00′W
33	41°57.00′N	83°10.00′W
34	41°57.00′N	83°08.00′W
35	41°57.00′N	83°06.00′W
36	41°57.00′N	83°04.00′W
37	41°57.00′N	83°02.00′W
38	41°57.00′N	83°00.00′W
39	41°55.00′N	83°02.00′W
40	41°55.00′N	83°04.00′W
41	41°55.00′N	83°06.00′W
42	41°55.00′N	83°08.00′W
43	41°53.00′N	83°08.00′W
44	41°43.00′N	83°22.00′W
45	41°42.00′N	83°22.00′W
46	41°42.00′N	83°24.00′W
47	41°43.00′N	83°24.00′W
48	41°43.00′N	83°20.00′W

Table X. Continued.

Location	Latitude	Longitude
49	$41^{o}45.00'$N	$83^{o}20.00'$W
50 GS	$41^{o}45.00'$N	$83^{o}22.00'$W
51	$41^{o}45.00'$N	$83^{o}24.00'$W
52	$41^{o}44.00'$N	$83^{o}25.00'$W
55	$41^{o}40.50'$N	$83^{o}29.80'$W
56	$41^{o}37.50'$N	$83^{o}32.50'$W
57	$41^{o}45.00'$N	$83^{o}18.00'$W
58	$41^{o}47.70'$N	$83^{o}18.00'$W
59	$41^{o}47.00'$N	$83^{o}16.00'$W
60	$41^{o}49.00'$N	$83^{o}16.00'$W
61	$41^{o}49.00'$N	$83^{o}14.00'$W
63	$41^{o}51.00'$N	$83^{o}12.00'$W
64	$41^{o}53.00'$N	$83^{o}12.00'$W
65	$41^{o}55.00'$N	$83^{o}12.00'$W
66	$41^{o}55.70'$N	$83^{o}14.00'$W
67	$41^{o}55.00'$N	$83^{o}16.00'$W
68	$41^{o}55.00'$N	$83^{o}18.00'$W
69	$41^{o}53.00'$N	$83^{o}18.00'$W
71	$41^{o}53.00'$N	$83^{o}16.00'$W
72	$41^{o}53.00'$N	$83^{o}14.00'$W
73 GS	$41^{o}51.00'$N	$83^{o}14.00'$W
74	$41^{o}51.00'$N	$83^{o}16.00'$W
75	$41^{o}51.00'$N	$83^{o}18.00'$W
76 GS	$41^{o}51.00'$N	$83^{o}20.00'$W
78	$41^{o}49.00'$N	$83^{o}24.00'$W
79	$41^{o}47.00'$N	$83^{o}26.00'$W
80	$41^{o}47.00'$N	$83^{o}24.00'$W
82	$41^{o}49.00'$N	$83^{o}22.00'$W
83	$41^{o}49.00'$N	$83^{o}20.00'$W
84	$41^{o}49.00'$N	$83^{o}18.00'$W
85	$41^{o}47.00'$N	$83^{o}20.00'$W
86	$41^{o}43.00'$N	$83^{o}26.00'$W

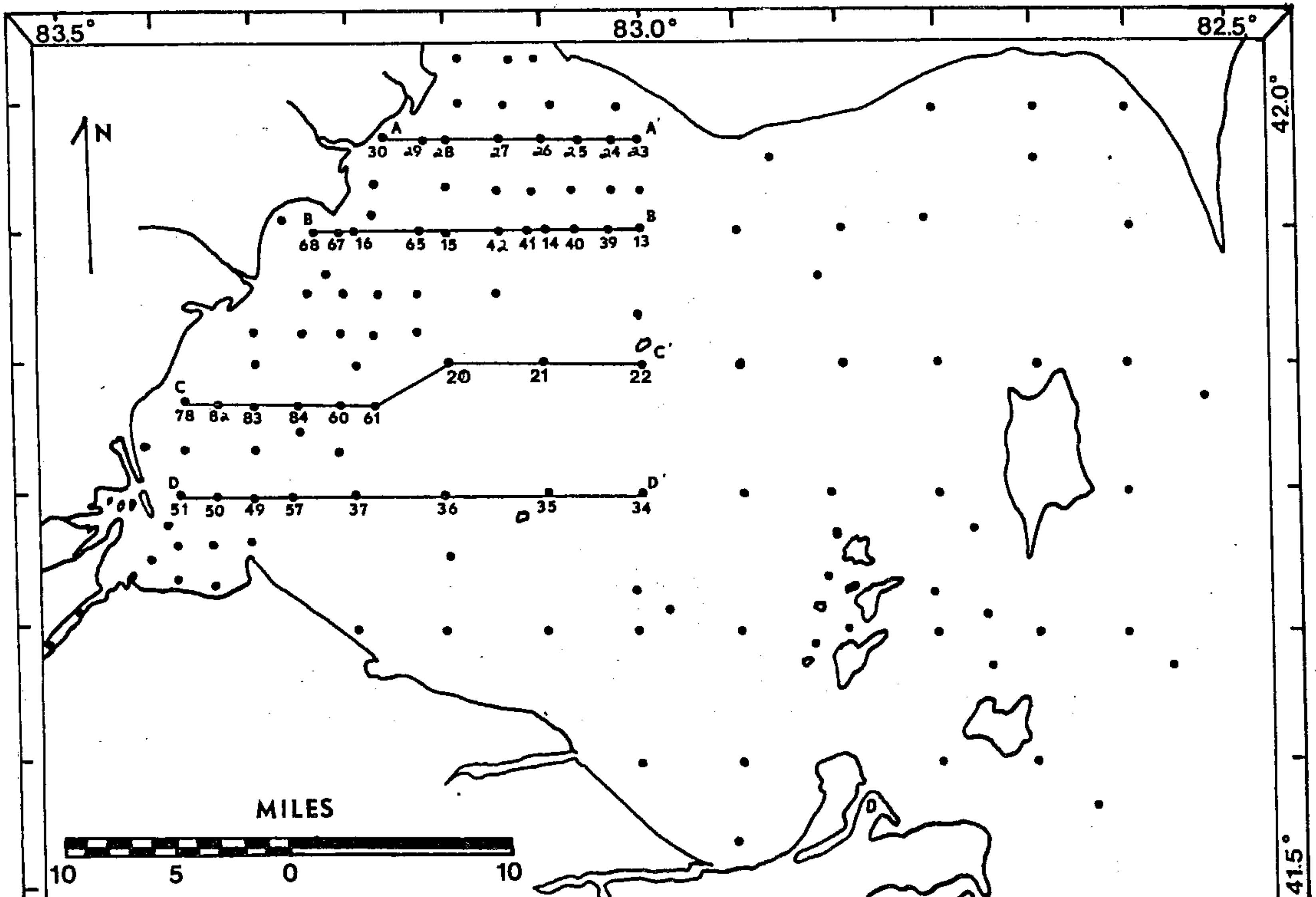

Figure 12. Sample and cross section locations used in this study (Walters and Herdendorf, 1975).

not be obtained due to the composition and depth of the bottom sediments.

Walters and Herdendorf (1975) used four cross sections (AA′ to DD′ shown in Figure 12) to illustrate various changes in mercury concentrations both laterally across the basin and vertically within the core. In this thesis, the same four cross sections will be used to show the variations of sediment size and character in the western basin.

PROCEDURES

Core Sectioning

The core-tube liners and cores were cut with a hacksaw in the following manner: from 0 to 16 centimeters (cm), sectioned every 2 cm; 16 to 40 cm, every 4 cm; everything over 40 cm was sectioned every 10 cm. Care was taken to prevent any tubing material from contaminating the sample by removing any plastic slivers present with a small brush and/or forceps. These 2, 4, and 10 centimeter sections were stored in polyethylene containers and frozen. The grab samples were also transferred from their collection bages to polyethylene containers and frozen.

Disaggregation

Prior to size analysis, the samples had to be properly disaggregated in order to obtain accurate size distributions.

This was especially important due to the flocculation of clay particles into silt-sized aggregates, as well as the massive amounts of silt and clay-composed fecal pellets in the western basin. Freezing helped in the disaggregation process because the expansion of the ice broke up many of the aggregates. For complete disaggregation, however, the samples were thawed, then 5 to 15 grams were removed and placed in larger polyethylene bottles. These bottles were then filled with a dispersant (peptizer) made up of 0.005 M sodium carbonate (Na_2CO_3) and 0.005 M sodium oxalate ($Na_2C_2O_4$), and shaken vigorously for about 90 seconds. The bottles (up to six at one time) were then placed in a Sonogen-Z Ultrasonic Transducer for a period of 10 to 15 minutes. This final step insured the complete disaggregation of any clay-silt aggregates in the sediment sample. This fact was verified by the presence of Brownian movement in the clay particles of the disaggregated sample.

Dispersant Selection

The selection of the sodium carbonate-sodium oxalate mixture as a dispersant for this research was based upon two factors. The primary reason concerned the apparent density changes of various chemical dispersants with time. According to Walters (personal communication, 1977), this was definitely the case with Calgon (sodium hexametaphosphate), which is probably the most popular dispersant used today. In order to determine the most stable dispersing agent for use in this research, four different dispersing agents were tested with a hydrometer for density changes over a two-week period. The peptizers tested included 0.1 M "old" Calgon (non-chlorinated), 0.1 M "new" Calgon (chlorinated), 0.005 M sodium oxalate, and the sodium carbonate-sodium oxalate mixture, as well as a control sample of distilled water. After 336 hours, density changes for the four dispersants were 25%, 27%, 50%, and 9%, respectively. These density variations were measured at the same temperature in order to eliminate any temperature-related changes. Because of the relatively low (9%) density changes of the 0.005 M sodium carbonate-sodium oxalate mixture, that dispersant was used in this research. According to Griffiths (1967, p. 50), a combination of a strong base (Na_2CO_3) and a weak acid ($Na_2C_2O_4$) makes the best peptizer. This worker tested the effectiveness of this solution with modern clay samples. Clays in this dispersant showed definite Brownian movement, indicating complete de-flocculation. This dispersing agent consisted of a mixture of 10.6 grams of sodium carbonate and 13.4 grams of sodium oxalate, which was added to 20 liters of distilled water.

<u>Settling-Tube Calibration</u>

A settling tube was used in the sand-analysis portion of the total grain-size distribution analyses. The settling tube (Figure 13) was patterned after one designed by Emery (1938) as described by Poole (1957), with a sample-introduction mechanism modelled after that described by the U. S. Inter-agency Committee of Water Resources Subcommittee on Sedimentation (1957, p. 87). The bottom of the tube was calibrated in 2 millimeter increments up to 8.2 centimeters for the purpose of measuring the amount of sand accumulating at the bottom of the tube at any one time during settling.

The settling tube was calibrated using three modern sediment samples from the western basin of Lake Erie. Each was disaggregated and dispersed in the manner described previously, then wet-sieved through a 4 phi (0.063 mm) U. S. Standard Sieve. The <4 phi (silt and clay) fraction was stored in beakers for later study. The >4 phi (sand) fraction was checked for cleanliness (lack of mud) and disaggregation with a binocular scope, and was then dried overnight at 92° Centigrade. The dried fraction was then re-disaggregated by hand (finger-rolling) and visually re-inspected with a binocular scope. The sand was then sieved into $\frac{1}{4}$ phi-unit intervals using calibrated U. S. Standard Sieves. Each fraction was weighed and stored in dispersant in order to acclimate the sand to moisture.

The actual settling-tube calibration procedure began with the splitting of each $\frac{1}{4}$ phi fraction down to about 5 grams. This was done so that the sand accumulating at the bottom of the tube did not exceed the calibrated 8.2 centimeter

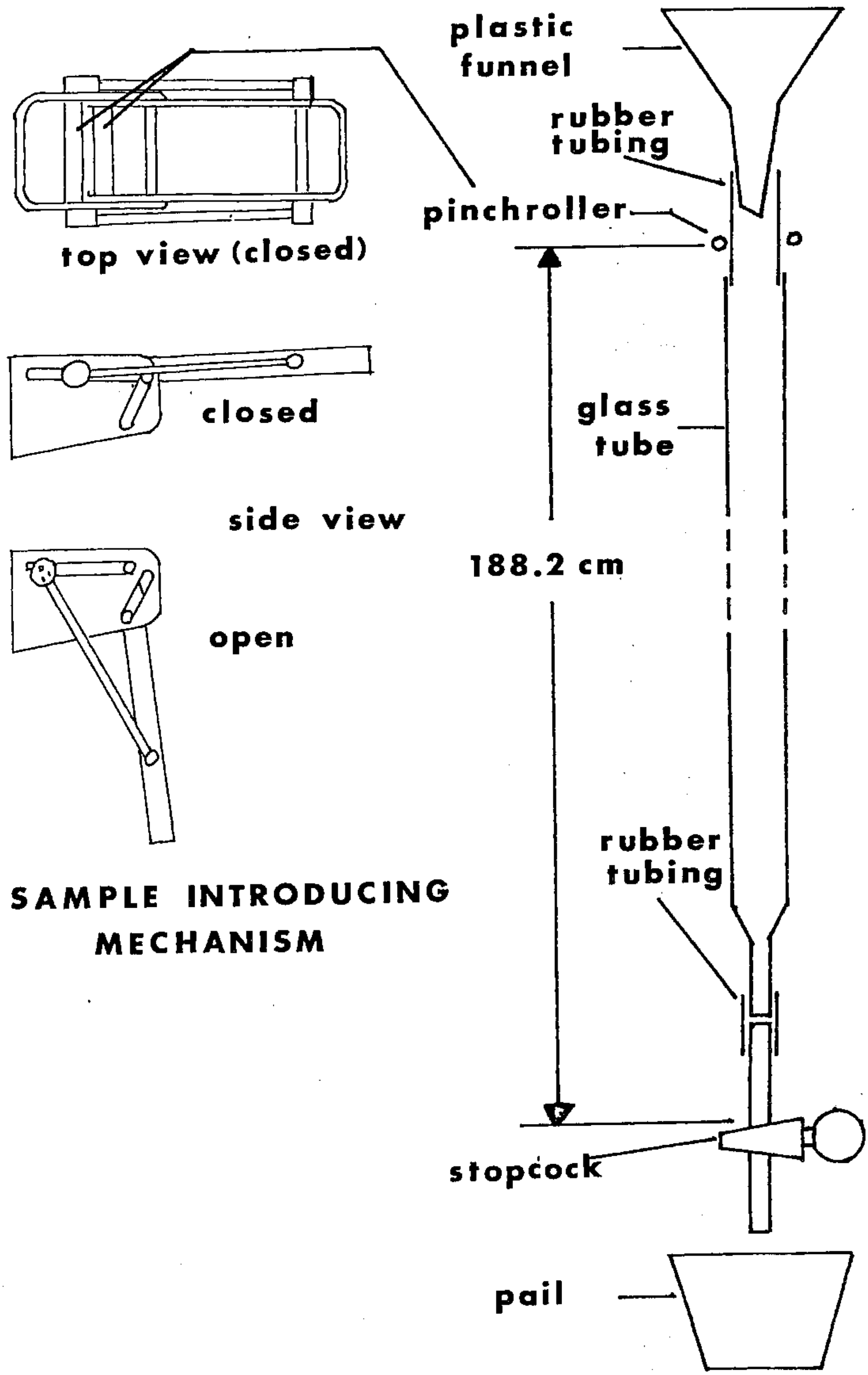

Figure 13. Diagram of the settling tube at Bowling Green State University (after Cunningham, 1974, p. 12) that was used in this study.

height. The tube was then filled to the pinch rollers with 0.005 M sodium oxalate-sodium carbonate dispersant, and the temperature of the solution was measured to the nearest 1° Centigrade. It was observed that no temperature change in the solution occurred during the length of time required for one sample to be settled, a maximum of about ten minutes.

The quarter phi-unit sand fractions, which had been stored in dispersant for at least 24 hours, were loaded into the sample-introduction mechanism, which was closed with the pinch rollers shut. The sand was washed into the mechanism with dispersing solution and the funnel walls were thoroughly washed down to insure that all the sand was in position just above the rollers.

A Panasonic Model RQ-409S "Harlan" tape recorder was used to record each sample run in the settling tube. Realistic C-60 low-noise, high-frequency tapes were used in the recorder. Tests using a Leonidas stop watch with 0.1-second divisions indicated that this recording system possessed a maximum variation of only ± 0.5 seconds over a ten-minute span ($<0.01\%$ error). Prior to the beginning of each sample run, the recorder was activated and the sample number, time, and temperature were recorded on tape and noted in writing.

Next, the sample-introduction mechanism was activated to release the sand sample. Simultaneously, the operator gave an oral cue which was recorded on tape, and then quickly moved to the floor in order to watch the sand accumulate at the bottom of the tube. As the largest particle arrived at the bottom of the tube, representing the onset of accumulation (zero per cent), an oral cue was given. As the sand column reached each 2 millimeter gradation, the operator called out the value of that increment. This process continued until all the sand grains from that quarter phi-unit interval had settled. If the total accumulation during a sample run exceeded the measured 8.2 centimeters at the bottom of the tube, a smaller split of that sample was made and run again. Each quarter phi-unit calibration sample was run through the settling tube twice to insure the accuracy of the results. Following this analysis, the sand fractions were stored for later reference.

After each sand fraction was analyzed, the tape was rewound and the settling times for each 2 millimeter division were determined using a Leonidas stop watch with 0.1-second divisions. The times for the two runs were averaged and recorded for future use.

After all the quarter phi-unit calibration samples had been run, the data, consisting of the settling times, fall distances, and temperatures, were entered into a computer program written by C. P. Cunningham (1974), and revised by L. J. Walters, Jr. (personal communication, 1977). This program was designed to convert data from the B. G. S. U. settling tube into a size distribution using a calibration function based on NBS standard glass beads and Stokes' Law (Cunningham, 1974, p. 17). Using the method of moments, the program also calculated the mean size and standard deviation, both in millimeters and phi units, of each quarter phi-unit sand fraction according to the equations proposed by McBride (1971, p. 117). The formulae used are:

mean $$\bar{x} = \frac{\Sigma f\ m}{n}$$

standard deviation $$S.\ D. = \sqrt{\frac{f(m-\bar{x})^2}{n}}$$

where

f = volume per cent frequency in each grain-size grade present

m = midpoint (mean) of each grain-size grade in phi units

n = total number in the sample, which is 100 when f is in per cent

Because the accuracy of the settling tube is not precisely known, more sensituve statistics such as skewness and kurtosis were not included in this program (Cunningham, 1974, p. 24).

The problems involved with the use of the method of moments for grain-size analysis have been documented by many workers (Friedman, 1967, p. 327-354; Griffiths, 1967, p. 27-92; Folk, 1974, p. 49-50; McBride, 1971, p. 118; and Krumbein and Pettijohn, 1938, p. 239-254). Because of the potential statistics derived from the method of moments and the increased availability of computers to do the calculations, the method of moments has become an extremely favorable statistical technique used in sediment analyses.

As previously stated, this program calculated the mean size of each quarter phi-unit calibration sample in both millimeters and phi units. By plotting the average of these observed means (midpoints) versus the midpoints of the calibrated sieves (data in Table XI), a calibration curve specific for sands from the western basin of Lake Erie was constructed (Figure 14).

Ideally, this should be a straight line graph, but two prominent deviations are noticeable. One variance shows the expected tail-off of grains greater than 0.00 phi units in diameter, due to the interaction of the sand grains with the sides of the settling tube, the actual diameter of the tube, and other physical design features. The second deviation, or bulge, located between 2.00 and 3.50 phi units, is caused by the increased concentrations and occurences of heavy minerals in this size interval, which causes these grains to behave similar to larger, less dense, sand particles. Therefore, this curve is a unique calibration graph for the sand samples in the western basin of Lake Erie.

The calibration curve shown in Figure 14 was entered into the program of Cunningham (1974) for use with later sand analyses. A ninth-order polynomial function representing the curve in Figure 14 was calculated using a least-squares polynomial-regression program. The resulting function, which is shown below, was inserted into the settling-tube program of Cunningham (1974) by Walters (personal communication, 1977). The function is:

$$y = 0.0027389450\,x^9 - 0.04654022\,x^8 + 0.3148399\,x^7 -$$

Table XI. Data for Calibration Curve

Phi Interval	Observed Midpoint [1]	Actual Sieve Midpoint [2]
-1.25 to -1.00	NR	-1.1720
-1.00 to -0.75	-0.1425	-0.9010
-0.75 to -0.50	-0.1048	-0.6455
-0.50 to -0.25	0.0650	-0.4085
-0.25 to 0.00	0.1700	-0.1745
0.00 to 0.25	0.2750	0.0860
0.25 to 0.50	0.4510	0.3380
0.50 to 0.75	0.7230	0.5840
0.75 to 1.00	0.9800	0.8540
1.00 to 1.25	1.1970	1.0985
1.25 to 1.50	1.4060	1.3110
1.50 to 1.75	1.5945	1.5650
1.75 to 2.00	1.8165	1.8485
2.00 to 2.25	1.9380	2.0810
2.25 to 2.50	2.0840	2.3155
2.50 to 2.75	2.2585	2.5870
2.75 to 3.00	2.5545	2.8250
3.00 to 3.25	2.9240	3.0800
3.25 to 3.50	3.2370	3.3550
3.50 to 3.75	3.7140	3.6300
3.75 to 4.00	3.8700	4.0230

[1] Observed midpoints obtained from the average of the three calibration sands from the program of Cunningham (1974).

[2] Actual sieve midpoints obtained from calibrated sieve program CALSIV (Cunningham, 1974).

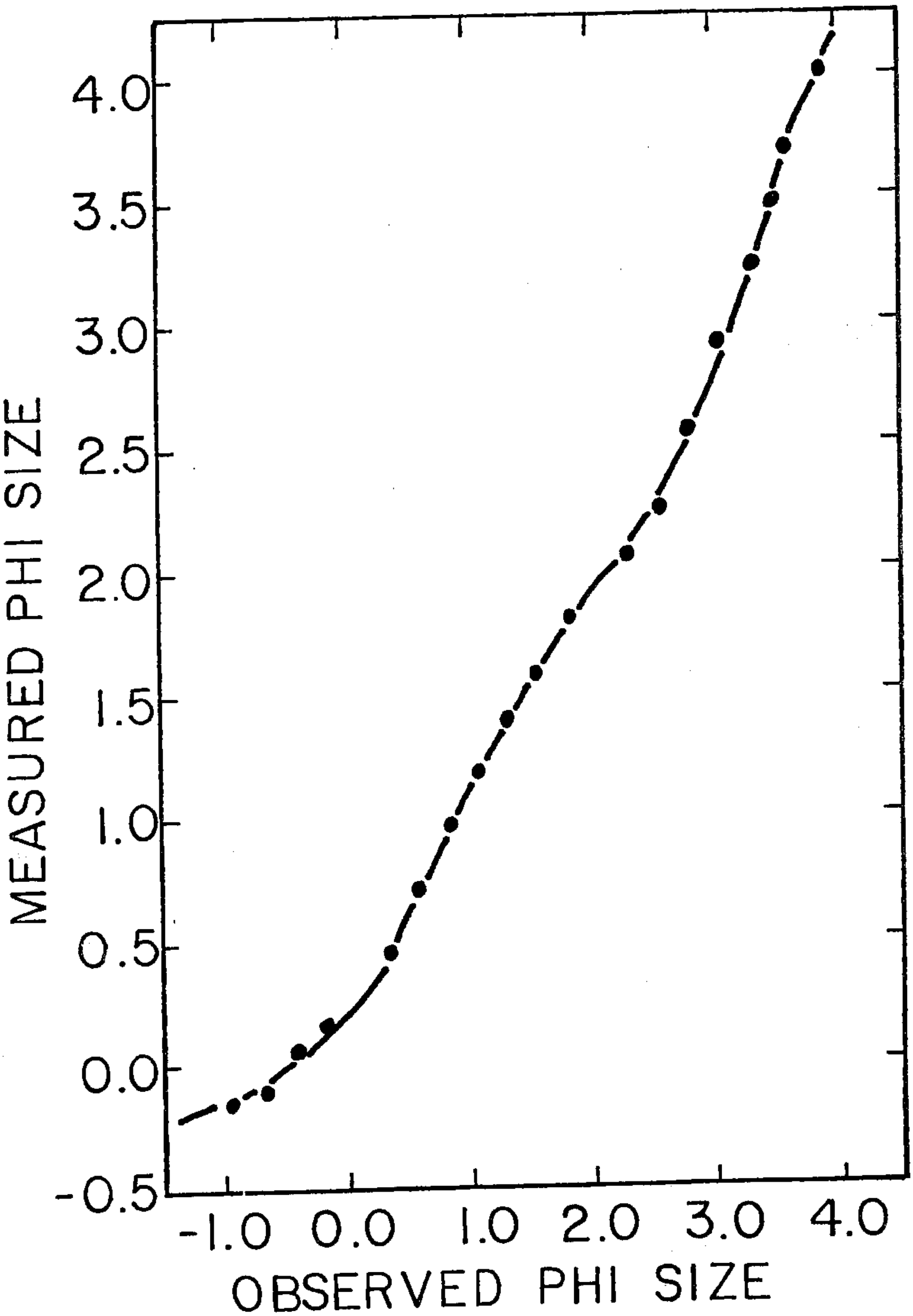

Figure 14. Calibration curve for settling-tube analysis of western Lake Erie sediments.

$$1.0696963\, x^6 + 1.9051163\, x^5 - 1.8210476\, x^4 + 1.4316176\, x^3 - 1.6023699\, x^2 + 2.223855\, x - 0.4693892$$

where y = the midpoint of the calibrated sieves, and x = the midpoint of the observed calibration samples, in phi units. The revised settling-tube-analysis computer program is listed in Appendix I.

Using the observed midpoints for each sand fraction, the settling time and velocity of the midpoint of each quarter phi-unit interval can be calculated. The times for all three calibration samples, as well as the mean settling times, are given in Table XII.

In the 3.75 to 4.00 phi-unit interval, the average observed midpoint for the three calibration samples is 4.023 phi units, or 0.062 millimeters in diameter. The corresponding settling time for this mean value is 276 seconds. It can be therefore assumed that after 276 seconds (4 minutes and 36 seconds), all sediment particles greater than or equal to 4.0 phi units (0.0625 millimeters) in diameter have settled to the bottom of the settling tube. Because mixed sand-silt-clay samples are to be run in the settling tube, this is a vital and necessary assumption.

The average settling velocities calculated for these calibration samples are compared with those proposed by other researchers in Table XIII. The values obtained in this research most closely correspond with the values proposed by Watson (1969), using the modified Rubey Formula, and the

Table XII. Settling Times for Calibration Sands [1]

Phi Interval	Sample I	Sample II	Sample III	Average
-1.00 to -0.75	11.9	12.749	NR	12.325
-0.75 to -0.50	12.6	12.9	NR	12.750
-0.50 to -0.25	NR	14.066	NR	14.066
-0.25 to 0.00	16.0	14.905	NR	15.453
0.00 to 0.25	NR	17.120	14.7	15.910
0.25 to 0.50	18.5	17.791	18.7	18.330
0.50 to 0.75	20.85	20.418	20.1	20.456
0.75 to 1.00	27.80	23.857	25.85	25.836
1.00 to 1.25	31.95	25.071	28.6	28.540
1.25 to 1.50	32.549	31.685	34.25	32.828
1.50 to 1.75	41.025	35.393	38.45	38.289
2.00 to 2.25	48.219	45.803	47.15	47.057
2.25 to 2.50	70.160	63.964	72.50	68.875
2.50 to 2.75	89.486	79.234	89.50	86.073
2.75 to 3.00	120.445	105.032	105.00	110.159
3.00 to 3.25	155.195	140.894	135.50	143.863
3.25 to 3.50	181.143	177.771	176.00	178.305
3.50 to 3.75	227.156	227.946	247.032	234.045
3.75 to 4.00	268.747	283.777	277.743	276.756

[1] all times in seconds

Table XIII. Comparison of settling velocities for sands.[1]

Particle size (phi)	This Paper	Stokes'[2]	Rouse[3]	Gibbs[4]	Modified Rubey's[5]	Waddell[6]	Woods Hole Institute[7]
-1	16.99	-	28.0	27.463	19.826	-	19.608
0	13.88	-	16.7	15.340	13.597	-	14.085
1	7.22	22.438	7.75	7.627	8.822	14.360	8.850
2	3.05	5.609	3.60	3.247	4.925	3.590	4.762
3	1.24	1.402	1.10	1.135	1.989	0.897	2.000
4	0.69	0.351	0.350	0.329	0.574	0.224	0.625

1 all velocities

2 derived from Stokes' Law

3 Blatt, Middleton, and Murray (1972)

4 Gibbs _et al._ (1971)

5 Watson (1969)

6 Stokes' diameter x 0.64 (Krumbein and Pettijohn, 1938)

7 Schlee (1966)

Woods Hole Oceanography Institute (Schlee, 1966).

One important fact concerning the calibration of the settling tube must be made. Opinions vary concerning the necessity and feasibility of the using natural sand grains in the calibration of settling tubes. Cunningham (1974, p. 27) proposed that the behavior of sand grains is accurately approximated by the behavior of glass beads in the settling tube. The U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957, p. 44, 92) favors an extremely complicated and time-consuming calibration method involving the settling of individual sand grains. Although the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957, p. 44) states that the use of glass beads is inadequate and inaccurate, no estimate of the actual error resulting from the use of glass beads to directly calibrate a settling tube was proposed. Therefore, in order to accurately calibrate the settling tube, natural sands from the western Lake Erie basin were used. Assuming that these sands are typical of the sands in the western basin, it is the opinion of this worker that these sands will imprint the settling tube calibration with any specific characteristics possessed by the sands. This includes the various proportions of heavy minerals indigent to the sands of the western basin.

One further note must be made concerning the actual settling of sand grains in the settling tube. It was assumed that percentages of sand based on volume do not differ significantly from percentages based on weight, as in sieve analyses. This assumption is supported by the U.S. Interagency Committee on Water Resources Subcommittee on Sedimentation (1957, p. 37), and is accepted as valid in this thesis.

Sand Analysis Using the Settling Tube

The procedure used for sand analysis of western basin samples was identical to that used in calibration, with two exceptions:

1) Prior to analysis, each prepared sample was run through a -1 phi (2 mm) sieve to remove all gravel-sized material. Also, most of the shells and shell fragments were removed by hand from the sample.

2) After 276 seconds (the theoretical time when all 4 phi and coarser particles have settled), the sand accumulated at the bottom of the tube was drawn off by way of the stop cock at the base of the settling tube. This sand was then washed with distilled water to remove the dispersant as well as much of the organic material. The sand is then dried at 92° Centigrade, weighed, and stored for later analysis.

The remaining sample in the settling tube (silt and clay) was drained into a one liter beaker for later pipette analysis. Material in the tube was rinsed into the beaker with dispersant to insure that all the sample was removed and collected.

The time-distance of fall data obtained from each sample run was analyzed using the computer program listed in

Appendix I in order to calculate the size distribution. This procedure was limited due to the fact that only sand fractions which have a mass of greater than 0.1 gram or a volume of greater than 2 millimeters in the settling tube could be analyzed in this manner. Using the data provided by this program, a size classification was attached to each analyzed sand fraction. The Udden-Wentworth sediment-grade scale (Folk, 1974, p. 25), shown in Table XIV, was used for this and all other references to grain size in this thesis.

Mud Analyses

The mud left in the settling tube after the sands were removed was analyzed in two different manners, depending on the presence of mud in the sample. Extremely low-percentage mud samples (very high sand concentrations) were settled, decanted, and transferred to pre-weighed polyethylene containers. These containers were placed in an International Centrifuge for ten minutes at about 2,000 to 2,500 revolutions per minute. Following this centrifugal separation, the fluid was decanted and the sample and container dried overnight at 92° Centigrade. After the container cooled to room temperature, the weight of the silt-clay portion of the sample was gravimetrically calculated. After weighing, the sample was discarded. The centrifugal mud analysis was performed on only 37 of the 457 western Lake Erie sediment samples.

Table XIV. The Udden-Wentworth sediment grade scale.*

Grade Limits			
mm	microns	phi-units**	Wentworth Size Class
			Boulder
256	-	-8	
			Cobble
64	-	-6	
			Pebble
4	-	-2	
			Granule
2	-	-1	
			Very Coarse Sand
1	-	0	
			Coarse Sand
0.5	500	1	
			Medium Sand
0.25	250	2	
			Fine Sand
0.125	125	3	
			Very Fine Sand
0.063	63	4	
			Coarse Silt
0.031	31	5	
			Medium Silt
0.016	16	6	
			Fine Silt
0.008	8	7	
			Very Fine Silt
0.004	4	8	
			Clay
0.002	2	9	
and finer			

* Modified from Folk (1974, p. 25)

** phi-unit = $-\log_2 \frac{\text{diameter in mm}}{1.00 \text{ mm}}$

locations within the basin. The vertical analysis was conducted on 37 separate cores from a like number of locations.

In addition to core samples, several grab samples were also analyzed. The sediment incorporated in each grab sample was successively split until a small enough portion was obtained. The grain-size distribution of this portion was then determined using the same analytical techniques that were employed with the core samples. The results of these sediment-size-distribution analyses for the western basin are given in Table XVI. This table lists the calculated percentages of the gravel, sand, silt, and clay for each of the 459 sediment intervals that were analyzed.

A detailed size analysis was performed on the sand fractions of some of the sediment intervals. Because of mass and volume limitations, only 203 sediment intervals were examined using this method. The results of this computer-calculated size analysis, in terms of mean diameter of the sand fraction in millimeters, are also listed in Table XVI.

Due to the greater number and closer spacings of sediment samples in the western half of the western basin, a more detailed description of the bottom sediments in that area can be presented. Because the influence of the Detroit and Maumee sediment plumes is greatest in the area west of longitude $82^\circ\ 55'$ west, dense sampling is necessary in order to delineate the locations and extents of these features. East of longitude $82^\circ\ 55'$ west, however, the Detroit and Maumee Rivers

Table XVI. Grain-size distribution of western Lake Erie.[1]

Sample Station	Depth Interval[2] (cm)	CRUISE 1 Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
4	0-2	-	9.85	64.77	25.38	0.092
5	0-2	-	3.32	74.79	21.89	-
6	0-2	-	26.67	61.31	12.02	0.114
8	0-2	-	11.72	66.37	21.91	0.098
9	0-2	-	2.14	61.03	36.83	-
10	0-2	-	2.20	60.00	37.80	-
11	0-2	-	1.66	72.47	25.87	-
12	0-2	-	0.64	77.66	21.70	-
	2-5	-	2.63	91.93	5.44	-
	10-11	-	0.49	75.37	24.14	-
	19-20	-	1.70	85.85	12.45	-
	59-60	-	0.60	86.92	12.48	-
13	0-2	-	3.64	76.75	19.61	-
	5-6	-	7.42	52.72	39.86	-
	6-9	-	7.06	81.22	11.72	-
	9-10	-	7.78	85.65	6.57	-
14	0-2	-	2.60	87.95	9.45	-
	4-6	-	14.72	78.49	6.79	-
	8-10	-	20.31	69.24	10.45	-
	12-14	0.51	11.79	81.08	6.62	-
	16-19	0.32	17.19	73.68	8.81	-
15	0-2	-	2.19	52.87	44.94	-
	4-5	-	1.30	51.71	46.99	-
	10-11	-	16.67	47.93	35.40	-
	24-26	1.14	46.69	43.03	9.14	-
16	0-2	-	4.02	74.40	21.58	-
	4-9	-	17.39	64.70	17.91	-
	10-15	-	18.29	72.03	9.68	-
	16-22	-	9.15	77.98	12.87	-
	27-28.4	-	13.16	71.68	15.16	-
17	GS	41.34	11.09	30.66	16.91	0.263
18	0-2	-	21.31	56.08	22.61	0.166
19	GS	0.89	76.55	13.87	8.69	0.206
20	GS	3.28	55.25	31.23	10.24	0.193
	0-1	-	37.16	57.63	5.21	0.280
	1-2	19.48	27.60	46.83	6.09	0.137
	2-3	-	33.57	53.43	13.00	0.095
	3-4.5	-	41.37	47.20	11.43	0.095
22	0-2	-	0.26	75.73	24.01	-
	2-5	-	0.59	57.13	42.28	-
	5-6	-	0.34	63.71	35.95	-
	6-9	-	0.48	63.97	35.55	-
	9-10	-	0.39	62.99	36.62	-
23	0-2	-	5.89	72.18	21.93	0.116
	2-4	-	3.09	77.23	19.68	-
	4-6	-	6.77	72.02	21.21	0.126

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
23	6-8	-	4.34	70.86	24.80	-
	8-10	-	3.62	68.51	27.87	-
	10-12	-	7.26	70.28	22.46	0.106
	12-14	-	8.31	76.11	15.58	0.105
	14-16	-	12.25	76.90	10.85	0.101
	16-20	-	28.71	60.58	10.71	0.121
	20-24	-	40.69	50.56	8.75	0.147
	24-28	1.31	35.58	56.65	6.46	0.132
	28-33	-	35.96	62.52	1.52	0.115
24	0-2	-	5.08	59.79	35.13	0.165
	2-4	-	1.45	70.94	27.61	-
	4-6	-	0.92	66.23	32.85	-
	6-8	-	2.58	61.93	35.49	-
	8-10	-	1.80	72.13	26.07	-
	10-12	-	1.82	67.21	30.97	-
	12-14	-	1.76	75.57	22.67	-
	14-16	-	1.23	72.84	25.93	-
	16-20	7.04	43.45	37.18	12.33	0.142
	20-24	-	1.59	59.79	38.62	-
	24-27	1.75	43.23	42.86	12.16	0.146
	27-30.5	0.31	39.91	47.36	12.42	0.140
25	0-2	-	4.36	56.16	39.48	0.099
	2-4	-	1.40	65.33	33.27	-
	4-6	-	1.56	53.11	45.33	-
	6-8	-	0.53	54.53	44.94	-
	8-10	-	1.77	76.77	21.46	-
	10-12	-	1.51	53.82	44.67	-
	12-14	-	1.40	72.32	26.28	-
	14-16	-	8.44	53.21	38.35	0.111
	16-20	-	26.18	51.99	21.83	0.135
	20-24	15.70	39.13	31.90	13.27	0.182
	24-28	-	14.28	54.23	31.49	0.170
	28-32	-	4.25	72.32	23.43	-
	32-36	-	8.50	45.84	45.66	-
	36-40	-	27.93	55.86	16.21	0.156
	40-44	-	66.18	27.83	5.99	0.186
26	0-2	-	6.09	70.11	23.80	0.134
	2-4	-	6.33	59.93	33.74	0.157
	4-6	-	15.52	54.59	29.89	0.196
	6-8	0.56	10.73	52.59	36.12	0.184
	8-10	-	8.21	57.49	34.30	-
	10-12	-	6.05	59.75	34.20	0.152
	12-14	-	5.03	61.16	33.81	-
	14-16	-	13.61	53.00	33.39	0.224
	16-20	-	6.82	56.33	36.85	0.211
	20-24	-	0.39	60.41	39.20	-

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
26	24-28	-	1.52	54.43	44.05	-
	28-32	-	0.94	62.65	36.41	-
	32-36	-	1.29	61.13	37.58	-
	36-40	-	2.12	48.22	49.66	-
	40-50	21.24	14.26	43.29	21.21	0.260
	50-55	21.37	55.64	12.86	10.13	0.324
27	0-2	-	5.34	85.42	9.24	0.111
	2-4	-	16.21	67.81	15.98	0.096
	4-6	-	3.85	70.40	25.75	0.113
	6-8	-	5.07	63.44	31.49	0.110
	8-10	-	6.53	45.17	48.30	0.117
	10-12	-	2.12	70.06	27.82	-
	12-14	-	1.54	72.93	25.53	-
	14-16	-	1.78	68.13	30.09	-
	16-20	13.58	5.55	52.59	28.28	0.122
	20-24	-	5.53	56.52	37.95	-
	24-28	-	4.77	65.31	29.92	-
	28-32	-	27.03	55.68	17.29	0.179
	32-36	0.77	72.25	15.46	11.52	0.261
	36-40	14.24	69.90	14.07	1.79	0.258
	40-42.5	33.61	50.39	11.42	4.58	0.259
28	0-2	8.60	74.90	16.50		0.182
	2-4.5	63.50	33.10	3.40		0.207
29	0-1.5	69.10	19.10	11.80		0.268
	1.5-3	67.40	16.60	16.00		0.332
30	0-2	54.80	40.10	5.10		0.209
	2-4	49.10	47.90	3.00		0.252
31	0-2	1.32	64.50	17.16	17.02	0.196
32	0-2	-	7.08	55.48	37.44	0.105
33	0-2	-	1.18	52.23	46.59	-
34	GS	-	1.15	57.89	40.96	-
	0-2	-	2.79	55.81	41.40	-
	2-5	-	8.09	70.97	20.94	-
	5-6	-	0.05	55.89	44.06	-
	17-18.5	-	0.11	72.31	27.58	-
	29-30	-	0.04	85.32	14.64	-
	37-38.5	-	0.03	68.69	31.28	-
35	0-2	-	3.60	69.19	27.21	-
	5-6	-	0.73	56.35	42.92	-
	6-10	-	2.10	55.06	42.84	-
	10-11	-	0.31	71.05	28.64	-
	19-20	-	4.59	71.08	24.33	-
	52-53	-	0.66	80.28	19.06	0.820
36	0-1	3.03	64.22	32.75		0.160
	1-2	-	88.35	11.65		0.198
	2-5	-	6.24	66.36	27.40	0.075
	5-6	4.99	60.74	34.27		0.189

Table XVI. Continued

Sample Station	Depth Interval (cm)	Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
36	6-9	2.51	87.07	11.41	6.01	0.126
	9-10	-	74.07	25.93		0.129
	10-12	-	38.32	38.67	23.01	0.130
	12-13	-	3.80	57.92	38.28	-
37	0-2	-	0.11	51.52	48.37	-
	2-5	-	0.03	52.57	47.60	-
	5-6	-	0.26	44.66	55.08	-
	6-15	-	0.12	54.85	45.03	-
	15-16	-	1.05	50.54	48.41	-
	28-29	-	12.45	51.41	36.14	0.157
	52-53.7	-	0.27	33.02	66.71	-
40	0-2	-	11.90	60.23	27.87	0.228
41	GS	31.51	63.34	3.35	1.80	0.349
42	GS	7.57	90.95	0.38	1.10	-
43	0-2	-	0.54	45.82	53.64	-
44	0-2	-	0.27	43.78	55.95	-
45	0-2	-	53.19	26.82	19.99	0.194
46	0-2	-	67.42	19.19	13.39	0.154
47	0-2	-	41.51	38.21	20.28	-
48	0-2	-	15.37	66.69	17.94	-
52	0-2	-	4.28	57.75	37.97	-
53	0-2	-	82.56	6.88	10.56	-
55	0-2	-	1.45	43.37	55.18	-
56	0-2	-	32.70	54.61	12.69	-
			CRUISE 2			
5	0-2	-	4.44	59.09	36.47	-
6	0-2	-	0.65	56.13	43.22	-
7	0-2	-	0.35	60.73	38.92	-
	2-4	-	0.35	60.17	39.48	-
	4-6	-	0.19	58.71	41.10	-
	6-8	-	0.18	58.76	41.06	-
	8-10	-	0.15	57.27	42.58	-
	10-12	-	0.02	52.82	47.16	-
	12-14	-	0.04	58.23	41.73	-
	14-16	-	0.46	56.40	43.14	-
	16-20	-	0.42	61.55	38.03	-
	20-24	-	0.29	53.90	45.81	-
	24-27	-	0.84	64.59	34.57	-
9	0-2	-	2.04	73.62	24.34	-
10	0-2	-	8.96	43.20	47.84	-
11	0-2	-	30.94	35.46	33.60	-
12	0-2	-	6.09	54.39	39.52	-
37	0-2	-	3.68	67.34	28.98	-

Table XVI. Continued.

CRUISE 4

Sample Station	Depth Interval (cm)	Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
2	0-2	-	94.72	1.82	3.46	-
3	0-2	-	39.08	44.44	16.48	0.309
5	0-2	-	51.10	40.61	8.29	0.100
11	0-2	-	88.84	6.83	4.33	0.181
15	0-2	-	90.44	8.31	1.25	0.214
17	0-2	-	47.60	46.37	6.03	0.082
18	0-2	-	72.11	15.35	12.54	0.215
19	0-2	-	3.93	63.53	32.54	0.102
21	0-2	-	98.40	1.60		0.294
	2-4	-	97.40	2.60		0.291
	4-6	-	97.80	2.20		0.289
	6-8	-	98.40	1.60		0.292
	8-10	-	97.30	2.70		0.280
	10-12	-	98.00	2.00		0.295
23	0-2	-	5.89	72.18	21.93	0.116
	2-4	-	3.09	77.23	19.68	-
	4-6	-	6.77	72.02	21.21	0.126
	6-8	-	4.34	70.86	24.80	-
	8-10	-	3.61	68.52	27.87	-
	10-12	-	7.26	70.28	22.46	0.106
	12-14	-	8.31	76.11	15.58	0.105
	14-16	-	12.25	76.90	10.85	0.101
	16-20	-	28.71	60.58	10.71	0.121
	20-24	-	40.69	50.56	8.75	0.147
	24-28	1.31	35.58	56.65	6.46	0.132
	28-33	-	35.96	62.52	1.52	0.115
24	0-2	-	5.08	59.79	35.13	0.165
	2-4	-	1.45	70.94	27.61	-
	4-6	-	0.94	66.26	32.70	-
	6-8	-	2.58	61.93	35.49	-
	8-10	-	1.80	72.13	26.07	-
	10-12	-	1.82	67.21	30.97	-
	12-14	-	1.76	75.57	22.67	-
	14-16	-	1.23	72.84	25.93	-
	16-20	7.04	43.45	37.18	12.33	0.142
	20-24	-	1.59	59.79	38.62	-
	24-27	1.75	43.23	42.86	12.16	0.146
	27-30.5	0.31	39.91	47.36	12.42	0.140
25	0-2	-	4.36	56.16	39.48	0.099
	2-4	-	1.40	65.33	33.27	-
	4-6	-	1.56	53.11	45.33	-
	6-8	-	0.53	54.53	44.94	-
	8-10	-	1.77	76.77	21.46	-

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent				Mean Sand Size (mm)
		Gravel	Sand	Silt	Clay	
25	10-12	-	1.51	53.82	44.67	-
	12-14	-	1.40	72.32	26.28	-
	14-16	-	8.44	53.21	38.35	0.111
	16-20	-	26.18	51.99	21.83	0.135
	20-24	15.70	39.13	31.90	13.27	0.182
	24-28	-	14.28	54.23	31.49	0.170
	28-32	-	4.24	72.33	23.43	-
	32-36	-	8.50	45.84	45.66	-
	36-40	-	27.93	55.86	16.21	0.156
	40-44	-	66.18	27.83	5.99	0.186
26	0-2	-	6.09	70.11	23.80	0.134
	2-4	-	6.33	59.93	33.74	0.157
	4-6	-	15.53	54.59	29.88	0.196
	6-8	0.56	10.73	52.59	36.12	0.184
	8-10	-	8.21	57.49	34.30	-
	10-12	-	6.05	59.75	34.20	0.152
	12-14	-	5.03	61.16	33.81	-
	14-16	-	13.61	53.00	33.39	0.224
	16-20	-	6.82	56.33	36.85	0.211
	20-24	-	0.39	60.41	39.20	-
	24-28	-	1.52	54.43	44.05	-
	28-32	-	0.94	62.64	36.42	-
	32-36	-	1.29	61.13	37.58	-
	36-40	-	2.12	48.22	49.66	-
	40-50	21.24	14.26	43.29	21.21	0.260
	50-55	21.37	55.64	12.86	10.13	0.324
27	0-2	-	5.34	85.42	9.24	0.111
	2-4	-	16.21	67.81	15.98	0.096
	4-6	-	3.85	70.40	25.75	0.113
	6-8	-	5.07	63.44	31.49	0.110
	8-10	-	6.53	45.17	48.30	0.117
	10-12	-	2.12	70.06	27.82	-
	12-14	-	1.54	72.93	25.53	-
	14-16	-	1.78	68.13	30.09	-
	16-20	13.58	5.55	52.59	28.28	0.122
	20-24	-	5.53	56.52	37.95	-
	24-28	-	4.77	65.31	29.92	-
	28-32	-	27.03	55.68	17.29	0.179
	32-36	0.77	72.25	15.46	11.52	0.261
	36-40	14.24	69.90	14.07	1.79	0.258
	40-42.5	33.61	50.39	11.42	4.58	0.259
28	0-2	8.60	74.90	16.50		0.182
	2-4.5	63.50	33.10	3.40		0.207
29	0-1.5	69.10	19.10	11.80		0.268
	1.5-3	67.40	16.60	16.00		0.332
30	0-2	54.80	40.10	5.10		0.209

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Percent Sand	Percent Silt	Percent Clay	Mean Sand Size (mm)
30	2-4	49.10	47.90	3.00		0.252
31	0-2	-	7.88	69.90	22.22	-
33	0-2	-	9.48	68.55	21.97	-
34	0-2	-	4.46	67.66	27.88	-
35	0-2	-	3.58	69.90	26.52	-
36	0-2	-	3.12	56.46	40.42	-
37	0-2	-	1.24	63.92	34.84	-
38	0-2	-	1.30	79.19	19.51	-
39	0-2	-	4.64	83.65	11.71	0.111
	4-6	-	2.28	58.33	39.39	-
	8-10	1.08	4.99	78.23	15.70	-
	12-14	-	4.01	81.62	14.37	-
	16-20	-	3.80	79.33	16.87	-
	24-28	-	4.04	66.43	29.53	-
40	0-2	-	2.41	79.13	18.46	-
	4-6	-	2.05	64.16	33.79	-
	8-10	-	1.26	59.53	39.41	-
	12-14	-	0.56	50.20	49.24	-
	16-20	-	6.55	77.62	15.83	-
	24-28	-	1.32	69.97	28.71	-
	40-50	-	1.25	76.32	22.43	-
41	0-2	-	5.83	86.78	7.39	-
	2-4	-	1.98	92.26	5.76	0.084
	4-6	-	8.33	88.01	3.66	0.078
	6-8	1.97	7.35	86.84	3.84	0.087
	8-10	31.74	3.65	62.70	1.91	0.145
	10-12	25.06	7.90	63.94	3.10	0.109
42	0-2	-	5.77	58.73	35.50	-
	4-6	1.24	47.27	31.47	20.02	-
	8-10	-	6.38	76.27	17.35	-
	12-14	-	5.09	76.07	18.84	-
	16-20	-	3.65	76.26	20.09	-
	24-28	-	1.72	61.23	37.05	-
	28-32	-	30.05	57.09	12.86	-
43	0-2	-	74.31	16.42	9.27	0.213
44	0-2	-	14.10	74.80	11.10	-
45	0-2	-	55.26	24.95	19.79	-
46	0-2	27.61	22.45	44.89	5.05	-
47	0-2	-	20.91	48.16	30.93	0.132
48	0-2	-	56.99	35.95	7.06	-
49	0-2	-	28.91	57.06	14.03	0.087
	2-4	-	24.82	56.99	18.19	0.090
	4-6	-	27.45	59.68	12.87	0.090
	6-8	-	31.67	50.86	17.47	0.090
	8-10	-	27.39	60.71	11.90	0.092
	10-12	-	25.20	57.78	17.02	0.104

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent				Mean Sand Size (mm)
		Gravel	Sand	Silt	Clay	
49	12-14	-	20.23	63.62	16.15	0.084
	14-16	-	8.87	68.12	23.01	0.087
	16-20	-	22.43	48.05	29.52	0.245
	20-24	-	23.66	67.55	8.79	0.096
	24-28	-	4.95	86.08	8.97	-
	28-32	-	2.33	75.23	22.44	-
	32-36	-	11.22	64.54	24.24	0.083
	36-40	-	10.41	70.69	18.90	0.105
	40-50	-	2.58	75.53	21.89	-
	50-60	-	8.73	68.99	22.28	0.115
	60-65	-	9.60	57.61	32.79	0.129
50	0-2	16.10	82.00	1.90		0.255
	2-4	88.60	10.90	0.50		0.303
	4-6	82.80	16.20	1.00		0.255
51	0-2	-	49.70	36.27	14.03	0.081
	2-4	-	49.26	43.63	6.61	0.088
	4-6	-	58.44	39.63	1.93	0.087
	6-8	-	29.76	60.85	9.39	0.120
	8-10	53.44	30.60	12.22	3.74	0.431
	10-12	39.43	26.22	29.95	4.40	0.447
	12-14	-	17.36	75.92	6.72	0.113
	14-16	-	21.62	72.30	6.08	0.116
	16-21	-	44.39	54.98	0.63	0.115
52	0-2	-	30.22	62.67	7.11	-
54	0-2	-	71.86	21.85	6.29	-
56	0-2	1.36	3.96	53.63	41.05	-
57	0-2	-	1.71	77.09	21.20	-
	2-4	-	2.68	58.77	38.55	0.073
	4-6	-	4.27	64.24	31.49	0.086
	6-8	-	4.58	57.02	38.40	0.090
	8-10	-	3.82	57.18	39.00	0.098
	10-12	1.51	9.17	56.28	33.04	0.164
	12-14	-	1.58	59.25	39.17	-
	14-16	-	1.46	59.80	38.74	-
	16-20	-	0.28	53.46	46.26	-
	20-24	-	0.26	51.65	48.09	-
	24-28	-	0.33	49.95	49.72	-
	28-32	-	0.18	60.68	39.14	-
	32-36	-	0.42	54.48	45.10	-
	36-40	-	0.35	54.95	44.70	-
	40-50	-	0.99	49.61	49.40	-
	50-58	-	1.23	69.59	29.18	-
	58-66	-	12.85	56.56	30.59	-
58	0-2	-	3.65	40.92	55.43	-
59	0-2	-	1.24	49.59	49.17	-
60	0-2	-	6.42	50.90	42.68	-

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Percent Sand	Percent Silt	Percent Clay	Mean Sand Size (mm)
60	4-6	-	5.25	79.91	14.84	-
	6-8	-	12.42	43.94	43.64	-
	8-10	-	4.38	52.06	43.56	-
	10-12	-	41.58	32.21	21.21	-
	12-14	-	49.48	34.97	15.55	-
	14-16	-	61.52	15.71	12.77	-
	16-20	-	8.90	57.08	34.02	-
	20-24	-	3.85	64.24	31.91	-
	24-28	-	30.67	39.20	30.13	-
	28-32	-	55.56	28.72	15.72	-
61	0-2	-	91.70	8.30		0.188
	2-4	4.50	83.00	12.50		0.215
	4-6	-	94.40	5.60		0.200
	6-8	-	94.30	5.70		0.199
	8-10	-	57.80	42.20		0.204
	10-12	-	37.78	51.32	10.90	0.163
	12-14	-	50.42	40.98	8.60	0.175
	14-17	-	29.84	56.07	14.09	0.167
63	0-2	6.93	64.92	15.56	12.59	0.159
64	0-2	-	12.16	75.99	11.85	-
65	0-2	-	2.80	72.16	25.04	-
	4-6	-	3.79	41.38	54.83	-
	8-10	-	2.85	62.57	34.58	-
	12-14	-	1.42	53.72	44.86	-
	16-20	-	3.15	55.39	41.46	-
	24-28	-	30.19	56.36	13.45	-
	28-32	-	24.62	65.29	10.09	-
66	0-2	-	20.75	66.63	12.62	0.121
67	0-2	-	2.15	64.42	33.43	-
	4-6	-	12.44	60.21	27.35	-
	8-10	-	10.76	69.16	20.08	-
	12-14	-	12.78	61.02	26.20	-
	16-20	-	10.39	66.66	22.95	-
	24-27	-	41.29	50.92	7.79	-
68	3-7.5	59.80	38.30	1.90		0.374
69	0-2	-	95.78	1.45	2.77	-
71	0-2	-	4.07	51.85	44.08	-
72	0-2	-	22.02	54.86	23.12	0.113
73	0-2	19.62	74.84	2.26	3.28	0.248
74	0-2	-	83.99	8.07	7.94	0.148
75	0-2	35.69	33.73	24.56	6.02	0.161
76	0-2	-	92.73	6.32	0.95	-
78	0-2	50.89	12.52	30.67	5.92	0.094
	2-4	13.51	24.41	49.32	12.76	0.124
	4-6	-	25.25	66.88	7.87	0.161
	6-8	-	11.57	82.06	6.37	0.143

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Percent Sand	Percent Silt	Percent Clay	Mean Sand Size (mm)
78	8-10	-	8.63	85.20	6.17	0.092
	10-12	-	6.00	86.98	7.02	0.086
	12-14	-	6.47	86.77	6.76	0.095
	14-16	-	6.09	89.44	4.47	0.097
	16-20	-	4.75	88.98	6.27	0.084
	20-24	-	1.69	88.38	9.93	0.115
	24-27	-	2.29	85.36	12.35	-
79	0-2	8.26	60.13	25.02	6.59	-
80	0-2	-	3.59	63.54	32.87	-
82	0-2	-	5.78	71.59	22.63	-
	2-4	-	80.05	10.56	9.39	0.163
83	0-2	-	64.73	16.85	18.42	0.181
	2-4	-	68.81	23.70	7.49	-
	4-6	-	79.67	14.59	5.74	-
	6-8	-	59.57	31.41	9.02	-
	8-10	-	76.99	14.15	8.86	-
	10-12	-	71.44	20.74	7.82	-
	12-14	-	63.61	24.63	11.76	-
	14-16	-	65.92	25.39	8.69	-
	16-20	-	86.79	7.04	6.17	-
84	0-2	-	8.22	50.29	41.49	0.154
	2-4	-	43.74	31.63	24.63	-
	4-6	-	53.99	33.26	12.75	-
	6-8	-	70.29	26.29	3.42	-
	8-10	-	70.57	23.22	6.21	-
	10-12	-	58.14	30.53	11.33	-
	12-14	-	60.59	25.95	13.46	-
	14-16	-	69.94	19.26	10.80	-
	16-20	-	74.43	19.75	5.82	-
	20-24	-	24.14	58.58	17.28	-
85	0-2	-	3.10	57.64	39.26	-
86	0-2	-	47.48	32.29	20.23	0.124
			CRUISE C			
50	GS	9.15	87.08	2.37	1.40	-
54	GS	-	4.04	74.53	21.43	-
55	GS	57.63	39.21	3.16		0.563
56	GS	-	0.33	65.41	34.26	-
57	GS	-	3.53	96.47		-
58	GS	-	0.36	40.93	58.71	-
59	GS	-	3.04	57.70	39.26	0.089
60	GS	-	0.93	60.08	38.99	-
61	GS	-	8.82	91.18		-
65	GS	-	28.18	42.77	29.05	0.261
66	GS	-	8.09	91.91		-

Table XVI. Continued.

Sample Station	Depth Interval (cm)	Percent Gravel	Sand	Silt	Clay	Mean Sand Size (mm)
67	GS	-	9.13	72.24	18.63	-
68	GS	-	6.49	76.68	16.83	0.077
70	GS	-	5.12	94.88		-
74	GS	-	3.32	69.40	27.28	-
75	GS	-	72.60	14.59	12.81	-
76	GS	17.27	80.29	2.44		0.345

[1] All samples are cores with the exception of intervals labeled GS, which indicates a grab sample was analyzed.

[2] All depths are measured from the sediment-water interface.

have a minor effect on the bottom sediments. Therefore, more widely spaced samples were analyzed.

The inter-island-area bottom sediments have been intensely studied by many workers, including Hartley (1961), Benson (1971), and Herdendorf and Braidech (1972). Therefore, only a few samples were analyzed in order to correlate and compare the results of this study with those of other researhers. For the most part, the data of Herdendorf and Braidech (1972) and Benson (1971) will be used in describing the sediments of the island area, and the western half of the basin will be described using data contained in Table XVI.

Two different bottom-sediment studies were performed. One study dealt with all the surficial sediments (0-2 cm or grab samples) from the study area (138 locations). This study was used to horizontally delineate the various sediment zones in the western basin. Maps showing sand, silt, and clay concentrations, as well as sand/mud ratios, sediment textures, and mean-sand size have been constructed using the grain-size distribution data derived from the surficial sediments. These figures will be discussed in detail later.

The second type of sediment study dealt with the cross sections used by Walters and Herdendorf (1975), which were described earlier in this thesis. Various intervals down the cores were analyzed in order to determine any vertical variations in sediment composition during the depositional history at any one location along the cross section. These cross sections are situated so as to transect the locations of the sediment plumes proposed by Walters and Herdendorf (1975) in order to further describe the locations of these fluvial channels. The vertical sediment distributions, textures, and sand sizes for cross sections A-A′, B-B′, C-C′, and D-D′ are presented, as well as any variations within the cores. Additional discussion concerning these cross sections will be presented later in this thesis.

Description of Modern Lake Erie Sediments

Modern Lake Erie deposits are either directly derived from the reworking and entrainment of glacial tills and glaciolacustrine sediments or indirectly from the erosion and subsequent transportation of these older deposits by the many rivers and streams in the drainage basin. Since the formation of modern Lake Erie, up to 12 feet of watery, poorly consolidated, silty mud has been deposited in the western basin (Benson, 1971, p. 24). These modern sediments conformably overlay glaciolacustrine clays in the deeper areas of the basin whereas they transgress older till deposits along the margins of the lake. This modern sequence is directly related to basin infilling under conditions of rising water levels in Lake Erie (Sly and Thomas, 1974, p. 820).

Several attempts to approximate modern sedimentation rates in the western basin have been made. Sly (1976, p. 361) calculated the average maximum rate of mud accumulation since the onset of lacustrine enviroments, and arrived at a figure of 0.3 millimeters per year. However, the time span of 12,000 years includes several periods of non-deposition and subaerial erosion. Wolery and Walters (1974) used mercury concentrations to calculate sedimentation rates of 0.6 to 15.1 millimeters per year in the western basin, with an average rate of 4.4 millimeters per year. This study dealt only with modern Lake Erie sediments deposited within the past 50 years. A map of sedimentation rates (Walters and Herdendorf, 1975) based on these mercury concentrations is given in Figure 7. Kemp et al.(1974, p. 216) have also calculated a maximum modern sedimentation rate for the western basin, using pollen analyses and arriving at a figure of 7.6 millimeters per year.

Modern sedimentation in the inter-island area varies widely due to current velocities and directions. Hartley (1961, p. 8) has proposed an average sedimentation rate of 9 millimeters per year in the island area. Work by Herdendorf (1968, p. 188), however, shows variability of sediment accumulation with both location and season. Average sedimentation rates up to one millimeter per day persist in the reef area, and higher rates are present in deeper, inter-reef waters (Herdendorf, 1968, p. 200). Sedimentation also tends to be greater in the spring than in the summer months. These figures are much higher than those proposed by Hartley (1961, p. 8), but this is due to the fact that sedimentation in the island area is not generally permanent (Herdendorf, 1968, p. 198). Much of the material deposited in the area is eventually eroded, transported, and redeposited elsewhere in the basin, thus explaining the variations between the data of Hartley (1961) and Herdendorf (1968).

Most of the modern Lake Erie sediments are unconsolidated and watery in nature. Kemp et al. (1976, p. 442) report that at the sediment-water interface, a reddish-brown floc, which extends from zero to a few millimeters below the surface, is present at some places in the Lake Erie basin. This floc overlies a light-to-dark gray ooze, which is highly viscous to a depth of 10 to 15 centimeters. This worker discovered that this floc normally occurs at locations with extremely low sand concentrations in the deeper, more central portions of the western basin.

Water-content values up to 90% by weight are common in surface samples. This produces a highly viscous mud which predominates in the center of the western basin. Values usually decrease to 50-60% at depths of about one meter. Variations in water content in each core parallel the sediment-particle-size distribution with coarser sediment possessing lower water contents (Kemp et al., 1976, p. 442-444). The decrease in water content reflects the increasing compaction of the sediments with depth of burial.

Sediment pH is variable. Kemp et al. (1976, p. 442) report that pH normally decreases from values between 7.0 to 7.5

at the sediment-water interface to constant values between 6.7 and 7.0 at depths of one meter. The decrease in pH is probably due to the decomposition of sediment-organic matter and the subsequent release of CO_2 and NH_4 into the interstitial water (Kemp *et al.*, 1972,p. 277).

Mineralogical analyses of modern Lake Erie sediments show them to have a composition similar to the till and glacial-lake deposits. The only variations are a decreased percentage of chlorite and illite and an increase of mixed-layer clays (Benson, 1971, p. 23). Besides these detrital particles, this worker has also discovered the presence of other materials. Numerous bivalve and gastropod shells occur in zones within the top few centimeters of sediment. Plant detritus and wood fragments are also present in varying proportions. In addition, fly ash is normally prevalent in the surface sediments. This ash is derived from local industrial sources and the widespread shipping traffic within the western basin.

In the study area, organic matter is decomposed prior to accumulating in the bottom sediments (Kemp, 1971, p. 543). This is the primary reason for the low concentrations of organic carbon in Lake Erie sediments (Kemp and Dell, 1976, p. 1070). Kemp (1971, p. 542) reports that the presence of organic carbon increases with clay occurence in Lake Erie, with values of 0.46% for sand, 1.38% for silt, and 2.47% for clay.

Sediment-mixing is prevalent from the sediment-water interface to between 3 to 20 centimeters in depth (Kemp *et al.*, 1976, p. 460; and Thomas et al., 1976, p. 400). The mixing may be due to bioturbation by bottom-dwelling organisms and/or gas movement from underlying sediments. Methane-gas release is greatest in the western basin of Lake Erie (Mallard and Frea, 1972, p. 87), while Tubificid populations are extremely high in the basin, especially near the mouth of the Detroit River (Brinkhurst et al., 1968, p. 45).

Sediment Dynamics in the Western Basin

Before analyzing the results of the surficial sediment distribution within the study area, it is necessary to discuss the dynamics of sediment input and circulation within the western basin. Because of its shallow, enclosed nature, sediment deposited in the basin is constantly subject to resuspension and redeposition at other locations either within or outside of the basin. This causes the western basin to be an open system where both sediment and water are constantly circulating due to the overly abundant enviromental energy present in the area. In addition to the internal circulation, water and sediment are also being brought into the system from numerous sources, as well as leaving the basin by way of two primary exits (the Pelee Passage and South Passage) (Thomas et al., 1976; Herdendorf and Braidech, 1972; and the Federal Water Pollution Control Administration, 1968). Because of this circulation, a graded grain-size gradient away from the shoreline is commonly invalid for the western basin.

Therefore, the surficial sediment distribution in western Lake Erie presents a complex, atypical pattern which is directly related to four major factors: the enviromental energy within the basin, the shallowness within the basin, the varied inputs of water and sediment from numerous sources, and the irregular bedrock topography within the basin, especially in the vicinity of the inter-island area.

Due to the enclosed nature of the basin, as well as the relatively narrow and restricted nature of the passages out of the basin, the export of sediment from western Lake Erie is minor with respect to the total input of material from sources around the study area. The fact that sediment is actually being expelled from the basin has been debated by some workers, but it is in the opinion of this worker that such sediment transfer does exist. Turbidity values, which are extremely high in the western basin, are probably the most significant means of affirming the presence of this sediment outflow from the study area.

These high turbidity values are indicative of massive resuspension of bottom sediments (Powers et al., 1960, p. 64; and the International Joint Commission, 1969, p. 101). The turbidity of the lake water is caused primarily by phyto-plankton, organic detritus, and suspended inorganic material. The material consists of clays, either resuspended from the lake bottom or brought in by rivers and nearshore erosion.

A series of turbidity measurements for the western basin is presented by Burns (1976b).

Turbidity values are greatest in the spring and late fall, indicating that most subaqueous reworking of pre-existing deposits, as well as suspension of incoming sediment material, occurs during these months (Burns, 1976b, p. 490-491). NASA ERTS photographs support this hypothesis, as shown by photos taken on April 14, 1973; April 27, 1974; April 4, 1975; April 7, 1976; and September 7, 1976. Low turbidity is seen in ERTS photographs taken on June 20, 1974; July 15, 1976; and August 18, 1973. The values for these high turbidity periods range up to 20 Jackson Turbidity Units (J. T. U.), and average about 8.4 J. T. U. for the basin (Burns, 1976b, p. 492). Using the values from the highly turbid periods in coordination with water-flow data, Burns (1976b, p. 492) has estimated that approximately 3.4×10^8 kilograms of fine-grained sediment are transported from the western basin every year. This proposed outflow is only 6% of the annual sedimentation in the western basin of Lake Erie of about 5.9×10^9 kilograms (Kemp et al., 1976, p. 457). Therefore, this estimation confirms previous workers' theories that although outflow does indeed occur, comparatively little sediment actually leaves the basin.

Lewis et al. (1966, p. 180) also discovered the presence of scour channels between the western and central basins, which suggests that some sediment is being transported between the basins. It can be assumed that any sediment deposited west of the inter-island area in the deeper parts of the basin is probably relatively stable and remains within the basin. However, sediment within the inter-island area and along the basinal margins is more apt to be transported into the central basin because of the more powerful currents and the shallowness of these areas.

Thomas _et al._ (1972) have proposed a zonal classification of Lake Ontario which relates skewness and kurtosis to variable sediment distribution within the lake. Using this classification, Thomas _et al._ (1976) have discovered several interesting features in the western basin of Lake Erie. As expected, high energy sand-gravel zones with positive skewness and leptokurtic distribution occur in the shallow nearshore areas around the basin, as well as in the vicinity of Point Pelee. However, the majority of the western basin is characterized by mixed sand-clay sediment zones, which are platykurtic and either positively or negatively skewed, depending on the sand/clay ratio. Silt concentrations are relatively uniform in this area. Although a few small negatively skewed, leptokurtic clay zones are also present in the western basin, they are minor and anomalous with respect to the dominant sediment distribution in western Lake Erie.

The high concentrations of fine-grained sediment in the western basin seem to be out-of-place with respect to the shallow nature of the area. However, because of the large imbalance in the sediment import/export budget (Burns, 1976b, p. 477; and Kemp, 1975, p. 373), as well as the deficiency of coarse-grained material input by the Maumee and Detroit Rivers (U. S. Geological Survey, 1968, 1971b, 1974, 1975c, and 1976), it can be assumed that the sediment in the western basin represents a re-distribution of much of the fine-grained material input from the suspended loads of these two rivers (Thomas et al., 1976, p. 400). The excess energy in the basin is therefore used to resuspend and "mix" the sediments in the study area, as well as cause large-scale subaqueous erosion and reworking of the older deposits (tills and glaciolacustrine deposits) in the western basin. The net accretion of fine-grained sediment in a high-energy depositional basin caused Thomas et al. (1976, p. 402) to describe the western basin as being in textural dis-equilibrium. This is the only portion of Lake Erie to be classified in this manner, due to the relative equilibrium between enviromental energy and sediment distribution in the Sandusky, central, and eastern basins.

Kemp (1975) has accumulated much of the data concerning the amount of fine-grained sediment entering Lake Erie from various sources. At present, there is not enough data to calculate the input of sand and gravel-sized materials to the lake. Although this is the first such attempt to construct a sediment budget for Lake Erie, it is "... surprising that such close agreement is found between the inputs and the outputs" (Kemp et al., 1976, p. 455).

The sediment budget (Figure 15) has been arranged so that the three major basins in Lake Erie can be properly

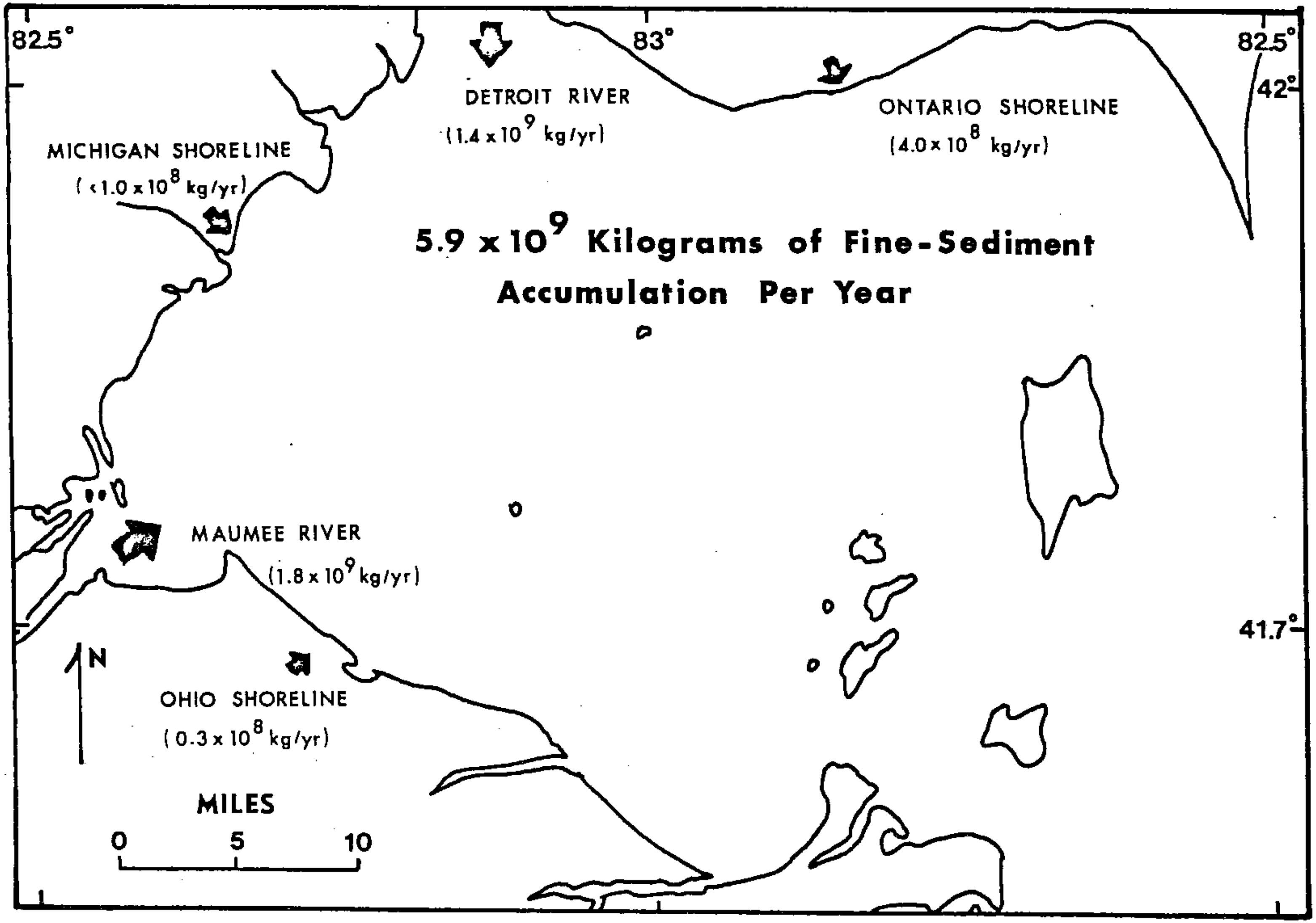

Figure 15. Sediment budget for fine-grained material entering the western basin of Lake Erie (after Kemp, 1975, p. 372); all figures are in kilograms per year.

examined. Net loading of fine-grained sediment in the western basin totals 5.9×10^9 kilograms per year. Of this, 3.2×10^9 kilograms (54.2%) per year are derived from inputs of the Maumee and Detroit Rivers, whose values are 1.8 and 1.4×10^9 kilograms, respectively.

Shoreline erosion contributes only 5.3×10^8 kilograms (9%) of the annual fine-grained sediment accumulation in western Lake Erie. The nearshore-sediment input is divided into three sections. Intermittent bluffs between the Detroit River and Point Pelee contribute about 4.0×10^8 kilograms of silt and clay-sized material per year to the lake. Although erosion rates are very high (up to 8 meters per year) between the Maumee River and Sandusky, the low relief and minor exposures yield an average of only 0.3×10^8 kilograms of fine-grained sediment per year. It is assumed by Kemp (1975) that less than 1.0×10^8 kilograms of sediment are contributed from the nearshore zone between the Maumee River and the Detroit River along the Michigan shoreline because it is highly similar to the Ohio shoreline.

The remaining 2.17×10^9 kilograms (36.8%) of sediment is divided among four different sources: airborne particles, subaqueous erosion, autochthonous organic matter, and dredged spoils. Although no accurate data is available for the contributions of these four sources to the western basin, some estimations can be made. Airborne particulate matter contributes between 0.2 and 3.3×10^9 kilograms of material to the entire lake basin every year (Whelpdale, 1974, p. 295). It can be assumed that a large portion of this material is deposited in the western basin, due to the area's proximity to major industrial centers and the shipping lanes on the lake. Autochthonous organic matter is responsible for about 1.0 x 10^9 kilograms of material being input to Lake Erie every year. Western basin samples contain less organic matter than the other three basins (Kemp et al., 1976, p. 442-444), and the abundance of autochthonous organic material entering the western basin can be assumed to be much less than one-third of the total input for the lake.

The International Working Group (1974, p. 117) reports that about 1.4 x 10^9 kilograms of dredged spoils are deposited in Lake Erie every year. Extensive dredging in the shallow western basin is probably responsible for much of this sediment. To support this proposal, the International Joint Commission (1969, p. 209) reports that Toledo and Monroe contributed about one million cubic meters of dredged spoils to the western basin in 1968. Assuming water content of 75% by weight and a silt-clay content of 50% of all solids (Kemp et al., 1976, p. 455), these two dredged sources alone contribute about 1.0 x 10^9 kilograms of fine-grained sediment to the western basin. The remaining percentage of fine-grained sediment input to the basin is derived from subaqueous erosion in the nearshore areas (Lewis, 1966, p. 125; Rukavina and St. Jacques, 1971, p. 387; and Thomas et al., 1976, p. 402). This figure is probably relatively high for the western basin, due to the shallowness, water circulation, and turbidness within the basin.

In an attempt to further differentiate the sediment zones in Lake Erie, Herdendorf (1970a, p. 44) constructed a sedimentation map of the lake which differentiates between zones of mud deposition and non-deposition and/or subaqueous erosion (Figure 16). Data shows that 56% of the lake bottom in the western basin is within the area of mud deposition proposed by Herdendorf (1970a, p. 37).

Carter (1977) has presented a detailed study of the amount of coarse and fine-grained sediment that is derived from both subaerial and subaqueous erosion of tills and glaciolacustrine clays along the U. S. shoreline of Lake Erie. The study is based on recession rates along the lake, which were measured from the 1870's to the 1970's. According to Carter (1977, p. 7), 1.37×10^8 kilograms of fine-grained sediment and 0.46×10^8 kilograms of sand and gravel are derived every year from the erosion of shoreline areas in Ottawa and Lucas Counties in northwestern Ohio. Recessional rates in this area are normally slow, ranging from 0 to 3 feet per year along the till bluffs that are present along the shoreline.

In the Maumee Bay area, where glaciolacustrine silts and clays are subjected to erosion, recessional rates range from 0 to 5 feet per year. However, recession in the Maumee River area ranges up to 15 feet per year. Using these recessional rates, Carter (1977, p. 7) has reported that 1.21×10^8 kilograms of silt and clay are deposited every year in the western

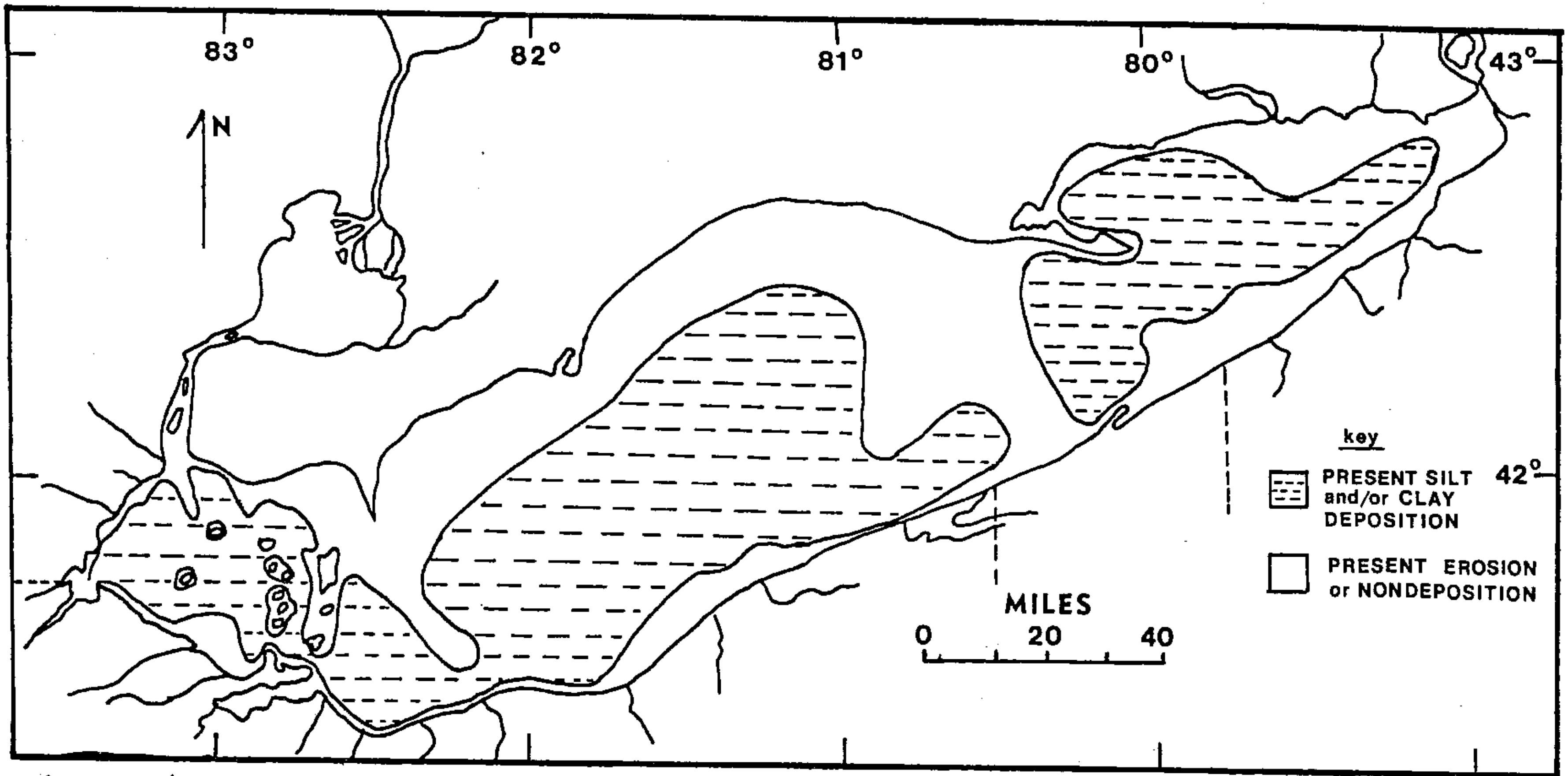

Figure 16. Distribution of Lake Erie bottom deposits showing areas of assumed deposition and erosion (Herdendorf, 1970a, p. 44).

basin from this area. Along the Michigan shoreline in Monroe and Wayne Counties, 5.2×10^8 kilograms of silt and clay plus 1.29×10^8 kilograms of sand and gravel are input every year to Lake Erie by way of nearshore erosion. Recession along the shoreline in Michigan ranges from 0 to 5 feet per year, depending on location (Carter, 1977, p. 24).

Combined with the 1.82×10^8 kilograms of fine-grained sediment derived from erosion of the bluffs in southwestern Ontario between the Detroit River and Point Pelee, Carter (1977) has proposed that a total of over 9.6×10^8 kilograms of silt and clay and 1.75×10^8 kilograms of sand and gravel are input to the western basin every year due to subaerial and subaqueous erosion of nearshore tills and glaciolacustrine clays. Upon comparison with Kemp's (1975) data for sediment derived from nearshore erosion, it can be seen that Carter's (1977) data is over two times greater. The increase in the input of sediment from these shoreline sources around the western basin would seriously affect Kemp's (1975) sediment budget, which was discussed earlier in this section. However, Kemp's (1975) sediment budget basically outlines the various sources of material in the western basin area, and plays an important part in the understanding of sediment loading in this portion of Lake Erie. Eventually, Carter's (1977) data will be used to up-date the sediment budget of the study area.

Surficial Sediment Distribution

Figure 17 shows the distribution of the sand observed in the surficial sediments of the western basin. High-sand concentrations (>50%) are present at various locations within the basin. The high-sand zones are further illustrated by Figure 18, which shows the sand-to-mud ratio of the surficial sediments. This map was constructed by plotting the various sand to silt-and-clay proportions at the sample locations in the study area. Using the ratio map in correlation with the sand concentration map, the various areas of sand (>0.063 mm) occurence can be differentiated.

The areas at the mouths of the Detroit and Maumee Rivers offer very significant results. The lower Detroit River contains high-sand concentrations in the east (94.72%) and west (51.1%) channels, and the middle of the river contains somewhat less (39.07%) sand. Using ERTS photography (taken on April 27, 1974), it can be seen that a highly turbid area is present along the southern shore of Lake St. Clair. This zone can be followed as it enters the Detroit River, where it remains in the eastern channel. As the river enters Lake Erie, the turbid plume extends southward into the basin until it disappears. Outflow from the Detroit River's east channel also swings to the east along the Ontario shoreline, forming a very high-sand (95%) zone. This zone, which extends from the Detroit River along the coast for about 10 kilometers (to Comet, Ontario), is also due to the northwest

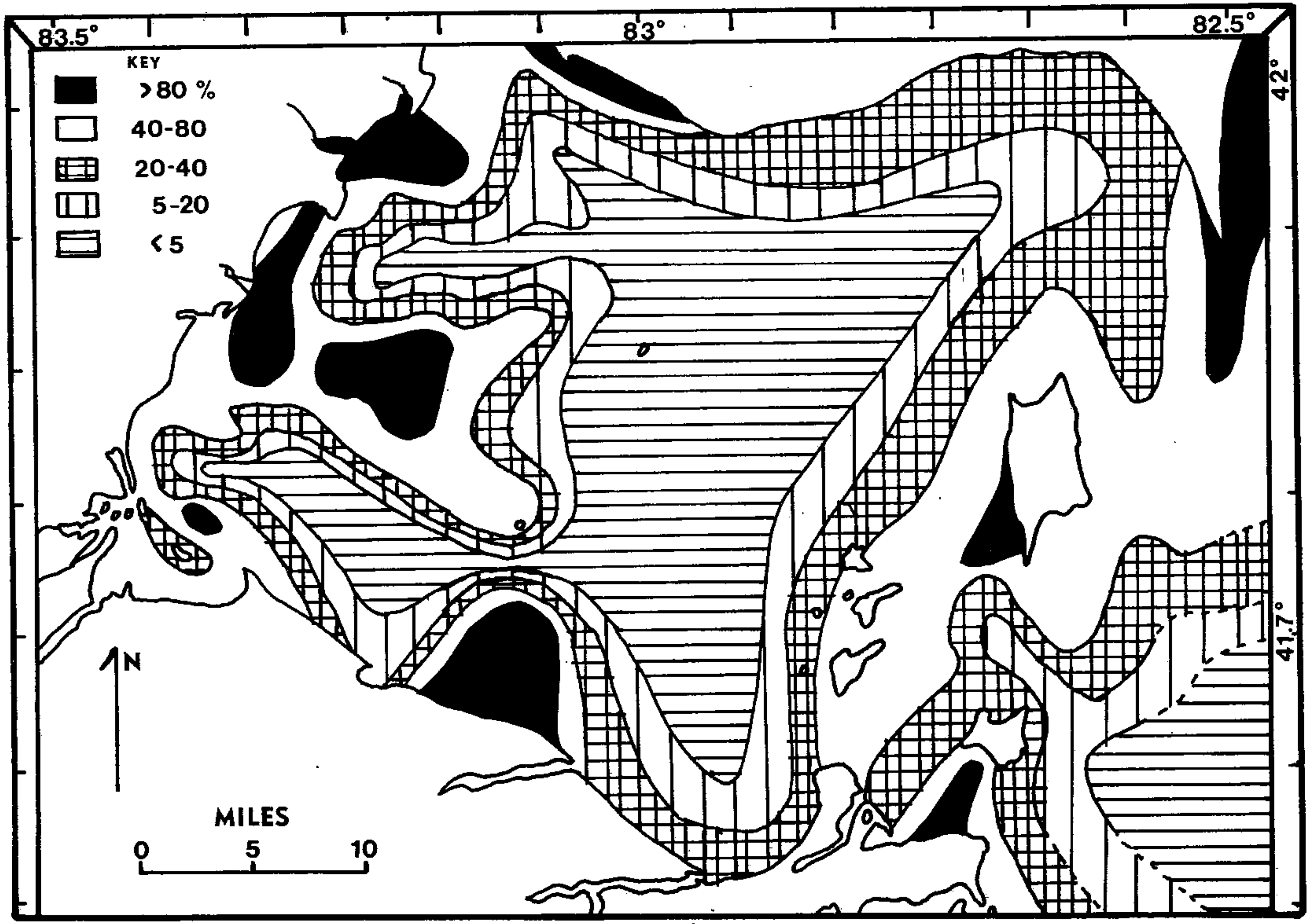

Figure 17. Sand distribution in the surficial sediments of western Lake Erie.

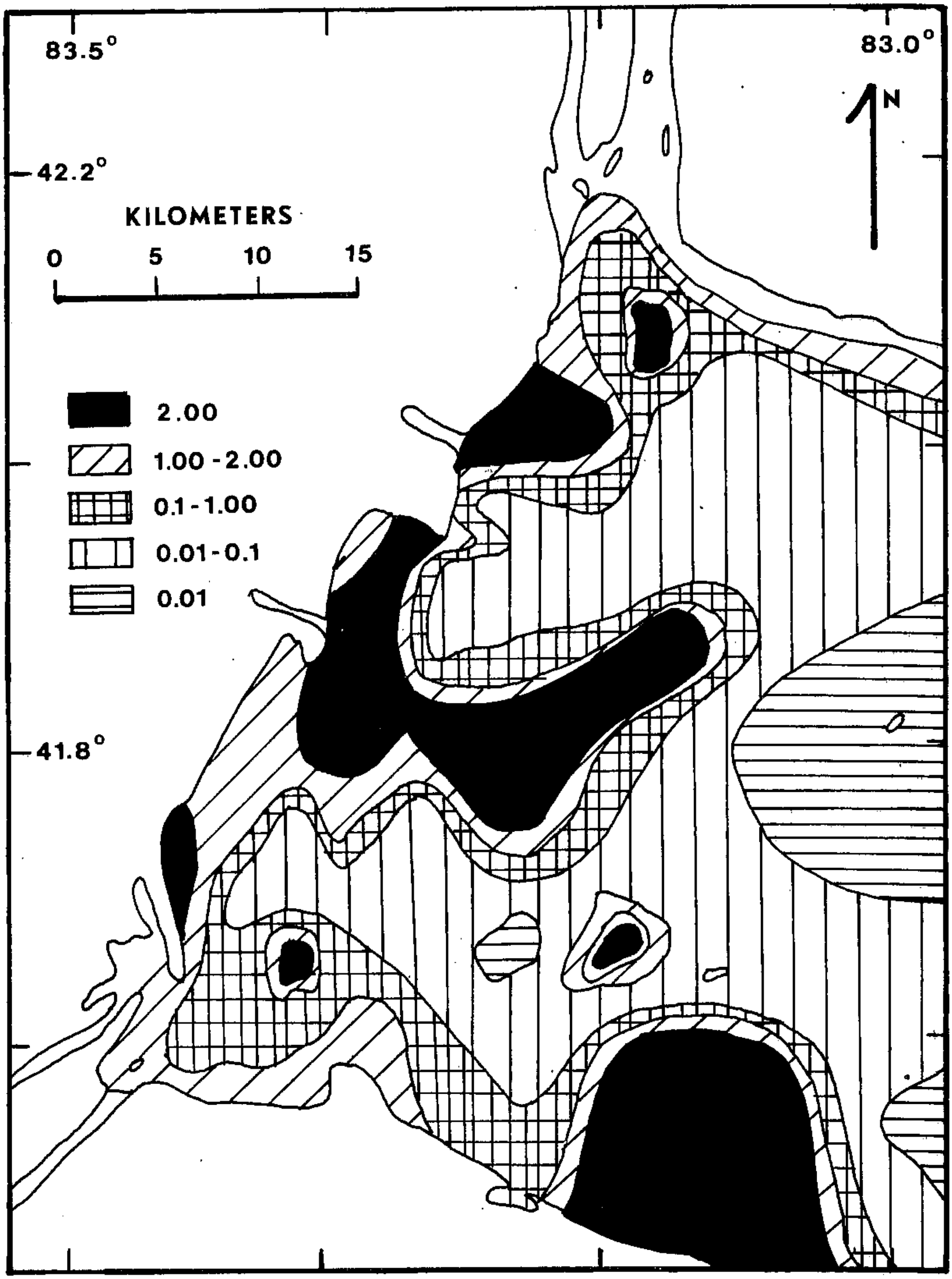

Figure 18. Sand/Mud ratios in the surficial sediments.

flowing littoral drift in the area. The backflow eddy erodes the till bluffs along the Ontario shore (Coakley and Cho, 1972, p. 356), and retains the sediment within the eddy. In addition to bluff erosion, the offshore zone in this area is also subjected to subaqueous erosion, as reported by Walters (1974).

The west channel of the lower Detroit River contains about 40% less sand than the east channel. As this section of the river enters Lake Erie, grain size decreases considerably. The low-sand channel in the middle of the river can be attributed to the presence of Grosse Ile, which is directly north of this zone. Grosse Ile is the largest of a series of islands which physically bisects the lower section of the Detroit River. The island barrier creates the presence of a lower energy "void" zone, thus forming a low-sand area within the river.

Between the outflow of the Detroit River and the Michigan shoreline (from the Huron River to Stony Point), a lag-deposit zone is present. The nearshore area contains average current velocities in excess of 0.75 feet per second (Herdendrof, 1970a, p. 35), and the bottom sediments are subsequently subjected to winnowing and subaqueous erosion (Walters, 1974). The inflow from the Detroit River combines with the local currents and relative shallowness (1 to 3 feet) of the area to remove most of the finer material and form the lag deposits that are present.

One additional feature in the Detroit River area is the presence of an isolated, high-sand (72%) zone just south of the river's mouth. This area of coarser sediment, which has also been reported by Lewis (1966) and Verber (1957), can be attributed to a combination of three possible factors: immediate deposition from the Detroit River, reworking of bottom sediments, and the dumping of dredged spoils in the area (National Oceanic and Atmospheric Administration, 1972).

The mouth of the Maumee River is also interesting due to the apparent lack of sand in the immediate area of Maumee Bay. Although high-sand (71.86%) concentrations are present in the lower portions of the river (Herdendorf, 1970b), the only areas outside the river with greater than 50% sand are located along the eastern shore to Little Cedar Point. The remainder of Maumee Bay is mostly muddy, with sand values of less than 50%. This fact has also been documented by the U.S. Army Corps of Engineers (1970). An isolated sand high (88.1%) occurs just north of Maumee Bay near Turtle Island. This area may be the result of littoral drift (and be an extension of Little Cedar Point) or the reworking of bottom sediments by current action. However, one must also consider the possibility that the dumping of dredged spoils may have contributed some of the sand and gravel to the area because of its proximity to the highly dredged approaches to the Port of Toledo. A further explanation of this area with respect to the Maumee sediment plume will be presented later.

Most nearshore deposits are very sandy (>50%). The Michigan shoreline-area sediments are consistently sandy, with the highest values occuring off Monroe (95.75%) and the Swan Creek area (94.9%). Subaqueous erosion is very prominent in the area east and northeast of Monroe (Walters, 1974). Another feature of the nearshore Michigan zone is the apparent lower sedimentation rates in the immediate offshore areas, especially at locations 30, 78, and 79 from cruise 4 (Walters, 1974). This seems to indicate that material is being redistributed from the nearshore zones to deeper portions of the basin in the east.

The extreme southwest Lake Erie shore, just north of the Michigan-Ohio state line, possesses very low-sand concentrations. Although sand is relatively abundant both east and south of North Cape, the area of the Ottawa River estuary and Indian Island is extremely muddy (Graves, 1977). This is in part due to the protected nature of the area.

A narrow (about two kilometers wide) sandy strip is present along the southwest Ontario shore from Comet, Ontario, to Point Pelee (Coakley, 1972, p. 334). The size of this nearshore zone is due to a combination of features. The lake-bottom gradient in this area is much steeper than along the other shores of the western basin, which results in a much more rapid drop-off into deeper water. In addition, the poor drainage of the St. Clair Clay Plains in southwestern Ontario contributes very little coarse-grained sediment to the lake (Ongley, 1976, p. 471). Therefore, almost all the sand along this stretch of shore must be derived from the erosion and subsequent transport of material from the intermittent bluffs along the coastline. This is accomplished by the eastward-flowing littoral drift. The presence of the narrow sandy strip along the Ontario shore is confirmed by the relatively low-sand values (3.32 and 9.85%) in samples 4 and 5 from cruise 1, which are located from three-to-five kilometers offshore in Pigeon Bay. The only variations in this narrow nearshore zone occur off Littles Point, where bedrock outcrops at Grecian Shoals, and near Pelee Point, where the sand zone spreads out areally and contains abundant gravel deposits (Coakley, 1972, p. 334). Kindle (1933), Coakley (1972), and Coakley and Cho (1972) have studied the Pelee area in detail, and should be referenced for any additional information concerning the sediment distribution in the area.

The Ohio shore is very sandy from the Maumee River to Little Cedar Point, as previously explained. The sand zone continues southeast along the coast for about six kilometers to the vicinity of Reno Beach. In this zone, northwest-flowing littoral drift predominates, as proven by the formation of Little Cedar Point. The sand along this stretch of shore is probably derived from the nearshore erosion of till material.

Very low-sand concentrations are located from Reno Beach to Metzger Marsh, although some gravel is also present.

From Metzger Marsh to Locust Point, however, a very high sand-gravel zone (94.98%) predominates. This lag-deposit area, which extends lakeward into the basin for about ten kilometers, is probably due to the predominant southwest-flowing bottom currents of the area, which range from 0.50 to 0.75 feet per second in velocity (Herdendorf, 1970a; and Herdendorf and Braidech, 1972), as well as the bottom topography of the basin, which is dotted with numerous Silurian reefs (Benson, 1971). The currents in this area of the western basin constantly rework the bottom sediments of this shallow, reef-dotted zone. Erosion of till material probably supplies a large portion of the coarse sediment to the area. A muddy channel separates this area from a small sand (67%) zone located near West Sister Island. Further discussion of this zone with respect to the clockwise currents of the area will be presented later in this section.

The remainder of the Ohio shoreline in the western basin consists of a relatively narrow sand-gravel nearshore zone, which grades into muddier sediments along the west side of Catawba Island (Benson, 1971). An additional feature of the Ohio shoreline concerns the immediate beach-offshore area. Although sandy beaches predominate along the shoreline, the offshore zone (about two kilometers wide) is mostly composed of clayey material (Verber, 1957). This clayey zone probably represents either glacial till and/or glaciolacustrine deposits, which are in the process of being reworked by wave and current action.

One final important sand concentration is present in the western half of the basin. This zone, which is located immediately offshore from Monroe and the Raisin River, extends into the lake for about fifteen kilometers. This sand "plume" then splits into two diverging branches, which die out within three to four kilometers. The larger, southern branch may extend to the high-sand area near West Sister Island, as proposed by Verber (1957). Sand concentrations in the sediments of this zone range from 67 to 95%, with variable gravel occurences. A detailed explanation of the origin of this bottom sediment feature will be dealt with at the end of this section.

Sand concentrations in the island area vary with location. High sand concentrations (>50%) are present north and west of Pelee Island, between Marblehead Peninsula and Kelleys Island, and both east and west of South Bass Island. Elsewhere among the islands, sand values range from 40 per cent to almost nothing due to the complex currents and rugged bedrock topography. These results, although obtained using widely spaced samples, compare very favorably with those of Herdendorf and Braidech (1972), Benson (1971), and Hartley (1961), who have analyzed the sediment distribution of the island area using many more samples. The same basic sediment zones, as well as the various gravel-sand-silt-clay percentages, presented by these workers have also been verified by the results obtained in this research, as shown in

(1957), and Benson (1971) all make note of sandy areas along the Ohio shore, in the island area, and lakeward from Monroe. However, a few discrepancies are present. Thomas et al. (1976) makes no mention of the sand zones near the Detroit River, and Verber (1957) reports the presence of less sandy areas along parts of the Michigan shoreline.

As previously stated, the sand/mud ratio map (Figure 18) can also be used to delineate the high-sand zones in the surficial sediments of the western basin. Large, high-ratio (>2) areas are present along the Ohio shoreline (18.4 to 66.6), east of Monroe (2.3 to 46.4), from the eastern channel of the Detroit River (17.9) to Comet, Ontario (61.5), and east of the Swan Creek area (5.1 to 18.6). Two smaller high-ratio zones are located near West Sister Island (2.1) and just north of North Cape (2.2). Much of the Michigan shoreline has lower ratios (1.7 to 1.1) than the areas located to the east in the lake. This seems to indicate that although large quantities of sand are present in the nearshore area, silt and clay also occur in the 30 to 40 per cent range. The lower sand/mud ratios seem to represent lower energies in the nearshore zone along parts of the Michigan shoreline. Most of these zones are located in the vicinity of Brest and La Plaisance Bays.

Silt distribution in the surficial sediment of the western basin is shown in Figure 19. As expected, very low (<20%) values are present in the areas of high sand concentration. However, this map depicts the Detroit River as a bimodal

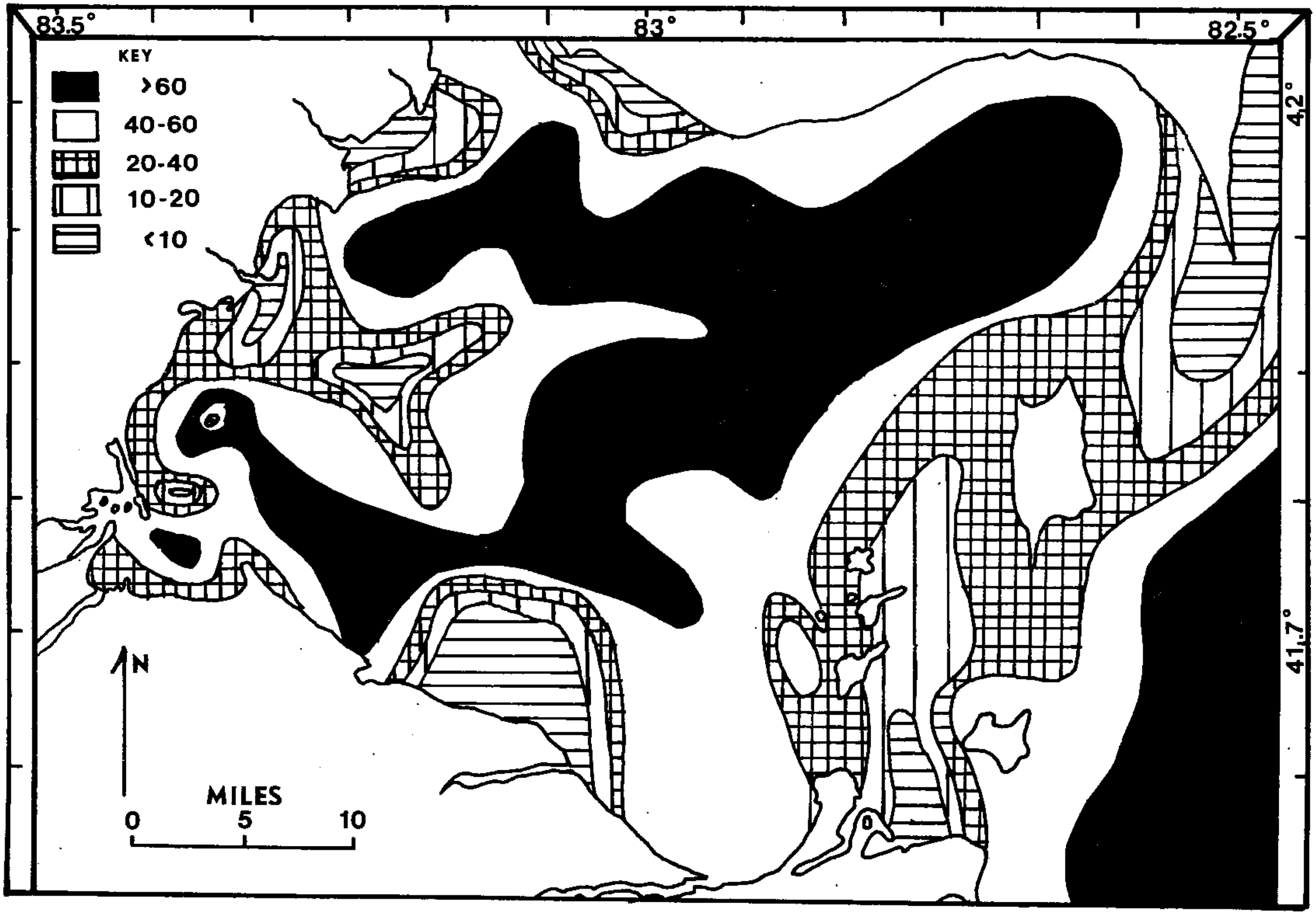

Figure 19. Silt distribution in the surficial sediments of western Lake Erie.

stream with respect to silt occurence. Extremely low (1.8%) values are present in the sandy eastern channel, and fairly constant silt concentrations (40.6 to 44.4%) occur in the central and western sections of the river. It can be assumed that any coarse materials exiting the Detroit River as bedload are primarily derived from the eastern channel, and silts and clays are present in the bedload of the central and western channels.

A high-silt zone (>60%), which appears to originate from the Detroit River, extends southward about 25 kilometers, and then bifurcates into two separate branches. One extends southwest towards Monroe, where it eventually dies out as it collides with the Monroe-Raisin sand zone. The other branch trends due east for about 15 kilometers, until another bifurcation occurs. From this point, one branch extends east towards the Pelee Passage, and eventually disappears in the coarser deposits located south of Point Pelee. The other branch trends towards the Bass Islands, where it fades out and disappears.

The other-high silt zone is located just north of Maumee Bay. This semi-circular feature surrounds Turtle Island, and then stretches eastward towards West Sister Island. The zone then veers northeast until it connects with the "Detroit River" silt plume. A small sub-branch seems to maintain an eastward bearing towards the South Passage, but this feature dies out within too short a distance to be interpreted in any detail.

High-silt concentrations are normally absent in the island area, with the exception of an anomalous zone located west of South Bass Island. Silt concentrations increase to the east of the islands, and high values (>60%) are again found in the Sandusky basin.

One other zone on the silt distribution map should be discussed. Between the Bass Islands and the high sand zone north of Locust Point, relatively high (40-60%) silt concentrations are present. The sediment in this area contains extremely low (<2%) sand concentrations and very high (~1) silt/clay ratios. This seems to indicate that this area is an extremely quiescent basinal zone which is in textural equilibrium with the corresponding sediments. This muddy area was also recognized by Benson (1971), Herdendorf and Braidech (1972), Verber (1957), Herdendorf (1968), and Thomas et al. (1976).

The silt distribution proposed by Thomas et al. (1976, p. 397) most closely resembles that in Figure 19. The only significant difference between the two deals with the actual percentages of silt in certain areas. This discrepancy may be due to various factors, most notably the grain-size determination techniques. The work of Verber (1957) fails to differentiate silt from clay within the basin, but the muddy zones in his report correlate very well with the high silt-clay areas documented in this thesis. A few western basin samples analyzed by Kemp et al. (1976) also compare favorably with this study. Only Herdendorf and Braidech (1972) and Benson (1971) propose data which varies significantly from the particle-size distribution presented here, and the explanation for this discrepancy will be discussed later.

For the most part, the clay-distribution map (Figure 20) corresponds very well with the silt-occurence map (Figure 19) in that the same basic features are outlined. The highest clay values are present west of the Bass Islands (53-58%) and north-northeast of Maumee Bay (55.4%). Probably the most significant feature of this map is the more detailed delineation of the sediment "plume" exiting the Detroit River. Using this figure, the plume can be seen to leave the river trending southeast, and eventually split into three different branches. One extends towards Monroe, one continues southeast towards the Bass Islands, and the third parallels the Ontario shore as it stretches towards the Pelee Passage.

The deposition of silt and clay-sized sediment in the western basin merits additional explanation, because two non-related features seem to be prevalent in the muddy sediments. Both these features cause some sort of aggregation of fine-grained particles. The resultant aggregates, most of which are sand to silt-sized, behave similar to coarser sediments in aqueous enviroments because of their increased mass and larger hydraulic diameters. The two aggregation processes are probably the cause of several anomalously high areas of clay concentrations where current velocities are too high to permit settling of individual clay-sized particles directly

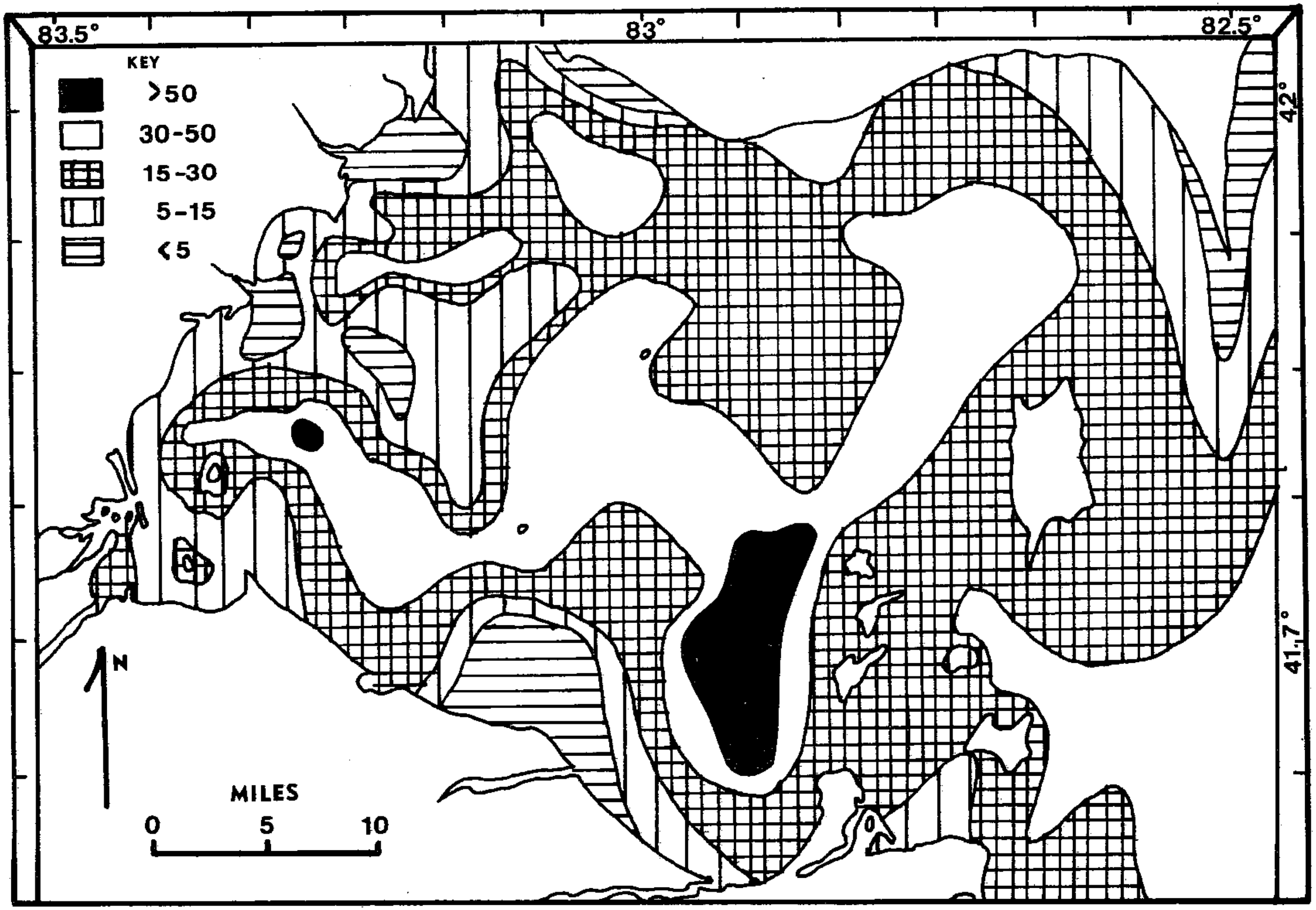

Figure 20. Clay distribution in the surficial sediments in western Lake Erie.

from the water column, although silt and sand-sized material can be deposited.

Whitehouse and Jeffrey (1954) and Sherman (1953) have shown that clay materials are not deposited as individual particles, but rather as aggregates or floccules. Pfister et al. (1968, p. 113) have stated that floc-forming bacteria and algae may attach themselves to clay-sized particles while in suspension. This clay-organic combination forms a silt-sized aggregate which settles to the lake bottom and becomes incorporated in the sediment under low turbidity conditions. These workers have also determined that these floccules contain certain biological nutrients and chlorinated pesticides.

In addition to this flocculation process, bottom-dwelling macroinvertebrates also have a profound effect on silt and clay-sized particles in the basin. These organisms, listed in order of decreasing abundance, are oligochaete worms, dipteran larvae, Chironomidae midges, leeches, flatworms, roundworms, clams, and snails (Herdendorf and Braidech, 1972, p. 13). Most of these bottom dwellers produce voluminous amounts of fecal pellets, which are composed of aggregates of clay and silt-sized particles that have been ingested by the organisms and excreted. The pellets behave much like sand in aqueous enviroments, settling at much greater velocities than individual silt and clay particles (Oertel, 1973, p. 33). Frey (1975), Rhoades (1963), Haven and Morales-Alamo (1966), Harrison and Wass (1965), and Harrison (1972), to name a few, have done large-scale research on various filter-feeding organisms and their respective types of silt and clay-composed fecal material. Under microscopic examination, the excretory pellets can be seen to be definitely composed of mostly silt-sized material, although some clay is obviously present. The pellets are all sand-sized, with most of the aggregates occurring in the medium to very fine-sand range (0.25 to 0.063 mm). The fecal pellets are well-rounded to botryoidal, with some minor cavity-like features, as well as possessing an overall frosted appearance.

Because of these features in the sediments, especially those with high silt-clay contents, special procedures had to be undertaken in order to insure complete disaggregation of the samples. Complete destruction of the aggregates is necessary because a settling tube was used in the analyses of sand-sized material in the western basin. If these floccules or pellets were included in the analyses, the results would be seriously affected due to the behavior of the silt and/or clay-composed aggregates in an aqueous medium. For example, although sand-sized fecal pellets may possess the actual diameters of medium sand, the pellets would behave similar to particles possessing smaller diameters because of the variations of mass and hydraulic equivalence within the various fecal aggregates. Therefore, the grain-size distributions presented in this thesis illustrate the actual percentages of sand-silt-clay-sized material without the effect of flocculation and fecal aggregation.

The problems of aggregation of fine-grained sediments have been documented by several workers. Both Herdendorf and Braidech (1972) and Benson (1971) have reported that very small concentrations of clay-sized material were present in their sediment analyses of the western basin. However, both reports went further to explain that large amounts of clay are indicated to be present by means of x-ray diffraction (Benson, 1971, p. 15) and source-area studies (Herdendorf and Braidech, 1972, p. 31). These workers have attributed this discrepancy between the proposed and actual presence of clay material to the flocculation of clay into silt and sand-sized aggregates, as well as insufficient disaggregation procedures. It should also be added that fecal pellet formation is also responsible for this phenomena.

As previously mentioned, great care was taken to insure complete disaggregation of the pellets and floccules in order to obtain "accurate" grain-size distributions for the modern sediments of the western basin. This procedure was apparently successful, as shown by the high silt and clay values obtained in this study. The flocculation of clay minerals is probably the cause of several anomalously high clay concentrations at various locations in the basin. Three of the most obvious anomalies are located just southeast of the Detroit River, southeast of Stony Point, and north-northeast of Maumee Bay (Figure 20).

It is questionable whether a sediment-size distribution based on complete disaggregation of fecal pellets and clay floccules presents a proper perspective of the sedimentation processes that occur in the western basin. With the disaggregation procedure used in this research, Harrison (1972, p. 107) reports that the fecal pellets, as well as the clay floccules, are totally destroyed, and the resultant sediment is described as being "fine-grained." However, a "natural" analysis (in which no effort is made to break up any silt and/or clay-composed aggregates) would indicate a high percentage of sand-sized sediment (Harrison, 1972, p. 107). Such an analysis would seem to be a better indicator of the hydraulics of sediment deposition in the study area. In fact, these sand-sized aggregates, which can be transported intact from site of production to a different location of deposition by suspension or traction transport (Kerhin, 1977, p. 15), may represent a portion of the actual depositional processes that occur in the western basin. As previously stated, Thomas et al. (1976, p. 385) have determined western Lake Erie to be in hydraulic disequilibrium, but this proposal was based on the presence of large proportions of fine-grained sediment in the basin. However, if the sand-sized pellets and floccules, which are abundant in the study area, are considered as being indicative of the sediment in portions of the western basin, western Lake Erie may be re-classified as being more in equilibrium with the enviromental energy present in the area.

Although one can debate the uses of complete disaggregation and "natural" analyses, each method has its own definite advantages and disadvantages. An answer to the problem may be to analyze modern sediments according to both procedures, and compare the results in an effort to correlate aggregation processes with natural deposition.

Two final diagrams dealing with the surficial sediments of the basin are presented. Figure 21 deals with the textural classification of the surficial sediments in the basin. The classification and corresponding nomenclature is based on Shepard's (1954) triangular diagram (Figure 22). Using this diagram, the various bottom-sediment zones within the basin can be differentiated. The Ohio, Ontario, and northern Michigan shorelines are all sandy (G) in nature, whereas the remaining Michigan shoreline is composed of silty sand (F). The sand zone east of Monroe is composed of a combination of sand (G), sand-silt-clay (J), and clayey sand (H). The area south of the Detroit River is a composite of silt (C) and clayey silt (D), whereas the high-clay areas are silty clays (B).

The final diagram concerns the mean-sand diameters of certain surficial sands (Figure 23). Medium sands dominate the nearshore areas, with the exception of Maumee Bay and the extreme southern Michigan coast. The Maumee Bay sediment is composed of very fine sand, as is the Detroit River area. Fine sands occur in the southern Michigan nearshore zone, as well as in the sand area east and southeast of Monroe.

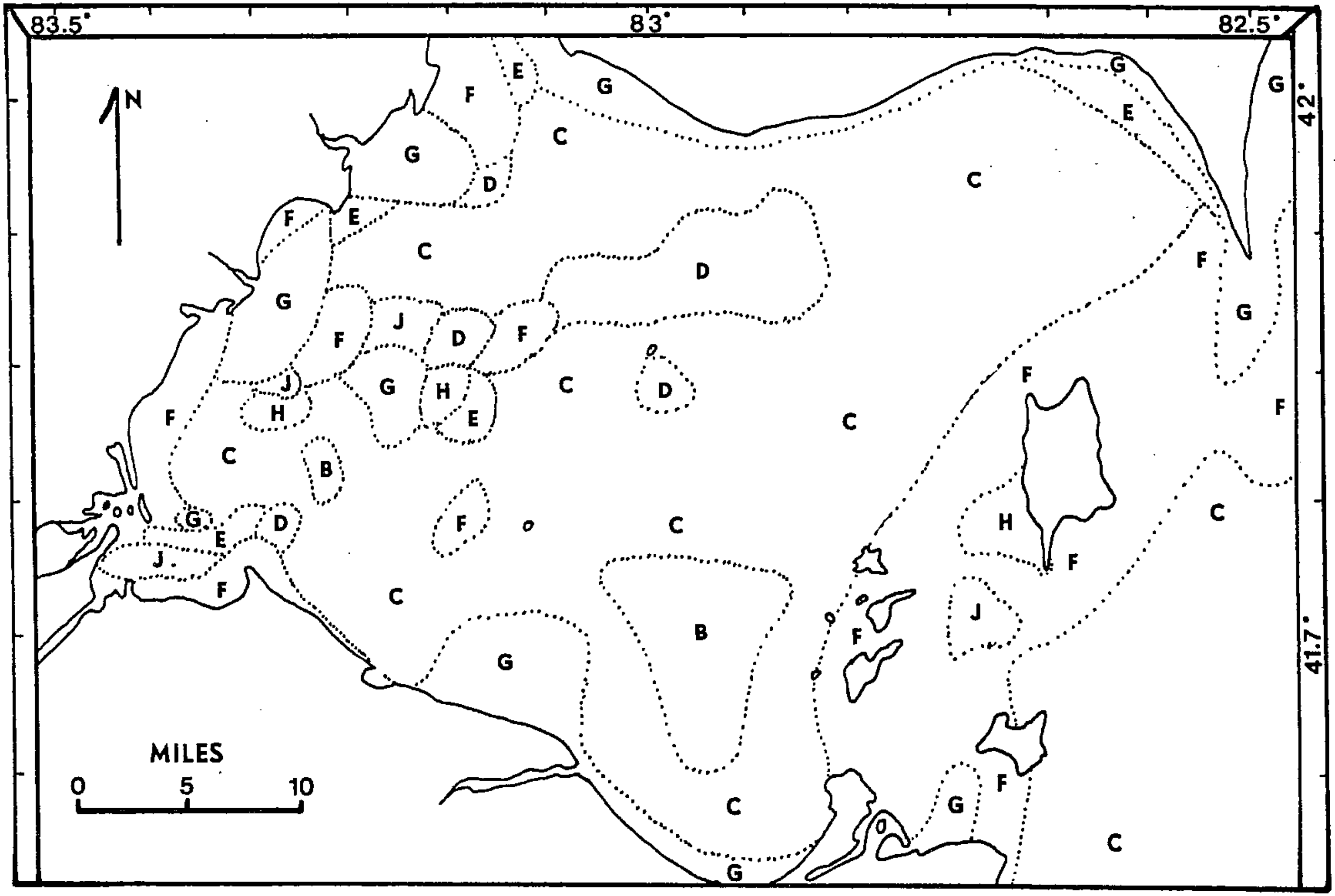

Figure 21. Textural classification of the surficial sediments in the western basin based on Shepard s (1954) classification, which is shown in Figure 22.

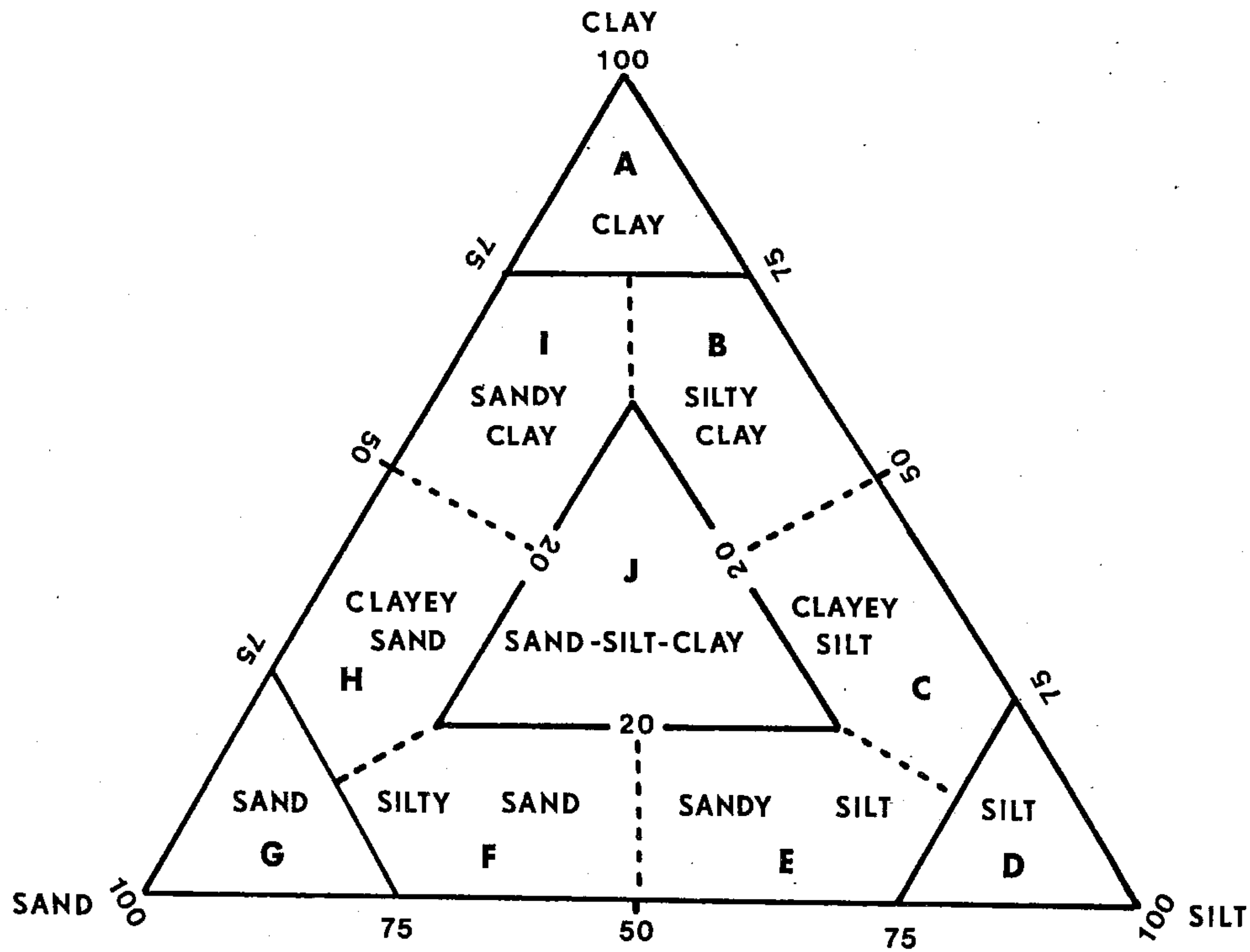

Figure 22. Triangular diagram proposed by Shepard (1954) for the classification of modern sediments.

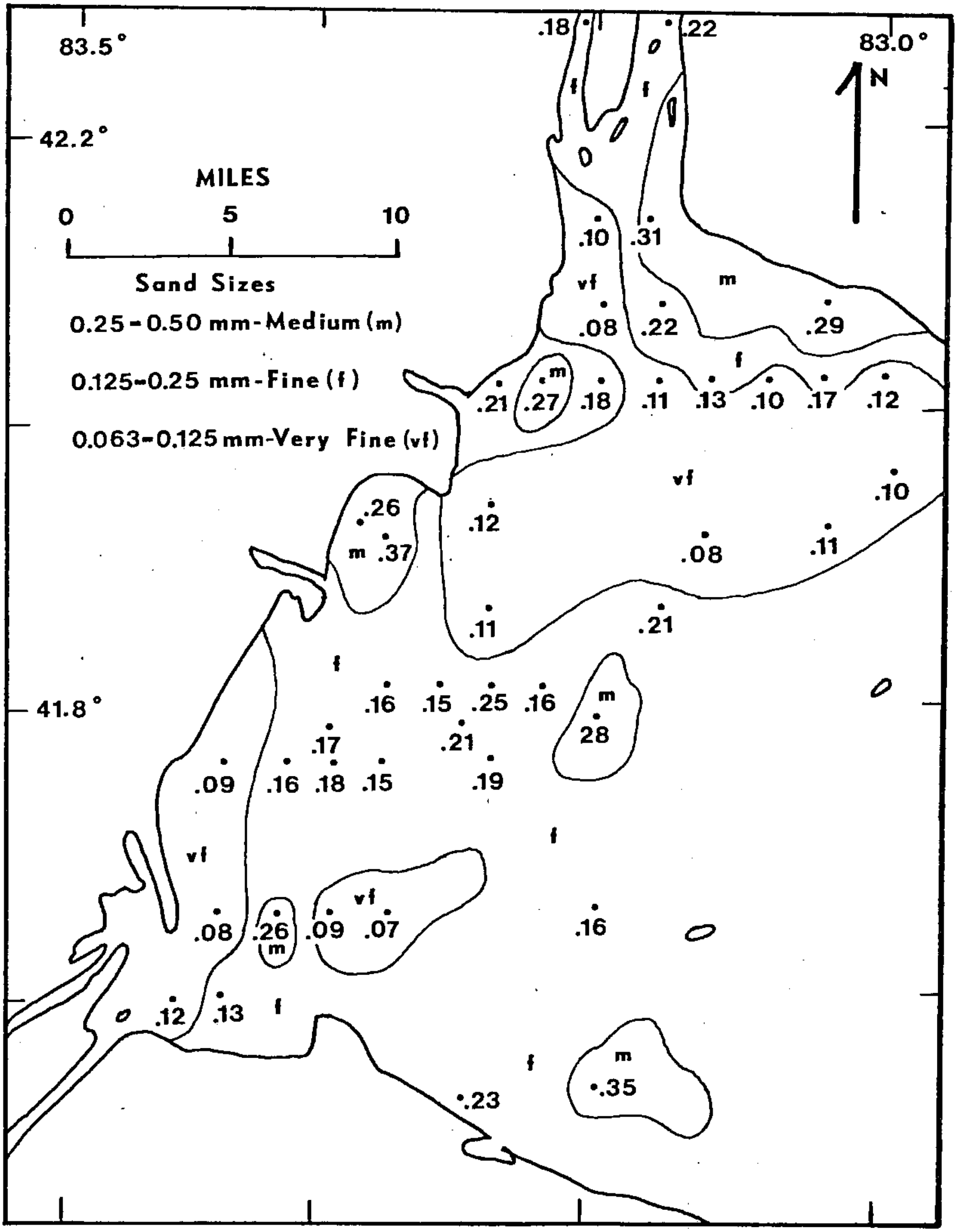

Figure 23. Mean size (in millimeters) of the sand fractions in the western basin surficial sediments.

One consistent feature manifests itself in the sand-size analysis. Along the Michigan shore, the sands present in the immediate nearshore waters grade into coarser sand particles as one moves lakeward. This is also the case with the sands located north of Reno Beach in northwestern Ohio. The lakeward coarsening seems to support the theory that the shoreline zones at certain areas of the western basin possess lower-energy enviroments than those located farther offshore in the lake.

Using the data supplied by the analyses of the surficial bottom sediments, the locations and extents of the Maumee and Detroit sediment plumes can be discussed. In addition, the presence of the Monroe-Raisin plume will be incorporated into the discussion of the bottom-sediment zones within the western basin.

Characteristics of the Detroit, Maumee, and Raisin Rivers

Prior to discussion of the occurence of the various bottom-sediment features within the basin, the sources of these fluvial channels should be discussed and compared in terms of morphology, hydrology, and sediment load.

The Maumee River drains a flat, gently rising till plain which is covered by a thin veneer of glaciolacustrine silts and clays, as well as some small sand ridges. The drainage basin is heavily populated (1.1 million people) over its entire length from Fort Wayne to Toledo. Although the Maumee River supplies much less water to the western basin than does the Detroit River (only one-eighteenth of the total water inflow), it still ranks as the second-most prolific polluter of the area (Limnos, 1972b, p. 22).

River-deposited alluvium, which is derived from the older glacial sediments, ranges from olive-gray muds to yellow-brown pebble and cobble zones. Herdendorf (1970b, p. 3) reports that surface samples contain average grain-size distributions of 25% gravel, 54% sand, and 21% mud (silt and clay). Surface sands are medium to well-sorted, with a median diameter of 0.7 millimeters. Gravel layers also occur at the bottom of two-thirds of the test-bore holes (Herdendorf, 1970b, p. 7).

According to Kemp (1975, p. 372), 1.8×10^9 kilograms of fine-grained sediment are deposited in the western basin by the Maumee River every year. The drainage and sediment loading has increased drastically since the 1880's due to the excavation of drainage ditches in northwestern Ohio (Sly, 1976, p. 361). The silt contained in the outflow from the Maumee River makes up about 25% of the total silt-loading to Lake Erie (Limnos, 1972b, p. 22).

Because the Maumee River has a very gentle stream gradient of only 1.3 feet per mile over its entire length (Herdendorf and Cooper, 1975, p. 12), currents sometimes vary depending on wind direction and velocity. Normally, surface and bottom currents move downstream in a northwestern direction with average velocities of 0.33 and 0.28 feet per second, respectively (Herdendorf, 1970b, p. 7). However, winds from the north-northeast with velocities greater than 15 miles per hour are adequate to stop downstream flow and cause both top and bottom currents to move upstream with an average velocity of 0.23 feet per second (Herdendorf, 1970b, p. 7). The current velocities in the Maumee River are insufficient to erode sand, but are adequate to transport particles as large as coarse-grained sand once the particle is in motion (Postma, 1967, p. 158).

The Maumee River is typical of all the streams and creeks along the western and southern shores of the western basin in that the river and creek mouths are in a state of submergence (Herdendorf, 1970b, p. 7; and Liu, 1970, p. 360). This causes the actual mouth of the Maumee River to be located just upstream from the Maumee-Perrysburg Bridge. The submergence is due to the slow upward tilting of the lake on the Canadian side which has depressed the lower Maumee River to a point where Lake Erie has encroached on the valley, forming the estuary that is present today (Brant and Herdendorf, 1972, p. 713). This tilting is the result of isostatic rebound due to the removal of glacial ice. Moore (1948, p. 697), has calculated that the Toledo area is being depressed at a rate of 0.72 feet per century due to isostatic rebound on the north side of Lake Erie. This drowning of the Maumee River therefore plays a significant factor in the extent and size of the Maumee sediment plume.

The Detroit River supplies over eighteen times more water to the western basin than the Maumee River, but these waters contain less sediment than do the waters of the Maumee. Over 1.4 x 10^9 kilograms of fine-grained sediment enter the western basin every year from the Detroit River (Kemp, 1975, p. 372). Most of the sediment is derived directly from Lake St. Clair, and indirectly from southern Lake Huron. Because of this factor, much of the sediment contained in the outflow from the Detroit River contains the same sedimentological characteristics as does the St. Clair River (Duane, 1967, p. 115). Although the water entering Lake St. Clair is relatively unpolluted, the Detroit River is considered to be the major polluter of Lake Erie (Limnos, 1972b, p. 23). This is due to the heavily populated (4.7 million) and highly industrialized region which surrounds the drainage area of the river.

The northern section of the Detroit River is island-free except for two small islets near Lake St. Clair. This part of the river has an average width of 2,400 feet with a mean depth of 25 feet. The stream bottom at this point is composed mostly of clayey material (U.S. Department of Health, Education, and Welfare, 1965, p. 152). The river currents average 1.80 feet per second, with an average direction of 202° (Herdendorf, 1970b, p. 7).

The lower portion of the Detroit River is much wider and shallower than the upper section, and is separated into two channels by several islands. The channel bottoms are composed of material ranging from medium and fine-grained sands to silts, although some anomalous gravel zones occur along the river banks and in the vicinity of the inter-river islands. Despite its gentle stream gradient of 0.09 feet per mile (U.S.Department of Health, Education, and Welfare, 1965, p. 151), the average velocity of the surface flow of the Detroit River is about 1.5 feet per second (O'Leary, 1966, p. 343). Bottom currents are somewhat more gentle. The high current velocities allow the river to pick up and transport a vast range of material. Subsequently, the large water influx (193,000 cfs) of the Detroit River combines with the one mile per hour current to dominate both water and sediment circulation in the western half of the basin.

The discharge of water from the Detroit River has not been constant over the past 190 years. Eighty years ago, engineers began dredging the river to improve navigation in the area. These channel changes have succeeded in effectively lowering the levels of Lakes Huron and Michigan by at least two feet (Hough, 1963, p. 107). The lowering has resulted in an average water-discharge increase in the Detroit River outflow of at least 1,000 cfs over the past eighty years (Brunk, 1968, p. 1345), as well as a corresponding increase of sediment discharge.

The average-sediment discharge of the Detroit and Maumee Rivers is highly variable due to a variety of interrelated factors. Because of these variable effects, much discrepancy exists between the several proposed sediment-load values for the two rivers. Because it is virtually impossible to measure actual bedload flow into the western basin, all sediment-load figures deal with the suspended load of the rivers. Methods of calculating the sediment load vary from direct measurements to theoretical estimations based on such constants as delivery ratios and basin size.

Probably the most widely accepted data for sediment loads in the Lake Erie basin is proposed by the International Joint Commission (1969). Kemp (1975) used this data to construct a sediment budget for Lake Erie. According to these figures, the fine-grained sediment influx of the Maumee and Detroit Rivers is 1.8 and 1.4×10^9 kilograms per year, respectively. However, the IJC describes this input as the tributary waste discharge to Lake Erie in 1966-67, and calls the inputs "suspended solids" (International Joint Commission, 1969, p. 201). Suspended solids consist of all suspended sediment plus "... small particles of solid pollutant that resist separation by conventional means" (Izaak Walton League of America, 1973, p. 89). These suspended solids also include municipal and industrial wastes, as well as agricultural runoff (International Joint Commission, 1969, p. 201).

The U.S. Geological Survey published a series of articles in which estimates of the average annual sediment deposition of several Michigan and Ohio rivers was reported. The data reported consisted of estimations of the inputs of erosion sources to various rivers in the Lake Erie basin. However, sediment-load figures were based on theoretical calculations, not direct measurements. The sediment load for the Maumee

River was calculated to be 1.1×10^9 kilograms per year (Federal Water Quality Administration, 1970, p. 315). This figure is over 7.0×10^8 kilograms per year less than the loading proposed by the IJC (1969, p. 202).

The U.S. Department of the Interior has published water-quality reports every year in cooperation with the states of Ohio and Michigan. In these publications, values for the suspended sediment of the Maumee, Detroit, and Raisin Rivers are reported. The figures are based on direct measurements at water quality stations along these rivers. Suspended sediment in the Maumee River was measured at Waterville, Ohio, which is only a few kilometers upstream from the actual mouth of the river. The data is therefore fairly indicative of the suspended sediment load in the lower portion of the Maumee River due to the rather constant current velocities in this section of the river. The average suspended-sediment load for 1967, 1969, 1973, and 1974 was 1.5×10^9 kilograms per year (U.S.Geological Survey, 1968, 1971b, 1974, and 1975c). Sediment loads ranged from 1.1×10^9 kilograms per year in 1969 to 2.1×10^9 kilograms per year in 1974.

Suspended-sediment load in the Detroit River has been recorded only once by the U.S. Department of the Interior, and it was calculated that 2.15×10^9 kilograms of suspended sediment entered Lake Erie during the 12-month period of measurement. Measurements were made at the Detroit Municipal water intake, which is about 20 miles upstream from the mouth of the river, and currents in this area are somewhat more powerful than those in the lower stretches of the Detroit River. These higher currents may be responsible for the rather high figure for the suspended-sediment load from the Detroit River.

A five-year average for suspended sediment in the Raisin River is also present (U.S.Geological Survey, 1970, 1971a, 1973, and 1975a). The sediment load, measured at Monroe, has decreased from 1.3×10^8 kilograms per year in 1968 to 0.4×10^8 kilograms per year in 1973. The average over this five-year span is 0.7×10^8 kilograms per year, but present-day sediment load is probably much more equivalent to the load capacities measured in 1973 because of the damming of the lower stretches of the Raisin River.

One additional reference to suspended sediment load will be presented here. Walters and Herdendorf (1975) presented data for the sediment load in the Maumee River from 1949 to 1968. Values ranged from 0.27×10^9 kilograms per year in 1964 to 2.1×10^9 kilograms per year in 1952. The average over this nineteen-year period is 1.04×10^9 kilograms of suspended sediment per year.

As one can see, the sediment influx from the Maumee and Detroit Rivers, as well as the other minor streams in the western basin area, is highly variable and open to debate. This is due to stream flow, precipitation, runoff, and current patterns, which tend to vary from time to time. In addition,many other intangible physical characterictics also tend to affect sediment load. When one combines all the variables with the various methods of measurements that are used to calculate sediment loads, numerous discrepancies can be expected. The differences between various reporting agencies is illustrated in Table XVII, which lists several suspended-sediment load values for the rivers of the western basin.

In addition to suspended-sediment loads, the U.S.G.S. also calculated the particle-size distribution of the suspended sediment at various times of the year. In 1974-75, the entire suspended load of the Detroit River at Detroit was found to be finer than 0.062 millimeters in diameter, with the exception of October, 1974, when only 87% of the suspended load was finer than 0.062 millimeters in diameter (U.S. Geological Survey, 1975b, and 1976). These figures definitely support the theory that the Detroit River is a silt-carrying stream. Suspended sediment load in the Maumee and Raisin Rivers was analyzed for particle-size distribution by the U.S. Geological Survey (1968, 1970, 1971b, 1972, 1973, 1974, and 1975c), and the results are presented in Table XVIII.

The Location and Extent of the Sediment Plumes in the Western Basin

Figure 24 illustrates the approximate locations and extents of the Maumee and Detroit River sediment plumes, as well as a semi-circular, sand-gravel zone which this worker has termed the Monroe-Raisin plume.

Table XVII. Various sediment loads for the rivers in the western basin area.[1]

River	A [2]	B [3]	C [4]	D [5]	E [6]
Detroit	16.0	-	23.7	-	-
Maumee	20.0	11.8	16.7	11.4	-
Raisin	0.04	1.2	0.7	-	-
Portage	0.27	1.1	-	-	1.3
Huron	0.02	0.65	-	-	-
Sandusky-Toussaint	-	2.26	-	-	2.7

[1] all figures are in 10^8 kilograms per year

[2] International Joint Commission (1969)

[3] Federal Water Quality Administration (1970)

[4] U. S. Geological Survey (1968, 1970, 1971a, 1971b, 1972, 1974, 1975a, 1975b, 1975c, and 1976)

[5] Walters and Herdendorf (1975)

[6] Ohio Division of Water (1953)

Table XVIII. Size distribution in the suspended sediment load of the Maumee and Raisin Rivers.

	Percent Finer than the Size (mm) Indicated										
Maumee River [1]	Year	.002	.004	.008	.016	.031	.062	.125	.250	.500	1.00
	1966-67	74	82	88	93	96	98	98	99	99	100
	1968-69	75	81	90	97	98	99	99	100		
	1972-73	77	87	93	96	98	99	100			
	1973-74	75	83	91	94	96	97	97	97	100	
	Average	75	83	90	95	97	98	99	99	99	100
Raisin River [2]											
	1967-68	45	60	73	89	94	97	100			
	1968-69	56	67	79	87	92	96	98	100		
	1969-70	45	60	77	87	93	98	100			
	1970-71	54	65	76	84	92	98	100			
	1971-72	55	70	75	82	90	96	100			
	Average	51	64	76	85	92	97	99	100		

[1] U.S. Geological Survey (1968, 1971b, 1974, and 1975c)

[2] U.S. Geological Survey (1970, 1971b, 1972, 1973, and 1975c)

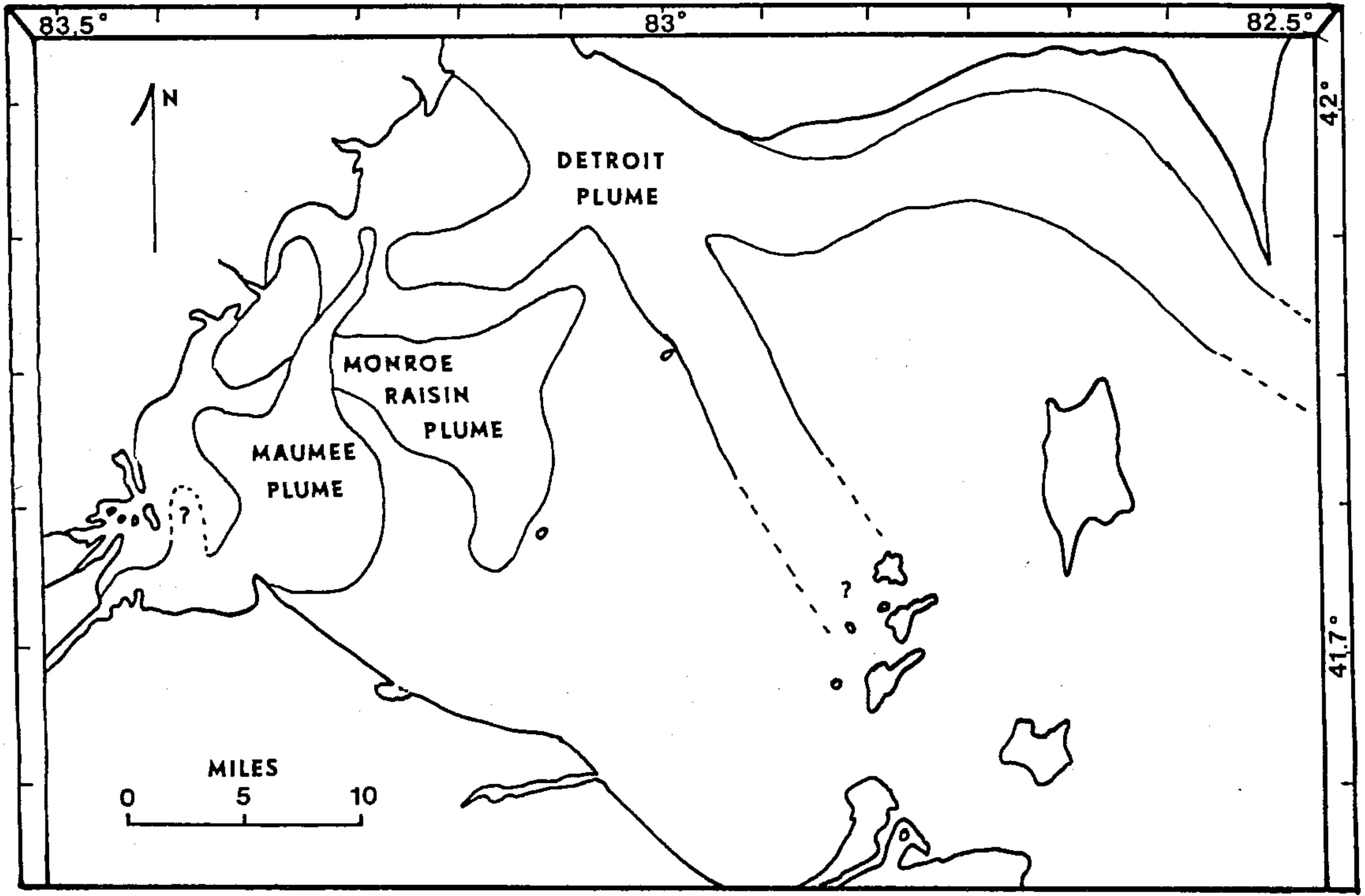

Figure 24. Sediment plumes of the Detroit and Maumee Rivers, plus the Monroe-Raisin plume.

The Detroit River plume has already been partially described in the discussions of the silt and clay distributions in the western basin (Figures 19 and 20). This plume is relatively easy to delineate because of the large size of the Detroit River water mass, which controls a majority of the flow patterns in the western basin. The plume, which is extremely muddy, moves south-southeast from the mouth of the Detroit River. One small branch breaks off towards the Michigan shoreline and disappears near Stony Point. The main body of the plume moves southeast en masse, and a bifurcation occurs in the vicinity of longitude 83° 00′ to 83° 05′ west and latitude 41° 55′ north. The main branch of the sediment plume then extends eastward towards the Pelee Passage and the central basin by following a route that parallels the Ontario shoreline. The much weaker, secondary branch maintains a southeast bearing towards the Bass Islands and the South Passage. The location and extent of this Detroit River plume agrees very well with the Detroit River plume proposed by Walters and Herdendorf (1975) in Figure 7, which was based on mercury concentrations and sedimentation rates.

The initial location and extent of the Detroit River plume can be verified with the aid of NASA ERTS photographs. Photos taken during the summer months, when low turbibity conditions predominate (Burns, 1976b, p. 488), best illustrate the presence of this fluvial feature. The ERTS photos, which were taken on August 18, 1973, June 20, 1974, and July 15, 1976, clearly depict a plume-like feature emerging from the Detroit

River. The plume is seen to extend into the basin for about 25 kilometers in a south-southeasterly direction. Although ERTS photographs taken during the high turbidity seasons (spring and fall) do not depict the Detroit plume as clearly as do the summer pictures, the plume can still be identified in photographs taken on September 7, 1976, April 27, 1974, April 7, 1976, and April 4, 1975.

In comparison, the sediment plume of the Maumee River is much more complex and difficult to explain. This is due to the relative size of the Maumee River water flow, which is only one-eighteenth that of the Detroit River (Federal Water Pollution Control Administration, 1968, p. 34). Because of this factor, the actual Maumee plume is broken up and dispersed by other hydrologic features in the basin, and most of the sediment in the plume is removed from suspension in a relatively small area.

As previously stated, the Maumee River contains very little sand in its bedload, as proven by the minor occurences of sand in the Maumee Bay area and the suspended-load analysis conducted at Waterville, Ohio (U.S. Geological Survey, 1968, 1971b, 1974 and 1975c). Because the suspended load of the Maumee River contains significant percentages of silt-sized particles, it can logically be assumed that any resultant sediment plume would be extremely muddy in nature. The initial Maumee plume confirms this assumption. The fluvial channel exits the river and passes through the eastern half of Maumee Bay as it heads northeast into the lake basin. This movement is illustrated by ERTS photographs taken on June 20, 1974 and August 18, 1973. A minor portion of the plume veers to the east and follows the Ohio shoreline, as documented by Hartley (1961), and dissipates after a few kilometers. At this point, the Maumee sediment plume achieves its maximum width, and extends from latitude 41° 45′ north, 83° 20′ west to latitude 41° 45′ north, longitude 83° 13.6′ west, a distance of about 15 kilometers. The Maumee sediment plume then turns northward and continues as a single unit for about 12 kilometers. Eventually, the plume intersects a sand-gravel zone (the Monroe-Raisin plume) at a point southeast of Monroe. From this location (latitude 41° 50′ north, longitude 83° 15′ west), a small, minor plume veers due west for about 8 kilometers, until it disappears off the Michigan coast.

In the area north of the intersection of the Maumee sediment plume and the Monroe-Raisin plume, grain-size distribution seem to indicate that a portion of the silty Maumee plume "bisects" the coarse-grained Monroe-Raisin plume and extends northward to the area just south of Stony Point (Figure 24). This apparent "channel", which is also shown on the sand, silt, and clay distribution maps (Figures 17, 19, and 20), is very narrow, with a maximum width of only 4 kilometers. This northward extension of the Maumee plume has also been reported by Walters and Herdendorf (1975) and is shown in Figure 7. Hydrologically, it is physically improbable for the Maumee sediment plume to bisect an active

Monroe-Raisin plume, which is an area of coarse sediment created by subaqueous erosion of bottom material.

This apparent extension of the Maumee plume through the Monroe-Raisin plume may be attributed to a combination of two possible hydrologic causes. The Federal Water Pollution Control Administration (1968) has reported that the nearshore area between Stony Point and Toledo contains a series of swirling current features. O'Leary (1966) has also reported that the southeast Michigan shoreline is characterized by several eddy-like features in the nearshore areas. It is possible that these swirling currents may be partially responsible for the silty northward extension of the Maumee plume by "pulling" sediment northward from the main body of the Maumee plume. In addition to the swirling currents in the area, variations in water and sediment output from the Raisin River may have played a significant role in the formation of this northward extension of the Maumee plume during the most recent sedimentation history of the western basin. Upon remembering that this extension of the Maumee plume is based on analysis of surficial (0-2 cm) sediment, it may be possible that the damming of the lower portions of the Raisin River may have significantly affected water and sediment movements in the offshore area. These physical variations may have resulted in a "re-routing" of a portion of the Maumee sediment plume through an inactive zone of the Monroe-Raisin plume. In addition to these two possibilities, silt in suspension from the Maumee plume may completely "overshoot" the Monroe-Raisin plume, and eventually be deposited north of the coarse-grained bottom-sediment feature.

The origin of the Monroe-Raisin sediment plume is complex and difficult to explain. Apparently, a combination of features create a massive reworking of the bottom sediments in the area which form the coarse nature of the sediment zone. This subaqueous erosion has been reported by Walters (1974) to be occurring both north and east of the offshore Monroe area. The reworking can be traced to many influential factors. The Raisin River enters the lake at Monroe, and contributes an average of 714 cubic feet of water per second to the basin (Federal Water Pollution Control Administration, 1968, p. 34). In addition to the water input, over 0.7×10^8 kilograms of sediment per year (U.S. Geological Survey, 1970, 1971a, 1972, 1973 and 1975a) are also contributed to the western basin from this river. Although these figures are small when compared to the input data of the Detroit and Maumee Rivers, it probably is sufficient to significantly affect the enviroment of the lake bottom in this area. In addition, the lake bottom in the vicinity of the Monroe-Raisin plume is slightly shallower than the surrounding area, due to the underlying Silurian bedrock, and this factor may also contribute significantly to the reworking of the bottom sediments in the Monroe-Raisin plume.

More important than all these features, however, are the current-flow patterns of the area. Southward-flowing waters from the Detroit River move along the Michigan coast and collide with the eastward-flowing Raisin River water mass and the northward-flowing Maumee River water mass to create the complex currents which control the subaqueous reworking of the bottom sediments in this area. This results in the formation of an eastward-trending feature which appears to emanate from the Raisin River. On the west side of the Maumee plume extension, the Monroe-Raisin plume is only about eight kilometers wide, and the eastern portion is much larger, extending from about fifteen kilometers off-shore to the vicinity of West Sister Island. The shape of this feature is directly related to the southward-flowing water mass of the Detroit River, which deflects the eastward-trending sand body to the south in a circular, clockwise pattern towards West Sister Island and the Ohio coast. The sand body located near West Sister Island may be directly related to this feature, as proposed by Verber (1957). This clockwise-swirling feature is also the primary cause of the northwest-flowing littoral drift along the Ohio shoreline from Reno Beach to Little Cedar Point, and the resultant high-sand zone along this section of the Ohio coast. The longshore current is eventually superseded by the outflow from the Maumee River. Aside from this southern branch, a minor, northeast-trending body also extends from the main portion of the Monroe-Raisin plume. The clockwise flow of this southwestern Lake Erie sediment feature has been documented by numerous workers, including Hough (1958), the

Page 158 is blank

Federal Water Pollution Control Administration (1968), and Simons (1976).

One additional bottom-sediment feature in the western basin should be discussed in further detail. This feature is the extremely high-sand zone which is located just north of Maumee Bay near Turtle Island, as shown in Figure 17. Both Hartley (1960) and Verber (1954) attribute this sandy zone to the northwest littoral drift that is predominant along the northwest Ohio shore. According to these two workers, the longshore current carries sand along the Ohio shoreline, as well as depositing sand across the mouth of the Maumee Bay from Little Cedar Point to Turtle Island. None of the sand originates from the Maumee River due to the sluggishness in the lower reaches of the river (Herdendorf and Cooper, 1975, p. 16). This fact is supported by the presence of muds in the lower reaches of the Maumee River, as well as in most of Maumee Bay. According to Hartley (1960, p. 72), almost all of the sand located in Maumee Bay is derived from either sources in the lake itself or from the proposed sand bar that stretches across the mouth of the bay. Finer sand in the underwater sand bar is re-suspended by wave action from the open lake, and the suspended material is transported into Maumee Bay. This results in the occurence of medium to fine sands in the bay, whereas the lower reaches of the Maumee River contain much more silt and clay (Herdendorf and Cooper, 1975, p. 129-131). A more detailed description of the sediment sources and energy zones in Maumee Bay have been documented by McBride (1975).

The proposed extension of an underwater bar across the mouth of the Maumee River is valid except for one important question: how does the longshore current cut across the water mass of the Maumee River as it exits Maumee Bay and enters the western basin? Hydrologically, it is possible for some material to be transported to the vicinity of Turtle Island by longshore currents, but it is the opinion of this worker that other factors play a significant part in the formation of this extremely coarse-grained bottom-sediment feature. Southerly-flowing longshore currents along the Michigan shoreline carry large amounts of sediment in suspension, as shown by the formation of Woodtick Peninsula and North Cape. As this flow nears Maumee Bay, however, it is possible that it collides with the outflow from the Maumee River, and subsequently dumps most of its sediment (both bedload and suspended material) in the Turtle Island area. In addition to this collision of currents, the dumping of dredged spoils in the area may also contribute significant amounts of coarse-grained material to this area, as reported by the U.S. Army Corps of Engineers (1974, p. 1-85).

Sediment Cross Section Analyses

The cross sections used by Walters and Herdendorf (1975) roughly transect the proposed sediment plumes in the western basin (Figure 12). Analysis of the cores along these cross sections should clarify the presence of the fluvial channels of the Maumee and Detroit Rivers, as well as the extent of the Monroe-Raisin plume. Any variations in the depositional history at any one sample location will also become evident. These variations should reveal any changes in the location and extent of the sediment plumes which may have been caused by lake level changes and/or fluctuations of sediment and water input.

The results of each core analysis have been calculated and transferred to cross sections. The appropriate sand and silt concentrations, as well as the sand/mud ratio, mean-sand size, and textural classification for each core interval are recorded on these cross sections, which have an average vertical exaggeration of 27,000 times.

One additional analysis was also conducted. Walters and Herdendorf (1975) calculated the depth of the original mercury increase in the cores they analyzed, which occurred in 1939 (Walters and Herdendorf, 1975). Using this data, the total amount of sediment deposited since that time can be calculated. The resultant sedimentation rates obtained from this research were used to construct the map in Figure 7, and these same rates of deposition will be used to additionally delineate the locations of the Detroit and Maumee sediment plumes, as well as the other depositional areas in the western basin. Table XIX lists the sedimentation rates for the sample locations used in this study.

Table XIX. Sedimentation rates for some of the samples used in this study.

Location	Sedimentation rate (cm/yr)[1]	Location	Sedimentation rate (cm/yr)
2	0.19	48	0.31
3	0.50	49	1.88
5	0.31	50	NR
11	0.63	51	0.25
15	0.27	52	0.19
17	0.97	55	1.19
18	1.77	56	0.88
19	2.22	57	1.81
21	erosion	58	1.13
23	0.56	59	1.13
24	0.84	60	1.00
25	1.25	61	0.31
26	1.56	63	NR
27	1.13	64	0.50
28	NR	65	0.88
29	erosion	66	1.14
30	0.06	67	0.75
31	0.50	68	erosion
33	0.44	69	erosion
34	1.25	71	1.13
35	2.19	72	0.19
36	0.19	73	NR
37	0.75	74	0.44
38	1.00	75	1.59
39	0.31	76	NR
40	1.25	78	0.19
41	erosion	79	0.25
42	0.88	80	1.75
43	0.97	82	0.25
44	1.13	83	0.63
45	0.38	84	0.63
46	0.38	85	0.88
47	1.00	86	1.13

[1] from Walters (1974)

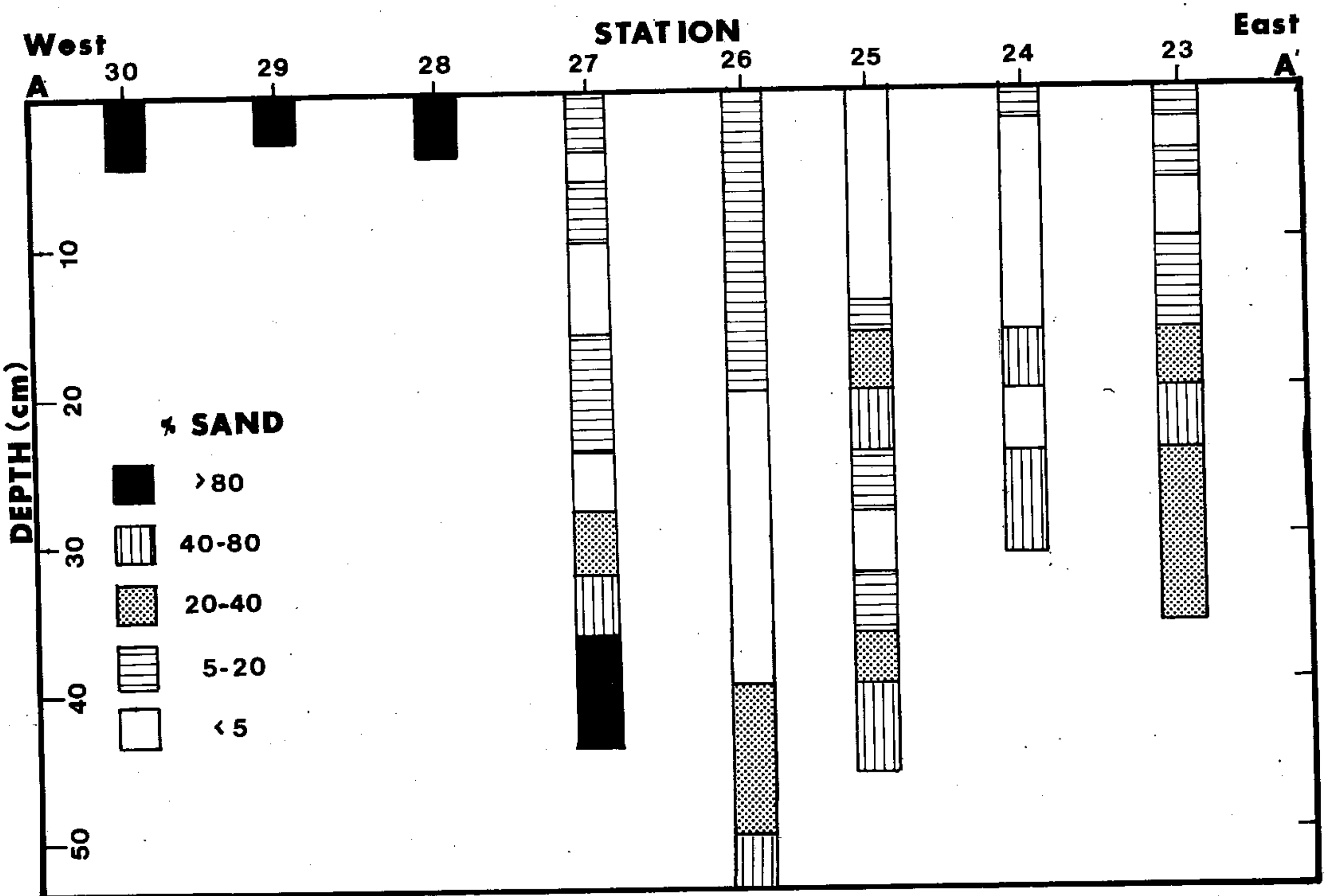

Figure 25. Sand concentrations in the core intervals along profile A-A′: station locations are shown in Figure 12.

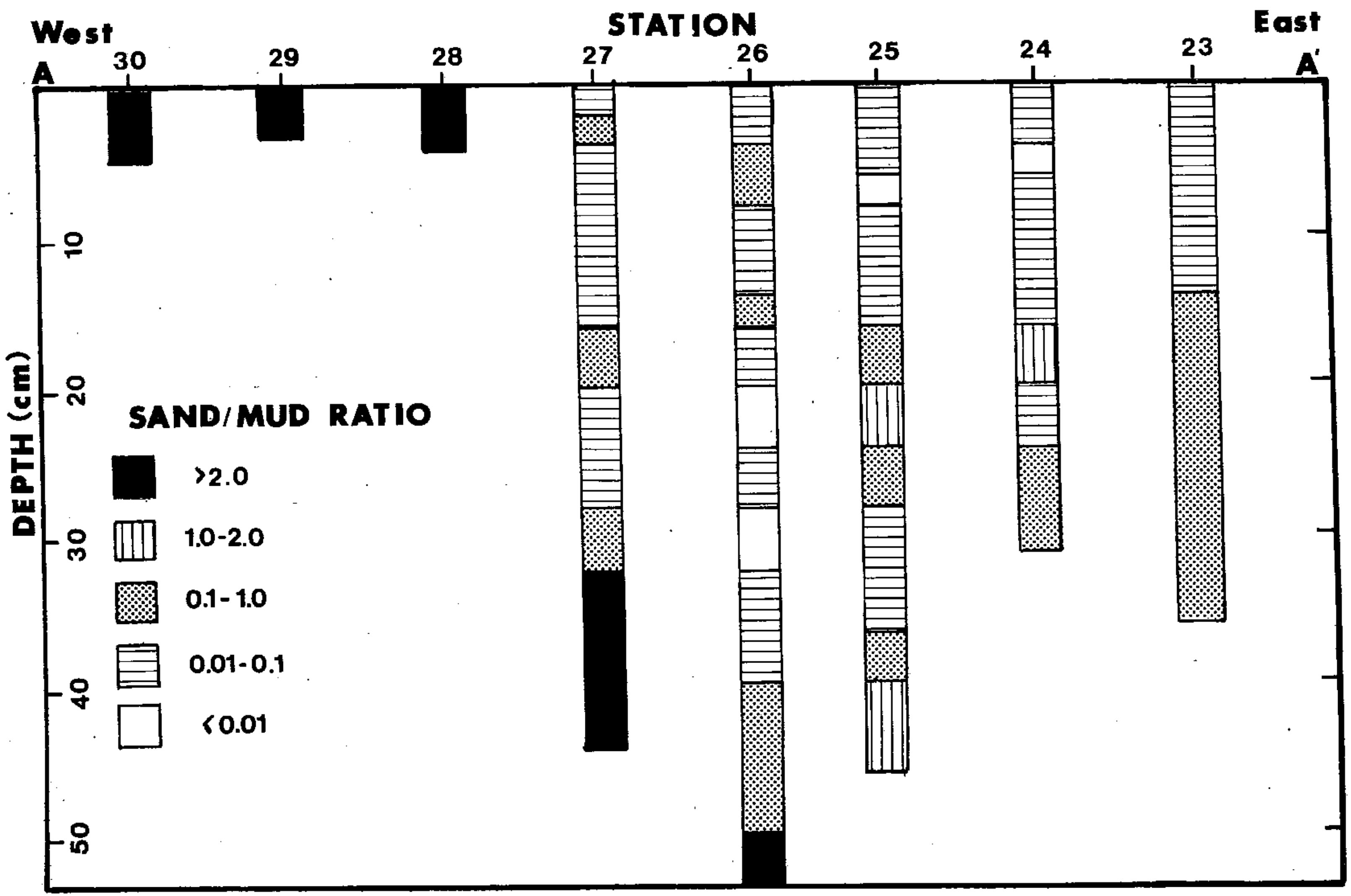

Figure 26. Sand/mud ratios in the core intervals along profie A-A'; station locations shown in Figure 13.

sand intervals in each core, which range from 20 to 50 centimeters in depth, were all deposited about 1940, whereas the upper sand lenses in cores 24 and 25 were deposited about 1953. The similar ages of these sand features seem to indicate that they are related to some physical changes in the enviroment of the entire western basin, instead of being related to a random variation in sedimentation. This is definitely the case with the deepest sand lenses, which were deposited during a period of low lake levels and minimum water input from the Maumee and Detroit Rivers (Walters and Herdendorf, 1975).

The grain size of the sand fractions within the core intervals of this cross section parallel sand concentrations (Figure 27). Medium to fine sands (0.15 to 0.332 mm) are present in the nearshore zone (cores 28, 29, and 30), as well as in the sand lenses located in the Detroit sediment plume. However, the majority of the sands in the Detroit plume are very fine to fine (0.09 to 0.15 mm) in nature, although over half of the intervals in this section of the profile (cores 23 to 27) contain insufficient sand to analyze. This is an additional indicator of the fineness of the sediments within the Detroit River plume.

Silt concentrations in this cross section range from 2 to 85% (Figure 28). The sandy nearshore samples contain expectedly small amounts of silt (<15%), as do the sand lenses in cores 26 and 27. The remaining sand lenses in the Detroit plume contain higher silt concentrations of up

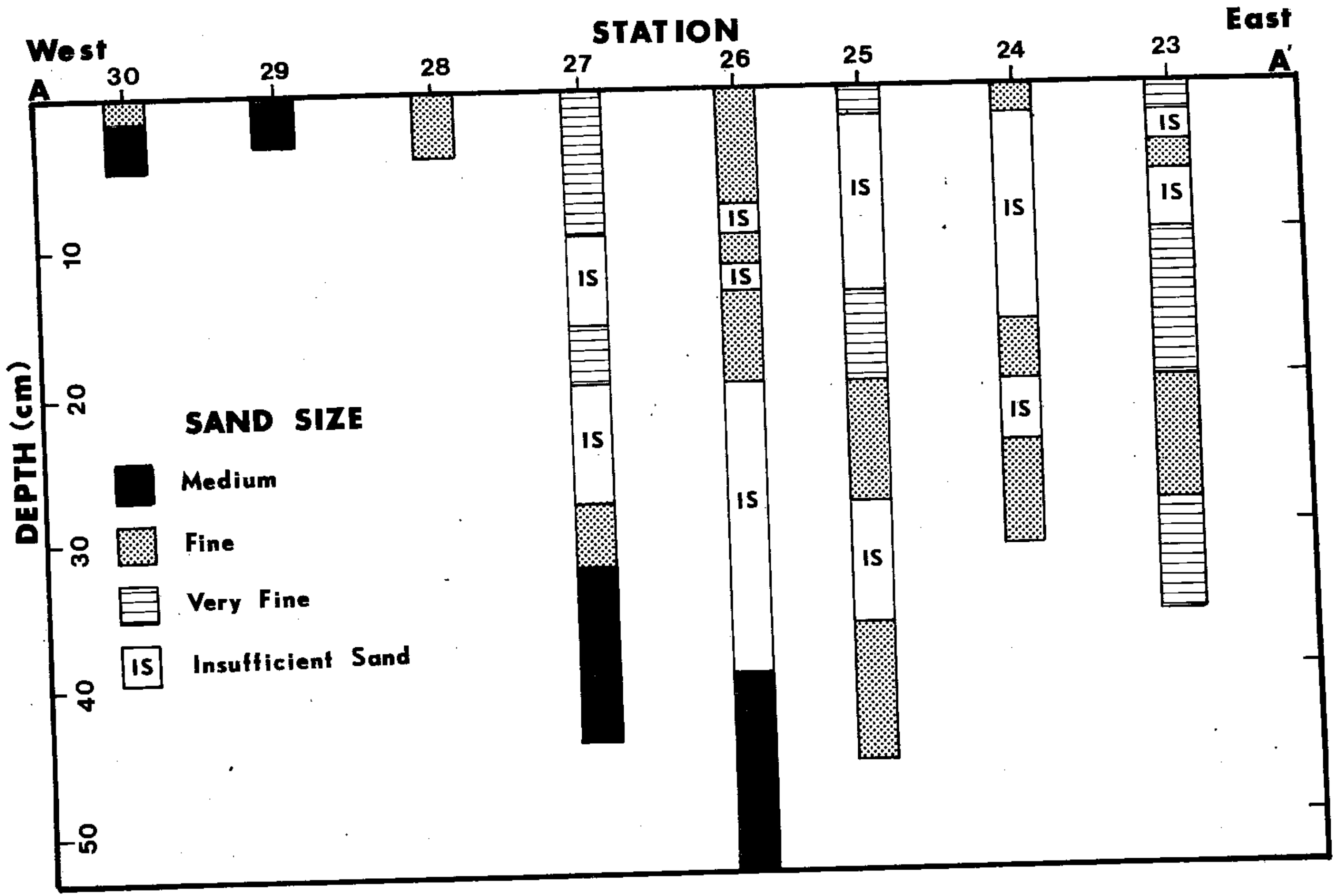

Figure 27. Mean size (in mm) of the sand fractions in the core intervals along profile A-A′; station locations shown in Figure 12.

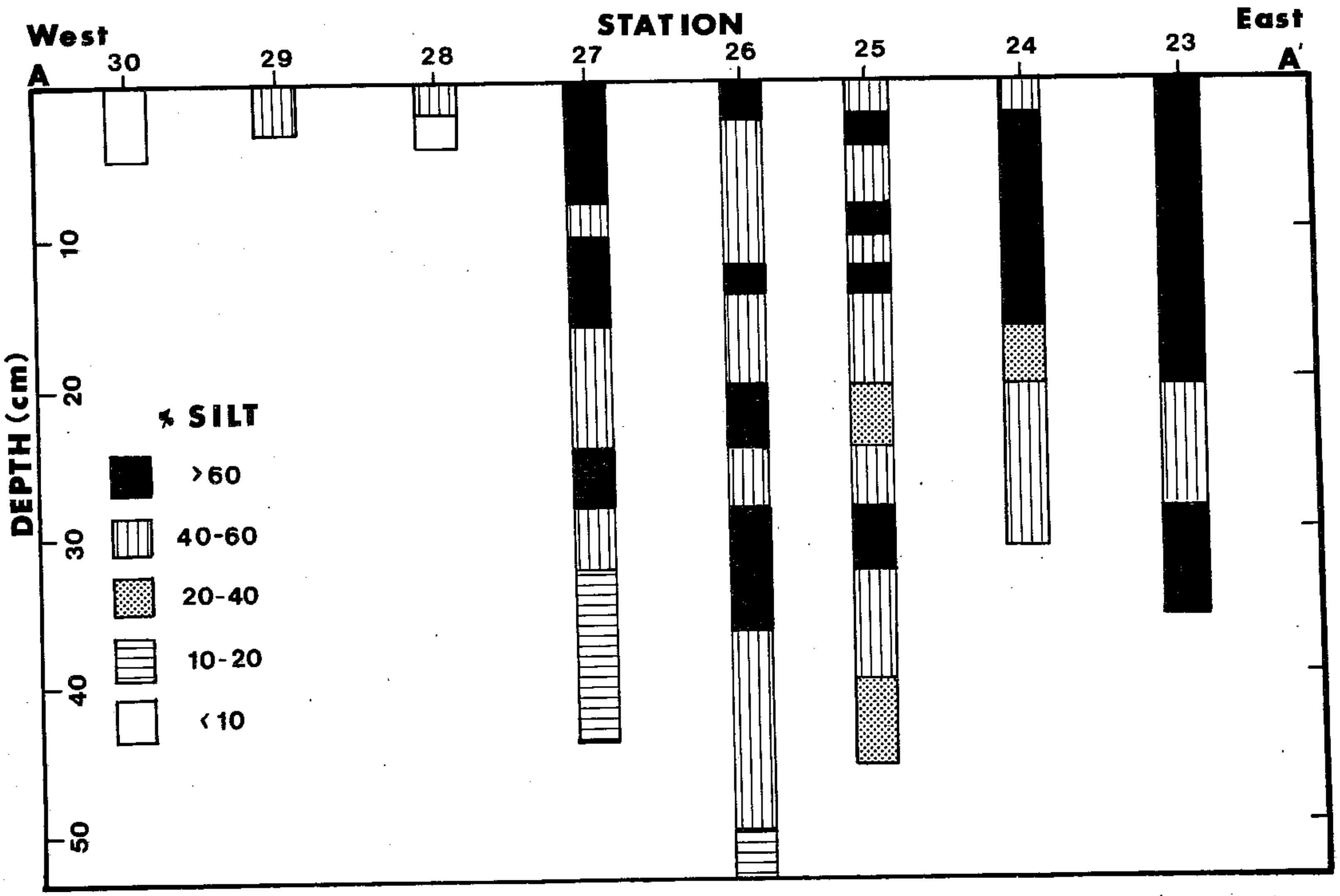

Figure 28. Silt concentrations in the core intervals along profile A-A′: station locations shown in Figure 12.

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to 50%. Apart from these sand zones, silt concentrations are fairly consistent in that almost all of the intervals within the plume contain greater than 50% silt. The only noticeable trend within the silt occurences in Figure 28 is the apparent increase in silt concentrations from west to east across the Detroit River sediment plume, which is over 21 kilometers wide in cross section A-A′.

Texturally, the sediment within the plume is mostly composed of clayey silt and silt, as shown in Figure 29. The sand lenses located in the deeper portions of cores 23, 24, and 25 are marginal sand-silts, depending on the concentrations of fine-grained sediment. The sand zones in cores 26 and 27, as well as the nearshore-sand zone, are all sandy according to Shepard's (1954) textural classification.

Figure 30 illustrates the various accumulations of sand (and gravel), silt, and clay in cross section A-A′ since 1939. In the nearshore zone, only core 30 presents any detectable depositional history, and this is relatively minor, as indicated by the small sedimentation rate (0.06 cm/year) calculated by Walters (1974). The other two cores in the nearshore zone (28 and 29) show no sediment accumulation since 1939 because of subaqueous erosion in this shallow (1 to 3 foot) area.

The Detroit sediment plume, on the other hand, illustrates a significant depositional history. Up to 52 centimeters of sediment have been deposited since 1939,

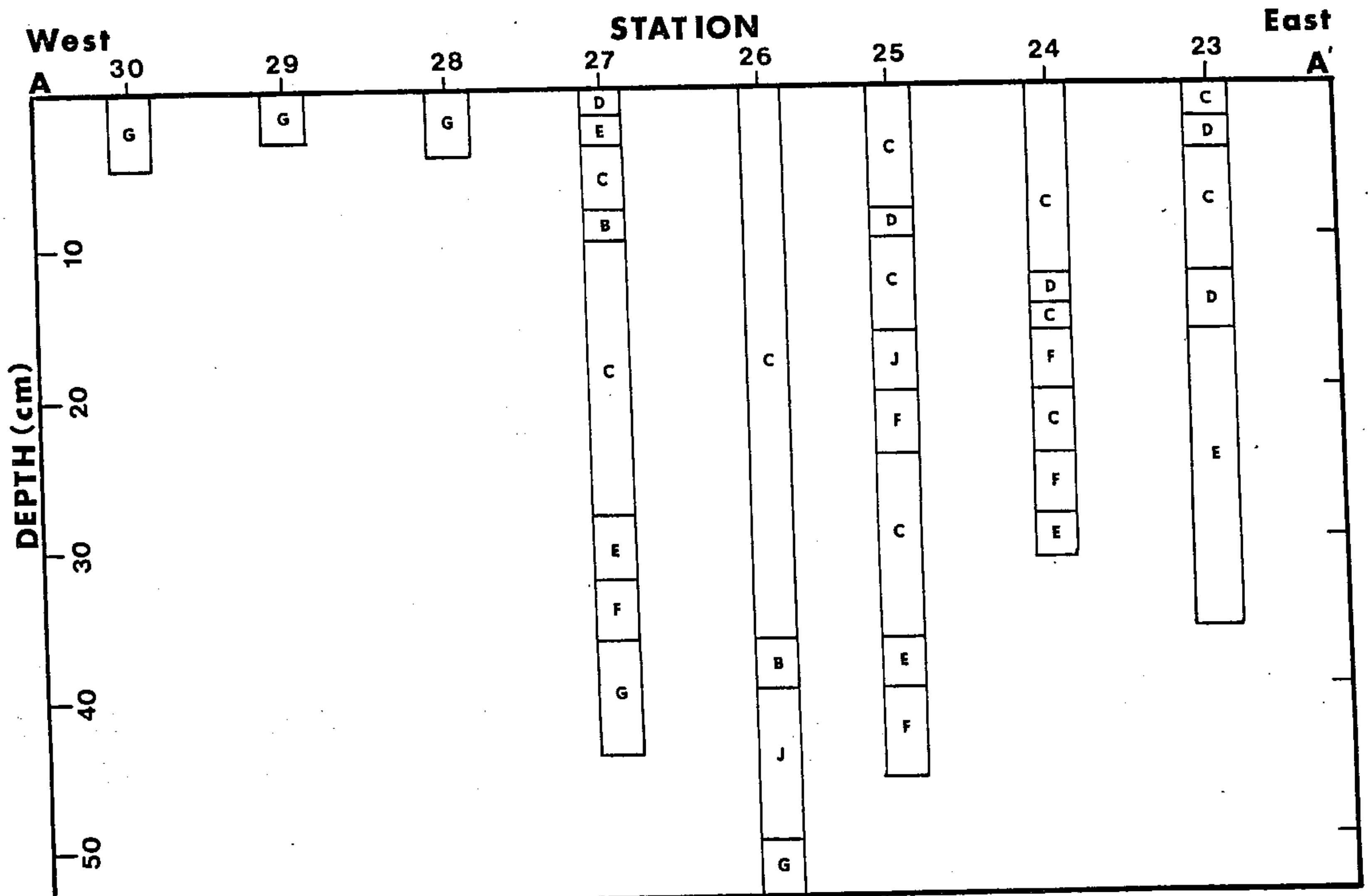

Figure 29. Textural classification of the core intervals along cross section A-A′ based on diagram shown in Figure 22; station locations are shown in Figure 12.

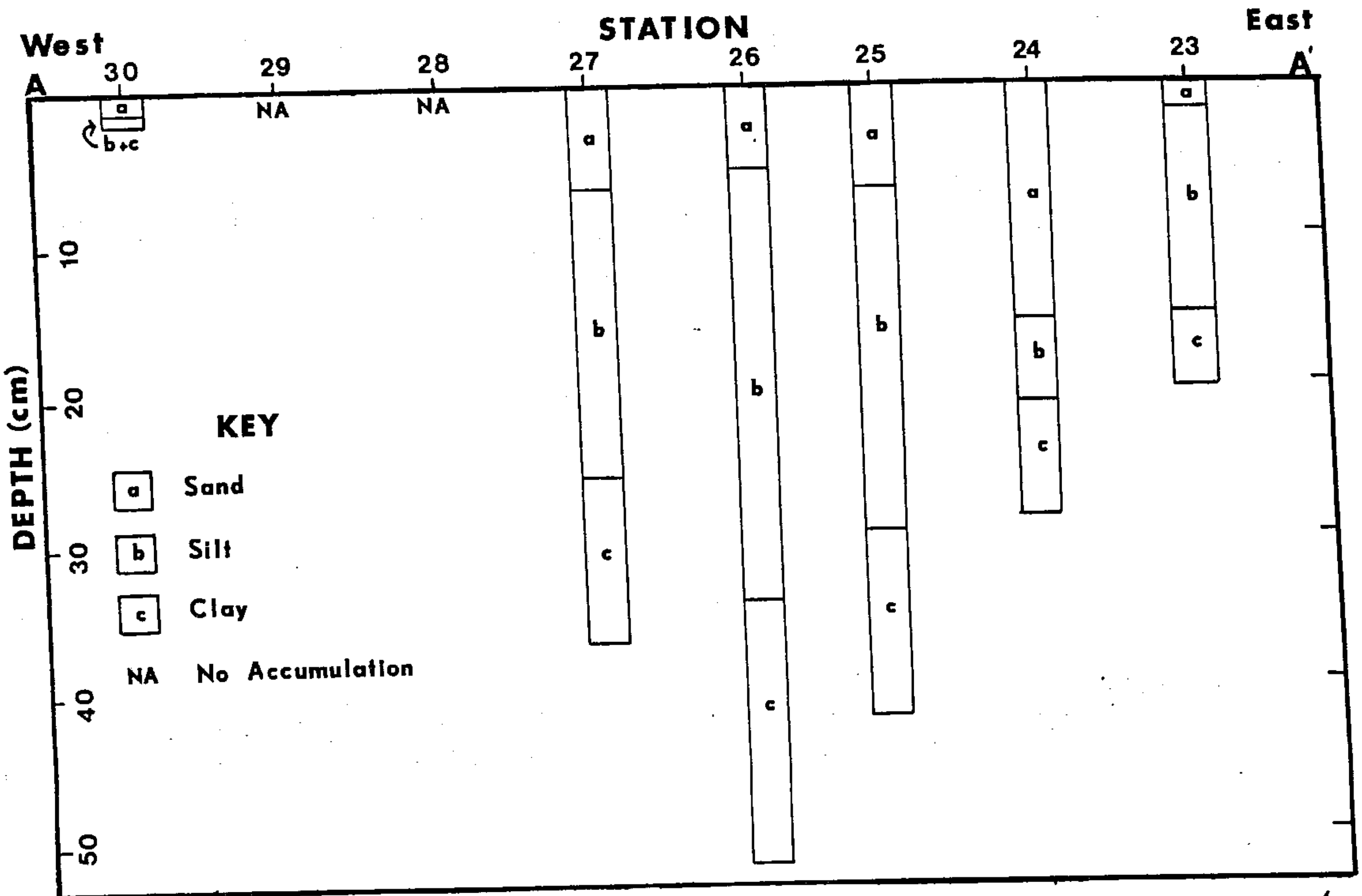

Figure 30. Sand, silt, and clay accumulations since 1939 in cross section A-A′; station locations are shown in Figure 12.

with silt being most abundant. Maximum sedimentation has occurred at core 26 (52.0 cm), which seems to indicate that this location (latitude 41° 59′ and longitude 83° 06′ west) is near the main channel of the Detroit plume. Sediment deposition at the surrounding core locations indicate that the plume east of the main channel is over three times wider than the plume on the western side of the channel (Figure 30). The lateral extent of the plume corresponds with the proposed eastward extension of the Detroit sediment plume as it moves deeper into the western basin of Lake Erie.

Cross Section B-B′

Cross section B-B′ crosses parts of five depositional zones as it transects the western basin along latitude 41° 55′ north. From west to east, these features are the Michigan-nearshore zone at core 68 (longitude 83° 18′ west); the northward extension of the Maumee plume at cores 67 and 16 (longitude 83° 16′ west to 83° 14′ west); the western branch of the Detroit plume at cores 65 and 15 (longitude 83° 12′ west to 83° 10′ west); the northeast extension of the Monroe-Raisin plume at cores 14, 41, and 42 (longitude 83° 10′ west to 83° 06′ west); and the main body of the Detroit plume at cores 39, 40, and 13 (longitude 83° 06′ west to 83° 01′ west). These depositional zones can be partially differentiated using the sediment-analyses results obtained from the core intervals along this cross section.

The sand concentrations along this cross section are presented in Figure 31. In the west, the nearshore zone off Michigan is characterized by high sand-gravel occurences up to 88 per cent. The northern extension of the Maumee plume, which is only about 4 kilometers wide, contains rather low (<4%) sand values which gradually increase to 10-20% with depth. The coarsening down the core may be related to fluctuations in sedimentation in the area. As previously explained, the damming of the Raisin River has significantly affected both water and sediment input to the western basin from that river. The low sand concentrations in the top 4 centimeters of cores 67 and 16 (Figure 31) may be the result of the increase in silt concentrations northward from the main body of the Maumee sediment plume. The higher sand values present below the 4 centimeter depth may be indicative of a smaller influx of silt prior to the damming of the Raisin River. This factor may have combined with other hydrologic conditions to form the coarser sediments that are present in the middle portions of cores 67 and 16.

Moving eastward into the western branch of the Detroit plume (cores 65 and 15), which is only about 7 kilometers wide at this point, sand values in the surficial sediments maintain rather low (<5%) concentrations. This is especially the case in core 65, where the low sand zone extends to a depth of about 20 centimeters. Below 20 centimeters, however, sand values increase to over 24%, as shown in Figure 31. Using Walters' (1974) sedimentation-rate data, these sandier

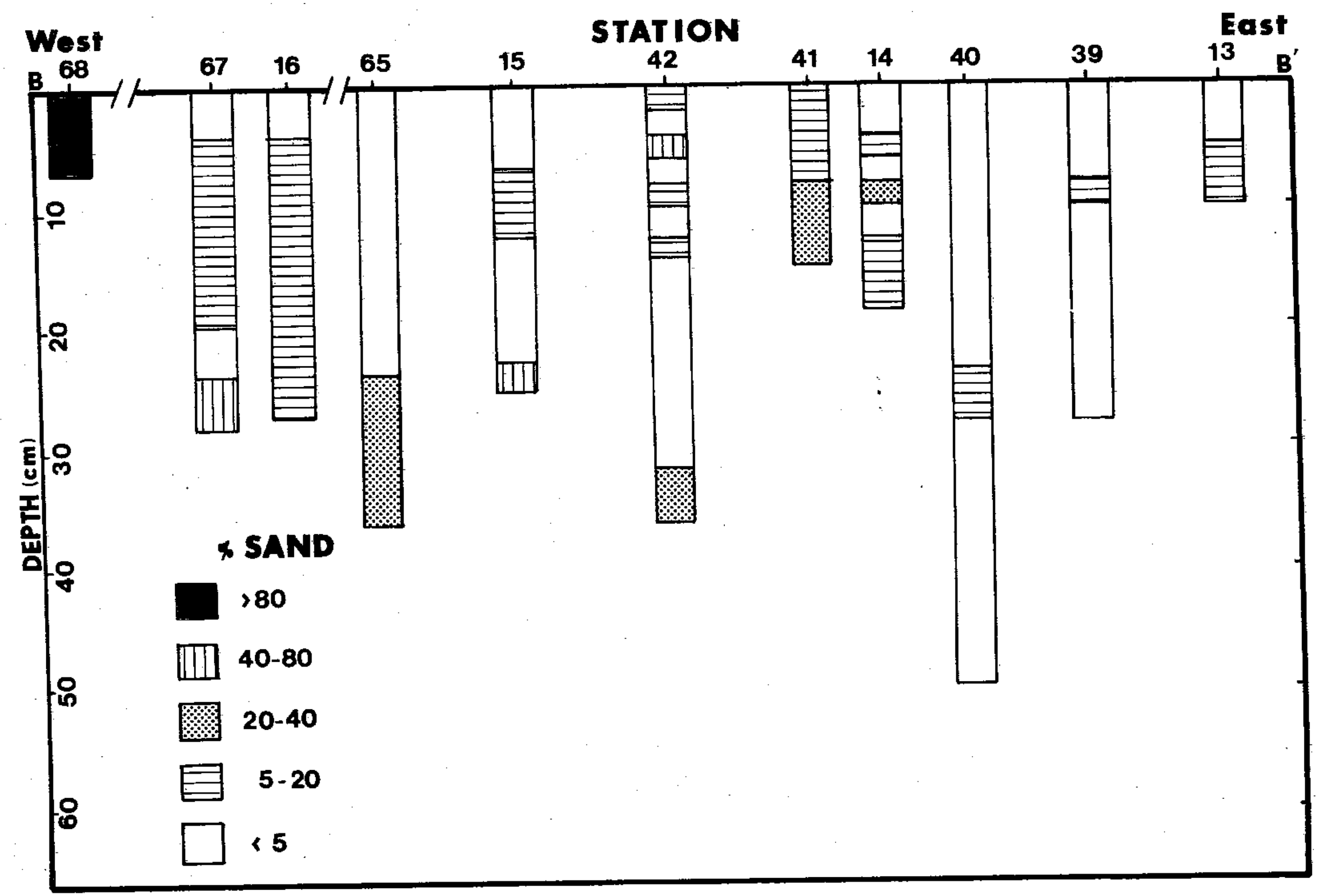

Figure 31. Sand concentrations in the core intervals along cross section B-B ; station locations shown in Figure 12.

zones can be dated as having been deposited during the period from 1940 to 1942. As previously explained, low lake levels, as well as below average water inputs from the Detroit and Maumee Rivers, must have resulted in the formation of a higher energy enviroment in this section of the lake basin. This factor also explains the presence of the sandy (41%) interval in core 67, which has also been dated as having been deposited in the early 1940's.

Cores 41, 42, and 14 illustrate the influence of the northeast branch of the sandy Monroe-Raisin plume by the presence of consistently higher sand concentrations than are located in the surrounding cores (Figure 31). From 0 to 16 centimeters, sand values from 5 to 48% are present in the core intervals. The variability of sand occurence throughout these three cores is probably related to lake-level fluctuations during past sediment deposition.

In the main body of the Detroit sediment plume, sand values in the 0.9 to 7.8% range are present (Figure 31). Most of the core intervals contain very low (<5%) sand concentrations, with the exception of a sandier lens which is present throughout the three cores (13, 39, and 40). This coarser lens is dated to have been deposited during the early 1940's during low lake levels. The slight increase of sand within the lens can be attributed to deviations in the depositional history of the Detroit sediment plume caused by the variations in lake level. The additional sand was probably derived from the Monroe-Raisin plume to the west, which was also much sandier during the low-lake period from 1940 to 1944.

Sand/mud ratios basically parallel the previous discussion of sand concentrations along this cross section (Figure 32). Very high ratios (>2) only occur in the extremely coarse-grained nearshore zone (core 68). Much of the remaining cross section is characterized by ratios between 0.1 to 1.0, especially in the western and main branches of the Detroit sediment plume. Relatively high (1-2) values are present in the coarser Monroe-Raisin plume, as well as in the northward extension of the Maumee plume.

Silt concentrations in cross section B-B′ are also very good indicators of the different depositional zones in this section of western Lake Erie, as shown in Figure 33. As expected, the nearshore zone contains very little silt (1.5%). The northern extension of the Maumee plume contains high values (>60%) which are relatively constant throughout these two cores (67 and 16). This fairly constant silt occurence seems to indicate that any changes in the enviromental energy within this portion of the basin affect sand and clay to a much greater extent than silt, which seems to remain constant. The western branch of the Detroit plume contains high (>60%) silt values in cores 65 and 42, whereas lower values (<60%) are present between these two cores at station 15, as shown in Figure 33. This parallels the sand concentrations of the plume which indicate that core 15 is consistently sandier than the eastern and western sides of the Detroit

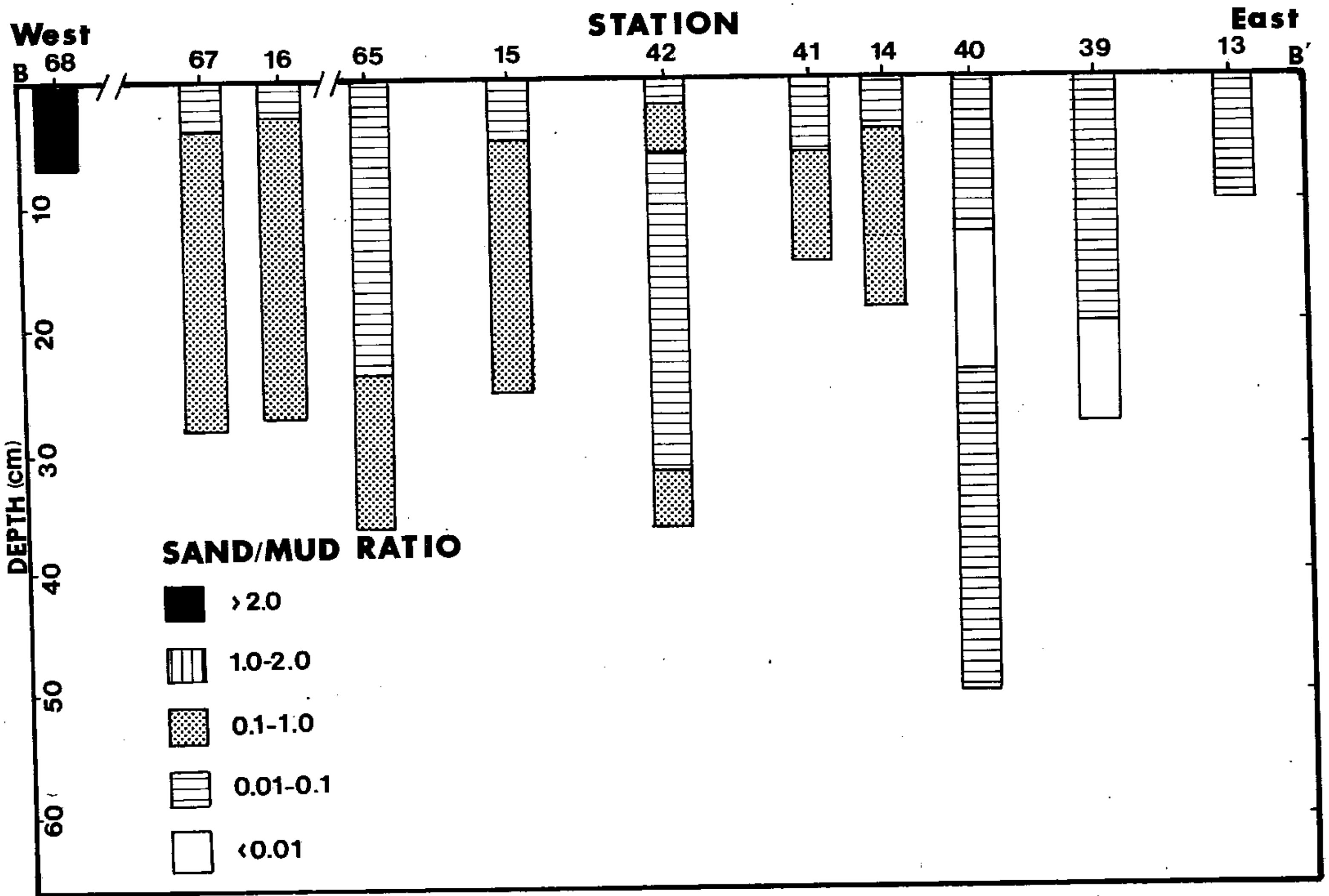

Figure 32. Sand/mud ratios for the core intervals along profile B-B′; station locations shown in Figure 12.

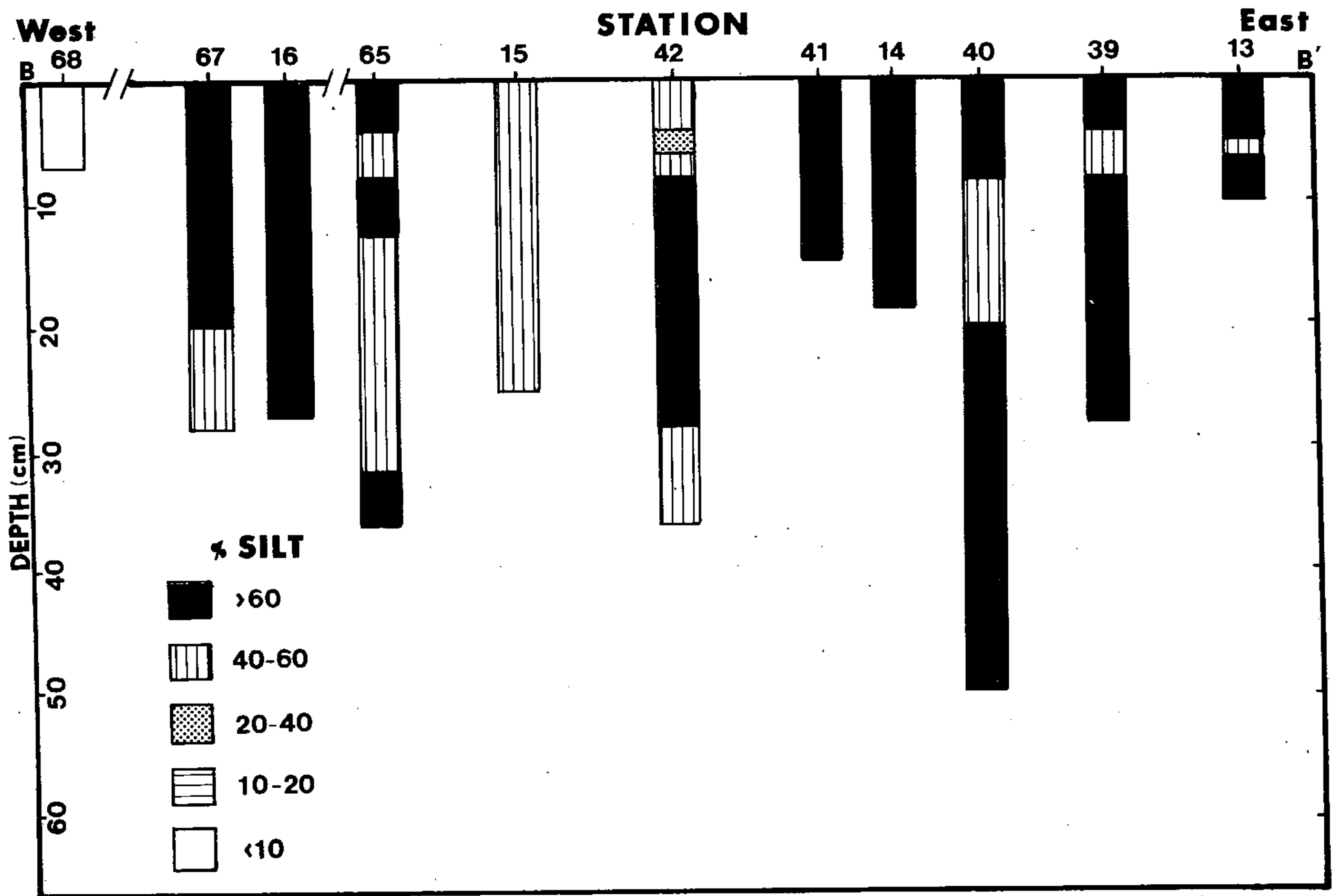

Figure 33. Silt concentrations in the core intervals along profile B-B′; station locations shown in Figure 12.

plume.

In the Monroe-Raisin plume, it is interesting to note that although this is a supposedly sandier feature, as shown in Figure 31, high (60 to 93%) silt concentrations are usually present. This fact seems to demonstrate that the northeast branch of the Monroe-Raisin plume is primarily a silt-depositing feature with very little clay included in the sediments. Both east and west of this zone, however, clay concentrations are normally much higher due to the different currents within the Detroit plume at both these locations (cores 65 15, 40, 39, and 13).

The main body of the Detroit plume contains relatively high (60-85%) silt concentrations, except in a slightly coarser lens which runs through the three cores that are present in the plume (cores 13, 39, and 40). Combined with the low sand occurences in the plume (Figure 31), this seems to verify that clay values are fairly consistent throughout the area of the Detroit sediment plume.

Texturally, much of profile B-B′ can be classified as either a silt or silty clay, with a few exceptions, as shown in Figure 34. The nearshore zone is sandy in nature, while a few sandy silt, silty clay, and silty sand intervals are present in cores 14, 15, 16, 41, and 65. Of the five depositional zones encountered in this profile, only the cores in the main body of the Detroit plume contains relatively consistent grain-size distributions.

Figure 35 illustrates the total sediment accumulation

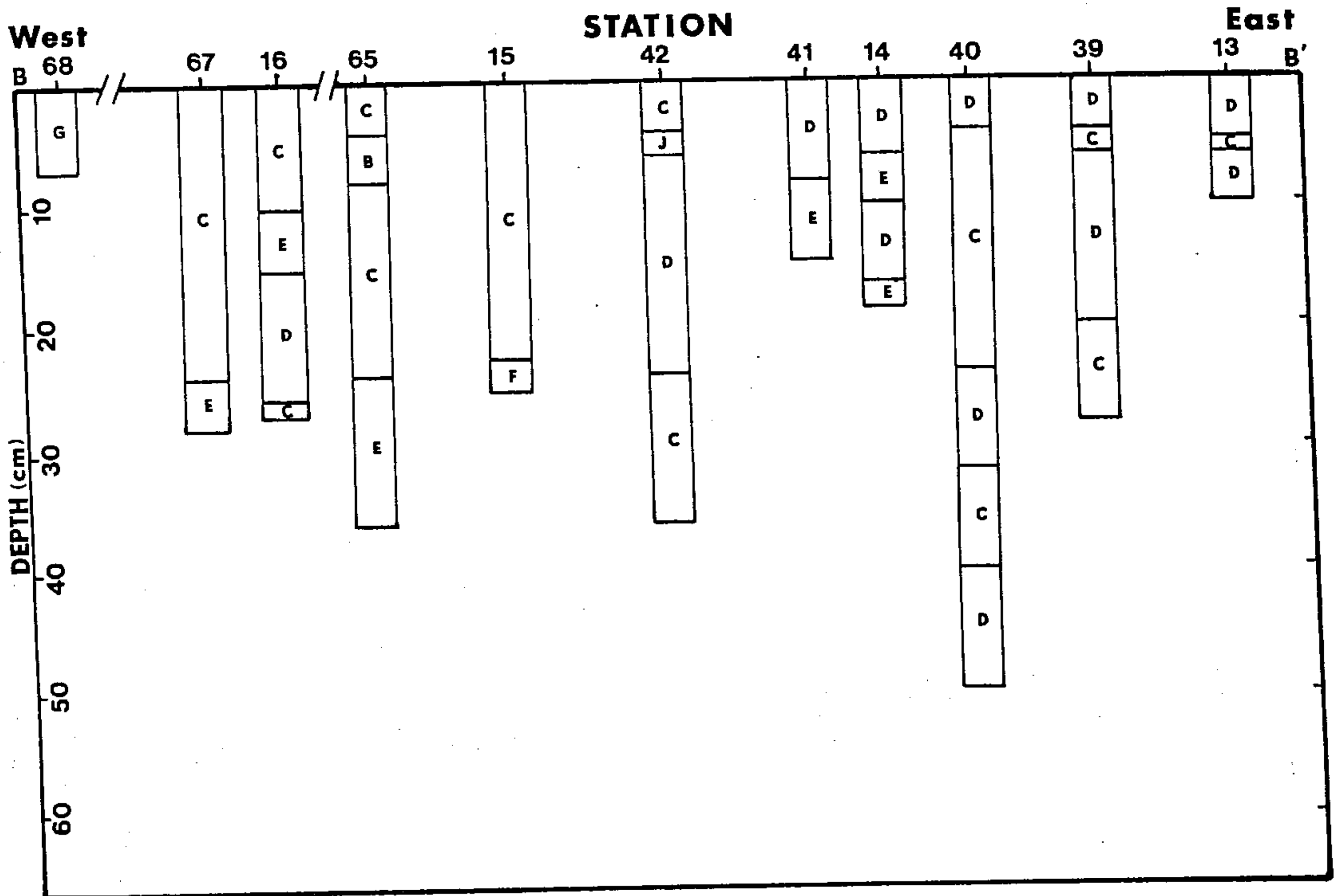

Figure 34. Textural classification of the core intervals along cross section B-B′ based on the diagram shown in Figure 22; station locations are shown in Figure 12.

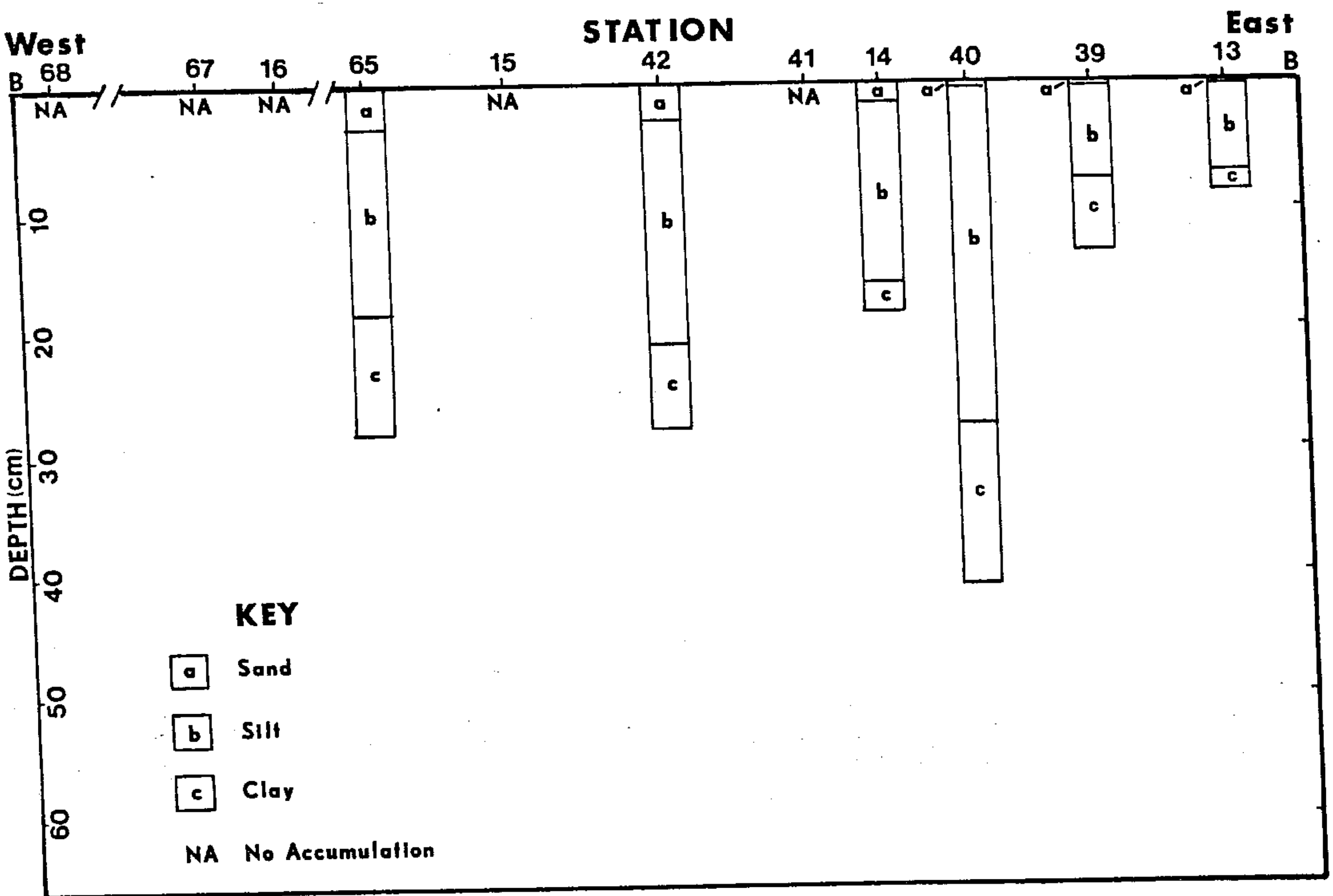

Figure 35. Sand, silt, and clay accumulations since 1939 in cross section B-B'; station locations are shown in Figure 12.

in the cores since 1939 in this cross section. In the nearshore zone (core 68) and the northward extension of the Maumee plume (cores 16 and 67), no depositional history exists due to subaqueous erosion (Walters, 1974) caused by the complex currents located in this section of the western basin (O'Leary, 1966). In the western branch of the Detroit plume, only core 65 contains any appreciable sediment accumulation since 1939. Over 28 centimeters of material have been deposited at this location, with silt making up almost 56% of the sediment. According to Walters (1974), subaqueous erosion has destroyed any evidence of deposition since 1939 in core 15. In the Monroe-Raisin plume, sedimentation has occurred in cores 42 (29 cm) and 14 (19 cm), while no information is present for core 41. In this feature, silt also predominates, making up an average of over 71% of the deposited material.

The main body of the Detroit plume possesses an interesting sedimentation history since 1939, as shown in Figure 35. Over 41 centimeters of sediment have been deposited at the location of core 40, on the western side of the plume, with silt composing almost two-thirds of the material. Moving eastward to cores 39 and 13, however, sedimentation since 1939 drastically decreases to only 10 and 7 centimeters, respectively. In these two cores, silt makes up between 74 and 85% of the deposits. This large discrepancy in sediment accumulations within the plume seems to indicate that core 40 is located at or very near the main channel of the Detroit sediment plume. Upon connecting the apparent main channels of the Detroit plume from cross sections A-A′ and B-B′, it can be seen that the main portion of the Detroit plume is extending southeast into the western basin with an azimuth of about 130°. An important feature shown by this data is the apparent lack of lateral, westward extension of the main body of the Detroit plume. This is possibly due to the position of the Monroe-Raisin plume with respect to the main portion of the Detroit plume.

Cross Section C-C′

Cross section C-C′ is the most complex of the four basinal transects because of its location with respect to the Maumee sediment plume and the clockwise-swirling, southern branch of the Monroe-Raisin plume. Cores 78 to 60 are located within the Maumee sediment plume which is about 11 kilometers wide at this point as it extends along latitude 41° 49′ north between longitude 83° 24′ and 83° 16′ west. Cores 78 and 82 are located in the minor westward extension of the main body of the Maumee plume, which was previously discussed. Core 61 is located within the actual Monroe-Raisin plume, although core 20 may also be considered to be included in this depositional feature because it is situated on the extreme eastern edge of the plume. The Monroe-Raisin plume is about 9 kilometers wide as it extends from latitude 41° 49′ north, 83° 14′ west to latitude 41° 50.2′ north, 83° 10.1′ west. Both core 7 and 22 are located in the deeper portions of the western basin, and they are only mildly affected by the numerous sediment features in this section of Lake Erie. In fact, core 22 (latitude 41° 50′ north, longitude 83° 00′ west) is probably typical of the muddy deposits that are formed in the deeper portions of the western basin.

The sand concentrations in the core intervals in this cross section are presented in Figure 36. In the western extension of the Maumee plume, core 78 contains high sand values (63%) in the top two centimeters, which gradually decrease to less than 10% at a depth of only 8 centimeters. Core 82, on the other hand, is the reverse of core 78 with respect to sand concentrations; that is, low (<10%) sand values in the top 2 centimeters of core 78 increase to over 60% at a depth of only 8 centimeters. These radical transitions may be due to fluctuations in the path and extent of the western extension of the Maumee plume, as well as variations in the current patterns and velocities in the nearshore area.

In the main body of the Maumee plume, sand values in the surficial 10 centimeters decrease from values of over 60% in core 83 to values of less than 15% in core 60. This eastward fining is probably due to current energy within the Maumee plume. Higher current velocities in the vicinity of core 83 produce coarser sediments, and milder currents in the eastern portion of the plume cause the deposition of more fine-grained material. Vertically within these three

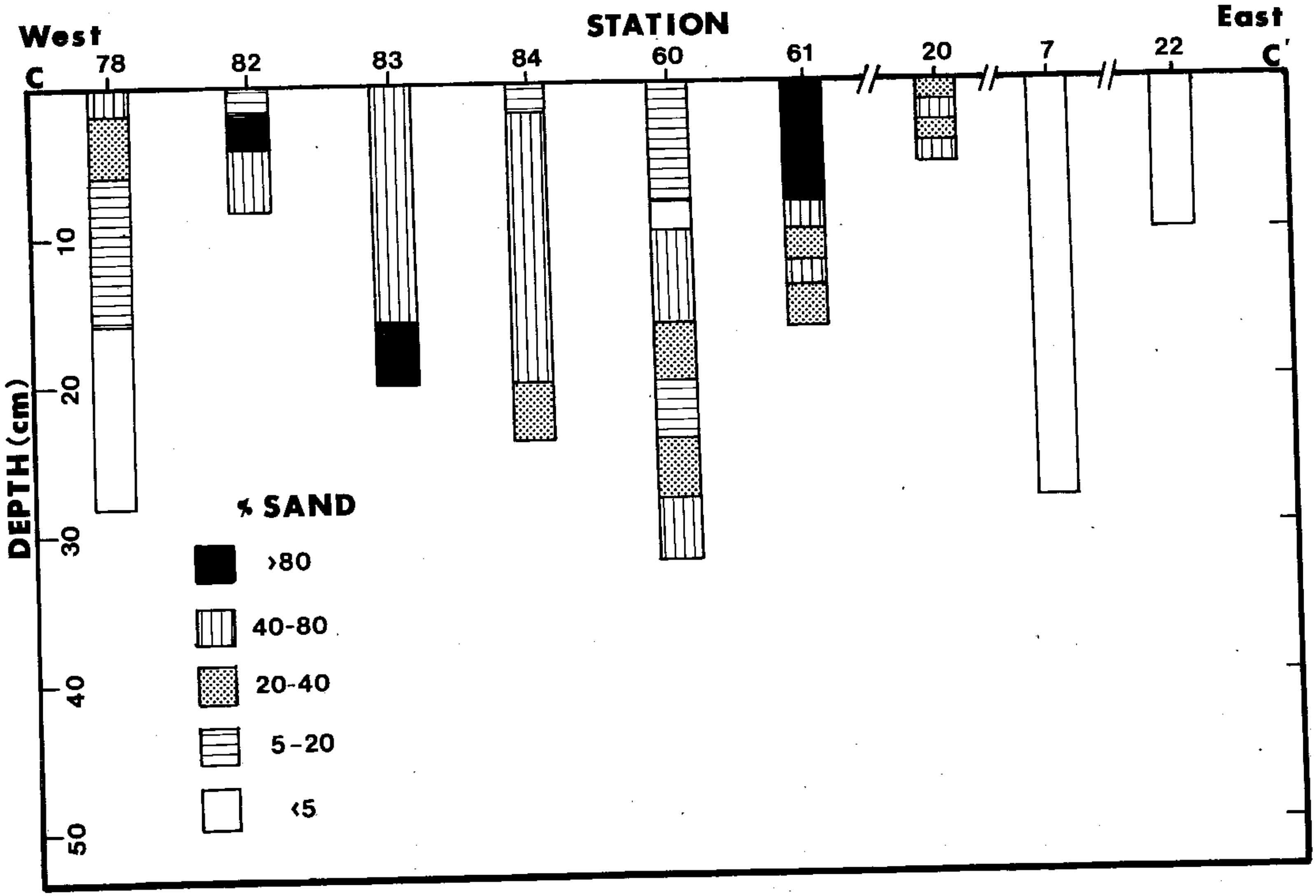

Figure 36. Sand concentrations in the core intervals along profile C-C ; station locations shown in Figure 12.

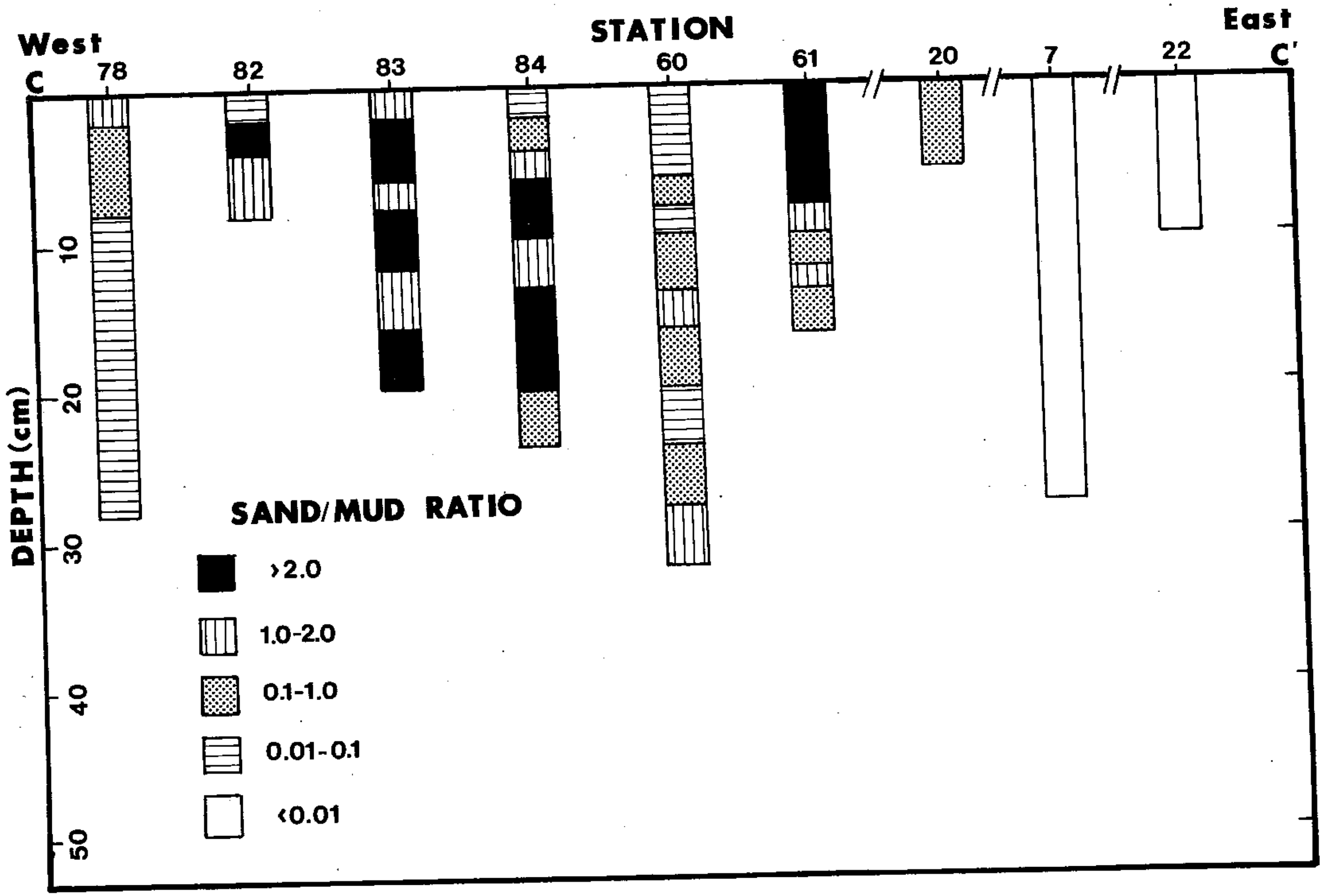

Figure 37. Sand/mud ratios in the core intervals along profile C-C′; station locations shown in Figure 12.

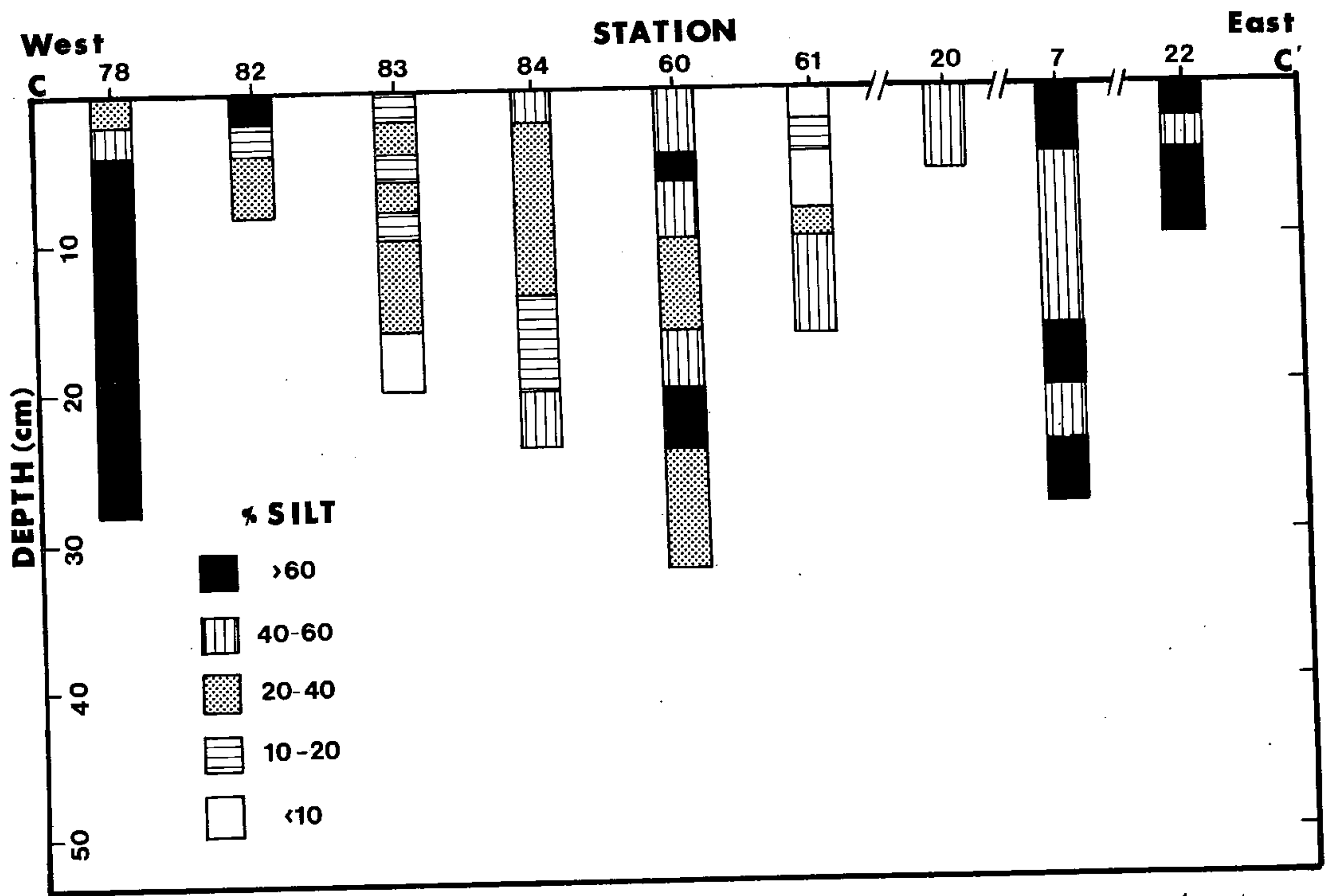

Figure 38. Silt concentrations in the core intervals along profile C-C′; station locations shown in Figure 12.

the Maumee plume, consistent silt values in core 83 parallel the constant sand values that are also present at this location, indicating sandier deposition in recent years. The grain-size variations in core 84 and 60 are further illustrated by the increase of the silt concentrations to the east within the Maumee plume, as indicated by the depostion of more silt-sized material in core 60. Cores 61 and 20 in the Monroe-Raisin plume contain moderate silt occurences (40-60%) everywhere except in the upper 8 centimeters of core 61. Cores 7 and 22 seem to maintain their equivalent natures in the deeper portions of the western basin, as indicated by the high, relatively constant, silt concentrations in the area, as shown in Figure 38.

The deposits in this cross section possess a wide variation of textures because of many grain-size fluctuations, as shown in Figure 39. Silts dominate the western extension of the Maumee plume, although clayey sands, sandy silts, silty sands, clayey silts, and sands are also present in this variable deposition zone. Moving east across the main body of the Maumee plume, sediment textures grade from clayey sands to silts and clayey silts. The coarser materials within the plume are sand-silt-clays according to the textural classification proposed by Shepard (1954). In the Monroe-Raisin plume, sands are present in the upper 8 centimeters of core 61, whereas sandy silts are present in the remainder of the plume. The deeper, basinal sediments (cores 7 and 22) are almost exclusively clayey silts, with the exception of one

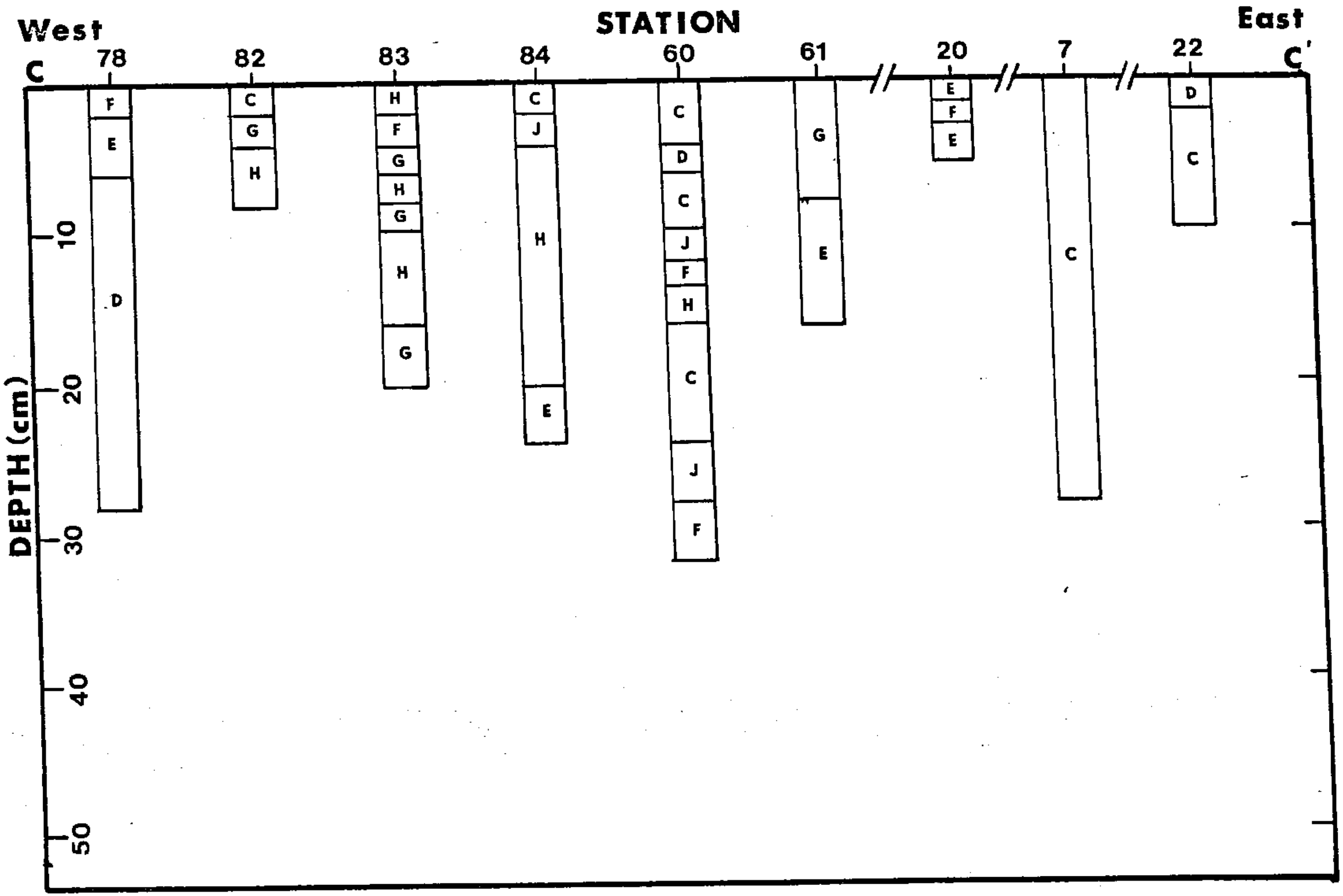

Figure 39. Textural classification of the core intervals along cross section C–C′ based on the diagram shown in Figure 22; station locations are shown in Figure 12.

silt interval at the surface in core 22.

The sediment accumulation in the cores along this cross section since 1939 is presented in Figure 40. An average of 8.2 centimeters of sediment has accumulated at cores 78 and 82 in the western branch of the Maumee plume. However, of this sediment, less silt (34.3%) has been deposited at core 82 than at core 78 (55.1%). Assuming uniform sedimentation rates, this variation indicates that the silty Maumee plume was present in the vicinity of the siltier core 78 for a longer time than it was present at core 82. Sediment accumulation in the main body of the Maumee plume has been relatively constant since 1939, ranging from 20 to 32 centimeters. However, of this accumulation, much more sand was deposited in both core 83 (72.5%) and 84 (55.5%) in the western part of the plume, whereas only 23.7% of the sediment deposited at core 60 is sand. The large concentrations of silt and clay-sized material at core 60 (70%), as well as the fact that the greatest accumulation of sediment occurred at this core, seem to indicate that the main channel of the silty Maumee plume is located near the eastern edge of this depositional feature.

Sediment deposition in the Monroe-Raisin plume has been relatively minor since 1939, as indicated by the accumulation of 10 and 4.5 centimeters of material at cores 61 and 20, respectively. This is probably due to the enviromental energy within this sediment plume, which creates a constant reworking of the bottom sediments and therefore erases much

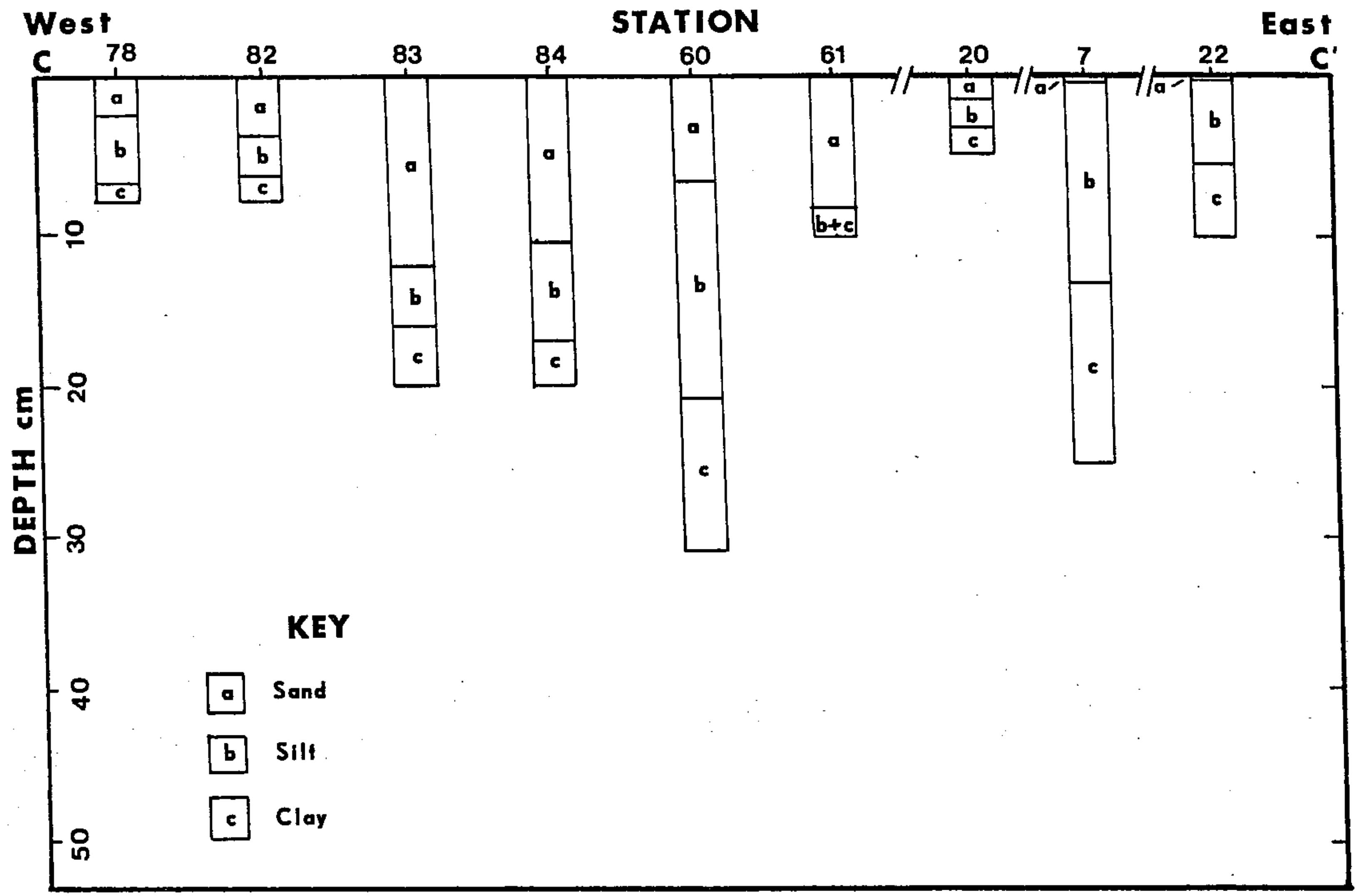

Figure 40. Sand, silt, and clay accumulations since 1939 in cross section C-C′; station locations are shown in Figure 12.

of the depositional history of the Monroe-Raisin plume. Cores 7 and 22 in the deeper portions of the western basin offer surprisingly different sediment-accumulation results, as shown in Figure 40. Although extremely small (<0.05 cm) amounts of sand have been deposited in this area, over 24 centimeters of fine-grained material have accumulated at core 7 since 1939, whereas only 10 centimeters of sediment have been deposited since 1939 at core 22. This is probably due to the position of core 7 with respect to the Monroe-Raisin plume. The plume, which contains clockwise-swirling currents, is "throwing" suspended sediment eastward into the basin. Apparently, much of this fine-grained sediment is deposited in the vicinity of core 7, and smaller amounts of suspended material reach the vicinity of core 22.

Cross Section D-D′

Cross section D-D′, located just north of Maumee Bay, is directly influenced by the Maumee sediment plume. The characteristics of the sediment in this cross section accurately illustrate the location and extent of the Maumee sediment plume as it enters western Lake Erie from Maumee Bay. The main body of the plume is located between cores 49 and 37, along latitude 41° 45′ north between longitudes 83° 21′ and 83° 13.6′ west, a distance of over 11 kilometers. West of the plume, two minor features are present at cores 51 and 50. Core 51 (latitude 41° 45′ north, longitude 83° 24′ west) is located within a sandy sediment zone which may be the result of littoral drift along the Michigan shoreline. On the other hand, grab sample 50 (latitude 41° 45′ north, longitude 83° 22′ west) is located within the isolated, extremely coarse, sand-gravel zone near Turtle Island. East of the Maumee plume, the southern extension of the Monroe-Raisin plume is intersected at core 36 near West Sister Island (latitude 41° 45′ north, longitude 83° 10′ west). Cores 35 and 34, located in the deeper portion of the western basin, are primarily composed of muddy sediment, which dominates the area (along latitude 41° 45′ north between longitude 83° 00′ and 83° 05′ west).

The sand concentrations along cross section D-D′ are shown in Figure 41. Within the main body of the Maumee plume, sand values in the surficial (0-10 cm) sediments grade from relatively sandy deposits (25-32%) in core 49 to extremely small (<1%) occurences in core 37. This eastward fining is similar to that found in the Maumee plume in profile C-C′. The isolated low sand (9%) interval in core 49, and the high sand intervals (>10%) in cores 57 and 37 illustrate the effect of changes in sediment input from the Maumee River, as well as variations in lake levels (Walters and Herdendorf, 1975).

In the western section of the cross section, cores 51 and 50 possess vastly different sand concentrations, as shown in Figure 41. The nearshore zone (core 51) contains varied sand occurences (17 to 84%) within the 21 centimeters of the core. The variation is not surprising upon considering the position of this core with respect to the Michigan nearshore

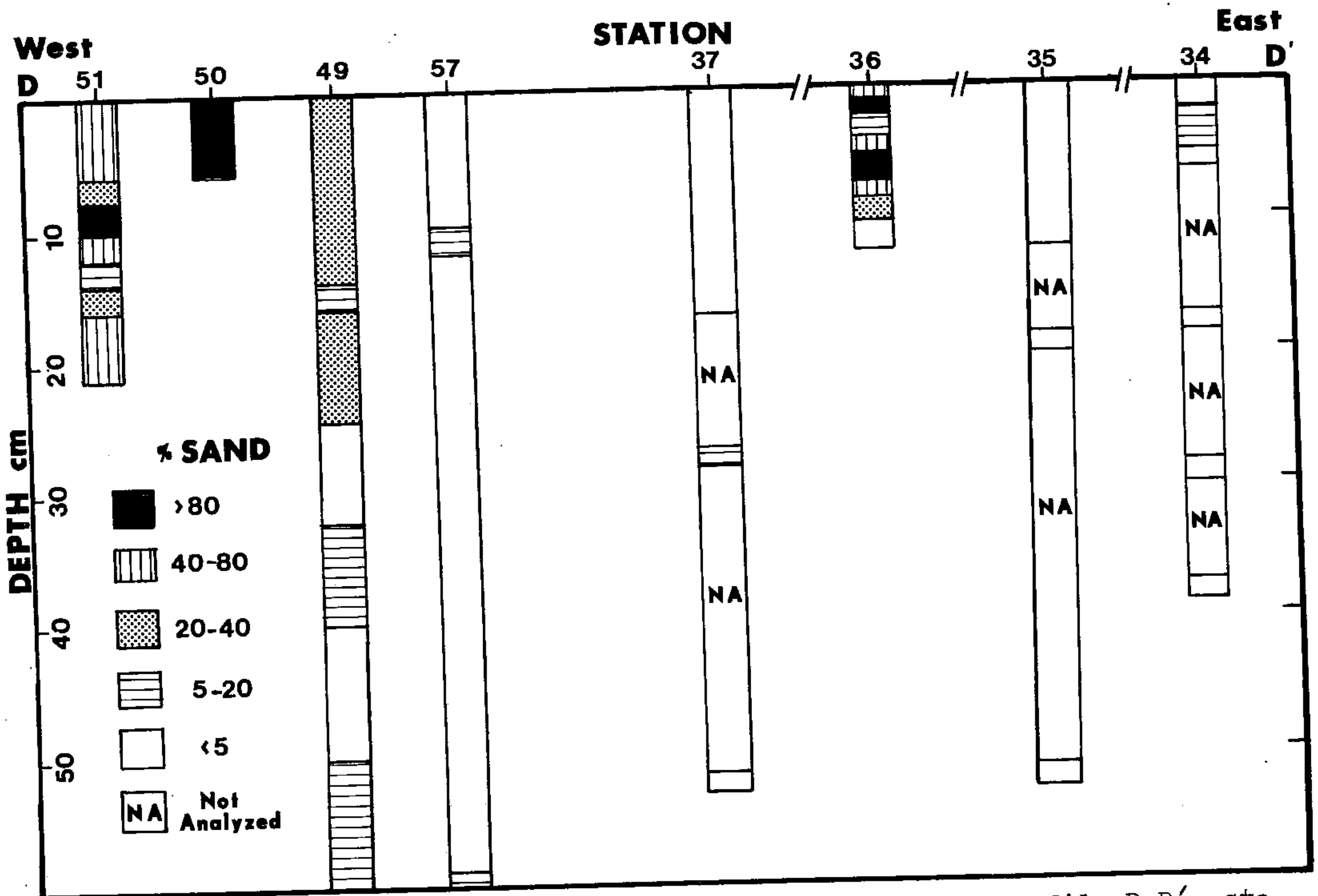

Figure 41. Sand concentrations in the core intervals along profile D-D'; station locations shown in Figure 12.

zone which is subject to changes in current direction and velocity with varying lake levels and wind directions. On the other hand, station 50, near Turtle Island, contains consistently high concentrations of sand and gravel (>99%), which is typical of this isolated sand zone.

Core 36, located in the southern extension of the Monroe-Raisin plume, as shown by Verber (1957), contains variable sand concentrations within the core. These values, which range from 3.8 to 88%, are indicative of the transitory nature of the Monroe-Raisin plume, which seems to be very sensitive to changes in lake levels and current patterns. In the deeper portions of the western basin, cores 35 and 34 contain consistent sand concentrations of less than 5% throughout the cores, with the exception of an inexplicable higher sand (8.1%) interval between 2 to 5 centimeters in core 34.

Sand/mud ratios in this profile also illustrate the various sediment zones within this section of the western basin (Figure 42). The Maumee plume possesses fairly constant values within the separate cores located in the plume. Core 49 contains ratios of greater than 0.1, which grade into lower ratios in cores 57 (<0.1) and 37 (<0.01). The varied nature of both the nearshore zone in core 51 and the Monroe-Raisin plume extension in core 36 are further illustrated by the wide variation of sand/mud ratios at these two locations, as shown in Figure 42. Extremely high and consistent values (90 to 199) are present at location 50, near Turtle Island. Ratios in the deeper portions of the western basin (cores

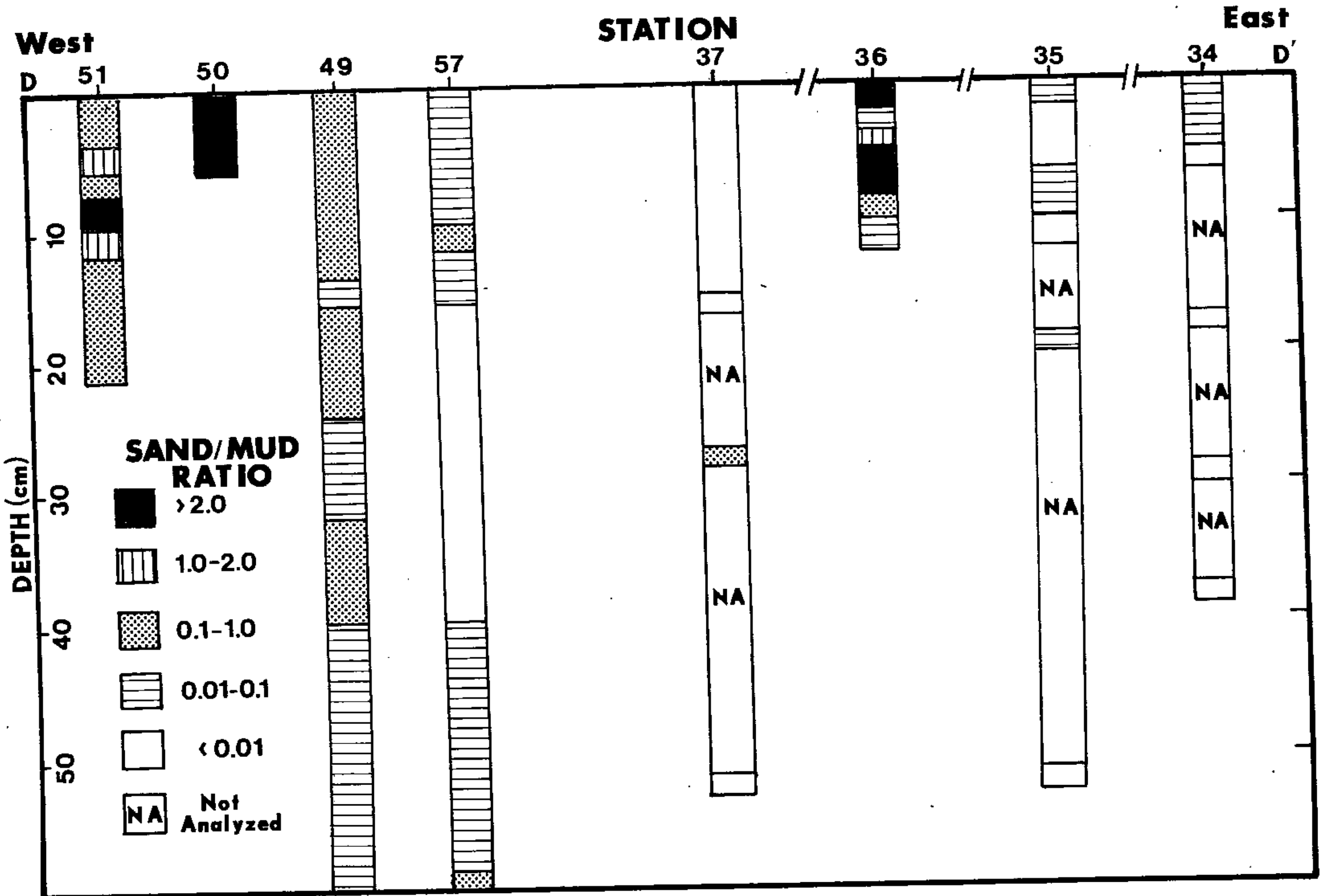

Figure 42. Sand/mud ratios in the core intervals along profile D-D′; station locations shown in Figure 12.

35 and 34) seem to decrease with depth, from values of greater than 0.01 in the top 6-10 centimeters to extremely small values (<0.01) below 10 centimeters. The recent coarsening of the sediment in these basinal locations may indicate that additional sand has been deposited in this section of Lake Erie during the recent depositional history of the area.

The mean size of the sand fraction in the core intervals of this cross section is shown in Figure 43. Very fine sands predominate in cores 49 and 57 of the Maumee plume, although two coarser intervals are present within the cores. The eastward fining of the plume is further indicated by the eastward increase in the amount of core intervals that contain insufficient sand to analyze. The nearshore zone (core 51) contains a wide range of sand sizes which vary from very fine sand in the top 8 centimeters to medium sands from 8 to 12 centimeters to very fine sands below 12 centimeters. Station 50 is consistent in that only medium sands are present, as shown in Figure 43. The variable sand zone in the Monroe-Raisin plume near West Sister Island (core 36) contains fairly consistent sand-size values which basically range around the very fine to fine-sand boundary. Intervals in cores 35 and 34 in the deeper portion of the basin almost entirely contain insufficient sand to analyze, with the exception of a very fine-sand interval deep (52 cm) in core 35.

Silt concentrations along profile D-D′ are illustrated in Figure 44. Silt concentrations within the Maumee plume have varied through time, as shown by the migration of high

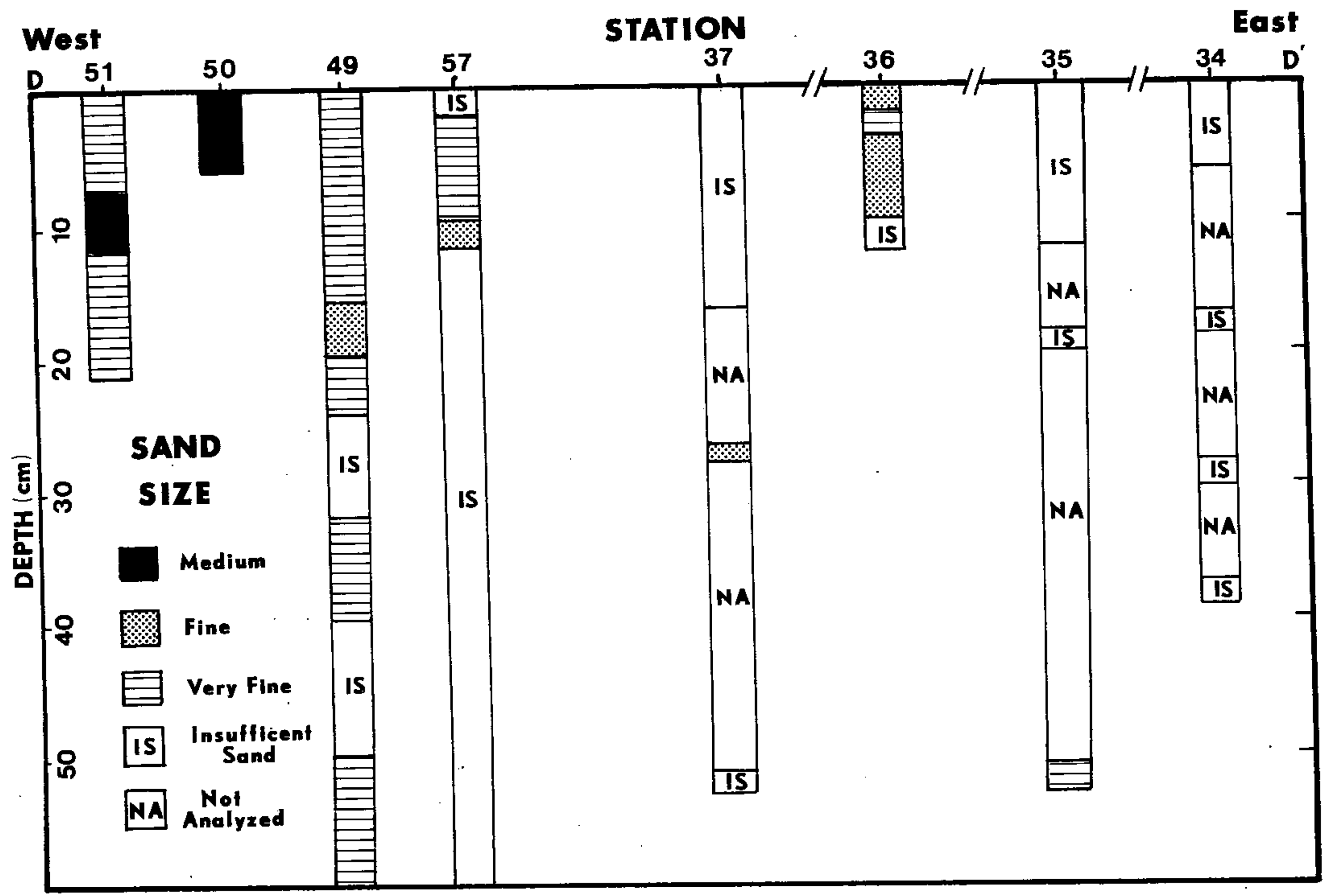

Figure 43. Mean size (in mm) of the sand fractions in the core intervals along profile D-D′; station locations shown in Figure 12.

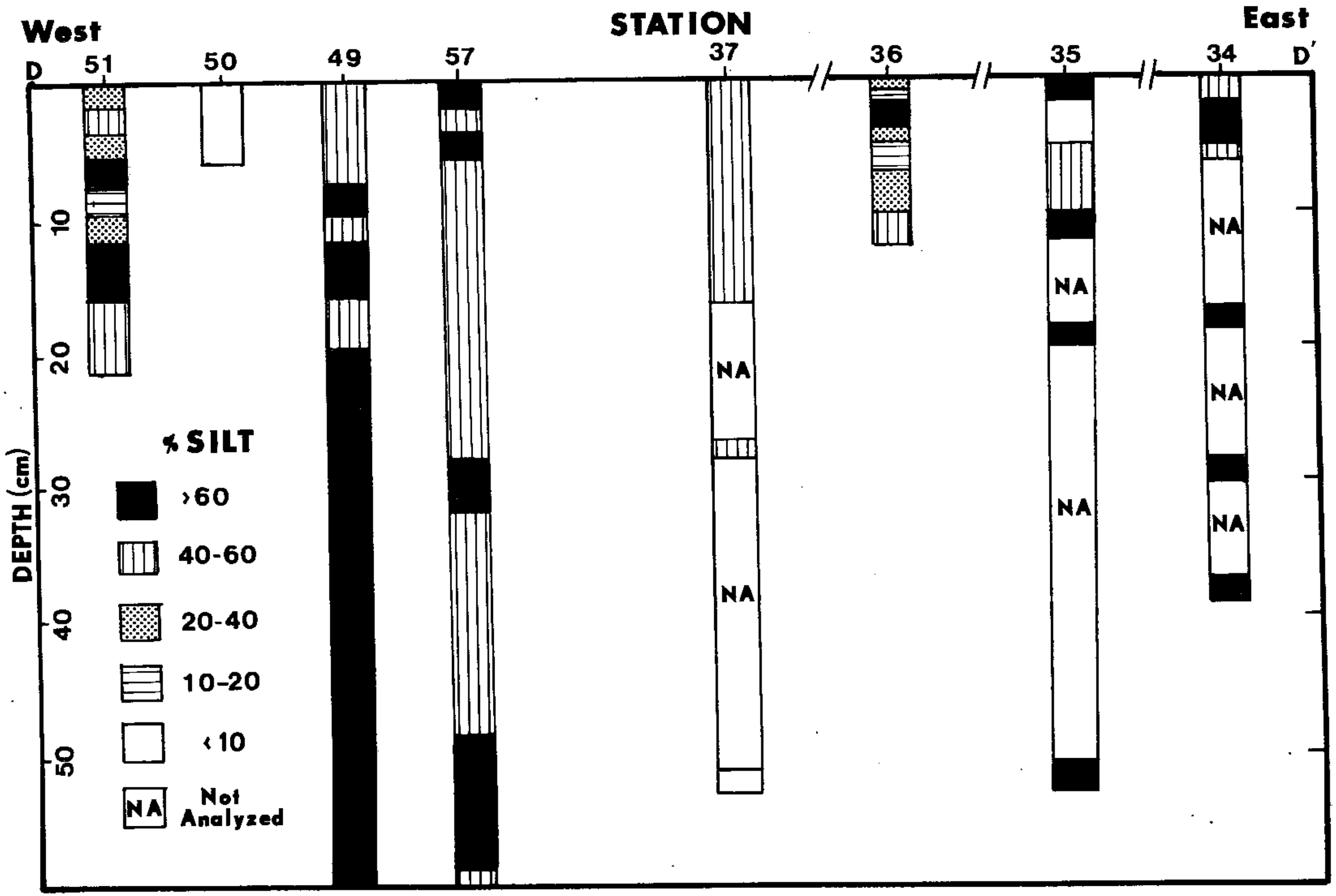

Figure 44. Silt concentrations in the core intervals along profile D-D′; station locations shown in Figure 12.

silt occurences (>60%) from core 49 to 57 in recent years. On the other hand, silt occurences in the eastern portion of the Maumee plume have maintained fairly consistent (44-55%) values over the same time period. In addition to the highly variable silt values in cores 51 and 36, cores 35 and 34 possess slight variations, especially in the upper 10 centimeters, where values fluctuate between 55 and 71%.

Texturally, the Maumee plume is composed of silts and clayey silts in the eastern two-thirds of the plume and sandy silts in the western section of the plume, as shown in Figure 45. The nearshore zone (core 51) varies between sandy silts and silty sands, while the sediment in the vicinity of Station 50, is extremely sandy in nature. The southern extension of the Monroe-Raisin plume contains sands, silty sands, sand-silt-clays, and clayey silts in the vicinity of core 36. Cores 35 and 34 are almost entirely composed of silty clays, with the exception of a silt interval deep in core 35.

The total sediment accumulated in cross section D-D′ since 1939 is presented in Figure 46. In the Maumee plume, sedimentation varies from over 60 centimeters in core 49 to 26-29 centimeters in cores 57 and 37. The large accumulation of sediment in core 49, which consists of 21.3% sand and 67.4% silt, seems to indicate that this station is located very near the main channel of the Maumee plume. When combined with the proposed main channel in cross section C-C′, the main body of the Maumee plume can be seen to enter the western basin trending northeast with a bearing of about 30°.

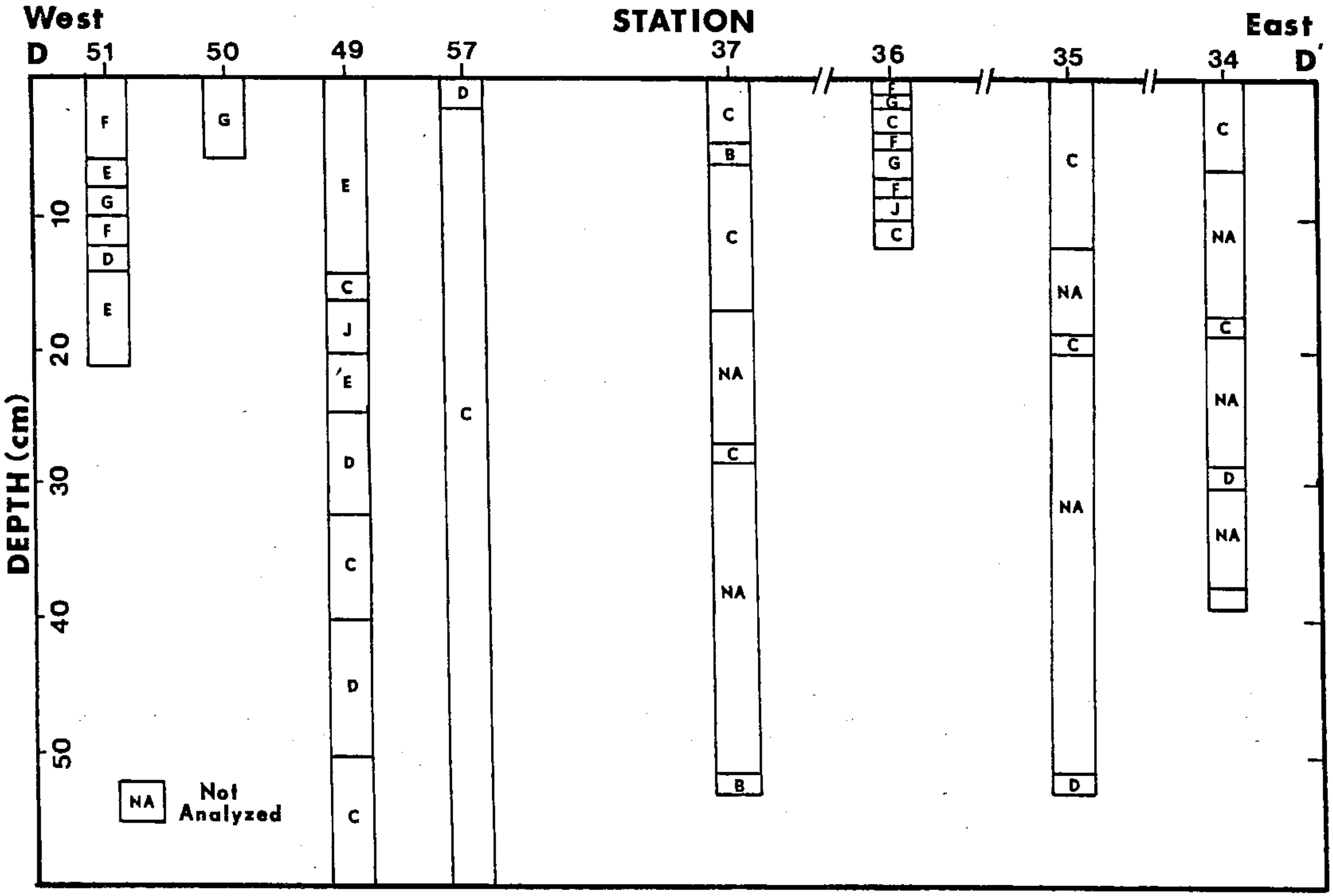

Figure 45. Textural classification of the core intervals along cross section D-D′ based on the diagram shown in Figure 22; station locations are shown in Figure 12.

West of the Maumee plume, only 8.1 centimeters of material have been deposited in the vicinity of core 51. Of this sediment, only 46.7% is sand-sized. This rather small accumulation since 1939 is indicative of the nearshore area along the Michigan shoreline, as previously discussed. No sediment accumulation data for location 50 can be presented, because only a grab sample was collected at this location due to the coarse sand-gravel deposits that are present. Core 36, in the Monroe-Raisin plume, has had about 13 centimeters of deposition since 1939, with sand making up 50.6% of the material, as shown in Figure 46. In the deeper portion of the western basin (cores 35 and 34), conditions tend to parallel those in the same section of cross section C-C′. Over three times more material has been deposited at the location of core 35 (20 cm) than at the location of core 34 (6 cm) since 1939. As previously explained, this is due to the clockwise currents within the Monroe-Raisin plume, which tend to transport suspended sediment eastward from the plume. The suspended material is eventually deposited in the area of core 35, and very little sediment is deposited in the vicinity of core 34.

HEAVY-MINERAL ANALYSES

Heavy-mineral separation and analyses were performed on 23 sand samples from the western basin, as well as Detroit and Maumee River sands (Figure 47). The total percentage of heavy minerals in each sand sample is listed in Table XX.

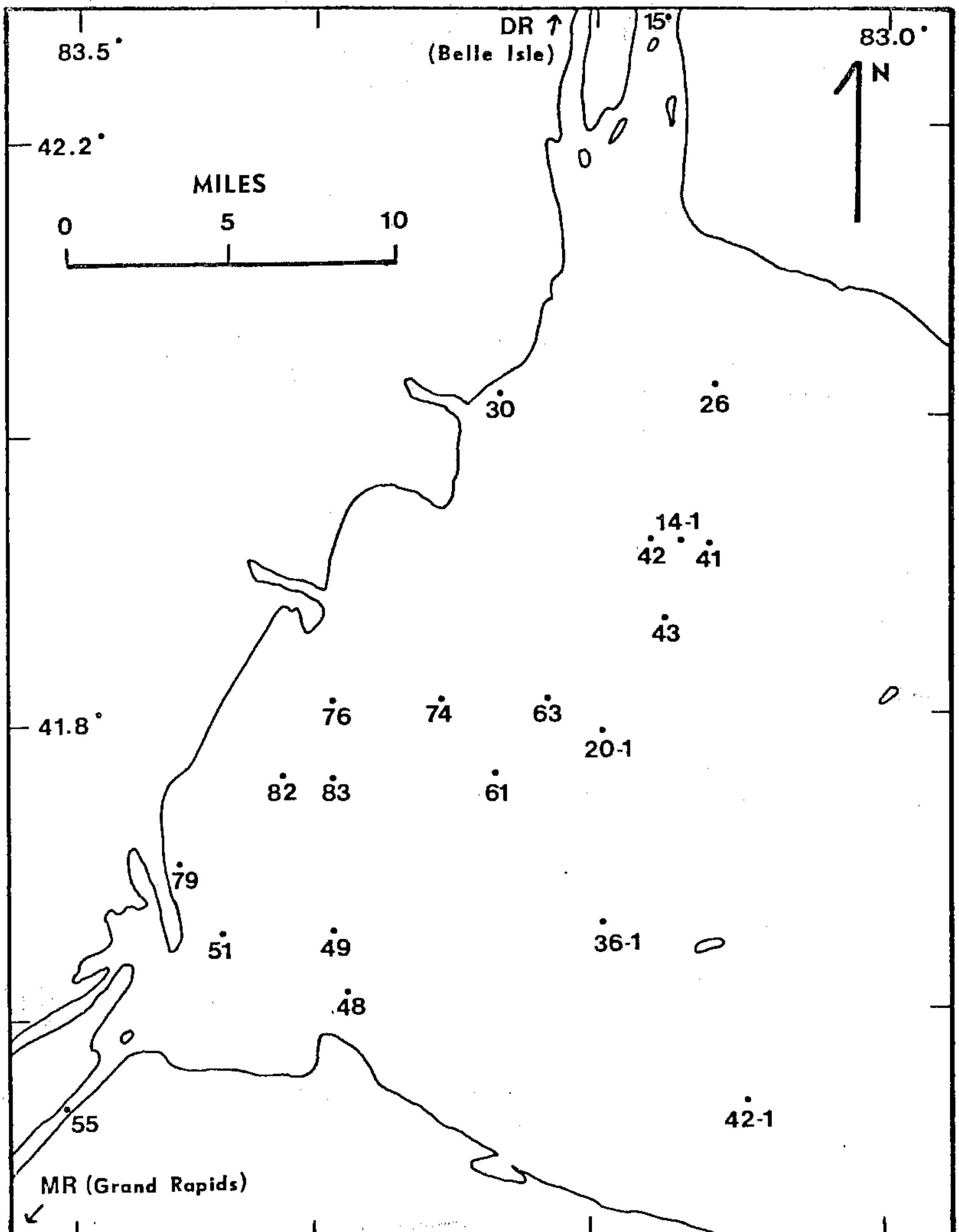

Figure 47. Sample locations of the sands used in the heavy-mineral analyses conducted in this study.

Table XX. Total and magnetic percentages of heavy minerals in the sand fractions from the study area.

Sample Location [1]	Heavy Minerals [2] %	Magnetic [3] %
61-4	4.40	9.98
36-1	4.94	2.75
83-4	3.82	10.89
76-4	4.55	16.67
43-4	4.59	7.95
55-4	7.02	40.71
MR	2.15	15.67
DR	4.29	29.21
49-4	5.62	28.49
41-4	3.44	31.90
82-4	4.81	15.39
26-4	5.17	14.58
42-4	2.52	4.93
20-1	4.92	32.01
14-1	2.68	12.68
42-1	9.88	7.45
51-4	3.63	25.19
30-4	7.18	28.38
48-4	6.45	19.05
79-4	5.81	29.92
74-4	8.50	28.57

[1] sample locations shown in Figure 47

[2] total heavy-mineral percentages of entire sand fraction

[3] total magnetic percentage of the heavy-mineral fraction

Using this data, a general trend for the western basin can be postulated. The lowest total heavy-mineral concentrations are present in the Detroit River (3.72%) and its sediment plume (3.45%), while greater accumulations occur in the sediments of the Maumee (4.72%) and Monroe-Raisin (5.74%) plumes. Sample MR, located in the Maumee River near Grand Rapids, contains very low values (2.15%) due to the extreme coarseness of sand sample. The most frequent occurence of heavy minerals is present in the nearshore sands (6.45%). The gravimetrically calculated magnetic portion of each heavy-mineral fraction is also listed in Table XX. Although values range from 40.71% (sample 55-4) to 2.75% (sample 36-1), no significant diagnostic trends can be recognized. The Maumee plume and nearshore sands tend to contain slightly more magnetic heavy minerals (21.43% and 19.56%) than the Detroit and Monroe-Raisin plume (17.72% and 17.65%).

Several heavy-mineral studies of the western Lake Erie area have been conducted by numerous workers. Pettijohn and Ridge (1933, p. 92) identified a suite of 15 minerals in their studies of Cedar Point. Hornblende, garnet, hypersthene, and diopside were the most abundant members of this suite. Metter (1953, p. 27) and Pincus et al. (1951, p. 16-19) identified the heavy minerals in the nearshore zone of the Sandusky Bay area and proposed a suite of hornblende, hypersthene, garnet, magnetite-ilmenite, diopside, augite, and zircon. Benson (1971, p. 18) analyzed the sands of the island area and described a similar suite of heavy minerals, with the inclusion of rutile and apatite, was proposed by Herdendorf and Braidech (1972, p. 13) in their study of the sediments of the inter-island area. Kemp and Dell (1976, p. 202), in an attempt to correlate the bluff and lake sediments of the Erie-Ontario area, identified an abundance of hornblende, pyroxene, dolomite, garnet, magnetite, and pyrite in the western Lake Erie area.

A heavy-mineral suite similar to those proposed by previous workers was identified in this thesis. Identification was based on descriptions found in Krumbein and Pettijohn (1938), Ford (1949), Milner (1952), and Owen (written communication, 1975). The results of this study are given in Table XXI. The most abundant minerals in this suite are hornblende, garnet, augite, diopside, tourmaline, magnetite-ilmenite, hematite, hypersthene, and zircon. Minerals found in minor amounts included sphene, rutile, dolomite, apatite, epidote, tremolite-actinolite, pyrite, aragonite, leucoxene, and staurolite, as well as some rock fragments.

The most significant trend within the heavy-mineral fractions that were analyzed concerns the ratio of white (clear) garnet to pink garnet. Even though the lower sections of the Maumee River contain low ratios (1.29), the Maumee sediment plume possesses very high values (5.3 to 17.0) as it emerges from Maumee Bay. These values decrease (1.8 to 2.30) as the plume extends northward into the basin. The white/pink garnet ratios in the Monroe-Raisin plume are similar to those in the Maumee plume (1.50 to 2.60), with one exception,

Table XXI. Percentages of separate heavy minerals in western Lake Erie samples.[1]

Heavy Mineral	61-4	36-1	83-4	76-4	63-4	43-4	55-4	15-4	49-4	41-4	82-4	26-4
Hornblende	41.5	43.7	35.3	41.7	36.7	40.7	30.7	35.3	33.0	42.9	33.0	34.6
Garnet (white)	11.0	7.3	9.8	5.7	5.8	7.3	9.0	5.7	10.2	3.1	9.1	3.2
Garnet (pink)	9.3	9.6	4.2	4.7	3.2	4.0	7.0	1.3	1.9	0.6	14.9	4.5
Augite	9.6	11.3	18.3	16.7	14.3	13.5	9.3	9.0	20.0	22.8	20.4	23.3
Diopside	3.7	5.3	6.2	5.3	7.8	5.6	5.0	9.8	6.0	6.5	3.6	5.2
Tourmaline	10.6	10.6	5.9	8.7	17.2	8.9	9.7	21.0	10.5	10.5	4.9	11.0
Ilmenite	4.0	3.3	3.3	2.0	3.2	3.3	3.3	6.3	2.2	1.9	2.6	3.2
Hemetite	2.0	0.7	2.9	3.3	0.6	-	15.0	2.0	5.4	0.6	1.9	4.2
Hypersthene	3.7	0.7	1.3	2.3	1.9	2.0	2.0	2.0	0.3	0.3	1.0	3.2
Zircon	2.0	3.0	3.3	3.3	1.6	4.3	3.3	3.3	3.5	4.0	1.9	1.9
Staurolite	-	-	2.3	-	-	-	-	-	0.3	-	1.6	-
White/Pink Garnet Ratio	1.18	0.76	2.31	1.21	1.80	1.83	1.29	4.25	5.33	5.00	0.61	0.71
Others	2.3	3.7	9.7	5.9	7.3	10.5	5.6	6.3	8.0	6.7	6.7	5.4

[1] total heavy-mineral percentages of each sample add up to 100%

Table XXI. Continued.

Heavy Mineral	42-4	20-1	14-1	42-1	51-4	30-4	48-4	79-4	74-4	MR	DR
Hornblende	38.3	40.4	37.0	15.3	45.0	28.5	38.7	33.8	32.1	37.7	31.5
Garnet (white)	3.3	6.8	1.0	2.7	0.7	13.9	4.8	4.4	11.8	3.8	6.6
Garnet (pink)	5.7	2.6	1.0	2.7	0.7	8.7	0.3	6.9	8.2	13.1	3.8
Augite	21.0	18.6	8.7	6.8	18.0	13.6	20.2	20.6	16.1	13.1	4.3
Diopside	4.0	4.9	5.3	1.0	4.7	5.9	6.6	8.8	3.7	3.8	4.3
Tourmaline	6.7	6.5	30.0	6.8	9.3	7.4	13.4	7.2	10.7	11.9	18.5
Ilmenite	5.3	1.6	2.0	4.7	3.0	3.7	1.4	3.1	3.4	9.3	6.4
Hematite	5.7	3.6	-	57.9	2.3	1.9	2.6	2.8	3.4	3.4	3.5
Hypersthene	2.0	2.0	1.7	0.3	-	3.1	0.9	2.2	0.6	0.8	0.9
Zircon	2.7	4.9	3.3	-	3.0	4.6	2.6	1.3	3.9	1.7	2.6
Staurolite	-	-	-	-	0.3	-	0.9	-	1.1	-	-
White/Pink Garnet Ratio	0.59	2.62	1.00	0.63	7.50	1.61	17.0	0.64	1.45	0.29	1.77
Others	5.3	8.1	10.0	2.7	6.8	8.6	8.6	9.1	8.9	8.0	8.4

sample, 36-1, where the ratio drops to 0.78. This may be due to the isolated nature of this station and its association with the bedrock high at West Sister Island.

The Detroit sediment plume, on the other hand, shows very low (<1) garnet ratios within the plume. Studies in this section of the lake are handicapped by the lack of sand in the Detroit plume as it extends into the basin. Nearshore sediments show a significant trend with respect to the white/pink garnet ratio in that the nearshore sands located south of profile C-C′ (latitude 41° 49′ north) possess very low values (<1), while samples north of this line contain significantly higher values (1.2 to 1.6). Using a student t-test, all the plumes were found not to be significantly different from each other at the 0.05% level. However, when the white/pink garnet ratios are plotted on the sample-location map (Figure 47), the ratios within the Maumee plume are generally greater than those within the Detroit plume.

All the other heavy minerals in the study area show no significant variations or trends with respect to the different sediment plumes, with the exception of staurolite, which is present in very small concentrations (~2%) only in the Maumee sediment plume.

SUMMARY AND CONCLUSIONS

Using surficial sediment analyses, it is possible to determine four different depositional zones in the western basin of Lake Erie (Figure 48). The muddy (silt and clay) Detroit sediment plume dominates the distribution of the bottom sediments in the study area. The main body of this plume emerges from the western and central channels of the Detroit River and moves south-southeast into the basin, and a plume from the sandy eastern channel hugs the Ontario shoreline after exiting the river. A few miles into the lake, a small branch from the plume swings to the southwest towards the Michigan shoreline, and the main body of the plume continues en masse until it bifurcates in the vicinity of the latitude 41° 55′ north and longitude 83° 02′ west. The main branch then veers eastward and parallels the Ontario shoreline as it heads towards the Pelee Passage and the central basin, and the weaker, secondary branch maintains a southeast bearing towards the Bass Islands and the South Passage.

The Maumee sediment plume, which contains a higher proportion of sand than does the Detroit plume, exits the Maumee River and remains in the eastern half of Maumee Bay until it enters the western basin. Although a minor branch turns east along the Ohio shoreline, the main portion of the plume extends northeast into the basin, where it achieves its maximum width of about 15 kilometers. About 10 kilometers into the basin, however, the Maumee plume intersects the sand and gravel-composed Monroe-Raisin plume southeast of Monroe. From this point, a minor extension of the Maumee plume veers to the west towards the Michigan shoreline. A minor northward extension of the Maumee plume then procedes

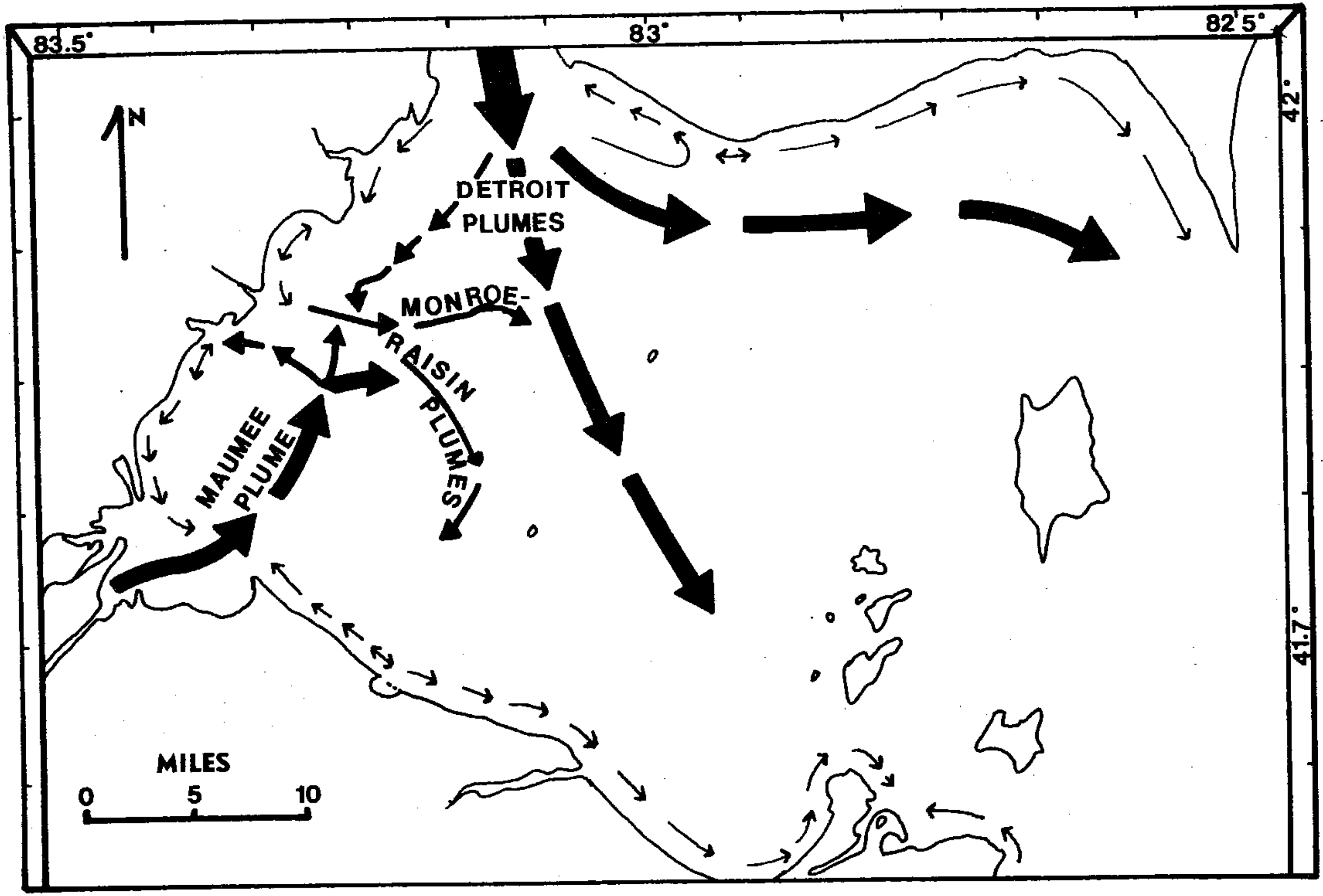

Figure 48. Generalized sediment transport in the western basin.

to "bisect" the Monroe-Raisin plume. Although it is hydrologically improbable for the Maumee plume to bisect the Monroe-Raisin plume under its own power, it is possible for a combination of current flow and variations in the sediment and water input to "pull" siltier sediment northward from the main body of the Maumee sediment plume. This apparent channel, which has been identified in the surficial (0-2 cm) bottom sediments of this section of the western basin, eventually dissipates near Stony Point.

The sand and gravel zone located lakeward from Monroe and the Raisin River has been termed the Monroe-Raisin plume by this worker. Converging currents of various velocities, a slightly elevated lake bottom, and both water and sediment influence from the Raisin River combine to form this feature, which extends eastward from Monroe for about 25 kilometers. This plume, which is apparently split by the northward extension of the Maumee sediment plume, splits into two separate branches as it "collides" with the southeast-flowing Detroit River water mass. A minor section of the Monroe-Raisin plume veers to the northeast, and the main branch is deflected to the south towards West Sister Island. This southerly deflection and subsequent clockwise flow form a semi-circular-shaped sand zone in this portion of the plume.

The other depositional zones indicated by the surficial sediment analyses are the various nearshore areas around the basin. The Ontario shoreline is extremely sandy from the Detroit River to Comet, Ontario, from where a very narrow high-sand, nearshore belt extends eastward to Point Pelee. The Michigan shore is characterized by a very high-sand zone between the Detroit River and Stony Point, which extends into the basin for about 10 kilometers. The southern Michigan coast, on the other hand, is a transition zone characterized by low sediment accumulation because of the funneling of sediment into deeper portions of the basin. The Ohio shoreline is dominated by the presence of a very high sand-gravel area which extends lakeward from Locust Point for about 8 kilometers. The shoreline both east and west of this zone contains less sandy, narrower, nearshore deposits.

The analyses of the cores contained within the four cross sections leads to a further differentiation of the overall location and extent of the various sediment zones in the western basin. Variations in sediment character within various cores can be correlated with changes in the actual depositional history of the sediment plumes. These changes can be caused by a variety of factors, including periods of low or high lake levels and fluctuations in both water and sediment input from the Maumee, Detroit, and Raisin Rivers.

The heavy-mineral analyses identified two separate trends within the sand fractions of the western basin. The lowest total percentages of heavy minerals were found to occur in the Detroit sediment plume (3.45%), while increasingly higher values are present in the Maumee plume (4.72%), the Monroe-Raisin plume (5.74%), and all the nearshore areas (6.45%). With a few minor exceptions, the heavy minerals recognized in this thesis compares favorably with those identified by previous workers. However, only one definite trend is present in this suite that can be used to differentiate the Maumee and Detroit plume areas. The white/pink garnet ratio of the Maumee plume is very high (up to 17.0) as it initially enters the lake basin. Although this ratio decreases as the plume extends into the basin, it remains between 1.1 and 2.6 at all locations within the Maumee plume. The garnet ratio of the Monroe-Raisin plume closely corresponds to those of the Maumee plume in that its values also range from 1.1 to 2.6. The Detroit plume and its associated area, on the other hand, contain very low white/pink garnet ratios, and values of less than 1.0 are common. In addition to this major trend, one minor trend is apparent in that staurolite is present in small (~2%) quantities only within the Maumee plume.

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APPENDIX I.

Listing of Settling Tube Analysis Program

```
C      PROGRAM CPC 222
C
C      WRITTEN BY C.P. CUNNINGHAM   DECEMBER  1973
C
C      THIS PROGRAM CALCULATES THE SIZE DISTRIBUTION OF SAND
C      GRAINS FROM VISUAL ACCUMULATION TUBE DATA.  DATA IS
C      INPUTED IN THE FOLLOWING FORM:  DISTANCE FALLEN (MM),
C      TIME (SEC),AND TEMPERATURE (DEGREES CENTIGRADE).
C               CARVER, PROCEDURES IN SEDIMENTARY PETROLOGY
C  REFERENCES: CRC HANDBOOK, 49TH ED.
C
C
C
C
C.......................................................
C
       REAL*8  A, SDIS, TIME, TEMP, XMU, XDIS, NBS, X, LASDIS
      *,RHO,SUM, VPERC, RSUM,RHOMM, XBARMM, PHINBS, TEMPER, Y
      *,F,XBAR,DLOG10,DLOG,DSQRT,B,C
       DIMENSION  X(45),F(45),A(8),B(10)
C
       DATA A/          0.8751160855112413D 01,
      *     0.1054154187747976D 03,   0.5485240651830751D 03,
      *     0.1527951842747672D 04,   0.2410593020748144D 04,
      *     0.2160174323706054D 04,   0.1024143743291469D 04,
      *     0.1995248693965413D 03/
C
       DATA B/         -0.46938916962916480000D 00,
      *     0.22238550238013740000D 01,  -0.1602369942455452D1
      *,    0.14316175546346240000D 01,  -0.1821047604313958D1
      *,    0.19051163205359080000D 01,  -0.1069696295133933D1
      *,    0.31483990573844610000D 00,
      *-0.4654022380875681D-1,
      *     0.27389450515584190000D-02/
C
C      READ PROBLEM PARAMETER CARD, LB= SAMPLE NO., N= NO
C      CARDS IN SAMPLE
C
  600 READ (5,1, END= 800)  LB, N, LASDIS
      LASDIS = 188.2 - LASDIS/10.D0
C
C**************************************************************
C      WRITE THE SAMPLE NUMBER
       WRITE(6,4)  LB
C      WRITE THE HEADING
       WRITE (6,5)
C
       I=1
C  READ THE INPUT DATA
  110 READ (5,2) SDIS, TIME, TEMP
      SDIS =  (1882-SDIS)/10
C
C      THE FOLLOWING STATEMENT CALCULATES VISCOSITY (POISES)
```

```
      XMU=10.**((1.3272*(20.-TEMP)-.001053*(TEMP-20.)**2)/
     *(TEMP+105.)+0.0008677)*.01
C
C     THE FOLLOWING STATEMENT CALCULATES STOKES EQUIVALENT
C     DIAMETER(MM)
C
      XDIS=DSQRT(SDIS/TIME)/DSQRT(1618.96D0/(18.D0*XMU))*10.
C
      XDIS = DLOG10(XDIS)
C
C     THE FOLLOWING SECTION CALCULATES THE NBS EQUIVALENT
C     DIAMETER(MM)
C
      NBS= A(1)
      DO 117 J=2,8
  117 NBS = NBS + A(J)*XDIS**(J-1)
C
      NBS = 10.**NBS
C
      VPERC=((188.2-SDIS)/(188.2-LASDIS))*100.0
C
C THE FOLLOWING SECTION CONVERTS SIZE FROM MM TO PHI
      PHINBS= (-DLOG(NBS))/(DLOG(2.D0))
      C =B(1)
      DO 118 J=2,10
  118 C=C+B(J)*PHINBS**(J-1)
C
C THE FOLLOWING SECTION CALCULATES PHI MIDPOINT.
      IF(I.GT.1) GO TO 150
      X(I) = 0.0
      GO TO 160
  150 X(I) = (PHINBS+Y)/2
  160 Y = PHINBS
C
C  THE FOLLOWING SECTION ACCUMULATES INDIVIDUAL PERCENT IN
C     AN ARRAY
C
      IF (I.GT.1) GO TO 500
       TEMPER=0.0
  500 F(I) = VPERC - TEMPER
       TEMPER = VPERC
C
C     WRITE DATA IN TABLE
      WRITE (6,3) SDIS,TIME,TEMP,VPERC,F(I),NBS,PHINBS,X(I)
      I=I+1
      IF(I-N) 110,110,100
C*****************************************************************
C
C  THE FOLLOWING SECTION CALCULATES THE MEAN GRAIN SIZE.
  100 SUM=0.0
      DO 300 I=1,N
  300 SUM=SUM + F(I)*X(I)
      XBAR=SUM/100.
```

```
C
C  THE FOLLOWING SECTION CALCULATES THE STANDARD DEVIATION.
      RSUM=0.0
      DO 400 I=1,N
  400 RSUM=RSUM+(F(I)*((X(I)-XBAR)**2))
  410 RHO=DSQRT(RSUM/100.D0)
C
C  THE FOLLOWING SECTION CONVERTS THE MEAN AND RHO TO MM
      XBARMM= 2.**(-XBAR)
      RHOMM= 2.**(-RHO)
C
C***************************************************************
      WRITE(6,6)
C     WRITE XBARMM, XBAR, RHOMM, RHO
      WRITE(6,7) XBARMM, XBAR, RHOMM, RHO
C
      GO TO 600
C
    1 FORMAT (A6, I3, F6.1)
    2 FORMAT (3F8.0)
    3 FORMAT (4F15.2,1F10.2,2F10.4,1F8.4)
    4 FORMAT (11H1   SAMPLE   ,A6///)
    5 FORMAT(4X,'FAIL DISTANCE',9X,'TIME',8X,'TEMPERATURE',
     *4X,'PER CENT',2X,'PER CENT',4X,'MM',7X,'PHI',3X,
     *'MIDPOINT')
    6 FORMAT(// 10X,'MEAN',21X,'STANDARD DEVIATION'/6X,'MM',
     *7X,'PHI',16X,'MM',14X,'PHI'/)
    7 FORMAT(2F10.3, F22.3, F13.3)
C
  800 STOP
      END
```

APPENDIX II.

Listing of Program PIPET

```
C     PROGRAM PIPET WRITTEN AND REVISED BY LESTER J. WALTERS
C     20 SEPTEMBER 1977
C
C     REFERENCES:  FOLK(1974) AND ROYSE(1970)
C
      DIMENSION W(6),T(10,6),VIS(10),CM(6)
      INTEGER T
      REAL*8 XID
      BASE=ALOG(2.0)
      BLANK=0.0231
      DATA CM/20.,10.,10.,10.,5.,5./
      DATA VIS/.010573247,.010308778,.010060838,.009812899,
     *      .0095814887,.0093555881,.0091407071,.0089313359,
     *      .0087329842,.0085346325/
      DO 80 I=1,10
   80 VIS(I)=VIS(I)*100.
      DO 90 I=1,6
   90 T(I,1)=20
      T(1,2)=120
      T(1,3)=480
      T(1,4)=1919
      T(1,5)=3838
      T(1,6)=15360
      T(2,2)=117
      T(2,3)=468
      T(2,4)=1871
      T(2,5)=3742
      T(2,6)=14940
      T(3,2)=114
      T(3,3)=456
      T(3,4)=1826
      T(3,5)=3651
      T(3,6)=14580
      T(4,2)=111
      T(4,3)=445
      T(4,4)=1781
      T(4,5)=3563
      T(4,6)=14280
      T(5,2)=109
      T(5,3)=435
      T(5,4)=1739
      T(5,5)=3478
      T(5,6)=13920
      T(6,2)=106
      T(6,3)=425
      T(6,4)=1698
      T(6,5)=3396
      T(6,6)=13560
      T(7,2)=104
      T(7,3)=415
      T(7,4)=1659
      T(7,5)=3318
      T(7,6)=13260
```

```
      T(8,2)=101
      T(8,3)=405
      T(8,4)=1621
      T(8,5)=3242
      T(8,6)=12960
      T(9,2)=99
      T(9,3)=396
      T(9,4)=1585
      T(9,5)=3169
      T(9,6)=12660
      T(10,2)=97
      T(10,3)=387
      T(10,4)=1549
      T(10,5)=3099
      T(10,6)=12420
      WRITE (6,2)
    2 FORMAT ('  INPUT VALUES FOR ID,WEIGHT OF 6 PIPET ',
     *     'FRACTIONS, TEMPERATURE,'/'  AND WEIGHT SAND')
  100 READ (5,*) XID, (W(I),I=1,6),TEMP,SAND
      WRITE (6,1) XID
      ITEMP= TEMP +.1-17.
    1 FORMAT (///10X,'SAMPLE   ',A8)
      CUMF=0
      SP=4
      CUMT=0
      WF4=50.*(W(1)-BLANK)
      WP=WF4
      TWS=SAND+WF4
      SAND=SAND/TWS*100.
      WRITE (6,4)
    4 FORMAT (//'  TIME     MAXPHI     MINPHI    DIAMETER-CM'
     *     ,'  %SMPL  %SED ')
      DO  130 J=2,6
      WF=50.*(W(J)-BLANK)
      IF (WF .LT. 0.) GO TO 110
      GO TO 120
  110 DIFF=0.
      DIFT=0.
      WF=WP
      GO TO 125
  120 CONTINUE
      DIFF=(WP-WF)/WF4*100.
      DIFT=(WP-WF)/TWS*100.
  125 CONTINUE
      SIZE=SQRT(CM(J)*VIS(ITEMP)*9./(2.*(2.66-.997)*980.222*
     *     T(ITEMP,J)))*2.
      PHI=-ALOG(SIZE)/BASE
      WRITE (6,3)T(ITEMP,J),SP,PHI,SIZE,DIFF,DIFT
      WP=WF
    3 FORMAT(/I7,2F10.3,F15.4,2F6.2)
      SP=PHI
      CUMT=DIFT+CUMT
      CUMF=DIFF+CUMF
```

```
130 CONTINUE
    DIFF=100.-CUMF
    CLAY=DIFF*CUMT/CUMF
    SILT=CUMT
    DIFF=WF/WF4*100.
    DIFT=WF/TWS*100.
    PHI=14.
    WRITE (6,3 ) T(ITEMP,6),SP,PHI,SIZE,DIFF,DIFT
    WRITE (6,6) SAND ,SILT,CLAY
  6 FORMAT ( '  SAND = ',F6.2,'     SILT = ',F6.2,
   *'       CLAY = ',F6.2///)
    GO TO 100
    END
```