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A SEDIMENTOLOGICAL STUDY OF MODERN AND ANCIENT LACUSTRINE ENVIRONMENTS AT MICHAEL BAY, LAKE HURON

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B.Sc.

In Partial Fulfillment Of The Requirements For
The Master Of Arts Degree In Geography

Wilfrid Laurier University
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1977

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ABSTRACT

Modern and ancient environments associated with Lakes Algoma and Huron were studied according to attributes of stratigraphy, sediment texture parameters, sediment size distributions, bedforms, and primary sedimentary structures. Results from a computation of wave refraction diagrams and from an examination of the wave climate characteristics indicate that the modern embayment is low energy.

A sediment texture comparison between modern and ancient environments indicates that higher energy prevailed in the ancient environment relative to the present day environment. The cobble and gravel sediments as well as an extensive belt of foredunes preserved in the ancient environment are evidence of this high energy.

Sediment textural parameters of mean, standard deviation, skewness, and kurtosis were combined in bivariate plots to test their reliability for discriminating between environments. Results from four combinations of these parameters were not totally favourable. Only a plot of standard deviation versus skewness proved useful.

Component populations are useful discriminators of depositional environments. Inferred environments of beach, fluvial, and dune as well as modern lacustrine sediments could be identified by the characteristics of their component population curves. Moreover, characteristic curves that represent various subenvironments for the modern nearshore zone are evident. These have been assimilated into a grain size distribution facies indicator.

Provision of a facies model for a barred-lacustrine bayhead was made possible by an examination of preserved bedforms and primary sedimentary structures. High energy bedforms of parallel laminae and massive bedding are always preserved subjacent to low energy ripple cross-laminae. The sequence of ripple cross-laminae that forms in response to increasing energy are as follows: symmetrical, asymmetrical, oscillatory, and combined flow. An examination of such preserved features yields information that can be used to decipher flow directions, energy gradients, and flow characteristics within specific subenvironments.

ACKNOWLEDGEMENTS

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CHAPTER ONE INTRODUCTION

Physiographic features throughout Southern Ontario are primarily relics from Wisconsinan glaciation. Many of these features were modified by glacial lakes which inundated large areas of the province. Glacial lakes such as Warren (12,900 yr. B.P.), Algonquin, and Iroquois (12,400 yr. B.P.) have formed many well-preserved and continuous features on the present day landscape (Prest, 1970). Post-glacial lakes such as Nipissing and Algoma (4,000 yr. B.P.) have also left identifiable features in large and numerous areas throughout the province (Prest, 1970).

Sediments associated with Lake Algoma and Lake Huron were examined in the bayhead area of Michael Bay at Manitoulin Island. This particular area exhibits lacustrine features such as foredunes, multiple longshore bars, lagoons, and beach ridges formed within an embayed environment of Holocene age.

Aims, Scope, And Objectives

Reconstructing ancient depositional environments and understanding modern sedimentological process-response relationships are major research themes in geomorphology. This dissertation adopts these themes in an examination of sediments associated with both modern and ancient bayhead environments.

The study is designed to provide an account of the types of depositional environments found within the area and to present facies models for both modern and ancient sediments. Furthermore, it attempts to elucidate relative energy and processes that would be necessary to generate beach ridge morphology in the ancient sediments. An examination will be made of morphological and sedimentary characteristics of the topographic features with particular emphasis on the stream bank exposures and excavation of appropriate sites.

The rationale for selecting this particular study evolves from the understanding that most studies of glacial and post-glacial lakes have been only concerned with mapping of morphological characteristics such as shorelines and associated features. In addition to this, other types of studies included shoreline correlations through survey and time- uplift data, (Spencer, 1891; Goldthwait, 1910; Leverett and Taylor, 1915; Johnston, 1916; Deane, 1950). Geochronology has been researched primarily through the use of 14C dating methods (Karrow et al., 1961, 1975; Terasmae and Mott, 1963; Hough, 1966; Farrand and Miller, 1968; Lewis, 1969, 1970). Moreover, most attempts to identify nearshore facies have pertained to modern marine environments (Clifton et al., 1971; Hayes, 1972;

Davidson-Arnott and Greenwood, 1974, 1976), while ancient examples have concerned lithified, pre-Quaternary sediments (Michaelis and Dixon, 1969; Campbell, 1971; Baldwin, 1973; Brenner and Davies, 1973; Exum, 1973). Thus, there is apparently much scope provided for the type of research selected for this dissertation. The modern environment sediments will be studied by adopting procedures that have been successfully applied by Clifton et al. (1971) and Davidson-Arnott and Greenwood (1974) in marine environments. The results from this study will enable a complete chronological account of the depositional history as well as a means of inferring processes that have long since terminated in the ancient environment. It will also enable comparison of energy levels relative to the ancient environment.

The thesis problem comprises three objectives. An attempt will be made:

i) to examine processes related to bar morphology in the modern environments;

ii) to examine sedimentological attributes of grain size, bedforms, and sedimentary structures for both the modern and ancient environments;

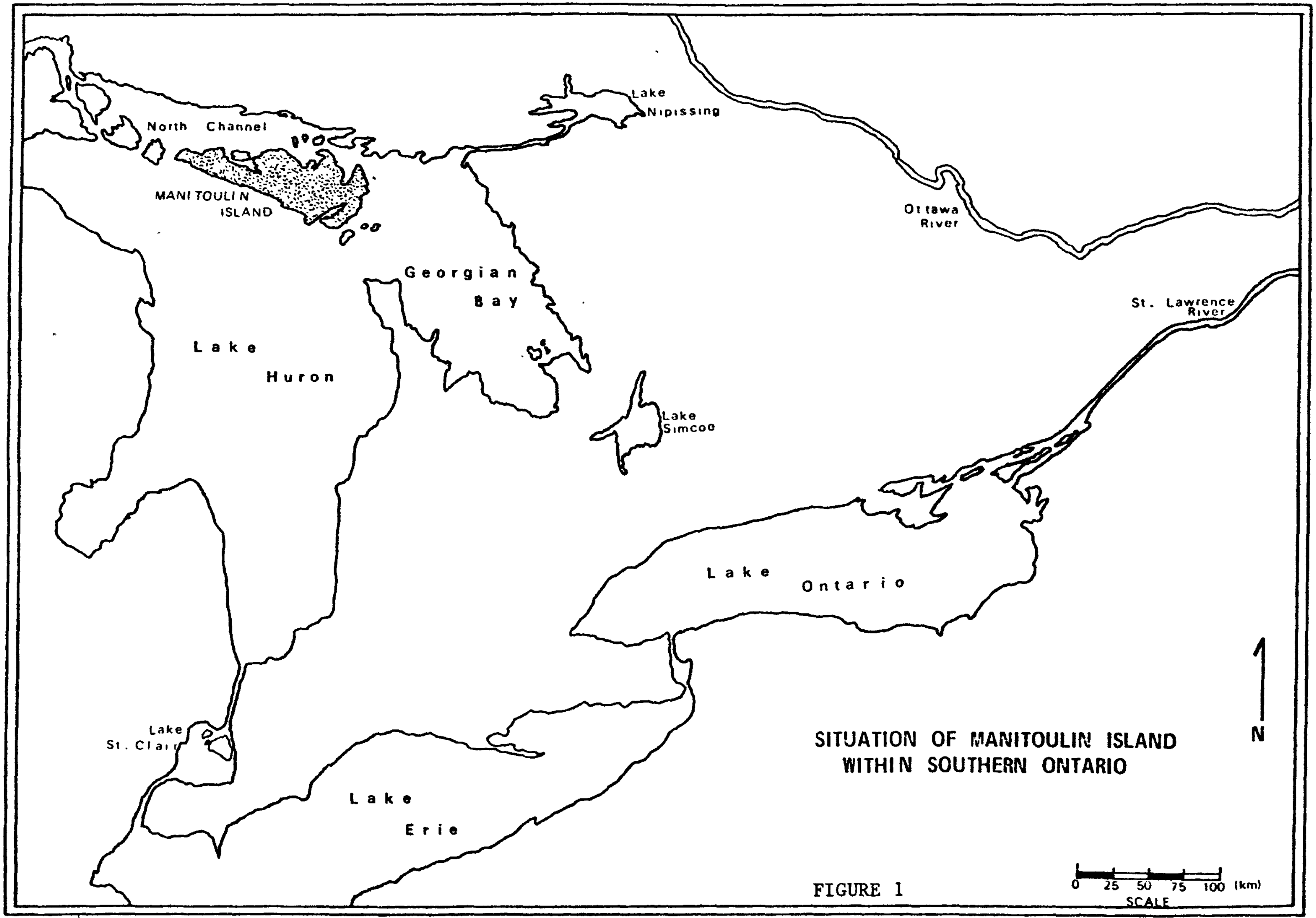
iii) to examine and model the facies of the ancient foreshore and the modern nearshore zone (U.S. Army Coastal Engineering Research Center--(C.E.R.C.), 1973).

Location Of Study Area

Manitoulin Island is situated within the northern margin of Southern Ontario, and is bounded by waters of the North Channel to the north, Georgian Bay to the east, and Lake Huron to the south and west (Fig. 1).

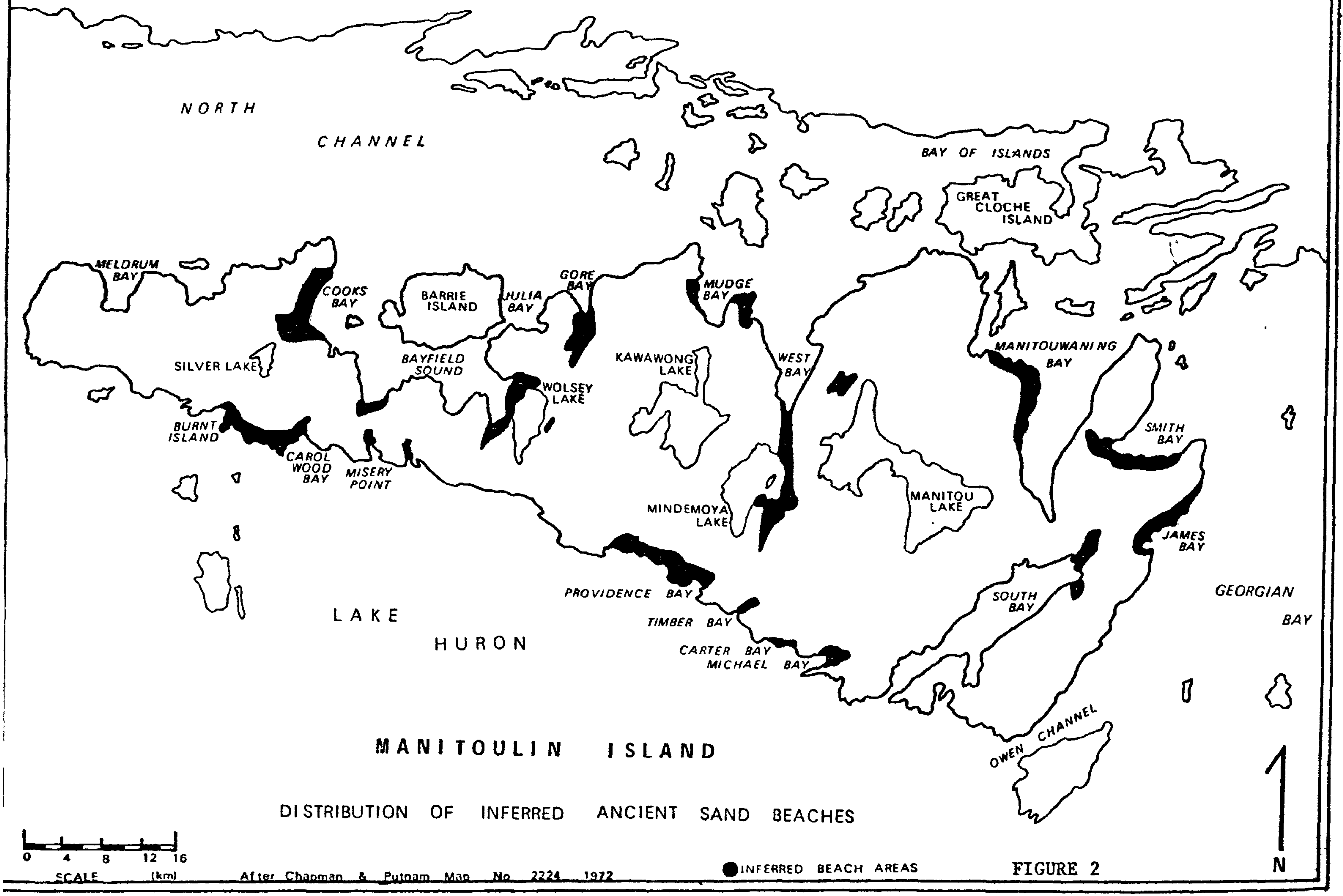
The physiographic features of "Manitoulin" have been of considerable interest to geologists and geomorphologists, since the surficial stratigraphy exhibits depositional environments reflecting both the pre-Quaternary and Quaternary history. The pre-Quaternary bedrock is the most prevalent topographic feature. This mainly comprises Paleozoic strata which include limestone, dolomite, and dolomitic limestone of Ordovician and Silurian Age (Liberty, 1957). Paleozoic shales of Upper Ordovician and Silurian Age are also evident but these only attain prominence in localized areas through a central portion and northern extremities of the Island.

The Quaternary sediments are thin as a result of scour by glacial ice and erosion by waves during glacial Lake Algonquin (Chapman and Putnam, 1966). Those surficial Quaternary sediments which display lacustrine sequences are primarily found on the periphery of the Island. Figure 2 indicates the distribution of ancient beach environments as mapped by Chapman and Putnam (1972, Map Number 2224).



SITUATION OF MANITOULIN ISLAND WITHIN SOUTHERN ONTARIO

FIGURE 1



MANITOULIN ISLAND

DISTRIBUTION OF INFERRED ANCIENT SAND BEACHES

After Chapman & Putnam Map No. 2224 1972

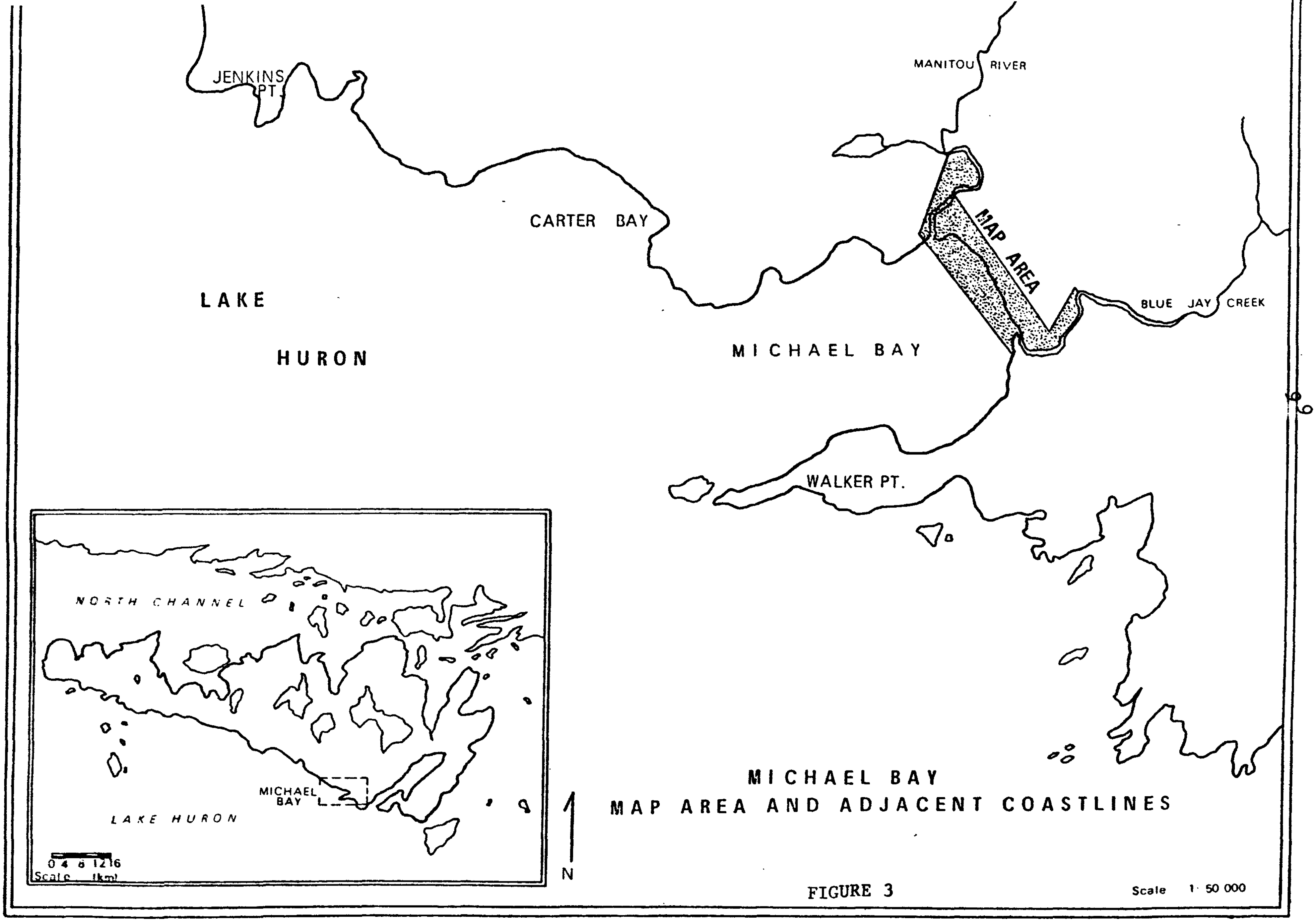
FIGURE 2

Manitoulin Island has provided considerable scope for lithostratigraphical and geobotanical correlations with the Michigan Basin and the Bruce Peninsula (Bell, 1863, 1866; Comstock, 1904; Ami, 1906; Foerste, 1912; Williams, 1919; Caley, 1936; Liberty, 1954; Bolton, 1957; Robertson et al., 1972; Liberty and Bolton, 1971). Geographical reconnaissance has been carried out by Chapman and Putnam (1966) as well as Cunningham (1957), while a pedological survey was performed by Hoffman et al. in 1959. With the exception of Chapman and Putnam's map (1972, No. 2224), Stanley's report (1937b) on a Lake Algonquin beach deposit at Sucker Creek, and Lewis's (1970) 14C dating of gyttja for isostasy purposes and mapping of Nipissing strands, no sedimentological studies, to the writers knowledge, are available for any of the Quaternary sediments on Manitoulin Island. This is especially true for facies of glaciolacustrine and early Holocene origin in the entire Great Lakes Basin. The only notable exception is that of Martini (1975) who examined and provided a facies model for Algonquin-Nipissing barrier sediments at Wasaga Beach, Georgian Bay.

Map Area And Chronology

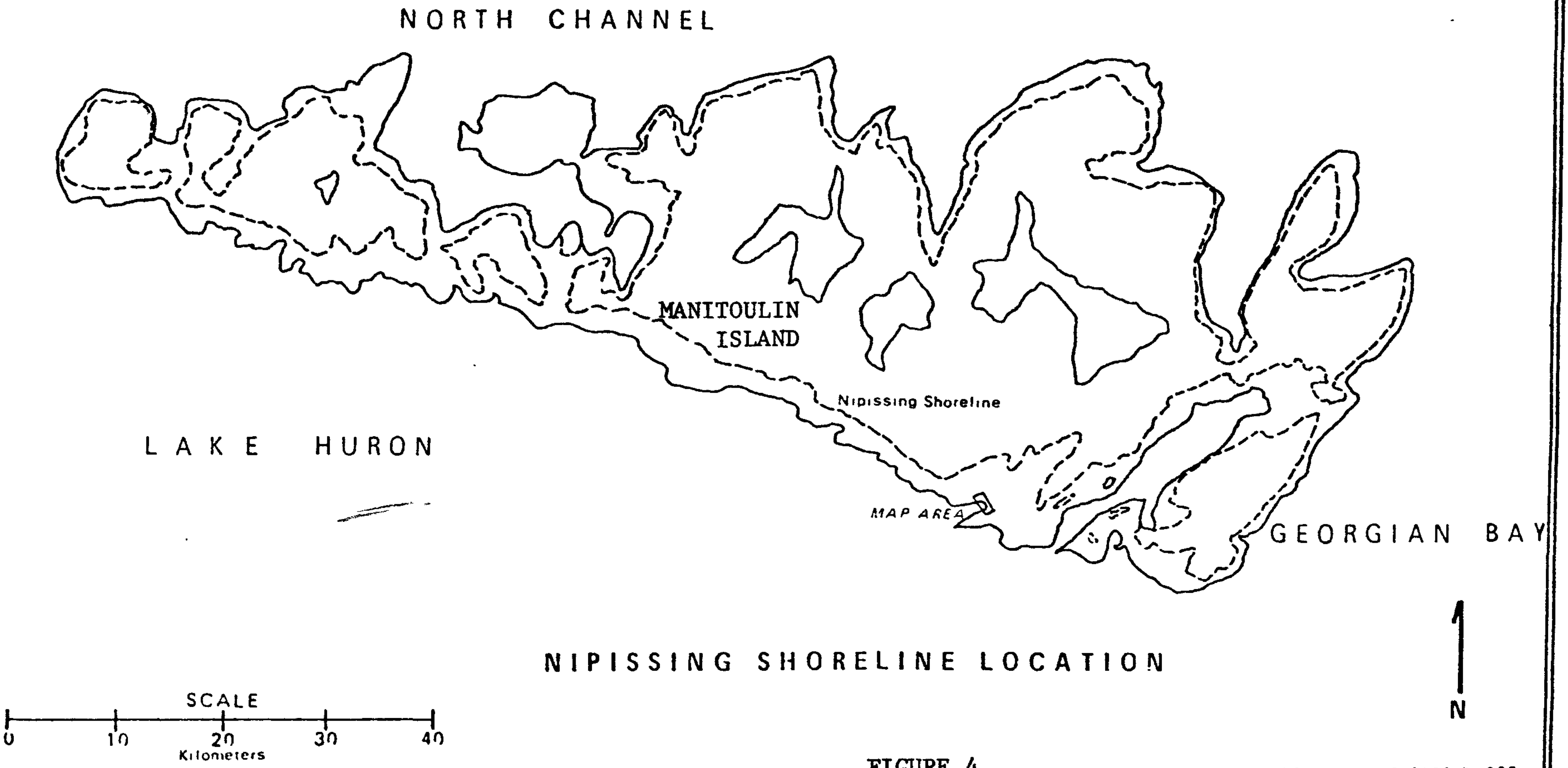
The site investigated for this dissertation involves Michael Bay which is situated on the south-facing shore of Manitoulin Island. Specifically, the site encompasses the modern nearshore zone and associated early Holocene raised shorelines (Fig. 3). These are thought to be contemporaneous with the post-Nipissing Great Lakes phase (Leverett and Taylor, 1915; Coleman, 1941; Hough, 195). This is further substantiated by Lewis (1970) who carried out an isostasy study of Manitoulin and mapped the Lake Nipissing shoreline (Fig. 4). An examination of this map reveals the situation of the Nipissing Great Lakes strand as it relates to the position of the Michael Bay map area. The inferred Nipissing shoreline is obviously situated farther inland than the raised Michael Bay strands. Therefore, these raised strands are most probably Lake Algoma and early Lake Huron correlatives.

Post-glacial lake levels in the Manitoulin region have responded to the effects of differential uplift in two ways. First, when the Lake Nipissing drainage (9,000 years B.P.) was flowing north through the North Bay outlet, lake levels were in a transgressive phase and eventually submerged all but the central portion of the Island. Secondly, when the southern Port Huron outlet opened about 6,000 years B.P., Nipissing lake levels became regressive and Manitoulin Island emerged (Lewis, 1968b; Prest, 1970). Thus, the Lake Algoma stage, which occurred 4,000 years B.P., is believed by



MICHAEL BAY
MAP AREA AND ADJACENT COASTLINES

FIGURE 3



NIPISSING SHORELINE LOCATION

FIGURE 4

After: LEWIS 1970 P. 667

Hough (1958) to represent a pause in the downcutting of the Port Huron outlet at 176.8 metres above sea level. He also suggested that this pause could be attributed to a process of lateral migration in the St. Clair River channel in response to establishing a more stable gradient. Additional downcutting and subsequent stabilization of the Port Huron outlet channel resulted in the present Lake Huron level at 181.4 metres above sea level approximately 2,500 years B.P. (Hough, 1963). Therefore, this additional evidence suggests that the Michael Bay ridges are Lake Algoma and early Lake Huron correlatives.

The modern and ancient shorelines are best shown in Figure 5, which is a composite, stereoscopic view of the bayhead. The littoral zone comprises parallel and subcrescentic longshore bars that are flanked by the Manitou River to the north and Blue Jay Creek to the south. The shoreline is cuspate in plan and exhibits weak development of horns and embayments. The ancient environment clearly displays the swales and ridges, which are crescentic in plan and associated with Lake Algoma. The swales comprise a lagoonal environment while the ridges in the study area are primarily relict foredunes that have become heavily vegetated. It is apparent that as lake level subsided, aeolian sedimentation was a major process. Since foredunes are


AREA OF STUDY
MICHAEL BAY
MANITOULIN ISLAND
73 4525
3 82
North

FIGURE 5

associated with onshore winds (C.E.R.C., 1973--see U.S. Army Coastal Engineering Research Center), this connotes higher wave energy during the Lake Algoma phase. The author did not carry out reconnaissance throughout this entire area however, the ridges that were traversed were not easily perceptible when travelling westward although they are striking features on the air photographs. The maximum amplitude of the ridges is less than four metres and they never form distinct topographic or morphological breaks when seen on the ground.

Silurian bedrock outcrops of the Amabel and Fossil Hill formations are also prevalent within this area. They provide an important source for the ancient beach sediments.

CHAPTER TWO CONCEPTUAL BASIS FOR RESEARCH

Although the glacial and post-glacial lake shorelines in the Great Lakes basin have received substantial attention, the evidence obtained from analysis of these features has been diverse, incomplete, and not always diagnostic of the nature of the sedimentary environments. Therefore, consideration must be given to a research scheme involving an outline concerning salient problems such as diagenesis and epigenesis, which are associated with the study of sedimentary environments; provision of useful criteria such as Key Environmental Indices, which are useful for examining sediments; and an outline of sedimentological methods that are worthy of implementation in this study.

Sedimentary Environments

A sedimentary environment, as defined by Gould (1972, P. 1), is simply a place of deposition. Physical, chemical, and biological processes are factors that can generate and affect the development and form of a sedimentary environment. An underlying problem is that physical processes only occur in present day deposition and have long since ceased in ancient environments. The examination and reconstruction of an inferred, ancient lacustrine environment entails several additional problems. Contradictory information can result from stratigraphical evidence that suggests one climatic interpretation, whereas biological evidence can indicate another. For example, a palynological examination can suggest that a certain species of plant existed in one climatic regime; in fact, the grains may not be indigenous having been transported by wind over a considerable distance and then deposited. Similarly, the preservation potential or differential rate of decomposition all affect the interpretation of the environment. Exposed relict sediments may not be truly representative of an ancient environment, since such sediments are temporally susceptible to many diagenetic and epigenetic processes.

Key Environmental Indices

Miller and Olson (1955) have grouped quantitative measures of properties of sedimentary environments into Environmental Indices. These Indices are listed according to three categories. These provide sole discrimination of (i) modern environments that have undergone little or no diagenetic change, and (ii) ancient environments that have undergone diagenesis. However, the Key Environmental Indices are (iii) those which will provide a discrimination of modern environments while undergoing little or no change from diagenetic processes.

The Key Environmental Indices for this study are: sediment texture and grain size, sedimentary structures, and stratigraphic sequences. It must be noted that texture is specifically applied as a synonym for grain size although it can be applied as a general term to include properties of grain shape, surface texture, and primary fabric.

Sedimentological Attributes

Sediment Texture And Grain Size

Sediment texture parameters, which are applied to differentiate between depositional environments, have been subjected to conflicting opinions. Folk and Ward (1957), Mason and Folk (1958), Friedman (1961), Sahu (1964), Koldjik (1968), Moiola and Weiser (1968), Greenwood (1969), Dickas (1970), Solohub and Klovan (1970), Veerayya and Varadachari (1975) have indicated that textural parameters of mean size, standard deviation, skewness, and kurtosis are environmentally sensitive under certain conditions. In contrast, Shepard and Young (1961), Schlee et al. (1964); Sevon (1966) have presented data which indicate that textural parameters cannot be employed to differentiate between marine and fluvial sands.

While grain size is a measure, which may be interpreted in terms of the processes of sedimentation

(Griffiths, 1967), the different laboratory methods employed to derive the size frequency curve and the different computational procedures used for calculating the textural parameters do not necessarily render commensurable results. Laboratory methods include: dry sieving, settling tube, hydrometer, loose grain measurement, and thin section; whereas, computational procedures include either moment measures or graphical. The published conclusions derived from them have not been fully comparable as a result of these differences in analytical procedures.

The application of textural parameters to environmental discrimination assumes that the parameters do in fact reflect the physical conditions prevailing at the site of deposition (Greenwood 1969). However, "the process-response relationshps existing between sediment texture and the hydrodynamics of depositional environments are incompletely understood" (Greenwood and Davidson-Arnott 1972, P. 679). The variability in laboratory procedures, sampling methods, and parameter computations may be important factors that contribute to this problem of associating sediment texture with the hydrodynamics of an environment. Within these limitations, most sedimentologists believe that textural parameters are both useful and valid for interpreting depositional environments. In some cases, these parameters may indeed enhance the interpretation of depositional processes (Solohub and Klovan, 1970; Moiola and Spencer, 1973).

The author believes that sediment texture as a Key Environmental Index for sedimentological studies is useful and justified, although qualifying restrictions must be recognized.

Sedimentary Structures

Probably the two most important Key Environmental Indices that can be applied in any study of modern and ancient sedimentological environments are the preserved bedforms and sedimentary structures. Although it is possible to locate structures that are similar and yet produced in different depositional environments, it has long been recognized that bed deformations or bedforms exhibit regular variations in shape as they respond to flow conditions. Moreover, where the sedimentary structures are preserved, they can be used to elucidate the type of depositional environment.

Most studies of bedforms and structures produced by wave activity have been performed in either the offshore, the zone where rapid transformation begins, or in the foreshore area where wave energy dissipates. Some detailed offshore investigations include those of

Inman (1957), Tanner (1959, 1963) Newton (1968), Clifton et al. (1971). The structures formed in the foreshore zone have been described in even greater detail as a result of their accessibility at low tide. Such studies include the work of Gresswell (1937), Thompson (1937), King and Williams (1949), Davis et al. (1972), Hayes (1972).

Research carried out on bedforms and the structures found in the nearshore zone has been very limited with notable exceptions being Clifton et al. (1971), Hunter et al. (1972), Davidson-Arnott and Greenwood (1974, 1976). A facies model can be defined by the various characteristics of the sedimentation units within a stratigraphic sequence. So far, such models have been absent for bayheads in a lacustrine environment, and only available for barred, non-barred and barrier marine environments.

Stratigraphic Sequence

By using Walther's Law, vertical and lateral facies relationships can be considered as useful Key Environmental Indices for a prograding shoreline.

One seldom finds a shoreline "outcrop" that can be traced for great distances in both lateral and vertical extents. Nor is it feasible to examine an entire shoreline in any other dimension than lateral. In a prograding shoreline system, one can assume that each foreshore facies will eventually be superjacent to the facies that was previously offshore from it. Therefore, moving vertically down-section is analogous to moving offshore into deeper water where wave and current conditions are less active. Carefully used, these inferences about environmental and hydrodynamic constraints can add to our understanding of primary sedimentary structures and sequential changes of bedforms in vertical sections (Harms et al. 1975).

From the preceeding discussion, the Key Environmental Indices for this thesis project are: bedforms and sedimentary structures, stratigraphy, and sediment texture.

Application Of Indices For This Study

Stratigraphical evidence obtained from a visual evaluation of bedding sequences within each sample site should permit classification of the type of depositional environment. Sediments obtained from the sample sites will enable sediment texture parameters to be computed and combined in bivariate plots as a test of their reliability for discriminating between environments. The discriminating ability of sediment size distributions will be demonstrated by analyzing their component populations. Finally, information accrued from an examination of subenvironment bedforms and sedimentary structures will be assimilated into a facies model for the modern environment. This facies model can be used in an evaluation of sediments preserved in the ancient environment.

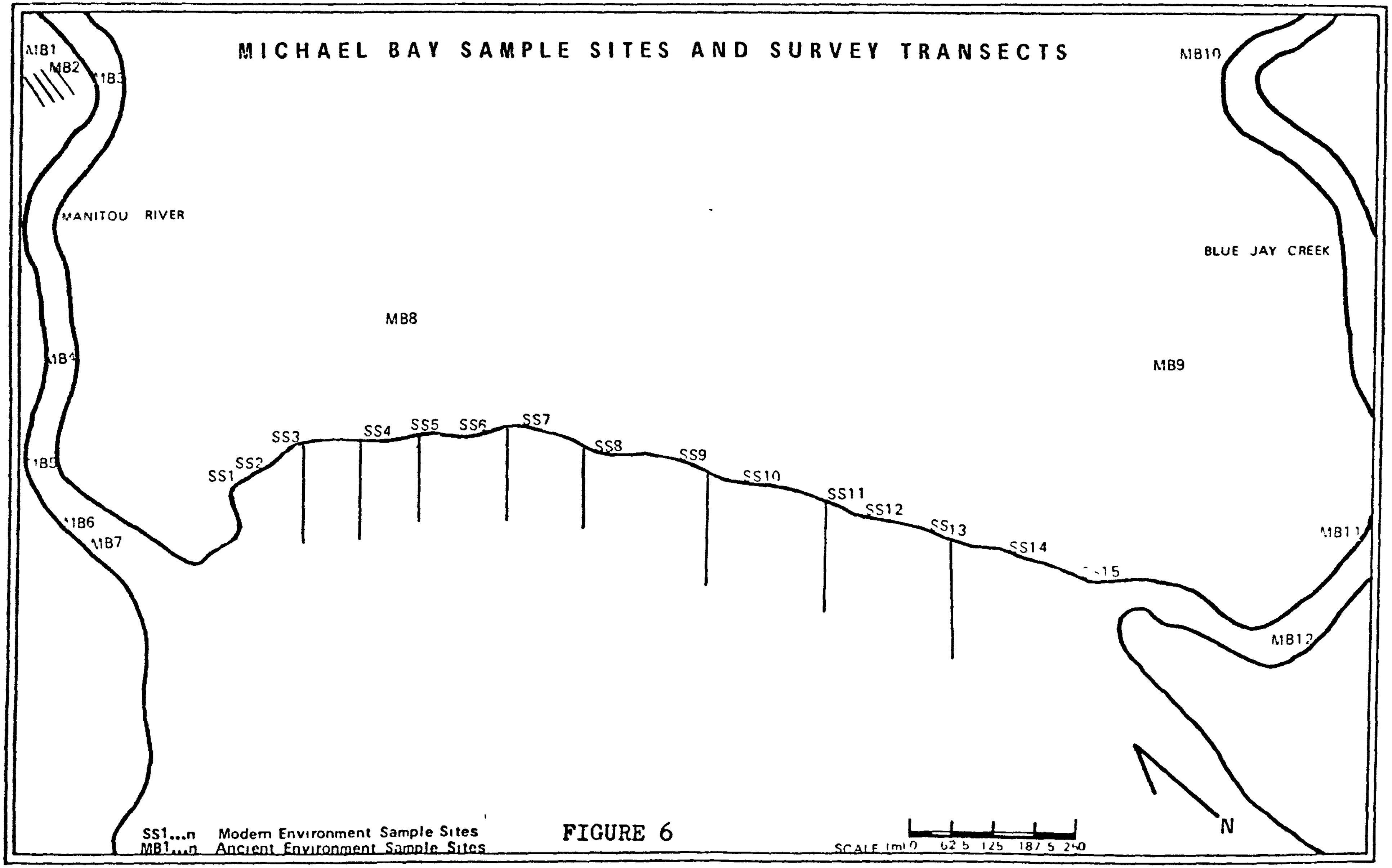
CHAPTER THREE DATA ACQUISITION AND ANALYSES

The procedure for data collection employed in this research can be outlined according to primary and secondary sources. The primary source includes field study data obtained from surveying and sediment sampling. Secondary sources are based on data resulting from the hindcasting of waves, the construction of refraction diagrams from a wave energy-refraction computer programme (May, 1974), and the use of air photographs as well as Canada Topographic Series 1:50,000 maps.

Primary Data

Survey Procedure

The surveying was accomplished by means of an engineer's level, a metric stadia rod, Brunton compass, Abney level and metric tape. Twelve transects were surveyed in both modern and ancient environments, (Fig. 6). The ancient ridges were surveyed normal to the inferred shoreline, and the modern nearshore to the maximum limit of wading along a line normal to the beach. This procedure enabled contour maps to be drawn of littoral zone and raised shoreline topographies. Survey measurements were linked to a permanent beach mark on the backshore, since it could be used as datum for all maps and profiles.



MICHAEL BAY SAMPLE SITES AND SURVEY TRANSECTS

SS1...n Modern Environment Sample Sites
MB1...n Ancient Environment Sample Sites

FIGURE 6

Sediment Sampling

Sediment sampling consisted of photographing sections and removing sediment samples from individual sedimentation units in sequence throughout a vertical section as well as from surficial units along the transects. Care was required, since the unit to be sampled could be contaminated by other units in such a manner that an erroneous size distribution would result when the data were computed. The sampling technique is a modification of a scheme outlined by Ann (1969), and is a stratified systematic sampling procedure. By sampling individual units from a vertical section, stratigraphical and spatial control are insured. Textural parameters and grain size distributions were determined for subenvironments both normal and parallel to the transects. Another sampling alternative is the systematic grid technique. Although this method is apparently free of operator bias, it is actually less amenable because the interbedding of thick beds with extremely thin beds can lead to inconsistencies whereby some thin units are omitted. The additional equipment required for demarcating the grid and for selecting the samples also makes this procedure cumbersome and time consuming.

Sediment samples and resin peels of sedimentary structures from the modern littoral zone were obtained from sediments contained within a stainless steel, wedge- shaped box core sampler. This sampling device measured 35 cm in height by 25 cm in width and 15 cm in depth. The coring technique is a modification of a scheme proposed by Klovan (1964) as implemented by Davidson-Arnott and Greenwood (1974). This technique permitted continual use of the coring device because a galvanized sheet metal liner, which fitted within the corer, could be immediately removed upon completion of sampling from each site. Upon removal, each liner was then packed with dry sand to prevent the core from fracturing, and a lid bearing the orientation and sample number was fastened by two screws. These units were returned to the laboratory where all peels were simultaneously cast. Figure 7 shows the coring device as well as one sample unit ready for transport to the laboratory. Care must be exercised to insure that the core is sampled vertically, since deviation from this will result in sedimentary structures that display improper dip as a result of operator error.

The peels were cast by using a modified version of a method originally outlined by Burger et al. (1969). CIBA chemicals #6010 epoxy and #850 hardener were mixed in a one to one ratio and poured over the core. This was accompanied by muslin cloth, which was immediately applied to provide a firm backing when

FIGURE 7

BOX CORING UNIT
COMPLETE WITH ONE SAMPLE

polymerization was completed. This method not only eliminates two chemicals and additional costs but also is directly applicable to either fresh or saline water conditions. Immediately after the peels were made, sediment samples corresponding to individual sedimentation units were taken from the remaining core sediments. Each sedimentation unit was defined by primary sedimentary structures. Sampling consisted of scraping sediments from the surface of each unit. This procedure was applied to sedimentation units within vertical sections for both modern and ancient environments.

Sieve Analysis

Samples acquired from each site were prepared for grain size analysis by washing with distilled water. No organic material was present. Sieving of 189 samples was carried out in accordance with the methodology of Folk (1974). Tyler sieves in one-quarter phi increments and a Ro-Tap machine were used for sieve purposes. Sample weights for sands were 90 grams, while 250 gram samples were necessary for fine gravels. After a sieving time of ten minutes, a chemical balance was utilized to weigh size fractions to 0.001 gram. Folk textural classifications, frequency distributions, and size frequency statistics of mean particle size, standard deviation, skewness, kurtosis, and relative entropy were calculated by a Fortran IV computer programme (Kane and Hubert, 1963). The size frequency statistics were computed and exhibited according to the method of moments as well as those of Inman (1952) and Folk and Ward (1957).

Secondary Data

By utilizing an air photograph series (73 425 3 82-3 84), a Canada Topographic series map (49/G/9/E), and a Canada Hydrographic Bathymetric chart (#2298), it was possible to select areas that were accessible and to locate twelve ancient sample sites (Fig. 6).

Wind Data And Wave Hindcasting

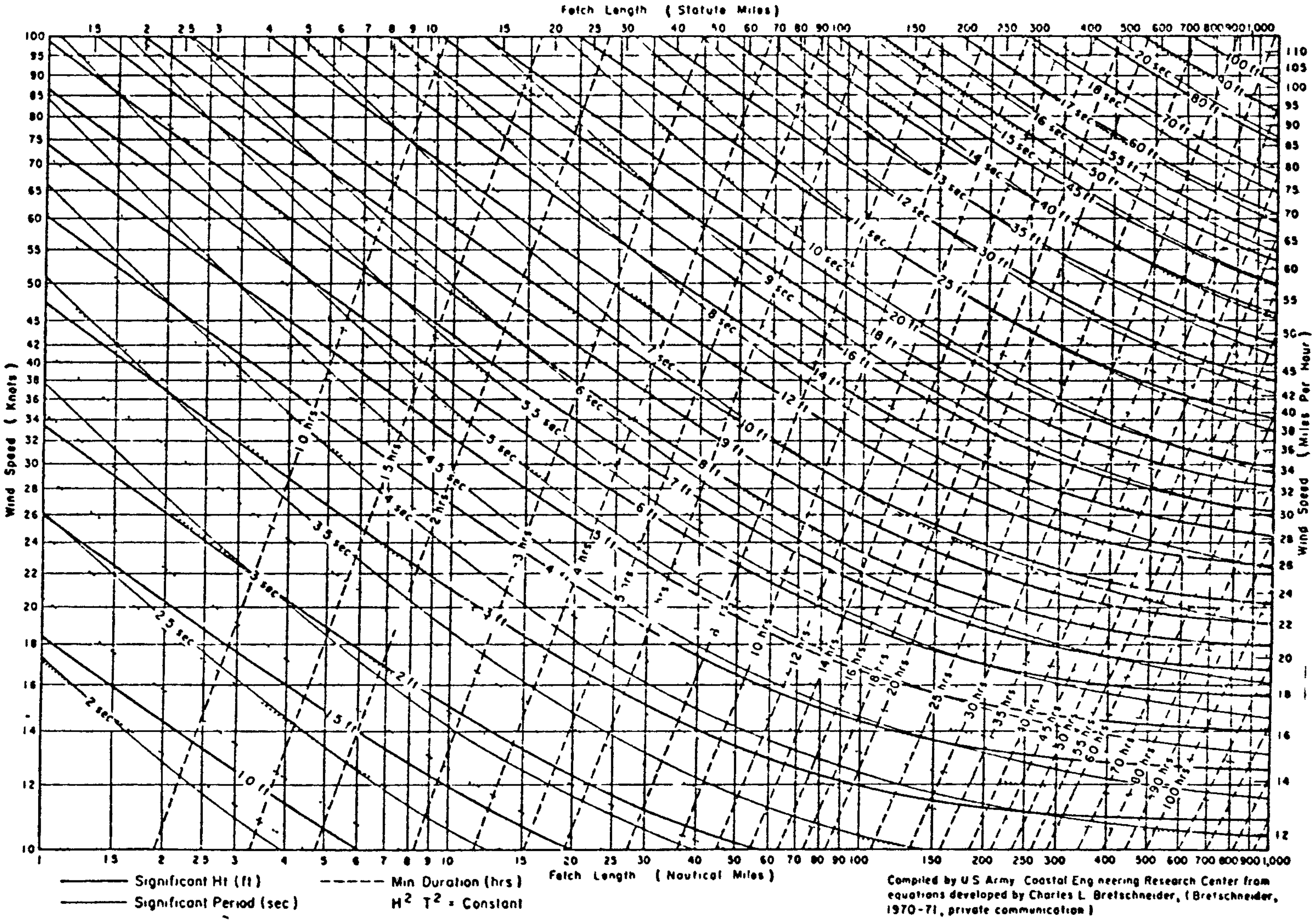
The generation of waves, for the most part, depends on the transfer of energy from wind to the water surface. The period and significant height of the waves can be determined by the wind speed, direction, duration, and fetch length. These wind characteristics were obtained for Michael Bay from 1975 hourly wind data measured at South Bay, Maritoulin Island. The data are recorded and assembled by the Canadian Department Of Transport, Downsview, Ontario.

Data were employed in the Sverdrup, Munk, and Bretschneider (S.M.B.) wave hindcast method, as outlined by the U.S. Army Coastal Engineering Research

Center (C.E.R.C.) in 1973, to determine the significant wave heights and periods for the various fetch lengths.

The S.M.B. method of hindcasting deep water waves from wind data is essentially the result of many wave observations that were collected to establish empirical relationships between the variables affecting the growth of waves and the wave characteristics. For example, the curved lines indicating the significant wave height (Fig. 8), were modified by Bretschneider (1952) after Sverdrup and Munk (1947). He combined additional empirical information concerning the wave spectrum and wave generation parameters to refine the accuracy of this hindcast procedure. His work concerned a combination of the following ratios: Co/U versus gF/UU and gH/UU versus gF/UU. Co is the deep water velocity measured in feet per second, U is the mean surface wind speed in either miles per hour or knots, F is the fetch length in either statute or nautical miles, H is the significant deep water wave height in feet, and g is the component of gravitational acceleration in feet per second squared.

Wave characteristics from this wave hindcast were employed in a Fortran IV computer programme (May, 1974) to determine the wave refraction pattern for Michael Bay. This computer programme was compatible for a



Compiled by U S Army Coastal Engineering Research Center from equations developed by Charles L. Bretschneider, (Bretschneider, 1970-71, private communication)

SMB WAVE HINDCAST CHART

FIGURE 8

After, CERC, 1973, P. 3 36.

Control Data (CDC) 6500 computer system and was amended for use on a Xerox Sigma 7 computing system.

<u>Wave Refraction</u>

Refraction patterns for an area are important because they permit description of coastal processes and an explanation of shoreline morphology. In addition, predictive statements can be made concerning coastal change when combined with percentage frequency of occurrence data such as storm wind parameters and depth of disturbance conditions.

WAVENRG (May, 1974) is a computer programme that was implemented to calculate the refraction patterns and the littoral power gradient. The wave period, deep water wave height, direction of propagation, and bathymetry are input data. Output from this programme includes:

i) tracking of individual rays to a point where the wave breaks;

ii) total breaker power (joules/m-sec.);

iii) the effective shore parallel component of breaker power (joules/m-sec);

iv) the mean longshore current velocity (m/sec.) and the direction of resultant flow normal to the propagation direction.

The criterion for breaking waves is 0.78 or where the ratio of wave height to water depth exceeds this value. The total breaker power gives an indication of the potential energy within one point along the wave ray as well as along the entire wave front. Kinetic energy is indicated by the shore parallel component of breaker power, since this index relates to bed friction.

There are some assumptions within this programme that must be pointed out. It is assumed that no significant energy loss occurs as a result of internal friction, free surface friction, adverse currents or percolation into the bed. However, Lamb (1945) demonstrated that internal friction as a cause of wave energy loss is negligible for water because of its low viscosity. The effect of free surface friction is eliminated by assuming absence of wind. The bottom friction is negligible for water depths exceeding one-half the wavelength.

Computer "noise" that would be generated when running closely spaced rays was alleviated by running individual wave rays for each direction of wave propagation.

CHAPTER FOUR EXAMINATION OF MODERN AND ANCIENT ENVIRONMENTS

Modern Environment

The investigation of the embayment included the refraction, bathymetric, and sedimentological characteristics.

Wave Refraction

Wave refration diagrams for Michael Bay were constructed by using the wave characteristics from wave hindcasting and data collected by the Canada Hydrographic Service as well as data from littoral zone surveying. The method applied to draw the refraction diagrams is a numerical technique described by May (1974). An alternative method is the graphical technique, but this approach requires manual construction of the diagrams (King, 1972; C.E.R.C., 1973).

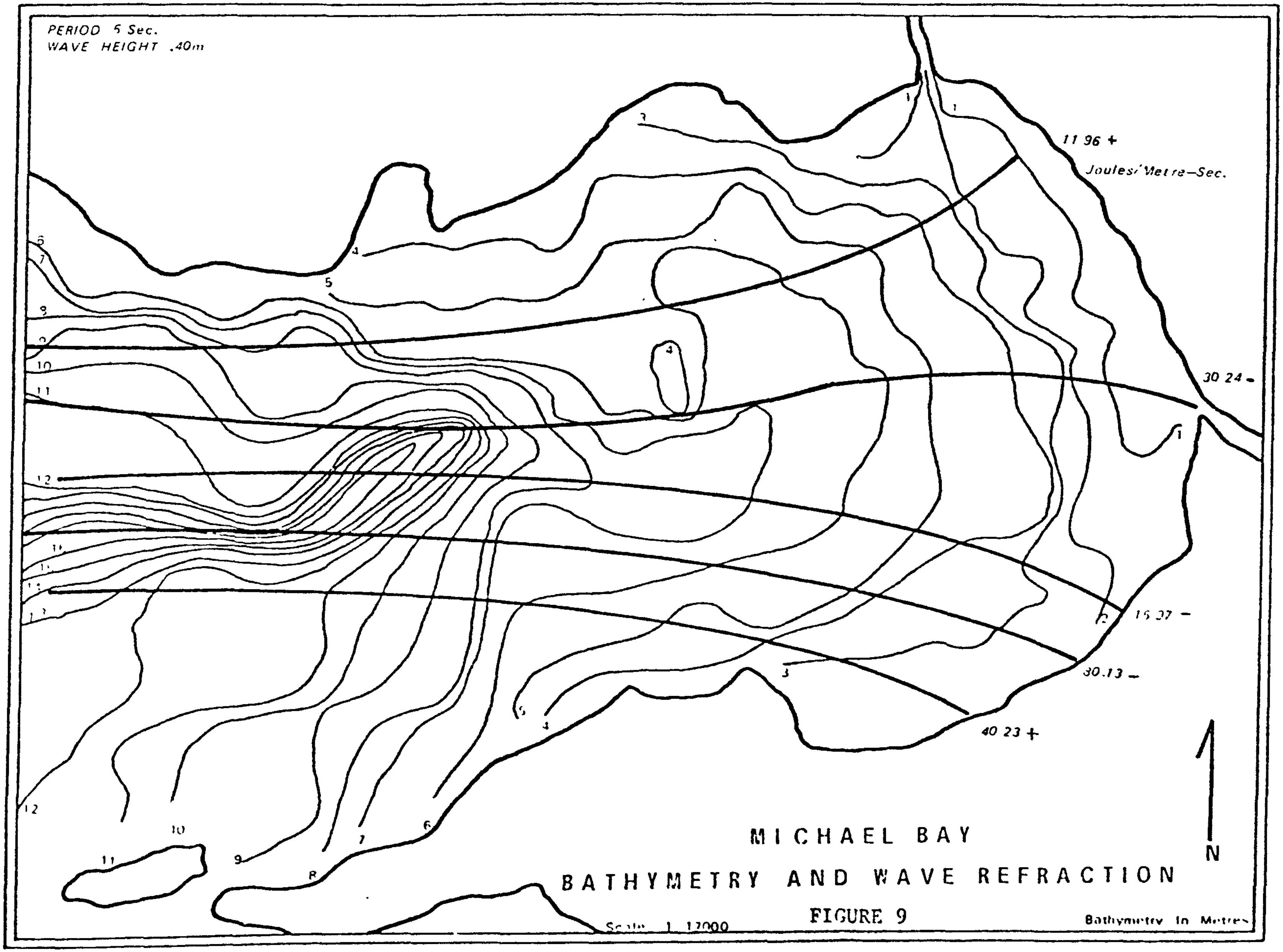
Grand means for wave period and significant deep water heights for each direction of propagation were used as input data. These represent the most frequent occurrence of refraction patterns for winds generated from the west and the southwest. In addition wave rays were generated from the south southwest by using the southwest wind data. This was necessary since discrete data were not available for this direction. Winds arriving at the embayment from other directions are not significant owing to the enclosed nature of the site. For example, northwest, northeast, and north winds are ineffective owing to the presence of land. Similarly, Walker Point would cause attenuation of waves from the south. Table 1 exhibits the data that were employed in this refraction study.

Wave refraction diagrams for Michael Bay are illustrated in Figures 9, 10, and 11. The number at the terminus of each ray is the breaker wave power parameter (joules/metre-second), which was determined within the computer programme. This can be considered a relative measure of wave energy. The deep water wave lengths for each of the diagrams are unrelated, since the mean wave heights and periods for each wave direction are different. Therefore, these breaker-wave power parameters are only comparable between wave rays within each diagram. Positive and negative values indicate the direction of longshore transport as viewed from offshore. The positive sign refers to transport towards the right while the negative sign conversely indicates transport to the left.

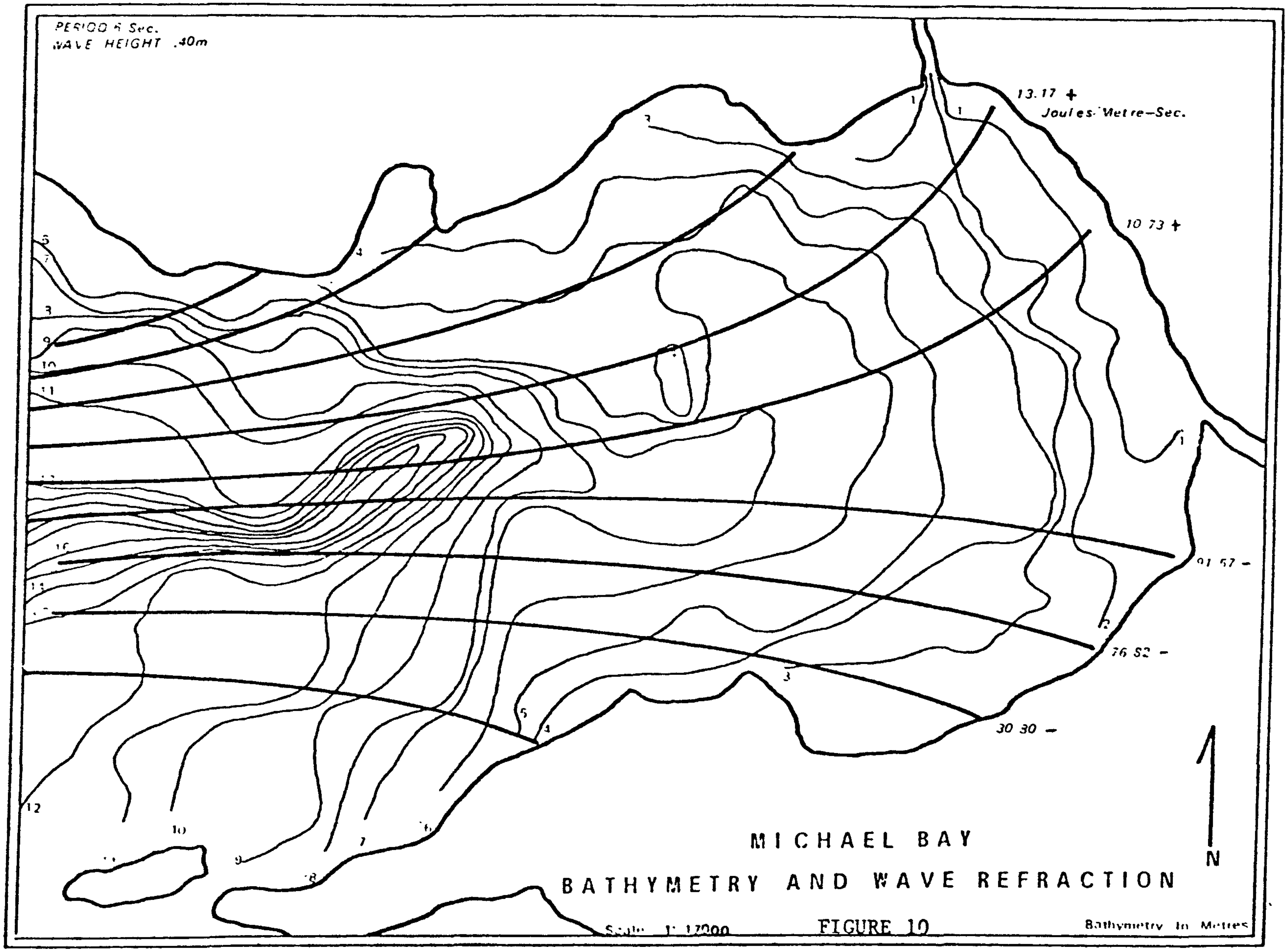
TABLE 1

SUMMARY OF WAVE CHARACTERISTICS FOR MICHAEL BAY WAVE REFRACTION DIAGRAMS

Wind Direction	Mean Significant Height (m)	Mean Period (Sec)	Fetch Length (km)
West	.40	5.3	117.12
Southwest	.43	6.4	173.92
South Southwest	.43	6.4	160.52



MICHAEL BAY
BATHYMETRY AND WAVE REFRACTION
FIGURE 9



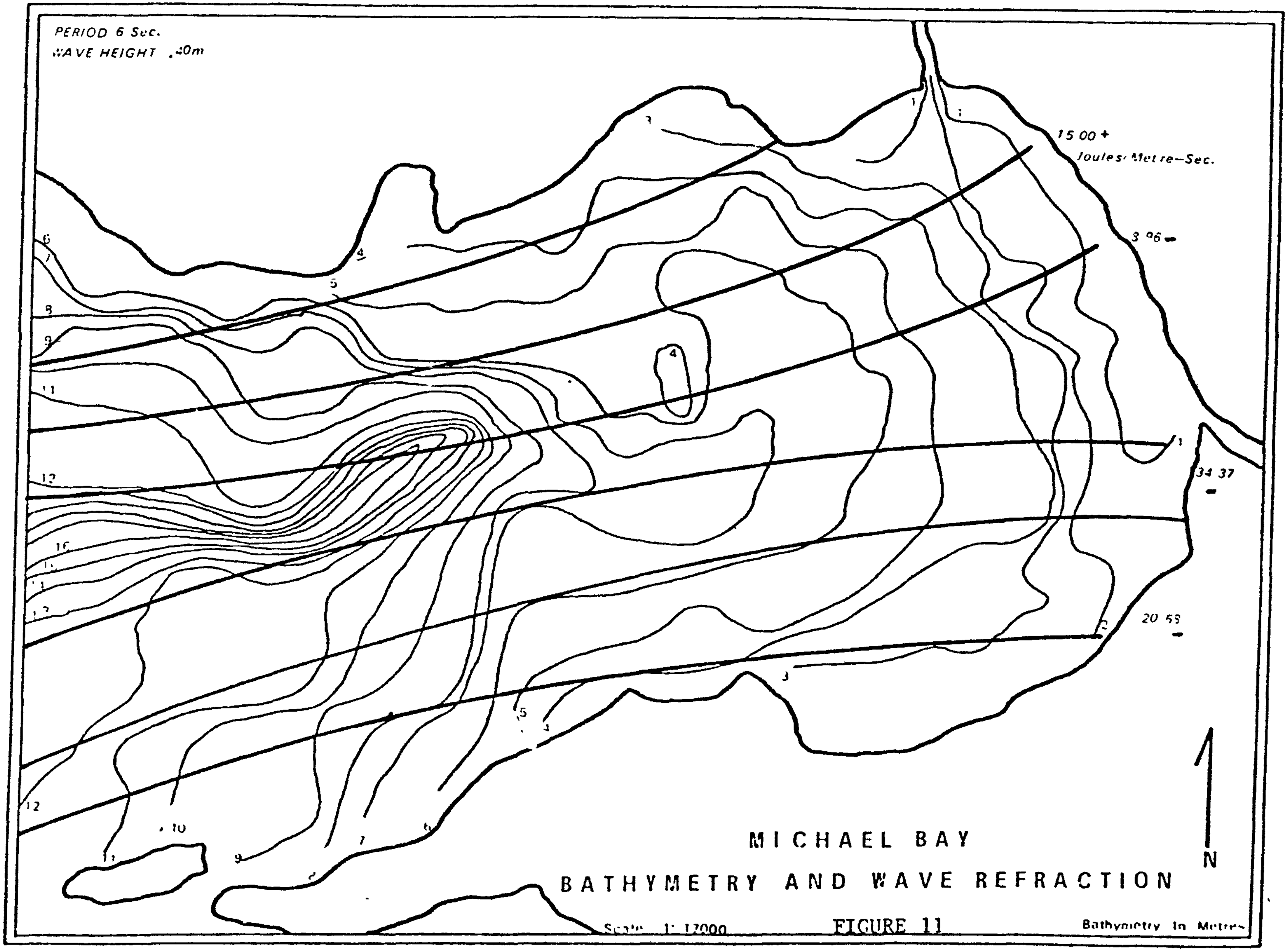
MICHAEL BAY

BATHYMETRY AND WAVE REFRACTION

Scale 1:17000

FIGURE 10

Bathymetry In Metres



MICHAEL BAY

BATHYMETRY AND WAVE REFRACTION

FIGURE 11

When waves approach from the west, as shown in Figure 9, the wave power parameters indicate low wave energy in the bayhead (11.96 to 15.97 joules/m-sec.), whereas, relatively higher wave energy (30.24 to 80.13 joules/m-sec.) occurs in the area south of Blue Jay Creek. Figure 10 exhibits highest values of wave energy distribution and transport direction. These high energy values occur for southwest waves and are explained by the greater magnitude and frequency of winds. It also signifies that higher and longer duration waves will occur and these are capable of producing more work at the shoreline. The refraction pattern for southwest wind data for waves generated from the south southwest represents the lowest values of the significant wave spectra that would influence Michael Bay. Wave power values are lowest while transport directions are similar to the other two diagrams.

The results for each wave refraction diagram indicate areas of potential erosion and transport direction. The area to the south of the Michael Bay -Blue Jay Creek interface exhibits a net transport direction to the north while the bayhead is characterised by only localized transport as indicated by the lower wave power values and by the variability in transport direction. This embayment can be classified as low energy, since significant breaker height will be frequently less than one metre, (Clifton et al., 1971). The results also indicate that magnitude and frequency of winds are more important than the fetch. This is in agreement with results obtained by Johnson (1946).

Littoral Zone Bathymetry

The Michael Bay littoral zone at the bayhead spans 1.2 kilometres and consists of a broad shoal zone lakeward of the cuspate shoreline. Also present is a multiple longshore bar system that comprises two to three bars which are shaped either subcrescentic or parallel in plan. Figure 12 displays these features as well as the bathymetry. Figures 13 and 14 are better indications of the subaqueous topography with the survey lines corresponding to those shown in Figure 5.

Longshore Bar Topography

Longshore bars can occur as either single or multiple features. "The number of bars is greater where the gradient is flatter" (Hands, 1976). This serves as a possible explanation for the series of bars within the embayment, since the mean gradient is approximately 1:80. Kindle (1936) noted as many as ten longshore bars present within Chesapeake Bay. These possessed a wavelength of 25 metres and were attributed

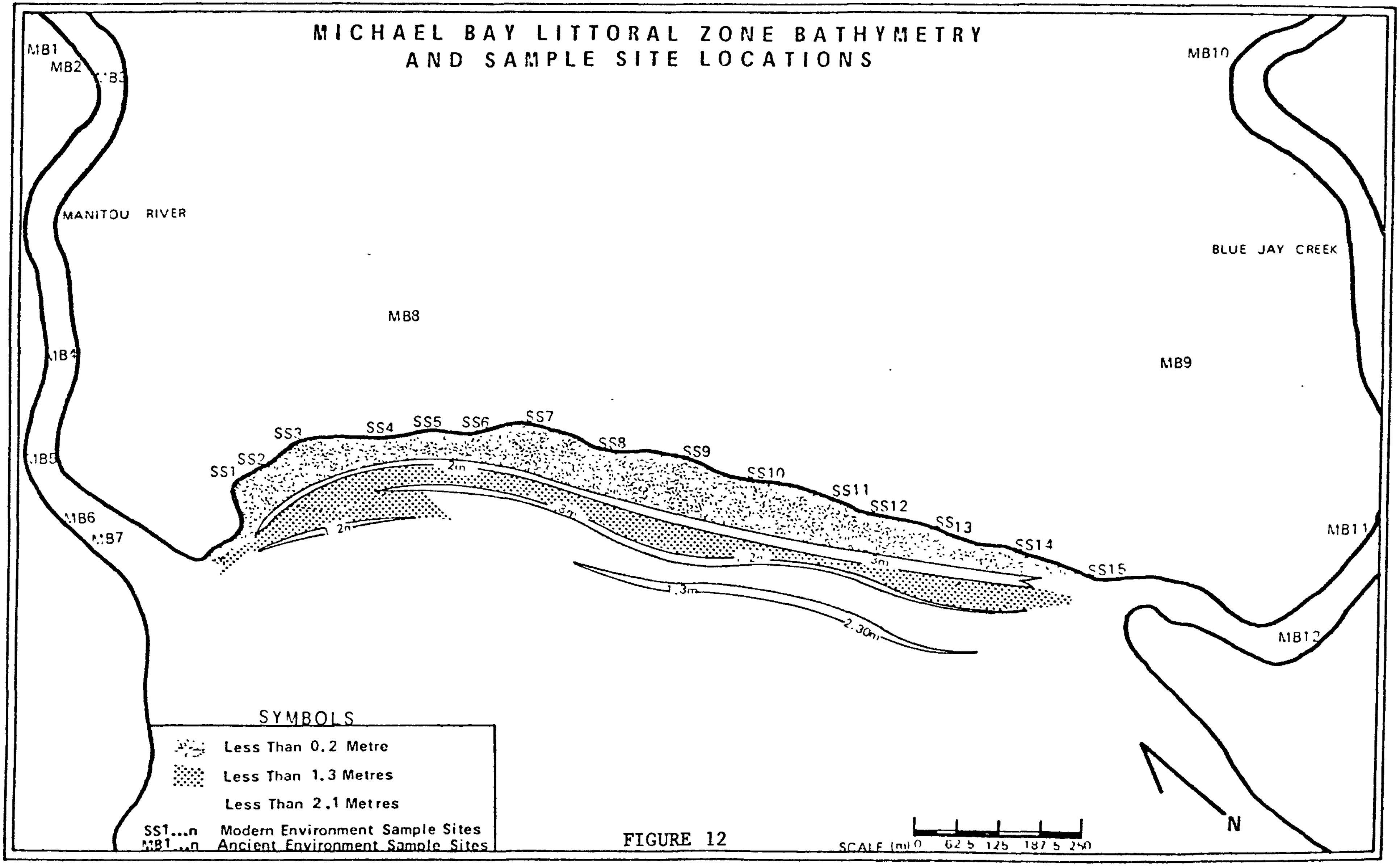

MICHAEL BAY LITTORAL ZONE BATHYMETRY AND SAMPLE SITE LOCATIONS

FIGURE 12

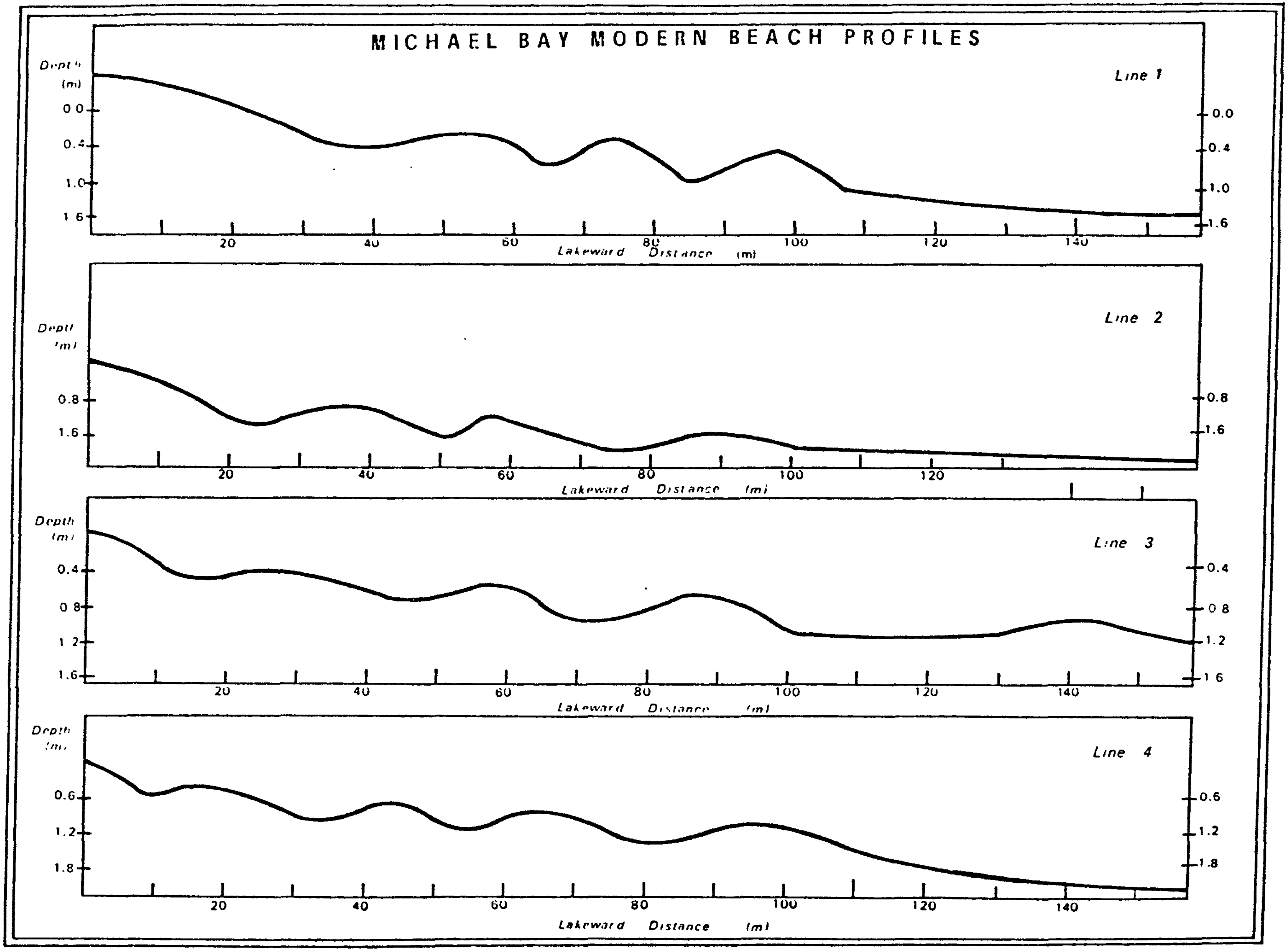

MICHAEL BAY MODERN BEACH PROFILES
Line 1
Line 2
Line 3
Line 4
Depth (m)
0.0
0.4
1.0
1.6
0.8
1.2
0.6
1.8
20
40
60
80
100
120
140
Lakeward Distance (m)

FIGURE 13

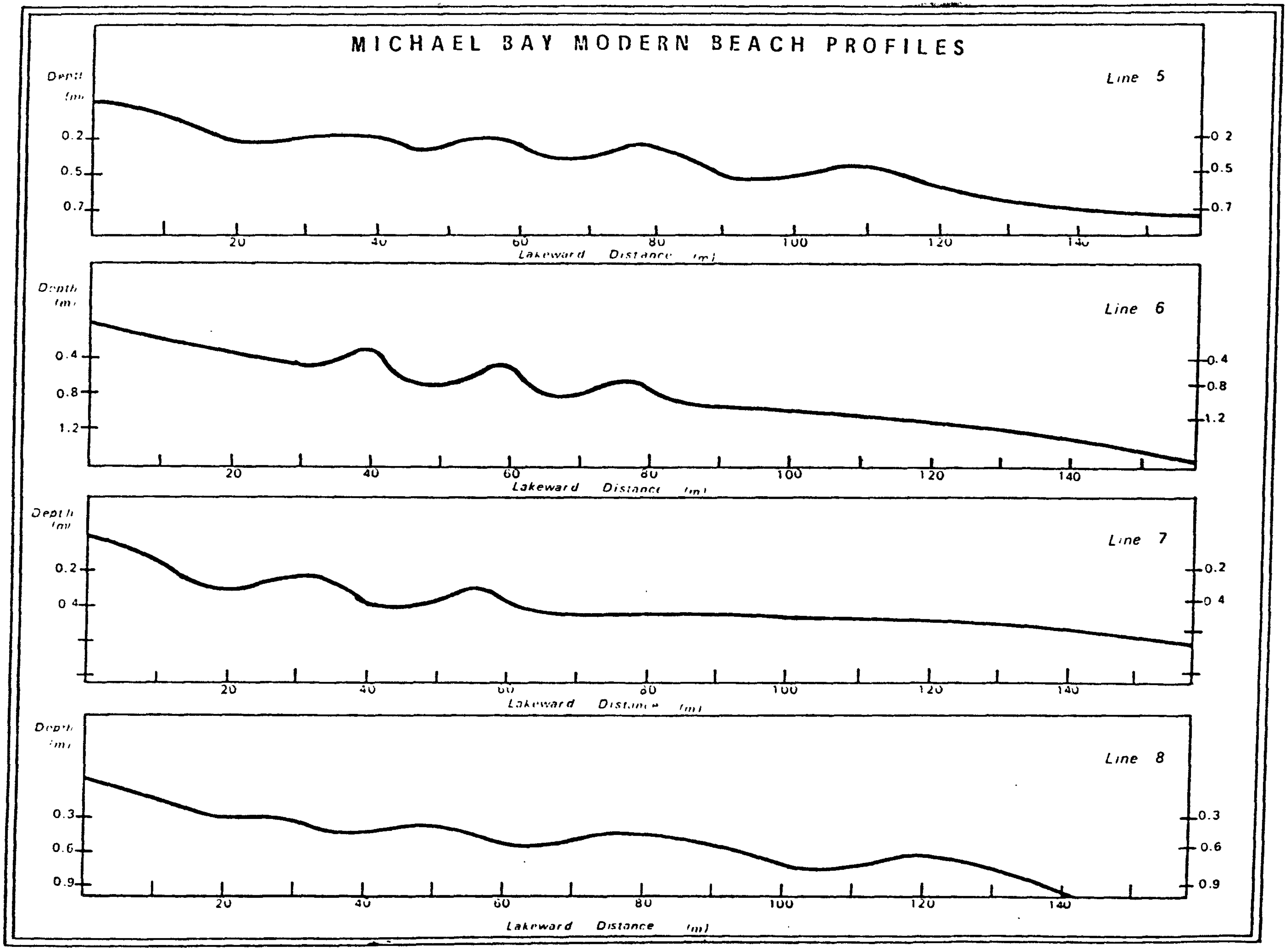

MICHAEL BAY MODERN BEACH PROFILES
Line 5
Depth (m)
0.2
0.5
0.7
20
40
60
80
100
120
140
Lakeward Distance (m)
Line 6
Depth (m)
0.4
0.8
1.2
Line 7
Depth (m)
0.2
0.4
Line 8
Depth (m)
0.3
0.6
0.9

FIGURE 14

to a gentle gradient. Evans (1940) reported that three bars were commonly present for fine sediments in the eastern shore of Lake Michigan. In Michael Bay, a mean surficial sediment size of 3.1320 is the primary factor that contributes to this gradient, while a secondary factor is the basin configuration whereby headlands are capable of protecting the shoreline from erosion by high energy waves. Moreover, minimum wave energy is concentrated in the bayhead.

The relative spacing of bars can be best explained by the characteristics of the wave climate. The bars occupy a wide zone across the bayhead but only extend lakeward within a range of 160 metres. A mean wavelength of 20 metres between the landward and central bar, and 30 metres between the central and lakeward bar is indicative of low energy, since higher energy waves would obviously create a bar topography farther lakeward with a greater wavelength between successive bars or troughs, (Keulegan, 1948; King and Williams, 1949; Carter, Lui, and Mei, 1973; Lau and Travis, 1973). Thus, the characteristics of the wave climate, the littoral zone gradient, and the fine sediment size are apparently conducive to this pattern of multiple bar topography.

Sediment Samples

Sediments sampled from 43 sites extending from the berm through other subenvironments were examined to determine the textural pattern of surficial sediments and textural properties of bedforms evident in vertical sections (Fig. 15). Twenty seven sites were sampled for both surficial sediments and subsurface sediments, while the remaining sixteen sites were sampled solely for surficial sediments throughout the littoral zone.

Ancient Environment

Twelve sites within the ancient bayhead were sampled for their textural properties. Six of these sites were then selected for more detailed analyses concerning their sedimentological and morphological attributes. The six sites are depicted in Figures 16 to 21. They illustrate the bedding characteristics for each site, and they respectively correspond to sample sites: MB1, MB3, MB5, MB6, MB10, and MB12.

Interpretation Of Sites

An interpretation will be made of these photographed sections in an attempt to determine the type of depositional environment. This interpretation consists of information from visual evaluation of sedimentary structures, provenance of sediments as well

BEACH PROFILE AND RELATED TERMS

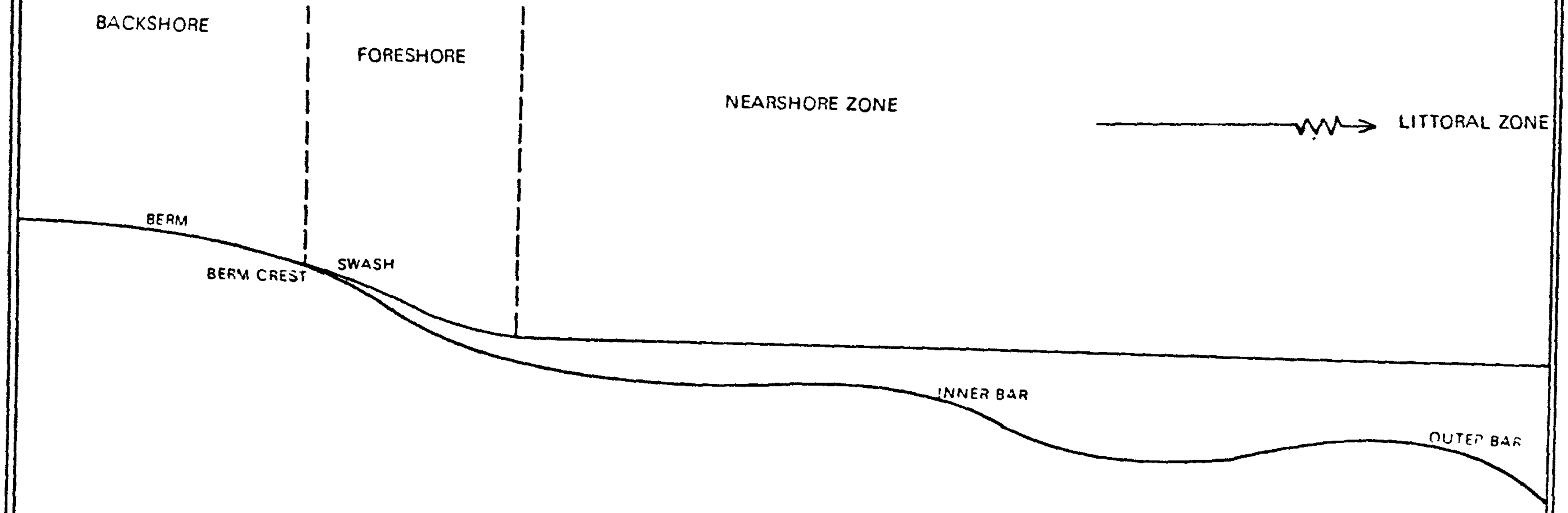


FIGURE 15

After C.E.R.C. 1973 V. 3 P. A 35

FIGURE 16

SAMPLE SITE: MB1 Ancient Beach Ridges And Corresponding Sediments

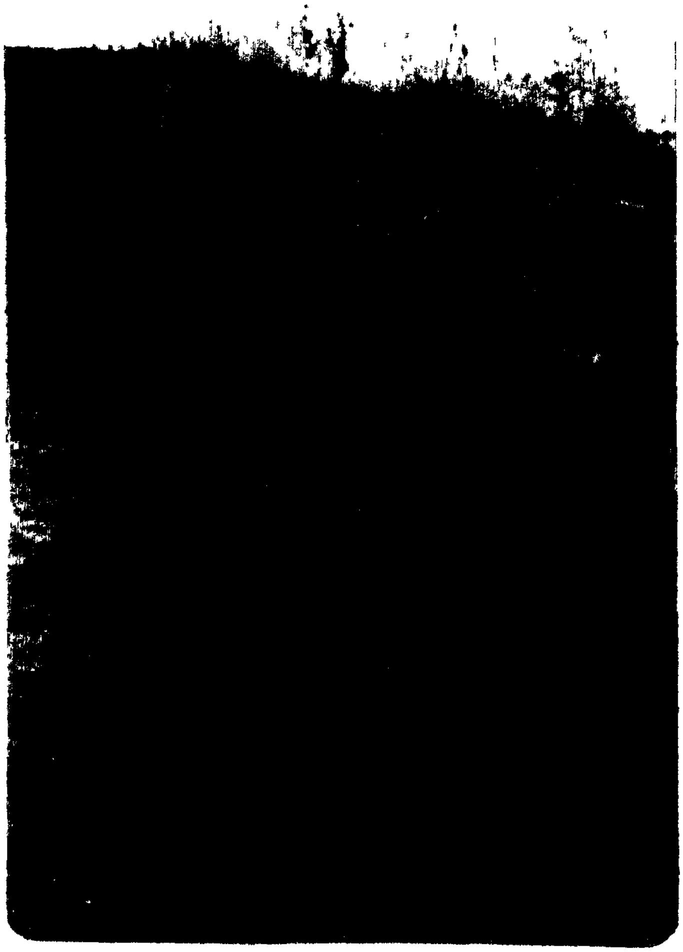


FIGURE 17
SAMPLE SITE: MB3
Fluvial Sediments
Scale 1 Metre

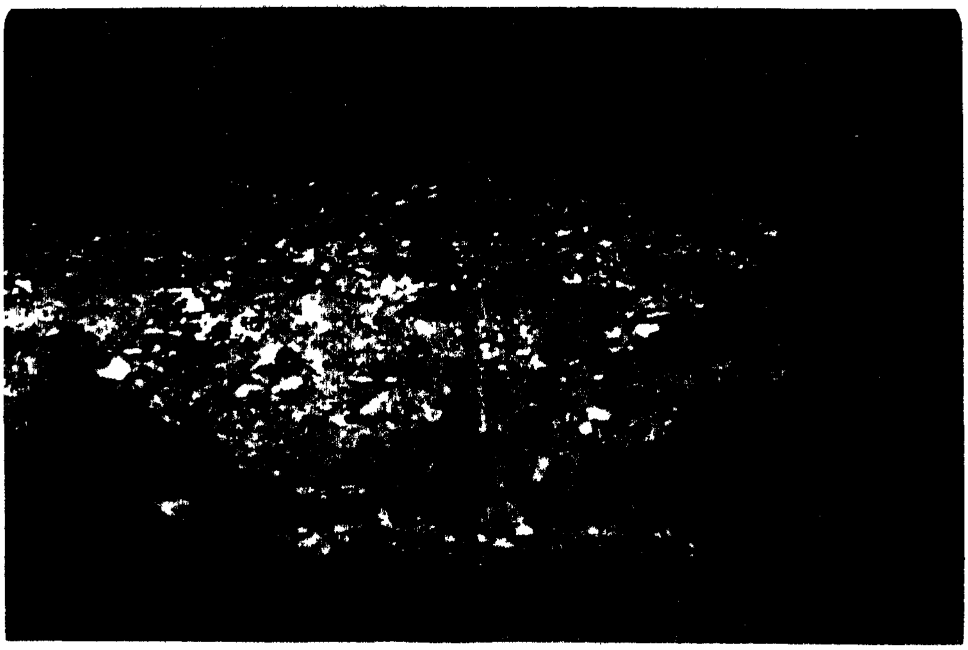


FIGURE 18

SAMPLE SITE MB5: Ancient Beach Ridge
Bottom Photograph Shows Beach Sediments
That Are Located Beneath The Shovel Of
The Top Photograph
Scale 1 Metre

FIGURE 19

SAMPLE SITE MB6
Ancient Beach Sediments
Top Scale 1 Metre
Bottom Scale 6 cm

FIGURE 20
SAMPLE SITE: MB10 Ancient Dune And Subjacent Beach Sediments
Scale 1 Metre

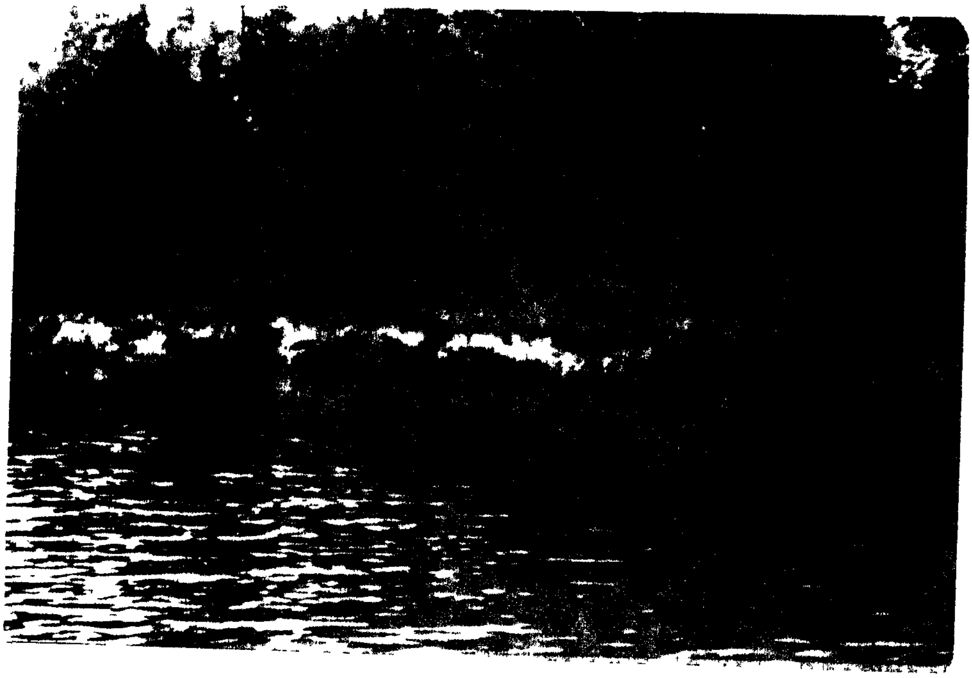


FIGURE 21
SAMPLE SITE: MB12 Ancient Beach Ridge Sediments

Scale 1 Metre

as from morphology of the features. Visual evidence from the photographs suggests that the deposits can be classified as lacustrine (Figs. 16, 18, 19, 21), fluvial (Fig. 17), and dune (Fig. 20).

Figure 16 displays the morphology of two ridges as well as sediments within the ridge in the background, (Sample Site MB1). These are inferred as beach sediments because they are stratified in a lakeward direction and the imbrication clearly reflects the clast-supported sorting characteristic of lacustrine beach sediments. Sediment sizes range from -8.250 to -5.500. The sediment morphology exhibits roundness values that range from .22 for the cobbles to .83 for the pebbles. Mean roundness is .515 for these sediments. Measurements of axes carried out according to Folk (1974) indicate that pebbles (-5.500 to -5.750) are very platy and platy; small cobbles (-6.000 to -7.000) are very elongated and elongated; and large cobbles (-7.500 to -8.250) are compact, bladed and bladed. In plan, these ridges extend within a range of 140 to 200 metres in length and are genetically related to the local bedrock. The profiles shown in Figure 22 indicate the ridge morphology for the sample area. Sediments within shallow exposures along the central portion of the centre and most lakeward ridge were poorly sorted and almost diamictic,

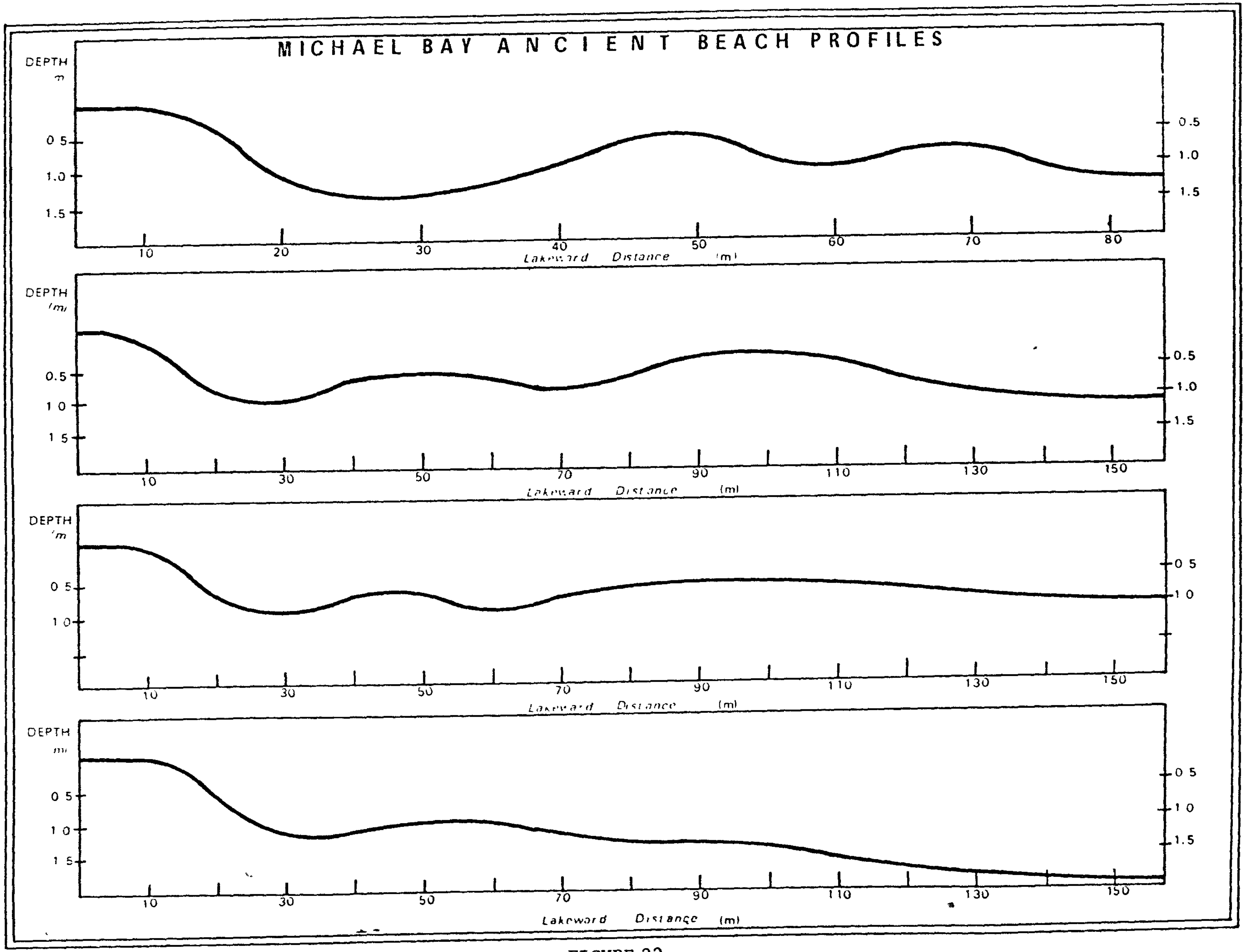

MICHAEL BAY ANCIENT BEACH PROFILES
DEPTH m
0.5
1.0
1.5
10
20
30
40
50
60
70
80
Lakeward Distance (m)
DEPTH (m)
0.5
1.0
1.5
10
30
50
70
90
110
130
150
Lakeward Distance (m)
DEPTH m
0.5
1.0
10
30
50
70
90
110
130
150
Lakeward Distance (m)
DEPTH m
0.5
1.0
1.5
10
30
50
70
90
110
130
150
Lakeward Distance (m)

FIGURE 22

while the western portion of these same ridges exhibited definite imbrication and sequence of stratification. The only possible explanation for this disruption in lateral continuity of sorting arises from sediment disturbance by inhabitants of the Michael Bay Village. These ridges are not believed to be induced or modified by fluvial processes, since the trough between these ridges exhibits a weak boulder pavement that is considered a lag deposit formed by lacustrine processes. Moreover, fine sand clay or mud, were not evident in any of these zones nor were they overlying the coarse sediments found in the crest zone of the ridges. The absence of fine sediments in these zones tends to indicate that fluvial processes relating to channel lag, point bar, and channel bar activity were absent.

The fluvial sediments shown in Figure 17 (Sample Site MB3) indicate that drainage from a western source succeeded lacustrine processes in the area. This interpretation is justified because the fluvial sediments in this section are not subjacent to either lacustrine or dune sediments. Instead, it appears that this was a minor, local outlet for drainage into the present Manitou River.

The photographs of Sample Site MB5 (Fig. 18) pertain to sections which display ridge and lower foreshore sediments. These sediments are characterised by inverse grading, which is typical of regressing waters, and a strong lateral persistence of sedimentation units which is common to wavelain environments. The gravels and sands correspond to lower foreshore sediments, while the shingle and cobbles are evidence of higher energy swash and berm sediments. The source of the shingle can be ascribed to two large bedrock outcrops situated to the west and east. These are situated less than 200 metres from this site in conjunction with two minor surficial outcrops that are located in closer proximity to this site.

The Sample Site MB6, shown in Figure 19, is located 78 metres south or lakeward of Sample Site MB5. The lowest units in this site are landward dipping and are subjacent to lakeward sloping foreshore sediments. It is suggested that this is a berm sequence.

The dune sediments shown in Figure 20 of Sample Site MB10 represent a migrating foredune that overlies beach sediments. Figure 21 depicts another beach ridge sequence that is subjacent to a thin unit of dune sands.

CHAPTER FIVE SEDIMENTOLOGICAL CHARACTERISTICS AND SEDIMENTARY PROCESSES

Textural Parameters

As a result of the interaction of depositional and post-depositional processes, sediments found in different environments exhibit many different forms. These forms of sediment deposition have resulted in attempts to find measures that describe the deposits and to determine the processes that act or have acted upon them. Grain size is a measure that Griffiths (1967) considers to provide information which may be interpreted in terms of sedimentation processes and is a reflection of the manner in which the sediments were deposited.

Size-frequency distributions obtained from grain size analysis have been used to calculate textural parameters. These parameters have been employed widely in many studies because they are thought to reflect processes, which enable discrimination between environments. Friedman (1961) suggests that textural parameters are significant because the processes they reflect are the mode of transportation and the energy of the transporting medium. Greenwood (1969) has also pointed out that sediment dynamics and energy levels within different environments are readily recognized as influencing the resulting sedimentary deposit.

Most sedimentologists believe that the application of textural parameters is useful and valid for interpreting environments. Some researchers, however, have not considered these parameters to be environmentally sensitive. Shepard and Young (1961); Schlee et al. (1964); Sevon (1966) have presented data obtained from settling tubes to indicate that textural parameters are not environmentally sensitive and these parameters were unreliable for differentiating between modern lacustrine and fluvial sands.

Various measures have been proposed for the derivation of textural parameters. Folk and Ward (1957) made use of graphic measures as a computational technique, since it enabled the use of a wider range of the total distribution. A limitation in this measure is the few number of points from the cumulative curve that can be employed in computations of textural parameters. Therefore, characteristics of the size distribution may not be exhibited, and the computation of an environmentally sensitive parameter such as skewness would not be possible. This would occur if the weight percentage of either the finest or coarsest grain size class exceeds five per cent. An efficient estimator of the population parameters is the method of moments. Its use involves the entire frequency distribution rather than selected percentiles as in the graphical measure.

Geological Significance Of Textural Parameters

The application of textural parameters for discrimination between environments requires acceptance of the assumption that these parameters reflect processes of sedimentation and the energy of the transporting medium. This implies that each of the parameters can be defined by their geological significance as follows:

i) Mean Size of a particle is a measure of the average particle size present in a sedimentation unit. It can be interpreted as a measure of the kinetic energy or mean velocity of the depositing agent.

ii) Standard Deviation is an index of sorting that measures the dispersion of a distribution about a central tendency such as the mean. Well sorted sediments are indicated by a low numerical value whereas, poorly sorted sediments are represented by high values. This index can also describe energy conditions within an environment, since good sorting in a beach environment is associated with constant energy conditions and decreasing mean size.

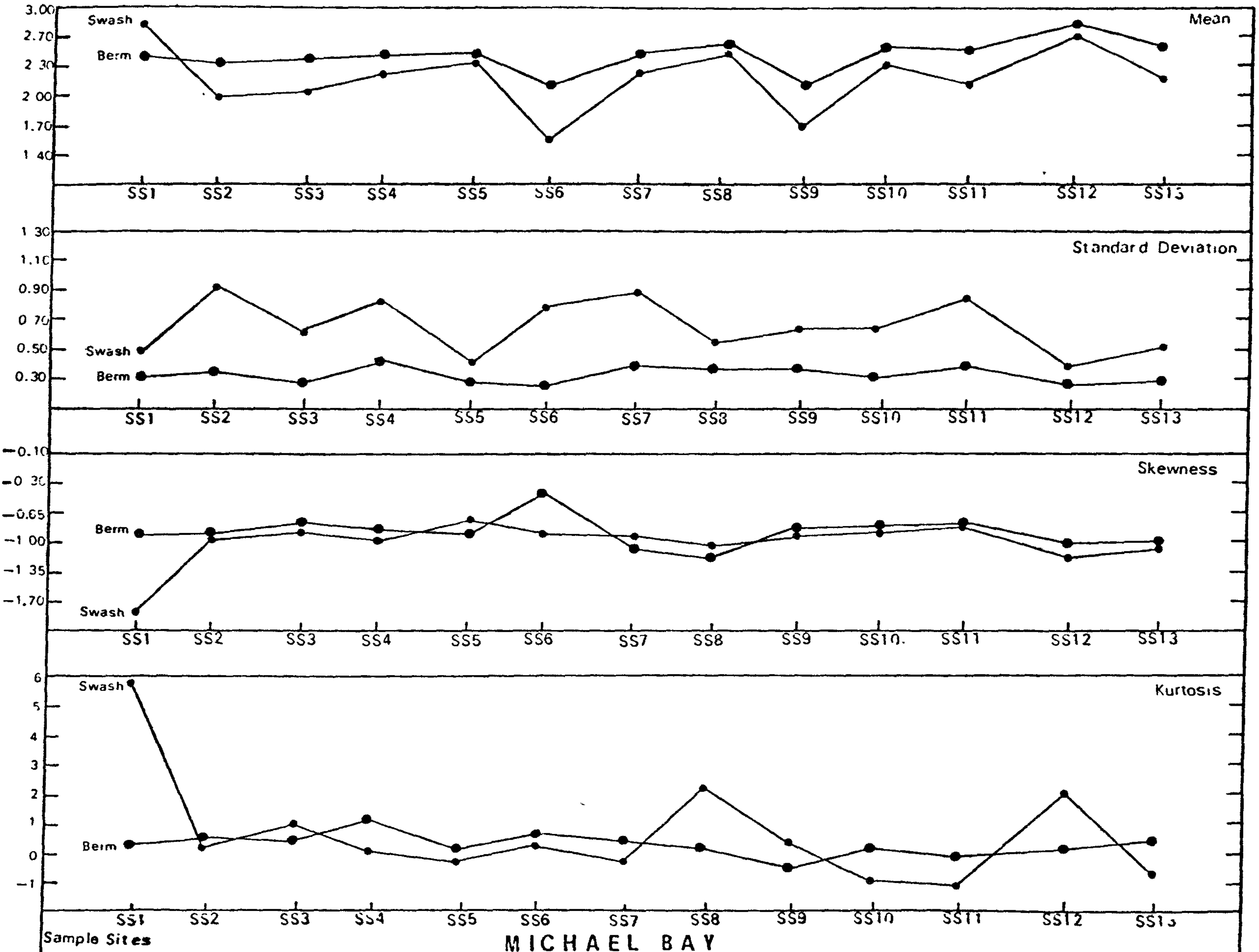
iii) Skewness can be described as the tendency of a distribution to depart from a symmetrical form, and it measures the symmetry and distribution in the tails of the curve. A negatively skewed grain size distribution possesses a concentration of coarse material and a deficiency in fine grain size fractions. Studies pertaining to modern beach and dune deposits have indicated that the sediments are respectively negatively and positively skewed.

iv) Kurtosis is an index of sorting and the degree of peakedness of a given curve. The peakedness of a curve is measured and if the central portion is more peaked than the tails, the curve is described as leptokurtic and better sorted. But if the relative frequencies are similar in the tails relative to the central portion then the curve is platykurtic.

Surficial Sediments

Textural parameters for surficial sediments corresponding to swash and berm subenvironments along the beach and barred topography subenvironments across morphodynamic zones are respectively shown in Figures 23 and 24 (also see Sites 6-7, Fig. 12).

Swash and berm parameter plots of mean size indicate that the berm sediments tend to be finer than swash and occur within a more limited range of grain



MICHAEL BAY

SURFICIAL SEDIMENT SIZE PARAMETER DISTRIBUTION *(Beach)*

FIGURE 23

Computed From Moment Measures

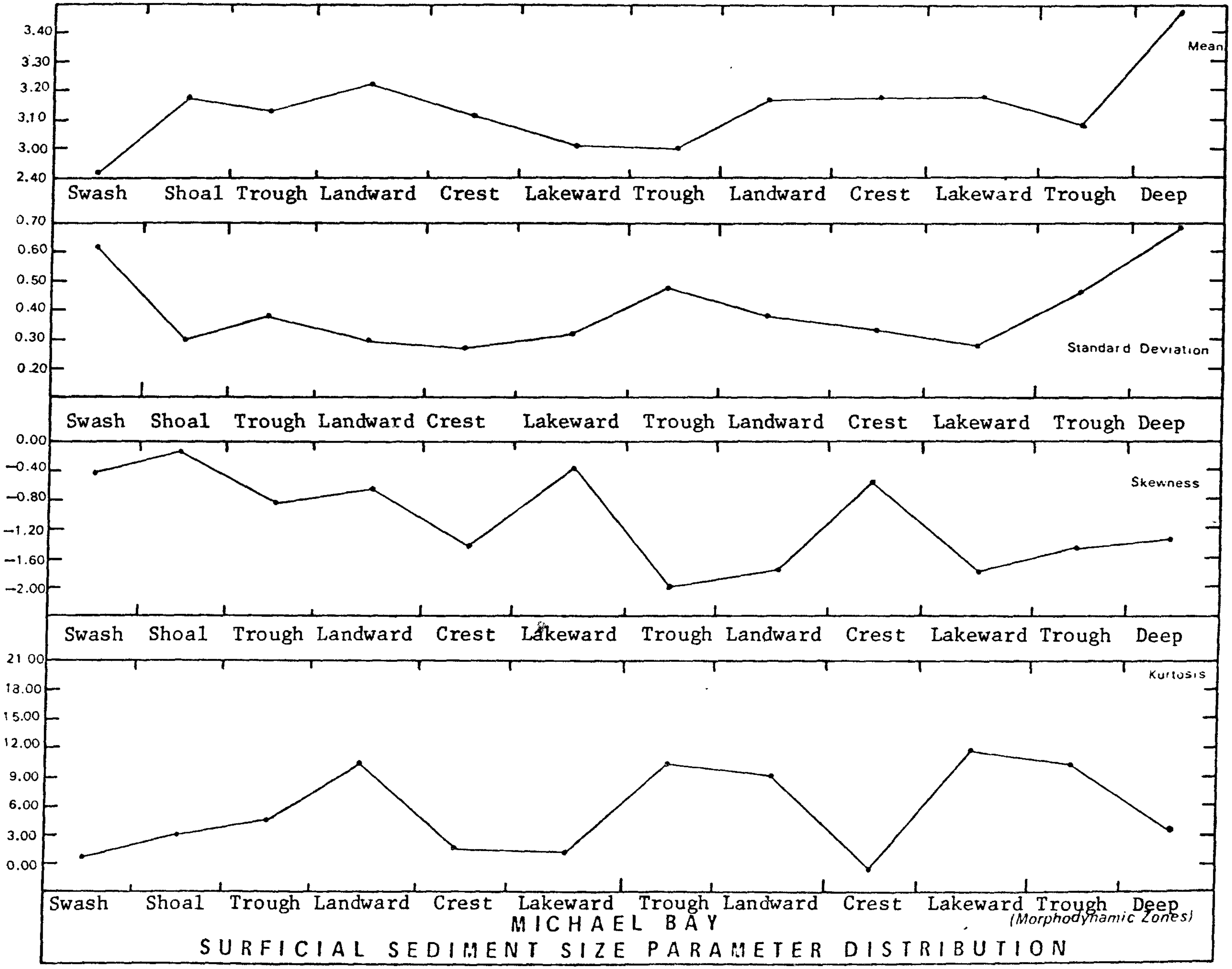


FIGURE 24

Computed From Moment Measures

sizes (Fig. 23). A process of selective sorting and preferential deposition by decreasing wave energy from the lower foreshore to the upper foreshore is evident. Therefore, deposition of fine sediment at the berm results from a decrease in swash velocity. The berm sediments are not associated with aeolian activity owing to the presence of swash marks. These marks also indicate that the sediments were associated with decreasing swash velocity. Since swash sediments display a greater range of mean sediment sizes, they reflect the relative energy prevailing at sites where sediments were sampled. Coarser sands were sampled from the horn or apex of the cuspate shoreline, while the finer swash sands reflect the embayment of this shoreline morphology. All swash samples were taken when the water receded because the textural properties and size distributions are more accurately represented. For example, sampling during swash or backwash will incorporate suspended load. This load will influence the characteristics of the resulting sediment parameters and size distributions.

Sorting, skewness, and kurtosis parameter plots for berm samples also fluctuate less in range than the swash samples. This may be ascribed to more constant energy levels in the berm which result in a more homogeneous distribution of sediment. In contrast, the action of swash-backwash farther down the foreshore induces poorer sorting by mixing coarse and medium size grains.

Surficial sediment profiles normal to shore indicate that coarsest sediments are situated in the swash and trough subenvironments (Fig. 24). The trough zones are characterised by coarser less well sorted sediment. Other subenvironments within the transect exhibit better sorting and distinct variations in presence of either coarse of fine sediments. For example, the landward slope nearest to shore has well sorted sediments that primarily comprise fine sediment. This is evident when these slope sediments are compared with the adjacent crest sediments which exhibit similar sorting but contain coarser sands. The discrete variations of sediment size for the subenvironments reflect hydrodynamic processes. The bar crest sediments are coarser because the shallow water depth enables breaking waves and passing troughs to transport fine sediments from this zone. As a result of these processes, only coarser sediments prevail. The subenvironments of the most lakeward bar are characterised by finer grained and homogeneous surficial sediment sizes. These sediment sizes reflect the decrease in competency of the waves as a result of an increase in water depth over this entire feature.

This increase in water depth reduces the ability of a passing wave form to entrain coarser sediments.

Techniques Employed For Distinguishing Between Environments

Bivariate Analysis

According to Mason and Folk (1958), differentiation between marine, aeolian, and fluvial sediments could be obtained from plotting combinations of textural parameters. Friedman (1961) found that good separation resulted from plotting skewness versus standard deviation, while Moiola and Weiser (1968) favoured mean diameter versus skewness for differentiation between environments. Plots of mean versus standard deviation, skewness, and kurtosis, and a plot of skewness versus standard deviation will be made for the Michael Bay sediments of modern berm and swash, and inferred ancient environments of beach, fluvial, and dune.

Friedman and Moiola and Weiser did not plot three depositional environments on their diagrams. Sediments from beach and fluvial environments (Friedman, 1967) as well as from fluvial and dune environments (Moiola and Weiser, 1968) were used for plots of mean versus standard deviation. Beach and fluvial (Friedman, 1967) and beach and dune (Moiola and Weiser, 1968) environments were compared by plotting mean versus skewness values. Beach and fluvial environments were compared by the authors in plots of standard deviation versus skewness.

In this study, two objectives are fulfilled by plotting modern environment sediment parameters separately from the ancient parameters. The first permits a comparison of the known modern lacustrine sediments with the works of Friedman (1961, 1967) and Moiola and Weiser (1968). The second enables a comparison of the modern beach sediments with the inferred ancient lacustrine, fluvial, and dune sediments.

Component Population Analysis

Visher (1969) related the shape of the grain size curve to the mode of transport by plotting phi increments versus cumulative frequency percentage on arithmetic-probability paper. This analysis was based on the identification of subpopulations within individual sample distributions.

Results from confirmative research have indicated that these curves are useful for either differentiation between environments or interpretation of depositional processes (Upchurch, 1970; Greenwood, 1972; Kolmer, 1973; Middleton, 1976).

Bivariate Plots showing four combinations of moment measures are illustrated in Figures 25 through 32. These plots include sediments from both modern and ancient environments. Modern environment swash and berm samples were plotted separately from the inferred ancient beach, fluvial, and dune sediments.

Plots of mean diameter versus standard deviation indicate that finer grained swash and berm sediments are well sorted in the modern environment (Fig. 25). However, no meaningful separation was evident between the distribution of these lacustrine sediments and the limits set by Friedman (1967) and Moiola and Weiser (1968) for discriminating their environments. These beach sediments plot as both beach and fluvial according to Friedman's work, while they plot as dune and fluvial in Moiola and Weiser's diagram. The inferred beach and fluvial sediments of Figure 26 also exhibited the same trends. Only the inferred dune sediments are clearly discriminated.

An examination of inferred ancient beach sediments indicates that they are better sorted than the inferred ancient fluvial sediments (Fig. 26). An area is also present where ancient fluvial sediments cannot be differentiated from the modern beach and inferred ancient beach sediments. This is also the

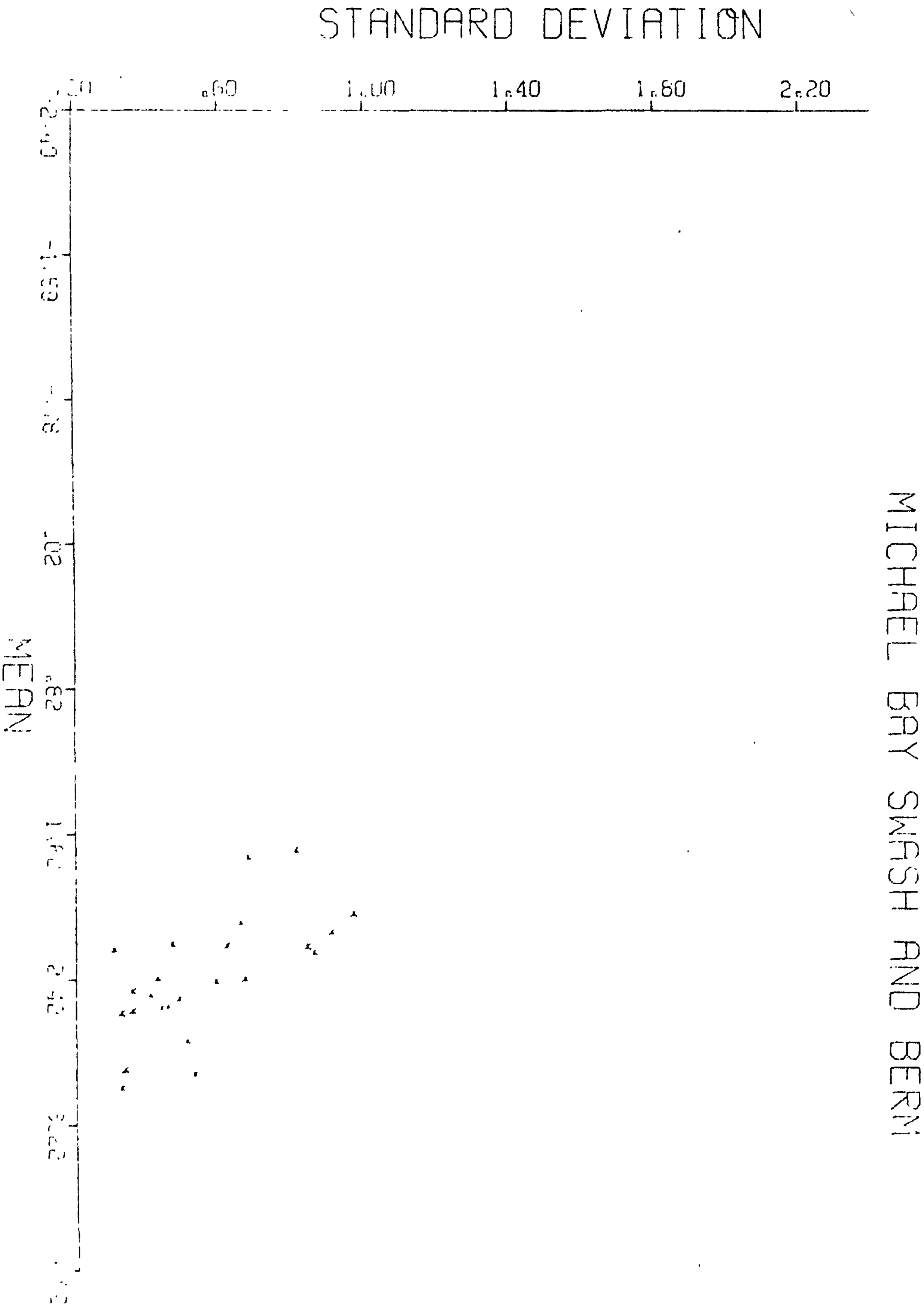
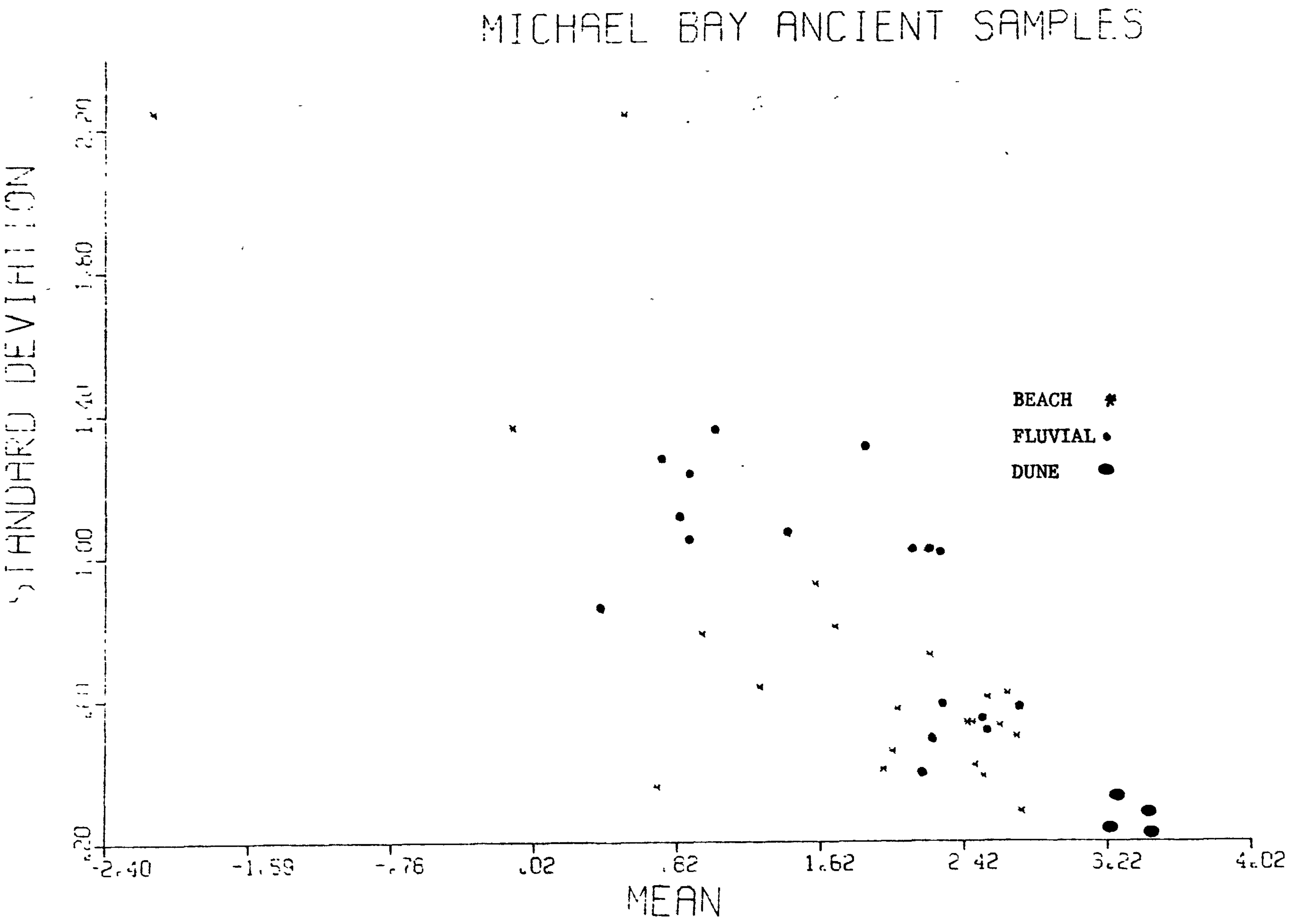

STANDARD DEVIATION
.20
.60
1.00
1.40
1.80
2.20
MEAN
-2.40
-1.60
-.80
.00
.80
1.60
2.40
3.20
4.00
MICHAEL BAY SWASH AND BERM

FIGURE 25



MICHAEL BAY ANCIENT SAMPLES
STANDARD DEVIATION
2.20
1.80
1.40
1.00
.60
.20
-2.40
-1.59
-.76
.02
.62
1.62
2.42
3.22
4.02
MEAN
BEACH
FLUVIAL
DUNE

FIGURE 26

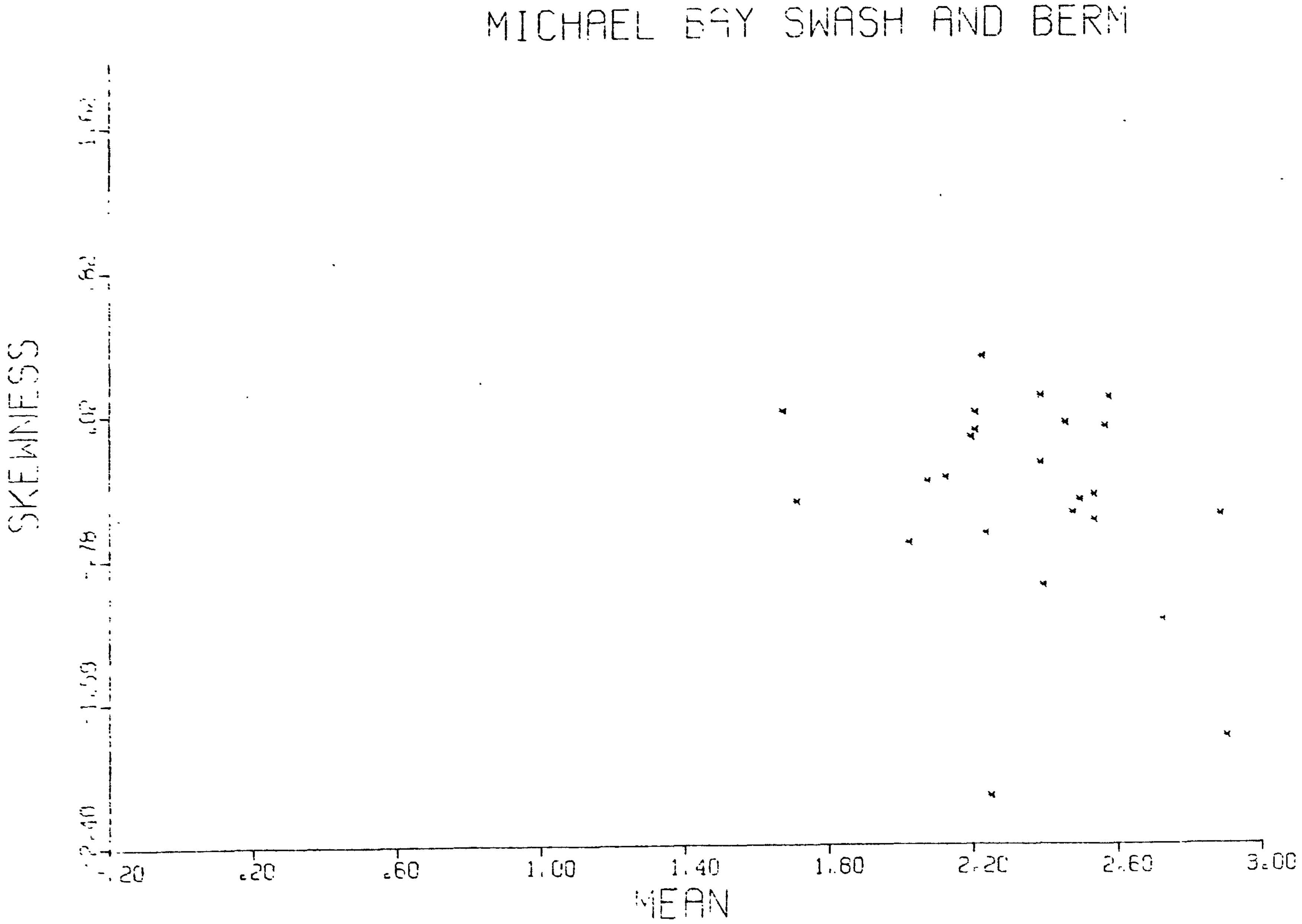

MICHAEL BAY SWASH AND BERM
SKEWNESS
1.62
.82
.02
-.78
-1.59
-2.40
-.20
.20
.60
1.00
1.40
1.80
2.20
2.60
3.00
MEAN

FIGURE 27

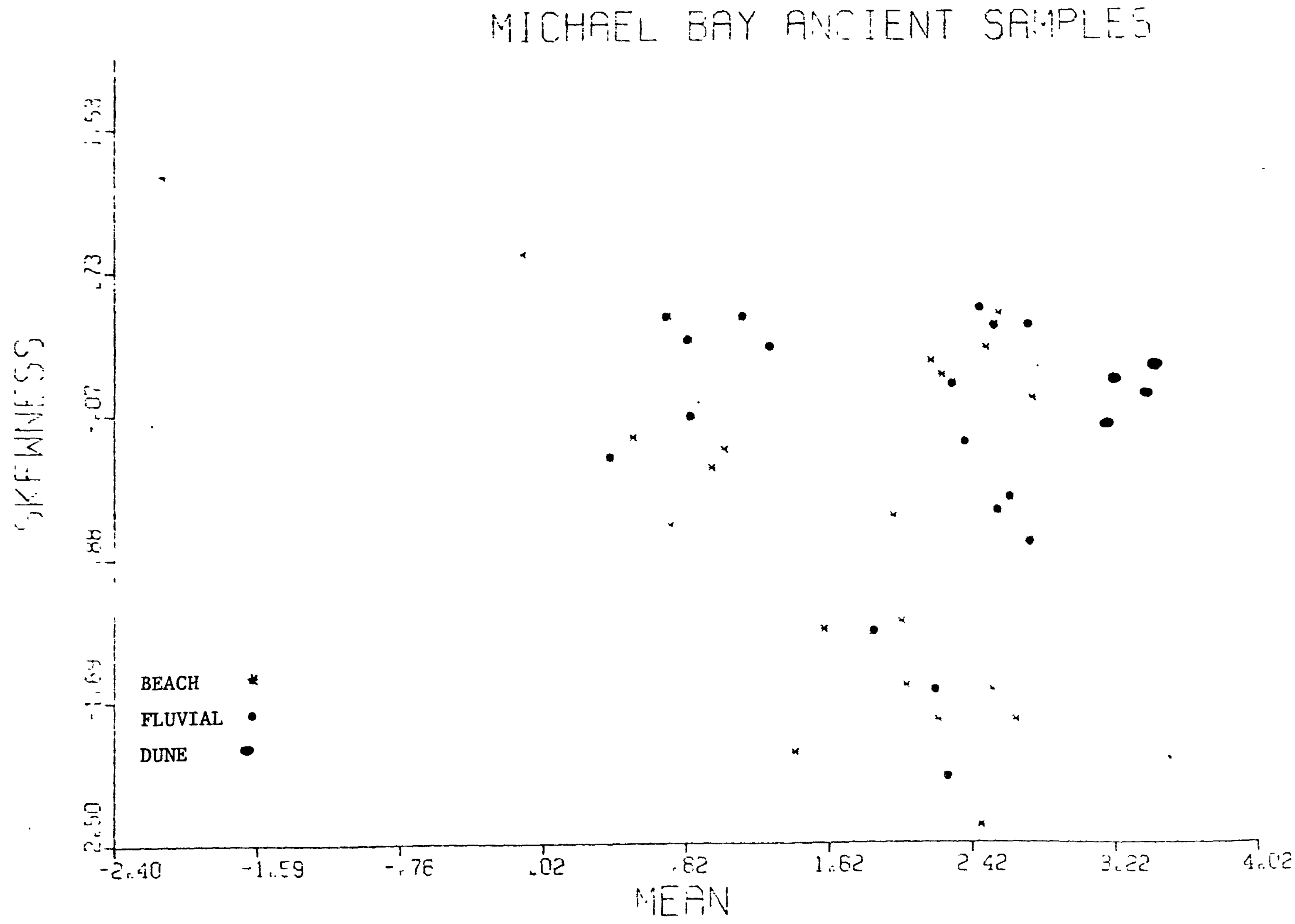

MICHAEL BAY ANCIENT SAMPLES
SKEWNESS
1.53
.73
-.07
-.88
-1.69
-2.50
MEAN
-2.40
-1.59
-.76
.02
.82
1.62
2.42
3.22
4.02
BEACH
FLUVIAL
DUNE

FIGURE 28

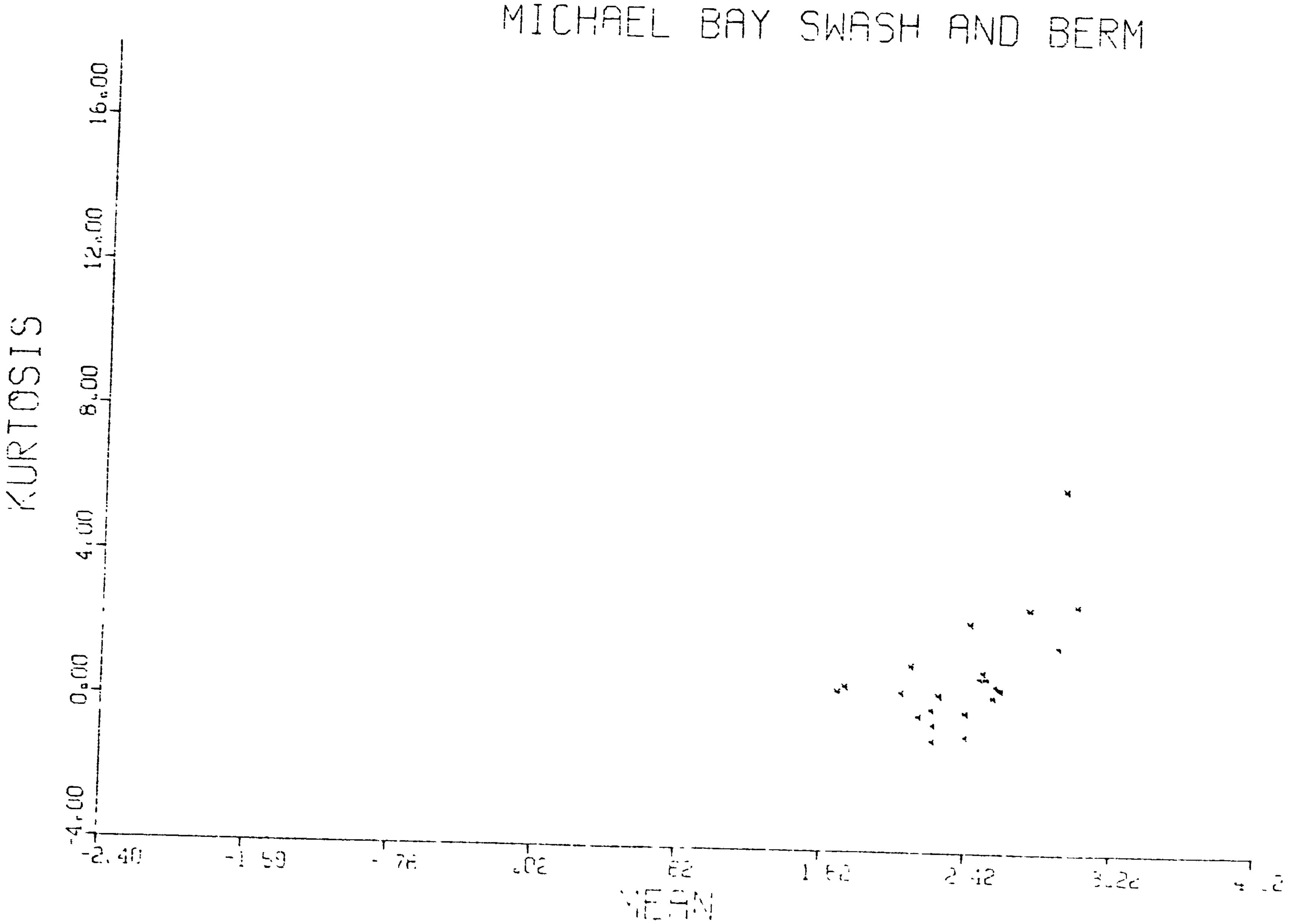

MICHAEL BAY SWASH AND BERM
KURTOSIS
16.00
12.00
8.00
4.00
0.00
-4.00
-2.40
-1.59
-.78
.02
.82
1.62
2.42
3.22
4.02
MEAN

FIGURE 29

MICHAEL BAY ANCIENT SAMPLES

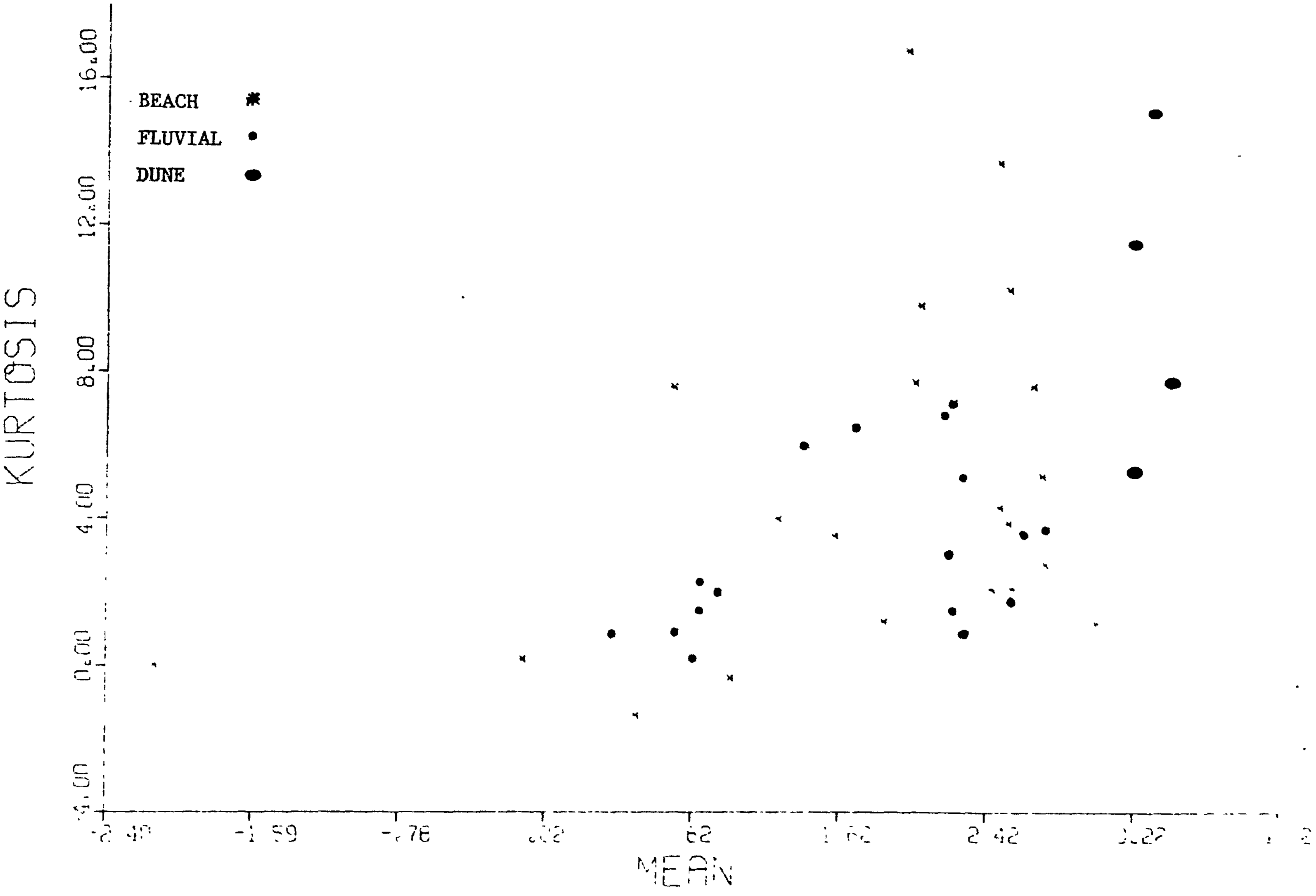


FIGURE 30

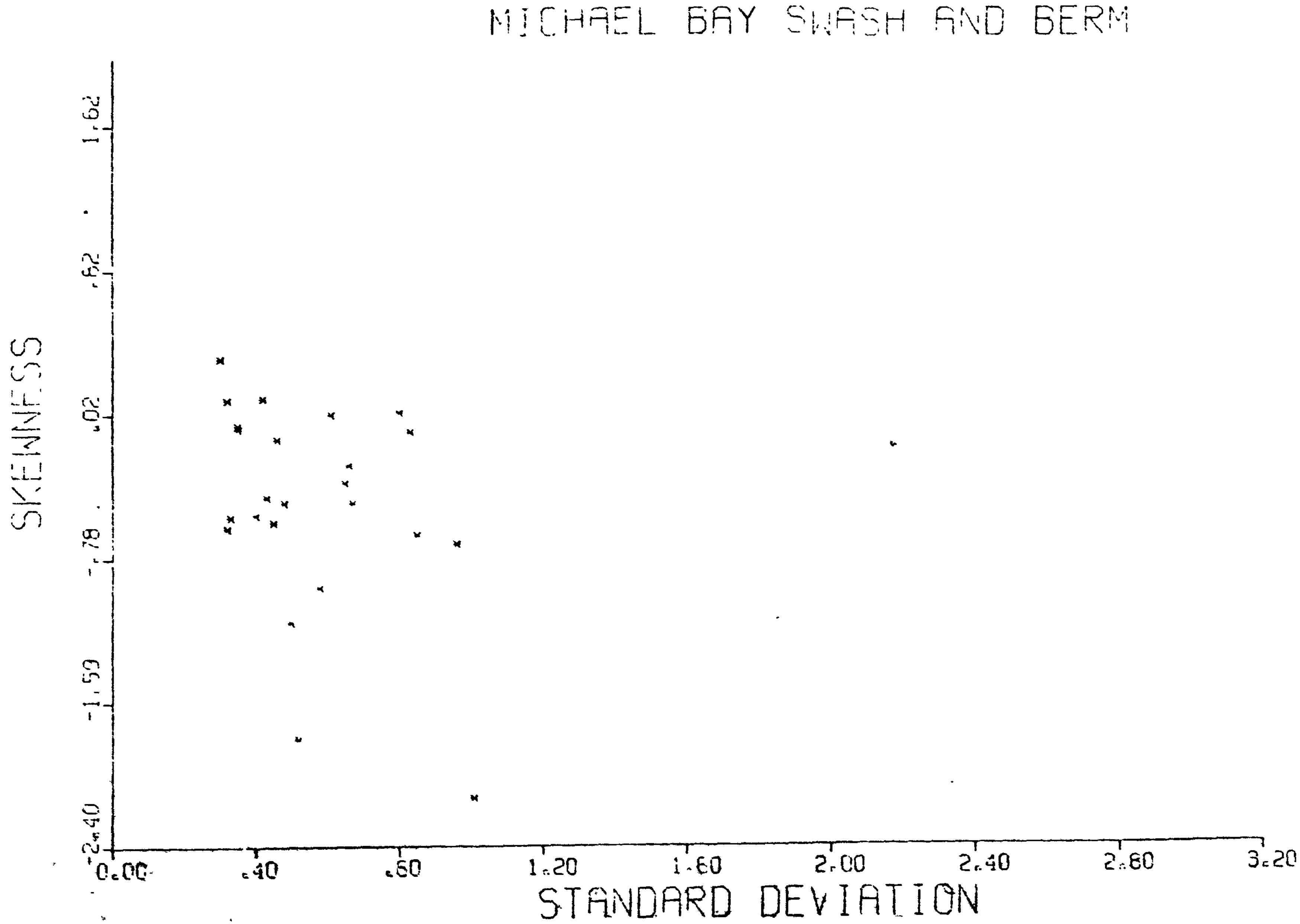

MICHAEL BAY SWASH AND BERM
SKEWNESS
1.62
.82
.02
-.78
-1.59
-2.40
0.00
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
STANDARD DEVIATION

FIGURE 31

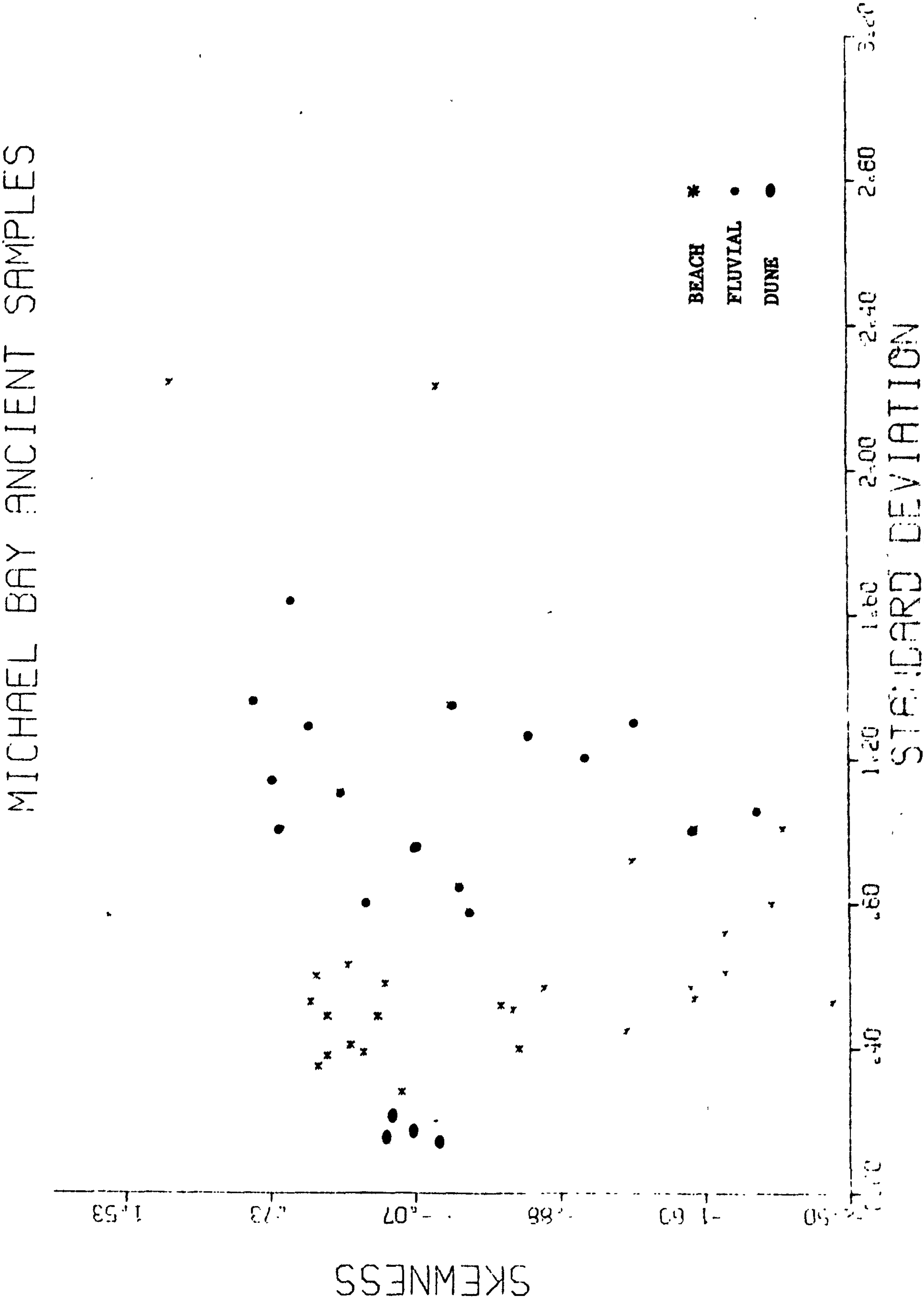

MICHAEL BAY ANCIENT SAMPLES
SKEWNESS
1.53
.73
-0.07
-.88
-1.69
-2.50
STANDARD DEVIATION
0.00
.40
.80
1.20
1.60
2.00
2.40
2.80
3.20
BEACH *
FLUVIAL •
DUNE ●

FIGURE 32

same area (2.420) where the known modern beach could not be discriminated from the fluvial and dune environments of Friedman and Moiola and Weiser. Thus, a plot of mean versus standard deviation is not a sufficient measure for discriminating between environments.

Modern swash and berm environment plots of mean versus skewness compares favourably with Friedman's (1961) dune versus beach environment plots. A beach environment is accurately represented by this plot (Fig. 27). The ancient sediments do not exhibit discernable trends because many of the inferred fluvial and beach sediments are assigned to a dune environment (Fig. 28).

The controlling parameter is the mean size which probably reflects the competency differential within the modern environment; whereas, skewness appears to be of only relatively minor usefulness. This can be explained by the environmental sensitivity that indicates both positive and negative values for both the modern beaches and the inferred ancient fluvial and lacustrine sediments. This environmental sensitivity may be a result of diagenesis.

The mean diameter versus kurtosis plot for the modern environment shows a platykurtic trend for the swash and berm sediments (Fig. 29). The inferred ancient beach sands are more leptokurtic, while the fluvial sands attain platykurtic properties with decreasing grain size (Fig. 30). Only the inferred dune sediments (Fig. 30) plot separately from the other ancient sediments and the modern beach sediments (Fig. 29). There are no discernable trends from a comparison of plots between the modern beach plots versus the ancient sediments. Nor are there any trends exhibited from solely examining patterns of inferred ancient fluvial and beach sediments.

Figures 31 and 32 are plots of skewness versus standard deviation, and these are the most effective discriminators. They compare the best with the patterns and limits outlined by Friedman (1961, 1967) and Moiola and Weiser (1968). Similarly, a comparison of the swash and berm diagram of Figure 31 with the ancient sediment plots of Figure 32 exhibit a distinct pattern of separation for both modern and inferred beaches as they relate to the ancient fluvial and dune sediments. This pattern indicates that when skewness is plotted against standard deviation, a distinct zone is present for both modern and ancient beaches. These are better sorted than the inferred fluvial sediments.

The beach samples may reflect a more limited and constant range of energy level than the fluvial sediments.

The results from this analysis show that for all cases inferred dune sediments can be discriminated from beach and fluvial environments. Discrimination between inferred beach and fluvial environments occur best in a plot of skewness versus standard deviation. This concurs with results from Friedman's research. Other plots concerning mean diameter versus standard deviation, skewness, and kurtosis are not diagnostic of depositional environments.

The results from an application of bivariate plots have not been successful for distinguishing environments. Only the results obtained from plots of skewness versus standard deviation exhibit trends that are fully comparable between modern and ancient diagrams as well as with published results. The inferred ancient beach sediments plot in a pattern that is commensurable with the known modern beach environment as well as the limits outlined by Friedman (1961, 1967). Moreover, the inferred fluvial and dune samples also fall within their respective areas when compared to Friedman's work.

Investigations of Component Populations from grain size distributions by Visher (1969), Upchurch (1970), and Greenwood (1972) have shown that grain size plots on arithmetic probability paper enable a differentiation to be made between dune and beach environments.

Beach sediments of swash origin usually exhibit two saltation populations, in addition to the bedload and suspension populations. Kolmer (1973) has demonstrated by using a wave tank, that these two saltation populations are related to processes of swash and backwash. In contrast, most deltaic environments are characterised by a well-developed single saltation population. A fine size fraction of silts and clays contribute to a large suspension population. Deltaic sands can also possess a single large saltation and bedload population, while others can exhibit two saltation populations much similar to beach distributions. Aeolian sediment curves are characterised by a large, single saltation population and also possess small bedload and suspension components that occur within a limited size range. Therefore, by using these curve characteristics as well as those obtained from the modern lacustrine environment, it should be possible to determine the depositional environments of the ancient sediments.

It must be noted that according to Visher (1969, P. 1094), "size curves can differ between modern and ancient environments". Ancient samples differ because diagenesis can produce fine grained sediments that would result in different sorting characteristics for a given sample. This modifies the resulting curve shape. Such a process must be recognised before grain size distributions of ancient sediments are interpreted.

Characteristic curves for various modern and ancient sample sites are shown in Figures 33 to 38. These are believed to be diagnostic of both modern and ancient environments. Moreover, a careful examination of curves for modern environments reveals definite trends that enable characteristic curves to be presented for specific subenvironments within the modern nearshore.

Berm and swash subenvironment samples from the modern beach have curve types that indicate well sorted sediments are present in each subpopulation. This is indicated by the slope of the curve, and the most distinguishing characteristic of these modern samples is the steepness of the suspension population. Percentage occurrence of suspended sediment is greater in the berm samples. This may also reflect the competency range of the wave activity. The absence of a strongly developed suspension population in the

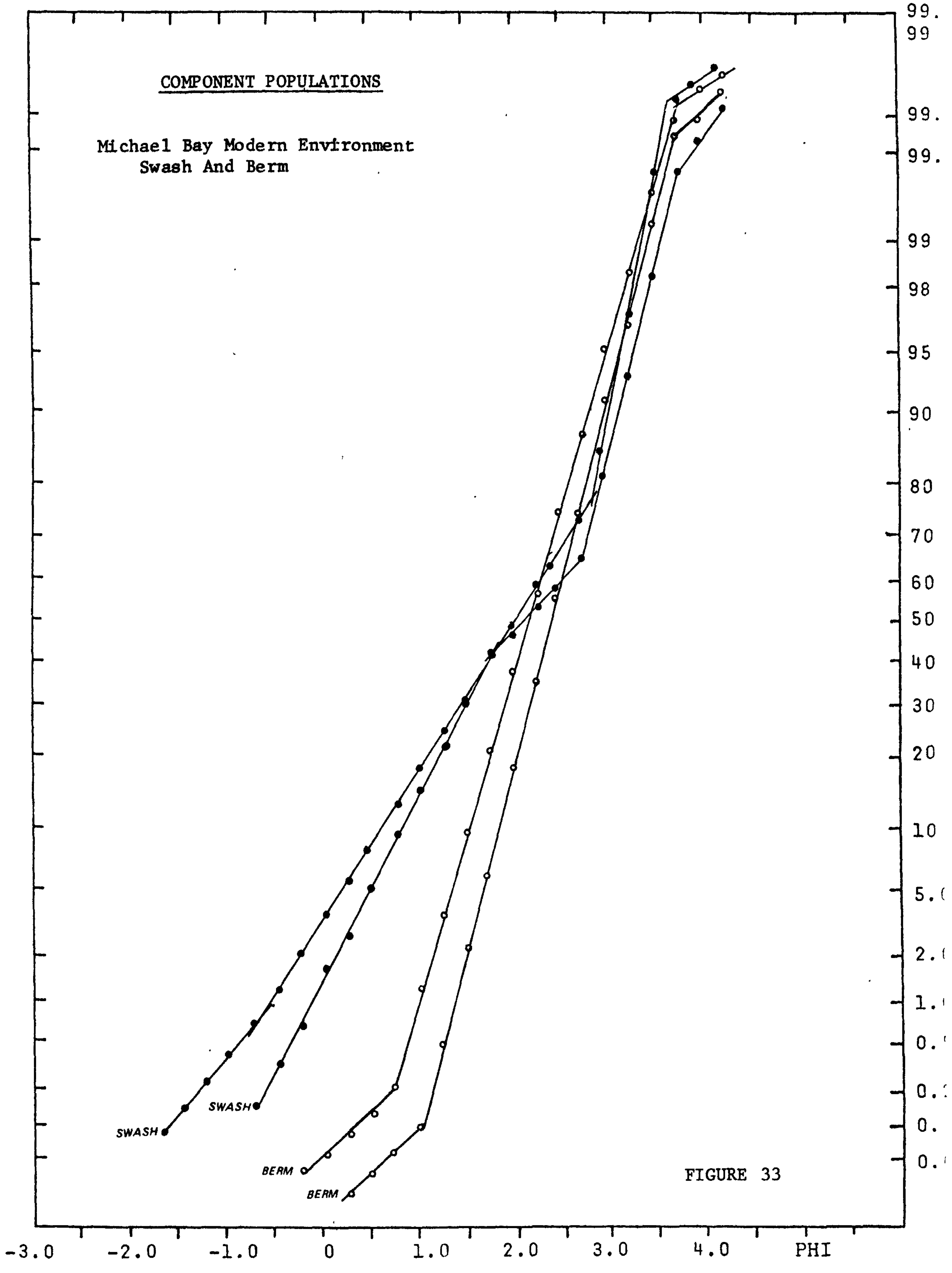
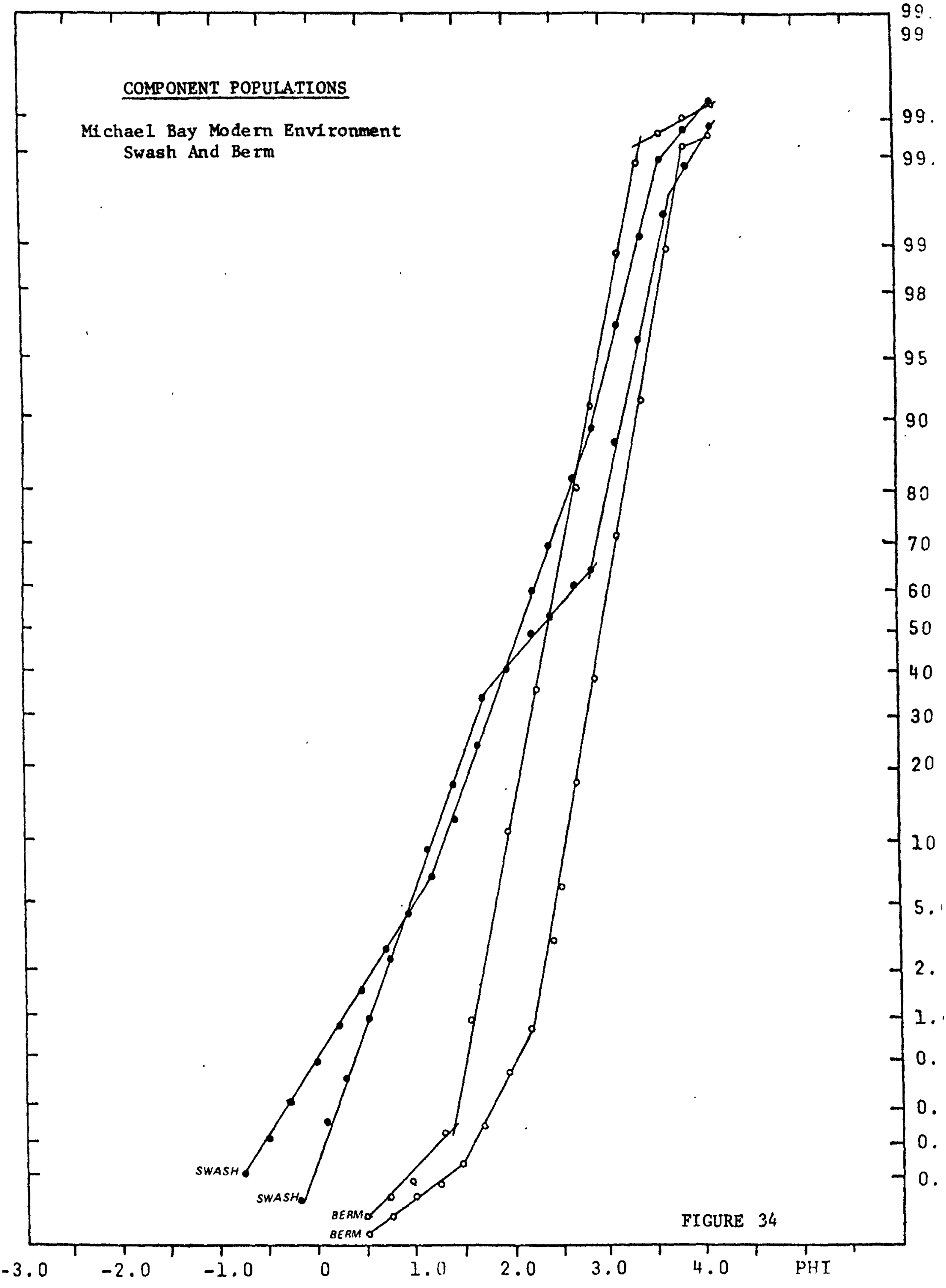

COMPONENT POPULATIONS
Michael Bay Modern Environment
Swash And Berm
SWASH
SWASH
BERM
BERM
99.
99
99.
99.
99
98
95
90
80
70
60
50
40
30
20
10
5.
2.
1.
0.
0.
0.
0.
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
PHI

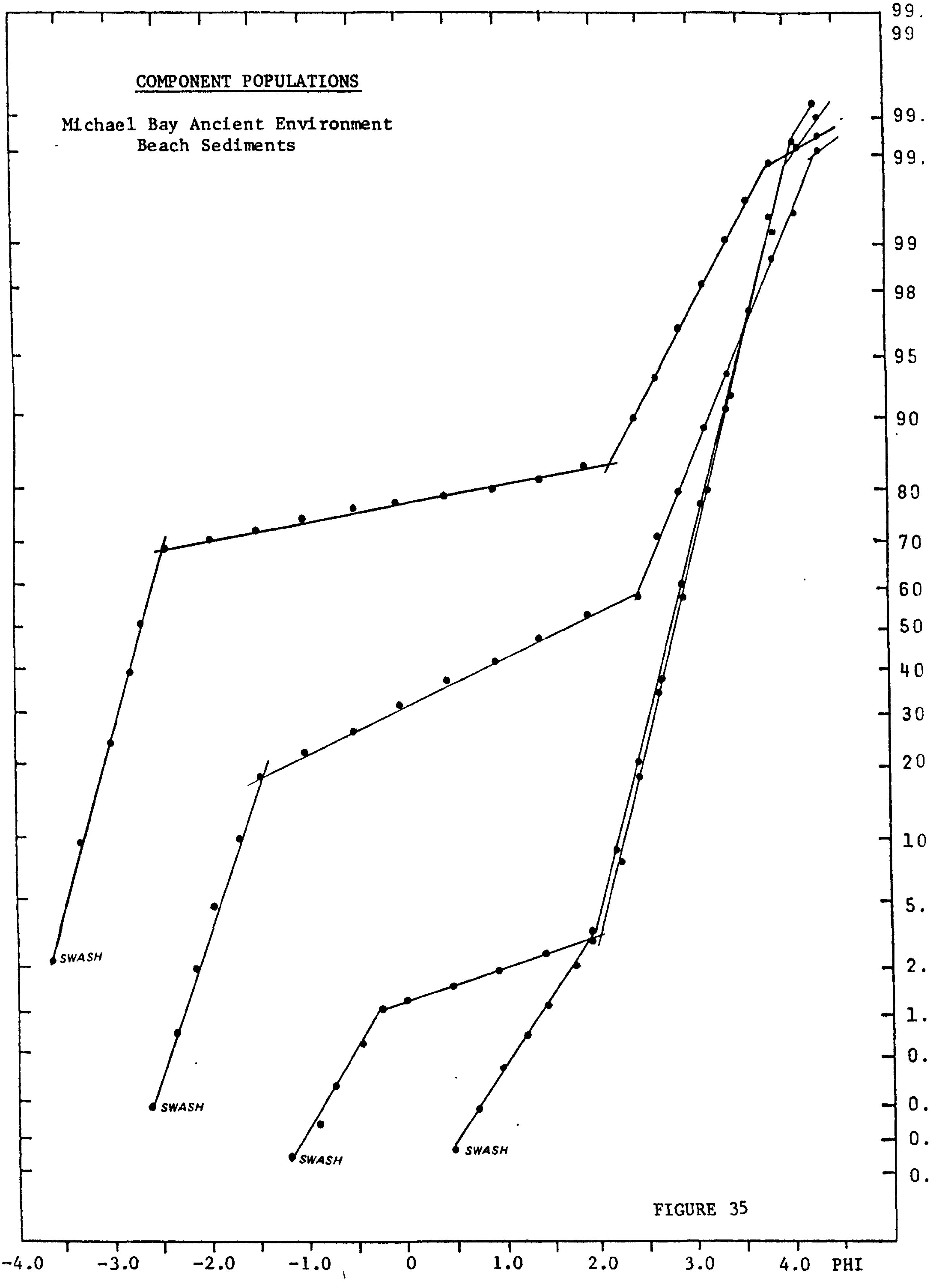
FIGURE 33



COMPONENT POPULATIONS

Michael Bay Modern Environment
Swash And Berm

FIGURE 34



COMPONENT POPULATIONS

Michael Bay Ancient Environment
Beach Sediments

FIGURE 35

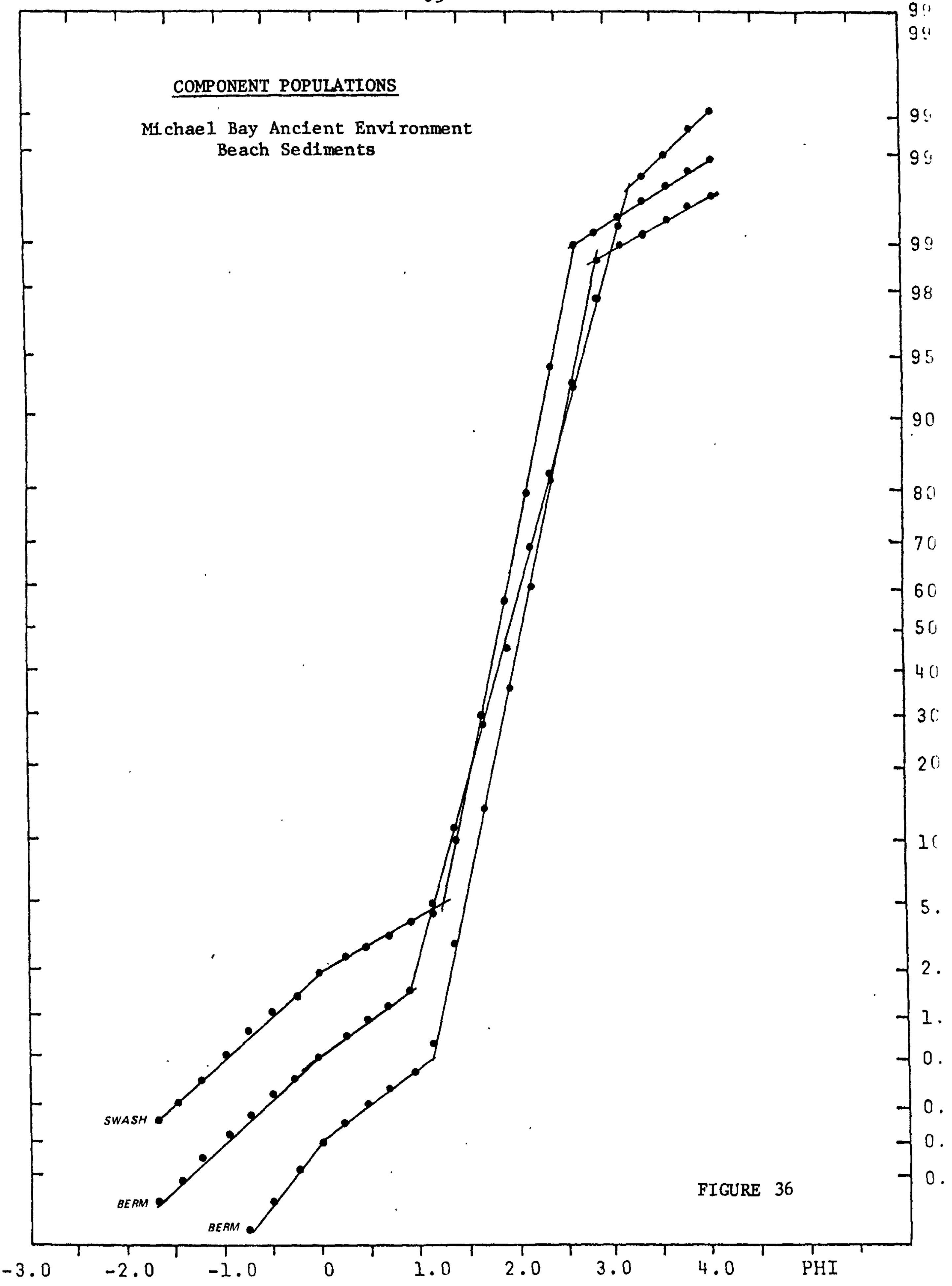

COMPONENT POPULATIONS
Michael Bay Ancient Environment
Beach Sediments
SWASH
BERM
BERM
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
PHI
99
99
99
99
98
95
90
80
70
60
50
40
30
20
10
5.
2.
1.
0.
0.
0.
0.

FIGURE 36

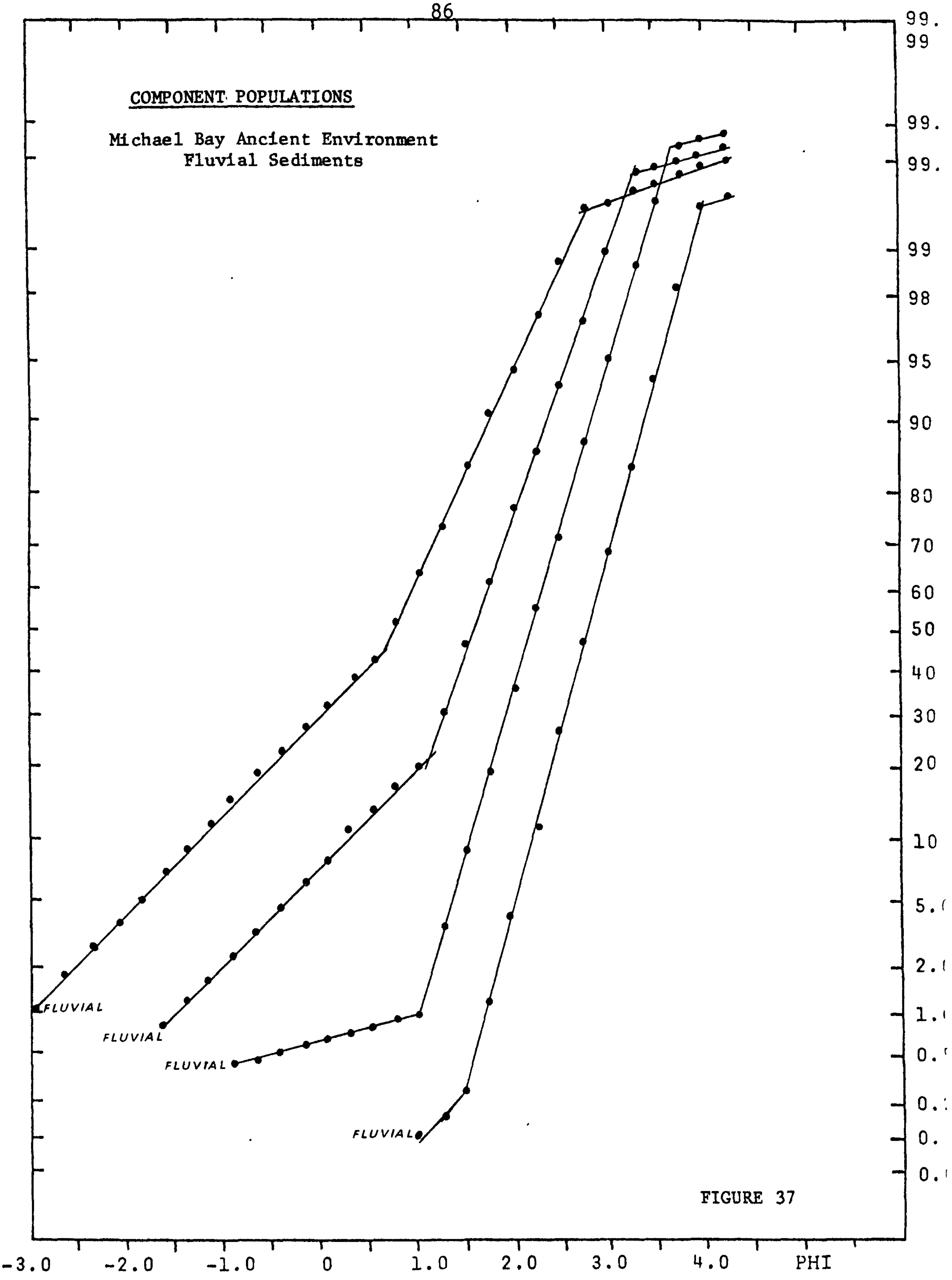
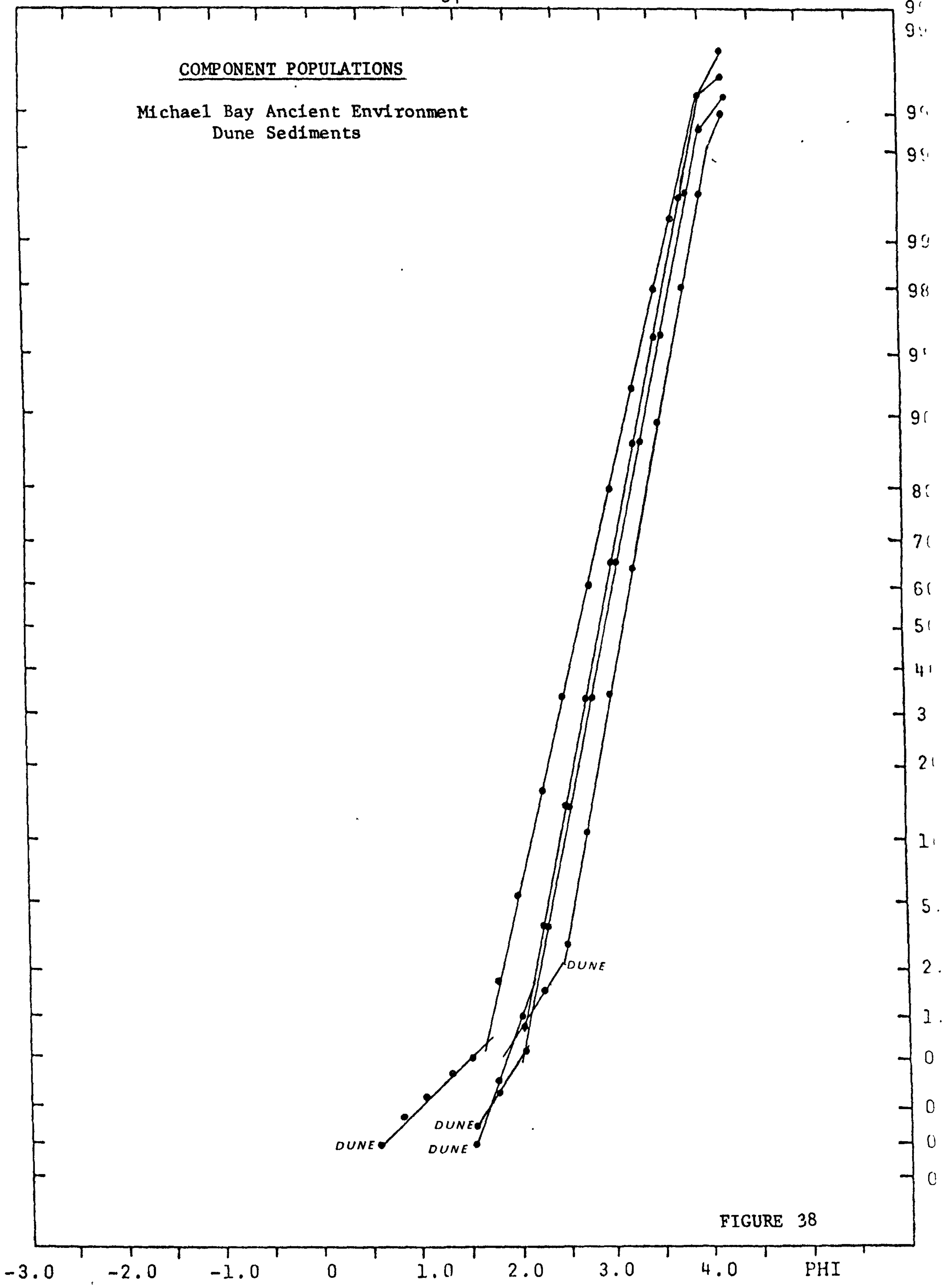

COMPONENT POPULATIONS
Michael Bay Ancient Environment
Fluvial Sediments
FLUVIAL
FLUVIAL
FLUVIAL
FLUVIAL
99.
99
99.
99.
99
98
95
90
80
70
60
50
40
30
20
10
5.
2.
1.
0.
0.
0.
0.
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
PHI

FIGURE 37



COMPONENT POPULATIONS

Michael Bay Ancient Environment
Dune Sediments

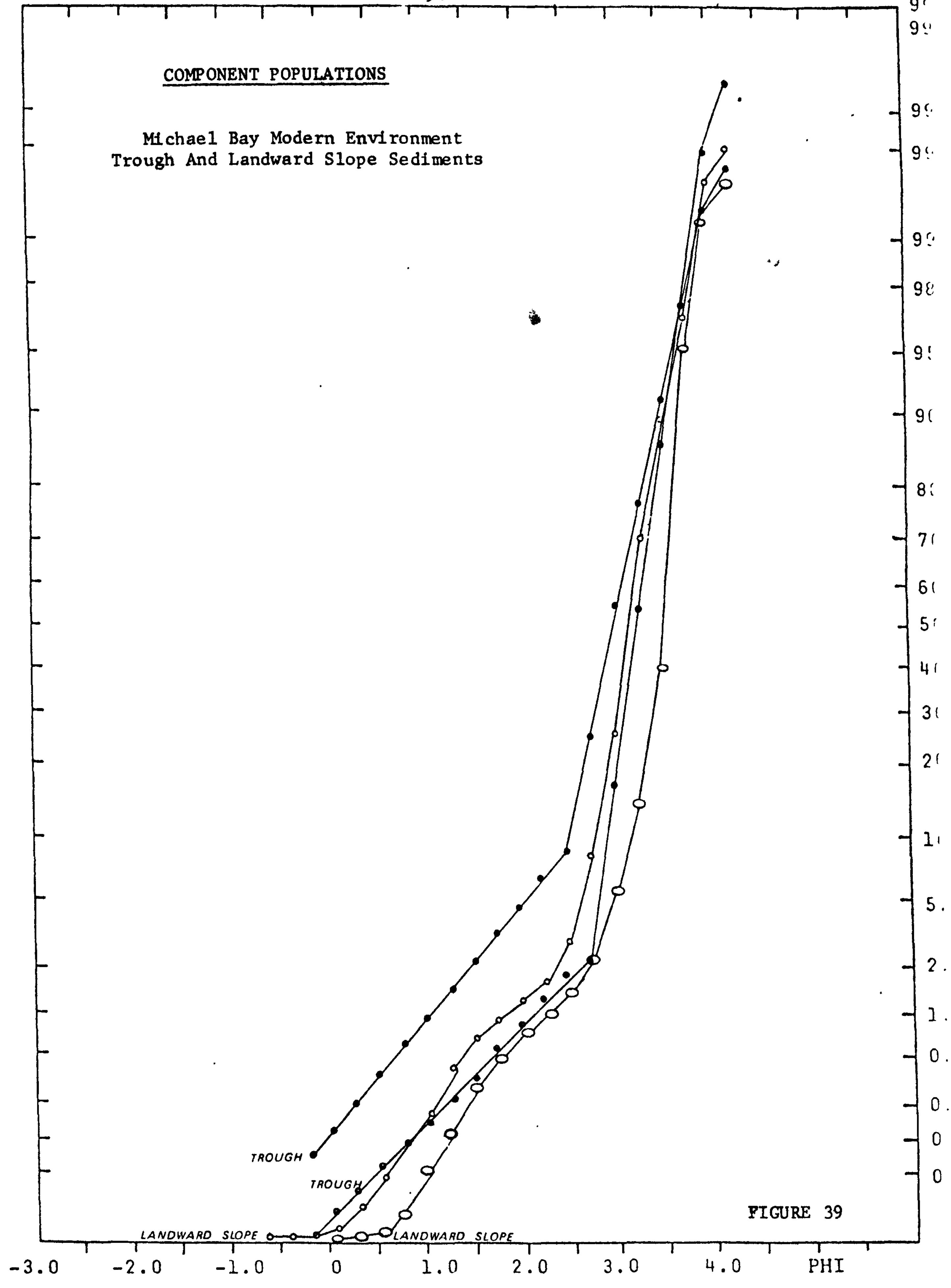
FIGURE 38

swash sediments may be a result of saltation and suspension population mixing (Spencer, 1963). The presence of two saltation populations is an inherent characteristic of the majority of Michael Bay sediments. Two of the swash samples only exhibited one saltation component, and this tends to reflect the unimodal distribution of sediments within the sample. One of these curves is shown in Figure 35. Similarities between the modern swash and ancient beach curves are evident in a comparison of Figures 33 and 34 with Figures 35 and 36. These suggest a swash environment for the lacustrine sediments sampled from the ancient beaches. In addition, all ancient swash sediments were sampled from units which were subjacent to sands that exhibited berm or dune curve characteristics. This trend reflects the sedimentological properties of beach facies formed within an environment of regressing water level.

Examples of sediments sampled from Sample Site MB3 are shown in Figure 37. Many of these curves are apparently similar to ones from modern and ancient beach environments. However, they do have discernable properties that allow for differentiation between the two types of environments for all sediment size ranges. For example, the main curve characteristics that can be applied to all samples are: a low slope suspension population, a predominating saltation population with a moderately high slope, and a bedload slope of intermediate steepness relative to the saltation and suspension populations. This low angle suspension component indicates relatively poor sorting and is evident in coarse and fine samples. The saltation population exhibits fair to good sorting in both types of samples, while the bedload population in the coarse and fine sands show moderate to good sorting.

Figure 38 shows dune sediments characteristic of sites MB7 to MB12. The most useful criterion for distinguishing dunes is the unusally high proportion of sediment in the saltation population . This represents all but a small percentage of the total distribution for a given sample. Its slope is steep which is indicative of well sorted sediment, and the suspension population, which exhibits good sorting, comprises only a small percentage of the distribution. The bedload component is always present and exhibits good sorting characteristics.

Component population curves for barred nearshore subenvironments of trough, landward slope, crest, and lakeward slope are shown in Figures 39 and 40. Sediment samples were obtained from units of the box core sections. The subenvironments and corresponding



COMPONENT POPULATIONS

Michael Bay Modern Environment
Trough And Landward Slope Sediments

FIGURE 39

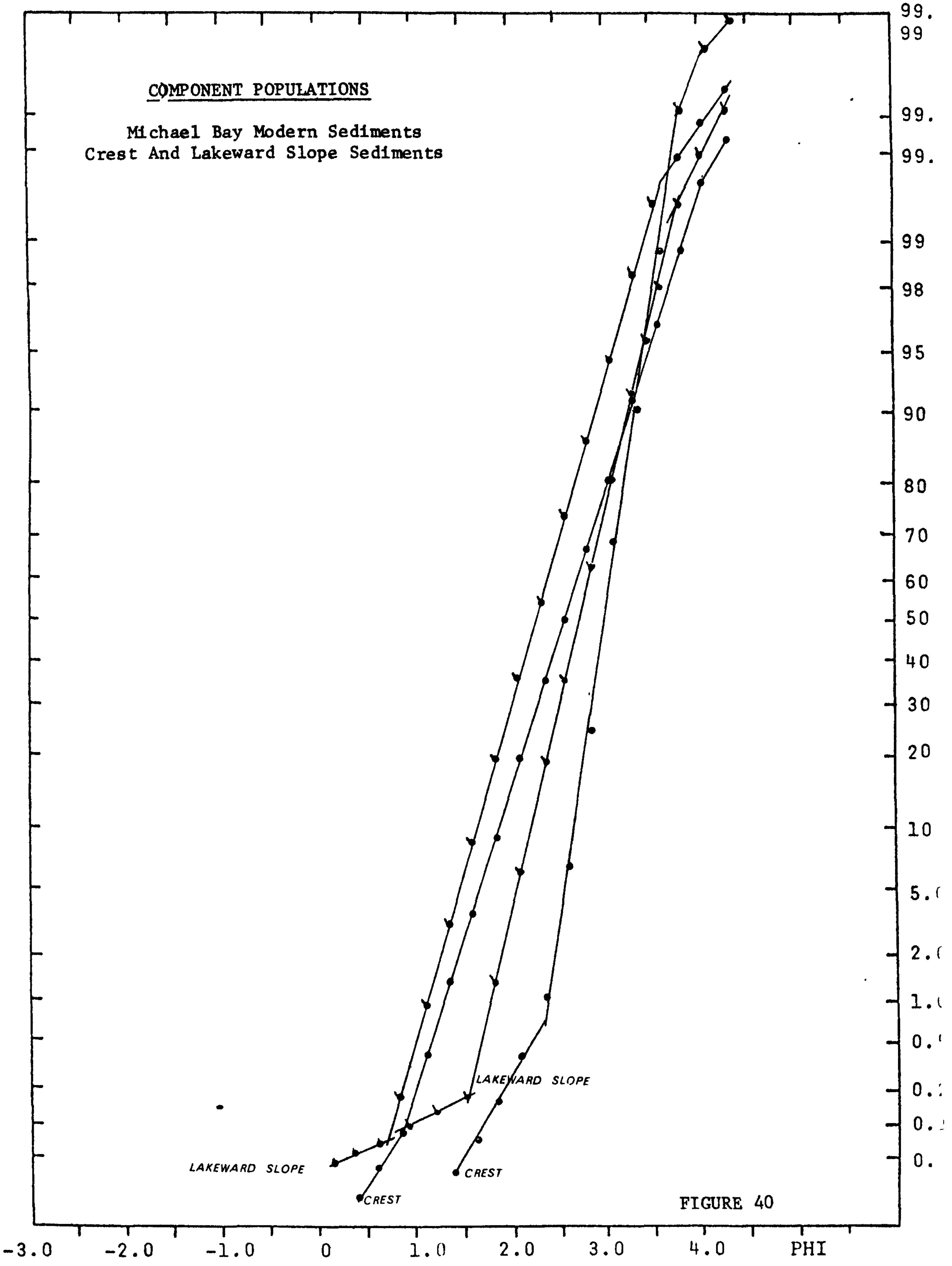

COMPONENT POPULATIONS
Michael Bay Modern Sediments
Crest And Lakeward Slope Sediments
LAKEWARD SLOPE
LAKEWARD SLOPE
CREST
CREST
99.
99
99.
99.
99
98
95
90
80
70
60
50
40
30
20
10
5.
2.
1.
0.
0.
0.
0.
-3.0
-2.0
-1.0
0
1.0
2.0
3.0
4.0
PHI

FIGURE 40

bedforms that were sampled are: trough-asymmetrical ripple cross-laminae; landward slope-massive bedding; bar crest-symmetrical ripples; lakeward slope-oscillation ripple cross laminae.

Figure 39 shows cumulative population curves for trough sediments. These curves exhibit a distinct bedload component of moderate sorting, and single suspension and saltation populations that display good sorting.

Landward slope curves exhibit poorest sorted suspension populations while the remainder of the curve displays segments that have no significance as they relate to specific populations (Fig. 39). Such sorting suggests that not only wave energy is important in sediment transport and sorting but also gravity is an additional energy source, since it causes avalanche of sediment down this slope.

Crest curves, shown in Figure 40, are primarily dominated by a single saltation population. Bedload population is very well sorted and occupies a relatively small percentage of the distribution.

The lakeward slope subenvironment curves, also shown in Figure 40, have the best sorting characteristics in the suspension and saltation populations. The bedload population is only moderately sorted but is characterised by its small percentage in the distribution.

A facies model can be defined by the various attributes of the sedimentation units within a stratigraphic sequence. One attribute that can be used is the grain size distribution. When plotted as cumulative frequency curves for the modern nearshore subenvironments and for the ancient beach, fluvial, and dune environments, they are believed by the author to be useful as a facies indicator. Thus, characteristics of component populations are presented as a facies indicator that solely pertains to use of the grain size distribution (Table 2). Furthermore, only commensurable results can be accrued by comparison with fine grained nearshore sediments in a bayhead, and for specific ranges of grain size in ancient environments. These sizes are listed on Table 2 as well as graphical illustrations of typical cumulative curves, percentage occurrence of bedload, saltation, and suspension components, and slope inclinations. The curves are representative of 73 ancient environment samples as well as 68 modern environment samples.

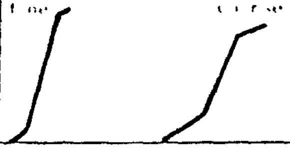
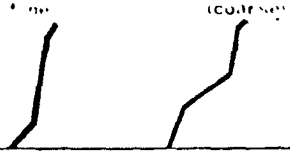
GRAIN SIZE FACIES INDICATOR	TYPICAL PROBABILITY CURVE	SLOPE CHARACTERISTICS			PERCENTAGE OCCURRENCE OF POPULATIONS			COMPETENCY RANGE	
		BEDLOAD	SALTATION	SUSPENSION	BEDLOAD	SALTATION	SUSPENSION	MAXIMUM	MINIMUM
MODERN									
SWASH		64	55 80	56	8-20%	60-90%	.8-.11%	-2/4.250	.5/4.250
BERM		43	76	44	.05-.15%	92.7-99.6%	.06-.14%	-.25/4.250	.5/4.250
TROUGH		46	80	65	2-9.5%	89-97%	.16-.31%	-.50/4.250	-.25/4.250
LANDWARD SLOPE		--	--	--	------	------	--------	-.75/4.250	
CREST		59	79	57	.13-.46%	99.5-99.7%	.04-.16%	.25/4.25	1.0/4.25 0
LAKEWARD SLOPE		24	75	63	.05-.11%	99.3-99.7%	.21-37%	-.50/4.250	-.25/4.250
ANCIENT									
FLUVIAL		Fine 45	73	16	.06-.13%	99.3-99.6%	.2-.6%	.25/4.250	
		Coarse 36	78	17	.4-43%	47.3-99.3%	.03-.13%	-5/4.250	
BEACH		Fine 59	50 75	60	1.15-6.36%	63-94%	.02-.11%	-.5/4.250	1.0/4.25
		Coarse 52	28 76	41	.05-74%	19.8-98.2%	.08-.23%	-4.5/4.250	-2/4.250
DUNE		58	79	55	.3-.8%	97.2-99.8%	.03-.2%	.5/4.250	1.5/4.25

TABLE 2

The author does not wish to imply that absolute facies identification from component populations is always possible or simple to achieve. Size curves from other researchers will possibly deviate to either a greater or lesser extent than the illustrated typical curves. This most probably depends on one's sampling techniques. In many instances, a definite affinity to one environment-subenvironment grain size facies or another could be difficult to discern. These limitations will be noticed particularly when interpretations are restricted to single samples. However, with proper use, especially in conjunction with other sources of information such as bedforms, mineralogy, fossils, and biota, component population analysis can reveal important aspects concerning specific depositional locales.

Summary

Statistical parameters of mean grain size, standard deviation, skewness, and kurtosis employed in bivariate plots provide only limited satisfactory identification of depositional environments. Sorting is apparently the most significant statistical parameter while the other parameters do not adequately reflect variations within size distributions. As a result, the bivariate plots do not render results that are consistent with claims of other workers. Only a plot of skewness versus standard deviation as suggested by Friedman (1961) is useful for discriminating between environments.

Component populations typically display two or more straight segments that apparently reflect bedload, saltation and suspension components of sediment transport. The attributes of these curves have proven useful for discriminating between beach, dune, and fluvial environments. The most significant attributes are as follows: the relative importance of the bedload, saltation, and suspension components, the slope or sorting displayed by these components, the phi range of occurrence for each component, and the phi range that each environment or subenvironment sample comprises. Depositional processes can be elucidated from a detailed study of a combination of these attributes. Interpretations are only reliable for embayed environments that consist of fine sand and for ancient beach sediments that occur within the outlined phi or competency range. These become more meaningful when used in conjunction with additional sedimentological, biological or paleontological evidence.

CHAPTER SIX NEARSHORE FACIES IDENTIFICATION BASED ON PRIMARY SEDIMENTARY STRUCTURES AND BEDFORMS

Probably the most important sedimentological attributes that can be used in a study of facies are the primary sedimentary structures and bedforms preserved within a vertical section. Although it is possible to find structures that are similar and yet produced in different depositional environments, it has long been recognized that bedforms exhibit regular variations in shape as they respond to differences in flow conditions. Where the sedimentary structures are preserved, they can be used to elucidate the type and processes of depositional environments.

Direct observations of sediment transport processes are difficult, especially during high energy conditions or in a zone of rapid wave transformation. Therefore, a study of bedforms and sedimentary structures from these and other zones can be useful for obtaining information relating to prevailing bed conditions, sediment transport directions, and nearshore processes that have occurred within subenvironments of morphodynamic zones.

An examination of sedimentary structures for barred nearshore subenvironments was possible by use of box coring and by casting resin peels. Structures in the foreshore were examined by trenching sections, all of which were photographed. This evidence was used to build a lacustrine facies model for barred nearshore subenvironments in the bayhead (Fig. 41). This model is also applied to bedforms preserved in the ancient lacustrine environments.

Six subenvironments are presented in this model. They include facies of foreshore, shoal, landward slope, crest, lakeward slope and trough (Fig. 41). The four subenvironments of landward slope through trough recur in a multibarred nearshore. These subenvironments are worthy of study because they have distinct patterns of sedimentary structures which can be related to specific bedforms that result from changes in properties of wave characteristics. Results from studies of marine barred topography and facies by Harms et al. (1975) and Davidsion-Arnott and Greenwood (1976) have led to the contention that most of the preserved sedimentary structures originate under high energy conditions. As a result of these conditions, nearshore sediment transport rates are highest during high energy conditions and strongest longshore currents are generated in the troughs. Many of the structures and bedforms displayed within the subenvironments do reflect this tendency of high energy bedform

MICHAEL BAY NEARSHORE FACIES BASED ON BEDFORMS AND SEDIMENTARY STRUCTURES

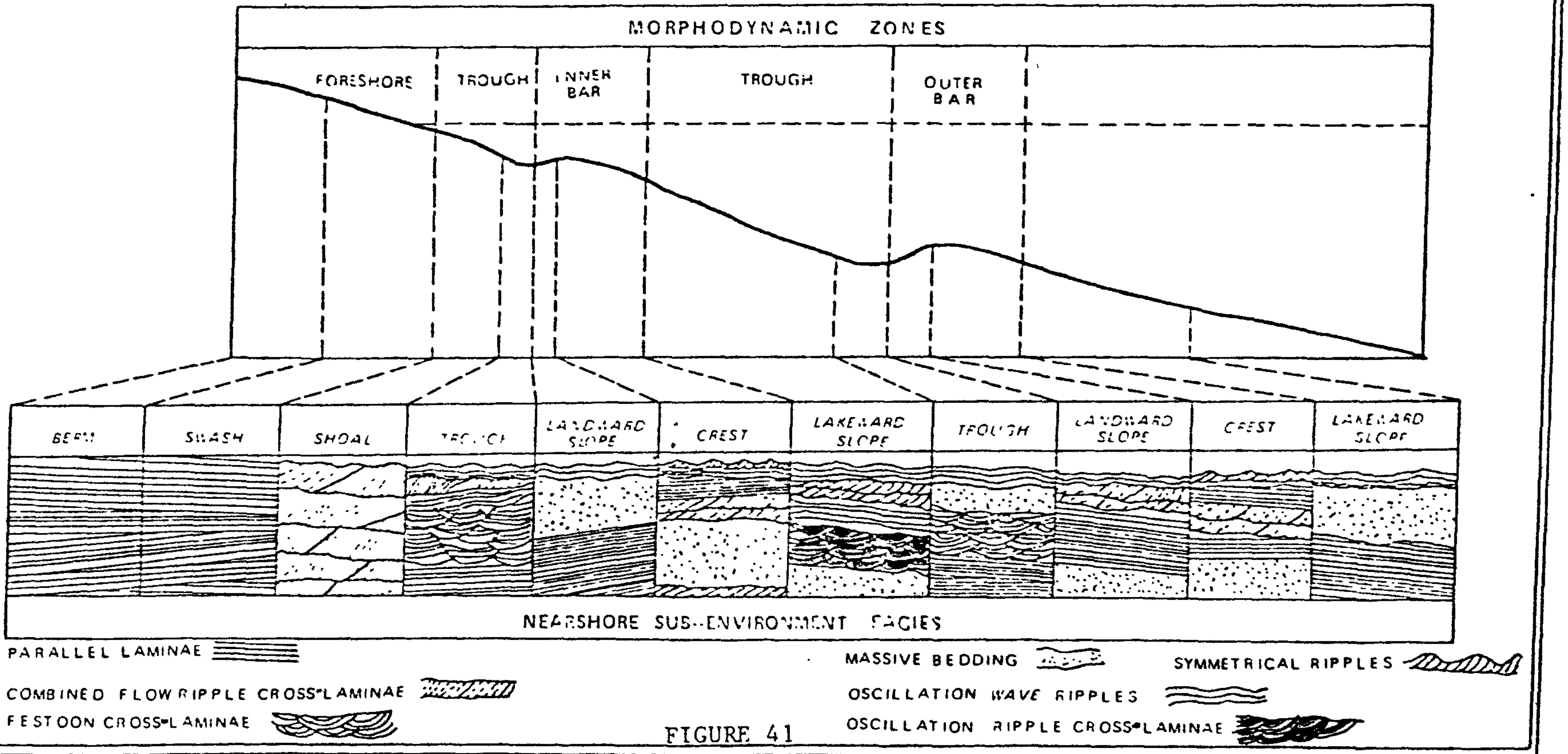


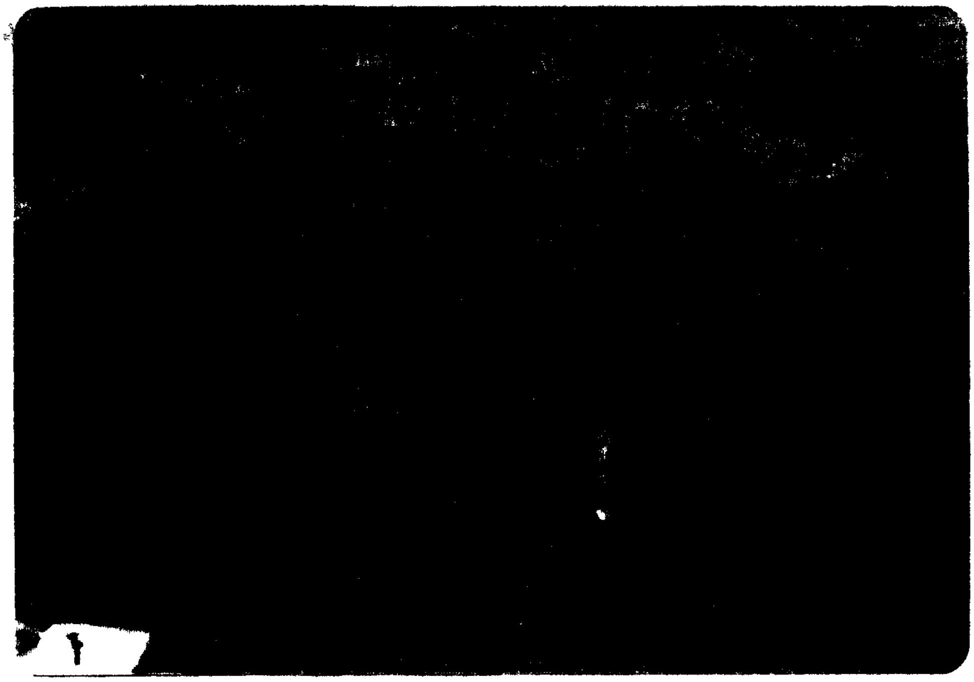
FIGURE 41

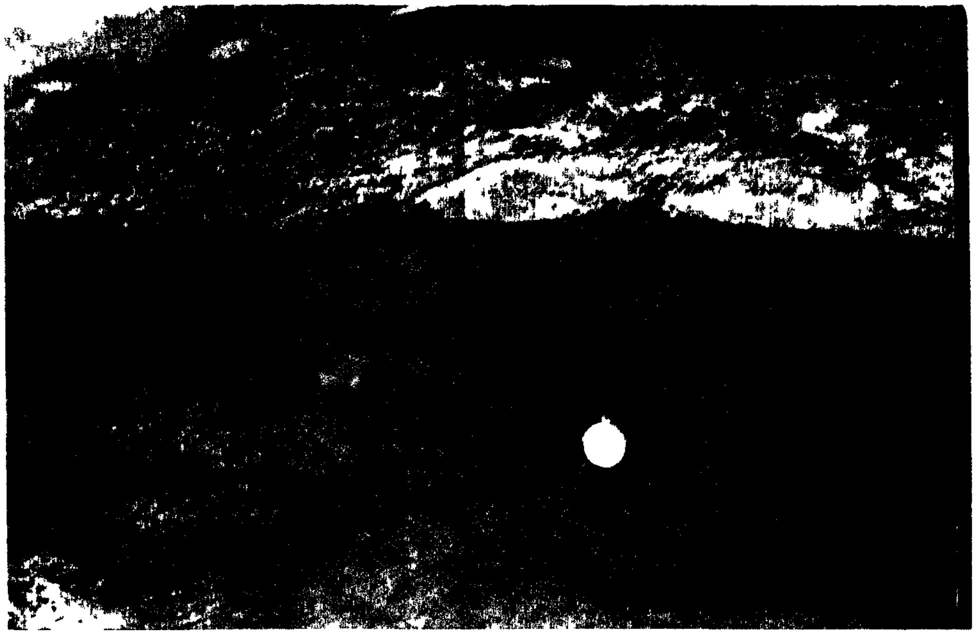
preservation. However, the Michael Bay bar topography is a composite of energy regimes because higher energy bedforms are always preserved subjacent to those of lower energy. This sequence of preserved low energy bedforms reflects the prevailing wave conditions during the time of sampling. Vertical sequences of sedimentary structures and bedforms are shown in Figures 42 to 45.

Swash-Berm Facies

Trenches made within the berm reveal parallel laminae that dip landward and lakeward (Fig. 42). According to Clifton (1969), these evenly laminated sands were deposited from suspension under the influence of waning wave energy. Saltation and bedload are additional modes of transport in this subenvironment. The swash-backwash process is responsible for this characteristic bedding. The parallel laminae indicate the slope of the existing beach face during the time of deposition. The distinguishing characteristics of this facies are the parallel laminae which display: low angle dips of less than ten degrees, landward and predominatly lakeward dipping units, and distinct erosional contacts.

Trough and antidune structures form attendant types of bedforms that have been found by others





LAKEWARD DIPPING PARALLEL LAMINAE ARE EVIDENT IN BOTH PHOTOGRAPHS. A LANDWARD DIPPING PARALLEL UNIT IS INDICATED BY THE WATCH IN THE BOTTOM PHOTOGRAPH (Scale 5.5 cm in width)

FIGURE 42

BERM FACIES

LANDWARD: To The Right
SCALE: Width = 22 cm

SHOAL FACIES

CHARACTERISED THROUGHOUT BY COMBINED FLOW RIPPLE CROSS LAMINAE

LANDWARD SLOPE FACIES

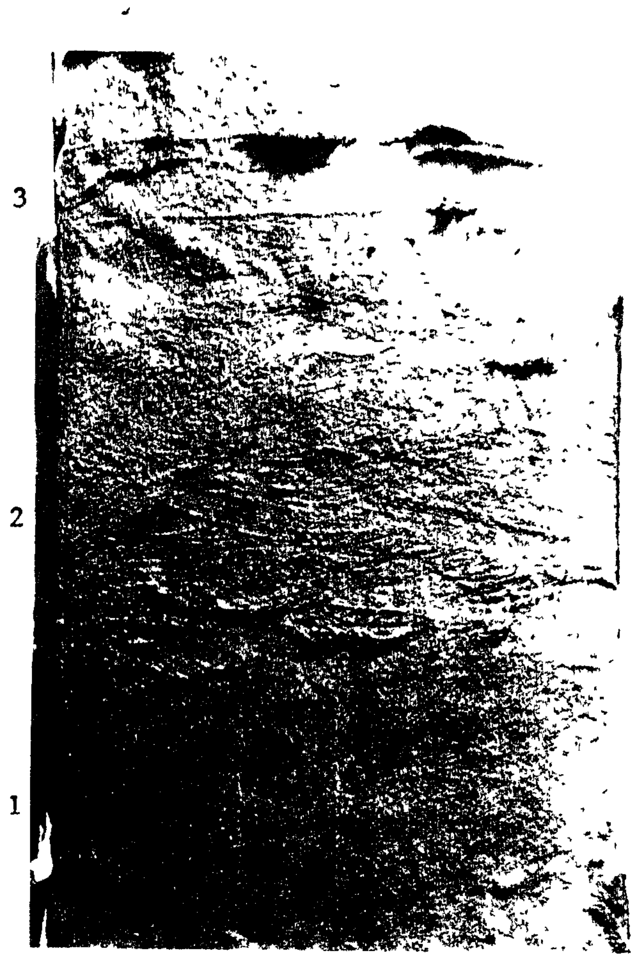
1 = Landward Dipping Parallel Lamin
2 = Avalanche Sands
3 = Small Scale Ripple Cross Lamina

FIGURE 43
SHOAL AND LANDWARD SLOPE FACIES

LANDWARD: To The Right
SCALE: Width = 22 cm

CREST FACIES

1 = Massive Bedding
2 = Weakly Defined Oscillation Ripple Cross-Laminae
3 = Parallel Laminae
4 = Oscillation Ripple Cross-Laminae
5 = Symmetrical Ripple Cross-Laminae

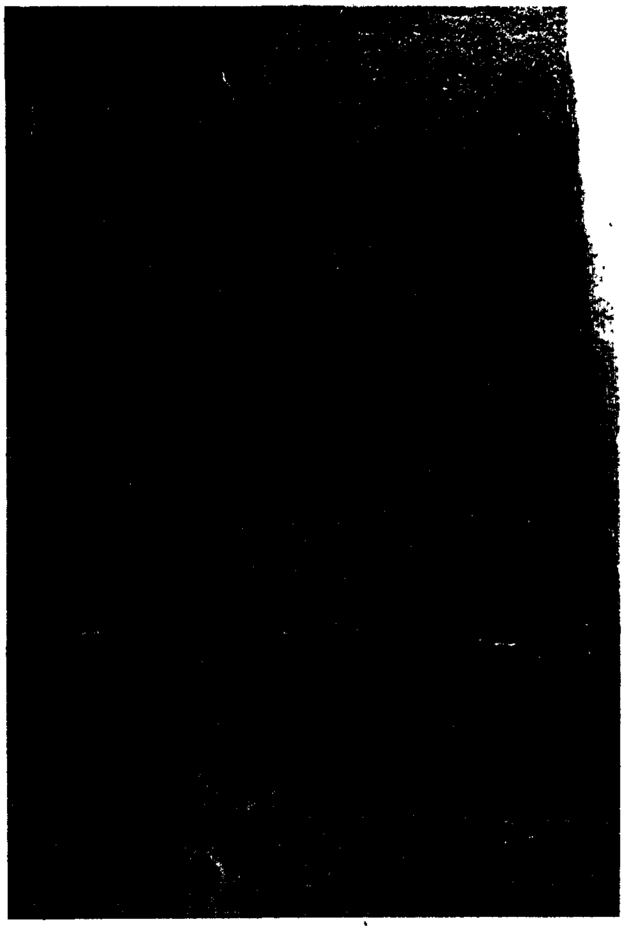


LAKEWARD SLOPE FACIES

1 = Massive Bedding
2 = Oscillation Ripple Cross-Laminae
3 = Small Scale Symmetrical Cross-Laminae

FIGURE 44
CREST AND LAKEWARD SLOPE FACIES

LANDWARD: To The Right
SCALE: Width = 22 cm



Small Scale Asymmetrical Cross-Laminae

Weakly Defined Festoon Cross-Laminae

Parallel Laminae

FIGURE 45
TROUGH FACIES

(Hayes, 1972; Howard and Reineck, 1972; Wunderlich, 1972). However, these structures were not evident in any of the Michael Bay sections. The trough cross bedding is associated with open coasts where wave incidence is a dominant factor in generating alongshore drift and currents, which in turn are responsible for producing this particular bedding. The foreshore antidune structures have been only documented in marine conditions and are related to effects from tides, since examples of these structures have been indicated in the low tide foreshore. Transport direction in the Michael Bay sites is related to dominant flow and transport normal to shore.

Shoal Facies

The small scale, combined flow ripples (Harms et al., 1975), shown in Figure 43, are indicative of shoal environment bedforms. Such ripples are associated with predominantly unidirectional transport of coarser grains in the direction of wave propagation. The internal laminae produced by these ripples indicate that the flow and the sediment transport are oriented in the landward direction. In addition, the laminae are not trough strata in form; instead they are convex upward units that tangentially connect to lower bounding surfaces (Harms et al., 1975). The presence of cross-laminae indicates low wave energy. Parallel laminae exemplify the initial low, deep water wave energy and its consequent dissipation in this subenvironment.

Landward Slope Facies

Bedforms associated with this facies type are landward dipping parallel laminae of fine sand (3.170), which grade upward into coarser, poorly sorted avalanche sands (2.820) that are subjacent to finer (2.990) small scale ripple cross laminae (Fig. 43). In higher energy conditions when waves break on the bar crest as a result of high waves or storms which generate steep, short period waves, both parallel laminae are generated and gravitational avalanche of sediment occurs (Fig. 43). This avalanche unit is weakly defined but can be identified by a sporadic occurrence of coarse clasts within a finer sand matrix. Oscillatory currents with a greater landward component form the small scale ripple cross-laminae. These laminae would form under low wave heights relative to the greater wave heights required to generate parallel laminae. They would form under low energy and wave conditions when wave transformation in shallow water over the bar crest is incomplete or non-existent.

Bar Crest Facies

The principal bedforms associated with this facies are massive sands, lakeward dipping parallel laminae, oscillatory wave ripples (Harms et al., 1975), and symmetrical ripples (Newton, 1968), (Fig. 44). Interpretation of structures in this subenvironment is made difficult owing to the variability of crest migration, which results from high concentrations of wave energy. Coarsest sediments of the entire bar form are found in facies of this subenvironment. Figure 44 illustrates the massive sands (3.120). A piece of wood is also embedded in this unit. This massive unit grades upward into weakly defined oscillatory ripples (2.520) that are overlain by lakeward dipping parallel laminae of 2.730 size. Another unit of oscillatory wave ripples (2.770) occurs, and these underlie symmetrical ripples of 2.730.

Literature concerning the presence of a massive bed within a marine vertical section is replete with bioturbation cited as the controlling process; while no attention has been given to the hydrodynamics that would be capable of generating this bedding. Structures such as dwellings, escape traces, burrows, and borings constitute some of the obvious evidence employed to decipher bioturbation activity. However, when such evidence is lacking, bioturbation is still maintained as the primary process responsible for massive bedding. In this case, hydrodynamic processes most probably dominate. This is evident in the crest facies massive bed (Fig. 44). This unit is distinctly interbedded with landward dipping parallel laminae and weakly defined wave oscillation ripple cross-laminae. Bioturbation evidence is not present and the author believes that this unit derived from deposition of sediment load in the form of either suspended or saltating load. The bedform is either a plane bed or a antidune because these bedforms possess characteristics of massive bedding.

The parallel laminae are indicative of higher flow velocities than the ripple cross-laminae, and the lakeward dip of this unit is controlled by the bar slope at the site of deposition (Fig. 44). Overlying these are the wave oscillation ripples that form when wave motion dominates. The internal laminae appear as symmetrical laminae that resemble preserved troughs between ripple crests. Although the laminae could be mistaken for small scale troughs in one orientation, attention to a vertical section normal to this clearly indicated that subparallel evenly laminated units were present. These are properties that are inherent to oscillation ripples. The small scale symmetrical ripples situated at the top of the section possess an internal structure indicating landward transport is the dominant component. This is evident by the foreset laminae that dip in a landward direction (Fig. 44). The symmetry is maintained by the orbital path of the wave (Newton, 1968). These ripples also indicate the lowest energy level relative to the other bedforms.

Lakeward Slope Facies

The lakeward slope facies is characterised by a massive bed (3.090), which underlies oscillation ripple cross-laminae (2.730), while the top units of the section comprise small scale symmetrical ripples of 3.090 (Fig. 44).

Evidence from bedding and mean grain size suggests that varying intensities of shoaling waves are responsible for the sediment textures and the bedform types in this facies.

The massive bed can be related to lakeward and landward components of sediment transport. The lakeward component originates at the bar crest where passing troughs erode crest sediments and rapidly deposit them in this subenvironment. The landward component of sediment transport results from passing troughs of the incoming wave form. Sediment is transported up this slope with coarser fractions rapidly deposited in this subenvironment and finer sizes deposited offshore. The oscillation ripple cross-laminae reflect higher energy than symmetrical ripples which indicate that lakeward and landward components are equally dominant.

Trough Facies

This facies type exhibits primary sedimentary structures of small scale asymmetrical ripple cross-lamination (3.140), weak festoon cross-laminae (2.840), and parallel laminae (2.790) (Fig. 45). These parallel laminae occur in the lowest units. Erosional contacts are distinct which indicates that wave energy was optimal during deposition. Moreover, they are representative of lower landward slope sediments. Sorting in these units as well as the festoon units is poor and this refects the presence of both coarse and fine sediments. The controlling property is the water depth.

As water depth increases in the trough zone, the effects of oscillatory currents on the bed decrease. Thus, coarse sediments will be deposited in this zone in addition to fine grain sediments. Various researchers have pointed out that this is a zone where longshore currents predominate (Inman and Bowen, 1963; Bowen and Inman, 1969; Davidson-Arnott and Greenwood, 1976). This accounts for the occurrence of festoon units within this facies. They have formed under unidirectional flow conditions but have been displayed normal to the flow direction (Fig. 45).

The asymmetrical ripple cross-laminae dip normal to shore and can be ascribed to a landward component of flow generated by wave activity. The fine texture of these cross-laminae and their morphology suggests that trough infilling occurs during low energy levels.

Bedform Generation

A study of a sedimentological attribute such as bedforms and sedimentary structures has provided some relevant information on the nature of subenvironments within the nearshore zone. This information pertains to flow directions, sequence of bedform development, and flow conditions that occur within specific sites of deposition.

Flow directions, as deduced from cross-laminae for the Michael Bay barred nearshore topography, are primarily preserved in the landward and lakeward direction for both high and low intensities of wave energy. Berm facies exhibit low angle parallel laminae that primarily dip lakeward. These make a distinct erosional contact with landward dipping laminae that are indicative of incipient berm or ridge development (Fig. 42). Combined flow ripple laminae preserved in the shoal facies are associated with unidirectional flow in the direction of wave propagation.

Other subenvironments within the barred topography exhibit laminae that consistently dip either landward or lakeward (Fig. 41). The only exception is the landward slope of the outer bar which exhibits lakeward dipping parallel laminae (Fig. 41). Preservation of these laminae may be related to a process of bar migration in the lakeward direction.

The bar subenvironments exhibit sedimentary structures that have originated under both high and low energy conditions. All facies indicate that high energy conditions preceeded low energy conditions (Fig. 41).

Bedform sequences are vertically contiguous responses to changes im wave energy conditions. Although low energy conditions are characterised by development of ripples, there is a succession of ripple bedforms that develop within this category. These ripple bedforms in order of increasing energy are as follows: symmetrical, asymmetrical, oscillation, and combined flow. As wave energy increases, the combined flow type is washed out during increasing energy levels and transformed into parallel laminae and massive beds. Flow conditions concerning critical entrainment velocities and wave ripple formation can be approximated by using results from a study carried out by Inman (1957-from C.E.R.C. 1973, P. 4-65). The minimum wave induced bottom velocity necessary to initiate sediment motion for 3.00Ø sands of Michael Bay is 10.65 centimetres per second, while ripples will form and disappear at a maximum velocity of 67.06 centimetres per second.

The modes of sediment transport that contribute to deposition are bedload and saltation. Kennedy and Locher (1972) and Mogridge and Kamphuis (1972) have provided information that indicate passing troughs are responsible for removal of fine sediment by suspension. Thus, only faster settling, coarser sand grains are available for deposition by bedload and saltation.

Application Of Modern Facies To Ancient Sediments

A comparison of sediment size in ancient bayhead sediments with the modern subenvironments obviously shows that higher wave energy had existed in the ancient beaches. For example, the shingle and gravel size sediments shown in Figures 16 and 13 exhibit clasts that range from -5.50Ø to -3.25Ø. Cumulative size distributions of these coarse clasts are shown in Figure 35. Critical entrainment velocities required to move this size range are approximately 120 centimetres per second to 300 centimetres per second. These are minimum estimates for this range of size clasts. Estimates were made from consulting a Hjülstrom particle size versus velocity diagram. Justification for use of this diagram results from confirmative, empirical research carried out by Novak (1972). His study concerned use of natural tracers and an event recorder in a marine environment to determine the critical velocities necessary to transport beach sediments. The natural tracers comprised in situ beach sediment, which ranged from -5.00Ø to -3.200Ø, that were marked by paint and were situated throughout the foreshore.

The vertical sequence of sediments shown in Figure 19 (Sample Site M36) correspond to a berm development sequence whereby landward dipping units of sand and peboles are sharply truncated by lakeward dipping, evenly laminated upper foreshore sands.

The remaining beach sections reflect a vertical sequence of nearshore sediment which grade upward into beach and dune sediments (Figs. 19, 20, 21). It appears that where beach ridges occur, they tend to reflect foreshore subenvironments of lower foreshore, berm, and swash. Moreover, it is apparent that only highest energy events are preserved within vertical sequences. This is substantiated by the presence of preserved, parallel laminae in the modern foreshore sands (Fig. 42). Preservation of cobble and shingle sediments in the ancient environments are directly comparable with the modern beach at Providence Bay (Fig. 2). This embayment has cobble and shingle sediments that are proximal to bedrock and adjacent to a sandy bayhead beach. Storm and high wave energy conditions are responsible for developing a section of foreshore that is analogous to the ancient Michael Bay ridges.

It is suggested that preservation potential of longshore bars is low because bar migration in the lakeward direction is believed concomitant with prograding shorelines or regressive lake level. For these bars to be preserved they would have to migrate landward under low wave conditions until a portion merges with the foreshore and is subsequently buried by sediment (Hayes , 1972). In this situation, only the lower landward slope facies would be evident.

Summary

Primary sedimentary structures have been studied as they relate to specific subenvironments of deposition within the modern nearshore zone.

Information concerning these structures has been assimilated into a facies model for low energy nearshore sediments of a lacustrine-bayhead environment. This model represents subenvironments of berm, swash, shoal, trough, landward slope, crest, and lakeward slope.

Careful examination of bedforms and structures enables useful statements to be made concerning flow directions, sequences of bedform generation, and flow conditions within specific depositional subenvironments. Cross-laminae were used to determine flow directions for the modern nearshore.

Berm facies display low angle parallel laminae that primarily dip lakeward. These make distinct contact with landward dipping units that are indicative of incipient berm or ridge development. Higher energy bedforms were absent. Shoal facies are characterised by combined flow ripples that exhibit a predominant landward component of flow which results from shoaling waves. The trough facies have high and low energy bedforms that indicate flow directions in this subenvironment are both parallel and normal to shore. Flow direction parallel to shore is indicated by weakly defined festoon units. Flow normal to shore occurs in both landward and lakeward directions. Small scale asymmetrical ripple cross-laminae consistently dip landward, whereas, parallel laminae dip both lakeward and landward. Bedforms associated with the landward slope facies are parallel laminae, avalanche sands; and small scale combined flow ripple cross-laminae. Flow directions are preserved in the landward direction with the exception of the outer bar facies. Lakeward dipping parallel laminae are present in the landward slope of the outer bar, and these may be relict lakeward slope units that have been preserved during lakeward bar migration. Variability in flow direction is also evident in the crest facies. The ripple cross-laminae of symmetrical and oscillatory wave ripples indicate that flow was landward, while parallel laminae exhibit lakeward and landward components of flow. Lakeward slope facies exhibit massive bedding, oscillation ripple cross-laminae, and small scale symmetrical ripple cross-laminae. The ripple laminae indicate the landward component of flow.

Bedforms evident in this facies model are responses to high and low energy conditions. High energy bedforms of parallel laminae and massive bedding are always preserved subjacent to low energy ripple cross-laminae. The ripples formed in response to increasing energy are as follows: symmetrical, asymmetrical, oscillatory, and combined flow. These ripple cross-laminae form and become obliterated within a velocity range of 10.65 to 57.06 centimetres per second.

Results from a comparison of these characteristics with the ancient beach sediments indicate that high energy events have been preserved in foreshore bedding sequences. The same bedding characteristics have been formed in the modern Providence Bay beach sediments. These characteristics can be ascribed to storm or high wave conditions. Critical entrainment velocities necessary to initiate sediment motion and to form these ridges range from 150 to 300 centimetres per second.

Relict longshore bars were not evident in any of the ancient sections. The ability of the bar topography to migrate lakeward in response to either decreasing lake level or high wave energy conditions is the reason for their lack of preservation. Preservation may occur under low wave conditions which will cause migration of the bar form to the foreshore where it merges and becomes buried.

CHAPTER SEVEN CONCLUSIONS

Modern and ancient environments associated with Lakes Algoma and Huron were studied according to attributes of stratigraphy, sediment texture, sediment size distributions, bedforms, and primary sedimentary structures.

The longshore bar topography and sedimentological characteristics of the modern environment can be related to wave refraction and the energy distribution patterns. These patterns indicate that low wave energy for west, southwest, and south southwest hindcast waves occurs in the bayhead. The morphological and sedimentological characteristics of the subaqueous topography reflect this low wave energy. The characteristics are as follows; the narrow relative spacing of the longshore bar system, the gentle littoral zone gradient of 1:30, and the fine surficial sediments that occur throughout the nearshore zone.

A sediment texture comparison between modern and ancient environments indicates that higher energy prevailed in the ancient bayhead relative to the modern environment. The cobble and gravel sediments as well as the extensive belt of foredunes preserved in the ancient environment are evidence of this high energy.

Sediment texture parameters were also combined in bivariate plots to test their apparent reliability to discriminate between environments. The results indicated that for all cases inferred dune sediments could be discriminated from modern beach and inferred environments of beach and fluvial. Only plots of skewness versus standard deviation for the modern and ancient environments proved useful, since they exhibited patterns that were fully comparable amongst themselves as well as with the patterns delimited by Friedman (1961, 1967). Other plots of mean versus standard deviation, skewness, and kurtosis proved unreliable when compared with each other and with published results. This form of analysis is not regarded as a useful discriminator for environments.

Component populations are useful discriminators of depositional environments. Modern and ancient lacustrine environments could be discriminated from ancient fluvial and dune environments by their component characteristics. Sediments sampled from bedforms of modern subenvironments exhibited distinct curve characteristics. These characteristics have been assimilated into a grain size facies indicator that displays typical cumulative curves, percentage occurrence and slope inclination of bedload, saltation, and suspension components, and the phi competency range. In addition to these, ancient sediments from lacustrine, fluvial, and dune environments were exhibited. The depositional locale for the ancient lacustrine sediments is foreshore owing to the presence of two distinct saltation populations. Component populations have proven useful for interpreting the depositional environment of ancient sediments. Moreover, discrimination of nearshore subenvironments can be made by analysing curves of samples taken from bedforms representing the subenvironments.

Provision of a facies model for a barred, lacustrine bayhead was made possible by an examination of preserved bedforms and primary sedimentary structures. This model represents subenvironments of berm, swash, shoal, trough, landward slope, crest, and lakeward slope. Bedforms preserved in these subenvironments are responses to high and low energy conditions. Parallel laminae and massive bedding reflect high energy conditions, whereas, ripple cross-laminae characterise conditions of low energy. The high energy bedforms are always preserved subjacent to those of low energy. The sequence of ripple cross-laminae formed with increasing energy is symmetrical, asymmetrical, oscillatory, and combined flow. These ripples will form and disappear during a wave induced bottom velocity range of 10.65 to 67.06

centimetres per second. The examination of cross-laminae yields additional information that can be used to decipher flow directions and flow characteristics within the subenvironments.

An examination of ancient beach sediments and bedding characteristics as they relate to the facies model indicates that bedding sequences are foreshore and reflect deposition from high energy. A comparison of ancient beach sediments and bedding characteristics with the facies model indicates that high energy foreshore bedding sequences have been preserved. This is substantiated by evidence from bedding sequences observed in a modern bayhead beach. The critical entrainment velocities that are necessary to initiate sediment motion and form these ridges range from 150 to 300 centimetres per second. Relict longshore bars were not evident in any of the ancient sections. The lakeward migration of these features in response to processes of decreasing lake level and high wave energy conditions is inimical to their preservation. These processes occurred during formation of the ancient beaches. However, preservation of longshore bars may occur under low wave conditions which will cause migration of the bar form to the foreshore.

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