SHORELINE PROCESSES ON LAKE WINNIPEG

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ABSTRACT

Shoreline recession is an ever present problem on Lake Winnipeg and is accentuated during storm periods and high lake levels. With the ever-increasing value of property along the shoreline, this recession can cause serious damage.

Before any works are constructed to halt shoreline recession, it is necessary to understand the littoral processes acting upon the shoreline and how these processes are related to sources and losses of material, natural and man-made littoral drift barriers, and fluctuations in the lake levels. This thesis gives a general analysis of the processes acting upon the shoreline from Riverton to Sans Souci on the west and from Elk Island to Balsam Bay on the east. Furthermore a detailed study of the shoreline at Winnipeg Beach was made with the aid of a model.

The author fully realizes that this study is only preliminary in nature but hopes that it will give some insight into the problems of shoreline recession and that it will stimulate thoughts, discussions and further studies into this challenging problem.

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CHAPTER I

INTRODUCTION

Shoreline recession is a recurring problem on Lake Winnipeg. Since the turn of the century as much as 150 feet of property has been eroded in some areas; the majority of the erosion occurring during high water years.

Each major storm on the Lake results in a flurry of construction of shoreline structures constructed in an attempt to halt this intrusion of the Lake. Most of this work is done privately and is thus uncontrollable; however major structures have been built by public authorities without giving due consideration to the effect of the structures on the shoreline processes. An understanding of the processes is mandatory in the proper planning of future works and in the analysis of present works. It is the aim of this thesis to:

1) study the shoreline processes on Lake Winnipeg and determine how these are related to sources and losses of littoral material and natural and man-made littoral drift barriers;

2) study qualitatively with the aid of a model, the shoreline processes at Winnipeg Beach.

Chapter II sets the historical background to the problem and outlines the previous studies that have been undertaken on Lake Winnipeg and stresses the need for the present study. A review of lake stages, geology, soils, relief and depths of Lake Winnipeg is given in Chapter III, whereas Chapter IV is devoted to an analysis of winds and waves. The shoreline processes on Lake Winnipeg are analyzed in Chapter V. Chapter VI is devoted wholly to the model study of Winnipeg Beach. The final chapter summarizes the conclusions of the study.

Appended to the thesis are five appendices A to E Appendix A consists of seven tables listing calculated significant wave heights for seven locations around Lake Winnipeg with varying lake levels and wind velocities. The questionnaire sent out to the property owners constitutes Appendix B. Appendix C comprises of a discussion on the selection of model scales and outlines the construction procedure used in the Winnipeg Beach model. A detailed description of the numerous factors affecting littoral processes is given in Appendix D for those readers who wish to pursue this field further or who may desire more background information for the complete understanding of Chapter V. Appendix E lists the further studies required.

Due to time limitations there are still numerous questions pertaining to shoreline processes that remain unanswered and particularly the model study of Winnipeg Beach was somewhat limited; however it is the author's opinion that this thesis will give some valuable insight into the shoreline processes on Lake Winnipeg.

CHAPTER II

HISTORICAL SETTING OF PRESENT STUDY

History of Development

The farmland along Lake Winnipeg was initially settled in the latter part of the 19th century by settlers from Iceland, the Ukraine and Poland with the Icelandic people claiming land north of Boundary Creek. Most of the permanent population engaged itself in farming, fishing or supporting trades. The recreational potential of Lake Winnipeg became fully realized in the early part of the 20th century when the Canadian Pacific Railway constructed a line from Winnipeg to serve Winnipeg Beach and Gimli. In order to accommate the numerous boats and yachts that began to travel to the Winnipeg Beach area, the Federal Government constructed a 600 foot long breakwater in 1910. Harbour facilities for fishing and recreational needs were also constructed at Gimli, Hnausa, Gull Harbour and Victoria Beach during later years. A detailed map of Lake Winnipeg is shown on Figure 2.

The permanent and summer residents[1] in the major centers around Lake Winnipeg are listed in Table I below.

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1 These figures include permanent populations, summer cottage dwellers, summer employees and campers.

TABLE I

PERMANENT AND SUMMER RESIDENTS IN MAJOR CENTERS AROUND LAKE WINNIPEG

Center	Permanent Population	Summer Population
Gimli (including Loni & South Beach)	1,841	5,000
Sandy Hook	70	1,700
Winnipeg Beach (including Boundary Park)	807	3,500
Ponemah) Whytewold) Matlock)	232	1,500
Grand Beach	20	22,500
Grand Marais	300	-[1]
Victoria Beach	275	-[1]

Previous Studies

The first extensive study of Lake Winnipeg was done in 1958 by the Lakes Winnipeg and Manitoba Board (52). The aim of the study was to determine ... "what further developments and controls of these water resources in its judgement would appear to be physically practicable with particular reference to (a) flood control and (b) hydro-electric power". No consideration was given to the possible effects that lake regulation might have on the shoreline except that the Board suggested that the governments involved pay for necessary shoreline protective works in return for flood easements.

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1 Not known.

In 1966 the Water Control and Conservation Branch, Province of Manitoba undertook a study ... "to obtain a preliminary assessment of the cost of flood control measures and shoreline erosion protection on the settled portion of the Lake Winnipeg shoreline". (48) The study was restricted to determining the capital cost of protection measures but also briefly considered the causes of shoreline erosion, and furthermore listed future studies that would be required before shoreline protective works could be properly designed. Studies into the littoral processes and shoreline recession were considered to be of prime importance. Dr. P. Bruun, former Director, Port and Coastal Engineering, National Engineering Science Company, Washington, D.C., was engaged by the Province of Manitoba to advise on the costs and technical aspects of shoreline protection measures.

Several minor studies have been undertaken of various portions of the Lake Winnipeg shoreline. One study worth mentioning is the proposed boat marina east of the Grand Beach public swimming area (35). This plan proposes the construction of a breakwater into the lake to protect the harbour entrance; however, the long-term effect of this breakwater on the littoral processes and consequently on the Grand Beach public beach were not determined. Professor Kuiper of the University of Manitoba, in a study for the Manitoba Water Commission (53) has suggested the creation of an artificial beach around the settled portion of the lake by artificial nourishment from onshore areas.

Need for Present Study

Previous studies have not considered the overall problem of shoreline erosion, whether it be natural or man-made. Numerous structures have been built along the lake and in fact more are planned without any consideration being given to the long-term effects that the structures may have on the shoreline. Before these long-term effects can be understood and determined quantitatively, a thorough knowledge of the shoreline processes is necessary. The author hopes that this study will give some much-needed insight into the problem of shoreline erosion on Lake Winnipeg and he hopes that it will stimulate thoughts, discussions and further studies into this most fascinating field.

CHAPTER III

DESCRIPTION OF LAKE WINNIPEG

General

Lake Winnipeg is a vast shallow lake and is a remainder of the ancient glacial Lake Agassiz. The relative size and location of Lake Winnipeg in comparison to the other major lakes on the North American Continent is shown on Figure 1, while Figure 2 outlines the southern portion of the shoreline in detail. The lake may be divided into the vast uninhabited northern pool and the settled southern pool. In the present study only the southern pool from Riverton to Sans Souci on the west and from Balsam Bay to Elk Island on the east is considered. A brief description of the lake is given below.

Lake Stages

The three main rivers discharging into Lake Winnipeg are the Red, Winnipeg and Saskatchewan Rivers. The annual variations in water levels on Lake Winnipeg are governed by the annual variations in precipitation in the watersheds draining into the lake. Short term rises are due to wind set-up associated with storms. Lake elevations have been recorded at Winnipeg Beach from May

1913 to August 1966 and at Gimli since then. A stage hydrograph of mean monthly elevations is shown on Figure 3 and a stage duration curve is shown on Figure 4. The mean monthly lake levels (wind effect eliminated) have varied from 717.53 (July 1966) to 709.62 (February 1940). The maximum daily water level (wind effect eliminated) experienced on the Lake was 717.6 (July 1966).

Geology and Soils

The western shore of Lake Winnipeg consists of lacustrine deposits of various textures and thin lacustrine deposits over glacial till (32). The area is sometimes subdivided into four local areas, namely the Fisher River Plain, the Icelandic River Lowland, the Red River Plain and the Winnipeg Lake Terrace. The eastern shoreline may be subdivided into two "natural landscape areas" (33). The Red River Valley Plain consists of lacustrine deposits up to 60 feet in thickness while the Winnipeg Lake Terrace area is a complex of land forms that has resulted from the deposition of glacial till, glacio-fluvial outwash and shallow lacustrine sediments. Outwash deposits in some areas have been modified by wind and generally both relief and texture of the surface deposits are extremely varied.

The soils that have developed in the various areas are greatly dependent on the soil forming factors of parent material, relief, drainage, climate and vegetation (33). Figure 2 shows the soil series adjacent to the shoreline and indicates the percentages of sand, silt and clay in each type. The numerous subdivisions in each series as given by the Soil Reports (32, 33) are not shown but rather only the composition of the main series are indicated.

Hydrography

Whereas other major lakes on the North American Continent such as the Great Lakes, attain a depth of up to 800 feet, Lake Winnipeg is very shallow in relation to its size. The maximum depth in the southern pool is approximately 50 feet. The 18 foot contour and the classification of bottom deposits as obtained from the Department of Mines and Technical Surveys, are shown on Figure 2.

Ice Formation

Lake Winnipeg is covered with ice during almost six months of the year. Shoreline slopes of unconsolidated material may steepen as a result of ice being pushed up but with the onset of wave action and higher lake levels in the spring, this steepening disappears (40). Ice may also pry off exposed bedrock; a process which is irreversible.

CHAPTER IV

ANALYSIS OF WINDS AND WAVES

General

The natural configuration of a given shoreline is closely related to the transport of sand which is a consequence of the movement of water, which in turn is a consequence of winds and waves (20). The frequency of occurrence of extreme winds and the frequency of occurrence from the various directions was determined for Lake Winnipeg. Wave heights were calculated for selected points along the lakeshore for varying lake levels and wind velocities. The waves were also analyzed to determine the percentages of total wave energy from the various directions.

Wind Analysis

Meteorological stations in the vicinity of Lake Winnipeg are at Gimli and Winnipeg and since 1961 wind velocities have been measured on a dredge which travels between Selkirk and the mouth of the Red River. Wind records obtained at these stations are over-land winds and appropriate factors would have to be applied to convert the records to over-water winds. To convert wind velocities obtained from the dredge to over-water velocities would be difficult as the factors relating the two velocities would vary according to the position of the dredge, which is not specified. Thus the wind velocities as measured on the dredge were used in the computations. The error resulting from this simplification is realized, however as the main objective of the wind analysis is to determine the wave energy distribution and as this is on a percentage basis, the error in the wind velocities is not inherited in the wave energy distribution.

Several studies dealing with wind tides, wave uprush, seiches and design winds for Lake Winnipeg and Southern Manitoba have been made (14, 18, 34). As the main aim of this thesis is not a wind frequency study, these previous studies were heavily relied upon in obtaining design wind velocities. Buie (14) found that the relationship of hourly average wind speed versus the return period in years for Winnipeg and Gimli was the same. The hourly wind speed for a return period of ten years was found to be in close agreement to that calculated by McKay (34). The relationship determined by Buie is shown on Figure 5. Average Winnipeg winds and the frequency of occurrence from each direction as determined by McKay is listed in Table II below.

TABLE II

AVERAGE WINNIPEG WINDS, 1939 - 1954
APRIL TO OCTOBER, OBSERVATION HEIGHT 77 FEET

	N	NE	E	SE	S	SW	W	NW	C
% Frequency	16.3	9.8	5.1	11.0	21.0	8.1	10.3	18.4	*
Average Speed (m.p.h.)	14	12	11	14	16	14	14	17	-

* Less than 1/2 per cent.

McKay observed that for design purposes, extreme winds may be assumed to be isotropic.

The hourly wind records from the dredge for 1961 to 1966 were analyzed and the average direction, duration and velocity for the period of record are shown on Figure 6. The wind velocities were not available for the whole period but the period of record considered was generally continuous from June to September. A total of 15,531 readings were used in the present analysis. The frequency of occurrence from the various directions compared favourably with McKay's data except that calm winds on the dredge occurred during 13.20 percent of the time while McKay found calm winds to occur during less than 1/2 per cent of the time. This is partly due to the difference in the definition of calm. In the present study, calm winds were considered to have a speed of three miles per hour or less while McKay considered calm winds to have zero velocity.

Wave Analysis

Numerous studies have been made on deepwater waves and their mathematical equations. Forecasting curves showing the relationship between wind speed, fetch, length and wind duration have been developed (16). These deep-water equations however are not applicable to shallow water bodies such as Lake Winnipeg since wave characteristics are greatly affected by the water depth. The height of waves that can be generated in any shallow lake is governed by wind velocity, wind duration, fetch, depth of water and lake bottom characteristics (17). Usually one or the other factor limits or controls.

To date, two separate approaches to the problem of forecasting wave heights in shallow waters have been made. The first method of Thysse and Schyf (16) is an empirically determined relationship between the forecasting parameters. They are presented as two sheaves of curves showing the relationship between gF/V^2 and gH/V^2 for various values of gd/V^2 as well as the relationship between gF/V^2 and $Lg/2\ V^2$ for various values of gd/V^2. The symbols used are:

g = acceleration of gravity

d = mean depth over the fetch

V = wind speed

F = available fetch

L = wave length

H = wave height.

The second method, that of Bretschneider (5) takes friction and percolation in the permeable sea bottom into account. Since to date there is insufficient wave data (6) to verify the relationships derived and since the choice of the friction factor needed in the relationship is rather arbitrary, this method was not found to be suitable in the present study. In 1955 an extensive investigation was undertaken by the Corps of Engineers, U.S. Army, on the significant wave heights[1] on Lake Okeechobee (17). Relationships between wave heights, depths and wind speeds were determined but the results are not applicable to Lake Winnipeg as its depth is well outside the range of depths studied on Lake Okeechobee. Dimensionless ratios of wave height, fetch and depth of wind velocity were determined from wind-actuated model studies at the University of California (17). Further studies by Bretschneider on Lake Okeechobee and the analysis of shallow water ocean waves in the

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1 Significant wave height is defined as the average height of the one-third highest waves of a given wave group (16).

Gulf of Mexico yielded slightly lower average significant wave height values than those determined by the University of California studies. The design curve for the average significant wave heights as determined from these latter studies is shown on Figure 7 in addition to the envelope curve. The figure shows the relationship between gD/V^2 and gHs/V^2 where:

D = depth in feet,

V = wind velocity in feet per second,

Hs = significant wave height in feet.

As the Bretschneider and Gulf of Mexico studies did not consider fetch parameters while studies at the University of California did and since either the fetch or the depth may govern wave heights on Lake Winnipeg, it was also necessary to determine a relationship between the average significant wave height and the fetch. It was assumed that the difference between the envelope curve as determined from the University of California studies and the average significant wave height would be the same when the fetch governs as the difference indicated on Figure 7 when the depth is the governing factor. The plot of dimensionless wave height and fetch parameters is shown on Figure 8. These two figures were used in the determination of average significant wave heights on Lake Winnipeg.

Average significant wave heights were calculated for Lake Winnipeg for water levels of 713, 716 and 719 and for wind velocities corresponding to average return periods of 5, 10, 20 and 50 years for seven locations around Lake Winnipeg; namely Hnausa, Gimli, Winnipeg Beach, Matlock, Balsam Bay, Grand Beach and Victoria Beach. For each location, the average depth over the fetch and the effective fetch were calculated for the various over-water wind directions possible at the point in consideration. The effective fetch was calculated in accordance with the procedure proposed by Saville, McClendon and Cochran (56). Average significant wave heights for the various conditions and locations are tabulated in Tables A1 to A7 of Appendix A.

At present, the calculated average significant wave heights cannot be compared with actual recorded values. There is a definite lack of wave data on Lake Winnipeg. An attempt was made to obtain wave data to verify the Winnipeg Beach model, but unfortunately, as described later, this was not successful. Studies done by Buie indicated significant wave heights slightly lower than those of the present study but this is in great part due to the sensitivity of the wave heights to the location of the design curve on the dimensionless plot of the fetch, depth and height parameters.

The percentages of total wave energy from all directions was determined from the wind records obtained from the dredge. The power or energy contained in a wave per foot of length is proportional to the wave height squared times the wave period (H^2T). Studies on Lake Okeechobee (17) determined a relationship between the dimensionless parameters gT/V and gD/V^2 where T is the significant wave period. The exact slope and position of the prediction curve can not be specified. Values obtained from the prediction curve for various wind velocities varied from about 6.5 seconds to 4.5 seconds. Buie found a range from 3.82 to 5.83 seconds. An average significant wave period of 5 seconds was used in this study. Wave heights and wave energies were calculated for the four ranges of wind velocities used in the wind rose diagram, Figure 6, and using an average depth of 29 feet on the lake. The percentages of total wave energy from all directions are summarized in Table III. These figures do not represent the wave energy distribution for any specific location, but rather for the whole lake. The wave energy distribution for other locations were determined as well and are discussed in subsequent sections.

TABLE III

WAVE ENERGY FROM ALL DIRECTIONS

Direction	N	NW	W	SW	S	SE	E	NE
Percentage	25.4	14.9	13.6	4.7	19.1	7.6	8.3	6.3

Figure 9 illustrates the distribution of the wave energy.

CHAPTER V

ANALYSIS OF THE SHORELINE PROCESSES ON LAKE WINNIPEG

Introduction

The shoreline configuration of Lake Winnipeg is related to the movement of littoral material and this movement in turn is related to:

a) sources and losses of material,

b) natural and man-made littoral drift barriers,

c) predominant wind direction and,

d) lake levels.

In this chapter an attempt is made to analyze the above factors as they pertain to Lake Winnipeg and show how this general analysis of the littoral processes can be applied to determine the effect of existing and proposed shoreline works on the Lake. Other approaches to shoreline analysis by previous investigators are mentioned.

A complete treatment of littoral processes is given in Appendix D for those wishing a more extensive background into this subject. Many of the factors affecting the processes on Lake Winnipeg are presently unknown and the urgent need for a systematic field measurement program is outlined in Appendix E.

Data Available and Field Investigations Made

Field observations of the shoreline were made during the record high water levels experienced in 1966[1] and numerous trips were made during the summer of 1968. Aerial photographs were available for either portions or the whole lakeshore for the years 1924, 1946, 1954, 1961, 1966 and 1967. A questionnaire was distributed during the summer of 1968 to lakeshore cottage owners in order to determine the relationship between erosion and water level, and erosion and protective measures. The questionnaire and accompanying letter is shown in Appendix B.

Much information and knowledge regarding the problems of shoreline recession on Lake Winnipeg were obtained from personal communications with local residents.

Approaches to Shoreline Analysis

Shoreline recession consists of two major components, beach erosion and bluff failure. Generally when reference is made to shoreline recession, the term beach erosion is used and at times is used as the designation for the entire problem (15). Beach erosion refers to material removed from the zone extending from the low-water mark to

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1 The author was employed by the Water Control & Conservation Branch, Province of Manitoba during 1966 when a study into the measures for flood protection and shoreline erosion was undertaken.

the high-water mark or to the base of the cliff or bluff where present. The beach and bluff terminology as used by Chieruzzi (15) and the Coastal Engineering Research Center (16) was used throughout this chapter. A definition diagram of the pertinent terms is shown in Figure 10. The terms shore zone and lake front were used rather than the more common terms of coastal area and coast respectively as the study pertains to a lakeshore rather than an ocean coast. Bluff erosion is similar to natural slope failures except that the additional forces induced by waves and ice are present. Chieruzzi notes that bluff erosion is still present at times in areas where the beach is stable and where the wave action is expended upon the beach.

In the present analysis of Lake Winnipeg a distinction was made between bluff erosion and beach erosion in areas where the bluff is subjected to wave attack. It should be realized that bluff erosion due to natural slope failure cannot be halted economically with present-day knowledge.

A detailed classification of the shore features with an auxiliary classification of the types of beaches of the Ohio shoreline of Lake Erie has been made by Pincus (40). The main subdivisions used in his classification of the shoreline features are:

a) sandy bodies of low relief lying parallel to the lake bottom contours,

b) areas of low relief consisting of silt and clay exposed when an ancestral lake retreated,

c) mouths of streams,

d) bluffs and,

e) artificial shorelines.

Pincus has further classified beaches into three groups, namely:

a) sand,

b) pebble, cobble, or boulder and,

c) shingle.

Wave energy was also classified according to its orientation to the shoreline. A distinction was made between waves approaching perpendicular or parallel to the shoreline.

The classifications as outlined by Pincus were found to be applicable to Lake Winnipeg in discussing the shoreline, however in the present study, more emphasis was placed upon the sources and losses of littoral material to a specific beach area rather than the classification of the shoreline features and the beach material. The local material along the shoreline was determined from reconnaissance soil surveys (32, 33). The major soils classifications are shown on Figure 2 according to their respective percentages of sand, silt and clay. In areas where the beach is predominantly sandy and the bluff consists of clay, the source of the sand was determined by considering the predominant littoral drift into the area. It is felt that an insight into the movement of littoral material is more important in the analysis of existing and proposed shoreline protective works than a thorough shoreline classification. Shoreline classification would no doubt be important in the final detailed design of the protective works but not in the overall planning of the works.

Method of Analysis

The Lake Winnipeg shoreline from Riverton to Sans Souci on the west and from Elk Island to Balsam Bay on the east was divided into five reaches and for each the analysis was made on the basis of the:

a) sources and losses of littoral material. The three main natural sources of material to any beach segment are 1) material moving into the area by natural littoral transport from adjacent areas, 2) contributions by streams and, 3) contributions through erosion of lakeshore formations other than beaches exposed to wave attack (16). The principal processes by which material is lost from a specific beach area are 1) movement of material laterally out of the area, 2) movement of material offshore into deep water, 3) movement of material into submarine canyons and, 4) movement of material due to wind. As there are no submarine canyons on Lake Winnipeg, this process may be neglected in the present study. Data regarding the movement of material offshore into deep water is lacking, however some general statements may be made on this topic,

b) effect of natural and man-made littoral drift barriers. Headlands and inlets may be classified as natural littoral drift barriers while man-made barriers include groins, breakwaters and seawalls,

c) magnitude of shoreline recession. An attempt was made to determine the theoretical annual shoreline recession according to the analysis proposed by Bruun (see reference 55 and Appendix D). The information obtained from the questionnaires is included in this section.

The analysis is very general in nature but should give some valuable insight into the littoral processes on Lake Winnipeg.

Reach 1 - Riverton to Willow Point

General Description of the Reach: The shoreline of Lake Winnipeg from Riverton to Willow Point varies from low marshy areas east of Riverton to high bluffs near Camp Morton. Serious flooding in the Riverton area occurred during the record high water levels of 1966 while extensive flooding occurred as well in the Gimli, Loni Beach, and South Beach areas during the storm periods. Shoreline recession in the Gimli-Loni Beach area consisted chiefly of beach erosion whereas bluff erosion was the major component of shoreline recession in the Camp Morton and the Spruce Sands-Spruce Bay area. Photographs of this reach of shoreline are shown in Photographs Nos. 1 to 6 inclusive. An aerial photograph of the Gimli area is shown in Plate 1.

The location of Reach 1 is shown on Figure 14. A detailed analysis of the littoral processes in this reach is given in the following paragraphs.

Sources and Losses of Material: The very strong northward littoral drift at Sandy Bar, the northern extremity of the reach, may be deduced from a wave energy analysis. It was found that the predominant wave energy at Hnausa (Figure 11) is from the southern sector (south and south-east) and thus the prevailing littoral drift is northward. Since Sandy Bar is north of Hnausa, it may be concluded that the predominant littoral movement at Sandy Bar is northward. This northward movement is verified by the shoreline configuration of Sandy Bar. There is no material moving into the area from either Hecla

Island or Black Island. The littoral currents around Hecla Island promote the growth of Sandy Point, see Figure 14, in a northward direction and it is not likely that there is any sand moving from the island to the mainland. The predominant littoral drift direction at Willow Point is southward. This may be deduced from a wave energy analysis (see Gimli wave energy distribution on Figure 11) as well as from the buildup of sand in the Gimli area (see Plate 1). Immediately south of the main point of Willow Point north of Sandy Hook, there is a local reversal resulting in a net littoral movement in the northward direction but this material does not move into the Riverton to Willow Point reach as the southward drift is much more predominant than the northward drift from the local reversal. It may be concluded that there is no significant volume of material moving into the area by natural littoral transport from adjacent beach areas.

The second source of material to any beach segment is from contributions by streams. There are no major streams flowing into Lake Winnipeg in the reach from Riverton to Willow Point, however there are numerous small drains, both natural and man-made, that discharge the spring and summer runoff into the lake. Examination of the creek outlets into lake revealed no indications of sand being transported and no evidence of deposited material on the beach was found. It must be noted that observations of the creeks were not made during the spring freshet. Two drains that could conceivably contribute to the beach material since they drain areas of loamy fine sand and sandy loam are the drain emptying into the lake between Loni Beach and Gimli and the drain emptying into the lake at a point approximately 2,000 feet south of the Gimli harbor. Detection of material transported by these drains would be difficult as the former drain as shown on Photograph No. 3 discharges into the lake at a point where the beach is very well developed and any added material would be undetected while the latter drain discharges into the lake through the seawall and any material carried by the drain would be removed by the reflected waves. A grain size analysis of the sediment load carried by the streams would have to be made in order to obtain further information. A soils formation classified as silt may contain up to perhaps 20% sand and this percentage of sand could be a substantial factor in the shoreline processes if the total sediment load is significant. From the knowledge presently available, it is concluded that the contribution of material by streams is negligible in this reach.

The third source of material to a beach is from erosion of lakeshore formations other than beaches. The distinction between this erosion, commonly called bluff erosion, and beach erosion has been described in preceding sections. Serious bluff erosion occurred in this reach during 1966 due to the record high water levels combined with severe storms and evidence of this erosion is still apparent in 1968 as shown on Photographs Nos. 1 and 2. This bluff erosion, especially in the Camp Morton area is due, not only to high water levels and wave attack but also due to natural slope failures caused by excessive groundwater seepage and heavy rainfall. As shown on Figure 2, the Camp Morton area is comprised of bluffs having a composition, by mechanical analysis, of 56% sand, 35% silt and 9% clay while all other portions are predominantly clay. Thus it is seen that the major source of sand in reach 1 is from the Camp Morton bluffs (referred to as the Morton Complex in reconnaissance soil survey reports). As the predominant littoral drift at Camp Morton is southward, as determined by interpolating the wave energy distribution diagram, Figure 11, for Hnausa and Gimli, the major portion of the material derived from the bluff erosion moves southward toward Gimli and Willow Point thus creating the beaches in these areas. A comparison of the beaches north and south of Camp Morton clearly shows that the beaches are much more developed in the Gimli area than in the Spruce Bay-Spruce Sands area. It is also evident that the beach material is distinctly different from the local parent material, this being particularly the case in the Spruce Bay-Spruce Sands area.

The first method by which material is lost from a specific beach area is by the movement of material laterally out of the area. Due to the very strong northward littoral drift at Sandy Bar and the southward littoral drift at Willow Point, some littoral material could be moving out of the reach. The volume moving northward past Sandy Bar would be relatively minor as the beaches are not very well developed in this area. Since the breakwater at Gimli acts as a littoral drift barrier, the volume of material moving to Willow Point has greatly decreased since the construction of the Gimli harbor. It is believed that accretion of material at Willow Point has been halted. Whether the beach is in equilibrium or whether it is eroding is difficult to determine. Material moving out of this reach is probably derived from Willow Point rather than from updrift beaches.

The second method by which material is lost from a specific beach area is by the movement of material off-shore into deep water. In the Riverton to Willow Point reach, no concrete evidence of material moving offshore into deep water was found. Navigation maps showing depths and the nature of the lake bottoms, indicate no sand deposits in the offshore areas. As there are no major streams entering the lake in this reach, no material would be lost to the offshore zone due to the action of streams flowing into the lake and depositing sand in depths where it cannot be picked up by littoral currents. Wave reflection at Gimli breakwater could cause some movement of littoral material into deep water.

A minor process, not generally mentioned in the literature, by which material is lost, occurs when sand is deposited on areas of low relief but still high above the normal water level as a result of storms combined with exceptionally high water levels. Deposition of material and the consequent loss of material from the beach is evident in Loni Beach where material was deposited high above the normal water level during the Fall of 1966.

<u>The Effect of Natural and Man-Made Littoral Drift Barriers</u>: The effect of Willow Point and Sandy Bar on the movement of material into and out of the reach has already been mentioned, however it is interesting to note the probable origin of the former littoral barrier. The build-up of sand at Willow Point has been underway for some 7,000 years, even since the beginning of the present-day

Lake Winnipeg. Initially the buildup at the point was probably due to the deposition of littoral material in this natural shallow portion of the lake and a further barrier to the littoral drift was the existence of a glacial till high at the eastern extremity of the point. Northerly winds created the sand dunes. With the buildup of the point over the years, as a result of the predominant southward littoral drift, it became more and more effective in acting as a littoral drift barrier to the movement of material into the southern portion of the lake. Its effect was diminished with the construction of Gimli harbor as the harbor now became the main littoral drift barrier to material moving southward. Buildup of the point has been virtually halted by the harbor and as virtually no material is now moving into the area, erosion of the northern part of the point and the consequent deposition on the eastern part as well as movement of material around the point may be expected in the future.

Field observations indicated the existence of several limestone outcroppings in the area north of Camp Morton. These outcroppings would act as littoral drift barriers during low water levels but their effect would be almost negligible during high water levels.

As stated before, Gimli harbor acts as a serious littoral drift barrier. This is very apparent from Plate 1 at the end of this section. It is doubtful whether any material moves around the main northerly pier as there is no evidence of deposition of material along the pier and dredging of the harbor entrance is not required. Material transported by the littoral currents along the beach during periods of north and north-east winds would be reflected off the north pier and deposited in deep water where it would be out of reach of the normal forces due to waves. Sampling of the lake bottom north of the pier would indicate whether this assumption is valid. The serious erosion along the seawall south of the Gimli harbor has resulted from the absence of littoral material combined with the erosion associated with the reflection of waves from the vertical face of the seawall.

Minor man-made littoral drift barriers that have been constructed in the Riverton to Willow Point reach include several low rock groins at Camp Morton as shown on Photograph No. 1. The effect of these groins on the shoreline processes in this reach would be negligible, however it is believed that they have a local beneficial effect.

The Magnitude of Shoreline Recession: Accurate data related to shoreline recession in the Riverton to Willow Point reach is not available. Signs of erosion are apparent at Spruce Sands where a lakeshore road is no longer passable. Bluff erosion at Camp Morton has threatened the safety of several buildings. The erosion here is estimated to be in the order of ten to twenty-five feet. Bluff erosion caused by natural landslides has occurred at the Lakeside Fresh Air Camp, located four miles north of Gimli. At Loni Beach and South Beach, shoreline recession has been halted by means of protective works, however beach erosion, particularly at South Beach, has endangered the protective shoreline works. A comparison of aerial photographs was made, but no appreciable changes could be noted.

The validity of Bruun's equation[1] relating a rise in lake level to shoreline recession was tested for this reach. The following figures were assumed:

e = 10 feet (elevation of the shore above a water level of 715).

a = 7 feet (the rise in lake level from June 1941 to June 1966).

b = 2000 feet (width of shelf or the width over which sand is deposited).

d = 20 feet (depth to which material moves).

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1 See Appendix D for a full treatment of this equation.

Thus:

$$x = \frac{a\ b}{e + d}$$

$$= \frac{7\ (2000)}{10 + 20}$$

$$= 465 \text{ feet.}$$

Since a 25 year period of record was considered the annual shoreline recession would be approximately 19 feet. This figure does not appear to be realistic. One possible source of error could be the choice of values for "b" and "d" as no measurements of this were available. Bruun has noted that the equation is applicable only to beaches having steep profiles as there is a substantial time lag between rise in lake level and the subsequent erosion for beaches with a mild profile. Thus this equation can not be applied to Lake Winnipeg. Another qualification that must be met before the equation is applicable is that the area under consideration must be in equilibrium, that is, the volume of littoral material moving into the area must equal the volume moving out. This equilibrium point or nodal point on the shoreline could be determined from a wave energy analysis and would be approximately at Spruce Sands, midway between Hnausa and Gimli. The term "annual shoreline recession" has little meaning when applied to Lake Winnipeg as the majority of erosion is caused during storms combined with high lake levels. It is therefore suggested that this term should not be used in connection with Lake Winnipeg.

Reach 2 - Willow Point to Sans Souci

General Description of the Reach: The shoreline of Lake Winnipeg from Willow Point to Sans Souci lies generally below 725 and during the record high water levels of 1966 combined with severe storms, major portions of it were affected by the high lake levels. The location of Reach 2 is indicated on Figure 14 and a detailed analysis of this reach of the shoreline is given in the paragraphs below.

Sources and Losses of Material: The first source of material to any beach segment is material moving into the area by natural littoral transport from adjacent beach areas. The volume of material moving southward out of Reach 1 is equal to the volume of material moving into Reach 2. It has been previously noted that since the construction of Gimli harbor, the volume of material moving to Willow Point and consequently the volume of material moving into the Willow Point to Sans Souci reach has decreased. There is a strong southward littoral drift in this reach as is apparent from the wave energy analysis for Winnipeg Beach and Matlock as shown on Figures 16 and 12. The only major exception to this is north of Sandy

Hook in the vicinity of Husavick, immediately south of Willow Point, where, due to the presence of the Point, the area is protected from north and north-east winds resulting in a northward littoral drift. The local reversal is apparent from aerial photographs.[1] The local reversal results in the buildup of material in a spit north of Sandy Hook and consequently prevents the movement of material in a southward direction. Due to the very strong southward littoral drift at Matlock and Sans Souci, there is no net movement of material from the Red River delta area northward into the reach.

The second source of material to any beach segment is from contributions by streams. The creeks draining into Lake Winnipeg in this reach are Willow Creek near Willow Point, Boundary Creek at Winnipeg Beach and Fugela Creek at Whytewold. As the creeks drain predominant clay areas, there is no significant contribution of material from these creeks.

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1 The 1924 aerial photographs show this local reversal very distinctly.

The third source of material to a beach is from the erosion of lakeshore formations other than beaches. During 1966, serious bluff and beach erosion occurred at Sandy Hook and beach erosion was prevalent at Winnipeg Beach, Whytewold and Matlock. As seen on Figure 2, the percentage of sand in the local material is less than 20% and consequently the erosion of bluffs in this area would not add a substantial volume of material to the reach. The erosion of beaches at Sandy Hook and Winnipeg Beach also provided some material for downdrift beaches. Generally there is an acute shortage of littoral material in this reach resulting in poorly developed beaches.

The first method by which material is lost from a specific beach area is by movement of material laterally out of the area. As stated previously, no material moves northward out of the reach but due to the very strong southward littoral drift at Matlock (Figure 12) a substantial volume of material is lost southward to the Red River delta. A comparison of maps and aerial photographs indicates that the Red River outlet has been continually shifting back and forth and dredging of sand from the outlet is constantly required. The volume of dredging from the outlet is not known consequently the volume of littoral drift moving southward from the reach cannot be estimated.

The second method by which material is lost from a specific beach area is by the movement of material offshore into deep water. In the Willow Point to Sans Souci reach, there is no indication of material moving offshore. Surveys made at Winnipeg Beach indicate movement of material up to depths of only about 12 feet and navigation maps of the area indicate no offshore sand deposits. It is doubtful whether Willow Creek and Boundary Creek, the two major creeks flowing into the lake in this reach, would carry an appreciable amount of beach material into deep water where it could not be picked up again by littoral currents. There is no evidence of a delta formation at the Winnipeg Beach harbor, the outlet of Boundary Creek.

One process by which material is lost is the deposition of sand in areas of low relief but high above normal water levels. During the storms in 1966, vast quantities of sand were washed ashore in the northern portion of Sandy Hook as well as on the north side of the Ponemah headland. Unless this material is pushed back onto the beaches, it will not be available to maintain the beaches downdrift.

<u>The Effect of Natural and Man-Made Littoral Drift Barriers</u>: The three major headlands in the Willow Point to Sans Souci reach are in the northern part of Sandy Hook, south of Winnipeg Beach (called Stephenson's Point) and in the northern portion of Ponemah. Due to the orientation of the headlands (generally pointing southeast) they do not cause a complete reversal of littoral transport under all wave conditions and do permit the passage of littoral drift. The relatively wide stable beach on the updrift shore and the narrow beach at the downdrift end is shown clearly on the aerial photograph of Ponemah and to a lesser extent on the photos of Sandy Hook and Winnipeg Beach (see Plates 3 and 4). The direction of the predominant littoral drift is apparent, from the aerial photo of Winnipeg Beach (Plate 4).

Several small rock outcroppings were detected in this reach but during high water levels and storms, these would cause no hindrance to the movement of littoral material.

The most extensive man-made littoral drift barrier in this reach is the Winnipeg Beach breakwater. The accretion north of the breakwater and the resultant erosion south of the breakwater is apparent from Plate 4. A detailed analysis of the Winnipeg Beach shoreline is given in Chapter VI. An offshore breakwater constructed at the southern extremity of Matlock (Plate 6) acts as a partial littoral drift barrier as indicated by the accretion of sand between the breakwater and the shoreline. Downdrift erosion is not apparent as the percentage of littoral material intercepted by the breakwater is probably low and once the area between the breakwater and the shoreline has been built up, the breakwater will no longer act as a littoral drift barrier.

The Magnitude of Shoreline Recession: The extent of shoreline recession in the Willow Point to Sans Souci reach has varied from nil in areas where seawalls protect the shoreline to approximately 150 feet over a period of 30 years in the southern portion of Sandy Hook. Many types of protective works have been constructed in an attempt to halt this recession; the success of these works has generally been proportional to the capital expended upon their construction. In cooperation with Mr. N. Mudry, Chief, Planning Division, Water Control and Conservation Branch, Province of Manitoba, Professor V.J. Galay, Assistant Professor, The University of Manitoba and Mr. B. Morlock, Chairman, Lake Winnipeg Property Owners Association, approximately 55 questionnaires were distributed to lakeside cottage owners in Sandy Hook, Ponemah, Whytewold and Matlock in order to obtain a better insight into the problem of shoreline recession, particularly with regard to the relationship between lake levels, erosion and protective works. The questionnaire used and the accompanying letter are shown in Appendix B. Of the 55 questionnaires distributed only 15 were returned, the low number being in part due to the national mail strike. Table IV summarizes the findings of the questionnaire.

Even from the small number of questionnaires that were returned, several comments and conclusions may be drawn. Of the eight returns that had experienced no shoreline recession, seven had used protective measures. Six people listed 1966 (the year of the record high water levels) as the year during which the most serious erosion occurred while the years 1967, 1965, 1952 and 1950 were each listed once. Several persons constructed extensive shoreline protective works after the Fall of 1966. The questionnaires do not give a complete picture of the shoreline recession as in areas where private property is skirted by a lakeside road, returns generally listed no erosion but erosion may have occurred. One other factor

TABLE I.

RESULTS OF THE QUESTIONNAIRES

	Location	No. of Yrs. of Summer Residence	Shoreline Recession in Feet and Year	Type of Protective Works Used
1.	Sandy Hook	5	None	Concrete Seawall
2.	Sandy Hook	10	None	Rock
3.	Sandy Hook	5	10' - 1965 4' - 1966	Rock (partly in place in 1966 & 1965)
4.	Sandy Hook	10	None	-
5.	Sandy Hook	13	15' since 1955	Rock
6.	Sandy Hook	4	None	Rock
7.	Sandy Hook	5	17' - 1966 7' - 1967	None
8.	Matlock	45	10' - 1966	Wooden Piles & Rock
9.	Matlock	3	None	Wooden Piles & Rock
10.	Matlock	19	20' - 1952 Some in 1966	Wooden Piles & Rock
11.	Whytewold	4	10' - 1966	Wooden Piles & Rock and Concrete Seawall
12.	Whytewold	5	None	Wooden Piles & Rock
13.	Whytewold	20	None	Concrete Seawall
14.	Whytewold	15	None	Concrete Seawall
15.	Whytewold	20	5' - 1950 5' - 1966	Wooden Piles & Rock Concrete Seawall built in 1967.

that should also be mentioned is that generally people considered only the rapid bluff erosion that occurred during storms and not the almost ever present but not as readily apparent beach erosion. Personal reports of people in Sandy Hook indicate that up to 150 feet of property has been lost at the North Sandy Hook Clubhouse and up to 120 feet of private property has been lost in other areas of Sandy Hook since about 1920. Since Sandy Hook was registered in 1912, approximately 2,000 feet of the lakeside boulevard (from First Street to Seventh Street) has been eroded.

Reach 3 - Elk Island to Victoria Beach

General Description of the Reach: The third reach consists of Elk Island which is almost uninhabited and Victoria Beach. From Figure 2, Elk Island may appear to be a separate reach of the shoreline but as discussed below, it is believed that the shoreline processes of Elk Island affect the processes at Victoria Beach. The extent of Reach 3 is shown on Figure 14.

Sources and Losses of Material: The first source of material to any beach segment is material moving into the area by natural littoral transport from adjacent beach areas. From Figure 13 it is seen that the predominant wave energy at Victoria Beach is from the north and the north-west and thus the predominant littoral drift direction is south and south-east. The spit at the southern tip of Elk Island has been formed by the strong southward littoral drift. However as shown on Figure 14, a spit has also formed at the northern extremity of Victoria Beach, an indication of a northward littoral drift and consequently a local reversal. This local reversal would seem to preclude any net movement of littoral material from Elk Island to Victoria Beach. Movement of some material from the island to the mainland could occur during prolonged periods of northerly storms. It is doubtful however, that, due to the rocky headlands in the northern portion of Victoria Beach, acting as littoral drift barriers, whether this transported material would move into the public beach area. The accretion and erosion pattern at Victoria Beach, as shown on Plate 7 clearly indicates a southward littoral drift. It cannot be postulated at the present whether there is a net littoral movement from the spit south of Victoria Beach to Hillside Beach or vice versa. Some material may be moving from Hillside Beach northward into the reach.

As there are no streams draining into the lake in this reach, no material moves into the beach segment from contributions by streams.

The third source of material to a beach is from the erosion of lakeshore formations other than beaches. As the area north of Victoria Beach and Elk Island are almost totally undeveloped, only the Victoria Beach area will be discussed. Serious erosion of the high sandy bluffs northwest of the public beach is apparent on Photograph No. 7. These bluffs provide the littoral material for the beach area.

The first method by which material is lost from an area is by movement of material laterally out of the area. Movement of material between Elk Island and Victoria Beach is not considered as a loss of material as both areas were included in the same reach. Since it was previously mentioned that there is a negligible interchange of material between the southern spit of Victoria Beach and Hillside Beach, it may be concluded that there is little or no material moving laterally out of the reach. Eroded material is generally deposited on spits. No other methods by which material is lost from this reach are presently known.

<u>The Effect of Natural and Man-Made Littoral Drift Barriers</u>: The rocky headlands between the spit at the northern extremity of Victoria Beach and the public beach area acts as littoral drift barriers. The headland immediately north of the public beach is shown on Photographs Nos. 7 and 8. The rocky headland at the southern extremity of the public beach area also acts as a littoral barrier and prevents the movement of littoral material from the beach. The aerial photograph, Plate 7, of Victoria Beach clearly indicates the accretion updrift of the headland and the erosion on the downdrift shore.

The major man-made littoral barrier in this reach is the pier projecting from the rocky headland at the southern extremity of the public beach (Plate 7). Due to the presence of the rocky headland immediately updrift of the pier, it is doubtful whether any littoral material moves around the headland and to the pier. Samples of the bottom in the vicinity of the pier would have to be taken over a number of years in order to determine whether deposition is occurring west of the pier. Numerous low rock groins, as shown on Photograph No. 7, have been built along the public beach at Victoria Beach. The configuration of the shoreline at the groins indicates that some deposition has occurred updrift, however the effect of these groins in trapping littoral material during periods of high lake levels would be negligible in comparison to the total volume of littoral drift.

<u>The Magnitude of Shoreline Recession</u>: The shoreline recession that has occurred over the years in the developed area of Victoria Beach is negligible. Bluff erosion has occurred at the headland north-west of the beach area but as long as this erosion endangers no property, no measures should be taken to halt it since these bluffs provide the beach building material for the beach downdrift. Some erosion of the bluffs has also occurred at the rocky headland near the government pier. This erosion is causing no problems at the present. Beach erosion at Victoria Beach is negligible.

<u>Reach 4 - Victoria Beach-Grand Marais Point</u>

<u>General Description of the Reach</u>: The shoreline of Lake Winnipeg from Victoria Beach to Grand Marais Point consists of generally high sandy bluffs terminating at the southern extremity into a bay mouth bar (Grand Beach). The rocky Grand Marais Point, an end moraine formed during the ice age, is the southern boundary of this beach. The location of Reach 4 is shown on Figure 14. A detailed description of the reach is given in the paragraphs below.

Sources and Losses of Material: The first source of material to a beach segment is material moving into the segment by natural littoral transport from adjacent beach areas. As mentioned previously, the volume of material moving from Reach 3 to Hillside Beach is unknown and is probably negligible. The wave energy distribution diagram for Grand Beach, shown on Figure 13, indicates a strong southward littoral drift and consequently no material would move around the rocky headland from the western shores of Grand Beach to the bay mouth bar. A wave refraction analysis of the headland would show the severe wave attack upon the point and indicate the reversal of littoral transport for all wave directions.

As there are no streams draining into the lake in this reach, no material moves into the beach segment from contributions by streams.

The third source of material to a beach is from the erosion of lakeshore formations other than beaches. During the record high water levels and the storms of 1966, serious bluff erosion of the high sandy cliffs occurred. This erosion supplies the majority of beach building material for this reach.

The first method by which material is lost from an area is by the movement of material laterally out of the area. It is felt that no material moves out past

Grand Marais Point and that there is a negligible loss of material from the Hillside Beach spit to the Victoria Beach spit.

Material may also be lost from a particular beach segment by movement offshore into deep water but no signs of offshore movement were observed in the Victoria Beach to Grand Marais Point reach. It appears that the by-passing of littoral material across the bay mouth bar at Grand Beach is predominantly by means of a bar as shown on Photograph No. 12, and consequently little or no material is flushed out into offshore areas where it cannot be picked up again by the littoral currents. Aerial photographs (1924 and 1966 series) indicate the formation of sandy spits on the bay side of the inlet. This deposited material is no longer available to maintain the littoral drift and is thus lost to the beach segment. The formation of this bay mouth is discussed in greater detail in the following sub-section.

The third method by which material is lost from this reach is by wind action at the Grand Beach public beach. Due to the predominant onshore winds, material is removed from the beach and deposited in the lee of bushes and other projections, the result being a vast ridge of sand dunes extending for about two miles along the beach as shown on Photograph Nos. 10 and 12. The present sand dunes are less extensive than before as large areas of the dunes were levelled in order to facilitate the construction of a parking lot.

The Effect of Natural and Man-Made Littoral Drift Barriers: The major natural drift barrier in this reach is the inlet connecting the bay and Lake Winnipeg at Grand Beach. Generally an inlet presents a serious interruption of the normal longshore drift. If by-passing across the inlet is by means of "tidal flow transfer" the inlet will be almost a complete littoral drift barrier, whereas if by-passing is by means of a bar, the littoral drift is almost unhampered.[1] Transfer of material at the Grand Beach inlet is by means of a bar as evidenced on Photograph No. 12. Verifying this mode of transfer by means of Bruun's classification (see Appendix D) is not possible at this time as M net (littoral drift quantity up minus downdrift) and Q max (maximum discharge) are not known. Migration and orientation of the inlet are apparent from a comparison of aerial photographs. The present orientation of the bar is north-west, indicating a strong westward

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1 A complete discussion of this is given in Appendix D.

littoral drift at this point. The inlet differs from the tidal inlet researched by Bruun in that the tidal flow is replaced by the flow into and out of the bay due to wind setup and setdown respectively.

Presently there are no major man-made littoral drift barriers in this reach, however the planned construction of a breakwater to protect a proposed boat marina on the eastern extremity of the Grand Beach bay could have serious repercussions on the beach. Model studies undertaken by Queen's University for the Department of Public Works determined an optimal plan for the harbor layout which would limit the sediment deposition in the harbor or in the vicinity of the harbor entrance (35), however more extensive studies would have to be made to determine the effect of the proposed harbor on the long-term littoral processes. The breakwater may have a similar effect on the shoreline as the breakwaters at Gimli and Winnipeg Beach.

The Magnitude of Shoreline Recession: Bluff erosion was serious in this reach during the extreme high water conditions experienced in 1966. Erosion of bluffs often results in the accretion of material on downdrift beaches. Reports of the buildup of the sandy spit at

Hillside Beach as a consequence of the 1966 storms, have been made. Beach erosion occurred during 1966 in the Belair area but with a return to normal lake levels, deposition of sand in this area is expected. It is possible that once the beach returns to its equilibrium profile, it will be more developed than before.

Reach 5 - Grand Marais Point to Balsam Bay

General Description of the Reach: As little information is known about the Balsam Bay area and since it is sparsely populated, the discussion in this section will be restricted generally to the Grand Beach and Grand Marais areas. The shoreline in these latter two areas consists of high sandy bluffs with numerous boulders embedded into the sand cliffs as shown on Photograph No. 11. The only areas of low relief and susceptible to flooding are the southern extremity of Grand Marais and the Patricia Beach vicinity. The extent of Reach 5 is shown on Figure 14.

Sources and Losses of Material: Since no material is being lost from Reach 4 southward into the Grand Marais Point to Balsam Bay reach and as the very strong southward littoral drift at Balsam Bay (see wave energy distribution diagram, Figure 12) precludes any net littoral movement northward into the reach, it may be concluded that no littoral material is moving into the reach from adjacent beach areas.

The second possible source of material into a beach segment, from contributions by streams may be omitted as there are no major streams draining into the Lake in this reach.

The major source of material is from the erosion of bluffs, this erosion being particularly serious in Grand Beach and Grand Marais during 1966. Photograph No. 12 shows the serious erosion experienced at Grand Marais Point.

The major loss of material from this reach is the movement southward into the Red River delta area. This movement is somewhat hampered by the headland at Patricia Beach, however from a cursory examination of this shoreline configuration, it is felt that it does not act as a complete littoral drift barrier. An internal loss of material within the reach is the deposition of material on the spit south of Grand Marais. Heavy deposition occurred during the abnormal high lake levels experienced in 1966 and this material is unavailable for littoral drift until high lake levels accompanied by storm waves return.

The Effect of Natural and Man-Made Littoral Drift Barriers: No major natural or man-made littoral drift barriers exist in this reach.

The Magnitude of Shoreline Recession: Bluff erosion in Grand Beach and Grand Marais is the major component of shoreline recession however accurate figures on the magnitude of this recession cannot be given at the present.

Summary of Shoreline Analysis

A qualitative analysis of the Lake Winnipeg shoreline has been made. The results of this analysis are shown on Table V. These will prove to be extremely vital in describing the shoreline processes and also should prove to be useful in planning and analysis of present and future shoreline structures. As an example, the desirability of groins at Winnipeg Beach may be determined by the following steps:

a) determine the location of the proposed works. Winnipeg Beach is in the Willow Point to Sans Souci reach as shown on Figure 14,

TABLE V

SUMMARY OF SHORELINE ANALYSIS

REACH	SOURCES & LOSSES OF LITTORAL MATERIAL		LITTORAL DRIFT BARRIERS		SHORELINE RECESSION
	Major Sources	Major Losses	Natural	Man-Made	
1. Riverton - Willow Point	Bluffs in the Camp Morton area.	Movement south past Willow Point. Deposition of material on the shore above normal lake levels.	The two extremities of the reach - Sandy Bar & Willow Point. Limestone outcroppings north of Camp Morton.	Piers at Gimli Harbor. Small rock groins at Camp Morton.	Bluff erosion at Camp Morton. Beach erosion south of Gimli Harbor.
2. Willow Point - Sans Souci	Bluffs and beaches at Sandy Hook and Boundary Park. Beach at Winnipeg Beach.	Deposition of material on the shore above normal lake levels. Movement southward into the Red River Delta.	Sandy Hook headland, Stephenson's Point (Winnipeg Beach), Ponemah headland, and other rock outcroppings.	Winnipeg Beach Harbor. Offshore breakwater Matlock. Small rock groins in places.	Varying from 150 feet to nil, depending on location and protective measures used. Serious beach and bluff erosion at Sandy Hook. Beach erosion at Winnipeg Beach along seawall.
3. Elk Island - Victoria Beach	Bluffs at Elk Island and Victoria Beach.	Very little material moves out of the reach. Eroded material generally deposited on spits.	Numerous rocky headlands resulting in pocket beaches. No continuous movement of material along the reach.	Pier at Victoria Beach. Small rock groins at Victoria Beach.	Bluff erosion northwest of public beach at Victoria Beach. Not considered serious at the present.
4. Victoria Beach - Grand Marais Point	Sandy bluffs between Hillside Beach and Grand Beach.	Wind action removing sand & building up baymouth bar.	Inlet at baymouth bar at Grand Beach acts as a partial littoral drift barrier.	None at present. Proposed marina and breakwater could act as a serious littoral drift barrier.	Bluff erosion along the whole shoreline during record high water levels in 1966. Not considered serious at the present.
5. Grand Marais Point - Balsam Bay	Bluffs at Grand Beach and Grand Marais.	Movement southward into the Red River Delta. Deposition of material on spit south of Grand Marais.	No substantial barrier. Headland south of Patricia Beach acts as a partial littoral drift barrier.	No substantial barrier.	Serious bluff erosion at Grand Beach south of Grand Marais Point in areas where the shore is not protected by rock rip-rap.

b) determine the predominant littoral drift direction from Figure 14. If the proposed works is near a local reversal, a more detailed study of the littoral drift characteristics may be required. The predominant littoral drift direction at Winnipeg Beach is south and thus the proposed groins should be located at the southern extremity of the beach as deposition would occur on the northward side,

c) determine the sources and losses of littoral material. The major source of material for the Winnipeg Beach area is the Sandy Hook and Boundary Park area. A soils investigation of the material in these two areas would indicate the characteristics of the littoral material. The losses updrift of Winnipeg Beach are seen to be minimal,

d) determine the natural and man-made littoral drift barriers updrift of the proposed works. The major barrier updrift would be the Winnipeg Beach breakwater,

e) determine the extent of past shoreline recession at the site of the proposed works. Serious beach erosion occurred at Winnipeg Beach during 1966 but this was mainly due to the presence of the vertical seawall.

The success of the groins would greatly depend on the volume of littoral drift. Since the major source areas consist of predominantly clay banks and as the Winnipeg Beach harbor acts as a partial littoral drift barrier, the volume of littoral drift along the proposed groins would be minimal and consequently the success of the groins would be doubtful.

There are several major differences between the shoreline processes on Lake Winnipeg and coastal areas. Whereas all coastal shorelines have a distinctive summer and winter profile, resulting from summer swells and winter storms, Lake Winnipeg does not have a winter profile as it is icebound during almost six months of the year. In coastal areas, a winter profile is generally associated with a steep berm and offshore bars while a summer profile is characterized by a mild berm and a lack of offshore bars. The question thus arises whether there are any characteristic spring, summer, and fall beach profiles on Lake Winnipeg. Spring and autumn are the windiest seasons, summer the least windy, but the mean seasonal speeds do not differ greatly (29). As the spring storms generally occur when the lake is still partially icebound, the fall storms would likely have a greater effect on the shoreline processes than spring storms. A systematic field investigation would have to be initiated in order to determine seasonal changes in beach profiles.

As the majority of shoreline recession on Lake Winnipeg occurs during storms combined with a high lake level, the term "annual shoreline recession", has little meaning when applied to Lake Winnipeg. The Lake experiences very rapid fluctuations in lake levels due to wind setup and this enables the storm-whipped waves to attack the shoreline high above the normal lake level. These rapid fluctuations in water level do not occur to the same extent on deeper lakes and oceans.

CHAPTER VI

WINNIPEG BEACH MODEL STUDIES

Introduction

Serious shoreline erosion occurred at Winnipeg Beach during the record high water levels experienced in 1966. Portions of the seawall failed and the outermost section of the harbor breakwater was destroyed. The effect of the newly constructed breakwater on the littoral processes along this reach of shoreline and the general stability of the beach can best be determined by means of a model study since with the present state of technical knowledge, these processes can not be expressed mathematically. The model investigations undertaken are described in this chapter.

Since the beginning of the twentieth century, Winnipeg Beach has been one of the most popular resorts on Lake Winnipeg. Its popularity dwindled during the fifties and thus in an attempt to revitalize the area to the bustling place it was in earlier days, the town of Winnipeg Beach and the provincial and federal governments have held negotiations to plan the reconstruction of the area. The Parks Branch of Manitoba's Department of Tourism and Recreation is responsible for the redevelopment which is expected to take from five to seven years. The attractiveness of a specific area is closely allied to the presence of a beach which in turn is closely associated with water levels as well as the natural and artificial characteristics of the shoreline in the area. Since regulation of Lake Winnipeg will not be undertaken for some time, and since the natural characteristics of the shoreline cannot be altered, only the man-made characteristics of the shoreline such as the breakwater and the seawall can be planned and constructed with a view to minimizing shoreline erosion. The Parks Branch is very interested in knowing the effect of the breakwater and the seawalls on the stability of the beach and what further structures if any are necessary to maintain a stable beach area. The Department of Public Works of Canada, who are responsible for the maintenance of the Winnipeg Beach harbor, are interested in the optimum configuration of the breakwater to minimize the annual costs of dredging. Due to the limited testing program, definite recommendations cannot be proposed at this stage; however preliminary conclusions can be drawn and further investigations are recommended.

History of Winnipeg Beach Shoreline

A 600 foot long breakwater was constructed by the Department of Public Works, Federal Government on the north side of the mouth of Boundary Creek in 1910 to create a safe harbor for boats. This breakwater was later extended and remained intact until 1966 when high water levels and several storms destroyed the south-eastern section. A new breakwater with a crest elevation of 723, consisting of earthfill and rock was constructed during the winter of 1967-1968 along the north side of the old breakwater. Periodic dredging is necessary to maintain a navigable channel in the harbor. When the old breakwater failed in 1966, vast volumes of sand that had been deposited north of the breakwater were washed into the harbor entrance. Material dredged from the harbor is dumped some 2,000-3,000 feet offshore.

During the fifties a seawall was constructed from the Old Pavillion in the Amusement Area to approximately Oak Avenue as shown on Figure 18. Portions of the wall failed during the storms of 1966. Failure was caused by the erosion at the toe of the seawall as a result of wave reflection and may have also been partly due to the lack of proper drains to alleviate the excessive groundwater in the area. The serious erosion experienced along the old seawall is depicted in Photograph No. 14. The seawall was repaired and a new 400 foot extension, as shown in Photograph No. 15, built southward from the old section.

During the winter of 1967-1968 a number of 4 foot square concrete blocks were placed some 500 feet offshore in a line parallel to the shore as shown in Photograph No. 15. The aim of this measure is to reduce wave action along the beach and cause deposition of littoral material shoreward of the blocks.

Field Measurements Made

During March 1968 profiles were run out from the Winnipeg Beach shoreline as shown on Figure 18. The nature of the lake bottom was determined by probing into the bottom and bringing up the material. A sieve analysis was made of several sand samples to determine characteristic grain size. The profiles were re-surveyed after the June 30th storm and compared to the spring profiles as shown on Figure 17. Further surveys would have to be made before any trends can be established.

Two staff gauges to record wave height, were set up at Winnipeg Beach during July, one approximately 1,000 feet east of the end of the breakwater and the other about 500 feet to the west. As the model was tested only with northeasterly wind directions and since no major storms from this direction occurred during the summer of 1968, no wave measurements were obtained. There is a definite need to initiate, as soon as possible, a wave measurement program.

Prior to the June 30th storm, approximately 500 cubic yards of sand were dumped in front of the seawall. After the storm it was observed that most of the sand had disappeared. From Figure 17 it is difficult to postulate where the sand moved to since the quantity transported is negligible as compared to the extent of the beach area.

Design of the Model

Horizontal Scale: The main factor that determines the horizontal scale of a model is the size of space available. A scale of 1:160 was chosen so that a 5,000 foot long section of the Winnipeg Beach shoreline would fit into the basin measuring 33' x 18.7'. The shoreline was orientated within the basin in order to leave ample room for the wave paddle. The limits of the model in the offshore direction must be chosen to reproduce correctly the refraction phenomena of waves approaching the shoreline from any direction. The wave celerity (and hence refraction) is sensibly altered for a water depth of less than one-third of the wave length. A wave of 5 second period has a length of 128 feet in deep water and hence the model would have to extend to the 43 foot depth contour if the refraction phenomena is to be eliminated; however the maximum depth of the lake in this vicinity is only 31 feet (710.5 datum) at a distance of eight miles offshore. A refraction analysis of a north-east wave crest commencing at the 31 foot depth contour indicated that the wave front at the offshore limits of the model would still be essentially north-east and consequently it was not necessary to extend the offshore limits of the model to this depth contour. The extent of the horizontal limits of the model is shown on Figure 18.

Vertical Scale: A vertical scale of 1:50, resulting in a distortion of approximately 3:1, was used in the model. A distorted model is necessary and desirable as waves scaled down to the horizontal scale would be greatly affected by surface tension and would require extremely accurate wave measurement equipment and in addition in a movable bed model, it is necessary only to reproduce similitude of effect. The vertical scale of 1:50 was used for both wave length and wave height. A more thorough discussion on the selection of scales is given in Appendix C.

Wind Direction Tested: It may be noted from the wave energy distribution diagram, Figure 16, that the predominant wave energy at Winnipeg Beach is from the north. However, due to the offshore limits of the model, a north wind direction could not be tested as one end of the wave paddle would have been in very shallow water (a 3 foot depth at normal lake levels), while the other extremity would have been in much deeper water (approximately 12 feet deep). A refraction analysis showed that the wave front in the shallow portion would be greatly affected by the bottom contours while the wave front in the deeper portion would be less affected. Due to this refraction phenomenom and since north-east storms have a more serious affect than north storms along this reach of shoreline, it was decided to test the model under the influence of a north-east wind.

Bed Material Used: Generally a material lighter than sand is used as the movable material for models (see Appendix C). The light weight material used in the Winnipeg Beach model was ground walnut shells, which have a specific gravity of 1.28. A sieve analysis (Appendix C) indicated a median size of 0.70 mm. This compared with a median size of 0.15 mm for the sand in the field. Ground walnut shells have been used in movable river bed models (22) and found to behave in a manner similar to sand. Previous use of this material in coastal models is not known of presently and studies into the graduation and settling characteristics of the shells as compared to beach sand would have to be made before quantitative results can be deducted from model studies. Since the characteristic profile of a beach is a function of wave heights, wave period and time of uprush, the latter being a function of beach material characteristics, a study into equilibrium profiles on the model under varying conditions can not be made until further investigations into the characteristics of the walnut shells are made. As outlined in Appendix C, the choice of the vertical scale is governed by the material used.

Construction of the Model: The model was constructed on the basis of the surveys undertaken in March 1968. The clay was represented by cement mortar while ground walnut shells were used to represent the sand. A detailed description of the construction procedure with accompanying photographs is given in Appendix C.

Aim of Model Investigation

The aim of the Winnipeg Beach model study was to study qualitatively the littoral processes along this particular beach and how these processes are related to and affected by:

1) fluctuations in lake levels,
2) the newly constructed breakwater,
3) shoreline structures, and,
4) variations in breakwater design.

It was not the intention of the model study to forward definite conclusions as these could only be arrived at after an exhaustive testing program and due to time limitations, further testing was not possible at the present. A more extensive testing program for future studies is outlined in Appendix C.

Testing Procedure

The steps in the testing procedure were as follows:

1) the ground walnut shells were placed to the proper elevation with the use of plywood templates, the elevations being based on the March 1968 surveys,

2) the basin was filled to the desired lake level,

3) the water was then drawn down in two foot (prototype) intervals and at each contour a white string was laid out to follow the water line,

4) photographs were taken of the initial conditions,

5) the basin was then re-filled to the desired water level,

6) the wave machine was then started and run for one to two hours. In some tests, material was added updrift of the breakwater at specified intervals,

7) wave heights in front of the paddle as well as in the beach area were measured and recorded during the test,

8) at the termination of the test, the water level was again drawn down in two foot intervals (prototype), strings were laid out and photographs taken of the final contour configurations,

9) for some of the tests, the weight of walnut shells transported past the zone of the wave front was measured.

The eccentricity of the crank was set to give an average wave height of five feet in front of the wave paddle with a water level of 717. This setting was kept constant and thus wave heights varied slightly with different water levels. The variable speed pulley was set to give the proper wave period in the model (five second wave in prototype). The wave period was kept constant for all tests.

Discussion of Test Results

A summary of the testing program is shown in Table VI and the tests are discussed in detail in the paragraphs below.

TABLE VI

SUMMARY OF MODEL TESTING PROGRAM

Test No.	Nature and Purpose of Test	Lake Stage (feet)	Offshore Wave Height (feet)	Length of Test (hours)	Addition of Littoral Material Updrift of Breakwater
1.	Natural conditions. Determining littoral movement along beach.	715	4.3	1	None during the duration of the test.
2.	Natural conditions. Determining littoral movement along beach.	712	3.0	2	20 lbs. after 1 hour 5 lbs. after 1 hour 25 minutes.
3(a)	Natural conditions. Determining littoral movement along beach.	717	4.9	2	10 lbs. after 1 hour 15 minutes.
3(b)	Follow up to 3(a). Determining the effect of a lower water level.	714	3.8	2	20 lbs. added prior to test. 20 lbs. at 1 hour.
4.	Natural conditions. Determining whether material dredged from the harbor moves onshore to the beach.	714	3.8	1	None during the duration of the test.
5.	Offshore blocks located as shown on Photo 20. Determine effect of blocks on littoral movement.	714	3.8	1	Unknown weight of material added after 45 minutes.
6.	Offshore blocks located as shown on Photo 21. Determine effect of blocks on littoral movement.	714	3.8	2	Material added periodically to maintain supply of littoral material updrift of breakwater.

continued

TABLE VI (Continued)

Test No.	Nature and Purpose of Test	Lake Stage (feet)	Offshore Wave Height (feet)	Length of Test (hours)	Addition of Littoral Material Updrift of Breakwater
7.	Solid offshore breakwater as shown on Photo 22. Determine effect of breakwater on littoral movement.	713	3.5	1	None during the duration of the test.
8(a)	Extension of breakwater 20° into entrance. Determine effect on littoral movement.	717	4.9	2	Material added periodically to maintain supply of littoral material updrift of breakwater.
8(b)	Follow up to 8(a)	714	3.8	2	ditto
9(a)	Extension of breakwater 20° away from entrance. Determine effect on littoral movement.	717	4.9	2	Material added periodically to maintain supply of littoral material updrift of breakwater.
9(b)	ditto	714	3.8	2	ditto
10(a)	Submerged breakwater at crest elevation 714.0. Orientated 20° into entrance. Determine effect on littoral movement.	717	4.9	2	Material added periodically to maintain supply of littoral material updrift of breakwater.
10(b)	ditto	714	3.8	3	ditto.

Tests 1, 2 and 3(a) were run at water levels of 715, 712 and 717 respectively to determine the relationship, if any, between material movement and lake level. It was found that for the lower lake levels, material moved around the breakwater and to the shoreline in the vicinity of Oak Street; the motion being via bars (Photographs Nos. 17 and 18). However, for a lake level of 717, it was found that material moving around the breakwater was deposited in the harbor, and furthermore as the motion of material to the beach area was thus reduced, serious erosion occurred in front of the rock rip-rapped section (Photograph No. 19). With a drawdown in lake levels to 714 in Test 3(b), it was found that the material deposited in the harbor during Test 3(a) moved by means of a bar, to the beach. Motion of material was along the shore zone only and the offshore erosion experienced during Test 3(a) was not alleviated. In these tests, it was found that material moved much more rapidly around the breakwater during a high lake level than during a low lake level.

To determine whether dredged material could be dumped in an area where it would move onshore and replenish the downdrift beach, material was dumped 1,000 feet offshore (prototype) along the extension of the centerline of the breakwater (Test 4). The material was noted to move in a south-westerly direction under the north-east wind conditions. Material dumped updrift of the breakwater moved around the breakwater with a portion of it redepositing in the harbor (water level 714).

The effect of offshore blocks on littoral movement was determined in Tests 5 and 6. The location and approximate extent of the blocks is shown in Figures 21A and 21B as well as in Photographs Nos. 20 and 21. The erosion previously experienced in the vicinity of the rock rip-rap and old seawall was chiefly eliminated by the offshore blocks in Test 5 as an extensive bar was formed along the shoreline (Figure 21A). The blocks as located in Test 6 (Figure 21B) seemed to have little or no effect on littoral movement as the material moved along the shore zone inside the blocks (Figure 21B). In Test 7 a solid offshore breakwater was located in the same location as the offshore blocks in Test 5. A heavy buildup of material occurred between the breakwater and the shoreline and the erosion experienced in this area during Tests 1, 2 and 3 was eliminated. The depth of buildup behind the breakwater was somewhat misleading as the breakwater settled significantly during the first part of the test.

Tests 8, 9 and 10 involved alterations to the existing breakwater (Figures 22B, 23A and 23B). With a 160 foot extension of the breakwater (prototype) orientated 20^{o} into the entrance of the harbor, it was found that during Test 8(a) (Water level 717) only a small bar was developed in the harbor with the majority of the material being swept around the tip of the breakwater and in the direction of the seawall (Photograph No. 24). With a drawdown in lake level to 714 (Test 8(b)) and after adding material updrift of the breakwater, it was found that a minor bar developed in the harbor and that this bar progressed to the shoreline in the area updrift of the rock rip-rap. Motion of the material was along the shore zone and erosion offshore in the area of the rip-rap was apparent (Photograph No. 25). With a 160 foot extension of the breakwater (prototype) orientated 20^{o} away from the entrance of the harbor, (Figure 23A) it was found that during Test 9(a) (water level 717) an extremely heavy buildup of material occurred in the harbor entrance and with the subsequent lowering of the water level to 714, some of this material moved towards the shore in the area of the rock rip-rap. Serious erosion occurred offshore as indicated on Figure 23A. A modification of Tests 8(a) and 8(b) constituted Tests 10(a) and 10(b). In these tests the extension to the breakwater was set at a crest elevation of approximately 714 rather than the 723 crest elevation of the existing breakwater. A small bar was formed inside the harbor during Test 10(a) and with the subsequent lowering of the water level to 714 during Test 10(b), this bar progressed towards the shoreline as shown on Figure 23B. It was also noted that as the movement of littoral material around the breakwater was reduced, the bar in the harbor had a tendency to move further into the harbor entrance. Further discussion of this point is not warranted as the transition between the existing breakwater and the extension, as constructed in the model, was rather abrupt and would need refinements before further conclusions can be made.

Conclusions

As the purpose of the model study was not to come up with any definite quantitative answers but rather a qualitative assessment of the problems of shoreline recession at Winnipeg Beach, the following conclusions are general in nature.

1) With the present conditions and under the influence of northerly winds, littoral material would move around the breakwater and deposit in the harbor entrance. During high lake levels (717) this deposition would be

severe whereas under lower lake levels, the deposition is reduced as the material has a greater tendency to move towards the shoreline in a series of bars. With lower lake levels and the resultant bar formations, erosion in the area of the rock rip-rap and the north end of the seawall is reduced.

2) If it is physically possible, dredged material from the harbor entrance should be dumped south of the tip of the breakwater and as close as possible to the beach. The model studies indicated that material dumped offshore would move towards the shore zone; however this result should be viewed with some reservations as the model did not accurately represent the mass transport of material in deep water. Studies into the mass transport of material indicate that the model surface should be roughened with a special trowel (35) in order to reproduce with some degree of accuracy the phenomena of mass transport.

3) Offshore blocks would be effective if they were within the zone influenced by the breakwater. Material moving around the breakwater and encountering the blocks would deposit in the shore zone, the magnitude of this deposition being governed mainly by the elevation of the top of the blocks in relation to the water level. If the blocks were designed to be effective during high lake

levels, they would be aesthetically undesirable during low lake levels. The existing blocks at Winnipeg Beach could not be tested on the model as they were near the outer limit of the wave front of the model. However, it is felt that these blocks would have very little effect on the littoral processes along the beach as the blocks are outside the zone of littoral movement. Material moving around the breakwater would not be intercepted by the blocks.

4) A solid offshore breakwater, located within the zone influenced by the breakwater, would be effective in building up material in the shore zone, however the cost of such a structure would probably be prohibitive.

5) Deposition of material in the harbor entrance could be reduced by means of an extension orientated into the entrance. An extension, which would be submerged during high lake levels would also be effective, however more investigations into this matter are required. Some investigators believe this to be an economical solution to an annual dredging problem (51).

6) The public beach could probably be partially or even wholly restored through artificial nourishment; however since this alternative was not tested in the model, the optimum location to dump material can not be specified.

If it is in the interests of recreation to dump more material before further model investigations are made, it is suggested that the material be deposited updrift of the old seawall and that the median grain size of the dumped material be equal to or greater than the natural beach material.

CHAPTER VII

CONCLUSIONS

The aim of the thesis was outlined as:

1) to study the shoreline processes on Lake Winnipeg and determine how these are related to sources and losses of littoral material and natural as well as man-made littoral drift barriers;

2) to study qualitatively with the aid of a model, the shoreline processes at Winnipeg Beach.

The conclusions reached in this investigation are summarized as:

1) The major source of material for the beaches, from Riverton to Sans Souci on the west and from Victoria Beach to Balsam Bay on the east, is from bluffs in the Camp Morton and Sandy Hook areas along the western shoreline of the Lake while the eastern beaches, especially Grand Beach, derive the majority of littoral material from the sandy bluffs prevalent along almost the whole eastern shoreline. This bluff erosion must not be halted completely if the littoral drift necessary to replenish downdrift beaches is to be maintained.

2) The major loss of material from the beaches along the Lake is movement into the Red River Delta.

3) The most extensive natural littoral drift barriers are Willow Point and Grand Marais Point while the most extensive man-made barriers are the Gimli and Winnipeg Beach breakwaters.

4) With the use of the general shoreline analysis, the effectiveness of existing or proposed shoreline structures in different reaches may be easily ascertained.

5) Under present conditions at Winnipeg Beach, serious deposition of littoral material would occur in the harbor entrance, resulting in a shortage of littoral material to replenish the beach area. This shortage combined with the poorly designed seawall along the beach will result in continued erosion problems.

6) Material dredged from the harbor entrance at Winnipeg Beach should be dumped downdrift of the breakwater in order that it will become available for downdrift replenishment.

7) An extension to the present breakwater orientated southward and perhaps partially submerged, would reduce the silting problem in the harbor entrance and consequently provide more littoral material for downdrift replenishment.

8) Offshore blocks, if located outside the zone of littoral movement around the breakwater, would have a negligible effect on the littoral processes. A solid offshore breakwater would be more effective but very costly.

9) Further investigations are required before the littoral processes can be understood and described fully. The author realizes that many factors are still unknown and recommends that before any further extensive studies are undertaken regarding this problem, a thorough program of data collecting be initiated (see Appendix E).

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A P P E N D I X   A

WAVE HEIGHT DATA

TABLE A1

LOCATION HNAUSA

REFERENCE PT. Beach to the E. of Church

LAKE STAGE	FRE. YRS.	V MPH	NORTH D	NORTH Fe	NORTH Fm	NORTH Hs	NORTH-WEST D	NORTH-WEST Fe	NORTH-WEST Fm	NORTH-WEST Hs	WEST D	WEST Fe	WEST Fm	WEST Hs	SOUTH-WEST D	SOUTH-WEST Fe	SOUTH-WEST Fm	SOUTH-WEST Hs	SOUTH D	SOUTH Fe	SOUTH Em	SOUTH Hs
713	5	54.2	15.3	3.1	9.1	4.0	23.3	14.9	29.2	6.6	37.5	20.3	29.2	9.2	35.5	17.3	34.2	8.6	19.1	9.1	34.2	5.8
	10	56.7				4.2				6.9				9.6				9.1				6.0
	20	59.2				4.4				7.0				9.8				9.4				6.1
	50	62.5				5.1				7.6				10.6				10.0				6.6
716	5	"	18.3	"	"	"	26.3	"	"	7.2	40.5	"	"	9.2	38.5	"	"	8.6	22.1	"	"	6.4
	10									7.5				9.8				9.1				6.6
	20									7.6				10.2				9.6				6.8
	50									8.2				11.0				11.0				7.2
719	5	"	21.3	"	"	"	29.3	"	"	7.8	43.5	"	"	9.2	41.5	"	"	8.6	25.1	"	"	6.5
	10									8.0				9.8				9.1				6.8
	20									8.2				10.2				9.6				7.2
	50									8.8				11.8				11.0				8.0

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A2

LOCATION GIMLI

REFERENCE PT. End of Concrete Pier

LAKE STAGE	FRE. YRS.	V MPH	NORTH				NORTH-WEST				WEST				SOUTH-WEST				SOUTH			
			D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Em	Hs
713	5	54.2	20.5	10.7	48.8	6.1	38.5	19.5	48.8	9.2	34.5	17.7	33.4	8.7	25.5	19.7	19.9	6.6	15.0	2.4	19.7	3.5
	10	56.7				6.3				9.6				9.0				7.0				3.7
	20	59.2				6.4				10.0				9.2				7.4				3.9
	50	62.5				6.9				10.8				9.9				8.0				4.5
716	5	"	23.5	"	"	6.3	41.5	"	"	9.2	37.5	"	"	8.8	28.5	"	"	6.6	18.0	"	"	3.5
	10					6.6				9.6				9.2				7.0				3.7
	20					6.7				10.1				9.6				7.4				3.9
	50					7.2				11.4				10.5				8.4				4.5
719	5	"	26.5	"	"	7.0	44.5	"	"	9.2	40.5	"	"	8.8	31.5	"	"	6.6	21.0	"	"	3.5
	10					7.3				9.6				9.2				7.0				3.7
	20					7.6				10.1				9.6				7.4				3.9
	50					8.2				11.8				11.0				8.4				4.5

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A3

LOCATION WINNIPEG BEACH

REFERENCE PT. End of Breakwater

LAKE STAGE	FRE. YRS.	V MPH	NORTH				NORTH-WEST				WEST				SOUTH-WEST				SOUTH			
			D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs
713	5	54.2	26.5	23.7	53.8	7.2	32.5	22.1	53.8	8.4	25.5	14.5	33.8	7.0	18.5	8.1	16.0	5.7	12.5	2.0	9.9	3.3
	10	56.7				7.5				8.6				7.3				5.8				3.5
	20	59.2				7.7				8.8				7.4				6.0				3.7
	50	62.5				8.2				9.5				8.0				6.4				4.2
716	5	"	29.5	"	"	7.8	35.5	"	"	8.9	28.5	"	"	7.6	21.5	"	"	6.1	15.5	"	"	"
	10					8.1				9.2				7.9				6.4				
	20					8.2				9.6				8.0				6.6				
	50					8.9				10.0				8.6				7.1				
719	5	"	32.5	"	"	8.4	38.5	"	"	9.6	31.5	"	"	8.2	24.5	"	"	6.1	24.5	"	"	"
	10					8.6				9.8				8.5				6.4				
	20					8.8				10.0				8.7				6.8				
	50					9.5				10.8				9.3				7.8				

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A4

LOCATION MATLOCK

REFERENCE PT. E. of Intersection of Lakeview Ave., & Allice Road

LAKE STAGE	FRE. YRS.	V MPH	NORTH D	NORTH Fe	NORTH Fm	NORTH Hs	NORTH-WEST D	NORTH-WEST Fe	NORTH-WEST Fm	NORTH-WEST Hs	WEST D	WEST Fe	WEST Fm	WEST Hs	SOUTH-WEST D	SOUTH-WEST Fe	SOUTH-WEST Fm	SOUTH-WEST Hs	SOUTH D	SOUTH Fe	SOUTH Fm	SOUTH Hs
713	5	54.2	25.0	22.7	57.8	7.0	30.5	20.2	57.8	8.0	18.5	10.4	19.9	5.6	13.5	4.8	14.6	4.5	12.5	0.7	1.4	2.1
	10	56.7				7.2				8.3				5.8				4.7				2.2
	20	59.2				7.4				8.4				6.0				4.8				2.3
	50	62.5				8.0				9.6				6.4				5.1				2.7
716	5	"	28.0	"	"	7.6	33.5	"	"	8.6	21.5	"	"	6.3	16.5	"	"	4.9	15.5	"	"	"
	10					7.8				8.8				6.5				5.1				
	20					8.0				9.0				6.6				5.4				
	50					8.6				9.8				7.1				5.9				
719	5	"	31.0	"	"	8.0	36.5	"	"	9.1	24.5	"	"	6.8	19.5	"	"	4.9	18.5	"	"	"
	10					8.4				9.4				7.1				5.1				
	20					8.6				9.6				7.2				5.4				
	50					9.2				9.7				7.8				6.2				

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A5

LOCATION BALSAM BAY

REFERENCE PT. One Mile North of Beaconia

LAKE STAGE	FRE. YRS.	V MPH	NORTH				NORTH-WEST				WEST				SOUTH-WEST				SOUTH			
			D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs
713	5	54.2	25.5	22.9	33.2	7.0	28.5	19.9	33.2	7.6	22.5	12.4	23.2	6.4	14.0	5.7	15.3	4.6	12.5	1.7	3.1	3.1
	10	56.7				7.3				7.8				6.7				4.8				3.2
	20	59.2				7.5				8.1				6.8				4.9				3.3
	50	62.5				8.0				8.6				7.3				5.3				3.8
716	5	"	28.5	"	"	7.6	31.5	"	"	8.2	25.5	"	"	7.0	17.0	"	"	5.3	15.5	"	"	"
	10					7.9				8.5				7.3				5.5				
	20					8.1				8.6				7.5				5.6				
	50					8.6				9.3				8.0				6.0				
719	5	"	31.5	"	"	8.2	34.5	"	"	8.7	28.5	"	"	7.2	20.0	"	"	5.3	18.5	"	"	"
	10					8.5				9.0				7.8				5.6				
	20					8.6				9.2				8.0				5.8				
	50					9.3				10.0				8.6				6.7				

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A6

LOCATION GRAND BEACH

REFERENCE PT. W. of Intersection of Parkview and Grand Beach Road

LAKE STAGE	FRE. YRS.	V MPH	NORTH D	NORTH Fe	NORTH Fm	NORTH Hs	NORTH-WEST D	NORTH-WEST Fe	NORTH-WEST Fm	NORTH-WEST Hs	WEST D	WEST Fe	WEST Fm	WEST Hs	SOUTH-WEST D	SOUTH-WEST Fe	SOUTH-WEST Fm	SOUTH-WEST Hs	SOUTH D	SOUTH Fe	SOUTH Fm	SOUTH Hs
713	5 10 20 50	54.2 56.7 59.2 62.5	37.5	26.9	38.2	9.2 9.6 9.8 10.7	34.5	19.4	38.2	8.7 9.0 9.2 9.9	27.5	13.0	19.4	7.4 7.7 7.9 8.4	24.5	11.2	14.6	6.8 7.1 7.2 7.8	21.5	9.8	13.5	6.2 6.5 6.6 7.1
716	5 10 20 50	"	40.5	"	"	9.8 10.1 10.3 11.1	37.5	"	"	9.1 9.6 9.8 10.6	30.5	"	"	7.6 8.0 8.4 9.1	27.5	"	"	7.1 7.5 7.8 8.4	24.5	"	"	6.8 7.1 7.2 7.8
719	5 10 20 50	"	43.5	"	"	10.2 10.7 10.9 11.8	40.5	"	"	9.1 9.6 10.0 11.1	33.5	"	"	7.6 8.0 8.4 9.7	30.5	"	"	7.1 7.5 7.8 9.0	27.5	"	"	6.8 7.1 7.5 8.4

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

TABLE A7

LOCATION VICTORIA BEACH

REFERENCE PT. West of Patricia Road

LAKE STAGE	FRE. YRS.	V MPH	NORTH				NORTH-WEST				WEST				SOUTH-WEST				SOUTH			
			D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs	D	Fe	Fm	Hs
713	5	54.2	32.5	14.1	28.0	7.8	36.7	16.0	28.0	8.4	39.0	16.2	22.0	8.4	35.3	13.9	23.0	7.8	26.0	8.9	23.0	6.4
	10	56.7				8.2				8.8				8.8				8.2				6.8
	20	59.2				8.7				9.2				9.3				8.6				7.1
	50	62.5				9.5				10.4				10.8				10.0				8.2
716	5	"	35.5	"	"	7.8	39.7	"	"	8.4	42.0	"	"	"	38.3	"	"	"	29.0	"	"	"
	10					8.2				8.8												
	20					8.7				9.2												
	50					10.0				10.7												
719	5	"	38.5	"	"	7.8	42.7	"	"	8.4	45.0	"	"	"	41.3	"	"	"	32.0	"	"	"
	10					8.2				8.8												
	20					8.7				9.2												
	50					10.0				10.7												

D: Average Depth
Fe: Effective Fetch
Fm: Maximum Fetch
Hs: Significant Wave Height
V: Wind Velocity
Freq: Return Period.

APPENDIX B

QUESTIONNAIRE

THE UNIVERSITY OF MANITOBA

PARTMENT OF CIVIL ENGINEERING

WINNIPEG, CANADA

May 1968

Dear Sir or Madam:

I am presently completing a Master of Science thesis at the University of Manitoba. My thesis will deal with sand motion and the problem of shoreline erosion on Lake Winnipeg, a problem with which I am sure you are quite familiar.

Determining erosion that has occurred over the years along the lakeshore is vital to this study and thus I hope that you will take the time to complete the enclosed questionnaire and return it in the self-addressed stamped envelope.

The undersigned people have given their approval to this study.

Your cooperation in this is greatly appreciated.

Yours truly,

W. M. Veldman.

Enclosure

PLANNING DIVISION
CONTROL & CONSERVATION BRANCH

Assistant Professor
University of Manitoba

PROPERTY OWNERS
TION

QUESTIONNAIRE

1. Name ____

2. Permanent Address ______________________________________

3. Summer Residence ______________________________________
Lot Street Town

4. No. of Years that you have resided at above address __________

5.H Have you lost any property due to erosion ? ______________

6. If yes, approximately how many feet and during what years?

______________ ft. in 19____

______________ ft. in 19____ etc.

7. Please check type of protective measures used.

- ☐ None
- ☐ Rock
- ☐ Concrete Seawall
- ☐ Wooden Piles
- ☐ Others (specify) ________________

8. If protective measures were used, were these in place during the serious erosion years? ____________

9. General comments and other remarks that you may wish to make regarding shoreline erosion. (Use back of page if extra space is required.)

____

____

____

10. If you have any old photos of the lakeshore at your property, these would be greatly appreciated and would be returned upon request.

A P P E N D I X   C

WINNIPEG BEACH MODEL STUDIES

Selection of Scales for Winnipeg Beach Model

The sediment movement in the littoral zone occurs in the form of bed load (material rolled and pushed along the bottom by shear stress) and suspended load (material maintained in suspension by action of waves and currents). "Two-phase motion" (fluid and bed material) occurs in the vicinity of the bed and is completely defined by specifying the following seven independent quantities:

- ρ density of fluid
- γ kinematic viscosity
- D any typical diameter of bed material (e.g. D_{50}, $D_{max.}$, etc.)
- γ_s specific weight of the bed material in fluid
- U mean orbital velocity
- T wave period
- V velocity of the translational motion

The Buckingham Pi Theorem provides an excellent tool by which these quantities can be organized into the smallest number of significant, dimensionless groupings, from which an equation can be evaluated. The theorem states that, if there are "n" physical quantities "q" (such as density, period and diameter) and "k" fundamental dimensions (such as force, length and time, or mass, length and time), then mathematically

$$F1 \quad (q_1, q_2, q_3, \ldots\ldots, q_n) = 0$$

This expression can be replaced by the equation

$$\phi \quad (\pi_1, \pi_2, \pi_3, \ldots\ldots, \pi_{n-k}) = 0$$

where any one "π" term depends on not more than (k + 1) physical quantities "q" and each of the "π" terms are independent, dimensionless, nominal functions of the quantities "q". The dimensionless variables calculated using the Buckingham Pi Theorem are:

$$X = \frac{UD}{\gamma} \; ; \quad Y = \frac{\rho U^2}{\gamma_s D} \; ; \quad Z = \frac{UT}{D} \; ; \quad W = \frac{U}{V} \; \ldots. \; (1)$$

Now if it is assumed that the geometrical properties (independent of the absolute size) are specified, that is the form of the grains and the form of the grain-size distribution curve then dynamical similarity of the two-phase motion at corresponding places and times is given by the identity of the dimensionless variables in model and prototype are $\lambda_x = 1, \lambda_y = 1, \lambda_z = 1, \lambda_w = 1 \; \ldots. (2)$

where $\lambda = \frac{\alpha''}{\alpha'}$ where α'' model value of α and α' prototype value of α where α is any quantity. It is found that if in model and prototype the same fluid (water) is used, it is found that the model bed material must be considerably heavier than that of the prototype. Hence in practice simultaneous consideration of all conditions in (2) is not possible.

If the main subject of the study is the transport of bed material from one place to another (i.e., the formation of shoals and deeps whilst small-scale formations like ripples are neglected) it is found that the erosion or accretion does not depend on the period T and thus $\lambda_Z = 1$ $(Z = \frac{UT}{D})$ can be relaxed. Thus changes in bed level arising from accretion and erosion should be correct in order to preserve geometrical similarity when measured on the vertical scale of the model λy.

If the wave height scale is made equal to the vertical scale of the model, the following pertinent relationships may be derived

$$\lambda x = \lambda y^{5/2}$$
$$\lambda T = \lambda y^{1/2}$$
$$\lambda \gamma s = \lambda y^{3/2}$$
$$\lambda H = \lambda y$$

Now if the model bed material is ground walnut shells where $\gamma s'' = .28$, $\lambda \gamma s = \frac{\gamma s''}{\gamma s'} = \frac{.28}{1.65} = \frac{1}{5.9}$
then we get

$$\lambda y = \lambda \gamma s^{2/3} = \left(\frac{1}{5.9}\right)^{2/3} = \frac{1}{3.26}$$

and

$$\lambda x = \lambda y^{5/2} = \left(\frac{1}{3.26}\right)^{5/2} = \frac{1}{19.2}$$

which are impossibly large scales in practice. It is thus apparent that the above method of calculating scales is not applicable in the present study and a more realistic method must be found.

Studies done by the Civil Engineering Department at Queen's University in Kingston, Ontario (31) showed that with a vertical distortion of 3:1 a material of specific slightly greater than one was required to ensure transport similitude, that is similitude of the critical speeds of erosion. The material chosen by Queen's University was gilsonite (S.G. 1.03) which was shown to give good similitude as far as the critical speed for the onset of motion was concerned on a horizontal bed. On a beach slope the mass-transport of water under wave action tends to move particles on the bottom towards the shore. This is counterbalanced by gravity acting down the beach slope. Thus the equilibrium slope of the model bed material should be three times as steep as the equilibrium slope of the sand if a 3:1 vertical distortion is used. Tests in a two-dimensional flume on a ground walnut beach would have to be performed to determine a relationship between wave height and equilibrium slope of beach and from this the wave height corresponding to the proper equilibrium beach profile could be chosen. As time was not available for these tests in the present study, a 3:1 vertical distortion and a 5 foot wave height at a water level of 715 were used. It would be necessary to perform two-dimensional flume tests before any quantitative results can be derived from a model incorporating walnut shells; however the shells give an accurate indication of the motion of material under various conditions.

The following scales were used for the Winnipeg Beach model study:

horizontal scale	(λ_x)	1:160
vertical scale	(λ_y)	1:50
wave height scale	$(\lambda_H = \lambda_y)$	1:50
wave period scale	$(\lambda_T = \lambda_y^{1/2})$	1:7.07

The above discussion on the derivation of model scales has been liberally derived from papers and reports written by Le Mehaute, Collins, Yalin and Russell (31,49,50).

Construction of the Model

The model was constructed on the basis of a contour plan which was drawn up from the survey taken in March 1968. A two-foot square grid system was laid out on the model floor and contours were drawn in. Wooden eye screws were put into one-inch square wooden posts and the posts glued on the contours lines. String was then suspended from post to post and the wood screws were adjusted to the exact elevation associated with the contour line. The string of course could not be bent to the exact shape of the contours but since sufficient posts were used to take into account all the major changes in contour alignment and since the beach profile is gently sloping and smooth, it was felt that the strings would be sufficient. Soft galvanized wire was attempted at first but when the wire was bent to conform to the contours, the wooden posts became unglued. This difficulty could be overcome by placing a layer of 3/4" plywood on the floor of the model and inserting the wooden posts into holes cut into the appropriate locations. The model was filled up with gravel to about one inch from the string in the area where a clay bottom exists and to about two inches from the string in the area where sand is present. A layer of cement mortar, about one inch thick, was then placed on the gravel and made level with the strings in the clay area and lower than the string in the sand area. After the concrete hardened, the wooden posts were cut off and templates made to correspond with the beach profile in the sand areas.

The seawall was made of sections of plywood. No attempt was made to reproduce the curved upper portion of the old seawall as this would add little to the overall accuracy of the results. The breakwater was constructed of wood and pebbles cemented into the cement mortar to similate the rough lakeward slope.

A wave machine with a 12 foot long paddle was constructed for the model. A 5 horsepower electric motor with a variable speed Roto-Cone pulley combined with a crank assembly was used to generate the waves. The wave heights in the model were measured by two electrically connected point gauges. The point gauges were wired up to two neon bulbs and a 90 volt dry cell battery and connected to a rolling frame which was positioned on a moveable bridge.

With this arrangement it was possible to obtain a wave height at any location in the model. The wave height was obtained in the following manner; initially the two point gauges were zeroed to a still water level. Then one pointer was positioned at the crest of the passing waves such that one neon bulb would just flash on and the other pointer was positioned at the trough of the passing waves such that the neon bulb would just flash off. The difference between the two gauge readings gave the model wave height which was converted to the prototype wave height by the appropriate scale. The wiring of the wave height indicator is shown on Figure C-1 and it is clearly depicted in Photograph C-4. The setup was tailored after a study done by the Water Control and Conservation Branch, Province of Manitoba (47).

Further Studies Required

Due to time limitations, the tests performed on the model were somewhat limited. Before any further testing is undertaken, it is desirable to undertake two-dimensional studies in a flume in order to determine the wave height to give the proper equilibrium profile on a ground walnut beach. Also before further studies are initiated, the length of the wave paddle should be increased to reproduce more accurately the motion of sand around the breakwater and the action of waves at the southern extremity of the seawall. Additional tests that could be undertaken are:

1) tests to determine the effect of groins for various lake levels and at various locations along the beach;

2) further investigations into offshore blocks and offshore breakwaters;

3) further tests on the alignment of the extremity of the breakwater so as to reduce siltation in the harbor and to act as a minimum littoral drift barrier;

4) further tests to determine the effects of fluctuating water levels;

5) tests to determine the optimum rate of feeding in littoral material updrift of the breakwater. For equilibrium conditions, the volume added should be balanced by the volume moving downdrift of the area under study.

A P P E N D I X   D

LITTORAL PROCESSES

Introduction

Winds and the resultant waves are the driving forces required to move littoral material. The close relationship between the movement of littoral material and the resultant shoreline configuration has been mentioned previously. The mechanics of littoral transport and the factors that determine the magnitude of the transport are discussed in this chapter. In addition, sources and losses of littoral material are outlined and the various indicators of the predominant direction of littoral drift are discussed. The effect of man-made structures such as groins, breakwaters and seawalls and natural shoreline occurrences such as headlands and inlets on the littoral transport are outlined. Attempts to relate littoral processes to changes in water levels are also reviewed in this section, and finally theoretical shorelines are discussed. It is interesting to note that World War II was instrumental in changing the analysis of littoral processes from a qualitative approach to a quantitative approach (27) as the precise knowledge of beach characteristics was essential in planning suitable landing areas for amphibian vehicles. Many phenomenon can still only be described qualitatively.

Littoral Transport

Because of its importance in river technology, sediment transport has long been of interest to engineers. The movement of sediments, even in its simplest form, represents an extremely high degree of unsteady, non-uniform flow because the stream bed changes continuously and thereby influences water as well as sediment flow conditions. The motion of material in the littoral zone under the influence of waves and currents is even more complex than sediment transport in rivers because of the oscillating water motion in wave action and because of the irregularity of the currents in the material-transport littoral zone (10). The mechanics of littoral transport are not precisely known (16), but it may be stated that littoral material is moved by one of three basic modes of transport:

a) material known as beach drift moved along the shoreline in a zigzag path due to the obliquely approaching wave;

b) material moved in suspension in the surf zone by longshore currents and due to turbulence;

c) material, known as bedload, moved close to the bottom by sliding, rolling, and saltation, within and seaward of the surf zone by the oscillating currents of passing waves.

Figure D1 shows the basic modes of transport. Johnson in 1956 (27) stated that the movement of sand takes place in two manners, namely, in suspension and by rolling in a zig-zag motion along the beach face. Johnson also stated that Saville (1950) found that movement during storm periods was mainly by suspension, while movement during calm periods was a result of rolling in a zigzag motion along the beach face. It is believed that as much as 80 per cent of the material moved by wave action is moved in the area shoreward of the breaking point (Mason, 1953), but sufficient tests have not yet been made to prove this conclusively (45).

When a wave crest approaches the shore obliquely, the crest tends to become parallel to the shoreline through the phenomenon of wave refraction. This phenomenon occurs when the depth becomes less than one-half the deep water wave length and when the wave begins to "feel" the bottom resulting in a change in wave height, length and celerity. The waves generally break at a relatively small angle with the shoreline resulting in the generation of a longshore or littoral current. The intensity of this current, which is present almost exclusively between the surf zone and the shore depends on the characteristics of the waves (angle of approach, height, and period) and on the characteristics of the shore (slope and roughness).

At the present, a precise relationship between wave energy and littoral transport has not been determined. Munch-Peterson in 1938 first attempted to relate the rate of littoral transport to the wave characteristics and the angle of incidence of the waves to the shoreline (10). His formula states that:

$$M = K\ E \cos \alpha_o$$

where:

M = amount of material transported

K = an undetermined coefficient

E = wave energy

α_o = angle of incidence of the waves.

He later (4) modified his formula to:

$$M = \frac{KH^2L \cos \alpha}{8}$$

Where:

H = the wave height

L = the wave length

Due to a lack of wave data used in the derivation of the formula, it is limited in its application but has been used for preliminary evaluation of the direction of littoral drift in some European countries. A quantitative approach based on practical experience by the Los Angeles District of the Corps of Engineers resulted in the formula (10):

$$M = \frac{1}{2} k_1 We \sin 2\alpha_b$$

where:

M = total amount of sand moved in littoral drift past a given point per year by waves of given periods and direction;

k_1 = factor varying with beach slope, grain size, and other undetermined variables and has not been evaluated;

W = total work accomplished by all waves of a given period and direction in deep water during an average year;

e = the ratio between the distance between orthogonals in deep water and at the shoreline;

α_b = angle between the wave crests at the breaker line and the shoreline.

Because of the limitations of present knowledge of wave action in the littoral zone, the results of the above equation are questionable. In more recent work, Castanko (54) determined the percentages of wave energy dissipated in friction losses and in wave breaking (turbulence). He found that maximum sand transport occurred when α is between 45° and 60° where α is the angle between the shoreline and the wave orthogonal. Johnson (27) found that the maximum rate of transport occurs when the angle of wave approach is between 30^{o} and 40^{o}. Other researches (27, 10) state values of α between 45^{o} and 54^{o} while Grym (20) states that values from tests have varied from 30^{o} to 60^{o} but he states further that, if it is assumed that littoral transport is a function of sin 2α (as in the Los Angeles equation above) it will have its maximum value for $\alpha = 45^{o}$. A suggested relationship between longshore littoral transport in cubic yards per day on the longshore energy in millions of feet-lbs., per day per foot of beach has been compiled by Savage (16) utilizing data of other investigators. The relationship states that:

Littoral transport =

$$f\left[\frac{E_o}{2}\text{(No. of waves per day)}\,(\sin\alpha_b \cos\alpha_b)\,(K_R{}^2)\right]$$

where:

E_o = deep water wave energy per wave

K_R = refraction coefficient

α_b = angle between breaking wave crest and the beach.

An approximate order of magnitude value of littoral transport can be obtained from this for shallow water depth by ignoring refraction in the calculation of the wave characteristics. The relationship as determined by Savage is shown in Figure D2.

The rate of littoral transport is also related to wave steepness. Laboratory experiments by Saville in 1950 show that the maximum transport for the same wave effect occurs when the wave steepness is between 0.02 and 0.03 (10) where wave steepness is defined as the ratio of wave height to wave length. Bruun (10) feels that the ratio is lower in the field and states that it is important to realize that it is not the relatively steep storm waves that cause a large littoral transport but rather the intermediate or summer waves which are the major factor in shoreline processes. It is true that storm waves remove large quantities of sand from beaches, but this material is moved offshore into deeper water and moved back onto the beach during sustained periods of waves having a relatively small steepness.

Various laboratory studies have indicated that the major part of the alongshore movement of sand occurs in the turbulent region of the breaker zone, however along natural shorelines the depth to which transport occurs is varied. Because of "slope sorting" (the sorting of grain size with respect to beach slope, the larger particles being higher on the beach) the material in littoral transport moves generally within a depth range compatible with its size or resistance to transport (16). The movement of material is affected by water level variability, wave exposure and ground water level and has been reported in depths up to 200 feet or more (16). Median grain size is a satisfactory parameter for generally evaluating the transportability of littoral material, although particle density and shape are also factors.

Sources and Losses of Littoral Material

The three main natural sources of material to any beach segment are (16):

a) material moving into the area by natural littoral transport from adjacent beach areas;

b) contributions by streams;

c) contributions through erosion of coastal formations, other than beaches, exposed to wave attack.

Other researchers (26) also list wind action as a major source of sand supply. All of these factors may be important on some reaches of the shoreline; whereas in other reaches only one or two of these factors may be of importance. The largest source of material is generally littoral drift eroded from updrift reaches, however care should be taken in determining the source of material as material on any one beach may be the product of several source areas. Petrographic analysis (38) of samples of the littoral and possible source materials may establish a correlation between the mineral content of the littoral material and that of the source area. The volume of littoral material contributed by streams is greatly dependent on the geology of the watershed and over the years empirical methods have been developed for estimating the sedimentation rate. On a coastline such as California, the contribution from streams is of major importance (26); whereas, the effect of a sediment carrying stream on a lakeshore is greatly influenced by the location of the stream delta in relation to the shoreline configuration and the predominant littoral drift. As an illustration, a stream discharging into the southern portion of a narrow lake with a predominant littoral drift in the southward direction will contribute very little littoral material to the whole shoreline[1]. The contribution of materials from cliffs by direct wave action is generally small for most coastlines but may be a major source of material along lakeshores (26, 16). Closely related to cliff erosion is the contribution of material by landslides which may be caused by wave action, rain impact, runoff, weathering action, frost action and subsurface moisture.

The principal processes of loss of littoral material from a specific beach areainclude (16):

[1] This is the case of the Red River discharging into Lake Winnipeg.

a) movement of material laterally out of the area;

b) movement of material offshore into deep water;

c) loss of material into submarine canyons;

d) loss of material by wind action.

The movement of material out of the area is a loss to the area under consideration but a source of material for a downdrift segment of the shoreline. Material may be moved into deep water under the forces of a river or by wind action and the forces of wave action and coastal currents may not be sufficient to move the material shoreward. The quantity of material lost to offshore depths cannot in itself be determined at the present (16) and the problem is even more complicated with varying lake levels. Where a submarine canyon is situated adjacent to the shoreline, the loss of material to the canyon may be substantial (26) but in the absence of canyons, this factor may be disregarded. The loss of littoral material by wind action or deflation increases as the beach widens and the expanse of dry sand increases. If the predominant wind is offshore the sand is deposited in the water and could be redeposited in a downdrift area; however, if the wind is onshore, a dune belt will be developed and the sand lost as littoral material.

Determination of the Direction of Littoral Transport

The direction of littoral drift at a particular time is dictated by the alongshore component of the wave velocity at the breaking point. Analysis of the following factors will indicate the predominant direction of littoral drift over a normal climatic cycle (16):

a) accretion or erosion at existing structures;

b) shore patterns at headlands;

c) configuration of banks and beds of inlets and streams;

d) statistical analysis of wave energy;

e) characteristics of beach and bed materials;

f) current measurements.

Generally the most reliable method of determining the direction of littoral transport is from evidence at groins, jetties and breakwaters. Because of the large quantities of sand generally stopped by jetties and breakwaters, they indicate the predominant direction while groins may indicate only seasonal effects. Headlands, which are frequently rock outcrops, may or may not indicate the direction of littoral transport and no general rule can be stated that will apply to all conditions. Over a long period of time an inlet or stream will migrate in the direction of littoral transport. The direction of the predominant littoral transport can also be ascertained from the wave energy rose diagram. Generally speaking, the median grain size will decrease with distance from the source; thus a comparison of beach material samples (1) will indicate the direction of the predominant littoral transport. This method however is subject to questioning because of the wide variation in grain size along beach and nearshore slopes, the effect of exposure and underwater topography upon sorting and because of the varied sea conditions that may occur just prior to or during the sampling (16). Current measurements by means of floats outside the breaker zone and flourescein dye inside the breaker zone are sometimes used to indicate the littoral transport direction, however they are frequently unreliable and time consuming. Accretion on the updrift side of a structure and erosion on the downdrift side usually is the most reliable indication of the predominant littoral transport direction.

The Effect of Man-Made and Natural Littoral Barriers on Littoral Processes

The erosion and the resulting configuration of a shoreline is due to either natural or man-made causes. It is not a matter of coincidence that reaches of serious erosion are closely related to reaches of concentrated development (8). The effect of various man-made structures on the shoreline configuration as well as the effect of headlands and inlets on littoral transport will be discussed in this section. The exact size and shape of the various structures will not be discussed as no general statement can be made regarding these points. Another very important natural cause of shoreline erosion, namely a rise in lake level, will be discussed in a following section.

Groins: A groin as defined by the Coastal Engineering Research Center (16) is a "shore-protective structure designed to build or maintain a protective beach by trapping littoral drift or to retard the erosion of an existing beach". The extent to which a groin modifies and stops the littoral drift depends on the height, length and permeability of the groin. Many investigations (28, 6, 42, 23) have been made to determine the motion of sand around groins and to find the optimum height, slope, and configuration of the groins, however it is felt that studies to determine the optimum shape of groins so as to reduce downdrift erosion are pointless since downdrift erosion is inevitable if the groin functions properly.

Breakwaters: A breakwater as defined by the Coastal Engineering Research Center (16) "is a structure protecting a shore area, harbour, anchorages or basin from waves". Breakwaters may be either shore-connected or offshore and may be constructed by various means. A shore-connected breakwater interposes a total littoral barrier until such time that the impounding capacity of the structure is reached and natural bypassing of the material is resumed. An offshore breakwater reduces waves and consequently littoral transport. As the waves are dissipated, sand is deposited within the geometric shadow of the breakwater and this sand deposit then acts as a groin causing more and more sand to deposit, until the sand eventually begins moving seaward around the structure.

Seawalls: A seawall as defined by the Research Center (16) is a "structure separating land and water areas, primarily designed to prevent erosion and other damage due to wave action". The reflection of the wave from the seawall increases the orbital velocity of the water near the bed in proportion to the wave amplitude causing material to be put into suspension and allowing it to be carried away by currents (42). Seawalls cause serious erosion in areas where the sand supply is limited.

Headlands: A headland may be defined as (16) "a point or portion jutting out into the sea, a lake, or other body of water". In some instances the headland is so oriented as to cause a reversal of direction of littoral transport under all wave conditions. The headland may act as a partial or a complete littoral barrier.

<u>Inlets</u>: An inlet may be defined as (16) "a short, narrow waterway connecting a bay, lagoon, or similar body of water with a large parent body of water". Numerous investigations have been made (12, 9, 7) to determine the manner in which sand moves across the inlet. It has been found that if the ratio (r) between the net predominant drift (M net) and the maximum discharge of inlet flow (Q max.) is less than 30, by-passing will be predominantly "tidal flow transfer", that is the material is flushed out of the inlet by ebb currents carrying the material away from the inlet entrance to the offshore area and possibly in the downdrift direction. If the ratio "r" is high, by-passing will be predominantly by bars. The type of bar that will be formed is dependent on the volume of littoral transport moving into the area and the wave action. The effectiveness of a tidal inlet as a littoral barrier is thus greatly determined by the mode in which material is by-passed; if by-passing is by means of "tidal flow transfer", the inlet will be almost a complete littoral barrier but if by-passing is by means of a bar, the inlet will not hamper littoral drift.

The Effect of Fluctuations in the Water Levels on Littoral Processes

It has been stated by Bruun (55) that "any change in lake level, whether short term or long term, will cause an adjustment of the offshore bottom to the new water table", and studies in the Netherlands (44) have shown that the erosion caused by a heavy gale is closely related to the mean water level accompanying the gale. King (30) has shown that a gently sloping wave-cut platform is associated with a slowly rising water level while in the case of a slowly falling water level, a slope parallel to the original one will replace it.

Bruun has done extensive investigations into the theory of erosion by rise of water level and the theory outlined below is an excerpt from one of his papers (55). His theory states that a rise in water level of "a" feet will cause a deposition to a depth of "a" on the bottom profile, the source of this deposited material being the beach. The quantity eroded from the beach is equal to the quantity deposited on the bottom profile. Mathematically this may be expressed by:

$$xe = a\,(b-x)\,d$$

$$x\,(e+d) = ab$$

where:

x = shoreline recession in feet

e = elevation of the shore above water level in feet

a = rise in water level in feet

b = width of shelf

d = depth to which material moves in feet

The definition diagram is shown in Figure D3. The validity of the theory was tested on shoreline recessions on the Florida shores and the recession (x) as calculated appears to be realistic, however Bruun further notes that the erosion probably depends to a large extent on the slope of the offshore bottom. A gentle sloping bottom will slow down the littoral drift and thus for a rapid rise in water level, there will be a phase difference between the rise in water level and the erosion. A steep profile will adjust itself quickly to a rise in water level and no significant phase difference will occur. It should be noted that the above refers to an equilibrium beach, that is the same quantity of material that is passing in from the updrift side is also passing out downdrift.

Theoretical Forms of Shorelines

It has been stated that the configuration of sandy shores and the changes in it depends completely on the variation in the transport of sand above the sea-bottom (20). The volume of littoral transport is closely related to the angle that the waves approach the shoreline and on the supposition that littoral transport is ruled by the function sin 2α, Grym (20) investigated the theoretical shorelines that could exist. By solving the mathematical relations by computer, Grym obtained many theoretical shorelines for different wind directions and concluded that the basic shoreline shape must fall within certain octants, however he states that before further studies are made, "it seems necessary to investigate whether the results we have obtained can be recognized in nature or not". Other investigators (3) have studied the theoretical shape and the stability of river deltas but more work will have to be done in this area before anything definite can be said.

A P P E N D I X   E

FURTHER STUDIES REQUIRED

Further model investigations recommended for the Winnipeg Beach area have been listed in Appendix C. Available field data related to shoreline processes is almost non-existent for Lake Winnipeg. The following field investigations are a prerequisite for a detailed shoreline analysis:

a) A detailed hydrographic survey along the shoreline up to approximately the 20-foot contour. The existing hydrographic maps published by the Department of Transport of the Federal Government lack the desired detail.

b) Several locations should be selected (e.g. Winnipeg Beach, Matlock and Grand Beach) and a systematic program of surveys initiated to determine the changes in beach profiles as they are related to lake levels, wind direction, and swell and storm conditions.

c) A field program of wave measurements should be initiated as soon as possible. Recommended locations for wave measurements are Gimli, Matlock, Victoria Beach and Grand Marais Point. Manual gauges could be observed by local residents during storm conditions, however a self-recording device, though it may not have a higher degree of accuracy, would be more dependable.

d) Grain size analysis should be made at numerous locations along the shoreline. The stable slope of a beach is governed by the grain size of the sand (Bascom has done extensive research into this field). This information or data would aid in the evaluation of the stability of the existing beaches and would also be required in determining the optimum grain size for artificial nourishment.

e) Tracer studies should be conducted in areas where the movement of littoral material is too complex to be analyzed by other methods.

It is also suggested that a more complete questionnaire be sent out to lakeshore cottage owners and in addition to this, that public meetings be held with the local residents to gain a better knowledge of the shoreline recession problems. These meetings can lead to much worthwhile knowledge presently lacking.

During the course of the investigation, an attempt was made to estimate the shoreline recession by comparing aerial photographs. This was found to be rather difficult but would be facilitated by a lower altitude flight pattern. Annual surveys would be desirable.

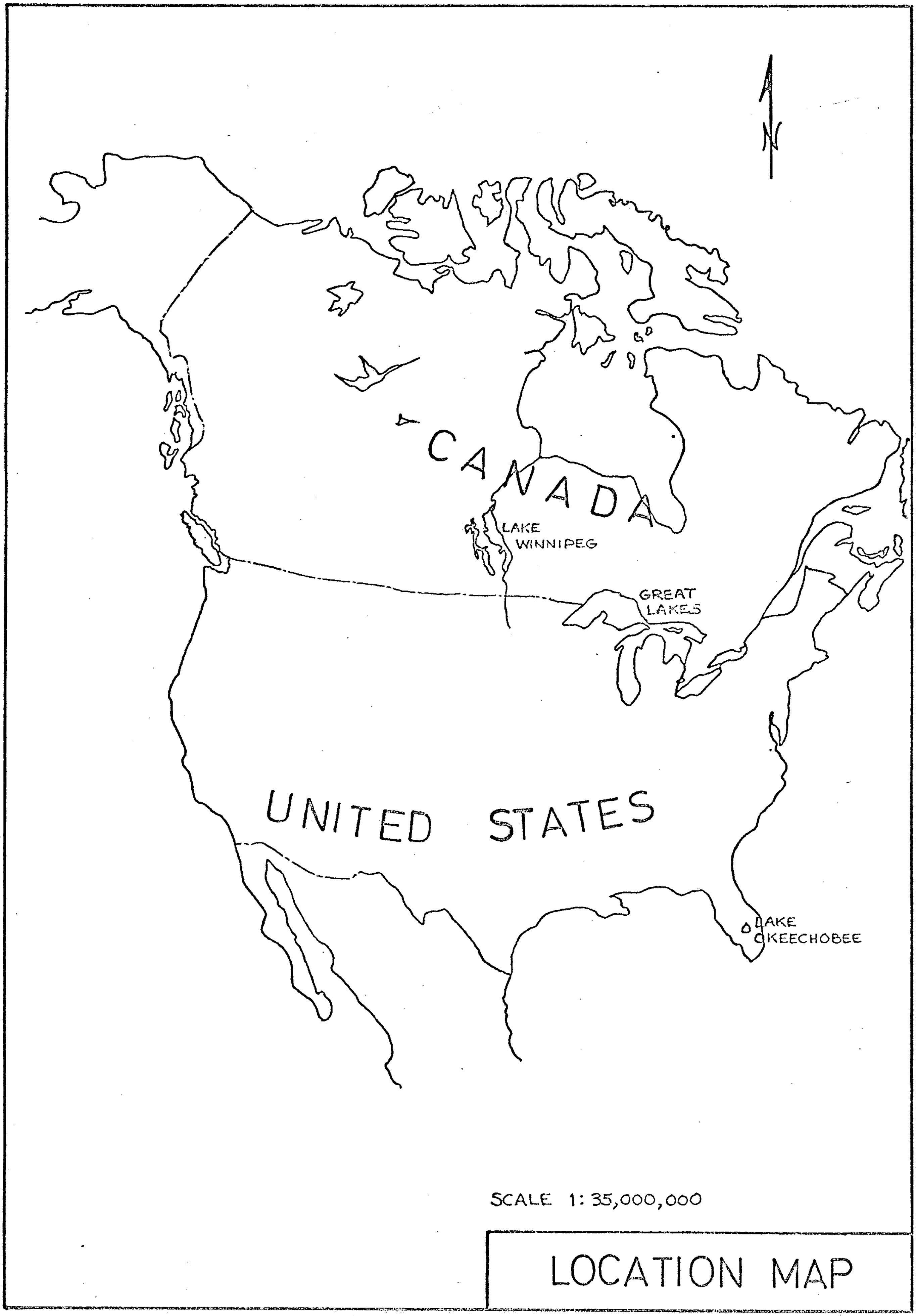
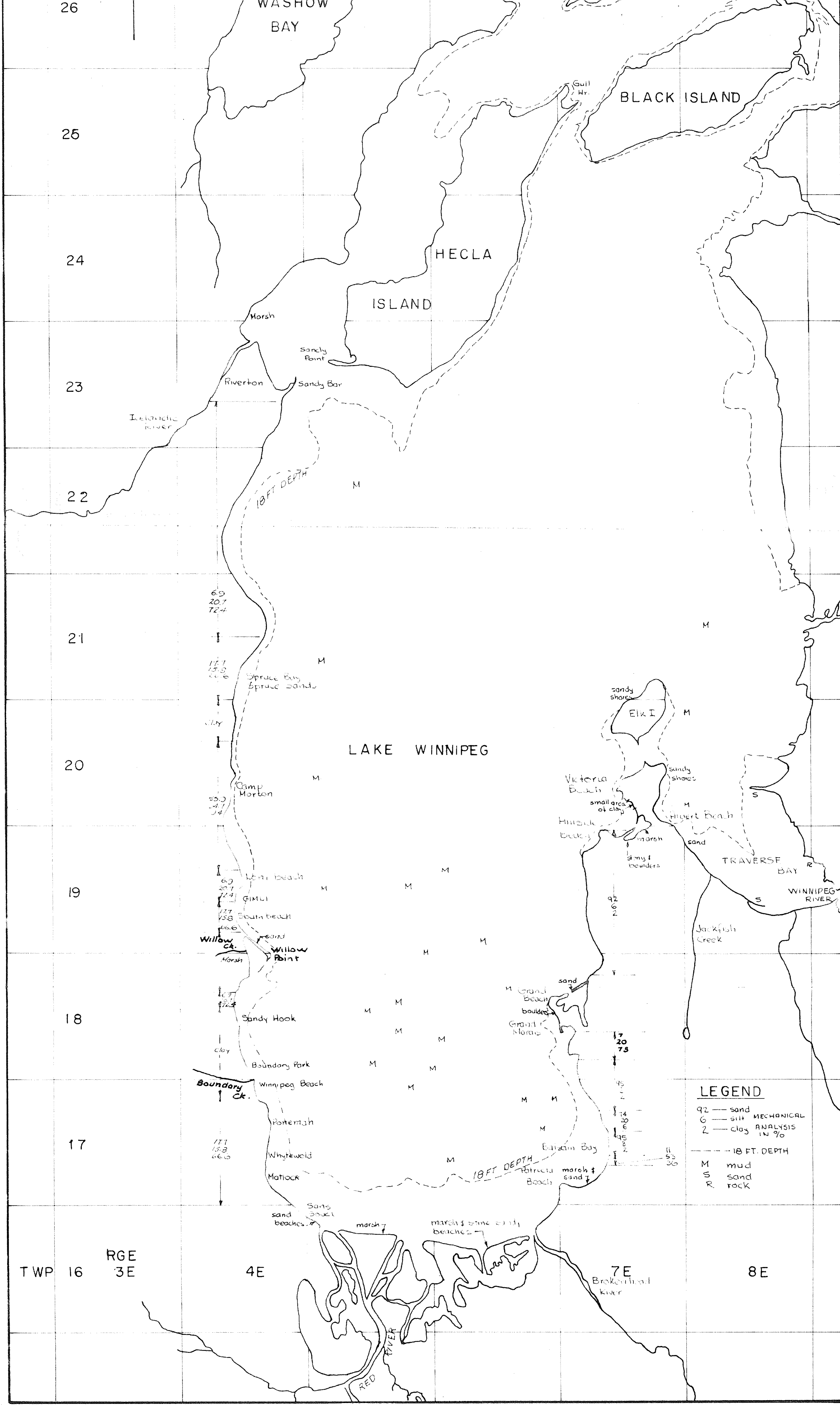
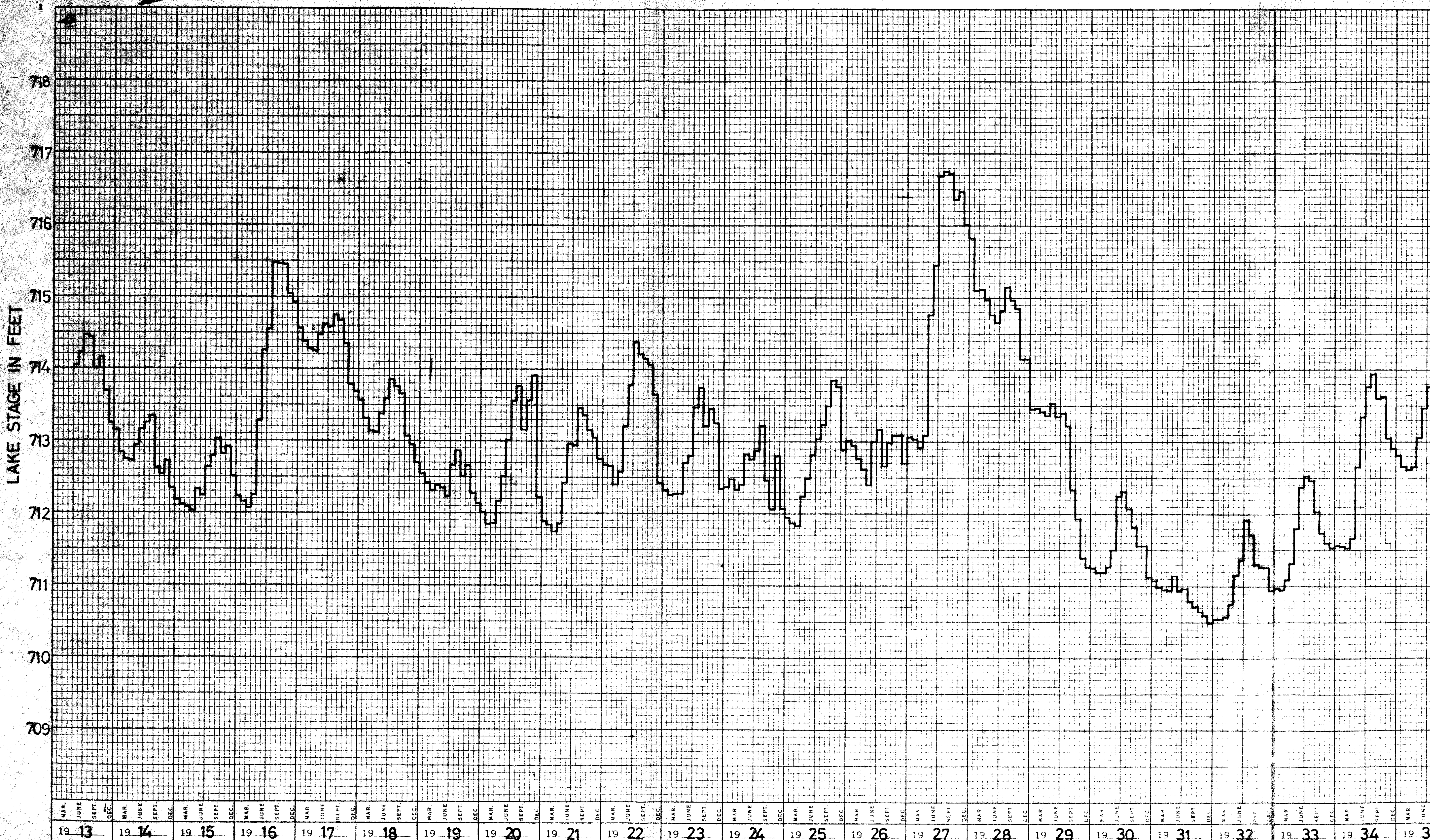

N
CANADA
LAKE WINNIPEG
GREAT LAKES
UNITED STATES
LAKE OKEECHOBEE
SCALE 1: 35,000,000
LOCATION MAP

FIGURE I

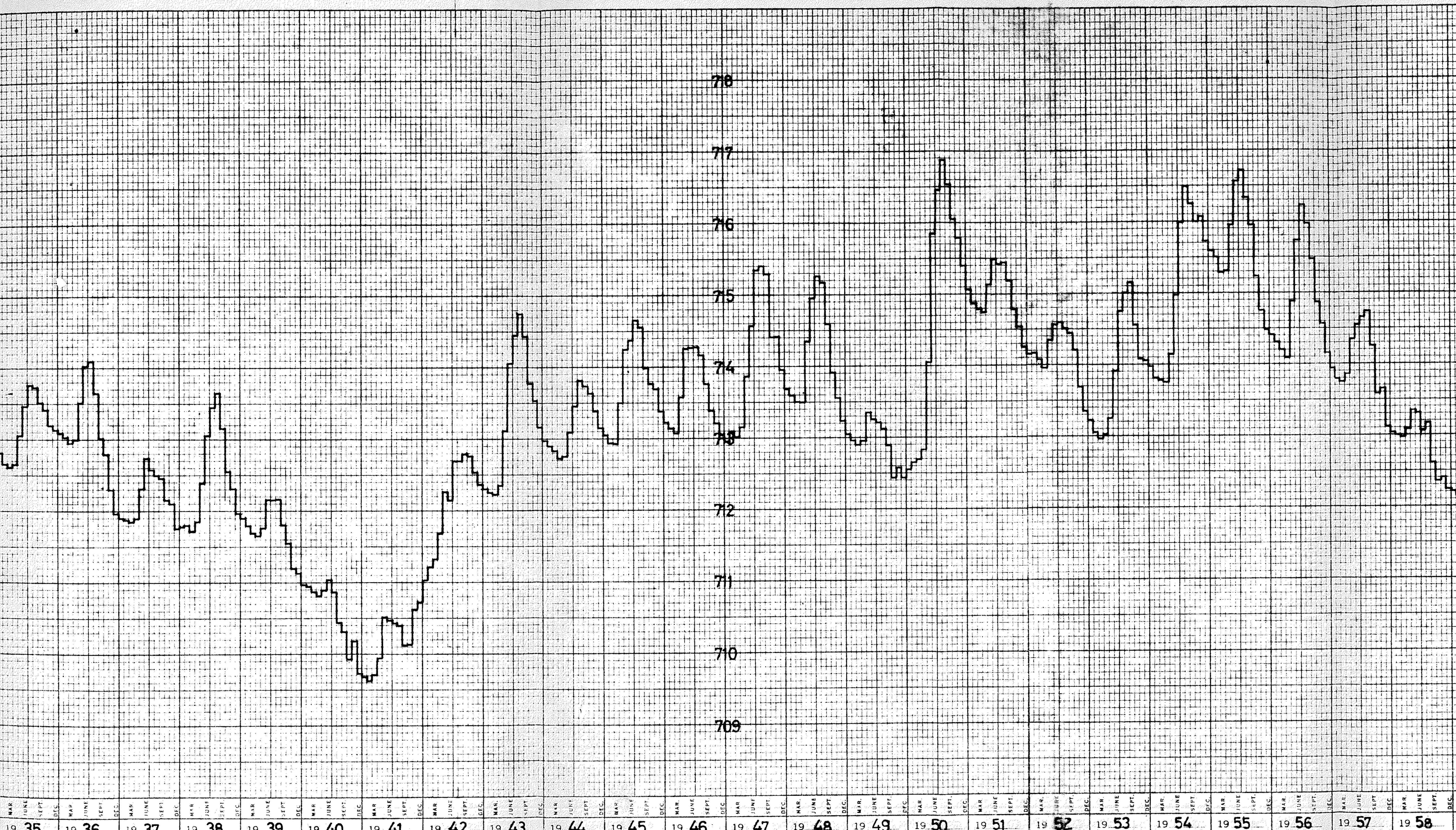


LAKE WINNIPEG

FIGURE 2



LAKE STAGE IN FEET
718
717
716
715
714
713
712
711
710
709
MAR.
JUNE
SEPT.
DEC.
1913
1914
1915
1916
1917
1918
1919
1920
1921
1922
1923
1924
1925
1926
1927
1928
1929
1930
1931
1932
1933
1934



718
717
716
715
714
713
712
711
710
709
MAR. JUNE SEPT. DEC.
19 35
19 36
19 37
19 38
19 39
19 40
19 41
19 42
19 43
19 44
19 45
19 46
19 47
19 48
19 49
19 50
19 51
19 52
19 53
19 54
19 55
19 56
19 57
19 58

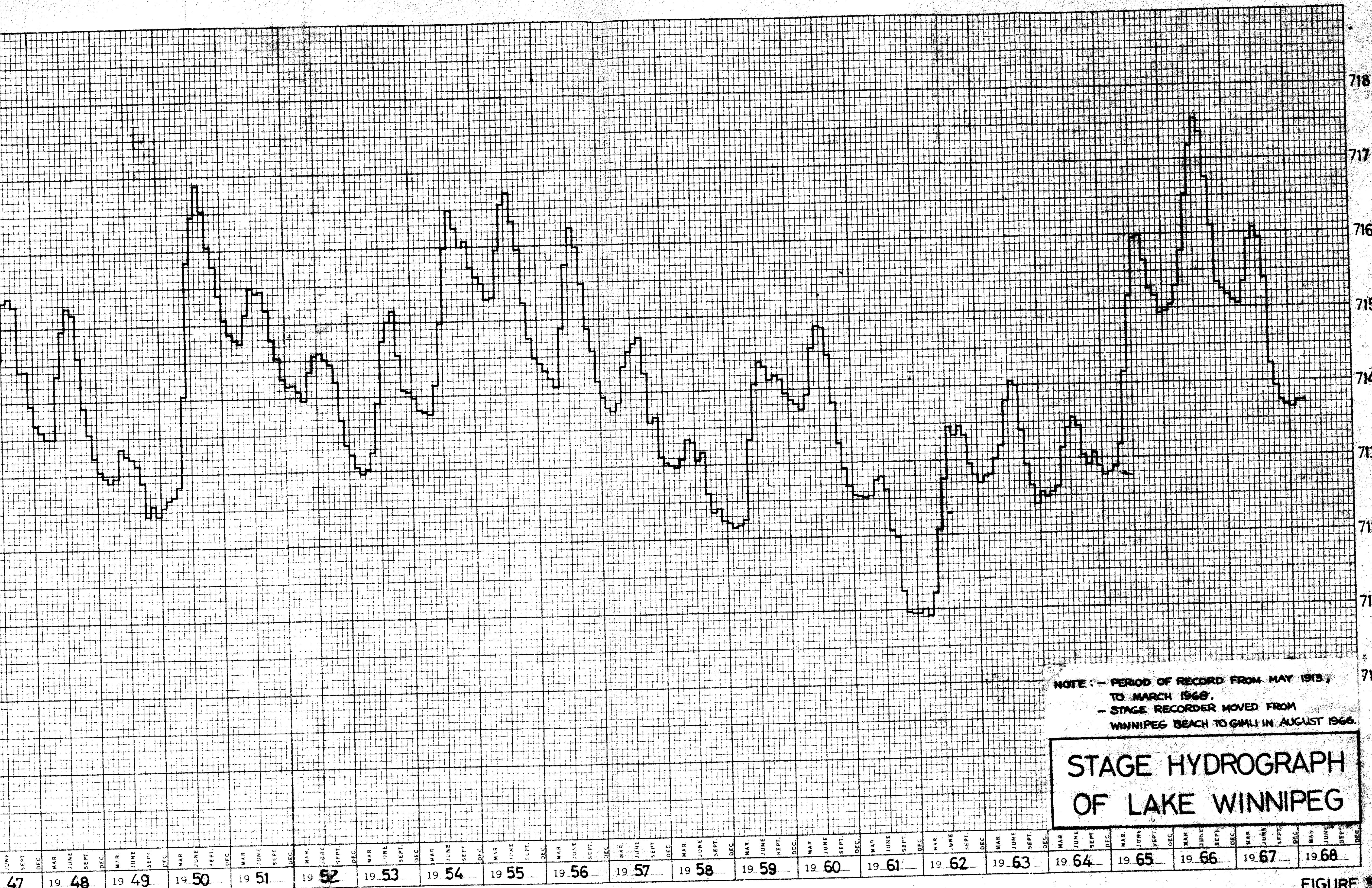
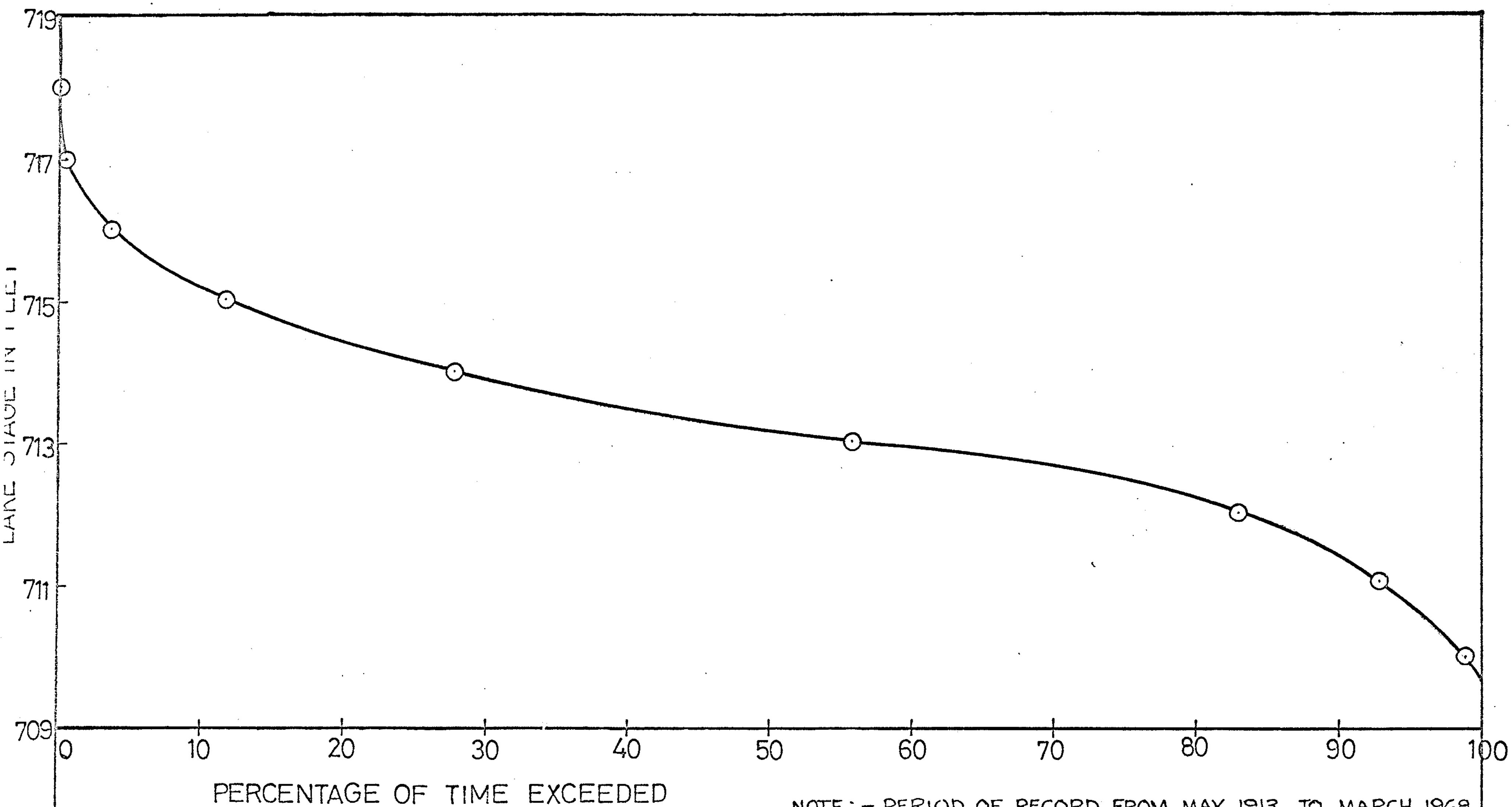

718
717
716
715
714
713
712
711
710
NOTE: - PERIOD OF RECORD FROM MAY 1913, TO MARCH 1968.
- STAGE RECORDER MOVED FROM WINNIPEG BEACH TO GIMLI IN AUGUST 1966.
STAGE HYDROGRAPH OF LAKE WINNIPEG
47
19 48
19 49
19 50
19 51
19 52
19 53
19 54
19 55
19 56
19 57
19 58
19 59
19 60
19 61
19 62
19 63
19 64
19 65
19 66
19 67
19 68

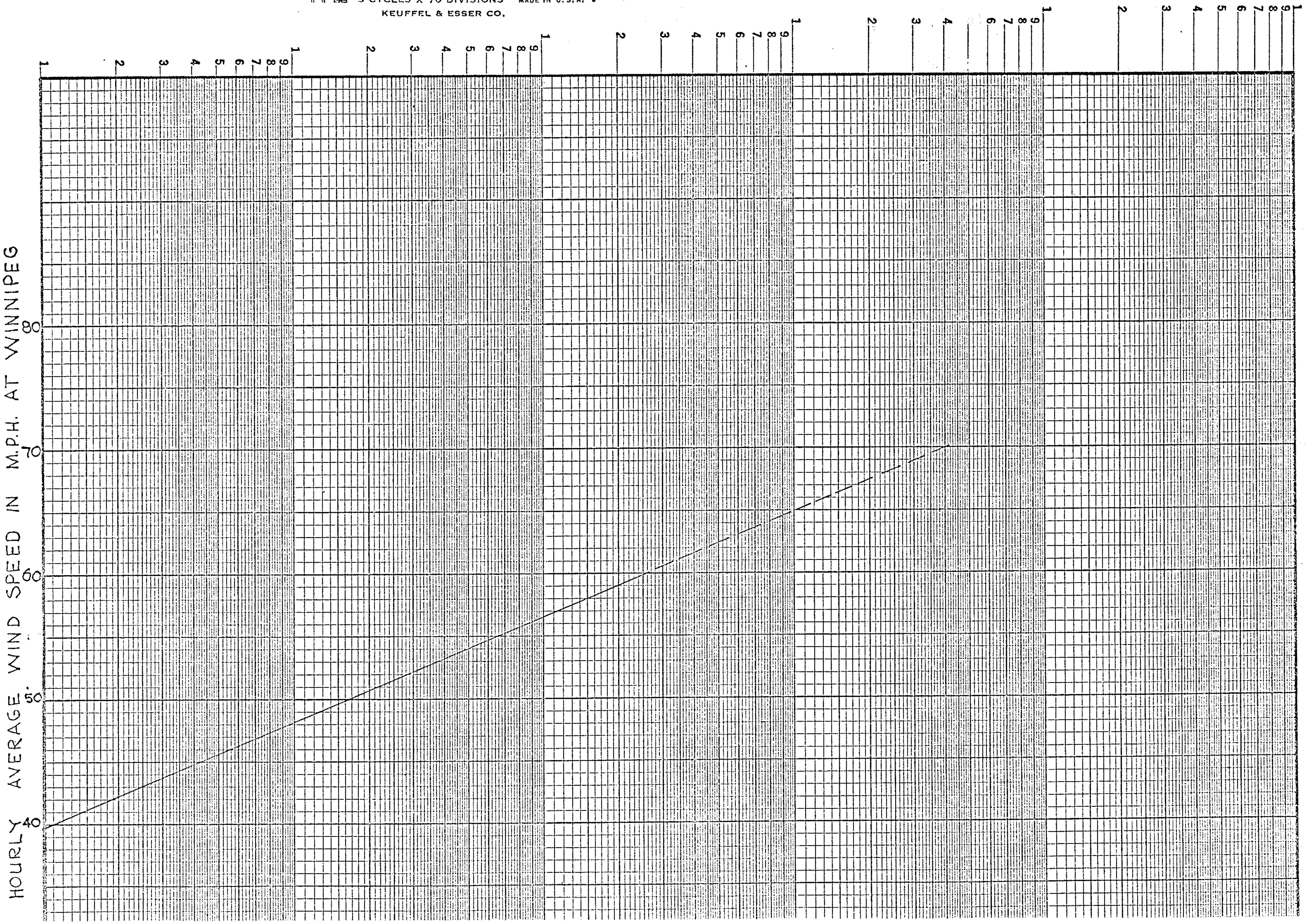
FIGURE 3

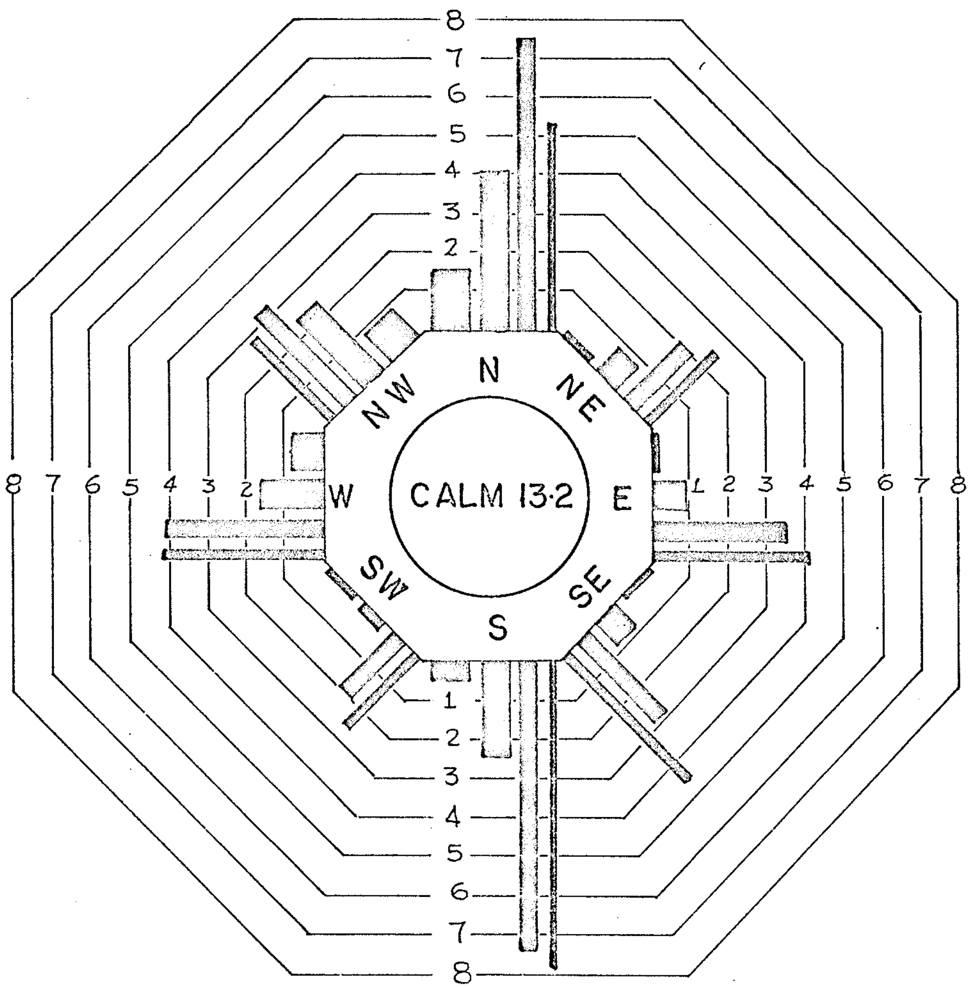


NOTE: - PERIOD OF RECORD FROM MAY 1913, TO MARCH 1968.

- STAGE RECORDER MOVED FROM WINNIPEG BEACH TO GIMLI IN AUGUST 1966.

MONTHLY STAGE DURATION OF LAKE WINNIPEG


HOURLY AVERAGE WIND SPEED IN M.P.H. AT WINNIPEG
80
70
60
50
40

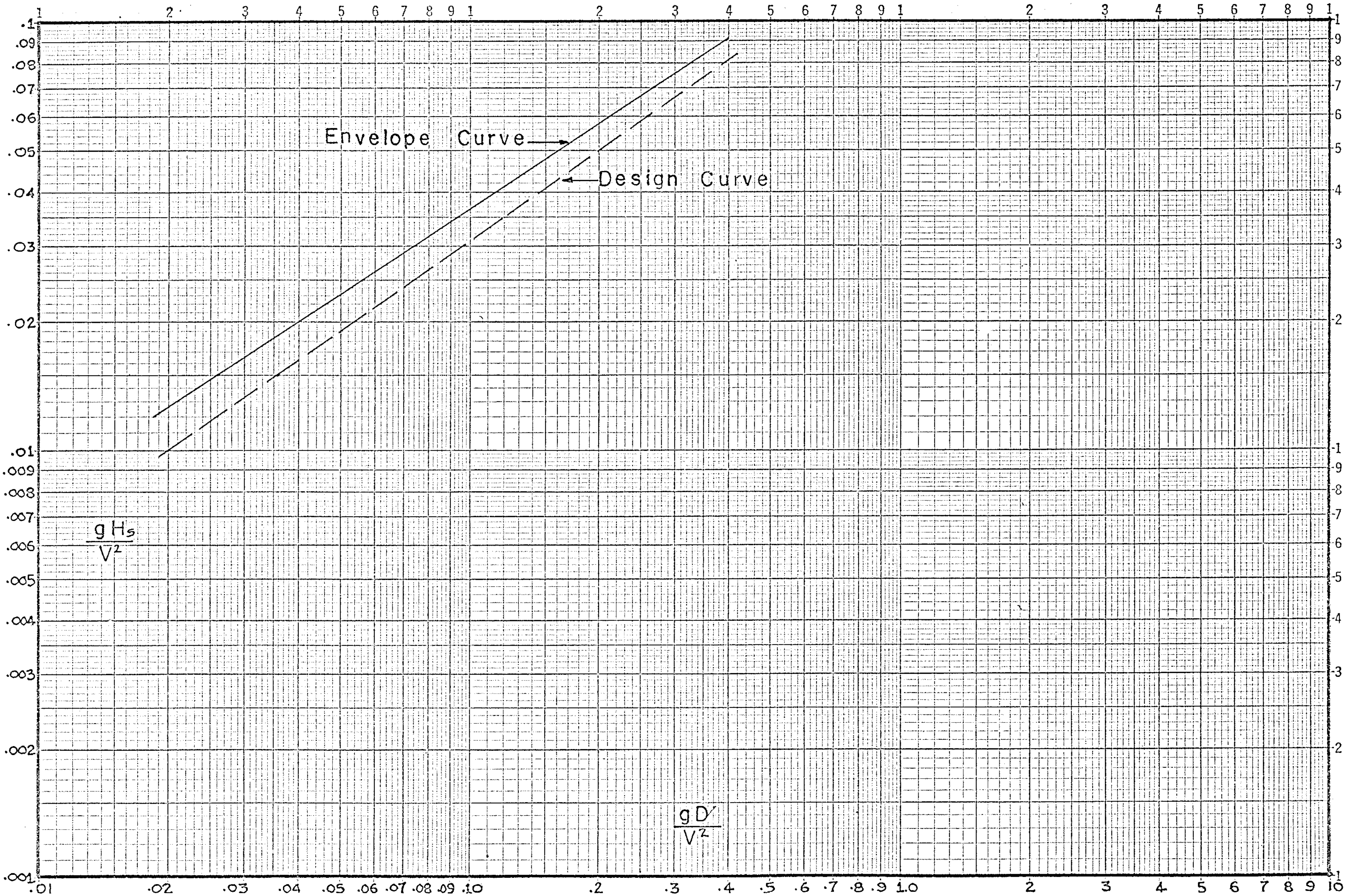


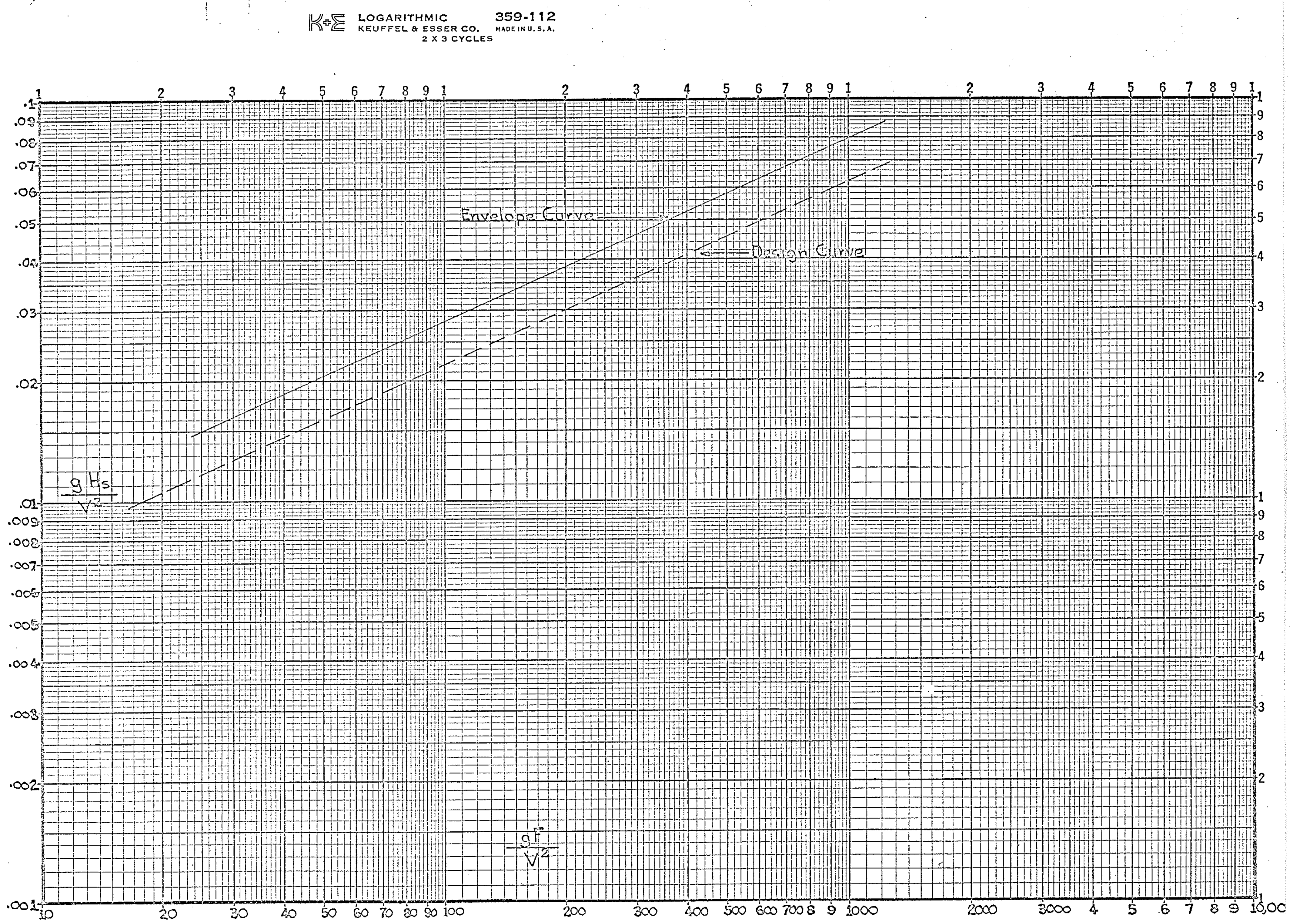
NOTE: All figures in percent
Data from DPW Dredge No·201
Period of record - 1961-1966

LEGEND
3 - 10
11 - 20
21 - 30
31 + mph·

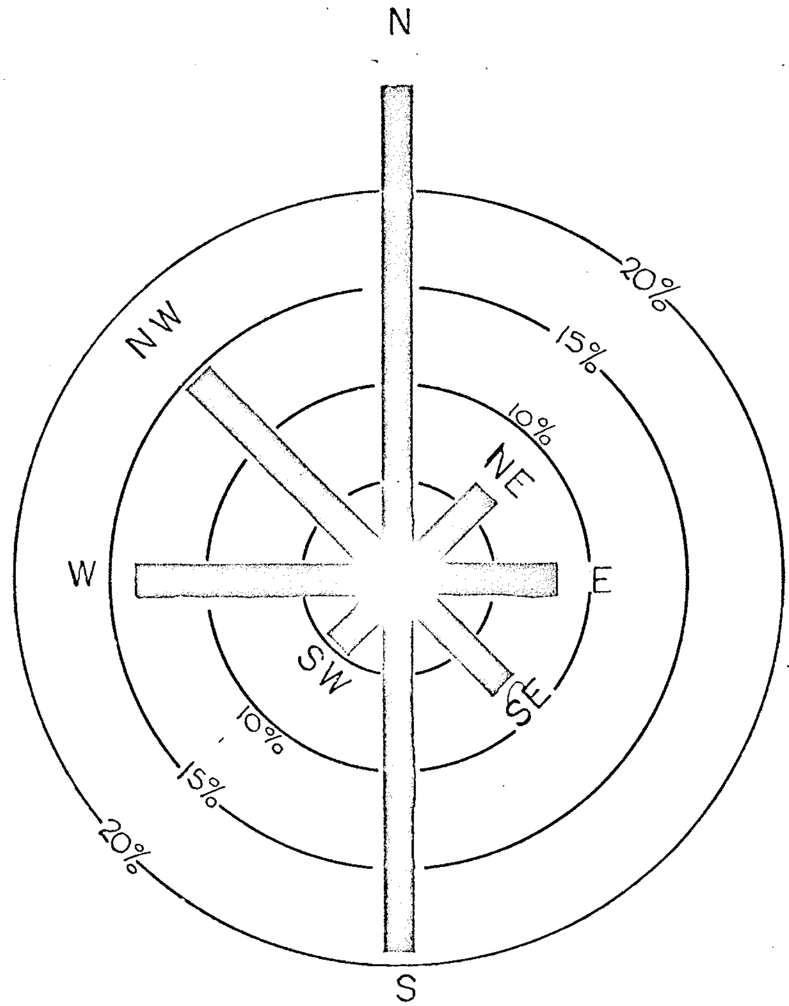
WIND ROSE DIAGRAM

FIGURE 6


Envelope Curve
Design Curve
$\frac{gH_s}{V^2}$
$\frac{gD}{V^2}$
.01
.02
.03
.04
.05
.06
.07
.08
.09
.10
.2
.3
.4
.5
.6
.7
.8
.9
1.0
2
3
4
5
6
7
8
9
10
.001
.002
.003
.004
.005
.006
.007
.008
.009
.01
.02
.03
.04
.05
.06
.07
.08
.09
.1

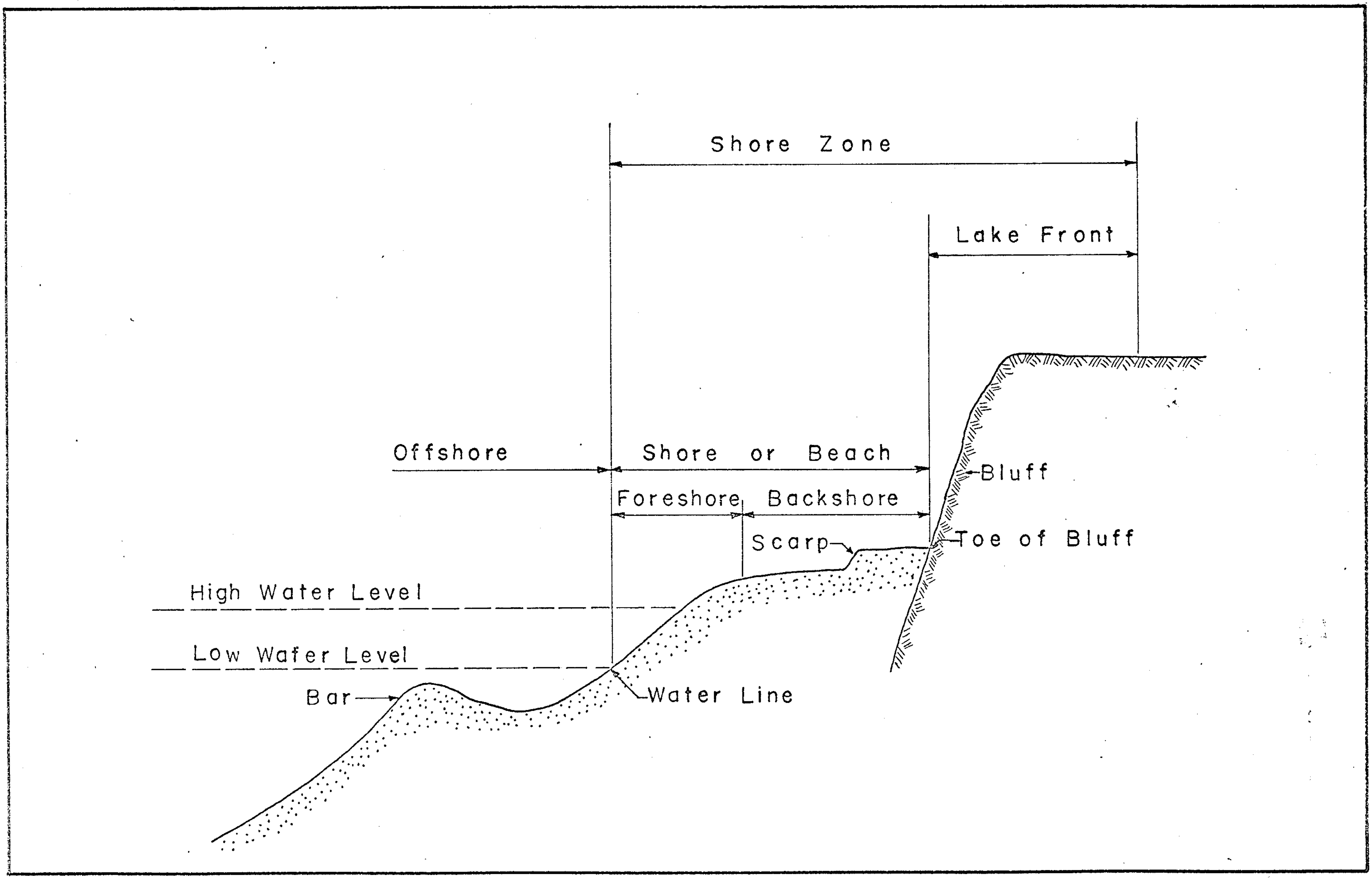


K+E LOGARITHMIC 359-112
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 3 CYCLES
Envelope Curve
Design Curve
$\frac{gH_s}{V^2}$
$\frac{gF}{V^2}$

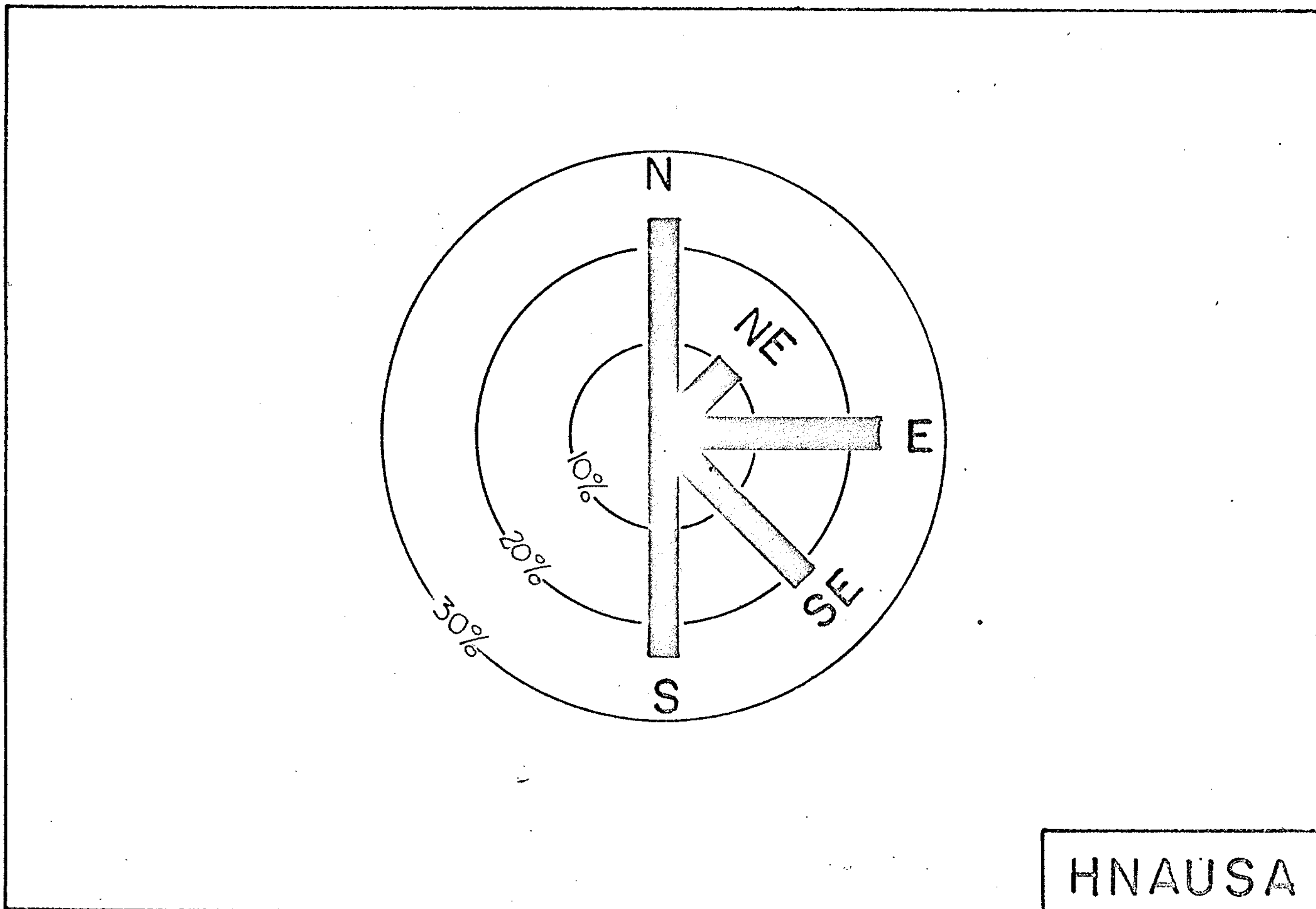


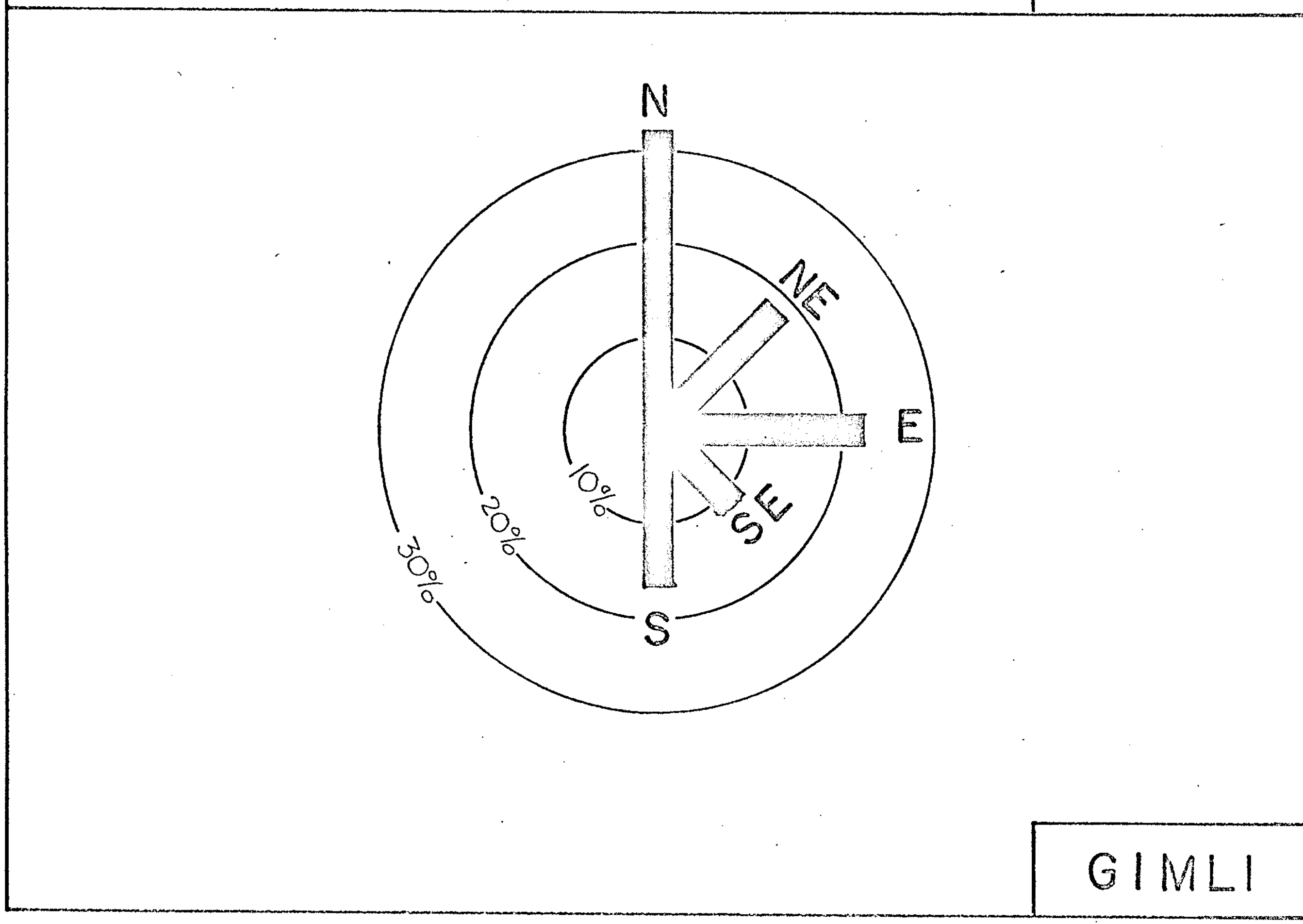
WAVE ENERGY DISTRIBUTION, LAKE WINNIPEG

FIGURE 9



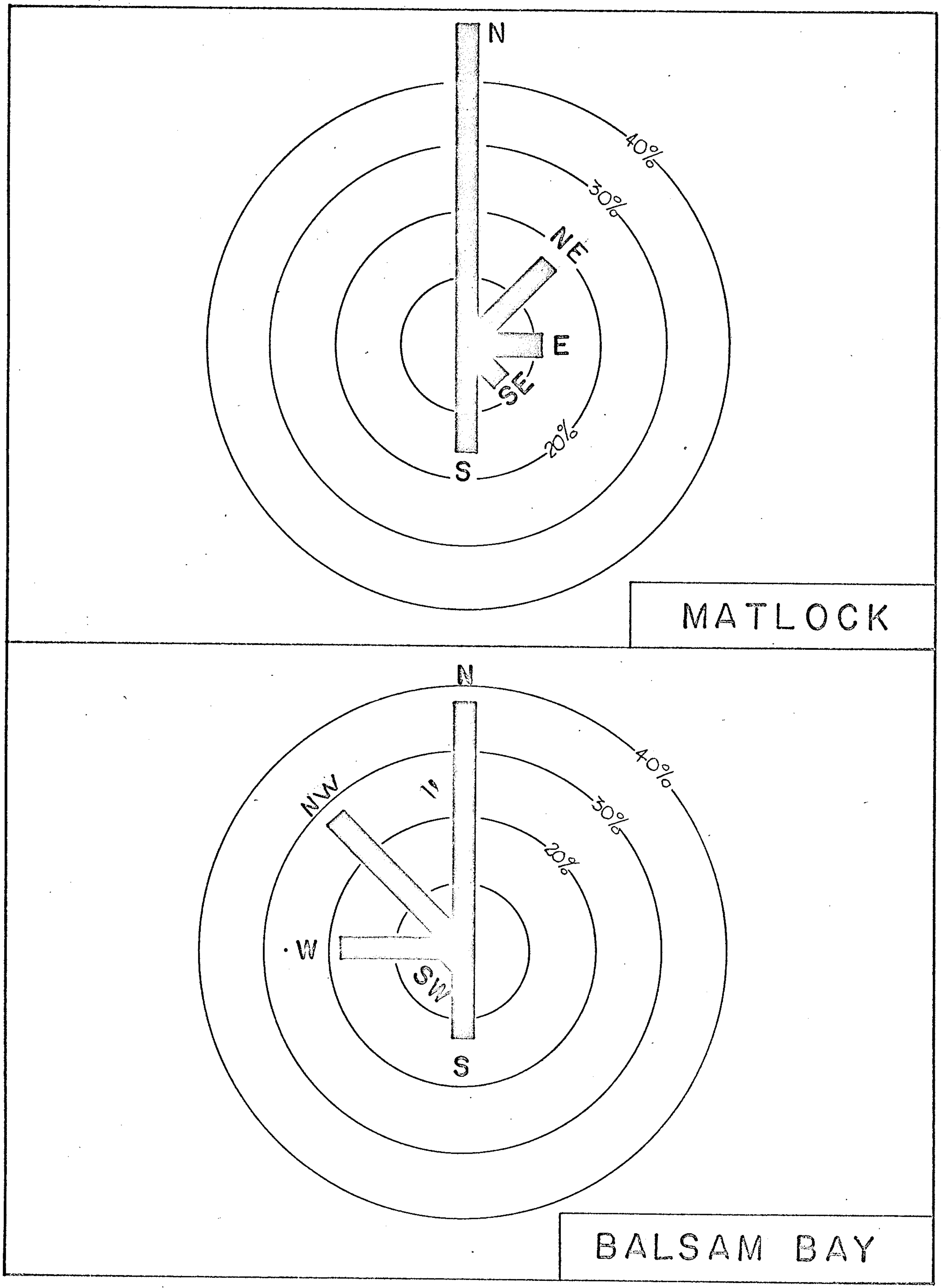
BEACH AND BLUFF TERMINOLOGY (Ref. 6)





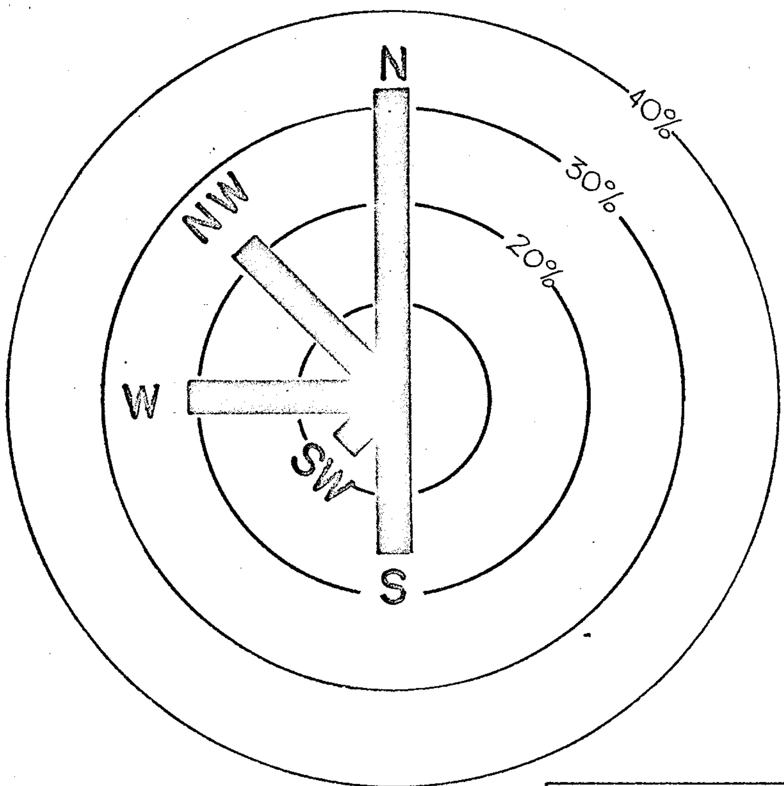
WAVE ENERGY DISTRIBUTION

FIGURE 11

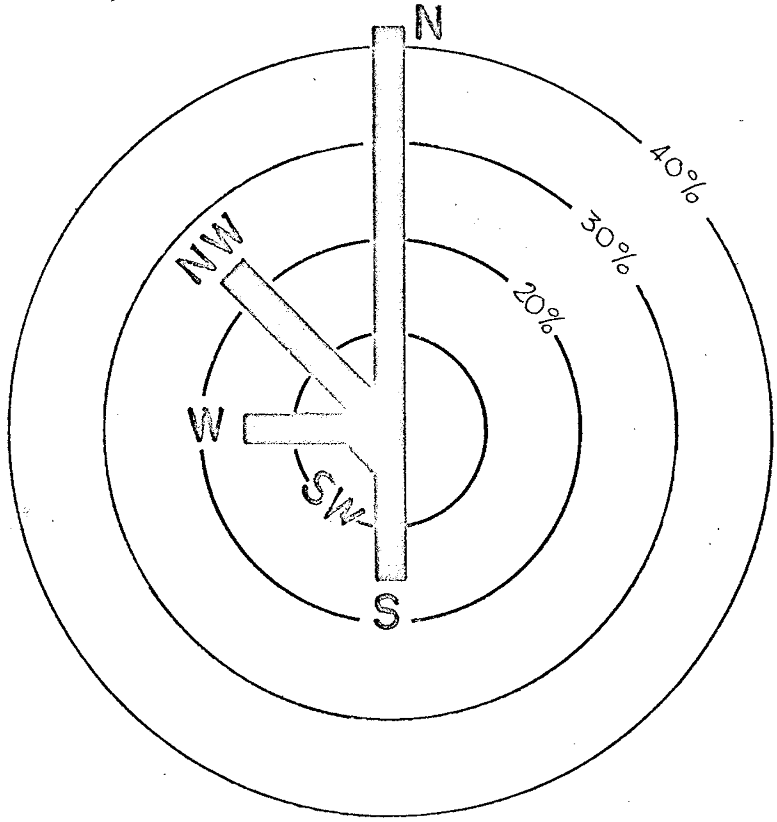


WAVE ENERGY DISTRIBUTION

FIGURE 12



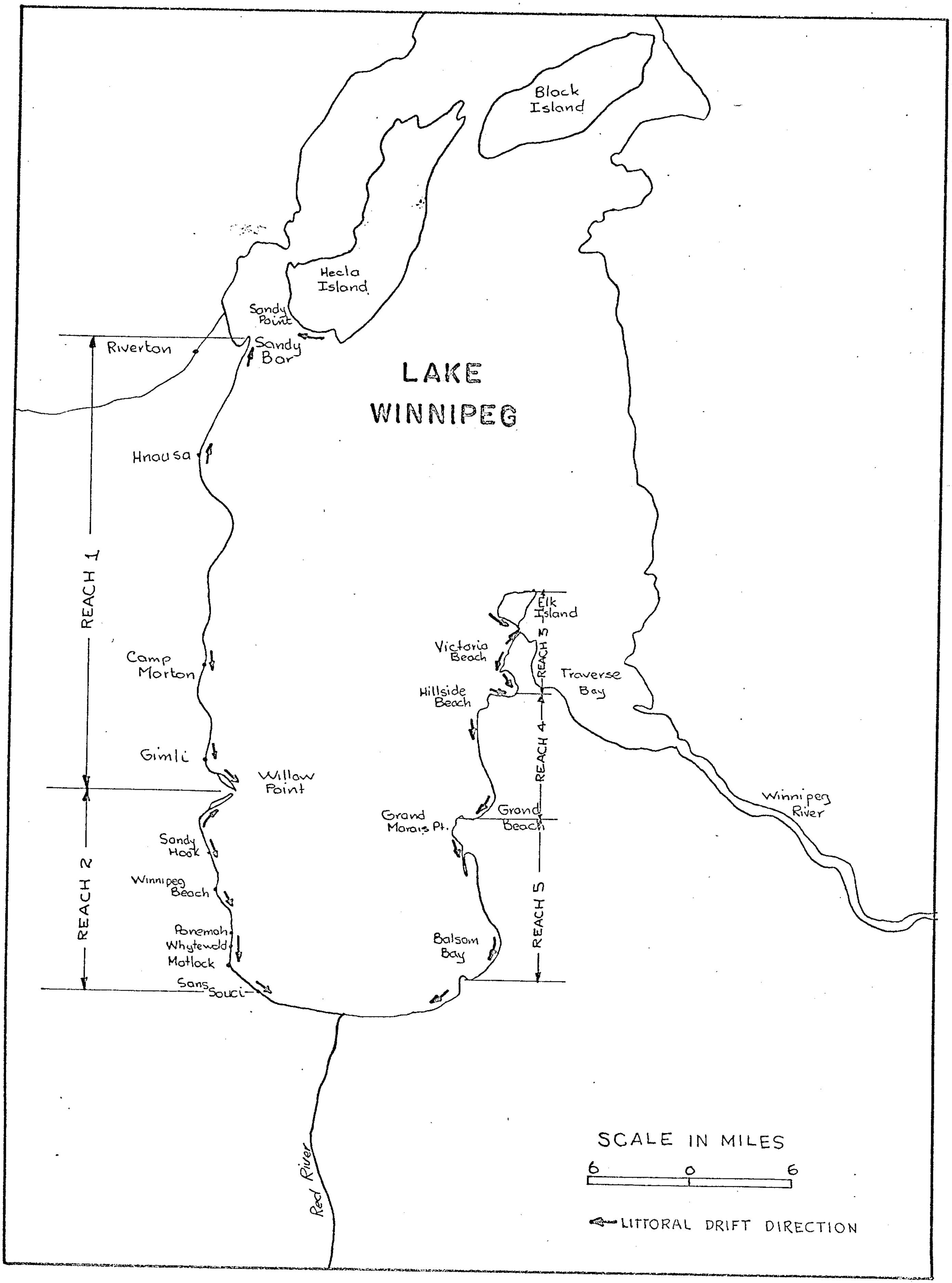
VICTORIA BCH.



GRAND BEACH

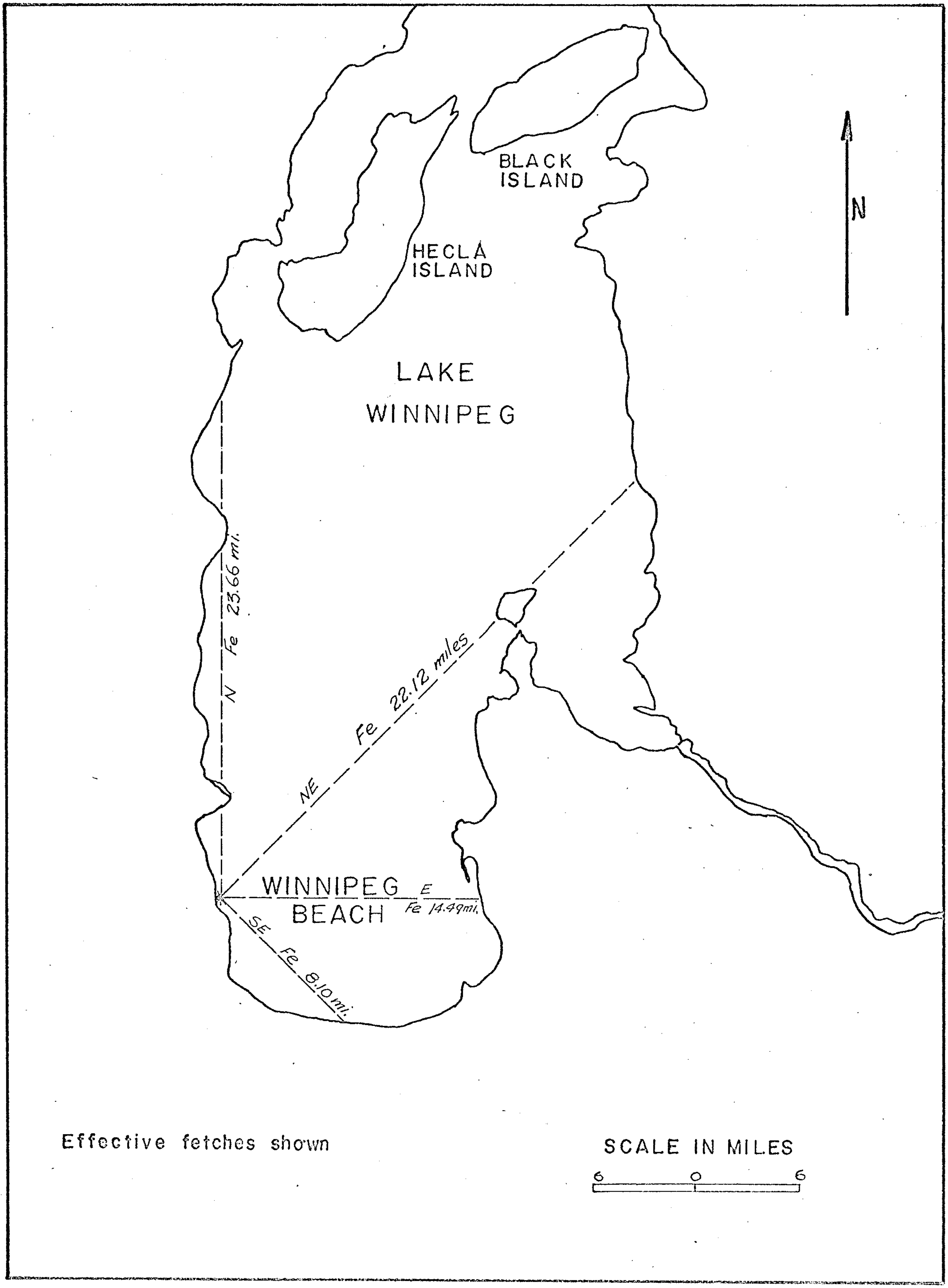
WAVE ENERGY DISTRIBUTION

FIGURE 13



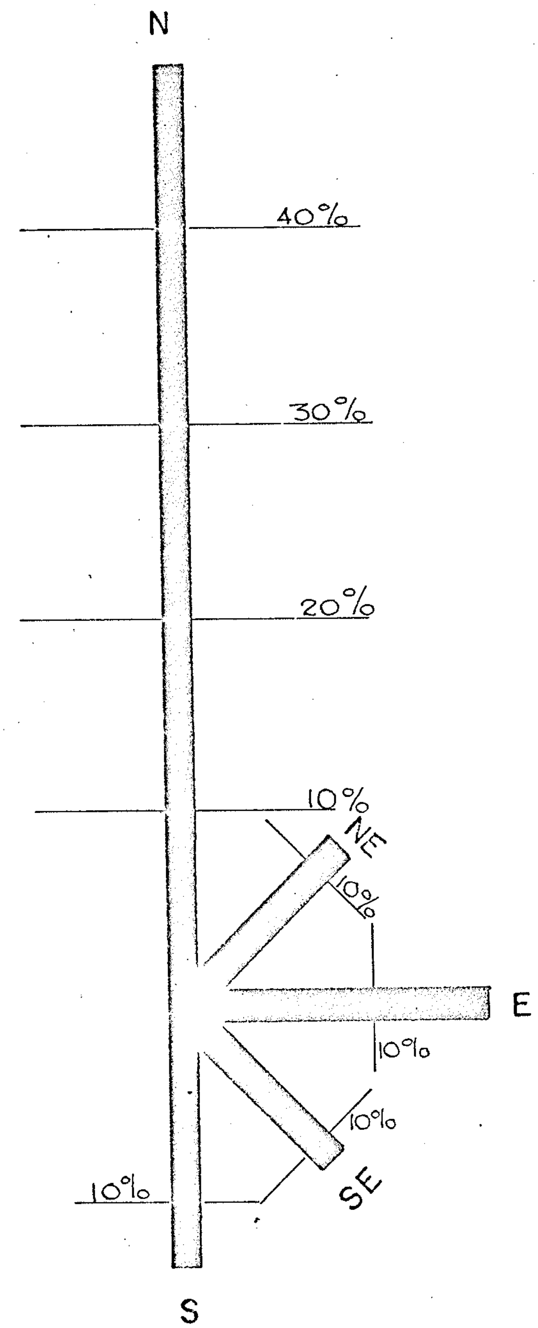
PREDOMINANT LITTORAL DRIFT DIRECTIONS

FIGURE 14



LOCATION MAP, WINNIPEG BEACH

FIGURE 15



WAVE ENERGY DISTRIBUTION, WINNIPEG BEACH

FIGURE 16

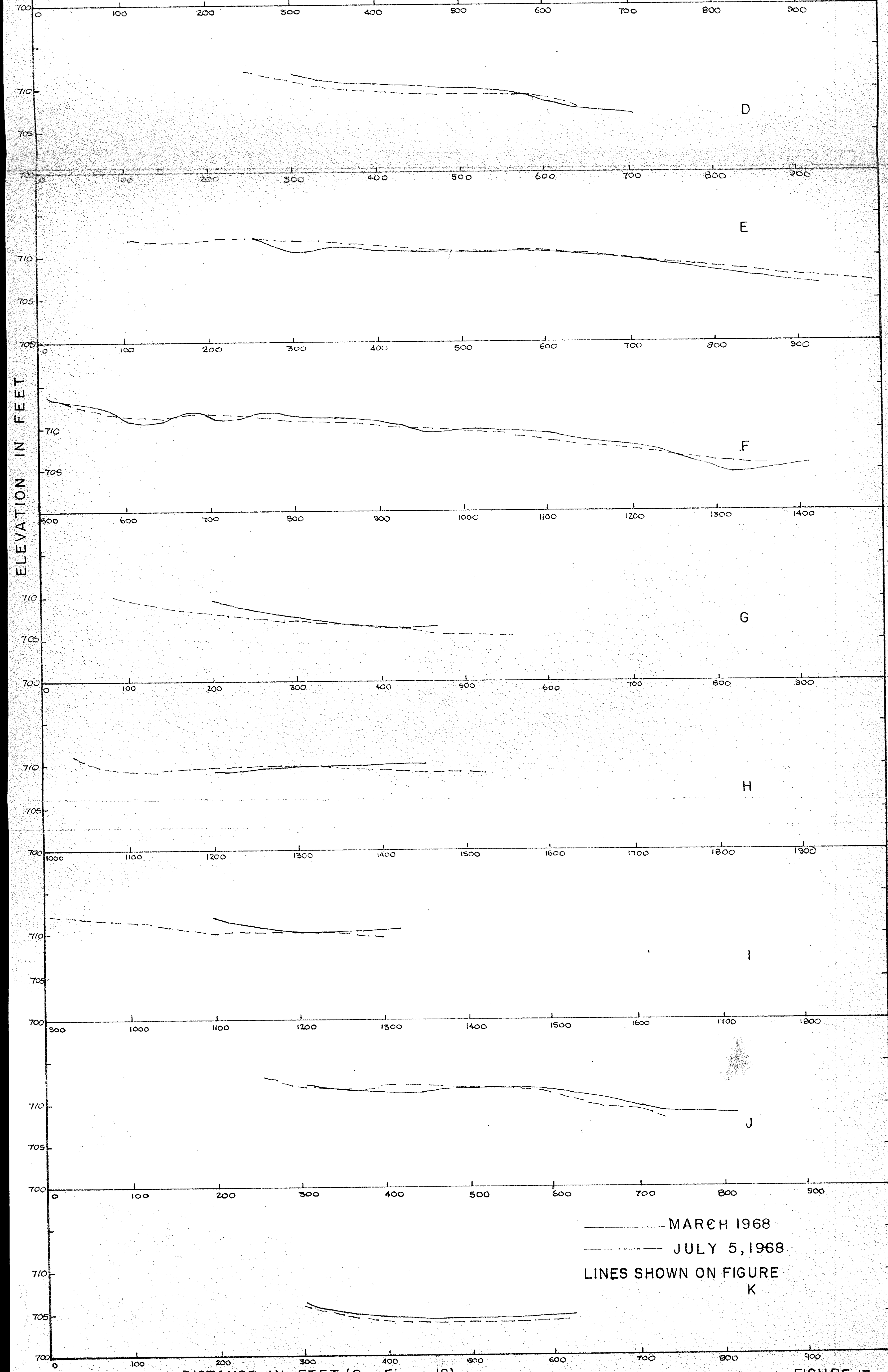
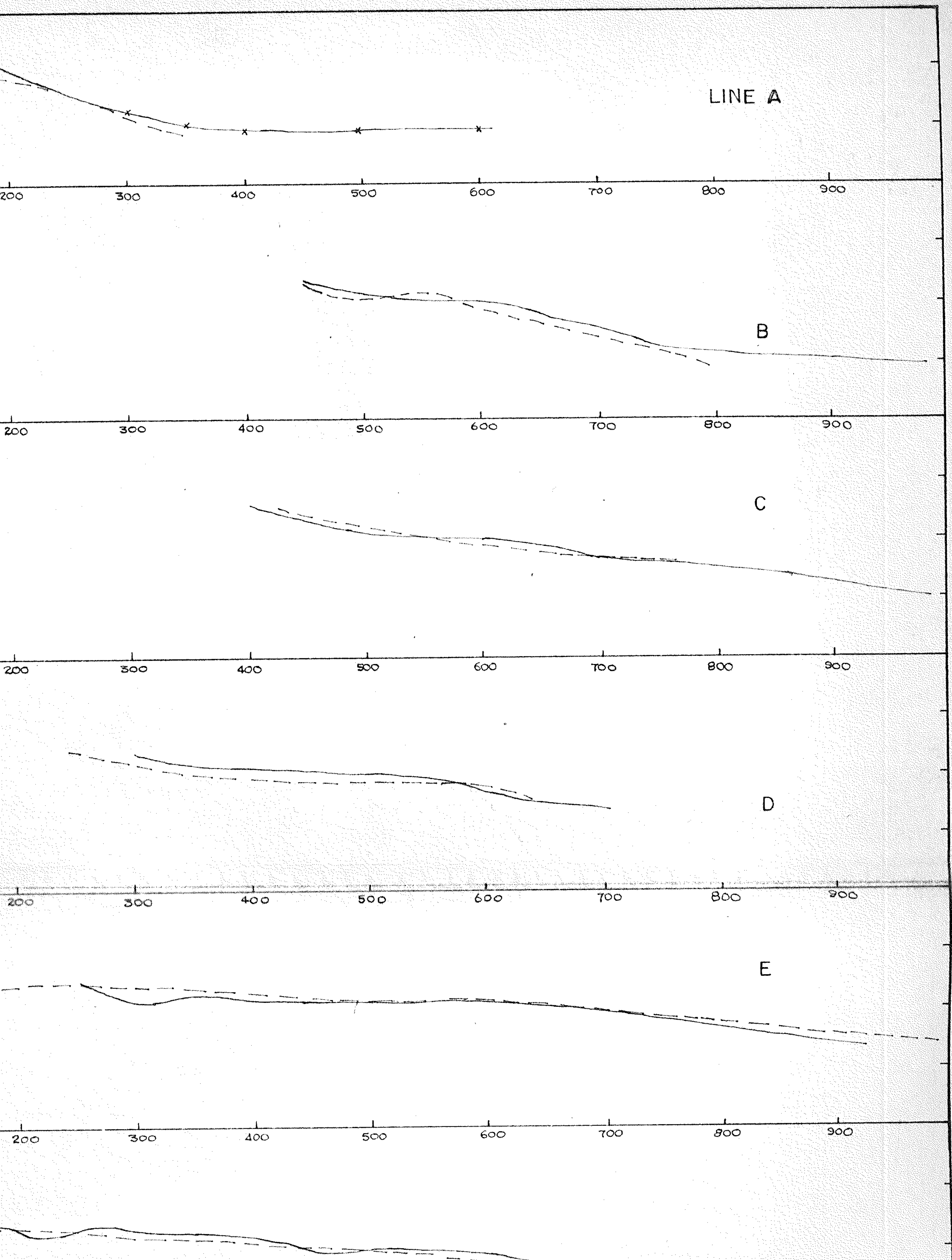
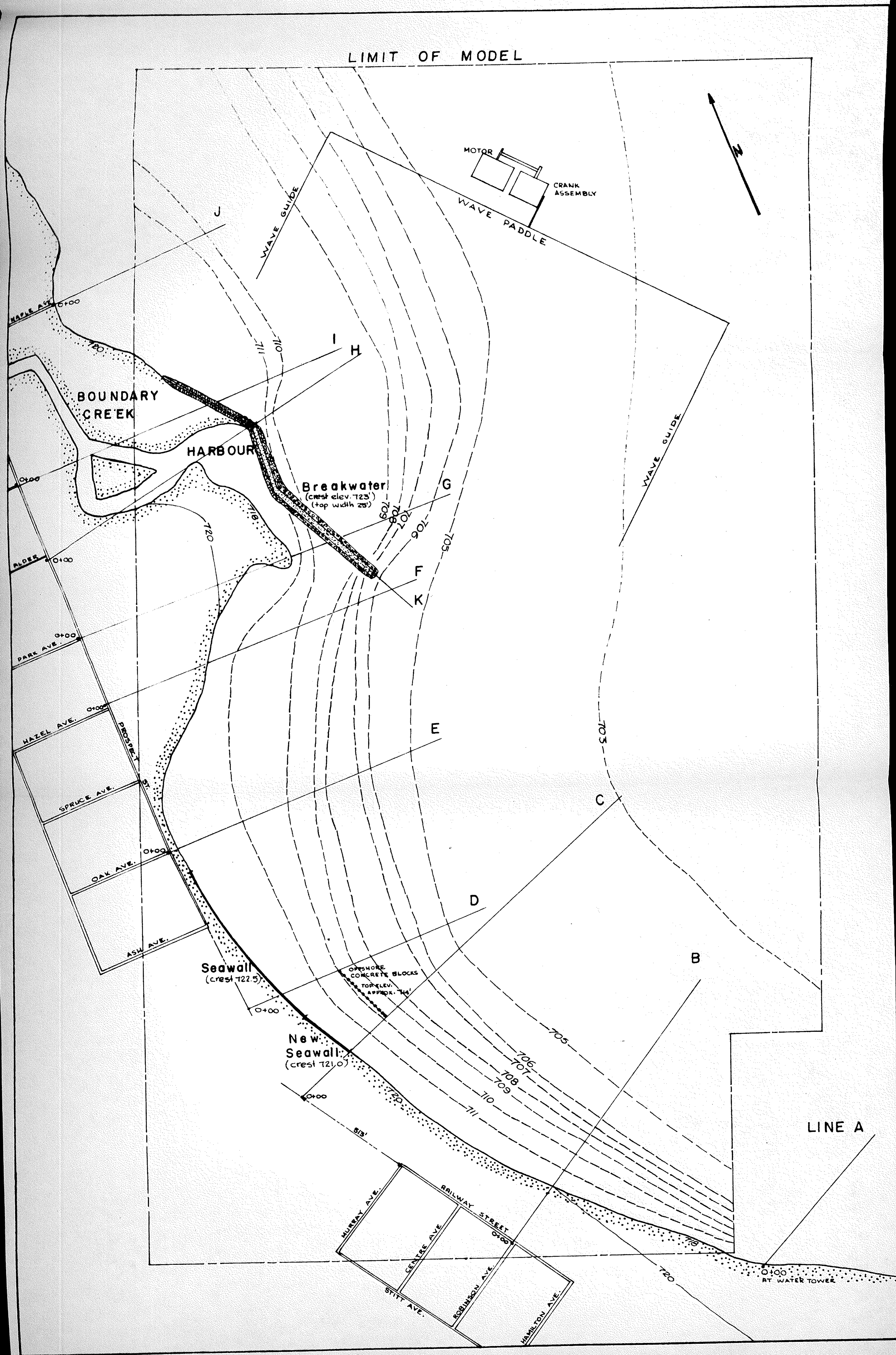


FIGURE 17

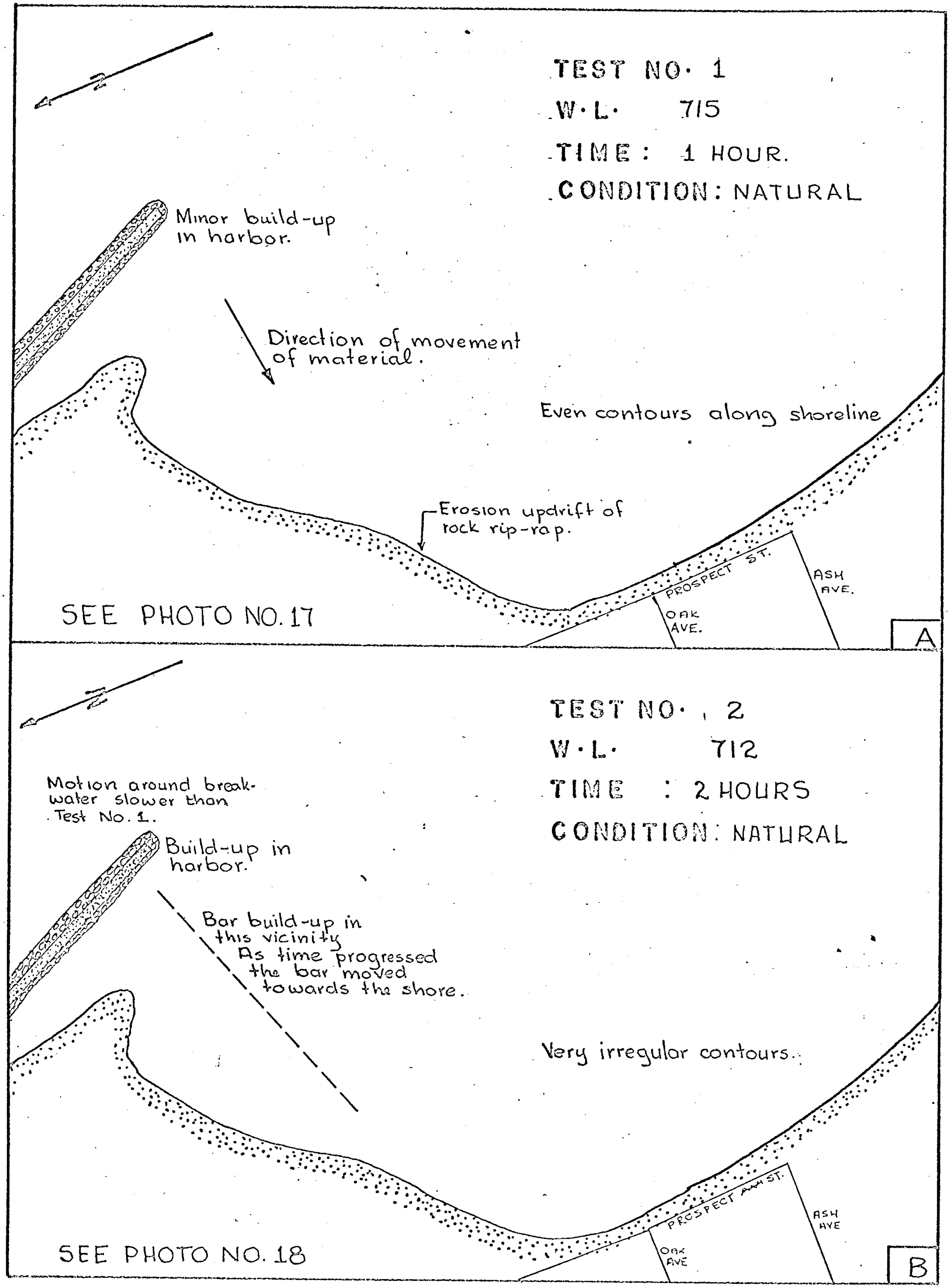
COMPARISON OF PROFILES, WINNIPEG BEACH



LINE A
B
C
D
E
200
300
400
500
600
700
800
900

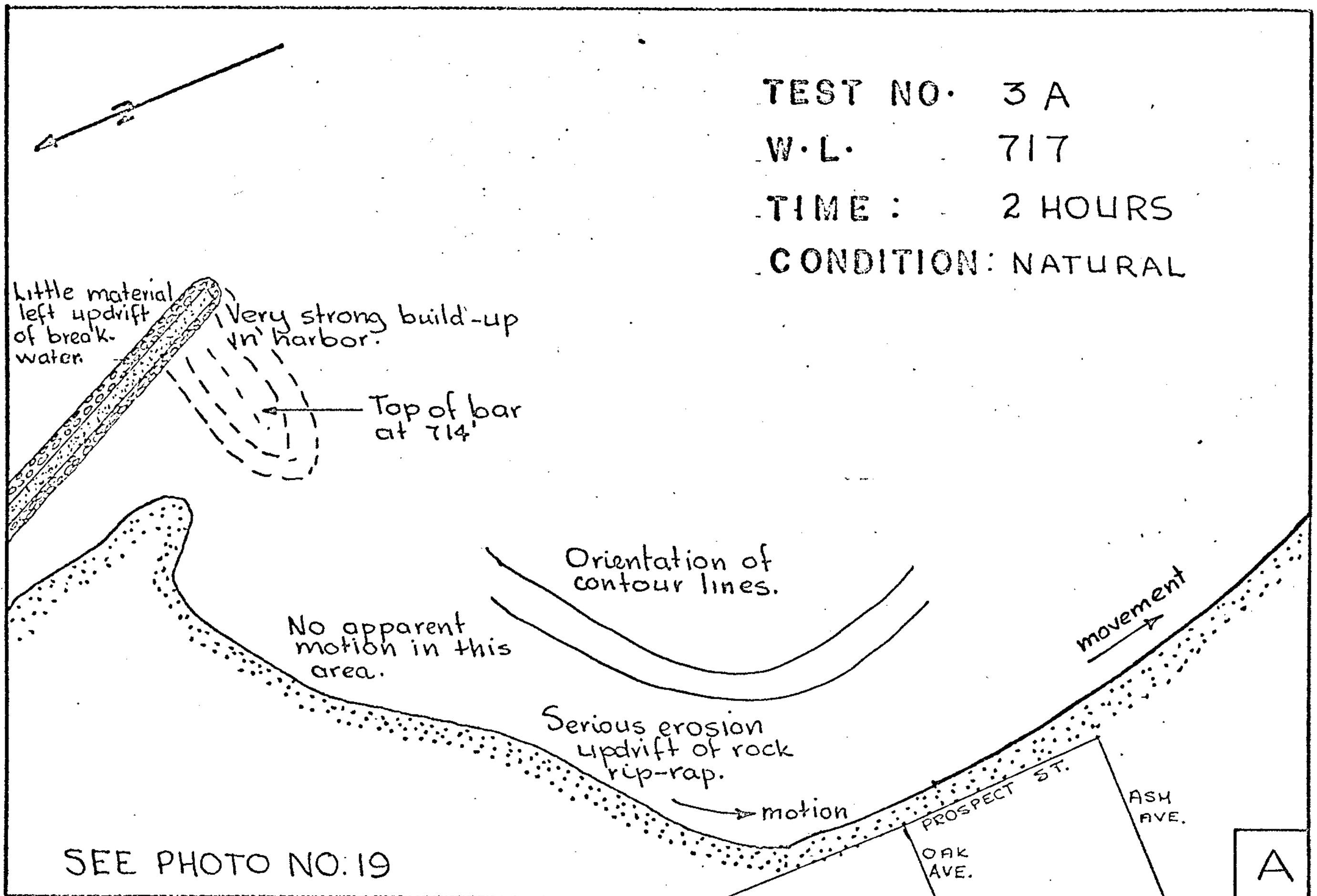


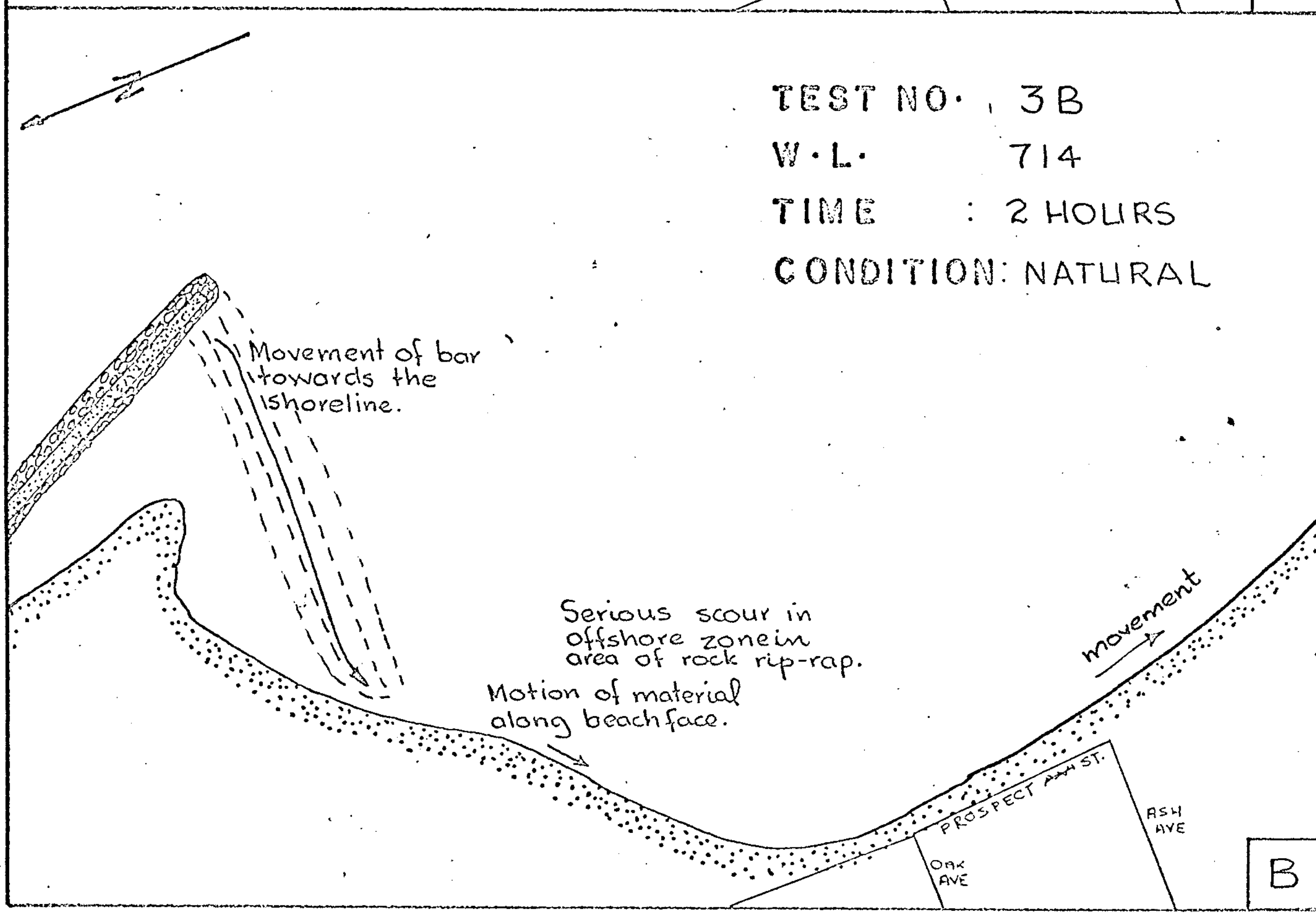
... WINNIPEG BEACH MODEL STUDY



MODEL STUDY RESULTS

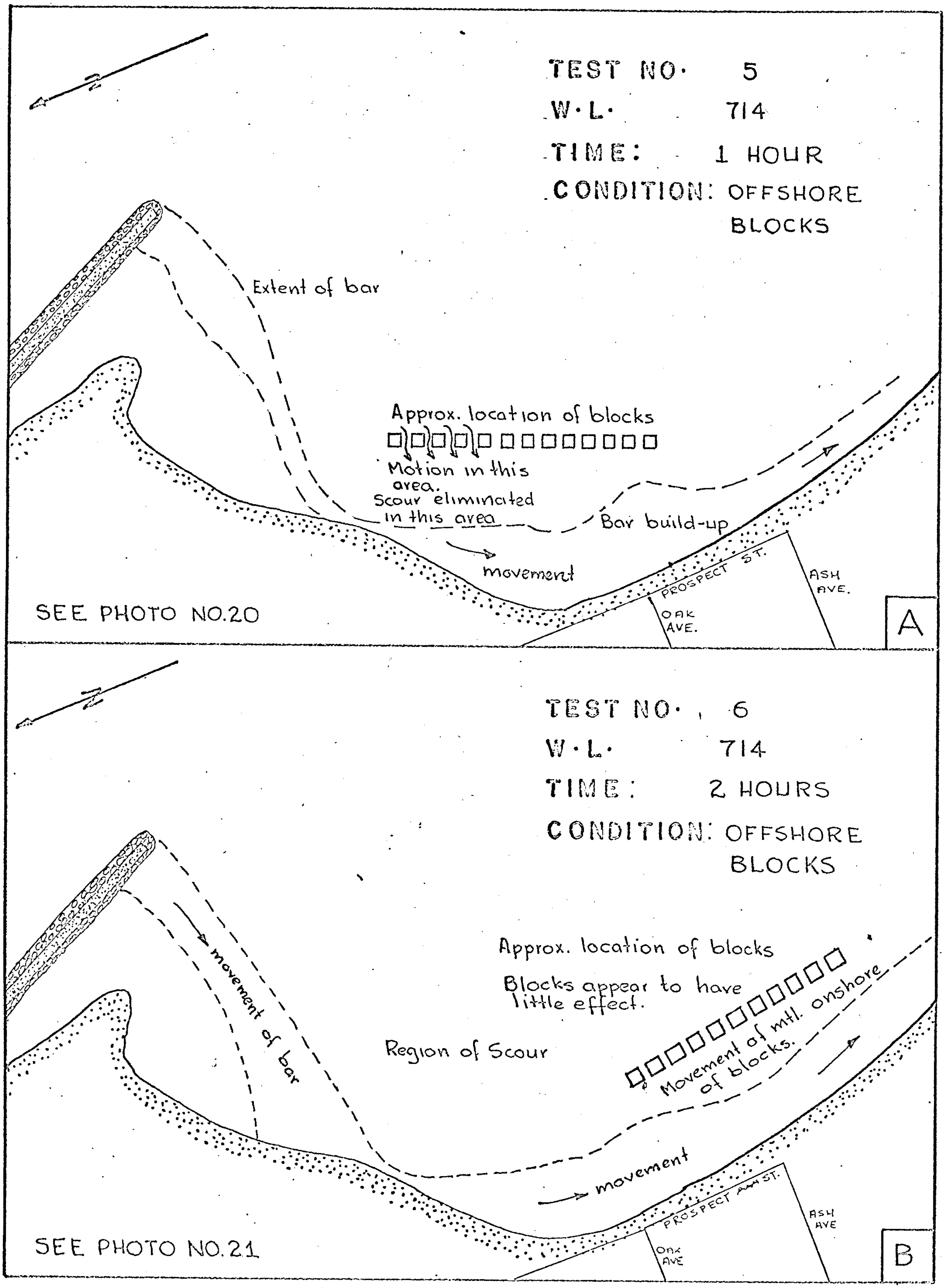
FIGURE 19





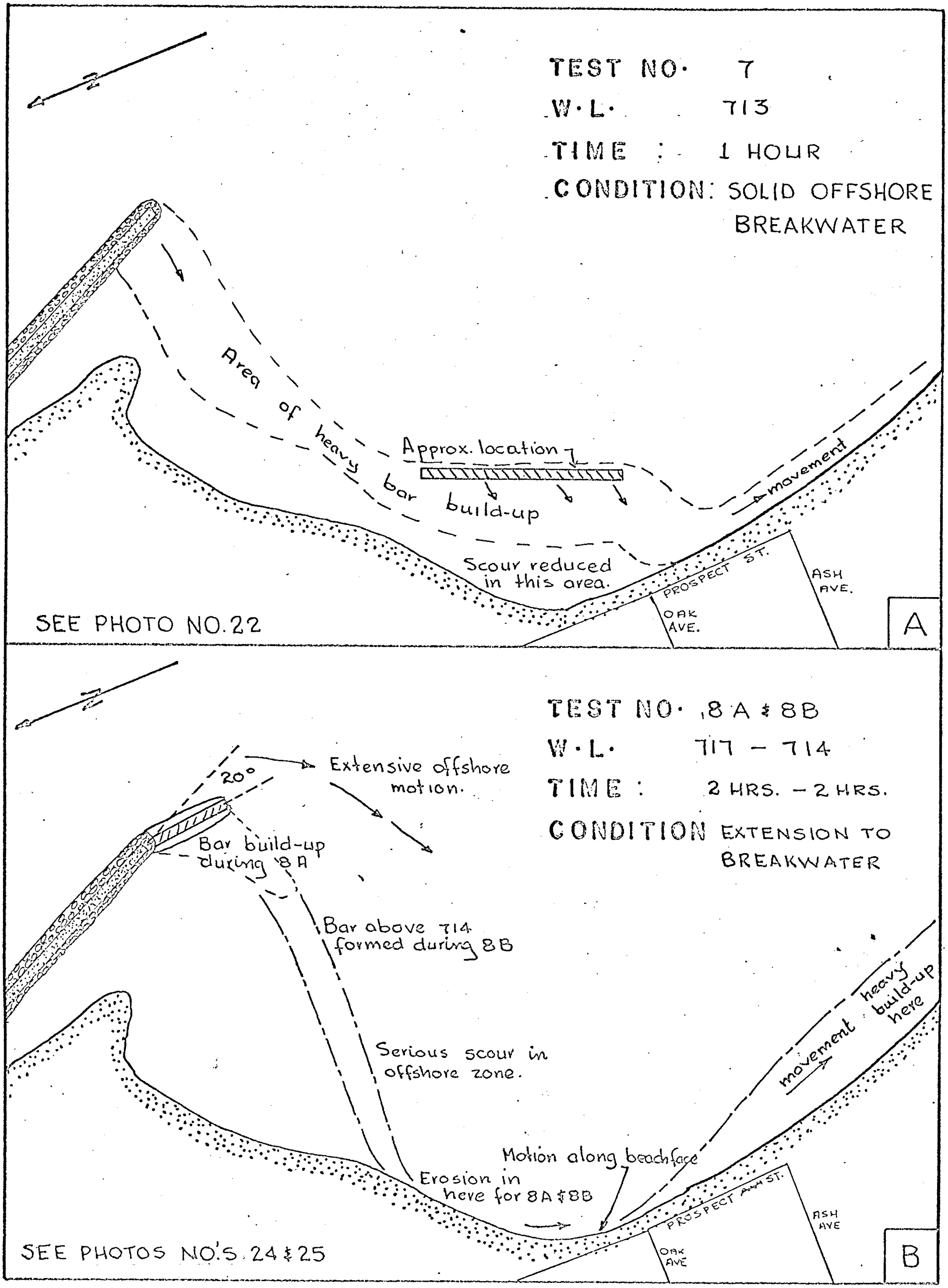
MODEL STUDY RESULTS

FIGURE 20



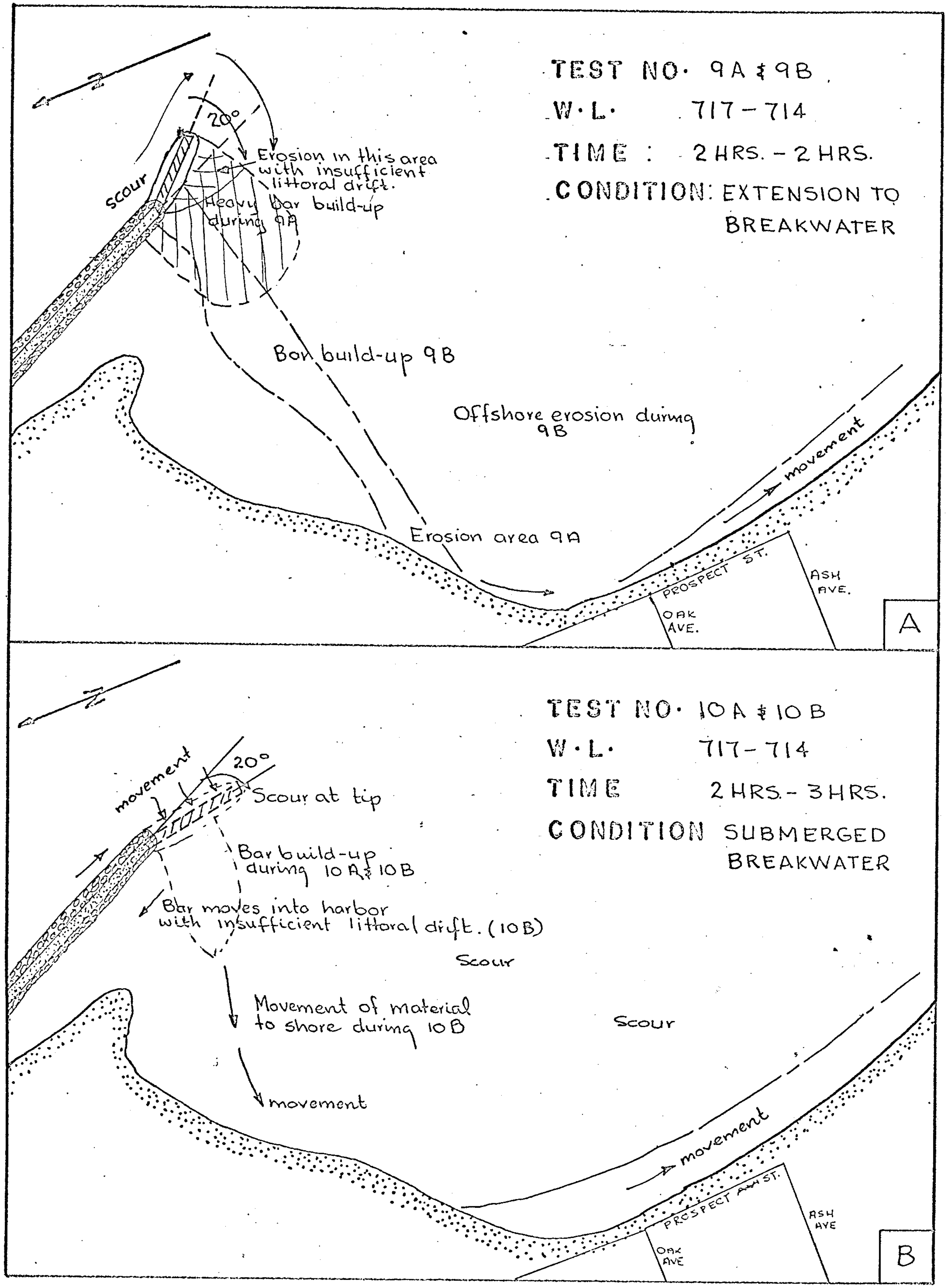
MODEL STUDY RESULTS

FIGURE 21



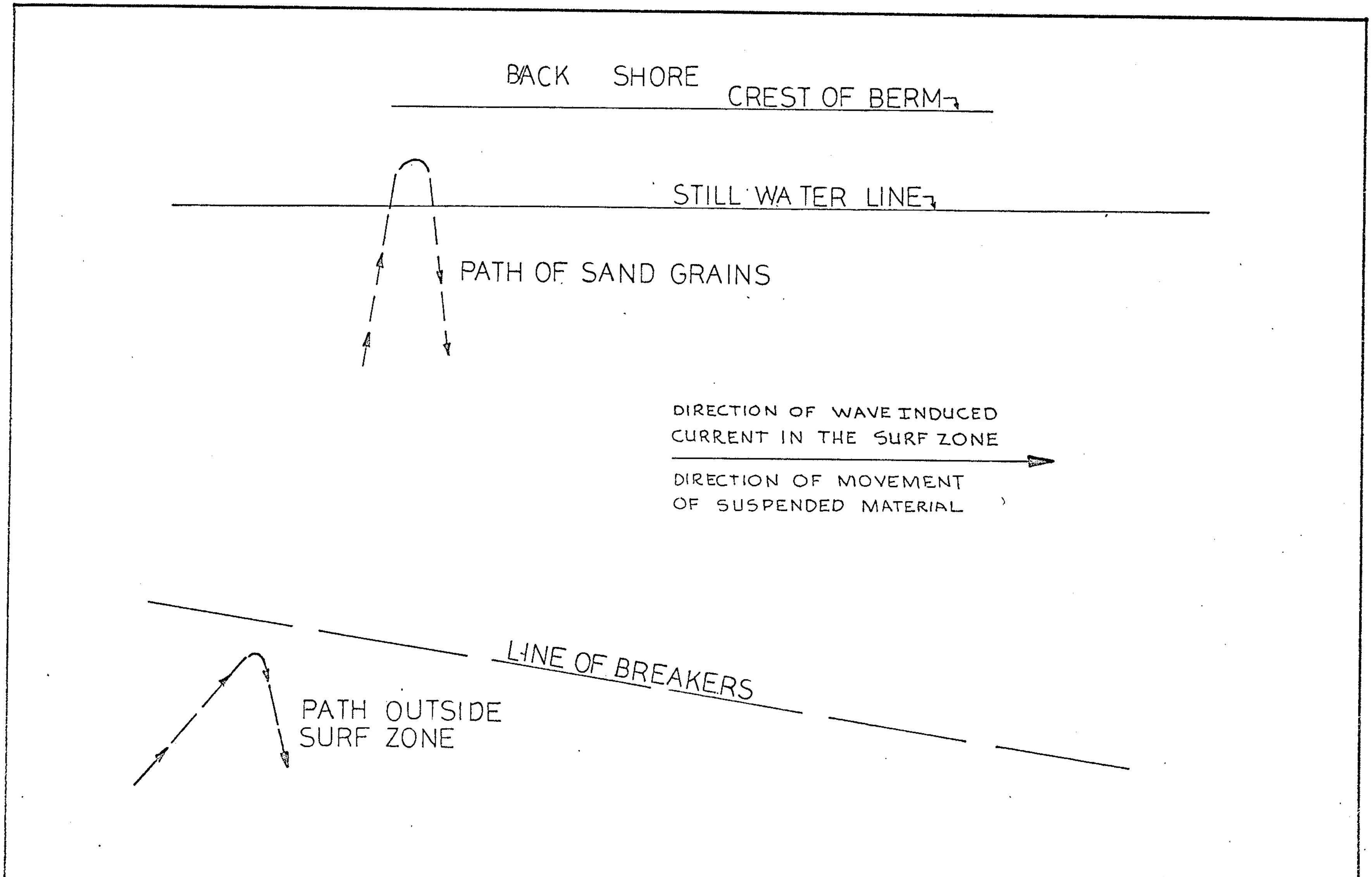
MODEL STUDY RESULTS

FIGURE 22

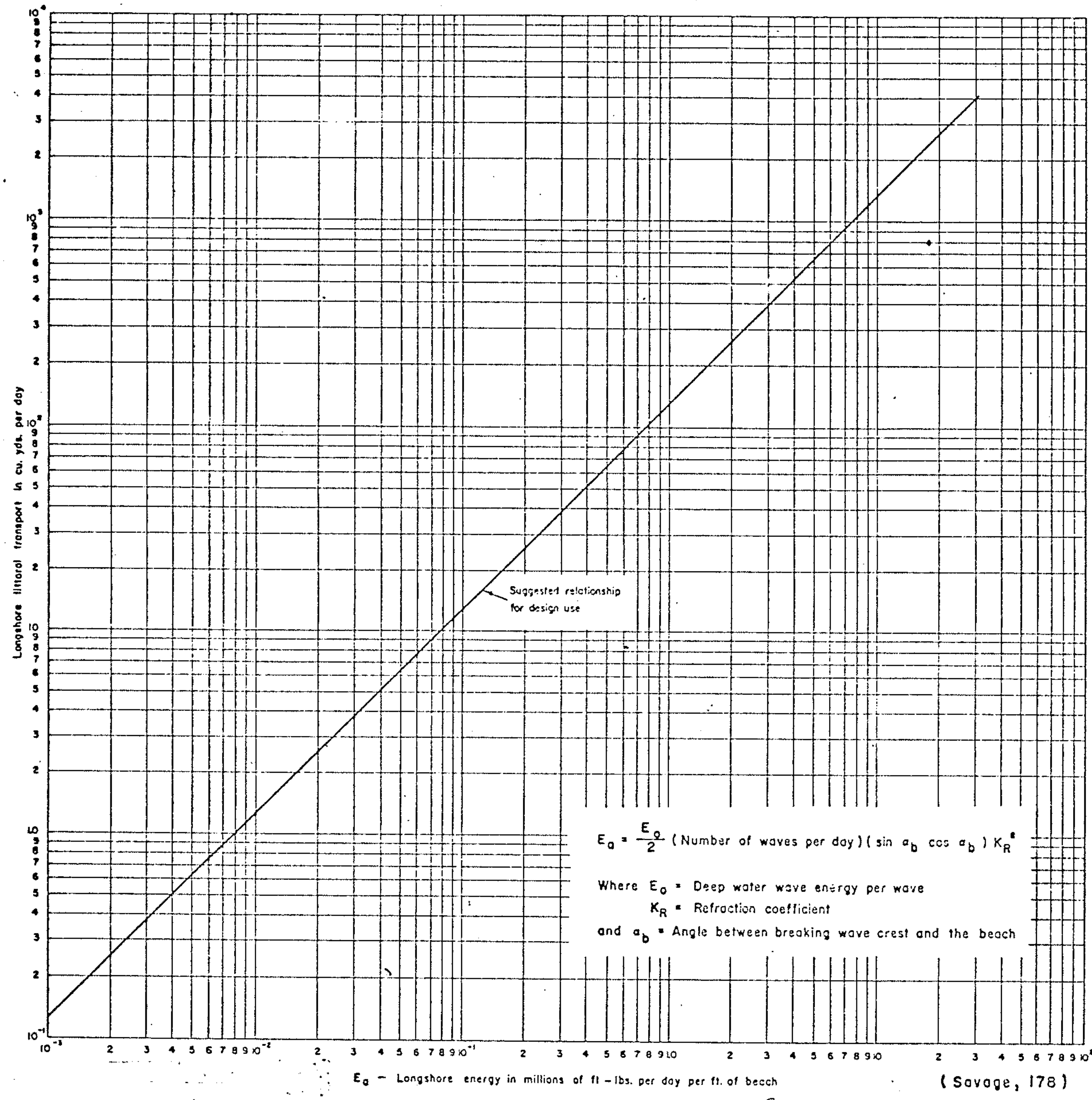


MODEL STUDY RESULTS

FIGURE 23



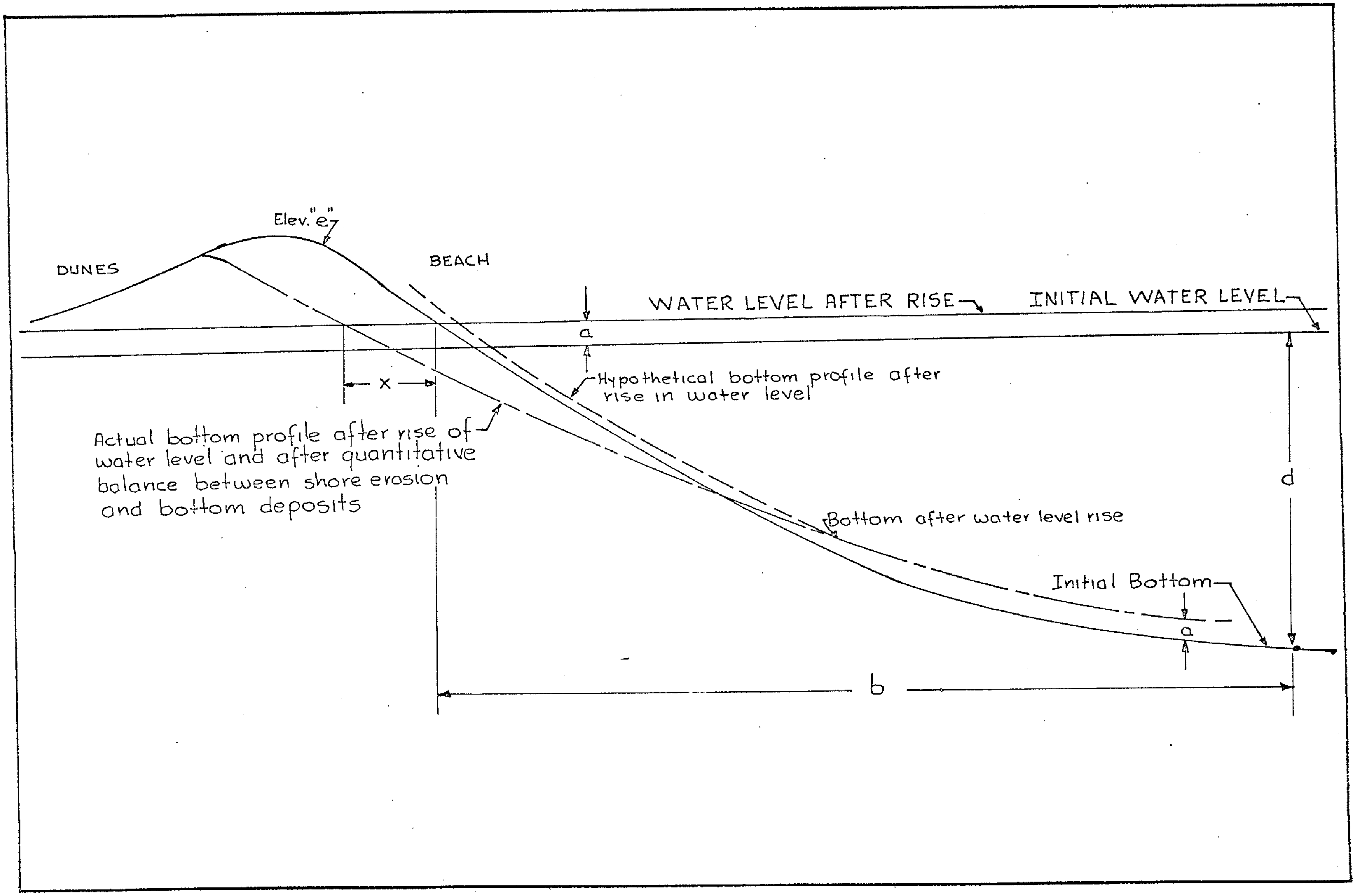
LONGSHORE MOVEMENT OF LITTORAL DRIFT (REF 16)



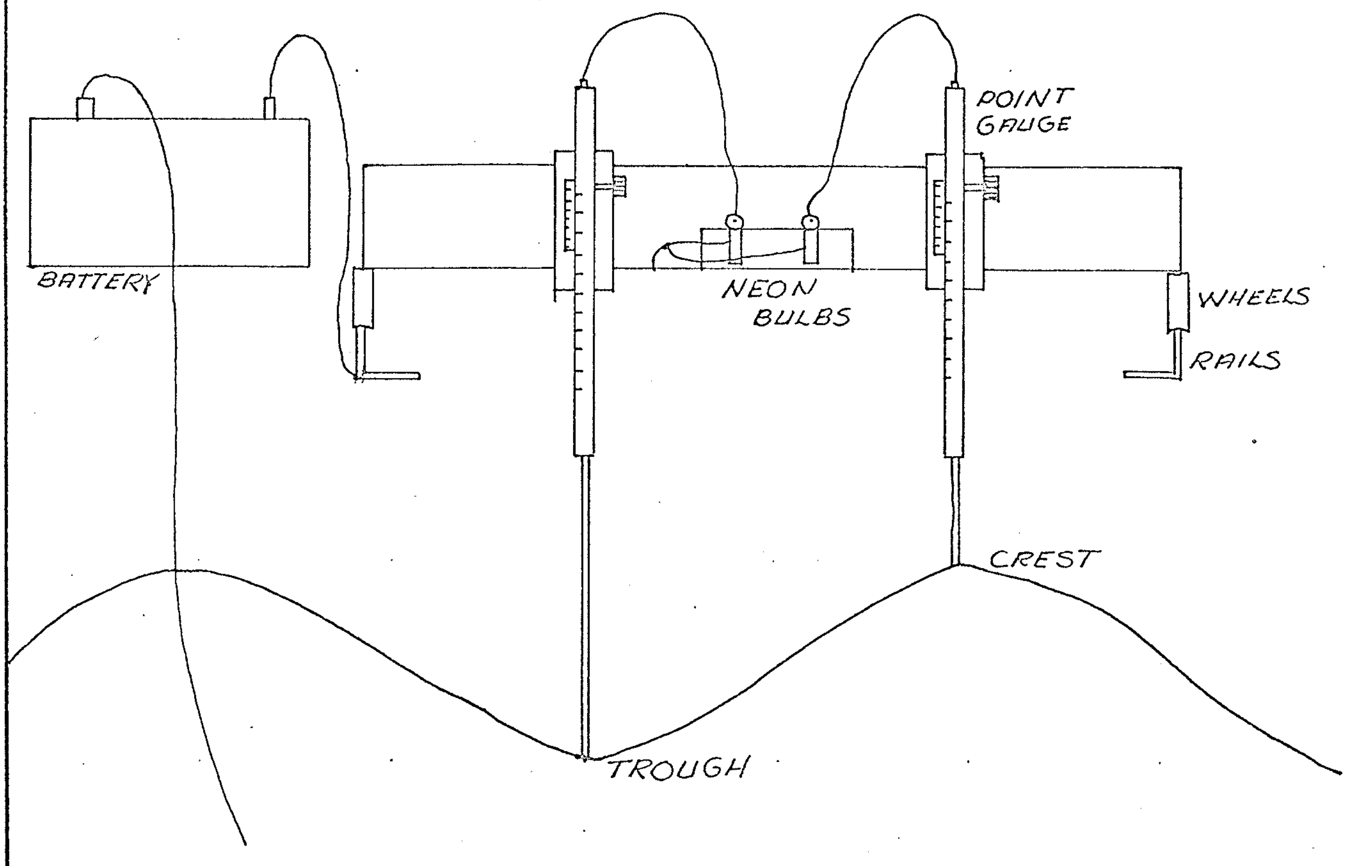
(Savage, 178)

RELATION BETWEEN LONGSHORE COMPONENT OF WAVE ENERGY AND LITTORAL TRANSPORT RATE

FIGURE D-2

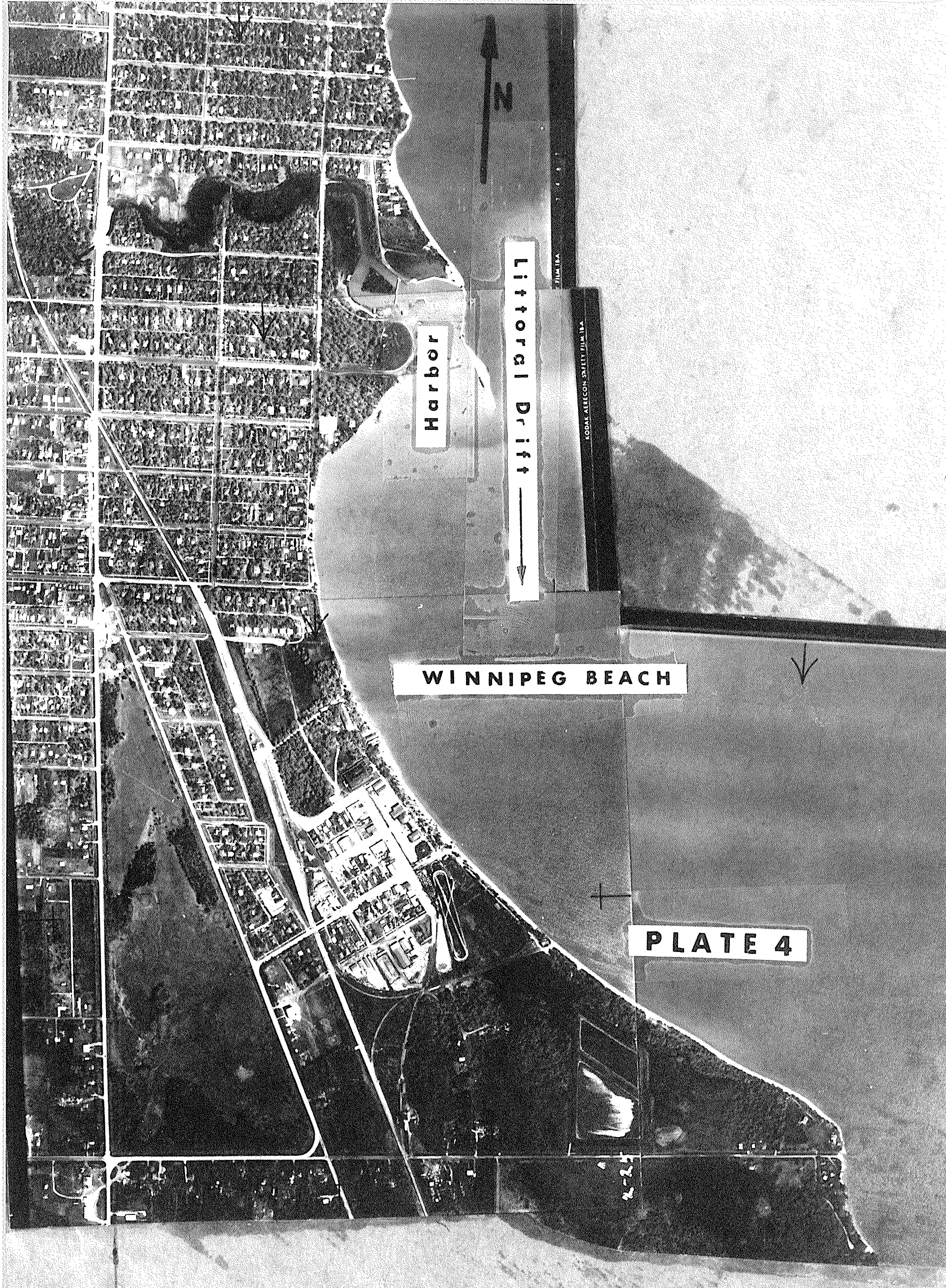


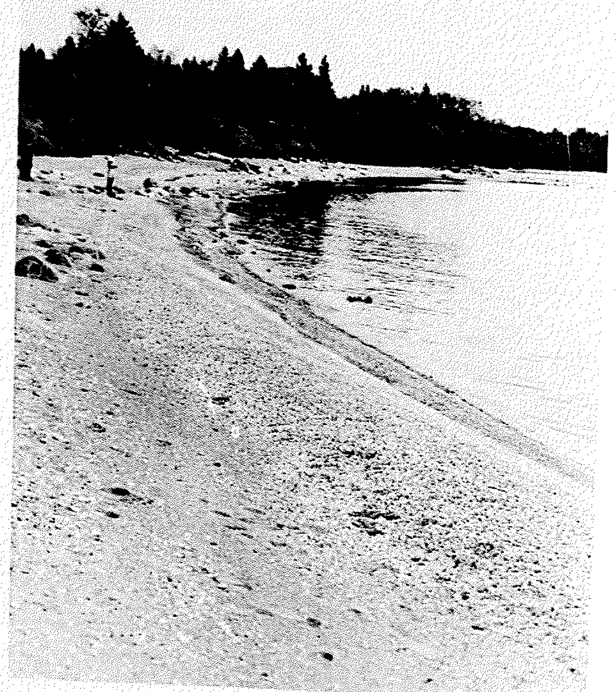
EFFECT OF A RISE IN WATER LEVEL ON BEACH PROFILES



WAVE HEIGHT INDICATOR

FIGURE C-1


N
Harbor
Littoral Drift
WINNIPEG BEACH
PLATE 4



PHOTOGRAPH NO. 1

Camp Morton, looking northward. Note serious bluff erosion and pebbly beach. Rock groins are visible in the background.

PHOTOGRAPH NO. 2

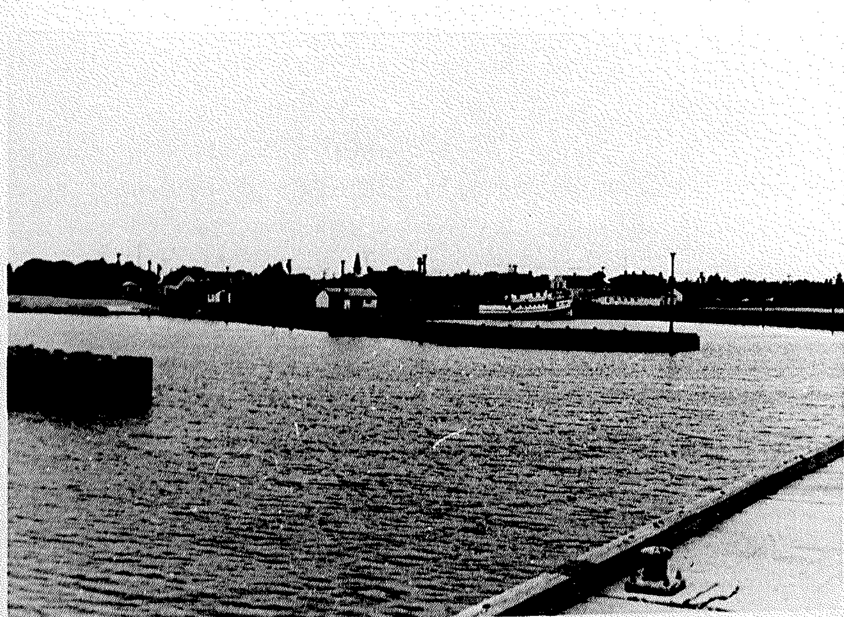
Camp Morton, looking northward.

June 1968.

PHOTOGRAPH NO. 3

Gimli Beach looking southward from Loni Beach to the harbor.

June 1968.



PHOTOGRAPH NO. 4

Gimli Harbor, looking northwest from end of main pier.

June 1968.

PHOTOGRAPH NO. 5

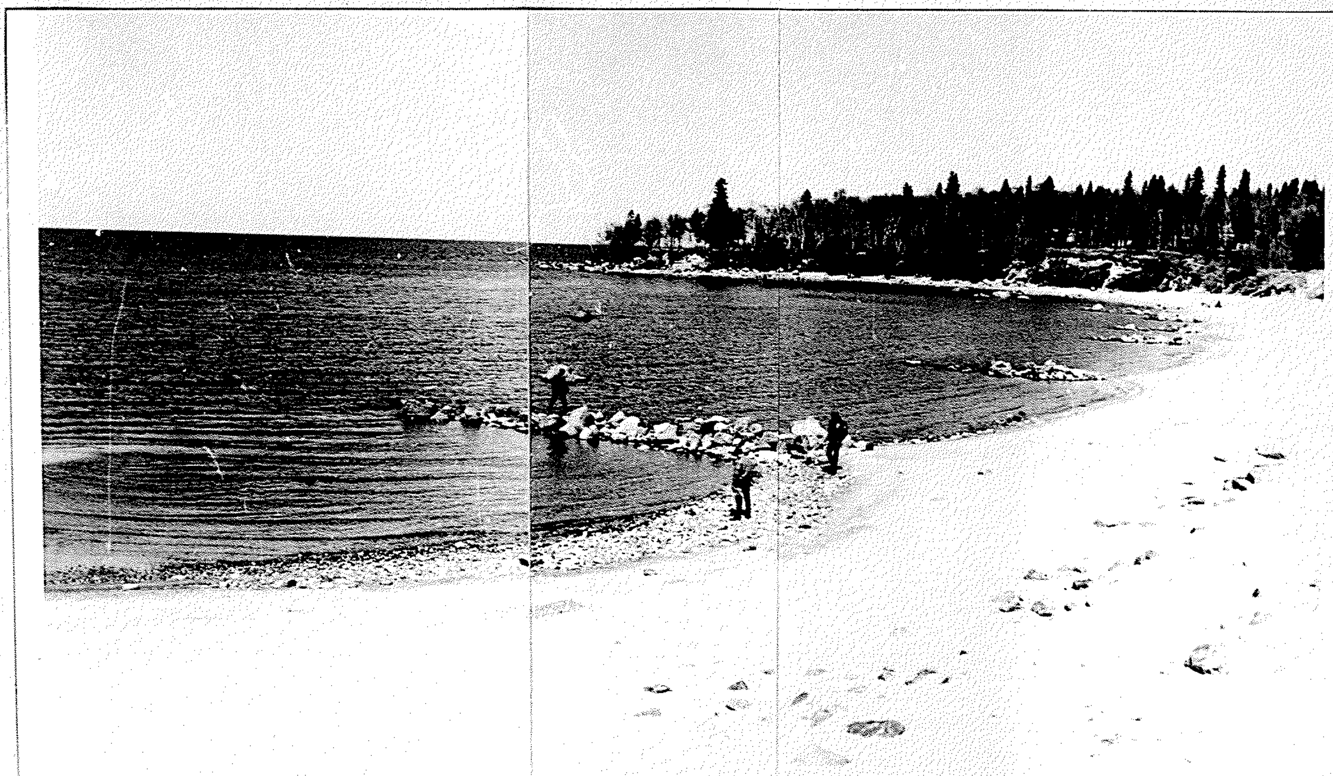
Willow Point, looking east along the entrance road. Note gabions and rock rip-rap used to protect the road.

June 1968.

PHOTOGRAPH NO. 6

Willow Point, looking eastward approximately one mile east of photograph No. 5.

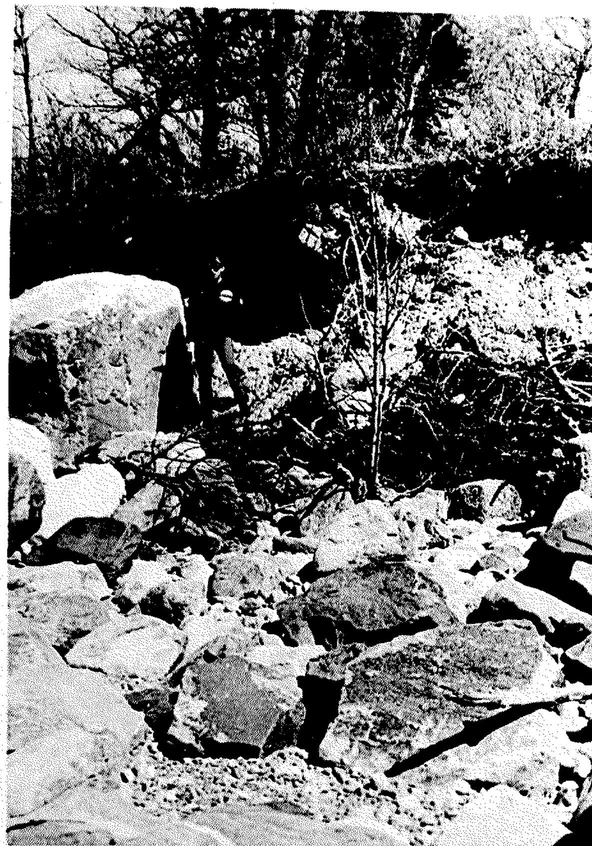
June 1968.



PHOTOGRAPH NO. 7

Victoria Beach, looking northward along the public beach. Note rock groins, fine sand and serious erosion in the background.

May 1968.



PHOTOGRAPH NO. 8

Victoria Beach, north of public beach area. Author standing beside huge boulders.

May 1968.

PHOTOGRAPH NO. 9

Shoreline along Traverse Bay, looking northward toward Victoria Beach.

May 1968.

PHOTOGRAPH NO. 10

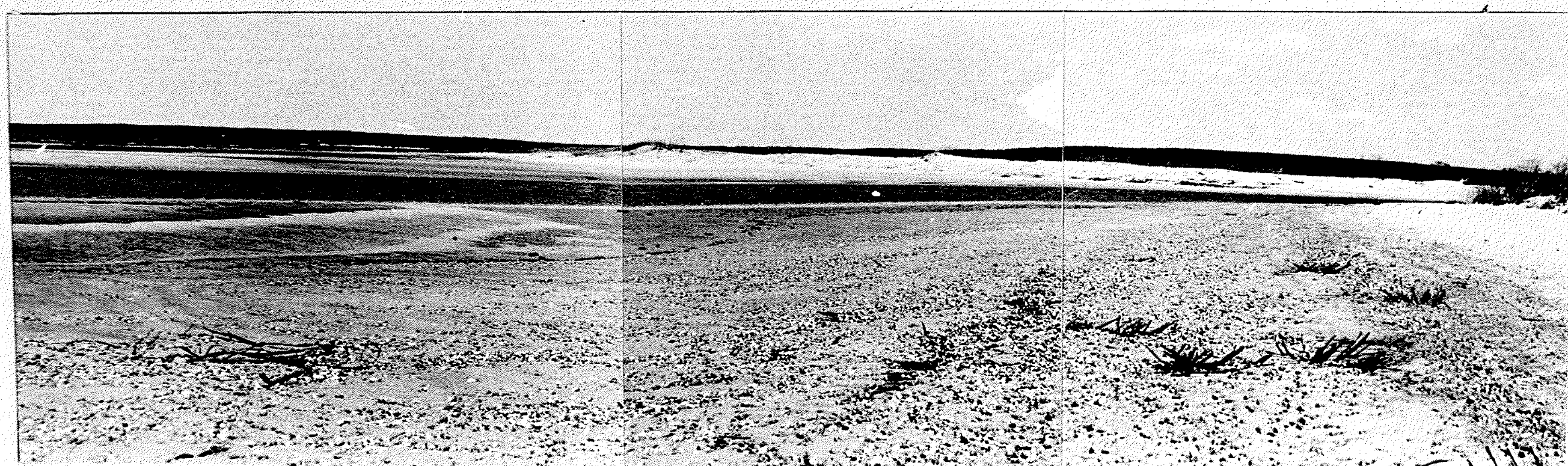
Grand Beach, looking south-east from Grand Marais Point to the public beach.

May 1968.

PHOTOGRAPH NO. 11

North-west point at Grand Beach, looking southward. Note large boulders in foreground and bluff erosion in background.

May 1968.



PHOTOGRAPH NO. 12

Inlet to the lagoon at Grand Beach, looking eastward. Note high sand dunes in the background.

May 1968.

PHOTOGRAPH NO. 13

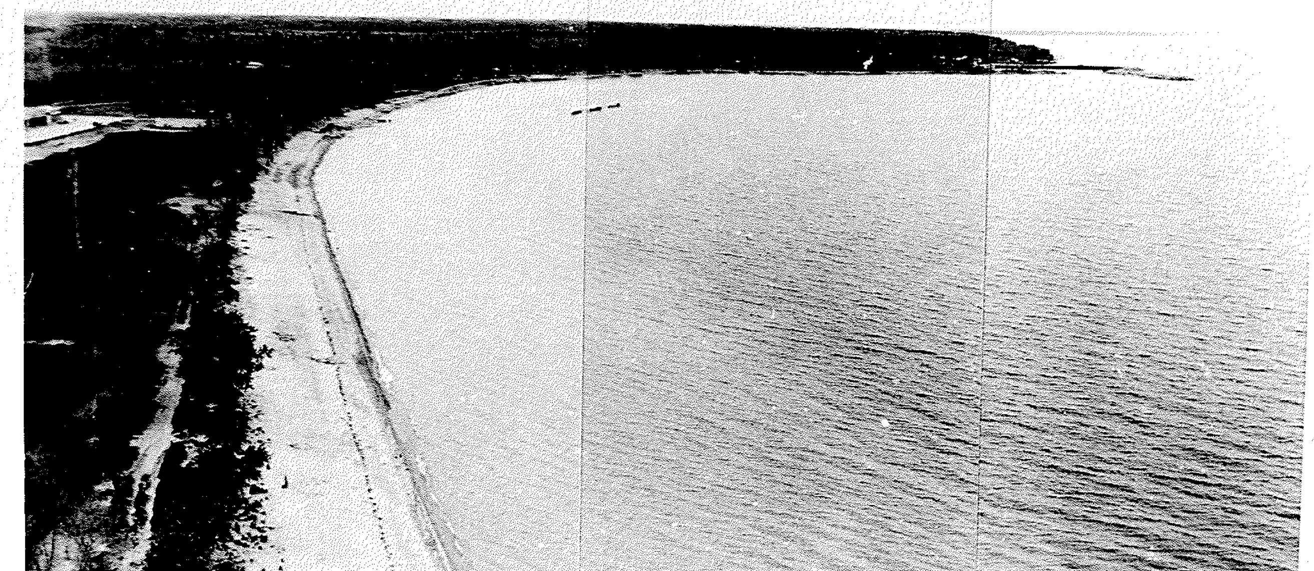
Winnipeg Beach. View of newly constructed seawall, looking northward.

June 1968.

PHOTOGRAPH NO. 14

Winnipeg Beach. View of old portion of seawall. Sand was previously to the level of the second step. Portions of the seawall failed in 1966.

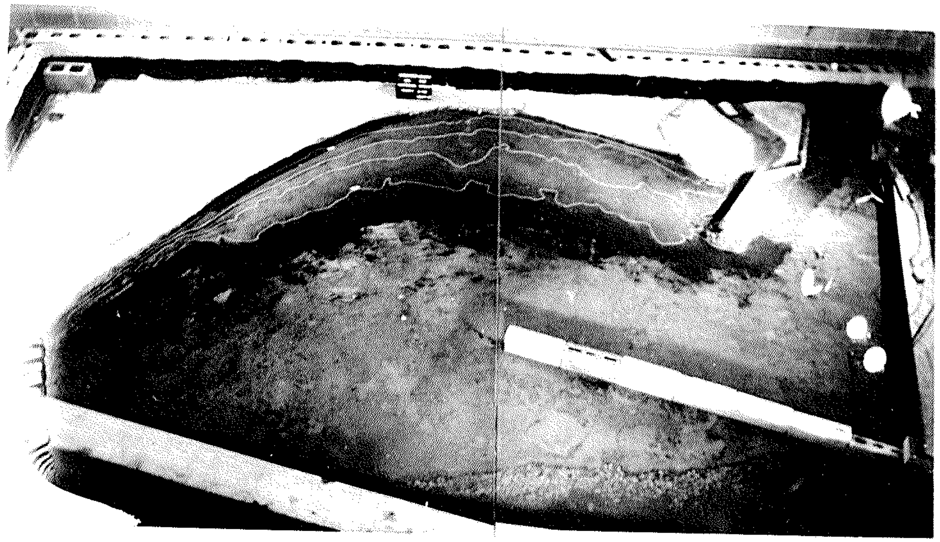
June 1968.



PHOTOGRAPH NO. 15

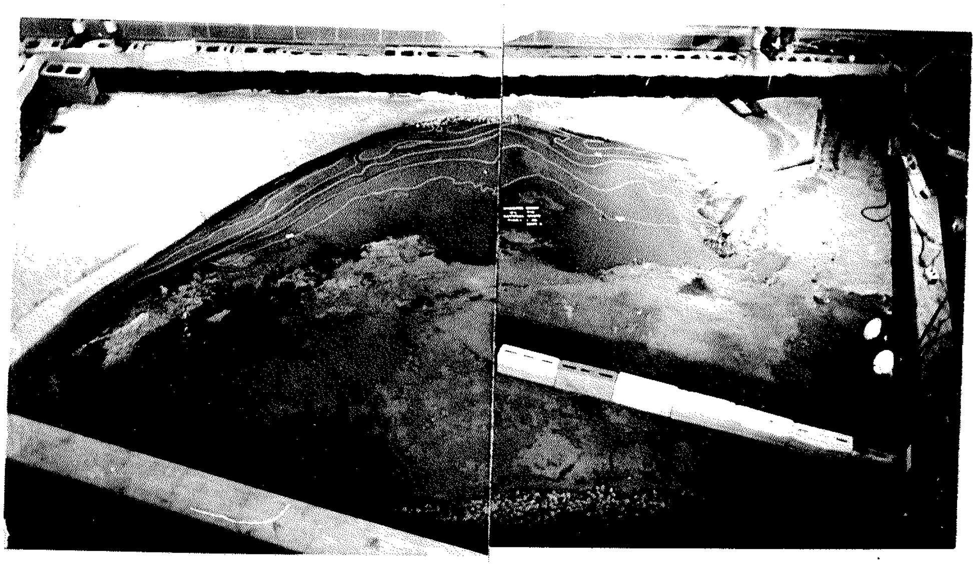
View of Winnipeg Beach looking northward from the water tower. Rock breakwater can be seen in upper right hand corner. Dashed line indicates location of offshore breakwater.

June 1968.



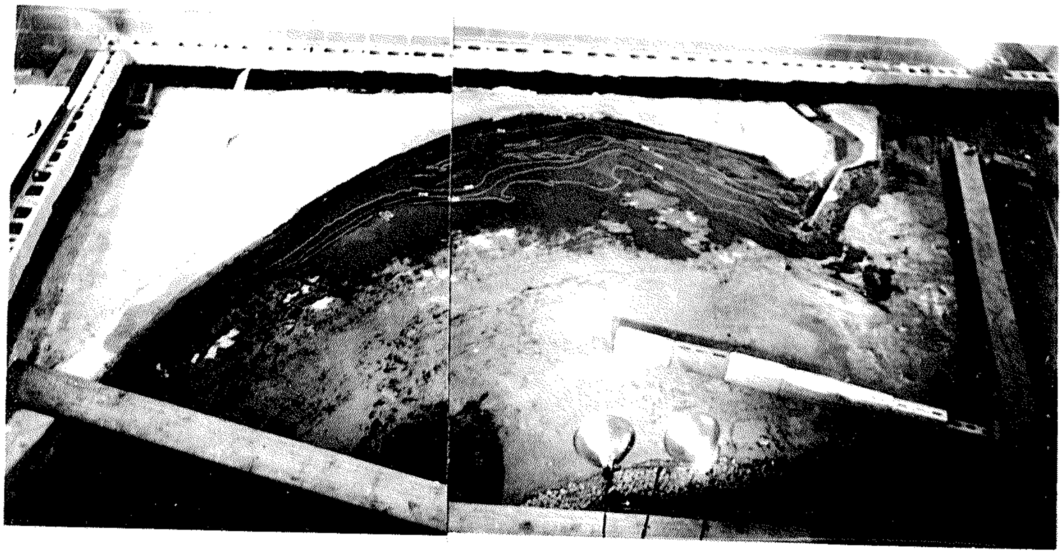
PHOTOGRAPH NO. 16

Contour lines before initiation of test. (Based on March 1968 survey).



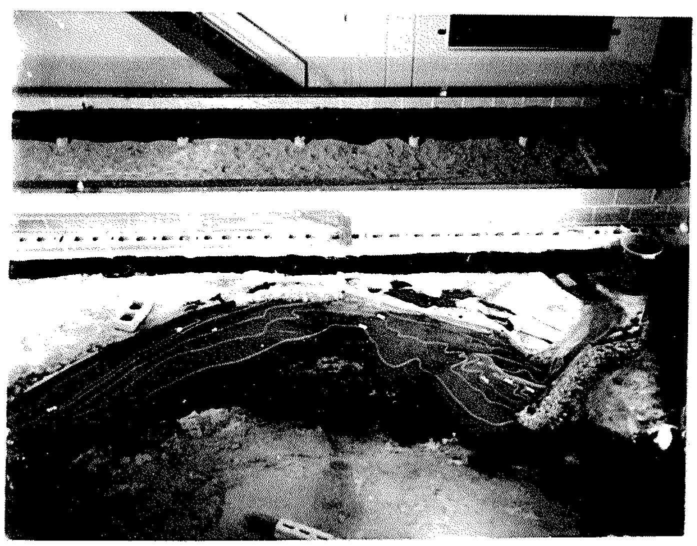
PHOTOGRAPH 17

Contour lines at termination of Test No. 1



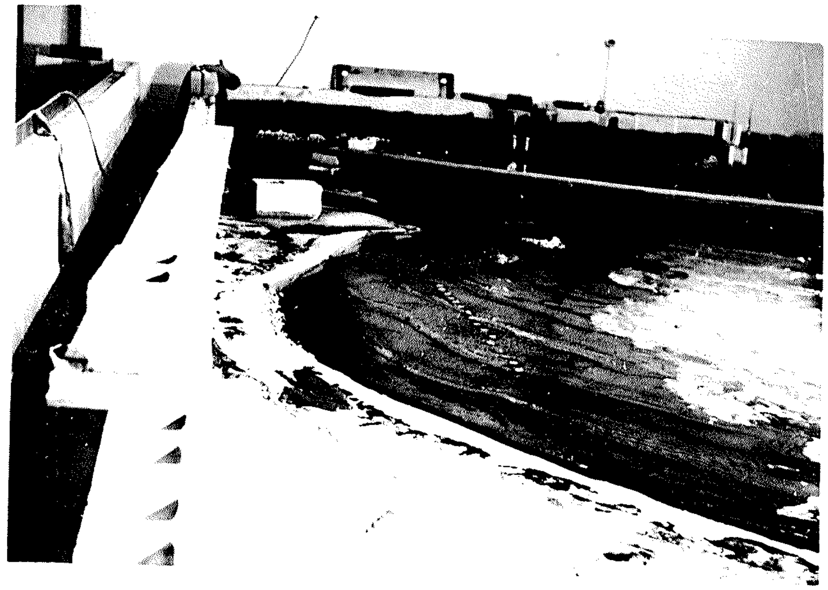
PHOTOGRAPH NO. 18

Contour lines at termination of Test No. 2



PHOTOGRAPH NO. 19

Contour lines at termination of Test No. 3(a). Note heavy bar buildup in harbor and scour near rock rip-rap.



PHOTOGRAPH NO. 20

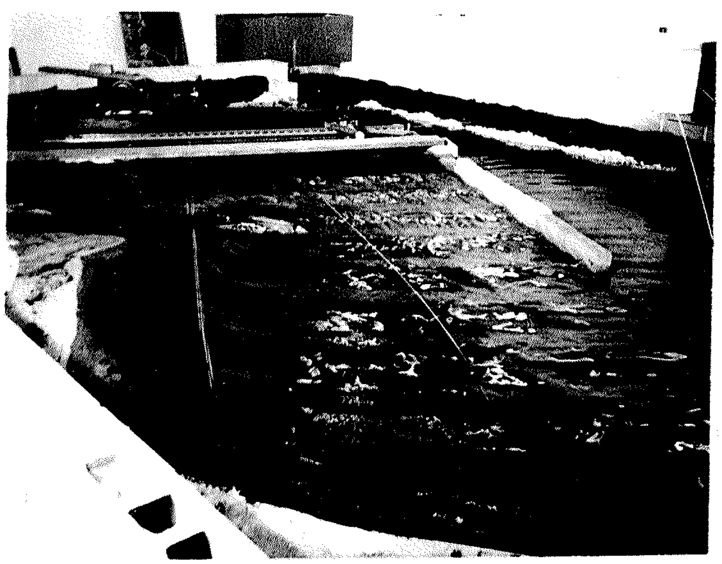
Test No. 5 in progress. Note little effect of blocks on waves.

PHOTOGRAPH NO. 21

Beach condition at termination of Test No. 6. Note negligible deposition onshore of the blocks.

PHOTOGRAPH NO. 22

Beach condition at termination of Test No. 7. Note heavy deposit around breakwater.



PHOTOGRAPH NO. 23

Wave action with extension of breakwater 20° into entrance.

PHOTOGRAPH NO. 24

Contour lines at termination of Test No. 8(a). Note bar buildup in harbor.

PHOTOGRAPH NO. 25

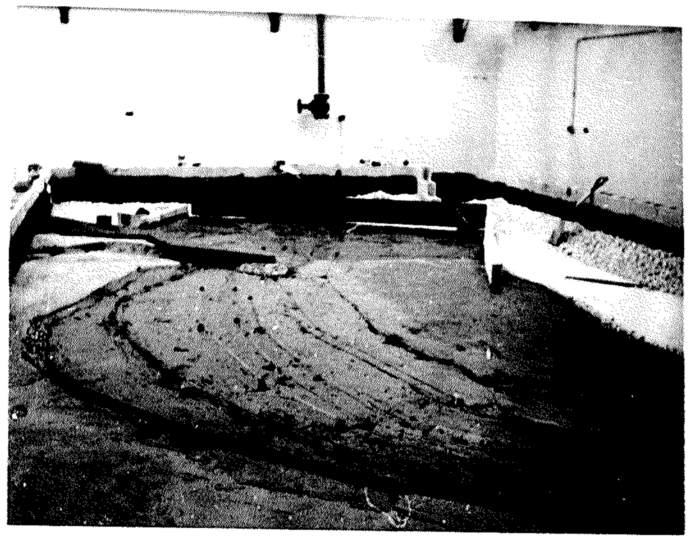
Contour lines at termination of Test No. 8(b). Note that bar of 8(a) has extended to the beach.

PHOTOGRAPH NO. C-1

Grid System laid out on the basin floor.
Aug. 1968

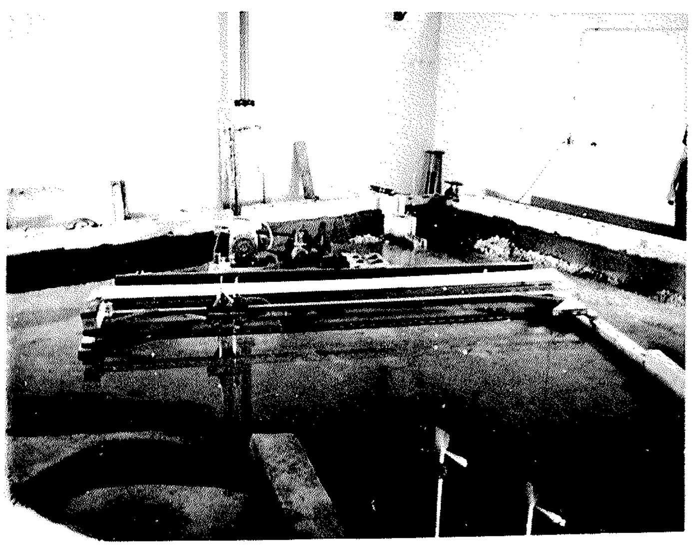
PHOTOGRAPH NO. C-2

Contours laid out and wooden supports for contour lines in place.
Aug. 1968



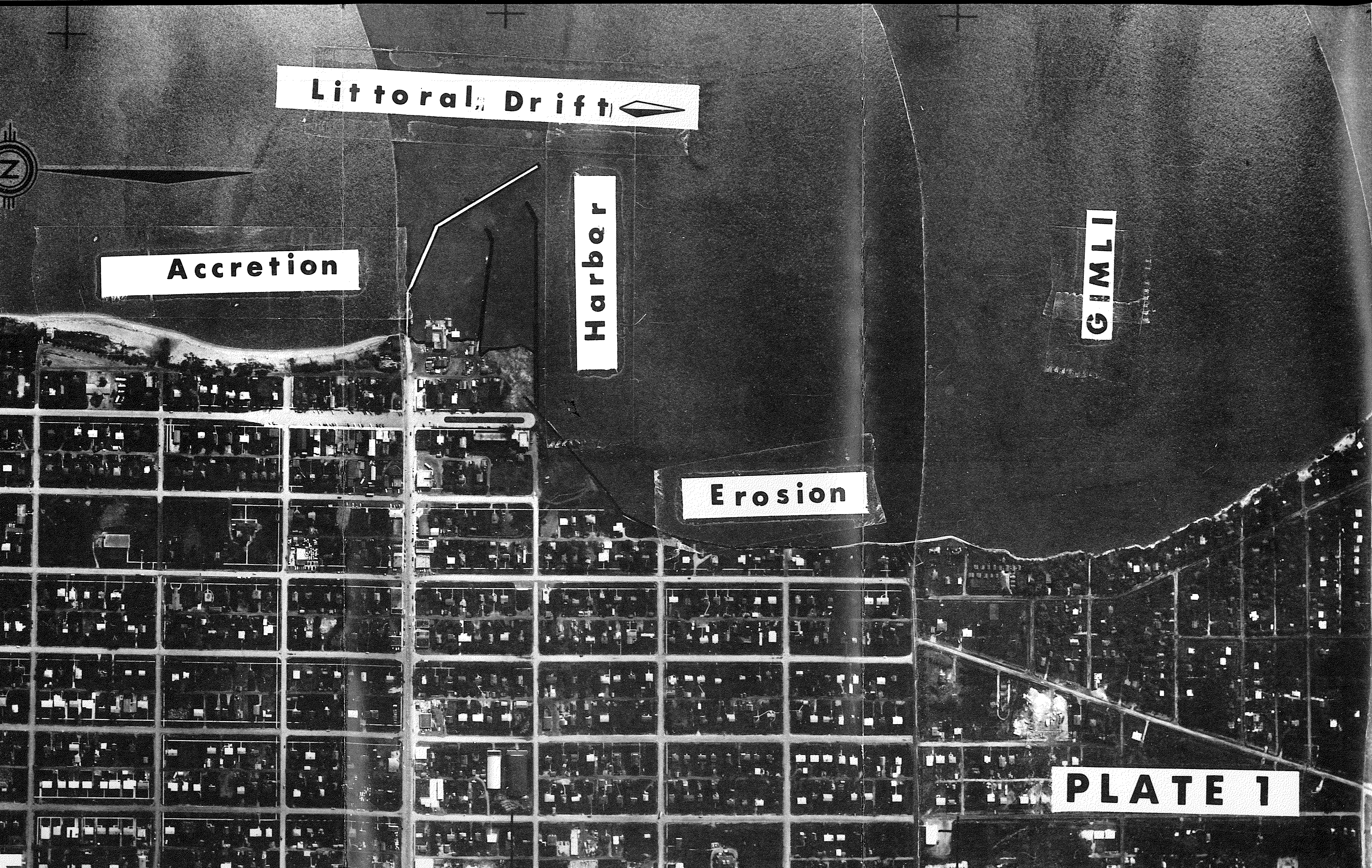
PHOTOGRAPH NO. C-3

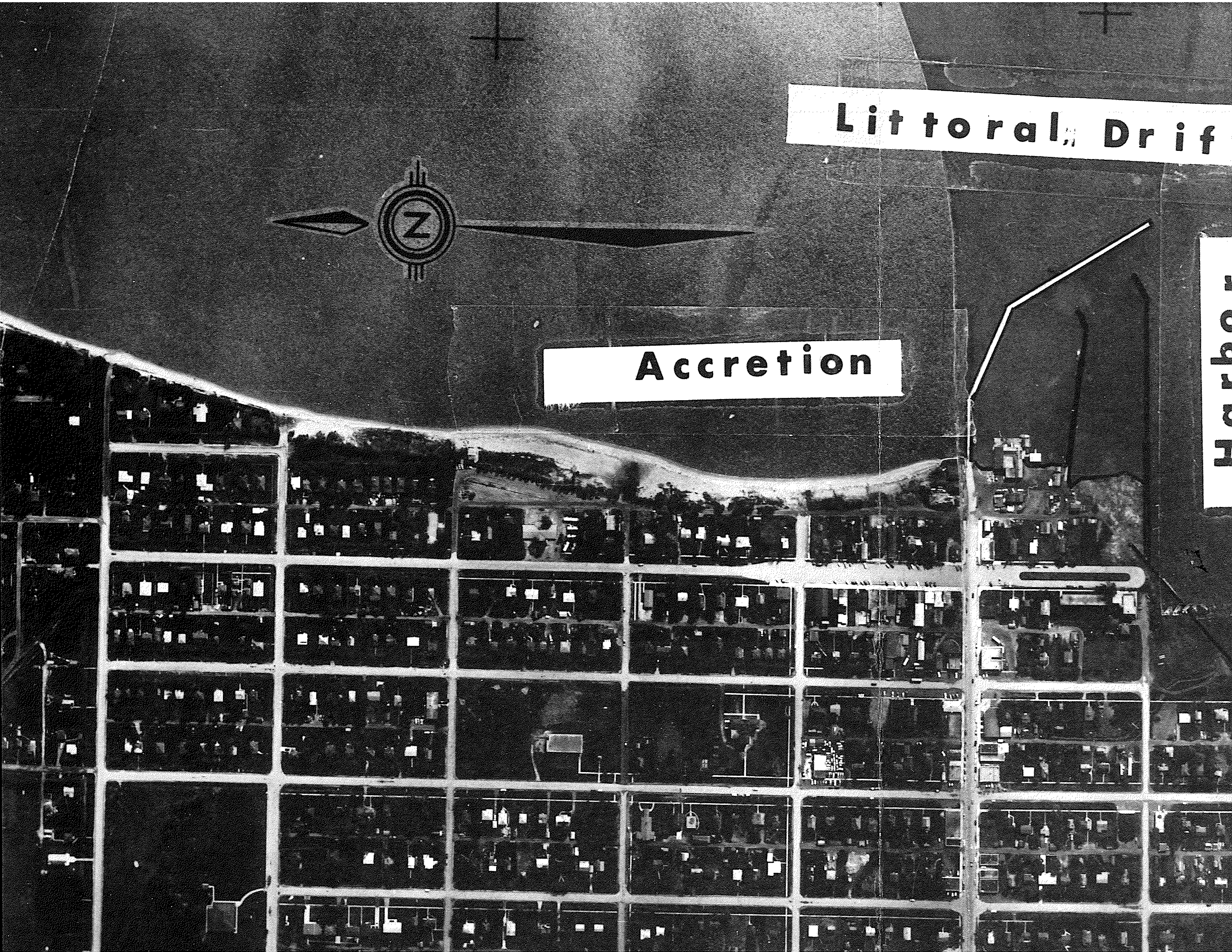
View of completed model. The wooden posts were removed before testing.

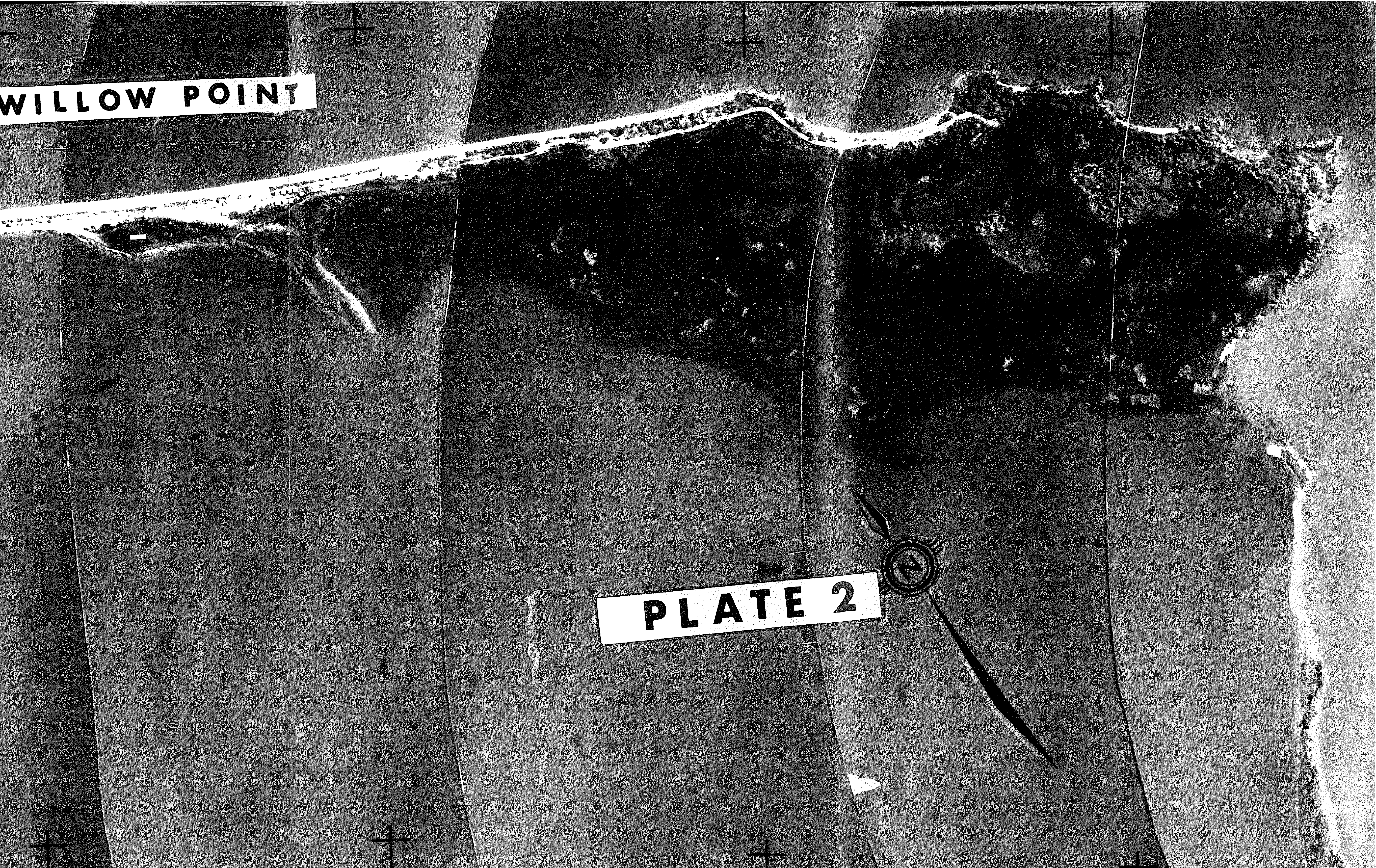


PHOTOGRAPH NO. C-4

View of wave machine and wave height indicator.

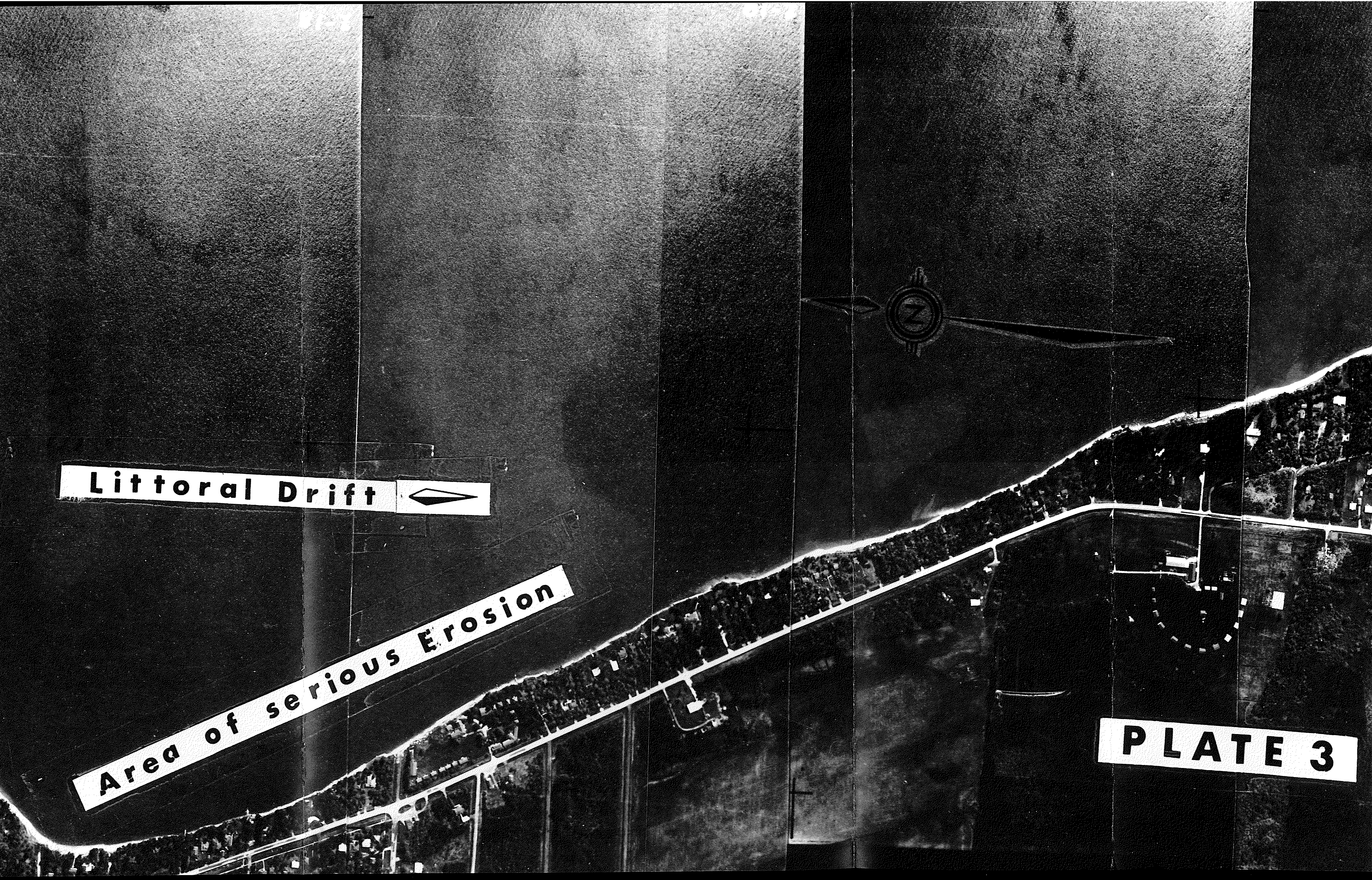

Littoral Drift
Accretion
Harbor
GIMLI
Erosion
PLATE 1

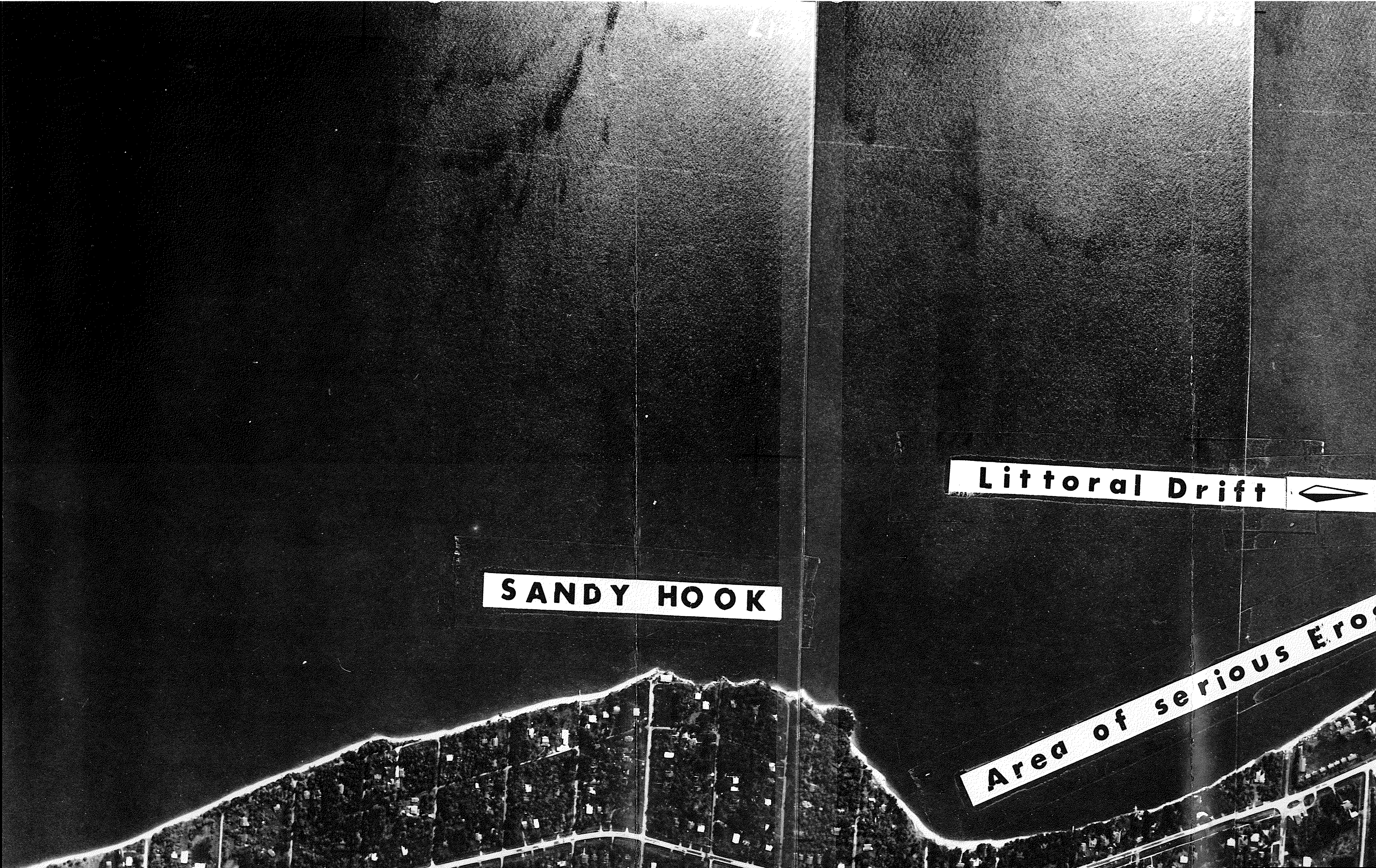

Littoral Drif
Accretion
N
Harbor

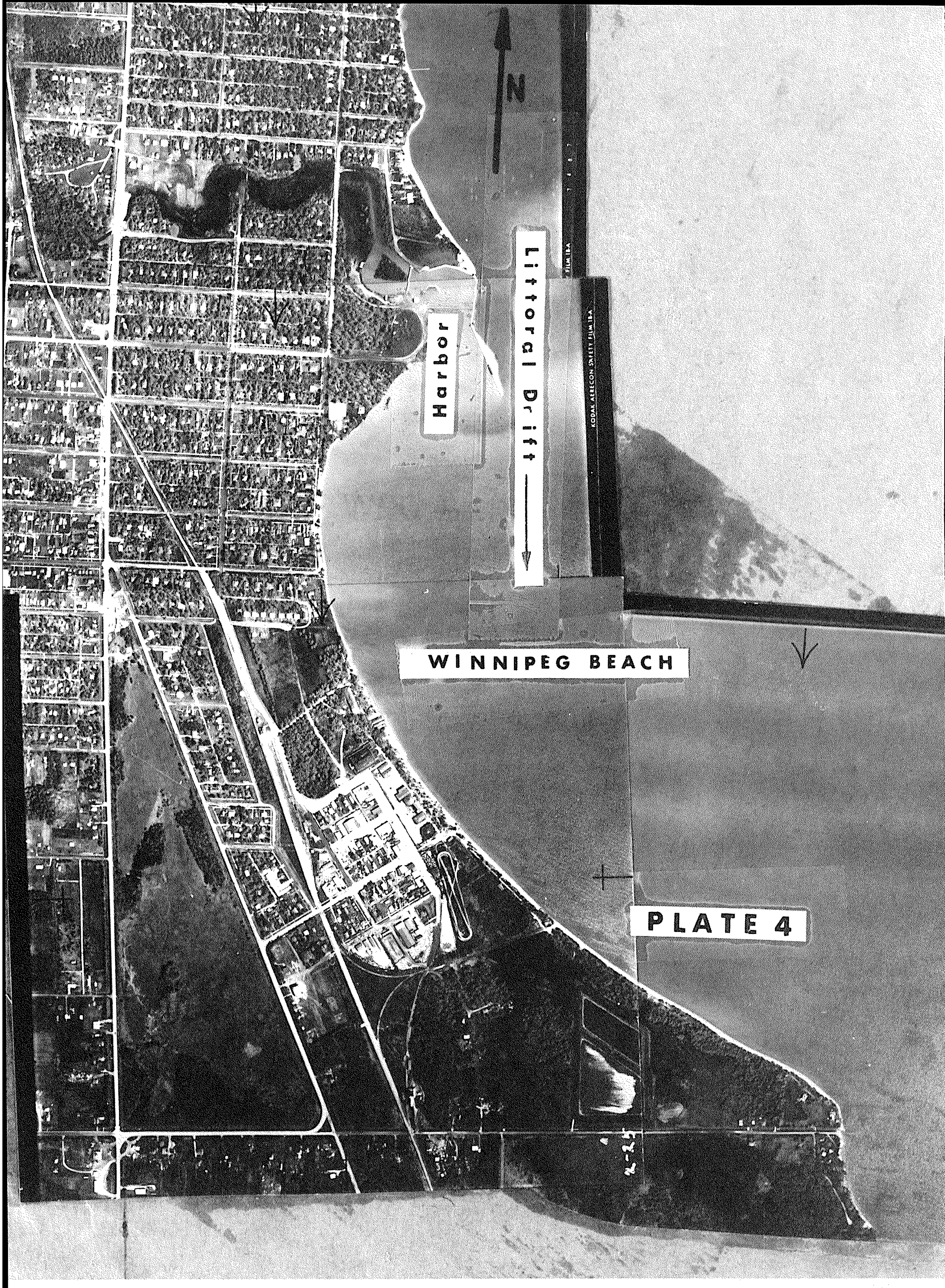

WILLOW POINT
PLATE 2
N

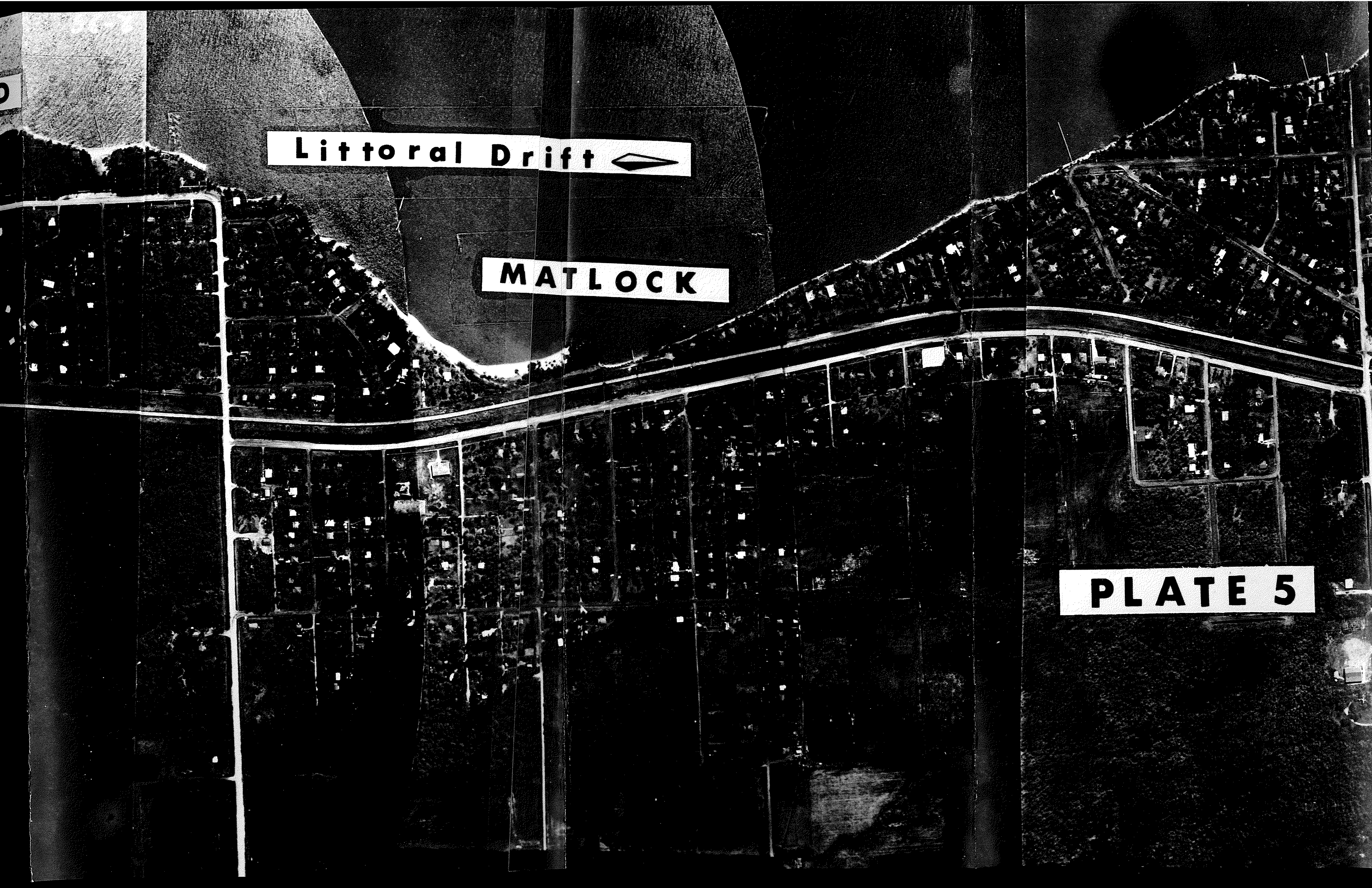

CH
Littoral Drift
WILLOW


SOUTH BEACH
Littoral Drift

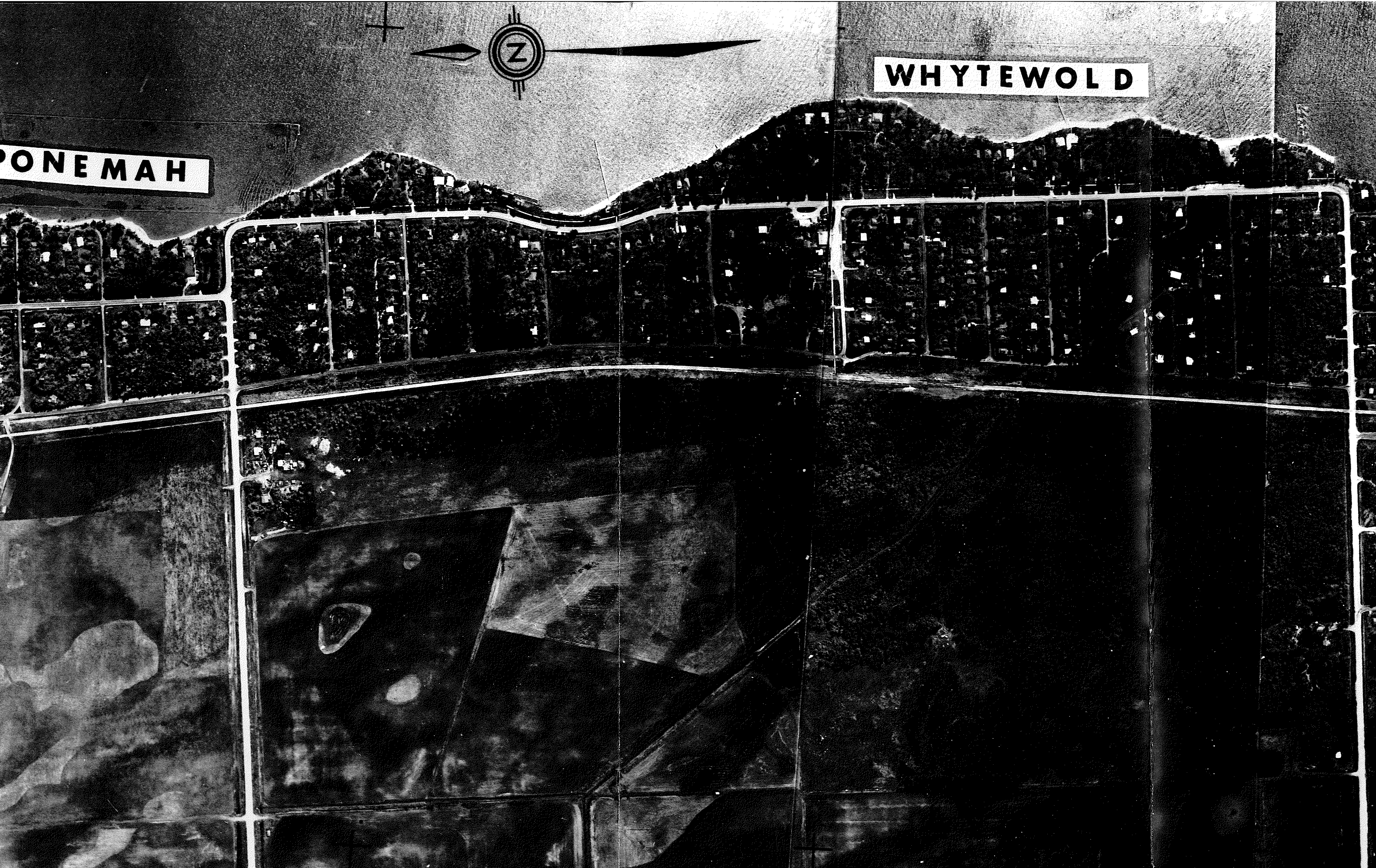

Littoral Drift
Area of serious Erosion
N
PLATE 3


Littoral Drift
SANDY HOOK
Area of serious Ero


N
Harbor
Littoral Drift
WINNIPEG BEACH
PLATE 4



Littoral Drift
MATLOCK
PLATE 5


N
WHYTEWOLD
PONEMAH

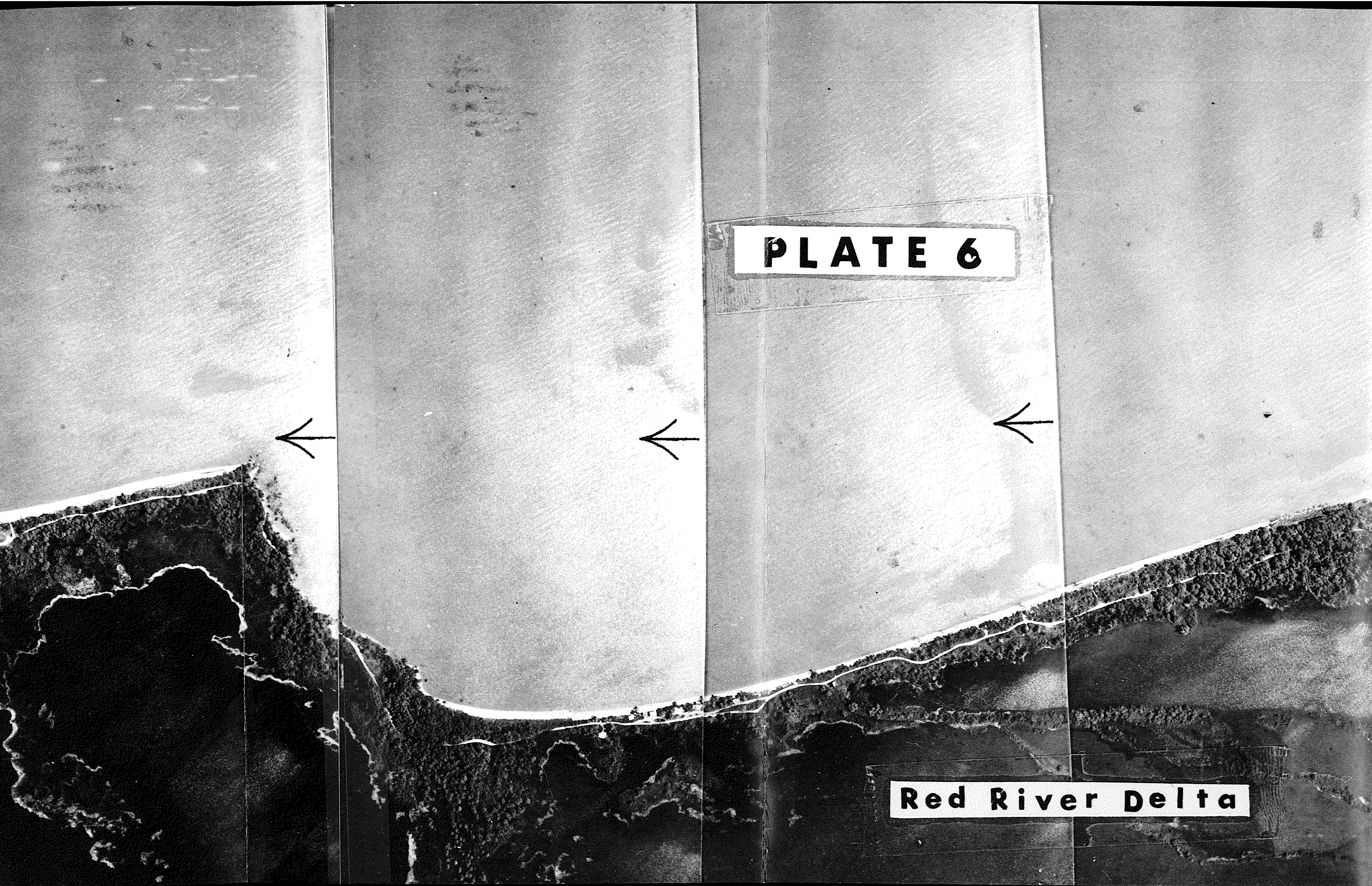
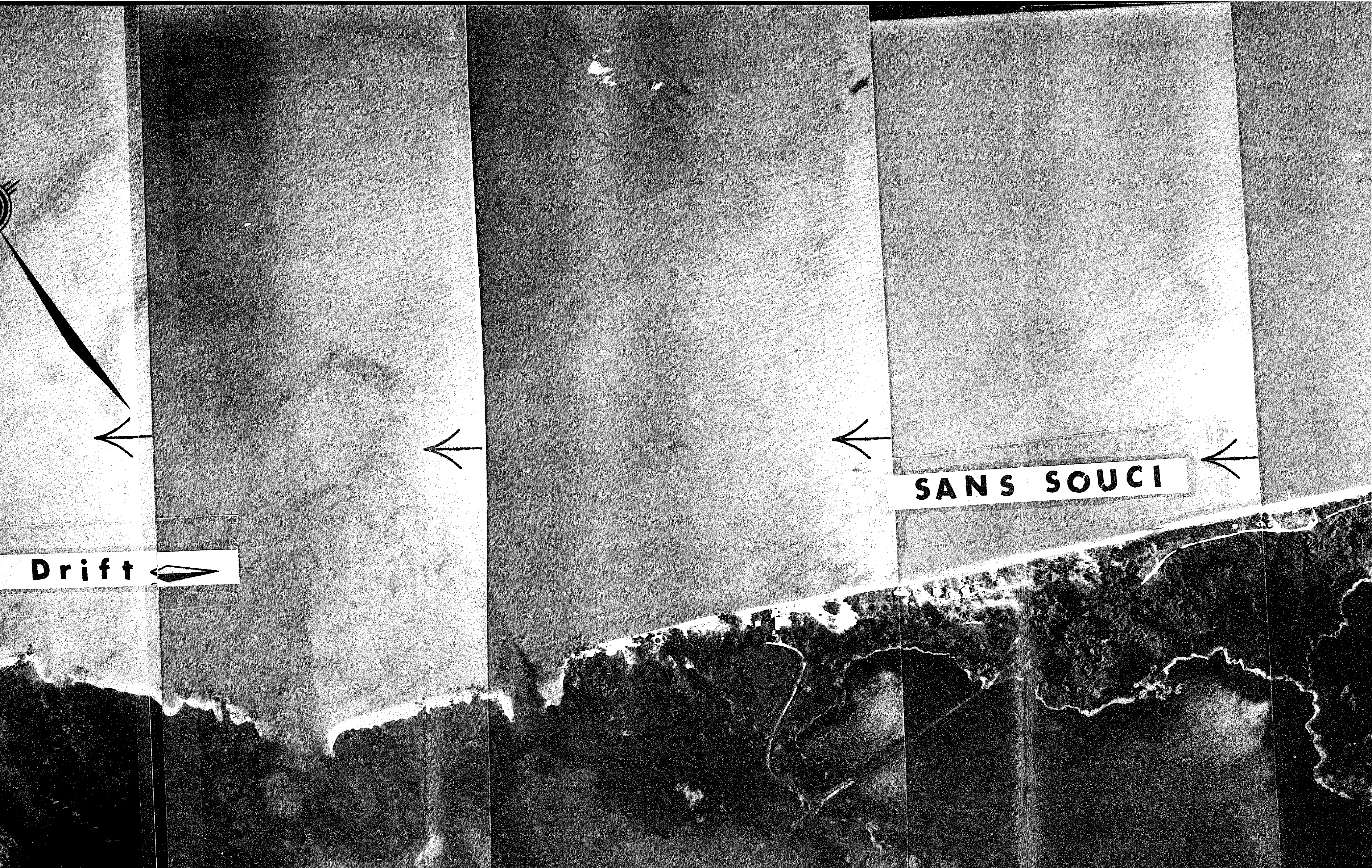
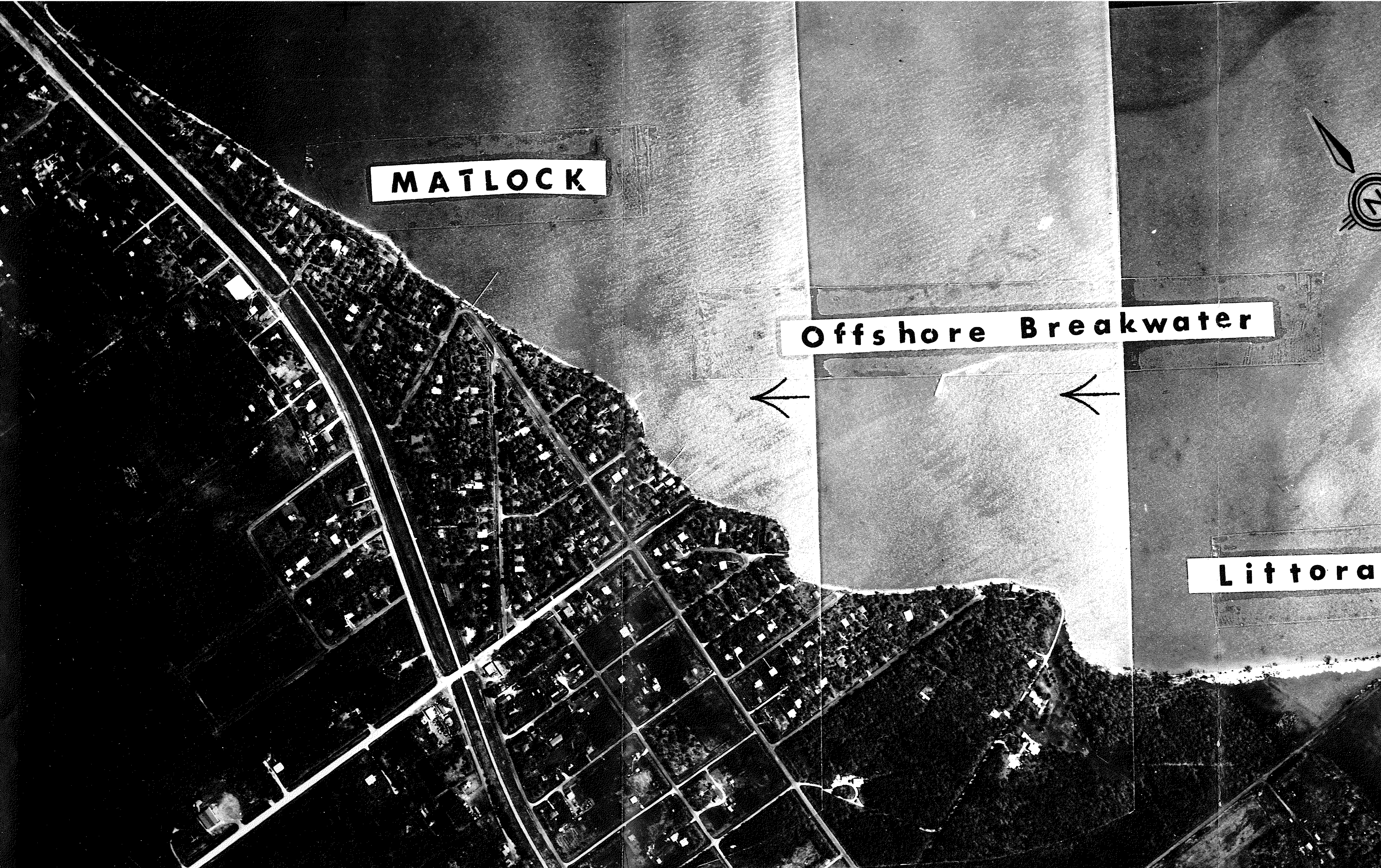


PLATE 6
Red River Delta


Drift
SANS SOUCI


MATLOCK
Offshore Breakwater
Littora

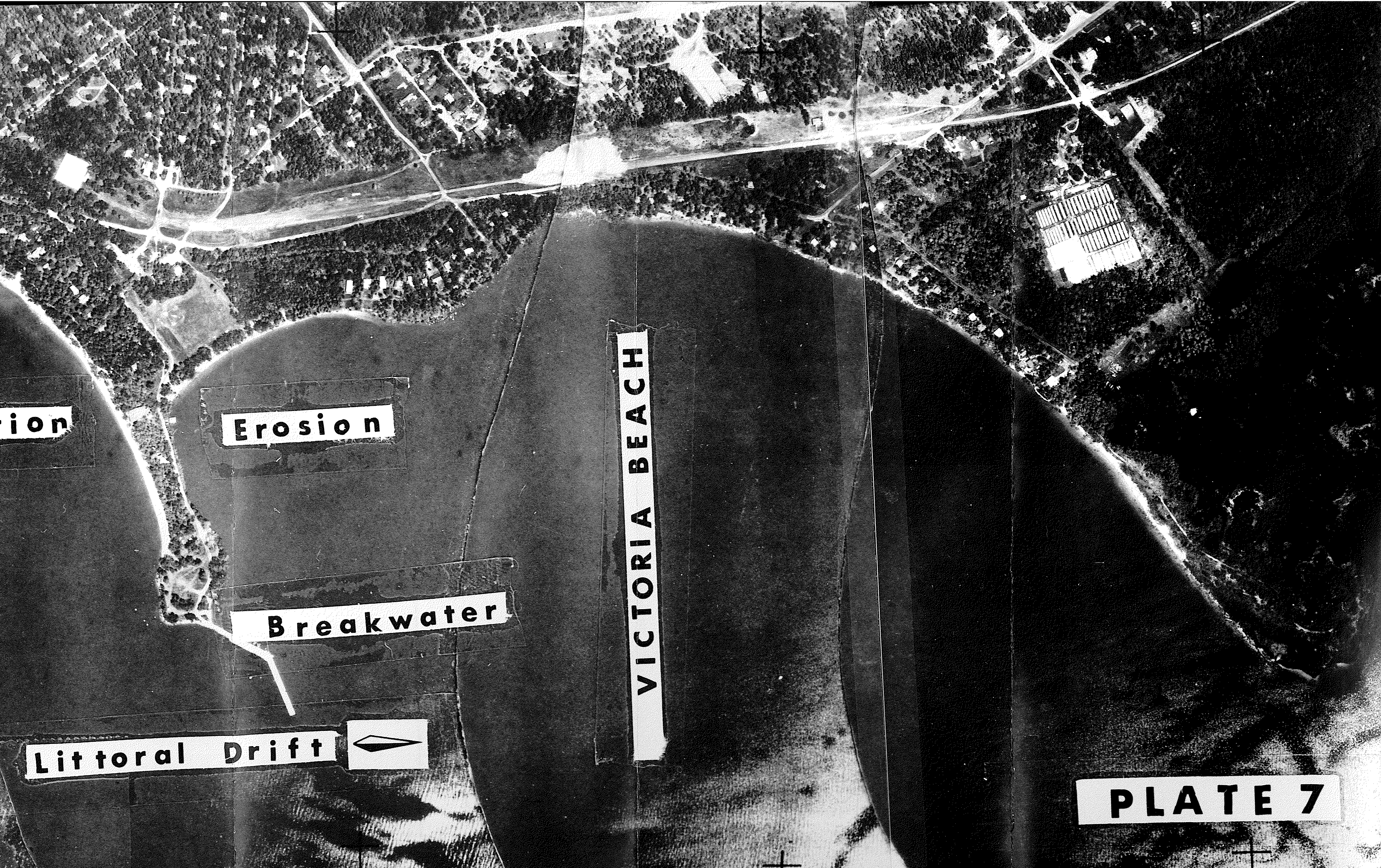
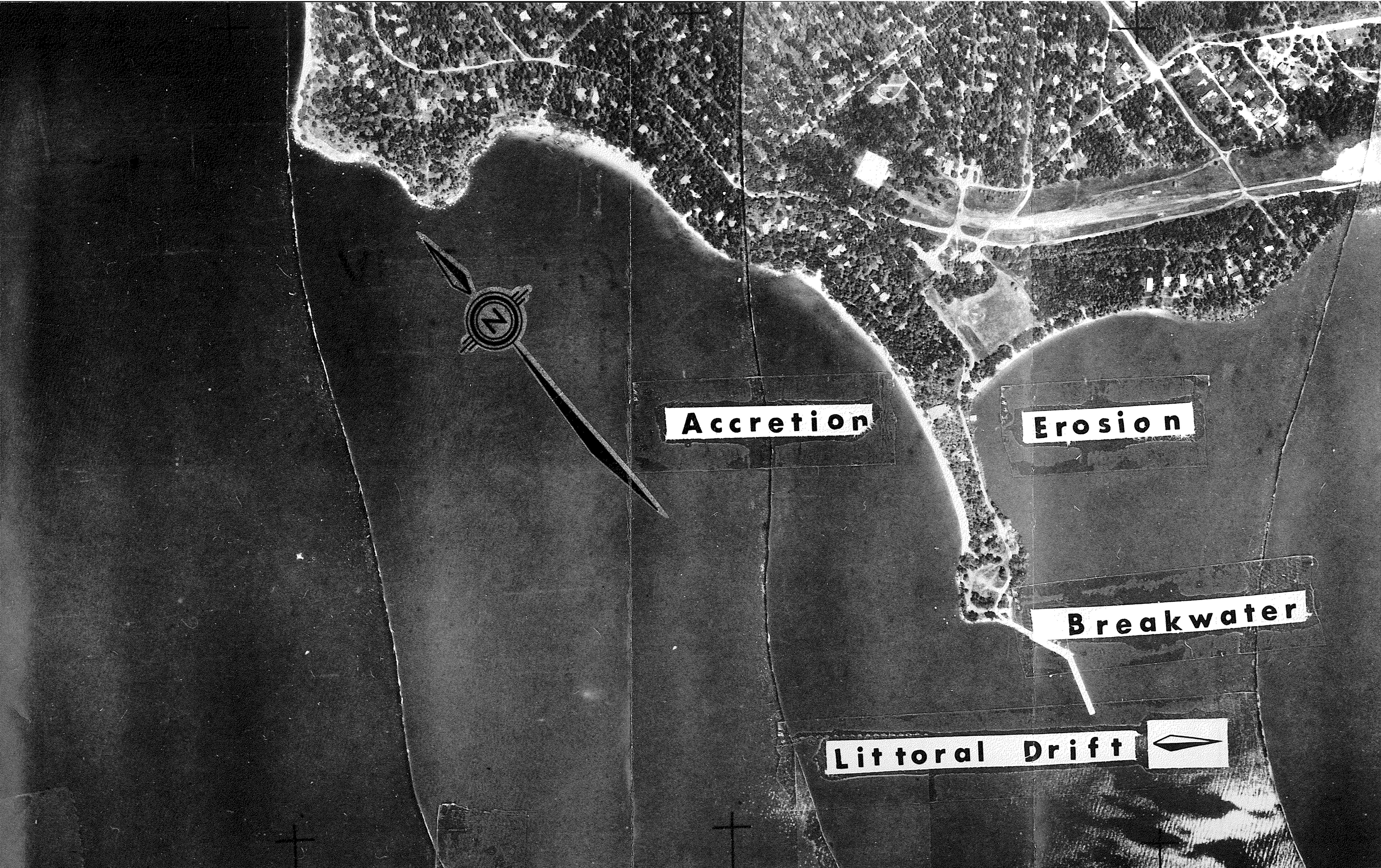
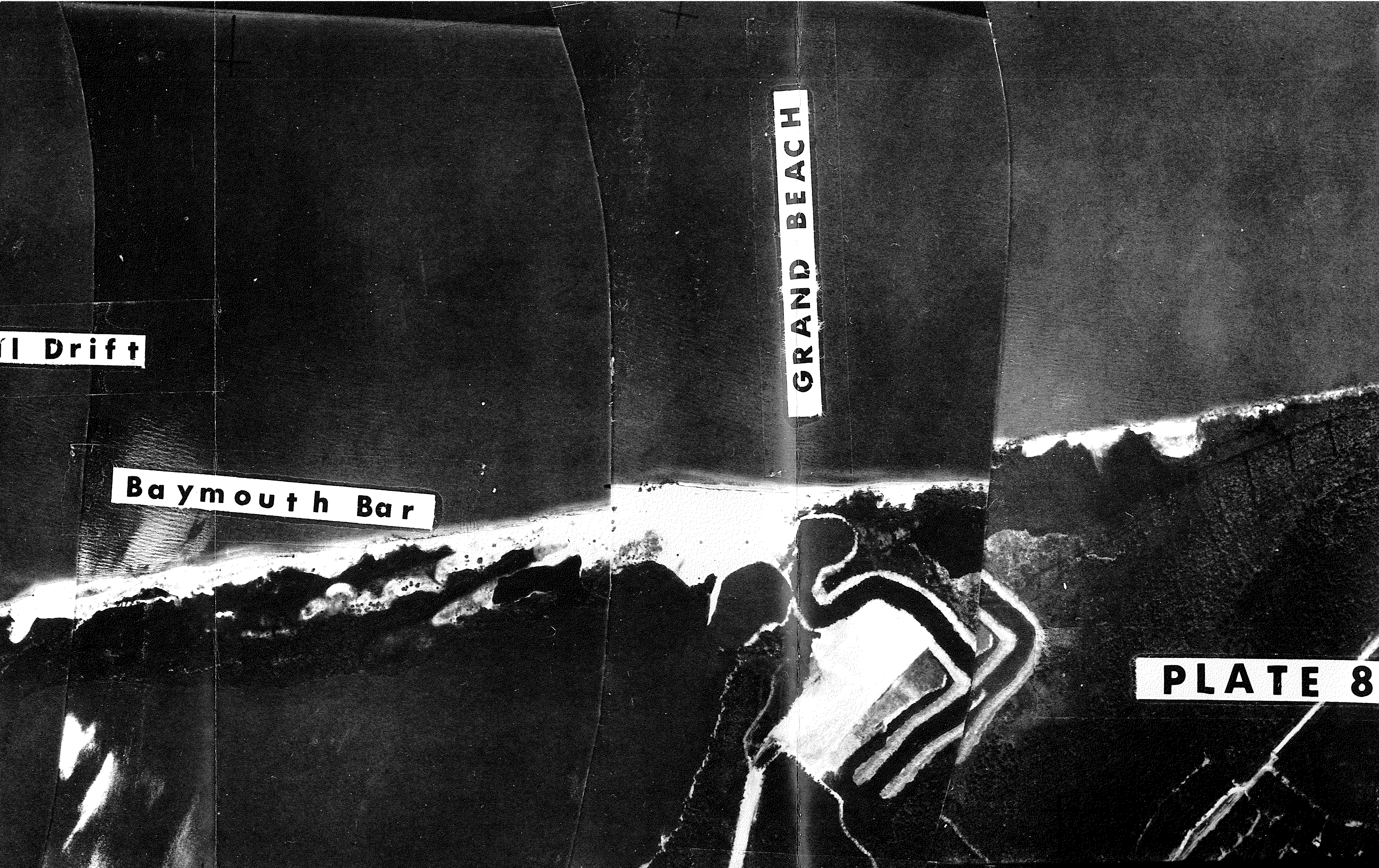


PLATE 7

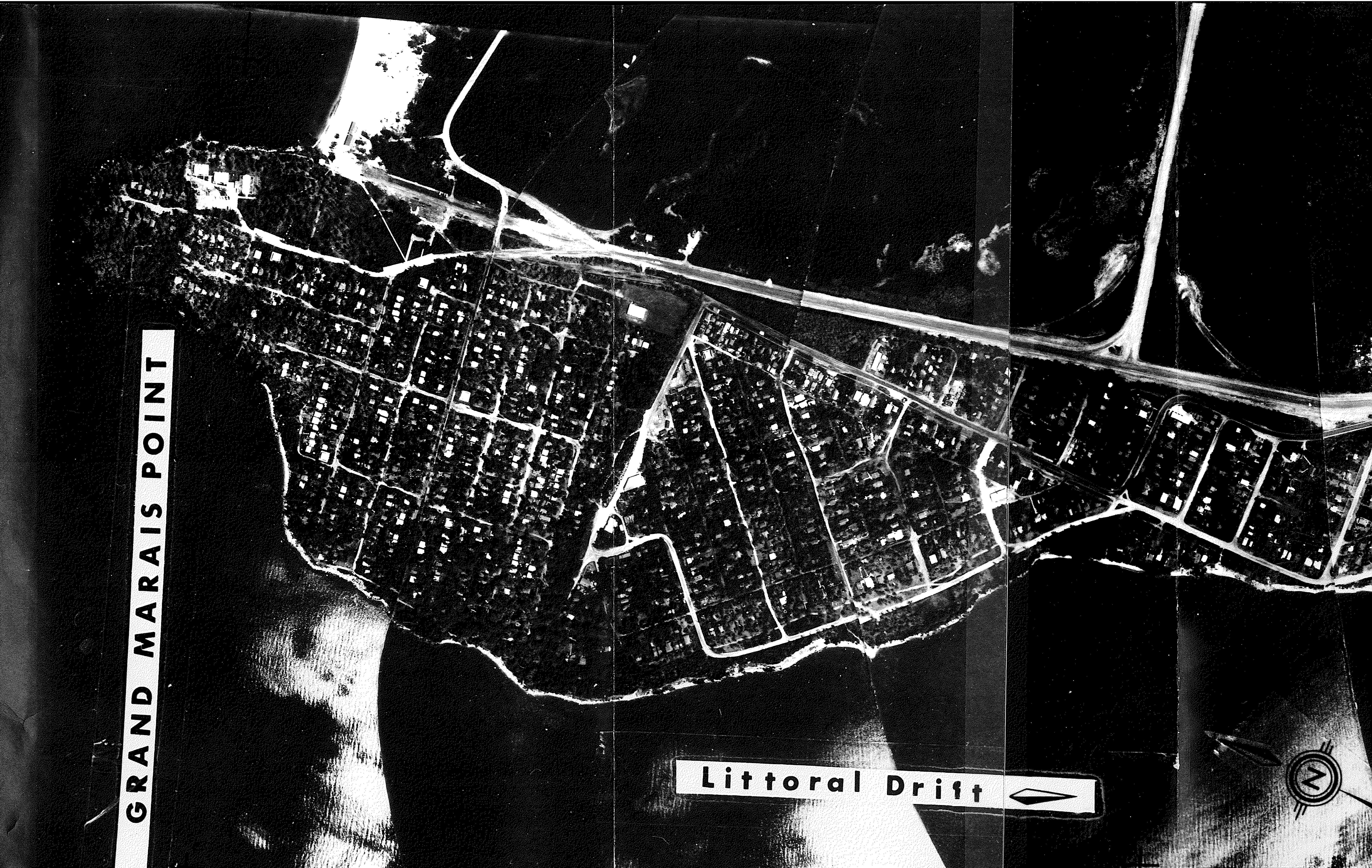


Accretion
Erosion
Breakwater
Littoral Drift


Drift
Baymouth Bar
GRAND BEACH
PLATE 8

GRAND MARAIS POINT
Sand Dunes

PLATE 9


GRAND MARAIS POINT
Littoral Drift