Geological Report GR94-1

# Sedimentology and Geomorphic Evolution of the South Shore of Lake Winnipeg

By Erik Nielsen and Glenn Conley

Manitoba
Energy and Mines
Geological Services

*Front cover: Landsat (5) image showing part of the south basin of Lake Winnipeg including Netley Marsh, the Red River and the City of Winnipeg.*

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By Erik Nielsen and Glenn Conley
Winnipeg, 1994

Energy and Mines

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# INTRODUCTION

## OBJECTIVES

Lake Winnipeg, with an area of 23,698.5 km$^2$, is the twelfth largest fresh water lake in the world (Fig. 1). An understanding of the physical and biological environments has long been recognized, but few coastal studies have been undertaken in the south basin of the lake. Those that have been done were primarily engineering studies concerned with modelling shoreline processes. To date, there have been no systematic geological surveys of the area.

A major objective of this survey was to examine the recent evolution of the beaches that form the south shore of Lake Winnipeg, between Beaconia Lake to the east and Matlock to the west (Fig. 2). Specifically, sediment provenance, coastal geomorphology and lithofacies studies, in association with radiocarbon dating, were undertaken at selected sites to determine the dynamic geological processes responsible for the formation of the shoreline. It is hoped that the results of this study will provide a foundation on which future coastal surveys can build so that up-to-date information can be maintained and accurate information can be provided to make sound coastal management decisions.

## PREVIOUS WORK

One of the earliest reports dealing with the history and geography of the area was by The Lakes Winnipeg and Manitoba Board in 1958 (unpublished). This report details early accounts of water level fluctuations in Lake Winnipeg before systematic recording was started in 1913. It also includes case histories of shore erosion primarily along the west shore, north of Matlock. Although the report presents rare and interesting accounts of written briefs, oral presentations and personal interviews pertaining to water level fluctuations and erosion, there is no mention of the south shore of the lake.

Solohub (1967) undertook the first sedimentological study of the shoreline sediments in an unpublished M.Sc. graduate thesis dealing with depositional environments at Grand Beach. In a brief interpretation of the provenance and dispersal of the sediments, he concluded that the sand had been transported south by longshore currents from eroding cliffs north of the beach. Unfortunately, Solohub (1967) made little use of early aerial photography or maps in constructing the recent sedimentary history of the bay-mouth-bar at Grand Beach.

One of the most comprehensive studies of shoreline erosion was an unpublished M.Sc. thesis by Veldman (1969). He used airphotos dating back to 1924, in addition to site surveys, to map the predominant littoral drift directions. With few exceptions, littoral drift was found to be southward on both the east and west sides of the lake, south of Camp Morton and Elk Island. Veldman (1969) also

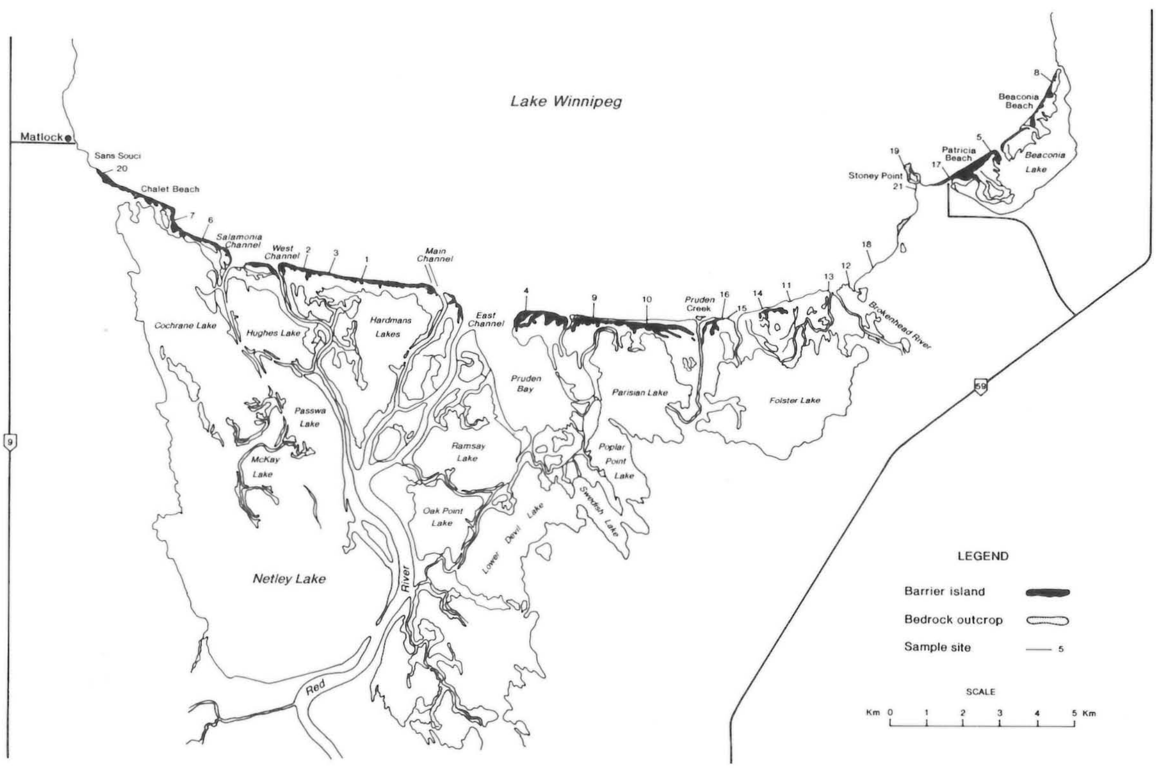



*Figure 2: Location map showing the extent of the barrier islands at the mouth of the Red River and the bay-mouth-bar at Beaconia Lake.*

concluded that from Balsam Bay around Stoney Point (Fig. 1) toward the barrier islands north of Netley marsh, sediment transport was southwestward, but he made no observations or measurements past Stoney Point. On the west side, he similarly concluded that sediment was transported from Sans Souci southeastward on to the barrier islands, but again made no observations past Sans Souci.

The off-shore sediments in the south basin of Lake Winnipeg were described in an unpublished M.Sc. thesis by Kushnir in 1971. The study was a general reconnaissance of the nature and origin of the bottom sediments and sedimentary environments in the south basin, but was limited to that area at a depth of at least 2 m, which was the draft of the sampling ship. Kushnir mapped three more or less concentrically shaped units, comprising a clay unit in the centre of the basin, a mud unit 'shoreward' of the clay unit and a mixed nearshore unit consisting of sand, gravel and a variety of relict glacial and Lake Agassiz sediments. Minor amounts of silt and clay also occurred in the nearshore mixed unit. Using echograms, Kushnir (1971) mapped what he believed was an extensive terrace near the Narrows at an elevation of 208.5 m (684 ft). This terrace is 8.8 m below the present lake level (216.3 m or 713 ft). Kushnir (1971) was the first person to recognize lower post-Lake Agassiz levels of Lake Winnipeg, although his observations seem to have been largely missed by subsequent workers.

In an unpublished M.Sc. thesis, Cheng (1972) reported on his investigations on longshore transport in the south basin of Lake Winnipeg. This was a continuation of the work started by Veldman (1969). Cheng (1972) was interested in finding the mechanism that caused the sudden increase in shoreline recession that began in the mid-1960's. From beach surveys along the east and west shores of Lake Winnipeg and from wave spectrum analysis, he concluded that the cause of shoreline recession was not due to the 10 per cent increase in wave energy resulting from the 1.5 m increase in water depth, but rather due to the fact that the waves were now attacking bluffs that were not previously reached before the water level rise.

The most comprehensive study of the Lake Winnipeg south basin was that of Penner and Swedlo (1974). Some of the objectives of this engineering study were to determine the rate of shoreline recession, the characteristics of the sand regime and to study ice conditions and how they would be affected if the water level was regulated. Unlike previous studies, the south shore of the basin was included to a limited degree. The shoreline recession study indicated that erosion rates in the last hundred years were on the order of about 60 cm per year with extremes of 0 to 8 m per year. The upper rates, which appear excessively high, at least along the south shore, did not take into consideration water level fluctuations due to climate and the apparent effect that this would have on a sandy shore with a low profile. In places, they may have mapped shoreline positions and not erosion rates.

Brunskill and Graham (1979) published the results of the only geological survey of the surface sediments of Lake Winnipeg undertaken to date. This report details the results of particle size and geochemical analyses of surface sediments and water samples from 50 stations and 1 to 2 m long cores from 13 stations. Sedimentation rates of 0.5 and 0.9 mm/year for the Lake Winnipeg basin were estimated from sonar penetration and Red River sediment supply rates.

Verbiwski (1986) prepared an unpublished report entitled Netley-Libau Marshes Resource Development and Management Proposal. Unfortunately, no consideration was given to the geological setting nor to the processes acting along the shore or in the marshes, in spite of the fact that the study was commissioned to investigate mitigation against destruction of the marshes due to washovers breaching the barrier islands. The report concluded by recommending that the water level in the marshes be regulated by a system of dykes and canals.

## METHODS

### Surveys

Most of the barrier islands between the north end of Beaconia Lake and Sans Souci were investigated by boat from the Lake Winnipeg side. Profiles were surveyed at roughly equally spaced intervals at sites considered to be representative of that stretch of shore. Elevations at 1 m spacings were surveyed with a transit starting at the waters edge, extending across the beach and ending at the edge of the marsh on the landward side of the barrier island. Measured elevations were later converted to metres above sea level by relating them to the lake level recorded at Gimli for that particular day. The sites were resurveyed at intervals throughout the summer to determine sand budgets at the various sites. The resurveying indicated that water levels along the south shore of Lake Winnipeg at that time were as much as 10 to 20 cm higher or lower than levels recorded at Gimli. This was due to wind setup or setdown on any particular day. For this reason, surveyed profiles can only be considered to be approximations of the true elevations.

### Stratigraphic mapping

Due to the generally low profile of the shore, stratigraphic sections were seldom observed, however, at several sites, up to 1m of stratigraphic section was exposed on the foreshore during periods of low water. Elsewhere, the shore was eroding fast enough to expose approximately 1 m high sections in dunes or previously deposited beach ridges. The few available stratigraphic sections were mapped and sampled.

### Sediment texture

The main lithofacies were identified along each surveyed profile and at least one representative sediment sample of each facies was collected for laboratory analysis. A total of 114 samples were sieved at 0.5Ø intervals, between -5.0 and 4.0Ø, and moment measure statistics and cumulative frequency curves were calculated.

### Carbonate content

The carbonate content of the sand fraction between, 0.25 and 0.125 mm (2-3Ø), was analysed by two methods.

In the first method, the total carbonate content was determined by weight loss on acidification. With this technique approximately 5 g of sediment is acidified with 50 ml 20% HCl and allowed to stand for 24 hours. The liquid is decanted and the remaining sediment rinsed four times with distilled water and then dried and weighed. The difference between the initial weight and final weight is expressed as a per cent of the initial weight.

The second method to determine carbonate content was by atomic absorption. In this method the amount of Ca and Mg is determined by atomic absorption and the values converted into equivalent amounts of calcite, dolomite and total carbonate (Ross, 1986). The two methods give comparable results for total carbonate (Fig. 3), but the atomic absorption method is preferred because it is faster and gives results for both calcite and dolomite in addition to total carbonate. This distinction is important as calcite appears to be derived equally from the comminution of Paleozoic carbonate bedrock, modern shells and from local till deposits, whereas dolomite is derived only from the Paleozoic bedrock and derived till deposits. Dolomite is not derived from biogenic sources and can be used as an indicator of sediment provenance.

**Radiocarbon dating**

The elevation of subfossil wood, organic muck and shell samples was recorded in relation to the lake level and later recalculated to metres above sea level. The samples were submitted to the Brock University radiocarbon laboratory, except for two samples that were submitted to the Geological Survey of Canada laboratory. The radiocarbon dates were converted to calendar years using Stuiver and Pearson's (1986) calibration curve. The wood samples were identified at the Paleoecology Laboratory at the Geological Survey of Canada.

**Tree-ring analysis**

A black ash tree (*Fraxinus nigra*), a species which is sensitive to moisture levels, was sampled for dendrochronological analysis. The sample was collected near the mouth of Salamonia Channel. A tree-ring curve was prepared for the sample following the technique outlined by Fritts (1976). The resultant curve was compared visually to a preliminary master dendrochronological curve for bur oak (*Quercus macrocarpa*) for south-central Manitoba (Nielsen, in prep.), water-level records for Lake Winnipeg and precipitation records for Winnipeg to determine if tree-ring analysis can be used as a proxy indicator of Lake Winnipeg water levels.

**Archaeological and historical dating**

Shoreline changes during the last century were documented using a variety of maps and aerial photography. The earliest airphotos were a series of oblique photos dating from 1924 but these were of limited use. Airphotos from 1929, 1946, 1966, 1968, 1971, and 1987 and maps dating from 1888, 1895, 1898, 1912, 1932, 1951, and 1980, in conjunction with water level records from 1913 to the present, were used to document the changes. The airphotos and maps were obtained from the National Airphoto Library and Cartographic and Architectural Archives Division, National Archives of Canada in Ottawa. The water levels were obtained from Manitoba Department of Natural Resources, Water Resources Branch, in Winnipeg.

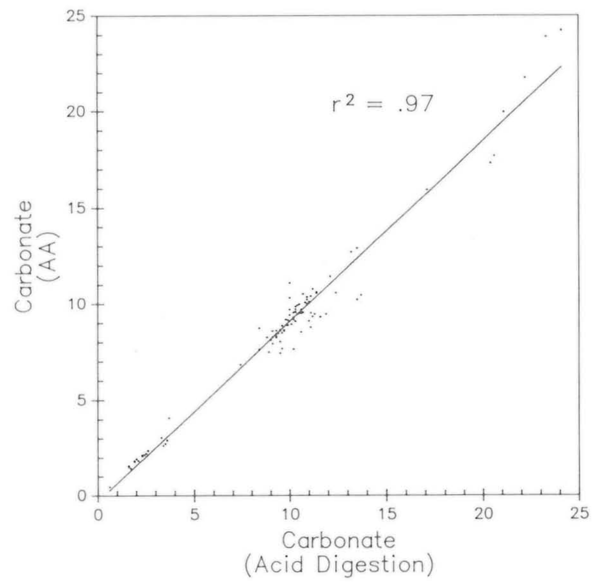



*Figure 3: Linear regression for the per cent carbonate determined by atomic absorption and weight loss on acidification.*

## PHYSIOGRAPHY

The south basin of Lake Winnipeg is approximately rectangular in shape, with a north-south orientation and a maximum length of 88 km and maximum width of 32 km (Fig. 1). The basin reaches a maximum depth of 13 m, southeast of Hecla Island. The distance from Winnipeg Beach to Balsam Bay (Fig. 1), across the southern part of south basin, is 25 km and the maximum water depth is only 8 m, 10 km north of the mouth of Main Channel.

The current Red River delta comprises approximately 24 000 hectares of marshes separated from the south end of Lake Winnipeg by a narrow (up to 100 m wide), 25 km long barrier island system. The barrier islands stretch from Sans Souci in the west to Stoney Point in the east (Fig. 2). East of Stoney Point, Beaconia Lake is separated from Lake Winnipeg by a 5 km long bay-mouth-bar. 3.2 km south of Lake Winnipeg, the Red River branches into three smaller channels, West, Main and East channels. Salamonia Channel branches off West Channel 2.4 km south of the lake. Almost continuous levees, in places breached by crevasses and crevasse splays, separate the channels from the surrounding marshes. The interchannel areas, which form the delta plain, are occupied by numerous marshes and lakes (Fig. 2). The extensive arcuate barrier islands at the north end of the delta identifies this as a high-destructive, wave-dominated delta (Scott and Fisher, 1969). West of Main Channel the barrier island is broken only by West and Salamonia channels, whereas east of Main Channel numerous breaches occur. The largest opening at Pruden Bay is 0.8 km wide. Breaches are smaller, but more numerous, between Pruden Bay and Stoney Point where the sediment becomes finer and the barrier island profile lower.

Sediment is supplied to the barrier island by coastal erosion, longshore drift from both the east and west shores of the lake and by fluvial transport of the Red River. Coastal erosion produces approximately 2.8 x $10^5$ tons of silt and clay and 2.3 x $10^5$ tons of sand and gravel each year (Penner and Swedlo, 1974). The same authors estimate 2.5 x $10^6$ tons of silt and clay and 8 x $10^4$ tons of sand are transported annually to the lake by the Red River. Work by Tam and Chacko (pers. comm., 1990) indicates that bottom sediments in Main, East, West and Salamonia channels consist on average of 5 to 58 per cent sand, 16 to 64 per cent silt and 15 to 35 per cent clay (Fig. 4). Much of the fine grained suspended sediment, brought to the prodelta environment by coastal erosion and the Red River, is transported inland through breaches in the barrier island system and deposited in lagoons on the delta plain during periods of high wind setup.

Between Salamonia Channel and Chalet Beach the barrier island is typically about 70 m wide and 3 m high and

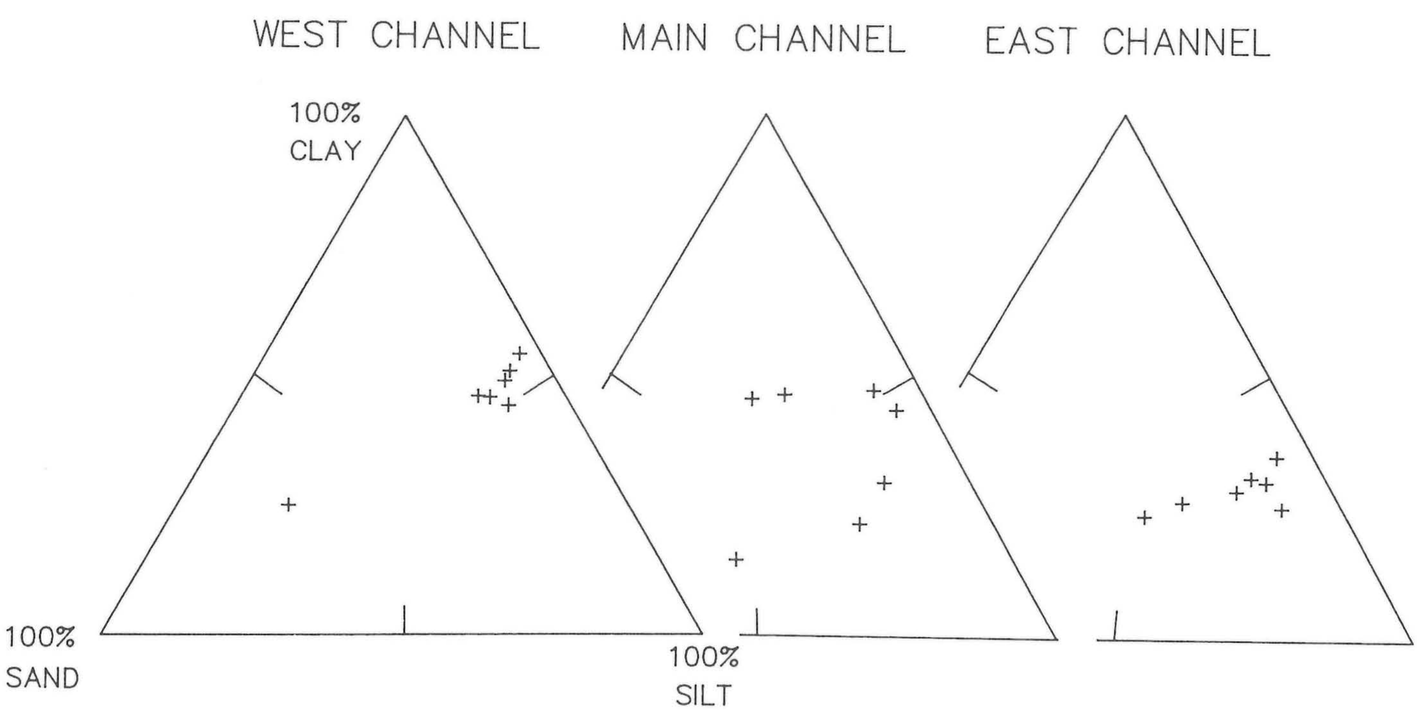



*Figure 4: Texture of bottom sediments from the Red River (K.C. Tam and V.T. Chacko, pers. comm., 1990). Note sand = 2.00 to 0.075 mm, silt = 0.075 to 0.005 mm and clay = less than 0.005 mm.*

comprises a variety of foreshore and backshore sand and gravel facies and a single heavily vegetated beach ridge.

Between West Channel and Main Channel the backshore becomes wider and the slope lower. Multiple barrier island beach ridges have developed at the eastern end of this reach near the mouth of Main Channel.

In the reach between Main Channel and Pruden Creek the barrier island is less than 2 m high. The width varies from about 20 m in the west to over 100 m in the east. The ridge crest decreases in height to the east.

A 2 to 4 m high, 30 to more than 100 m wide baymouth-bar separates Beaconia Lake from Lake Winnipeg. The southwest end of the bar is the widest and has the lowest profile.

## BEDROCK GEOLOGY

Penner and Swedlo (1974), Cheng (1972) and Manitoba Energy and Mines (1979) indicate that although the south shore of Lake Winnipeg is underlain by the Ordovician Red River Formation, there were no observed bedrock outcrops in the area. During the present survey, almost continuous bedrock outcroppings were observed on the foreshore of Stoney Point (Fig. 2, 5). Shattered bedding-plane surfaces of the Doghead Member of the Red River Formation (R. Bezys, pers. comm., 1991) forms the northeast, north, and west shores of Stoney Point for a distance of approximately 1 km (Fig. 5). The small jut of land on the shore, 1.5 km south of Stoney Point, also exposes bedrock as evidenced by shoals offshore. The occurrence of bedrock outcrop around Stoney Point is consistent with reports of shallow overburden and outcrops along Brokenhead River (Tyrrell and Dowling, 1900; Bannatyne and Jones, 1979). Two drillholes have been put down on the barrier island at a site north of Parisien Lake (Fig. 2) where 3.7 m of overburden was reported (Bannatyne and Jones, 1979).

*Figure 5: Ordovician Doghead Member of the Red River Formation outcrop on Stoney Point.*

## LAKE LEVEL FLUCTUATIONS

The Water Resources Branch of the Manitoba Department of Natural Resources monitors water levels at numerous stations around Lake Winnipeg. Daily water level records from Gimli were used to establish elevations above sea level for the transit surveys during the summer of 1990. Figure 6 shows the daily water level fluctuations recorded at Gimli for 1990. In any one year the mean monthly water level reaches a peak in mid summer and drops as much as 0.50 m during the winter months.

Records for Winnipeg Beach and Gimli, published in "The Lake Winnipeg Shoreline Handbook" (Department of Mines, Resources and Environmental Management, Water Resources Division, 1977) present an unbroken history of water level fluctuations from 1913 to the present (Fig. 7A). There are, however, no detailed analysis of the hydrographs. Penner and Swedlo (1974) summarized the extremes recorded before the 1977 regulation of the lake level (Table 1).

**Table 1: Recorded lake levels in metres (Penner and Swedlo, 1974)**

| | | |
|---|---|---|
| Extreme daily low: | 216.0 | October 29, 1940 |
| Extreme daily high; | 219.1 | September 5, 1966 |
| Extreme instantaneous high: | 219.4 | September 5, 1966 |
| Extreme monthly low: | 216.3 | February, 1941 |
| Extreme monthly high: | 218.7 | July, 1966 |
| Long term mean: | 217.4 | |

Comparison of the mean annual lake levels (Fig. 7A) and the mean annual precipitation records for the city of Winnipeg (Fig. 7B) clearly indicates a reasonable correlation despite the fact that Winnipeg precipitation data is from a single site, whereas the Lake Winnipeg water level data reflects the water budget of the entire drainage basin. From 1913 to 1926 the lake levels were uniformly low, averaging 217.35 m. The following two years, 1927 and 1928, had higher water levels. This was followed by 13 years ( 1929 to 1942) with exceptionally low levels averaging 216.98 m but even this generally dry period experienced relatively high water levels from 1934 to 1936. Water levels after 1942 were generally much higher than in the early part of the century. The years 1943 to 1948 had uniformly high levels but were followed by a year with low water levels. From 1950 to 1957 lake levels were even higher than the 1940's but were followed by seven years (1958 to 1964) with low levels comparable to those of the 1920's. In the 12 years prior to regulation in 1977, the lake reached levels higher than anything experienced previously, with the notable exception of 1968 and 1973 when relatively low levels were recorded. The average level for this 12 year period, including the two low years, was 217.96 m.

Short term water level fluctuations due to persistent winds are common on Lake Winnipeg. As the wind blows over the open lake, the surface water begins to move, piling up on the windward shore. The increase in lake level is referred to as wind setup. The corresponding drop in water level at the leeward end of the lake is called wind setdown. Wind setups of 30 cm are common, but setups as high as 1.15 m have been recorded (Penner and Swedlo, 1974).

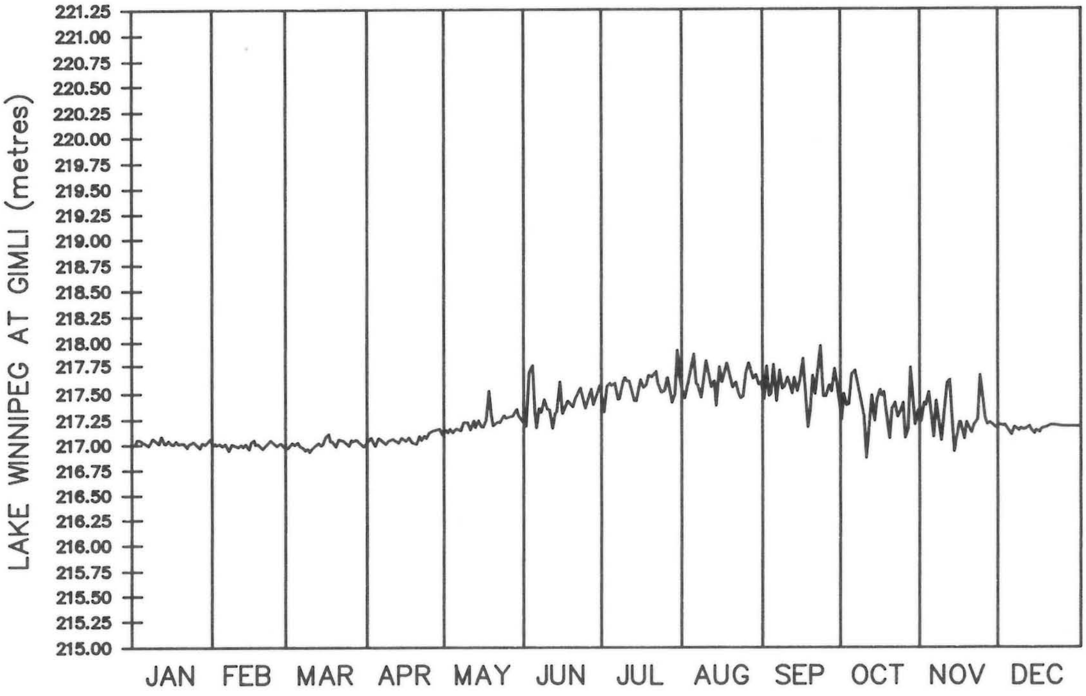



*Figure 6:* *Daily water level fluctuations of Lake Winnipeg for 1990 as recorded at Gimli (unpublished data, Manitoba Water Resources Branch).*

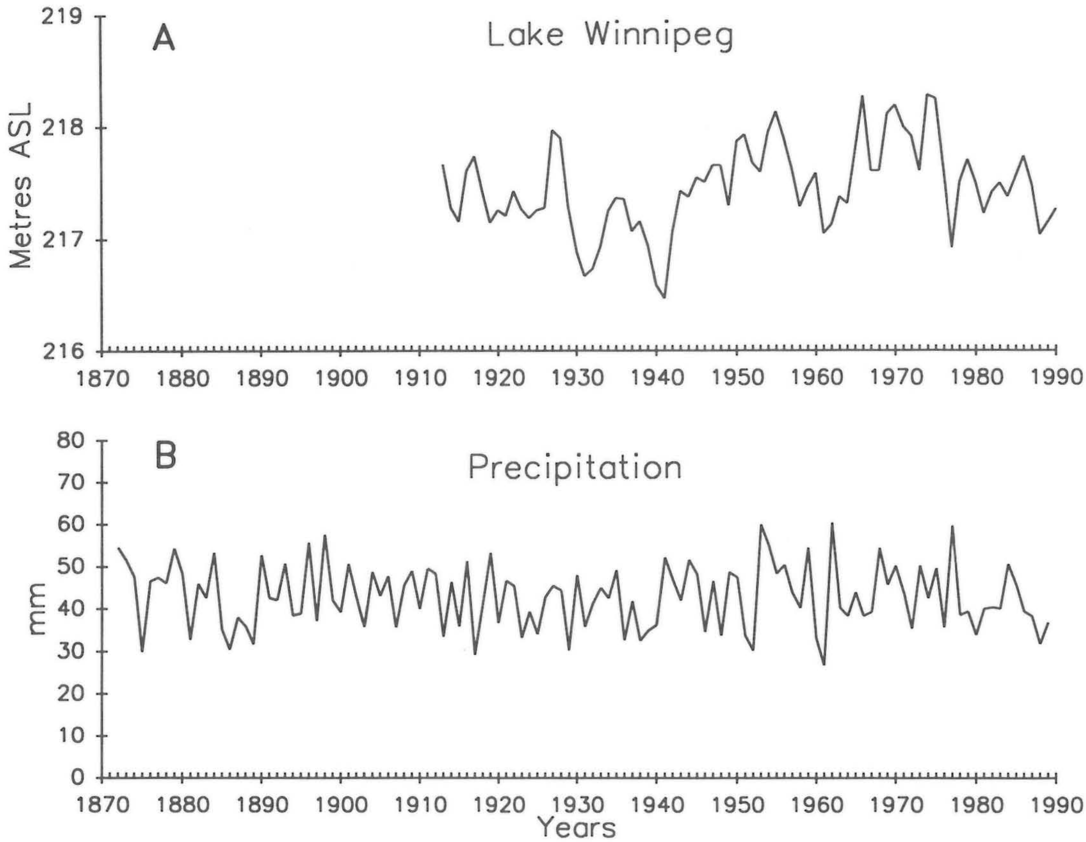



*Figure 7:* *Mean annual water levels for Lake Winnipeg from 1913 to 1990 and annual precipitation for Winnipeg from 1873 to 1990 (unpublished data from Manitoba Water Resources Branch and National Climate Archives).*

Water level increases of up to 45 cm due to variations in atmospheric pressure, termed seiches, also occur on the lake (Einarsson and Lowe, 1968). Seiches, in combination with wind setup or setdown, can result in substantial water level fluctuations even over short periods of time as is evident in the almost daily fluctuations shown on the hydrograph during the ice-free season (Fig. 6).

Although the occurrences of wind setups and seiches are largely erratic and unpredictable, their effects on the shore are similar to tides and the south shore of Lake Winnipeg can be classified as a microtidal coastline, using the terminology of Davis (1964) and Hayes (1979). A microtidal coastline has a tidal range of 0-2 m. During periods of wind setdown, broad "tidal flats" over 100 m wide are exposed in places along the south shore of Lake Winnipeg (Fig. 8).

*Figure 8: Upper foreshore exposed at Patricia Beach during period of wind setdown. Note the wide backshore and vegetated dunes. Scale bar is in centimetres.*

## SURFICIAL GEOLOGY

The south shore of Lake Winnipeg consists entirely of late Holocene barrier islands except for the bedrock outcroppings at Stoney Point. Figure 9 shows the general profile of the beach and nearshore zones and the terminology describing the various features of a barrier island. The sediments are primarily unconsolidated sand with minor amounts of gravel. Clay and silt, exposed in places on the lower foreshore, are interpreted as relict marsh sediments, although such sediments were generally not observed in the marsh immediately shoreward of the barrier island. South of Chalet Beach at Site 7, the area northeast of Brokenhead River including Site 21, and the north end of Beaconia Beach including Site 8 (Fig. 2), the foreshore comprises mainly eroded till as evidenced by the abundance of large boulders in these areas.

The bluffs north of Balsam Bay on the east, and Sans Souci on the west were not mapped during the present survey. Cheng (1972) described the shore between Beaconia and Balsam Bay as a bluff 4 to 5 m high comprising silty till overlain by sandy glaciofluvial outwash. The west shore north of Sans Souci, described by Cheng (1972) and Veldman (1969), is generally below 221 m in elevation and comprises till, overlain by Lake Agassiz silt and clay. Boulders, derived from both the erosion of till and deposition by people in an effort to halt erosion, are common along both the Matlock and Balsam Bay shores (Fig. 10).

## CLIMATE

Gimli, situated on the west shore of Lake Winnipeg records a mean annual temperature of 1.4°C. The average January temperature is -6.7°C and the average July temperature is 18.9°C. The mean annual precipitation is 50.8 cm of which 38.0 cm falls as rain and 12.8 cm falls as snow.

Lake Winnipeg is ice free from about May 8 to November 22. Spring breakup and fall freezeup may vary by about one week from these dates (Penner and Swedlo, 1974). The effects of lake ice on the shore is generally con-

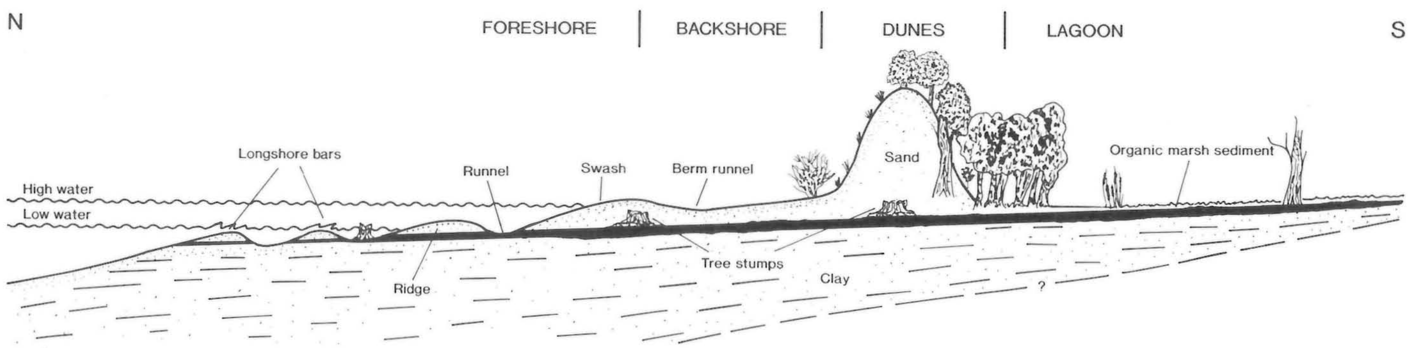



*Figure 9: Generalized profile of the beach and nearshore zones and the terminology describing the various features of a barrier island.*

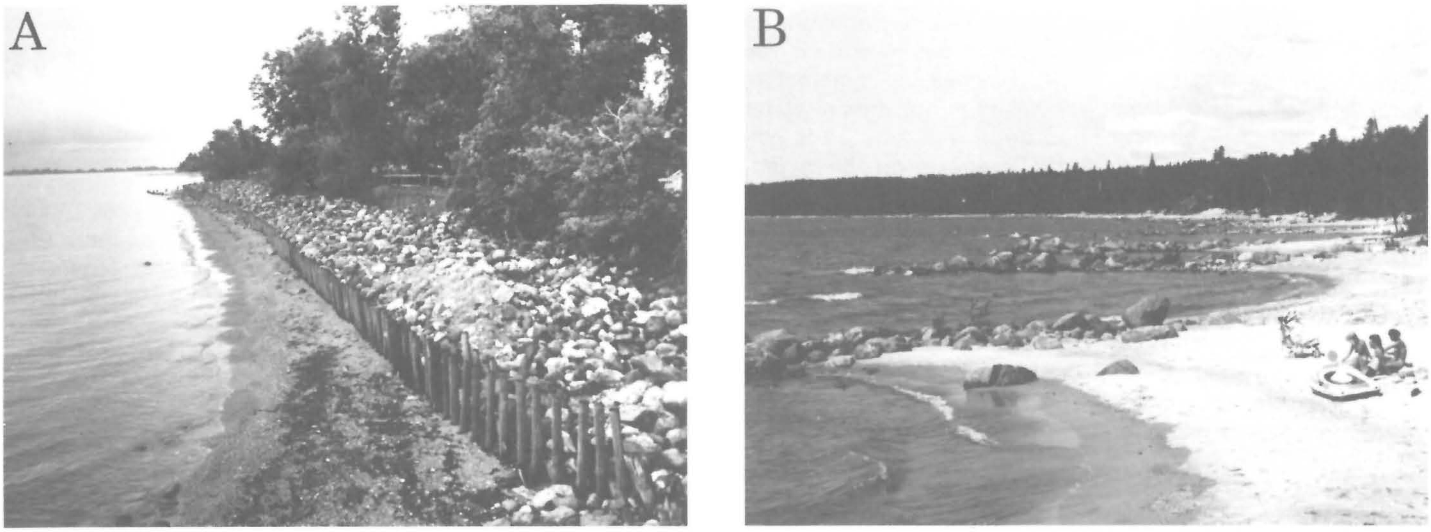


*Figure 10: (A) Sea-wall at Matlock, and (B) groynes at Balsam Bay constructed to halt shoreline erosion.*

*Figure 11: Trees pushed over by shore ice. Note the scars on the bark of the tree on the right.*

sidered to be minimal (Penner and Swedlo, 1974). Ice pushed boulders and frost boils occur on Stoney Point. Elsewhere, submerged trees on the lower foreshore have been plowed up or sheared off. Otherwise, shore ice appears to have little lasting effect on the shoreline. In places, trees are scarred or pushed over when ice is driven onshore by strong winds (Fig. 11).

Veldman (1969) compiled a wind rose diagram using data collected by the Department of Public Works Dredge No. 201, working at the mouth of Main Channel between 1961 and 1966. He concluded that the area was calm 13.2% of the time, *i.e.*, winds less than 4.8 km/hr. He further concluded that the wind blew from opposite points of the compass about equal lengths of time, but that the north and south directions were more common than the other directions, accounting for over 36% of the time (Table 2). Strong winds, over 32 km/hr, are more common from the north, northwest and west than from other directions.

**Table 2: Wind direction and strength as a percentage of the time it blows (Veldman, 1969).**

| Wind Speed | Direction and % of time | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| km/hr | N | NE | E | SE | S | SW | W | NW |
| 4.8-16 | 5.3 | 2.6 | 4.2 | 4.6 | 7.9 | 2.7 | 4.3 | 2.9 |
| 16-32 | 7.6 | 2.1 | 3.6 | 2.8 | 7.4 | 2.0 | 4.2 | 3.3 |
| >32 | 5.7 | 1.2 | 1.3 | 1.0 | 3.0 | 0.5 | 2.5 | 3.4 |

Veldman (1969) also related wave energy from all directions to the wind direction. His wave energy distribution diagram for Lake Winnipeg is reproduced in Figure 12. Cheng (1972) concluded that wave energy, delivered by winds of 13 km/hr and lower, is not significant compared to that delivered by winds of 16 km/hr and higher. The east coast of Lake Winipeg receives much higher wave energy than the west coast because the wind blows more frequently from the west. The east and west coasts receive high normal wave energy and a low parallel component due primarily to the southerly wind direction and the configuration of the lake bottom offshore. The parallel wave component generates longshore drift that, according to Veldman (1969) and Cheng (1972), transports sediment southward along both the east and west shores, on to the delta front (barrier islands). This conclusion is not based on current measurements or sediment provenance studies, but on limited wind and wave climate data. No systematic current measurements have been undertaken in Lake Winnipeg.

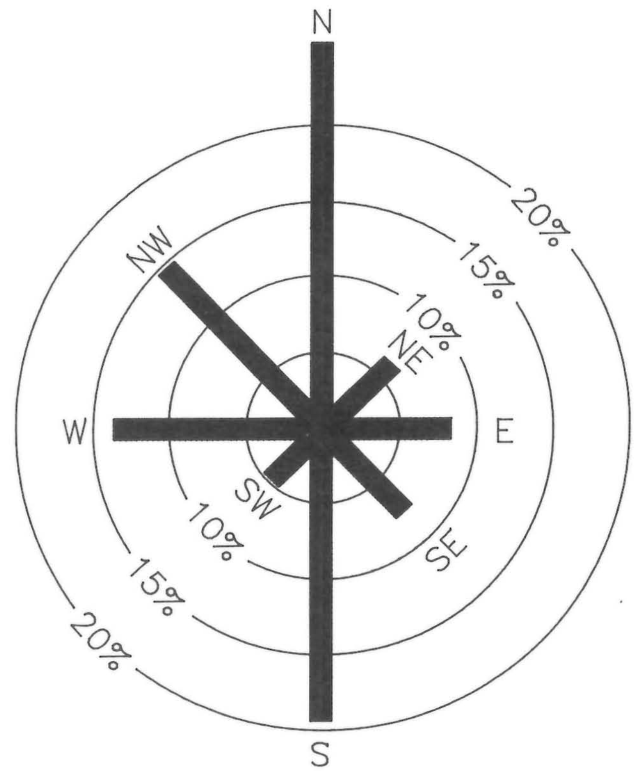



*Figure 12: Wave energy distribution diagram for Lake Winnipeg. Reproduced from Veldman (1969).*

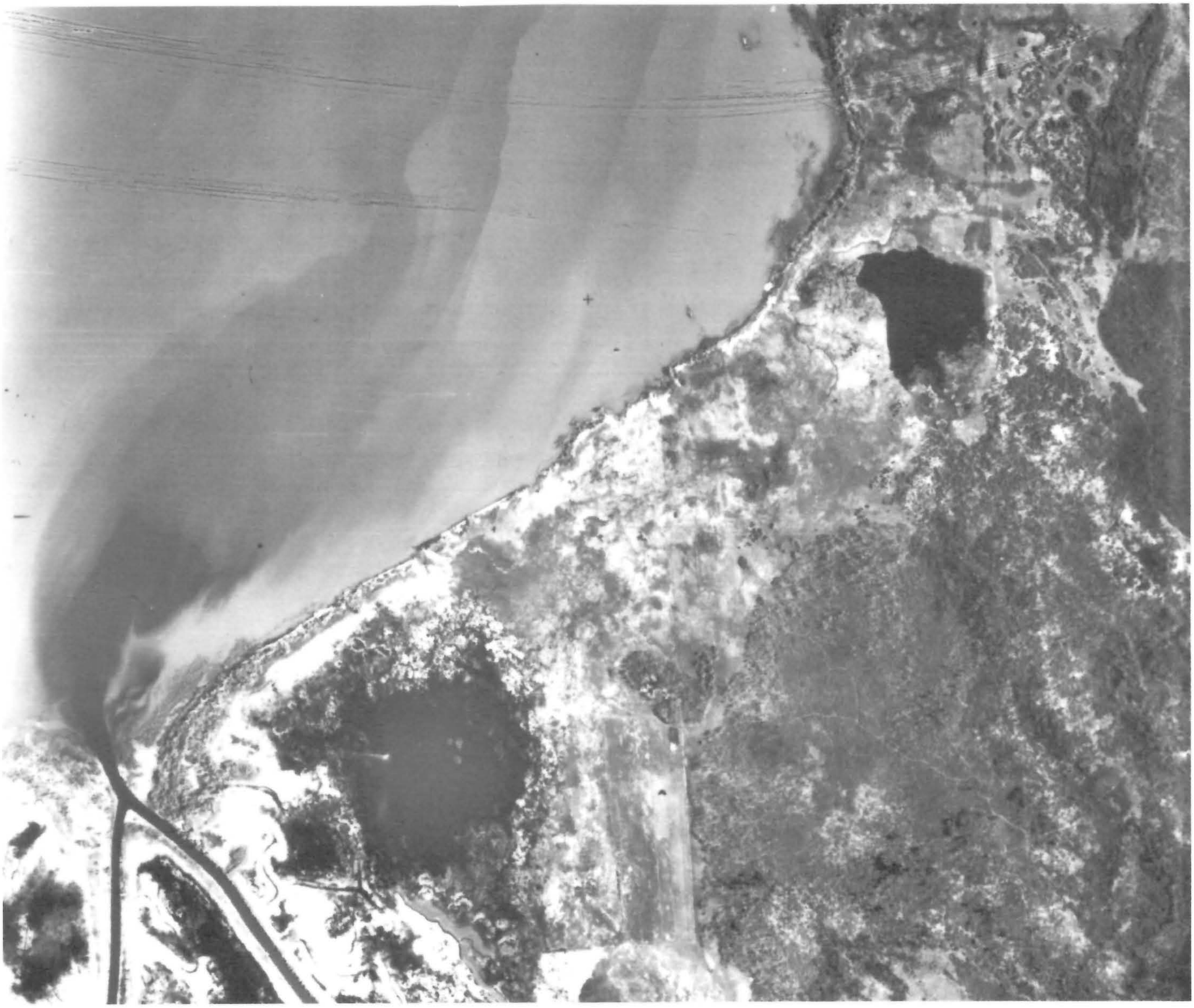


*Figure 13: Airphoto taken on April 21, 1946 over the mouth of Brokenhead River. The wind is from the west and the transparent water plume from Brokenhead River is moving to the northeast in a counter clockwise direction.*

## INTRODUCTION

The wind must be considered the singularly most important natural agent responsible for geomorphic change in the Netley Marsh area. Eolian modification of the landscape such as the formation of dunes is the most obvious effect; however, drift currents and waves, which are probably more important agents of sediment dispersal than eolian processes, are generated by the wind acting on the surface of the lake. A clear understanding of the wind regime in the area of the south basin of Lake Winnipeg is therefore paramount to understanding the sediment dispersal pattern along the south shore of the lake.

## DRIFT CURRENTS

Drift currents resulting from wind are important agents of sediment dispersal. These currents are controlled by wind speed and water depth and become more effective with decreasing water depth. Because Lake Winnipeg is so shallow, it is especially susceptible to the effects of drift currents.

Aerial photographs can be used successfully to map currents, but it is impossible to use these photographs to measure current speeds as consecutive exposures are only a few seconds apart, which is too short to see current-induced changes. On a flight line or satellite photo over an open body of water, it is commonly possible to see the effects of currents. Waves are generally discernible on aerial photographs, although there may be 180° ambiguity in the wave direction, except where they refract around islands, rocks or shoals. In some instances wind shadows are evident in the lee of islands or along leeward shores. Foam stripes, which commonly form the boundary between currents moving in slightly different directions, are commonly visible on aerial photographs, as well as, from the water. Where water of different densities or transparencies mixes, as in the case of turbid sediment-laden water and sediment-free water, currents and large plumes can commonly be seen on aerial photographs. Ice floe movement and lake ice breakup can also give valuable clues to current directions and water mixing.

Several aerial photographs have been selected to illustrate currents resulting from winds from different directions. Figures 13 and 14 show the mouth of Brokenhead River on April 21, 1946 when the wind was from the west, and on August 22, 1946 when the wind was from the southeast respectively. On April 21, 1946 (Fig. 13), waves are clearly visible moving in from the west and in places refracting around islands and rocks along the shore. A large plume of transparent, sediment-free water can be seen flowing out of Brokenhead River into the sediment-laden water of Lake Winnipeg. The plume circulates counter clockwise and extends 1 to 2 km to the northeast, parallel to the shore. When the wind is blowing from the southeast, as it was on August 22, 1946 (Fig. 14), there is no evidence of waves. The same large plume from Brokenhead River extends westward along the shore, for more than 1 km, indicating clockwise circulation. On July 5, 1946 (Fig. 15) when the wind was blowing from the southwest, plumes of transparent water flowing north from the marsh via Pruden Creek into Lake Winnipeg move eastward along the shore, again indicating the formation of counter clockwise currents in the south basin. Northwesterly winds, as illustrated on an airphoto from April 28, 1987, also produce counter clockwise currents that flow north around Stoney Point (Fig. 16). When counter clockwise currents are predominant, sediment appears to be deflected out into the lake north of Stoney Point rather than on to the shore at Patricia Beach or Beaconia Beach. Strong northerly winds produce turbulent sediment-laden water, all along the shoreline, that flows into the marsh due to wind setup as seen on an airphoto from October 10, 1971 (Fig. 17). There are no apparent current indicators to be seen in the lake during these times, but sediment plumes can be seen extending south into the relatively transparent water of the marsh behind the barrier islands through washovers, inlets and crevasse splays.

In summary, aerial photographs indicate counter clockwise currents along the south shore when the wind is from the southwest, west, northwest and north. On the other hand, southeast winds produce clockwise currents as do easterly and northeasterly winds, although this was not observed. There is no evidence from the currents that sediment is transported to the north or to the south around Stoney Point.

## WAVES

Waves are the most active agent of geomorphic change affecting the south shore of Lake Winnipeg. They generate longshore currents, modify the nearshore bottom topography and transport sediment.

Most of the time the beaches are subject to only moderate or low energy waves, during which time sediment accumulates; however, sediment is moved landward at a relatively slow rate compared to the rapid erosion taking place when storm waves are eroding the shore. Moderate to low energy waves repair the damage done during periods of storm activity only if there is sufficient time between storms.

During the low energy construction period, longshore bars, with accompanying ridges and runnels, form and slowly migrate landward to ultimately weld on to the beach. In the area from just west of the mouth of Salamonia Channel to just east of the mouth of Brokenhead River (Fig. 2), most of the wave energy is dissipated when the waves break over the longshore bars and relatively little wave energy reaches the beach under low wave energy conditions. Similar conditions exist along the middle part of the baymouth-bar at Beaconia Lake (Fig. 2) where longshore sand bars are common.

In areas where the nearshore slope is steeper, such as around Stoney Point and along the shore south of Chalet Beach (Fig. 2), even moderate or low energy waves may break on the beach. When high energy storm waves wash up on a low profile beach with sand bars or, when low to

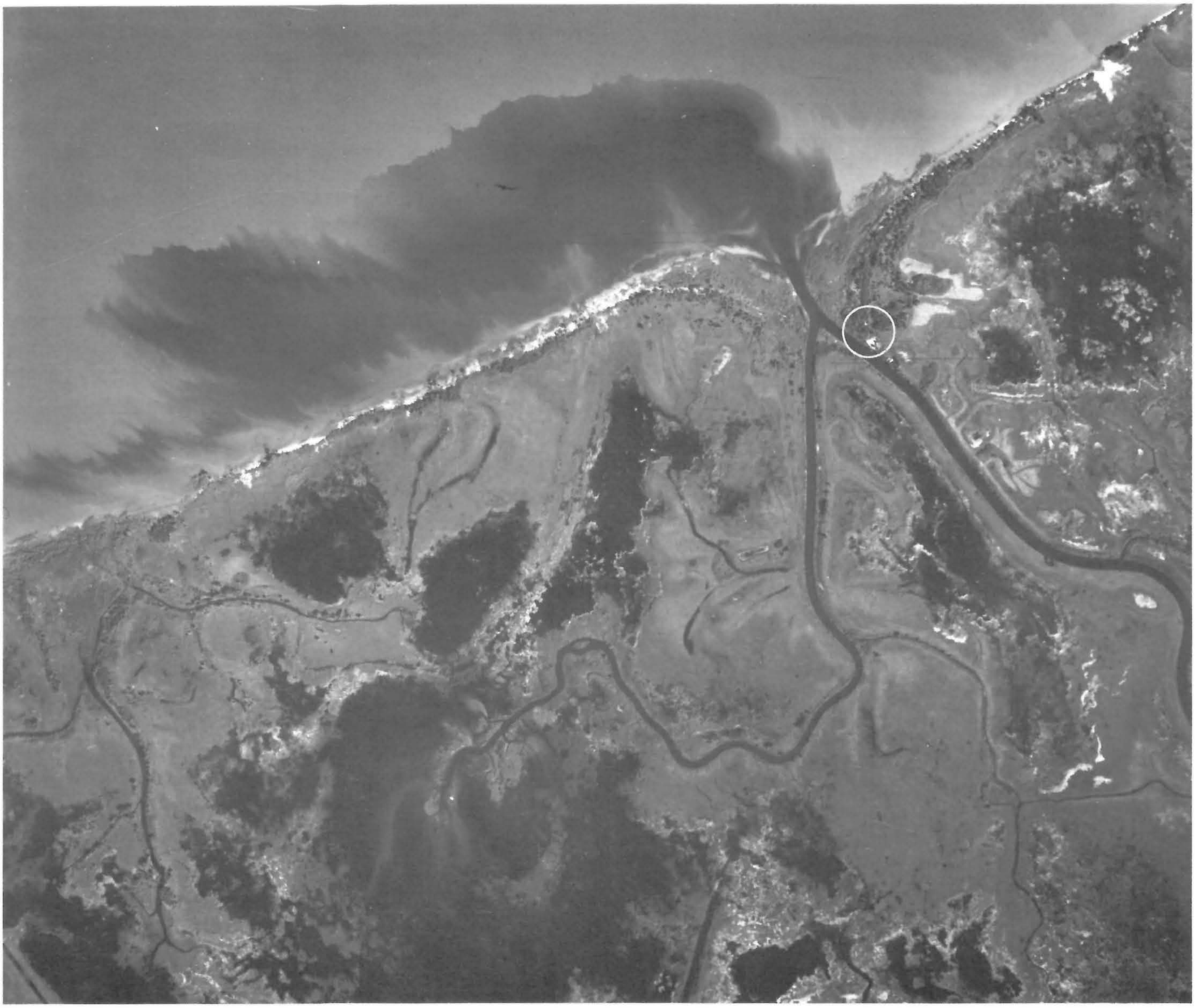


*Figure 14: Airphoto taken on August 22, 1946 over the mouth of Brokenhead River. The wind is from the southeast and the transparent water plume from Brokenhead River is moving to the west in a clockwise direction. Buildings at the mouth of Brokenhead River are indicated by a circle.*

*Figure 15: Airphoto taken on July 5, 1946 over the mouth of Pruden Creek. The wind is from the southwest and the transparent water plume from the channel is moving to the east in a counterclockwise direction. Note the symmetrical infill of the channel and the road indicated by an arrow, on the west side of the channel.*

*Figure 16: Airphoto taken on April 28, 1987 over Stoney Point and Beaconia Lake. The wind is from the northwest and the transparent water plume is moving in a counter clockwise direction and is deflected to the north by Stoney Point and away from the bay-mouth-bar at Beaconia Lake.*

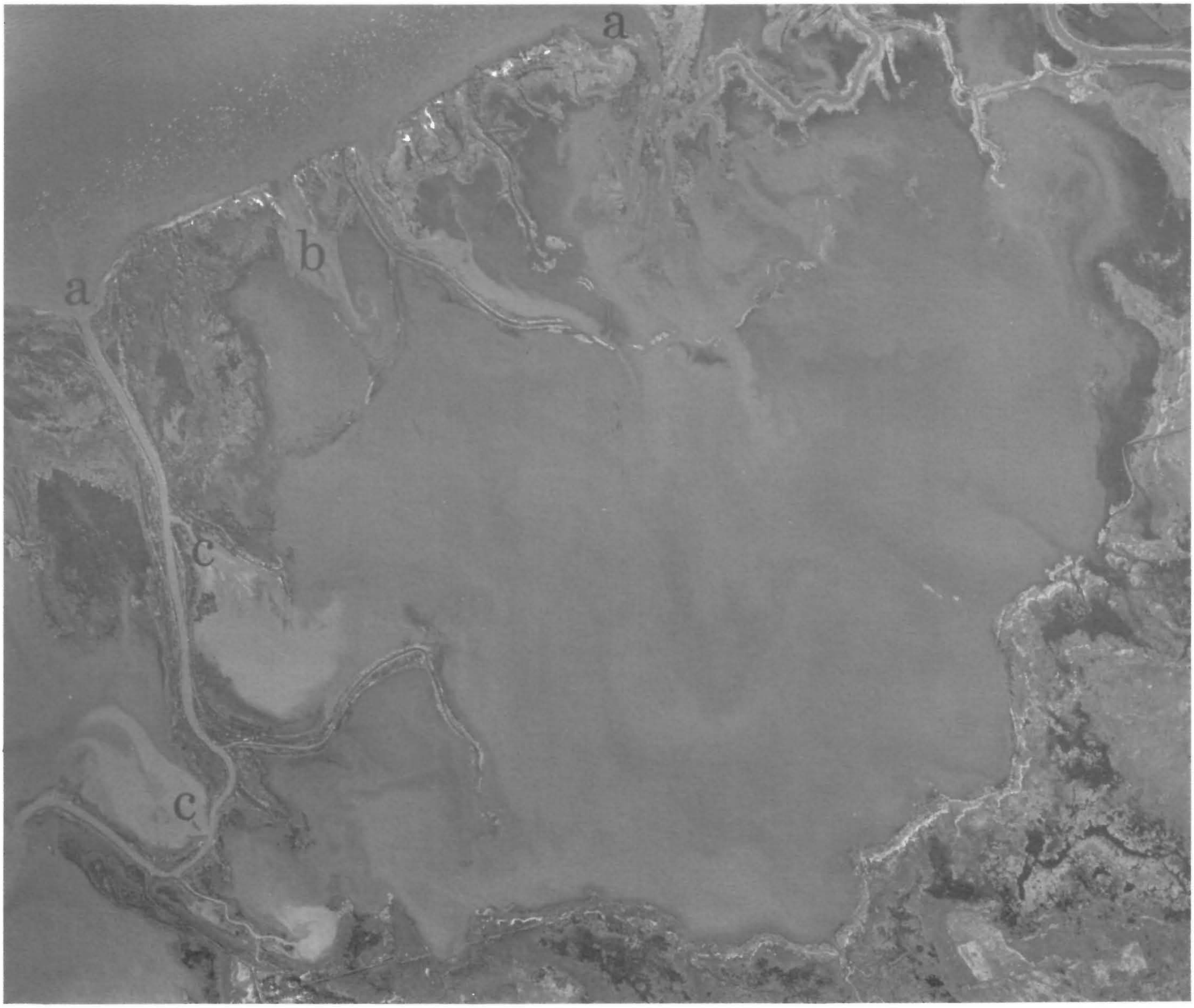



*Figure 17: Airphoto taken over Folster Lake on October 10, 1971 showing sediment transport south across the barrier island and into the marsh by way of inlets (a), washovers (b) and crevasse splays (c).*

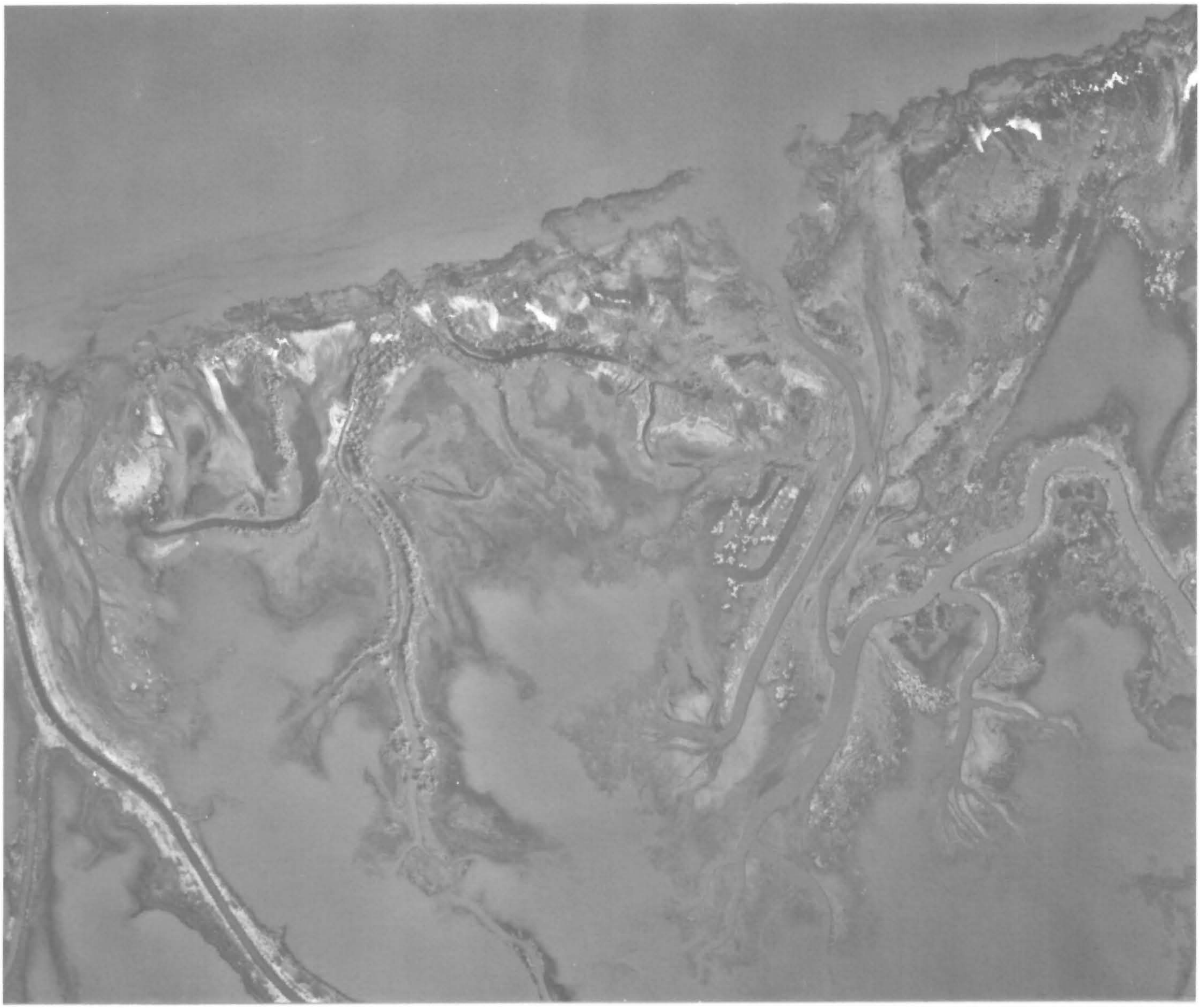


*Figure 18: Airphoto taken over Folster Lake on May 11, 1968 showing many generations of washovers. Note the 'cut off' creeks in the marsh that are no longer connected to Lake Winnipeg.*

moderate energy waves wash up on an unprotected beach, there is erosion of the foreshore and a resultant decrease in the nearshore slope. Sediment is moved into deeper water or put into suspension and carried away by longshore currents.

During periods of high water, such as during severe wind setup and coincident storms, sediment can be eroded from the foreshore and transported inland in the form of washover fans. Washover fans are deposited when wave runup continues up and washes over the crest of the barrier island, transporting sediment on to the delta plain or into the lagoon (Schwartz, 1982). At other times, when the water level is not high enough to keep the washover site continuously submerged, overwash may occur only from runup of large waves. In this case, sedimentation takes place intermittently on a surface that is normally subaerially exposed. Evidence of this type of washover, of many different ages, is found along the entire length of the barrier islands, indicating this is the dominant method of barrier island construction (Fig. 18). Depending on the elevation of the water, the shoreline may become totally submerged, in which case current action and sediment transport occur over the entire site. Airphotos of the barrier island taken on May 11, 1968 (Fig. 19) and October 10, 1971 (Fig. 17) indicate that this type of washover is common along the south shore of Lake Winnipeg.

Inlets and washovers provide a mechanism for sediment and water to be transported across or through the barrier island. Whereas washovers typically result from a single high energy event, sediment deposited in an inlet is the product of repeated flow of water into, or out of, the marshes behind the barrier island. Washover fans are deposited subaerially, whereas ebb and flood deltas associated with inlets are constructed under water (Friedman and Sanders, 1978). Water movement through the inlets, both in and out of the marshes, is due to wind setup and storms the same as washovers. Flow is also due to hydrological adjustment between lake and marsh water levels, overflow from rivers and, possibly to permit circulation in the lagoon, in through one inlet and out through another. In Netley Marsh, inlets are found primarily between the mouth of Pruden Bay and the Brokenhead River and at Beaconia Lake (Fig. 2). West of Pruden Bay the only currently operating inlet is Salamonia Channel, which is also an abandoned distributary of the Red River. Throughout Netley Marsh and Beaconia Lake, the large flood deltas and the relatively small ebb flow deltas associated with the inlets indicate the net sediment transport is into the marshes (Fig. 19). The ebb flow deltas along the shore of Lake Winnipeg are composed of fine- to medium-textured sand and are constantly being reworked and modified by nearshore processes. Nothing is known of the texture of the flood delta sediments.

## WIND

Sand dunes are common along the bay-mouth-bar at Patricia Beach and Beaconia Beach (Fig. 20), but they are small or nonexistent on the rest of the barrier island system.

At Patricia Beach and Beaconia Beach the 2 to 4 m high dunes are in places stabilized by large willows and ash trees but elsewhere there are active blowouts surrounded by grasses and shrubs. Active dune migration is evident along the road that ran to Balsam Bay in the 1930's; the road is now covered with 1 to 2 m of dune sand (see later section) as well as by the active blowouts, shadow dunes and wind ripples on the beach (Fig. 21). It is not clear when the dunes first formed or when they are most active; however, as the sand is derived from the backshore and foreshore, it is likely that the dunes are most active during periods of low water, such as during the 1930's and least active when the water is high, as it is today. The impact on dune stability by the increase in the number of people using the beach is unknown, but where vegetation is trampled and destroyed there will be increased wind erosion.

## ICE

Lake Winnipeg is ice covered for approximately five months of every year. Ice, or rather ice movement during breakup, is not considered an important agent of geomorphic change. This is largely due to the shallowness of the lake, which causes lake ice to ground in the offshore. Minor, localized ice-push features can be seen in the sand in the spring, but lasting effects such as ice-pushed ridges and scarred or bulldozed trees are rare (Fig. 11). Because of the ephemeral nature of ice effects, this aspect of the study was not pursued, with the notable exception of ice-push features, frost sorting and bedrock heaving on Stoney Point.

During periods of low water, a number of lasting effects of ice are observed along the shores of Stoney Point well into summer. Frost shattered and frost heaved "boils" are common on the bedrock surface on the west side of the point (Fig. 5 and 22).

Frost shattering is believed to take place because the ground surface comprises thinly bedded carbonate rock that is permanently saturated and probably goes through several freeze-thaw cycles each year. Frost shattering occurs because the growth of ice lenses and resulting thermal expansion is favoured along the pre-existing bedding planes and cracks. The resulting bedrock surface, which forms most of the foreshore, is covered almost entirely of shattered "discoid" shaped carbonate rock fragments. Local differential frost heaving that results in "boils" occurs because the pressure generated by the freezing water is directed in a vertical direction, possibly as the result of resistance to expansion by the surrounding rock (Fig. 5). The localized nature of the expansion may be due to the presence of fossils or, possibly textural variations in the bedrock. Alternatively, the boils may form at the intersection of two or more saturated vertical joints when water at the surface freezes and forms a seal. The downward freezing of the confined water exerts sufficient pressure in the unfrozen water to cause rupture (Dredge, 1992). Mounds or boils 10 to 20 cm high and 1 to 2 m in diameter scattered across the outcrop may result from either or both of these processes (Fig. 22).

Elsewhere on Stoney Point, frost shattered bedrock rubble appears to be undergoing active cryoturbation (Fig. 23).

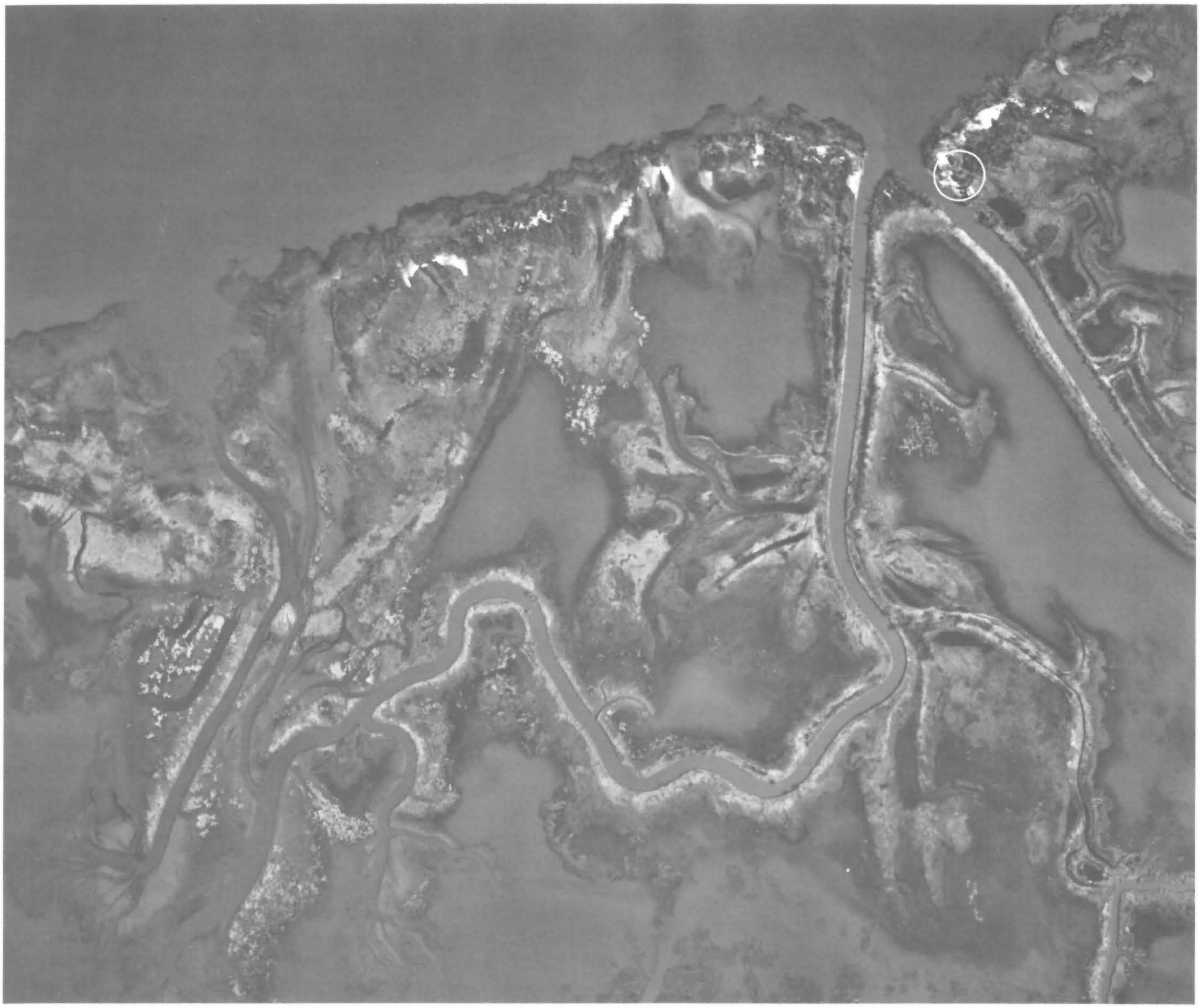


*Figure 19: Airphoto taken on May 11, 1968 over the mouth of Brokenhead River showing flooding and extensive washovers along the barrier island. Note the well developed distributary deltas at the south end of the channels.*

"Discoid" or tabular rock fragments that form by frost shattering of the bedrock are initially flat lying. After some time, and when a sufficient thickness of rubble has accumulated, the "discoid" shaped rocks stand on end, forming oriented stone circles with a larger more rounded rock at the centre of the circle. These features are similar to sorted polygons as described by Washburn (1973). The exact method of formation of the oriented stone circles is uncertain as this is not a permafrost area.

A single large ice-shoved boulder and groove was observed on the east side of Stoney Point (Fig. 24). This large glacial erratic, which is more than a 1 $m^3$ in size, was pushed more than 50 m across the frost shattered bedrock surface by wind driven lake ice.

*Figure 20: Sand dunes at Patricia Beach. Note the tree stump on the backshore in the foreground.*

*Figure 21: Aeolian shadow dunes and wind ripples on the backshore at Beaconia Beach. The coin is 2.5 cm in diameter.*

*Figure 22: Frost heaved bedrock mound on the upper foreshore at Stoney Point. The lens cap is 7 cm in diameter.*

*Figure 23: Oriented stone circle formed of discoid shaped rock fragments. The lens cap is 7 cm in diameter.*

*Figure 24: Ice-shoved boulder and groove on the upper foreshore at Stoney Point. Note the frost-shattered bedrock surface that composes the foreshore.*

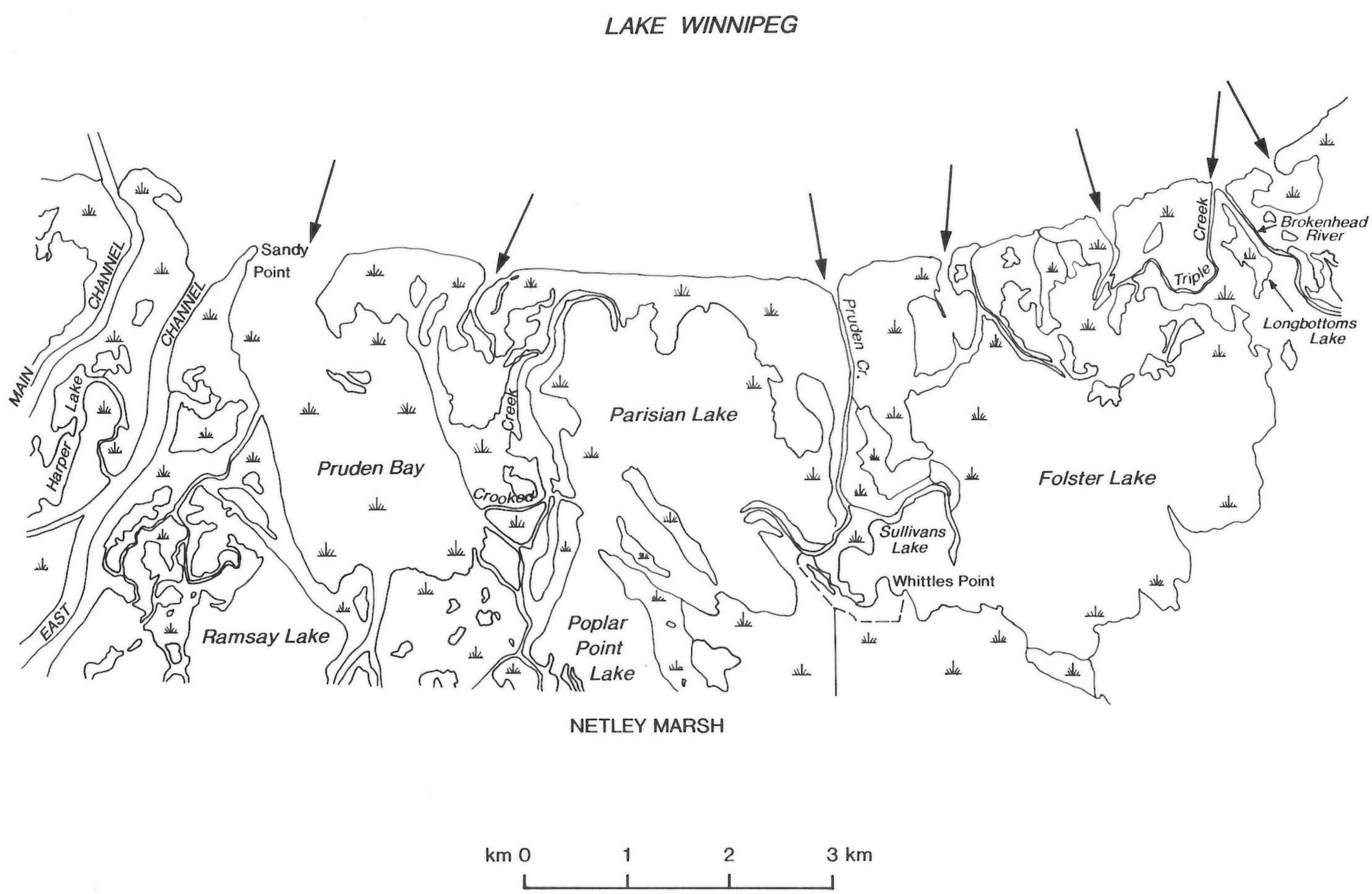



*Figure 25: Location of the inlets between East Channel of the Red River and Brokenhead River. Note the offset in the barrier island on either side of Pruden Bay.*

## INTRODUCTION

In the present study the relationship between landforms and sedimentology is termed morphodynamics. The landforms of Netley Marsh are constantly changing and the dominant processes responsible for these changes are sedimentological. Three major morphodynamic units recognized in the Netley Marsh area include inlets and foreshore, usually below the level of the lake, and barrier islands, normally above the water level.

## INLETS

### Distribution

Inlets are located mainly between the Main Channel of the Red River and Brokenhead River leading into Netley Marsh and through the bay-mouth-bar leading into Beaconia Lake (Fig. 25). The largest inlet is the 0.8 km wide opening into Pruden Bay, Ramsay Lake, Oak Point Lake, Lower Devil Lake, Swedish Lake and Poplar Point Lake. Six smaller inlets, generally from a few tens to a few hundred metres wide, including Pruden Creek and Triple Creek connect Parisian, Sullivans, Folster, Longbottoms and several small unnamed lakes to Lake Winnipeg (Fig. 2 and 25). The only inlet west of Main Channel is Salamonia Channel, which leads into Cochrane, McKay, Netley, Passwa and Hughes lakes (Fig. 2). Three small inlets, one at the north end and two near the middle of the bay-mouth-bar, join Lake Winnipeg and Beaconia Lake (Fig. 26).

### Origin

Ehlers (1988) indicated that pre-existing relief played a significant role in the location of tidal inlets along the shore of the Wadden Sea and suggested that they followed the course of buried channels. Little is known about the subsurface geology of the Netley Marsh area, other than the depth to bedrock appears to increase to the west (Bannatyne and Jones, 1979). Although the subsurface bedrock topography may have influenced the location of the inlets, it is not certain that this is the main controlling factor. The location of the widest inlet at Pruden Bay may be related to the ancestral Red River, which may have flowed across this general area at various times during the last 8000 years (Nielsen *et al.*, 1993), although the exact locations remain to be determined.

The barrier islands west of Main Channel are off-set approximately 0.8 km to the north of the barrier islands east of Main Channel (Fig. 2). Prominent off-sets in barrier islands similar to this have been described elsewhere by Galvin (1971) and Reinson (1980). The planform of inlets and associated barrier islands is related to the littoral drift, the ratio of setup or fluvial to longshore transport and the ratio of net to gross longshore transport rates. The gross longshore transport rate is the sum of littoral drift transported to the right and to the left past a point on the shore in a given time. The net longshore transport rate is the difference between the amounts of littoral drift transported to

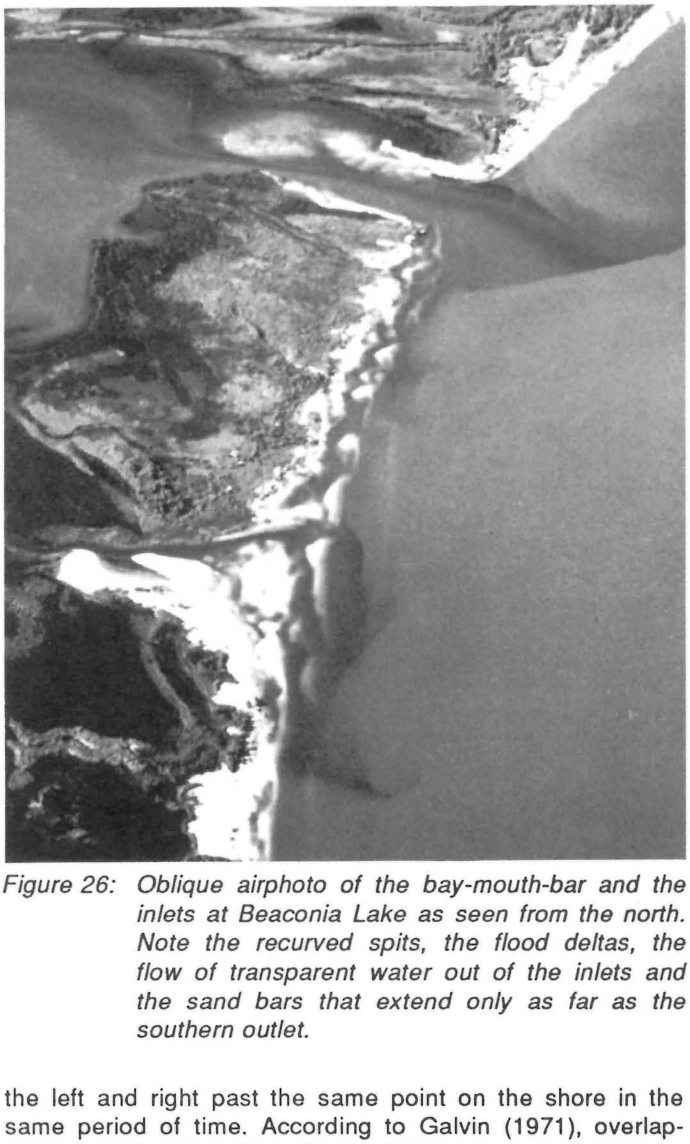


*Figure 26: Oblique airphoto of the bay-mouth-bar and the inlets at Beaconia Lake as seen from the north. Note the recurved spits, the flood deltas, the flow of transparent water out of the inlets and the sand bars that extend only as far as the southern outlet.*

the left and right past the same point on the shore in the same period of time. According to Galvin (1971), overlapping inlets develop where littoral drift is adequate, longshore transport rates are large but setup and fluvial flow is strong enough to maintain the inlet channel, and the ratio of net to gross sediment transport rates is high. The ratio of net to gross longshore transport is directly related to the distribution of wave directions, thus when all the waves come only from one side of the normal to the beach the ratio of net to gross longshore transport reaches its maximum value of 1.0. When there is significant offset updrift (Fig. 27) a significant proportion of the waves come from the downdrift side of the inlet, which means that the ratio of net to gross transport is low. The reversal in wave direction prevents significant overlap from developing because if overlap begins to develop the barrier protrudes into the lake and is more easily eroded by waves from the downdrift direction. Also, storms from the downdrift direction tend to push the inlet channel into the overlapping barrier island.

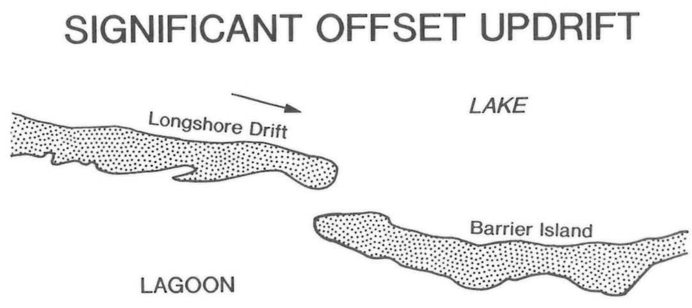



*Figure 27: Offset of barrier islands in relation to the drift currents. Redrawn from Reinson (1980).*

Using Galvin's classification, the inlet into Pruden Bay, which is also coincident with East and Main channels of Red River, is a 'significant offset updrift' inlet. This would indicate that the net to gross longshore transport ratio is <1.0 suggesting the area is affected more by northwesterly winds than by northeasterly winds. Sediment transport is predominantly easterly. The location of Main and East channels, coincident with the inlet at Pruden Bay, may lead to greater sediment input and water flow, which may make this inlet larger than other inlets, but has not otherwise influenced the planform of the inlet. The inlets to the east of Pruden Bay, including those at Beaconia Lake, have negligible offsets and are approximately symmetrical on either side of the channel indicating the ratio of net to gross transport for this area is near zero. This is a consequence of waves distributed equally about the normal to the shore, at least during periods of high sediment transport such as during storms and wind setup. Symmetrical sand spits at the lake end of the inlets, such as at Pruden Creek (Fig. 15), clearly indicate that the natural tendency is for the inlets to fill equally from the east and west and that they are only kept open by water flowing in and out through the inlet.

### Morphology

Two different kinds of inlets, one wide and short the other long and narrow, connect Lake Winnipeg and the marshes landward of the barrier islands (Fig. 28). Nothing is known of the bottom profile of any of the inlets.

Wide inlets, such as the one into Pruden Bay, are generally over 100 m across and were formed by overwash during storms (Fig. 28). Verbiwski (1986) indicates similar washover breaches into Hardmans Lake, Folster Lake and Beaconia Lake were formed during high water levels on Lake Winnipeg in 1960 and 1961, whereas others such as the one into Pruden Bay formed before the beginning of the last century. A washover, approximately 200 m wide, occurred into Hardmans Lake just east of West Channel, possibly in early 1971, although aerial photographs from 1968 indicate a small washover had already occurred. (A more detailed description of this washover is presented in a following section on historic changes). By 1990 longshore drift had closed the breach (Fig. 29) and the only evidence of the existence of the washover was the absence of trees along the shore and the presence of jetsam in the sediment. Breaches in the barrier island west of the Main Channel by washover appear to be infilled relatively quickly compared to areas further east, suggesting longshore drift and the accompanying sediment transport is more vigorous along this part of the shore or there is a paucity of sediment to the east.

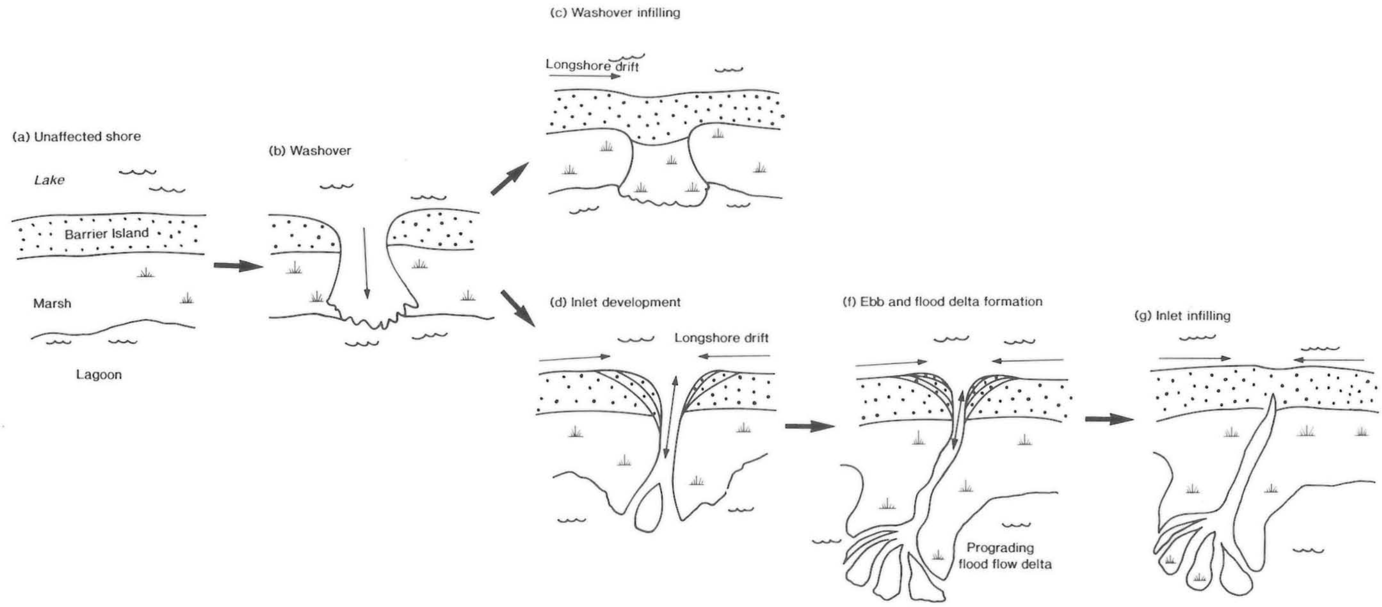



*Figure 28: Formation of washovers and inlets along the south shore of Lake Winnipeg.*

*Figure 29: 'Closed' washover at Site 2, near the mouth of West Channel. Note the absence of trees at the site of the washover and the southward extent of this and older washovers into the marsh as defined by rows of shrubs and trees. Notice the extensive longshore bars along the shore.*

The second type of inlet is a relatively long, narrow channel reminiscent of tidal creeks along the ocean. These creeks, such as Pruden Creek and Triple Creek are generally less than 100 m wide and 1 km or more long (Fig. 28). The creeks transport large quantities of fine-suspended sediment from the lake into the marshes where it accumulates as flood deltas (Fig. 19). Sand bars, reminiscent of ebb flow deltas, but more probably due to longshore drift commonly occur at the Lake Winnipeg shore. A series of symmetrical recurved sand spits at the north end of Pruden Creek indicate this creek was first formed as a washover inlet that was subsequently infilled by longshore drift from both the east and west. Other smaller washovers into Parisian and Folster lakes have small creeks at their landward end, indicating that they too initially formed by overwash and have been kept open by water circulating between the lake and marsh. Numerous "blind" creeks in both Netley Marsh and Beaconia Lake, presently not connected to the lake, were initially formed by overwash, the same as Pruden Creek. Water circulation between the lake and the marshes is not always sufficiently vigorous to maintain all the channels and as a result some of the openings become infilled (Fig. 28). Many generations of overwash, creek formation and infilling are represented by the myriad of channels found in the marshes (see Figures 14, 19, 49 and 56) .

### Ebb and flood flow deltas

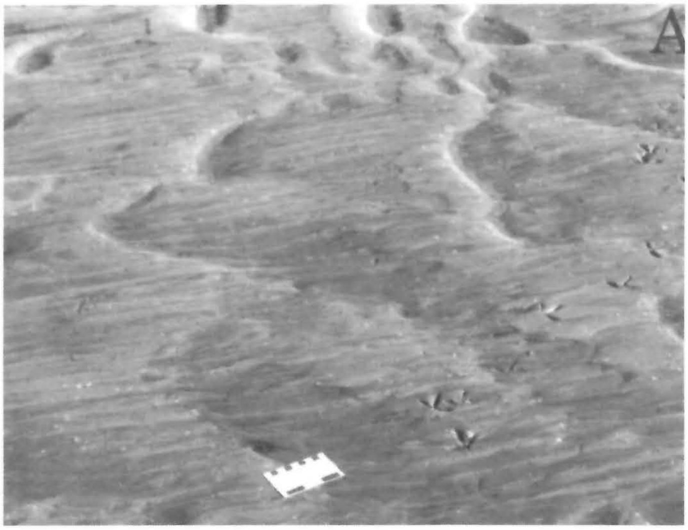
High water levels did not permit examination of the ebb and flood flow deltas except at a single site at Patricia Beach. At low water, the higher part of the flood delta is exposed adjacent to the large recurved spit near the inlet at the south end of Patricia Beach (Site 5, Fig. 2). Although the inlet was not sounded, it can be traversed on foot indicating that it is generally not more than about 1 m deep and at low water a significant part of the delta is exposed. The spit is composed of sand and minor gravel, whereas the adjacent delta is fine sand, silt and cohesive mud. Sinuous to linguoid current ripples produced by flood flow currents are found on the delta surface adjacent to the channel (Fig. 30A). Longitudinal ripples produced by currents flowing parallel to the ripple crests (Reineck and Singh, 1975) are superimposed on the current ripples indicating that wave propagation was at right angles to the current when they were formed (Fig. 30A).

The sequence of current ripples with superimposed longitudinal ripples is indicative of strong flood flow that results from wind setup produced by strong and persistent north winds. As longitudinal ripples are primarily erosional features produced by weak currents, they are believed to have formed as the flood flow was slacking. This conclusion is supported by the configuration of the longitudinal ripples in the current ripple troughs, suggesting that they are related to the flood flow. The only evidence of the ebb flow is slight erosion of the ripple crests as the delta surface became subaerially exposed and the water reversed flow back towards Lake Winnipeg (Fig. 30B).

The available evidence on the higher parts of the exposed flood deltas indicates sediment was transported landward into the marshes during wind setup, but little or no sediment was transported back out into the lake as the water returned to its normal level.

### Migration

There is no evidence from historic maps or aerial photographs that the inlets into Netley Marsh have migrated or changed position in the last hundred years. The inlets into Beaconia Lake, on the other hand, have changed significantly since the area was mapped in 1932 (see section on historic changes). The inlets through the bay-mouth-bar at Beaconia Lake do not appear to have migrated southwestward in response to updrift barrier accretion and downdrift barrier erosion as might be suspected from sediment textural or geomorphological variations. It appears rather that an inlet first opened in the north, probably in response to rising water levels. As this inlet became infilled a new inlet opened further south, which, in turn, infilled as yet another inlet opened further to the south. This opening, closing and moving of inlets is thought to be due to rising water levels and increased erosion at the headland to the north. Breaches in the barrier island formed during periods of wind setup, or during storms, are quickly infilled by sediment brought down the shore by longshore drift. Because the beach sediment is finer textured and the barrier profile lower further downdrift, this area is more susceptible to washover. The currents through the inlets are not strong enough to keep the inlets open during normal wave conditions, thus the longshore drift quickly fills the inlet with sediment.



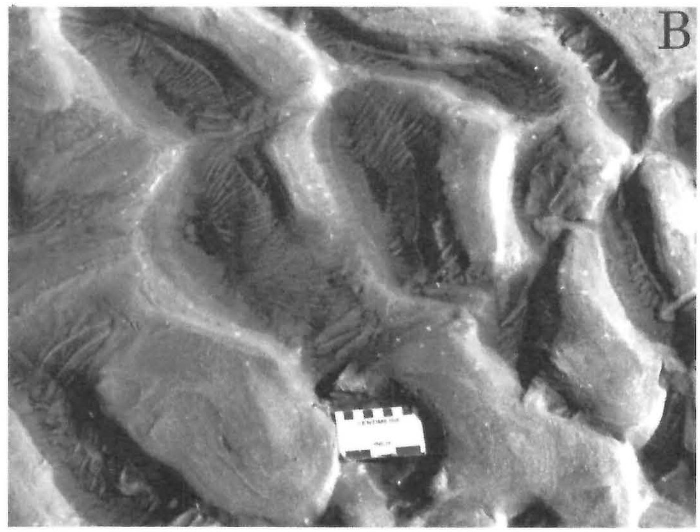




*Figure 30: (A) Current ripples and superimposed longitudinal ripples formed during flood flow, and (B) eroded ripple crests formed during ebb flow on the flood delta at the top of Figure 26.*

## UPPER FORESHORE

### Distribution

Due to the widely fluctuating water levels (Fig. 6) precise identification of the foreshore and backshore is difficult in some places. The upper foreshore is generally a relatively flat area characterized by the presence of migrating ridge and runnel systems that are separated from the backshore by a slight rise in the angle of the shore face (Fig. 31). The upper foreshore is dominated by wave processes, whereas the back shore is affected primarily by subaerial processes. Only during periods of high wind setup, or storms, is the backshore under water. Driftwood lines, welded bars and other features indicative of subaqueous processes occur on the backshore, but the area is dominated by aeolian processes most of the time.


*Figure 31: Ridge (a) and runnel (b) on the foreshore at Site 1, looking west. Note the swash marks, waterlines and the vegetation on the backbeach in the distance.*

Figure 32 shows profiles surveyed across the barrier islands at various times during the summer of 1990. Numerous discontinuous, subparallel longshore bars are found along the entire foreshore from just west of Salamonia Channel to the Brokenhead River and also along Patricia Beach and the southern part of Beaconia Beach (Fig. 33). South of Chalet Beach at Site 7, the area northeast of Brokenhead River including Site 21, and the north end of Beaconia Beach including Site 8 (Fig. 2), the foreshore comprises mainly eroded till. The eroded till surface is characterized by large boulders and cobbles that form an erosional lag, in places infilled by minor amounts of silt and clay deposited from suspension. The upper foreshore around Stoney Point is frost shattered bedrock with the odd large Precambrian glacial erratic suggesting that a thin layer of till has been eroded from the bedrock surface during transgression.

### Morphology

From one to four longshore bars, varying in shape from short and bulbous to long and narrow, occur in the foreshore (Fig. 33). During periods of wind setdown, generally only the longshore bar closest to shore becomes subaerially exposed forming a ridge and runnel system. The bars are typically about 20 cm and rarely up to 40 cm high and from 5 to 20 m or more wide, but some are >100 m long (Fig. 33).

### Minor sedimentary structures

A wide variety of minor sedimentary structures that provide information about sediment transport are commonly found on the ridges and runnels along the shore.

Swash marks formed by incoming waves on the lakeward side of the ridges are only preserved when the water level is dropping. In places where organic detritus is

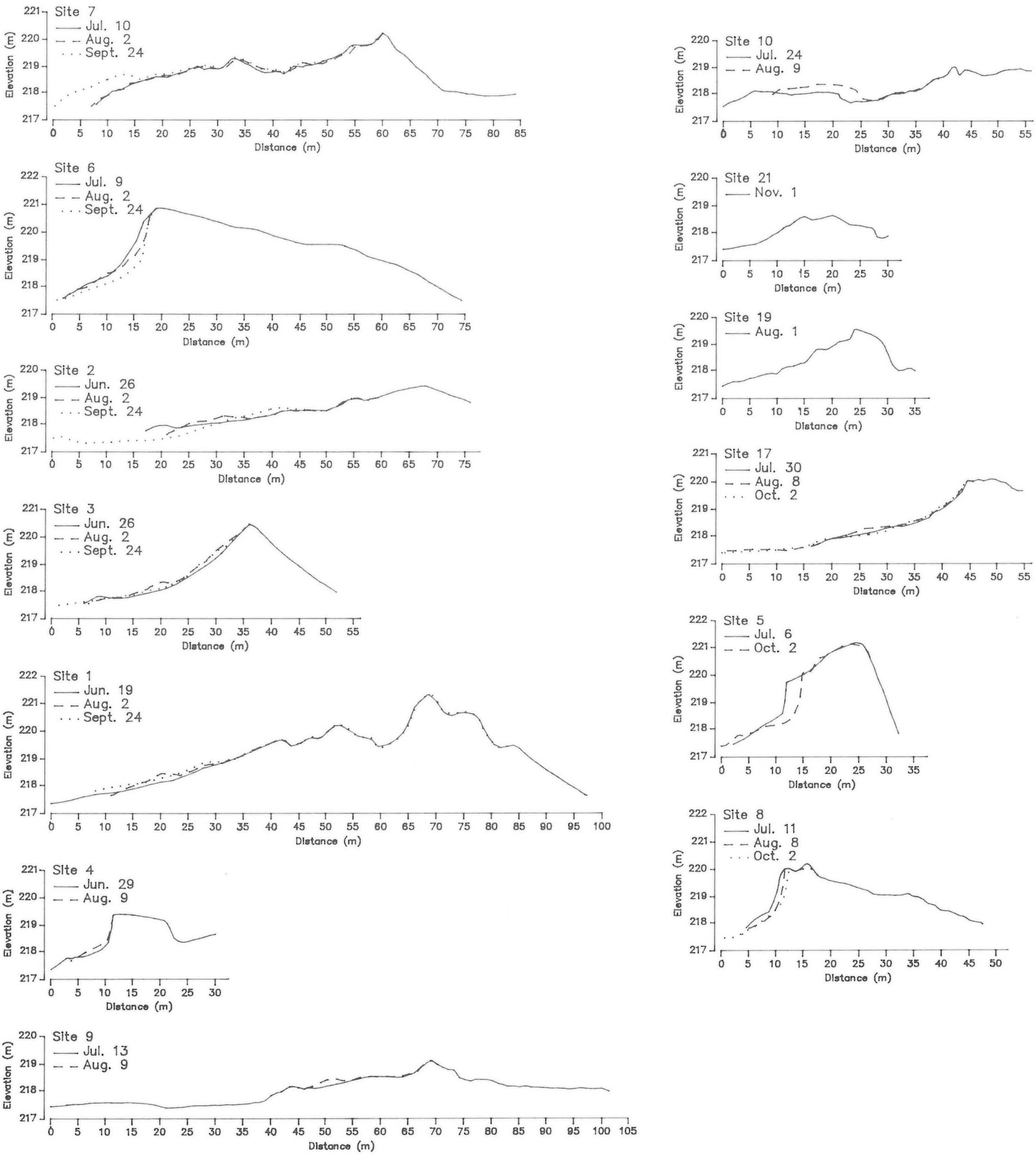



*Figure 32: Temporal variation in the surveyed profiles across the barrier islands.*

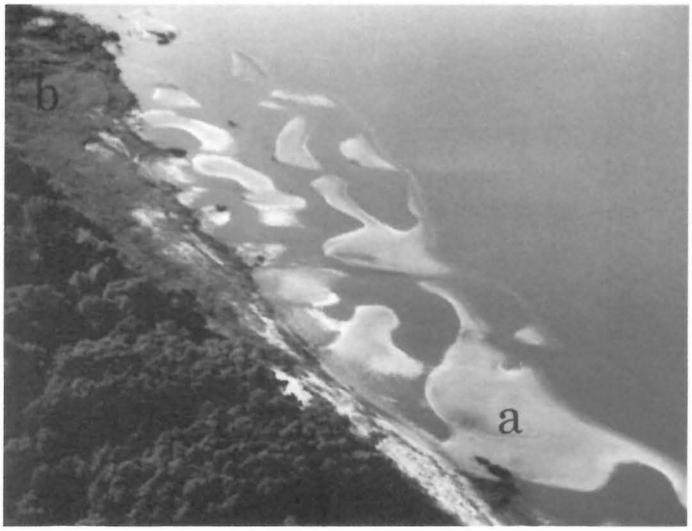



*Figure 33: Offshore sand bars (a) and ebb flow sand accumulations (b) at Site 9. The recent ebb flow sand deposits support only sedges and reeds.*

*Figure 34: Swash marks and waterline marks on the upper foreshore at Site 1. Trowel for scale.*

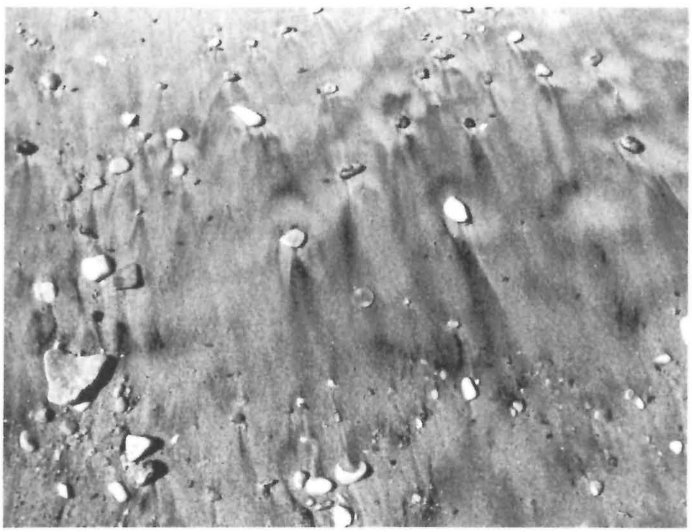


*Figure 35: Current crescents of heavy mineral concentrates on the foreshore at Site 6. Coin is 2.5 cm in diameter.*


*Figure 36: Ridge (a) and runnel (b) with undulatory small-current ripples on the foreshore at Site 2. Trowel for scale.*

abundant, swash marks and rill marks are exceptionally well developed (Fig. 34).

Current crescents (Reineck and Singh, 1975), formed where heavy minerals concentrate in the lee of pebbles, are common along the shore west of Salamonia Channel (Fig. 35). Pebbles and heavy minerals are less abundant further east and although current crescents may be present, there is less contrast between them and the surrounding sand. In places where there are no pebbles, current crescents commonly form behind small mollusc shells or other obstructions.

Water temporarily trapped between the backshore and the landward migrating ridges flows out through the runnels, parallel to the strike of the ridges. This is indicated by current crescents and a variety of ripples including undulatory and lingoid-shaped small current ripples (Fig. 36). The water drains back to the lake through small gaps between the ridges.

At Site 2, near the mouth of West Channel, megaripples composed of fine pebbles and small, poorly preserved current ripples of sand, trend perpendicular to the shore, indicating coast parallel sediment transport toward the east (Fig. 37).

Water-level marks produced by a discontinuously falling water level are common along the exposed sand waves and beaches. In places, notably east of West Channel, and to a lesser extent at the southwest end of Patricia Beach, water-level marks are, at certain times of the year, accented

*Figure 37: Megaripples and current ripples formed by coast parallel sediment transport towards the east at Site 2. Photo is looking west.*

*Figure 38: Waterline marks formed by varying concentrations of pelecypod shells at Site 2. Shovel for scale.*

by abundant small mollusc shells, tentatively identified as *Sphaerium striatinum* (Lamarck), that have been washed up from the offshore and concentrated by taphonomic processes (Fig. 38). It is not known why mollusc shells appear to be so common along the west shore and virtually absent from the rest of the beaches, but it may be related to currents or possibly higher sedimentation rates, in the offshore between Main Channel and Stoney Point, which might make this area a less suitable habitat.

Recurved sand ribbons, sand tongues, drainage channels and small deltas are common features of the upper foreshore (Fig. 39A, B, C and D). These ephemeral sedimentary structures form during periods of wind setdown when the water level is dropping. When the water reaches a depth of only a few centimetres, the wind drives the thin water film across the sand flats forming parts of the upper foreshore modifying the surface.

### Grain size

The mean grain size and sorting of selected sediment samples from the foreshore are shown in Figure 40A and 40B. The foreshore sediments in the west, at Sites 6, 2 and 3, are coarser than the sediments near the centre or the east end of the barrier island system. The mean grain size of the sediment samples from the three sites in the west is very coarse sand, whereas at sites east of Pruden Bay the mean grain size is medium sand to fine sand.

Although samples were not collected from the foreshore from Stoney Point to Beaconia Beach, the sediment clearly exhibits a decrease in the mean grain size from northeast to southwest. Gravel predominates in the northeast, whereas sand is common in the southwest (see Figure 61B and 3C).

### Dolomite content

The dolomite content of the foreshore samples show a slight decrease from Site 2 in the west to Site 12 in the east (Fig. 41). Although the decrease is small, it suggests the source of the dolomite is the till outcropping in the offshore south of Chalet Beach. Differential comminution of the softer dolomite, compared to the more resistant quartz and feldspar that comprises most of the sand, results in a gradual decrease in the dolomite content in the downdrift direction. The dolomite content therefore suggests the predominant longshore current and sediment transport direction is towards the east.

## BARRIER ISLANDS

### Distribution

The barrier islands that compose the backshore and dunes are dominated primarily by subaerial processes and include most of the study area. Occasionally during periods of high wind setup or storms, the backshore and less frequently the dunes are affected by subaqueous processes. Driftwood and other flotsam, as well as welded bars and other features indicative of subaqueous processes, are observed on the backshore (Fig. 42).

### Morphology

West of Salamonia Channel, the combined width of the backshore and dunes is approximately 75 m (Fig. 2). At Site 7, south of Chalet Beach, the barrier island is composed of a wide prograding and unvegetated sandy gravel backshore facies with a relatively thin and narrow wooded dune ridge (Fig. 43). Excavation of the dunes revealed fossiliferous pebbly sand of the backshore facies at a depth of 50 cm indicating that much of the accumulated sediment was deposited by subaqueous processes. Closer to Salamonia Channel, at Site 6, the backshore is about 10 m wide and the heavily wooded dunes up to 55 m wide. The dunes that are presently being eroded along the lake shore comprise eolian sand and backshore sediments deposited by wind and periodic overwash (Fig. 44).

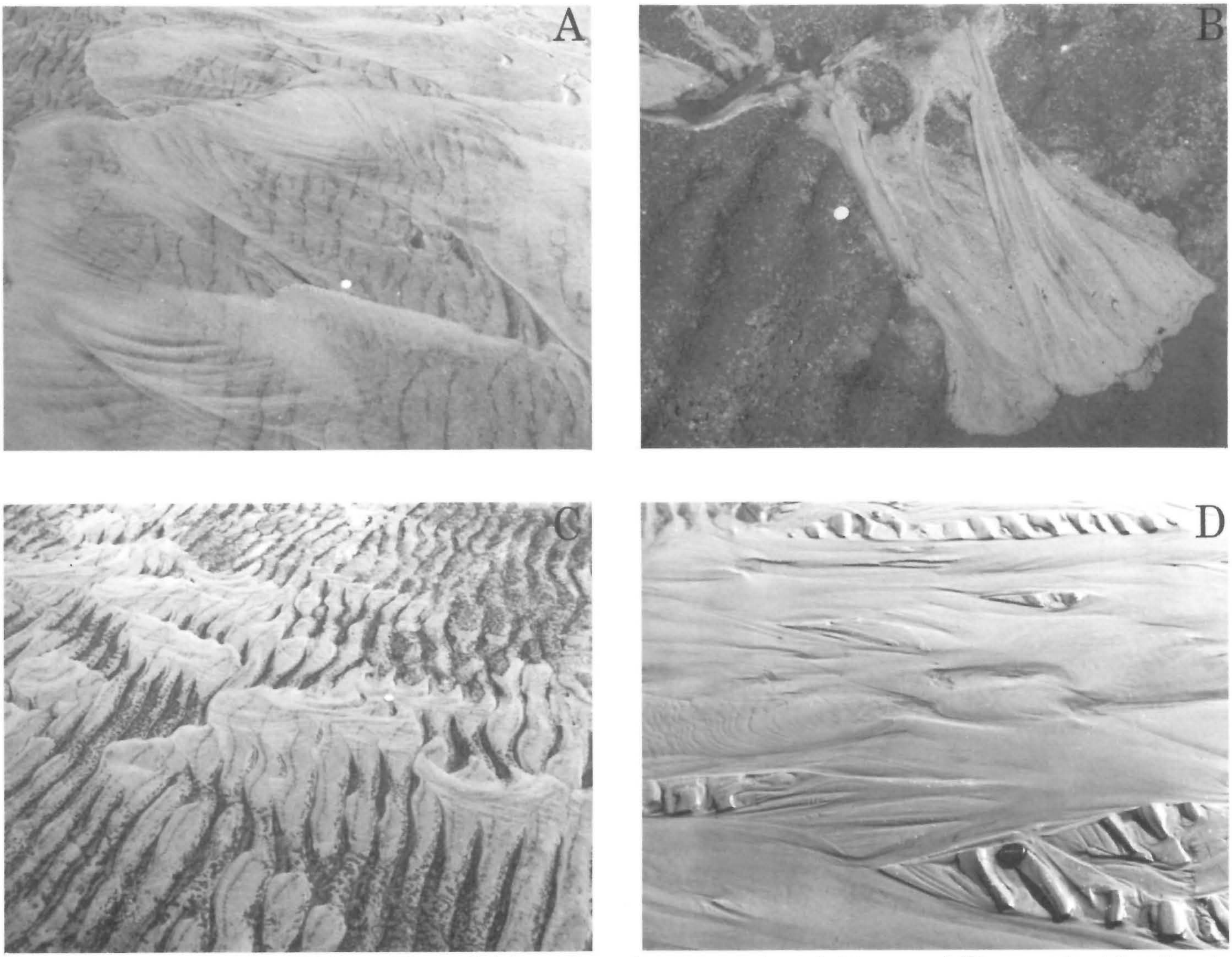



*Figure 39: (A) Recurved sand ribbons, (B) small deltas, (C) sand tongues and sand ribbons, and (D) streamlined flow lines in drainage channels produced by ebb flow currents and a wind driven water film at Patricia Beach. Coin is 2.5 cm in diameter and lens cap is 7.0 cm in diameter.*

The barrier island varies considerably in both height and width between West and Main channels. At the west end, at Site 2, the backshore and dunes are each approximately 35 m wide, but the maximum height of the dunes is only about 1.5 m above lake level (Fig. 32). At Site 3, approximately 1 km to the east, the 15 m wide backshore sits adjacent to a 30 m wide and 3 m high sharp-crested dune ridge. One kilometre farther east, at Site 1, two prominent and one poorly defined dune ridges, collectively about 65 m wide, occur landward of the approximately 25 m wide backshore (Fig 32). The more southerly dune ridge is heavily wooded and stands 3.5 m above the lake. This ridge is separated from the adjacent ridge to the north by a 2 m deep and approximately 10 m wide ravine. The middle dune ridge is less than 1 m high and approximately 10 m wide and is covered with 2 to 3 m high shrubs. The youngest dune ridge, situated along the distal part of the backshore, is in the early stages of formation and is poorly defined. The most prominent vegetation on this ridge consists of low willows, <1 m high. The relative ages of the dune ridges is clearly indicated by the vegetation zonation, which from north to south across the barrier island changes from small willows to large bushes to mature ash trees. Soil development shows a similar age relationship; it is nonexistent in the northern ridge, poorly developed in the middle ridge and relatively well developed in the southern ridge. The soil development and vegetation zonation clearly indicate that the barrier island, between Site 1 and Main Channel, has been accreting and actively prograding northward into the lake during the latter part of this century (see section on historic changes).

Between the entrance to Pruden Bay and the mouth of Brokenhead River, the barrier island is uniformly less than about 1 m high but varies between 25 to more than

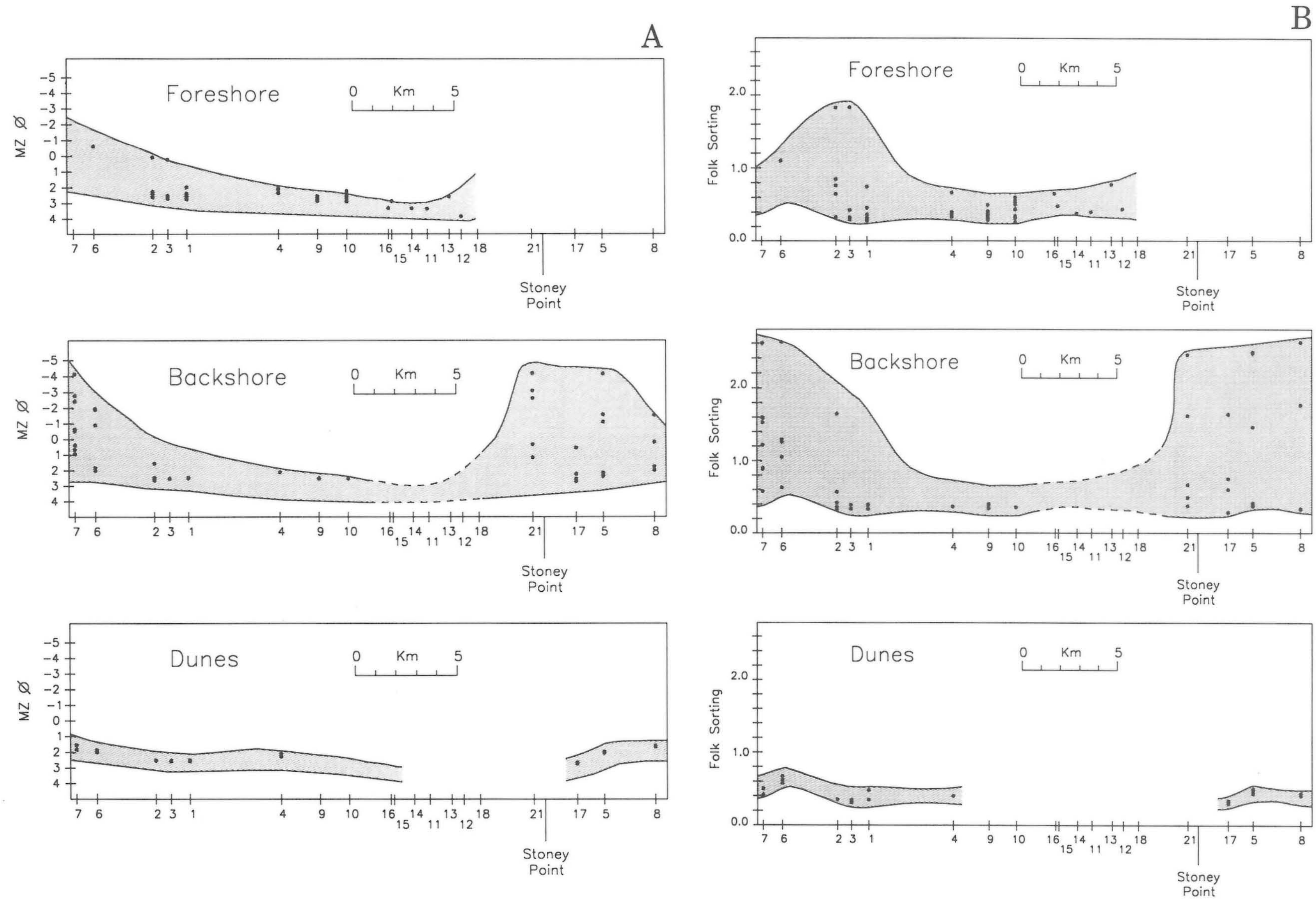



*Figure 40: Range of (A) mean grain size, and (B) sorting of foreshore, backshore and dune sediment samples collected between Chalet Beach and Beaconia Beach.*

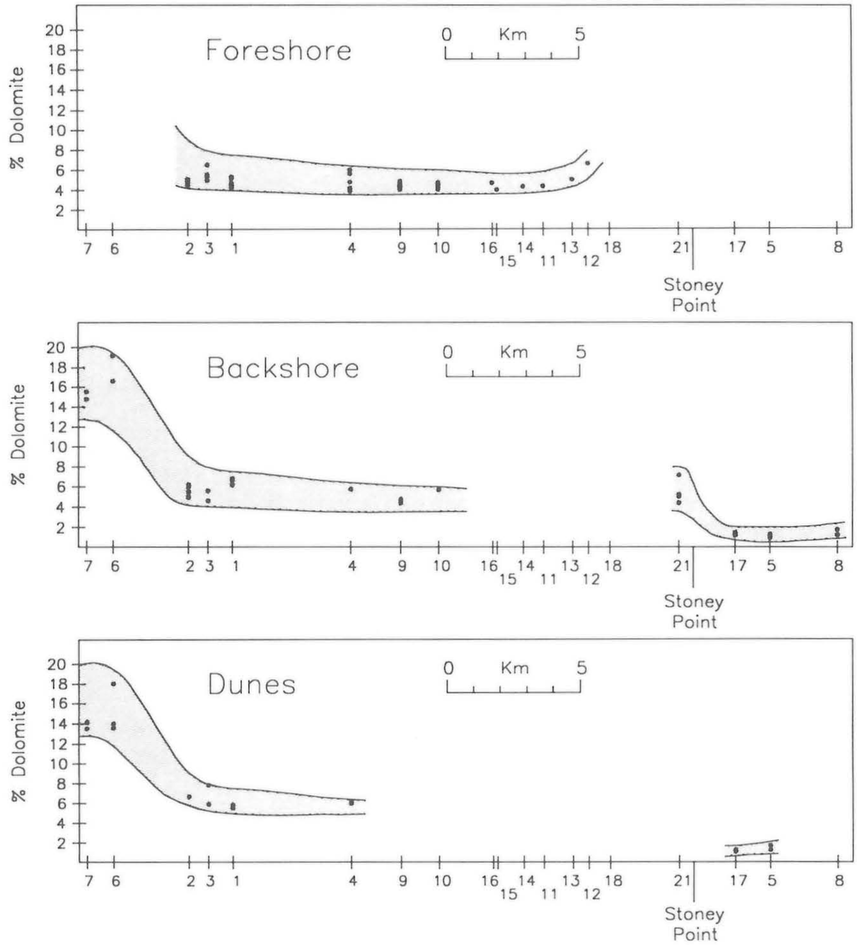



*Figure 41: Range of dolomite content of foreshore, backshore and dune sediment samples collected between Chalet Beach and Beaconia Beach.*

*Figure 42: Driftwood on the backshore at Site 2. Note the small willows on the backbeach to the left and the larger trees on the dune ridge to the right. Looking east.*

*Figure 43: Wide prograding gravelly backbeach at Site 7, south of Chalet Beach. Note the waterline marks and the vegetated dune ridge. Looking north.*

*Figure 44: Dune sand overlying coarse textured, fossiliferous backshore facies at Site 6. Coin is 2.5 cm in diameter.*

*Figure 45: Eroding backshore and dune ridge at Site 4.*

100 m in width (Sites 4, 9 and 10, Fig. 32). At Site 4, just east of Pruden Bay, the backshore is about 8 m wide and large mature trees growing on the dune ridge are being undercut by waves indicating active erosion along this part of the shore (Fig. 45). Two kilometres to the east, the backshore at Site 9 is similarly eroding as suggested by old concrete foundations on the upper backshore (see later section). Vegetation zonation at Site 10, similar to that observed west of Main Channel, is indicative of an actively prograding foreshore. At this site, however, the accretion along the north side of the barrier island is attributed to ebb flow and sediment transport out of Pruden Creek during periods of wind setdown (Fig. 33). The narrow or nonexisting backshore and low, heavily vegetated and eroding dune ridges between Pruden Bay and Stoney Point, as well as submerged buildings at the mouth of Brokenhead River and elsewhere, indicate that the shore is retrograding except at a few sites at the mouth of inlets where the regression has been temporarily halted.

The bay-mouth-bar across Beaconia Lake was profiled at three sites (Fig. 32). At Site 17, in the southwest, an approximately 20 m wide backshore is associated with a 2.2 m high dune ridge of about the same width. The steep backbeach at Site 5, 1.5 km to the northeast, is less than 10 m wide and is backed by an active dune ridge about 20 m wide and 4 m high (Fig. 32). The bay-mouth-bar at Site 8, at the north end of Beaconia Lake consists of a narrow, 5 m wide backshore and a 35 m wide dune ridge. During storms and periods of wind setup, waves actively erode the dunes along the northeastern two thirds of the bay-mouth-bar producing the characteristic steep profile observed at Sites 5 and 8. Patricia Beach, at the southwest end of the bay-mouth-bar, appears to be at equilibrium or accreting slightly.

### Temporal variations

Relevelling of the backshore and upper foreshore at intervals throughout the summer and early fall of 1990 gave a preliminary estimate of the sediment budget for the south shore of Lake Winnipeg, recognizing the shortcomings associated with the short recording period (Fig. 32). At Site 7 the shore prograded 5 m into the lake as an estimated 50 cm of sand and gravel was added to the lower backshore (Fig. 43). On the other hand, Site 6 lost up to 40 cm of sand and gravel from much of the backshore and the dune ridge was undercut and eroded in places east of this site.

Up to 35 cm of sand had accumulated on parts of the upper backshore at Site 2 by late summer while the lower backshore lost 40 cm as the beach profile was straightened during the latter part of September. The profiles at Sites 3 and 1 showed no significant changes during the monitoring period.

The profile at Site 4 shows a slight net accumulation of sand on the backshore, whereas the profiles at Sites 9 and 10 show little change other than the shoreward movement of the offshore bars. The profiles at Sites 21 and 19 were only surveyed once.

Patricia Beach showed a slight net loss of sediment on the middle part of the backbeach at Site 17 and the profile at Site 5 was lowered with the removal of about 40 cm of sand at the base of the dunes. There was no change in the beach profile at Site 8 on Beaconia Beach.

### Minor sedimentary structures

Zonation of beaches due to textural variations in the sediment and the distribution of flotsam is the most outstanding feature of the backshore (Fig. 8, 20, 42 and 43). Shadow dunes and wind ripples (Fig. 21) and raindrop impressions (Fig. 46) are the most common sedimentary structures preserved in the subaerial environments of the barrier island.

### Grain size

Mean grain size and sorting of backshore sediment samples are similar to those from the upper foreshore. The coarsest and most poorly-sorted sediments occur along the

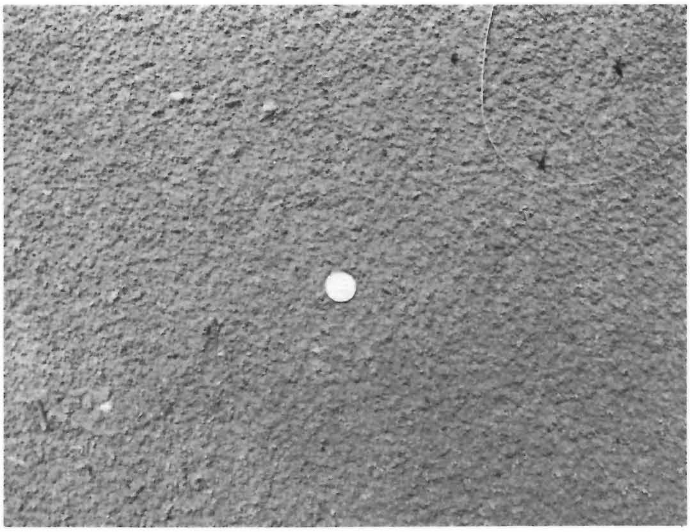


*Figure 46: Raindrop impressions preserved in the sand on the backshore at Site 1. Coin is 2.5 cm in diameter.*

western end of the barrier island, south of Chalet Beach (Fig. 40A and B). Both the mean grain size and sorting decrease toward the east indicating this is the predominant direction of longshore drift. Similarities in mean grain size and sorting between upper foreshore and backshore sediments suggest the same sedimentary processes are acting in these environments. Driftwood lines, flotsam and welded bars on the backshore further indicate subaqueous processes are responsible for most of the sediment transport on this part of the barrier island, in spite of the fact that the backshore is only occasionally under water.

Analysis of backshore samples from the bay-mouth-bar at Beaconia Beach indicate the coarsest and most poorly-sorted sediments are found to the northeast. The gravel facies, common on Beaconia Beach, gives way to sandier and better-sorted sediments on Patricia Beach to the southwest (Fig. 40A and B) (see also Figs. 8 and 61A and B).

The mean grain size and sorting of dune samples are uniform throughout the entire area (Fig. 40A and B), reflecting the selective sorting by the wind.

**Dolomite content**

Backshore samples from Sites 7 and 6, at the west end of the barrier islands, have the highest dolomite content of any samples collected (Fig. 41). Concentrations decrease rapidly towards Salamonia Channel but then decrease only slightly to Site 10, near Pruden Creek.

The bay-mouth-bar at Beaconia Beach has dolomite concentrations markedly lower than any of the samples from the barrier island clearly indicating a different provenance for these sediments. High dolomite concentrations on Stoney Point and the area to the west further indicates that sediment does not move from one area to the other. Stoney Point is therefore a barrier to sediment movement in both directions.

The dolomite content of the dunes reflects the dolomite concentrations found on the foreshore and backshore at the same site (Fig. 41). This suggests the foreshore and backshore are the sources of the sand that forms the dunes.

## INTRODUCTION

Fluctuating water levels in the south basin of Lake Winnipeg due to regional climatic changes and isostatic uplift of the outlet at the north end of the lake results in migration of the barrier islands separating the lake from the lagoons. These changes can be documented by comparing maps and aerial photographs spanning the last century. Unfortunately, the earliest available maps of the Red River delta bear little resemblance to the area (see for example Hind, 1858 and LaVerendrye's map of 1737 and others in McLeod, 1987). Not until the township surveys of the 1870's and 1880's were there reliable maps of the area. Even these maps do not display sufficient detail in the Beaconia Lake area to be of much use.

## BEACONIA LAKE AREA

The earliest reliable map of this area, dating from 1932 (Fig. 47), shows Beaconia Lake as a much smaller and isolated lake separated from Lake Winnipeg by a bay-mouth-bar with no apparent creeks or inlets into the lagoon. That the bay-mouth-bar was continuous at this time is further suggested by the presence of a surveyed road along the shore leading to Balsam Bay and Beaconia.

The 1 inch to 1 mile map of the Red River Delta from 1951, constructed using 1946 airphotos, shows a trail leading from Stoney Point at the south end of Balsam Bay, north along the southern part of Patricia Beach (Fig. 48). The road was not continuous along the bay-mouth-bar at this time, and examination of the 1946 airphotos shows two breaches in the bay-mouth-bar (Fig. 49A). At the north end of the bay-mouth-bar, a large washover had occurred due west of Beaconia and a prominent inlet had opened into the

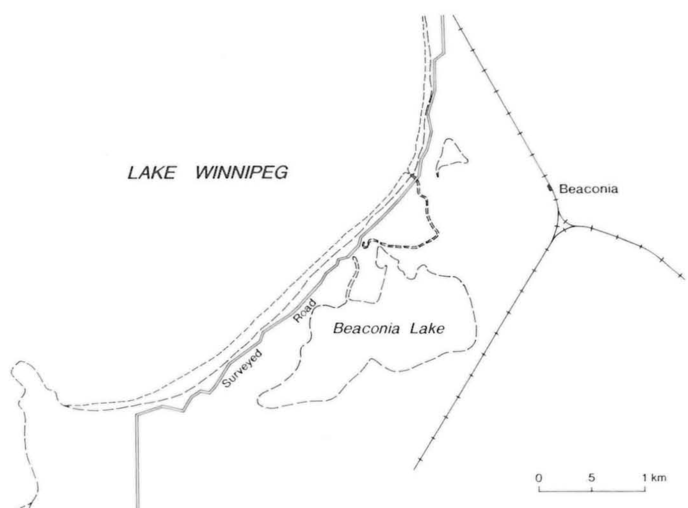



*Figure 47: Map of Beaconia Lake from 1932 showing the road to Beaconia and Balsam Bay across the bay-mouth-bar. Redrawn from Department of Mines and Natural Resources, Manitoba (1932).*

lagoon (location a, figure 49A). Near the middle of the bay-mouth-bar at location b, a smaller washover and inlet had formed. By 1946 the lagoon appears to be significantly larger than what was shown on the 1932 map (Fig. 47).

The inlet at location b (Fig. 49A) had enlarged significantly by 1966 and a large recurved spit, indicating southward sediment transport, had formed on the north side of the inlet (Fig. 49B). The northern inlet at location a, clearly visible in 1946, had closed by 1966 and the beach had become detached from the headland to the north indicating the sediment supply in the north had been cut off.

By 1971 the beach had been breached again at a site still further south (location c, Fig. 49C) where five years earlier only a small washover was evident (Fig. 49B). This inlet has become a major channel joining the lagoon and Lake Winnipeg whereas the inlet at location b appears to be closing.

As the inlets were opening and closing at various sites the bay-mouth-bar transgressed landward. Evidence for this occurs at Site 5 (Fig. 2) near the centre of the bay-mouth-bar where the remains of the road to Balsam Bay are exposed in the eroding dunes at the upper edge of the backshore (Fig. 50).

Evidence for higher than present day water levels are found around Stoney Point where a prominent gravel beach is situated 1.5 to 2 m above the present lake level. Freshwater pelecypods and driftwood are common in this beach (Fig. 51). Large trees that are still alive, but partly buried by gravel, suggest the raised beach is a relatively recent feature; a conclusion supported by a futuristic radiocarbon date of -500 years (BGS-1451) (500 years in the future) on driftwood that must have been alive during the atomic bomb testing of the 1950's and 1960's (H. Melville pers. comm. 1992) (see Table 3 next section). The beach is probably related to one of the high lake levels of either 1966 or 1974 (Fig. 7).

## PRUDEN BAY-MAIN CHANNEL

Significant differences in the shoreline configuration east and west of the Main Channel of the Red River, are evident between the end of the last century and the present. These changes may be due to a combination of natural and anthropogenic factors. Township plans, dating from 1888, show Main Channel of the Red River draining into the northwest part of Pruden Bay and a straight shoreline to the west (Fig. 52). West Channel of the Red River was maintained by dredging and was the route used by steamboats before 1893. An 1898 Public Works map showing improvements for navigation purposes indicated East Channel was maintained by dredging after 1893 and the West Channel had been abandoned. During the summers of 1900 and 1901 Main Channel was diverted from Pruden Bay to the northwest at a point approximately 300 m from the lake, in what must have been a major canal construction project by Public Works Canada (C. Colp pers. comm. 1991). The wood work, large boulders and associated rip-rap that formed the

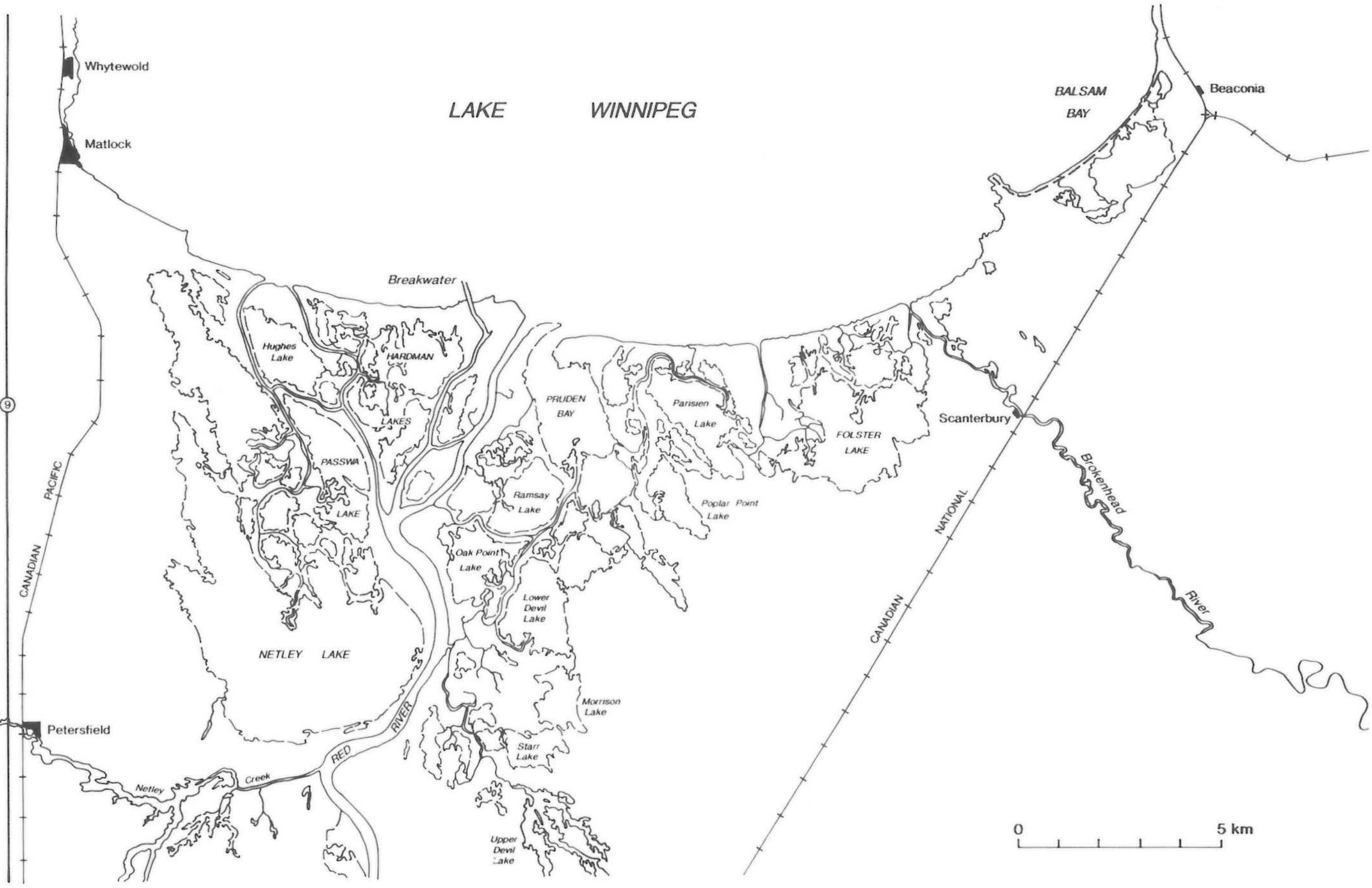



*Figure 48: Map of Netley Marsh based on 1946 airphotos. Redrawn from Department of Mines and Technical Services (1951).*

breakwater at the mouth of the new canal was put in place in 1910 and 1911. The breakwater, the remains of which can still be seen, was constructed perpendicular to the shore. Airphotos from 1946 (Fig. 53) clearly indicate that the breakwater acted as a sediment trap causing the shore to prograde lakeward on both sides of the channel. This conclusion is supported by "young growth" vegetation on the northern most beach ridge west of Main Channel.

East of Pruden Bay, the shore along the entire length to Stoney Point has eroded significantly during this century. Airphotos of the mouth of Brokenhead River show a single channel drained into the lake in 1946 (Fig. 14). Triple Creek flowed into the Brokenhead River from the west, just upstream of the mouth. A little further upstream a number of buildings are visible on the east shore of the Brokenhead River (Fig. 14). By 1987 the shore had eroded so far south that Triple Creek flowing in from the west now flows directly into Lake Winnipeg (compare Fig. 14, 19 and 54). The foundations of the buildings along the river bank, at the mouth of Brokenhead River, are permanently under water (Fig. 14). Similarly, a farm building that is clearly visible on the 1929 airphotos of the barrier island 2 km east of Pruden Bay, now stands on the upper foreshore (Fig. 55, 56). Just east of the mouth of Pruden Bay (Site 4, Fig. 2), remains from an old building, dated to the turn of the century by assorted ceramics and glassware (McLeod pers. comm. 1990), are observed on the upper foreshore, further testifying to the southward transgression of the lake.

East of Pruden Bay the shoreline has undergone significant changes since the 1929 airphotos were flown. The 1929 photos show extensive hay fields south of the barrier island, as well as a road from Whittles Point running north along Pruden Creek and west along the shore of Lake Winnipeg to Pruden Bay (Fig. 56A). By 1946 the barrier island had been breached by a washover approximately 1.5 km east of Pruden Bay and another smaller one, 0.5 km further east (Fig. 56B). By 1946 the hay fields appear to be gone and by 1966 they had given way to marsh and open water (Fig. 56C).

## SALAMONIA CHANNEL-WEST CHANNEL

Historic changes in the shoreline west of Main Channel are not as readily apparent as those further east, except near the mouth of West and Salamonia channels. The township plan of 1888 and airphotos from 1946 (Fig. 57A) show the shore between the two channels as concave to the north and much further south than east or west of this location. By 1929, extensive sand banks are visible to the west of Salamonia Channel; by 1946, these banks were largely overgrown (Fig. 57A). This point of land had been eroded

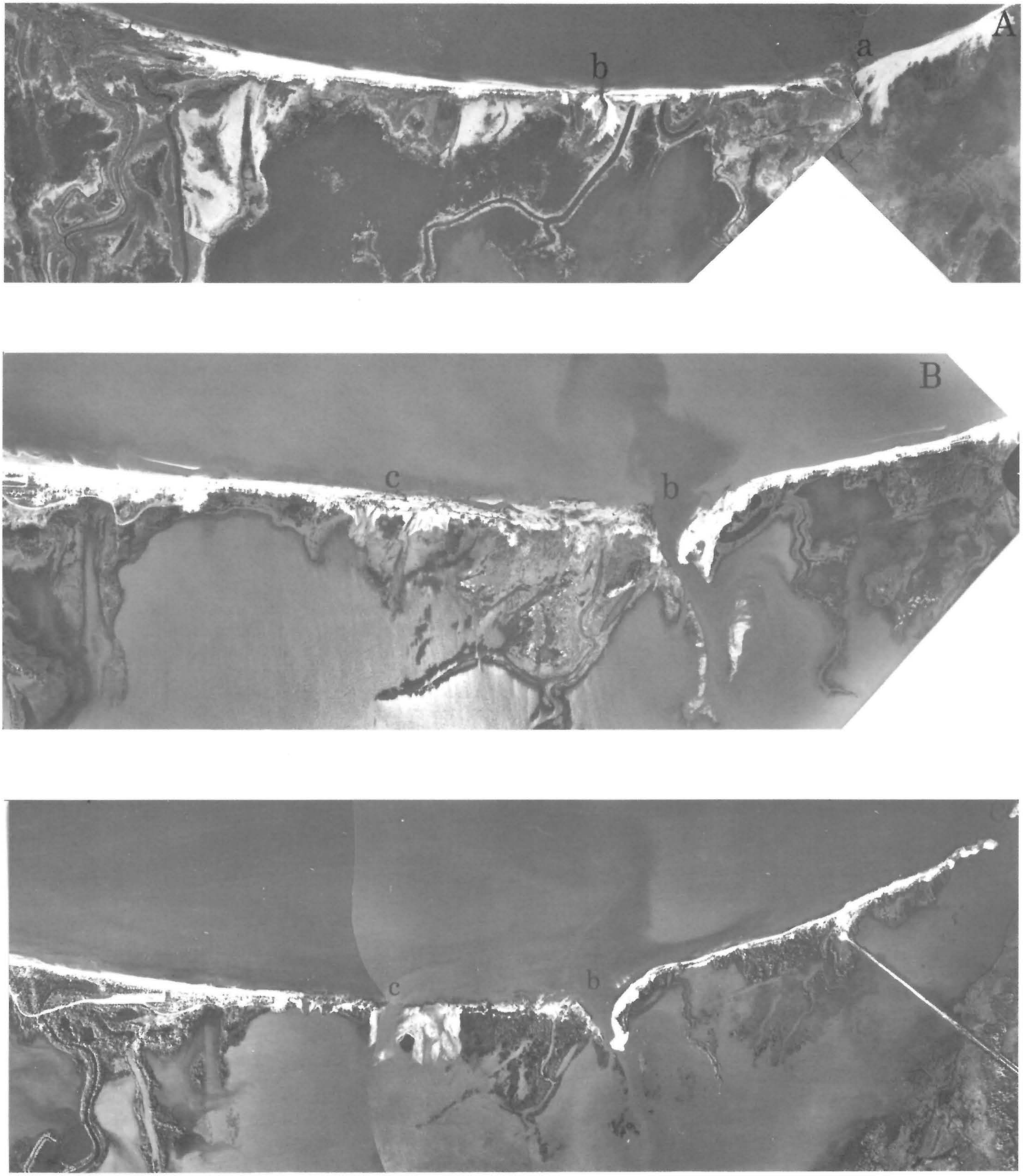



*Figure 49: Airphotos of the bay-mouth-bar at Beaconia Lake showing the changes in the inlets between (A) 1946, (B) 1966, and (C) 1971. The inlets are labelled (a), (b) and (c).*

*Figure 50: The 1932 road to Beaconia exposed in eroding sand dunes on the backshore at Patricia Beach. Rod divisions in cm.*

*Figure 51: Raised shingled beach on Stoney Point possibly dating from the high water level of 1966 or 1974. Shovel for scale.*

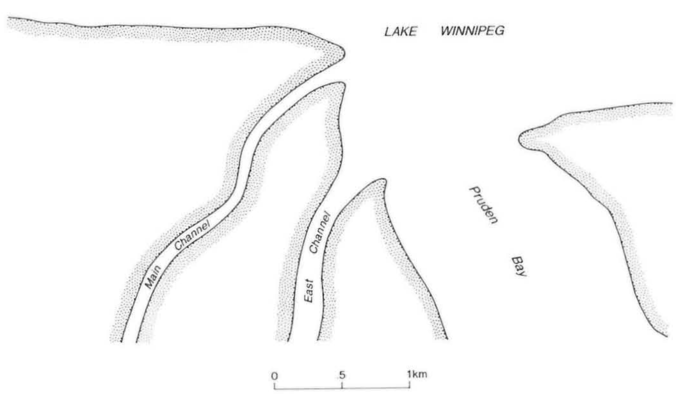



*Figure 52: Township map surveyed in 1888 showing the mouth of Main and East channels of the Red River. Notice Main Channel draining into Pruden Bay, the straight shore to the west of Main Channel and the off-set in the barrier island on either side of Pruden Bay. Redrawn from Department of the Interior (1897).*

again by 1966 and continues to be a focal point for landward erosion. The east shore of Salamonia and West channels, where they empty into Lake Winnipeg, also show significant erosion from at least 1966 onward. The shore between West and Main channels has remained relatively straight and only slightly concave to the north and is accreting in the east as the result of the construction of the breakwater at Main Channel. Along this stretch the shore appears to have been breached at only one site 0.8 km east of Main Channel. In 1946 the barrier island was continuous and covered with trees, but by 1966 a small washover had broken into the lagoon (Fig. 57B). The breach had widened considerably by 1971 when an approximately 200 m wide gap had opened allowing the free movement of water between the lake and the lagoon (Fig. 57C). The breach has subsequently been infilled by longshore drift, which has restored the barrier island to its pre-1966 condition. The only clue to the former washover is the absence of trees along this part of the barrier island (Fig. 29).

Evidence for higher water levels was found in two places between Chalet Beach and Salamonia Channel where large pelecypod shell accumulations were exposed in the eroding beach ridge approximately 1.5 m above the present lake level (Fig. 44). The shells are believed to have been deposited during a period of higher water, possibly coincident with a major storm. The shells have not been radiocarbon dated because of the problems related to dating of fresh water shells (Nielsen *et al.*, 1982, Nielsen *et al.*, 1987). As the shells occur at about the same elevation as the wood sample on Stoney Point, it is likely that they were all deposited during either the high water of 1966 or 1974. Alternatively, the shells may have been deposited during the high water stand recorded by fibrous sandy peat, exposed in the dunes at Grand Beach. The approximately 10 cm thick peat layer which represents deposition in the lagoon at Grand Beach, is exposed in sections on the back side of the dunes at an elevation of 218.5 m. Radiocarbon dating of the peat suggests that the high water stand occurred 270 ± 70 yrs BP (BGS-1662) (Nielsen, unpublished). Correlation of these two high water stands is suggested by the presence of mature (>100 years) trees on the top of the two sections between Chalet Beach and Salamonia Channel.

## TREE-RINGS AND WATER-LEVEL FLUCTUATIONS

A single tree stump of black ash (*Fraxinus nigra*) from the edge of the forest that forms the boundary between the backbeach and the dunes, was sampled for tree-ring analysis. The stump was located approximately midway between Salamonia Channel and Site 6 (Fig. 2). The elevation of the root collar was estimated to be approximately 1 m above the level of the lake. Ring-width measurements and cross-

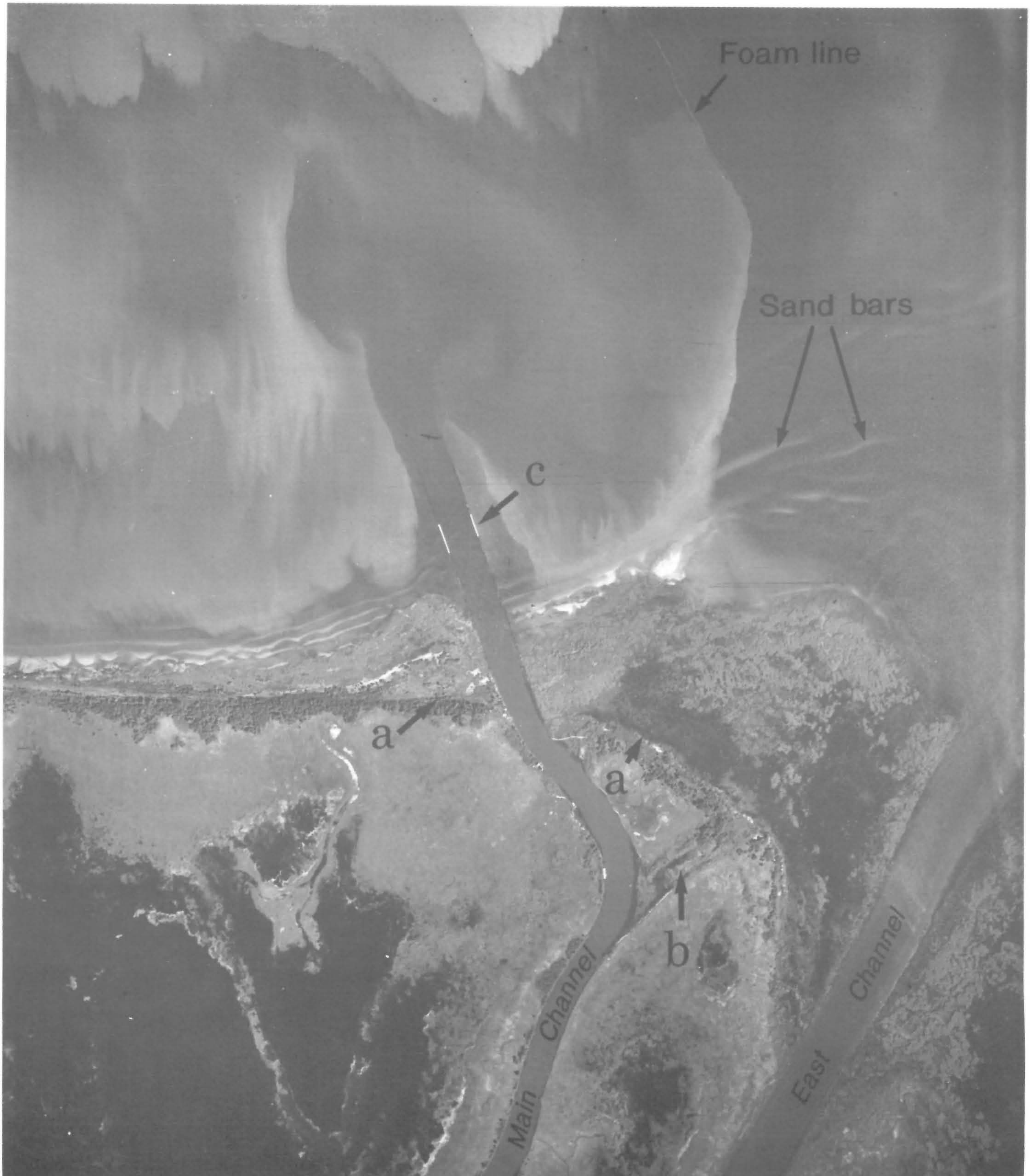



*Figure 53: Airphoto from 1946 showing the mouth of Main Channel. The pre-1900 shoreline is marked (a), the pre-1900 channel (b) and the breakwater (c). Note the foam line, longshore bars and differences in the water transparency.*

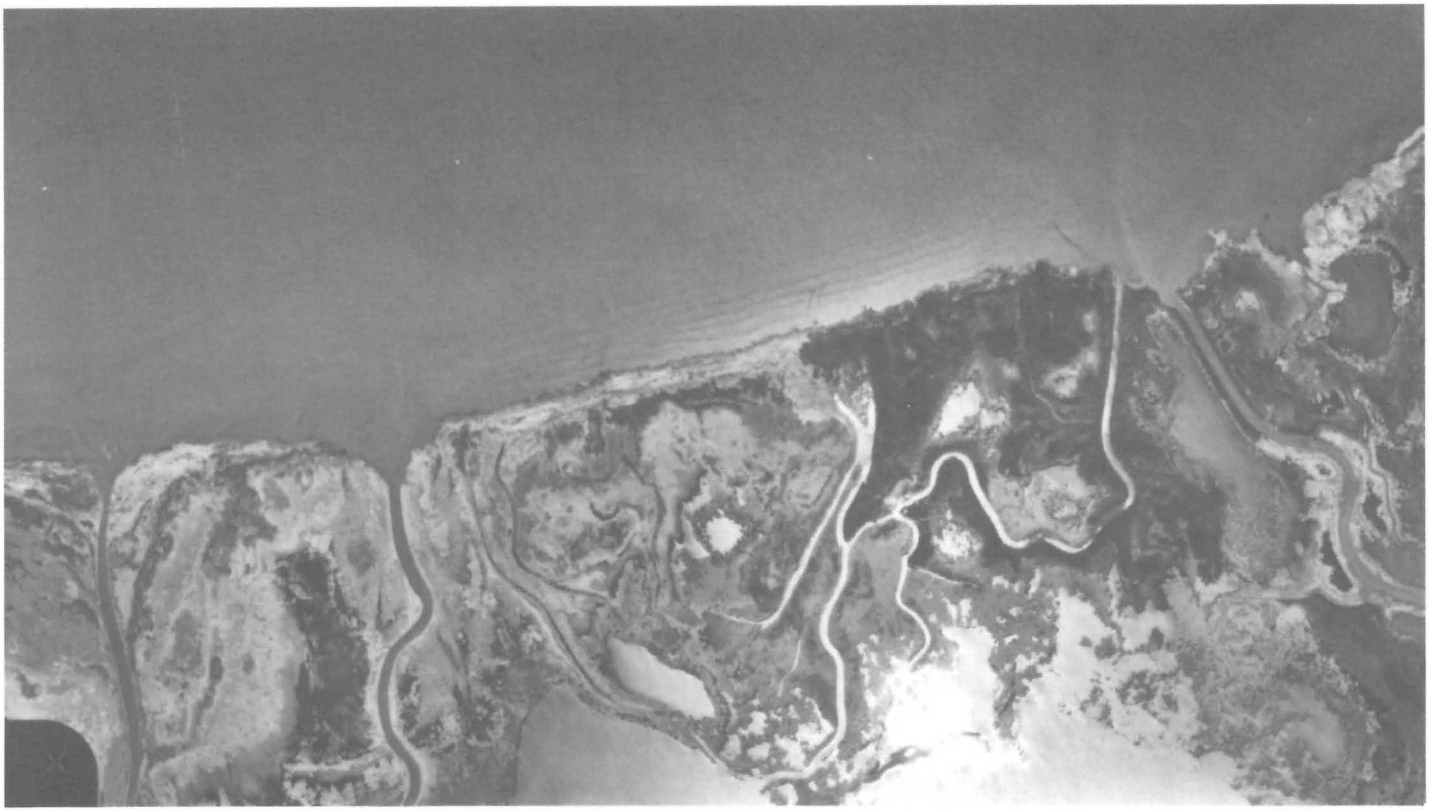


*Figure 54: Airphoto from 1987 showing Triple Creek and Brokenhead River entering Lake Winnipeg. Compare this with Fig. 14 and 19.*

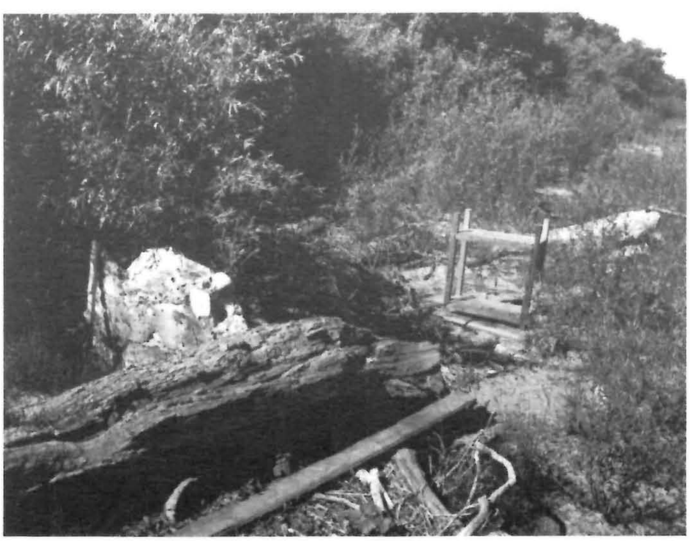


*Figure 55: Concrete foundation on the backshore near Site 9. Notice the driftwood line along the edge of the trees running through the former house.*

dating with live trees indicate the tree started to grow in 1909 and was felled in 1987. Comparison of the tree-ring curve and the water level records for Lake Winnipeg from 1913 to 1987 indicates good correlation (Fig. 58). During years of low water the tree rings tend to be narrow and during years of high water the rings are wide. The decreasing ring widths, with the age of the tree, may be a growth trend related to the age of the tree, the result of increased competition, or some other external factor not related to water level fluctuations. Analysis of additional samples from other sites would strengthen the nonrandom variation recorded in the tree-rings and extend the water-level record for Lake Winnipeg by at least a hundred years and possibly more. The result from this single sample indicates that tree-ring analysis is potentially a powerful technique for documenting prehistoric water-level fluctuations in Lake Winnipeg.

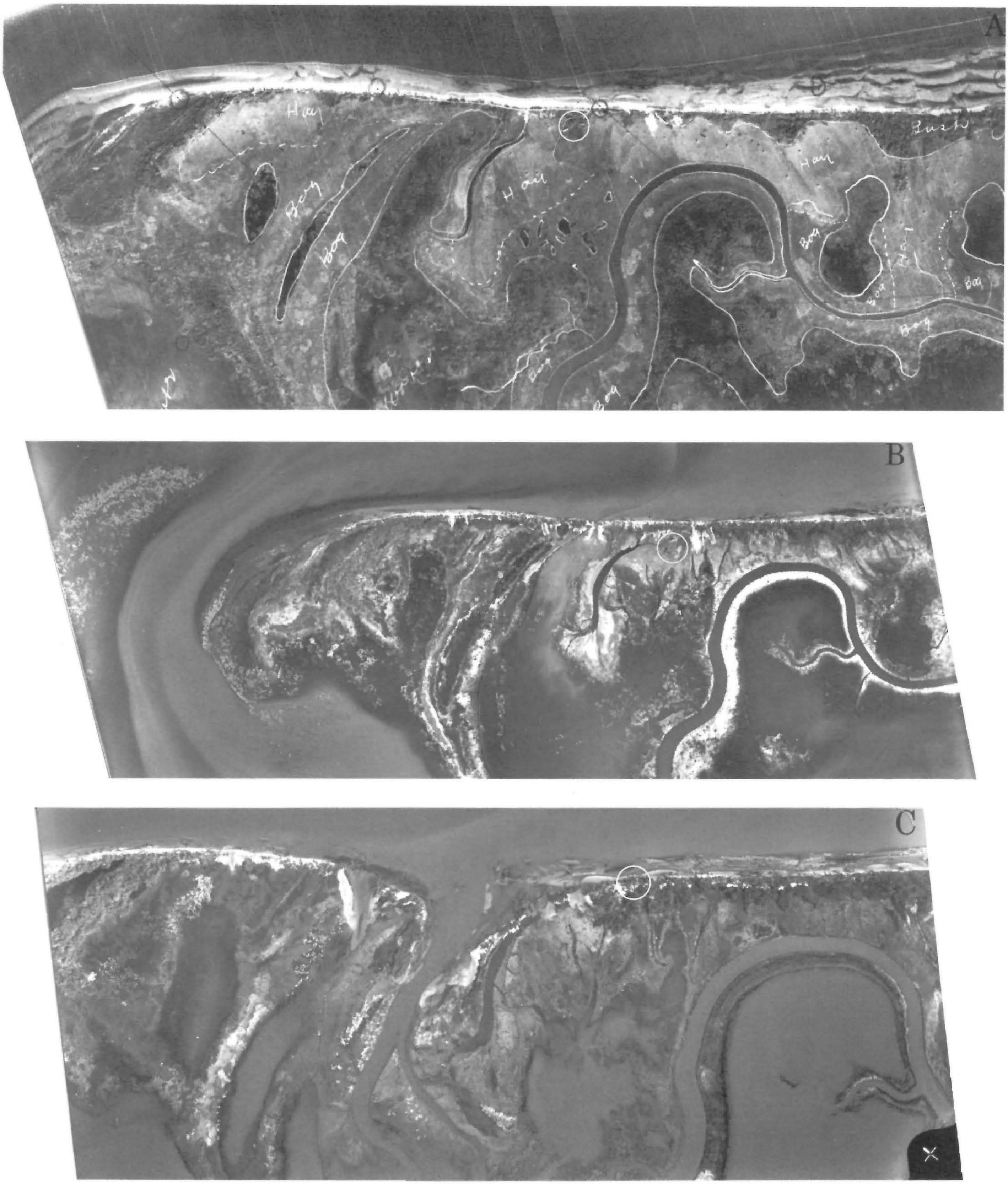



*Figure 56: Airphotos of the area just east of the mouth of Pruden Bay from (A) 1929, (B) 1946, and (C) 1966 showing the change from farms (circled), roads and haystacks to washover and inlet formation due to rising water levels.*

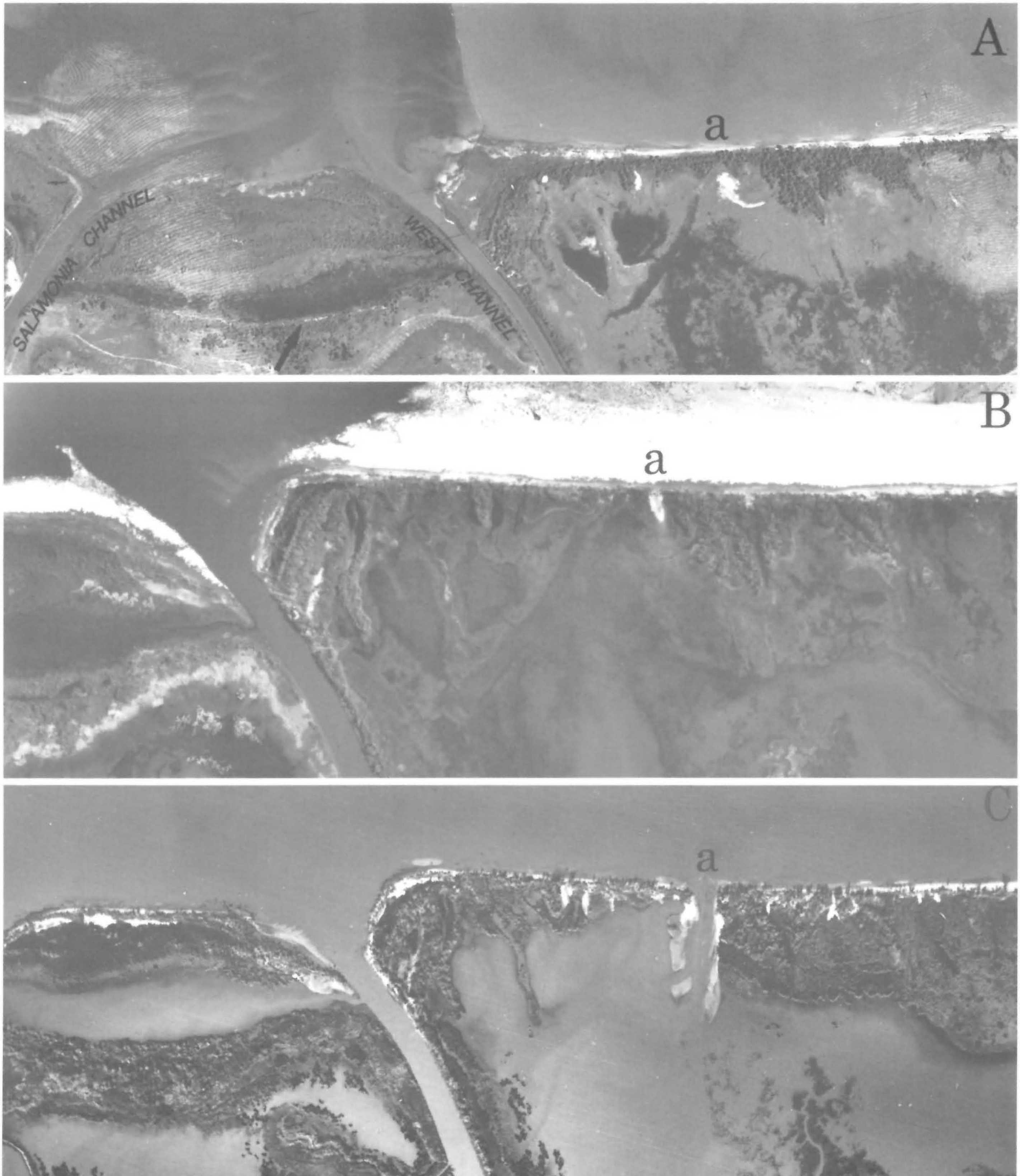



Figure 57: Airphotos of the mouth of West Channel from (A) 1946, (B) 1966, and (C) 1971 showing the development of a washover at (a). Compare this to Fig. 29. The arrow points to the 1888 shoreline west of West Channel.

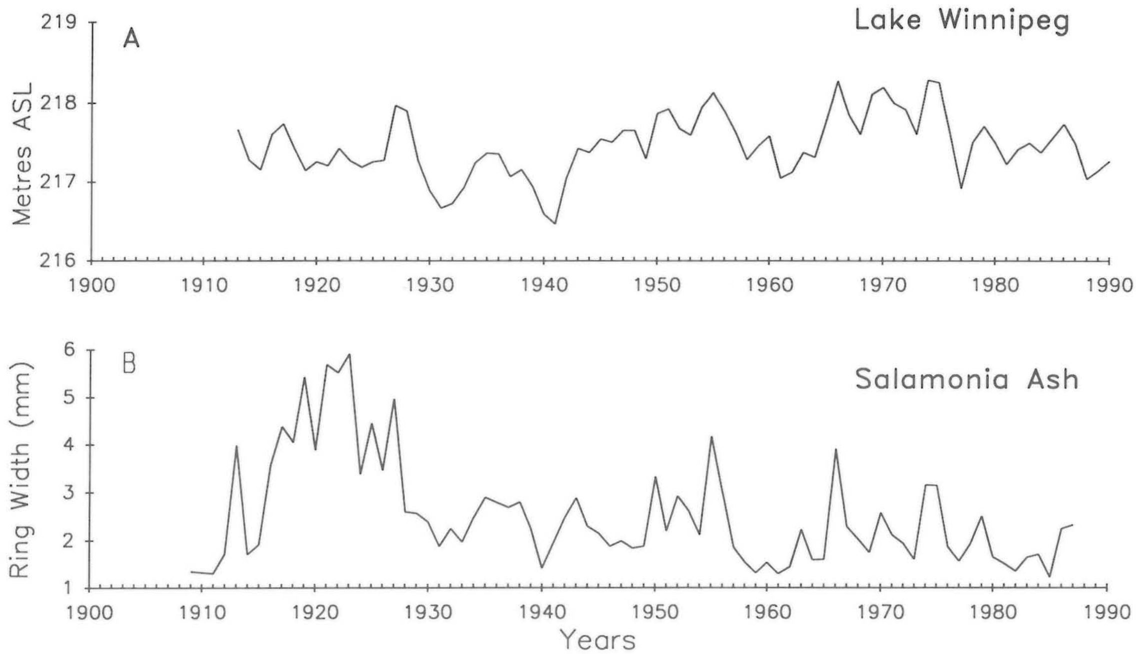



*Figure 58: (A) Water level fluctuations in Lake Winnipeg from 1913 to 1990, and (B) tree-ring curve for a single ash from near Salamonia Channel from 1909 to 1987.*

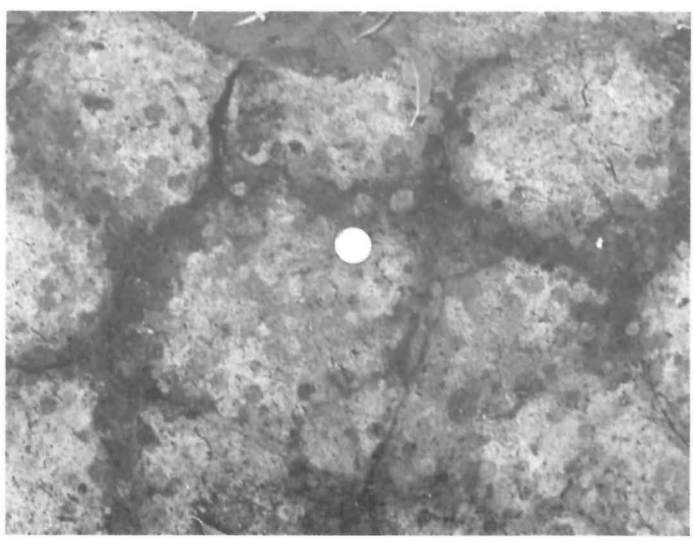


*Figure 59: Infilled desiccation cracks developed in Lake Agassiz sediment exposed on the foreshore at Sans Souci. Coin is 2.5 cm in diameter.*

## SITE INVESTIGATIONS

Six sites between Matlock and Beaconia Beach that show evidence of prehistoric coastal submergence were discovered along the south shore of Lake Winnipeg. A total of 16 wood and organic muck (undifferentiated fibrous marsh plant material, or organic silt) samples were collected for radiocarbon dating from these sites to determine the rate of water level rise in the south basin of Lake Winnipeg.

### Sans Souci, (Site 20)

A thick sequence of fine-textured sediments comprising Lake Agassiz and late Holocene muds are exposed on the lower foreshore at Sans Souci during periods of low water. The Lake Agassiz sediments, exposed at the north end of the beach, consist mainly of nonfossiliferous 'buff' coloured silty clay with large inclusions of ice-rafted till blocks. Iceberg turbate similar to this has been described for areas west of Sans Souci by Nielsen (1989). The upper part of the Lake Agassiz sequence appears to be devoid of iceberg turbate suggesting that the water depth may have been too low for bergs before the final draining of the lake. A prominent southeastward dipping unconformity separates the light coloured Lake Agassiz sediments from overlying late Holocene organic-rich mud. Infilled dessication cracks that form polygons 16 to 30 cm in diameter, occur in the top of the Lake Agassiz sediments directly under the unconformity (Fig. 59). Ellis and Shafer (1928) and Christiansen (1959) described similar structures in the Red River Valley and in the Swift Current area in Saskatchewan, and attributed them to dessication. They believe cracks in the ground open during periods of drought and are subsequently infilled by wind blown topsoil that forms the black wedge or polygon outline in the otherwise light coloured sediment. A sample of the wedge-filling organic-rich topsoil was radiocarbon dated at 3600 ± 80 yrs BP (BGS-1477) (Table 3) indicating that the cracks formed in a subaerial environment during the dry Hypsithermal interval (Ritchie, 1976). The late Holocene marsh sediments above the unconformity thicken to the southeast where the unconformity dips below the level of the lake. Consequently only about 50 cm of marsh sediment is exposed on the foreshore (Fig. 60A). A sample of fibrous plant material from the lowest exposed marsh sediments at an elevation of 216.9 m gave a radiocarbon date of 1200 ± 70 yrs BP (BGS-1478) (Table 3) and is the minimum date for the transgression of the lake across this area.

### West Channel, (Site 2)

Approximately 0.8 km east of West Channel, low water exposes a mud flat in places more than 100 m wide (Fig. 60B). Sand bars, and a thin discontinuous sand layer, move across the flat, in places blanketing the underlying mud. There are no vertical sections due to the low slope of the shore. The mud flat is, in places, covered with a thin discontinuous pebble lag of uncertain origin. Numerous logs, in varying states of decay, are found lying on the surface of the mud flat and although tree roots protrude from

**Table 3: Radiocarbon Dates from the South End of Lake Winnipeg**

| Site | Lab. No. | Age Yrs. B.P.* | Calendar Yrs. A.D. | Material | Elevation (m) |
|---|---|---|---|---|---|
| 2(a) | BGS-1439 | 335 ± 65 | 1620 | *Salix* | 217.2 |
| 2(b) | BGS-1448 | 230 ± 70 | 1660 | wood | |
| 2(c) | GSC-5258 | 20 ± 60 | modern | *Ulmus americana* | 217.6 |
| 4(i) | BGS-1440 | 290 ± 70 | 1640 | *Salix* | 217.3 |
| 4(w) | BGS-1450 | 210 ± 70 | 1665-1790 | wood | |
| 4(p) | BGS-1449 | 15 ± 70 | modern | peat | 217.3 |
| 5 | GSC-5269 | 90 ± 50 | 1890-1905 | *Salix* | 219.0 |
| 5(a) | BGS-1442 | 190 ± 65 | 1670-1775 | *Populus* | 217.4 |
| 8 | GSC-5264 | 610 ± 50 | 1310-1380 | *Larix* | 217.4 |
| 8(a) | BGS-1443 | 260 ± 80 | 1650 | organic muck | 217.4 |
| 8(i) | BGS-1444 | 185 ± 65 | 1675-1765 | *Salix* | |
| 8(j) | BGS-1445 | modern | modern | *Salix* | 217.0 |
| 9 | BGS-1446 | 230 ± 70 | 1660 | *Fraxinus* | driftwood not *in situ* |
| 19(b) | BGS-1451 | modern | modern | *Salix* | 219.0 |
| 20(a) | BGS-1477 | 3600 ± 80 | N/A | organic muck | |
| 20(b) | BGS-1478 | 1200 ± 70 | 850 | organic muck | 216.9 |

*Radiocarbon years are expressed as years before 1950




*Figure 60: (A) Marsh peat outcropping on the foreshore at Sans Souci, (B) tree roots exposed on the foreshore at Site 2, and (C) marsh peat on the foreshore at Site 4.*

the underlying clay, *in situ* tree stumps were not observed (Fig. 60B). Three wood samples were collected for radiocarbon dating; a willow root at an elevation of 217.2 m collected 17 m 'off shore' dated 335 ± 65 yrs BP (BGS-1439), another root from the shoreline and at the same elevation dated 230 ± 70 yrs BP (BGS-1448) and a large elm stump lying on the surface dated 20 ± 60 yrs BP (GSC-5258) (Table 3). The presence of numerous bison bones eroding out of the mud flat further indicates these deposits pre-date the latter part of the last century as bison became extinct in the wild in Manitoba in the 1870's (D. McLeod pers. comm. 1991).

The absence of *in situ* stumps, but the presence of roots in growth position, is believed due to erosion of the site by lake-ice which may have bulldozed the site to below the level of the root collar of the trees. In growth position, tree stumps would have been removed leaving only the roots. The dates from this site may thus represent a datum slightly higher than indicated by the elevation of the samples.

### Pruden Bay, (Site 4)

The slope of the foreshore at Site 4, (Fig. 2) is relatively steep and narrow, even at the lowest water levels. *In situ* rooted tree stumps and organic detritus, in places interbedded with sand and associated with numerous bison bones, occur on the lower foreshore (Fig. 60C). Two rooted tree stumps, one willow and one unidentified, and an organic detrital sample from an elevation of 217.3 m were collected for radiocarbon dating. Dates of 290 ± 70 yrs BP (BGS-1440) and 210 ± 70 yrs BP (BGS-1450) were obtained on the wood samples whereas a date of -15 ± 70 yrs BP (BGS-1449) (15 years in the future) was obtained on the detrital sample indicating this material is at least in part modern (Table 3).

### Parisian Lake, (Site 9)

'Old', reddish coloured, checked driftwood in varying stages of decay and easily distinguished from modern driftwood, is common on all the barrier island beaches. A single sample of ash driftwood from Site 9 (Fig. 2), was radiocarbon dated at 230 ± 70 yrs BP (BGS-1446). Although this sample was not *in situ*, the date suggests that the 'old' driftwood found along the shores was probably derived from submerged forests, some possibly thousands of years old, still preserved in the offshore.

### Patricia Beach, (Site 5)

During periods of low water, the foreshore at the north end of Patricia Beach (Fig. 2) exposes numerous rooted tree stumps and fibrous organic material interbedded with clay (Fig. 61A). A poplar stump in growth position and a large willow log lying on the mud flat, both at an elevation of 217.4 m, dated at 190 ± 65 yrs BP (BGS-1442) and 90 ± 50 yrs BP (GSC-5269) respectively (Table 3).



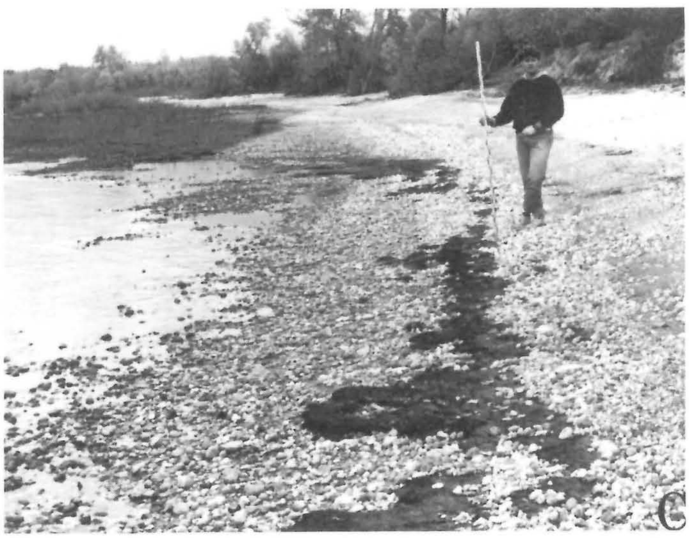



*Figure 61: (A) Rooted tree stumps on the foreshore at Patricia Beach, (B) "Drowned forest" on the foreshore at Beaconia Beach and (C) marsh peat on the foreshore at the north end of Beaconia Beach.*

**Beaconia Beach, (Site 8)**

The foreshore at the south end of Beaconia Beach exposes the most extensive drowned forest encountered along the entire barrier island system (Fig. 2). A total of twenty four willow stumps are rooted in clay and marsh peat at an elevation of 217.4 m at this site (Fig. 61B). A single stump from this site dated 185 ± 65 yrs BP (BGS-1444) (Table 3).

At the north end of the beach a prominent black fibrous organic muck layer, exposed on the lower foreshore at an elevation of 217.4 m (Fig. 61C) was radiocarbon dated at 260 ± 80 yrs BP (BGS-1443) (Table 3). A large allochthonous tamarack log lying on the clay surface was radiocarbon dated at 610 ± 50 yrs BP (GSC-5264) (Table 3). This date is clearly anomalous compared to the other dates from similar elevations, suggesting that the log may have been pushed up to this elevation by lake ice from an unknown source in the offshore.

Numerous dead trees, still in growth position, are found in the marsh on the landward side of the bay-mouth-bar at Beaconia Beach (Fig. 62). A large stump identified as *Salix* was radiocarbon dated at −1000 yrs BP (BGS-1445) (1000 years in the future) indicating the tree was alive in the 1950's and 60's during the atomic bomb testing (Table 3). High water levels in the late 1960's and early 1970's are believed to have inundated the roots and killed the trees.

## INTERPRETATION

The five sites described above expose *in situ* organic sediments or rooted tree stumps on the foreshore at low water and record basically the same sequence of events. Fine textured organic-rich sediments exposed at the base of the stratigraphic succession are interpreted to be marsh sediment similar to that being deposited in the lagoon today (Fig. 63). The clay is in places capped by a thin layer of nearshore lacustrine sand. The presence of marsh sediment on the foreshore clearly indicates that the barrier islands have moved landward in response to transgression of the lake (Reinson, 1984). Rooted tree stumps, roots, fallen logs or fibrous organic muck associated with the marsh sediment at the various sites represent trees and marsh plants that previously grew on the lagoon side of the barrier island. As the water level of Lake Winnipeg rose, the barrier islands transgressed landward, burying the trees and underlying marsh sediment (Fig. 63A and B). With continued transgression the tree stumps and marsh sediments became exposed on the foreshore where they are eroded by waves and drifting lake ice. Elsewhere the clay and logs are capped by nearshore sand and remain unexposed.

Using radiocarbon dates and elevations for selected tree stumps across the area, it is possible to determine both the rate of transgression and the distance the barrier island has moved shoreward during that time.

*Figure 62: Dead willow trees in the marsh at Beaconia Beach.*

## RADIOCARBON *vs* CALENDAR YEARS

Recent advances in high-precision radiocarbon dating and the development of suitable tree-ring chronologies have made it possible to calibrate the radiocarbon time scale (Stuiver and Pearson, 1986; Pearson and Stuiver, 1986). Although it has long been known that radiocarbon years and calendar years are not synonymous (Olsson, 1974 and references therein) it was not until the development of high-precision radiocarbon dating (standard errors in the 12 to 20 year range) and establishment of the Irish and German oak chronologies in the late 1970's and early 1980's that the details of the relationship became apparent. The complex fluctuations in the curve (Fig. 64) are attributed to climatic changes that result in carbon reservoir parameter changes, earth geomagnetic field intensity changes that result in a variable $^{14}C$ production and the sun's modulation of the solar wind magnetic properties that also results in variable $^{14}C$ production. The greater apparent age of samples from the twentieth century is due mainly to anthropogenic modification of the atmospheric $^{14}C/^{12}C$ ratio through the release of excess dead $^{14}C$ from the burning of fossil fuels (Stuiver and Pearson, 1986; Stuiver *et al.*, 1991; Terasmae, 1984).

The problems of directly equating radiocarbon years with calendar years is well illustrated by the radiocarbon dates obtained in this study. The majority of the wood and organic-rich muck samples were dated to between 185 and 335 radiocarbon years (± about 70 years) BP (Table 3). From examining Figure 64 it is evident that a radiocarbon date of, for example, 200 years BP (BP=before AD 1950) may in fact date from AD 1775 or it may be as old as AD 1660. Similarly, a radiocarbon date of 335 years BP may date from anywhere between AD 1520 and AD 1640. From the above discussion it is clear that radiocarbon dating is not the most suitable dating technique for the relatively young samples in this study because of the problem of relating radiocarbon and calendar years and, to a lesser extent, the problem of the very large error margins associated with conventional radiocarbon dates.

For the purpose of the present study the large error margins associated with each date may be ignored because of the relatively large number of samples and the close consistency in the dates. The actual radiocarbon dates are therefore considered to be good estimates of the true age (radiocarbon years). As to where the radiocarbon dates fall on the curve in Figure 64 is more problematical, but because the samples were all collected from approximately the same elevation (between 217.2 and 217.4 m) (Table 3) it may be argued that they are all approximately the same age. If the Lake Winnipeg radiocarbon dates are plotted on Figure 64 they may be assumed to fall between 1620 and 1675 calendar years AD. There are thus only about 55 years between the oldest and the youngest dates if they are changed into calendar years, a relationship consistent with their similarity in elevation.

## RATE OF SUBMERGENCE

Uncertainties associated with radiocarbon dating subfossil wood and organic muck from the upper foreshore of Lake Winnipeg, as well as assigning a water level datum to each sample, makes calculation of the rates of water level fluctuation tenuous. Assuming that the samples all date to between AD 1620 and 1675, as discussed in the previous section, then the major concern is establishing a water level for each sample. Sample 9, dated at 230 ± 70 radiocarbon years BP (Table 3), was a piece of *Fraxinus* (ash) driftwood that is common along the beaches and is therefore excluded from the following discussion. Of the remaining nine wood samples, four were identified as *Salix* (willow), one as *Populus* (poplar), one as *Ulmus* (elm) and one as *Larix* (tamarack) (R.J. Mott pers. comm. 1991). The remaining two samples were not identified. Although willow has a strong affinity for water, the root crown of most tree species will not tolerate being submerged indefinitely. The mean water level must therefore have been some distance below the root collar; a distance that will vary for each species. Measurements made during this survey indicate willows (the different species were not identified) grow to within a vertical distance of approximately 0.5 m of the present mean water level. However, it is not known if this limit to the distribution of willows is due to some ecological factor or if they are physically restricted from growing there by the action of shore ice. Figure 65 shows a plot of age (calendar years) *vs* elevation for the nine wood and three organic muck samples. A 50 cm correction has been applied on the right side of Figure 65 to account for the minimum difference between the mean lake level and the lowest elevation of the willows when they were growing. The slope of the line in Figure 65 indicates the mean water level in Lake Winnipeg has risen between 15 and 20 cm/century, in the last 300 years. A 15 cm/century rise is obtained if the samples are considered to have a mean elevation of 217.25 m and date from approximately 1650 AD. If on the other hand, the lowest sample at an elevation of 217.16 m is considered to be the minimum elevation for the growth of willows, the water level must have risen at least 20 cm/century, as all the samples must fall above the water plane.

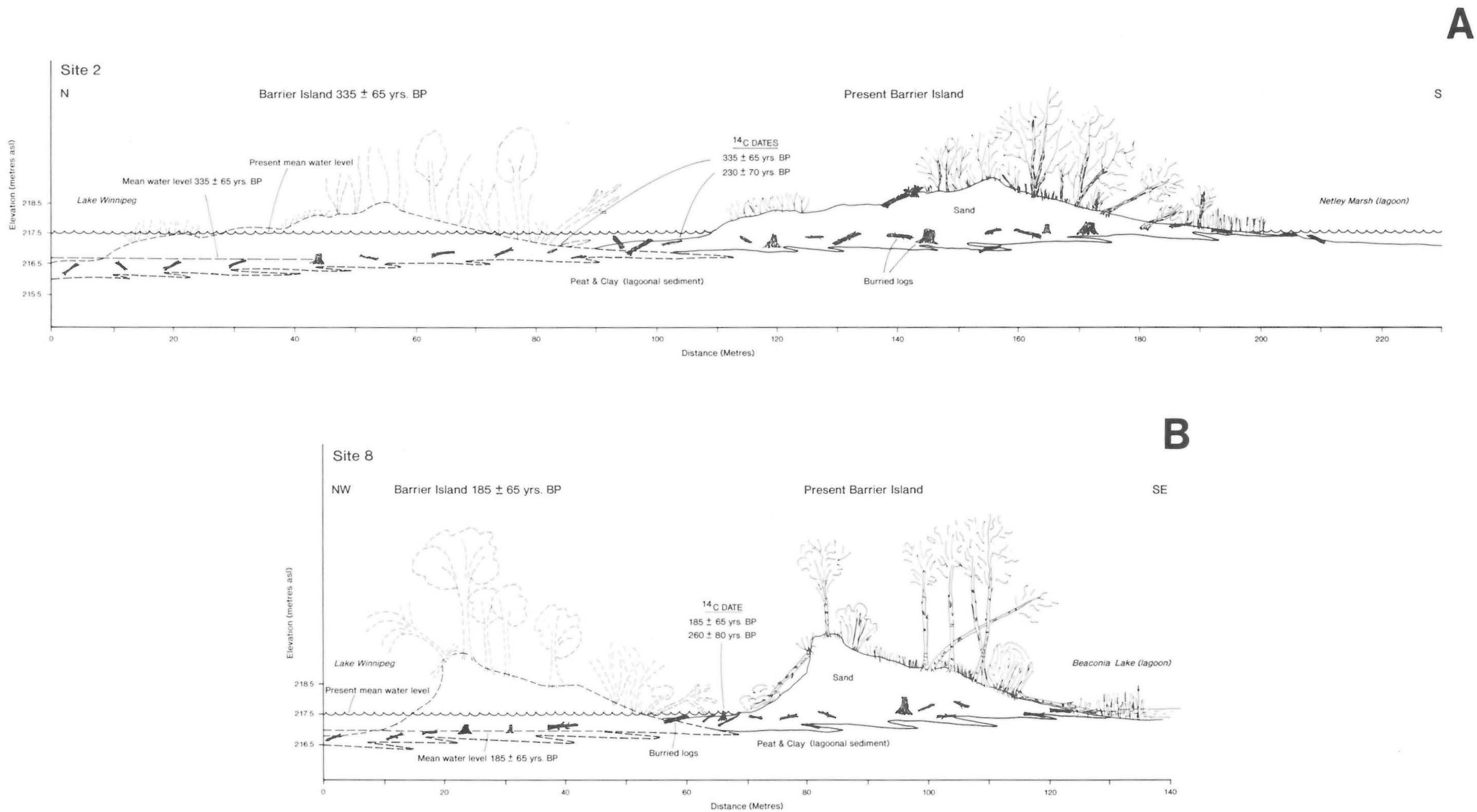



*Figure 63: Cross sections of (A) the barrier island at Site 2, and (B) the bay-mouth-bar at Site 8 showing the burial of logs due to rising lake levels and landward migration of the shore.*

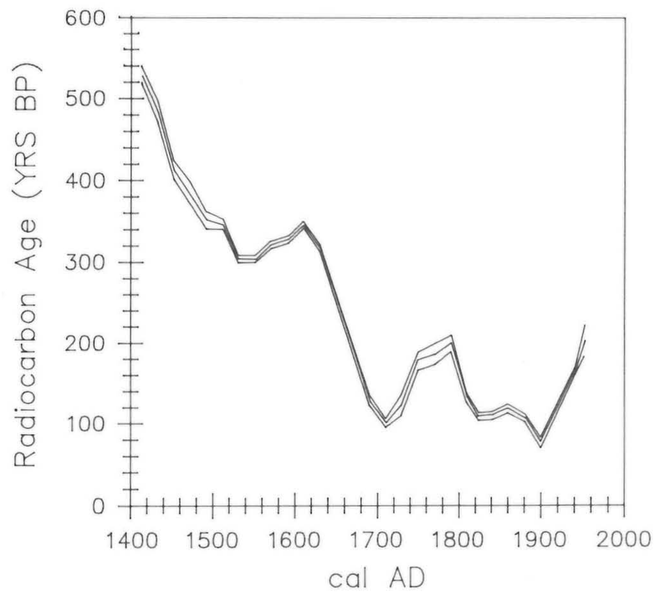



*Figure 64: Radiocarbon ages of wood samples of known age used to calibrate radiocarbon dates (from Stuiver and Pearson, 1986).*

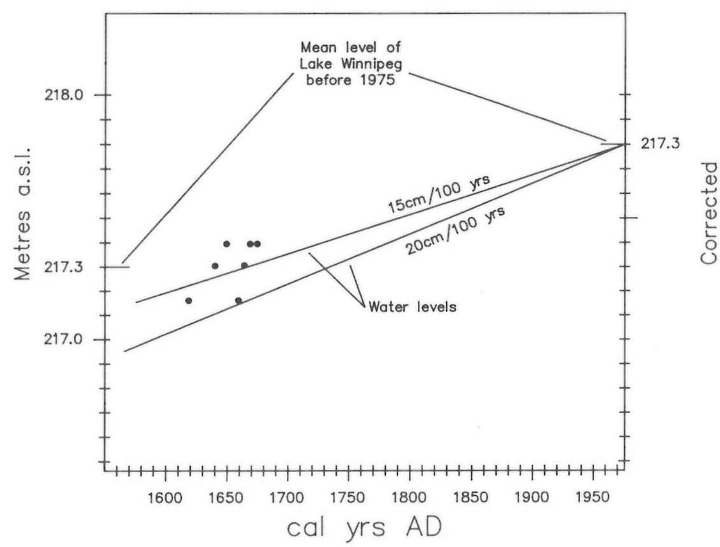



*Figure 65: Plot of elevation vs age, in calendar years, for radiocarbon samples from the foreshore of Lake Winnipeg.*

## REGIONAL UPLIFT

The presence of marine fossils in the Tyrrell Sea sediments of the Hudson Bay Lowland led to the early construction of isobases in northern Manitoba (Andrews, 1970). The lack of dateable material throughout the rest of the province and the absence of an obvious relationship between Lake Agassiz beaches and the marine beaches in the Hudson Bay Lowland precluded the extension of the isobases into the rest of the province. Isobases have, however, been constructed for Lake Agassiz beaches by numerous workers, including Johnston (1946), Elson (1967), Thorleifson (1983) and Teller and Thorleifson (1983). Of these only Thorleifson (1983) and Teller and Thorleifson (1983) indicated that isostatic uplift was continuing through to the present; the previous workers believed uplift had diminished to insignificant and imperceptible levels in the early Holocene. Based on lower mantle rheology, Peltier (1986) postulated a difference of approximately 35 cm/century between the present-day isostatic uplift at the north and south ends of Lake Winnipeg. Work by Penner and Swedlo (1974), Pettipas (1976) and work by Manitoba Hydro (1974 unpublished) suggests the level of Lake Winnipeg has risen approximately 3 m in the last 1660 radiocarbon years (1460 calendar years BP). This conclusion is based on analysis of samples collected from the top and bottom of a 40 cm thick peat layer, uncovered near Victoria Beach, about 3 m below the long term mean lake level and radiocarbon dated at 1660 ± 60 years (GSC-1977) and 1060 ± 210 years (GSC-1980) (Teller, 1980). These dates suggest the water level has risen approximately 20.5 cm/century through at least the last millennium and a half. Manitoba Hydro further concluded that the level of the lake was rising in the south with respect to the outlet based on the analysis of water level records at Berens River and Gimli. The 1914 to 1971 water level records for the winter months indicate Berens River may be rising relative to Gimli at a rate of 6.7 cm/century. The summer water level records suggest the rise is about 4.3 cm/century. Extrapolating these rates between the north and south ends of the lake, in a direction parallel to the direction of maximum isostatic tilting, gives water level rises of about 8 and 11.5 cm/century which is somewhat lower than the other estimates but understandable considering the large standard deviations associated with the water level records (Fig. 7). Work by Nielsen *et al.* (1987) on Lake Winipegosis showed that the north end of this lake, which drains to the south unlike Lake Winnipeg, has been uplifted an estimated 6 m in the last 5000 years although there is no indication of the change in the rate of uplift during this time.

The geologic data and radiocarbon dates from Netley Marsh are thus in agreement with the available data and suggest the water level at the south end of Lake Winnipeg is presently rising at a rate of about 15 to 20 cm/century, as the result of isostatic tilting of the outlet.

A single radiocarbon date of 160 ± 70 yrs BP (Nielsen, unpublished) on a rooted tree stump exposed on the foreshore at Observation Point (Fig. 66) indicates that at least some of the recent water level fluctuation may be basin wide. This would suggest that the level of Lake Winnipeg in the last few centuries may have been affected by climatic variations.

*Figure 66: Rooted tree stumps on the foreshore at Observation Point near Manigotagan.*

## TRANSGRESSION

Marsh facies sediments that outcrop on the upper foreshore indicates the barrier islands along Netley Marsh and the bay-mouth-bar at Beaconia Beach have migrated a minimum of 60 to 100 m (Fig. 63) since about 1650 AD in response to isostatic tilting of the basin.

## SUMMARY AND CONCLUSIONS

Climate data indicates that northerly to westerly winds predominate over the south basin of Lake Winnipeg with south winds less frequent. East winds are the least common. Counterclockwise drift currents occur as a consequence of both the westerly and northerly winds as shown by water movement on aerial photographs. During periods of strong westerly or northerly winds, sediment is transported from the west side of the lake along the south shore and out into the lake as indicated by sediment grain size variations, dolomite content, sedimentary structures, the up-drift off-set in the barrier islands at Pruden Bay and currents as seen on aerial photographs. Along the east side of the lake sediment transport is south along the shore towards Stoney Point and out into the lake due to clockwise circulation. During periods of high water and coincident storms, sediment is eroded from the foreshore and transported out into the deeper parts of the lake and into the marshes through inlets or by overwash. Overwash and sediment transport through the inlets that result in washover fans and flood deltas are the main processes responsible for the landward migration of the barrier islands fronting Netley Marsh and the bay-mouth-bar fronting Beaconia Lake. During periods of light winds and moderately strong currents the sediment eroded from the foreshore is replenished by sediment from the off-shore and by sediment eroded from the headlands in the up-drift direction. Where there is a sufficient sediment supply, such as west of Main Channel, destruction caused by storms is quickly repaired. East of Main Channel, washovers and inlets are more numerous and take longer to be infilled suggesting higher energy environments and a reduced sediment supply compared to areas further west.

Aerial photographs and maps from the last fifty or a hundred years record both long term changes due to isostatic tilting of the outlet and short term changes due to storms, wind set-up, regional flooding and climatic fluctuations. Lake level fluctuations due to climate changes probably have the greatest effect on the shoreline. Comparison of the lake level fluctuations from 1913 to 1977 with the mean monthly precipitation for Winnipeg for the same period shows that the lake levels, at least in part, reflect precipitation. During intervals of little precipitation and low lake levels, such as the early 1930's and early 1940's, the shoreline moved northward and what had been the upper foreshore became exposed to subaerial processes. Hay fields, farms and roads were established in many parts of Netley Marsh and it is probably during this time that sand dunes were most active. Increasing precipitation, such as occurred in the early to mid 1940's was accompanied by a slight transgression of the lake and shoreline erosion. Hay fields, roads and buildings established on the barrier islands and bay-mouth-bar during the earlier part of this century were gradually eroded and flooded by the post 1942 higher water levels.

Outcroppings on the upper foreshore of fine-textured silt and clay sediments, organic muck and subfossil wood initially deposited in the marsh, indicates landward migration of the barrier islands and bay-mouth-bar. Radiometric dating of these deposits suggest the lake level in the southern basin is rising 15 to 20 cm/100 years due to isostatic tilting of the outlet and possibly as a result of climatic fluctuations during the last few centuries. The shoreline has transgressed landward (south) an estimated 60 to 100 m since about 1650 AD.

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## GLOSSARY OF TERMS

**accreating** - The gradual or imperceptible increase or extension of land by natural forces acting over a long period of time.

**aeolian** - Pertaining to the wind, especially said of rocks, soils, and deposits (such as loess, and dune sand) whose constituents were transported (blown) and laid down by atmospheric currents, or of landforms produced or eroded by the wind, or of sedimentary structures (such as ripple marks) made by the wind or of geologic processes (such as erosion and deposition) accomplished by the wind.

**allochthonous** - Formed or occuring elsewhere than in place; of foreign origin, or introduced.

**anthropogenic** - Man made.

**atomic absorption** - Chemical analysis performed by vaporizing sample in a flame, usually in a liquid form, and measuring the absorbance by the unexcited atoms in the vapor of various narrow resonant wavelenghths of light which are characteristic of specific elements.

**backbeach** - The upper or inner, usually dry and narrow zone of the shore or beach, lying between the high-water line of mean spring tides and the coastline, and acted upon by waves or covered by water only during exceptionally severe storms or unusually high water levels.

**backshore** - A synonym for backbeach.

**barrier islands** - A long, low, narrow wave-built sandy island representing a broadened barrier beach that is sufficiently above high water level and parellel to the shore, and that commonly has dunes, vegetated zones and swampy terranes extending lagoonward from the beach.

**bay-mouth-bar** - A long, narrow bank of sand or gravel deposited by waves entirely or partly across the mouth or entrance of a bay so that the bay is no longer connected or is connected only by a narrow inlet with the main body of water; it usually connects two headlands, thus straightening the coast.

**beachridge** - A low, essentialy continuous mound of beach or beach-and-dune material (sand, gravel, shingle) heaped up by the action of waves and currents on the backshore of a beach beyond the present limit of storm waves or the reach of ordinary tides, and occurring singly or as one of a series of approximately parallel deposits. The ridges are roughly parallel to the shoreline and represent successive positions of an advancing shoreline.

**berm runnel** - A trough-like hollow, larger than that between ripple marks, formed landward of a ridge on the backshore of a tidal sand beach by the action of tides or waves.

**biogenic** - When something is produced directly by the phisiological activities of living organisms, either plant or animal.

**blowouts** - A general term for a small saucer-cup, or trough-shaped hollow, depression, basin, or valley formed by wind erosion on a preexisting dune or other sand deposit, especially in an area of shifting sand or loose soil or where protective vegetation is disturbed or destroyed; the adjoining accumulation of sand derived form the depression, where readily recognizable, is commonly included.

**breakwater** - An offshore structure (such as a mound, wall or jetty) that, by breaking the force of the waves, protects a harbour, anchorage, basin, beach or shore area.

**cobbles** - A rock fragment larger than a pebble and smaller than a boulder, having a diameter in the range of 64-256mm, being somewhat rounded or otherwise modified by abrasion in the course of transport.

**crevasse splays** - A small alluvial fan or other outspread deposit formed where an overloaded stream breaks through a levee (artificial or natural) and deposits its material on the flood plain.

**cryoturbation** - Describes the churning, stirring, modification, and all other disturbances of soil, resulting from frost action.

**current crescents** - A small semicircular or U-shaped, rounded ridge, convex upcurrent, commonly with a pit in the centre, and developed on a muddy surface by current action.

**delta** - The low, nearly flat, alluvial tract of land deposited at or near the mouth of a river, commonly forming a triangular or fan-shaped plain of considerable area enclosed and crossed by many distributaries of the main river, perhaps extending beyond the general trend of the coast, and resulting from the accumulation in a wider body of water of sediment supplied by a river in such quantities that it is not removed by tides, waves, and currents. Most deltas are partly subaerial and partly below water.

**dendrochronological** - The annual growth rings of trees for dating of the recent past.

**desiccation cracks** - A crack in sediment, prouced by drying.

**detritus** - A collective term for loose rock, mineral, or other material that is worn off or removed directly by mechanical means, as by disintegration or abrasion and moved from its place of origin.

**discoid** - Having the shape of a disc.

**dolomite** - A common rock-forming rhombohedral mineral.

**drainage channels** - A channel, conduit, or waterway, either natural or artificial, for draining or carrying off excess water from an area.

**dunes** - A low mound, ridge, bank, or hill of loose wind-blown, granular material (generaly sand), either bare or covered with vegetation, capable of movement from place to place but always retaining its own characteristic shape.

**ebb current** - The tidal current associated with the decrease in the height of a tide, generally moving seaward or down a tidal river or estuary.

**echogram** - The graphic record made by an echo sounder, in the form of a continuous profile.

**facies** - (a) The sum of all primary lithologic and paleontological characteristics exhibited by a sedimentary rock and from which its origin and environment of formation may be inferred; the general aspect, nature or appearance of a sedimentary rock produced under or affected by similar conditions; a distinctive group of characteristics that differs from other groups within a stratigraphic unit. (b) An exclusive, mappable and areally restricted part of a defined stratigraphic rock body, such as a stratum or group of strata differing in lithologic character or fossil contents from other beds deposited at the same time and in physical continuity; a lateral subdivision of a specified stratigraphic unit; a lithofacies.

**feldspar** - A group of abundant rock-forming minerals of general forjula; $MAl(Al,Si)_3O^8$, where M = K, Na, Ca, Ba, Rb, Sr, and Fe. Feldspars are the most widespread of any mineral group and constitute 60% of the Earth's crust; they occur as components of all kinds of rocks (crystalline schists, migmatites, gneisses, granites, most magmatic rocks) and as fissure minerals in clefts and druse minerals in cavities. Feldspars are usually white or nearly white and clear and translucent, have a hardness of 6 on Mohs' scale, frequently display twinning, exhibit monoclinic or triclinic symmetry, and possess good cleavage in two directions. On decomposition, feldspars yield a large part of the clay of soil and also the mineral kaolinite.

**flotsam** - Wreckage found floating.

**foreshore** - The lower or outer, gradually seaward-sloping zone of the shore or beach, lying between the crest of the most seaward berm on the backshore (or the upper limit of wave wash at high tide) and the ordinary low-water mark; the zone regularly covered and uncovered by the rise and fall of the tide, or the zone lying between the ordinary tide levels.

**fossiliferous** - Containing organic remains.

**frost shattering** - The mechanical disintegration, splitting, or breakup of a rock or soil due to the great pressure exerted by the freezing of water contained in cracks or pores, or along bedding planes.

**geomagnetic field** - The magnetic phenomena exhibited by the Earth and its atmosphere.

**geomorphology** - The science that treats the general configuration of the Earth's surface; specifically the study of the classification, description, nature, origin, and development of present landforms and their relationships to underlying structures, and of the history of geologic changes as recorded by these surface features.

**glacial erratic** - A rock fragment carried by glacial ice or by floating ice, and deposited when the ice melted at some distance from the outcrop from which the fragment was derived.

**glaciofluvial outwash** - Pertaining to the meltwater streams flowing from wasting glacier ice and especially to the deposits and landforms produced by such streams.

**groyne** - A low, narrow, rigid jetty constructed of timber, stone, concrete, or steel, usually extending roughly perpendicular to the shoreline, designed to protect the shore from erosion by currents, tides or waves, or to trap sand and littoral drift for the purpose of building up or making a beach.

**Holocene** - An epoch of the Quaternery period, from the end of Pleistocene to the present time.

**hydrograph** - A graph showing stage, velocity or other characteristics of water with respect to time.

**Hypsithermal interval** - Postglacial warm interval, extending from about 7000 to 2000 years B.P.

**ice lenses** - A discontinuous, horizontal ice layer that tapers out in all directions.

**ice-pushed feature** - A feature where the lateral pressure is exerted by the expansion of shoreward-moving ice, especially of lake ice; the ridge of material formed by an ice-push.

**inlets** - A small narrow opening, recess, indentation, or other entrance into a coastline or a shore of a lake or river, and through which water penetrates into the land.

**isobases** - A term used for a line which connects all areas of equal uplift or depression; it is used especially in Quaternery geology as a means for expressing movements related to postglacial uplift.

**isostacy** - The condition of equilibrium, comparable to floating, of the units of the brittle crust above the plastic mantle.

**jetsam** - A substance that is washed ashore.

**lacustrine** - Pertaining to, produced by, or formed in a lake or lakes; growing in or inhabiting in lakes.

**lag gravel** - A residual accumulation of coarse, usually very hard rock fragments remaining on a surface after the finer material has been washed or blown away.

**lagoon** - A shallow freshwater pond or lake, near or communicating with a larger lake or a river, partly or completely separated from it by a low, narrow, elongate strip of land; a stretch of freshwater cut off from a lake by a barrier.

**linguoid** - An aqueous current ripple mark characterized by a toungue-shaped outline or having a barchan-like shape whose horns point into the current.

**lithofacies** - The rock record of any sedimentary environment, including both physical and organic characters.

**littoral drift** - Sediment or other material (such as gravel, sand, and shell fragments) that is moved along the shore by a littoral current.

**longitudinal ripple mark** - A ripple mark with a relatively straight crest, formed parallel to the direction of the current, such as one related to oscillatory wave action; its profile may be asymmetric or symmetric.

**longshore currents** - Also called littoral current, is an ocean current caused by the approach of waves to a coast at an angle.

**longshore drift** - Also refered to as a littoral drift.

**mantle rheology** - The study of the deformation and flow of matter in the mantle.

**megaripples** - Large gentle ripple-like feature composed of sand in very shallow water situations.

**microtidal coastline** - A coastline with a tidal range from 0 to 2 m.

**Ordovician** - The second of the periods comprised in the Paleozoic era, in the geological classification now generally used.

**Paleozoic** - An era of geological time, from the end of the Precambrian to the beggining of the Mesozoic.

**pelecypod shells** - Any benthic aquatic mollusk belonging to the class Pelecypoda, characterized by a bilaterally symmetrical bivalve shell, a hatchet-shaped foot, and sheet-like gills.

**permafrost** - Permanently frozen subsoil.

**phi** - Particle-size diameter, expressed as the negative logarithm to the base 2 of the diameter in millimetres.

**physiography** - The study of the genisis and evolution of land forms.

**prodelta** - The part of a delta that is below the effective depth of wave erosion, lying beyond the delta front, and sloping gently down to the floor of the basin into which the delta is advancing and where clastic river sediment ceases to be a significant part of the basin-floor deposits; it is entirely below the water level.

**prograding** - A seaward advance of the shoreline resulting from the nearshore deposition of sediments brought to the sea by rivers.

**radiocarbon dating** - The determination of the age of a material by measuring the proportion of the isotope $^{14}C$ (radiocarbon) in the carbon it contains.

**radiometric dating** - Calculating an age in years for geologic materials by measuring the presence of a short-life radioactive element.

**retrograding** - The backward (landward) movement or retreat of a shoreline or of a coastline by wave erosion; it produces a steepening of the beach profile at the breaker line.

**recurved spit** - A spit whose outer end is turned landward by current deflection by the opposing action of two or more currents, or by wave refraction.

**ridge** - A low mound that is sometimes found above the water level on the foreshore of a sand beach during periods of low water.

**ripple** - A very small ridge of sand resembling or suggesting a ripple of water and formed on the bedding surface of a sediment. A small sand wave similar to a dune in shape but smaller in magnitude.

**runnel** - A trough-like hollow, larger than that between ripple marks, formed landward of a ridge on the foreshore of a tidal sand beach by the action of tides or waves. It carries the water drainage off the beach as the tide retreats and is flooded as the tide advances.

**runup** - The advance of water up the foreshore of a beach, following the breaking of a wave.

**sand flats** - A sandy tidal flat barren of vegetation.

**sand ribbon** - Sand structures formed by shallow wind-driven water resulting in miniature 'spits' oriented parallel to the wind direction.

**sand spits** - A narrow sand embankment, created by an excess of deposition at its seaward terminus, with its distal end (the end away from the point of origin) terminating in open water.

**sand tounges** - Flattened ripple crests eroded by shallow wind driven water forming long lobate sand structures approximately perpendicular to the wind direction.

**sedimentology** - The study of sedimentary rocks and the processes by which they are formed.

**seiches** - A periodic oscillation of a body of water whose period is determined by the resonant characteristics of the containing basin as controlled by its physical dimensions.

**shadow dunes** - Dunes formed by sand drifting across the beach that is deposited in the lee of an obstacle.

**shingled beach** - Coarse, loose, well-rounded, and water-worn detritus or alluvial material of various sizes.

**silt** - A rock fragment or detrital particle smaller than a very fine sand grain and larger than coarse clay, having a diameter in the range of 1/256 to 1/16 mm (4-62 microns, or 8 to 4 phi units).

**sonar** - An acronym that means sound navigation and ranging, a method used in oceanography to study the ocean floor.

**sorting** - The dynamic process by which sedimentary particles having some particular characteristic (such as similarity of size, shape, or specific gravity) are nautrally selected and separated from associated but dissimilar particles by the agents of transportation (esp. by the action of running water).

**spit** - A small point or low tongue or narrow embankment of land commonly consisting of sand or gravel deposited by longshore drifting and having one end attached to the mainland and the other terminating in open water, usually the sea; a finger-like extension of the beach.

**stratification** - The formation, accumulation, or deposition of material in layers; specifically the arrangement or disposition of sedimentary rocks in strata. It may be due to differences of texture, hardness, cohesion or cementation, colour, internal structure, and mineralogic or lithologic composition.

**subaerially** - Occurring beneath the atmosphere or in the open air; esp. said of conditions and processes (such as erosion) that exist or operate on or immediately adjacent to the land surface, or of features and materials (such as eolian deposits) that are formed or situated on the land surface.

**subaqueous** - Said of conditions and processes that exist or operate, or of features and deposits that are formed or situated, in or under water or beneath the surface of water, esp. of freshwater (as in a lake or stream).

**surficial** - Pertaining to, situated at, or formed or occurring on a surface, esp. the surface of the Earth.

**swash mark** - A thin, delicate, wavy or arcuate (convex landward) line or very small ridge on a beach, marking the farthest advance of wave uprush, and consisting of fine sand, mica flakes, bits of seaweed, and other debris.

**swash zone** - The sloping part of the beach that is alternately covered and uncovered by the uprush of waves, and where longshore movement of water occurs in a zigzag (upslope-downslope) manner.

**taphonomy** - The branch of paleoecology concerned with the manner of burial and the origin of plant and animal remains.

**terrace** - Any long, narrow, relatively level or gently inclined surface, generally less broad than a plain, bounded along one edge by a steeper descending slope and along the other by a steeper ascending slope; a large bench or step-like ledge breaking the continuity of a slope.

**tidal channel** - (a) A major channel followed by the tidal currents, extending from offshore well into a tidal marsh or a tidal flat. (b) Tidal inlet.

**tidal creek** - A relatively small tidal inlet or estuary.

**tidal current** - The periodic horizontal movement of ocean water associated with the vertical rise and fall of the tides and resulting from the gravitational attraction of the Moon and Sun upon the Earth. In the open ocean, its direction rotates $360^{\circ}$ on a dirunal or semidiurnal basis; in coastal areas, however, topography influences its direction.

**tidal inlet** - Any inlet through which water flows alternately landward with the rising tide and seaward with the falling tide; specif. a natural inlet maintained by tidal currents.

**topography** - The general configuration of a land surface or any part of the Earth's surface, including its relief and the position of its natural and man-made features. The natural or physical surface features of a region, considered collectively as to form; the features revealed by the contour lines of a map.

**transgression** - The spread or extension of the sea over land areas, and the consequent evidence of such advance (such as strata deposited unconformably on older rocks, esp. where the new marine deposits are spread far and wide over the former land surface). Also, any change (such as rise of sea level or subsidence of land) that brings offshore, typically deep-water environments to areas formerly occupied by nearshore, typically shallow-water conditions, or that shifts the boundary between marine and nonmarine deposition or between deposition and erosion) outward from the center of a marine basin.

**tree-ring analysis** - The measurement of tree ring widths.

**washover** - Material deposited by the action of overwash; specif. a small delta built on the landward side of a bar or barrier, separating a lagoon from the open sea, produced by storm waves breaking over low parts of the bar or barrier and depositing sediment in the lagoon.

**wave spectrum** - (a) The description of wave energy with respect to frequency by mathematical function. The square of the wave height is related to the potential energy of the surface of the sea. (b) A graph that shows, for a region of the ocean, the distribution of wave height with respect to frequency.

**welded bars** - A ridge that moves shoreward by the action of waves and attaches to the upper foreshore.

**wind ripples** - One of many wave-like, assymmetric undulations produced on a sand surface by the saltatory movement of particles by air currents (wind) and occasionally found in eolian rocks; it is generally longer and of smaller height than an aqueous ripple mark, but is similar in having a steep lee side (facing downcurrent) and a gentle windward side (facing upcurrent).

**wind set-up** - The vertical rise of the still-water level on the leeward side of a body of water, caused by the force of wind on the surface of the water; the difference between the leeward and windward sides of the form.

## APPENDIX I

List of airphotos used in this report.

A20442 - 4
A20399 - 11, 19, 25, 26
71382 - 105, 112, 114, 246
A1963 - 22, 24
A9710 - 90, 91, 94
A10492 - 22, 24, 27, 37
A9686 - 32, 45
MB87003 - 151
MB87001 - 70
A9805 - 32

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