"The Origin and Evolution of a Complex Cuspate Foreland: Pointe-aux-Pins, Lake Erie, Ontario"

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THE ORIGIN AND EVOLUTION OF A COMPLEX CUSPATE FORELAND: POINTE-AUX-PINS, LAKE ERIE, ONTARIO

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ABSTRACT The origin of Pointe-aux-Pins, a large, rounded, cuspate foreland protruding from the north shore of Lake Erie, is difficult to explain by conventional spit formation processes. Stratigraphic evidence from boreholes, the distribution of nearshore sediments, surface geomorphology, and previously published interpretations of Lake Erie water levels were combined to produce an hypothetical model of the development of the foreland from approximately 12,000 years BP to now. According to the model, the ancestral Pointe-aux-Pins began as a promontory caused by the intersection of the cross-lake Erieau moraine with the original lake shoreline, then located tens of kilometres lakeward of its present position. Lake levels at the time were about 30 m below present datum (173.3 m a.s.l.). Modern Pointe-aux-Pins dates from after the Nipissing "flood", at about 3500 BP, when the thereto-submerged sandy spit platform was again subjected to wave action, leading to beach ridge and dune formation. The age of the foreland of 3500 to 4000 years compares well with estimates based on the annual sand supply rate and the present sand volume in Pointe-aux-Pins.

RÉSUMÉ *L'origine et l'évolution de la pointe aux Pins, lac Érié, Ontario: une pointe de terre d'origine complexe*. L'origine de la pointe aux Pins, vaste avancée triangulaire arquée sur la rive septentrionale du lac Érié, est difficile à expliquer par les processus courants de formation des flèches littorales. Les éléments de preuves d'ordre stratigraphique trouvés dans les trous de forage, la répartition des sédiments sur le littoral, la géomorphologie des formations superficielles et les interprétations déjà publiées sur les niveaux du lac Érié ont été combinés afin de créer un modèle hypothétique de l'évolution de cette pointe de terre, depuis environ 12 000 ans BP. Selon le modèle, l'ancienne pointe aux Pins a d'abord été un promontoire qui s'est formé à l'intersection de la moraine d'Erieau et du rivage originel du lac, alors situé à des dizaines de kilomètres au large. Le niveau du lac était alors à 30 m au-dessous de la surface actuelle (173,3 m a.n.m.). L'actuelle pointe aux Pins est postérieure à «l'inondation» de Nipissing, survenue il y a environ 3500 ans BP, lorsque la plate-forme constituée par la flèche de sable a de nouveau été soumise à l'action des vagues, ce qui a entraîné la formation de crêtes de plage et de dunes. L'âge de 3500-4000 ans attribué à la pointe de terre correspond bien aux estimations fondées sur le taux annuel d'apport en sable et le volume actuel de sable à la pointe aux Pins.

ZUSAMMENFASSUNG *Ursprung und Entwicklung eines komplexen dreieckigen Strandvorsprungs: Pointe-aux-Pins, Erie-See, Ontario*. Der Ursprung von Pointe-aux-Pins, einem breiten, geschweiften dreieckigen Strandvorsprung, der aus dem Nordufer des Erie-Sees herausragt, ist nicht einfach aus den üblichen Prozessen der Landspitzenbildung zu erklären. Stratigraphische Nachweise aus Bohrlöchern, die Verteilung von küstennahen Sedimenten, die Oberflächengeomorphologie und früher veröffentlichte Interpretationen der Wasserspiegel des Erie-Sees wurden kombiniert, um ein hypothetisches Modell der Entwicklung des Strandvorsprungs von etwa 12 000 v.u.Z. bis heute zu entwickeln. Aus dem Modell geht hervor, dass die Ur-Pointe-aux-Pins-Landzunge als ein Vorgebirge begann, das sich am Schnittpunkt der quer durch den See verlaufenden Erieau-Moräne mit der ursprünglichen Seeküste bildete, die sich damals 10 km seeeinwärts von ihrer heutigen Position befand. Der Seewasserspiegel war damals etwa 30 m unter dem gegenwärtigen (173.3 m ü.M.). Die heutige Pointe-aux-Pins-Landzunge stammt aus der Zeit nach der "Überflutung" von Nipissing um ungefähr 3500 v.u.Z., als die hoch dazu untergetauchte Sandlandspitze wieder dem Einfluss der Wellen ausgesetzt war, was zur Bildung von Strandkämmen und Dünen führte. Das Alter des Strandvorsprungs von 3550 bis 4000 Jahren stimmt gut überein mit den auf die jährliche Sandzufuhrrate und das gegenwärtige Sandvolumen gestützten Schätzungen in Pointe-aux-Pins.

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INTRODUCTION

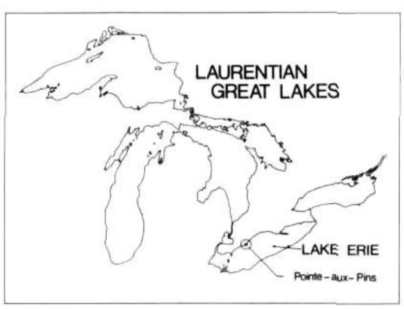
Pointe-aux-Pins, or Rondeau Peninsula, is a rounded cuspate foreland protruding some 7 km southward from the north shore of Lake Erie, in the province of Ontario (Fig. 1). From its junction with the shoreline, the eastern limb of the cuspate foreland widens from approximately 0.5 to 2 km near its southern extremity. The southwestern limb, however, is much narrower (less than 100 m in places), and is occupied by the town of Erieau. The entire foreland covers approximately 50 km^2, 60 % of which comprises an enclosed area of pond and marsh, Rondeau Bay. The bay is less than 4 m in depth, and much of the marsh that once existed along its northwestern shore has been drained for agricultural purposes.

The broader eastern limb of the foreland comprises a wooded beach ridge — dune complex, made up by a large number of sub-parallel ridges trending northeast to southwest, alternating with marshy swales, well-defined on aerial photographs (Fig. 2). These ridges are usually less than 5 m in height and are believed to have originated as storm beach ridges. The eastern limb of the foreland and the enclosed lagoon make up Rondeau Provincial Park.

PREVIOUS WORK

A comprehensive literature search and bibliography on Pointe-aux-Pins was prepared under contract to the National Water Research Institute (Mann and Coakley, 1978). Most of the early references comprised engineering reports dealing with either the construction of harbour works, or with shore protection. The earliest scientific attempt to interpret the origin and evolution of Pointe-aux-Pins was by Wilson (1908), in which he cited the growth and eventual merging of two simple spits (growing in opposing directions) as the mode of formation. These merging spits were purportedly nourished from materials eroded from adjacent shorelines on both sides. A similar genetic model, involving deposition from opposing littoral drift sources was repeated by Wood (1951) and by Warren (1974). Wood was the first to link the system of linear ridges noted on the foreland to successive shoreline positions occupied as the east limb prograded lakeward. None of these writers took into consideration the possible role of glacial geology or lake level history in their genetic models, nor otherwise explained why the foreland was formed at that particular place on the shoreline. Furthermore, because radiocarbon dates or pollen stratigraphic data were lacking in the area, estimates of the age of the foreland were questionable. Published ages range from older than 2300 years (Stothers, 1972) to 9000 years (Warren, 1974). Rukavina and St. Jacques (1978) placed the origin of Pointe-aux-Pins at 4000 years BP.

Basin-wide studies on the bottom sediments and glacial history of Lake Erie as were initiated by Lewis (1966), and continued more recently by Coakley (1985). In between, surveys of nearshore bottom sediments in the Pointe-aux-Pins area were conducted by Rukavina and St. Jacques (1978). Rukavina (1983) compiled a more specific data record for the area around the foreland, consisting of bottom sample descriptions, short cores, and jetting probes into the subsurface material. Deeper borehole information in the area was provided by Lewis *et al.* (1973) on a series of sites to the southeast of the foreland. Further interpretation based on these boreholes appears in Creer *et al.* (1976), Davis (1979), Fritz *et al.* (1975), and Zeman (1979).



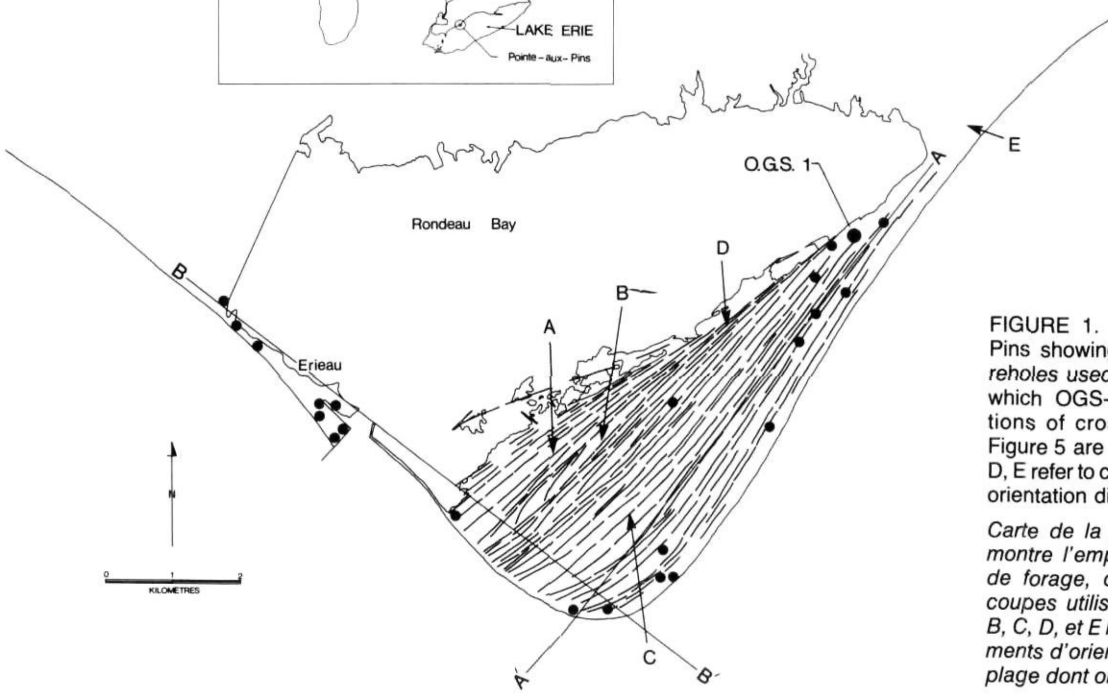


FIGURE 1. Map of Pointe-aux-Pins showing the location of boreholes used in the study, one of which OGS-1 is labelled. Locations of cross-sections used in Figure 5 are also shown. A, B, C, D, E refer to changes in beach ridge orientation discussed in text.

Carte de la pointe aux Pins qui montre l'emplacement des trous de forage, dont OGS-1, et des coupes utilisées à la figure 5. A, B, C, D, et E montrent les changements d'orientation des crêtes de plage dont on parle dans le texte.

Other borehole drilling on the point itself was carried out by the Ontario Geological Survey (A. J. Cooper, personal communication, 1982); Trow, Ltd.; Golder Associates; and Public Works Canada. Water well records archived by the Ontario Ministry of the Environment (London, Ontario) made up the remainder of the data base on Pointe-aux-Pins sediments.

BOTTOM SEDIMENTS, PHYSIOGRAPHY, AND STRATIGRAPHY

SEDIMENTS

Nearshore Surficial Sediments

Figure 3 shows the distribution of nearshore bottom sediment types close to Pointe-aux-Pins as reproduced from Rukavina and St. Jacques (1978). The distribution map is based on surface samples taken on a 2 km square grid, bottom photographs, and interpretation of north-south echosounder traverses run at 1 km spacing in the area.

a) *Till*. The dominant bottom sediment type is till, which crops out extensively off the southwestern shore of the foreland. A deposit of comparable size also occurs off the northeastern end. The till, though unidentified by Rukavina and St. Jacques (1978), is probably similar to the material identified by Creer *et al.* (1976) and Cooper (1977) as Port Stanley Till, a clay-rich till deposited during the Port Bruce Stadial (about 14,000 years BP).

b) *Glaciolacustrine clay*. Though now represented only in one small outcrop to the south of Pointe-aux-Pins and in an area to the west, these sediments appear to have originally overlain the till. Subsequent erosion by wave processes has apparently removed the deposit from most of the area. These sediments are stiff clays, often laminated, and generally associated with the youngest high-level glacial lakes (Whittlesey to Warren, and their successors) which occupied the basin intermittently until around 12,500 BP.

c) *Postglacial and modern sediments*. These sediments, comprising soft, silt/clay mixtures (mud, silt) in the deeper areas of the nearshore zone and grading shoreward into sandy mud and clean, sorted sands adjacent to the shoreline, are restricted to the eastern and southern portion of the area. On land the surface sediments consist of sorted sands (originally beach-deposited, but later modified by wind-related

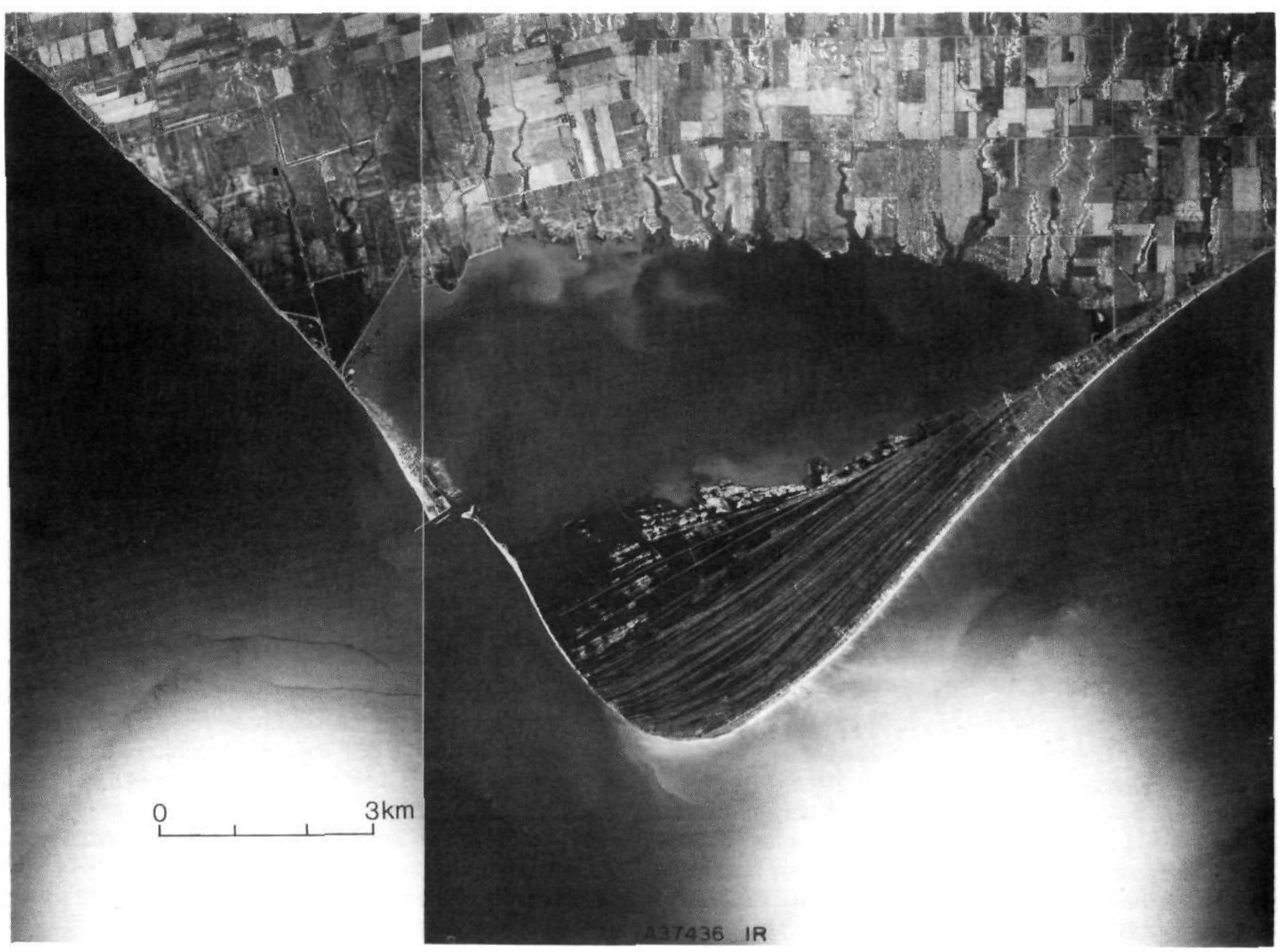


FIGURE 2. False-color infra-red aerial photograph of Pointe-aux-Pins, showing complex pattern of accreting beach ridges on east-facing limb, and narrow barrier facing south.

Sur cette photographie aérienne en fausses couleurs, on aperçoit du côté est la configuration complexe des crêtes de plage en voie d'accroissement et l'étroite barrière qui fait face au sud.

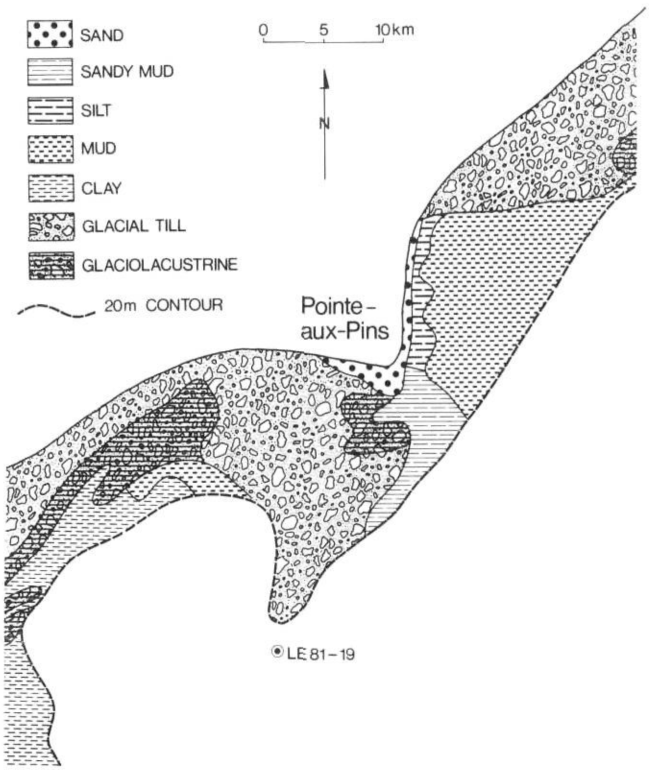


FIGURE 3. Map of surficial sediments in the nearshore zone of central Lake Erie near Pointe-aux-Pins out to water depths of 20 m below datum (from Rukavina and St. Jacques, 1978). The relationship of Core LE81-19, south of the Point, to the till "high" is also shown.

Carte des sédiments superficiels, à partir de la zone du littoral du centre du lac Érié, près de la pointe aux Pins, jusqu'à une profondeur de 20 m sous le niveau 0 (de Rukavina et St. Jacques, 1978). On montre également les relations entre le trou de forage LE81-19, au sud de la pointe, et la «pointe» de till.

processes) and fine-grained organic sediments (muck) in the sheltered lagoonal and inter-ridge topographic lows.

Offshore subsurface sediments

Resolution of the vertical sequence of subsurface lake sediments was based mainly on boreholes drilled from an offshore platform approximately 20 km south-east of Pointe-aux-Pins (Lewis *et al.*, 1973; Creer *et al.*, 1976), and on short gravity cores and water-jet probes closer to shore (Rukavina, 1983). The location of the offshore sample sites is shown in Figure 4. A 1 m long Benthos gravity core (LE81-19) taken by the author provided additional information, as did a 9.2 m piston core collected in 1977 by the University of Western Ontario (F-15).

According to Creer *et al.* (1976), the lake bottom sediments at the long borehole sites are composed of glacial materials (till overlain by glaciolacustrine clay) in the bottom portions of the cores, disconformably overlain by 9 m or less of postglacial materials (lacustrine mud). On the lake bottom, in depths less than 28 m below International Great Lakes Datum for Lake Erie (173.3 m a.s.l.), Lewis *et al.* (1966) noted a thin zone of coarse sand and shells overlying the glacial sediments. This is clearly a lag concentrate of the coarser sediment fraction less easily transported by bottom currents. Shoreward and toward the west, the glacial sediment sequence thins considerably, by apparent truncation of the glaciolacustrine layer, and modern sediments directly overlie till.

At the bottom of core LE81-19 (Fig. 3,4) collected at 23 m below datum (b.d.), a 10 cm thick layer, made up of anomalously coarse materials (sand, fine gravel, shells, and wood fragments, all coated with what appeared to be a ferromanganous oxide), occurs. The upward transition to fine, soft muds is gradational. Although the underlying material was not sampled in the core, its position atop the south-trending ridge (labelled the Erieau Moraine by Sly and Lewis (1972)), together with echo-sounder evidence, suggests that till underlies the core materials. The coarse layer is clearly a lag deposit, indicating a period of differential removal of the finer fraction, presumably in shallower, more wave-agitated water. The texture of these basal sediments suggests strongly that at the time of deposition, the water was much shallower than the present 23 m depth.

Sediments below Pointe-aux-Pins

Figure 1 shows the location of 23 boreholes drilled on Pointe-aux-Pins itself. The only borehole drilled for geoscience purposes, labelled OGS-1, formed part of the geological mapping and research work carried out by the Ontario Geological Survey (Cooper, 1977). The vertical sedimentary sequence noted in all boreholes generally consists of well-sorted sand and gravel (up to 10 m thick) overlying glacial sediments (Fig. 5). In the more shoreward areas where the foreland joins the mainland, layers of organic material or fibrous peat up to several metres thick occur below the sand unit. Below the eastern limb of the foreland, this peat layer occurs at an elevation of 8 to 10 m b.d., while below the southwestern limb, several apparently separate layers are noted at elevations of 5, 2, and 0 m, *i.e.*, at the datum level.

The peat layer below the eastern limb of the foreland overlies the glaciolacustrine clay substrate in the landward areas, and softer, apparently postglacial muds on the lakeward side. Below the southwestern limb, the upper peat layers are enclosed within the sorted sand unit, while the lowest layer overlies glacial sediment. The lateral extent of these peat layers could be traced for some distance below Rondeau Bay sediments (D.A. St. Jacques, unpubl. data, 1982).

PHYSIOGRAPHY

Postglacial surface topography

The glacial sediment surface below Pointe-aux-Pins shows an abrupt rise below the town of Erieau (Fig. 5, B.-B'), rising from lower than 10 m b.d. in the eastern portion of the cross-section, to 5 m or less, below Erieau and Rondeau Bay. This rise is apparently continuous with a bathymetric high immediately to the south, and with the subsurface glacial-sediment high interpreted at the site of core LE81-19 (Fig. 3,4). It is apparently also linked with the sand-capped bathymetric high mapped by Carter *et al.* (1982) off Fairport, Ohio (Fig. 4). This evidence supports the interpretation of Sly and Lewis (1972) that the feature is the topographic expression of the cross-lake Erieau moraine (Fig. 4).

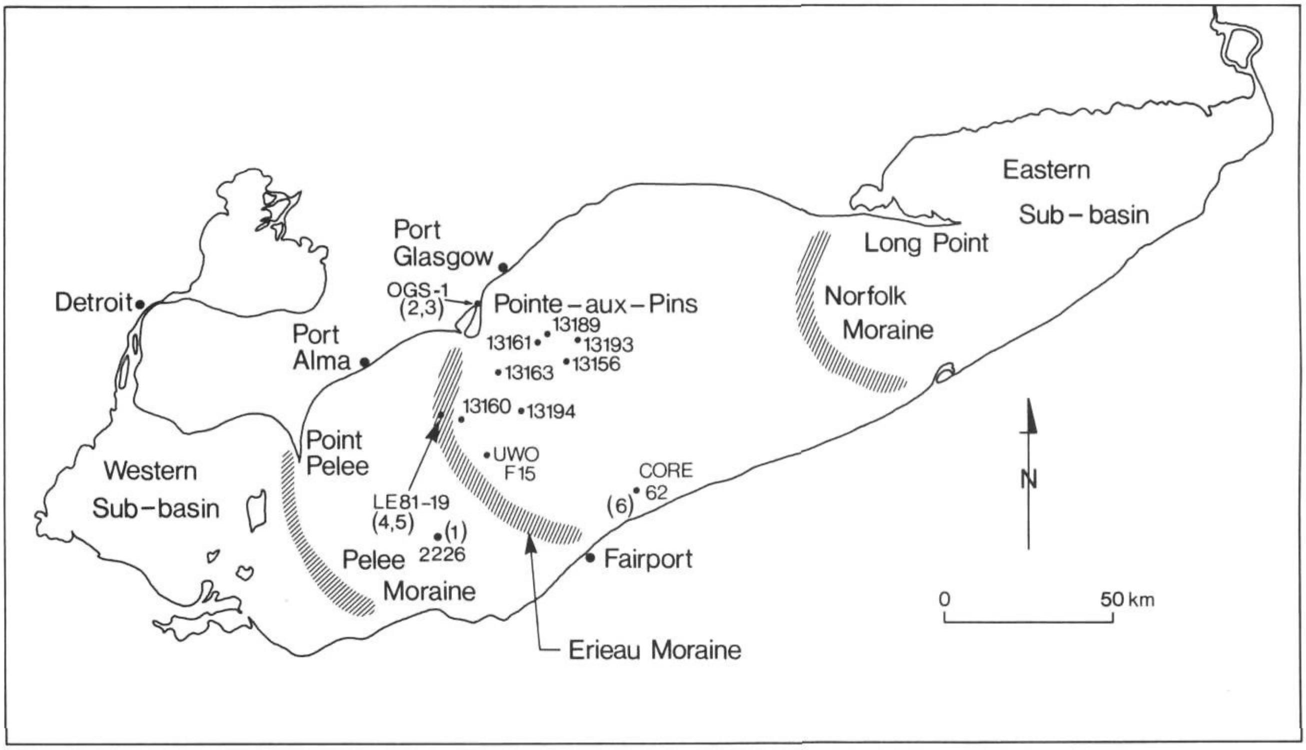


FIGURE 4. Physiographic features of the Erie basin and locations of important boreholes and cores referred to in text. Bracketed numbers refer to sites shown in Table I.

Caractéristiques physiographiques du lac Érié et emplacement des trous de forage et de carottage dont on parle dans le texte. Les numéros entre parenthèses correspondent aux sites mentionnés dans le tableau I.

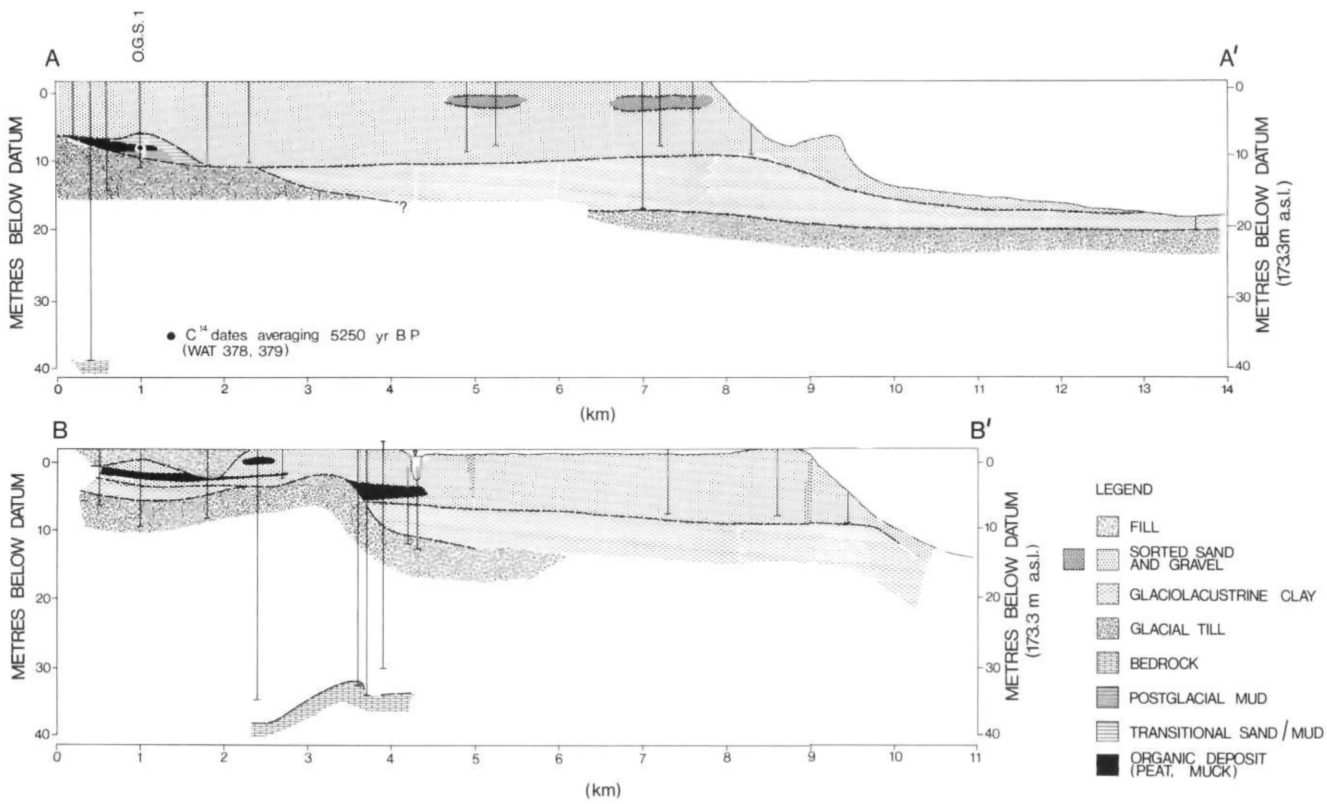


FIGURE 5. Vertical section through Pointe-aux-Pins along lines AA' and BB' (see Fig. 1 for locations), based on the borehole and nearshore survey data.

Coupes de la pointe aux Pins le long des lignes AA' et BB' (emplacement à la fig. 1), d'après les données de forage et des levés côtiers.

In the offshore areas, above elevations of 40 m b.d., the glacial sediment surface slopes gently shoreward, and is directly overlain in many areas by a thin coarse lag concentrate (Lewis *et al.*, 1966; Davis, 1979). However, below the east limb of the foreland itself, this surface is virtually level at approximately 10 m b.d. Both the gentle slope and the lag deposit are clear indications of a considerable period of wave abrasion in relatively shallow water. In the nearshore zone, the glacial sediment surface just to the east and south of Pointe-aux-Pins and also on the east flank of the Pelee Shoal area to the west shows a sharp break in slope at around 15 m b.d. (Fig. 8 in Rukavina and St. Jacques, 1978). This feature is interpreted here as a "wave-cut notch", indicating a previous shoreline position.

Relict beach ridges on Pointe-aux-Pins

Apart from the inferred topography of the glacial sediment surface, another important physiographic indicator in the evolution of the Pointe-aux-Pins foreland is the well-preserved series of relict beach ridges which occurs on the eastern limb of the foreland (Figs. 1, 2). Close inspection of the planform and orientation of these linear features suggest the following:

a) The eastern limb of the foreland is migrating eastward, while the southern limb is receding northward. This is inferred from the large number of these ridges preserved in the former, and in their absence in the latter. In addition, modern rates of change for the southern shoreline averaged around -1.5 and $+1.0$ m.y^{-1} for the eastern limb (Boulden, 1975).

b) Except for the most easterly (and presumably younger) ridges, all are truncated at high angles by the present south shore. This suggests strongly that they once extended much further southward.

c) The directional trend of the westernmost (oldest) ridges on the eastern limb is considerably more northeast-southwest than that of the present shoreline, which trends almost north-south. The angle between these ridges is now more than 30°.

d) The transition from the older western ridges to the younger ridges to the east follows three distinct stages, labelled, A, B, and C in Figure 1. Stage A, the oldest, is characterized by a linear to *concave-lakeward* trend. The point of rotation for the ridges in this stage is more or less fixed in location (point D), about 5 km south of its present position (point E). Stage C represents the present-day pattern, with beach ridge orientation at close to north-south. The ridges also show a definite *convex-lakeward* form in the more southerly areas, but change to *concave-lakeward* near their northern junction with the mainland. Stage B marks the transition between the two stages above, and is characterized by sharp increases in concavity (lakeward) of the ridges, and by their high-angle truncation by the younger stage C pattern.

e) The projection of the oldest identifiable ridge eastward passes to the south of borehole OGS-1, the southernmost point in which the peat layer was noted. Because the peat is probably of coastal marsh or lagoonal origin, it was likely deposited behind the earliest beach barriers to develop at the site of Pointe-aux-Pins. Thus, this projected beach ridge could correspond to the original shoreline of the foreland, and the radiocarbon age of the peat (averaging 5250 years old) could place the minimum date of this event. This initial assessment will be discussed further in the section on reconstruction of shoreline positions.

POSTGLACIAL STRATIGRAPHY

The change is sedimentation noted in vertical sediment sequences from the Pointe-aux-Pins area can provide useful information on postglacial evolution in the Lake Erie central basin. This information would be much enhanced if reliable time-stratigraphic references could be established in the sediments. The most useful and available markers are absolute radiocarbon dates on incorporated organic materials and relative dates from fossil pollen profiles.

Radiocarbon dates

Table I presents a compilation of radiocarbon dates available for the Pointe-aux-Pins area. The locations of the sites are shown (bracketed numbers) in Figure 4. The dates range from as old as 10,200 ± 180 years (GSC-330) on driftwood deposited in offshore muds (Lewis *et al.*, 1966), to 3140 ± 110 years BP (WAT-946) taken on wood in a clayey, pebbly matrix below the modern soft muds in LE81-19 about 15 km south of Erieau. The most important date was obtained from peat below the eastern limb of the Point (WAT-378, WAT-379) at OGS-1 (dates no. 2 and 3 in Table I). With the exception of the latter, all the dates were on material from fine-grained sediment, and thus were presumably related to organic material that moved down slope and was deposited in waters of some depth, rather than at the water-line. Samples from identical stratigraphic position in core LE81-19 showed a large discrepancy in radiocarbon ages. One (WAT-970, 7000 ± 370 years) was on shell material, while the other (WAT-946, 3140 ±

TABLE I

List of ^{14}C dates in the vicinity of Pointe-aux-Pins; the reference numbers are keyed to site numbers (bracketed) in Figure 4

Reference No.	Elevation (m b.d.)	^{14}C age (y BP)	Laboratory No.	Material and location
1	28.5	10,200 ± 180	GSC-330	Driftwood at base of offshore muds
2	6.3	5330 ± 250	WAT-378	Peat with shells and organic silt (OGS 1)
3	6.3	5180 ± 370	WAT-379	Peat with shells and organic silt (OGS 1)
4	23.5	3140 ± 110	WAT-946	Wood in shelly gravel below lake muds (LE81-19)
5	23.5	7000 ± 370	WAT-970	Shells from same layer as WAT-946
6	20.8	8250 ± 145	DIC-1329	Wood bits in muddy sand (Core 62, see Fig. 4)

110 years) was from a large wood fragment. The discrepancy might be explained by the presence of an inorganic carbonate silt matrix. This silt is difficult to remove completely from the shells, and could lead to contamination of the dated sample by "old", isotopically-depleted carbon. It is also possible that the two ages could also represent the time interval over which the lag deposit was developed, *i.e.*, during conditions when water depths were probably more than 10 m below present levels. Insofar as sedimentation history is concerned, however, the relative scarcity of dates near the Point limits the conclusions to be drawn to the following:

a) Sedimentation of fine-grained material in the central sub-basin at the site of date (1) was occurring more than 10,000 years ago.

b) The site of (2) was probably occupied by a coastal marsh (sheltered water) around 5200 years ago. Before that time, sedimentation at this site consisted of gray clayey silt with only minor organic matter.

Pollen stratigraphy

Pollen studies were carried out on cores taken from the central basin (Lewis *et al.*, 1966 (Core 2226; site no. 1 in Table I); Fritz *et al.*, 1975 and Creer *et al.*, 1976 (Core 13194)). The locations of these sites are shown in Figure 4. Interpretation of these authors regarding sedimentation trends in the area may be summarized as follows:

a) The site of core 2226 probably stood above water at the time of the low-water stage in the basin (Early Lake Erie, approximately 12,500 years BP), judging from the lack of the basal non-arboreal (grass, herbs) pollen zone noted in other pollen profiles from the western basin.

b) The pollen record at site 13194 revealed a more pronounced break in sedimentation lasting from around 12,500 to almost 8000 BP. This break suggests a rather prolonged period of subaerial exposure of the glacial surface, or at least a similar period of non-deposition in rather shallow water (probably less than 5 m deep).

c) In the soft postglacial muds making up the top portion of core 13194, a sharp rise in non-arboreal pollen was noted (T.W. Anderson, Geological Survey of Canada, personal communication, 1982). Anderson correlated this rise with the abrupt influx of marsh pollen into the central basin at the time of the Nipissing drainage resumption into Lake Erie, which was estimated to have occurred around 5000 BP (Coakley and Lewis, 1985).

RECONSTRUCTION OF THE POSTGLACIAL EVOLUTION OF THE POINTE-AUX-PINS AREA

The stratigraphic data presented above can be interpreted and used to reconstruct trends in lake levels with time. This interpretation can then be combined with the physiographic data to allow a reconstruction of the local shoreline evolution. Finally, by relating these shoreline patterns to the patterns of beach ridges on, and sediment profiles below, Pointe-aux-Pins, a model of the evolutionary sequence of this landform may be hypothesized.

LAKE ERIE WATER LEVEL HISTORY

The stratigraphical and physiographic data described in the previous section, in combination with data from other parts of Lake Erie, were used by Coakley and Lewis (1985) to deduce the postglacial history of water levels in the Erie basin (Fig. 6). The relevant parts of this history are summarized below.

Lake levels in the three major sub-basins of Lake Erie during the Early Lake Erie stage (12,000 to 10,000 BP) apparently behaved in a rather complex manner, with inter-basin sills initially operating to maintain different levels in each sub-basin. The lake level curve interpreted by Coakley and Lewis (1985), shown in Figure 6, was based primarily on radiocarbon dates from the western sub-basin. In central Lake Erie, no radiocarbon dates corresponding to this initial period are available, so the original lake level had to be inferred from physiographic evidence such as the lower limit of the wave-eroded glacial sediment surface and the depth of the buried channel through the Norfolk moraine to the east. These indicate an initial level of 30 m or more below present datum (Lewis, 1969).

From this elevation, lake levels rose relatively steeply in pace with isostatic rebound of the Niagara outlet, and the increasing inflows from glacial Lake Algonquin, then occupying the Upper Great Lakes. Levels in all sub-basins probably became confluent around 10,000 BP. This phase of rising levels ended when retreat of the glacial ice opened lower northern outlets for Lake Algonquin, thus cutting off inflows into the Erie basin from the upper lakes. When this effect is added to the drastically reduced rates of uplift at the outlet of the lake and climatic improvement throughout the region, it is conceivable that lake levels in the Erie basin might even

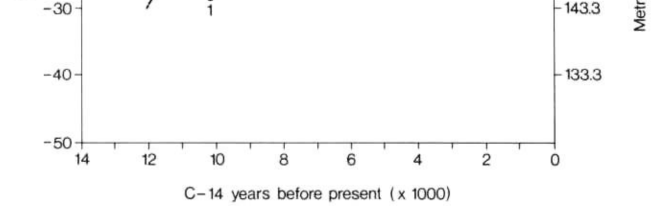


FIGURE 6. Postglacial lake levels in the Erie basin (from Coakley and Lewis, 1985). Only dates and elevations from near Pointe-aux-Pins are shown; these numerically keyed to Table I and Figure 4 (bracketed). Arrows indicate the inferred direction to water surface and estimated depth of water at the time.

Niveaux lacustres postglaciaires du lac Érié (selon Coakley et Lewis, 1985). Les niveaux et les dates ne sont donnés que pour les environs de la pointe aux Pins; les numéros correspondent à ceux du tableau I et de la figure 4 (entre parenthèses). Les flèches montrent la direction de la surface et donnent la profondeur estimée de l'eau à l'époque.

had declined somewhat between 8000 and 5000 BP. In fact, the scatter in the dated elevations suggests a relatively wide fluctuation in lake levels, possibly ranging from 5 to 15 m below datum (Coakley and Lewis, 1985). This overall reduced trend continued up until around 5000 BP by which time levels had reached approximately 5 m below present datum.

Between 5000 and 4000 BP, the curve shows an abrupt rise to levels as much as 5 m *above* present datum. This rise is postulated mainly on the basis of data from eastern Lake Erie (Barnett, 1985). The rise was apparenty short-lived, and by around 3500 BP, levels had fallen again to 3 to 5 m below datum. From this time, lake levels rose in a uniform fashion to their present position.

RECONSTRUCTION OF SHORELINE POSITIONS, CENTRAL SUB-BASIN, LAKE ERIE

In reconstructing initial shorelines, it must be kept in mind that of all the Lake Erie sub-basins, the central sub-basin has likely been the most altered by postglacial lacustrine processes. Unlike the other sub-basins, which are smaller and have bedrock close to the surface, this sub-basin was, from its inception around 12,500 years ago, a relatively large (approximately 7000 km^2) body of open water of less than 20 m depth. Thick glacial deposits also formed the shore. Intense postglacial erosion would account for the present low topographic expression of the cross-lake Erieau Moraine and the prominent wave-abraded platform below the modern sediments along the north perimeter of the sub-basin noted by Lewis (1966). The backflooding of the sub-basin resulting from the uplift of the Niagara outlet was accompanied by relatively intense erosion and possible occasional subaerial exposure of the nearshore platform (Davis, 1979; Lewis, 1966). These developments are likely reasons for the scarcity of identifiable relict shorelines below the present lake and along the north and south edges of this sub-basin.

For this reason, use had to be made of a combination of available stratigraphic data and inferences based on the intersection of the lake level plane with the original glacial sediment surface in the area in reconstructing the following shoreline positions. The reconstruction was made somewhat easier because it was not necessary to take differential isostatic uplift into account since the part of the sub-basin in question was located well to the west of the "hinge-line" for Early Lake Erie (Leverett and Taylor, 1915).

Reconstructed postglacial surface

Combining interpretations of the topography of the glacial sediment surface (Lewis, 1966, Early Lake Erie stage) with the borehole and core data described earlier, echograms from Rukavina (1983) and other sources, as well as seismic and vibracore data from Carter *et al.* (1982), an updated version of this original surface could be compiled for this area (Fig. 7).

An effort was made to allow for the undetermined, but significant, amount of erosion that the surface has undergone especially in those areas close to shore. Two cross-sections (D-D′, E-E′) were drawn across the lake immediately west and east, respectively, of Pointe-aux-Pins (Fig. 8). It was then assumed that the present hinterland surface had not changed significantly (in other words, ignoring surface modification processes such as solifluction and subaerial erosion, for example), and that the glacial surface in the deeper offshore areas of the profile had been preserved in its original position by the initial postglacial sedimentation. The original glacial sediment surface in the apparently eroded areas in between could then be interpolated by connecting these surfaces with a smooth line (Fig. 8). This technique allowed the preparation of a contour map of the reconstructed postglacial surface in the central sub-basin of Lake Erie. Because this approach takes bottom erosion into account, it provides a more realistic picture of the initial postglacial sediment surface than other attempts (Lewis, 1966) using the present glacial sediment exposure.

Evolution of Pointe-aux-Pins: 12,000 to present

Data from Figure 5 on lake level history, when combined with the reconstruction of the topography of the original surface onto which Early Lake Erie was imponded, allow us to locate the initial shoreline at the 30 m depth contour (Fig. 7). This provides the starting point in reconstructing the evolution of Pointe-aux-Pins. This exercise must rely greatly on inference and hypothesis, as there are few precise indicators preserved that may be used in the reconstruction. The indicators having the most weight are:

— The morphology and changing orientation of the relict beach ridges visible on the eastern limb of the Point (Figs. 1, 2);

— The nature of the sub-bottom till and glaciolacustrine sediment surface, including the till high (approx. 5 m b.d.) below Erieau and the very flat, almost-level, abraded glacial surface below the Point at approximately 10 m b.d. (Fig. 6);

— The subsurface peat deposit at 8-10 m b.d. at OGS-1, having a ^{14}C age of around 5350 BP;

— The interpreted "wave-cut notch" at approximately 15 m b.d. to the east and south of Pointe-aux-Pins (see section on postglacial surface topography).

a) *12,000 to 8000 BP*: The Erieau Moraine (Fig. 4) marks a stop made by the retreating Erie lobe of the Laurentide glacier, probably during the Port Bruce stadial (Dreimanis and Karrow, 1972). It is likely that, concurrently with the construction of the moraine, streams draining both the glacier and the hinterland to the north would flow along the ice-margin and would, over time, deposit large quantities of sand as deltas at the northern end of the moraine. Examples of these ice-margin deltas were interpreted in association with the Norfolk moraine to the east (Barnett, 1985), and eroded remnants of large sand deposits occur almost exclusively in shoreline sections immediately west of all three Lake Erie forelands: Point Pelee, Long Point, and Pointe-aux-Pins. The combination of cross-lake moraines and large sand deposits updrift (with reference to the prevailing wind and wave direction) was probably instrumental in the formation and evolution of all these forelands (Coakley, 1985).

After the inception of Early Lake Erie, the Pointe-aux-Pins area was probably occupied by a broad till-cored promontory, representing the surface expression of the Erieau Moraine. The tip of this foreland probably extended some 20 km further

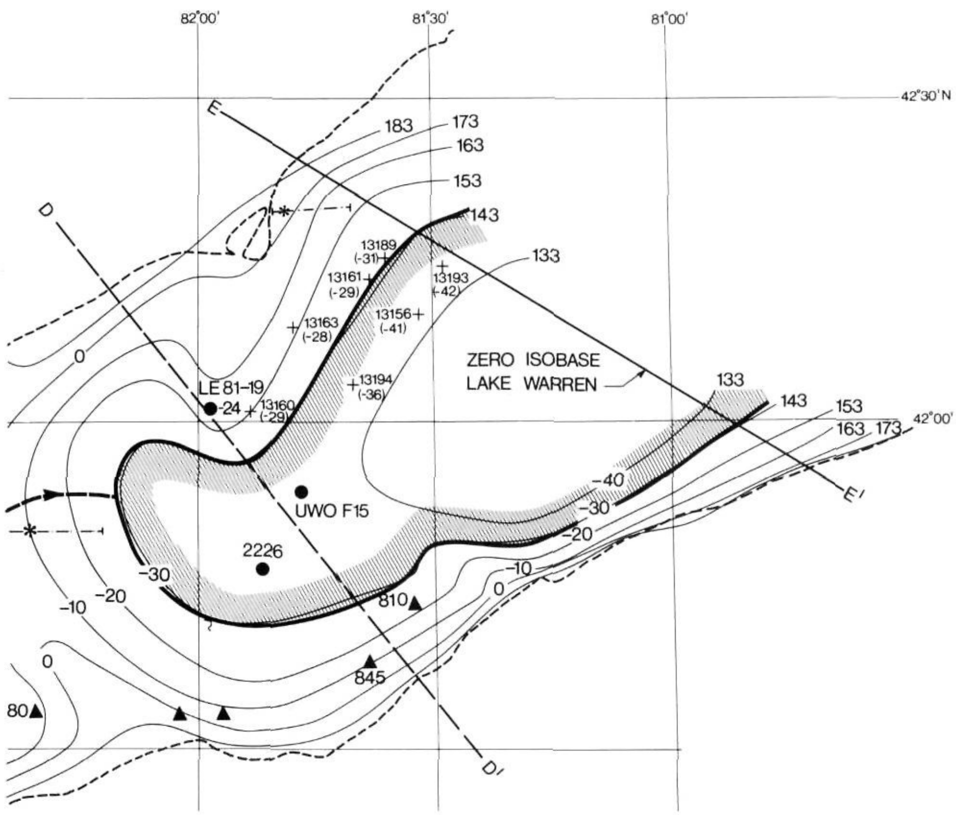


FIGURE 7. Reconstructed post-glacial surface topography in the central sub-basin of Lake Erie *ca.* 12,000 BP. Contours are referred to both elevation above sea-level and below datum. The reconstructed shoreline position is shown at an elevation of 143 m a.s.l. (*i.e.* at approximately 30 m b.d.) by the hatched pattern. Present shoreline is shown as a dashed line. DD' and EE' are locations of vertical sections shown in Figure 8.

Reconstitution de la topographie de surface postglaciaire dans le sous-bassin central du lac Érié vers 12 000 BP. Les courbes de niveau sont identifiées à la fois par leur altitude au-dessus du niveau de la mer et leur cote sous le niveau zéro. La ligne de rivage reconstituée (zone hachurée) apparaît à 143 m au-dessus du niveau de la mer (à peu près 30 m sous le niveau zéro). La ligne en tireté représente la ligne de rivage actuelle. DD' et EE' correspondent aux coupes verticales de la figure 8.

south than at present, and served as the focus for large-scale accumulation of sand derived from the deltaic deposits to the west and from local shoreline erosion in general.

During the period of rapid lake level rise (12,000 to 8000 BP), the dominant evolutionary trend is expected to have been the reduction in area of the subaerial portion of the foreland and a net shoreward retreat. As levels stabilized, erosional shoreline features such as the "erosion notch" at around 15 m b.d. mentioned above were probably cut. The more stable levels then prevailing would have allowed further accumulation of drifted sand along the sides of the foreland, leading to the development of beach ridges and dune fields above lake level. At this time, maximum wave fetches (and greatest wave energy), would probably have been from the east, so the dominant littoral drift was likely from the east, around the tip of the foreland, to the more sheltered southwest-facing side. The result would be the eventual transformation of the till-cored promontory into an asymmetrical cuspate foreland, probably with an elongated sand spit at the end as is the case at Point Pelee. Although no peat dating back to around 8000 BP was encountered in OGS-1, the elevation of the peat found (approx. 9 m b.d.) is close to the lake level at that time, prompting the speculation that a stream valley or lowland was located inland from the eastern side of the foreland (Fig. 9A).

b) *8000 to 4500 BP*: The slower rate of lake level rise allowed the quasi-level nearshore platform off the eastern limb of the foreland to be eroded as the shoreline retreated. In the meantime, increasing wave fetch distances to the southwest (due partly to the development of Sandusky Bay) resulted in a shift in the predominant littoral drift direction from westward to eastward. The postulated large sand deposit west of Pointe-aux-Pins then probably served as a major supply for sand transported around the Point to the east-facing side. The orientation of the earliest beach ridges (Figs. 1,2) supports this hypothesis. Furthermore, by 5000 BP, marsh vegetation (destined to become the peat sampled in OGS-1) was established in the low-lying ponds or drowned stream valley located behind the beach ridge at the OGS-1 site. By around 5000 BP, Pointe-aux-Pins probably appeared as sketched in Figure 9B.

c) *The Nipissing "flood"*, ca. *4500 BP*: Evidence from ^{14}C dated samples in the Erie basin suggest strongly that at around 4000 BP, lake levels rose to about 5 m above datum (Fig. 6). The result of such an event would be the whole-scale drowning of much of the low-lying dunes and beach ridges then making up the Pointe-aux-Pins foreland. Depending on the elevation of the foreland, the site would then have been occupied by either a shoal or a low island (Fig. 9C). The more open-water conditions might have contributed to the development of the gently-sloping platform in the glaciolacustrine sediment surface below Erieau (Fig. 5). Most of the sand submerged by the rise would be dispersed in the area in the form of a sand-covered shelf, or spit platform (Meistrell, 1966).

One question that might be asked concerns the lack of any clear erosional or shore-related feature on topographic maps at around the 178 m (a.s.l.) contour, *i.e.*, about 5 m above present datum. Perhaps the period involved was too short to leave a permanent record, or the offshore island/shoal provided sufficient protection from wave erosion.

d) *Modern Pointe-aux-Pins, 3500 BP to present*: By 3500 BP, however, lake levels had returned to close to their pre-

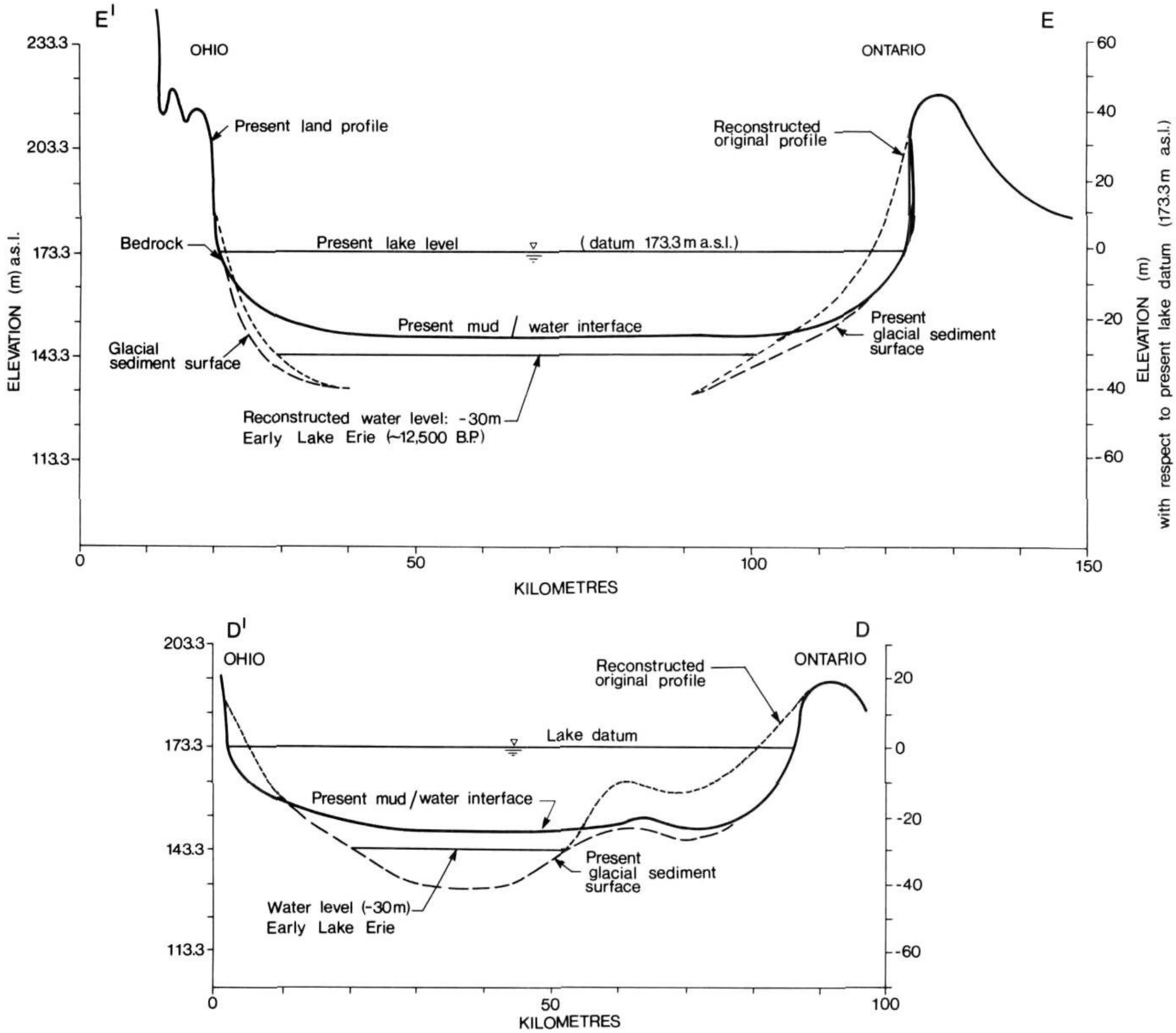


FIGURE 8. Vertical sections through the central sub-basin of Lake Erie (see Fig. 7 for locations) showing sub-bottom glacial sediment surface and reconstruction of original sub-basin profile at time of Early Lake Erie.

Coupes menées à travers le sous-bassin central du lac Érié (voir la localisation sur la fig. 7) montrant la surface des sédiments glaciaires de fond et la reconstitution du profil du bassin du paléo-lac Érié.

"flood" positions. Parts of the spit platform were again exposed to shallow-water wave action, and storm-beach barriers gradually developed at the site. This marked the beginning of the modern Pointe-aux-Pins foreland (Fig. 9D), originally consisting of a straight-to-convex-lakeward beach barrier, facing southeast, and, facing the shorter fetch to the southwest, a lower, concave-lakeward barrier through which an inlet into the marsh was probably located. A possible contributory factor to the barrier development was the concurrent flooding and change in orientation of the ancestral Long Point foreland to the east (Coakley, 1985), which would increase the wave energy from that direction and accelerate erosion of bluff shorelines to the east of Pointe-aux-Pins.

As lake levels rose again from their post-Nipissing lows in response to uplift of the lake outlet, waves from the east and southeast were still dominant, and with the abundant littoral drift supplied by the eroding bluffs to the east, the east side of Pointe-aux-Pins was able to maintain its position, and apparently, to prograde slowly lakeward. Subsequent barriers became more concave lakeward, indicating the inputs of sediments derived from the west as well, in other words, building out the eastern barrier at its southern extremity as well as at the base (Fig. 1, stage B). The south-facing barrier, however, being located at the updrift end of the next (west) shore reach, has apparently always received insufficient sediment supplies from either side to maintain its position, and thus has continued to transgress shoreward. The sheltered lagoonal area between the barriers expanded as levels rose, and marshes began to grow along the lee side of the south-facing barrier (now found as peat at elevations of around 3 m b.d. in the cores near Erieau, Fig. 5).

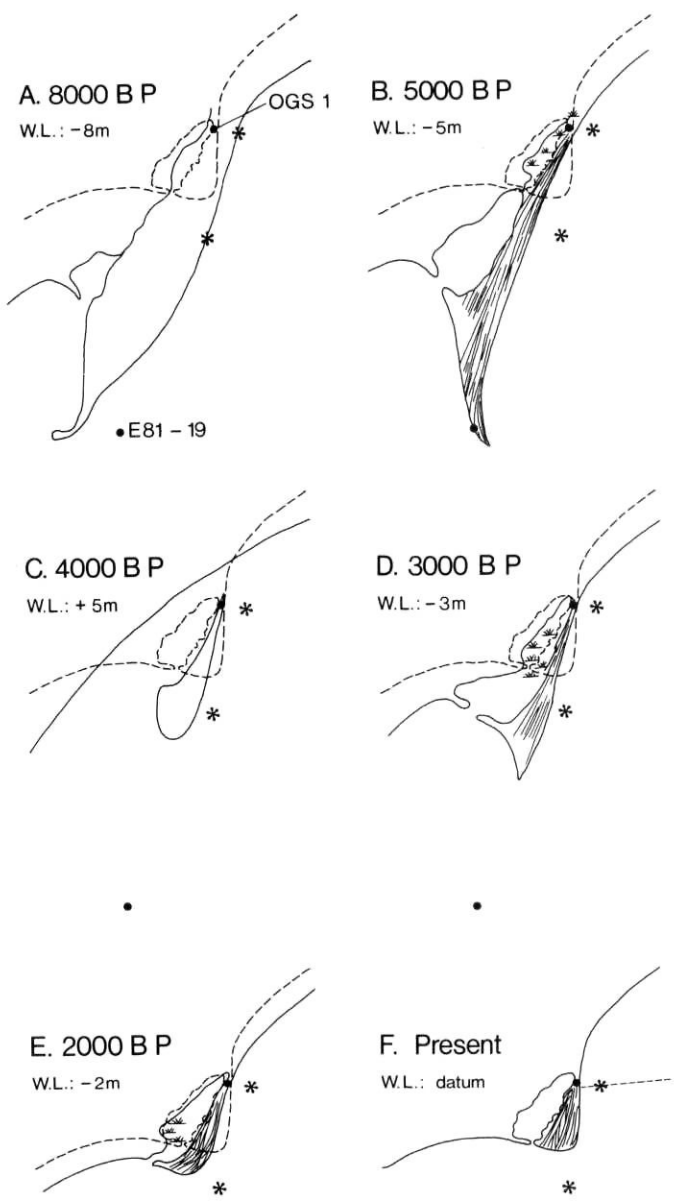


FIGURE 9. Schematic reconstruction of stages in the evolution of the Pointe-aux-Pins foreland. Dots mark the location of borehole OGS-1 and offshore core LE81-19; asteriks indicate sharp breaks in slope in glacial sediment surface. The present shoreline is shown dashed.

Reconstitution schématique des différents stades d'évolution de la pointe aux Pins. Les points marquent l'emplacement du forage OGS-1 et du carottage E81-19; les astérisques montrent les cassures dans la pente à la surface de sédiments glaciaires. Les tirets représentent le rivage actuel.

From around 2000 BP to present (Fig. 9E, F), the principal morphological developments at Pointe-aux-Pins were the gradual shift in the orientation of both sides with changes in the direction of maximum fetch distances and wave energy from the east and west. The east-facing barrier grew, by accreting beach ridges, to become aligned more north-south as developments at Long Point and embayment by erosion of bluff shorelines to the east increased the fetch of east, rather than southeast, waves. Similarly, the expanding area of the Sandusky Bay area (on the Ohio shoreline directly south of Point Pelee) served to increase wave fetches from the south — southwest, resulting in a more east-west orientation of the south-facing barrier of Pointe-aux-Pins.

Littoral supplies of sand had by now apparently declined considerably, and although the eastern barrier was still accreting lakeward, it appeared to be doing so more at the expense of the low, rapidly retreating southern barrier, than as a result of inputs from the adjacent bluff shoreline. The ongoing modern recession of the south-facing limb of the Point (Boulden, 1975) and the lack of preserved beach ridges there indicate that this limb sometimes acts as a source for littoral sediment, while the prograding eastern limb is clearly a sink, *i.e.*, a site of sediment accumulation. This is illustrated in the sharply defined truncation of the beach ridge system at its southern end, and in the more convex-lakeward form of the newer beach ridges of the eastern limb (Fig. 1, stage C).

DISCUSSION AND SUMMARY

The above reconstruction of the evolution of the Pointe-aux-Pins foreland is in close agreement with what is known about the lake-level history, stratigraphy, and glacial geomorphology of the Lake Erie basin. Further investigation, especially in the form of sub-bottom profiles in Rondeau Bay, and more boreholes and ^{14}C dates, would be useful in improving the reliability of the reconstructed sequences and their placement in time.

An independent way of assessing the approximate age of the foreland is to examine the present net annual sediment inputs to the Point, and compare this figure with the calculated sediment volume contained in the foreland. The only sediment now being added to Pointe-aux-Pins is littoral drift derived from the erosion of bluff shorelines and nearshore glacial deposits to the west and east. The section of shoreline serving as the sediment source extends from Port Alma in the west to Port Glasgow in the east (Fig. 3) (Rukavina and St. Jacques, 1978). Littoral sediments outside this reach move away from the Point. Rukavina and St. Jacques estimated the total annual sediment supply to Pointe-aux-Pins to be 38,000 $m^3.y^{-1}$ (17,000 $m^3.y^{-1}$ to the south limb and 21,000 to the east-facing limb). Because this figure is based on the total sand fraction in the source bluff material, including the fine 3 to 4 phi (0.125 to 0.062 mm) fraction that is rare in the present beach sediments, it is probably an overestimation of the actual supply of spit-building materials. Also, a certain quantity of the littoral drift is continually being lost from the Pointe-aux-Pins littoral system by comminution or by one-way transfer to offshore deposits. Although these amounts cannot be estimated with any precision, they could result in the actual net littoral drift inputs being considerably lower than the above figures.

A good estimate of the total volume of sand-sized materials contained in Pointe-aux-Pins can be obtained using the cross-sections shown in Figure 5. Because no tranverse sections were possible, the accuracy of the estimate depends greatly on the width assigned to the sand deposit. If an average width of 2 km is assigned to the east limb, 0.5 km to the south limb up to the harbour entrance, and 0.1 km for the remainder, then a figure of 195 x 10^6 m^3 is obtained. A reasonable error estimate for this figure would be around 10 %.

At a sand input rate of 38,000 $m^3.y^{-1}$ (Rukavina and St. Jacques, 1978), such a volume corresponds to an accumulation time of approximately 5100 years, assuming littoral drift as the sole source of the sand making up the point, and also that conditions and processes have remained constant. If pre-existing sand supplies from the original glacial deposits and the split platform are included, then the 3500 to 4000 year age proposed in the earlier reconstruction is well within reason.

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