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Impact of the Holocene Transgression on the Atlantic Coastline of Nova Scotia
Conséquences de la transgression marine holocène sur la côte atlantique de la Nouvelle-Écosse

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Résumé de l'article

Les données géologiques et les connaissances sur les changements du niveau marin relatif sont étudiées à trois échelles temporelles en tant qu'analogues des conséquences d'une future hausse du niveau marin sur la côte de la Nouvelle-Écosse. Le niveau marin relatif s'est rapidement élevé au cours de l'Holocène inférieur, jusqu'au taux maximal de 11 m/ka à 7500 BP. Des sédiments estuariens ou issus de marais salants et d'eau douce datant de cette période ont été localisés sur le plateau continental intérieur. Après 5000 BP le taux a diminué jusqu'à 2 m/ka. En dépit de la submersion de la région côtière et de son dégagement subséquent, les cordons littoraux de gravier ont persisté là où de grandes quantités de sédiments ont été mis en place sur le littoral par érosion des dépôts glaciaires. Les cordons montrent souvent des indices de phases de progression sous la forme de crêtes de graviers, partiellement ou entièrement submergés dans les lagunes situées derrière les plages de tempêtes contemporaines. Les données marégraphiques du siècle dernier font ressortir un taux de submersion d'environ 3,5 mm/a, taux nettement plus élevé que celui de la tendance à long terme. La réponse du littoral à cette hausse rapide est complexe. Les falaises non consolidées peuvent reculer jusqu'à 5 m/a au début de leur exposition aux fortes vagues et pendant les plus fortes tempêtes et à un rythme beaucoup plus lent (<0,5 m/a) après la formation de plages de protection, de hauts-fonds ou de structures de blocs. Le recul des plages est rapide (>8 m/a) par endroits, lent ailleurs; certaines plages sont presque immobiles depuis 10 ans, alors que les plages voisines se comportent de façon tout à fait différente. Les sédiments libérés par l'érosion littorale se retrouvent dans les estuaires les plus proches, provoquant l'expansion des deltas d'inondation et l'extension des marais. Si une hausse globale du niveau marin survenait, les processus d'érosion et de sédimentation qui se sont manifestés le long de la côte de la Nouvelle-Écosse pendant l'Holocène agiront de façon semblable, mais le rythme des changements augmentera dans plusieurs sites.

Géographie physique et Quaternaire, 1993, vol. 47, n° 2, p. 221-238, 17 fig., 1 app.

Essai

IMPACT OF THE HOLOCENE TRANSGRESSION ON THE ATLANTIC COASTLINE OF NOVA SCOTIA*

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ABSTRACT As analogs for impact of a future sea-level rise on the coast of Nova Scotia (eastern Canada), geological data and information on relative sea-level changes are examined at three different time scales. Relative sea level rose swiftly during the early Holocene, at a maximum rate of 11 m/ka at 7500 radiocarbon years BP. Freshwater, salt-marsh, and estuarine sediments that formed during this period have been located on the inner shelf. After 5000 BP the rate slackened to about 2 m/ka. Despite overall submergence and coastal retreat since that time, gravel barriers have persisted where large amounts of sediment have been added to the littoral system by erosion of glacial deposits. The barriers often display evidence of early progradational phases in the form of gravel beach ridges, partly or wholly submerged in lagoons behind contemporary storm beaches. Tide-gauge data from the past century show submergence rates averaging 3.5 mm/a, well in excess of the longterm trend. The response of the coastline to this rapid rise is complex. Unconsolidated cliffs (bluffs) retreat at up to 5 m/a during initial exposure to wave attack and during extreme storm events, but at lesser rates (<0.5 m/a) as protective beaches, lag shoals or boulder frames accumulate at the base of the cliffs. Beach retreat rates are sometimes very high (>8 m/a) in some locations, but low elsewhere, in some cases showing almost no movement over the past 10 years, and neighbouring beaches are sometimes observed to behave in completely different ways. Sediment released by coastal erosion finds its way into nearby estuaries, causing growth of flood-tidal deltas and marsh aggradation. If a global rise in sea level occurs, the processes of erosion and sedimentation operating along the coast of Nova Scotia during the Holocene are expected to continue in a similar fashion, but rates of change will increase at many locations.

RÉSUMÉ *Conséquences de la transgression marine holocène sur la côte atlantique de la Nouvelle-Écosse.* Les données géologiques et les connaissances sur les changements du niveau marin relatif sont étudiées à trois échelles temporelles en tant qu'analogues des conséquences d'une future hausse du niveau marin sur la côte de la Nouvelle-Écosse. Le niveau marin relatif s'est rapidement élevé au cours de l'Holocène inférieur, jusqu'au taux maximal de 11 m/ka à 7500 BP. Des sédiments estuariens ou issus de marais salants et d'eau douce datant de cette période ont été localisés sur le plateau continental intérieur. Après 5000 BP le taux a diminué jusqu'à 2 m/ka. En dépit de la submersion de la région côtière et de son dégagement subséquent, les cordons littoraux de gravier ont persisté là où de grandes quantités de sédiments ont été mis en place sur le littoral par érosion des dépôts glaciaires. Les cordons montrent souvent des indices de phases de progression sous la forme de crêtes de graviers, partiellement ou entièrement submergés dans les lagunes situées derrière les plages de tempêtes contemporaines. Les données marégraphiques du siècle dernier font ressortir un taux de submersion d'environ 3,5 mm/a, taux nettement plus élevé que celui de la tendance à long terme. La réponse du littoral à cette hausse rapide est complexe. Les falaises non consolidées peuvent reculer jusqu'à 5 m/a au début de leur exposition aux fortes vagues et pendant les plus fortes tempêtes et à un rythme beaucoup plus lent (<0,5 m/a) après la formation de plages de protection, de hauts-fonds ou de structures de blocs. Le recul des plages est rapide (>8 m/a) par endroits, lent ailleurs; certaines plages sont presque immobiles depuis 10 ans, alors que les plages voisines se comportent de façon tout à fait différente. Les sédiments libérés par l'érosion littorale se retrouvent dans les estuaires les plus proches, provoquant l'expansion des deltas d'inondation et l'extension des marais. Si une hausse globale du niveau marin survenait, les processus d'érosion et de sédimentation qui se sont manifestés le long de la côte de la Nouvelle-Écosse pendant l'Holocène agiront de façon semblable, mais le rythme des changements augmentera dans plusieurs sites.

* Geological Survey of Canada Contribution no. 52891

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INTRODUCTION

Numerous predictions of rapid sea-level rise due to global warming have been made during the past decade (National Research Council, 1979, 1985, 1987; Bindschadler, 1985; Hoffman *et al.*, 1983, 1986; Revelle, 1983; Meier, 1984). The Intergovernmental Panel on Climate Change (IPCC) working group (World Meteorological Organisation, 1990) predicted that mean sea level would increase by 16-32 cm by 2030, with a mean increase of 20 cm, and would increase by 33-75 cm, with a mean of 45 cm, by 2070. There are doubts that these predictions would apply across the globe. In this respect, the work of Mikolajewicz *et al.* (1990) is important: it shows that the increase in ocean depth due to thermal expansion would vary geographically.

Forecasts of higher sea levels have inspired a flurry of papers concerned with prediction of coastal impacts in various areas of the world, including Canada (Forbes *et al.*, 1989), the USA (Titus *et al.*, 1985; Gornitz, 1990), Ireland (Carter, 1990),the UK(Boorman et *al.*, 1989), and elsewhere (Wind, 1987). The approach taken in this paper is to examine how the Atlantic coast of Nova Scotia (Fig. 1) has responded to varying rates of sea-level rise during the Holocene, with the underlying assumption that past changes may be useful analogs for responses to future accelerated sea-level rise of the magnitude predicted by IPCC.

THE STUDY AREA

Mainland Nova Scotia (Fig. 1) forms a prominent peninsula on the eastern seaboard of Canada. Cape Breton Island continues the general line of the mainland to the northeast. The coastline of Nova Scotia can be subdivided into three regions (Owens, 1977) comprising (1) the Gulf of St. Lawrence and Northumberland Strait shores, which are microtidal, exposed to locally generated wind waves for 7 to 8 months of each year, and ice-covered during the winter; (2) the Bay of Fundy shores, which are tide-dominated, with large tidal ranges of 13 to 16 m at the head of the bay; and (3) the more exposed open Atlantic coast, which is low, mesotidal, and dominated by storm wave processes. This paper focuses mainly on the Atlantic coast of Nova Scotia.

Annual deep-water significant wave heights are in the 7-8 m range and 10-year significant wave heights are 10-13 m (Neu, 1982). Surges are generated by cyclonic depressions passing northeastward across the region and also by occasional tropical storms moving north along the U.S. eastern seaboard. Positive surges of 0.6 to 1.5 m can occur during persistent northeast winds (Galbraith, 1979) which are most common between October and March each year. Mean tidal range decreases from 3.7 m in southwestern Nova Scotia to less than 1 m in northern Cape Breton Island (Canadian Hydrographic Service, 1991). The coastal waters are largely ice-free, excepting estuaries and lagoons which may wholly or partly freeze during winter. Pack ice drifting south out of the Gulf of St. Lawrence via Cabot Strait can influence the outer coast in late winter.

The Atlantic coast of Nova Scotia is highly indented, with long narrow embayments, intervening headlands, and numerous rocky offshore islands. Many of the embayments originated as preglacial consequent streams which were overdeepened by glacial erosion and which have subsequently been drowned by the Holocene transgression. The

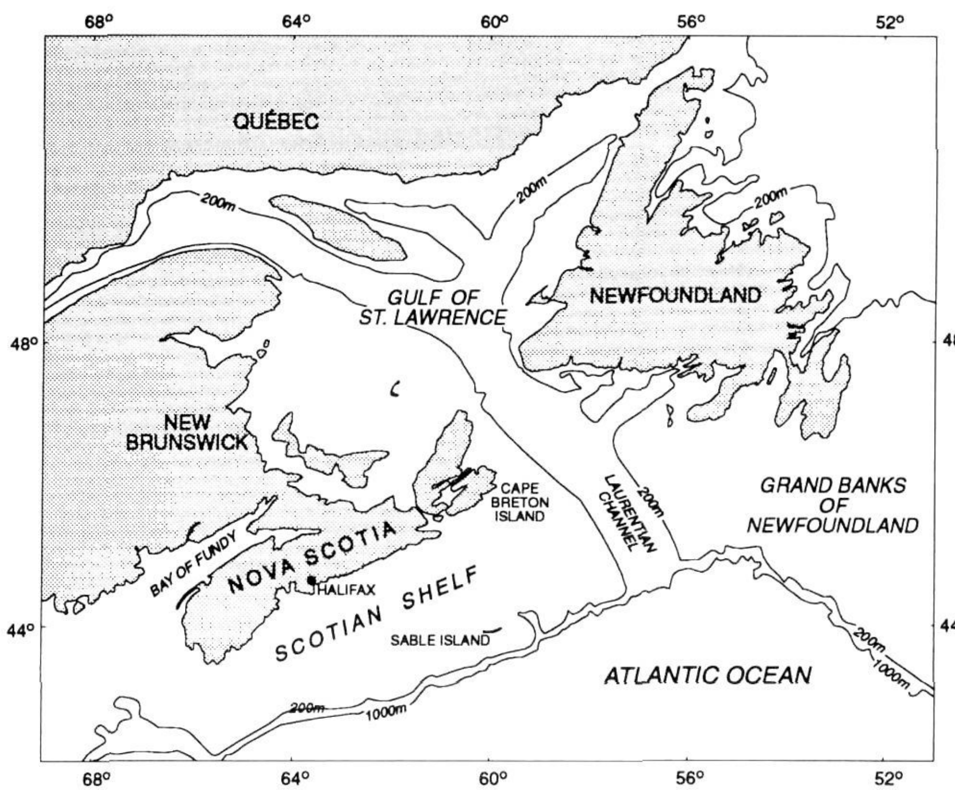

FIGURE 1. Location of Nova Scotia in eastern Canada and generalised bathymetry of the adjacent continental shelf.

Localisation de la Nouvelle-Écosse et bathymétrie générale du plateau continental.

resulting estuaries and their analogs in relict estuarine basins on the inner shelf are the principal sinks for sands and finer sediments in the coastal zone (Piper, 1980; Carter *et al.*, 1989, 1990b; Forbes *et al.*, 1991a). Close to the steep upland shores of Cape Breton Island, elevations reach almost 300 m, but relief is much more subdued elsewhere along the outer Atlantic coast, where low-lying coastal embayments and marshes are common. Glacial erosion and deposition have provided the main source of sediment for beach development. Glacial deposits are found as a thin mantle over bedrock and as thick deposits organised into fields of drumlins (Piper *et al.*, 1986; Forbes and Taylor, 1987). Multiple tills at some localities show a range of grain-size distributions and other geotechnical properties (Stea and Fowler, 1979; Sonnichsen, 1984).

THE HOLOCENE TRANSGRESSION

LONG-TERM RELATIVE SEA-LEVEL TRENDS

Changes of relative sea level in Nova Scotia have resulted from the interplay between discharge of glacial meltwater from late Quaternary ice sheets and isostatic adjustments of the crust (*cf.* Tushingham and Peltier, 1991; Quinlan and Beaumont, 1981, 1982). The sea-level curve for the inner Scotian Shelf (Fig. 2) is based on core data obtained from just offshore in the Halifax region (Forbes *et al.*, 1988, 1991a), together with data from other sources (Scott, 1977; Hall, 1985; Honig, 1987). Information on the index points is contained in Appendix I. The curve is constrained by the ages of salt-marsh materials at index points 5 and 13. Arguably, it could be steeper than indicated, with relative sea level as high as −10 m at 6000 BP, constrained by index point 19. However, the material dated for index point 19 is wood, which may be allochthonous. Index point 11 indicates that the (−20 m) sill of Bedford Basin, Halifax, was overtopped by 5830 BP. We have indicated an envelope containing possible sea-level curves, and have suggested a likely curve.

Relative sea level was below −40 m at 10,000 radiocarbon years BP, and rose rapidly from 8000 BP to 6000 BP. Thereafter, relative sea level increased less rapidly, and *ca.* 2000 BP the average submergence rate dropped below 2 m/ka. The highest rate of increase during the Holocene was approximately 11 m/ka at about 7500 BP. The peak acceleration of sea-level rise was 8 m/ka^2 at 8000 BP, and the peak deceleration was 4 m/ka^2 at 6500 BP. However, these calculations should be viewed with some caution — as we have suggested, the curve could be steep until 6000 BP, and it is possible that submergence during the past few thousand years (at least) was stepped, as van de Plassche (1991) has found in New England, and Tanner (1992) elsewhere.

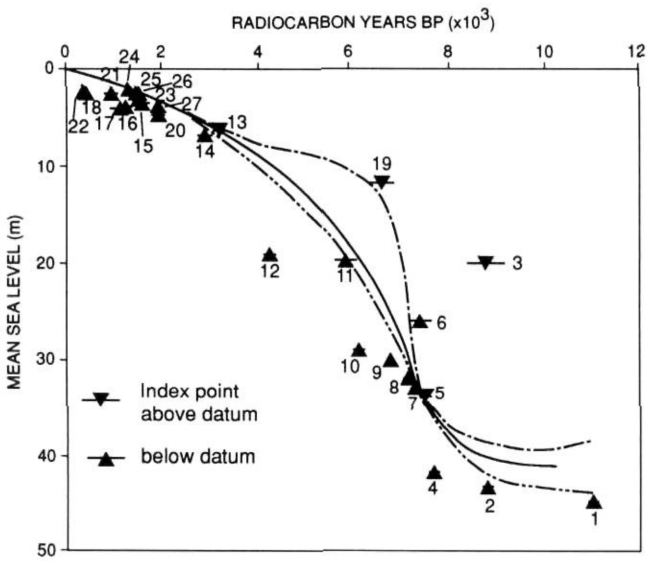

FIGURE 2. Relative sea-level changes on the inner Scotian Shelf during the past 10 ka, based on new and published radiocarbon dates (Forbes *et al.*, 1988, 1991a; Scott, 1977a; Hall, 1985; Honig, 1987). Information on the index points is contained in Appendix I, and the error bars are equivalent to two standard deviations. The solid line represents the most likely sea-level curve and the dashed lines define an envelope of possible sea-level curves.

Fluctuations du niveau marin relatif à l'intérieur du plateau Scotian depuis 10 ka fondées sur des datations au radiocarbone publiées ou nouvelles (Forbes et al., *1988, 1991a; Scott, 1977a; Hall, 1985; Honig, 1987). L'appendice donne les renseignements sur les points de repère. Les marges d'erreurs sont équivalentes à deux écarts types. La courbe pleine représente la courbe du niveau marin la plus plausible, tandis que les lignes brisées représentent des possibilités.*

RECENT RELATIVE SEA-LEVEL TRENDS

Relative sea level has been rising during the past century in Nova Scotia. Tide records were kept by the British Admiralty at Halifax in 1851-52 and 1861-62 (Shaw and Forbes, 1990a) but the earliest data presently available to researchers date from the 1890s, when a network of tidal stations was established in eastern Canada by Dawson (1918). Unfortunately, monitoring ceased at most stations just after the turn of the century. The Halifax record begins in 1896, ends in 1905, and recommences in 1920 (Canadian Hydrographic Service, 1951). Marine Environmental Data Services (MEDS) archives in Ottawa contain the main body of tidal data from Halifax and other tidal stations. Based on the continuous record since 1920, mean sea level has risen at 3.63 mm/a (Fig. 3); based on the complete data set, the rate of rise in mean sea level since 1896 is 3.18 mm/a. These are comparable to other published rates: Middleton and Thompson (1986) found a trend of 3.75 mm/a in data for the period 1920-82; Carrera and Vaníček (1988) had similar findings. Figure 3b shows that the rate of sea level rise has fluctuated somewhat and has slackened during the past decade.

Comparable rates of sea-level rise have been recorded at other locations in eastern Canada where long tidal records exist (Shaw and Forbes, 1990a). Apart from Halifax, most tidal records from Nova Scotia are relatively short. The Yarmouth data set includes isolated values from 1900 and 1956, but the continuous data set does not begin until 1967. At Pictou, the records are continuous back to 1965; there are also records from 1957-58 and about 20 years of data from the turn of the century. Additional tidal records beginning in the late 1960s or early 1970s are available from several other locations. Carrera *et al.* (1990) tackled the problem of how to extract trends of sea-level change from these relatively short records. Their results for sea-level trends in southeastern Canada are shown in Figure 4.

The rate of change registered by the Halifax tide gauge clearly exceeds the rates observed over the most recent few millennia. In fact, to find a comparable rate, we have to look as far back as 4500 BP. If the IPCC forecasts are used, then, by simply adding the projected increase to the rise now occurring, the rate of sea-level rise by 2070 would be 10 m/ka. This rate almost equals the maximum rate of sea-level rise during the Holocene transgression.

IMPACTS OF RELATIVE SEA-LEVEL RISE ON THE COASTLINE

EARLY TO MIDDLE HOLOCENE IMPACTS

It is almost impossible to determine in detail how the coast of Nova Scotia responded to the high rates of sea-level rise which pertained during the early to middle Holocene, because most of the evidence was destroyed during the transgression. The overall result was, of course, submergence of coastal areas. Former lakes occupying silled basins

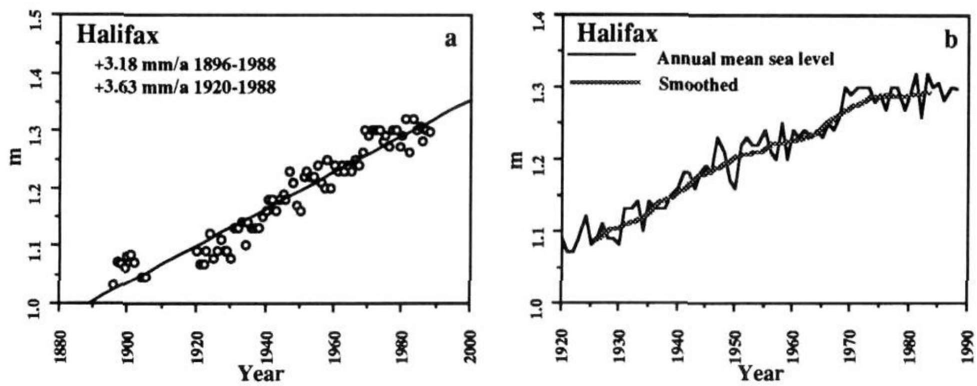

FIGURE 3. Tidal data collected during the past century at Halifax, Nova Scotia: a) with the linear trend superimposed, and b) data from 1920 with a simple 11-year moving average filter.

Données marégraphiques du dernier siècle recueillies à Halifax (Nouvelle-Écosse): a) avec superposition de la tendance linéaire; b) données à partir de 1920 avec lissage par moyenne glissante de périodes de 11 ans.

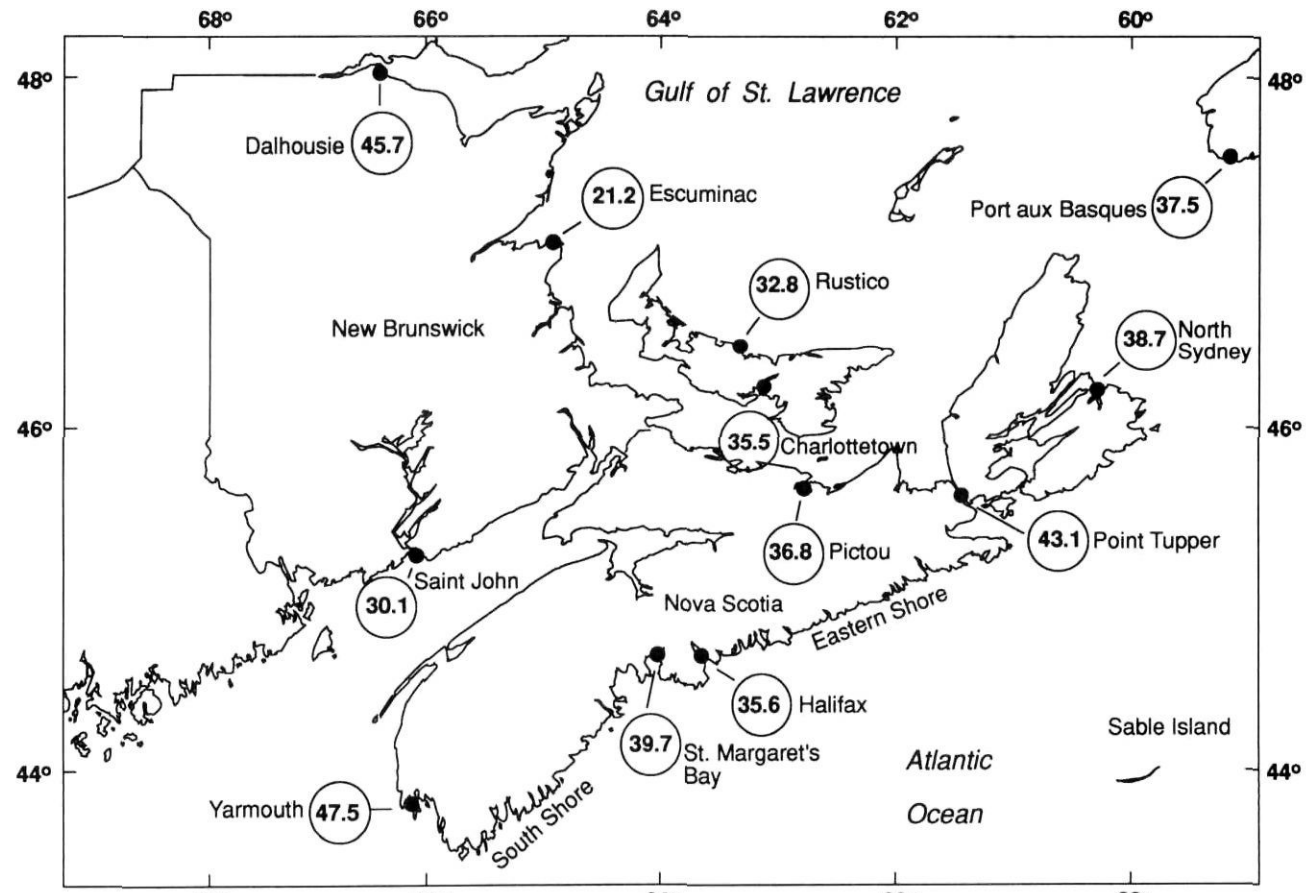

FIGURE 4. Rates of relative sea-level rise (cm/century) derived from tidal records at selected locations in Atlantic Canada (after Carrera *et al.*, 1990).

Taux de la hausse du niveau marin (cm/siècle) déterminés à partir des données marégraphiques de certains sites des régions atlantiques (d'après Carrera et al., *1990).*

in St. Margarets Bay and Mahone Bay on the South Shore (Fig. 1) were invaded by the sea at about 11,500 and 4500 radiocarbon years BP, respectively (Piper and Keen, 1976; Barnes and Piper, 1978). Where drumlin fields were flooded, a stepped progression of wave-cut cobble-boulder shoals marks the distribution of former drumlins (Wang and Piper, 1982; Piper, 1980). Along the Cape Breton shore (Fig. 1), the maximum early Holocene lowering of sea level was about 50 m below present; below this level the undulating till surfaces are preserved (Wang and Piper, 1982).

On the inner Scotian Shelf, off the Eastern Shore just east of Halifax (Fig. 5), fragmentary evidence of former coastal environments has been obtained. Using high-resolution shallow seismic reflection techniques it has been possible to locate remnant deposits of estuarine, freshwater and salt-marsh sediments down to present depths of at least 45 m (Forbes *et al.*, 1988; 1991a; see also Appendix I). Sedimentary sequences observed from coring these deposits closely resemble those observed from cores within existing estuaries (Honig, 1987; Carter *et al.*, 1989, 1990b). From the radiocarbon dating of shell and peat material found in the cores (Table 10 of Forbes *et al.*, 1988), it is clear that estuaries were present in the region in the early and middle Holocene. Salt marshes were also present, even during the peak of the transgression at about 7500 BP (Forbes *et al.*, 1988; Fig. 6 of Shaw and Forbes, 1990a). These estuarine and salt-marsh environments must have developed behind protective barriers, of which little evidence remains. Much of the sediment in the barriers moved shoreward, keeping pace with the transgression (Boyd *et al.*, 1987), although some gravel was abandoned on the inner shelf, forming an extensive thin veneer (Forbes and Boyd, 1989). Only in special settings have recognisable barrier deposits remained trapped on the inner shelf of eastern Canada (*cf.* Forbes *et al.*, 1991 b, 1993; Shaw and Forbes, 1992).

Using the sea-level curve (Fig. 2) and bathymetric charts, mean rates of coastal retreat have been calculated for the coastal segment between Chezzetcook Inlet and Ship Harbour (Fig. 5). At about 10,000 radiocarbon years BP, the average position of the coast was 10.0 km seaward of its present location; at 7000 and 5000 BP, the positions were 4.1 km and 1.5 km, respectively. These changes in shoreline position indicate mean retreat rates of about 2.0 m/a (10,000 to 7000 BP), 1.3 m/a (7000 to 5000 BP), and 0.3 m/a (5000 BP to the present).

LATE HOLOCENE IMPACTS

Compared with the early Holocene, much more is known about how the coast responded to sea-level changes during the past several millennia, primarily because beach deposits formed during the latter period still exist. Among the factors that control coastal evolution, sediment supply is of great importance (Forbes *et al.*, 1989; Shaw *et al.*, 1990). While coastal retreat may be pervasive, it is often counterbalanced

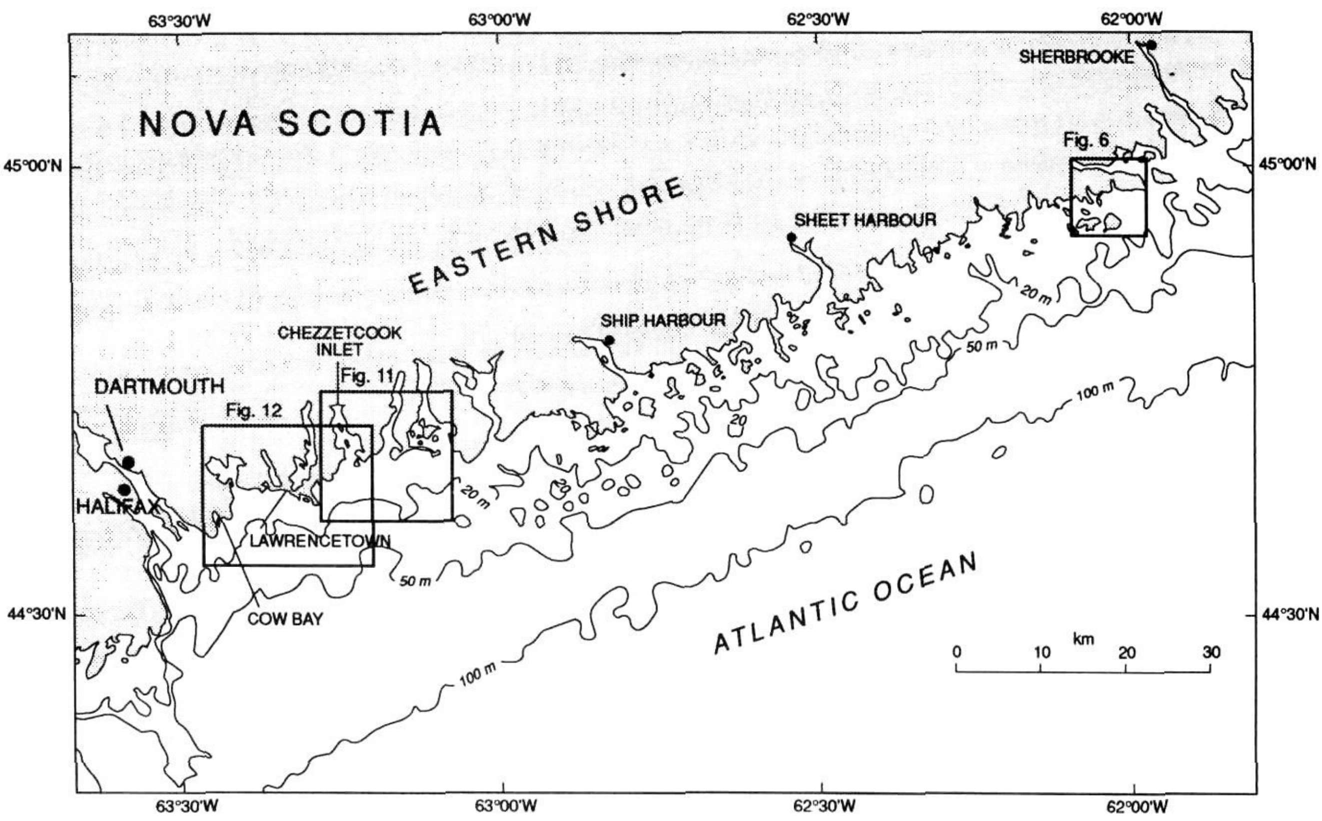

FIGURE 5. Eastern Shore of Nova Scotia showing long, narrow, shore-normal estuaries, complex bathymetry of the inner shelf, and place names referred to in text. The boxes show the locations of Figures 6,11 and 12.

Eastern Shore de la Nouvelle-Écosse montrant d'étroits et longs estuaires, la bathymétrie complexe du plateau continental intérieur et la toponymie employée dans le texte. Les carrés donnent la localisation des figures 6,11 et 12.

by local stability or even progradation where relatively large volumes of sediment are supplied to the littoral zone (Forbes *et al.*, 1990; Shaw and Forbes, 1992), either by erosion of glacial deposits (Boyd *et al.*, 1987) or from the disintegration of older beach systems (Sonnichsen, 1984).

The results of the interplay between rising sea level and sediment supply are observed at several sites along the Eastern Shore of Nova Scotia, where beach and barrier systems include prograded beach and dune-ridge complexes. At these sites, sufficient sediment must have been supplied to the coast to enable progradation to occur, despite rising sea level. These are not anomalous occurrences — similar prograded beach-ridge systems, partly or wholly submerged, occur in many places along the coastline of Nova Scotia (Goldthwait, 1924; Grant, 1975) and Newfoundland (Shaw and Forbes, 1987, 1990b, 1992; Forbes *et al.*, 1989).

The prograded, gravel barrier complex at Fancys Point, about 100 km east of Halifax (Fig. 6), is a representative example. The barrier encloses a tidal lagoon, Fancys Pond, and lies in front of the embayment of Smith Cove (Fig. 7). The upper shoreface consists of thin sand over a cobble-boulder substrate. The active beach is a steep, reflective, coarse gravel ridge with a crest 4.5 to 5.0 m above mean sea level (msl). Behind the active beach is a higher, lichen-covered beach ridge (Fig. 8) and a series of gravel beach ridges which descend to about 0.5 m above msl (Fig. 9). The base of a 0.25 m-thick peat layer overlying the backbarrier ridges is dated at 110±70 years BP (GSC-5138).

Although the lowest beach ridges at Fancys Point have been modified by man, there is sufficient evidence to postulate the evolution of the system during the past 1000 years or so. In an early phase (Fig. 10a), a gravel barrier is thought to have linked Smiths Red Heads with the headland to the south. The crest elevation of this oldest ridge was about 0.5 m above present msl. Assuming conservatively that the ridge formed 2.5 m above the contemporaneous sea level, then (based on Fig. 2a) it has an age of about 1 ka; if it formed higher than 2.5 m above former msl, it is older. At this stage, the drumlin at Fancys Point (Fig. 10a) was trimmed by wave action. A period of progradation ensued, resulting in an arcuate series of beach ridges (Figs. 7, 8, 10b). The source of the sediment is unknown — it may have resulted from the breakdown of another barrier system, possibly a barrier linking Barren Island (Fig. 6) to the mainland, or it may have been coastal bluffs located updrift of the barrier. Figure 10c shows the situation today. The active beach has built to a much higher crest elevation and has partially cannibalised the older ridges, especially at the north end where the submerged landward ridges are truncated by the present barrier (Fig. 7).

From the example of Fancys Point barrier and similar sites across Atlantic Canada, it is clear that rising sea level does not cause universal coastal retreat on a formerly glaciated coastline. Progradation can occur where pulses of sediment are released into the littoral system, either as a new glacial source is uncovered or as earlier barrier systems break down and shed sediment landward (see the example of Story Head — Fig. 11). Dwindling sediment supply results in cannibalisation of the prograded deposits by slow retreat of the frontal storm beach, which usually shows a growth in crest height.

The nature of estuarine sedimentation and the development of beaches and barriers along the outer coast are intimately related. Porters Lake (Fig. 12), which has a severely restricted connection with the ocean at the present time, has undergone a number of changes, from freshwater lake to estuary, to freshwater lake, to estuary again, over the past 2 ka. The transitions from freshwater to estuarine conditions have resulted in each case from rising relative sea level over-

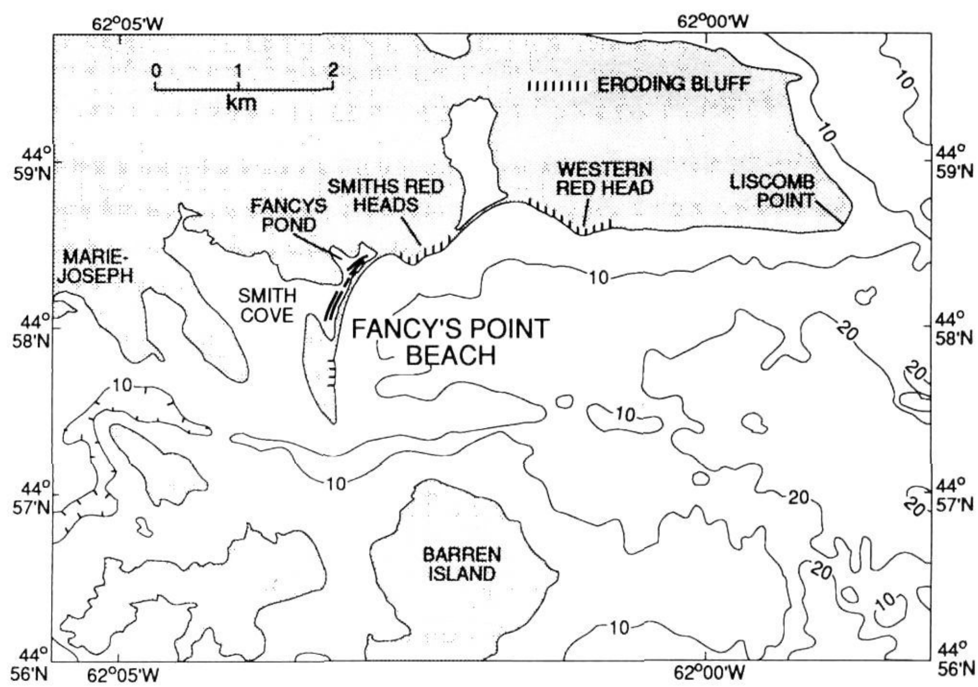

FIGURE 6. Fancys Point barrier, with eroding till bluffs along nearby shorelines to east and south (hachures). Bathymetry is in metres below chart datum (after Canadian Hydrographic Service, chart 4234).

Cordon littoral de Fancys Point avec des falaises en voie d'érosion le long des rivages avoisinants à l'est et au sud (hachures). La bathymétrie est en mètres (Service hydrographique du Canada, carte n° 4234).

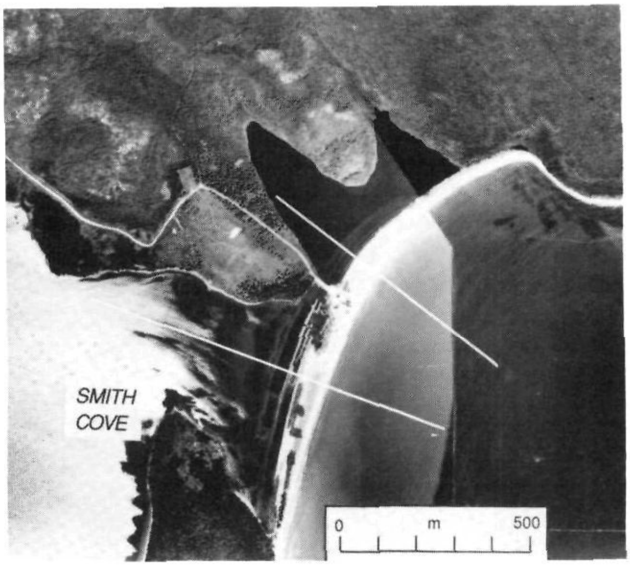

FIGURE 7. Vertical air photograph of the gravel barrier at Fancys Point, showing the locations of the two cross-shore profile lines illustrated in Figure 9. North is towards the top (from LRIS, Amherst photographs A80301-30 and 31, July 1980).

Photographie aérienne du cordon de gravier de Fancys Point montrant l'emplacement des deux profils illustrés à la figure 9 (LRIS, Amherst, photos nos A80301-30 et 31, juillet 1980).

FIGURE 8. Ground view looking southwest along the barrier crest, north line, Fancys Point, 17 June 1991.

Vue vers le sud-ouest le long de la crête du cordon, à Fancys Point, le 17 juin 1991.

topping sills at the seaward margin of the lake, initially *ca.* 2000 years ago and then about 1500 years later (Laidler, 1990). The intervening reversion to freshwater conditions resulted from the growth of Lawrencetown Beach, forming a barrier across the former estuary entrance (Oakey, 1985).

Some estuaries with narrow seaward sections have single tidal channels defined by prominent levees (Fig. 13). In others with broad entrances, such as Chezzetcook Inlet (Fig. 11), waves can propagate more easily into the outer part of the estuary. Some estuaries contain two or more sub-basins and the rates and processes of sedimentation vary between them (Honig, 1987; Carter *et al.*, 1989; Laidler, 1990). For Chezzetcook Inlet, Orford *et al.* (1991b) have proposed a four part sub-division: (1) an upper-estuarine zone representing the leading edge of the transgression and dominated by terrestrial infilling (Scott, 1980); (2) an upper-middle estuarine zone with channel levees, mud deposition, and salt-marsh accretion; (3) a lower-middle estuarine zone with flood-delta progradation and infilling of intervening embayments (Fig. 14a); and (4) a lower estuarine zone (the bay mouth), affected by the leading edge of the transgressive erosional front and containing partially eroded (over-run) remnants of flood-delta and other estuarine facies (Fig. 14b; Fig. 9 of Carter *et al.*, 1989).

In Lawrencetown Lake (Fig. 12), which has a narrow tidal-channel inlet, the sequence of Holocene deposits includes estuarine muds, tidal channel sands, flood-delta sands, and distal sand sheets, ranging from a few hundred to about 3000 years in age (Honig, 1987; Boyd and Honig, 1992). A number of these older units were associated with tidal exchange through a channel under the present west end of Lawrencetown Beach, predating the initiation of the present tidal inlet.

As this illustrates, estuarine sedimentation, particularly in the lower estuary, is intimately linked with the development and breakdown of beaches and barriers along the outer coast. We have speculated elsewhere (Forbes *et al.*, 1990) that large sandy beach systems such as Martinique Beach (Figs. 11 and 14 b) are initiated in a protected lower estuarine setting. Once initiated in the estuaries, the barriers later emerge at the outer coast as sea-level rise facilitates landward translation of the transgressive front.

COASTAL CHANGES THIS CENTURY

Changes in the coastline during this century have been documented at a number of sites in the province (*cf.* Cameron, 1965; Owens, 1971; Bowen *et al.*, 1975; Boyd and Bowen, 1983; Taylor *et al.*, 1985). Most change results from natural processes, but change at some sites has been precipitated by human intervention. For example, progradation at Waterside Beach (Pictou County) resulted from the construction in 1922 of a causeway to Caribou Island, while the near complete destruction of Silver Sands Beach at Cow Bay (Halifax County) was triggered by beach mining (Taylor *et al.*, 1985).

During the early part of the 20th century, ground surveys of shore erosion along Carboniferous rock cliffs in eastern Cape Breton Island were reported by Johnson (1925). Mean retreat rates at three sites were 2.6 m/a (1885-1900), 1.4 m/a (1907-1914) and 0.4-0.9 m/a (1907-1919).

Along the South and Eastern shores of Nova Scotia, rates of bluff-top retreat measured from air photos varied from 0.25 m/a in sheltered bays to 1.2-2.1 m/a at exposed headlands (Piper *et al.* 1986). Between 1981 and 1991 a network of sites around mainland Nova Scotia were monitored and resurveyed for both bluff top- and bluff-face erosion (Taylor *et al.*, 1985). These surveys, together with short-term studies by the Nova Scotia Department of Environment (1982) along the Minas Basin and by Boyd and Bowen (1983) along the

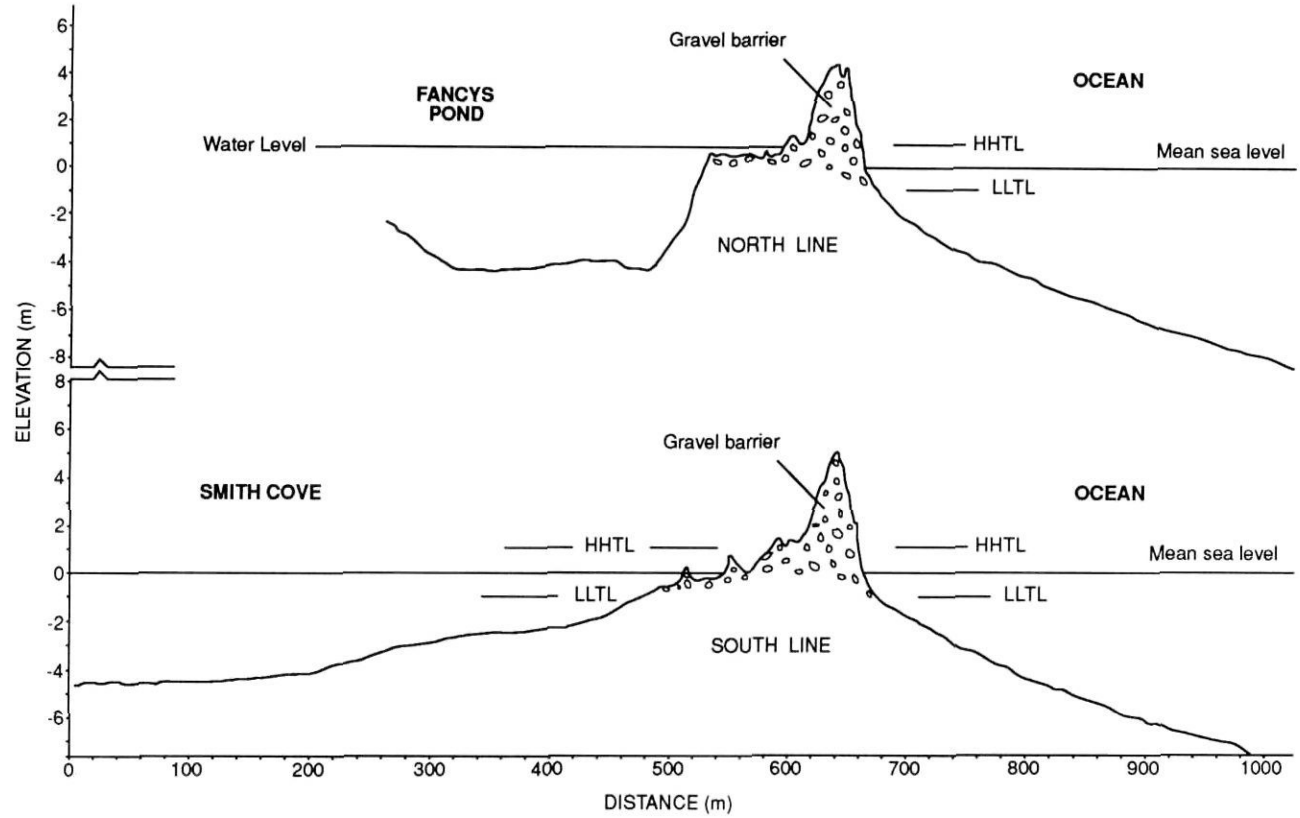

FIGURE 9. Surveyed profile lines across Fancys Point barrier (see Fig. 7 for locations). The north line shows two high beach ridges fronting older and lower ridges that terminate abruptly landward in Fancys Pond. The south line shows a single high beach ridge, also with lower ridges behind. The swales between the submerged backbarrier beach ridges have been artificially deepened for eel-breeding ponds. The gently shelving profile in Smith Cove may represent an old flood delta or a subaqueous barrier platform.

Profils au travers du cordon de Fancys Point (emplacement à la fig. 7). La ligne du nord montre deux levées de plage faisant front à des levées plus anciennes et plus basses qui se terminent abruptement dans le Fancys Pond. La ligne du sud montre une unique levée de plage élevée, avec derrière des levées plus basses. Les dépressions entre les levées de plage submergées ont été surcreusées pour la pisciculture des anguilles. Le profil doux vers le Smith Cove pourrait représenter un ancien delta d'inondation ou une plate-forme sous-marine.

Eastern Shore, provide a representative set of recent retreat rates for bluffs. Typical rates of bluff-top retreat were 0.2 to 0.4 m/a, but 0.6 m/a at more exposed sites (Fig. 15). During extreme storms, retreats of 1 to 12 m have been observed at exposed headlands (Newman, 1971; Boyd and Bowen, 1983).

However, these estimates should be interpreted with caution. Bluff-top retreat is extremely variable. Individual slumps often extend only a few metres along the cliff. Furthermore, bluff erosion is the result of a complex interaction between subaerial slope processes and marine effects, primarily wave attack. Storms accompanied by heavy precipitation can induce rapid erosion by surface runoff, groundwater percolation, and storm waves. However, as boulders and other coarse debris accumulate at the base of the cliff, wave energy is dissipated. In some cases, the boulder frame is sufficient to provide protection against all but extreme wave attack (Carter *et al.*, 1990a), and active erosion of the bluff can be reduced or halted. At a headland at Lawrencetown Beach (Fig. 12) erosion decreased from 0.4 m/a to 0.1 m/a during the 1980s. During extreme storm events, such as the Ground Hog Day storm of 1976, stable, vegetated bluffs can be reactivated (Grant, 1976).

Models of marine transgression through drumlin fields (Wang and Piper, 1982; Boyd *et al.*, 1987) have postulated barrier-beach sedimentation cycles based on the cyclic erosion and depletion of drumlin deposits as sea level rises. It was postulated that retreat would be rapid when a drumlin headland was initially attacked by waves (Forbes and Taylor, 1987). Recent field observations have confirmed this hypothesis and provided measurements of initial rapid retreat rates. The western headland of Chezzetcook Inlet (Fig. 11) was recently exposed to wave attack when the barrier beach in front of it was pushed landward onto the face of the drumlin in the early 1980s (Fig. 6 of Forbes *et al.*, 1990). Rates of retreat along the drumlin face since 1988 have averaged 5.4 m/a and have been as high as 7.6 m/a (Fig. 15).

Field observations of the Nova Scotia coast in the early part of the century by Goldthwait (1924) and Johnson (1925), supplemented by observations from sequential aerial photography (Owens, 1971; Forbes *et al.*, 1990, 1991b) and field observations later in the century by Bowen *et al.* (1975), Taylor *et al.* (1985), Shaw *et al.* (1990) and others, have documented progressive and often abrupt changes in coastal configuration and stability. A prime example is the collapse of Cadden Beach, on the South Shore. Before 1927 it was an

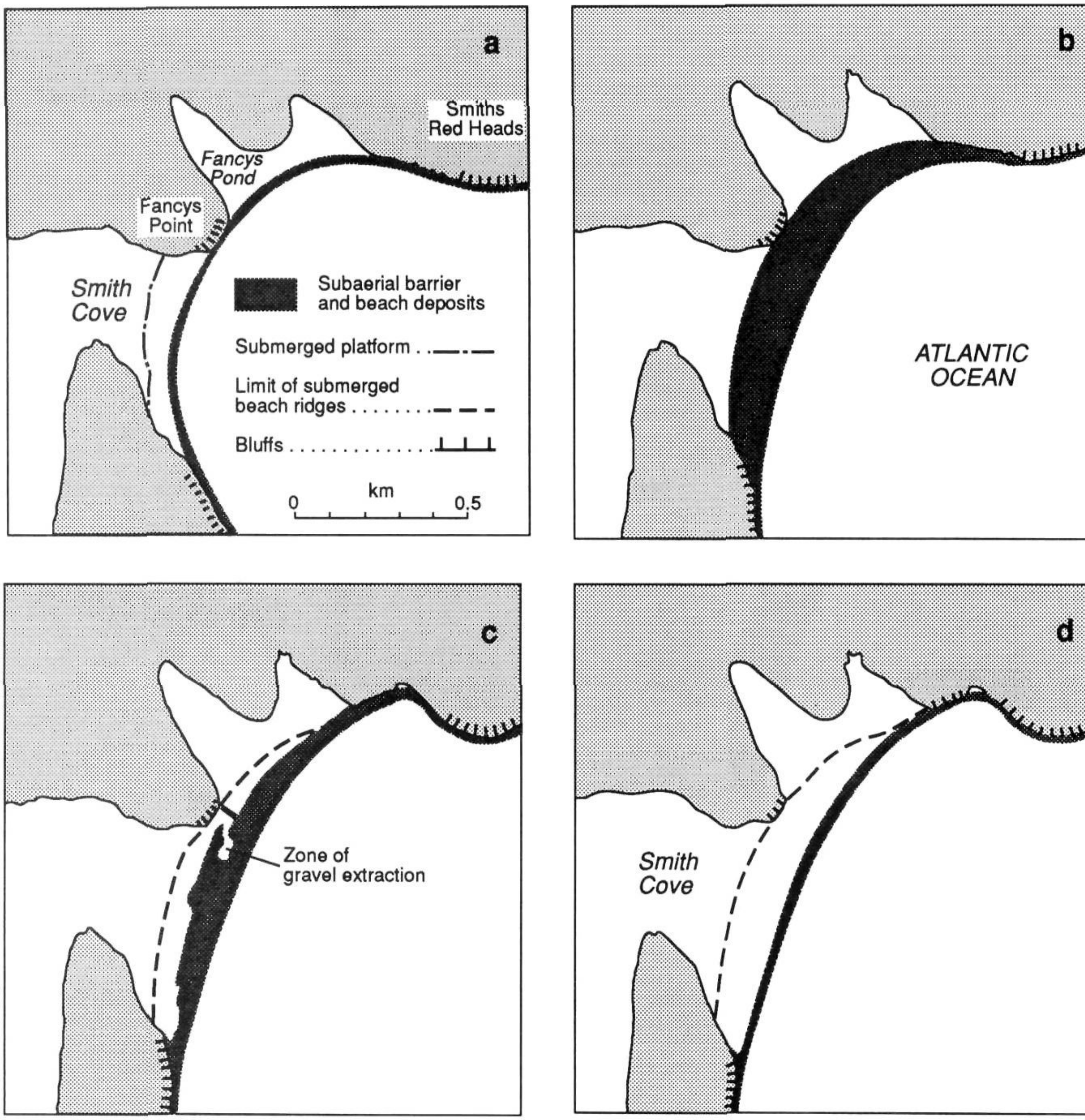

FIGURE 10. Postulated schematic development of Fancys Point barrier: a) an early single-ridge barrier; b) influx of sediment results in a prograded beachridge plain; c) present: sea-level rise has submerged the backbarrier ridges and the seaward edge of the barrier has retreated landward; d) future: in the case of a sea-level rise of 1 m over the next century the backbarrier ridges will be submerged and the main barrier will experience some landward retreat.

Schéma de l'évolution du cordon littoral de Fancys Point: a) cordon à crête unique en début de formation: b)progradation jusqu'à la formation d'une plaine littorale; c) présentement, la hausse du niveau marin a submergé les crêtes arrières et l'avant-cordon a reculé vers la terre; d) dans l'avenir, avec une hausse du niveau marin de 1 m au cours du prochain siècle, les crêtes arrières seront submergées et le cordon principal reculera vers l'intérieur.

extensive sand barrier fronting a large lagoon. By the mid 1970s, however, following at least two major failures and the reestablishment of tidal channels, the barrier had migrated landward and flood-tide deposits had infilled the lagoon (Bowen *et al.*, 1975, p. 54).

One of the best examples of extreme contrast in gravel barrier evolution comes from recent observations at Story Head and Long Beach (Figs. 11,12,16,17) on the Eastern Shore (Carter *et al.*, 1990c; Forbes *et al.*, 1990, 1991b). The Story Head barrier, at the mouth of Chezzetcook Inlet, is a low ridge (3 m above msl), composed of poorly sorted sand and gravel (Fig. 16a). It is overwashed several times per year. In the 1940s, the barrier was situated much farther seaward and linked Story Head to a now-vanished drumlin. Between 1954

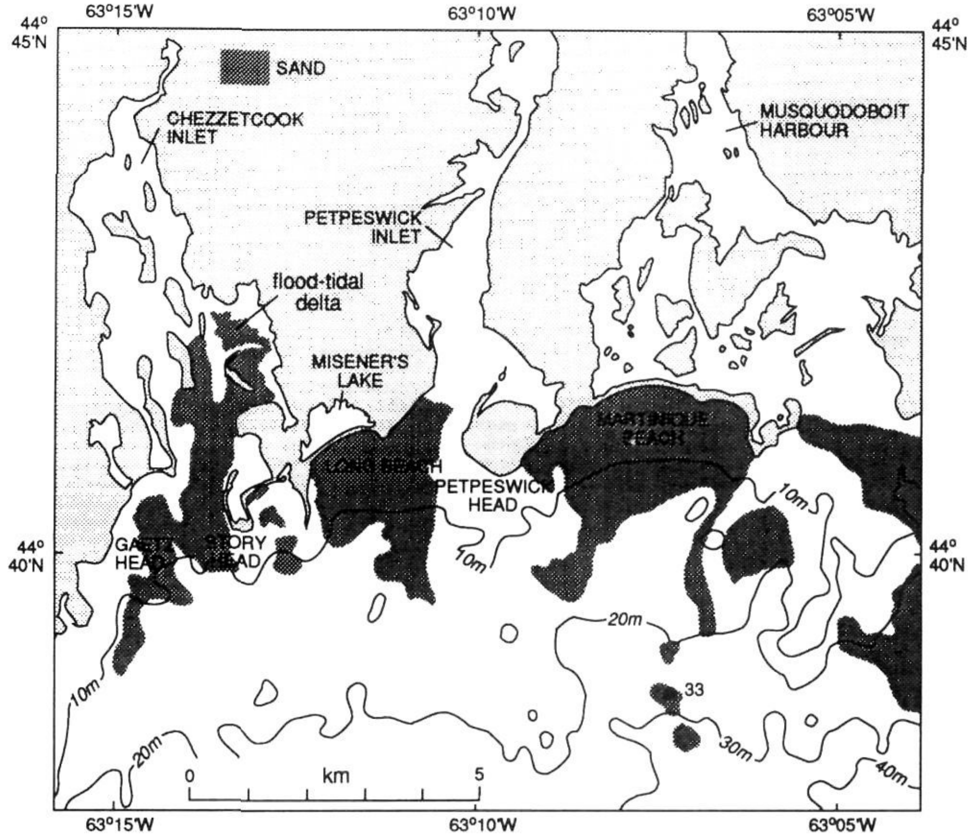

FIGURE 11. Location of the Story Head and Long Beach barriers, at the mouth of Chezzetcook Inlet, Eastern Shore. The point labelled 33, seaward of Martinique Beach, represents the location of a core in which salt-marsh peat with a radiocarbon age of 7500±120 years (index point 5 in Appendix I; GX-13972, Forbes *et al.*, 1988) was sampled 34 m below present sea level. Also shown is the distribution of sand (stipple) on the inner shelf and in Chezzetcook Inlet (extent of sand in other estuaries is omitted).

Localisation des cordons littoraux de Story Head et de Long Beach, à l'embouchure du Chezzetcook Inlet, Eastern Shore. Le point 33, au large de Martinique Beach, donne la localisation d'un sondage où l'on a daté une tourbe de marais salant à 7500±120 BP (repère 5 en appendice; GX-13972, Forbes et al., *1988). On voit également la répartition du sable (grisé) sur le plateau intérieur et dans le Chezzetcook Inlet (mais n'est pas donnée dans les autres estuaires).*

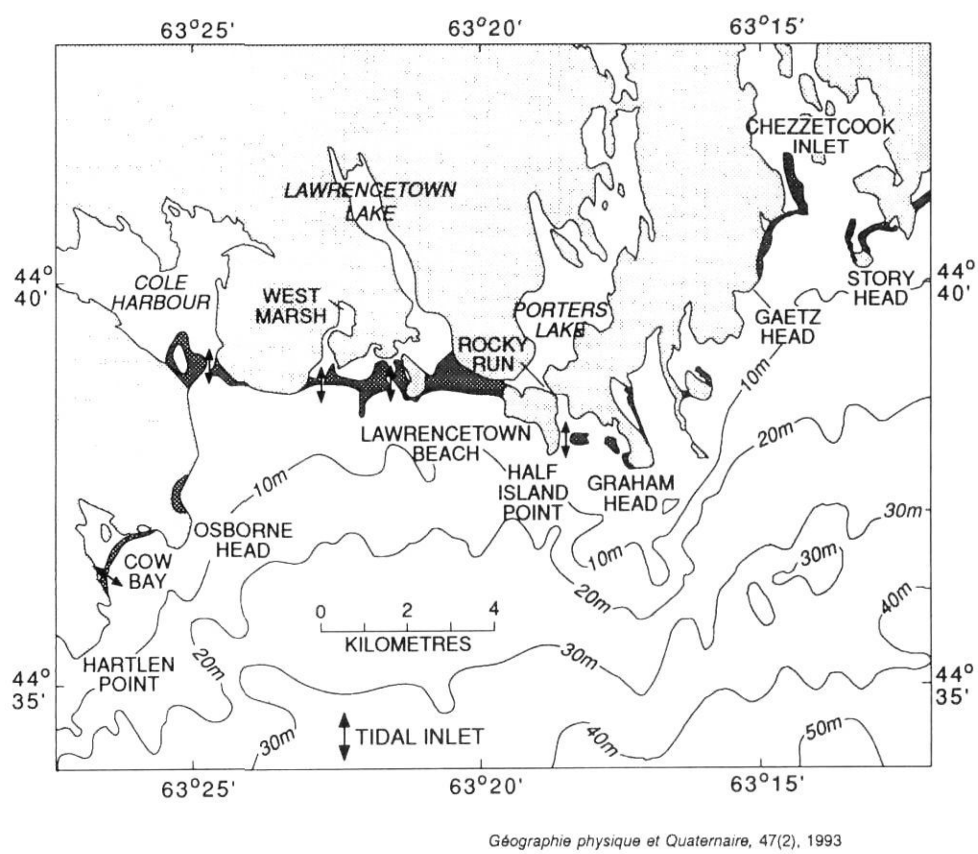

FIGURE 12. Map showing the location of estuaries and barrier systems (stippled) west of Chezzetcook Inlet.

Localisation des estuaires et des cordons littoraux (grisé), à l'ouest du Chezzetcook Inlet.

and 1982, the barrier migrated landward at an average rate of 8 m/a (Fig. 17), abandoning gravel deposits on the shoreface (Forbes *et al.*, 1991b). Orford *et al.* (1991a) argued that the migration rate of the seaward barrier shoreline had been proportional to both the annual rate and the 5-year smoothed rate of sea-level change.

Long Beach, located 1 km east of Story Head beach (Figs. 11, 16b), is a high gravel storm ridge rising to 4 m above msl, enclosing a freshwater pond. It has a steep beachface and well-developed cross-beach sediment size and shape sorting. The barrier appears to rest on bedrock. Gravel on the lower beachface is covered by a sandy apron, part of which is exposed at low tide. The beach has remained virtually in the same position for the past 7 years or more. Cobbles on the backbarrier slope are partially colonised by lichens and show little sign of recent washover sedimentation. Minor reworking of the barrier crest occurred during two major storms in the past 12 months, and local residents report that the last major overwash activity took place during a storm in 1975.

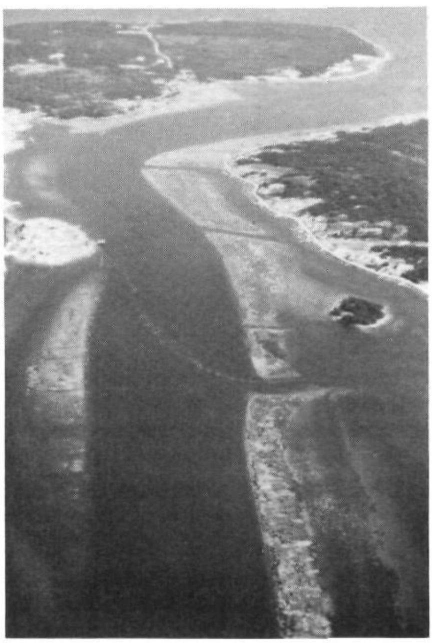

FIGURE 13. Oblique air photograph showing a central tidal channel with well-developed levees, Jeddore Harbour (30 March 1990).

Photo aérienne oblique montrant le chenal de marée central et ses levées latérales bien marquées, Jeddore Harbour (30 mars 1990).

Why the difference in stability between the two adjoining beaches? The overwashing and migration of the Story Head barrier has not been caused by higher levels of wave energy than at Long Beach — in the course of our surveys we have always noted much higher breaking waves at the latter. In fact, the stretching of the Story Head barrier would have caused wave energy levels to drop as it migrated.

Forbes *et al.* (1991b) have argued that the Story Head barrier was irreversibly modified during one or more years of exceptional storm activity, and that rising sea level played a role in its migration. They also noted that the Story Head barrier had migrated across backbarrier lagoonal deposits of mud with sand lenses, up to 4.5 m thick. Recent waterjet drilling and seismic surveys have established that the deposits are at least 10 m thick (possibly as much as 17 m) immediately behind the middle of the barrier. These deposits may be the key to the rapid migration of Story Head barrier. They provide a platform across which the barrier can migrate, but more importantly, it may be the quarrying of these sediments by wave action which helps maintain rapid migration. They may be susceptible to erosion during wave conditions below the threshold for barrier overwashing, and would be advected from the immediate shoreface in suspension.

By contrast, Long Beach and other barriers such as Fancys Point are fronted by coarser sediment which cannot be dispersed out of the immediate coastal compartment. This demonstrates that a close examination of both the subaerial and subaqueous architecture of barriers may provide answers to the problem of differential beach retreat.

During the past 30 to 50 years large-scale changes have been observed in some estuaries. In Chezzetcook Inlet, flood-delta deposits expanded by more than 230 000 m^2

FIGURE 14. a) Expanding spits and flood delta at Red Island, Chezzetcook Inlet (30 March 1990); b) flood delta deposits overrun by barrier migration, Martinique Beach, looking seaward (30 March 1990).

a) Flèche en voie d'expansion et delta d'inondation à Red Island, Chezzetcook Inlet (30 mars 1990); b) dépôts de delta d'inondation recouverts par le cordon littoral en migration, Martinique Beach, vue vers le large (30 mars 1990).

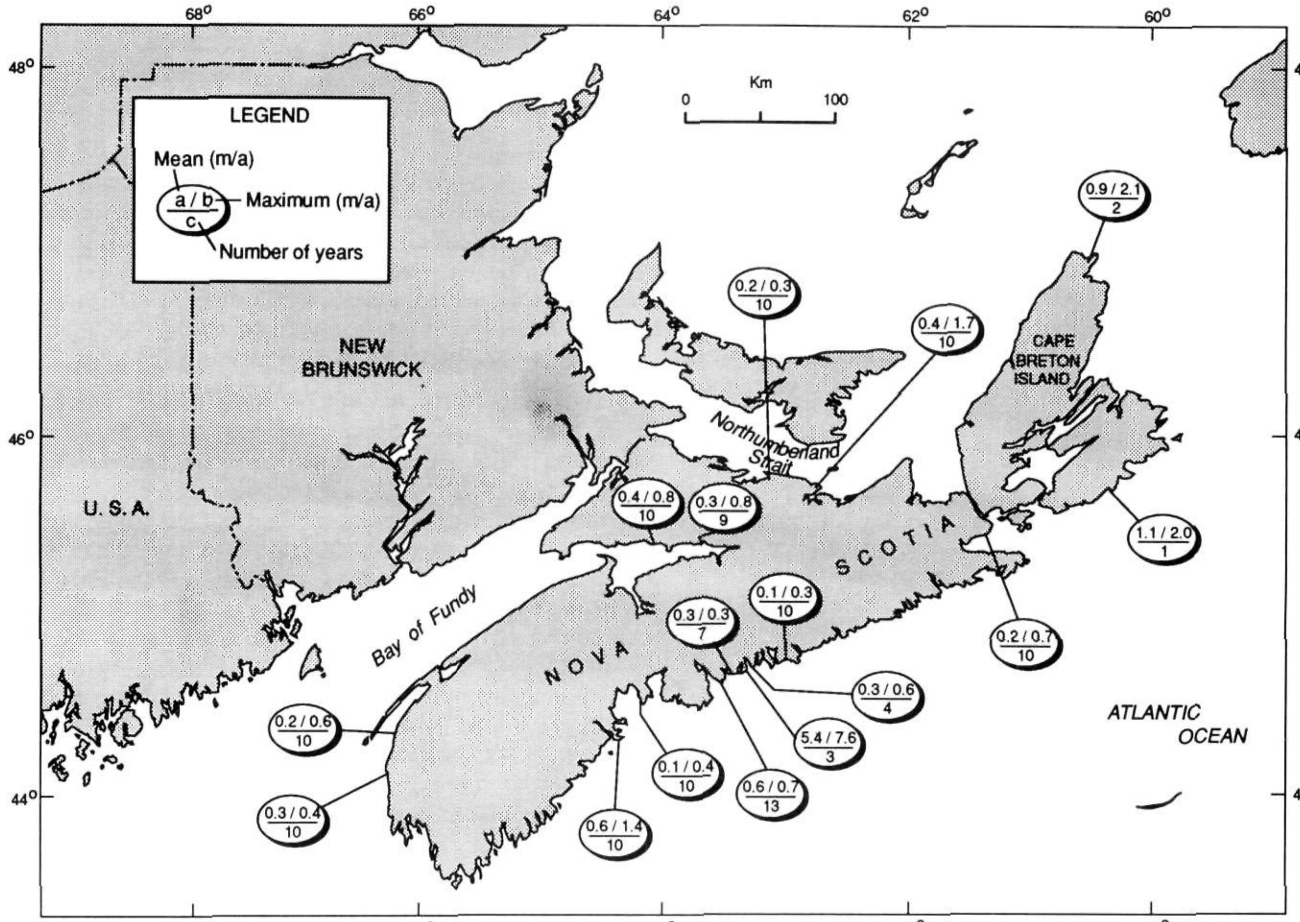

FIGURE 15. Mean and maximum rates of cliff-top retreat in unconsolidated bluffs at selected sites in Nova Scotia. The compilation is based on repetitive ground surveys between 1980 and 1991.

Taux moyens et maximaux du recul de la partie sommitale des falaises non consolidées à certains sites de la Nouvelle-Écosse. Compilation fondée sur de nombreux levés de terrain faits entre 1980 et 1991.

between 1954 and 1982 (Fig. 14 a; Fig. 5 of Carter *et al.*, 1990b). Despite the high rate of relative sea-level rise during the past 50 years (Fig. 3), salt-marsh deposits have also expanded in Chezzetcook Inlet since the 1940s (Scott, 1980). This process of rapid estuarine sedimentation can be directly related to the high rates of erosion at the outer coast (Forbes *et al.*, 1990, 1991b; Carter *et al.*, 1990b) and associated dispersal of sand and mud into the estuary. In other words, just as beaches and barriers along the outer coast may respond to high sediment supply by progradation, even under rising sea levels, so too the sedimentary and ecological response of estuarine systems to sea-level rise is strongly dependent on sediment supply. Coastal erosion and resulting sediment production may be accelerated under higher mean water levels. Under favourable circumstances, supply of sediment to nearby estuaries may increase at the same time, favouring maintenance or expansion of salt-marsh habitat despite the rise in sea level.

FUTURE IMPACTS

Does the spectrum of coastal changes which we have discussed provide useful analogs for the impact of accelerated sea-level rise of the magnitude described by the IPCC? The answer is a tentative yes. During the past several thousand years, while sea level was rising at mean rates of 0.2 m/century, the coastal response has apparently been cyclical: barrier systems have undergone phases of progradation, stability, and retreat as adjacent estuaries accumulated fine sediments. It could be argued that cyclic phases of progradation, stability and retreat will continue at an accelerated rate, so that the whole coastline will retreat faster, possibly at gross rates of 1-2 m/a as estimated from changes in paleo-shoreline positions observed during similar rates of rise in the past.

Changes at a specific coastal location will depend to a large extent on the stage of the present shoreline within the cycle of coastal development and on the history of that coastal segment during the late Holocene. Where shores have experienced pronounced progradation, for example at Lawrencetown Beach, a relatively large volume of sediment will be available for incorporation into future beaches and barriers. In the short term, parts of barriers may be submerged. At Fancys Point, for example, a sea-level rise of slightly over 1 m will submerge much of the low, old beach ridges behind the active beach (Fig. 10d); the barrier will become a single

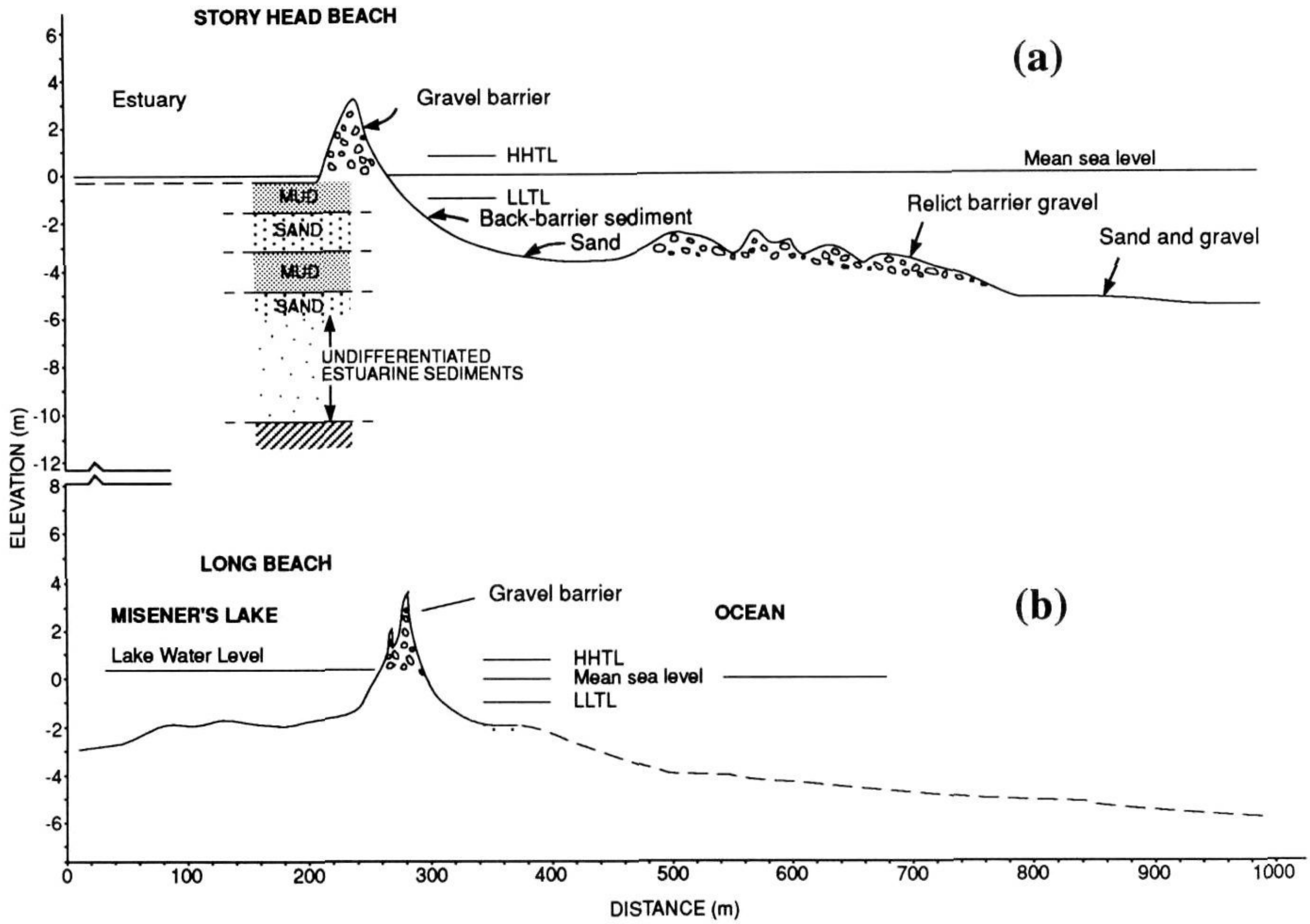

FIGURE 16. Profiles across barriers at (a) Story Head (b) Long Beach. At Story Head the barrier is overwashed a number of times each year and has migrated landward at an average rate of 8 m/a since 1954 (Forbes *et al.*, 1991b); the Long Beach barrier has remained stationary over the same period.

Profils des cordons littoraux à Story Head Beach (a) et à Long Beach (b). À Story Head Beach, le cordon est submergé plusieurs fois par année: il migre vers l'intérieur à un taux moyen de 8 m/a depuis 1954 (Forbes et al., *1991b); le cordon de Long Beach est demeuré stable au cours de la même période.*

ridge similar to Long Beach. Eventually, however, the large amount of gravel in the old ridges may be incorporated into a new barrier/beach system or may be overstepped (Forbes *et al.*, 1991b).

Where beaches have been in a retreat phase because of sediment depletion, and where no new local source of beach sediment exists, or where the backshore environment is extremely deep, they are apt to continue landward retreat or even be destroyed. Rapid beach retreat at some sites may have effects in adjacent coastal environments. At Story Head, for example, the beach retreat observed today cannot be extrapolated indefinitely, because the link with the drumlin headland (Fig. 17) has already been severed. Disengaged from this anchor point, the barrier may now undergo a transformation into a drift-aligned feature anchored to the mainland. The entire system of gravel barriers at the mouth of Chezzetcook Inlet is in the process of being reorganised. This will expose formerly quiescent backbarrier environments to wave attack. Fine sediment remobilised due to retreat of the muddy shoreface exposed in front of the barrier will be advected either to offshore basins (Piper *et al.*, 1986) or to inner-estuary salt-marsh and intertidal environments, enabling the latter to keep pace with sea-level rise. Coarse material liberated from the retreating prism of estuarine sediment will contribute to the formation of new flood-delta and beach deposits within Chezzetcook Inlet, in the manner described by Carter et *al*. (1990b).

The release of sediment into the littoral system as a result of the erosion of till bluffs will be an important supplement to sediment conserved during the transgression — both sources will supply new barriers and beaches. Bluffs will retreat at variable rates — initial wave attack of newly exposed drumlins will result in rapid retreat (up to 7 m/a or more) until boulder frames or gravel beaches accumulate, or bedrock platforms are exposed seaward; rates of recession will then diminish to less than 1 m/a.

However, we must be cautious in making these sorts of predictions, for they rest on the assumption that sea-level rise during the Holocene has been smooth. Van de Plassche (1991) and Thomas and Varekamp (1991) claimed that late Holocene sea-level rise was stepped, so that alternating periods of greater and lesser relative sea-level rise were embedded within an overall submergence. Tanner (1992) found

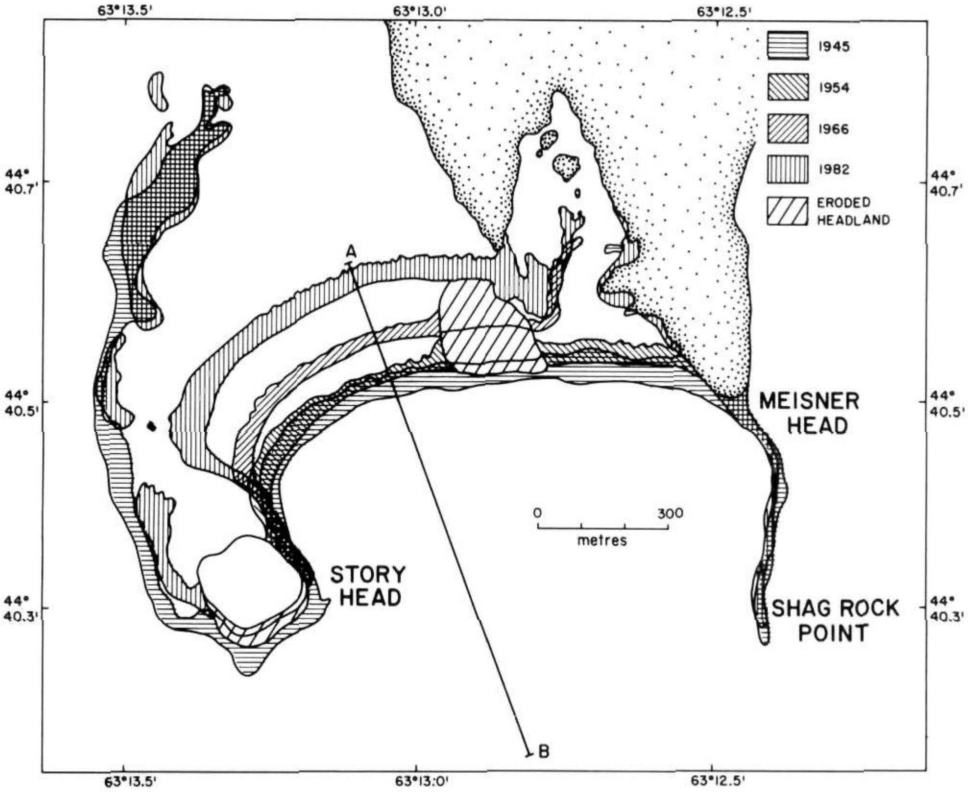

FIGURE 17. Landward migration of Story Head barrier since 1945 (from Forbes *et al.*, 1991b). A-B: approximate line of profile in Figure 16.

Migration vers l'intérieur du cordon de Story Head Beach depuis 1945 (Forbes et al., 1991b). AB-profil de la figure 16.

evidence in the Gulf of Mexico of three drops and two rises of sea level in the past 3.0-3.5 ka, with amplitudes of 1-2 m. He suggested that the most recent oscillation corresponded with the Little Ice Age and that the current sea-level rise is the recovery from a lowstand during that period. Closer to the study area, the Holocene transgression in the Tantramar marshes of New Brunswick is thought to have been interrupted at least 4 times during the past 3000 years (Grant, 1985).

If the late Holocene transgression was stepped, it is conceivable that cycles of barrier formation and breakdown have been controlled by fluctuations in the rate of sea-level rise (Orford *et al.*, 1991a). Perhaps the coastal progradation at some locations, as described in this paper, occurred only during phases of slow sea-level rise, whereas the rapid changes observed in this century are characteristic of phases of rapid sea-level rise such as the present (van de Plassche, 1991; Tanner, 1992). In this case, coastal erosion and retreat may become pervasive if predictions of a global rise in sea level are correct.

The uncertainty about future impacts could be lessened by directing our research towards two goals. The first is a better understanding of the age, morphodynamics, and sedimentary structure of estuarine and barrier systems. Was, for example, barrier progradation linked to cycles of sediment supply, or was progradation more common at certain periods, and did these correspond with minor regressions? These questions are linked to a second research objective: to determine the pattern of relative sea-level rise during the past several thousand years in Atlantic Canada, to a resolution of tens of centimetres and centuries. When progress has been made towards attaining these goals we will be able to make even better use of the geological record to predict future changes on the coast.

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APPENDIX I

RELATIVE SEA-LEVEL INDEX POINTS, AS SHOWN ON FIGURE 2

Many of the dates are on samples obtained during cruise 87-042, CSS *Dawson* (Forbes *et al.*, 1988). Relevant pollen data are from an unpublished AGC report by J. Shaw (pollen sum = arboreal pollen), and foraminiferal data from Honig (1988). RIDDL dates were obtained with the AMS method, and where shell was dated the fractionation correction is to a base of $\delta^{13}C = 0‰$, equivalent to a 410 year reservoir correction; for RIDDL-1078 the base was $\delta^{13}C = -25‰$. TO dates are AMS dates with a reservoir correction of 410 years in the case of shell material; TO dates on other organic materials are corrected to a base of $\delta^{13}C = -25‰$. However, GX and Beta (conventional dates) shell dates are normalised to a base of $\delta^{13}C = -25‰$. They are given here as reported, but an additional date, adjusted by 410 years, is also given, and is used to constrain the sea-level curve (msl = mean sea level; hhw = higher high water).

1. *Spisula polynyma* shell (non-estuarine shallow water — subtidal to intertidal) dated at 10,980±120 (RIDDL-1082), from 5.44 m in core 87042-039, water depth 39.5 m. Corrected for tides the sample is 44.9 m below msl. This sample was contained in sandy mud, in a zone of low pollen and spore concentrations. Arboreal pollen levels were low and sedge levels up to 30%. The sediment was barren of foraminifera.

2. *Polinices heros* shell (typically shallow water — subtidal to intertidal), dated at 9240±130 (GX-13974), contained in dark olive grey clayey silt at 3.84 m in core 87042-039, water depth 39.5 m. After subtracting 410 yr for the reservoir effect the date is 8830±130 BP. Adjusted for tides the sample is 43.3 m below msl. The sample was at a pollen zone boundary, with a herb/shrub assemblage below, and an overlying zone dominated by *Pinus* and *Betula*, with upwards increasing amounts of *Tsuga*. The foraminiferal assemblage was a restricted calcareous type dominated by *Elphidium excavatum* and *Buccella frigida*.

3. Freshwater detritus peat, dated at 8800±390 (GX-13973), from 2.72 m in core 87042-030, water depth 18.0 m. Compensated for tides, the sample is 19.9 m below msl. The 0.24 m thick peat layer had relatively high levels of *Nymphaea* and *Nuphar* pollen, in an early Holocene assemblage. It contained freshwater diatoms, and no foraminifera. Above the sharp (erosional) upper boundary was dark olive grey clayey silt with a mixed estuarine/marine foraminiferal assemblage. The underlying silty sand was barren.

4. *Macoma balthica* shell, dated at 7680±130 (RIDDL-1081) at 2.59 m in core 87042-039, water depth 39.5 m. Sample depth compensated for tides is 42.0 m below msl. The sample was contained in dark olive grey clayey silt with a Holocene pollen assemblage dominated by *Pinus*, with upward increasing levels of *Tsuga*. An estuarine foraminiferal assemblage was sampled slightly above, at 2.44 m.

5. Salt-marsh peat, dated at 7500±120 (GX-13972), from 4.30 m in core 87042-033, water depth 30.0 m. Compensated for tides the sample is 33.7 m below msl. The peat layer was about 20 cm thick, and was underlain by grey silty clay. It contained an early Holocene arboreal pollen assemblage. *Alnus* occurred in relatively high amounts, and there were small peaks in Gramineae and Chenopodiaceae pollen. The foraminiferal assemblage, comprising 96% *Trochammina macrescens* and 4% *T. comprimata*, was indicative of a salt-marsh environment. Overlying silty clay contained estuarine foraminiferal assemblages, and the underlying silty clay was barren.

6. Total organic carbon date of 7425±255 (GX-10027) on muddy sand with organic matter from 0.42-0.53 m in core 83-010-2 (water depth 26 m), off Cole Harbour, N.S. (Hall, 1985).

7. *Macoma balthica* shell, dated at 7280±100 (RIDDL-1080), from 3.38 m in core 87042-033, water depth 30.0 m, tide-compensated sample depth is 32.8 m below msl. The shell was in dark grey silty clay with a typical early Holocene pollen assemblage, dominated by *Pinus*, followed by *Tsuga, Picea, Quercus* and *Betula*, in descending order of importance. The estuarine foraminiferal assemblage contained *T. macrescens, T. squamata, T. comprimata,* and *E. excavatum*, in descending order of abundance.

8. *Mytilus edulis* shell, dated at 7190±120 (RIDDL-1079), 2.24 m in core 87042-033, water depth 30.0 m, tide-compensated sample depth 31.7 m below msl. The shell was contained in dark grey silty clay, with pollen and foraminiferal assemblages as for sample 7 (above).

9. A total organic carbon date of 6790±80 (Beta-19587) on a grab sample of olive estuarine mud (8606001) from the wall of a seafloor depression off Martinique Beach, water depth 30 m. The mud contained a typical Holocene pollen assemblage, with *Pinus, Tsuga, Picea, Quercus, Betula,* in descending order of abundance, plus foraminifera and marine planktonic diatoms.

10. *Portlandia* sp. shell at 1.31 m depth in core 87042-010, from a water depth 27.8 m, tide-compensated sample depth 28.9 m below msl. The sample is dated at 6130±110 (RIDDL-1077) and was contained in green-grey silty clay with a middle Holocene pollen assemblage and an estuarine foraminifera fauna.

11. A total organic carbon date of 5830±230 (GX-6806) on dark brown marine mud from 3.09-3.13 m in core 79-011-01 (Miller *et al.*, 1982), water depth 60 m in Bedford Basin, near Halifax. It is plotted at 20 m depth in Figure 1, since it indicates a sea level of at least −20 m (sill depth).

12. Seaweed from 1.70 m depth in core 87042-030 (water depth 18.0 m, tide-compensated sample depth 18.8 m below msl), dated at 4240±130 (RIDDL-1078), and contained in 4 cm of interlaminated sand and silt in pebbly medium sand. The pollen assemblage indicated Holocene Zone C-3 while the foraminiferal assemblage was characteristic of a nearshore environment.

13. Total organic carbon date of 3220±150 (GX-11342) on salt-marsh peat from 3.97 m depth (~6 m below msl) in core 15, Lawrencetown Lake (Boyd and Honig, 1992).

14. Total organic carbon date of 2900±150 (GX-11343) on brackish mud from a depth of 5.10 m (6.8 m below msl) in core 9A, Lawrencetown Lake (Boyd and Honig, 1992).

15. Shell sample from flood-tidal delta sediments, 2.80 m depth (~3.7 m below msl) in core 7, Lawrencetown Lake, dated at 1990±130 (GX-11344), from Boyd and Honig (1992). Adjusted for a 410 yr reservoir effect the date becomes 1580±130 BP.

16. Shells from a flood-tidal channel deposit, dated at 1650±180 (GX-12250), from 4.05 m depth (3.9 m below msl) in core 16, Lawrencetown Lake (Boyd and Honig, 1992). The reservoir-corrected date is 1240±180 BP.

17. Shells contained in basin mud, dated at 1535±220 (GX-12251), from 3.17 m depth (~4.2 m below msl) in core 3, Lawrencetown Lake

(Boyd and Honig, 1992). The reservoir-corrected date is 1125±220 BP.

18. Shells from a flood-tidal delta deposit, dated at 815±70 (GX-12249), from 1.25 m depth (~2.5 m below msl) in core 7, Lawrencetown Lake, N.S. (Boyd and Honig, 1992). After correcting for reservoir effect the date is 405±70 BP.

19. Small wood fragment in salt-marsh peat at the former hhw level, dated at 6625±240 (GX-4594) from 11.85 m below sea level, core V, Chezzetcook Inlet (Scott, 1977a).

20. Small wood fragment from an intertidal — shallow subtidal deposit, approximately 5.00 m below sea level in core X, Chezzetcook Inlet, dated at 1940±140 (GX-4652) (Scott, 1977a).

21. Small wood fragment dated at 915±130 (GX-4825), from 2.70 m below sea level in core XIII, Chezzetcook Inlet (Scott, 1977a).

22. AMS date of 330±50 BP (TO-3172) on a *Spisula polynyma* fragment contained in silty fine sand of a flood-tidal delta, from 1.87 m depth (2.37 m below msl) in vibracore 88301-007, Chezzetcook Inlet.

23. Date of 1840±70 BP (Beta-51312) on *Spisula polynyma* fragments from 2.78 m depth (3.28 m below msl) in vibracore 88301-007, Chezzetcook Inlet. The shells were part of a shell hash, 0.08 m thick, contained in flood-tidal delta medium sand. The date is normalised to $\delta^{13}C = -25‰$. Compensated for a 410 yr reservoir effect it becomes 1430±70 BP.

24. AMS date of 1290±70 BP (TO-3164) on *Spisula polynyma* fragments contained in estuarine sand, from 1.50 m depth (2.10 m below msl) in vibracore 08704-004, immediately behind Story Head barrier, Chezzetcook Inlet. The sample was contained in sand.

25. AMS date of 1440±90 BP (TO-3163) on two valves of *Macoma balthica* and fragments of a juvenile gastropod, contained in estuarine sand at 1.97 m depth (2.57 m below msl) in vibracore 08704-004, behind Story Head barrier, Chezzetcook Inlet.

26. AMS date of 1500±70 BP (TO-3162) on *Spisula polynyma* fragments contained in estuarine sand at 2.12 m depth (2.72 m below msl) in vibracore 08704-004, immediately behind Story Head barrier, Chezzetcook Inlet.

27. AMS date of 1890±60 BP (TO-3156) on a twig contained in estuarine mud from 3.25 m depth (3.85 m below msl) in vibracore 08704-004, immediately behind Story Head barrier, Chezzetcook Inlet.